Benjamin W. Roberts
Christopher P. Thornton *Editors*

Archaeometallurgy in Global Perspective

Methods and Syntheses

Springer

Archaeometallurgy in Global Perspective

Benjamin W. Roberts • Christopher P. Thornton
Editors

Archaeometallurgy in Global Perspective

Methods and Syntheses

Springer

Editors
Benjamin W. Roberts
Department of Archaeology
Durham University
Durham
United Kingdom

Christopher P. Thornton
Asian Section
University of Pennsylvania Museum
of Archaeology & Anthropology
Philadelphia
Pennsylvania
USA

ISBN 978-1-4614-9016-6 (Hardcover)
ISBN 978-1-4614-9017-3 (eBook)
ISBN 978-1-4939-3357-0 (Softcover)
DOI 10.1007/978-1-4614-9017-3
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013954783

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Contents

Contributors

Natal'ya Batanina Reserve "Arkaim", Chelyabinsk, Russia

Peter Bray Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford, UK

S. Terry Childs Department of the Interior, Washington, USA

Antoine Courcier Institut de Recherche sur les ArchéoMATériaux, Belfort, France

Andrea Dolfini School of History, Classics and Archaeology, Newcastle University, Newcastle upon Tyne, United Kingdom

Roger Doonan Department of Archaeology, University of Sheffield, Sheffield, UK

Kathleen L. Ehrhardt Research and Collection Center, Illinois State Museum, Springfield, USA

Jonathan Golden Departments of Comparative Religion and Anthropology, Drew University, Madison, USA

Praveena Gullapalli Anthropology Department, Rhode Island College, Providence, USA

Elizabeth G. Hamilton University of Pennsylvania Museum, Philadelphia, USA

Bryan Hanks Department of Anthropology, University of Pittsburgh, Pittsburgh, USA

Andreas Hauptmann German Mining Museum, Bochum, Germany

Julia Heeb Department of Archaeology, University of Exeter, Devon, United Kingdom

Brett C. Hoffman Department of Anthropology, University of Wisconsin-Madison, Madison, USA

Dorothy Hosler Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, USA

Louise Iles University of York, Department of Archaeology, York, UK

James Johnson Department of Anthropology, University of Pittsburgh, Pittsburgh, USA

Tobias L. Kienlin Institut für Ur- und Frühgeschichte, Universität zu Köln, Köln, Germany

David Killick Department of Anthropology, University of Arizona, Tucson, USA

Elena Kupriyanova Scientific and Educational Centre for Research on the Problems of Nature and Man, Chelyabinsk State University, Russia

Heather Lechtman Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, USA

Joseph W. Lehner Cotsen Institute of Archaeology, University of California, Los Angeles, USA

Katheryn M. Linduff Department of Art History, University of Pittsburgh, Pittsburgh, USA

Marcos Martinón-Torres Institute of Archaeology, University College London, London, UK

Jianjun Mei Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing, Beijing, People's Republic of China

The Needham Research Institute, Cambridge, UK

Heather M.-L. Miller Anthropology Department, University of Toronto, Mississauga, Canada

Michael R. Notis Department of Materials Science and Engineering, Whitaker Laboratory, Lehigh University, Bethlehem, USA

Barbara S. Ottaway Department of Archaeology, University of Exeter, Devon, United Kingdom

Ernst Pernicka Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters, Abteilung für Jüngere Urgeschichte und Frühgeschichte, Schloß Hohentübingen, Eberhard-Karls-Universität Tübingen, Tübingen, Germany

Derek Pitman Department of Archaeology, University of Sheffield, Sheffield, UK

A. Mark Pollard Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford, UK

Thilo Rehren UCL Qatar, University College London, Doha, Qatar

Benjamin W. Roberts Department of Archaeology, Durham, UK

Deborah Schorsch Sherman Fairchild Center for Objects Conservation, The Metropolitan Museum of Art, NewYork, United States of America

David A. Scott Cotsen Institute of Archaeology, University of California Los Angeles, Los Angeles, USA

Thomas R. Stöllner Ruhr-Universität, Bochum, Germany

Deutsches Bergbau-Museum Bochum, Bochum, Germany

Christopher P. Thornton Asian Section, University of Pennsylvania Museum, Philadelphia, USA

Joyce C. White Asian Section, University of Pennsylvania Museum, Philadelphia, USA

K. Aslıhan Yener The Department of Archaeology and History of Art, Koç University, Sariyer, Turkey

Dmitry Zdanovich Scientific and Educational Centre for Research on the Problems of Nature and Man, Chelyabinsk State University, Russia

About the Editors

Benjamin W. Roberts is a specialist in the early metallurgy and later prehistoric archaeology of Europe. He was the Curator of the European Copper and Bronze Age collections at the British Museum between 2007 and 2012 and is now a Lecturer in Prehistoric Europe in the Department of Archaeology at Durham University, UK.

Christopher P. Thornton is a specialist in the ancient metallurgy of the Middle East, combining anthropological theory with archaeometrical analysis to understand the development and diffusion of metallurgical technologies throughout Eurasia. He is currently a Consulting Scholar of the University of Pennsylvania Museum, where he received his PhD in 2009, and the Lead Program Officer of research grants at the National Geographic Society.

Chapter 1
Introduction

Christopher P. Thornton and Benjamin W. Roberts

Introduction

In March 2008, a session was held at the Society of American Archaeology (SAA) conference in Vancouver, Canada, which focused on the emergence of metallurgy in the Old and New Worlds. Before this session, paper drafts had been circulated among the authors and posted on the SAA website, thereby allowing the session itself to be consumed with discussion of both a theoretical and practical nature. When we had originally organized this session and sent out invites, we envisioned gathering a group of cutting-edge researchers from every major archaeometallurgical region in the world, and sitting them all together in a small, quiet room to hash out important issues such as metallurgical terminology, the best ways to teach slag analysis to archaeologists, and whether the "origins of metallurgy" was still a valid research topic. This was what was supposed to happen.

What actually happened in March 2008 was that our small, quiet "electronic symposium" ended up being moved to one of the largest ballrooms available in the conference center. Over a hundred people joined us for what became a standing-room-only event, in which the authors sat in a line of chairs facing the audience, while we peppered them with "big brushstroke" questions. We asked them questions like: "Do you think metals were fundamental to the rise of elites and complex social hierarchies?" "Is there a case to be made for both indigenous and diffusionist viewpoints on the origins and spread of metallurgy?" "Can we use examples from the Old World and apply them to the New World, and vice-versa?" Much to their credit, our superb group of authors-*cum*-panelists handled the situation marvelously, answering our questions (and those posed by audience members)

C. P. Thornton (✉)
Asian Section, University of Pennsylvania Museum, 3260 South St,
Philadelphia, PA 19104, USA
e-mail: cpt2@sas.upenn.edu

B. W. Roberts
Department of Archaeology, South Road, Durham, DH1 3LE, UK
e-mail: benjamin.roberts@durham.ac.uk

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_1,

clearly while remembering to stay focused on themes of broader archaeological and anthropological relevance. It was, if we may say, a great success, as it managed to engage an audience of archaeologists, anthropologists, and art historians with archaeometallurgical discussion without inducing sleep (or death).

The papers from this symposium were published in a two-volume edition of the *Journal of World Prehistory* (JWP) in late 2009. As outlined in our introduction to these volumes (Thornton and Roberts 2009) and expanded upon in an *Antiquity* article (Roberts et al. 2009), the symposium provided four major conclusions:

1. Studies of metallurgical "origins" have moved beyond simplistic culture history approaches toward more nuanced discussions on the mechanisms of technological transfer, including notions of "innovation," "adaptation," and "adoption" (a la Renfrew 1978; Ottaway 2001).
2. Scholars of ancient technologies are becoming more aware of the need to study multiple crafts in tandem in order to form more robust models of craft production and technological behavior in ancient societies (cf. Miller 2005).
3. Childean associations between metallurgical production and elite dominance are outdated and must be proven, not assumed. More than any other topic, the *in*significance of the early adoption of metallurgy was emphasized in multiple regions (cf. Bartelheim 2007; Kienlin 2010).
4. The study of ancient metallurgy must adopt what Shimada (2007) has called a "holistic approach" to past technologies, in which all material remains from ancient technical practice must be analyzed. This includes fuel (e.g., charcoal), mining sites (e.g., ores and hammerstones), reaction vessels (e.g., crucibles and furnaces), tools (e.g., molds and lithics), waste products (e.g., slag), and finished artifacts (see also Ottaway 1994).

After this session at the SAA, the publisher of the *JWP* (Springer) approached us about putting these papers, many of which were subsequently revised by the authors (Chaps. 16, 19, 28) together, into a "reader" of early metallurgy, to be used for teaching archaeometallurgy to undergraduate students. This was a novel idea[1], especially given the dearth of research (let alone courses!) on archaeometallurgy in the USA (Killick and Goldberg 2009) in contrast to the slightly better situation in Europe (Rehren and Pernicka 2008). We agreed under the condition that we could supplement the conference papers with additional regional syntheses as well as a section on methodologies.

The result is this two-part volume. In the first section, we were very lucky to enlist some of the foremost experts in archaeometallurgical research methods to provide introductory chapters about their particular specialization. These chapters were designed to be informal "lectures" with, where possible, a concise bibliography geared toward archaeological undergraduates with little-to-no scientific training. Within each specialization, the available texts tend to be either dispersed, inaccessible, or designed for the advanced student. Archaeometallurgy still lacks a fundamental textbook, although there are focused handbooks on individual methods as for slag analysis (e.g., Bachmann 1982), metallography (e.g., Scott 1991; 2011), and metal conservation (e.g., Scott 2002).

[1] One for which our editor at Springer, Teresa Krause, should be credited.

The volume begins with two magisterial overviews on the fundamentals of ore formation and smelting (Chap. 2) and the material properties of metal (Chap. 3). These precede the more methodologically focused chapters, beginning with the three most underutilized methods in the study of ancient metals: metallography (Chap. 4), slag analysis (Chap. 5), and the study of technical ceramics such as molds and crucibles (Chap. 6). These three laboratory-based chapters are then followed by three more field-based approaches in archaeometallurgy, including mining archaeology (Chap. 7), experimental archaeology (Chap. 8), and the use of ethnographic analogy or ‘ethno-archaeology’ (Chap. 9). To round out the first half of the volume, we were fortunate to receive papers from two of the leading archaeometrists who analyze ancient metals and summarize the use of chemical and isotopic methods (Chap. 10) as well as the debate over proveniencing metal artifacts back to their original ore sources (Chap. 11). Finally, an important chapter on the kinds of research carried out by conservators (Chap. 12) completes the methodological section of this volume.

The second half of this volume provides a number of syntheses on the early development of metallurgy from various regions around the world. These papers were again geared toward an archaeological audience interested in archaeometallurgy, but with greater emphasis on synthesizing all the literature written about early metals in each area. It was hoped that as a collection, these papers would form the most up-to-date world synthesis of early metallurgy since the seminal 1988 BUMA volume (Maddin 1988).

Over the past two decades, the amount of data from each metallurgical region has increased dramatically, making such syntheses more and more difficult, while changing geopolitics has added new regions of study such as “The Caucasus” (as opposed to individual Soviet states; see Chap. 22). Sadly, many important regions—such as western Africa (e.g., Killick 2004; Holl 2009), eastern South Asia (e.g., Lahiri and Chakrabarti 1996), Australasia (e.g., Bulbeck 1999), and the Arctic (e.g., Pringle 1997; Cooper 2011)—had to be left out of this volume due to problems in receiving qualified papers. However, this volume was never meant to be encyclopedic or entirely definitive; it is meant to be an educational guide for teaching archaeometallurgy to an uninitiated audience.

The second section of the volume begins somewhat unusually in North America (Chap. 13), Mesoamerica (Chap. 14), and South America (Chap. 15), although most syntheses of early metallurgy would begin in the Old World. This is a deliberate attempt to emphasize the independent development of metallurgy in the New World without biasing the syntheses with comparisons to Eurasian archaeometallurgy. Following these chapters, three complementary chapters covering the European continent are provided (Chaps. 16–18), followed by an incredible overview of the development of metallurgy in southern and eastern Africa (Chap. 19). From these Western regions, the volume moves east to the classical heartlands of early metallurgy: Anatolia (Chap. 20), the Levant (Chap. 21), the Caucasus (Chap. 22), and the Iranian Plateau (Chap. 23).

The regions to the east of these ‘heartlands’ are comparatively understudied but provide important information about local adoptions and innovations to metallurgy and metal artifacts. These include two papers on South Asia (Chaps. 24 and 25), one on the Eurasian Steppe (Chap. 26), a synthesis of the rise of metals in East Asia (Chap. 27), and a stimulating paper on the possible origins of metallurgy in Southeast Asia (Chap. 28). This latter paper, when first presented in the *JWP* (White and Hamilton 2009), ignited considerable debate among Southeast Asian scholars that continues to this day (e.g., Pryce et al. 2010; Higham et al. 2011). Whether the conclusions put forth in Chap. 28 prove to be 'right' or 'wrong' is beyond the scope of this introduction. However, their innovative model of cultural transmission of metal technology using archaeometrical and archaeological data provides a significant intellectual landmark in archaeometallurgy. Due to the ever-increasing speed of scientific advancement, it is a sad truth that the data included in most of these synthetic chapters will be out of date before they are actually published. Thus, the emphasis should be on how each author combined archaeometrical and archaeological data with anthropological and sociological theory in order to reach conclusions about the role of metallurgy and metals in the lives of ancient peoples.

What is particularly striking about the superb papers in the second section of this volume is the emphasis upon anthropological theories of technological behavior and the social effects of/on technology (a la Lemmonier 1992; Pfaffenberger 1992; Dobres and Hoffman 1994). Up until the 1990s, these were largely missing from most archaeometallurgical syntheses, and their inclusion in these papers is a welcome addition, one that hopefully signals a paradigmatic shift in early metallurgical research (Thornton 2009). In archaeometallurgy (if not in all academic disciplines), such 'paradigm shifts' are never as final as they sound. Just as the introduction of copper did not cause the cessation of lithic production, the introduction of a new theoretical paradigm did not and does not necessitate the extinction of its predecessors. In fact, more than one paradigm can operate in tandem—see, for example, the prolonged existence of 'culture history' despite two highly touted paradigmatic shifts to 'processualism' in the 1960s and to 'post-processualism' in the 1980s (see Roberts and Vander Linden 2009 for further discussion).

Similarly, the study of ancient metallurgy has various schools of thought, many of them regionally based, which are complementary to each other in many ways. Some emphasize scientific analysis over theoretical understanding, seeking "facts" about the past and seeing humans as mostly rational beings that can be modeled and understood. Others apply lessons learned through ethnographic field research to understand the behavioral and cultural sides of ancient metallurgy, often using only a smattering of analytical data to argue for direct historical analogy. Neither is entirely right or wrong in its approach, but the best research usually results from collaboration between these two extremes. This volume was designed to seek a middle ground between analysis and theory, placing it firmly within the Anglo-American schools of thought in archaeometallurgy.

However, what *are* the Anglo-American schools of thought on ancient metallurgy? Can we even speak of a single paradigm in a discipline with practitioners from so many different academic fields (geology, archaeology, material science, etc.)? Archaeometallurgy as a field of study can only be traced back to the nineteenth century, when scientists such as John Percy began to report on their analyses of metal artifacts within archaeological publications. Early twentieth-century scientists such as William Gowland combined ethnographic accounts with archaeological and analytical data for the first time. It was not until the mid-twentieth century, however, that the study of ancient metal artifacts would become 'mainstream.' This florescence was driven in no small way by the rise of Marxian archaeology under the great prehistorian V. Gordon Childe (1930; 1944), whose theories on social evolution and class construction through technological advancement (particularly metals) and craft specialization continue to influence modern archaeological interpretation (see Rowlands 1971; Trigger 1986; and various papers in Wailes 1996). Remarkably, Childe was able to create these synthetic models and theories about ancient metallurgy without a hint of scientific analysis, which led the way for archaeologists not trained in metallurgy to enter the discussion.

The lack of scientific analysis should not diminish the importance of Marxian and Childean thought in archaeology and, by extension, to archaeometallurgy. Indeed, some of the most influential writers on metallurgical theory in the past few decades have also dealt with only limited technical analysis. For example, the famous Wertime–Renfrew debate on the origins of metallurgy (e.g., Renfrew 1969; Wertime 1973a, b), which has become the archetypical discussion on "diffusion" vs. "independent invention," was carried out with little mention of possible analyses to prove or refute their hypotheses (see Muhly 1988, p. 15). Even the great Russian scholar Evgenii Chernykh (1992), whose "metallurgical province" model is perhaps the most influential theory on ancient metallurgical production since Childe, only loosely refers to the technical analysis of over 60,000 metal artifacts that he oversaw from sites across the former Soviet Union.

The connection between analytical techniques and archaeological theory was first made in the 1970s by a group of scholars who are as notable for their excellent metallurgical research as for their enduring legacy as excavators and mentors. In Germany, Gerd Weisgerber and Hans-Gert Bachmann championed scientific methods of analysis in collaboration with archaeological investigations of ancient mines and metallurgical sites. In England, Ronald Tylecote and Beno Rothenberg were the first to successfully combine archaeological fieldwork, scientific analysis, and experimental reconstruction in order to understand firsthand the interaction between ancient societies and their metallurgical technology (Killick 2001; Cleere 1993). In the USA, the dominant 'archaeometallurgical paradigm' arose in the material sciences, with scholars at Massachusetts Institute of Technology (MIT), such as Cyril Stanley Smith, Martha Goodway, and Heather Lechtman, and at the University of Pennsylvania, such as Robert Maddin, Tamara Stech, James Muhly, and Vincent Pigott. All of these great men and women were instrumental in introducing metallography to studies of ancient metallurgical technology (Goodway 1991, p. 706) and convincing anthropological archaeologists that studies of ancient metallurgy could lead to a broader understanding of human behavior and social interactions.

As early as the mid-1980s, the American school of 'technological behavior' was rapidly gaining converts, but mainly among scholars interested in ancient ceramics (e.g., Wright 1985; various papers in Kingery 1986; Gosselain 1992; Hegmon 1992). It was not until the 1990s that archaeometallurgists began to adopt this paradigm (e.g., Childs 1991; Epstein 1993; Hosler 1994; Reedy 1997; Friedman 1998) often in conjunction with larger discussions about the social organization of craft production (e.g., Brumfiel and Earle 1987; Costin 1991, 2001; Pfaffenberger 1992).

More recently, this new paradigm has become almost de rigueur among American archaeometallurgists (see Killick 2004).

While the American school has not had the same effect on European archaeometallurgy as it has in the States, there has still been a theoretical shift, although of a different nature. In Britain, for example, the 'innovation-adoption' school, which came out of Colin Renfrew's work on Southeastern European metallurgy (Renfrew 1969, 1973) and the Varna cemetery (Renfrew 1978, 1986), has had a dramatic effect on the ways in which archaeologists study metallurgy and metal artifacts (e.g., Sørensen 1989, 1996; Kienlin 1999; Sofaer Derevenski 2000; Kim 2001; Ottaway 2001). A theoretical shift can also be seen to some extent in Continental Europe, where the social organization of technology (if not the cultural aspects of its production and use) has become a dominant theme (e.g., Vandkilde 1996; various papers in Pare 2000; Ottaway and Wager 2002; Kienlin 2010). More recently, the trendy though ill-defined 'materiality' school in Britain has been dominating theoretical discussions of ancient technologies (e.g., DeMarrais et al. 1996; Renfrew 2001; DeMarrais et al. 2004; Miller 2005; but see also Ingold 2007 and responses), although we await proof that this theory has any relevance to scientific studies of ancient materials (see Jones 2004 and responses in *Archaeometry* (2005) vol. 47.1).

While the apparent shift in British and European discussions of metallurgy and other technologies is indeed significant, theoretical trends like 'materiality' are mostly archaeological paradigms with little interest in scientific data. Such approaches threaten to widen the gap between archaeometrists or archaeological scientists and more theoretically inclined archaeologists. As the papers in this volume demonstrate, it is the use of empirical data in conjunction with archaeological and anthropological interpretation that can provide the most holistic view of ancient technologies in their social and cultural contexts. This occurs either through close collaboration between scientists and archaeologists or by educating students in both analytical techniques and archaeological theory. Without both aspects informing the other in a discursive relationship (i.e., theory structuring practice just as practice changes theory), we are only understanding half of the story.

Bibliography

Bachmann, H.-G. (1982). The identification of slags from archaeological sites. London: Institute of Archaeology

Barnard, N. (1961). *Bronze casting and bronze alloys in ancient China*. Canberra: Australia & Lagya.

Barnard, N. (1993). Thoughts on the emergence of metallurgy in pre-Shang and Early Shang China, and a technical appraisal of relevant bronze artifacts of the time. *Bulletin of the Metals Museum, 19,* 3–48.

Bartelheim, M. (2007). *Die Rolle der Metallurgie in vorgeschichtlichen Gesellschaften: Sozioökonomische und kulturhistorische Aspekte der Ressourcennutzung. Ein Vergleich zwischen Andalusien, Zypern und dem Nordalpenraum*. Forschungen zur Archäometrie und Altertumswissenschaft 2. Rahden.

Brumfiel, E. M., & Earle, T. K. (Eds.). (1987). *Specialisation, exchange and complex societies*. Cambridge: Cambridge University Press.

Bulbeck, F. (1999). The Bronze-Iron age of South Sulawesi, Indonesia: Mortuary traditions, metallurgy and trade'. In F. Bulbeck & N. Barnard (Eds.), Ancient Chinese and Southeast Asian bronze age cultures: The proceedings of a conference held at the Edith and Joy London Foundation property, Kioloa NSW (pp. 1007–1076). Taipei: SMC Publishing Inc.

Chernykh, E. N. (1992). *Ancient metallurgy in the USSR*. Cambridge: Cambridge University Press.

Childe, V. G. (1930). *The Bronze age*. New York: Biblio and Tannen.

Childe, V. G. (1939). The Orient and Europe. *American Journal of Archaeology, 43*(1), 10–26.

Childe, V. G. (1944). Archaeological ages as technological stages. *Journal of the Royal Anthropological Institute of Great Britain and Ireland, 74,* 7–24.

Childs, S. T. (1991). Style, technology and iron-smelting furnaces in Bantu-speaking Africa. *Journal of Anthropological Archaeology, 10,* 332–359.

Cleere, H. (1993). Archaeometallurgy comes of age. *Antiquity, 67,* 175–178.

Cooper, H. K. (2011). The life (lives) and times of native copper in Northwest North America. *World Archaeology, 43*(2), 247–265.

Costin, C. L. (1991). Craft specialization: issues in defining, documenting, and explaining the organization of production. In M. B. Schiffer (Ed.), *Archaeological method and theory (Vol. 3, pp. 1–56)*. Tucson: University of Arizona Press.

Costin, C. L. (2001). Craft production systems. In G. M. Feinman, & T. D. Price (Eds.), *Archaeology at the millennium: A sourcebook* (pp. 273–328). New York: Kluwer Academic/Plenum Publishers.

DeMarrais, E., Castillo, L. J., & Earle, T. K. (1996). Ideology, materialization, and power strategies. *Current Anthropology, 37,* 15–31.

DeMarrais, E., Gosden, C., & Renfrew, C. (Eds.). (2004). *Rethinking materiality: The engagement of mind with the material world*. Cambridge: McDonald Institute for Archaeological Research.

Dobres, M.-A., & Hoffman, C. R. (1994). Social agency and the dynamics of prehistoric technology. *Journal of Archaeological Method and Theory, 1*(3), 211–258.

Epstein, S. M. (1993). *Cultural choice and technological consequences: Constraint of innovation in the late prehistoric copper smelting industry of Cerro Huaringa, Peru*. Ph.D. dissertation, Department of Anthropology, University of Pennsylvania.

Friedman, E. S. (1998). *Technological style in Early Bronze Age Anatolia*. Ph.D. dissertation, Near Eastern Languages and Civilizations, University of Chicago.

Goodway, M. (1991). Archaeometallurgy: Evidence of a paradigm shift? In P. B. Vandiver, J. Druzik, & G. S. Wheeler (Eds.), *Material issues in art and archaeology II* (pp. 705–712). Pittsburgh: Materials Research Society.

Gosselain, O. P. (1992). Technology and style: Potters and pottery among Bafia of Cameroon. *Man, 27*(3), 559–586.

Hauptmann, A., Pernicka, E., Rehren, Th., & Yalcin, U. (Eds.). (1999). *The beginnings of metallurgy.* Der Anschnitt, b. 9. Bochum: Deutsches Bergbau-Museum.

Hegmon, M. (1992). Archaeological research on style. *Annual Review of Anthropology, 21,* 517–536.

Higham, C., Higham, T., Ciarla, R., Douka, K., Kijngam, A., Rispoli, F. (2011). The origins of the Bronze Age of Southeast Asia. *Journal of World Prehistory, 24*(4), 227–274.

Holl, A. F. C. (2009). Early west African metallurgies: New data and old orthodoxy. *Journal of World Prehistory, 22*, 415–438.

Hosler, D. (1994). *The sounds and colors of power: The sacred metallurgical technology of ancient West Mexico*. Cambridge: MIT Press.

Ingold, T. (2007). Materials against materiality. *Archaeological Dialogues, 14,* 1–16.

Jones, A. M. (2004). Archaeometry and materiality: Materials-based analysis in theory and practice. *Archaeometry, 46*(3), 327–338.

Kienlin, T. L. (1999). *Vom Stein zur Bronze. Zur soziokulturellen Deutung früher Metallurgie in der englischen Theoriediskussion*. Tübinger Texte 2. Materialien zur Ur- und Frühgeschichtlichen Archäologie. Rahden/Westf.: VML.

Kienlin, T. L. (2010). *Traditions and transformations: Approaches to Eneolithic (Copper Age) and Bronze Age metalworking and society in Eastern Central Europe and the Carpathian Basin.* BAR International Series 2184. Oxford: Archaeopress.

Kim, J. (2001). Elite strategies and the spread of technological innovation: The spread of iron in the Bronze Age societies of Denmark and Southern Korea. *Journal of Anthropological Archaeology, 20,* 442–478.
Kingery, W. D. (Ed.). (1986). *Ceramics and civilization: Technology and style*. Columbus, OH: The American Ceramic Society, Inc.
Killick, D. (2001). Science, speculation and the origins of extractive metallurgy. In D. R. Brothwell, & A. M. Pollard (Eds.), *Handbook of archaeological sciences* (pp. 483–492). Chichester: Wiley.
Killick, D. (2004). Social constructionist approaches to the study of technology. *World Archaeology, 36,* 571–578.
Killick, D. J., & Goldberg, P. (2009). A quiet crisis in American Archaeology. *SAA Archaeological Record, 29*(1), 6–10.
Lahiri, N., & Chakrabarti, D. K. (1996). *Copper and its alloys in ancient India*. Delhi: Munshiram Mahoharlal Publishers.
Lechtman, H. (1977). Style in technology: Some early thoughts. In H. Lechtman & R. S. Merrill (Eds.), *Material culture: Styles, organization, and dynamics of technology* (pp. 3–20). St. Paul: West Publishing Co.
Lechtman, H. (1979). Issues in Andean metallurgy. In E. P. Benson (Ed.), *Pre-Columbian metallurgy of South America* (pp. 1–40). Washington D.C.: Dumbarton Oaks.
Lechtman, H. (1980). The Central Andes: Metallurgy without iron. In T. A. Wertime, & J. D. Muhly (Eds.), *The coming of the age of iron* (pp. 267–334). New Haven: Yale University Press.
Lemonnier, P. (1992). *Elements for an Anthropology of technology. Anthrological Papers No. 88*. Ann Arbor: Museum of Anthropology, University of Michigan.
Maddin, R. (Ed.). (1988). *The beginning of the use of metals and alloys*. Cambridge: MIT Press.
Miller, D. (Ed.). (2005). *Materiality*. Durham: Duke University Press.
Muhly, J. D. (1988). The beginnings of metallurgy in the Old World. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 2–20). Cambridge: MIT Press.
Ottaway, B. S. (1994). *Prähistorische Archäometallurgie*. Espelkamp: Marie L. Leidorf.
Ottaway, B. S. (2001). Innovation, production, and specialization in early prehistoric copper metallurgy. *European Journal of Archaeology, 4,* 87–112.
Ottaway, B. S., & Wager, E. C. (Eds.). (2002). *Metals and society*. BAR International Series 1061. Oxford: Hadrian Books Ltd.
Pare, C. F. E. (Ed.). (2000). *Metals make the world go round: The supply and circulation of metals in bronze age Europe*. Oxford: Oxbow Books.
Pfaffenberger, B. (1992). Social anthropology of technology. *Annual Review of Anthropology, 21,* 491–516.
Pringle, H. (1997). New Respect for Metal's role in Ancient Artic Cultures. *Science 277*, 766–767
Pringle, H. (2007). Seeking Africa's first iron men. *Science, 323,* 200–202.
Pryce, T. O., Pollard, A. M., Martinón-Torres, M., Pigott, V. C., & Pernicka, E. (2010). Southeast Asia's first isotopically defined prehistoric copper production system: When did extractive metallurgy begin in the Khao Wong Prachan Valley of Central Thailand. *Archaeometry, 53*(1), 146–163.
Reedy, C. L. (1997). *Himalayan bronzes: Technology, style, and choices*. London: University of Delaware Press/Associated University Presses, Inc.
Rehren, Th., & Pernicka, E. (2008). Coins, artefacts and isotopes-archaeometallurgy and archaeometry. *Archaeometry, 50*, 232–248.
Renfrew, C. (1969). The autonomy of the south-east European Copper Age. *Proceedings of the Prehistoric Society, 35,* 12–47.
Renfrew, C. (1973). *Before civilization*. London: Penguin Books.
Renfrew, C. (1978). The anatomy of innovation. In D. Green, C. Haselgrove, & M. Spriggs (Eds.), *Social organisation and settlement: Contributions from anthropology, archaeology, and geography (pp. 89–117)*. BAR International Series (Supplementary) #47. Oxford: Oxford University Press.
Renfrew, C. (1986). Varna and the emergence of wealth in prehistoric Europe. In A. Appadurai (Ed.), *The social life of things* (pp. 141–168). Cambridge: Cambridge University Press.

Renfrew, C. (2001). Symbol before concept: Material engagement and the early development of society. In I. Hodder (Ed.), *Archaeological theory today* (pp. 122–140). Cambridge: Polity Press.

Roberts, B. W., & Vander Linden, M. (Eds.). (2009). *Investigating archaeological cultures: Material culture, variability and transmission*. New York: Springer.

Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity, 83,* 1012–1023.

Rowlands, M. J. (1971). The archaeological interpretation of prehistoric metalworking. *World Archaeology, 3,* 210–224.

Scott, D. A. (1991). *Metallography and microstructure of ancient and historic metals*. Singapore: The Getty Conservation Institute.

Scott, D.A. (2002). Copper and bronze in art: corrosion, colorants, conservation. Getty Trust Publications: Getty Conservation Institute.

Scott, D. A. (2011). *Ancient metals: microstructure and metallurgy* (vol. 1). CSP: Conservation Science Press.

Shimada, I. (Ed.). (2007). Craft production in complex societies: Multicraft and producer perspectives (Foundations of archaeological inquiry series). Salt Lake City: University of Utah Press.

Smith, C. S. (1977). *Metallurgy as a human experience: An essay on man's relationship to his materials in science and practice throughout history*. Metals Park, OH: American Society for Metals.

Sofaer Derevenski, J. (2000). Rings of life: The role of early metalwork in mediating the gendered life course. *World Archaeology, 31,* 389–406.

Sørensen, M.-L. S. (1989). Ignoring innovation—denying change: The role of iron and the impact of external influences on the transformation of Scandinavian societies 800–500 BC. In S. E. Van der Leeuw & R. Torrence (Eds.), *What's new? A closer look at the process of innovation* (pp. 182–202). One World Archaeology, 14. London: Unwin Hyman.

Sørensen, M.-L. S. (1996). Woman as/and metalworkers. In A. Devonshire & B. Wood (Ed.), *Women in industry and technology: From prehistory to the present day* (pp. 45–50). London: Museum of London.

Thornton, C. P. (2009). Archaeometallurgy: Evidence of a paradigm shift? In T. L. Kienlin & B. W. Roberts (Eds.), Metals and societies. Studies in honour of Barbara S. Ottaway (pp. 25–33, Universitätsforschungen zur prähistorischen Archäologie). Bonn: Habelt.

Thornton, C. P., & Roberts, B. W. (2009). Introduction: The beginnings of metallurgy in a global perspective. *Journal of World Prehistory, 22,* 181–184.

Trigger, B. G. (1986). The role of technology in V. Gordon Childe's archaeology. *Norwegian Archaeological Review, 19,* 1–14.

Vandkilde, H. (1996). *From stone to bronze: The metalwork of the late neolithic and earliest bronze age in Denmark*. Jutland Archaeological Society Publications XXXII. Moesgård. Aarhus: Aarhus University Press.

Wailes, B. (Ed.). (1996). *Craft specialization and social evolution: In memory of V. Gordon Childe*. University Museum Monograph 93, Philadelphia: University Museum of Archaeology and Anthropology/University of Pennsylvania.

Wertime, T. A. (1964). Man's first encounters with metallurgy. *Science, 146*(3649), 1257–1267.

Wertime, T. A. (1973a). How metallurgy began: A study in diffusion and multiple innovation. *In Actes du VIIIe Congres International des Sciences Prehistoriques et Protohistoriques (Beograd)* (pp. 481–492).

Wertime, T. A. (1973b). The beginnings of metallurgy: A new look. *Science, 182*(4115), 875–887.

Wertime, T. A., & Muhly, J. D. (Eds.). (1980). *The coming of the age of iron*. New Haven: Yale University Press.

White, J. C., & Hamilton E. G. (2009). The transmission of early bronze technology to Thailand: New perspectives. *Journal of World Prehistory, 22,* 357–397.

Wright, R. P. (1985). Technology and style in ancient ceramics. In W. D. Kingery (Ed.), *Ceramics and civilization: Ancient technology to modern science* (Vol. 1, pp. 5–25). Columbus: The American Ceramic Society, Inc.

Chapter 2
From Ores to Metals

David Killick

Introduction

Archaeometallurgy is one of the most interdisciplinary of all branches of historical inquiry. Disciplines that contribute essential insights into archaeometallurgy include archaeology, ethnoarchaeology, economic history, the history of technology, the history of philosophy (beliefs about transformations of matter), philology, social anthropology, mineralogy, petrology, geochemistry, economic geology, extractive metallurgy, physical metallurgy, foundry practice, blacksmithing and goldsmithing, ceramic technology, numismatics, forestry, and limnology.

No single person can be an expert in all of these fields, and few among us can hope to become even competent in more than three or four of them. All students of past mining and metallurgy must therefore rely upon the expertise of others, so archaeometallurgical projects are best carried out by teams of collaborating specialists. However, some forms of expertise are in very short supply in archaeometallurgy. One underrepresented perspective is that of economic geology, which is the study of how useful elements (mostly metals) are concentrated by geological processes to form ores and ore deposits. It may seem surprising that expertise in economic geology should be hard for archaeometallurgists to find, given that industrial societies are absolutely dependent upon the metals and minerals produced from ore deposits. This situation reflects the decline of interest in the subject within academic geology over the last 25 years. Few doctoral dissertations are now written in economic geology, and it is hard even to get well-qualified candidates to apply for the few university lectureships that are advertised in this field, given the great difference in the salaries offered by universities and mining companies.

My aims in this chapter are: (1) to provide a very brief introduction to the subject and its major findings; (2) to summarize the methods used to study ore minerals and their associations; and (3) to show how some knowledge of the properties and

D. Killick (✉)
School of Anthropology, Emil W. Haury Building,
1009 East South Campus Drive, Tucson, AZ 85721, USA
e-mail: killick@email.arizona.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_2,

distribution of ore minerals can help us understand the prehistory of extractive metallurgy (smelting).

What are Ores?

A useful starting point is the definition provided in a standard textbook: “(o)res are rocks or minerals that can be mined, processed and delivered to the marketplace or to technology at a profit” (Guilbert and Park 1986, p. 1). A large volume of ore is termed an ore deposit. For the purposes of archaeometallurgy, we need to detach this definition from the modern context of commodity markets, which have existed for only about 200 of the 10,000 years since humans first used metals. It is important, however, to retain the idea that the classification of a given volume of rock as an ore deposit is a relative judgment. Today what determines whether a volume of rock is an ore are: (1) the market price of the metal that it contains and (2) the cost of obtaining it from the ore and moving it to market. Before the modern era, the factors that determined whether a given rock or alluvial sediment was an ore were: (a) whether the metal(s) it contained were considered valuable and (b) the technologies available for mining, concentrating, and smelting the metal(s).

My first restriction of the definition requires explanation. Today, every element in the periodic table has its price, but this was obviously not so in the remote past. Many elements were not isolated as pure substances and named until the nineteenth or twentieth century. Even metals that were known in prehistory did not necessarily have value at all times and places. Gold offers a good example. Alluvial gold (concentrated in alluvial deposits because of its high specific gravity) occurs on all continents, and mobile populations (e.g., hunter-gatherers and pastoralists) were surely aware of its existence. Yet there is little evidence that it was even collected as a curiosity before about 4500 BCE. From this point on, gold became highly valued throughout Eurasia, beginning around the Black Sea (Chernykh 1992; see Kienlin; Yener and Lehner; Courcier, this volume). The use of gold also emerged, independently of the Old World, in parts of South America, Central America, and the Caribbean, beginning around 2000 BCE (Aldenderfer et al. 2008; see Hosler; Lechtman, this volume). However, there is no evidence of its use in sub-Saharan Africa (except in Nubia and areas adjacent to the Red Sea) until portions of the subcontinent were incorporated into Muslim trading networks after 750 CE (Killick, this volume). Nor was gold used in North America before the sixteenth century CE, or in Australia before the eighteenth century; in both these regions the first extraction of gold was by European colonists.

The point here is that metals do not have intrinsic value. Value is ascribed to metals by people, and their judgments of what was valuable, and what was not, varied widely through time and space. Thus, what we count as an ore today was not necessarily an ore in the remote past. Another very striking example of this is seen in some Bronze Age mines in Wales (Cwmystwyth, Great Orme, and Nantyreira) where the copper minerals were removed, but rich veins of the lead mineral galena

(PbS) were not (Ixer 1999; Timberlake 2003). Lead was not valued, so lead veins were not ores at that time.

My second restriction on the archaeometallurgical definition of ore resources reflects the fact that with technological advances the “cutoff” in metal content that makes a rock an ore declines. Thus, many mining districts have been mined over and over again, with each new period of mining attributable to an advance in technology. For an extended example, let us consider copper. Although we have, as yet, little direct evidence of the grade of ore used by the earliest copper smelters in the early fifth millennium BCE, it seems likely that the first crucible smelting technology would have required nearly pure hydroxycarbonate ores (malachite and azurite), which contain about 60 % copper by mass. If we fast-forward to the present, the huge open-pit copper mine at Sierrita, Arizona—about 40 km from where this article is written—is mining rock that contains, on average, only 0.25 % copper and some molybdenum. For this mine to be profitable at present world prices, at least 200,000 tons of rock must be mined and milled every day.

Advances in both the factors of production (the technologies of mining, extractive metallurgy, and transportation) and the organization of production (labor skills and coordination, finance, and marketing) have allowed the expansion of the term “ore deposit” to rocks of steadily declining metal content. Sierrita is one of several dozen gigantic open-pit mines that today produce most of the world’s copper from very low-grade porphyry copper deposits (Guilbert and Park 1986; Robb 2005). These are thought to contain more than 85 % of all the copper in the earth’s crust that can be considered ore under present and projected technological, economic, and social constraints. The change from underground to open-pit mining in the early twentieth century reflected the exhaustion of richer copper ore deposits; Gordon et al. (2006) estimate that 97.5 % of the 400 million metric tons of copper that have ever been extracted were mined since 1900. This represents about 26 % of the metal in all copper ore deposits that have been discovered so far in the earth’s crust. Since the amount of copper extracted per year is growing much faster than the amount added by the discovery of new copper deposits (Gordon et al. 2006, Fig. 4), it appears likely that within a century we will be unable to add newly mined copper to the stocks already in use. This is because the amounts of energy and water required to process the exponentially larger volumes of rock with copper contents below about 1000 ppm will be prohibitive.

An important consequence of this trend for archaeometallurgy is that many of the copper mines used in antiquity have already been destroyed. We cannot assume that those mines that have escaped destruction, however impressive, were the major sources used in prehistory. This point is well illustrated by the case of the impressive ancient mine at Rudna Glava, Serbia, which was once assumed to have been the major source for Eneolithic copper artifacts in that region of the Balkans. Yet lead isotopic analysis of a substantial sample of Eneolithic copper artifacts from the Balkans (Pernicka et al. 1993; Radivojević et al. 2010) showed that none of them derived from Rudna Glava ores. The search for ancient mines in alluvial ore deposits is a particularly fruitless task, for these have been repeatedly worked and reworked with advances in the technology for recovering ore from them. Artifacts dating as far back as the Bronze Age have been recovered over the last four centuries from alluvial tin gravels in southwest England (Penhallurick 1986), but no ancient mine has yet been found in these deposits. Nor should we expect to find a prehistoric mine in the alluvial goldfields of West Africa, which are known from historical documents to have been major sources of gold for the Muslim world (Levtzion and Hopkins 2000).

In other words, the ore resources of the world that we live in are very different from those that existed in prehistory. Most of our evidence for the types of ores used in the distant past, and how these were processed, must therefore come directly from examination of ore samples recovered from prehistoric smelting sites. However, the study of ores is the least developed part of archaeometallurgy, and the literature is full of poorly informed speculation about the ores used in the past (Ixer 1999). The main purpose of this chapter is therefore to introduce the topic and to plead for the training of more specialists in archaeological applications of ore geology. It will also show how the history of extractive metallurgy—the sequence in which the various metals were won from their ores—reflects the geological processes that formed ores, the chemical properties of particular ore minerals, and the slow growth of human understanding of these properties.

The Relative Abundance of the Metals in the Crust of the Earth

Ores contain, in all cases, a much higher concentration of the metal than the average concentration of that metal in the earth's crust. Geochemists have estimated the crustal abundance of the elements by: (1) calculating, from chemical analyses in the literature, the average composition of each of the major types of rock in the crust and (2) multiplying these averages by the estimated mass fraction of each of these rock types in the crust, as inferred from surface outcrop, boreholes, and remote sensing (magnetic and gravity surveys and seismic probes).

Estimates of average abundances of the major metals of industrial interest (extracted from Tables A.10 and A.11 in Faure 1991) are listed in Table 2.1. Looking at the first column (abundances averaged across the Earth's crust), we see that:

(1) aluminum, iron, magnesium, and titanium are geochemically abundant (>0.5 mass%) and thus will not be exhausted at any plausible level of demand;
(2) manganese, vanadium, chromium, and nickel are present above 100 ppm;
(3) all other metals are geochemically scarce (<100 ppm); and
(4) the precious metals (silver, gold, and platinum-group elements—PGEs) and mercury are ultra-trace elements (<0.1 ppm).

Slightly different values can be found in other texts (e.g., Krauskopf and Bird 1995) and reflect different assumptions about the mass fraction of the various rock types in the Earth's crust, but the rank order for the abundance of the metals is the same in each case.

Table 2.1 Estimated abundance by mass of selected metals in the earth's crust and in major rock types. Abundances in ppm except for Al, Fe, and Mg, which are in percent. (Adapted from Faure 1991, Tables A.10 and A.11)

	Crystal average	Ultramafic rocks	Basalt	High-Ca Granite	Low-Ca Granite	Shale	Sandstone	Carbonate rocks	Deep-sea clays
Al (%)	8.40	1.20	8.28	8.20	7.20	8.00	2.50	0.42	8.40
Fe (%)	7.06	9.64	8.60	2.96	1.42	4.72	0.98	0.33	6.50
Mg(%)	3.20	23.20	4.54	0.94	0.16	1.50	0.70	4.70	2.10
Ti	5,300	300	11,400	3,400	1,200	4,600	1,500	400	4,600
Mn	1,400	1,560	1,750	540	390	850	#	1,100	6,700
V	230	400	225	88	44	130	20	20	120
Cr	185	1,800	185	22	4	90	35	11	90
Ni	105	2,000	145	15	4.5	68	2	20	225
Zn	80	40	118	60	39	95	16	20	165
Cu	75	50	94	30	10	45	#	4	250
Co	29	175	47	7	1	19	0.3	0.1	74
Pb	8	0.5	7	15	19	20	7	9	80
Sn	2.5	0.5	1.5	1.5	3	6	0.1	0.1	1.5
W	1.0	0.5	0.9	1.3	2.2	1.8	1.5	0.6	1.0
As	1.0	0.8	2.2	1.9	1.5	13	1.0	1.0	13
Sb	0.2	0.1	0.6	0.2	0.2	1.5	0.01	0.2	1.0
Hg	0.09	0.01	0.09	0.08	0.08	0.40	0.03	0.04	0.10
Ag	0.08	0.05	0.11	0.05	0.037	0.07	0.01	0.01	0.11
Au	0.003	0.006	0.004	0.004	0.004	#	#	#	#

Insufficient data for calculation of mean abundance

Archaeometallurgists should immediately spot the paradoxes in this column. Why were the first metals to be used (copper, lead, and gold) among the scarcest? Why were six of the seven most abundant metals not used before the last two centuries? Keep these questions in mind, as we will return to them later in the chapter.

The other columns in this table show that some metals are more abundant in some types of rock than in others. The most extreme differences are for magnesium, cobalt, nickel, and chromium, which are concentrated in ultrabasic rocks (dunites, peridotites, etc.). Conversely, lead is found at higher concentrations in granitic rocks and in clays than in ultrabasic or basic rocks (gabbros and basalts). For some metals—manganese, copper, lead, zinc, and arsenic—the highest values are seen in marine clays. These elements tend to oxidize at the Earth's surface to form compounds that are soluble in water and thus are carried to the ocean. There they are adsorbed on the surfaces of clay particles and sink slowly to the ocean floor.

In no case, however, are the concentrations listed in Table 2.1 high enough for the average rock or sediment to be considered an ore under present or projected technological and market constraints. Ore deposits are often formed where subsurface geological processes have removed metals from common rock or from masses of molten magma, and have redeposited them in other locations at much higher concentrations. Alternatively, ore deposits are formed where surface processes have eroded minerals from rocks and concentrated them elsewhere. The degree of concentration above the values in the parent rock is called the *enrichment factor*. In the case of the Sierrita porphyry copper deposit, the parent rock is a low-calcium granite. If we assume this to have a typical copper concentration (from Table 2.1) of 10 ppm, then the enrichment factor for the ore body as a whole (0.25 % Cu) is about 250 times (250 ×). A piece of pure malachite (60 % Cu) within this ore body has a local enrichment factor of 60,000x. The highest known enrichment values are at the Almaden mercury mines of Spain (Silurian to Devonian age), where some ore bodies contain as much as 25 % mercury. The Almaden deposits have yielded about a third of all mercury ever mined, much of which was used to extract silver from Mexico and Peru during the Spanish colonial era. Geochemical research (Higueras et al. 2000) suggests that this mercury derived ultimately from basaltic magmas, which typically contain only 0.09 ppm Hg (Table 2.1). The enrichment factor for the richer mercury deposits at Almaden may therefore be as high as 2.8×10^6x.

How do Ore Deposits Form?

Ore deposits represent the most extreme examples of the chemical differentiation of the earth over the last 4.5 billion years. Slow cooling over this time converted an initial mass of relatively homogeneous superheated gas into a planet with a metallic (iron–nickel) core, a mantle of ultrabasic composition (mostly liquid with a viscous outer zone), and a thin, brittle, and highly differentiated crust. The major question addressed by academic geochemists is how the different rocks listed in Table 2.1 (and the many variants not listed) could all be produced from parent rocks that had the ultrabasic composition of the upper mantle. My discussion is restricted to the formation of ore deposits and is drawn largely from Guilbert and Park (1986), Ixer (1990), Robb (2005), and Dill (2010). Space does not permit the inclusion of diagrams to illustrate these processes; for these the reader should consult Robb (2005).

Ore Deposits Associated With Igneous Rocks

One way to form rocks of different chemical compositions from a molten magma is through *fractional crystallization*. Iron, chromium, titanium, and vanadium oxides and iron/magnesium silicates and aluminosilicates (olivines and pyroxenes) are the first minerals to crystallize from ultrabasic magmas. If these separate by settling under gravity, the remaining liquid will be relatively enriched in other elements, such as the alkalis, the rare earths, and some metals. The residual liquid will also contain more silicon, aluminum, water, and carbon dioxide than the crystal mush. Thus, the chemical composition of the residual melt will move towards those of the more silica-rich intermediate rocks (e.g., andesite).

The early-forming crystalline minerals in a magma chamber have different densities and may separate by gravitational settling to produce a layered suite of rocks.

Almost pure layers of magnetite (Fe_3O_4) ore—with or without ilmenite ($FeTiO_3$)—and chromite ($FeCr_2O_4$) occur in many ultrabasic igneous suites. Most of the exploitable world reserves of the PGEs are in a single chromite-rich layer in South Africa (the Merensky Reef) that is only 30–90 cm thick. The Merensky Reef formed within the largest known layered igneous intrusion, the Bushveld Igneous Complex (BIC), which goes from ultrabasic rocks at the bottom to acid rocks (rhyolites and granites) at the top. Chromium, iron, platinum, vanadium, and titanium ores are restricted to the ultrabasic and basic layers, while copper and tin mineralization is associated with the late-forming acid rocks at the top of the sequence. The sequence reflects typical changes in the compositions of magmas that are produced by fractional crystallization.

Most ore deposits associated with igneous rocks are however generated through the "conveyor-belt" mechanism of *plate tectonics*. At subduction zones, which are most commonly where oceanic crust is pushed against a continental plate, the denser, thinner basaltic crust is forced down beneath the continents. At depths of 60–170 km, the subducted plate melts to generate a magma. This magma has two significant features for ore formation: (1) The subducted plate has a veneer of sediment that (as shown in Table 2.1) carries relatively high concentrations of many metals, and (2) it has a higher water content than is typical of the upper mantle, due both to the sediment veneer and to reactions between basalt and seawater at the ocean floor. The resulting magma is buoyant and thus rises slowly through the upper mantle and overlying crust, or absorbs portions of crust to produce magmas of andesitic composition. Alternatively, the magma may transfer its heat to crustal rocks, which may melt in turn to form intermediate-to-acid magmas. Many of these magmas erupt at the surface as chains of volcanoes parallel to the subduction zone, forming either mountain chains (e.g., the Andes) if the melting occurs under continental crust, or island arcs (e.g., Indonesia) if the subduction zone lies offshore under continental margins. Some magmas solidify as plutons below the surface, and the reactions that occur with crustal rocks around these plutons generate important classes of ore deposits, including the porphyry copper and molybdenum deposits.

Elements that cannot be accommodated in the crystal lattices of the early-forming minerals concentrate in residual fluids due to fractional crystallization of these magmas. The most important such elements in ore genesis are hydrogen, carbon, sulfur, chlorine, and fluorine (as water and HCO_3^-, HS^-, $SO_4{}^-$, Cl^-, and F^- anions). These form hot brines and molten sulphides that effectively scavenge and transport metal ions from the original magma and from the crustal rocks through which the ascending fluids pass. Once almost all the magma has crystallized, many metals (Cu, Mo, Pb, Zn, Au, and Ag) can be concentrated in these fluids at several orders of magnitude above their original abundance in the magma. The amount of water in the magma and the degree of oxidation are thought to largely determine which metals are concentrated. The magmas that produce porphyry copper deposits are thought to have contained less water than those that produce the porphyry molybdenum deposits. Large volumes of fluids were certainly required to form ore deposits of the most *incompatible* metals, which are not readily accepted in the crystal structures of most rock-forming minerals. Incompatible metals (e.g., Sn and W) are geochemically very scarce (Table 2.1) and thus must be scavenged from large volumes of magma or rock by large volumes of fluids. Ores of these metals and of other incompatible elements (B, Be, Li, Cs, Nb, and Ta) are typically found at the very top of granitic plutons and in pegmatites.

All that remains to form ore deposits is to precipitate these metals from solution. Cooling lowers the solubility of metals in hot brines, as does the decrease of pressure near the earth's surface. These changes suffice to produce relatively low-grade ore deposits formed around the margins of large igneous intrusions, as in the porphyry copper deposits, which generally contain less than 2 mass% copper (Guilbert and Park 1986). The hot aqueous solutions typically spread out from the igneous intrusion into the enclosing host rocks and react with them, a process called *metasomatism*. For example, skarns are formed by metasomatism of limestones or dolomites and are important hosts worldwide for ore deposits of W, Sn, Mo, Cu, Pb, and Zn.

The average concentrations of metals in these deposits, though orders of magnitude above average concentrations in the crust, are too low to have been ores for early metallurgists. Patches of much higher grade can however form in suitable traps. These are generally joints and cracks in igneous or metamorphic rocks, or bedding planes in sedimentary rocks, which become filled with metallic minerals and associated *gangue minerals* (i.e., those without economic value) such as quartz, pyrite, carbonates, tourmaline, etc. These minerals are precipitated from brines and molten sulphides forced through these channels, which gradually fill to form veins and narrow sheets that can be very rich in metal content. These were the most important sources of copper, lead, zinc, silver, and tin before the era of open-pit mining. Quartz veins above igneous intrusions were important sources of gold in many areas—most of the gold exported from Great Zimbabwe and its successor states, for example, derived from the mining of quartz veins (Summers 1969). Most gold-bearing veins date to the Archean period (3000–2500 Ma), quite early in the evolution of the earth.

Hydrothermal Deposits: Ore Formation by Interaction of Surface Waters With Subsurface Magmas and Rocks

Since the earth's crust is solid, it encloses a fixed volume. Thus, any volume of plate subducted into the mantle must be balanced by an equal volume that is forced up into or through the crust. Most of this extruded material appears at *seafloor spreading centers*, which are linear volcanoes that build the basaltic seafloor. An important class of ores is formed here as seawater seeps down through the seabed along cracks initiated by the pressure of the underlying magma. These large volumes of water are heated, extract metals from the basaltic magma, and are expelled back through "black smoker" vents into the cold ocean, where metal sulphides (Cu, Zn, and Ni) immediately precipitate to form ores. These are called *volcanogenic massive Sulphide* (VMS) deposits. Most of these deposits have probably been destroyed by subduction, but some were fortuitously preserved when slabs of former ocean floor were torn off and thrust up over continental crust. These are known as ophiolite complexes. Two ophiolites—those of Oman and Cyprus—were extremely important ore sources for the Bronze Ages of Mesopotamia and the eastern Mediterranean, respectively (Hauptmann 1985; Stos-Gale et al 1997). Other historically important VMS deposits include the Rio Tinto Cu–Ag–Au mine in Spain and the Kuroko "black ore" Cu–Zn–Pb in Japan (though these may have formed at island arcs rather than at subduction zones).

A related class of massive sulphide deposits are the *sedimentary exhalative* (SEDEX) deposits, which contain about half of the known Pb and Zn ore reserves. These formed in relatively shallow waters (as in the Red Sea today) where major faults allow brines to descend deep below the surface and to return as hot solutions laden with metals, which precipitate as soon as they meet cool sea or lake waters.

VMS and SEDEX ore deposits are *syngenetic*, meaning that the ores were deposited at the same time as the sediments that host them. However, ore deposits can also form in sedimentary rocks by *epigenetic* mineralization, meaning that the metal ions originated elsewhere and entered the sediments long after the latter were deposited. These metals were introduced in low-temperature ($<150\,°C$) brines that moved through pore spaces and were precipitated by reaction with carbonates or by reduction by organic matter in sediments.[1] The Zambian/Katangan Copperbelt, the central European Kupferscheifer, and the Mississippi Valley Pb–Zn deposits are examples of epigenetic hydrothermal deposits.

For archaeometallurgists, a particularly important case of interaction of surface waters with metal-bearing rocks is that which occurs where copper sulphide ore deposits of igneous origin encounter surface waters and oxygen. The primary (*hypogene*) ore minerals in these deposits are mostly sulphides of copper and iron, particularly pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). These are oxidized by exposure to oxygenated surface waters to form carbonates, oxides, and hydroxides. Some iron remains at the surface as relatively insoluble oxides and hydroxides, which give a strong red color to the top few meters (known as *gossan* or *iron hat*) of the oxidized zone (Fig. 2.1). Some copper is retained within the oxidized zone, mostly as cuprite (Cu_2O, red), malachite ($Cu_2CO_3(OH)_2$, green), and azurite ($Cu_3(CO_3)_2(OH)_2$, blue). On present knowledge, these attractively colored minerals were first used for personal ornaments in the Middle East from the late 11th millennium BCE, preceding the development of agriculture by two millennia. They became widely distributed in Iran and the Levant in the eighth to ninth millennia, and were probably transported there with obsidian from Anatolia (Schoop 1995; Thornton 2002).

Native copper is formed in the oxidizing zone by the reaction:

$$2Cu_2S + 8Fe^{3+} + 12(SO_4)^{2-} \Rightarrow 2Cu^0 + Cu_2O + 8Fe^{2+} + 12H^+ + 14(SO_4)^{2-}$$

(Guilbert and Park 1986, Eq. 17.19).

Although native copper is very often noted in the oxidized zone, this does not necessarily mean that in any given deposit it occurred in pieces large enough to

[1] The temperatures of formation of ore deposits are largely inferred from the study of tiny fluid inclusions trapped within the solid minerals—see Guilbert and Park (1986: 252–260).

Fig. 2.1 The thin red layer is the gossan over the copper sulphide ore deposit at Bisbee, Arizona. The rock beneath this shows the typically bleached appearance of the supergene layer above the water table. The zone of supergene enrichment begins about 50 m below the level of the road. (Photograph by author)

be exploited. There has been much fruitless argument in archaeometallurgy about whether the use of native copper (forged but not melted) was a universal stage in western Eurasia before the development of smelting. Wertime (1973), Charles (1980), and Amzallag (2009) all assert that it was, but evidence for the use of native copper in western Eurasia is as yet surprisingly rare (Thornton et al. 2010). Whether this absence is apparent or real is hard to judge, as the chemical composition of the earliest copper is not necessarily a good clue. Although native copper is generally very pure (Rapp et al. 2000), there is no good reason to suppose that copper reduced in crucibles from masses of cuprite, malachite, or azurite in the oxidized zone would be any less pure. Metallographic examination is often more conclusive, but has rarely been applied to the earliest metals in Eurasia—the excellent work of Stech (1990) on the native copper industry of Çayönü in Anatolia (late ninth millennium BCE) is a notable exception. Finds of partially worked native copper are the best evidence but have rarely been noted in the Old World and never (so far) in South America. The contrast with North America, where there is abundant archaeological evidence for working of native copper, is very striking (see Ehrhardt, this volume). The direct forging of native copper began here around 4500 BCE (Martin 1999) and it remained the only metallurgical technology in North America (except for very rare instances of the forging of iron meteorites and native iron) until colonization by Europeans (Wayman et al. 1992).

Oxidation of the pyrite (FeS_2) in the oxidized zone produces sulfuric acid and ferrous sulfate. These acidic solutions leach copper from the oxidized zone down to the water table, where copper is precipitated, mostly as chalcocite replacing pyrite at the top of the original hypogene ore zone:

$$5FeS_2 + 14Cu^{2+} + 14(SO_4)^{2-} + 12H_2O \Rightarrow 7Cu_2S + 5Fe^{2+} + 24H^+ + 17(SO_4)^{2-}$$

(Guilbert and Park 1986, Eq. 17–39).

The excess acid is neutralized by reaction with gangue minerals and by slightly alkaline ground waters. This reaction produces a zone of *supergene enrichment*, with copper concentrations much higher than in the primary (*hypogene*) ore beneath it, and vastly greater than in the oxidized and leached zone above. Many copper mines today, such as the vast open-pit mine at Morenci in eastern Arizona, are only economically viable because of supergene enrichment.

Supergene enrichment is noted on all types of copper deposit, but its significance for prehistoric metallurgy varies with location. On stable continental surfaces, the enriched layer may be buried under a hundred meters or more of oxidized and leached overburden (as in Fig. 2.1) and thus would only be accessible to early metallurgists if exposed by erosion. In northern latitudes, much of the oxidized layer may have been scraped away by the advance of glaciers, bringing the enriched supergene sulphides, or even the hypogene ore, close to the surface (as in the Austrian Alps). In very arid areas, such as the Atacama Desert of Chile, the oxidized layer may retain, and even concentrate, much of the copper in the form of soluble sulfates and chlorides that in more humid climates would have been flushed down the profile. The point here is that copper deposits vary widely in their character. Thus, the simplified general model of a copper ore deposit used by many archaeometallurgists (after Charles 1980) is no substitute for a careful reading of the geological literature on the ore deposits of the region under investigation.

Ore Formation by Sedimentary Processes

As noted above, high-grade iron ores are often formed by settling in magma chambers to form magnetite layers, but for technological reasons (see below) these ores were rarely utilized before the development of blast furnaces. Iron smelters in earlier times preferred iron oxide ores formed by sedimentary processes. (Iron sulphides are abundant but have never been used as iron ores because even small amounts of intergranular iron sulphide cause iron to crumble when hot-forged.) Very large deposits of iron oxides were formed as *chemical sediments* (i.e., precipitated from aqueous solution) during three distinct periods of the earth's development—two in the Archean (3500–3000 and 2500–2000 Ma) and one in the Proterozoic (1000–500 Ma)—to form the ores known as banded iron formations (BIFs). These have layers of iron oxide (magnetite or hematite) or iron carbonate (siderite) alternating with silica-rich layers (usually chert). They are thought to have formed when periodic pulses of deep water containing Fe^{2+} ions were raised by upwelling along continental margins and converted to the less soluble Fe^{3+} by oxygenated surface waters. The silica-rich layers apparently derived by precipitation of dissolved silica, but after the evolution of marine creatures (diatoms) that built their skeletons of silica, there was no longer enough silica in solution to precipitate chert layers, so no BIF formed after this time (Robb 2005).

Although BIFs supply much of the world's iron today, there is little evidence for their use in prehistory, probably because: (1) they are mostly found in areas where iron was not smelted until European colonization (Australia and North America) and (2) they tend to be very hard, and thus laborious to mine by hand unless heavily weathered to iron hydroxides, as in Madagascar, where they were smelted in prehistoric times (Gabler 2005). The earthier and softer hematite and limonite (iron hydroxide) ores, such as the Jurassic ores of Alsace-Lorraine, were preferred in northern latitudes. These types of ore formed in shallow waters, often by chemical replacement of carbonates. In northern latitudes, *bog iron* ores were often the preferred source for small-scale iron smelting in prehistory. The presence of peat produces acid waters that can carry iron in solution, often as complexes with humic acids. These compounds are broken down in ponds by bacterial action, precipitating the iron as the hydroxides goethite and lepidocrocite (collectively called limonite). Bog ores are small but renewable resources (Ixer 1990), and these ores are easily smelted. Spring deposits of limonite also made suitable ores in some locations.

In the tropical zones of sub-Saharan Africa, Brazil, and Southeast Asia, the most widely available iron ores are *laterites*. These have formed over the last 100 million years on stable continental platforms (cratons) that are subjected to alternating very wet and very dry seasons. Under these conditions, all elements in the soil except the relatively insoluble iron and aluminum tend to dissolve and be leached away (Delvigne 1998). Iron and aluminum ions are slowly moved downwards during the rains but reprecipitate as oxides and hydroxides between the high and low annual levels of the water table during the dry season. Iron-rich laterites form over ultrabasic and basic rocks, and aluminum-rich bauxites form over acid rocks. While laterites are generally of relatively low grade, usually containing residual quartz and clay minerals, they are widely available. The largest known concentration of prehistoric bloomery iron smelting furnaces—34,683 in a 30-km stretch along the Senegal River in Mauritania—used low-grade ores from laterites (Robert-Chaleix and Sognane 1983; Killick 2013). Laterites that formed over ultrabasic rocks may also contain significant amounts of nickel, cobalt, and chromium. While chromium would not be reduced in small hand-blown furnaces (see below), nickel and cobalt would pass into the iron. Thus, prehistoric iron–nickel alloys cannot automatically be assumed to have derived from the forging of meteorites (as many archaeometallurgists have suggested).

Gold and the PGEs have much higher specific gravities than most rock-forming minerals and are not dissolved by most surface waters. When ores of these elements are eroded, the metal grains may be carried into streams, where the loose sediments are sorted by flowing water according to specific gravity and grain size. Concentrations of metals formed in this way are termed *placers*. Few (if any) large placer gold deposits remain today, but all historical "gold rushes" began with the discovery of placer gold. The earliest prehistoric "gold rush," which began around the western and northern shores of the Black Sea in the mid-fifth millennium BC and lasted about a thousand years, also exploited placer gold (Chernykh 1992; Kienlin, this volume). Inclusions of PGEs in gold suggest that the gold came from a placer deposit, since gold and PGEs are not usually found in the same primary ores. Hard PGE inclusions are pressed into soft gold flakes by tumbling in streams.

Heavy minerals that are chemically stable in surface waters also form placers. The most important of these for archaeometallurgists is cassiterite (SnO_2), the principal ore mineral of tin. Depressingly little work has been done on the early mining and metallurgy of tin, so it is not known whether tin for the earliest bronze of western Eurasia derived initially from placers, though this seems very likely. Tin/tungsten placers derived from the granite batholiths of Cornwall and Devon have been repeatedly worked and reworked since the Bronze Age (Penhallurick 1986), but are now exhausted, as are most terrestrial tin placers throughout the world. (The huge tin placers of Malaysia, the world's largest producer of tin, are almost entirely offshore.) It appears from studies in Cornwall and Devon (Tylecote et al. 1989; Malham et al. 2002) and in South Africa (Chirikure et al. 2010) that placer tin production can sometimes be distinguished from mined tin by the chemical composition of the slags produced from smelting the concentrates. This is because heavy minerals like ilmenite ($FeTiO_3$) and zircon ($ZrSiO_4$), which are not generally present in tin ores but have eroded from other rocks in the region, may be concentrated with cassiterite in the placers. These dissolve in the slags to give higher Ti and Zr concentrations than occur in slags produced from mined ores (Chirikure et al. 2010).

Methods for Studying Ores Recovered From Archaeological Contexts

Many of the ore deposits used by early miners and metallurgists no longer exist, although the astonishing discovery of unknown Bronze Age mines in Britain during the 1990s (Timberlake 2003) shows that we should never assume that none remain in a given region. Archaeometallurgists have generally tried to infer which ores were used by indirect means. One approach has been to look for clues in the chemical composition of the metals and slags recovered from archaeological sites; the other has been to look at the distribution of ore deposits on a very broad regional scale. Only in the German-speaking countries, where the study of ores with the microscope was first developed, has the systematic examination of the ore minerals recovered from archaeological sites been a consistent component of archaeometallurgical projects. Much of the publication of this research has been undertaken by the Deutsches Bergbau-Museum in Bochum, which currently lists some 165 monographs on the prehistory and history of mining and metallurgy. In Anglophone archaeometallurgy, only Robert Ixer, George (Rip) Rapp, and Alan Craig have done systematic work on ores (e.g., Ixer and Pattrick 2003; Rapp et al. 1990, 2000; Craig and West 1994), while in France, David Bourgarit, Benoit Mille, and their students have recently made major contributions (see references in Bourgarit 2007). In large part, this reflects the fact that English- and French-speaking archaeometallurgists usually have their primary training in physical metallurgy, while German-speaking archaeometallurgists have theirs in geology and geochemistry. Important recent contributions have also been made by the Iranian geologists Nima Nezafati and Morteza Momenzadeh, in collaboration with German archaeometallurgists (e.g., Nezafati et al. 2008).

Over the last century, economic geologists have used a number of methods to infer the large-scale processes that create ore deposits. These include field observation, the methods of structural geology, the optical microscope, and (since the 1960s) the scanning electron microscope, electron microprobe, and isotopic ratio measurements to identify characteristic associations of ore minerals in particular settings. Archaeometallurgists use many of these same techniques to study ores from archaeological sites, and to trace archaeological ore samples to the ore deposits described for the region in the geological and mining literatures. Studies of ores samples may also be useful in reconstructing how ores were treated before they were smelted. I will concentrate here on the use of optical and electron microscopes to identify minerals and document ore associations and textures; on the use of the electron microprobe and micro-X-ray fluorescence (μ-XRF) for chemical analysis; and on X-ray diffraction and Raman spectroscopy for mineral identification.[2]

Optical Microscopy

As most ore minerals are opaque in standard 30-micron-thin sections, classical ore microscopy centered on the examination of polished blocks with vertical reflected light. Ore microscopy was largely developed in the USA (e.g., Campbell 1906; Murdoch 1916) and in Germany by Paul Ramdohr (1890–1985) and his students. Essential references for ore microscopists include the text of Craig and Vaughan (1981) and the color atlases of Ixer (1990) (with an online version by Ixer and Duller (1998)) and Pracejus (2008).

The ore microscope is similar to the metallographic microscope, but has a rotating stage, is equipped with polarizer and analyzer, and requires a more powerful light source (at least 100 W). Minerals are identified by crystal form, twinning, color, reflectance, reflection pleochroism (change of color with rotation in reflected plane-polarized light, PPL), bireflectance (change of color or brightness with rotation in reflected cross-polarized light), internal reflections, and hardness (Craig and Vaughan 1981). Variations in color, pleochroism, and bireflectance, as well as internal reflections, are enhanced if oil-immersion objectives are used instead of the dry (air) objectives on metallographic microscopes. Since perception of the color

[2] For the use of heavy isotopes to infer the provenance of ores, slags, and metals, see the chapter by Ernst Pernicka in this volume.

and reflectance of a given mineral by the eye is conditioned by those of the minerals surrounding it, professional ore microscopists measure reflectance and color with spectrophotometers and light sources that produce monochromatic light at several wavelengths. The microhardness of grains (on the Vickers scale) is measured with a diamond micro-indenter identical to that used in metallography. Quantitative values for reflectance and microhardness for ore minerals are listed in standard reference works, such as the indispensible volume by Uytenbogaardt and Burke (1985). These are very expensive accessories, however, and if they are not available, the analyst can train his or her eyes for reflectance and color with reference samples and with the color atlases of Ixer (1990) and Pracejus (2008). The relative hardness of minerals in a given section can be judged from variation in the width of polishing scratches as they pass from one mineral into another.

Uytenbogaardt and Burke (1985) list optical and hardness data for more than 500 ore minerals and Pracejus (2008) provides color microphotographs of some 450. At least 30 of these are likely to be encountered by the archaeometallurgist in ore samples, inclusions of incompletely reacted ore in slags, as crystals formed from molten slags, or as minerals produced by the corrosion of metals (Table 2.2). Some occur in more than one of these contexts, while magnetite (Fe_3O_4) and cuprite (CuO) are seen in all four. Ore microscopy is usually done in reflected light on polished blocks, but not all ore minerals are opaque—for example, the copper carbonates, sphalerite (ZnS), and cassiterite (SnO_2) are not; nor are most gangue minerals. It is therefore preferable in some situations to prepare samples as polished thin sections that can be examined in both reflected and transmitted polarized light (Ixer 1990). The advantages of this can be appreciated by comparing Figs. 2.2a, b.

The ore microscopist not only identifies all of the minerals present in each sample but also documents the textures of the ores. This information is used to infer *paragenesis*—the mineral association in particular locations—and *paragenetic sequence*—the sequence of deposition of the minerals through time within an ore deposit. From examination of suites of samples across ore deposits, the ore microscopist tracks the evolution of the ore-forming fluids and can infer whether the deposit was formed by a single pulse of fluids or whether there has been partial replacement of the original assemblage by later fluids. Evidence of two or more distinct periods of mineralization within a single ore deposit would have obvious implications for provenance studies by lead isotopes (Ixer 1999; Pernicka, this volume). Archaeometallurgists can use the published studies of ore deposits to infer the possible provenance of ore samples from archaeological sites, even if the ore deposits have since been mined away.

Chemical Analysis

Many ore minerals look alike in reflected light even to the trained eye, so microchemical analysis is an essential complement to optical examination in the identification of ore minerals. Conversely, distinct minerals may have identical

Table 2.2 Common ore minerals of relevance to archaeometallurgists

Mineral name	Chemical formula	Most common occurrences
Native gold	Au	Hydrothermal veins, placers
Native copper	Cu	Supergene oxidised
Cuprite	CuO	Supergene oxidised
Malachite	$Cu_2CO_3(OH)_2$	Supergene oxidised
Azurite	$Cu_3(CO_3)_2(OH)_2$	Supergene oxidised
Cerussite	$PbCO_3$	Supergene oxidised
Smithsonite	$ZnCO_3$	Supergene oxidised
Siderite	$FeCO_3$	Hydrothermal veins, sedimentary ores, BIF
Chrysocolla	$(Cu,Al)_2H_2Si_2O_5(OH)_4nH_2O$	Supergene oxidised
Olivenite	$Cu_2AsO_4(OH)$	Supergene oxidised
Clinoclase	$Cu_3AsO_4(OH)_3$	Supergene oxidised
Scorodite	$FeAsO_4.2H_2O$	Supergene oxidised
Annabergite	$Ni_3(AsO4)_2.8H_2O$	Supergene oxidised
Haematite	Fe_2O_3	Supergene oxidised, skarns, BIF, hydrothermal veins, laterites
Goethite	FeO(OH)	Supergene oxidised, bog ores, laterites
Lepidocrocite	FeO(OH)	Supergene oxidised, bog ores, laterites
Magnetite	Fe_3O_4	Ultrabasic magmatic, VMS, BIF, skarns, placers
Ilmenite	$FeTiO_3$	Ultrabasic magmatic, placers
Cassiterite	SnO_2	Granitic hydrothermal veins, pegmatites, skarns, placers
Covellite	CuS	Supergene enriched, hydrothermal alteration
Chalcocite	Cu_2S	Supergene enriched, sedimentary syngenetic or epigenetic
Digenite	Cu_9S_5	Supergene enriched
Chalcopyrite	$CuFeS_2$	Hypogene porphyry, VMS, hydrothermal veins, sedimentary sulphides
Bornite	Cu_5FeS_4	Hypogene porphyry, VMS, sedimentary
Tetrahedrite	$(Cu,Ag)_{12}Sb_4S_{13}$	Hypogene porphyry, skarns,VMS, SEDEX
Tennantite	$(Cu,Ag)_{12}As_4S_{13}$	Hypogene porphry, granitic vein deposits VMS, SEDEX
Pyrite	FeS_2	Hypogene sulphides, VMS, SEDEX, hydrothermal veins
Pyrrhotite	FeS	Hypogene sulphide
Arsenopyrite	FeAsS	Hypogene sulphide, hydrothermal veins
Pentlandite	$(Fe, Ni)_9S_8$	Ultrabasic magmatic
Niccolite	NiAs	Hydrothermal alteration of ultrabasic rocks
Galena	PbS	Magmatic sulphides, VMS, SEDEX, hydrothermal veins, epigenetic sedimentary
Sphalerite	ZnS	Magmatic sulphides, VMS, SEDEX, hydrothermal veins, epigenetic sedimentary
Stibnite	Sb_2S_3	Skarns, granitic hydrothermal veins, sedimentary epigenetic
Acanthite	Ag_2S	Supergene enriched, hydrothermal veins
Stannite	Cu_2FeSnS_4	Granitic hydrothermal veins

chemical compositions—for example, hematite α-Fe_2O_3 (hexagonal) and maghemite γ-Fe_2O_3 (cubic). Optical microscopy, electron microscopy, and chemical analyses are therefore complementary, and any thorough investigation of ore samples will use all of these.

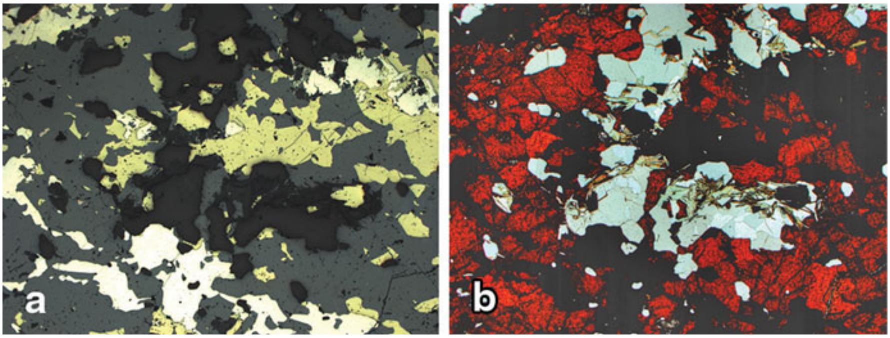


Fig. 2.2 **a** A copper–zinc ore from the Murchison Range, South Africa in reflected PPL. The width of the field is 6 mm. The two minerals identifiable in reflected plane polarized light are pyrite, FeS_2 (*white*) and chalcopyrite, $CuFeS_2$ (*yellow*). (Photograph by author). **b** The same field of view in transmitted PPL. This allows identification of a third ore mineral, sphalerite, ZnS (*orange*) and the gangue mineral quartz (*gray* to *white*) and mica (*small gray* and *brown needles*). (Photograph by author)

The standard methods for chemical analysis of individual crystals of ore minerals are energy-dispersive X-ray analysis (EDX), usually as an attachment to a scanning electron microscope, and wavelength-dispersive X-ray analysis (WDX) by electron microprobe. The lower spectral resolution of EDX can pose problems in the examination of sulphide minerals because it is unable to distinguish major X-ray peaks for lead, arsenic, and sulfur. The precision of EDX systems may also be inadequate for identifying opaque minerals that are easily distinguished by optical microscopy—for example, the common copper sulphides, digenite (Cu_9S_5, cubic) and djurleite ($Cu_{31}S_{16}$, monoclinic). WDX systems have much better spectral resolution and are preferred for quantitative analysis.

A useful alternative to EDX is μ-XRF, which focuses X-rays to a spot 10–30 microns in diameter. Samples for μ-XRF do not need to be coated to make them electrically conductive (as is required for chemical analysis with electron beams), and with the use of appropriate filters on the incoming X-ray beam, μ-XRF can achieve lower detection limits than WDX. μ-XRF units should not be confused with portable X-ray fluorescence units (p-XRF). The latter have less powerful X-ray generators, lower spectral resolution, and more limited software than μ-XRF units, and are restricted to the analysis of relatively large areas, typically rectangles about 5–10 mm on a side. p-XRF units are very useful in the field for rapid qualitative analysis, but are less suitable for quantitative analysis than WDX and μ-XRF.

Bulk chemical analyses of ore samples from archaeological sites are generally of limited value, whether for reconstruction of technology or for inferring provenance. It is often impossible to know whether scattered pieces of ore around smelting furnaces are representative of those charged to the furnace, or whether these were pieces discarded by the smelters as unusable after further sorting of material brought back from the mines. Non-ferrous ore lumps on archaeological sites are generally of more variable metal content than are lumps of ferrous ores, because veins and gossans are usually less homogeneous than chemical sediments, to which the great majority of iron ores belong. An exception must be made for gold and silver ores, where bulk chemical analyses or fire assays of larger samples are more meaningful indicators of precious metal content than are point analyses of individual mineral grains (though see Ixer (1999) on the implications of single-grain analyses for gold provenancing studies).

X-ray Diffraction and Raman Microscopy

Powder X-ray diffraction (XRD) is the default method of identifying minerals in an ore sample. Crushing the sample to powder ensures (except in the case of platy crystals like micas) a random alignment of crystal lattices, which ensures that all peaks for a given mineral will be present in the spectrum. This makes identification of crystalline compounds more certain than where only some of the peaks are represented, as they are with single crystals. XRD is however less sensitive than ore microscopy for detection of minerals present only in small proportion (typically less than 5 % wt) in the sample. These minor minerals may be important for inferring the geological provenance of the ore sample. Powder diffraction also requires a few grams of powder, which may be too much for small archaeological samples, and it cannot identify minerals that are poorly crystallized (cryptocrystalline), as some common minerals in the oxidized zone of copper ore deposits—such as iron hydroxides and chrysocolla (Table 2.2)—tend to be.

A powerful, swift alternative to powder XRD is Raman microscopy (Smith and Clark 2004). This is non-destructive, except for compounds (like some silver minerals) that are degraded by exposure to laser beams. It can be used on polished blocks and thin sections of ores, or even on unprepared specimens. Raman and infrared spectroscopies measure the same phenomenon, which is the momentary absorption and loss of vibrational energy by molecular bonds. Raman spectroscopy is generally the better technique for identification of inorganic molecules, and infrared spectroscopy for organic molecules, but many minerals can be identified by either method. Since Raman and infrared peaks correspond to molecular bonds, not crystal plane spacings as in XRD, both work well in identifying cryptocrystalline minerals.

While it takes about 4 h to obtain a publication-quality spectrum using powder XRD, a spectrum of comparable quality can be obtained by Raman spectroscopy in as little as 5 min, and a spectrum sufficient for identification in as little as 30 s. It is therefore an excellent technique for rapid screening of samples. When using a high-power objective (50 ×) on a polished surface, the spatial resolution is 1–2 microns, making Raman a perfect complement to optical ore microscopy. I have found it particularly helpful in studying copper ores from oxidized zones, where it is often not possible to distinguish by optical petrography between copper carbonates and copper arsenates, both of which typically form masses of very fine green needle-shaped crystals. Raman microscopy can easily distinguish between them. Raman spectrometers can even be added to some scanning electron microscopes—a shutter allows the user to switch between the electron beam and the laser beam.

The major limitations of Raman spectroscopy for mineral identification are:

(1) Some crystals with face-centered cubic (fcc) crystal structure are not Raman active (i.e., do not produce Raman peaks). These include metallic Al, Ni, Cu, Rh, Pd, Ag, Ir, Pt, Au, and Pb, and the mineral galena (PbS).
(2) Fluorescence can sometimes overwhelm the Raman peaks. For this reason, most Raman systems are equipped with at least two lasers of different wavelengths (typically 514 and 782 nm). The longer wavelengths are less susceptible to fluorescence, but produce smaller peaks.
(3) Raman spectra vary with the orientation of the lattice in the crystal under investigation, and with ionic substitutions. It is essential to bear this in mind when attempting to match unknowns to reference spectra.

A particularly useful database of reference spectra for archaeometallurgists is the RRUF website (http://rruff.info/). This provides free downloadable XRD, infrared and Raman spectra, and chemical compositions (by microprobe) for multiple reference specimens of each of more than a thousand minerals. It includes all minerals in Table 2.2, and is continually updated with the ultimate intention of incorporating all 3800 known minerals (Bob Downs, personal communication). The site also provides free software for automatic refining and matching of XRD and Raman spectra to reference samples in the database.

Smelting Ores to Metals

Aspects of preindustrial smelting technology are spread over three chapters in this book. Discussion of the hardware required for smelting—furnaces, crucibles, tuyeres, etc.—can be found in the chapter on technical ceramics (Rehren and Martinon-Torres, this volume). The study of slags (Hauptmann, this volume) informs us on the knowledge and degree of expertise of prehistoric smelters, as inferred from the fluxes (if any) used and the temperatures and furnace atmospheres achieved. In this section I focus on the thermodynamics and kinetics of the chemical reactions that convert ore minerals to metals, and relate these to the geological considerations that I introduced above.

(a) Native metals and oxides Gold is almost always found at the earth's surface as a native metal. The PGEs (rhodium, palladium, osmium, iridium, and platinum), copper, mercury, and silver sometimes occur as native metals, but iron is very rarely encountered as the metal at the earth's surface. It usually occurs as extraterrestrial iron–nickel meteorites, which contain 5–35 wt% Ni (Buchwald 1975; Knox 1987). In a very few locations, it occurs as "telluric iron"—i.e., iron–nickel or nickel–iron pellets (often containing carbon, making natural steels and cast irons) that usually result from the intrusion of ultrabasic or basaltic magmas into carbonaceous sediments. Pellets with Ni > Fe are reported from Oregon (USA) and New Zealand, and those with Fe > Ni from Russia, Germany, and Greenland. The only known use of telluric iron was in the Arctic, where small pellets from Disko Island, Greenland,

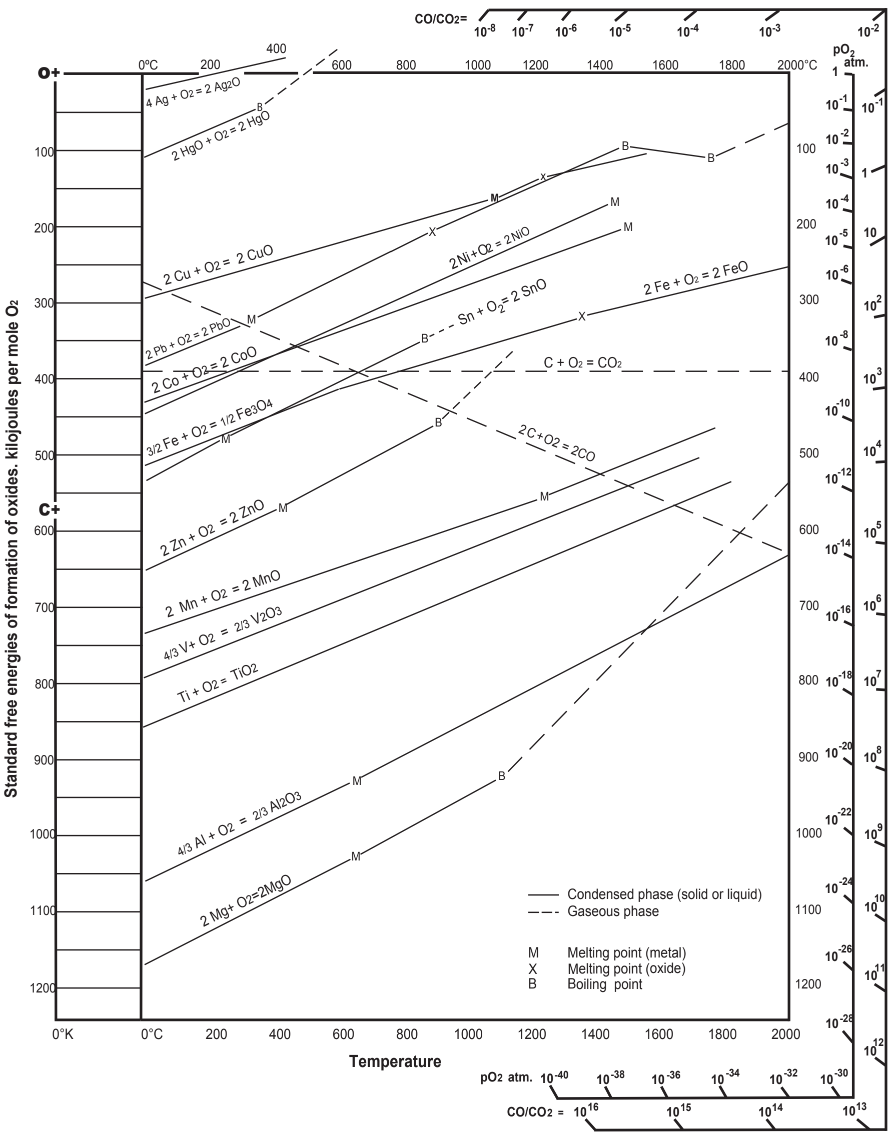


Fig. 2.3 The Ellingham diagram for the oxides of selected metals and carbon

containing up to 4 % Ni were cold-hammered by the Inuit for insertion into bone handles (Buchwald 1992). The other metals employed before the early Industrial Revolution (lead, zinc, and tin) are very rarely found as native metals.

These facts are well explained by the affinity of each metal for oxygen. Figure 2.3 is a plot of the Gibbs free energy of formation (ΔG) for the oxides of selected metals and carbon (*y*-axis) against temperature (*x*-axis) at 1 atmosphere pressure. This is known as an Ellingham diagram and is a tool of fundamental importance in the iron and steel industry. Below each line the metal is stable; above it the oxide is stable. Since ΔG is negative for all points on this plot, the reaction of each of these metals with oxygen is exothermic (releases energy). The more negative the free energy of formation, the stronger the chemical bond formed between the metal and oxygen. Gold is not on this diagram because gold oxide has positive ΔG in the range of temperatures plotted, and thus decomposes spontaneously. The oxides of the five PGEs are not plotted either for the same reason.

The reduction of oxide to metal is endothermic (absorbs energy) in all cases, and so the lines for ΔG versus temperature have positive slopes—each oxide becomes steadily less stable as the temperature is increased. Thus, a supply of heat is absolutely necessary for smelting metals from oxide ores. However, heat alone is not sufficient; the diagram shows that only Ag and Hg oxides will spontaneously decompose to the metal at temperatures below 2,000 °C. A reducing agent that has greater affinity for oxygen than the metal is therefore also required, and for rapid reduction, the reducing agent needs to be a gas. Hydrogen is the best choice, but preindustrial metalworkers had no way to produce it. Carbon monoxide (CO) is a good reducing agent and can be produced by the controlled reaction of air with pure carbon (charcoal or coke).

Carbon monoxide is the product of two sequential reactions. The first is an exothermic reaction producing carbon dioxide:

$$C + O_2 \rightarrow CO_2(\Delta H_f{}^o = -394.13\text{kJ per mole } O_2)^3.$$

The second step, known as the Boudouard reaction, is however endothermic:

$$CO_2 + C \rightarrow 2CO(\Delta H_f{}^\circ = +170.70\text{kJ per mole } O_2)$$

ΔG for both reactions is plotted as a function of temperature on the Ellingham Diagram (Fig. 2.3). While ΔG for the first reaction is a horizontal line, that for the Boudouard reaction has negative slope. The two lines cross at about 700 °C. Above this temperature, therefore, CO is more stable than CO_2, which will tend to react with charcoal to produce more CO.

The ratio of CO to CO_2 needed to reduce any metal from its oxide at any temperature in the range plotted can be found by laying a ruler across the plot from the point labeled *C+* on the *y*-axis to the intersection of the line for the relevant metal oxide at any selected temperature. Follow the ruler beyond the right side of the plot to its intersection with the scale labeled CO/CO_2. The value at the intersection with this scale is the minimum CO/CO_2 ratio required to reduce that oxide to metal at the given temperature. For CuO at 1,200 °C, for example, only 1 part CO to 10^3 parts CO_2 is required. For FeO at 1,200 °C, the required ratio is about 5 parts CO to 1 part CO_2. For Al_2O_3 at 1,200 °C, the ratio needed is about 10^9 parts CO to 1 part CO_2—a ratio that is impossible to achieve even in modern industry. Aluminum metal cannot be made by smelting aluminum oxide with charcoal; it is produced instead

---

[3] $\Delta H_f{}^0$ is the heat of formation (enthalpy) of a compound at a fixed temperature (273 K). It is related to ΔG by the equation $\Delta G = \Delta H + T \Delta S$, where ΔH is the enthalpy at a given absolute temperature T, and ΔS is entropy.

by electrolysis of molten aluminum oxide in a suitable flux, and thus the aluminum industry consumes vast amounts of electric power.[4]

We can now see that the Ellingham diagram solves the paradox that was noted above in the section on the geochemical abundance of the metals in the earth's crust. Why were the first metals used (Au, Pb, and Cu) among the geochemically scarce elements, while six of the seven most abundant metals (Al, Mg, Ti, Mn, V, and Cr) were not used until the nineteenth or twentieth centuries? The Ellingham diagram shows us that the historical sequence for the use of metals roughly corresponds to the relative affinity of each metal for oxygen. Gold oxide is unstable. Silver and copper are so weakly bound to oxygen that the oxides can be reduced to the metal by geological process, producing native metals. However, even when present as oxides, they are very easily reduced by the most rudimentary smelting technology—a shallow crucible filled with ore and charcoal, and blown with bellows or even a blowpipe powered by human lungs (Rehder 2000).[5] Lead oxide is much more stable than copper oxide at low temperatures, and thus lead very rarely occurs as a native metal. However, above 1,000 °C the ΔGs of PbO and Cu_2O are almost identical, so the two oxides are equally easy to reduce. This is why copper and lead were the two earliest metals to have been smelted. Mercury is easier to reduce than either but is a much rarer element, and thus appears later in prehistory.

Iron is bound more tightly to oxygen in FeO than are lead and copper in PbO or Cu_2O, and thus the reduction of FeO to Fe requires a much higher ratio of CO to CO_2. Developing the technology to consistently obtain the required ratio took a very long time. Copper and lead were smelted by 5000–4600 BC in both the Balkans (Radivojević et al. 2010; Kienlin, this volume) and copper by 5000–4500 BC in Iran (Frame 2009; Thornton, this volume), but close control of the composition of the reducing gas is simply not possible in the shallow dish crucibles, blown from above, that were used in the Near East. On the Iranian plateau, crucibles were preferred to furnaces until ca. 3000–2500 BC (Frame 2009).

Shallow-pit furnaces appeared in the Levant around 3800 BC (Thornton et al. 2010; Golden, this volume). Even small pit furnaces powered by blowpipes can attain sufficiently reducing conditions to reduce iron (Fig. 2.4), but there is no way to separate the iron from the copper in such a furnace. The iron is simply a contaminant that must be removed by refining, which is easily achieved by remelting the raw copper in an open crucible. Since iron has a greater affinity for oxygen than copper does (Fig. 2.3), it will reoxidize, and the molten iron oxide floating on the copper can be scraped or poured off.

Shaft furnaces with upright well-plastered airtight shafts, powered by bellows connected to tuyères projecting through the walls, were developed for greater productivity in copper smelting, but they also made possible the formation of pieces of iron bloom. This is because of the large difference in the melting points of copper

[4] Even though aluminum is the most abundant metal (Table 2.1), recycling makes good economic sense because much less energy is needed to remelt aluminum than to smelt an equivalent amount from alumina.

[5] Many archaeometallurgists greatly overestimate the difficulty of smelting copper from oxides.

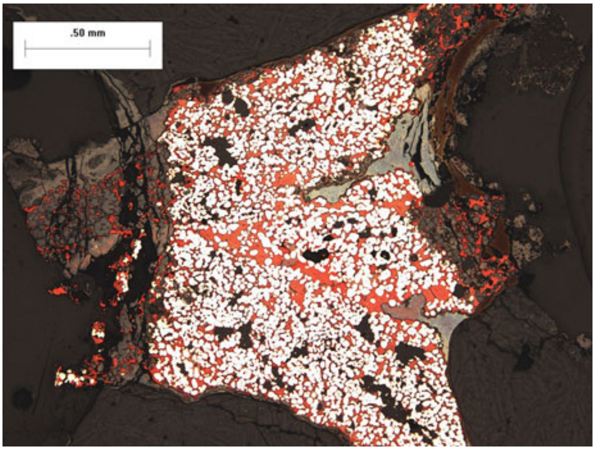


Fig. 2.4 A grain of a weathered copper–iron mineral (presumably originally a copper–iron sulphide), reduced to copper and iron metal, from a small lung-powered copper smelting pit furnace of the early second millennium CE on the Pampa de Chapparui, Lambayeque Province, Peru. (Photograph by author)

(1084 °C) and iron (1538 °C). In a shaft furnace, molten copper can drain to the base of the furnace, leaving tiny grains of hot solid iron suspended among charcoal. As these come into contact with each other, whether by consumption of the charcoal or being swept up in slag, the iron grain weld to each other. From time to time, therefore, copper workers may have found small lumps of metallic iron bloom in their furnaces.

About a dozen iron objects (including two daggers) are known from eastern Anatolia between 2800 and 2100 BC (EB II and EB III). Although some of these contain nickel, the concentrations are mostly too low for meteorites, and they are therefore tentatively accepted as smelted iron (Yalçin 1999; Jean 2001; Lehner and Yener this volume).[6] By this time there were certainly shaft furnaces in use and the use of iron oxides as fluxes in copper smelting was widespread (see Hauptmann, this volume). It is therefore possible that iron was made very occasionally as an accidental byproduct of the smelting of copper during this period. Iron is mentioned in Old Assyrian documents from about 1900 BC on as a rare and very valuable material, reserved for royal ceremony. It was not until the New Hittite period (1400–1200 BC) that written records mentioned the use of iron for weapons (Souckova-Sigelová 2001), so it was probably during this period that metalworkers began to regularly achieve the high ratios of CO to CO_2 needed to smelt iron. The magnificent gold-handled iron dagger in Tutankamun's tomb dates to this period and is thought to have been a gift from a Hittite ruler (Vallogia 2001).

The chemical composition of iron-fluxed copper slags is very similar to that of iron-smelting slags (Hauptmann, this volume), so iron smelting does not require higher temperatures than copper smelting. What makes iron smelting in small furnaces so much more difficult than copper smelting is the fact that the Boudouard

[6] Note, however, that Knox (1987) shows that nickel is leached from corroded meteoritic iron. As most of the earliest finds of iron are heavily corroded, the nickel content is not an infallible means of distinguishing between the two.

reaction ($CO_2 + C \Rightarrow 2CO$) is endothermic. To achieve the high CO/CO_2 ratio required to reduce FeO, much of the heat produced by the burning charcoal must be used to make CO. Yet the temperature of the furnace cannot be allowed to drop below 1,100–1,200 °C, or the slag will not be liquid enough to separate from the metallic iron (Hauptmann, this volume). When using small, poorly insulated furnaces the iron smelter must balance these two opposed requirements within a very narrow window (Rehder 2000).

From this perspective, it is easy to understand why so long an interval passed between the mastery of copper smelting and the mastery of iron smelting. It also explains quite well the widespread concerns of the last indigenous African iron smelters with witchcraft (Childs and Killick 1993). When one smelt succeeds, yet the next fails—even though it appears that the same materials and procedures were used—witchcraft provides a perfectly sensible explanation. This delicate heat balance also explains why iron smelting can only be conducted with charcoal or coke fuel. Wood, peat, and coal contain water that will absorb heat as it turns to steam, and that heat will be lost to the system as the steam leaves the furnace (Rehder 2000). Charcoal and coke are essentially pure carbon with a few percent ash (mostly oxides of calcium, potassium, and sodium).

The Ellingham diagram does not entirely explain the sequence of metallurgical innovation. Note that both nickel and cobalt are more easily reduced than iron and that nickel is more abundant than copper in the earth's crust, while cobalt is more abundant than lead (Table 2.1). The melting points of pure nickel (1,455 °C) and pure cobalt (1,495 °C) are close to the melting point of iron (1,538 °C), and both form alloys with carbon that have eutectics (minimum melting points) within the ranges of the larger charcoal-fuelled blast furnaces. Nickel and cobalt should also be reducible in the solid state by bloomery furnaces, as iron was before the innovation of the blast furnace. Yet there are, to my knowledge, no finds of smelted pure nickel or pure cobalt objects (or of their alloys with carbon) in antiquity; indeed, cobalt was only recognized as an element in 1735 AD, and nickel in 1751. This anomaly requires explanation, and for this we must turn to geochemistry instead of to thermodynamics.

As indicated in Table 2.1, both metals are strongly concentrated in ultrabasic rocks (dunites and peridotites), and much of the world's nickel supply now comes from laterites derived from weathering of these rocks. Nickel may be enriched in laterites to levels of a few percent and is mostly held in garnierites (nickel-bearing serpentine and talc). Most of these laterites consist of iron hydroxides, which are easily smelted. Iron–nickel alloys produced from laterites present in Sulawesi (Indonesia) form shiny (unetched) layers with 1–5 % Ni in some pattern-welded decorative blades (*keris*) from southeast Asia (Bronson 1987). We should also expect to find smelted iron–nickel alloys in those parts of Africa where laterites formed over ultrabasic rocks; the fact that these have not yet been noted is certainly a consequence of the very small number of chemical analyses of African iron that have been made to date.

Nickel can never be the major metal in laterites, but it certainly is in some sulphide ore deposits in ultramafic volcanic rocks and especially in komatiites (Guilbert and Park 1986: 362–367), where massive sulphides form puddles that have separated from the silicate lavas immediately above them. Nickel sulphide ores are also found in layered mafic and ultramafic intrusions that solidified below the earth's surface (Ixer 1990, pp. 24, 25). Both types of ultramafic rock were mostly formed quite early in the development of the earth's crust, and large nickel deposits are therefore only found where extensive areas of Archean rocks are exposed. These areas are predominantly in Australia, Canada, and the USA, where there was no smelting before European colonization. Major nickel deposits do however occur in South Africa, Zimbabwe, and Russia, and minor ones in Europe (e.g., Ixer 1990, pp. 38, 39). The necessary technological conditions for smelting nickel oxides have existed in these regions for 1800–2600 years. So why is there no evidence for it?

The main reason for this is probably that nickel and cobalt oxides are quite soluble in water (hence the high values of these elements in marine clays—see Table 2.1) and thus are almost never found in gossans. Thus, the fact that nickel and cobalt oxides are relatively easy to reduce is irrelevant—there were no oxide or carbonate ores of these elements available. Nickel and cobalt ore minerals are mostly sulphides and arsenides, which look very much like copper sulphides but are more difficult to reduce. This is known to have been a source of much frustration to medieval German copper smelters, who called the nickel ore mineral now known as niccolite (NiAs) "Kupfernickel" ("devil's copper"). Western metallurgists did not realize that these ores could be roasted to oxides, and then smelted to metal under conditions like those used for iron, until the middle of the eighteenth century.

Cassiterite (SnO_2) has very similar ΔG to FeO across the range of temperatures in the Ellingham diagram. Yet the first low-tin bronzes (with up to 3 % Sn) date to ca. 3000 BC—long before iron was smelted (Thornton 2007; Frame 2009). Some archaeometallurgists (e.g., Roberts et al. 2009) have suggested that the earliest bronzes resulted from the unintentional smelting of stannite (Cu_2FeSnS_4) or its oxidic weathering products, but there is no direct evidence for this. Stannite is rarely a major mineral in ore deposits; it occurs instead as a minor component in hydrothermal vein and VMS deposits (Taylor 1979; Ixer 1990). It is difficult to see how stannite could be concentrated enough to feed a furnace that could produce bronze with enough tin to be visibly or mechanically different from copper.

A more probable thesis is that the earliest bronzes with more than 5 % Sn were made with placer cassiterite, but that metallic tin was not involved. Bronze can be made instead by heating cassiterite in a crucible with copper metal under a thick cover of powdered charcoal. Objects of metallic tin are very rare indeed before the Late Bronze Age in Mesopotamia and the Aegean; the oldest known are in the Royal Cemetery at Ur (Early Dynastic III, ca. 2600 BC (Moorey 1999)) and a tin–iron bracelet from Thermi in the Aegean of about the same date (Begemann et al 1992). Tin metal can be smelted from cassiterite in small batches in sealed crucibles (to minimize loss of tin oxide as vapor) with the batches later remelted to form larger ingots. (The melting point of metallic tin is only 232 °C.) This procedure will obviously not work for iron, which has a melting point of 1,538 °C. We thereby arrive at a plausible explanation for the production of tin metal so much earlier than iron, but there is as yet no direct evidence for this scenario. In summary, tin remains the mystery metal in the archaeometallurgy of the Old World—we do not know how bronze was discovered, how metallic tin was first made, nor have we established the source(s) of the tin ores used in western Eurasia during the Bronze Age.

The early history of zinc and brass is better understood (Craddock 1998; see also the group of seven chapters in La Niece et al. (2007)). Zinc is geochemically much more abundant than tin (Table 2.1), yet brass appears later in the archaeological record than bronze. Setting aside the disputed claims for brass in the fourth and third millennia BC in China, the earliest known brass objects are at Thermi (Aegean) and date to the early third millennium BC. Thornton (2007, Table 2.1) lists 37 brass or gunmetal (copper + zinc + tin) objects dated before 1350 BC from the Aegean, Mesopotamia, Central Asia, Iran, and the Persian Gulf. However, brass did not become a common alloy in the Near East or the Aegean until the first century BC in the Roman Empire, though it was probably widespread much earlier in India. Metallic zinc appears very much later in the historical and archaeological record than brass. There are written references to it in Indian texts from the late first millennium BC (Craddock 1998) and the production of zinc appears to have been confined to South Asia until the Islamic era. It spread to, or was independently invented in China in the sixteenth century AD, but was not produced in western Europe until the eighteenth century.

These facts accord well with expectations derived from the Ellingham diagram (Fig. 2.4). Although zinc is frequently associated (as zinc carbonate) with lead and copper in oxidized ores, note that Zn has a much stronger bond to oxygen (more negative ΔG) than either Cu or Pb. With the typical CO/CO_2 ratios prevailing in early copper smelting, whether in crucibles or pit furnaces, ZnO will simply not be reduced. With the more reducing shaft furnaces, ZnO can potentially be reduced, though at CO/CO_2 ratios somewhat greater than those for FeO or SnO_2. However, metallic zinc boils above 907 °C to produce zinc vapor, which will be lost to the furnace and instantly reoxidized in contact with air. The several dozen brass objects known from early times must therefore represent very unusual circumstances where highly reducing atmospheres coincided with some means of preventing the escape of metallic zinc vapor. The only really plausible technology that satisfies both of these conditions is to heat metallic copper, zinc oxide, and powdered charcoal in a tightly sealed crucible. This was what the Romans did, and the remains of the very small lidded brass-making crucibles are among the most characteristic artifacts of Roman metallurgy (see Martinon-Torres and Rehren, this volume). The sporadic occurrence of brass in earlier millennia probably represents multiple earlier inventions of this technology that, for reasons unknown, did not become more generally adopted until the middle of the Roman era. The first production of metallic zinc, in India, required the invention of an ingenious piece of apparatus that combined an inverted crucible, packed with zinc oxide and charcoal, with a long tube to cool and condense the zinc vapor to liquid zinc. This is a form of distillation. It is not surprising that this innovation should have taken place in India, for Ayurvedic medicine had a long prior history of distillation to produce essential oils from plants (Craddock 1998).

Any oxide that is not reduced at the prevailing CO/CO_2 ratio will end up in the slag. This explains, for example, why prehistoric iron workers in South Africa were able to smelt magnetite/ilmenite ores containing up to 20 % TiO_2 (Miller et al. 2001), but modern blast furnaces cannot use iron ores containing more than 2 % TiO_2. The CO/CO_2 ratio in a furnace is a function both of its size and of the rate of air supply (Rehder 2000). The early hand-blown shaft furnaces used for smelting iron could not reduce the oxides of chromium, vanadium, or silicon but the early water-powered blast furnaces could. Higher CO/CO_2 ratios also favor the diffusion of carbon into metallic iron, and thus the production of cast iron (see Notis, this volume). Historic cast iron from water-powered blast furnaces contains up to 3.5 % silicon, though most of the silica will end up in the slag (Tylecote 1986, Tables 106 and 108).

Sulphide Minerals

An Ellingham diagram is also available for sulphides, but is not particularly useful for archaeometallurgists. This is because the conversion of sulphides to metals is much more complicated than the reduction of oxides to metals, requiring up to three separate operations. Sulphide ores are often physical mixtures of copper, iron, and copper–iron sulphides, sometimes also containing sulfosalts with arsenic and antimony (Table 2.2), as well as gangue minerals such as quartz and feldspars. Gangue can be reduced by washing away the lighter fraction, but iron sulphides cannot be separated from copper sulphides by washing because the specific gravities are too similar.

All of the major metal sulphides melt below 900 °C, and in a strongly reducing atmosphere pure sulphide minerals will simply melt and trickle to the base of the furnace to form matte (globules or plates of copper or copper–iron sulphides). Mattes are easily recognized by their glossy surfaces and their high specific gravity. Extracting the copper from matte requires two further operations. It must first be roasted in air to remove the sulfur as gaseous sulfur dioxide, leaving behind a mass of mixed copper and iron oxides. The copper is then separated from the iron by smelting this mixture with added quartz at CO/CO_2 ratios too low to produce any iron. Under these conditions, the iron oxides combine with silica to produce a fayalitic slag, while the copper is reduced to metal and separates from the slag by virtue of its higher specific gravity. This three-step process is called matte smelting.

An alternative is to eliminate the separation of matte, proceeding directly to the oxidation of the ore. When the sulphides are completely oxidized ("dead-roasted"), the ore is then smelted. The iron oxides combine with gangue (augmented with more quartz if necessary) to produce slag, which separates from the copper metal. Which of these two processes is more efficient depends upon a number of factors, including the proportion of gangue in the ore and the availability of water for improvement (beneficiation) of ore grade before thermal treatments. In both cases, the copper usually needs to be refined before use.

Both of these processes are historically well documented (e.g., Agricola 1950), but it seems unlikely that they were used in the earliest stages of extractive metallurgy because of their complexity when compared to the direct reduction of oxides. For this reason, it was long believed that the exploitation of sulphide ores was a stage in the development of metallurgy that began only after long experience with the smelting of oxide ores (e.g., Wertime 1973; Charles 1980). However, subsequent research suggests a more complicated picture. An important review article by David Bourgarit (2007) examines the mineralogy and chemistry of "slags" from 20 sites that provide some of the earliest evidence of the spread of extractive metallurgy across western Eurasia, from the fifth millennium BC (the Levant and Bulgaria) to the third millennium BC (France and Spain). Of these sites, five appear to have used oxide ores, four sulphide ores, and the remainder mixtures of oxides and sulphides. The chemistry and mineralogy of these "slags" is extremely variable. Most consist of patches of slag (i.e., assemblages of slag minerals, metals, and glass produced by crystallization of a melt) among unreacted or partly reacted ore and gangue minerals. In consequence, most do not have the mineral assemblages predicted by equilibrium phase diagrams for their chemical compositions (see Hauptmann, this volume).

These findings are prompting a major shift in thinking about the earliest smelting technologies. The remarkable scarcity of slag on the earliest copper-smelting sites in Eurasia is probably not, as previously supposed (e.g., Budd et al. 1992; Craddock 1999), a consequence of the smelting of very pure oxide ores ("slagless smelting"), but rather a consequence of the inability of many early metalworkers to effectively remove gangue as slag. The product would have had to be crushed to recover the copper, producing what Bourgarit (2007) calls "slag sands." This realization might have emerged earlier if Old World archaeometallurgists had been more familiar with the archaeometallurgy of South America. Moche and Sican copper smelters on the north coast of Peru (mid- to late-first millennium AD) smelted small batches of ores with blowpipes, and could not fully separate slag from metal. They had to crush the product to obtain the prills, producing slag sands that form stratified deposits up to a meter deep (Epstein 1993, Fig. 17). Perhaps the archaeological methods used so far in excavating the earliest smelting sites in the Old World are not recovering slag sands in many cases?

The occurrence of sulphide minerals at many of these early sites has also attracted much interest to the argument, first made by Rostoker et al. (1989), for the production of copper metal by cosmelting sulphides with oxides. They demonstrated the feasibility of this process through laboratory experiments, and proposed the following reactions:

$$2Cu_2S + 3O_2 \Rightarrow 2Cu_2O + 2SO_2$$

$$Cu_2S + 2Cu_2O \Rightarrow 6Cu + SO_2$$

The first reaction can be accomplished through partial weathering of sulphides exposed at the earth's surface, or by incomplete roasting of sulphide minerals by the smelters. The cuprous oxide then reacts with chalcocite to produce copper (cosmelting). This is an attractive suggestion because it offers a simpler *chaîne operatoire* than matte smelting or dead roasting, though it has yet to be demonstrated that it was actually employed in prehistory. Laboratory experiments under more controlled and systematically varied partial pressures of oxygen by David Bourgarit and colleagues suggest a more complicated picture when iron oxides are present as well. Iron compounds tend to remove oxygen as iron and copper–iron oxides in the slag, forcing the sulphides to form matte in mixed sulphide–oxide furnace charges instead of reacting with oxides to form copper metal (Bourgarit 2007, Table 2.2). (But see also the discussion of cosmelting experiments below in the section on copper/arsenic/antimony alloys.)

There is clearly much that we do not yet understand about the earliest copper smelting. The way forward from here is to continue to pursue smelting experiments, such as those of Lechtman and Klein (1999) and coupled laboratory experiments, like those conducted by David Bourgarit, Benoit Mille, and colleagues (summarized in Bourgarit 2007). The methods of ore geology must play a central role in studies of the earliest metallurgy, as many of the products are essentially partially reduced ores rather than slags in the modern sense.

In light of the discussion above of the absence of evidence for metallic nickel and cobalt in western Eurasia before the eighteenth century, it must be noted that copper–nickel coins (75 mass% Cu: 25 mass% Ni) were issued by the Graeco-Bactrian kingdom (northern Afghanistan) from 170 BC. This region was in contact with China, where some copper–nickel objects are dated as early as the Warring States period (ca. 475–221 BC). Since no objects of nickel are known from either region, one can assume that these alloys were made by smelting dead-roasted copper–nickel sulphide ores under more reducing conditions than those normally required to produce copper. The melting point of a 75Cu: 25Ni alloy is just below 1,200 °C. A ternary alloy called *paktong* was later developed in China, certainly by the Ming Dynasty (1368–1644) and perhaps before. This 60:20:20 alloy of copper, nickel, and zinc melts at around 1,130 °C and was used for coins; it was imported to Europe in the seventeenth and eighteenth centuries and stimulated the development of an equivalent alloy ("German silver"). Cobalt compounds were widely known and traded within the last 3,500 years in western Eurasia, and later in the East, as colorants for deep blue glasses (Moorey 1999), but copper–cobalt alloys melt at higher temperatures than their copper–nickel equivalents. This may explain their apparent absence from the archaeological record.

Arsenical and Antimonial Copper

In both western Eurasia and in South America, we see evidence of a stage between the first appearance of smelted (nearly pure) copper and the first appearance of tin bronzes, during which copper containing a few percent of arsenic and/or antimony was used. Arsenic hardens copper as effectively as tin up to about 10 mass% As (Budd 1991). The addition of more than 3 mass% arsenic and/or antimony makes harder, sharper tools than those made of pure copper, so this innovation represents a very significant advance in the history of metallurgy. At higher concentrations (10–25 mass%), both elements make copper too brittle to forge, but they make attractive casting alloys (as seen in the late Chalcolithic hoard at Nahal Mishmar in the southern Levant—see Golden, this volume).

Ever since this stage in the history of metallurgy was recognized in the late 1950s, it has been the subject of considerable controversy. From which minerals and ore bodies did the arsenic and antimony derive? Were these alloys simply fortuitous—the result of smelting ores that happened to contain arsenic and/or antimony? Or were the arsenic and antimony concentrations controlled by adding minerals or a "master alloy" to molten copper?

Both elements are geochemically scarce (Table 2.1) and many copper deposits contain negligible amounts of either element, but in some deposits arsenic and/or antimony minerals are major components of the parageneses. The continuous series of minerals from tennantite ($Cu_{12}As_4S_{13}$) to tetrahedrite ($Cu_{12}Sb_4S_{13}$) are known as fahlores (fahlerz), and may also be important ores of silver (which substitutes for copper). They occur mostly in epigenetic veins and were deposited from hydrothermal fluids at relatively high temperatures. Fahlores are dominant in ore deposits in some parts of the Alps, especially in Austria, and have been the subject of much speculation in archaeometallurgy as potential ores for early copper–arsenic alloys. Many of the porphyry copper deposits along the Andes also contain tennantite–tetrahedrite, or the parallel series from enargite (Cu_3AsS_4) to famatinite (Cu_3SbS_4) (Guilbert and Park 1986). Copper–arsenic alloys were widely used in Andean prehistory from ca. 800 CE to ca. 1450 CE (Lechtman and Klein 1999), but there are curiously few reports of prehistoric copper–antimony alloys from South America. Antimony is also found in quartz-stibnite (Sb_2S_3) veins, often with gold; these are most common in China. Ores with stibnite, galena, and arsenopyrite (FeAsS) often accumulate at structural traps in sediments, especially in carbonates. Arsenopyrite also tends to occur in high-temperature vein deposits around granitic intrusions, often with cassiterite (SnO_2) and tungsten minerals (Dill 2010).

Fahlores have frequently been suggested as the sources for the earliest arsenical coppers in Eurasia. (Antimonial coppers are less common.) This is unlikely for two reasons. The first is, as Ixer and Pattrick (2003) note, that tennantite and tetrahedrite are hypogene sulphides (contra Craddock 1995, p. 28). Thus, they are encountered only where the supergene layer has been removed by recent glaciation, or in mountain ranges where continuous, rapid erosion prevents the formation of a supergene layer. Elsewhere they were rarely accessible to prehistoric metallurgists.

The second reason is that direct smelting of tennantite or tetrahedrite will result in the loss of much of the arsenic and antimony to the brittle intermetallic copper/iron arsenides or antimonides, which are known as speiss. Conversely, if fahlores are dead-roasted before smelting, most of the arsenic and antimony will be lost to the air as the volatile (and poisonous) oxides As_2O_3 and Sb_2O_3, though enough can remain to allow the smelted copper to retain 2–3 % As or Sb (Höppner et al. 2005).

It has been widely assumed that during the spread of metallurgy across Europe from the Balkans (earliest metallurgy 5000–4500 BCE) to Britain (earliest metallurgy ca. 2400 BCE), early metalworkers were able to figure out fairly quickly how to smelt the various copper sulphide ores that they encountered. However, this view has recently been challenged. A few Neolithic copper slags, dating from 4500 to 4000 cal BCE (but see Kienlin this volume), have been recovered in the Innsbruck area of Austria, and analysis of them shows that smelting of fahlores was attempted.

However, lead isotopic analysis of many Neolithic copper artifacts from this region shows unequivocally that these cannot have been smelted from the fahlores, but were instead imports from eastern Europe. It was not until the Early Bronze Age (2500–2000 cal BCE) that the distinctive chemical and lead isotopic ratios of these fahlores appeared in the copper of central Europe (Höppner et al. 2005).

A popular alternative scenario for the first appearance of arsenical copper is that it reflects the direct smelting of arsenates, which occur in the supergene zone above copper–arsenic–sulfur ores (Table 2.2). This is an attractive proposition because: (1) copper, iron, and nickel arsenates are blue–green minerals that can be confused with copper carbonates and (2) they smelt directly to copper–arsenic alloys in mildly reducing atmospheres, thus avoiding the excessive losses of arsenic associated with dead roasting. The smelting of arsenates was strongly suggested as the solution to the question of the first occurrence of copper–arsenic alloys in Britain and Iran (e.g., Charles 1980; Budd et al. 1992; Pigott 1999). This is certainly a plausible option, but it is one that has the potential to entrap unwary archaeometallurgists. As the ore geologists Ixer and Pattrick (2003) have warned, the fact that arsenates appear on lists of minerals from a given mine does not mean that they were ever present in quantities large enough to be potential ores for prehistoric metallurgists. Nor does their presence on spoil piles mean that they were even present in the supergene zone. Ixer (1999) notes that spoil piles (which he terms "supragossans") are fertile environments for the growth of new minerals under very different conditions than those prevailing underground.

The same caution applies to the argument of C. S. Smith, summarized by Pigott (1999) that the earliest arsenical copper on the central Iranian plateau was made by simply dissolving the minerals domkeyite (Cu_3As) and algodonite (Cu_6As) from the Talmessi/Anarak/Meskani mining district into molten copper. At this point in time speculative arguments serve no further purpose; archaeometallurgists need to produce the proof, which can only come from very detailed studies of ores and slags from well-dated archaeological contexts. Frame (2009) shows the way forward with her identification by Raman spectroscopy of algodonite in Chalcolithic levels at Tal-i-Iblis. Lead isotope analysis of these minerals is compatible with those of Talmessi/Anarak/Meskani, some 500 km distant, in which algondonite is a documented ore mineral.

A third pathway to copper–arsenic–antimony alloys is through cosmelting of copper oxides with copper–arsenic–antimony-sulphide minerals. The viability of this pathway has been directly demonstrated by the smelting experiments of Lechtman and Klein (1999). Their work focused on understanding the production of these alloys in South America, and used actual ores from the region. Copper "oxide" minerals (actually the hydroxychloride minerals atacamite ($Cu_7Cl_4(OH)_4$) and paratacamite ($Cu_2Cl(OH)_3$), which are major ore minerals along the arid southern Peruvian coast) were mixed in varying ratios with enargite (Cu_3AsS_4) or arsenopyrite (FeAsS). These were smelted in uncovered crucibles (little exposure to CO), and also in a small furnace (full exposure to CO) at relatively low temperatures ($<1{,}100\,^{\circ}C$) and at mixtures from 1:1 to 4:1 of the hydroxychlorides and sulfosalts. Copper–arsenic metal was produced in all cases except for the 1:1 mixtures; arsenic contents in the metal were from 7 to 26 wt%, the higher contents occurring where arsenopyrite was used. Matte and speiss were also produced, but in most cases separated cleanly from the metal. The results obtained are not directly comparable to archaeological finds because their crucible and furnace charges generally contained too little silica to form silicate slags, but they do establish without doubt that oxide–sulphide cosmelting provides a plausible mechanism for the initial production of copper–arsenic–antimony alloys. Which of these potential *châ ines operatoires* was actually used at a given smelting site must however be established by very detailed investigation of all the material evidence—ores, mattes, speisses, slags, refractories, and metal—in each case by the appropriate specialists.

Conclusions

The main message conveyed here is that the historical development of extractive metallurgy cannot be fully appreciated without some understanding of ore geology and geochemistry. Although geological perspectives have been fully integrated into archaeometallurgy in the German-speaking areas, they have often been absent from Anglophone and Francophone archaeometallurgy. Anglophone archaeometallurgists have been particularly prone to poorly informed speculation about ores and ore sources used in the past.

The deeper we dig into the prehistory of metallurgy, the more we need teams of collaborating specialists. To investigate the prehistory of extractive metallurgy, we need teams that include (at minimum) specialists in economic geology; the archaeology of mines and metallurgical sites; the interpretation of ores, slags, refractories, and metals; experimental replication of smelting processes in field and laboratory; and in inferring the geological provenance of ores and metals by chemical and isotopic techniques.

References

Agricola, G. (1950). *De Re Metallica*. Latin edition: Hoover, H. C., & Hoover L. H. 1556 (translated and annotated by H.C. Hoover and L. H. Hoover). Dover Publications, New York.

Aldenderfer, M. S., Craig N. M., Speakman, R. J., & Popelka-Filcoff R. (2008). Four-thousand-year-old gold artifacts from the Lake Titicaca basin, southern Peru. *Proceedings of the National Academy of Sciences, 105*(13), 5002–5005.

Amzallag, N. (2009). From metallurgy to bronze age civilizations: The synthetic theory. *American Journal of Archaeology, 113*, 497–519.

Begemann, F., Schmitt-Streker S., & Pernicka E. (1992). The metal finds from Thermi III-V: A chemical and lead isotope study. *Studia Troica, 2,* 219–240.

Bourgarit, D. (2007). Chalcolithic copper smelting. In S. La Niece, D. Hook, & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 3–14). London: Archetype Publications.

Bronson, B. (1987). Terrestrial and meteoric nickel in the Indonesian kris. *Historical Metallurgy, 21*(1), 8–15.

Buchwald, V. F. (1975). *Handbook of Iron meteorites*, (Vol. 2). Berkeley: University of California Press.
Buchwald, V. F. (1992). On the use of iron by the Eskimos in Greenland. *Materials Characterization, 29,* 139–176.
Budd, P. D. (1991). *A metallographic investigation of eneolithic arsenical copper*. PhD Thesis, University of Bradford.
Budd, P. D., Gale D., Pollard A. M., Thomas R. G., & Williams P. A. (1992). The early development of metallurgy in the British Isles. *Antiquity, 66*,677–686.
Campbell, W. (1906). The microscopic examination of the opaque minerals. *Economic Geology, 1,* 751–766.
Charles, J. A. (1980). The coming of copper and copper-base alloys and iron: A metallurgical sequence. In T. A. Wertime & J. D. Muhly (Eds.), *The coming of the Age of Iron* (pp. 151–181). Yale University Press, New Haven.
Chernykh, E. N. (1992). *Ancient metallurgy in the USSR*, (trans. S. Wright). Cambridge University Press: Cambridge.
Childs, S. T., & Killick D.J. (1993). Indigenous African metallurgy: Nature and culture. *Annual Review of Anthropology, 22*, 317–337.
Chirikure, S., Heimann R., & Killick D. J. (2010). The technology of tin smelting in the Rooiberg valley, Limpopo Valley, South Africa, ca. 1650–1850 CE. *Journal of Archaeological Science, 37*, 1656–1669.
Craddock, P. T. (1995). *Early metal mining and production*. Edinburgh University Press, Washington.
Craddock, P. T. (Ed.) (1998). *2000 years of zinc and brass*, (2nd ed). (British Museum Occasiona Paper 50). London: British Museum Press.
Craddock, P. T. (1999). Paradigms of metallurgical innovation in prehistoric Europe. In A. Hauptmann, E. Pernicka, Th. Rehren, & Ü. Yalçin (Eds.), *The beginnings of metallurgy* (pp. 175–192). Deutsches Bergbau Museum: Bochum.
Craig, J. R., & Vaughan, D. J. (1981). *Ore microscopy and ore petrography*. New York: Wiley.
Craig, A. K., & West, R. C. (Eds.). (1994) *In quest of mineral wealth: Aboriginal and colonial mining and metallurgy in Spanish America*, Department of Geography and Anthropology, Geoscience and Man 33. Louisiana State University, Baton Rouge.
Delvigne, J. E. (1998). *Atlas of micromorphology of mineral alteration and weathering*. Ottawa: Mineralogical Association of Canada.
Dill, H. G. (2010). The "chessboard" classification of mineral deposits: Mineralogy and geology from aluminium to zirconium. *Earth Sciences Reviews, 100,* 1–420.
Epstein, S. M. (1993). *Cultural choice and technological consequences: Constraint of innovation in the late prehistoric copper smelting industry of Cerro Huaringa, Peru*. Ph.D. Thesis. University of Pennsylvania.
Frame, L. D. (2009). *Technological change in southwestern Asia: Metallurgical production styles and social values during the Chalcolithic and Early Bronze Age.* Ph.D. dissertation, University of Arizona.
Faure, G. (1991). *Principles and applications of geochemistry*, (2nd Ed.). Upper Saddle River: Prentice Hall.
Gabler, S. C. (2005). *Iron furnaces and future kings: Craft specialization and the emergence of political power in central Madagascar*. PhD dissertation, University of Michigan.
Gordon, R. B., Bertram, M., & Graedel, T. E. (2006). Metals stocks and sustainability. *Proceedings of the National Academy of Sciences, 103,*1209–1214.
Guilbert, J. M., & Park, C. F. (1986). *The geology of ore deposits*. New York: W. H. Freeman.
Hauptmann A. (1985). 5000 Jahre Kupfer in Oman. *Der Anschnitt, 4,* 1–137.
Higueras, P., Oyarzun R., J. Munhá, & Morata D. (2000). The Almaden mercury metallogenic cluster (Ciudad Real, Spain): Alkaline magmatism leading to mineralization processes at an intraplate tectonic setting. *Revista Soc Geol Espana, 13*(1), 105–119.
Höppner, B., Bartelheim, M., Huijsmans, M., Krauss, R., Martinek, K.-P., Pernicka, E., & Schwab, R. (2005). Prehistoric copper production in the Inn Valley (Austria) and the earliest copper in Central Europe. *Archaeometry 47,* 293–315.

Ixer, R. A. (1990). *Atlas of opaque and ore minerals in their associations*. New York: Van Nostrand Reinhold.
Ixer, R.A. (1999). The role of ore geology and ores in the archaeological provenancing of metals. In S. M. M. Young, A. M. Pollard, P. Budd, & R. A. Ixer (Eds.), *Metals in antiquity* (pp. 43–52). BAR international series 792. Oxford: Archaeopress.
Ixer, R. A., & Duller, P. R. (1998). *Virtual atlas of opaque and ore minerals in their associations*. http://www.smenet.org/opaque-ore.
Ixer, R. A. & Pattrick, R. A. D. (2003). Copper-arsenic ores and Bronze Age mining and metallurgy with special reference to the British Isles. In P. Craddock & J. Lang (Eds.), *Mining and metal production through the ages* (pp. 9–20). London: British Museum Press.
Jean, E. (2001). Le fer chez les Hittites: un bilan des données archeologiques. *Mediterranean Archaeology 14,* 163–188.
Killick, D. J. (2013). Iron smelting technology in the Middle Senegal Valley, ca. 500 BCE-1500 CE. In R. J. McIntosh, S. K. McIntosh, & H. Bocoum (Eds.), *Seeking the origins of Takrur: Archaeological excavations and reconnaissance along the Middle Senegal River Valley* (Chapter 7). Yale University Publications in Anthropology;New Haven. (in press).
Knox, R. (1987). On distinguishing meteoritic from man-made nickel-iron in ancient artifacts. *MASCA Journal, 4*(4), 178–184.
Krauskopf, K. B., & Bird, D. K. (1995). *Introduction to geochemistry* (3rd ed.). McGraw-Hill: New York.
La Niece, S., Hook, D., & Craddock, P. T. (Eds.) (2007). *Metals and mines: Studies in archaeometallurgy*. London: Archetype Publications.
Lechtman, H., & Klein, S. (1999). The production of copper–arsenic alloys (arsenic bronze) by cosmelting: modern experiment, ancient practice. *Journal of Archaeological Science, 26,* 497–526.
Levtzion, N., & Hopkins, J. F. P. (Eds.) (2000). *Corpus of early arabic sources for West African history*. Princeton: Marcus Wiener.
Malham, A., Aylett, J., Higgs, E., & McDonnell, J. G., (2002). Tin smelting slags from Crift Farm, Cornwall, and the effect of changing technology on slag composition. *Historical Metallurgy, 36*, 84–94.
Martin, S. (1999). *Wonderful power: The Story of Ancient Copper Working in the Lake Superior Basin*. Detroit: Wayne State University Press.
Miller, D., Killick, D. J., & van der Merwe, N. J. (2001). Metal working in the northern Lowveld, South Africa, A.D. 1000–1890. *Journal of Field Archaeology, 28,* 401–417.
Moorey, P. R. S. (1999). *Ancient Mesopotamian materials and industries*. Winona Lake: Eisenbrauns.
Murdoch, J. (1916). *Microscopical determination of the opaque minerals: An aid to the study of ores*. New York: Wiley.
Nezafati, N., Pernicka, E., & Momenzadeh, M. (2008). Iranian ore deposits and their role in the development of the ancient cultures. In Ü. Yalçin (Ed.), *Anatolian Metal IV* (pp. 77–90). Der Anschnitt (Vol 21). Bochum: Deutsches Bergbau Museum.
Penhallurick, R. D. (1986). *Tin in antiquity*. London: The Institute of Metals.
Pernicka, E., Begemann, F. & Schmitt-Streker, S. (1993). Eneolithic and early Bronze Age copper artefacts from the Balkans and their relation to Serbian copper ores. *Prähistorische Zeitschrift, 68,* 1–54.
Pigott, V. C. (1999). Heartland of metallurgy: Neolithic/Chalcolithic metallurgical origins on the Iranian Plateau. In A. Hauptmann, E. Pernicka, Th. Rehren, & Ü. Yalçin (Eds.), *The beginnings of metallurgy* (pp. 107–120). Bochum: Deutsches Bergbau Museum.
Pracejus, B. (Ed.) (2008). *The ore minerals under the microscope: An optical guide*. Amsterdam: Elsevier.
Radivojević, M., Th. Rehren, E. Pernicka, D. Slijvar, M. Brauns, & Boric, D. (2010). On the origins of extractive metallurgy: new evidence from Europe. *Journal of Archaeological Science, 37,* 2775–2787.

Rapp, G., E. Henrickson, and J. Allert. (1990). Native copper sources of artifact copper in Pre-Columbian North America. In N. Lasca & J. Donahue (Eds.), *Archaeological Geology of North America* (Centennial Special Volume 4). Geological Society of America, Boulder, CO.

Rapp, G., Allert, J., Vitali, V., Jing, Z., & Henrickson, E. (2000). *Determining geologic sources of artifact copper: Source characterization using trace element patterns*. Lanham: University Press of America.

Rehder, J. E. (2000). *The mastery and uses of fire in antiquity*. Montreal: McGill-Queens University Press.

Roberts, B. W, Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity*, *83*,1012–1022.

Robb, L. (2005). *Introduction to ore-forming processes*. Oxford: Blackwell.

Robert-Chaleix, D., & Sognane, M. (1983).Une industrie métallurgique ancienne sur la rive Mauretanienne du fleuve Sénégal. In N. Échard (Ed.), *Métallurgies Africaines: Nouvelles Contributions* (*pp. 45–62*). *Mémoires de la Societé des Africanistes 9*. Paris: Societé des Africanistes.

Rostoker, W., Pigott, V. C., & Dvorak, J. R. (1989). Direct reduction to copper metal by oxide-sulphide mineral interaction. *Archeomaterials, 3,* 69–87.

Schoop, U-D. (1995) *Die Geburt des Hephaistos: Technologie und Kulturgeschichte neolithischer Metallverwendung im Vorderen Orient*. Espelkamp: Verlag Marie L. Leidorf.

Smith, G. D., & Clark R. G. H. (2004). Raman microscopy in archaeological science. *Journal of Archaeological Science 31,* 1137–1160.

Souckova-Sigelová, J. (2001). Treatment and usage of iron in the Hittite Empire in the 2nd millennium BC. *Mediterranean Archaeology, 1,* 189–193.

Stech, T. (1990) Neolithic copper metallurgy in Southwest Asia. *Archeomaterials, 4,* 55–61.

Stos-Gale, Z. A., Maliotis, G., Gale, N. H., & Annets, N. (1997). Lead isotope characteristics of the Cyprus copper ore deposits applied to provenance studies of copper oxhide ingots. *Archaeometry, 3,* 83–123.

Summers, R. (1969). *Ancient mining in Rhodesia*. Salisbury: National Museums of Rhodesia, Museum Memoir 3.

Taylor, R. G. (1979). *Geology of tin deposits*. Amsterdam: Elsevier.

Thornton, C. P. (2002). *The domestication of metal. A reassessment of the early use of copper minerals and metals in anatolia and southeastern europe*. Unpublished M. Phil. thesis, University of Cambridge.

Thornton, C. P. (2007). Of brass and bronze in prehistoric southwest Asia. In S. La Niece, D. Hook, & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy*. London: Archetype Publications.

Thornton, C. P., Golden, J., Killick, D. J., Pigott, V. C., Rehren, Th., & Roberts, B. W. (2010). A chalcolithic error: Rebuttal to amzallag (2009). *American Journal of Archaeology, 114,* 305–315.

Timberlake, S. (2003). Early mining research in Britain: The developments of the last ten years. In P. Craddock & J. Lang (Eds.), *Mining and metal production through the ages*. London: British Museum Press. (pp. 21–42).

Tylecote, R. F. (1986). *The prehistory of metallurgy in the British isles*. London: The Institute of Metals.

Tylecote, R. F., Photos, E., & Earl, B. (1989). The composition of tin slags from the southwest of England. *World Archaeology, 20,* 434–445.

Uytenbogaardt, W., & Burke, E. A. J. (1985). *Tables for microscopic identification of ore minerals* (2nd revised ed.). New York: Dover Publications.

Vallogia, M. (2001). La maîtrise du fer en Egypte: entre traditions indigènes et importations. *Mediterranean Archaeology 1,* 195–204.

Wayman, M. L., King, J. C. H., & Craddock, P. T. (1992). *Aspects of early north American metallurgy*. British Museum, Occasional Paper 79, London.

Wertime, T. A. (1973). The beginnings of metallurgy: A new look. *Science, 182,* 875–87.

Yalçin, Ü (1999). Early iron metallurgy in Anatolia. *Anatolian Studies, 49,* 177–187.

Chapter 3
Metals

Michael R. Notis

Introduction

Until the seventeenth century AD, fewer than a dozen or so metals were known to man. Aitchison (1960) lists the seven metals known in antiquity as gold (Au), silver (Ag), copper (Cu), tin (Sn), lead (Pb), iron (Fe), and mercury (Hg). All, but mercury, are also mentioned in the Bible (Ginzburg 1989). Forbes (1950) adds zinc (Zn), arsenic (As), and antimony (Sb). Platinum (Pt) was discovered in the sixteenth century and Bismuth (Bi) sometime within a few hundred years before that. Today, we recognize about 86 elements in the periodic table as being metallic.

The purpose of this chapter is to introduce the reader to some basic features of metallic elements and metal alloys, their mechanical properties, and their forming or shaping limitations. It is meant to describe what you need to know about the 'metallurgy' in archaeometallurgy!

Metals and Their Bonding

If you examine the periodic table of the elements (Fig. 3.1), all of the elements can be divided into three groups (metals, metalloids, and nonmetals) according to the way in which they bond to form a solid. In fact, the overwhelming majority of the atomic elements are metallic in nature.

Metallic elements have only a few (1–3) outer negative electrons per atom, and these electrons are not locally bound to any specific atom in the solid. The electrons are effectively free to drift through the metallic solid, belonging to the metal as a whole, and forming a "sea of electrons." In a more quantum-mechanical view, the

M. R. Notis (✉)
Department of Materials Science and Engineering,
Whitaker Laboratory, Lehigh University,
5 East Packer Ave, Bethlehem, PA 18015, USA
e-mail: Mrn1@lehigh.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_3,

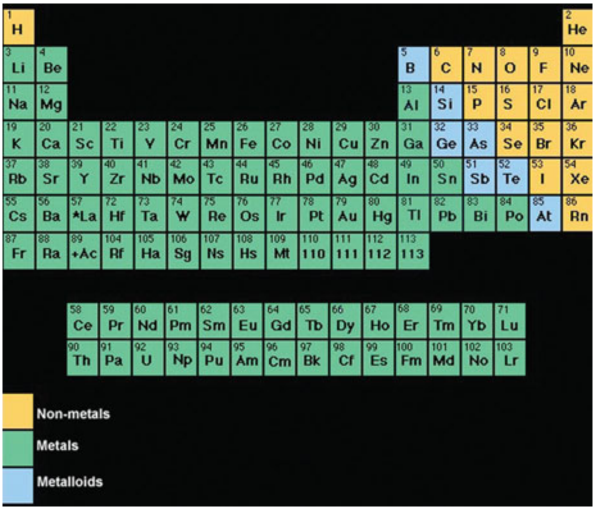


Fig. 3.1 Periodic table of the elements according to bonding type

conduction electrons divide their density equally over all atoms that function as neutral (noncharged) entities. As a consequence, the metallic bond is nondirectional in nature. The metal ion cores act very much like hard spheres and tend to pack together as closely as possible. Metallic bonding accounts for many physical properties of metals, such as strength, malleability, ductility, thermal and electrical conductivity, opacity, and luster.

Solids tend to have their atoms bonded and arranged in periodic lattice-like arrays in three dimensions. A perfect or near-perfect array would be a single crystal. However, a variety of disruptions to this perfection can occur (Fig. 3.2). The atomic lattice structure can be broken up in regions disoriented from each other by discontinuities called grain boundaries. The material is then polycrystalline in nature rather than a single crystal entity. Other defects are typically present in the lattice structure, such as vacant lattice positions (vacancies), or atoms located in between lattice positions (interstitials). Impurity atoms can occupy either normal lattice positions (substitutional impurities) or interstitial positions (interstitial impurities) depending on their size relative to the host atoms.

Crystal Structures

Close Packing

The structures of many metals can be described as close-packed arrays of spherical atoms. In a two-dimensional planar array, one central atom can be "close packed" or surrounded by only six other atoms of equal size, and their centers fall on a hexagonal

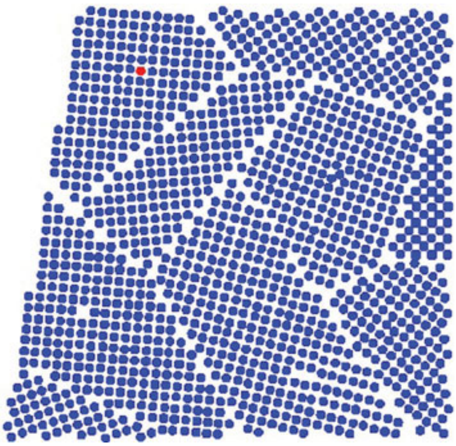


Fig. 3.2 Polycrystalline array with various point defects

point array. However, when these planar arrays are stacked in the third dimension, there are two alternate possible configurations:

Hexagonal Close Packing (HCP)—ABABAB

Cubic Close Packing (CCP)—ABCABC

Figure 3.3 illustrates the two packing sequences. The spheres of the second layer can be centered over either of the sites marked b or c; the symmetry is exactly the same regardless of the choice. However, when a third layer is added, it now has a choice of packing over the spheres in the original layer or over the sites marked as c in the diagram of the first layer. The former option leads to the ABABAB stacking characteristic of HCP, while the latter option leads to the ABCABC packing which defines a CCP structure.

The packing efficiency (volume of space occupied by the spheres/total volume) is the same, about 74 %, for both CCP and HCP schemes. The number of spheres (12; six in the plane and three both above and below) and distance between nearest neighbors is also identical for both HCP and CCP, but the second nearest neighbor coordination is different.

In addition to these two schemes, a fair number of metals adopt a body centered cubic (BCC) arrangement. In this structure type, the number of nearest neighbors is reduced from 12 to 8. This does not result in a close-packed array of spheres, and the packing efficiency drops to 68 %.

Crystallographic Unit Cells

A *unit cell* is a structural unit whereby continuous stacking in three dimensions will fill all of the volume of the larger structure. There are many possible unit cells that can serve this function, but the *conventional unit cell* is chosen such that it is easy to recognize the maximum symmetry of the structure.

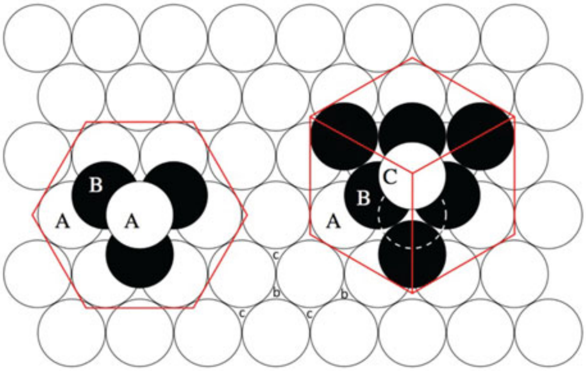


Fig. 3.3 Stacking sequences for close-packed structures

CCP leads to a structure with a conventional face centered cubic (FCC) unit cell as shown below. For this reason, CCP is sometimes called FCC packing.

It is not immediately obvious how the FCC unit cell is related to CCP stacking described above. To see this relationship, begin by finding the threefold rotation axes perpendicular to the layers in the ABCABC stacking scheme shown in Fig. 3.3. They should be fairly easy to spot. Next consider that the threefold axes run along the body diagonal in a cubic unit cell. Combining these two we see that the layers from the CCP stacking are perpendicular to the body diagonal of the FCC unit cell. This relationship is highlighted in Fig. 3.4.

The conventional unit cells for HCP, FCC, and BCC are shown together in Fig. 3.5.

Structures of Elemental Metals

Since the number and arrangement of nearest neighbors are identical in CCP and HCP, it is reasonable to expect that the bond energies of these two structures would be very similar. Thus, it should not come as a surprise that both structure types (along with BCC) are commonly observed. As can be seen from the periodic table (Fig. 3.6), most metals tend to have close-packed or nearly close-packed crystal structures.

Alloys and Phase Diagrams

Furthermore, the addition of small levels of impurities can lead to a change in the structure type. This has important technological implications in several areas, such as making steel from iron or bronze from copper. An *alloy* is a partial or complete solid solution of one or more elements in a metallic matrix. Complete solid solution alloys occur with single solid phase (defined below) microstructures just like pure elements, while partial solutions produce two or more phases that may be homogeneous in distribution depending on thermal (heat treatment) history. Alloys usually have different

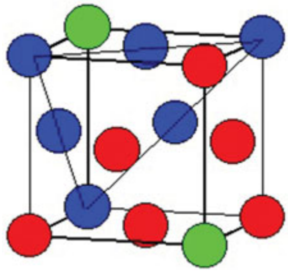


Fig. 3.4 Packing arrangement for the conventional FCC unit cell. Atoms in layer A are shaded *green*, those in layer B are *blue*, and those in layer C are *red*

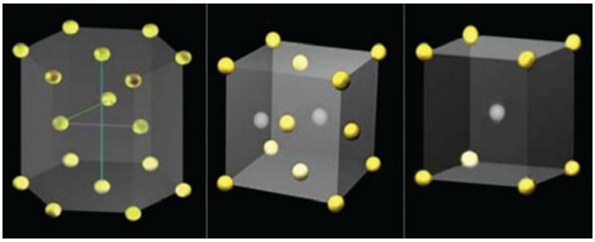


Fig. 3.5 Conventional unit cells for HCP, FCC, and BCC

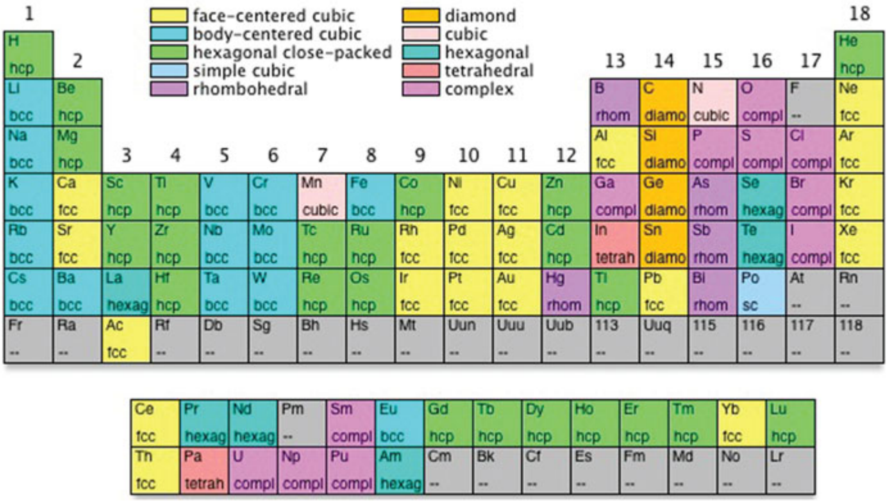


Fig. 3.6 Periodic table of the elements showing crystal structures

properties from those of their component elements. The thermal and composition relationships between these phases are usually expressed graphically by phase diagrams which plot temperature versus composition of each of the components in the system.

In order to understand the relationships expressed in a typical phase diagram, it is first necessary to define the terms "components" and "phases" more precisely:

Components—In thermodynamics, a **component** is a chemically distinct constituent of a system. In our context, it is usually identified with the elements of which the system is composed. For example, in the Ag–Au system, the two components are Ag and Au.

Phases—A **phase** is a form of matter that is homogeneous in chemical composition and physical state. Phases include solid, liquid, and gas, or different types of solids. Two immiscible liquids (such as oil and water) or liquid mixtures with different compositions, separated by a distinct boundary, are counted as two different phases, as are two immiscible solids. The Ag–Au system, which is completely miscible, can be considered to be composed of two phases: liquid Ag–Au of any elemental proportions and solid Ag–Au of any elemental proportions.

A phase diagram is therefore a map that shows which phases of a system are stable for a given set of conditions. Phases are depicted as regions on the map; *phase boundaries* are the borderlines between regions having different phases or numbers of phases. In a binary phase diagram (two components), the map is like a real estate boundary map (one-phase and two-phase regions alternating). Ternary phase diagrams (three components) are like topographic maps with the relative proportions of the three components in a two-dimensional plane and with temperature scale perpendicular to this plane.

A good example to consider for our discussion is the metal alloy known as *electrum*, a naturally occurring alloy of gold (Au) and silver (Ag), having only trace amounts of copper and other metals. *Electrum* was used in the making of some of the earliest ancient coins. The color of *electrum* ranges from pale to bright yellow, depending on the proportions of gold and silver. Gold content of naturally occurring *electrum* in Western Turkey often ranges from 70 to 90 % in contrast to the 45–55 % of *electrum* used in ancient Lydian coinage of the same geographical area (Keyser and Clark 2001; Wallace 2001)

The phase diagram for the gold–silver system is shown in Fig. 3.7. At room temperature, gold and silver are completely soluble in one another. The melting point of pure gold is 1064 °C and that of silver is 962 °C. The addition of silver to gold lowers the melting point as shown by the upper curve in the figure, called the *liquidus*; above this line only liquid (“L”) exists and has varying composition. The lower curve is called the *solidus* line and below it the alloy is completely solid. The region between these two curves is a two-phase region of liquid and solid in equilibrium together. For the Ag–Au system this region is very narrow; one consequence is that there is very little separation in composition upon melting or solidification. As a result, it was impossible for ancient people to separate the silver from the gold in *electrum*.

Thermodynamic considerations give rise to the rule that in a binary system there must be a single-phase region on each side of the phase diagram because there is some solubility for each of the two components in each other. Also, one-phase regions and two-phase regions must alternate as you go across the diagram. If you select any temperature and draw a horizontal line such that it crosses the phase boundary lines, these intersections give the compositions of each phase that are in equilibrium with each other in the two-phase region. The Cu–Ni binary alloy system (Fig. 3.8) has complete solid solubility just like the Ag–Au system, but there is a

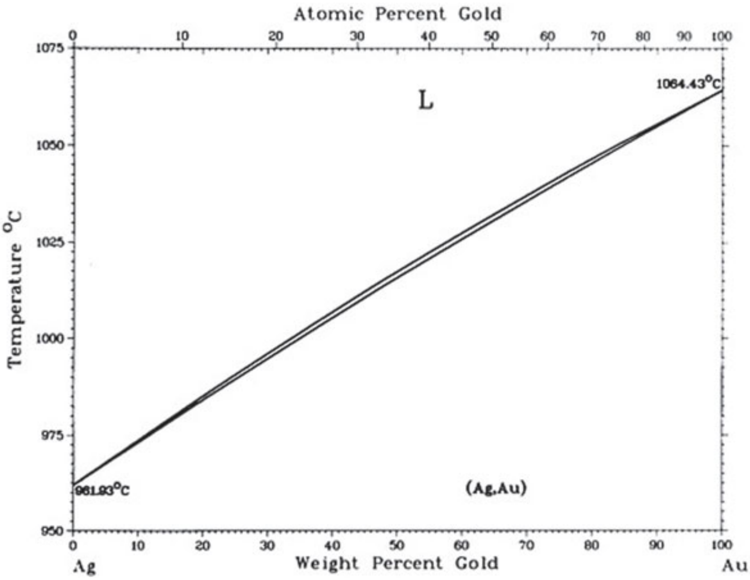


Fig. 3.7 The Ag-Au binary phase diagram

much larger difference in composition of the solid and liquid phases in equilibrium at the same temperature (i.e., the two-phase region is much wider). The result is that nonequilibrium solidification (i.e., casting at a fairly rapid cooling rate) produces significant nonhomogeneity in Cu–Ni alloys.

For example, an alloy containing about 32 wt% Ni will start to solidify at about 1,240 °C by separation of a more Ni-rich phase containing almost 45 wt% Ni. If solidified quickly, this will result in a nonhomogeneous material as the earlier metallic crystals will contain more nickel (relative to copper) than the later metallic crystals. However, if cooled slowly, such that diffusion between the solid and liquid is allowed to occur, the liquid will continue to change by picking up Ni from the solidified part and the overall alloy composition will move downward along the solidus line to the original composition, forming a homogeneous material. Thus, the rate of cooling controls the homogeneity of the alloy.

The copper–silver system (Fig. 3.9) is different in nature. At lower temperatures, there is separation into a copper-rich and silver-rich two-phase region because the elements have limited solubility in one another.

Note that in this case the liquidus temperature of silver is lowered by the addition of copper, and the liquidus temperature of copper is lowered by the addition of silver. These two curves meet at a particular composition and temperature—the **eutectic**—which is the lowest melting point composition in the alloy system (in this case an alloy containing 28.1 wt% copper). When this alloy solidifies, it immediately separates into two phases, one silver rich (with 8.8 wt% Cu) and the other copper rich (92 wt% Cu).

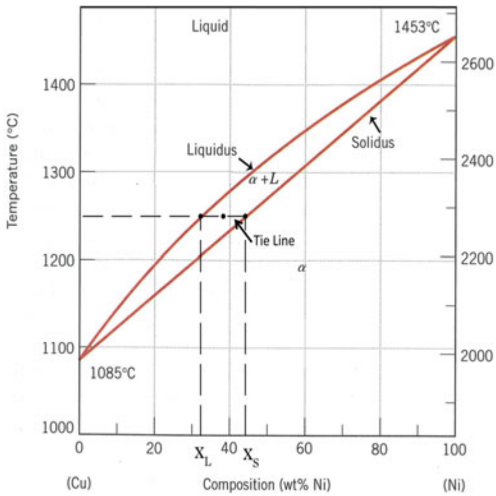


Fig. 3.8 The Cu-Ni phase diagram

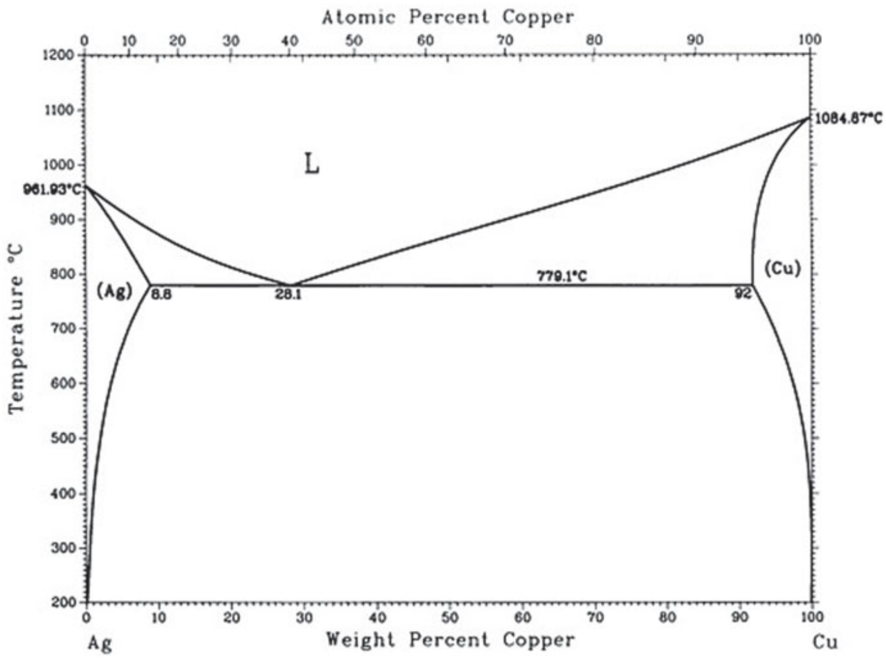


Fig. 3.9 The Ag-Cu phase diagram

Early Roman coins were quite pure in silver content, but as the Empire devalued its coinage (and, perhaps, its empire), the silver content decreased (Boon 1974). Thus, the composition and microstructure of Roman coins have been used to follow the history of this devaluation.

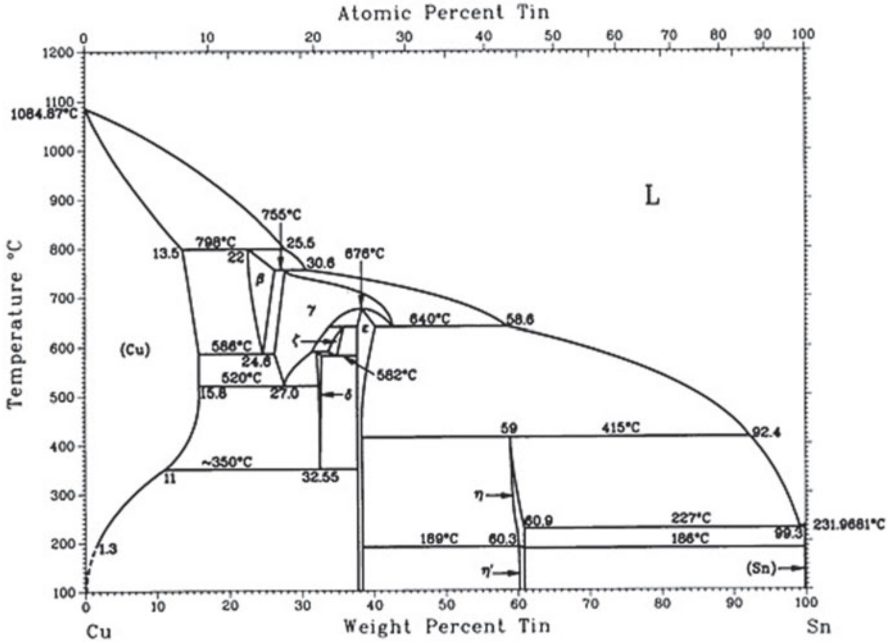


Fig. 3.10 The Cu-Sn phase diagram

The single-phase (Ag) region to the left side of the diagram is bounded at higher temperatures by the solidus line between Ag solid solution and liquid Ag. The lower boundary of this region is called the *solvus* line; if alloys in this region are taken below this line, then they become supersaturated.

The copper–tin alloy phase diagram (Fig. 3.10) is even more complicated. There are the two end-member phases, copper (Cu) and tin (Sn), and then there are a series of intermediate phases that form in this system. They are labeled β, γ, δ, ε, ζ, η, and η'. Some of these have relatively fixed composition (stoichiometric) like the ε phase, and some have a wide range in composition (nonstoichiometric) such as the γ phase. The ε and η phases are stable at room temperature, but the other phases decompose as temperature is lowered. The copper phase can dissolve up to 16 wt% tin, which is the basis for increased hardness in "low tin bronzes" with increased tin content.

Because of the awareness that alloy composition was related to mechanical behavior, the Chinese developed a formal series of alloy compositions that were used depending on the product (arrowhead, vessel, etc.) to be manufactured (Lianghui 1996). Most of the intermediate phases in the copper–tin system are brittle and cause problems with cracking when hammered without prior heating (i.e., "cold working"). However, craftsmen from Thailand and the Philippines found that heating an alloy in the β composition range and then quenching it allowed the formation of a nonequilibrium product phase that was ductile and could be formed into "magic ringing bowls" (Goodway and Conklin 1987; Goodway 1988a, b).

The last phase diagram to be considered is that for the iron–carbon system (Fig. 3.11). In fact, this is not truly an equilibrium phase diagram but rather a metastable diagram for the two-component system of the metastable compound Fe_3C (cementite); the true equilibrium diagram is between Fe and graphite (an allotrope of carbon with a simple hexagonal structure). The carbon composition corresponding to Fe_3C is 6.7 wt%C and this is at the right side of the phase diagram. Note especially the phase fields for γ (FCC) Fe, called *austenite*, and α (BCC) Fe, called *ferrite*. The composition at 0.76 wt%C and temperature of 772°C is called the **eutectoid** and is similar in form to the eutectic noted in Fig. 3.9. The eutectic in the Ag–Cu system produces a two-phase structure with alternating lamella of Ag-rich and Cu-rich solid solutions; an alloy in the Fe–C system with composition 0.76 wt %C above 772 °C, when slowly cooled, produces a two-phase structure with alternating lamella of ferrite and cementite. This alternating lamella structure is called *pearlite*. If this same composition is quenched from the austenite region (i.e., above 772°C) the carbon in the supersaturated FCC structure does not have time to separate out. Instead, it is trapped inside the lattice, straining it, and causing a transformation to a nonequilibrium single phase known as *martensite*.

Mechanical Properties

In order to understand why ancient people might have used one metal rather than another, it is important to review the basic mechanical properties of common metal materials. Metals can be weak or strong; they can be ductile or brittle. Ductility and malleability are needed to form a piece of metal into a useful object, but good stiffness and high strength are needed to maintain its shape and usefulness. These two sets of properties are often inconsistent with each other, and this demands further explanation.

Typical measurement of mechanical properties is done be taking a cylindrical metal specimen of known dimensions, clamping it, and applying a tensile load to it. The *stress* is the load (force) per unit of cross-sectional area applied to the material. The *strain* is the elongation that results from a given applied stress. A *stress–strain curve* is the graphical representation of the relationship between stress and strain. A simplified stress–strain curve might look as shown in Fig. 3.12.

Initially, the applied stress produces a strain that is elastic in nature, the relation between stress and strain being linear (Hooke's law). The slope of this line (E) is known as the *elastic modulus* and is a measure of the stiffness of the material (the higher the modulus, the higher the stiffness). A material with a low modulus is more flexible.

Strength is the ability to carry a load or stress (force per unit area).

At some point the material starts to deform plastically and produces permanent elongation. The stress that produces an observable permanent plastic offset strain of 0.2 % is usually defined as the *yield stress (YS)*. The maximum stress that the material can bear and which causes failure is called the *ultimate tensile strength (UTS)*.

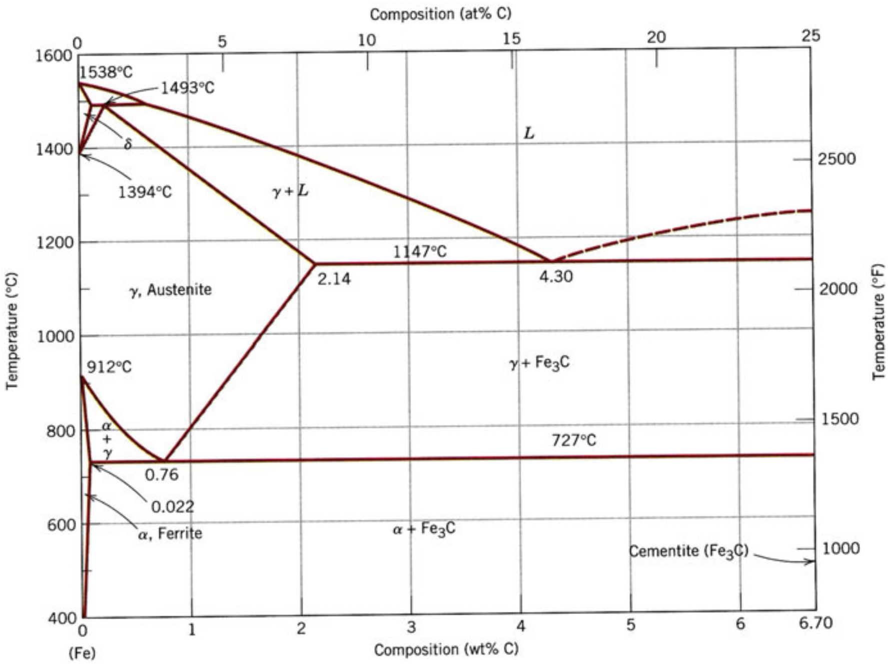
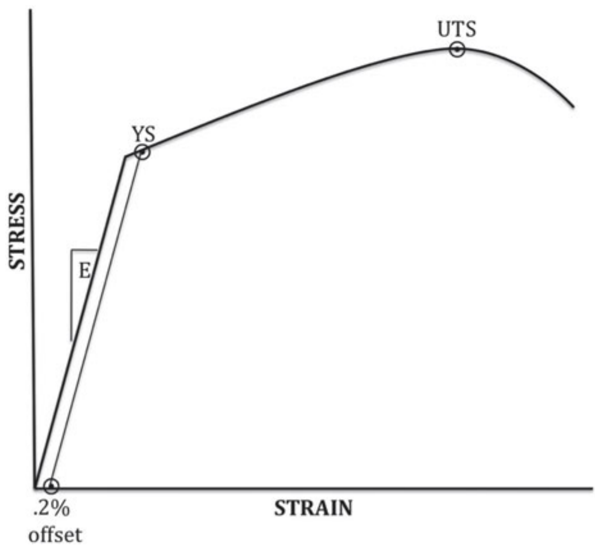


Fig. 3.11 The Fe–C metastable phase diagram

Fig. 3.12 A typical stress–strain curve for a metal



Hardness is the resistance to indentation or to a scratch. It has the same units of measurement as strength (force per unit area) but is measured by a different method. Strength and hardness are directly related to each other.

Ductility refers to a material's ability to deform under tensile stress; this is often characterized by the material's ability to be stretched into a wire. *Malleability*, a similar concept, refers to a material's ability to deform under compressive stress; this is often characterized by the material's ability to form a thin sheet by hammering or rolling. Ductility and malleability do not always correlate with each other; for instance, gold is both ductile and malleable, but lead is only malleable. Commonly, the term "ductility" is used to refer to both concepts, as they are very similar.

Toughness is the resistance to fracture of a material when stressed, or the ability to absorb energy. It is defined as the amount of energy per volume that a material can absorb before rupturing. A material is *brittle* if it is liable to fracture when subjected to stress; that is, it has little tendency to deform before fracture. This fracture absorbs relatively little energy, even in materials of high strength, and usually fails quickly. A brittle material has low toughness. Materials are said to be brittle when there is little or no evidence of plastic deformation before failure.

Strengthening/Hardening Mechanisms

The ability of a crystalline material to plastically deform depends on the ability of its atoms to move within a material. Therefore, impeding the movement of its atoms results in strengthening of the material. There are a number of ways to impede atomic movement, which include:

- Controlling the grain size (reducing continuity of atomic planes)
- Strain hardening (creating barriers and structural imperfections)
- Alloying (introducing impurity point defects)
- Precipitation or age hardening
- Quench hardening

Control of Grain Size

The size of the grains within a material has an effect on the strength of the material. The boundary between grains acts as a barrier to easy atomic movement and the resulting slip because adjacent grains have different orientations. The smaller the grains, the shorter the distance atoms can move along a particular slip plane. Therefore, smaller grains improve the strength of a material. Smaller grains can be achieved most easily by "cold working" or otherwise deforming metal plastically to compress the grains. If this metal is then heated (called "annealing") or if the plastic deformation is carried out after heating the metal (i.e., "hot working" or "forging"), then a single metallic grain will relieve strain by reforming as multiple smaller grains. Smaller grains can also be achieved by increasing the rate of solidification from the liquid phase—e.g., by quenching steel after it has been forged. Thus, the size and number of grains within a material is controlled by: (1) the rate of solidification from the liquid phase; (2) the amount of cold working that the metal had received before annealing; or (3) the annealing time during a given heat treatment.

Strain Hardening

Crystalline materials have directionality of packing to their ordered atomic bonds, and are therefore easier to deform in certain preferred atomic directions and within certain preferred atomic planes. In polycrystalline materials, this preferred directionality for deformation is hindered and cannot be extensively maintained. It becomes ever more difficult to continue to deform a polycrystalline material because individual grains are not necessarily in the right orientation to respond to the applied stress. This means that as polycrystalline metals such as copper or iron are cold worked, it becomes more difficult to continue working them because the internal atomic structural interference has the macroscopic effect of increasing the amount of stress needed to continue deformation. This process is called “work hardening” or “strain hardening” and is only relieved by heating the solid (annealing) to a temperature high enough to allow the stored mechanical energy to be dissipated through recrystallization of the metal.

Strain hardening can be easily demonstrated with piece of wire or a paper clip. Bend a straight section back and forth several times. Notice that it is more difficult to bend the metal at the same place. In the strain-hardened area, imperfections have formed, increasing the strength of the material. Continued bending will eventually cause the wire to break at the bend due to fatigue cracking. It should be understood, however, that increasing the strength by cold working will also result in a reduction in ductility.

Effects of Elevated Temperature on Strain-Hardened Material

When strain-hardened materials are exposed to elevated temperatures (e.g., annealing), the strengthening that resulted from the plastic deformation can be lost. This can be a bad thing if the strengthening is needed to support a load. However, strengthening due to strain hardening is not always desirable, especially if the material is being heavily deformed since ductility will be lowered.

Heat treatment can be used to remove the effects of strain hardening. Three phenomena can occur during heat treatment: *recovery*, *recrystallization*, and *grain growth* (Fig. 3.13).

When a strain-hardened material is held at an elevated temperature, an increase in atomic diffusion occurs that relieves some of the internal strain energy. Remember that atoms are not fixed in position but can move around when they have enough energy to break their bonds. Diffusion increases rapidly with rising temperature and this allows atoms in severely strained regions to move to unstrained positions. In other words, atoms are freer to move around and recover a normal position in the lattice structure. This is known as the recovery phase and it results in an adjustment of strain on a microscopic scale. Internal residual stresses are lowered due to a reduction in the imperfection density. There is no appreciable reduction in the strength and hardness of the material but corrosion resistance often improves. At a higher temperature, new strain-free grains nucleate and grow inside the old distorted grains and at the grain boundaries. These new grains grow to replace the deformed grains produced by the strain hardening. With recrystallization, the mechanical properties return

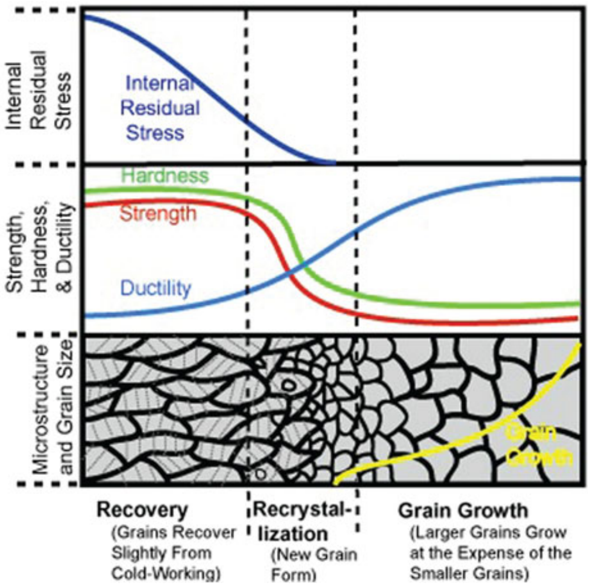


Fig. 3.13 Recovery, recrystallization, and grain growth during heat treatment

to their original weaker and more ductile states. Recrystallization depends on the temperature, the amount of time at this temperature, and also the amount of strain hardening that the material experienced. The more the strain hardening, the lower the temperature will be at which recrystallization occurs. Also, a minimum amount (typically 2–20 %) of cold work is necessary for any amount of recrystallization to occur. The size of the new grains is also partially dependent on the amount of strain hardening. The greater the strain hardening, the more the nuclei for the new grains, and the resulting grain size will be smaller (at least initially).

If a specimen is left at high temperature beyond the time needed for complete recrystallization, the grains begin to grow in size. This occurs because diffusion occurs across the grain boundaries and larger grains have less grain boundary surface area per unit of volume. Therefore, the larger grains lose fewer atoms and grow at the expense of the smaller grains. Larger grains will reduce the strength and toughness of the material.

Alloy Hardening

Alloy hardening or "solid solution hardening" depends on the addition of impurity elements that have significant size difference and/or valence electron number difference, but yet have significant solubility with respect to the host lattice. These impurities cause significant lattice strain in the surrounding atoms. Again, the result is inter-atomic disruptions that slip effectively, increasing the macroscopic yield strength of the metal. Figure 3.14 (Peckner 1964) shows this hardening effect for a number of alloy additions made to copper. Note that the impurity effect on strength depends on size differences relative to the host lattice and the amount of solubility in

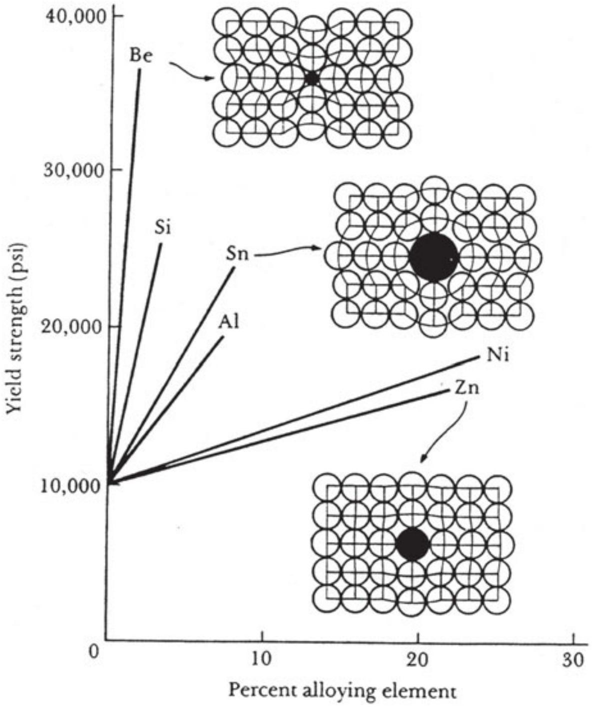


Fig. 3.14 Solid solution hardening of copper by various alloy additions

the host lattice. For example, Zn and Ni have very little effect even though they are quite soluble in Cu, while Sn has a significant effect even though it is only soluble to about 16 wt% due to the significant size difference between tin and copper. Modern copper alloys are hardened using Be, which has very limited solubility but a very large size difference.

Precipitation hardening (also called *age hardening*) is a heat treatment technique used to increase the yield strength of malleable materials. It relies on changes in solid solubility with temperature to produce fine precipitates of an impurity phase, which impede the movement of defects in a crystal lattice. The impurities play the same role as particulate substances in particle-reinforced composite materials.

Precipitation hardening of Ag–Cu alloys was extensively studied by Cohen in 1937 (Cohen 1937). Silversmiths use this method of hardening to strengthen sterling silver after fabrication. The so-called "925 sterling" silver contains 92.5 wt% Ag and 7.5 wt% Cu. Examination of the Ag–Cu phase diagram (Fig. 3.9) at this composition shows that the alloy is within the Ag phase region, but that as the temperature is lowered below about 550 °C, it crosses the *solvus* boundary between this phase and when the phase becomes supersaturated in Cu and enters the two-phase (Ag + Cu) region. As the alloy is held in this region, the excess Cu precipitates out as a fine dispersion. The lower the temperature, the greater is the supersaturation, but the slower is the diffusion that allows the precipitates to grow. Therefore, a silversmith would heat such an alloy to the upper temperature single-phase region and cool it slowly when he wants it to form, but will then reheat it and rapidly cool it to keep the copper in supersaturated nonequilibrium solution. Following this, the silversmith would reheat it to some temperature below the solvus to then produce a harder and more useful final product.

Handy and Harman (1914) suggest the following procedure for hardening sterling silver:

1. Heat the worked alloy to 745–760 °C.
2. Hold at temperature for 15 min.
3. Quench rapidly in cold water (softened condition).
4. Harden by heating to 315 °C for 30–50 min and then air-cool.

The resulting hardness is equivalent to the hardness obtained by cold working to a 50 % reduction.

Quench Hardening

As mentioned above, if an Fe–C alloy is heated up to the austenite region and quenched to room temperature, the carbon in the supersaturated FCC structure does not have time to separate out and is instead trapped inside the lattice, straining it, and causing a transformation to a nonequilibrium single phase known as *martensite*. Although ancient smiths did not know that steel contains carbon (the element carbon was not discovered until 1789 by Lavoisier), they found that quenching certain pieces of iron in water produced a very significant increase in hardness and strength. Muhly (1980, p. 51) refers to an often quoted Homeric description of quenching as producing a magical change in iron resulting in increased strength (Fig. 3.15)

In fact, in comparison to all other hardening mechanisms, quenching of iron to martensite has the most significant effect on strength, as shown in Fig. 3.16 (Smith 1967).

Figure 3.16 summarizes the principal ways of hardening metals. This figure plots hardness (DPH, measured with the Vickers diamond pyramid indenter, units kg/mm^2) against alloy composition. Pure copper when annealed has a hardness of about 40 kg/mm^2 (point a; 57,000 psi). Cold working hardens copper progressively to about 100 kg/mm^2 (point b; 142,000 psi) after 70 % reduction in thickness, and to a maximum of about 120 kg/mm^2 (171,000 psi), which is reached after 95 % reduction in thickness. Alloying copper with tin in amounts up to about 10 % (curve 1) progressively raises its hardness to about 110 kg/mm^2 (point c; 156,000 psi) if the alloys are annealed. The hardness can be further increased by cold working (curve 2) up to about 270 kg/mm^2 (point d; 385,000 psi). Pure iron, which has a DPH of about 60 (point e; 85,000 psi), is hardened by the addition of carbon, the essential element in steel. If steels are heated and allowed to cool naturally, the range of their hardness (curve 3) is slightly below that of worked bronzes, but they become spectacularly superior if quenched (curve 4).

Table 3.1 shows this comparison.

Some points to note from Table 3.1 are that, for steels at the same heat treatment condition (HR, CR, or OQ), the strength increases continuously with carbon content

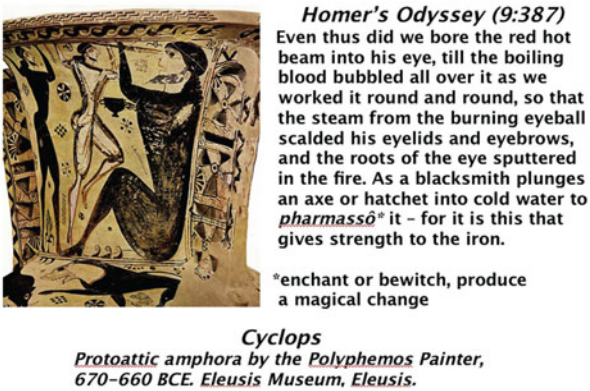


Fig. 3.15 Amphora and quote from Homer's Odyssey

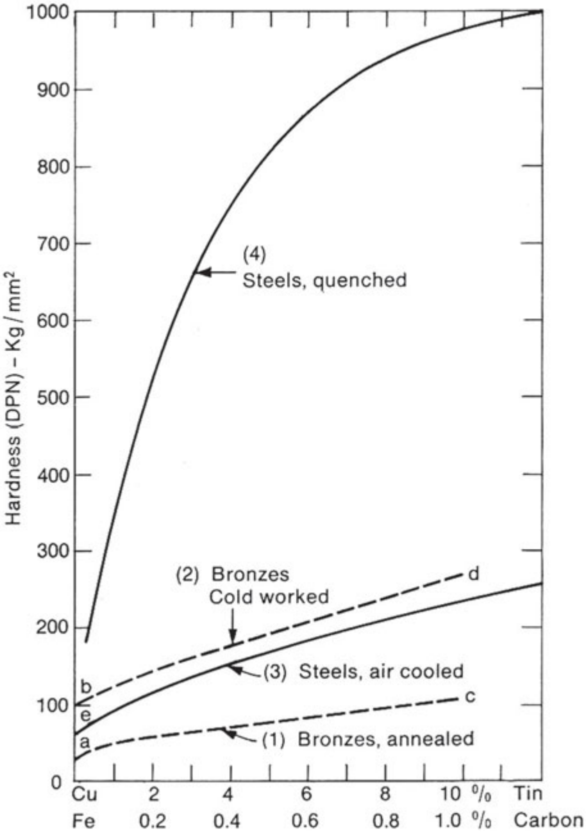


Fig. 3.16 Comparison of mechanical properties

and the elongation decreases. Furthermore, the elongation in the OQ condition is practically nil and the YS for copper increases by an order of magnitude due to work hardening.

Table 3.1 Typical room-temperature mechanical properties

Material	YS, MPa(ksi)	UTS, MPa(ksi)	E, GPa(10^6 psi)	El %	R(HB)
Steel, 0.1 %C wrought	205 (30)	345 (50)	185 (27)	30	100
Steel, 0.2 %C HR	275 (40)	415 (60)	200 (29)	35	120
CR	415 (60)	550 (80)	200 (29)	15	160
Steel, 0.4 %C HR	290 (42)	485 (70)	200 (29)	25	135
Steel, 0.6 %C HR	435 (63)	690 (100)	200 (29)	15	200
Steel, 0.8 %C HR	505 (73)	825 (120)	200 (29)	10	240
OQ	869 (125)	1240 (180)	200 (29)	2	360
Steel, 1.0 %C HR	570 (83)	930 (135)	200 (29)	10	260
OQ	965 (140)	1515 (220)	200 (29)	1	430
Cu, annealed	33(4.8)	209 (30)	125 (18)	60	–337
Cold drawn	330 (48)	344 (50)	112 (16)	14	
Cu–5 %Sn annealed	150 (22)	340 (49)	90 (13)	57	33

HR hot rolled, *CR* cold rolled, *OQ* oil quenched. Units: *MPa* MegaPascals, *psi* pounds per square inch, *ksi* 1000 psi

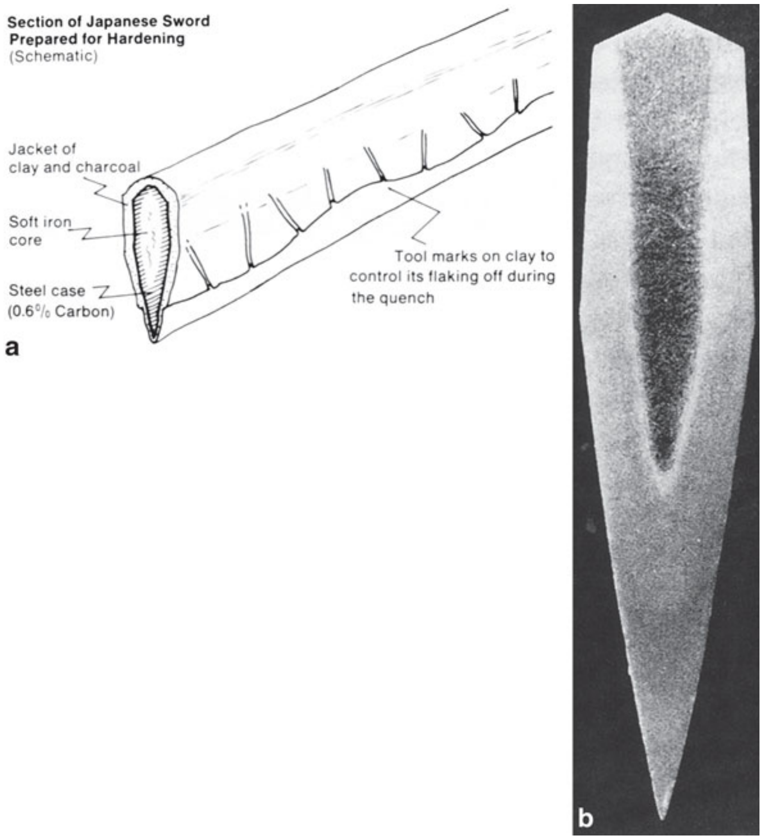


Fig. 3.17 **a** Schematic showing forged sword segments and clay coating ready for quenching. **b** Cross section of final composite microstructure. (**a** Smith 1967; **b** Kapp 1987)

In the Fe–C system, both ferrite (BCC Fe) and austenite (FCC Fe), as well as their combined slow-cooled product phases, would typically have relatively low strength, high toughness, and good ductility in comparison to martensite, which would have very high strength but would be brittle (have low toughness). This is a problem in material design. A swordsmith who desires to make a weapon that is both hard (strong) and can absorb energy (tough) therefore usually faces an interesting dilemma because these properties are incompatible. Today, a modern engineering approach would be to try to produce an object that would have a "balance of properties." Indeed, that is exactly what ancient Japanese swordsmiths did when fabricating Samurai swords. They would typically choose two different types of steel—a high carbon steel for the cutting blade edge, and a low carbon iron for the massive back of the blade. The forged high-carbon front piece would be inserted into a low-carbon iron piece shaped like a channel and the two segments forged together. The composite blade would then be coated with clay to thermally insulate the back part of the blade. The blade was then heated and quenched to produce martensite only along the front edge of the blade (Notis 2000) (Fig. 3.17).

References

Aitchison, L. (1960). *History of metals, the seven metals of antiquity*. (Vol. 1, Ch. VI, pp. 165–219). New York: Interscience.

Boon, G. C. (1974). Counterfeiting in Roman Britain. *Scientific American, 231,* 120–129.

Cohen, M. (1937). Ageing phenomena in a silver-rich copper alloy. *Transactions of the American Institute of Mining and Metallurgical Engineers, 124*, 138–157.

Forbes, R. J. (1950). *Metallurgy in antiquity* (Chap. VIII, pp. 231–271, and Chap. IX, pp. 272–289). Leiden: Brill.

Ginzburg, D. (1989). Exploitation and uses of metals in ancient Israel according to biblical sources and commentaries. *Earth Sciences History,* 8(1), 43–50.

Goodway, M. (1988a). Archaeometallurgy: Quenched high-tin bronze gong making—Part I. *Journal of Metals,* 4(3), 36–37.

Goodway, M. (1988b). Archaeometallurgy: Quenched high-tin bronze gong making—Part II. *Journal of Metals,* 4(4), 62–63.

Goodway, M., & Conklin H. C. (1987). Quenched high-tin bronzes from the Philippines. *Archaeomaterials,* 2, 1–27.

Handy & Harman. (1914). The handy book: containing tables, rules and other information regarding the working of the precious metals. New York.

Kapp, L. (1987). The craft of the Japanese sword. Tokyo: Kodansha International.

Keyser, P., & Clark, D. (2001). Analyzing and interpreting the metallurgy of early electrum coins. In M. S. Balmuth (Ed.), *Hacksilber to Coinage: New Insights into the Monetary History of the Near East and Greece*, (pp. 105–126). New York: American Numismatic Society.

Lianghui, Q. (1996). A preliminary study of the characteristics of metallurgical technology in ancient China. In F.D. Fan, R.S. Cohen (Eds.), *Chinese studies in the history and philosophy of science and technology* (pp. 219–241). New York: Kluwer.

Muhly, J. D. (1980). The bronze age setting. In T. A. Wertime, J. D. Muhly, (Eds) *The Coming of the age of iron* (pp. 25–68). New Haven: Yale University Press.

Notis, M. (2000). The history of the metallographic study of the Japanese sword. *Materials Characterization, 45*(4–5), 253–258.

Peckner, D. (1964). *The Strengthening of metals*. New York: Reinhold Publishing Corporation.

Smith, C.S. (1967). The interpretation of microstructures of metallic artifacts. In W.J. Young (Ed.), *Application of science in examination of works of art* (pp. 20–52). Boston: Research Laboratory of the Museum of Fine Arts.

Wallace, R. 2001. Remarks on the value and standards of early electrum coins. In M. S. Balmuth (Ed.), *Hacksilber to Coinage: New Insights into the Monetary History of the Near East and Greece* (pp. 127–134). New York: American Numismatic Society.

General References

Baker, H. (1992). Alloy phase diagrams (Vol. 3). ASM Handbook.

Callister, W. D., & Rethwisch, D. G. (2008). Fundamentals of materials science and engineering: An integrated approach. Wiley.

Chapter 4
Metallography and Microstructure of Metallic Artifacts

David A. Scott

What is Metallography?

Metallography is the application of microscopic techniques to sections or polished surfaces of ancient metallic materials for the purpose of gaining information concerning composition, microstructural components, extent of corrosion, or method of fabrication. Metallography was first applied to archaeological materials in the early decades of the twentieth century and has been of use to archaeologists ever since. Comparatively few metallographic studies were published between the World Wars, although the impact of such studies on archaeology became apparent in the 1940s–1960s through the publications of prominent scholars such as H. H. Coghlan at the Borough Museum, Newbury, Berkshire, and, later, Cyril Stanley Smith at Massachusetts Institute of Technology (M.I.T).

Metallography can help to inform us about the use and value of metallic materials in the past as well as aspects of their extraction from ore and subsequent fabrication into finished artifacts. The primary distinction to be made in a great number of initial studies concerns whether the metal or alloy has been cast to shape, or whether it has been worked and annealed to shape. Often, artifacts are selectively worked by hammering to harden them. This kind of evidence may demonstrate technological and sociocultural differences between metalworkers and metal-using societies as they relate to production practices.

Metal objects may be plated or coated with other metals, which limits the extent to which nondestructive analysis can be used to provide definitive answers. For example, precious metal alloys such as silver–copper and gold–copper alloys are often finished by surface-enrichment depletion gilding, or some other form of surface treatment. In such cases, metallography provides further information and can determine, in

D. A. Scott (✉)
Cotsen Institute of Archaeology, University of California Los Angeles,
308 Charles E Young Dr. North, A210 Fowler Building/Box 951510,
Los Angeles, CA 90095-510, USA
e-mail: dascott@ucla.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_4,

conjunction with chemical analyses of the polished cross section, the technique used to create the surface coating (see below).

Metallographic studies of early copper artifacts show more than just how objects were shaped and worked. Such research is also the only way to really prove the use of native (naturally occurring) copper instead of copper that was smelted from ores. The transition from native to smelted metal marks an important stage in early metallurgical development. Thus, metallography is an essential tool for answering questions about the origins of complex metallurgy.

One of the most important applications of metallography is to ancient ferrous materials. In Southwest Asia, the earliest iron artifacts were made from native (i.e., meteoritic) iron and later by the bloomery process in which the iron was never really molten. With metallography, the researcher can determine whether the artifact is made of native iron, whether it has been made of a number of pieces forged together, whether the cutting edges have been quenched to harden them, or whether the artifact is made of wrought iron from a bloomery process or a low-carbon steel. In China, early ferrous materials were often made in cast iron; softer tools and weapons could be fabricated by decarburizing white cast iron. Information relating to these developments and the utilization of particular materials must be obtained by metallography.

Finally, numerous questions relating to the authenticity of ancient metallic artifacts, particularly silver and bronze artifacts from uncertain contexts, can be answered through metallographic methods in combination with elemental and isotopic data. In cases of authenticity, it is often possible to adduce enough information from the metallographic section to avoid the need for further studies. This is particularly true in the case of ancient bronzes, where the extent of patina (corrosion) penetration and the type of patina may be sufficient evidence to condemn the artifact as a modern reproduction.

Sampling and Interpretation

Usually, a small sample has to be taken from the object under study in order to carry out the metallographic examination. The artifact is often sampled by cutting a small section with a jeweler's saw and the resulting sample is then embedded in a suitable mounting medium, such as Buehler© epoxide resin in a 1- or 1.25-in. diameter casting mould. The orientation of the sample in the mould should be carefully noted, as different metallurgical or microstructural detail may be seen in a transverse (or "cross-") section as compared with a lateral section. The mounted sample is then ground and polished using wet silicon carbide papers and diamond powder suspension in water. When mounted samples are studied, the surface of the metallic specimen should be examined first in the freshly polished state, followed by etching with a suitable chemical reagent to draw out specific features in the metallic structure through 'selective corrosion'. In some etching techniques, there is no selective corrosion, but differential deposition of a complex chemical film on the surface of the sample, as in color or tint etching. In samples where the interface between the original corrosion crust and the metal must be examined, it is important to study them in the polished condition only. Etching may attack the corrosion crust even as it reveals the metallic structure.

Examination of the polished section can utilize a number of scientific methods that each provides different types of information. The reflected light microscope (or metallograph) is the most common (and cheapest) method and can be used to determine manufacturing techniques, degree of corrosion, and questions of authenticity. The samples can also be placed in an electron microprobe (electron probe microanalyzer, EMPA), scanning electron microscope (SEM), or studied with X-ray fluorescence (XRF) techniques. All of these analytical methods provide information about the composition of the metal and, more indirectly, about the methods employed for the production of the metal(s) used to make that object (e.g., ore types, firing temperatures, and alloying).

It is possible with large objects, or with the edges of coins, to polish selected areas of objects in order to examine the metallographic structure *in situ*, in cases where it may be impossible to cut or remove a section from the object. Microstructural features may be selectively etched or preserved in corrosion on metallic surfaces, which allows this technique to reveal micromorphology directly. One should remember that a polished section is a two-dimensional view of a three-dimensional structure and is only a small part of a larger (and internally heterogeneous) artifact. Thus, supplementary techniques such as X-radiography can be employed to reveal the internal structure of the entire object.

There are often severe restrictions on the quantity of metal which can be removed from an artifact for metallographic examination, especially non-ferrous metalwork. On the other hand, even a very small sample (smaller than a pinhead) can be mounted and polished for examination, although great care has to be exercised at all stages of preparation if samples are that small. It is obviously much easier to work with larger samples although, by archaeological standards, samples the size of a pea can be considered ‘large’, unless whole artifacts or substantial fragments are available for sectioning.

There are a number of criteria that should be considered before any sampling is undertaken:

1. What questions are you trying to answer with metallography? The nature of the questions determines where you sample the artifact, how you mount the sample in resin, and how you analyze the mounted section.
2. The microstructure of the samples should not be altered in the process of removal. Thus, excessive heat or physical deformation of the object during sampling should be avoided at all costs, as it will change the interpretation of the artifact.
3. The sample should be representative of the object as a whole, or should be selected to study a particular feature or area of the object.
4. The location and orientation of the sample (in its dimensional relationship to the artifact) should be marked on a photograph or a drawing of the object, as different information is obtained from observing different sections.

5. The sample should be assigned a unique laboratory number together with sufficient documentation to enable its identity to be preserved.
6. The object should be photographed or drawn before the sample is taken. This is especially important if the dimensions of the object are fundamentally altered by the material removed.

The range of features that may be observed in prepared metallographic sections is variable and depends upon the type of specimen examined and how it is prepared. Details not apparent in the freshly polished state or even after using one etchant may become visible only after another reagent has been employed (which often requires an intermediary return to the grinding and polishing wheels). The following are some of the major microstructure features that can be examined:

1. The range, size, and shape of grains present. Their size can be compared with an eyepiece marked with grain sizes for comparison or with American Society for Testing Materials (ASTM) standard grain size numbers. This sort of data informs us about the fabrication of the artifact (e.g., how intensively the object was hammered before annealing).
2. The presence of different phases, which can be observed either in the corrosion crust or in the metal. This can give us an indication of the ores used to smelt the original metal, the amount of alloying agents added to the base metal, and even how fast the molten metal was cooled (e.g., in an insulated mold or quenched in water).
3. Gross heterogeneity or differences between various areas of the sample. This is important for determining native versus smelted copper, the level of sophistication with which early metalworkers cast metal artifacts, and areas of intensive surface hardening (e.g., working edges of tools).
4. The distribution of inclusions, slag particles, or porosity in the artifacts, which can tell us about the metal refining and casting processes (e.g., in air or under reducing conditions) and sometimes about the direction of hammering due to porosity/inclusion alignment.
5. The presence of any surface coating or gilding. Careful examination at high magnification is necessary to establish the presence of surface treatments that may have corroded or eroded away from macroscopic view.
6. The distribution of any corrosion products present and the existence within corrosion layers of pseudomorphic remnants of grain structure (i.e., grain shapes preserved as 'ghosts' in the corrosion) or other microstructural features (e.g., layering).
7. The presence of twin lines (or "annealing twins") within the grains and whether these twins are straight, curved, or bent. In metals such as copper, silver, and gold alloys, these twins result from the repetitive hammering and annealing of artifacts, thus providing indications of manufacturing techniques.
8. The presence of strain lines (or "slip lines") within the grains. These features are common in copper and copper alloys and result from excessive hammering without a following annealing step.

9. Whether dendrites (a structure which is common in cast alloys and which may look like an intersecting snowflake pattern) show indications of coring, and the approximate spacing, in microns, of the dendritic arms (if these are clearly visible). These data inform us about the speed at which the cast alloys were cooled.
10. The presence of intercrystalline or transcrystalline cracking in the polished section, which tells us about the mechanical properties of the alloy and the manufacturing techniques used to make the artifact (e.g., high-tin bronzes will crack under excessive hammering without annealing).

Metallographic studies should be integrated as far as possible with contextual data, provenance, chemical composition, and technology of manufacture to extract the maximum amount of information from the removal of a single, small sample from an artifact.

Phase Diagrams

One of the most useful aids to the study of ancient metals is the equilibrium diagram, also called the phase diagram. Since many alloys are mixtures of two or three different components, phase diagrams are used to plot temperature against composition and to map out the different phases which occur at varying compositions or temperatures in the system concerned. Alloys do not have a particular melting point; they soften and pass through a pasty stage between temperature zones shown on the phase diagram as solidus and liquidus curves. The solidus is the line in the phase diagram that separates the pasty stage of the alloy (usually a mixture of solid and liquid—think of “slush” as opposed to water or ice), from the completely solid alloy (found in temperatures below the solidus line). The liquidus is the line on a phase diagram that shows the temperature at which the alloy begins to cool (i.e., solidify) from the melt. The boundary region between these lines can be narrow or broad. In some alloys of importance in antiquity, such as copper–tin or gold–copper–silver, there is considerable separation between liquidus and solidus curves. This separation exacerbates the difficulties of attaining equilibrium cooling conditions from the melt (i.e., achieving a homogeneous metal alloy), thereby enhancing the segregation effects that can be observed in these alloys. Metastable phases (or regions of compositional variation) may remain within the alloy for thousands of years.

A simple example of a phase diagram is that of the silver–copper system as shown in Fig. 4.1. Copper and silver are not very soluble in each other and form a phase equilibrium where there is a small amount of silver dissolved in copper at one end of the diagram (the alpha phase), and another phase of a small amount of copper dissolved in silver at the other end (the beta phase). Much of the phase diagram is taken up with a two-phase field called the eutectic, which is a mixture of the alpha and beta phases. This results in a whole series of different alloy types in the silver–copper alloys (Scott 2011). Copper and lead, in contrast, are mutually insoluble at room temperature. They will mix together in a melt but rarely will they stay together in a homogenous solution (similar to mixing vinegar with oil to produce a temporary

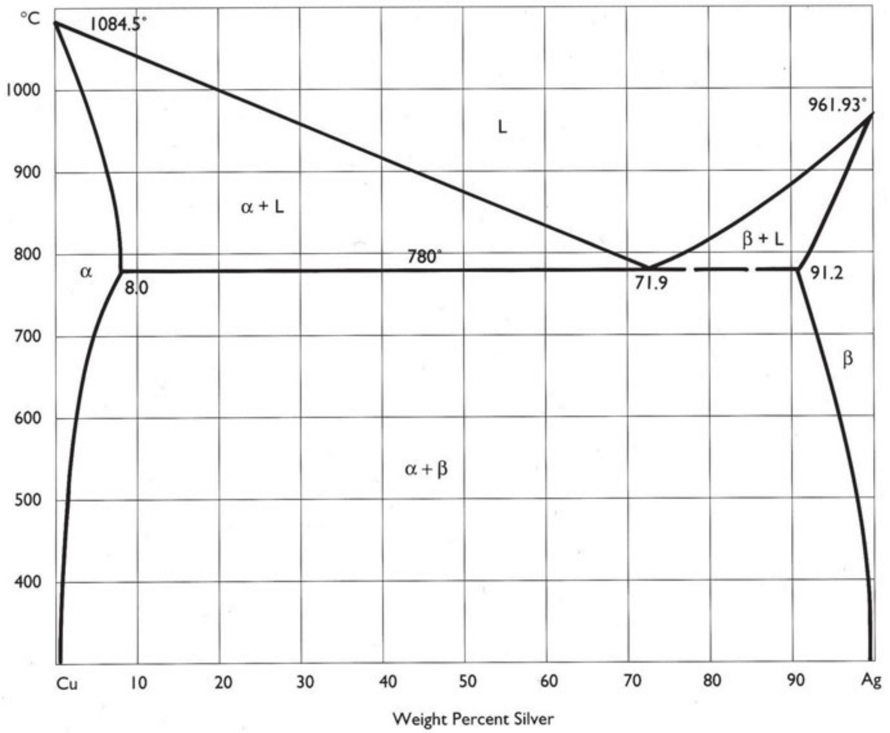


Fig. 4.1 The silver–copper equilibrium diagram (after Scott 2011). The solidus line is the *straight line* running horizontally across the diagram at 780 °C. The liquidus lines are the *two upper sloping lines* which intersect at 71.9 % silver. The $\alpha + \beta$ phase *below the solidus line* is solid. The *L* phase *above the liquidus lines* is liquid. The $\alpha + L$ and $\beta + L$ phases *between these lines* is a pasty or "slushy" intermediary phase

vinaigrette that must be shaken constantly to remain in solution). For example, if a copper–lead alloy is left to cool too slowly, the resulting metal will be weakened by large globules of lead that separate out of solution. Copper–silver alloys do not have this problem.

To the left of this diagram is pure or nearly pure copper ("α"; melting point of pure copper: 1084.5 °C) and to the right, pure or nearly pure silver ("β"; melting point of pure silver: 961.93 °C). When copper and silver are mixed together, the alloy system creates a low melting-point eutectic ("$\alpha + \beta$") at temperatures below 780 °C, i.e., far below the melting point of the two pure constituents (thereby explaining one of the main benefits of alloying metals). This eutectic will have a composition of roughly 71.9 wt% Ag and 28.1 wt% Cu at 780 °C, which is the "eutectic point" at which liquid metal will cool instantly to the solid phase without an intermediary pasty or "slushy" stage. Under ideal conditions, the system will always move toward the eutectic point.

For example, let us say that you have a molten alloy with 30 wt% silver and 70 wt% copper. As the melt cools, metal will begin to solidify (into the pasty "$\alpha + L$" phase) at the liquidus line (around 950 °C, in this case). What crystallize first, however,

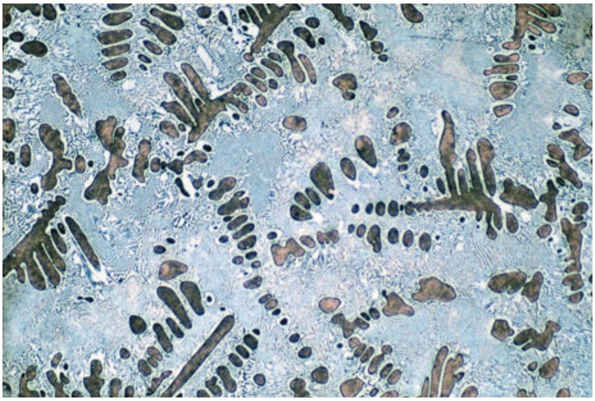


Fig. 4.2 Photomicrograph of a cast laboratory copper–silver ingot with a composition close to the eutectic point. Slow movement toward equilibrium in this binary system (i.e., slow cooling times) resulted in copper-rich dendrites (*brown*) surrounded by the eutectic mixture (*blue*), which consists of the α and β phases as a fine interlaced mixture. Etched in potassium dichromate, × 260

are dendrites containing 70 wt% Cu and 30 wt% Ag. This solidification obviously removes more copper from the melt than silver, thereby changing the composition of the remaining melt to something more like 32 wt% silver and 68 wt% copper. Changing the composition of the melt also changes its cooling point on the liquidus line—in this case, shifting it to the right, thereby lowering the melting temperature. As more metal crystallizes out of solution, the molten alloy will 'slide' down the liquidus line towards the eutectic point. Once the alloy goes below 780 °C, the entire melt is now solid. What you see in the microstructure, then, are dendrites of varying compositions (in this hypothetical case, with Ag:Cu ratios ranging from 3:7 to 7:3) surrounded by a matrix of eutectic (i.e., metal with a composition of 71.9 wt% Ag and 28.1 wt% Cu). This sort of microstructure can be seen in Fig. 4.2.

In contrast to the example shown in Fig. 4.2, alloys which are high in silver, such as a typical sterling composition silver (about 8 % copper and 92 % silver), will form only small areas of the eutectic mixture with large dendrites of silver-rich β phase. The same kind of structure is found at the copper-rich end of the phase diagram, with copper-rich α dendrites surrounded by a small matrix of the α + β eutectic. However, in ancient silver alloys (which may or may not be remelted for casting), this kind of ideal structure may be overshadowed by metastable copper within the silver-rich grains that gradually segregates out of solution over the millennia. Such metastable copper can appear due to quenching of silver alloys during working (thereby freezing the metal into metastable alloys) or due to dendritic segregation, in which the initial dendrites are just flattened out by hammering into thin stringers and never actually disappear from the microstructure.

In most of these equilibrium diagrams, we talk about a phase. A phase is usually a component of variable composition which occurs within set boundaries of variation in terms of composition and temperature. For example, the alpha phase in the copper–tin system may contain as much as 14 % of tin and still be a homogeneous single phase. More commonly, if the alloy is not thoroughly annealed, the amount of tin which enters into solid solution with copper in the alpha phase is variable and usually between 5 and 8 wt% Sn. The remainder forms what is called a "eutectoid phase," which in the bronze system arises from the decomposition of a higher temperature

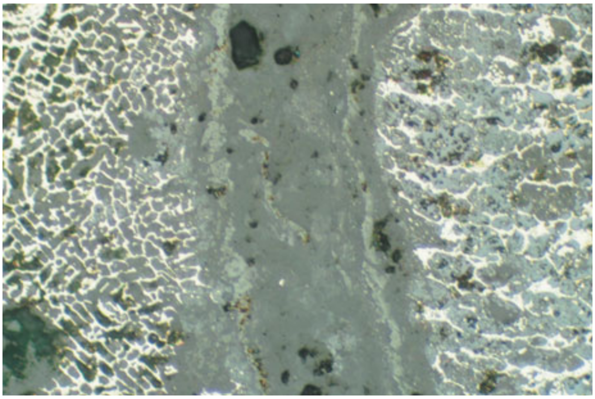


Fig. 4.3 Photomicrograph of a section through a face stud from the site of La Compaia, Los Rios Province, Ecuador, dated to about the tenth century AD. On the *left-hand side* is the as-cast dendritic structure of the spherical ball of silver–copper alloy used for the head. To the *right* is the worked and annealed structure of the shaft of the face stud, which has been joined by depressing the worked shaft into the heated ball of the head. Corrosion (*gray, in middle*) has occurred extensively at the join area. Unetched, × 220

Fig. 4.4 Linear Elamite silver bucket dated to about 2000 BC. The inscriptions on this very rare artifact cannot be read, which has led scholars to suggest that the bucket is a forgery. (Photograph courtesy of Pieter Meyers, Los Angeles County Museum of Art)

phase (which is why it is called a eutectoid rather than a eutectic). Dendritic growth, which is a form of compositional segregation during cooling, tends to dominate the world of ancient castings. Once formed, the segregation caused by dendritic growth is hard to eliminate, even by extensive working and annealing to shape (see Fig. 4.3).

Many silver objects were made with deliberate but small additions of copper, these alloys frequently having 1–6 % of added copper. If the copper additions are sufficient, some of the copper is kept in metastable solid solution with the silver during working and annealing. The result is a slow precipitation of the copper over long periods of time, resulting in the grain boundaries of the silver becoming displaced and forming small meanders in the solid. This is due to the discontinuous precipitation of copper at the grain boundaries, and is good evidence of age. A nice example of this is shown in Fig. 4.4, which is a Linear Elamite-inscribed silver bucket originally from southern Iran now in the collections of the Los Angeles County Museum of Art. This bucket

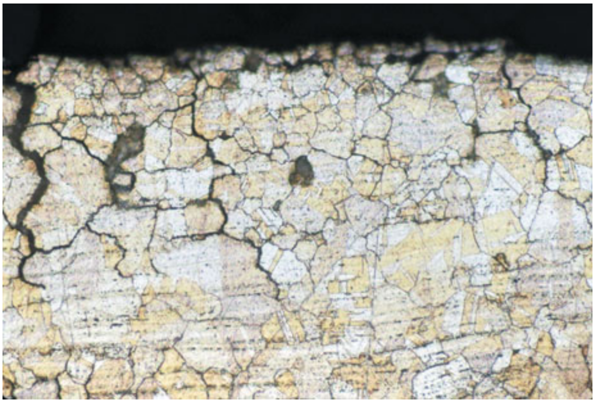


Fig. 4.5 Microstructure of the Linear Elamite silver bucket, showing cracking through some of the grains due to corrosion and weathering. Occasional twinned crystals suggest working and annealing. More importantly, discontinuous precipitation of copper at grain boundaries (visible as *thin black lines* strung out *horizontally across the sample*) results in the meandering boundaries seen here and provides nearly incontrovertible evidence of authenticity. Etched in acidified potassium dichromate, × 270

of uncertain provenance was dismissed by many art historians as a fake, given that there is practically no corrosion and Linear Elamite inscriptions are rare and not well understood.

However, metallographic analysis of a section from this bucket demonstrates the classic discontinuous microstructure shown in Fig. 4.5. There can be no doubt whatsoever that this bucket is authentic.

Case Studies

Melting and Casting

Metallic materials can be deformed by hammering ("plastic deformation") or they can be melted and cast into shape. The temperatures attainable with an enclosed charcoal fire or a wood fire with forced draught are generally high enough to melt most of the metals and alloys used in antiquity, with the exception of wrought iron and platinum (neither of which were used from the molten state). On a microscopic level, casting of most metals produces a segregation (or "compositional separation") of different alloy components of the melt as they freeze or solidify out of the cast state. Dendritic segregation, in which small fernlike growths solidify out of the melt and grow toward each other until the liquid metal is consumed (i.e., the metal is now entirely solid), is the most common form of compositional separation as a result of casting.

A fine example of dendritic segregation can be seen in a tin–bronze dagger handle from Luristan, Western Iran, containing about 17 wt% tin (Fig. 4.6). Due to differential freezing temperatures among alloys of varying compositions, the primary alloy

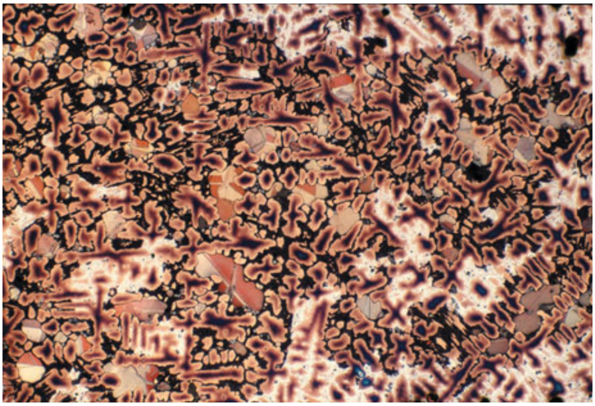


Fig. 4.6 Photomicrograph of a tin–bronze dagger handle from Luristan, Western Iran, dated to ca. 1500 BC, which shows a fine cast structure of the handle with about 17 % of tin. The metal is heavily cored between low-tin (*redder*) and high-tin (*whiter*) phases and contains twinned crystals of redeposited copper as a result of corrosion. Color etched in lead thiosulfate to reveal the segregation in the cored alpha phase, × 280

tends to solidify in these snowflake-like patterns, pushing extra components of the metal to the background areas around the resulting dendrites (white and black phases in Fig. 4.6). Among the dendrites and background matrix, twinned crystals of redeposited copper can be seen (e.g., bottom left of Fig. 4.6). Redeposited copper often appears in ancient copper and bronze alloys because of the breakdown of copper due to environmental factors in deposition. The loss of the tin-rich phase may be another reason why copper redeposition occurs in this bronze.

Etching the polished surface of a metallographic section is necessary to look for evidence of casting structures, although in some cases it is too destructive to the patina to use an etch if the corrosion crusts must be examined. It should be mentioned that in addition to dendritic segregation, so-called "inverse segregation" may also occur in ancient metals. This phenomenon, in which the lower melting point constituent, such as tin or arsenic is preferentially forced to the outside surface of the casting, is particularly common in copper alloys. For example, "tin sweat" occurs in tin bronzes when tin-rich liquid, which is the last phase to solidify, moves through copper-rich solidified dendrites to form a whiter surface enriched in tin at the expense of the bulk alloy.

Hammering and Annealing

One of the most common applications of metallography in archaeology is to determine the manufacturing techniques used to make metal objects in the past. As discussed in the chapter by Notis in this volume, the plastic deformation of metals through hammering and annealing (or simply hot working/forging) causes a number of changes to the internal structure of the metals. These microstructural features,

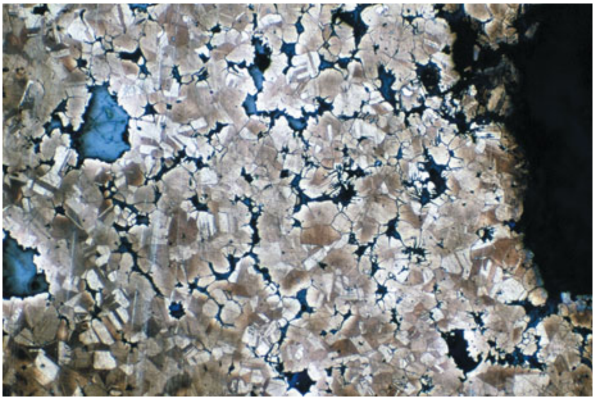


Fig. 4.7 Section through a tin–bronze flanged axe from Ireland dated to 1700 BC and containing roughly 8 wt% tin. The recrystallized grains show annealing twins, while crystals of redeposited copper appear blue as a result of corrosion. Strain lines, just visible *on the edges* of the image, occur as a result of the slip of crystal planes over one another in the bronze. Color etched in acidified thiosulfate, × 320

such as dendrites, grain boundaries, annealing twins, slip/strain lines, and so forth, can be observed and documented using only metallographic methods.

An example of a copper alloy that has been cast, cold worked, and annealed is shown in Fig. 4.7. The section was taken from an Early Bronze Age flanged axe dated to about 1700 BC from County Clare, Ireland. Although the flanged axe was cast in an open mold and might be expected to show a dendritic structure, these Bronze Age axes were often finished by hammering and annealing of the cast form to shape the final product. When an annealed object with twinned grains is cold worked, the twin lines become deformed and will no longer appear straight. This is indicative that the final stage of fabrication was cold working. Additional features that indicate a final cold-working step after annealing include strain lines, which may be visible in the metal after etching.

Quenching of Bronze Alloys

For low-tin bronzes, rapid cooling (such as quenching the hot metal in water) affects the extent of dendritic growth, but the overall effects upon the microstructure and mechanical properties of these bronzes would be slight. However, if the tin content is raised to around 20 %, then some of the higher temperature phases present in the copper–tin phase diagram (see figures later in the chapter) can be retained by quenching, producing an alloy with very different working properties than the cast equivalent. If such high-tin bronzes are used to produce mirrors or decorative vessels, then the mechanical differences are not so important for the functional use of the object. These differences become significant if the object is finished by turning on a lathe or if it has to be cut and decorated after casting. Then the advantages of quenching these bronzes become apparent because the alloy is considerably less brittle in the beta-phase region and can be turned on a lathe or hot worked, which the high-tin alloys can usually never be. The beta bronzes allow metalworkers to produce slivery-colored alloys with high-tin content, without the brittleness associated with bronzes of the same composition which have been allowed to cool slowly, resulting in a microstructure of alpha + (alpha + delta). Such alloys have no ductility whatsoever, and if dropped on a hard surface, they will shatter into pieces, breaking along the delta phase. Quenching suppresses this microstructure completely.

Two versions of the copper-rich end of the copper–tin phase diagram are shown in Fig. 4.8. The left-hand view shows what the lower tin-content alloy phases would be at full equilibrium under normal casting conditions, while the right-hand view shows the typical limit of the alpha solid solution under different casting conditions. If the bronze is cooled more quickly, as in chill casting, there is less of the alpha phase and more of the alpha + delta eutectoid, while if it is cooled more slowly, more of the tin is taken into solid solution with the copper, and the field of the alpha phase expands to incorporate more tin and less eutectoid.

An example of the microstructural effects of quenching is shown in Fig. 4.9, part of a high-tin bronze bowl (22.7 wt% Sn and 76.2 wt% Cu) from the site of Ban Don Ta Phet, Thailand, dated to about 100 AD. Examination of the etched section shows the presence of some alpha-phase copper-rich grains, which occur in areas with specific orientation as well as in a random scatter, showing that the metalsmiths were aiming for a specific composition which had a combination of mechanical toughness, high hardness, and a lustrous surface. The technological process was therefore very sophisticated and was dependent on being able to cast an initial alloy with very closely defined composition parameters. If the tin content was too low, around 18 % the beta phase would not form, and if the tin content was too high, the mechanical properties of the alloy might not be so amenable to turning on a lathe or hot working followed by quenching. The fact that the microstructure consists of a mixture of twinned alpha grains with an acicular infill of beta needles argues for the mechanical benefits of the intimate mixture of the two phases in improving workability from the quenched state. The alpha grains are softer and can act as stress-relieving areas or as softer components of the structure which allow for the manipulation of the alloy by hot working more readily or by acting as areas of softer metal for turning on a lathe to finish part of the surface decoration. The relationship between technological process and alloy composition in this case is a very precise and well-controlled one. Analysis of some of the background phases even allows us to reconstruct the temperature of the bowl when it was quenched. This give us important information about what the ancient metalworker was trying to accomplish, as quenching high-tin bronzes at different temperatures will result in metals with very different properties. The sophisticated metallurgy of these bowls would be impossible to unravel without metallographic investigation.

In some metals, such as tin bronze, gold alloys, and iron alloys, there may be advantages to quenching the alloy from a high temperature. These benefits include

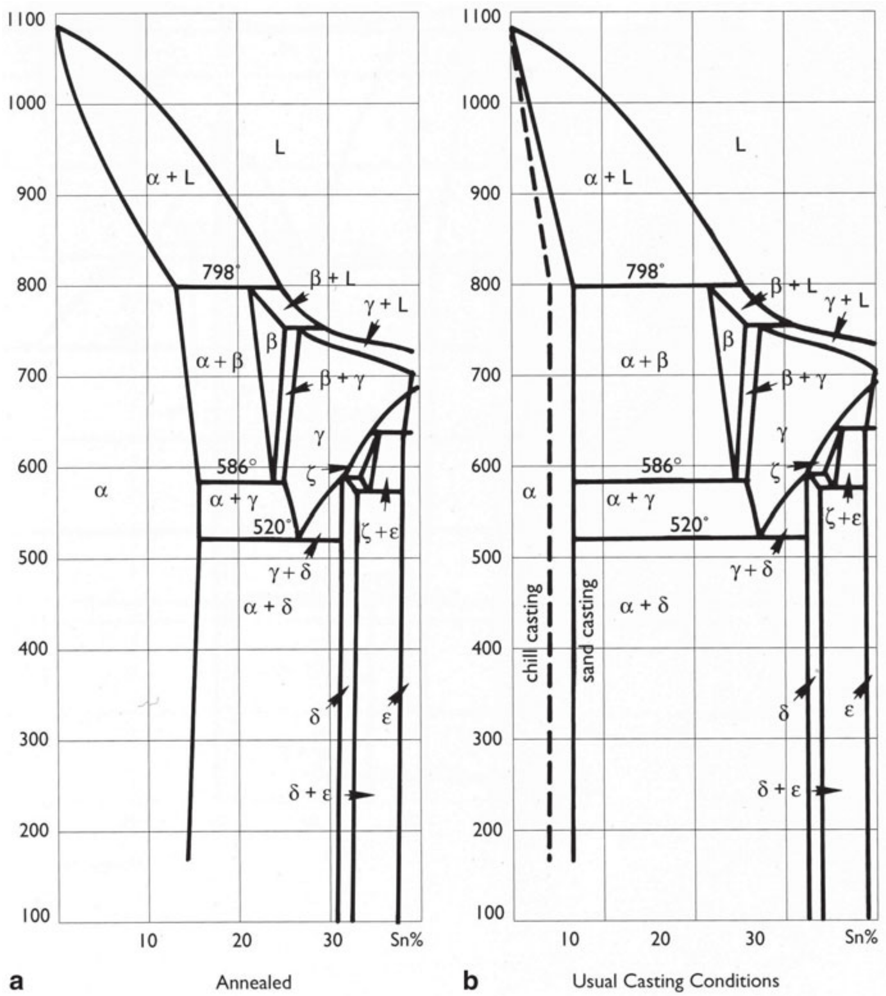


Fig. 4.8 Partial versions of the copper–tin phase diagrams showing **a** the full equilibrium view of the extent of alpha solid solution and **b** the actual extent of solid solution depending on casting conditions. (Redrawn from Scott 2011)

either retaining certain phases which are only present at high temperatures, or preventing lower-temperature phases from forming, which might lead to embrittlement. Thus, many gold alloys are quenched to prevent ordering reactions from occurring. Ordering reactions result in the formation of compounds with fixed composition which behave more like minerals than metals. They have very limited ductility and are responsible for cracking and hardening of some alloys over time. These ordering reactions produce phases of fixed composition such as AuCu, which have rather limited ability to be deformed by hammering or working, and which can result in

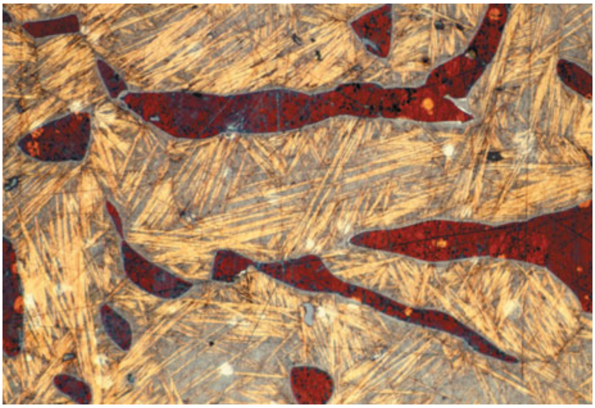


Fig. 4.9 Section of a high-tin bronze bowl from the site of Ban Don Ta Phet dated to about 100 AD with a composition of 22.7 wt% tin and 76.2 wt% copper. The beta-phase needles appear *straw colored* and the copper-rich alpha-phase grains appear *red*. Twins in the alpha phase can just be seen, showing that the bowl has been hot worked from the beta region. Color etched in Klemm's number 2 reagent, $\times$ 280

cracking of the gold alloy on working. Hence, in this case, quenching makes the metal softer and less brittle, while many steels are quenched to form martensite (a high-temperature phase), which makes them harder and brittle; therefore, the technological processes associated with quenching have to be tailored for the alloy concerned.

Surface Treatments

Metallic artifacts are often not what they pretend to be, but are treated on the surface to look like a different metal (e.g., gold or silver plating). Figures 4.10 and 4.11 show the microstructure of a bronze belt buckle from the Han Dynasty of China, the surface of which was dipped in metallic tin (known appropriately as "tinning"). The common metallic phase which results from many of these tinned surfaces is the so called η phase, which has a composition of Cu_6Sn_5, rather than metallic tin *per se*.

Many different kinds of surface treatments and coatings have been developed in different cultures for different purposes. Figure 4.12 shows a section of a Roman coin of Augustus, plated with a silver–copper alloy, which is then treated to create a silver-enriched layer on the surface. The plating of the silver–copper alloy could be carried out either by a dipping process or by the application of silver–copper filings to the surface followed by heating ("fusing") in place.

Another example is a Parthian silver rhyton in the collections of the J. Paul Getty Museum that has been gilded, although this time the base metal is silver. The lion rhyton is shown in Fig. 4.13: a masterpiece of ancient silver working.

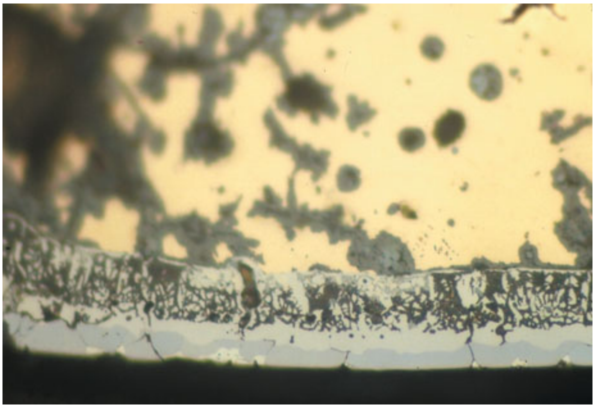


Fig. 4.10 Section through a Han period Chinese belt buckle showing that the surface has been tinned. The very *white* phase *near the outer surface* is metallic tin, followed by the *grayish* eta (η) phase, the *whitish* epsilon (ε) phase, and the (α + δ) eutectoid phase before the low-tin bronze of the cast belt buckle is reached. Unetched, × 460

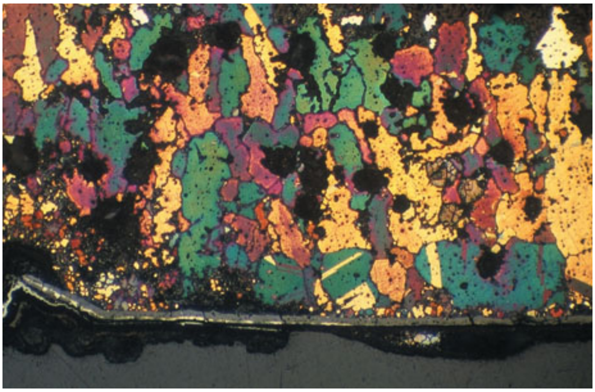


Fig. 4.11 Photomicrograph of a tinned Han belt buckle showing the essentially cast matrix of the buckle. Note the presence of a few annealing twins toward the outer, tinned surface, showing that some working and annealing has been employed to shape the surface before the application of the tin. Color etched in lead thiosulfate etchant, × 150

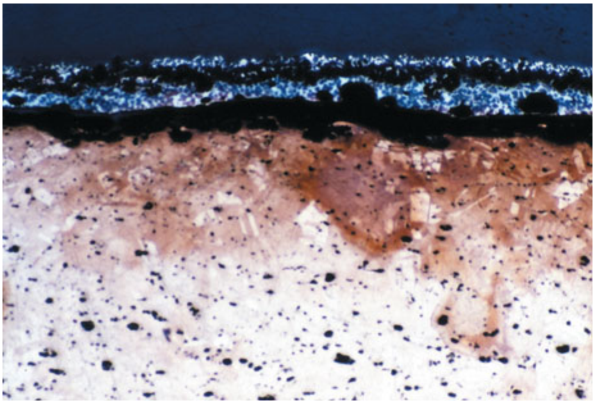


Fig. 4.12 Etched view of a Roman bronze coin of Augustus, showing silver fusion-plated over leaded copper. The silver coating is close to a eutectic mix to prevent melting the coin when applied. Etched in alcoholic ferric chloride, × 280

A section was taken from a small break under the body of the rhyton and the extent of the gilding investigated. The gold foil is quite thick and has been applied by diffusion bonding of the foil to the underlying silver, as seen in Fig. 4.14. Diffusion

Fig. 4.13 Lion rhyton in the collections of the J. Paul Getty Museum, Parthian first century BC. The lion is also decorated with garnets. (Photograph by David A. Scott. Also by courtesy of the J. Paul Getty Museum at the Villa, Malibu, California)

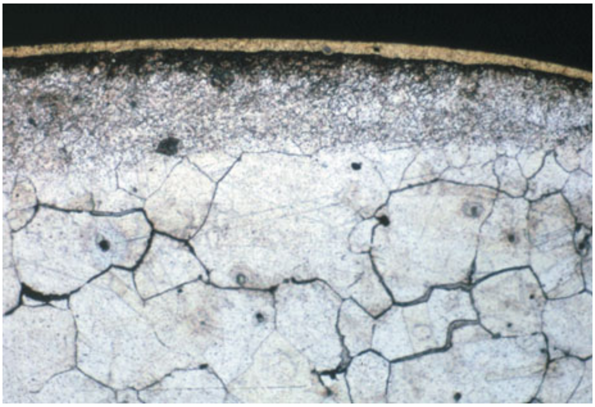


Fig. 4.14 Gilded silver rhyton in the collections of the J. Paul Getty Museum, showing thick gold foil and the characteristic cracking and discontinuous precipitation of the silver grains. Etched in acidified potassium dichromate, × 320

bonding is the application of a metal coating to a substrate, with careful heating to bond the two metals together. The two different metals will diffuse into each other at different rates, but produce a bond which is metallurgical and not mechanical, as the hammering of a gold foil over silver would be. The metallurgical bonding achieved by diffusion bonding is much more permanent than those bonds achieved by mechanical methods because in the mechanical attachment there are no permanent metallic bonds created by the union of the two components.

In pre-Columbian South America, the preferred surface treatment technology was “depletion gilding”, in which gold–copper–silver alloys (“tumbaga”) are pickled in plant or other corrosive substances to leach out most of the copper. Silver is not removed in this process as the plant juices cannot complex with the silver. This process leaves a gold-enriched surface on an artifact that may only contain 15–20 wt% of gold, but which appears to be solid gold on the surface. An example of this technique from Panama is shown in Fig. 4.15, where the thin, spongy, gold-enriched surface was burnished to create a flat, golden surface (with only about 25 wt% gold content) over the artifact.

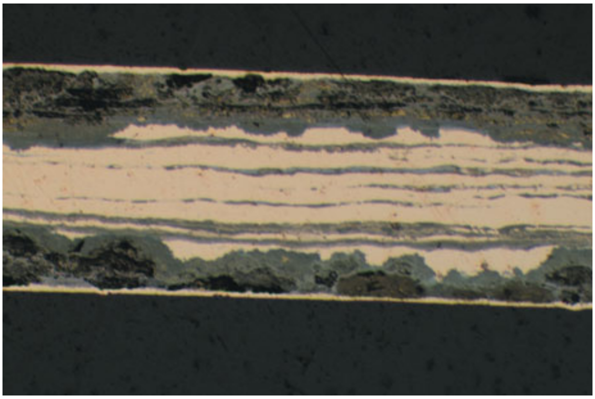


Fig. 4.15 Photomicrograph of a fragment of a sheet gold ornament. It is a tiny fragment (so the nature of the original artifact is not known) from excavations at the site of Sitio Drago, Panama, dated to about 1100 AD. This golden-colored artifact was shown through metallography to be a depletion-gilded gold–silver–copper alloy with heavy corrosion under the gilded surfaces. The striated interior structure of the tumbaga fragment was caused by heavily working the metal into a thin sheet, leading to some dendritic segregation of the different components of this ternary alloy, which are strung out along the length of the sheet as a result of the working and annealing process. Subsequent corrosion beneath the depletion-gilded surfaces has exaggerated the compositional differences. Unetched, × 180

In Peru, different techniques of surface treatment were employed, using mineral pastes capable of removing both copper and silver from the surface of the artifacts. Metallographic examination of these surface-treated alloys is essential for the proper identification of the materials used and interpretation of the technological processes used in their manufacture.

Corrosion

Examination of corroded sections is often an essential component of authenticity studies of antiquities, and metallographic studies are crucial to this process. In copper-base alloys, the presence of cuprite (Cu_2O) within the corrosion crust and the degree to which cuprite has penetrated into the metal are both indicators of authenticity. For example, a series of bronze plaques that were supposedly found in the Fayum region of Egypt have appeared in a number of museums (see Fig. 4.16). If authentic, these plaques are important because they are inscribed with some of the earliest Greek writing known to scholars.

Metallographic examination of this plaque (Fig. 4.17) reveals a clear cuprite layer between the copper-base metal and the malachite-base corrosion (i.e., patina). This sequence of layers as seen in the photomicrograph is generally a good indication of authenticity.

Fig. 4.16 Greek plaque reputedly found in the Fayum region of Egypt and dated to the ninth century BC based upon the inscription. The plaques, of which five probably existed, preserve one of the earliest versions of the Greek language. (Photograph courtesy of Professor Bruce Zuckerman, University of Southern California, Department of Religion)

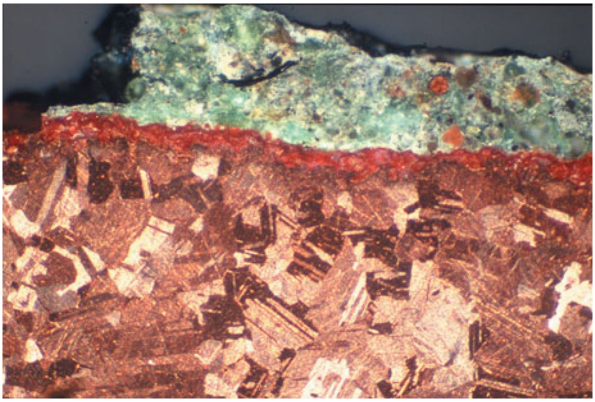


Fig. 4.17 Cross section of the Greek copper plaque from Fig. 4.16, showing the presence of a good red cuprite layer overlaying twinned and recrystallized grains of worked copper. The red cuprite layer is overlain by a complex, principally malachite corrosion layer incorporating mineralized wood fragments, dirt and other mineral grains, and charcoal fragments. Etched in alcoholic ferric chloride, × 340

Iron and Steel

The first iron materials used by man were meteoritic, which had fallen from the skies and could be picked up as small pieces or laboriously broken off from larger masses of iron. The problem with the use of meteoritic iron was that it contained a substantial

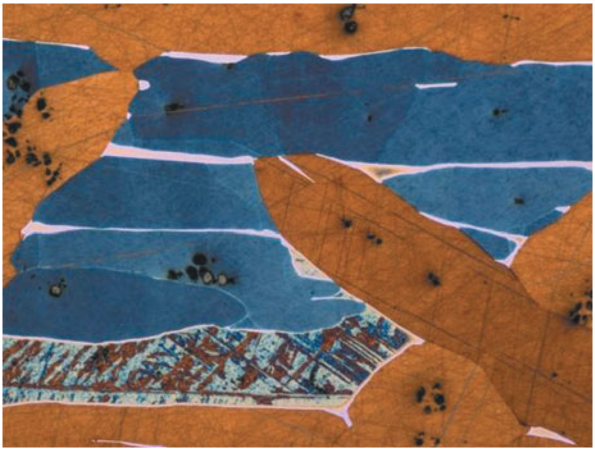


Fig. 4.18 Polished and etched photomicrograph of a meteorite from the Gibeon, Great Nana Land, Namibia, showing part of the complex structure of this iron–nickel alloy. The phase called taenite here etches a *yellow* color, while kamacite is *blue*. A plessite field can be seen in the *crosshatched pattern toward the bottom* of the picture. Color etched in Klemm's number 1 reagent, × 230

amount of nickel and often carbon as well, resulting in an incredibly hard material which could not be molten and could only be shaped by hammering with considerable difficulty. Figure 4.18 shows a color-etched interference-tint photomicrograph of a meteorite from the region of the Gibeon, Great Nana Land, Namibia, where large falls of small pieces of meteoritic iron resulted in their use for jewelry and personal adornment at an early date. The metallographic image shows part of the structure of the meteorite with iron-rich phases in pale yellow and the iron–nickel alloy in dark blue, with a fine precipitate under the blue laths in the picture being a precipitate of one iron–nickel phase in another. This is the unworked microstructure of the different phases in the meteoritic iron.

Iron and low-carbon steel alloys, particularly in the Western tradition, were usually produced from bloomery iron, which means that they have never been molten or cast (instead exiting the furnace as a spongy, slaggy mass that must be refined through forging). Bloomery iron artifacts are often made from small pieces of iron/low-carbon steel welded together to create the finished object. As a result, weld lines, enrichment zones, phosphoric iron, and low-carbon steel areas may all be present in the same object. A typical wrought-iron/low-carbon steel, albeit from a twentieth-century sculpture ("Night Presence II" in San Diego), is shown in Fig. 4.19. Examination of the section reveals a "Widmanstätten" structure. This structure arises from the decomposition of a solid solution phase at a higher temperature into two distinct phases at lower temperatures. So here, the higher-temperature austenite solid solution decomposes on cooling into alpha grains of iron and an infill of the eutectoid phase of alpha iron (ferrite) and cementite, known as pearlite, because iron of the eutectoid composition fractures with a pearly luster if the carbon content is about 0.8 %.

The carbon content of early iron artifacts may be variable too, most being made of low-carbon steel with less than 0.8 % carbon (often much less than that). Steels may have up to 1.2 % carbon, the 0.8 % level being the eutectoid, known as pearlite, which is a fine mixture of ferrite and cementite. Ferrite is essentially pure iron, while cementite is a compound of fixed composition (Fe_3C). Phases of fixed chemical

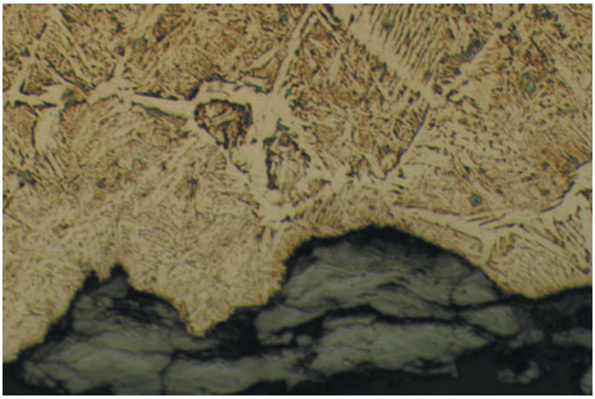


Fig. 4.19 Section of the sculpture "Night Presence II" in San Diego, showing corrosion penetration and the jagged structure of the low-carbon steel used to fabricate it. The use of this heterogeneous low-carbon steel has resulted in extensive corrosion failure. Etched in 2 % nital, × 450

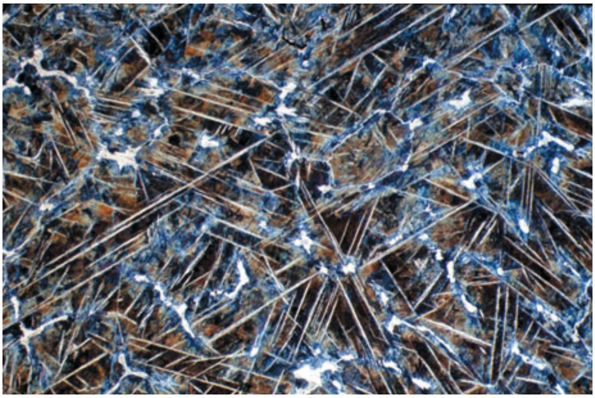


Fig. 4.20 A hypereutectoid steel Wootz cake from the Deccan region of India showing a very clean iron microstructure with no slag. The carbon content is about 1 % and the microstructure has a mixture of cementite needles and finely-spaced pearlite, here etched a *dark brown* in Klemm's number 1 reagent, × 300

compositions such as cementite are usually hard but lack ductility. The great variation in the microstructure of steels, depending upon heat treatment and alloying components, causes the microstructure of steels to be especially revealing of technological processes. An example of a high-carbon steel is shown in Fig. 4.20, from the Deccan region of India. This Wootz steel ingot was made in a crucible during the eighteenth century AD and is effectively a cast product. The long white needles in the photomicrograph are of cementite and the background is of pearlite.

Quenching wrought iron has little effect upon the working properties of the metal. However, with a more significant carbon content (0.3–0.7 %), it was soon appreciated that quenching could produce a much harder alloy. By quenching a forged iron blade, a much stronger edge could be achieved.

Cast iron was manufactured in China long before the Western world was able to produce it. Chinese metalsmiths excelled in the production of white cast iron, in which the excess carbon is taken up as cementite rather than graphite. An example of a Chinese cast hoe is shown in Fig. 4.21. The carbon content of this cast iron is about 3.5 %, and it is a white cast iron. The principal problem with Chinese cast iron

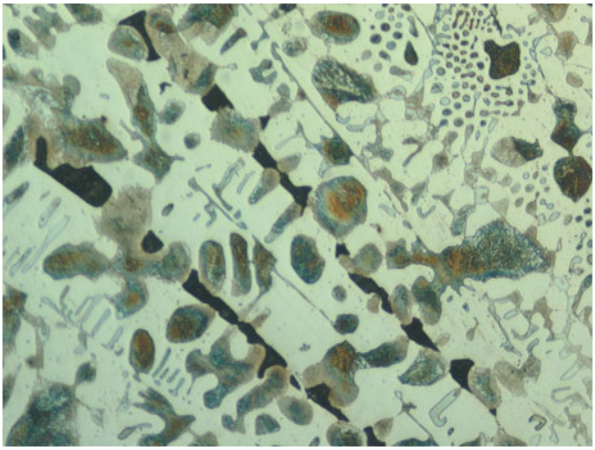


Fig. 4.21 White cast-iron hoe from the Gansu region of China, Warring States Period. The structure shows primary laths of cementite (the *long white phase*) with proeutectoid pearlite (the *straw-etching phase*) and patches of the eutectic ledeburite (the *structure with a series of fine holes*). Etched in 2 % nital, × 340

was that, unlike the wrought iron and low-carbon steel used in the West, the carbon content of cast iron has to be reduced in order to make useful tools and weapons.

The process of decarburization, that is, the deliberate loss of carbon as a result of heating in air, can be used to reduce the carbon content of cast irons or high carbon steel, to make a softer product, especially since cast irons are very brittle. Decarburization was often used to make iron artifacts of lower carbon content out of cast iron. When high-carbon steels or cast irons are heated to high temperature and a blast of air applied to the melt, some of the carbon content is oxidized, the brittleness associated with the higher-carbon cast iron is lost, and the whole mass begins to solidify as the carbon is reduced. This is the process of decarburization. The Han sword section shown in Fig. 4.22 is unusual in that it appears to have been hammered from bloomery iron. Extensive segregation bands (in copper and nickel) have resulted from the making of this sword, probably as a result of a series of folded laminations from a hammered-out bloom of iron. These laminations are also typical of low-carbon and phosphoric iron from the West, but here the Chinese example is very much cleaner with practically no slag inclusions and has a carbon content close to that of the eutectoid composition at 0.8 % carbon, which is a high-quality carbon steel product. As the iron in the West was produced in the bloomery process, it was never fully molten and the mass of material that was worked up by the metalsmith included unreacted ore, glassy slag waste, and heterogeneous iron lumps. With forging, the impurities were mostly removed with some slag occurring as stringers within the worked bloom. Phosphoric iron results from the use of iron ores containing phosphorus, so that some of the phosphorus is present in the smelted iron bloom and causes a number of changes in properties of the iron, some of which are beneficial. For example, phosphoric iron may be harder and take a better edge than pure wrought iron. Since most of the iron of the ancient world was produced in the bloomery process, the iron needed to be heated to red heat and hammered out to consolidate it, removing in the process most of the slag, but some iron artifacts retain a lot of slag stringers within the finished object. Slag, usually the glassy mineral

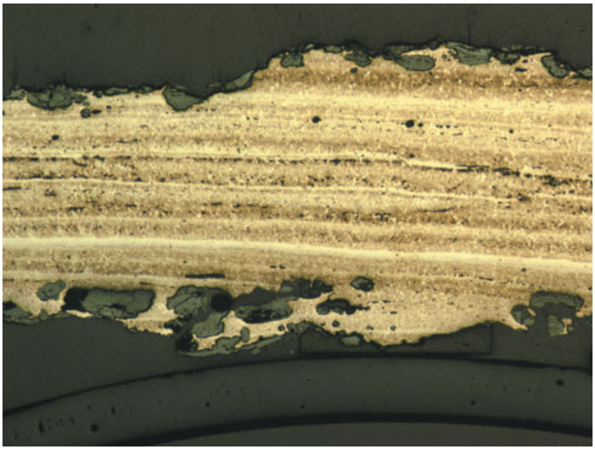


Fig. 4.22 Microstructure of a Han Dynasty sword blade from Gansu Province, China, showing a finely laminated structure as a result of folding and working of the hypereutectoid steel used to make this blade. The *white bands* are enrichment zones (usually at weld lines) of copper or nickel. The number of parallel laminations probably results from the folding of the iron over and over again to create this type of microstructure, often seen in low-carbon steel blades in the West. Etched in 2 % nital, × 160

fayalite in ferrous materials, cannot recrystallize on working of the iron and becomes elongated and flattened during hammering into stringers.

Summary

Metallography is the science of the examination of metallic materials employing optical microscopy or SEM to investigate structure and composition of the polished surfaces of the object. Metallography is an indispensible tool in the study of ancient metals and the by-products of metallurgical processes. It can tell us a great deal about the process of fabrication of ancient metals and alloys, revealing casting, cold working, annealing, heat treatments, alloying, and quenching. Metallography can reveal the nature of surface coatings, gilding, silvering, or other forms of surface treatment. The extent of corrosion, deterioration, or aging of alloys can also be investigated. The future of metallography includes the increasing use of nondestructive techniques to probe inside the structure of metals without the need to remove a sample, as well as new methods of nanoscale analysis which will enhance the interpretation of microstructure of ancient materials. Conventional metallography will continue to be an important part of a comprehensive study of metallic materials from a culture or excavation and it should always be incorporated in comprehensive site reports and publications. The use of digital file sharing will mean that many color images of microstructures can be studied in the years to come, without the current restrictions on the use of color in published books, which has always acted as a hindrance to the full appreciation of the metallography of ancient metals. Continued progress in the study of ancient metals reveals to us the often complex nature of the metallurgical developments which took place in different periods and cultures: metallography has a central role to play in understanding how societies manipulated materials and made choices as to how their technology was going to be developed or utilized. The examination of cross sections of ancient artifacts is especially important in heterogeneous materials, such as early wrought iron and steel, in which metallography can reveal so much concerning the fabrication history of the artifacts and the kind of alloy chosen for use and is important in the study of coated or gilded materials where a bulk analysis will not reveal the nature of the interior of the artifact distinct from the surface zones, which may be of very different composition. Aspects of authenticity in terms of the extent of corrosion, discontinuous precipitation, or type of corrosion are important components of the study of ancient metals, especially bronzes, and in the case of embrittled alloys, such as ancient silver.

Suggested Reading

Craddock, P. T. (1995). *Early metal mining and production*. Edinburgh: Edinburgh University Press.
Metcalf, D. M., & Oddy, W. A. (Eds.). (1980). *Metallurgy in Numismatics*. London: Royal Numismatic Society.
Scott, D. A. (2002). *Copper and bronze in art: Corrosion, colorants, conservation*. Los Angeles: Getty Press.
Scott, D. A. (2011). *Metallurgy and microstructure Volume I: Copper and copper alloys*. Los Angeles: CSP Press.
Smith, C. S. (1981). *A search for structure*. Massachusetts: MIT Press.
Smith, C. S. (1988). *A history of metallography*. Chicago: University of Chicago Press.
Tylecote, R. F. (1976). *A history of metallurgy*. London: The Metals Society.

Chapter 5
The Investigation of Archaeometallurgical Slag

Andreas Hauptmann

Introduction

Since the Late Neolithic Period in the Old World, metallurgical slags have been relatively common on archaeological sites alongside pottery, metal artifacts, flint/chert, bones, and charcoal. Therefore, they form one of the most important types of archaeological remains, and we must ask what kind of information we can take from them. While finds such as pottery and metal artifacts are usually classified by the naked eye according to typological features, the most important information from slag can be obtained only by scientific analysis. Therefore, archaeologists and scientists are forced to cooperate in order to answer questions about ancient technological behavior. The investigation of ancient slags requires a closer look into the micro-composition of the materials, as they result from technical processes which, depending on time period and from region to region, vary considerably in their shape and design. A classification according to macroscopic features may help in many cases, but the conclusions we can draw are limited. To decipher the history of slags—e.g., the kind of ore from which they originated, their formation by high-temperature processes, the technological skill of ancient metallurgists, and the social and technological behaviors they preserve—we depend on mineralogical and chemical analyses.

The modern definition of slag states that metallurgical slag consists of silicates consisting of silica (SiO_2) and various oxides (e.g., CaO, Al_2O_3, P_2O_5, MnO, FeO, and MgO) formed during the smelt. These silicates result from the gangue of the ore's host rock (i.e., from the parts of the rock that are not metal bearing ("ore"), such as quartz or feldspar) and from added fluxes (i.e., materials added to improve the smelting process). In the ideal smelt, the metal is almost completely separated from the slag. Due to its lower density, slag forms a layer on top of the metallic phase

A. Hauptmann (✉)
German Mining Museum, Am Bergbaumuseum 28, 44791 Bochum, Germany
e-mail: Andreas.hauptmann@bergbaumuseum.de

Research Laboratory for Archaeology and Materials Sciences,
Hernerstraße 45, 44787 Bochum, Germany

Ruhr-Universität, Universitätsstraße 150, 44780 Bochum, Germany

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_5,

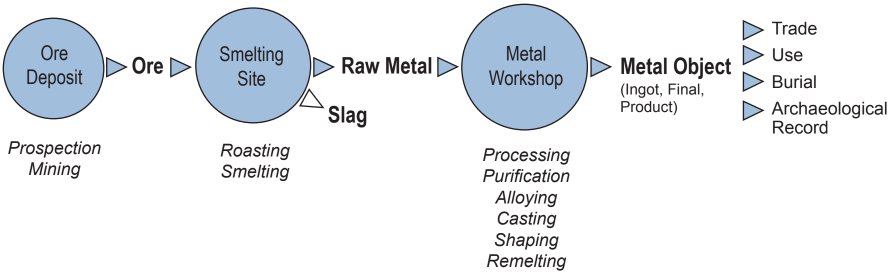


Fig. 5.1 The metallurgical chain from ore to metal offers information in a double sense: it shows the *chaîne opèratoire* of human activities within metal production, and it provides information on the material transformations during metallurgical operations. Slags are mainly formed by smelting ores or by melting metal (e.g., by casting, alloying, or refining processes)

and solidifies in many cases into a glassy mass. Slag, therefore, is a waste product and generally remains in the locality where it was formed.

The modern definition of slag can be applied to archaeometallurgical slags as well, but we have to be aware that ancient slags were often formed under unusual conditions. As opposed to modern slags, which are smelted in a blast furnace, ancient slags were produced under limited firing control in small smelting furnaces or crucibles. Thus, archaeometallurgical slags often did not reach the fully liquid state. They may be rich in metal or metal-bearing phases (e.g., copper, copper sulfide, lead, lead silicates, and tin oxide). The processes that produced such messy slags cannot always be clearly defined. It is important to understand the term “slag” as it is used here (as defined in the mining regulations of Goslar in 1360 AD), which describes more generally any metal-containing material that has been fired or melted once. This includes the actual waste products as well as any intermediate products containing metal. These may be metal-rich slag, scrap metal, casting remains, etc.

Slags are mainly residues of ore-smelting processes, but they can also be formed by a variety of other metallurgical activities within the “metallurgical chain” (Fig. 5.1), regardless of whether these belong to copper, silver, lead, iron, or tin metallurgy. Slag can be formed by smelting ores, melting metal, remelting slag or metal, and refining or casting metal. The most conspicuous ancient slag heaps were found at smelting sites such as Rio Tinto (Spain), Skouriotissa (Cyprus), or Faynan (Jordan), where thousands of tons of slag accumulated over the centuries (Fig. 5.2) in close proximity to the ore deposits where the raw material was won by mining activities. However, these slag heaps are generally rather young, dating from the Late Bronze Age to the Byzantine Period.

Slags from the earlier stages of metallurgy, which are usually found only in amounts of a few kilograms, are much less spectacular. They date from the late sixth millennium in southeastern Europe and the Middle East and, as a rule, these slags are never found near the ore deposits but rather in workshop areas in settlements. We conclude from this that ores were transported from the raw sources to villages, often over distances of > 100 km. Examples of such ore transportation can be found in the Near East, but also at sites in the Eastern Alps as well as on the Iberian Peninsula.

Fig. 5.2 Huge slag heaps accumulated close to the copper deposit of Skouriotissa, Cyprus, during the Roman and Byzantine Period. Tap slags with a weight of 50 kg or more were produced by smelting copper ores. Note the flow structures of the slag cakes, which is very similar to the frozen texture of volcanic rocks. They indicate that these slag cakes were tapped from a smelting furnace in the fully liquid state and solidified outside the furnace very quickly

In the Near East, the transport of valuable ores from the source to the settlement parallels the tradition of moving exotic materials such as obsidian, silex, or native copper over supra-regional distances.

Slag Investigations: The Beginnings and Tendencies

The modern scientific investigation of slag is a relatively young field of research in archaeometallurgy. It developed alongside the "New Archaeology" in the late 1960s, when archaeologists recognized the potential of scientific methods as an integral part of their research strategy. It is bound to the perception that the production of metal and the distribution of metals was the basis of economic wealth in many regions.

It was also in the 1960s that pioneering work was done on ancient mines and slag heaps by Beno Rothenberg. He recognized the potential of the industrial remains of early copper production at Timna, Israel, and organized an interdisciplinary team of scientists to investigate the materials found there. It was Hans-Gert Bachmann in cooperation with Alexandru Lupu and Ronald F. Tylecote who modeled the first hypotheses on early copper smelting and melting for this locality. The focus of Bachmann's work was a mineralogical and chemical analysis of slag in order to reconstruct the technological parameters of ancient smelting processes.

At the same time, the metallurgists G. R. Morton and J. Wingrove (1969, 1972) published their studies of Roman and Medieval bloomery slags from England. They determined the mineralogical constituents and the chemical composition of these slags, and discussed their composition in phase diagrams. C. Milton (1976) and his team analyzed a few slag samples from Timna (Israel) using the same principles and analytical methods. F. Koucky and A. Steinberg (1982) undertook the study of the (pre)historic copper slag of Cyprus. Due to the sheer mass of slag accumulations from different time periods on Cyprus, it was difficult to come up with a reasonable classification.

Although these other works were important early steps in the study of archaeometallurgical slags, it was Bachmann's intensive study of the smelting slags from the ore district of Timna that set the standard. Bachmann carefully determined their mineralogical phase content, analyzed their chemical composition, identified the metal inclusions, and calculated their viscosity. Most importantly, in 1982 he edited the very valuable booklet *The Identification of Slags from Archaeometallurgical Sites*—to this day the definitive "textbook" for slag analysis. Bachmann's studies have been considerably advanced by mineralogical–petrographic studies carried out by German mineralogists such as A. Kronz and I. Keesmann. They have broadened our knowledge of the mineralogy and petrology of archaeometallurgical slag, best exemplified by an investigation of Medieval iron production in the Lahn-Dill area in Germany (Kronz and Keesmann 2007).

In the early stage of slag research, mainly conspicuous examples of tap slag (i.e., slag that has been "tapped" from the furnace during the smelting process) were collected from larger slag heaps of later periods, i.e., from the Late Bronze Age and periods of more advanced technology. These tap slags originated mainly from the production of copper, iron, lead/silver, and zinc. Often it happened that the archaeological context was not fully included in these investigations. The occurrence of the almost omnipresent phenomenon of crushing slags to extract trapped metallic prills for remelting was often neglected in interpretations. Surprisingly, metallurgical remains that were produced in the early periods of metallurgy, as well as slags from early tin and bronze production, are extremely rare in the archaeological record, as are remains from gold and silver processing. Still today, the understanding of archaeological finds from technological processes, unearthed from smelting sites or from metal workshops, is a topic of confusion. The intention, therefore, to reconstruct organizational patterns of metallurgical activities in ancient times is hampered. These lacunas perhaps will direct future trends in slag investigation.

How to Answer Questions: Methods of Scientific Slag Investigation

The investigation of archaeometallurgical slag involves asking questions about both technological aspects, and also questions about the provenance of the ore charge. Both are the basis for reconstructing economic and craft-related systems in the past.

Technological questions that can be asked are:

- Which metal or alloy was produced by a metallurgical operation that led to the formation of a specific slag?
- Can we identify slags from smelting processes vs. those from melting or refining metals?

- What was the nature of the ore that was originally smelted? Can we find evidence for a deliberate addition of fluxes, or have ores been selected that effectively fluxed themselves ("self-fluxing ore")?
- What were the firing conditions that led to the formation of slags (temperature, gas atmosphere, and duration of the process)?
- Can we determine the locations of the ore sources used and whether such ore was transported?

After slags are unearthed from secure archaeological contexts (e.g., from slag heaps or workshops), their analysis has multiple stages. First, slags should be classified visually based on color, porosity, texture, etc. Second, the slag should be subjected to a series of scientific analyses to identify bulk chemistry, specific mineralogical and metallurgical phases, and for lead isotope provenance. These can be accomplished through a number of different analytical techniques using either mounted and polished samples or petrographic thin sections of the slags.

Due to rapid cooling, archaeometallurgical slags generally consist of a fine-grained mixture of different phases. They usually have a complex composition, depending on the bulk chemistry. Therefore, optical microscopy is an indispensable method, particularly for the determination of slag phases and texture analysis. To perform microscopic investigations under transmitted and reflected (polarizing) light, surface-polished thin sections are preferable.

If the size of the slag allows, the macroscopic analysis of the fabric or texture (meaning the orientation and distribution of particular phases or other structural constituents) should be investigated. This is especially possible for slags produced in small-scale operations, which often lead to heterogeneous compositions. In early iron metallurgy, this is particularly important for fist-sized, so-called "plano-convex bottom" ("PCB") or "smithing" slags, produced throughout the Old World as a by-product of iron working. The chemical and mineralogical composition of smithing slag is often very similar to bloomery slag, which is produced during iron smelting. It is therefore impossible to use chemical and mineralogical composition alone to ascertain which process produced the slag.

In Chalcolithic and Early Bronze Age copper metallurgy, slags with a size comparable to smithing slags also occurred. Such slags usually result from smelting in small reaction vessels (e.g., in crucibles). They differ from the smelting slags of later periods in their rather high content of trapped metal, and they also contain many inclusions of undecomposed fragments of quartz and gangue (Figs. 5.3 and 5.4). Incidentally, metallurgical operations in crucibles that produced small slag cakes were also performed in Phoenician and Roman silver metallurgy.

While metal inclusions (or those that bear a concentration of metal, such as sulfide inclusions) in slags can be identified without problems, it is often difficult to determine mineralogical phases by optical microscopy alone, with the exception of main components such as olivine (fayalite, Fe_2SiO_4 or tephroite, Mn_2SiO_4), spinel (magnetite, Fe_3O_4 or hercynite, $FeAl_2O_4$), and pyroxene (e.g., hedenbergite, $CaFeSi_2O_6$). Sometimes, as was the case at Faynan, Jordan, or with lead-smelting slags, the slags have even solidified in a glassy state, although such 'glasses' show transitions to a

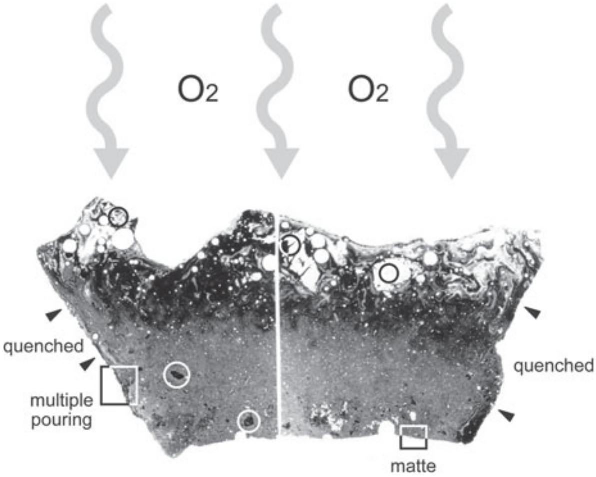


Fig. 5.3 Section of an Early Bronze Age (mid-third millennium BC) slag cake from Shahr-i Sokhta (Iran), composed of two thin sections. The macrotexture provides important information on the history of this piece of slag. It shows a horizontal division into two parts. The *upper part* is rich in white inclusions of gangue/ore (*black circles*) and gas bubbles embedded in a dark matrix. Here, the slag is enriched in magnetite and glass that formed in the presence of air during cooling. Note the streaks of glass. The *lower part* is almost fully crystallized; it contains predominantly hedenbergite and reveals inclusions of ore (*white circles*). The side surface is *quenched* and indicates that the slag was poured into an irregularly formed cold ground. Multiple layering of magnetite may result from *multiple pouring*. The rim *at the bottom* shows the size of the original regulus of matte and copper that could not be fully separated from the slag, as remains of *matte at the bottom* show. Diameter of the upper size of the slag: 8 cm. (From Hauptmann et al. 2003)

Fig. 5.4 Tepe Hissar, Iran, Early Bronze Age. Section through a copper-smelting slag (half of a slag cake with a diameter of ca. 17 cm). The main component of the *lower dark part* that was fully liquefied is fayalite, forming a typical bulky spinifex texture. The slag was probably tapped from a furnace into a fore-hearth, where reactions between slag and the clay bottom of the hearth formed a rim of gas bubbles. The *upper part* of the slag is covered by a layer of light inclusions of quartz and gangue of the ore. The texture looks like a breccia. The ore obviously was crushed to a grain size of a few millimeters. The *dark* and the *light layers* of the slag were welded together. The contact zone is rich in magnetite and suggests a sudden presence of air caused by a hiatus during tapping. From Hauptmann (2007)

microcrystalline state formed in residual melts. In these cases, X-raydiffraction of a powdered slag sample can help to identify all phases. Scanning electron microscopy (SEM) and electron microprobe analysis (EMPA) have gained increasing importance in slag analysis, as they provide fast and reliable (quantitative) spotanalyses for phase identification. Such analyses, however, require a thorough mineralogical knowledge. A set of micrographs of various smelting and melting slags is shown in Fig. 5.5.

It has proven advisable to carry out bulk chemical analyses, including trace elements, by conventional analytical methods such as X-ray fluorescence spectroscopy (XRF) or optical emission spectroscopy coupled with a plasma source(ICP-OES). A precondition for such analyses is a sufficient, representative quantity of material. This varies between a few grams and a kilogram depending on the original size of the sample. If the archaeological context allows for it, it proves prudent to analyze a whole series of samples to obtain good statistical results.

The interpretation of bulk chemical analysis of slags can be impaired by the heterogeneous composition of a slag. This is particularly the case when the slag still contains undecomposed constituents of the original ore charge, as can often be observed in ancient lead- or copper-smelting slags. In such cases, it is more useful not to analyze powdered slag samples, but to study single sections via thin section or mounted samples on the microscale. This can be carried out by energy-dispersive X-ray analysis in an SEM or with an electron microprobe. This method has the added advantage that the composition of inclusions and the surrounding molten slag can be studied separately.

It can sometimes be observed that ores were brought to a smelting site or to a settlement far away from ore sources. This was observed, for example, in the Faynan and Timna copper districts in Jordan and Israel, and on the Cycladic islands in Greece. During the Early Bronze Age, ore was transported to carefully selected smelting sites from elsewhere for metal production in wind-powered furnaces. Lead isotope analyses have to be performed to search for the origin of the ore. The principle of this method is based on omnipresent lead impurities in almost all sorts of ores (this implies that the method is in no way restricted to lead ores or slag). The ratios of lead isotopes in the ore stay unchanged after (s)melting processes. To identify possible ore sources, the isotope ratios of slags under investigation have to be compared with the ratios of ores collected in various databanks. Several types of mass spectrometers are in use today in special laboratories.

Closely connected to the question of provenance is the necessity of dating metallurgical activities. Very often smelting sites are almost void of datable pottery and therefore scientific methods are required to identify the time period(s) when slags accumulated. Because slag production in furnaces or crucibles is unavoidably bound to the use of certain quantities of charcoal, a most suitable material is available for radiocarbon dating. Inclusions of charred twigs or branches can easily be extracted from slag specimens or from layers in between. Thermoluminescence is another method that can be used to date metallurgical slags, although it has rarely been used for this purpose.

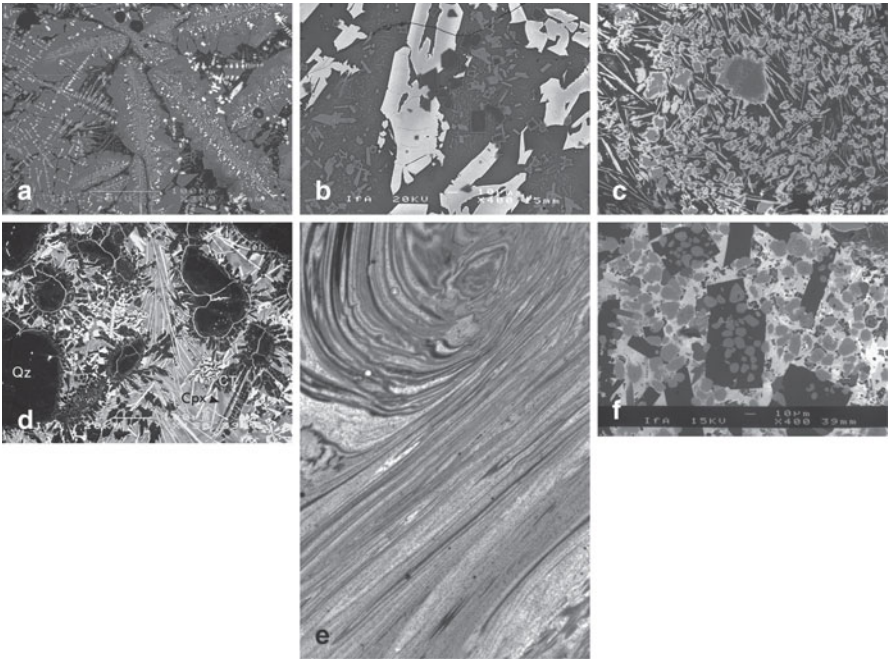


Fig. 5.5 **a** Lauchheim (Germany), La Tène-period. Iron-rich silicate slag from iron smelting containing wuestite in two generations: the primary precipitation forms rounded dendrites; the second generation of wuestite is intergrown with the main component fayalite. Some of the fayalite crystals are "divided" by a thin rim of wuestite in the middle. The matrix in between (*black*) consists of glass and some iscorite (Fe–ironsilicate). SEM-image. (From Yalcin and Hauptmann 1995). **b** Linsenhofen (Germany). Slag from Medieval iron smelting. Chains of fayaliteskeletons (*white*). The fine-grained matrix consists of small crystals of pyroxene (hedenbergite, *middle gray rhombi*). Intensive zonations show hercynite with an iron-rich rim (*black crystals with light rim*). **c** Norşuntepe (Eastern Anatolia), Chalcolithic (mid-fourth millennium BC). Copper-smelting slag, very rich in oxidic mineral phases. Magnetite (*white grains*) are surrounded by stems and laths of delafossite. These main phases indicate a smelting process under rather oxidizing conditions. Just *in the center of the picture*, an undecomposed crystal of chromite. Occasionally tiny droplets of cuprite. SEM-image. 9From Hauptmann et al. 1993). **d** Wadi Fidan 4, Faynan (Jordan). Chalcolithic copper slag from crucible smelting. Reaction between liquefied slag (*gray matrix*) and quartz (*Qz*), the latter being a relict from the copper-bearing sandstone. Quartz grains have *light colored* fissures. They are transformed from the core to the outer edge into high-temperature phases of quartz (*CT* cristobalite, tryidymite). In the glassy matrix, columnar delafossite, magnetite, and pyroxene. SEM-picture. (From Hauptmann 2007). **e** Wadi Ghwair, Faynan (Jordan), Early Bronze Age (mid-third millennium BC). Copper-smelting slag. Yellowish-brown glass with laminar flow texture and pigmentation through cuprite and copper prills in single streaks. Width of the picture ca. 2 mm. **f** Xanten (Colonia Ulpia Traiana; Germany), Roman settlement and military camp. Silver refining slag from a crucible. Rounded Ca–Pbsilicates (*gray*) and melilite crystals (complex Ca–Al–Mg–Fe–Alsilicates, *black*); the matrix (*white*) consists of Pb-silicates. SEM-image. (From Rehren and Hauptmann 1995)

Chemical Analyses and Phase Diagrams

Due to the composition of the charges in ancient furnaces (usually composed of limonite + quartz + clay minerals + ore + possible fluxing agents), and due to the only slightly reducing firing conditions accessible in ancient times, we tend to find high concentrations of iron oxides and silica in archaeometallurgical slags. These are termed iron-rich silicate slags. Their predominant mineralogical constituent is usually fayalite. Such compositions also occur in bloomery (and smithing) slags, and in slags from base-metal smelting as well. In most cases, FeO, SiO_2, CaO, and Al_2O_3 will make up to 80 weight percent or more of the slag's bulk chemistry. In addition, these slags may contain varying amounts of oxides such as MgO, BaO, Na_2O, K_2O, P_2O_5, CuO, PbO, SnO, or ZnO. All of these oxides can be used to determine the thermodynamic and physical properties of slags, such as the temperatures under which they were formed in a reaction vessel or their viscosity.

The way to do this is to make use of suitable ternary or quaternary phase diagrams as they are known in material science. The interpretation and evaluation of phase diagrams is a sophisticated field. It is beyond the scope of this chapter to present this subject in detail. The reader is referred to standard textbooks on physical chemistry, while phase diagrams for ancient slags can be found in the Slag Atlas (Verein Deutscher Eisenhüttenleute 1995).

For many archaeometallurgical slags, a number of ternary systems within the materials tetrahedron of CaO–SiO_2–FeO–Al_2O_3 can be suitable—e.g., the system SiO_2–FeO–Al_2O_3 (Fig. 5.6), where the chemistry of a large number of ancient slags is located, or the system CaO–SiO_2–FeO. Looking "from above" on the liquidus surfaces, where the temperatures of solidification of a liquid is shown, we can recognize in the first ternary system a region of low-melting compositions around fayalite at around 1200 °C. The small extent of this low-melting region is surrounded on the SiO_2-rich and on the Al_2O_3-rich sides by very steeply arising liquidus surfaces, up to more than 1500 °C. Here, highly refractory phases (i.e., resistant to heat and chemical alteration) such as quartz or spinel (hercynite) are located. In ancient furnaces, such high temperatures were not generally reached.

To place the slag of interest into a phase diagram, the main components are converted to $SiO_2 + FeO + Al_2O_3$ to equal 100 % (or $CaO + SiO_2 + FeO$, respectively). This is a so-called "reduced analysis." These values are then inserted into the ternary system to see whether a slag was workable or not—i.e., whether it could have been tapped in a free-flowing state from a furnace. In the ideal case, the reduced bulk chemical analysis should plot into a low-melting region of a system. Hence, the melting temperature of a slag determined by a plot in a phase diagram can give a rough estimation of the working temperature of the furnace. In reality, the minor elements in a slag (e.g., the oxides) will affect its melting and solidification behavior, so phase diagrams are merely an approximation. However, phase diagrams are a useful tool for the discussion of temperatures.

Until recently, it was assumed that the tight clustering of ancient iron-rich silicate slag compositions on a phase diagram reflected the technical skill of ancient metalworkers who, having found a suitable charge composition to produce a useful product

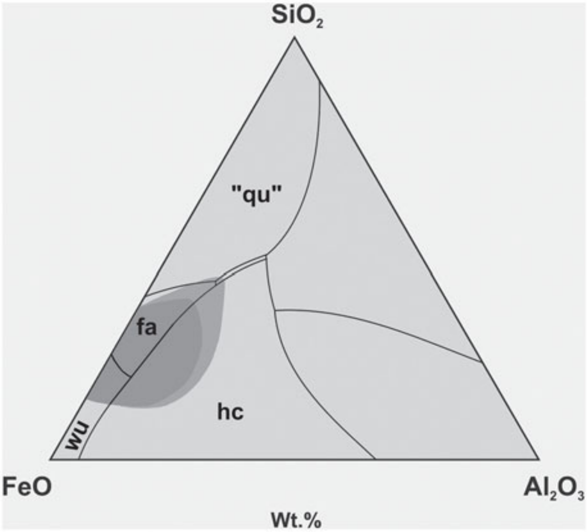


Fig. 5.6 Average composition of archaeometallurgical slags from copper smelting (*medium-shaded area*) and iron smelting (*dark-shaded area*) shown in the ternary system $FeO–Al_2O_3–SiO_2$ (weight percent). The compositions match mainly the eutectic area of the fayalite region (*fa*) in the system. It is surrounded by steeply arising areas of quartz ("*qu*") and spinel (*hc* hercynite). These are components which crystallize from very high temperatures or, vice versa, they are stable up to high temperatures. (From Hauptmann 2007)

on one occasion, were then able to reproduce that charge again and again to produce a similar result. In view of the limited control that ancient metallurgists could have had over the raw materials as well as the smelting processes, and yet the lack of significant differences among most of the slag found over a wide geographical and chronological range, the idea of a skilled metalworker mass-producing a standardized product is a highly unlikely assumption (Hauptmann 2007). In reality, given the interdependence of all these procedural parameters, there are only a very few ways in which all the low-melting slags could have been produced throughout the world. Most of the studied slags, mainly from the later periods of early metallurgy, fulfill these technical conditions insofar as they have compositions which are close to the low-melting parts of ternary or quarternary systems. A clustering toward iron-rich silicate slags is noticeable simply because of the character of the raw material (i.e., ores high in iron and silica). In addition, furnace walls made of clay or rock act as a source material for the final tuning of low-melting compositions (as a function of oxygen pressure and temperature), in that they supply minerals (such as SiO_2 or CaO) to the molten slag.

In reality, the charged ore does not pass over from the solid to the liquid state at a distinct temperature, but parts of the material form a liquid as soon as the temperature of the lowest eutectic is reached. This follows the principle of partial melting in petrology. It is therefore far more informative to study the formation of slag during gradual heating of the ore charge, from the first liquefying of the components at lower temperatures to a complete *liquefaction* of the charge (i.e., small solid components behaving like liquid, such as a mudslide). The successive liquefaction of slag might be seen as a "view from below" in contrast to a "view from above" when discussing the solidification of slags as explained above.

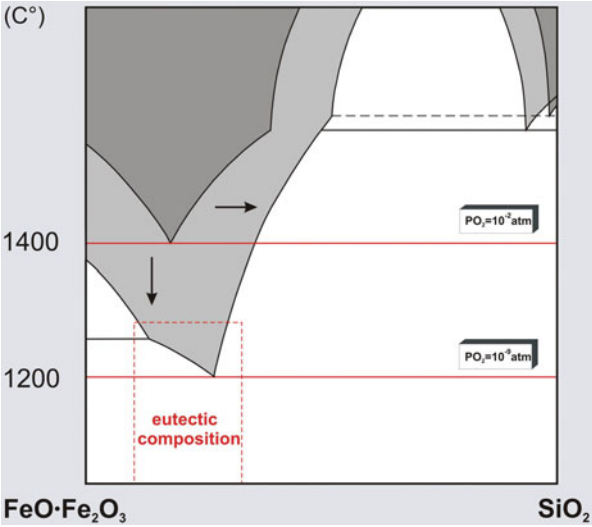


Fig. 5.7 The binary system *FeO/Fe*$_3$*O*$_4$*–SiO*$_2$ shows that iron-rich silicate melts are formed at ca. 1200 °C (which can be assumed as a reasonable temperature level in ancient furnaces) only in a limited range of composition that comes closest to a fayalitic composition. If too much quartz (*SiO*$_2$) is added, or too much iron oxide such as magnetite or hematite, then the charge will only be partially liquefied. (From Hauptmann 2007)

During liquefaction, successively more solid parts dissolve into the liquid melt. It is now a question of firing temperature and time as to whether all components will dissolve in the primarily formed liquid. Partial melting starts at those points where the components of the charge have suitable proportions to form a low-melting liquid. This is a eutectic point. We assume that our charge is composed of limonite (iron hydroxide) and quartz. While limonite will be quickly dehydrated and reduced to various iron oxides, the highly refractory quartz remains unaltered for a certain time. As depicted in a simplified version in the system FeO/Fe_3O_4–SiO_2 (Fig. 5.7), only a small region of composition will reach the fully liquid state at temperatures of 1200°C, which is reasonable for ancient smelting furnaces. This means that the quantity of liquid slag formation depends on how close the charge comes to the eutectic composition in the system. For example, if the charge is composed of ca. 35 weight percent of iron oxide (calculated as FeO) and 65 weight percent of SiO_2, then the whole charge will be liquefied at 1200 °C. If too much quartz is present from the gangue of an ore, not all of it will react with iron oxide at that temperature. In such cases, pieces of quartz will be found undecomposed as "resisters" or "relicts" in the slag. As a result, the smelting operation will not end up with a fully liquefied slag. This, of course, hampers the separation of metal from the slag and eventually "clogs" up the smelting furnace or crucible.

It has been demonstrated by texture analyses of slags from the early stages of extractive metallurgy that, almost as a rule, they contain undecomposed inclusions. Examples are known from the third millennium BC copper slags from Iran and Jordan (Fig. cc), and from the first millennium BC lead–silver-smelting slags from Monte Romero, Iberian Peninsula. In the past, these slags were named not very appropriately "free silica slags" (they often also contain undecomposed resisters of other refractive mineral phases such as chromite, barite, or periclase) and the inclusions were often uncritically and rashly interpreted as deliberately added fluxing agents.

Redox Conditions and Reactions

Archaeometallurgical slags were generally formed under reducing conditions limited by the burning of charcoal. They were subject to fluctuations of the oxygen pressure in the gas atmosphere, controlled by the CO/CO_2 ratio (redox conditions) depending on the size and shape of the reaction vessels in which they were (s)melted, on the sort of tuyères that were used, and on some other manual techniques. At the beginning of metallurgy, only those metals that could be smelted under just slightly reducing conditions in an open crucible with a low charcoal cover using blowpipes were produced. These metals were copper, silver, lead, and tin. Iron and zinc were produced later in the first millennium BC under much stronger reducing conditions in furnaces with larger amounts of charcoal.

Metal oxides, such as CaO, MnO, MgO, etc., could not be reduced to metal because they require extremely strong reducing conditions, which the ancient metallurgists were not able to produce. Instead, these metals are captured as oxides in the slags. We can reconstruct the redox conditions because most of the ancient slags are iron-rich silicate slags that react during their formation very sensitively to the oxygen content. This leads to the crystallization of mineral phases with differing $Fe^{2+,3+}$ or $Cu^{1+,2+}$ ratios at a constant chemical composition, identifiable directly from the mineralogical composition in the slag. Minerals that can be used as oxygen barometers are listed in Fig. 5.8. One of the most important equations that represent this issue is the following:

$$3Fe^{2+}{}_2SiO_4 + O_2 < - - - > 2FeO^{2+}Fe^{3+}{}_2O_3 + 3SiO_2$$

This is the quartz, fayalite, and magnetite (QFM) buffer equilibrium, which depicts the following: If the oxygen concentration in the gas atmosphere is sufficiently high, magnetite and a silica-rich compound such as pyroxene crystallize first, so that iron is mainly bound as an oxide. If oxygen is low, no magnetite will be formed, but the frequent mineral phase fayalite (or even metallic iron) precipitates. In fact, fayalite in very early slags is a phase that only rarely occurs, but phases such as cuprite and delafossite are frequently observed in most ancient copper slags. Bronze Age slags are characterized by the phase associations fayalite + magnetite, while bloomery slags from iron production contain fayalite + wuestite + metallic iron. As shown in Fig. 5.8, there are a number of other mineral phases, which can be used to reconstruct redox conditions.

The Role of Sulfides

Many copper-based sulfides are quickly liquefied at temperatures of ca. 900 °C or even less. This is far below the temperatures necessary for the formation of a liquid slag. Different melting points might have been important for the separation of specific components, especially during the gradual liquefaction of ores with rising temperatures and the lengthening duration of the reaction. These physical and chemical effects were probably known to the ancient metalworkers.

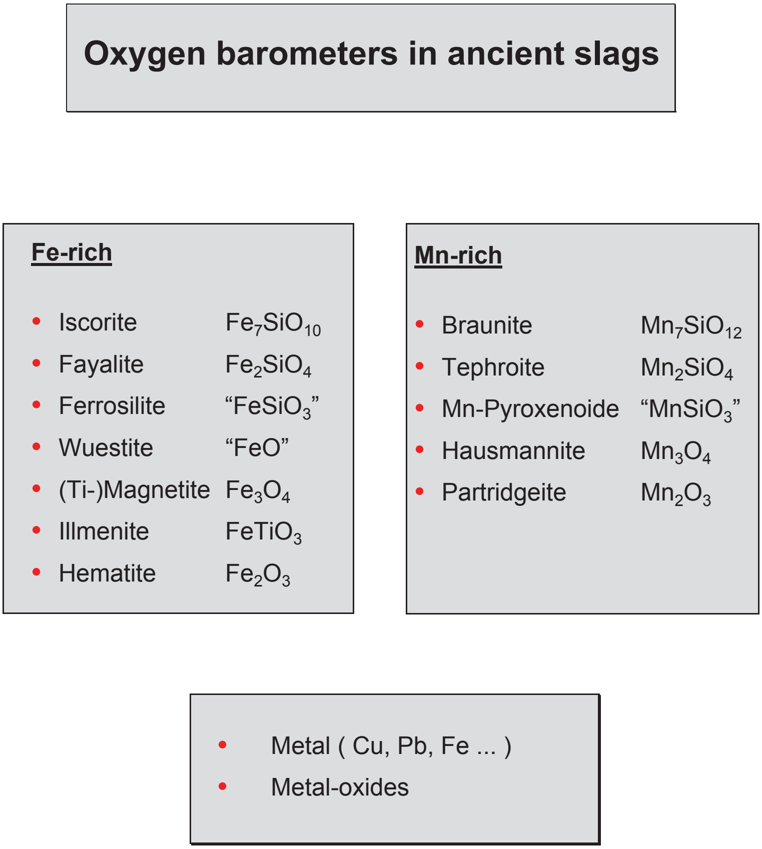


Fig. 5.8 Frequent mineral phases in ancient slags that can be used to reconstruct the redoxcondition of metallurgical operations. These are called barometers. They are rich in metal with several valencies. In a similar way, several metals and metal oxides can also be used

During the smelting of complex sulfide ores (mainly copper ores), droplets liquate from only partially melted slag. Due to their high density and their low viscosity, these droplets of copper sulfide ("matte") accumulate into a "cake" at the bottom of a furnace or crucible. If the sulfides are required as a final product from the smelting process (as in modern matte smelting), then the matte cake is further processed elsewhere, and the smelter does not care much about producing a fully liquefied slag. Such "immature" slags with many inclusions of refractive minerals from the gangue of the ore are frequently found in Bronze Age copper-smelting sites. Usually they were withdrawn from the furnace with a stick and then crushed to mechanically extract the remaining metallic and sulfide prills, because complete segregation between the two phases was never reached. In certain cases, the sulfide/metal cake leaves a negative imprint at the bottom of the slag, as shown in Fig. 5.2 in the slag from Shahr-i Sokhta, Iran.

Very often, sulfide cakes envelop oval-shaped metal prills. The sulfide acts like a lubricant to separate such prills from the silicate slag. The metal may have segregated out of the sulfide ore itself or may have originated from the reduction of oxidic ores (often found associated with sulfidic ore). In any case, metal precipitation in smelts with mixed oxidic and sulfidic ores is enhanced by any smelting process carried out under slightly oxidising redox conditions. In such cases, the sulfur is oxidized and forms metal according to the so-called roast reactions:

$$2Cu_2S + 3O_2 > 2Cu_2O + 2SO_2$$

$$Cu_2S + 2Cu_2O > 6Cu + SO_2$$

These equations explain many ancient copper slags, particularly those that result from the intentional roasting of copper sulfide ores (as a preliminary step before smelting) or with mixed oxidic–sulfidic ore smelts. Intergrowths between copper and copper/ironsulfides, or inclusions of sulfides, are not necessarily evidence for a deliberate matte smelting. Such inclusions may result from the casual smelting of mixed oxidic and sulfidic ores, which often occur side by side in ore deposits.

We do not know when matte smelting developed as a secondary metallurgical process for the increased production of metal. Such a process might imply the deliberate roasting of ores (and of matte) which, from the archaeological point of view, is difficult to identify at least for the early stages of metal production. However, the useful effects of a nonhomogeneous liquation of a charge at different temperatures, and their separation from each other, are frequently seen in ancient slags, and should be more intensively considered in archaeometallurgical studies. It is most probable that the benefits of such a heterogeneous process were known to ancient metalworkers.

Synopsis

All of these investigations and aspects of scientific slag investigation provide valuable information to decipher the technological practice of ancient metalworkers. For the most part, however, the data produced are physicochemical details. To reconstruct manual details and to understand social complexities of metal making, it is important to add other sources. For example, we can learn a lot from written sources such as Theophilus Presbyter (Hawthorne and Smith 1979), Georg Agricola (Hoover and Hoover 1912), and Vannoccio Biringuccio (Smith and Gnudi 1959), who described in detail the smelting and melting techniques used between the twelfth and sixteenth centuries AD. John Percy (1861/1890) published traditional techniques used by metallurgists still in the nineteenth century. There are many other sources like that. Of special importance are ethnographic studies, such as in Africa where many ethnographic studies on iron and copper smelting and processing, and on bronze making, were undertaken (Bisson 2000; Förster 1987). Last but not least, it is a great help to understand and to identify archaeometallurgical finds by comparing them with results from experimental metal production. One of the most interesting studies was undertaken by Hanning et al. (2010), who replicated the Chalcolithic copper smelting exemplified by the finds from Zambujal on the Iberian Peninsula.

References

Bachmann, H. G. (1978). Schlacken: Indikatoren archäometallurgischer Prozesse. In H. W. Hennicke (Ed.), *Mineralische Rohstoffe als kulturhistorische Informationsquelle* (pp. 66–103). Hagen, Verlag Deutscher Emailfachleute.

Bachmann, H. G. (1982). The Identification of Slags from Archaeological Sites. Institute of Archaeology, University of London, Occasional Papers 6.

Biringuccio, V. (1540). Pirotechnia. Reissued 1959 (trans: H. S. Mudd 1942) Massachusetts Institute of Technology, Cambridge, Mass.

Bisson, M. S. (2000). Precolonial copper metallurgy: Sociopolitical context. In J. Vogel (Ed.), *Ancient African Metallurgy* (pp. 83–145). Walnut-Creek, Altamira-Press.

Förster, T. (1987). Glänzend wie Gold. Gelbguss bei den Senufo, Elfenbeinküste. Veröffentl. Mus. Völkerkunde Berlin, Abt. Afrika, IX.

Hanning, E., Gauß, R., & Goldenberg, G. (2010). Metal for Zambujal: Experimentally Reconstructing a 5000-year-old Technology. *Trabajos de Prehistoria, 67*(2), 287–304.

Hauptmann, A. (2007). The early metallurgy of copper. Evidence fom Faynan, Jordan. In G. A. Wagner, B. Herrmann (Eds.), *Natural Science in Archaeology* (p. 270). Springer: Heidelberg.

Hauptmann, A., Rehren, Th., & Schmitt-Strecker, S. (2003). Early Bronze Age copper metallurgy at Shahr-i Sokhta (Iran), reconsidered. In T. Stöllner, G. Körlin, G. Steffens, J. Cierny (Eds), *Man and Mining—Mensch und Bergbau*. Studies in honour of Gerd Weisgerber on occasion of his 65th birthday. Der Anschnitt, Beiheft 16, Deutsches Bergbau-Museum Bochum, pp. 197–213.

Hawthorne, J. G., & Smith C. S. (transl.) (1979).*Theophilus: On Divers Arts*. New York, Dover Publications.

Hoover, H. C., & Hoover, L. H. (1912). (trans: G. Agricola). *De Re Metallica*. London.

Kronz, A., & Keesmann, I. (2007). Fayalitische Schmelzsysteme – Ein Beitrag zur vorneuzeitlichen Eisen- und Buntmetalltechnologie im Dietzhölzetal. In: Das Dietzhölzetal-Projekt. Archäometallurgische Untersuchungen zur Geschichte und Struktur der mittelalterlichen Eisengewinnung im Lahn-Dill-Gebiet (Hessen). Marie Leidorf, Rahden, Westf.

Koucky, F., & Steinberg, A. (1982). The ancient slags of Cyprus. In J. D. Muhly, R. Maddin, V. Karageorghis (Eds.), *Early Metallurgy at Cyprus, 4000–500 B.C*. Acta of the International Archaeologival Symposium, Larnaca 1981.

Milton, C., Dwornik, E., Finkelman, RB., Toulmin III P. (1976). Slag from an ancient copper smelter at Timna, Israel. *Journal of Historical Metallurgy Society, 10,* 24–33.

Metten, B. (2003). Beitrag zur spätbronzezeitlichen Kupfermetallurgie im Trentino (Südalpen) im Vergleich mit anderen prähistorischen Kupferschlacken aus dem Alpenraum. Metalla 10, Heft 1, 2, 1–122.

Morton, H., & Wingrove, J. (1969). Constitution of bloomery slags. Part I: Roman. *Journal of Iron and Steel Institute, 207,* 1556–1564.

Morton, H., & Wingrove, J. (1972). Constitution of bloomery slags. Part II: Medieval. *Journal of Iron and Steel Institute*, *210*, 478–488.

Percy, J. (1861/1890). Metallurgy (vol. 4). London.

Rehren, Th., & Hauptmann, A. (1995). Silberraffinations-Schlacken aus der CUT (Xanten), Insula 39: Mineralogische Untersuchung und archäometallurgische Interpretation. Xantener Berichte, Bd 6, 119–137.

Smith, C. S., & Gnudi, M. T. (transl.) (1959). Vannoccio Biringuccio. Pirotechnica. Dover Publ., Mincola NY.

Verein Deutscher Eisenhüttenleute (Eds.). (1995). Slag atlas. Düsseldorf, Verlag Stahleisen.

Yalcin, Ü., & Hauptmann, A. (1995). Zur Archäometallurgie des Eisens auf der Schwäbischen Alb. Forschungen und Berichte zur Vor- u. Frühgeschichte in Baden-Württemberg (Bd 33, pp. 269–309).

Chapter 6
Technical Ceramics

Marcos Martinón-Torres and Thilo Rehren

Introduction

Ceramics are inorganic, non-metallic solids obtained by firing a mixture of fine clay minerals (the main raw material) and coarser secondary materials (e.g. plant remains and sand) at high temperatures (generally above 700 °C). The term 'technical ceramics' refers generally to any ceramics used in metallurgical or other high-temperature operations, such as pottery production or glass making. The main types of metallurgical technical ceramics found in archaeological sites are furnaces, crucibles, tuyères and moulds. Indeed, the vast majority of furnaces, crucibles, tuyères and moulds documented archaeologically was made of ceramic, although moulds have frequently been made from other materials such as stone, metal, and even antler. The fundamental role of technical ceramics in early metallurgy is increasingly recognised by archaeometallurgists, as the vast majority of past metallurgical processes would have required their use. Such technical ceramics were used chiefly to contain the reactions (in crucibles and furnaces), to channel the oxygen necessary for the combustion (through tuyères), or to provide the moulds that would allow the casting of the metal. The development of metallurgy is inextricably linked to the development of technical ceramics; thus, the study of technical ceramics adds at least as much to our understanding of ancient metallurgy as the study of the finished objects, if not more.

Technical ceramics are essential tools for almost all metallurgical processes, and as such were routinely exposed to a variety of conditions that they had to cope with. Although not all of these technical challenges were present in every metallurgical reaction, most metallurgical ceramics would generally be expected to show some

M. Martinón-Torres (✉)
Institute of Archaeology, University College London,
31–34 Gordon Square, WC1H 0PY London, UK
e-mail: m.martinon-torres@ucl.ac.uk

Th. Rehren
UCL Qatar, University College London,
Hamad bin Khalifa University, Doha, Qatar
e-mail: th.rehren@ucl.ac.uk

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_6,

degree of thermal refractoriness (i.e. ability to withstand high temperatures without collapsing), thermal shock resistance (i.e. ability to survive sudden temperature changes without shattering) and general mechanical or tensile strength (i.e. ability to hold substantial charges, reaching several kilograms, while being manipulated in a hot state). In addition, chemical refractoriness (i.e. ability to resist chemically aggressive materials) is required of some technical ceramics, particularly in iron/steel metallurgy and in the processing of lead and lead–silver alloys.

Experimental studies have shown that most common clays will withstand temperatures up to around 1,100 °C without 'failing' (i.e. melting), but not much above that range. Given that most early metals melt between 900 and 1,200 °C (pure copper, for instance, melts at 1,083 °C), early technical ceramics allowed only a relatively small window of opportunity for some metallurgical processes to occur. In this sense, while most archaeologists think that one of the main challenges for early metalworkers was to achieve high temperatures, many now realise that keeping those high temperatures without unduly exceeding them was even more challenging. In fact, many metallurgical ceramics appear to have been exposed to the very limit of their thermal ability. Whatever the case, it seems that early metalworkers had no knowledge of (or felt no need to use) special clays that could have withstood even higher temperatures (what are called 'refractory' clays). Instead, they very frequently tried to improve the functionality of local clays by optimising wall thickness or vessel shape and by processing their clays in ways different from domestic pottery. Most notably, early metalworkers often mixed various types and amounts of secondary inclusions (what is called 'temper') into the clay to increase the ability of the ceramic to expand and contract under varying temperatures without cracking or failing. Only much later in history were special 'refractory' clays selected for high-temperature operations, reflecting larger developments in humanity's understanding of material properties as well as changes in the reactions performed by ingenious metallurgists. Thus, through selection or adaptation, metalworkers optimised the material properties of the ceramics in order to ensure a satisfactory performance. Depending upon their specific use, the formal and material properties of metallurgical ceramics could also be modified to adjust the thermal conductivity of the fabric (i.e. the ability of the ceramic to transmit or insulate heat), to ensure the proper redox conditions within a vessel (i.e. how much oxygen reached the contents), or the vessel's stability and ease of manipulation within a given metallurgical process.

The variability of metallurgical processes carried out by early metalworkers, the huge diversity of technological and cultural traditions through space and time, and the range of raw materials available across the globe have led to a great variety in the design and use of technical ceramics. The study of technical ceramics charters this evolution of knowledge and skills through time and space, at the interface of metallurgical and ceramic technology, several millennia before written documents give us any insight into such developments. As such, their study is highly informative on the technological decisions of ancient craftspeople and the transmission of cultural and technical knowledge, contributing to wider archaeological and anthropological questions well beyond a mere history of metallurgy.

The Analysis of Technical Ceramics

The study of metallurgical ceramics has involved an ever-growing variety of approaches over the past few decades. Technical ceramics were often discarded as waste after use, and sometimes they appear so distorted through use that the research approach has to be adapted to the nature of the samples in hand. Due to its technical nature, the interpretation of the data requires a fairly broad knowledge of material and geological sciences, analytical chemistry, and both metallurgical and ceramic technologies in order to understand both the ceramic design and the metallurgical processes involved. However, the wealth of research results can be very rewarding. Like any other ceramic material recovered by archaeologists, crucibles, tuyères, furnace fragments and moulds can be investigated to determine their production and provenance in order to discern the choices made by their manufacturers and the scale or direction of trade routes. Additionally, the analytical study of these ceramics informs our reconstruction of the nature and scale of metallurgical activities carried out at a given site, and the extent to which the raw materials available were modified to optimise their technical performance within the accepted social or cultural rules. In general, as an interface between metallurgical and ceramic technologies, metallurgical ceramics offer insights into craft specialisation as well as cross-craft interactions in specific contexts.

This chapter is structured in sections outlining different approaches to the study of metallurgical technical ceramics. First, we focus upon their nature as ceramic artefacts, and then subsequently on the metallurgical residues they often contain. However, we will be stressing that both dimensions of the study should inform each other, and their respective results should be integrated and discussed together.

Terminological Issues

Before outlining the main research approaches to metallurgical ceramics, it is worth clarifying some terminological issues since a number of technical terms have been used variedly, contributing to a degree of confusion in the archaeological literature. The term 'technical ceramics' will be predominantly used here, but the reader should be familiar with alternative denominations, particularly 'refractories'. The latter is adopted from modern usage where most technical ceramics have refractory properties, but the term is often misleading, even outright incorrect in an archaeological context. Although, as discussed in this chapter, outstanding heat resistance or refractoriness was often a desirable quality of metallurgical ceramics, for several thousand years metalworkers routinely 'made do' by putting to technical use locally available ceramics that would never qualify as refractory by modern standards. Refractories are defined as materials that are particularly resistant to heat and chemical attack, that is more so than normal ceramics. In view of the wide variety of ceramics considered 'normal' by different cultures, refractoriness in an archaeological context is clearly a relative term. As we shall see later, proper refractories, that is specific clays selected for their thermal or chemical properties, were with a few exceptions only employed from the late Iron Age onwards, while some clearly refractory materials were frequently used for domestic pottery, simply because they were locally available.

The next issue concerns the ceramic installations and tools used in metallurgy. Here, we define furnaces as typically immobile structures that contain the charge, such as charcoal and minerals, and are used for the smelting of ore to metal, or the melting of metal for casting. Crucibles fulfil the same purpose, but are free-standing, movable ceramic vessels and typically significantly smaller than furnaces. Both of these can be seen as containers or reaction vessels being used for high-temperature metallurgical processes, sometimes in combination with each other. Achieving and containing high temperatures is only one aspect of successful metallurgical operations; controlling the amount of gases such as oxygen or carbon monoxide in the reaction vessel is equally important, and differentiates furnaces and crucibles from the common bonfire or cooking oven. Thus, a crucial aspect determining their design is the need to maintain a specific balance between enough oxygen to allow the fuel to burn, and at the same time limiting air access to ensure the reducing conditions required to transform ore into metal, or to prevent the metal from burning before it is being cast. The exclusion of ambient air from the reaction chamber is achieved through the ceramic walls of the furnace or crucible. Blowpipes and tuyères then allow us to manipulate airflow direction and quantity to control combustion rate and redox conditions according to the process requirements. Blowpipes are typically made from organic material such as reeds and may have only a small ceramic tip to protect them against heat, while tuyères are almost exclusively made from ceramic. They could function by channelling air on their own, or attached to a variety of bellows. The former type of tuyères is found in natural draft furnaces, where the chimney effect of rising hot air within the furnace shaft sucks in fresh air through the tuyères near the bottom, or where specific aerodynamic conditions create a low-pressure zone directly above the furnace, as in wind-powered furnaces in regions with strong constant wind and suitable landscapes; the latter type appears in forced draft furnaces or in Bronze Age melting crucibles where the air is supplied from the top. Finally, moulds are the hollowed-out blocks where the metals are cast into the desired shapes.

A source of discussion is the differentiation between crucibles and furnaces, as both of them functioned as containers for metallurgical processes. In archaeology we tend to use the criterion of 'mobility' as the discerning one, and this is the one followed in this chapter. However, it should be noted that small, portable furnaces have been documented, while modern metallurgists sometimes use the term crucible to refer to the bottom part of large furnaces—even if these may be fixed and immobile.

A further terminological issue is the use of the term 'furnace' as opposed to other terms, such as kilns, ovens or hearths. We reserve the term furnace for metallurgical (and glass making) operations, whereas 'kilns' refer to pottery-making installations and 'ovens' to cooking activities. The term 'hearth' typically refers to more ephemeral structures and/or those operating at lower temperatures. In archaeometallurgy, the term ‘hearth’ relates to open structures, most notably for the ‘smithing hearths’ where iron was heated for forging, or intentionally oxidising installations used in the refining of certain metals. Although exceptions abound (such as high-fired ceramics or low-temperature metallurgy), there is a general decreasing trend in the operating temperatures of these structures, with furnaces achieving the highest and ovens working at the lowest ranges.

Last, there is a common misunderstanding in the assumption that furnaces were only used for smelting minerals, whereas crucibles were used exclusively for melting and casting metals. Most smelting furnaces were charged directly with ores and fuel for mineral reduction, but furnaces would also be necessary for melting and casting operations—for instance, to heat the crucibles containing the metal, or to melt directly in the furnace large quantities of bronze or iron for large castings. On the other hand, there is abundant evidence of crucibles employed for a variety of reactions other than melting for casting. For many centuries at the beginning of metallurgy, metal was smelted from its ores in crucibles, and even after the emergence of furnaces for metal smelting numerous special operations still relied on crucibles, such as the small-scale assay of ores to test their richness, the refining of gold and silver, or the production of zinc and brass. Sometimes these crucibles were heated inside furnaces, whereas in other cases the reaction took place within the crucible alone, with the vessel serving both as a container for the charge and as the heating structure. Such variability highlights the versatility of ceramics to be adapted to function, as well as the frequent need of analytical approaches in order to clarify the design and utilisation of ancient metallurgical ceramics.

Macroscopic Approaches

As with any archaeological artefact, the importance of a thorough visual assessment of metallurgical ceramics prior to instrumental analysis cannot be emphasised enough. A detailed macroscopic inspection should always be the first step in the study of these remains, as the amount of information that one can extract from such an inexpensive approach is sometimes surprising.

The number and outward design of furnaces, including aspects such as profile and size, and the systems for air supply (forced vs. natural) and slag removal (tapping vs. non-tapping) can be a proxy for the production scale and specific technological traditions at play in a particular region. For example, several iron-smelting regions have been demarcated in Eastern Africa based upon the preponderance of characteristic furnace designs, which are thought to relate to specific ethnic or cultural groups (Fig. 6.1). In disturbed sites or waste dumps, sometimes only fragments of furnace walls are preserved, but their layered internal structure can be used as evidence that the furnaces would have been relined with clay and repaired to be used more than once, while their curvature may be used to estimate furnace diameters (Fig. 6.2).

Similarly, the number and diameter of tuyères indicates the type of air supply used in a particular metallurgical process. For instance, tuyères with a very small

Fig. 6.1 Iron-smelting furnace from Zimbabwe, showing decoration that resembles female breasts. (Photo: Shadreck Chirikure)

Fig. 6.2 Inner surface *(left)* and cross-section view of a fragment of a precolonial lead-smelting furnace from Porco, Bolivia. Note the layered structure resulting from the successive relining of the slagged, inner surface of the furnace with fresh clay in between smelts. (Photo: Marcos Martinón-Torres)

internal diameter (e.g. 1 or 2 cm) would only work if attached to bellows (Fig. 6.3), whereas a large number of tuyères with a larger diameter may indicate the use of natural draft (Fig. 6.4). These aspects can be very important, as tuyères are made of non-perishable materials and thus survive in archaeological sites, while bellows or blowpipes are often made from perishable materials and thus do not survive well.

Fig. 6.3 Lateral (*top*) and bottom view of a Late Bronze Age ceramic tuyère from Qantir - Pi-Ramesses, Egypt. Note the very small orifice facing downwards, which would channel the air from the bellows into the charcoal-filled crucibles. (Photo: Axel Krause/Excavation Qantir)

Fig. 6.4 Furnace base with numerous, relatively wide tuyères to channel the natural draft into the combustion zone. (Photo: G. Celis)

The design of crucibles was often strongly constrained by their intended use. Thus, their typology reflects their function while also being influenced by cultural traditions. The most fundamental division in crucibles concerns their mode of heating. Until the later Iron Age of Eurasia, crucibles were almost exclusively heated from the inside,

Fig. 6.5 Top view (*top*) and cross section of two Late Bronze Age crucibles from Qantir - Pi-Ramesses, Egypt, associated with copper metallurgy. Note the higher thermal distortion of the inner surface, resulting from the heating with the charcoal within the crucible rather than outside, as well as the green staining indicative of copper corrosion products. (Photo: Axel Krause/Excavation Qantir)

with charcoal and airflow provided from above. Accordingly, these crucibles are relatively shallow vessels with large mouths, heavily vitrified and slagged on their interiors (to the extent of bloating and melting), while the core is less vitrified and the exterior is only slightly baked. To ensure heat retention and mechanical stability of the typically non-refractory technical ceramics employed, these crucibles are thick-walled and rich in organic temper, which increases heat retention through insulation in a highly porous fabric (resulting in a steep thermal gradient, with the inside far hotter than the outside of the vessel, over the course of just a couple of centimetres in wall thickness; Fig. 6.5).

Later crucibles were often heated from the outside, either being placed directly in a bed of charcoal or heated indirectly through radiation and hot air in a furnace structure. Their typical shape is that of deep vessels with a relatively narrow opening, often accentuated by a pouring spout (Fig. 6.6). These crucibles have to be sufficiently refractory to maintain their mechanical stability when at full operating temperature, often well in excess of 1,100 °C. Such refractory ceramics are often distinctly different from the local domestic pottery, typically more white-firing through the selection of clays rich in alumina and poor in iron oxide (Fig. 6.7), or coloured black through the addition of graphite or other carbonaceous material (Figs. 6.8 and 6.10). The external heating means that the ceramic reached the same temperature throughout the body, and the degree of vitrification is therefore constant throughout the fabric. To improve thermal shock resistance and facilitate better heat flow through the fabric than in vessels tempered with organic materials, these crucibles are typically tempered heavily with sand. All of these parameters are easily identified by visual inspection, and need to be evaluated in comparison to the local domestic pottery.

Fig. 6.6 Medieval crucible from England. Note the globular shape and pouring spout. (Photo: LAARC)

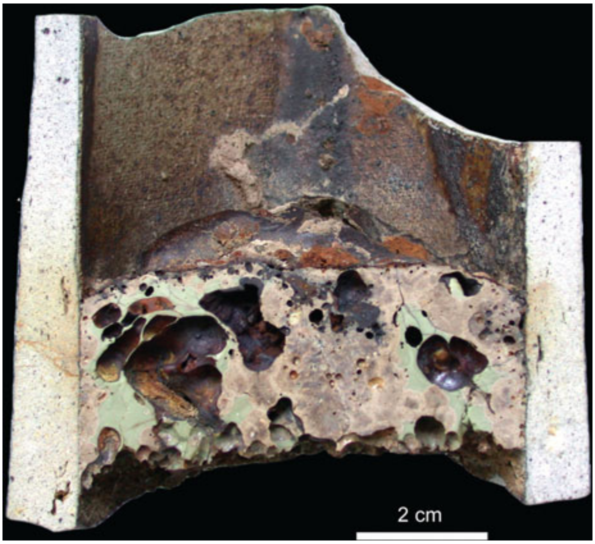


Fig. 6.7 Section through part of a medieval steel-making crucible from Akhsiket, Uzbekistan. Note the clean interface and lack of interaction between the slag and the white ceramic, denoting the high refractoriness of the latter. (Photo: Marcos Martinón-Torres)

Crucibles with closed profiles or lids are indicative of reactions requiring particularly reducing atmospheres, such as the processing of volatile metals such as zinc or brass (where the closed shape helps minimise metal losses through evaporation, Fig. 6.9), the production of crucible steel (Fig. 6.10) or the parting of gold and silver using chlorine-rich vapour. On the other end of the spectrum, shallow ceramic dishes or 'scorifiers' (Fig. 6.11) have been employed since medieval times for oxidising reactions such as cupellation, which separates silver from lead. Similarly, the profile of crucible bases is rarely coincidental. Although there are exceptions to this pattern, rounded and pointy bases in externally heated crucibles suggest heating infrastructures where the crucible would sit in an uneven bed of charcoal, or where

Fig. 6.8 Lower half of a post-medieval graphite-tempered crucible from central Europe. (Photo: Marcos Martinón-Torres)

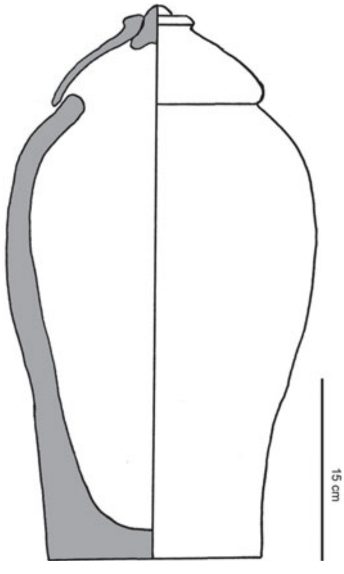


Fig. 6.9 Drawing of a late medieval crucible from Zwickau, Germany, employed for the production of brass by cementation. Note the large size and closed profile. (Image: Marcos Martinón-Torres)

the metalworker expected to collect a very small amount of metal, as was the case in some assaying operations. In contrast, crucibles with flat bases are more common from the late Middle Ages, as they sat in newly developed furnaces, often heated by convection, with a flat platform where the crucibles sat separate from the burning fuel. The presence of pouring spouts, often preserving traces of metal adhering, indicates that the metalworkers cast the crucible contents while hot, as opposed to other reactions, such as crucible steel making, where the crucibles were left to cool before breaking them to remove a solid ingot. The size and volume of crucibles will also be adjusted for specific technological issues. In the Middle Ages, large crucibles with

Fig. 6.10 Steel-making crucible and crucible lid from Sri Lanka. The closed shape facilitates a reducing atmosphere, which is also aided by the abundant carbonaceous rice-husk temper in the fabric. (Photo: Stuart Laidlaw)

Fig. 6.11 Ceramic dish or 'scorifier' from Oberstockstall, Austria, employed for oxidising metallurgical reactions. Note the round depression left on the slag by the *regulus* of metal collected in the centre. (Photo: Marcos Martinón-Torres)

volumes of several litres tended to be used for the large-scale processing of cheaper metals such as bronze or brass. Conversely, the metallurgy of precious metals such as gold and silver required more careful control and typically involved the use of smaller vessels made from finer ceramics to ensure a smooth surface minimizing metal loss.

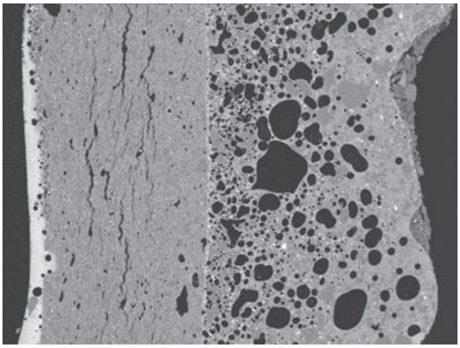


Fig. 6.12 SEM image of a polished cross section of a Roman crucible from Xanten, Germany, showing, from *left* to rigth: a thin, bright layer of lead-rich slag adhering to the inner surface; the main crucible body, made of relatively refractory ceramic; and an outer layer made of less refractory clay that appears heavily vitrified and bloated. Image width is ca. 2 cm. (Photo: Thilo Rehren)

There are further relevant aspects of crucibles that can be discerned through rigorous macroscopic assessment. The degree of bloating or vitrification of the paste may provide a first qualitative indication of the temperatures involved in the operations. For example, the melting of lead or pewter (requiring temperatures around 300 °C) will cause virtually no heat damage to the vessel, whereas melting copper requires much more heat and will leave obvious traces of heat impact.

Many Roman and later crucibles are built with two layers of ceramic; an inner layer of refractory but brittle ceramic and an outer layer of easily fusible clay (Fig. 6.12). The outer layer is often rather roughly applied and conceals the original shape of the carefully formed inner crucible. The softened outer ceramic often shows impressions of the charcoal lumps from the fuel bed in which the crucible sat, or even impressions from the tongs used to manipulate the vessel when hot.

Last but certainly not least, the visible residues adhering to the inner surfaces of crucibles are also informative. For instance, residues from copper-base metallurgy tend to show a green staining after mild corrosion (Fig. 6.5); gold, as a much nobler metal, is often preserved in the form of minuscule globules that can be noticed under a magnifying glass (Fig. 6.13). Under oxidising conditions such as those required for cupellation, lead oxidises and reacts strongly with the ceramic crucible (if it is rich in silica), forming viscous slag glazes that may be brightly coloured from yellow through red to black (Fig. 6.11). If the preservation of the crucibles is good enough, it is sometimes possible to visually distinguish the presence of different layers such as metal at the bottom and slag higher up in the crucible profile, reflecting how these layers would have separated by density inside the vessel.

The importance of a visual inspection of metallurgical moulds is obvious. It is only through macroscopic assessment (and, often, painstaking reconstruction efforts with fragmentary remains) that one can determine the nature and shapes of the objects cast in a workshop. Careful visual examination and refitting of mould fragments, for example, continue to be prominent research strategies to reconstruct the complex piece-mould casting technology employed by Bronze Age metalworkers in China (Fig. 6.14). In other regions, mould fragments attest to the use of the casting technique known as ‘lost wax’ or *cire perdue*. Often, such moulds are built from different layers of clay, finer fabric on the interior for a smooth surface finish, and coarser fabric on the

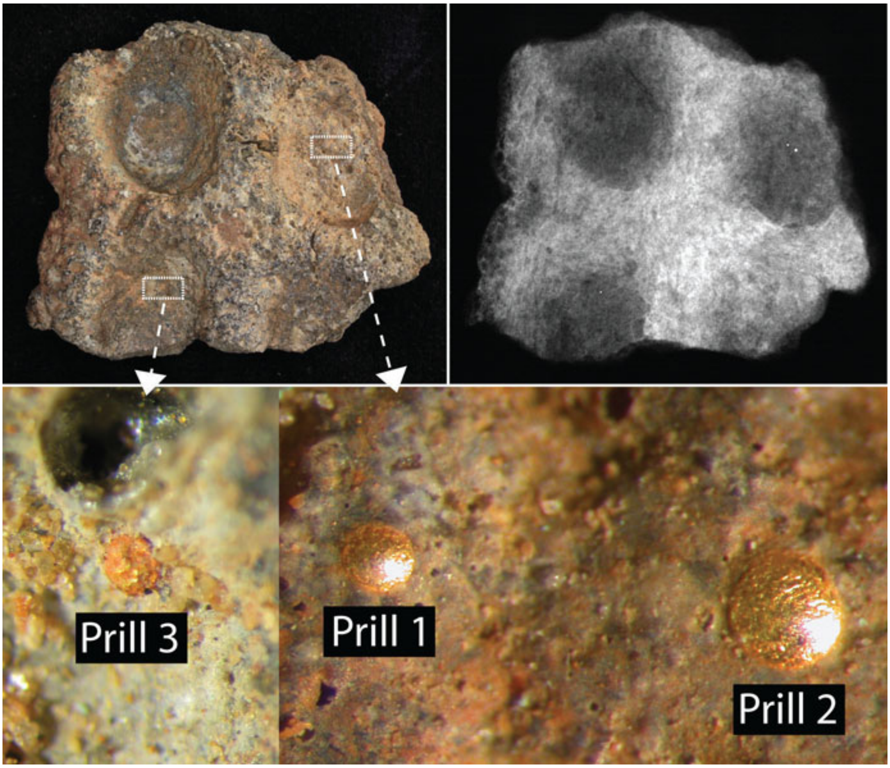


Fig. 6.13 Optical and X-ray view of an Islamic coin mould from Tadmekka, Mali, and details of minuscule gold prills trapped in the inner surface under the microscope. (Images C2RMF, X-radiography (T. Borel) and optical microscopy (D. Bagault))

Fig. 6.14 Western Zhou clay mould from Zhouyuan, China, employed for the casting of a very ornate bronze vessel using the piece-mould casting technology. (Photo: Marcos Martinón-Torres)

exterior to increase the strength of the mould and probably to economise on the use of fine clay. When selecting and inspecting mould fragments from workshop remains, researchers must not overlook seemingly amorphous or unbaked clay lumps, as these may constitute the cores employed to cast hollow or socketed artefacts.

A final point should be made with regard to the visual assessment of metallurgical ceramics, which is the importance of documenting not only the presence, but also the absence of such remains. To name but two examples, and assuming good archaeological preservation, a lack of crucibles or moulds suggests that no casting of artefacts took place on site (possibly because the workshop in question was specialised on smelting), just as the absence of tuyères should always prompt hypotheses as to alternative strategies of air supply, such as perforations on the furnace wall.

Bulk Chemical Analyses

Like any other ceramic artefact, metallurgical ceramics can be subjected to bulk chemical analyses employing techniques such as inductively coupled plasma spectrometry (ICP), neutron activation analysis (NAA) or X-ray fluorescence (XRF), in order to establish a chemical fingerprint that may allow us to relate them to their original kiln or geological source (see Pollard & Bray, this volume). Specifically for technical ceramics, such analyses also inform about the suitability of the clay (and resulting ceramic) for the required task, since refractoriness is a direct consequence of the chemical and mineralogical make-up of the fabric. Where possible, it is advisable to select unused ceramics for this type of study, in order to minimise the risk of distorting the results by contamination of the ceramic fabric by the metals, fuel or minerals processed within. These approaches can be informative of the degree of standardisation in the choice or supply of technical ceramics, as well as of aspects of the early trade of specialised equipment such as crucibles (Fig. 6.15).

For earlier periods and large ceramic structures such as furnaces, the clays employed for metallurgical ceramics tend to be locally (or at least regionally) sourced, but it is always advisable to confirm this through analysis. Recent provenance studies of triangular crucibles, icons of the advanced skills of late Medieval and Renaissance metalworkers, have shown that a great number of these can be traced back to a very small number of sources in central Europe, thus revealing a highly specialised international market for technical ceramics (Fig. 6.16).

Even in cases when the provenance of the technical ceramics may be in doubt or cannot be identified, comparisons of their bulk compositions with other ceramics from the site can be very informative about the selection of clays for specific technical purposes and the underlying practical knowledge that such choices may reveal. In general, ceramics with higher alumina levels are more heat resistant, whereas high levels of other oxides such as lime (CaO), soda (Na_2O) or potash (K_2O) decrease the refractoriness of the ceramic in question (Fig. 6.15). By comparing the compositions of different ceramics, it is possible to assess the extent to which high-refractory clays were selected for more demanding applications. For example,

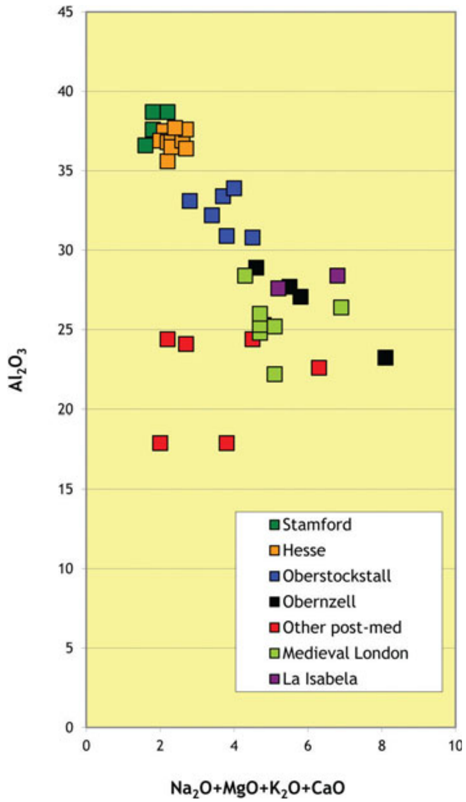


Fig. 6.15 Scatter plot comparing the refractoriness of several groups of crucibles by plotting selected oxides from their chemical analysis. Those ceramics with higher alumina and lower alkali levels are more resistant to heat. (Image: Marcos Martinón-Torres)

Fig. 6.16 Some triangular crucibles from Oberstockstall, Austria. The flat bases make them suitable for sitting on the flat platforms of assaying furnaces. The triangular mouth is an easy technical solution to create three pouring spouts. (Photo: Andreas W. Rausch)

in several pre-colonial iron-smelting sites in Eastern Africa, tuyères were made of highly refractory kaolinitic clay, whereas the furnace walls were made using more ordinary, less heat-resistant clay. For the thin-walled tuyères, which would protrude into the hottest area of the furnace, refractoriness was key to preserve their structural stability during the operations. In contrast, the furnace walls were simply made much thicker, so that even if part of their inner layers melted during the operation, there would be enough structural stability for the smelt to proceed.

Fig. 6.17 Some archaeological cupels from the site of Kapfenberg, Austria, made with a mixture of bone ash and wood ash, now heavily impregnated with lead and other base metal oxides. *Inset:* a modern cupel with the silver *regulus* still in place. (Photos: Marcos Martinón-Torres)

In other cases, the study of technical ceramics and slag compositions has revealed the opposite pattern: tuyères or crucibles that were deliberately made with low-refractory clays and therefore expected to melt during the smelt. The technical reason for this choice seems to be that the molten ceramic would contribute to bring down the melting point of the forming slag, thus working as an effective flux (see Hauptmann, this volume). In these cases, the need to more frequently replace the tuyères or create new crucibles appears to have been a good investment in order to ensure the success of the smelt.

Bulk chemical analyses may even reveal that the metallurgical ceramic in hand is not even clay-based. The most frequent case in point is that of cupellation hearth lining or small vessels (called 'cupels') employed for small-scale noble metal refining. Prior to the Middle Ages, cupellation hearth material is generally so thermally distorted, and soaked up with the absorbed lead oxide, that only chemical analyses may serve to suggest the original material substrate where cupellation took place. Very frequently, besides the strong lead oxide signature, chemical data show the use of low-silica, high-lime materials such as chalk-rich clays, crushed shells, bone or wood ash, which were preferred to silica-based ceramics due to their porosity and chemical inertness. Standardised bone ash cupels emerged during the Middle Ages and became the norm for mint and silversmiths workshops from the early modern period onwards (Fig. 6.17). However, these inferences from the chemical data should normally be tested via microanalysis (see below).

The addition of temper to technical ceramics obviously modifies their bulk chemical signature, potentially complicating provenance studies (see Pernicka, this volume). More importantly, the choice of temper is an important technical decision and should be documented and explained. These and other factors make microanalytical studies of metallurgical ceramics particularly advisable.

Microscopy and Microanalysis

The examination of metallurgical ceramics by optical and electron microscopy is extremely informative. Ceramic surfaces may be examined under the microscope for traces of metal residues adhering to them (Fig. 6.13) or, in the case of moulds, to

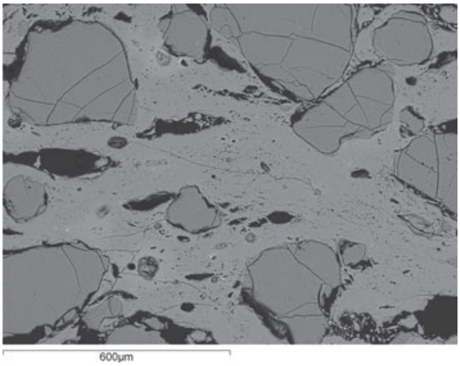


Fig. 6.18 SEM image of a polished cross section of a quartz-tempered crucible. (Photo: Marcos Martinón-Torres)

determine the presence of 'release agents' such as charcoal ash that were sometimes added to their surfaces to facilitate the separation between metal and mould. However, the most common microanalytical strategy involves the analysis of small cross sections that are cut from the ceramics, mounted in resin and subsequently polished to a mirror-like finish suitable for microanalysis. Even when microscopes are not available, freshly cut transversal sections of metallurgical ceramics can reveal many of the aspects discussed below. In fact, when working with large assemblages, it is not uncommon to cut a relatively large number of samples for preliminary observations, before selecting a few for mounting and polishing.

Optical microscopy under reflected or transmitted light is useful in determining the nature, abundance, size, sorting and distribution of any natural or artificial inclusions present in the fabric of metallurgical ceramics, as well as an assessment of their internal porosity. Typically, crucibles are heavily tempered, as the abundance of non-plastic inclusions greatly improves the thermal shock resistance and toughness of the vessels. One of the most common tempering materials is quartz (often in the form of sand), which, as a highly refractory mineral, also enhanced their thermal stability (Fig. 6.18). Other mineral inclusions such as feldspars or iron oxides, if present in large quantities or as relatively large grains, can be detrimental for the performance of the crucibles. These types of inclusions melt during high-temperature processes and act as flux for the surrounding ceramic matrix, thereby creating weak points within the fabric. Other temper types have been documented in archaeometallurgical remains. Organic materials such as chaff, for example, were the almost universally common temper in prehistoric smelting crucibles. Upon burning out during firing, these inclusions would leave small elongated voids in the fabric that can be easily recognised in cross sections (Fig. 6.19). The effect of these voids in the ceramic would be twofold. On the one hand, these voids typically run parallel to the vessel's surface and deter crack propagation across the fabric, thereby increasing the vessel's resistance to potential fractures due to uneven thermal gradients or sudden temperature changes. On the other hand, voids function as thermal insulation systems: for prehistoric crucibles, which were heated from within, such an ingenious technical solution helped to minimise heat losses and maintain the mechanical integrity of the bulk of the vessel's fabric even if the interior melted and failed.

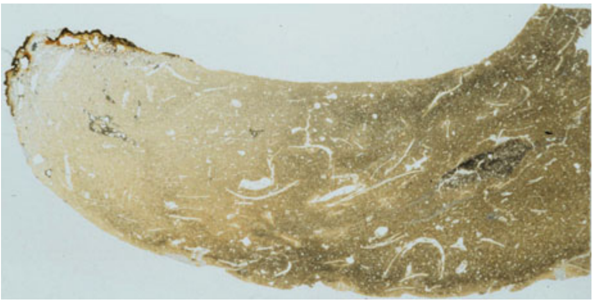


Fig. 6.19 Cross section through a sherd of a prehistoric crucible from Stäfa-Uerikon, Switzerland, showing the elongated voids left by burnt-out vegetal temper. Image width is ca. 3 cm. (Photo: Thilo Rehren)

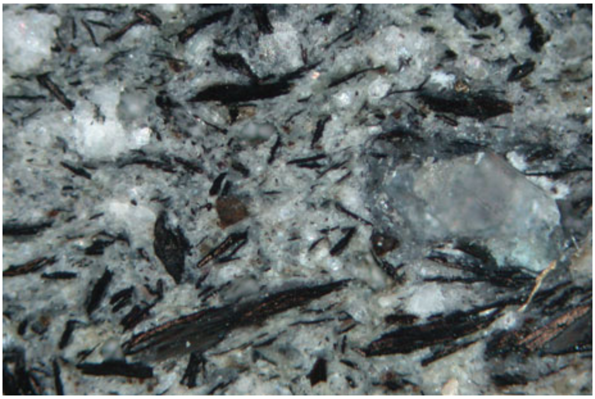


Fig. 6.20 Photomicrograph of a polished cross section of a post-medieval crucible, showing abundant flakes of black graphite. Image width is ca. 2 mm. (Photo: Marcos Martinón-Torres)

A different example of resource optimisation is offered by medieval and early modern central European crucible makers, who took advantage of the occurrence of graphite in the region, which could be present naturally in sedimentary clays or artificially crushed and mixed in as temper (Fig. 6.20). For crucibles to be heated from the outside in structures such as furnaces, graphite enhanced their thermal conductivity, thus allowing savings in time and fuel. Furthermore, the thermal and mechanical properties of graphite resulted in greatly enhanced thermal and chemical refractoriness, thermal shock resistance, toughness and tensile strength. It is not surprising then that graphite crucibles remain in use to this day.

Furnace walls and tuyères were also variously tempered, sometimes even more coarsely than crucibles, with materials such as not only those mentioned above but also grass, wool, charcoal, or even crushed slag—all reflecting technical ingenuity as much as cultural traditions. Conversely, the clays used for the working face of moulds tended to be extremely fine grained, to ensure a smooth surface finish of the casts.

The microscopic study of cross sections of metallurgical ceramics is also useful to discern details of the different layers often present. For example, cross sections of early crucibles from East and Southeast Asia sometimes show a thin, quartz-rich slurry lining their internal surfaces, presumably used to protect the ceramic from chemical attack by the hot charge. As mentioned before, since Roman times and until the late Middle Ages, it was very common to find an outer layer of clay covering

Fig. 6.21 A sequence of samples employed for refiring experiments to assess the refractoriness of Qantir crucibles. (Photo: Axel Krause / Excavation Qantir)

European crucibles' external surfaces. This outer layer is typically untempered and less refractory than the main ceramic body, which results in extensive vitrification during use. Even if lacking any structural strength in itself (which would be provided by the crucible proper), this viscous layer may have helped in distributing the heat more evenly throughout the vessel, while also potentially sealing any cracks that could develop in the crucible body during use (Fig. 6.12). In some late examples, however, this outer layer has become so thin that it is hard to see how it would have served any technical purpose. Rather, it could just constitute a remnant of an old tradition. As in any other arena of material culture, non-technical cultural factors also affected the design and use of metallurgical ceramics.

The use of microanalytical techniques such as scanning electron microscopy–energy dispersive spectrometry (SEM–EDS) or electron probe micro-analysis (EPMA) greatly improves our ability to study and understand metallurgical ceramics by allowing even higher magnification than optical microscopes, and through their capability to perform chemical analyses in selected areas or spots (as opposed to bulk chemical analyses). Besides potentially contributing to any of the above research lines, these techniques allow researchers to analyse the ceramic matrix separately from any inclusions, which can help determine, for example, whether the crucibles and moulds employed in a workshop were made of the same raw clay but tempered in different ways. Electron imaging can also aid in assessing the homogeneity of the ceramic, which is indicative of the degree of refining or 'levigation' to which the clay could have been subjected before use.

High-magnification topographic images are useful in determining the vitrification stages of ceramic matrices, which may be used as a proxy for the temperatures to which they were subjected. As ceramics lose water, the original clay minerals recrystallise and finally vitrify and melt through increasing exposure to high temperatures. Their structure becomes glassier, whereas their internal porosity becomes rounder, leading eventually to extreme stages of catastrophic bloating or ceramic melting (Fig. 6.12). By comparing the vitrification stages of technical ceramics to those of control briquettes fired under known conditions, it is possible to estimate the temperatures to which the archaeological samples were exposed (the so-called refiring methods; Fig. 6.21). When studying the vitrification of metallurgical ceramics, it is interesting to compare between used and unused specimens, thereby differentiating

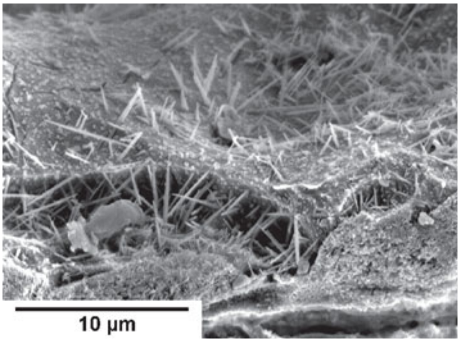


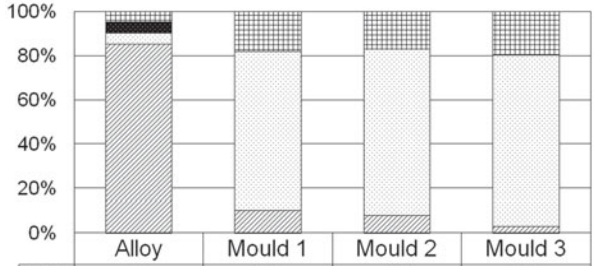
Fig. 6.22 High-magnification SEM image of an unpolished area of a crucible from Hesse after etching in HF. The image shows fine needles of mullite developed through the high pre-firing of the alumina-rich body. (Photo: Alice Hunt)

the firing of the crucibles in the pottery kiln when they were first made, from the further thermal distortion that may have been caused during use. For example, a study has shown that the famous crucibles from Hesse, sought after by alchemists and metalworkers across the world since the late Middle Ages, partly owed their technical quality and market success to an exceptionally high pre-firing temperature. These vessels were made of a well-refined, alumina-rich, kaolinitic clay, tempered with quartz and fired to temperatures in excess of 1,300 °C. As a result, the crucibles underwent a high-temperature test before reaching the consumer. More importantly, the high pre-firing led to a highly vitrified matrix reinforced by fibres of newly crystallised 'mullite' in the ceramic paste—an extremely strong and refractory aluminium silicate that continues to be used for crucibles to this day (Fig. 6.22).

Besides the potential lines of enquiry mentioned above, a major bonus of microanalysing cross sections of technical ceramics is that these techniques allow a detailed investigation of the slag or metal residues adhering to their inner surfaces, in ways comparable to those employed for the usual study of metal objects or slag lumps (see Scott or Hauptmann, this volume). The possibilities of such approaches will be developed in the next section.

Residues in Metallurgical Ceramics

Understandably, many studies of metallurgical ceramics focus upon identifying the metals that were processed in them. As mentioned before, visual features can provide strong clues, but this approach is often complemented with qualitative analyses of the inner surfaces of metallurgical ceramics employing XRF. Without any prior sample preparation, the direct scan of a ceramic surface by XRF can allow the identification of traces of the metals in a fast and relatively inexpensive manner. The traces of metals in crucibles can then be correlated, for example, with the crucible typologies, in order to discern whether specific forms correspond with special metals. The same strategy can be employed to investigate whether specific workshops at a given site were focused upon different metals. Using this approach, a study of Viking



	Alloy	Mould 1	Mould 2	Mould 3
Pb	5	20	18	20
Sn	5	0.04	0.05	0.08
Zn	5	78	80	79
Cu	85	11	8	3

Fig. 6.23 Bar chart based on an experimental study, comparing the composition of a copper alloy and the relative proportions of the traces of different alloying constituents detected by XRF after the metal was cast in three moulds. (Image: Marcos Martinón-Torres)

urban metallurgy has shown that, contrary to common assumptions of workshop sub-specialisations, both silver and copper-base alloys were routinely melted and cast in the very same workshops. Many other examples exist of simple XRF studies allowing the identification of the metals cast at a given site.

There are, however, important limitations to the use of surface XRF scans, and researchers must be aware of these in order to avoid hasty conclusions. The first one is that this type of chemical analysis will not discriminate between contaminations stemming from separate events of use. If a crucible was once used for melting copper, and later for melting tin, the XRF will simply detect traces of both, and one might thus be tempted to assume that the crucible was used for melting bronze. The same could be thought of a mould that was used for both copper and pewter, where the data might lead some to infer that the alloy being cast was leaded bronze. The second problem, and perhaps the most important one, is that the relative proportions of different metals detected in a crucible or mould may differ dramatically from those in the original melt. Recent experiments with casting moulds used for copper alloys have shown that zinc contamination is always highly exacerbated, even if only present in the original alloy in small concentrations, whereas the nearly exact opposite occurs with tin (Fig. 6.23). The different contaminating behaviour of these and other metals is due to their specific thermo-chemical properties, especially their volatility. Thus, one should be aware of these properties before interpreting analytical data. A related factor to be borne in mind is that the 'metal of interest' is not necessarily the one most abundantly left behind in technical ceramics: a paradigmatic example of this is the refining of silver by cupellation, where a skilled metalworker will leave abundant lead oxide but very little silver behind.

A final limitation of surface XRF analyses of metallurgical ceramics is the unsuitability of this type of data to reconstruct more specific parameters of the processes carried out. This problem is particularly acute with crucibles, given the great variety of reactions (beyond metal melting) for which they were employed. For instance, XRF can detect traces of copper on a crucible surface, but researchers may be interested in determining whether the crucible was used for smelting, refining, or simply melting this metal. Another common question emerges when both tin and copper are detected, as to whether the vessel would have been employed for the remelting of scrap, the alloying of fresh metal, or even the smelting of tin minerals with metallic copper. In order to answer these and other questions, microanalysis becomes a must.

The examination of cross sections of crucibles and other technical ceramics by optical and electron microscopy is one of the most powerful tools to reconstruct the metallurgical processes carried out within. Given that this method is more invasive and time consuming than XRF, it is always advisable to start the study with a screening analysis of a large number of ceramics by XRF, as a basis to raise further questions and inform decisions on the subgroups that will be targeted for microanalysis. Just as the ceramic fabric can be investigated in more detail under the microscope (see above), so too can adhering residues offer many more clues for a technological reconstruction. Although these residues are sometimes only tiny specks or layers much thinner than 1 mm (e.g. Fig. 6.12), even these are big enough to allow informative microanalytical studies.

Microanalytical techniques permit the identification of different residual phases or new crystals that can tell us about the raw materials or alloys used, redox conditions and temperatures involved, and the effects of any post-depositional corrosion (and hence the reliability of the data). The most important peculiarity in the analysis of metal prills trapped in crucibles (compared to the analysis of metal artefacts), beyond their smaller size, is the potentially significant distortion of alloy composition in the prill. Selective oxidation of metals such as tin, zinc or lead will concentrate these elements as oxides in the surrounding slag, while the residual metal prill will be almost pure copper, silver or gold. Such selective oxidation has been exploited for millennia in the fire refining of metals (e.g. cupellation), but today it can significantly hamper the interpretation of microanalytical data from crucible studies. On the other hand, the examination of the interface between the slag and the crucible ceramic—and the extent of chemical interaction between the metal, slag and ceramic—can inform us about the duration of the operation, the temperatures reached, the degree to which the atmosphere in the crucible or furnace was controlled, and whether chemically stable fabrics were selected (or not) for particularly corrosive reagents.

If the ceramic appears to be melting and reacting with the forming slag, then our interpretation of the crucible slag should take account of this chemical contribution, just as one would do with the furnace or tuyère material when analysing furnace slag. This is particularly relevant in the context of early metallurgy, when attempting to distinguish between smelting and melting crucibles; both will have more-or-less clean copper prills embedded in the molten material covering the inner surface of the crucible. To identify smelting of copper minerals, it is important to show that the molten material surrounding the metal prills is not just the ceramic fabric vitrified with some fuel ash component, but that there is a substantial contribution to the slag from the fusion of gangue components, such as silica or iron oxide, in excess of the amount present naturally in the ceramic. Only microanalysis of a carefully selected and prepared cross section can provide the necessary compositional data for the unaltered ceramic of the crucible's body, the fully vitrified region near the inside, and the apparent copper-rich slag layer at its surface.

Further Approaches to Metallurgical Ceramics

The previous pages have presented a summary of the most established approaches to the study of metallurgical ceramics. However, the repertoire of analytical strategies is broader and continues to grow.

The study of metallurgical ceramics by X-ray diffraction (XRD) not only contributes to a more detailed mineralogical characterisation of the clays employed, but it can also aid in estimating operating temperatures. Given that different crystal phases decompose and recombine at specific temperatures, their presence/absence as detected by XRD can suggest specific temperature thresholds, when compared to the original phases present in unused ceramics or the local clay minerals. The observation of heat-induced mineral transformations, however, can also be performed during SEM-EDS analysis. Often it is possible to identify sub-rounded glassy areas within the fabric, corresponding to molten minerals that can be chemically analysed. For example, a ceramic where plagioclase feldspars appear molten but potassium feldspars remain unaltered would have been exposed to temperatures between 950 and 1,050 °C.

More recent approaches to technical ceramics have combined a study of their thermal conductivity, considering aspect such as composition, inclusions and porosity, prior to modelling their behaviour using computer-based finite element analysis. These parameters, together with a detailed documentation of the thermal gradient recorded in the furnace fabric, have allowed researchers to estimate the typical duration of a smelt in a Bronze Age furnace.

Finally, one should not underestimate the potential of metallurgical ceramics to date metallurgical activities. For example, some American Pre-Columbian metalworking cultures made votive offerings of gold work that are often found with no other datable materials or contextual associations. Frequently, it has been possible to date these through radiocarbon determinations performed on the carbon-rich cores preserved inside hollow objects cast by the lost wax technique. In Sub-Saharan Africa, where the dating of the earliest metallurgy remains a contentious issue partly owing to ambiguous radiocarbon dates, it has been proposed that thermo-luminescence dating of furnace wall material may offer a more reliable dating tool.

Final Remarks

From a technological viewpoint, having good-quality metallurgical ceramics was as important as the metals themselves in most ancient metallurgical workshops. The thermal and mechanical properties of these ceramics often limited the size of objects that could be cast in a single process in the pre-Classical Old World (the availability of large quantities of very fine-grained loess clays was probably a decisive factor behind the astonishing levels of piece-mould casting achieved in Bronze Age China). Similarly, the melting and casting of true steel (as opposed to cast iron) only became possible once suitably refractory materials had been developed to withstand the necessary high temperatures. Refining and assaying of gold and silver relied for centuries on the availability of specialised ceramics made from bone and plant ash, and no furnace could be built without a great deal of ceramic, even if only holding together building blocks hewn from stone.

This chapter has highlighted the crucial role played by ceramics in the production and processing of metals across the world, a role undiminished to this day. In addition, it has outlined some of the most fruitful avenues for the exploration of these technical ceramics. When adequately studied, metallurgical ceramics offer data not only on specific metallurgical reactions, but also on technological choices and knowledge transfer, the changing understanding of different materials and their properties, the optimisation of resources for specific technical needs, and the existence of different traditions that may respond to specific cultural backgrounds as much as to technological schools and traditions.

Notwithstanding the huge potential of studying technical ceramics from archaeometallurgical sites, a final word of caution is needed, applicable to this as much as to any other area of ancient technologies. Before highlighting the uniqueness or technical sophistication of a particular ceramic design, we should confirm that this was indeed a conscious choice made on the basis of technical considerations. For example, metalworkers could have exploited extremely refractory clays simply because these were the clays most readily available to them. Likewise, the use of graphite temper is documented not only in early crucibles but also in coeval domestic pottery, which suggests that perhaps colour, and not necessarily thermal conductivity or refractoriness, was the crucial factor behind the choice of this temper in early stages. In order to avoid precipitate conclusions, our studies should incorporate non-technical ceramics such as domestic pots or roof tiles for comparison, as well as an assessment of the archaeological and geological environment to determine the range of options available to ancient metalworkers.

As emphasised above, a thorough macroscopic assessment of metallurgical ceramics, ideally combined with a visual examination of fresh sections, can be extremely informative, especially when coupled with an understanding of metallurgical principles and practices. More sophisticated questions are greatly aided by analytical studies, specifically microscope-based ones. However, just as these enhance our investigative power, so do they increase the risk of error. An adequate selection of samples and analytical techniques relevant to the questions asked is essential, together with an assessment of the potentials and limitations of the resulting data. Probably the most important aspect of studying technical ceramics, however, is that these are typically waste material, often occurring in huge quantities and of little aesthetic value. Subjecting them to analysis, particularly invasive analysis as is necessary to obtain cross sections and quantitative analytical data, is a hugely productive process, generating a plethora of information not otherwise obtainable. This is not a destructive analysis—it is a constructive analysis of the first order.

References

Bayley, J., & Rehren, Th. (2007). Towards a functional and typological classification of crucibles. In: S. LaNiece, D. Hook, & P. Craddock (Eds.), Metals and Mines–Studies in Archaeometallurgy (pp. 46–55). London: Archetype.

Freestone, I. C. (1989). Refractory materials and their procurement. In: A. Hauptmann, E. Pernicka, & G. A. Wagner (Eds.), *Old World archaeometallurgy*. *Proceedings of the International Symposium, Heidelberg 1987*, (pp. 155–62), Der Anschnitt Beiheft 7. Bochum: Deutsches Bergbau-Museum.

Freestone, I. C., & Tite, M. S. (1986). Refractories in the ancient and preindustrial world. In: W. D. Kingery (Ed.), *Ceramics and Civilization 3: High-technology ceramics: past, present and future. The nature of innovation and change in ceramic technology* (pp. 35–63). Westerville: The American Ceramic Society.

Kearns, T., Martinón-Torres, M., & Rehren, Th. (2010). Metal to mould: alloy identification in experimental casting moulds using XRF. *Historical Metallurgy, 44*(1), 48–58.

Martinón-Torres, M., & Rehren, Th. (2009). Post-medieval crucible production and distribution: A study of materials and materialities. *Archaeometry, 51*(1), 49–74.

Rehren, Th. (2003). Crucibles as reaction vessels in ancient metallurgy. In: P. Craddock & J. Lang (Eds.), *Mining and Metal Production through the Ages*, (pp. 207–215 and 147–149). London: British Museum.

Chapter 7
Methods of Mining Archaeology (Montanarchäologie)

Thomas R. Stöllner

Introduction

Mining archaeology is a multidisciplinary approach to understanding people's roles and relations to raw materials, especially with respect to the social and economic consequences of their exploitation. It has become a specialized field within archaeology, and therefore, it may be justified to outline the methodological framework of this field. Mining archaeology has traditionally been seen as a study of the mining technologies used in the past, but only rarely has it engaged with the socio-economic and cultural aspects of these practices (Weisgerber 1989/1990; Pfaffenberger 1992; Steuer and Zimmermann 1993; Knapp et al. 1998; Stöllner 2003; Topping and Lynott 2005). Critical to the advancement of this field has been the realisation that mining archaeology is the study of systems used to describe long-term historical processes that have been influenced by other technologies, innovations and raw materials equally. If one looks, nowadays, at projects focussing on ancient mines, one must always engage with various other subjects including trade, settlement patterns and socio-economic systems such as class and its relation to the exploitation and distribution of resources. It is, therefore, a logical consequence not to speak about mining archaeology on its own but to use terms like the archaeology of raw materials, Montanarchäologie (montan-archaeology) and economic archaeology (e.g. Clarke 1953; Zimmermann 2000)[1].

[1] The German term "Montan"(based on the Latin "res montanarum") does not translate well into the English language, but I have suggested introducing the loan-word "Montan" as a term for a kind of "raw material archaeology" whose main focus is on the entire chain of mineral resource production practices and its socio-economic consequences (e.g. Stöllner 2008b, pp. 149).

T. R. Stöllner (✉)
Ruhr-Universität, Institute of Archaeological Studies
Am Bergbaumuseum 31, 44791 Bochum, Germany
e-mail: thomas.stoellner@ruhr-uni-bochum.de

Deutsches Bergbau-Museum Bochum,
Department of Mining Archaeology
Herner Straße 45, 44789 Bochum, Germany

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_7,

If one accepts the broadening of the terminology, then one has to engage with three levels of consideration. First, what is the relation between archaeology of mining and the various technological approaches that were used throughout history to extract raw materials? Second, if archaeologists want to reconstruct the ancient economy, then mining must be considered as just one part of an entire production chain, including processing, trade and usage of raw materials. Third, the broadened field of "Montanarchäologie" must deal with all aspects of the production process, which must take into account the ideological, social and spatial spheres of human behaviour (Stöllner 2008a, 2008b). The level on which we choose to explore ancient mining has consequences for the methods used.

Methodological Issues: Basic Concepts and Problems

Acquiring raw materials was, in all societies, a costly and time-consuming (but nonetheless essential) task. This process nowadays has shifted to a global level and its consequences are not as apparent for each individual. However, in the past, the level of spatial and societal interactions between people and communities was the most important; as such interactions were responsible for the dissemination of societal knowledge, techniques and of new materials and products. Thus, the regional and chronological context of ancient mining is critical, as hunter–gatherer groups of the African Iron Age had very different mining processes than urbanized Bronze Age miners of Central China.

Over the years, several special research areas of mining archaeology have been outlined and investigated more precisely. These research areas provide a theoretical framework with which one can approach the different questions that are always part of resource management.

The Importance of the Chaîne Opératoire

There is no doubt that functionality is a basic prerequisite for understanding ancient mining, but there are also ideological, cultural and social reasons why people behave in particular ways. For this reason, the French archaeologist Claude Leroi-Gourhan developed the idea of the *chaîne opératoire* or "chain of operations" for any productive practice (Leroi-Gourhan 1964). Essentially, this means that we must study each step of a particular productive process and look for social and cultural influence within each step. For example, the mining of sulphidic copper ores involves the extraction, the preprocessing (beneficiation and/or roasting) and the smelting of such ores (e.g. Eibner 1993; Herdits 1993). Given a specific level of technological experience, one can propose a several-step process that one may describe within a *chaîne opératoire*. This proposed model logically depends upon the complexity of the process for how interdisciplinary the network has to be developed. That is, the more complex process chains must incorporate multiple materials (e.g. stone tools,

Table 7.1 Various major levels to describe a mining region within a historical, economic and a social process

Natural landscape	Quality, sustainability and accessibility of raw materials
	Ecological preconditions of the natural landscape (favourable settling conditions; favourable conditions for subsistence economies)
	Traffic precondition especially for long distance trade
Cultural landscape	Regional economic balance with subsistence economy (e.g. stress factors in landscapes)
	Importance of the hinterland (size, structure of settlement) regional traffic lines and their improvement
	"Social abilities" (technological knowledge handed over; local tribal and political organisation)
Mode of production	Reconstructing the technological process (chaîne operatoire)
	Degree of specialization
	Interaction and labour division
Duration of time	Longue durée in specialized landscapes (imprinting phases in mining regions)
	1. Initial or inventing phase
	2. Phase of stabilisation or consolidation (radiation)
	3. "Industrial" phase
Society (ethnic, social and cultural tradition)	Tradition of labour
	Social control of winning and distribution
	Integration of different social and ethnic groups (children, women, foreigners etc.)
Trading modes	Dependency on trade (spatial standard/scale of trade; importance in regard to the economic scale)
	Organisation of trade (technical and logistical; social: exchange and symbiosis with other groups)
	Trading level (e.g. long-distance trade, trade by stages, ports of trade)
Historical processes	Changes in supply and demand structure (by crises, epidemics or wars, etc.)
	Changing of ritual and fashion demands
	Technical Innovations
	Processes of colonization

copper ore, water, timber and charcoal production), which requires researchers from different methodological disciplines (e.g. archaeobotanists; mineralogists and metallurgists) (general e.g. Ottaway 1994; Hauptmann 2007a). The advantage of working with process chains is that archaeologists, metallurgists and mining historians are able to model resource and working patterns in more predictable ways, and then look for the influence of social and cultural factors on past behaviours.

The Importance of the Natural (Landscape) and the Geological Preconditions (Table 7.1)

Determining the quality and the sustainability of a mineral deposit, as well as the accessibility and actual content of the deposit, was essential for early societies (general e.g. Stöllner 2003, p. 421; Strahm and Hauptmann 2009, pp. 121) to make decisions about the mining technologies to be used and to what extent. This very general statement forms the background for discussing the beginning and end of a long-term production process. What has rarely been considered are the short-term effects of small bonanza-type deposits (e.g. a "gold rush"), or how the irregularities within ore deposits may cause unpredictable situations. In other words, to what extent do varying deposits affect the blossoming or the collapse of a *chaîne opératoire* ? In certain case studies from historical periods, researchers have traced back such collapse situations to complex socio-economic situations (e.g. the cost increase associated with deeper and more laborious mining) (e.g. Harz: Bartels 1997), rather than more obvious geological reasons (e.g. the vein is "mined out"). However, we must remember that the geographical preconditions (e.g. relations to agricultural zones, the climate and vegetation— for instance, in relation to fuel resources; Engel and Frey 1996; Hillebrecht 1999) are also determining factors. For example, traditional mining in steppe zones can clearly be differentiated from those in arid or desert areas or from high mountain ranges. To what extent mining groups in these regions were restricted by food or water supplies is reasoned by assessing landscape conditions, but also their general subsistence pattern (e.g. herders vs. farmers: Cribb 1991; Alizadeh 2004). As long as raw material acquisition remained on a small tribal or familial level, resource exploitation was at least as successful as in specialized mining communities, due to the more limited geographical and subsistence restrictions.

Cultural Landscapes, the Longue-Durée and Societal and Trading Patterns (Table 7.1)

There are several cultural factors that influence the productive sphere of a society. For example, in my own research I have tried to distinguish between natural landscapes and culturally reorganised landscapes (Stöllner 2008a; 2008b). Many regions of the world were cultivated very early on and the exploitation of raw materials was a major part of their success as farmers. As mentioned above, landscape conditions influence not only the techniques of extraction but also the *long durée* of mining processes (e.g. Braudel 1977; for mining: Stöllner 2010, esp. 297–301). Social complexity could grow slowly and sustainably in cultural landscapes over centuries on the basis of local tribal and social organisational patterns, as has been shown for salt-producing communities in the Alps (Bergier 1989; Kern et al. 2009), for amber "fishing" in the Baltic Sea, for Cypriot copper (Ganzelewski and Slotta 1996) or for the lapis lazuli mines of Afghanistan (Kuhlke 1976).

What should not be underestimated is the influence of socio-cultural traditions on the manner of production, trade and division of labour within communities. For example, given that mining was a practice generally associated with men, only particular social values decided whether children and women were included and, if so, in which part of the process. Of course, there are also examples of women carrying out resource exploitation without men. For instance, red ochre, used as make-up and body paint, could have been mined by those who wore it, such as the women of the Himba in Namibia (Pickford et al. 1998). In addition, the inclusion or

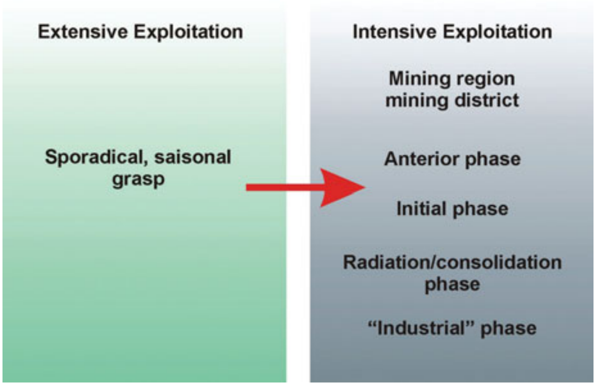


Fig. 7.1 Production modes and their relation to imprinting processes (intensive exploitation). (After Stöllner 2008a, p. 77, Fig. 5)

exclusion of foreigners was culturally determined, as their inclusion inevitably led to a gradual disintegration of traditional working patterns in that particular society.

Another factor that is directly related to production processes is the structure of markets and trade. Basic mechanisms of supply and demand were dependent upon trading networks whose efficiency had a direct influence on the success of an extracting process over time. The geographical location was often responsible for structuring markets, as the traffic routes and the mechanisms of trade determined the degree to which particular resources could be exploited.

Spatial Organisation

Exploitation activities are always linked with the landscape and geographical setting, but they are also dependent upon the economic and societal demands. Therefore, it is not surprising that by studying the spatial organisation of mining enterprises, one can also come to understand the social and ecological impacts. It is useful here to make a division between different spatial structures that also reflect different modes of production—i.e. between extensive, impermanent winning modes and more intensive, deposit - and site-based exploitations (Stöllner 2003, pp. 430–433; Stöllner 2008a) (Fig. 7.1). Extensive mining is normally associated with small-scale expeditions and can still be found in some traditional societies today. Such exploitations often left nearly invisible traces and were often obliterated by later and more intensive periods of winning. But this does not mean that a sporadic or seasonally based operation is a "simpler" mode of production or related to less advanced traditional societies. Oftentimes, such small-scale operations were also a consequence of the geographical setting, such as when deposits are situated in hostile landscapes that only allow an impermanent and seasonal access.

What can be described archaeologically is a core part of functional interrelation that we may call an "*ensemble*" (Stöllner 2003, pp. 429–430). An ensemble is defined by the relationship between two elements of a characteristic workflow, such as a smelting site and a mine, or a smelting site and a metal workshop. Within an extensive,

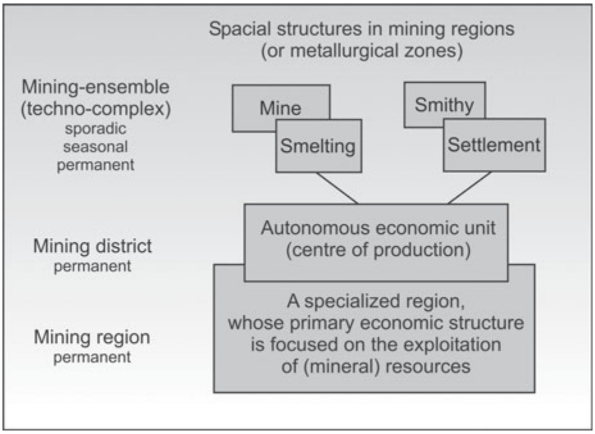


Fig. 7.2 Scheme of spatial structures of early mining enterprises and their interconnection in a functional mode. (After Stöllner 2008b, p. 169, Fig. 31)

sporadic mining enterprise, an "ensemble" may not be linked topographically—the mineral source and its first stage of processing could lie a great distance apart. Analysing such chain links by interdisciplinary approaches allows a reconstruction of functionality, and thus the embedding of the mining into either an isolated or a more complex economic cycle.

The determination of such economic systems leads mining archaeologists to the idea of "mining districts". A "district" should be understood as locally concentrated, intensive exploitation of a deposit: Generally, one could understand them as large and permanent production units. Often they are parts of an even larger unit, the so-called "mining region" ("Montanlandschaften") that assembles different production and functional units on the larger scale of a landscape (Fig. 7.2). In such cases, there are certain preconditions that have enabled a regionally stable and long-lasting development. Such stability is often the result of a combination of various positive social, economic and geographical circumstances. After decades of research, such landscape systems are much better understood, yet still there are only a few examples such as the Harz ore deposits (copper/lead-silver) studied by German Harz-Archaeology (e.g. Seegers-Glocke 1999; Bartels et al. 2007; Alper 2008); the Cypriot copper mines studied by Bernard Knapp and colleagues (Given and Knapp 2003); the Fenan copper mines studied by Andreas Hauptmann, Gerd Weisgerber, the team of Graeme Barker as well as Thomas Levy's work during last 15 years (Hauptmann 2007a; Barker et al. 2008; Levy et al. 2002; Levy 2009) or the Eastern Alpine Salt Mines (Kern et al. 2009; Stöllner 2010). In these few examples, the integration of archaeological, interdisciplinary and historical data has allowed a decent reconstruction of a broad economic history for the region.

Temporal Development—Stratification in Time—Adaptive Cycles

The temporal development of a mining operation, especially within economic zones dependent upon such exploitations, is considered to be an important approximation for describing complex economic interrelations more generally. In reference to the landscape being used and exploited, we may call this an "imprinting" process. Such a process usually lasts for several centuries (if not longer) and can be understood as a transformative process by which a landscape is changed into a zone with a special social and economic role. This stratification can be described within a four-phased concept:

- An *initial or inventing phase* (*invention phase*) sees the introduction of a new concept (new technology, new strategies of exploiting) into a district of a deposit or into a landscape. It occasionally superseded the *anterior phase* of part-time exploitation.
- A *phase of stabilisation or consolidation* (*radiation phase*) leads to the first successful exploitations and to the formation of successful working units (regional diffusion). Such activities have a notable influence on the local society and environment. For example, successful exploitations can result not only in a major improvement in living conditions, in the emergence of new professions and in the development of social hierarchies, but also in the degradation of landscape and the local environment. In the regional context, initial and consolidation stages are often difficult to distinguish, as is the case in Feinan's Early Bronze Age copper production. On a regional or even interregional scale, this extension (consolidation) was often the basis for the general "industrial" stage (e.g. in Feinan during the Early Bronze Age; in the Alps during the Late Bronze Age: in this way discussed by Stöllner 2008a, esp. 80–86).
- An *industrial phase* (*establishing phase, innovation phase*) is characterized by an abundant growth in exploitation in a regional context, in combination with considerable effects upon society and the natural environment as well as cultural landscapes. The expression "industry" is not used in connection with "industrialisation" but means a manner of frequent and standardized mass exploitation.
- This simplified schema for the development of exploitative practices in a region can be concluded by a phase of *collapse and reorganisation*. An industrial phase often imbues also the reasons for a following collapse of an economic or ecological system either by greedy over-exploitation or by over-expenditure of technological or economic resources. Besides internal reasons for a collapse, there are also external ones that must be considered, such as the changing of demand, the influence of historical events or the general economic crises that affect also the production sphere. Often multiple reasons led to a crisis and scenarios of disasters are usually reconstructed in great haste. Archaeology compounds its problems in detecting historical coincidences either because of the incorrect synchronisation of events or through the inability to securely identify the cause and effect adequately.

Such adaptive cycles (from invention to collapse) are frequently used in sociology and history to describe long-term processes in society or economy. If we adopt, for instance, the adaptive cycles that have been again discussed in recent years (Kondratiev 1984; Holling et al. 2002), we are able to model a cyclical system of occasional usage of deposits according to preconditions such as demand, trade or

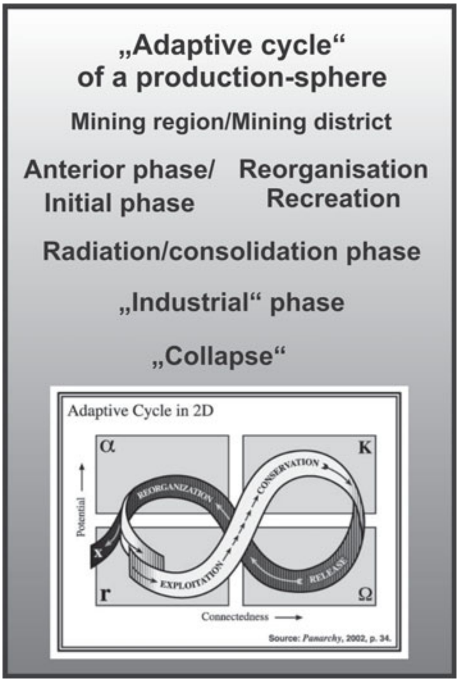


Fig. 7.3 Scheme of procession steps within a production sphere as an adaptive cycle system. (After Holling et al. 2002, p. 34; Stöllner 2010, p. 77, Fig. 5)

general technological ability (Fig. 7.3). In the light of empirical data, we have to stress that a cyclical economic development is not self-evident. Indeed, we often observe that after the collapse of an exploitation system, no phase of reorganisation has followed simply because the collapse did not allow any renewed rise.

The Importance of Econometrics:

One of the problems of economic archaeology is to present reliable data with concern to production intensity and economic profit. This basically is reasoned in the structure of our data sets, but partly also reasoned in research strategies that generally have not developed methods of this kind. It is undoubtedly of high value if production cycles and the up and down of the market may be understood in their full complexity. Econometric questions and methods, therefore, need to be developed according to specific research layouts and production cycles.

Concerning production intensity, the societal investments and the economic outcome have to be calculated (e.g. for agricultural societies: Kerig 2008). That said, it is still difficult to discuss the scale of ancient labour forces and subsistence strategies. We need to know the exact time span of production, the mean values of production progress and the number of persons involved. Using agent-based modelling seems helpful for narrowing down limiting factors (Holland and Miller 1991; Bloch and

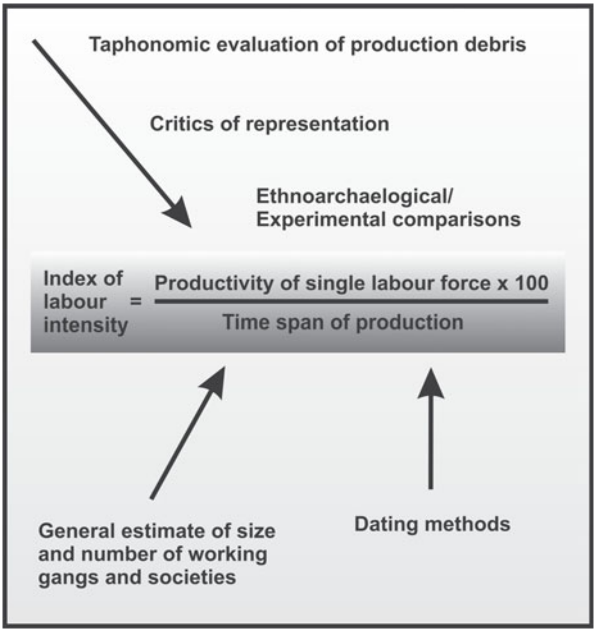


Fig. 7.4 Scheme of parameter to calculate an index of production intensity and different factors that are basic for calculations or influence such calculations. (After Stöllner 2012, p. 436, Fig. 3)

Bonabeau 2002). Such data can only be collected if excavations apply exact taphonomic studies in relation to the qualitative information of the production workflow (e.g. Stöllner 2012, pp. 435–436, Fig. 3). On the basis of such information, a productivity index can be calculated that allows independent comparisons through cultural complexes and periods (Fig. 7.4). Discussing the productivity, technological level and the general cost level, in accordance with the general economic activities (e.g. agriculture, herding and stock-breeding, crafts and trade), allows the estimation of the added value's chain.

As important as those questions may be, there are still considerable empirical biases; the estimation of production outputs can only start with archaeological remains (e.g. for mines, look at the calculations for the Mitterberg-Mines: Zschocke and Preuschen 1932; Stöllner et al. 2011a). Mines are often not accessible any longer, difficult to excavate or entirely destroyed by later exploitation. Slag heaps may be partly destroyed and require survey before any reliable calculations can be made. Indeed, a study of the smelting debris must be considered in the general production chain in case the amount of copper that was produced should be considered in relation to production investments.

Systematics of Montan-Archaeology

The classification of prehistoric and early historical mining methods helps to understand basic factors of operation chains. In this respect, there is less necessity to construct a simple disseminated history of mining for only one period, territory or

Fig. 7.5 Systematics of a basic description of mining and metallurgy in archaeological, historical and archaeometric research—the canon of mining and metallurgy. (After Stöllner 2008b, p. 152, Fig. 6)

Systematics of Mining and Metallurgy

Mining Operations

1. Prospecting
2. Opening the deposit
3. Winning methods
4. Working the deposit (exploitation)
5. Supporting
6. Riding
7. Hauling
8. Draining
9. Ventilation
10. Light
11. Art of surveying mines

Metallurgy and Metal crafts

12. Beneficiation
13. Charcoal burning and forestry
14. Smelting
15. „Refinery"
16. Fabrication
17. Decoration processes (metal crafts)

Economy of Mining

18. Operating, Organization
19. Mining rights
20. Ideology, religion
21. Economy: Theoretical factors

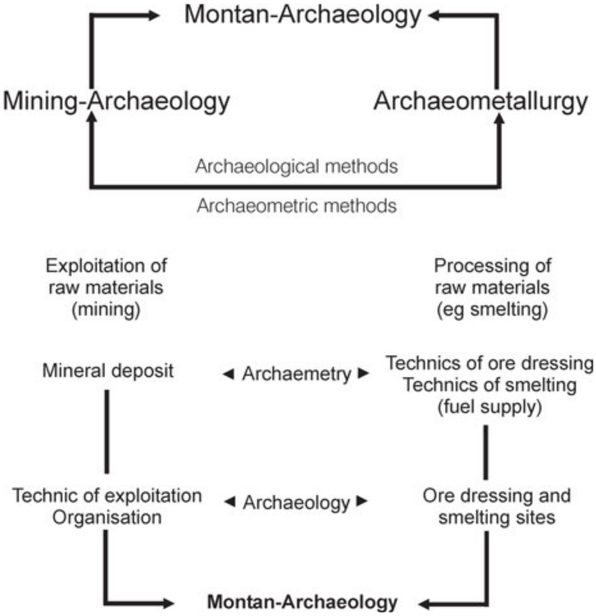


Fig. 7.6 Mining archaeology and archaeometallurgy in definition as it has been used since the 1980s, e.g. at the German Mining Museum Bochum as "montan-archaeology". (After Stöllner 2008b, p. 150, Fig. 4)

district. It is more important to show how the accumulated observations, knowledge and information represent the evidence of production processes like mining, smelting or fabrication. Montan-archaeology offers a specific contribution to historical knowledge, beginning with mining activities, winning of raw materials by mining or quarrying, preparation, handling and/or smelting (Fig. 7.5). It searches for and interprets evidence of activities in the sphere of mineral exploitation and preparation. Thus, montan-archaeology is associated with the peculiarities of particular resources, so that it cannot be fully evaluated by itself. From the early years of mining research, it has usually been left to an interdisciplinary group of scholars working together (Fig. 7.6). Henceforth, montan-archaeology is a methodological field not bound to a particular period or epoch, but interested in special resources and processes on or below the surface.

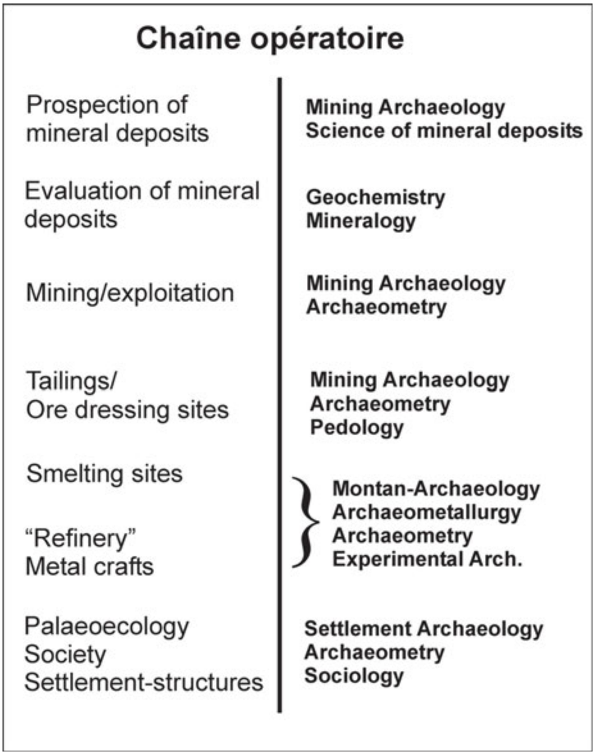


Fig. 7.7 Chaîne opératoire of research in the fields of mining archaeology and archaeometallurgy. (After Stöllner 2008b, p. 151, Fig. 5)

Natural sciences, within the sphere of a specific mining archaeology, can contribute to the interpretation and understanding of such remains. This is especially so for ores, furnace remains, technical pottery and slag (Hauptmann 2004, 2007b, 2008). As Fig. 7.7 shows, such research is always a multi- or even interdisciplinary work that combines methods and knowledge from several academic and non-academic fields. The exploitation processes as a whole can be enumerated best into 20 categories, structured around mining, smelting and fabrication activities (Weisgerber 1989/1990, 2003; renewed and added Stöllner 2008a, 2008b). They describe a specific *chaîne opératoire* of such productions. Of these twenty, fifteen are technical, three represent social, economic and political aspects and the two remaining include inter-regional and ideological factors which influence mining and smelting in a wide scale (Fig. 7.5). The systematics model presented here and elsewhere does not comprise all different raw materials but is more focussed on metals. Other raw materials (e.g. salt, ochre, pigments or fossilized wood) had their own preconditions that created specific workflows, but these are beyond the scope of this paper.

Only by using correct terms from several fields of engineering science is it possible to reconcile or absorb the material or even to communicate unequivocally. Terms are comfortably available in handbooks of mining, smelting and quarrying of the nineteenth century and early twentieth century. Because of the modern mining techniques introduced in the twentieth century (e.g. gigantic opencasts, electricity, motors, etc.), the terms of modern mining science often cannot help or even have changed meanings. Regarding what has been said above, it is worth discussing the systematic model of ancient mining and metallurgy. It is a general approach that helps to structure any discussion about prehistoric and ancient raw material exploitation.

Empirical Work and Modelling a Socio-Economic Process

With the methodological issues in mind, the second part of this paper will deal with the empirical work in montan-archaeology that should help to achieve the necessary database. Montan-archaeology, like many applied sciences, is based on specific scientific questions and is—as mentioned—primarily interdisciplinary. Nevertheless, it is an archaeological field and, as a consequence, it finds its methodological basis there. I therefore will restrict myself to describing specific empirical fields.

Disciplines Connected with the Investigation of Early Raw Material and Archaeo-Metallurgical Studies

The investigation of mining and metallurgy requires the integration of methods and knowledge of several related fields. One may call them the methodological canon of montan-archaeology, including several academic fields of mining and metallurgy (Berg- und Hüttenkunde), but also related fields of exploration geology (Lagerstättenkunde) and tectonics and structural geology (Tektonik und Strukturgeologie).

The multiple disciplines that comprise montan-archaeology can be described as the following:

Exploration geology (*Lagerstättenkunde*) is the basic requisite for describing the mineability of a deposit and the possible content of an already exploited deposit (Pohl 2005; Warren 2005). It helps to understand the yield of an ancient mining process. If the mining archaeologist wants to calculate the average ore content of a mine, whose cavity he has already investigated and measured, he has to consult exploration geologists to ascertain the ancient exploration yield.

Mining archaeology (*Bergbauarchäologie*) can be described as the basic archaeological method to survey, excavate and evaluate ancient exploitation areas such as underground mines and quarries.

Archaeometallurgy (*Archäometallurgie*) deals with field investigation of ancient smelting sites and other metallurgical sites and workshops (casting, smithing). It has to consider experimental and ethnoarchaeological approaches as well as specific taphonomic methods to get closer to the specific technical workflows (Ottaway 1994; Hauptmann 2007a, 2007b).

Archaeometry (*Archäometrie*) *of metals* is science based and uses different methods of mineralogy and geochemistry (especially of isotopic chemistry) to answer questions of metallurgical workflows or the provenance of materials (e.g. several articles in Wagner 2007; Begemann et al. 1989).

Mining engineering (*Bergbaukunde*) delivers the basic analogies for ancient technologies applied to specific types of deposits. Technologies themselves adhere to an ancient technical solution and can often be deduced from solutions known in traditional and historical records. Mining engineering provides the basic nomenclature of all types of exploitation processes (Gätzschmann 1846; Hoover 1909; Reuther 2010).

Tectonics and structural geology (*Tektonik und Strukturgeologie*) helps to understand and reconstruct alterations of rock texture by rock mechanics (e.g. pressures, lateral dislocations). This is especially important when discussing the situation underground (e.g. mineability of a deposit) or specific technical solutions (e.g. how to secure an area by timbering).

Mining surveying (*Markscheidewesen*) deals with both the reconstruction of the ancient surveying knowledge and the application of modern technique to the documentation of exploitation sites.

The science of economic ore dressing and metallurgy (*Aufbereitungs- und Hüttenwesen*) is today an academic sub-field in the mining sciences (Montanwissenschaften) that can be explained in analogy to the mining engineering.

Traditional technologies can be reconstructed by historical recipes and by modern ways of evaluating their economic efficiency. Experimental processing or even the interpretation of ancient descriptions (the most famous being those of Plinius the Elder, Theophilus Prespyter, and Agricola) needs the experience and the knowledge of specialists of that field.

There is no doubt that besides the disciplines mentioned, other fields have to be considered for a full reconstruction of old raw material exploitations to be reached. Such fields (e.g. palaeo-environmental reconstruction) certainly belong to any modern archaeological research project and do not need specific discussion here.

Field Methods—Survey

Survey methods constitute a basic component for any archaeological fieldwork but are even more important within montan-archaeology. Mining landscapes are generally too large to excavate extensively. Therefore, surveying methods have to replace in-depth field studies by a sophisticated combination of several methods. For example, if a large slag heap is excavated fully within several months of field work, it is simply too expensive to repeat the same operations at several other slag heaps (e.g. methods as discussed in Ullrich et al. 2007; Stöllner et al. 2011a). Therefore, a combination of surveying and soundings must be practiced, which always have to be tied to further questions about dating and lifespan, about stratigraphy and taphonomic structure of the dumping process (Fig. 7.8).

It is self-evident that mining, smelting and further production processes do require a special surveying methodology. Road or river cuts are very helpful especially in fully overgrown landscapes or forests. By following streams, for instance, slag heaps can often be found by following the trail of eroded slags in the stream bed (e.g. F.-A. Linke in: Seegers-Glocke 1999).

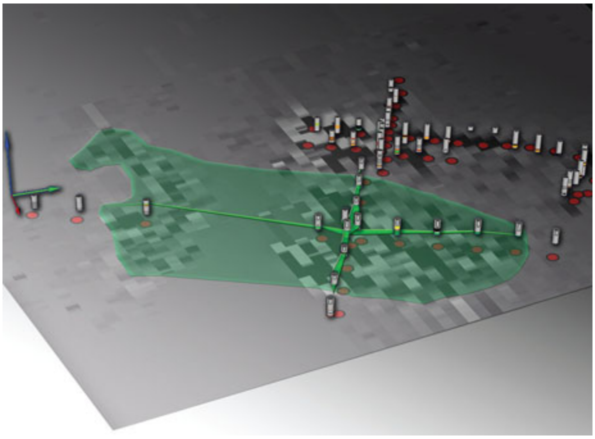


Fig. 7.8 Smelting site SP 14 in the Mitterberg area, Austria. Result of the combined survey in 3D: magnetic survey in combination with drilling survey. In *green*: reconstruction of the slag heap's extension. (After E. Hanning in Stöllner et al. 2011a, Fig. 2)

Detecting mines or interpreting depressions as traces of exploitation is much more difficult if there are no visible traces such as dumps, remnants of tools and so forth. Geophysical methods have the potential to detect mine openings or even to investigate the deposit itself by detecting the filling of mining depressions as well as the depth of the exploited area. In contrast to seismic surveys or geoelectrical tomography, ground-penetrating radar or geo-electric magnetometric survey are not very capable methods for detecting mines (e.g. R. Herd in Stöllner et al. 2009, pp. 124–129). However, geo-magnetic surveying is very useful for detecting smelting sites consisting of slag heaps, furnaces or roasting installations or charcoal pits. Today it counts among the most frequently used surveying methods (J. Fassbinder in: Wagner 2007, pp. 53–73).

A very specific surveying technique is applied to underground mines because of speleological methods of measuring and entering narrow or even dangerous areas. Mapping and describing includes also the third dimension, and the traces of mining work that provide good technological and chronological indications, especially on the basis of the different usage of mining tools (e.g. hammerstones, wedges, metal picks, explosives), are hard to find (Weisgerber 1989/1990). It is the careful observation that enables an experienced eye to carry out a first differentiation and interpretation of an underground mine (Fig. 7.9).

A most helpful and powerful surveying device is the core drilling of tailings, mining depressions or shafts. In recent years, drilling became as important as small sounding investigations. It always has to be accompanied by pedological expertise, but it does deliver most instructive information, not only about soil development but also about the stratigraphy and preservation of the archaeological features.

Field Methods—Excavation:

Excavation must be carried out in a special way in mining archaeology. Excavations underground mean that it is often not possible to work in a horizontal way. Usually

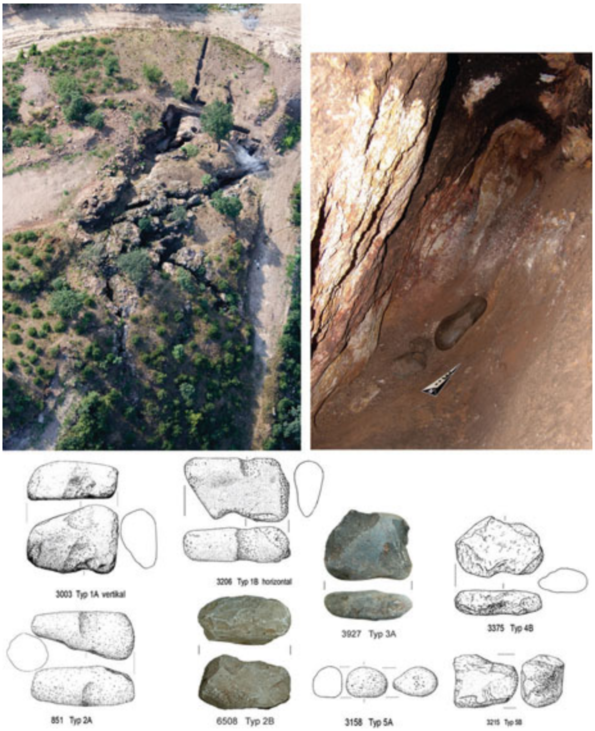


Fig. 7.9 Sakdrissi gold mine, late fourth millenium BC, Georgia. *Top left*: aerial photography of the mining area after cleaning the vegetation and with excavation trenches 2008. *Top right*: underground gallery with hammerstone deposition and fire-setting traces on the ceiling (sooted area). *Bottom*: types of hammerstones for the getter's work. (DBM, Th. Stöllner)

one can proceed only vertically by cutting sections, and through interpretation of these sections and profiles, retrieve the most relevant information about filling layers and mining debris (Fig. 7.10). This is especially true in elongated galleries or mines which are already completely filled or compressed and destroyed (e.g. descriptions of the methodology of underground excavations of the Deutsches Bergbau-Museum Bochum: Stöllner 2002/2003, pp. 24–35; Stöllner et al. 2009; Stöllner et al. 2011b). With respect to taphonomic questions, excavation proceeds along natural layers in order to reconstruct information about layer genesis and filling volume. This is crucial to get sufficient information for the interpretation of a layer either as an occupational level or as debris that emerged through local mineral extraction or that had been dumped from elsewhere. Mining layers generally are as complex as settlement layers and have to be differentiated carefully. Mining techniques are a basic precondition for any underground excavation, including the loading and carrying of material railways and wagons and the use of special advancing techniques such as pneumatic drills (Fig. 7.11). Safety must always be considered first before excavation takes place.

Besides underground excavation, other production sites often require special techniques. For example, iron smithing sites should be wet sieved in order to find even small debris such as magnetite prills and scales of the hammer stroke (general: Jöns 1997; Ganzelewski 2000). The same holds true for small copper slags or grinding debris. Whenever possible, such debris has to be fully recovered, quantified and

Fig. 7.10 Sakdrissi gold mine, late fourth millenium BC, Georgia. Side gallery A3 in depression A, filling with late antique gravel (*top*) and late fourth millenium BC mining debris in the lower part. Example for a vertical strata sequence in a mining gallery. (DBM, Th. Stöllner)

Fig. 7.11 Sakdrissi gold mine, late fourth millenium BC, Georgia. Excavation process with documentation within the mining depression A. (DBM, Th. Stöllner)

qualified. Dry and wet sieving, therefore, is absolutely necessary, not only for archaeobotanical debris or small artefacts. The largeness of sites is usually the main problem which often cannot be solved without the use of machinery. This does make mining archaeology expensive, and means that it is dependent upon the experience and practical knowledge of civil and underground engineering. In this way, mining archaeology is similar to underwater archaeology or the archaeology of wetland sites.

Field Methods—Sampling and Sieving

As mentioned above, sampling and sieving strategies are absolutely necessary and several basic questions must be answered in order to carry out these operations. First, a researcher has to understand the taphonomic value of the archaeological sediment: is it preserved more or less undisturbed? Is it the result of a production process or has it been re-dumped? How far has the material been degraded by soil erosion or other soil processes (e.g. human dumping) above ground? Besides the question of preservation, sieving and sampling has the taphonomic value of revealing *in situ* eco- and artefacts. On the other hand, the sedimentary record tells us about the fractioning of materials during procedural working steps or simply about which kind of rock deposit has been worked. In addition to estimating the quality and composition of the debris, it is also necessary to measure the quantity of the debris (a basic precondition for any econometric calculation) (E. Hanning in: Stöllner et al. 2011a).

Second, a critical estimation of the size of the labour force and any social or cultural effects upon the creation and deposition of the waste material is compulsory. For example, if one compares the different taphonomic structures of Alpine copper and salt mining during the Bronze and Iron Ages, one can see both variables at play. While the Bronze Age mining systems were careful not to dump rubbish within the mines themselves, the opposite is true of the Iron Ages (e.g. Aspöck et al. 2007; Kern et al. 2009; Stöllner et al. 2009). This difference has to do with the organisational patterns of Iron Age large-scale mining (staying underground, large working groups), but also with a different form of cultural behaviour caused by different conceptions of waste management.

Field Methods—Visualization

Surveying is one of the special cases by which mining archaeology especially is distinct from other archaeological fields. This is reasoned especially by the speleological character of underground mines: such archaeological monuments require the documentation of the third dimension because information cannot be visualized only by a projection into a second-dimension depiction (as can be done by a 2.5-dimensional situation in the case of excavations and surfaces). Although architectural three-dimensional displays are more common in archaeology today, it is still too difficult to solve all the problems that have to be faced by an irregular cave-like mine, such as undercutting surfaces and highly exact depiction of surfaces covering all the traces of ancient miners' work. All these efforts are serving essentially as the necessary means to display complex underground excavation and survey work.

Despite all these modern methods, the mapping of mines still depends on conventions that have been developed and standardized since the nineteenth century. Traditional surveying work with compass and a gradiated arc is the basic precondition for any further visualization work but allows no impressions of complex hollow

Fig. 7.12 **a** Traditional mapping underground, Slovakia, Poniky. Medieval to modern times mine. **b** Laser scanning underground, Sakdrissi Gold Mine. (**a** DBM, Th. Stöllner; **b** DBM, Th. Rabsilber)

structures on walls and ceilings (Heller et al. 2002; Steffens 2008) (Figs. 7.12a, b). A mapped documentation of a mine, a quarry or any producing area has to display two kinds of information—the archaeological and the technical. The latter has to follow traditions that are usual in mining surveying, including information of the geological deposit, the extraction technique and the surface of the extraction gallery.

There is a broad spectrum of methods now being included to visualize complex surface and cave-like structures: Besides laser-scanning and photogrammetry, more simple techniques also have to be mastered, especially when working in narrow areas (e.g. by photogrammetry: Arles et al. 2011; by laser-scanning: Schenk and Hanke 2009; general: Grussenmeyer et al. 2010). Highly engineered devices often fail because of the narrow space or other difficulties that are affected by special underground conditions. Whatever the special requirements of documentation are, it depends on a workflow that has to be developed individually. The technical development of soft- and hardware generates rapid progress which generates ongoing technical adoptions: recent research efforts are concentrated on higher detailed and photo-like texturing of surfaces using 3D-information systems.

Laboratory Methods—Written Sources

Historical records are utilized regularly for general information about the technological processes that were carried out at a particular time, but they are seldom exact enough to match the circumstances of an archaeological excavation. Old surveying maps or historical travel accounts are helpful for detecting sources and sites (e.g. the historical record of the mines of Hallstatt, Dürrnberg and Mitterberg: Kern et al. 2009; Stöllner 2002/2003; Zschocke and Preuschen 1932). Historical mining often followed and reopened older exploitations, so such information was often recorded in great detail (Treptow 1907, 1918). Often such older mining traces posed serious dangers to historical mining processes. The "Old Man" (Alter Mann), as such older mining was called, was both feared and respected by the miners, but also noted in historic accounts.

Laboratory Methods—Dating

Providing chronological context for mines is compulsory but often difficult. This is especially true if one considers the complex stratigraphic situation within mines and other production sites (including re-dumping and the relocation of debris). One often has to differentiate between the primary exploitation of the mine, quarry or installation and the secondary filling of such contexts. Usually, working techniques (e.g. working traces on pillars, ceilings and walls) cannot be dated as finely as fillings (on the basis of artefacts or radiometric dates). Rather, one attempts to date an entire technological complex (e.g. fire-setting and hammer tools and bone wedges as a typical tool kit). That said, archaeological artefacts are seldom represented in a producing area's debris.

These problems explain why radiometric methods (e.g. radiocarbon dating: Kromer 2008) and dendrochronology have such a high importance for montan-archaeology. Even then, the exact dating of the operation time is only approximately possible. This is even truer for other radiometric dating methods, such as thermo-luminescence that can be used to date the last heating of feldspars and quartzes (e.g. in slags) (Wagner 2008). The only method which provides a secure and exact dating of operation periods is dendro- (tree ring-) chronology, but only if the wood can be shown to be in a primary context (Pichler et al. 2010a, b).

Laboratory Methods—Geographic Information Systems or Global Imaging Systems

Geographic Information Systems or Global Imaging Systems (GIS) was introduced to montan-archaeology in the mid-1990s and has revolutionized the field. Besides basic mapping, GIS allows the implantation of complex data and digital images that,

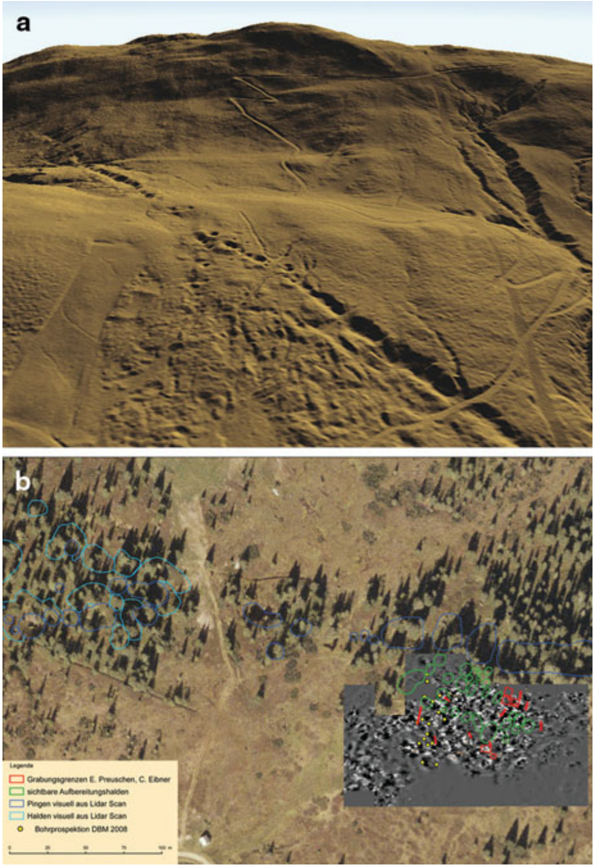


Fig. 7.13 Mitterberg, Austria, Middle to Late Bronze Age mining (seventeenth to ninth century BC). **a** The main-lode mining depression that follows the ancient underground galleries, lidar scan in 3D. **b** GIS mapping of results from lidar survey, magnetic survey, excavation and drillings in the area of the eastern part of the main lode and in the area of a large beneficiation area. (DBM, Annette Hornschuch, P. Thomas)

at higher resolutions, can now automatically detect mining depressions, platforms, tailings or ditches and wall systems. The combination of both GIS and light detection and ranging (LIDAR)-scan systems has proven to be more powerful than other remote-sensing methods (e.g. satellite images or aerial photos), as airborne-laser-scanning provides information even in areas where vegetation and forests cover most of the relevant surface structures (e.g. Devereux et al. 2005) (Figs. 7.13a, b).

Despite great progress in digitizing mining landscapes, everything depends upon the structure of the data being administered in a GIS program. Generally, such systems are only applied usefully to projects that expect a high amount of artefacts (e.g. a complex excavation site) or a landscape that is surveyed and investigated over many years. For example, a mining region with production and settlement sites is ideal for GIS, as questions of territoriality can be investigated either by procedural workflows (e.g. deposit—ores of a special geochemical composition—beneficiation— smelting—final processing) or by morphological and topographical preconditions of the landscape (e.g. traffic, visibility, site-catchment or the analysis of the nearest neighbours). There is a wide range of possible applications that cannot be discussed here in detail (e.g. Hiebel et al. 2010; Hiebel et al. 2012).

Fig. 7.14 Sakdrissi, Georgia—hammerstone kit as prepared by B. Craddock in 2011 used for the fire-set experiment 3/2011 underground (*top*). Exfoliation of wall parts after the fire-set (*bottom left*) and the heavy smoke during the experiment (*bottom right*). (Photos: DBM, K. Stange)

Laboratory Methods—Statistical Approach and Techno-Complexes

A further basic evaluation considers the techno-complexes and their interrelation with other parts of the workflow. It is primarily a qualitative question that secondly has also been accompanied by statistical methods. Timbering and timber use in a mine provides an example (e.g. Cauuet 2000; Thomas 2012). After a first step of differentiating artefacts and working chips, the archaeologist has to consider the representativeness of the sources: are the materials interrelated or is something under- or over-represented? One always has to keep in mind that everything which is used in a production process must have been brought for a specific purpose. Is there a technological progress—i.e. can one detect the individual hand of single craftspeople—or is it possible to reconstruct societal knowledge and work tradition of landscapes? In the Middle Bronze Age mine of Arthurstollen, scholars were able to identify and distinguish the tool marks of wood-working axes on supporting timbers found in the mine (e.g. Thomas 2012, pp. 140–149). These tool marks suggest that only one or two tools were being used, perhaps by a small number of experienced miners. Hammerstones or metal picks often provide a similar window into ancient mining, and it is very informative to combine it with experimental archaeology (Timberlake 2007) (Fig. 7.14). The weight and preparation of these objects have often been standardized according to common knowledge and ideas about how to use them (Pickin 1990).

Therefore, any noted differences embed interesting information about crafting traditions, the adoption of a deposit, as well as the access to resources (e.g. special stone varieties).

Laboratory Methods—Econometric Analysis

Quantitative analyses of mining processes also have to be based upon the technological chain as well as the statistical approach. As before, the taphonomic argument has to be faced: what is representative of a working process? Which various steps of re-dumping are reconstructable in the allotted time? Has the dump been reduced by later reuse? Fieldwork has to face the quantitative questions from the very beginning and during the documenting and sampling processes. There is no other way to get sufficient data. If one wants to calculate the mean value of the use of lighting devices (e.g. oil; wooden tapers), one has to know how many tapers had to be used by a single miner per day. This figure should be then juxtaposed with the debris and layer content in order to understand its value to the archaeological interpretation.

Conclusions

Montan-archaeology is basically an interdisciplinary sub-field of archaeology, which means that full information can be gained only through joint projects and modelling of multiple lines of evidence. There is no other way to work on the complex scientific questions and historical frameworks involved in the social and economic exploitation of resources. Everything depends on the quality of data and the level of argumentation. Often, single mining and production ensembles are well investigated and understood, while the whole mining district or even the region lacks further comprehension. While on the level of a single ensemble it is preferable to deal with single-phase production, diachronic observations allow insight into broader historical processes and into general questions that are linked to raw material production as embedded in societies and settlement history. Montan-archaeology is, therefore, able to describe long-term developments and is but one angle on the societal and economic development of mankind. However, it has to be fed back into the general historical and cultural development in order to be relevant.

References

Alizadeh, A. A. (2004). Mobile pastoralism and prehistoric exchange. In T. Stöllner, R. Slotta, & R. Vatandoust (Eds.), *Persiens Antike Pracht. Bergbau, Handwerk, Archäologie* (pp. 76–91). Bochum: (= Veröffentl. Deutsches Bergbau-Museum 128).

Alper, G. (2008). The Eastern Harz Mountains during the middle ages—the Impact of mining and metal production. In C. Bartels & C. Küpper-Eichas (Eds.), *Cultural heritage and landscapes in Europe* (pp. 467–487). Landschaften: Kulturelles Erbe in Europa. Proc. Internat. Conf. Bochum 2007. Bochum: Veröff. Deutsches Bergbau-Museum Bochum 161 (Bochum 2008).

Arles A., Busdraghi F., Guyot J. & Heckes J. (2011). La photogrammétrie appliquée à l´archéologie miniére: premiers essais saint-mariens. In Fluck P. (ed.) PCR "Altenberg: fonderies et mines d'argent, Xe-XVIIe siécles", Straßbourg, 2011, 52–72.

Aspöck, H., Boenke, N., Kofler, W., Oeggl, K., Picher, O., & Stöllner, T. (2007). The Dürrnberg miners during the iron age—New results by Interdisciplinary Research. In P. Trebsche, I. Balzer, C. Eggl, J. Koch, H. Nortmann, & J. Wiethold (Eds.), *Die unteren Zehntausend—auf der Suche nach den Unterschichten der Eisenzeit. Beiträge zur Sitzung der AG Eisenzeit, Jahrestagung des West- und Süddeutschen Verbandes für Altertumsforschung, Xanten 2006* (pp. 109–126). Beiträge zur Ur- und Frühgeschichte Mitteleuropas 47 (Langenweissbach 2007).

Barker, G., Gilbertson, D. D., & Mattingly, D. J. (2008). *Archaeology and desertification. The Wadi Faynan Landscape Survey, Southern Jordan*. Oxford: Oxbow.

Bartels, C. (1997). Strukturwandel in Montanbetrieben des Mittelalters und der frühen Neuzeit in Abhängigkeit von Lagerstättenstrukturen und Technologie. In: H.-J. Gerhard (Ed.), *Struktur und Dimension* (pp. 27–70). Festschrift für Heinrich Kaufhold zum 65. Geburtstag 1 (1997).

Bartels, C., Fessner, M., Klappauf, L., & Linke, F.-A. (2007). *Kupfer, Blei und Silber aus dem Goslarer Rammelsberg von den Anfängen bis 1620*. Montanregion Harz 8, Bochum.

Begemann, F., Schmitt-Strecker, S., & Pernicka, E. (1989). Isotopic composition of lead in early metal artefacts. Results, Possibilities and Limitations. In A. Hauptmann, E. Pernicka, & G. A. Wagner (Eds.), *Archäometallurgie der Alten Welt* (pp. 269–278). Der Anschnitt, Beiheft 7.

Bergier, J.-F. (1989). *Die Geschichte vom Salz*. Frankfurt.

Bloch, M. R., & Bonabeau, E. (2002). *Agent-based modeling: Methods and techniques for simulating human systems*. Proceedings of the National Academy of Sciences May 2002, 7280–7287.

Braudel, F. (1977). Geschichte und Sozialwissenschaften. Die longue durée. In C. Honegger (Eds.), *Schrift und Materie der Geschichte. Vorschläge zu einer systematischen Aneignung historischer Prozesse* (pp. 47–85). Frankfurt am Main.

Cauuet, B. (2000). Techniques de Boisages dans les Mines d'Or Gauloises e Sud-Ouest du Massif Central. *Gallia*, *57*, 129–158 (2000).

Clarke, G. (1953). *The economic approach to prehistory*. London.

Cribb, R. (1991). *Nomads in archaeology*. Cambridge.

Devereux, B. J., Amable, G. S., Crow, P., & Cliff, A. D. (2005). *The potential of airborne lidar for detection of archaeological features under woodland canopies* (pp. 648–660). Antiquity 79/3005.

Eibner, C. (1993). Urzeitliche Bergbautechnik in den Ostalpen. In H. Steuer & U. Zimmermann (Eds.), *Montanarchäologie in Europa. Int. Koll. "Frühe Erzgewinnung und Verhüttung in Europa" Freiburg 1990* (pp. 83–88). Arch. u. Gesch. Freiburger Forsch. 4, Sigmaringen.

Engel, T., & Frey, W. (1996). Fuel resources for copper smelting in antiquity in selected woodlands in the Edom highlands to the Wadi Arabah/Jordan. *Flora, 191,* 29–39.

Ganzelewski, M., & Slotta, R. (1996). *Bernstein—Tränen der Götter. Katalog zur Ausstellung*. Bochum: Veröffentl. Deutsches Bergbau-Museum 64.

Ganzelewski, M. (2000). Archäometallurgische Untersuchungen zur frühen Verhüttung von Raseneisenerzen am Kammberg bei Joldelund, Kreis Nordfriesland. In A. Haffner, H. Jöns, & J. Reichstein (Eds.), *Frühe Eisengewinnung in Joldelund, Kr. Nordfriesland. Ein Beitrag zur Siedlungs- und Technikgeschichte Schleswig-Holsteins 2* (pp. 3–100). Universitätsforschungen zur Prähistorischen Archäologie 59, Bonn 2000.

Gätzschmann, M. F. (1846). *Die Lehre von den Bergmännischen Gewinnungsarbeiten*. Freiberg.

Grussenmeyer, P., Cazalet, B., Burens, A., & Carozza, L. (2010). Close range terrestrial laser scanning and photogrammetry for 3D-documentation of the bronze age cave "Les Fraux" in Peridgord (France). In P. Anreiter et al. (Eds.), *Mining in European history and its impact on environment and human societies* (pp. 411–421). Proceed. 1st Mining in European History—Conference SFB HiMAT 12–15. November 2009 (Innsbruck 2010).

Leroi-Gourhan, A. (1964). *Le Geste et la parole. 1. Techniques et langage*. Paris: Albin Michel.

Given, M., & Knapp, A. B. (2003). *The Sydney Cyprus survey project. Social approaches to regional archaeological survey*. Los Angeles: Monumenta Archaeologica 21.
Hauptmann, A. (2004). Schlacke. In J. Hoops (Ed.), *Reallexikon Germ* (pp. 124–132). Berlin: Altertumskde. 27.
Hauptmann, A. (2007a). *The Archaeometallurgy of Copper. Evidence from Faynan, Jordan*. Natural Science in Archaeology, Springer.
Hauptmann, A. (2007b). Alten Berg- und Hüttenleuten auf die Finger geschaut: Zur Entschlüsselung berg- und hüttenmännischer Techniken. In G. Wagner (Ed.), *Einführung in die Archäometrie* (pp. 115–137). Berlin: Springer.
Hauptmann, A. (2008). Vom Erz zum Metall—naturwissenschaftliche Untersuchungen innerhalb der Metallurgiekette. In A. Hauptmann & V. Pingel (Eds.), *Archäometrie. Methoden und Anwendungsbeispiele naturwissenschaftlicher Verfahren in der Archäologie* (pp. 125–140), Stuttgart.
Heller, M., Steffens, G., & Stöllner, T. (2002). *Hohlraummodellierung—von der Vermessung zum Informationssystem* (pp. 132–143). Proceedings of 2. Altbergbaukolloqium Clausthal 2002.
Herdits, H. (1993). *Zum Beginn experimentalarchäologischer Untersuchungen einer bronzezeitlichen Kupferverhüttungsanlage in Mühlbach, Salzburg* (pp. 31–38). Archaeologia Austriaca 77. (1993).
Hiebel, G., Hanke, K., & Hayek, I. (2010). GIS supported implementation of ontology based data management for multidisciplinary research. In P. Anreiter et al. (Eds.), *Mining in European History and its Impact on Environment and Human Societies* (pp. 405–409). Proceed. 1st Mining in European History—Conference SFB HiMAT 12.-15. November 2009 (Innsbruck 2010).
Hiebel, G., Hanke, K., & Hayek, I. (2012). Grundlagen, Anwendungen und neueste Entwicklungen der HiMAT GIS-Datenbank. In: K. Oeggl & V. Schaffer (Eds.), *Die Geschichte des Bergbaues in Tirol und seinen angrenzenden Gebieten*. Proceedings 6. Milestone-Meeting Klausen 2011. Innsbruck: University Press.
Hillebrecht, M.-L. (1999). Der Wald als Energielieferant für das Berg- und Hüttenwesen. In C. Seegers-Glocke (Ed.), *Auf den Spuren einer frühen Industrielandschaft* (pp. 83–86). Naturraum—Mensch—Umwelt im Harz. Arbeitshefte Denkmalpflege Niedersachsen 21, Hannover.
Holland, J. H., & Miller, J. H. (1991). Artificial adaptive agents in economic theory. *American Economic Review, 81*(2), 365–371.
Holling, C. S., Gunderson, L. H., & Peterson, G. D. (2002). Sustainability and panarchies. In L. H. Gunderson & C. S. Holling (Eds.), *Panarchy: Understanding transformations in human and natural systems* (pp. 63–102). Washington.
Hoover, H. C. (1909). *Principles of mining. Valuation, organization and administration. Copper, gold, lead, silver, tin and zinc*. New York.
Jöns, H. (1997). *Frühe Eisengewinnung in Joldelund, Kr. Nordfriesland. Ein Beitrag zur Siedlungs- und Technikgeschichte Schleswig-Holsteins 1*. Universitätsforschungen zur Prähistorischen Archäologie 40: Bonn (1997).
Kern, A., Kowarik, K., Rausch, A., & Reschreiter, H. (Eds.). (2009). *Kingdom of Salt. 7000 years of Hallstatt*. Vienna: Veröffentlichungen der prähistorischen Abteilung 3.
Kerig, T. (2008). *Als Adam grub… Vergleichende Anmerkungen zu landwirtschaftlichen Betriebsgrößen in prähistorischer Zeit* (pp. 375–402). Ethnograph.-Arch. Zeitschr. 2007.
Knapp, A. B., Pigott, V. C., & Herbert, E. W. (Eds.). (1998). *Social approaches to an industrial past. The Archaeology and Anthropology of Mining*. London: Routledge.
Kondratiev, N. D. (1984). *The long wave cycle*. New York: Richardson & Snyder.
Kromer, B. (2008). Radiokohlenstoffdatierung. In A. Hauptmann, & V. Pingel (Eds.), *Archäometrie. Methoden und Anwendungsbeispiele* (pp. 144–153). Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.
Kuhlke, H. (1976). Die Lapislazuli-Lagerstätte von Sare Sang (Badakhshan). Geologie Entstehung, Kulturgeschichte und Bergbau. *Afghanistan Journal, 1,* 43–56.

Levy, T. E., Adams, R. B., Hauptmann, A., Prange, M., Schmitt-Strecker, S., & Najjar, M. (2002). *Early Copper Age metallurgy: newly discovered copper manufactory in southern Jordan* (pp. 425–437). Antiquity 76 (2002).

Levy, T. E. (2009). Pastoral nomads and iron age metal production in ancient Edom. In J. Szuchmann (Ed.), *Nomads, tribes and the state in the ancient near east* (pp. 147–177). Chicago: University of Chicago. (Oriental Inst. (Seminars 5 2009)).

Ottaway, B. S. (1994). *Prähistorische Archäometallurgie*. Espelkamp.

Pichler, T., Nicolussi, K., Klaunzer, M., & Goldenberg, G. (2010a). Dendrochronological Analysis and Dating of Wooden Artifacts from Prehistoric Copper Mine Kelchalm/Kitzbühel (Austria). In P. Anreiter et al. (Eds.), *Mining in European history and its impact on environment and human societies* (pp. 227–232). Proceed. 1st Mining in European History—Conference SFB HiMAT 12.-15. November 2009 (Innsbruck 2010).

Pichler, T., Nicolussi, K., Thurner, A., & Goldenberg, G. (2010b). Dendrochronological Dating of Charcoal Originating from an Early Iron Age Fire-Set Pit in the Mining Area of Schwaz/Brixlegg (Tyrol, Austria). In P. Anreiter et al. (Eds.), *Mining in European history and its impact on environment and human societies*. Proceed. 1st Mining in European History—Conference SFB HiMAT 12–15. November 2009 (Innsbruck 2010).

Pickford, P., Pickford, B., & Jacobsohn, M. (1998). *Himba—Die Nomaden Namibias*. Göttingen.

Pickin, J. (1990). Stone tools and early metal mining in England and Wales. In P. Crew & S. Crew (Eds.), *Early mining in the British Isles* (pp. 39–42). London: Plas Tan y Bwlch Snowdonia National Park Study Centre.

Pfaffenberger, B. (1992). Social anthropology of technology. *Annual Review of Anthropology, 21*(1992), 491–516.

Pohl, W. (2005). *Mineralische und Energie-Rohstoffe. Eine Einführung zur Entstehung und nachhaltigen Nutzung von Lagerstätten*. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.

Reuther, E.-U. (2010). *12 Lehrbuch der Bergbaukunde*. Essen: VGE-Verlag.

Schenk, S., & Hanke, K. (2009). *Genetic Algorithms for Automatic Registration of Laser Scans with Imperfect and Subdivided Features (GAReg-ISF). In Photogrammetrie—Fernerkundung—Geoinformation Heft 1/2009* (pp. 23–32). Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.

Seegers-Glocke, C. (Ed.). (1999). *Auf den Spuren einer frühen Industrielandschaft. Naturraum—Mensch—Umwelt im Harz*. Hannover: Arbeitshefte Denkmalpflege Niedersachsen 21.

Steffens, G. (2008). *Anwendung des neuen 2D-Profilscanners PS II zur Vermessung und Visualisierung von Altbergbau* (pp. 90–99). 8. Altbergbau—Kolloquium: TU Clausthal.

Steuer, H., & Zimmermann, U. (Eds.). (1993). *Montanarchäologie in Europa. Berichte zum Kolloquium "Frühe Erzgewinnung und Verhüttung in Europa", Freiburg 1990. Archäologie und Geschichte*. Freiburger Forschungen zum ersten Jahrtausend in Südwestdeutschland 4, Sigmaringen.

Stöllner, T. (2002/2003). *Der prähistorische Salzbergbau am Dürrnberg/Hallein II. Befunde und Funde der Untertageausgrabungen zwischen 1990–2000*. Rahden: Dürrnberg-Forschungen 3/1–2.

Stöllner, T. (2003). Mining and economy. A discussion of spatial organisations and structures of early raw material exploitation. In T. Stöllner, G. Körlin, G. Steffens, & J. Cierny (Eds.), *Man and mining. Studies in honour of Gerd Weisgerber* (pp. 415–446). Bochum: Der Anschnitt, Beiheft 16.

Stöllner, T. (2008a). Mining landscapes in early societies—Imprinting processes in pre- and protohistoric economies? In C. Bartels & C. Küpper-Eichas (Eds.), *Cultural heritage and landscapes in Europe. Landschaften: Kulturelles Erbe in Europa. Proc. Internat. Conf. Bochum 2007* (pp. 65–92). Bochum: Veröff. Deutsches Bergbau-Museum Bochum 161 (Bochum 2008).

Stöllner, T. (2008b). Montan-archaeology and research on old mining: Just a contribution to economic history. In Ü. Yalçın (Eds.), *Anatolian metal IV* (pp. 149–178). Bochum: Der Anschnitt, Beiheft 21 (Bochum 2008).

Stöllner, T. (2010). Copper and salt—Mining communities in the alpine metal ages. In P. Anreiter et al. (Eds.), *Mining in European history and its impact on environment and human societies* (pp. 297–314). Proceed. 1st Mining in European History—Conference SFB HiMAT 12–15. November 2009 (Innsbruck 2010).

Stöllner, T. (2012). Mining and elites: A paradigm beyond the evidence in European metal ages. In T. L. Kienlin & A. Zimmermann (Eds.), *Beyond elites. Alternatives to hierarchical systems in modelling social formations* (pp. 433–448). Universitätsforschungen zur Prähistorischen Archäologie 215. Habelt: Bonn.

Stöllner, T., Cierny, J., Eibner, C., Boenke, N., Herd, R., Maass, A., Röttger, K., Sormaz, T., Steffens, G., & Thomas, P. (2009). Der bronzezeitliche Bergbau im Südrevier des Mitterberggebietes—Bericht zu den Forschungen der Jahre 2002 bis 2006. *Archaeologia Austriaca 90*, *2006*(2009), 87–137.

Stöllner, T., Hanning, E., & Hornschuch, A. (2011a). Ökonometrie des Kupferproduktionsprozesses am Mitterberg Hauptgang. In K. Oeggl, G. Goldenberg, T. Stöllner, & M. Prast (Eds.), *Die Geschichte des Bergbaues in Tirol und seinen angrenzenden Gebieten* (pp. 115–128). Proceedings zum 5. Milestone-Meeting des SFB HiMAT vom 07.-10.10.2010 in Mühlbach (Innsbruck 2011).

Stöllner, T., Mireskanderi, M., & Roustaei, K. (2011b). Mining archaeology in Iran—investigations at Vešnāve. In collaboration with M. Mommenzadeh, T. Riese, G. Steffems, G. Weisgerber with contributions by M. Doll, R. Pasternak, W. Dörfler. In A. Vatandoust & H. Parzinger (Eds.), *Early mining and metallurgy on the western central Iranian Plateau* (pp. 535–608). *The first five years*. Arch. in Iran und Turan 9, Berlin.

Strahm, C., & Hauptmann, A. (2009). The metallurgical developmental phases in the old world. In T. Kienlin, & B. Roberts (Eds.), *Metals and societies—studies in honour of Barbara S. Ottaway* (pp. 116–129). Universitätsforschungen Prähist. Archäologie 169. Bonn: Habelt.

Thomas, P. (2012). *Studien zu den bronzezeitlichen Bergbauhölzern im Mitterberger Gebiet*. Phil. Diss. Bochum.

Timberlake, S. (2007). The use of experimental archaeology/archaeometallurgy for the understanding and reconstruction of early bronze age mining and smelting technologies. In Metals and mines: Studies in archaeometallurgy. Conference: *"Metallurgy, a touchstone for cross-cultural interactions" held at the British Museum, 28–30 April 2005 in honour of Paul Craddock* (pp. 27–36). London: Archetype Publications Ltd.

Topping, P., & Lynott, M. (2005). Miners and mines. In P. Topping & M. Lynott (Eds.), *The cultural landscape of prehistoric mines* (pp. 181–191). London.

Treptow, E. (1907). *Grundzüge der Bergbaukunde, Bd. 1; 1918, Bd. 2: Die Aufbereitung und das Brikettieren*. Leipzig.

Treptow, E. (1918). Der älteste Bergbau und seine Hilfsmittel. In *Beiträge zur Geschichte der Technik und Industrie* (pp. 155–191). Jahrbuch des VDI 8.

Ullrich, B., Meyer, C., & Weller, A. (2007). Geoelektrik und Georadar in der archäologischen Forschung: geophysikalische 3D-Untersuchungen in Munigua (Spanien). In G. A. Wagner (Eds.), *Einführung in die Archäometrie* (pp. 75–93). Berlin.

Wagner, G. A. (Ed.). (2007). *Einführung in die Archäometrie*. Berlin: Springer.

Wagner, G. A. (2008). Archäochronometrie: Lumineszenzdatierung. In A. Hauptmann, & V. Pingel (Eds.), *Archäometrie. Methoden und Anwendungsbeispiele* (pp. 171–182). Stuttgart: Schweizerbart'sche Verlagsbuchhandlung.

Warren, J. K. (2005). *Evaporites. Sedimentology, ressources and hydrocarbon*. Berlin: Springer.

Weisgerber, G. (1989/1990). Montanarchäologie—Grundzüge einer systematischen Bergbaukunde für Vor- und Frühgeschichte und Antike, Teil 1. Der Anschnitt 41, H. 6, 1989, 190–204; Teil 2. Der Anschnitt 42, H. 1, 1990, 2–18.

Weisgerber, G. (2003). Montanarchäologie. In J. Hoops (Eds.), *Reallexikon Germ* (pp. 180–199). Berlin: Altertumskde. 20.

Zimmermann, A. (2000). Auf der Suche nach einer Wirtschaftsarchäologie. Gesellschaften zwischen sozialer Harmonie und individuellem Gewinnstreben. In B. Gehlen, M. Heinen,

& A. Tillmann (Eds.), *Zeit-Räume. Gedenkschrift für Wolfgang Taute* (pp. 19–31). Bonn: (= Archäologische Berichte 14).

Zschocke, K., & Preuschen, E. (1932). *Das urzeitliche Bergbaugebiet von Mühlbach-Bischofshofen. Materialien zur Urgeschichte Österreichs 6*. Wien: Selbstverlag der Anthropologischen Gesellschaft.

Suggested Reading

Godoy, R. (1985). Mining: Anthropological perspectives. *Annual Review of Anthropology, 14,* 199–217.

Chapter 8
Experimental Archaeometallurgy

Julia Heeb and Barbara S. Ottaway

Introduction

Before exploring the details and potential of experimental archaeometallurgy, we should examine briefly the history, scope and theory of experimental archaeology in general. Why should we use experimental archaeology in the first place? What can it bring to the discipline of archaeometallurgy that other techniques and approaches cannot? The main components which have an input into experimental archaeometallurgy are:

Theoretical considerations
Ethnographic analogies (see Iles and Childs, this volume)
Literary and historical sources
Experimental work

This chapter does not discuss the second or third point, although ethnographic data and illustrations, mainly from 'De Re Metallica' written by Agricola in 1556 (see Hoover and Hoover 1912 translation) and the Annaberger Bergaltar, in Germany which was painted by Hans Hesse in 1521, will occasionally be used to clarify a point.

Theoretical Considerations

As we shall see, there is currently some contention as to the exact definition of experimental archaeology, and what sort of activities it should encompass. It is perhaps best expressed as meticulously recorded experiments on and with materials

B. S. Ottaway (✉)
Department of Archaeology, University of Exeter, Laver Building,
North Park Road, Exeter EX4 4QE, Devon, United Kingdom
e-mail: B.Ottaway@exeter.ac.uk

J. Heeb
e-mail: juliaheeb@googlemail.com

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_8,

and objects which were available at the time for a better understanding of methods of production and use.

Such activities are almost as old as the discipline of archaeology itself and early examples include many prehistoric technologies, such as the working of stone as well as metallurgy. It was Robert Ascher (1961) who wrote the first theoretical treatise on experimental archaeology. He distinguished between the use of experiments to evaluate modern techniques (in terms of both methods of excavation and artefactual analysis) and the so-called 'imitative experiment'. The imitative experiment can be defined as matter being 'shaped and used, in a manner simulative to the past', in order to answer specific questions and construct new inferences (Ascher 1961).

During the post-processual period in archaeological theory, experimental archaeology lost favour but this is now returning with greater interest in the individual, the society and context, but in particular with the realisation of the power of choices made during the operational sequences (Jackson 2009) and with a new fascination of hidden aspects of materials and processes.

The main goals of experimental archaeometallurgy are:

Enhancement of knowledge about ancient metallurgy
Obtaining new data and ideas
Verifying or falsifying hypotheses

Thus, experimental archaeometallurgy can be used to test hypotheses regarding aspects of the production processes of metal. If a hypothesis is falsified by experiments, then a new hypothesis has to be formulated and tested again. If it cannot be falsified and is supported by experiments, then it may be regarded as valid and the principles behind the hypothesis can continue to be used until falsified (see also Outram 2008). In this way, activities and sequences that *might* have happened in the past with materials that were available in the past can be illuminated.

Most of the experiments fall into two of Reynolds' (1999) five classes of experiments, namely the *construct* and the *processes and function experiments*. In the former, scale constructions test a hypothetical design for a structure, e.g. a furnace, which is based upon archaeological or ethnographic evidence. The latter experiments test how results could have been obtained in the past. This involves not only examining the results of technological processes, such as slag, but also looking at the tools, such as mining tools and material available in the past.

In the final part of his paper, Ascher (1961) deals with the 'logic' of the experiment in archaeology. The patterns and materials which form the basis of archaeological experiments are produced by humans in the past. Archaeological experiments are, therefore, inherently different from experiments carried out in the natural or social sciences. However, Ascher makes an important statement when he writes that: 'he (the experimenter) is not attempting to discover how a people did achieve an effect, he is testing whether or not they could have achieved an effect in the manner indicated by the limited working' (Ascher 1961). In other words, an unsuccessful experiment shows that the method employed was not used in the past, but a successful experiment, in which the hypothesis was validated, never proves that this way was the way it was done in the past, it merely shows one possibility. However, as noted by Merkel

(1990), and earlier by Ascher (1961) and Coles (1967), experimental results can only increase confidence about the proposed construction or technology.

Technologies and objects are not only shaped by socially determined actions or human agency, but physical laws and material properties also provide a frame of reference and a direct link to the formation processes of the past. Kucera (2004) proposed that in order to obtain the best results, the experimental process should be divided into a soft and a hard experiment. During the soft experiment, the experimenter gets to know the material, builds up expertise and experience, formulates and clarifies questions and defines what is possible to be found out in the first place (Kucera 2004, p. 12). Once the problem is clear and the methodology has become repeatable, a hard experiment can be carried out, through which theories regarding the production technology or function of an object can be tested (Kucera 2004, p. 12). On the one hand, it is absolutely vital to have enough experience and skill in a certain technique or technology in order to carry out meaningful experiments and, on the other hand, it is important to experience the techniques, materials and learning processes with one's own senses in order to understand a process in its entirety. The importance of the 'experience' gained in the soft experiments is fundamental in experimental archaeology. This subjective process can also lead to many new questions and avenues of research. One should always be careful, though, to distinguish between feelings of archaic nostalgia and sensory perceptions which can accurately inform on aspects of the past. The desire for experimental archaeology to be taken more seriously has led to strict proposed divisions within the discipline by influential practitioners, such as Peter Reynolds who stated that 'Living in the past', 'dressing in period costume', 're-enactment of past events' and teaching or carrying out primitive techniques have 'absolutely nothing to do' with experimental archaeology (Reynolds 1999, p. 156). Experience 'is a completely different issue' and there is 'a great gulf between the experimental and the experiential' (Reynolds 1999, pp. 156–157).

There are some generalisations in these statements which are not helpful. 'Living in the past', 'dressing in period costume' and 're-enactment of past events' all have the potential to contribute to a better understanding of the past, when they are carried out with specific questions in mind. To dismiss them entirely would be counterproductive, as would be the rejection of craft specialists whose main activity could be described as experiential. All these activities are part of the term experimental archaeology, but whether they are true scientific experiments is a different matter. As long as an activity is trying to answer a specific question, and the results are related back to the archaeological record, they are part of the experimental process, even if they cannot be described as an experiment (Cunningham et al. 2008a; Outram 2008; Lammers-Keijsers 2005). The boundaries between the different types of experimental archaeology are often fluid, and although there is 'always an element of experience in an experiment', there is 'not always an experiment in an experience' (Cunningham et al. 2008b, p. vi). The important issue is to be honest when writing up reports and papers, and only call an activity an experiment if it really was an experiment in the scientific sense of the word. Purely experiential activities should be written up as such and one of the most important issues in both experiments and experiential

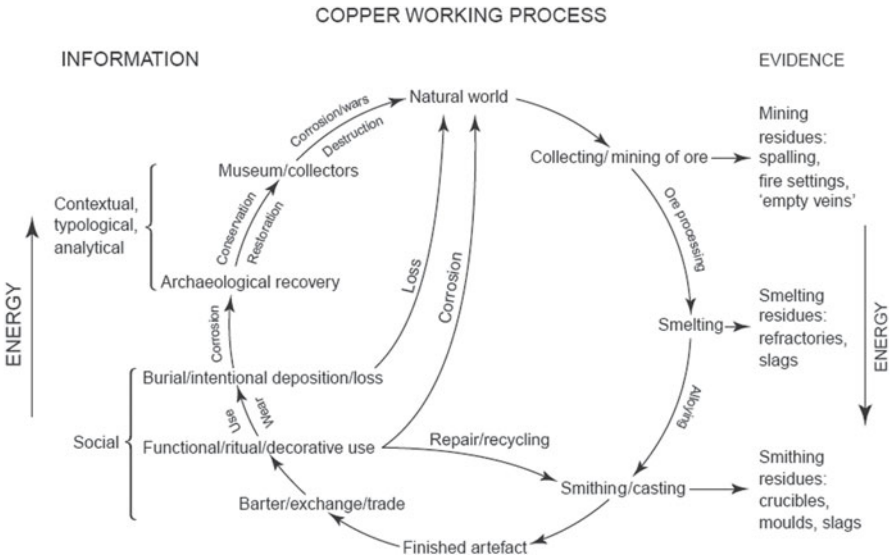


Fig. 8.1 The copper working processes from the mining of the metal to deposition in museums by the archaeologist. (After Ottaway 1994, Fig. 1)

activities is honesty and self-critique. Kelterborn summarises some key principles for experimental research in archaeology, which are precise and helpful (Kelterborn 2005), as are Outram's (Outram 2005) guidelines on publishing experimental work in archaeology.

In this paper, experimental projects investigating the various stages in the chain of production of metal artefacts will be discussed, using the cycle of the copper working process (Fig. 8.1) as a framework. Thus, experiments involving the mining, beneficiation and smelting of the ores and the alloying of the metal to producing the finished artefact by hammering and/or casting and using the finished product, will be discussed. Each section will start by looking at the archaeological evidence and will subsequently give examples of experimental work that has been carried out. The material presented here will deal primarily, but not exclusively, with the metallurgy of copper as this reflects the experiences of the authors.

Prehistoric Mining: The Archaeological Evidence

In Timna, Israel, excavated by Rothenberg (1990), empty ore veins (Fig. 8.2) have been excavated, indicating that prehistoric miners followed the ore vein underground, often to considerable length. Empty ore veins have also been excavated at the Bronze Age mine at the Great Orme in Wales, UK, which has been studied in great detail by E. Wager and dates to the second millennium cal BC (Wager 2009). At the Great Orme the underground shafts and galleries, which have been explored and surveyed, extend now to a total length of over 6,500 m and are still being excavated (Fig. 8.3.).

Fig. 8.2 Empty ore veins left behind after the removal of the copper ore at Timna, Israel. (Author's (BSO) photograph)

The traces of working in prehistoric mines often give a clear indication what methods of mining have been used. For instance, at Timna in Israel, clear mining traces have been excavated (Fig. 8.4). The upper half of the picture shows rounded indentations, indicative of the use of stone hammers, whereas the lower part shows sharp linear ones, suggesting that a metal-tipped tool had been used. In many prehistoric mines, stone hammers of various shapes occur in great numbers. Some of them have been carefully pecked, whereas others were completely unmodified, most of them show use wear (Ottaway 2003, Fig. 1). However, in mines where the ore-bearing rock was softer, as at the Great Orme, bone tools have been used.

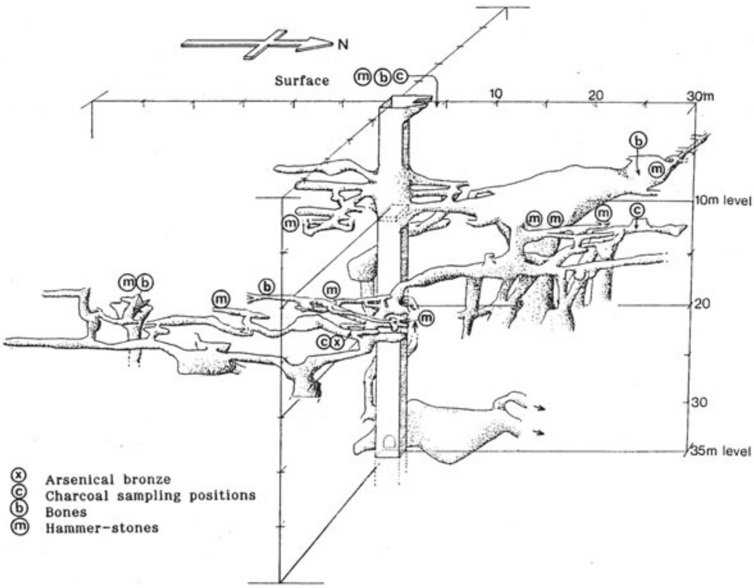


Fig. 8.3 Copper ore mining at the Great Orme, Wales. (Lewis 1990, Fig. 3)

Fig. 8.4 Tool marks left behind by prehistoric miners at Timna, Israel. The *upper* rounded marks indicate the use of stone hammers; the marks were at the bottom made by picks with metal tips. (Author's (BSO) photograph)

Fig. 8.5 Reconstruction of hafting of stone hammer by B. Craddock. (Author's (BSO) photograph)

Experiments with Mining Tools and Fire Setting

Experimental hafting and using of stone mining hammers have been conducted, for instance, by Brenda Craddock (1990). She used material available in the British Isles during the Bronze Age, such as withies of willow, hazel, raw hide and strings of hemp and the method of hafting similar to that of the 'Copper Man' found at Chuquicamata in northern Chile (Craddock et al. 2003). The hammers (Fig. 8.5) were used for 2

Fig. 8.6 Ore-crushing stone from the Mitterberg, Austria. (Photograph courtesy of G. Goldenberg)

hours, both for battering the ore-bearing rock face and in conjunction with antler picks and wedges. Frequent repairs were necessary and these must have been done on site, requiring a team of helpers and a toolkit of replacement materials. Experiments with a different hafting method for stone hammers, using the natural angle of wood where a branch leaves the stem of the tree, were found to be more suitable for the stone hammers of the alpine area (Rieser and Schrattenthaler 2004).

Experiments using fire setting to loosen the ore-bearing rock showed that the heat penetrated furthest into the rock face towards the top and immediately above the fire, as this was the area where most of the rock could be removed through spalling, leaving a concave irregular rock face (Timberlake 1990; Lewis 1990; Crew 1990). Similar patterns can be seen in the Bronze Age mines of the Great Orme (Lewis 1990, p. 55). At Bronze Age sites in Austria, the shape of the mine shafts as well as charcoal fragments excavated in the layers of sediments below the exploited area are indicative of fire setting techniques (Goldenberg and Rieser 2004).

The Archaeological Evidence for Beneficiation

Beneficiation consists of crushing, sorting and enriching the ore. The archaeological evidence is more ephemeral and often overlooked. Ore-crushing stones can be found, for instance, in Ireland, at Ross Island (O'Brien 2004), in France, at Cabrieres (Ambert et al. 2009, Fig. 3) as well as at the Mitterberg, Austria (Fig. 8.6).

Another form of beneficiation involves separation of the heavier, crushed ore from its lighter gangue by the use of water. Evidence for this method of beneficiation, in the form of very fine sediment containing small remains of crushed ore, coloured bones and small pieces of charcoal, was excavated at Ffynnon Rufeinig, on the Great Orme, ca 1 km away from the Bronze Age mine, near a small spring. It was ^{14}C dated to 1880–1680 cal BC and is thus contemporary to the mining activities at the Great Orme mine (Wager 1997).

Fig. 8.7 Ore crusher as depicted on the Annaberg Bergaltar (painted by H. Hesse in 1521). (Author's (BSO) photograph)

The longevity of these methods of beneficiation can be illustrated by reference to medieval paintings, such as the 'Annaberger Bergaltar' painted by Hans Hesse in 1521 and literature such as Agricolas 'De Re Metallica' of 1556. In the former the ore is crushed by an 'Ausschlaeger' (ore crusher) (Fig. 8.7) and beneficiated further by a woman. Agricola illustrates a series of wooden structures separating the heavier ore from the gangue using the water of a stream.

Beneficiating Experiments

There is just one published experiment studying the effects of ore processing, or beneficiation (Doonan 1994). Yet, beneficiation is known to have a great impact on fuel consumption during the smelt and on the composition of the resulting metal. The tedium of the work was overcome by social interaction, i.e. chatting and exchanging news amongst the workers. This has also been observed ethnographically. Craddock (2001) based his 'slag-less smelting' on using extremely pure copper ore, which can only be achieved by careful beneficiation.

Fig. 8.8 Simple bowl furnace, Timna, Israel (diameter c. 35 cm). (Author's (BSO) photograph)

Fig. 8.9 Excavation of a double furnace at the Jochberg, Austria. (Photograph by courtesy of G. Goldenberg)

The Archaeological Evidence for Prehistoric Smelting of Copper

Prehistoric smelting installations have been excavated in many shapes and sizes. There are crucibles and simple smelting basins as found at La Capitelle du Broum in France (Ambert et al. 2009, Fig. 6); bowl furnaces, consisting of little more than scooped out soil surrounded by large blocks of stone, as found at Timna, Israel (Fig. 8.8); furnaces of similar shape but repeatedly clay lined after each use, as found in Faynan, Jordan (Hauptmann 2007) and double furnaces of the Bronze Age

Fig. 8.10 Stone enclosure of roasting bed at the Jochberg in Austria. (Photograph courtesy of G. Goldenberg)

Fig. 8.11 Unexcavated iron smelting furnace, Nigeria. (Author's (BSO) photograph)

in Austria as excavated on the Mitterberg (Fig. 8.9). At many sites however, there are no formal furnace structures present or they have not been recognised. The many slag finds from settlement contexts at Belovode. Serbia for instance, clearly show that copper was smelted at the site. It is also the so far earliest evidence for smelting in the Old World (Radivojević 2012; Radivojević et. al. 2010).

Roasting beds, where the copper ore was dried prior to smelting and—it has been hypothesised—were used to drive off sulphur from sulphide copper ores, have been excavated in Austria, e.g. at the Jochberg (Fig. 8.10). It has been shown by experimental co-smelting of oxidic and sulphidic copper ores by Rostoker et al. (1989); Rostoker and Dvorak (1991) and Bougarit et al. (2003) that sulphidic copper ores also can be smelted without prior roasting.

For prehistoric iron smelting, there are splendid examples in Nigeria— circular furnaces, whose walls, on excavation, still stood up to 30 cm tall (Okafor 1998) (Fig. 8.11).

Then, there are the various methods of supplying air to the furnace, such as clay nozzles to protect the ends of blowpipes from burning away (Fig. 8.12) and tuyeres of various forms which were attached to bellows.

Perhaps the most ubiquitous archaeological remains of prehistoric smelting activities are slag. Since the early copper smelting processes did not completely separate the gangue from the copper metal, metal prills were caught within the slag. This

Fig. 8.12 Clay nozzles which were attached to the ends of blowpipes

Fig. 8.13 Bronze Age furnaces at Faynan, Jordan, surrounded by crushed slag. (Author's (BSO) photograph)

meant that the slag had to be crushed to extract the metal. Thus, many early smelting installations can easily be recognised by the scatter of broken up slag surrounding it (Fig. 8.13). Slag is rather indestructible and can thus be found in many structures in the vicinity of smelting sites. Slag can also be imbued with great ritual importance as at a Nigerian site where the King of Leija sits in court, surrounded by his elders, about to pronounce judgement on a woman who was accused of adultery (Fig. 8.14).

In Austria and South Tyrol, impressive Bronze Age installations near smelting and mining sites used water for the separation of metal and crushed slag leaving behind substantial layers of 'Schlackensand', rounded slag particles of a few millimetres diameter (Goldenberg and Rieser 2004; Cierny 2004).

As with the process of beneficiation, there is evidence that smelting installations have not changed much in some regions over a long period of time. The sixteenth-century painting found on the reverse of the Annaberger Bergaltar shows a double

Fig. 8.14 The King of Leija, Nigeria and his court—all sitting on blocks of iron slag. (Author's (BSO) photograph)

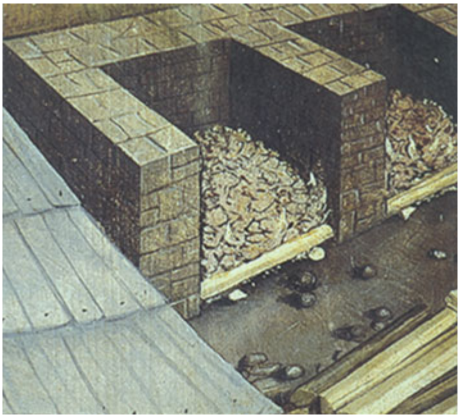


Fig. 8.15 The double furnace depicted on the reverse of the Annaberger Bergaltar. (Author's (BSO) photograph)

furnace (Fig. 8.15) very similar to that excavated at the Mitterberg, Austria belonging to the second millennium BC.

Some Examples of Copper Smelting Experiments

One of the early uses of experimental archaeology in archaeometallurgy was carried out at the famous excavation of the Bronze Age copper smelting sites at Timna, southern Israel. Starting in the 1970s, a programme of experimentation was initiated first by Tylecote et al. (1977), and later by John Merkel to look at different smelting techniques in furnaces and crucibles, as well as melting and working methods (Merkel 1990). The results of these studies greatly advanced our understanding of the process of early copper smelting, both in the Levant and across the globe. The findings demonstrate that the ancient copper smelters were aware of the subtle difference in the quality of the copper, and were able to control the variables affecting these differences.

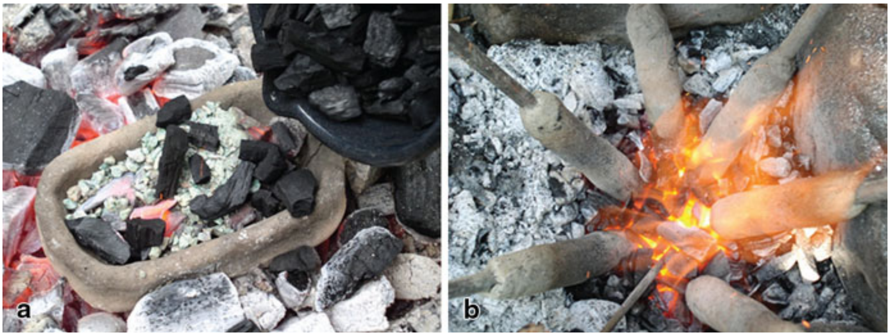


Fig. 8.16 Smelting experiment using crucible charged with ore and charcoal (**a**), and smelting experiment with blow pipes (**b**). (Photograph courtesy of Erica Hanning)

Numerous smelting experiments, often based on ethnographic studies of smelting furnaces, have been conducted, as they are very dramatic and can be great fun as well as hard labour. Alas, only few of them have been published with the necessary detail which is important to avoid repetition and to allow valid conclusions to be drawn from them. Some of these experiments were carried out in museums and for teaching purposes. Others find the sheer number of variables impossible to record. These variables include: the records of the material and type of furnace used; the time and temperature of preheating of the furnace; the precise measurements of the size and capacity of the furnace; the type, size and amount of fuel used; the type and measurement of air flow during the smelt; the accurate measurements of temperatures and placement of the thermocouples; and the exact description of type and quantity of slag and metal produced and the subsequent analyses of these products. This is a daunting list of variables which require a great amount of time, facilities and finances.

To explain the lack of specialised furnace structures in Bronze Age Britain, for example, Simon Timberlake has shown that it is possible to smelt oxide as well as sulphide copper ores in little more than a clay lined pit—leaving no permanent trace and no slag (Timberlake 2007, p. 34). Other experiments have also shown that it is possible to smelt primary copper ores in oxidising conditions, without a formal furnace structure being necessary (Craddock 1990, p. 70; Lorscheider et al. 2003, p. 306). These experiments also confirm the findings from Belovode. Serbia as no formal furnace structures have yet been found.

Another archaeologically often invisible process is the creation of the air supply necessary for smelting furnaces. It is often assumed that bellows must have been necessary, but a number of experiments have shown that other possibilities work as well, e.g. using only blowpipes with clay tips. We can therefore see that the type of smelting experiment carried out should always depend on the archaeological evidence. The great diversity in experiments only reflects the diversity in the archaeological record.

Smelting experiments have been conducted using blowpipes and the layout of excavated working areas, furnaces and mortars used for crushing the slag in Peru. In this way Merkel and Shimada (1988) were able to produce slag and metallic copper comparable to the archaeological finds. Blowpipes have also been successfully used for smelting by a team in Zambujal, Portugal (Fig. 8.16, Hanning 2000).

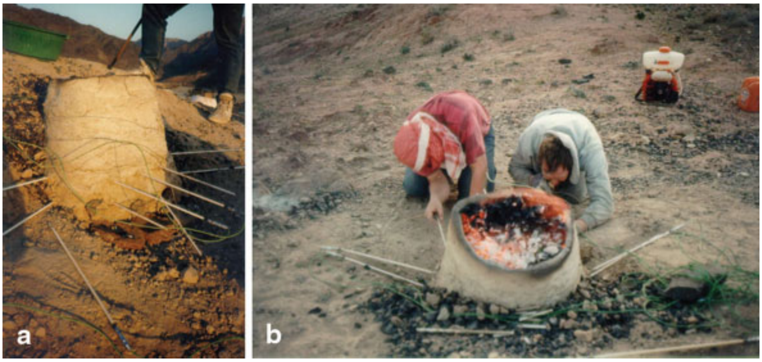


Fig. 8.17 Experimental reconstruction of the wind-powered furnaces at Faynan, seen from *below* (**a**), and from *above* (**b**). (Photograph courtesy of A. Hauptmann)

Fig. 8.18 Smelting experiment conducted by Erica Hanning in 2010 at the Mitterberg, Austria. (Photograph courtesy of Erica Hanning)

An experiment using the location of the series of separate furnaces excavated along a range of hills in Faynan in Jordan (see Fig. 8.17; Hauptmann 2007) used the strong natural wind blowing with predictable regularity to successfully smelt copper. It was observed that the temperature inside the furnace reached 1,200 °C within half an hour and was kept for several hours without any problems. Yet, another example of air supply in the process of copper smelting was tried on Crete, where large pieces of ceramics had been found with numerous circular holes. Their position right on the edge of a cliff was telling. The experiments carried out with some reconstructed furnaces showed that the wind coming through the holes helped to drive up the temperature, and, contrary to expectations, the oxidising environment was not a problem for reducing the ore to metallic copper (Betancourt 2005).

Well-documented smelting experiments were conducted by Erica Hanning during her recent PhD research, using the dimensions and layout of furnaces excavated in the Mitterberg region of Austria (Fig. 8.18)

Fig. 8.19 Wind-powered linear furnace of the seventh to eleventh century AD, excavated in Sri Lanka by Gill Juleff (1996)

An Iron Smelting Experiment

In terms of early iron smelting, the shaft furnace using forced draught supplied through bellows is often seen as the most efficient model, with furnaces using natural draught seen as less effective. A new furnace type excavated at the seventh to eleventh-century AD iron smelting site of Samanalawewa in Sri Lanka, by Gill Juleff in 1996, turned these ideas on their head (Fig. 8.19). The iron smelting furnaces were situated on the west sloping hill, and built with their rounded back walls into the slope. Several tuyeres were placed along the entire length of the furnaces at the bottom of the front walls. An experiment was set up to study the interaction between the furnaces and wind, and to test the hypothesis that the potential temperature could be reached and sustained. The furnace was an exact reconstruction of the archaeological furnaces (Fig. 8.20a). The front wall contained a line of tuyeres, which had a wider opening pointed towards the outside and a narrower opening pointing inside the furnace. The experiment showed that the furnace made best use of the monsoon winds and proved that it worked well using wind power only. Computational fluid dynamics (CFD) was applied to analyse the flow patterns around the furnace and the theoretical model could be verified. (Fig. 8.20b; Tabor et al. 2005)

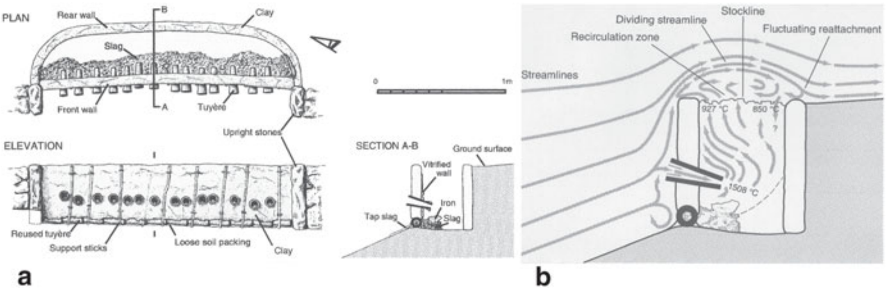


Fig. 8.20 **a** Experimental smelt in the reconstructed iron furnace in Sri Lanka. **b** Computational fluid dynamics analysing the flow patterns in and around the Sri Lankan experimental furnace. (Tabor et al. 2005)

Furthermore, the experiments showed that it was possible to not only produce the low-carbon iron blooms usually produced in shaft furnaces, but also produce high-carbon steel, probably setting the foundation for Asia's eminence in early steel production.

Alloying

The earliest alloy of copper in Europe was arsenical copper, later followed by tin bronzes. The archaeological evidence can only be demonstrated by examining the analyses of the metal. Looking at Fig. 8.21, one can suggest that one of the reasons for alloying could be a purely technical one, i.e. improved properties. For instance, the hardness of pure copper cannot be increased by working as much as by working alloyed copper. Further points in favour of alloyed copper are the lower melting point of alloys compared to pure copper and lowering of porosity with increased alloying elements (Fig. 8.22).

However, other social factors, such as the location of the source of the copper could have been deemed important. In such a way local, possibly copper sulphide ore might have been chosen, which would lead to copper-containing impurities, such as arsenic, antimony, silver, nickel, bismuth, iron and/or others, all contributing to the properties of the resulting metal. Alternatively, the colour of the metal might have been a decisive point in the choice of the metal.

The exact technology used to produce arsenic bronze is still debated. Experimental archaeometallurgy is able to shed some light on the possible processes involved. As early as 1964, Pazuchin (1964) demonstrated in Russia that it is possible to produce arsenic bronze by co-smelting oxide ores with sulphide ores containing arsenic. Looking into the production of copper–arsenic alloys in Peru, Lechtman (1999) carried out a series of experiments co-smelting both oxide and sulphide ores. The furnaces used for the experiments were based on archaeological examples from Batán Grande, Peru (see Lechtman, this volume). The resulting products clearly indicate that the prehistoric alloys could have been obtained fairly easily, deliberately or accidently, by a one-stage co-smelting process.

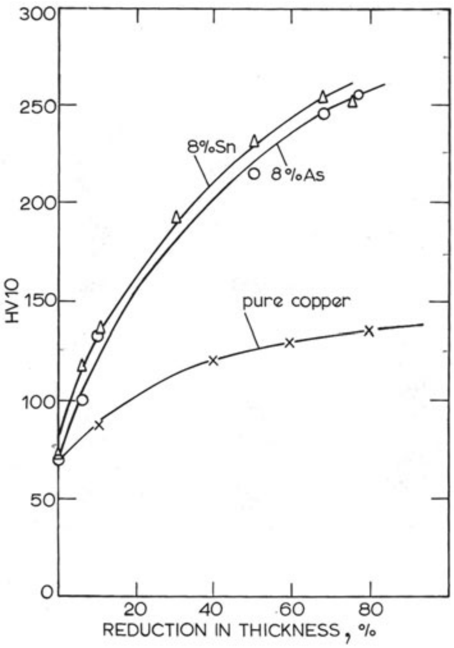


Fig. 8.21 The composition and work hardening of copper and some copper-base alloys. (After Tylecote 1976)

Fig. 8.22 Sections of the arsenical copper containing 0, 4 and 12 % As, showing an inverse relationship between arsenic content and porosity. (Author's (BSO) photograph)

For producing tin bronzes, four different methods have been suggested (see also Rovira et al. 2009):

- Melting a mixture of metallic tin and metallic copper
- Adding naturally occuring tin oxide, cassiterite, to already molten copper
- Smelting ore naturally containing both tin and copper
- Smelting copper ore together with cassiterite

In order to obtain metallic tin, the ore has to be smelted. Based on materials from a potential tin smelting site in Turkey, experiments were successful in smelting powdered cassiterite in crucibles mixed with charcoal by Yener (Yener et al. 2003). The samples which were rich in tin from the site Göltepe had undergone a concentration process after having been brought to the site from the nearby mines of Kestel. The concentrated samples were readily smelted using prehistoric materials, including blowpipes. The metallic tin obtained was suitable for alloying with copper (Earl and Özbal 1996). One of the main problems in tin smelting is that the metallic tin collects in the slag, if no fluxing agent is added. Experimental work based on the chemical compositions of tin slag from Cornwall has shown that early tin smelters did not add lime in order to displace the tin from the slag. Instead it was accepted that the metallic tin would be recovered in the form of prills by crushing the slag (Earl 1994).

Making the Artefact: The Archaeological and Experimental Evidence

Many of the simple artefacts were probably made by melting the metal in a crucible, pouring the molten metal into an open mould, or into an open pit into which the positive form of the artefact had been pressed and obtaining the final shape by hammering (Fasnacht 2009). The latter method would not leave any trace in the archaeological record. The archaeological evidence for making artefacts of copper consists of open moulds of stone and clay, closed, or bivalve moulds of stone and occasionally of bronze, such as those found in the Bronze Age Roseberry Topping hoard, England (Swiss and Ottaway, in press). Fragments of closed clay moulds have occasionally been excavated, but unless fired prior to use, they usually do not survive more than a couple of years in the ground (Ottaway 2003). Similarly, the lost-wax method of casting would leave very little in the archaeological record.

The earliest copper objects were hammered into shape, although the copper used was probably native copper, there was thus no need for smelting. Once copper was smelted, it is quite likely that objects were cast, as the technology to achieve sufficiently high temperatures had been developed. Copper and bronze can be molten and cast into their final shape. There are two main ways to melt copper and bronze. Both techniques can be achieved in simple bowl furnaces, and there is evidence that both have been used in prehistory. The difference between the two techniques lies in the air supply. The air can be supplied from the top, meaning the crucible sits underneath the opening of the tuyere, covered in charcoal (see Fig. 8.16b) The other possibility is that the air supply comes from the bottom or side of the crucible. Experimental work carried out by Jantzen (1993) was able to demonstrate that crucibles found

Fig. 8.23 Wooden models for a shafthole adze axe and a flat axe. The latter is a copy of the Iceman's axe, provided by Prof. Schindler. (Author's (BSO) photograph)

across continental Europe were used in a melting process where the air flow and thus the heat comes from the top, as the archaeological examples of crucibles often show a glazed rim (Jantzen 1993). The experimental crucibles used showed exactly the same vitrification patterns.

Most casting experiments, however, are concerned with the moulds and the mould material. Archaeologically, the number of copper or bronze objects stands in stark contrast with the comparatively low number of moulds. Especially during the first centuries of metal use this discrepancy is exceptionally evident. For some early cast objects, like the copper hammer axes and axe adzes from southeastern Europe, not a single mould has been recovered in Europe, although some have now been found in Asia Minor (Boroffka 2009). During the Bronze Age, there are moulds made from stone, clay and even bronze, but again their number is small compared to the large numbers of objects.

The lack of moulds in the archaeological record can only be explained through the use of an archaeological invisible mould material. One viable theory that has been put forward is the use of sand as mould material and a wooden model (Fig. 8.23).

A few experiments have been carried out looking into this possibility (Ottaway 2003; Eccleston and Ottaway 2002; Fasnacht 1995; Ottaway and Seibel 1998). It has been demonstrated by several experimenters that it is possible to cast bronze objects in a two-piece or bivalve sand mould. The main problem with casting in sand is that the sand must have the right properties. This can be achieved through adding horse or cow dung, animal fats or plant oil, such as flax oil (Fasnacht 2009) and be confined in a box so that the moist sand will keep its form well after the pattern is taken out. In such a way, the shafthole adze axe in Fig. 8.24 was cast in a bivalve mould of sand mixed with clay, using a core to create the shafthole. Intense labour was required to finish the object, removing the casting seams and polishing the metal with sand and wool.

There are still many questions regarding the production of the copper hammer-axes and axe-adzes from south-eastern Europe. The lack of mould finds seems to confirm the use of sand or unfired clay moulds, the exact shape of these moulds however is not so certain. The variety within the axes suggests that there were many different techniques and mould shapes in use. Experiments have shown that the shafthole of axes of the types Tg. Ocna-Nógrádmarcal and Szendrö was not cast with a core in place, but punched through the still hot metal after casting (Heeb in

Fig. 8.24 A shafthole adze-axe cast and finished by students at the University of Sheffield. (Author's (BSO) photograph)

Fig. 8.25 A copy of the bronze bivalve mould from the Roseberry Topping Hoard was experimentally produced and used to cast a socketed axe. (Swiss and Ottaway, in press)

prep., Heeb 2009). This wold imply that an open sand mould must have been used as it would otherwise be impossible to punch through the entire shafthole creating the characteristic 'lip' at the bottom of the axes (Fig. 8.24b). Other casting experiments carried out in the foundry of the University of Sheffield included copying the bivalve bronze mould from the Roseberry Topping Hoard and casting a socketed axe in this mould (Fig. 8.25). As in prehistory, experimental casting is not without failures (Fig. 8.26).

A comprehensive experimental project was carried out looking at the effects on the microstructure of the metal of (a) the mould material, (b) the composition of the metal and, in particular, (c) the post-casting processing methods, such as cold

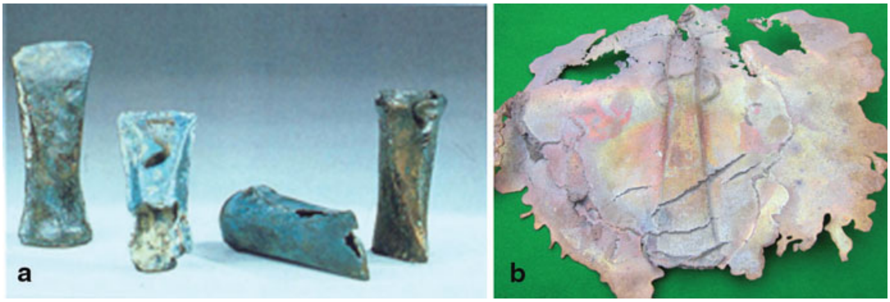


Fig. 8.26 Prehistoric miscasts (**a**), and modern experimental failures (**b**). (Author's (BSO) photograph)

Fig. 8.27 Bronze moulds used in casting experiments started to crack after the ninth casting. (Wang and Ottaway 2004, Figs. 5 and 13)

working or hot working. The aims were to study the mechanical properties and the behaviour of some copper alloys cast in differing mould materials and the creation of a reference collection of the microstructures of archaeologically relevant bronzes cast in mould material likely to have been used in prehistory (Wang and Ottaway 2005). This is vital to understand the ancient production processes of cast bronze artefacts. In these experiments, a flat axe was cast into moulds made from sand, clay and bronze. Other variables included the preheating regimes of the moulds, the cooling regimes of the cast flat axes and alloy composition of the metal.

It was found that bronze artefacts cast in clay moulds always had flashing but a finer surface than those cast in sand moulds. Thus, while less effort was needed to finish the surface of the artefact, more had to be spent taking off the flashing to finish the object. Bronze objects cast in clay and sand moulds and water quenched after casting had higher micro-hardness values than those left to cool at room temperature. Bronze moulds, even after preheating prior to casting, could, contrary to previous assumptions, be used only nine times before they started to crack (Fig. 8.27). The metal would most probably have been reused and thus also leave very few archaeological remains. However, the bronzes cast in these moulds had almost no flashing and very smooth surfaces. Thus in terms of finishing the artefact, they would be superior to casts made in sand or clay moulds.

Furthermore, the results show that the cooling down happens fastest in the bronze moulds, whereas the clay moulds are the slowest to cool down. The speed of cooling does have an effect on the microstructure, as the dendritic arm spacing in the objects

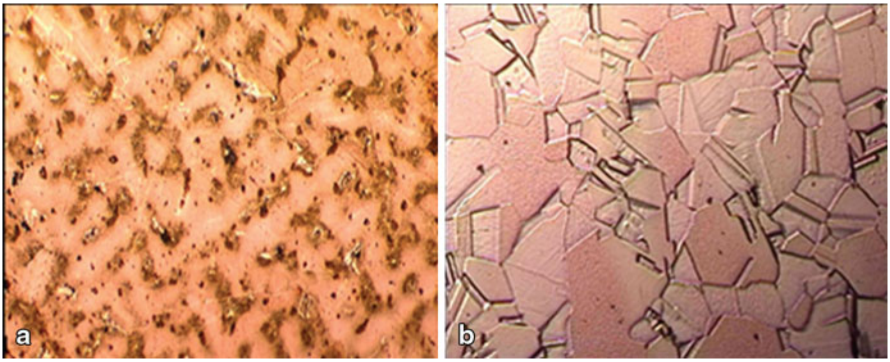


Fig. 8.28 **a** Photomicrograph of a cast 6 % Sn bronze showing dendritic microstructure (Wang and Ottaway 2004, Fig. 3.12). **b** A 6 % Sn bronze cold worked and annealed showing a fully recrystallised structure and annealing twins. (Wang and Ottaway 2004, Fig. 7.5b)

cast in the bronze moulds is much smaller than that seen in the objects cast in the sand and clay moulds.

These results were also corroborated experiments carried out by Jochum-Zimmermann (Jochum Zimmermann et al. 2002).

With the help of the microstructure, the cycle of production can be determined (Fig. 8.28a and b) as has been shown for the Copper Age Jaszladany axes (Kienlin's Horizon 1), which were cast and then left in the soft annealed state. In comparison, the slightly later Altheim and Vinca-type flat axes (Kienlin's Horizon 2) were cast, cold worked, annealed and then cold worked again. They were thus much harder than the Horizon 1 axes (Kienlin 2008; Kienlin this volume).

The last casting method to consider is the 'cire perdue' or 'lost wax' method. As an example we will look at the experimental casting of copper bells from Pre-Columbian Mexico (see Hosler this volume). Long (1964) used a historical ethnographic source on gold casting to fill the gaps in the knowledge on how these intricate bells were cast. In order to try if the gold casting technique would work for casting copper, Long (1964) followed the ethnographic description for casting gold using the lost wax method. A wax pattern was fashioned around a clay core containing a small stone. The finished wax pattern was then covered in a clay and charcoal mixture, and pieces of straw were inserted to allow for the gases to escape during the casting procedure. The crucible was directly attached to the stem of the mould, making a one-piece crucible and mould combination. The mould and crucible combination was then placed inside a furnace, with the mould part sitting at the bottom. Due to the low melting point of wax, it would melt quickly, leaving the mould cavity empty to be filled by the copper. After the cooling down, the mould was broken and the cast bell taken out. The clay core was broken up using an awl. The successful casting of copper bells using a sixteenth-century technique for casting gold showed that this method might have been used to make the Pre-Columbian copper bells.

The Forging of Iron

Whereas copper and bronze were and still are mainly cast, early iron objects were always forged. In Europe the first evidence for cast iron is found in medieval times. In China, on the other hand, cast iron was probably first produced between 200 BC and AD 200. In Europe, the smelting of iron remains a popular topic for experimenters, whereas later production stages, like the refining of the bloom and the forging of objects have hardly been explored experimentally. Some interesting experimental work was carried out at the Historical-Archaeological Experimental Centre, Lejre (Denmark) (Lyngstrøm 1997). All the steps after the initial smelt up to the finished object were carried out and the waste products were recorded where they fell in relation to the anvil and what they looked like. The waste collected from the refining of the ore was coarse, porous, and only partly magnetic. The waste products from the forging of a knife were much finer, compact and magnetic, and were concentrated around the anvil. The results show that such experiments are extremely valuable in order to interpret forging activities on archaeological sites.

An experiment looking at a different aspect of the forging process was carried out at the University of Exeter. There seems to be a puzzling lack of iron forging tools and anvils in the horizons of the first iron objects in Europe. In order to investigate this fact, an experiment was set up using hammer stones to forge simple iron rods on a wooden anvil. Hammer stones are found frequently, but are often thought to be only used for working stone or in mining activities. The aim of the experiment was the creation of a reference collection of specific use wear on the hammer stones, which can be compared to archaeological examples. The use wear achieved was indeed very distinctive and the results can be used in the future to compare to archaeological examples (Schroeder 2006).

Experiments in Use Wear Analysis

There have been numerous studies in use wear on flint implements but none had been carried out on metal finds. Yet, a great deal of information could be gleaned on a metal object's life cycle. For this reason, a pilot study was carried out, which examined the behaviour of a copper and a bronze axe on cutting tree trunks and stripping off bark (Fig. 8.29, Kienlin and Ottaway 1998). It was observed that, contrary to common belief, a copper axe was a perfectly good tool if used less than 30 min. After 30 min, however, the cutting edge was bent and in urgent need of resharpening (Fig. 8.30a). However, as the copper axe of Ötzi the Iceman has shown, his axe was used for a variety of purposes, such as stripping bark, cutting small branches, working some leather and stirring his porridge. None of these activities led to a deformation on the scale seen in Fig. 8.30a. We must assume that he would have resharpened his axe before it had reached such a state. Repeated resharpening leads to an asymmetric cutting edge, such as seen on the Ötzi axe. However, when looking at the cutting edge of a 6 % tin-bronze axe following the same experimental routine for 320 min (Fig. 8.30b), the advantages of a bronze over a copper axe become clear. Although

Fig. 8.29 A pilot study on experimental use wear: cutting tree trunks and stripping bark. (Author's (BSO) photograph)

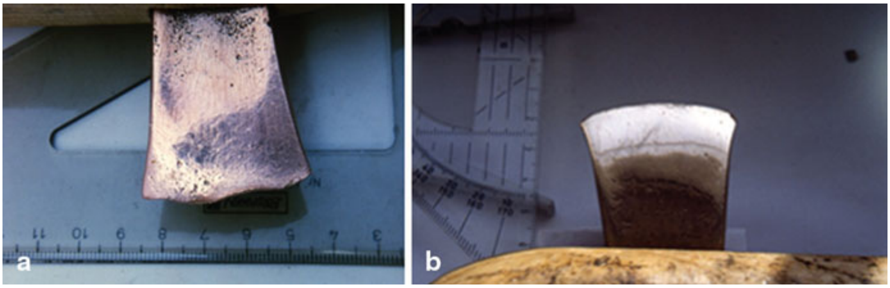


Fig. 8.30 **a** An experimentally cast copper axe after 30 min use. **b** An experimentally cast 6 % tin-bronze axe after 320 min use. (Author's (BSO) photographs)

striations and nicks (Fig. 8.31a) are visible on the experimental bronze axes' cutting edge under low magnification, its cutting edge is still fully functional after 320 min!

It is very encouraging that similar striations and nicks can be found on some of the prehistoric axes, where micro-wear studies have been carried out (Figs. 8.31b and c). There is a clear potential for further studies of this kind.

Comparing the wear traces of the archaeological axes found in different contexts, it is interesting to note that the axes found in graves and hoards do show considerable wear traces that are similar in character to the experimental axes. Interestingly, four axes recovered from river contexts had few or no traces of wear (Kienlin and Ottaway 1998). A use-wear study on socketed axes from Great Britain came to similar conclusions (Roberts and Ottaway 2003). The majority of the deposited axes showed considerable traces of wear indicative of having been used as multipurpose tools and/or weapons. These experiments clearly show how important and valuable it is to put the experimental results into the archaeological context.

Summary

Overall, archaeometallurgical experiments have informed us on the multitude of choices open to prehistoric miners and smiths throughout the entire operational sequence. This includes the choice between open and closed knowledge transfer which

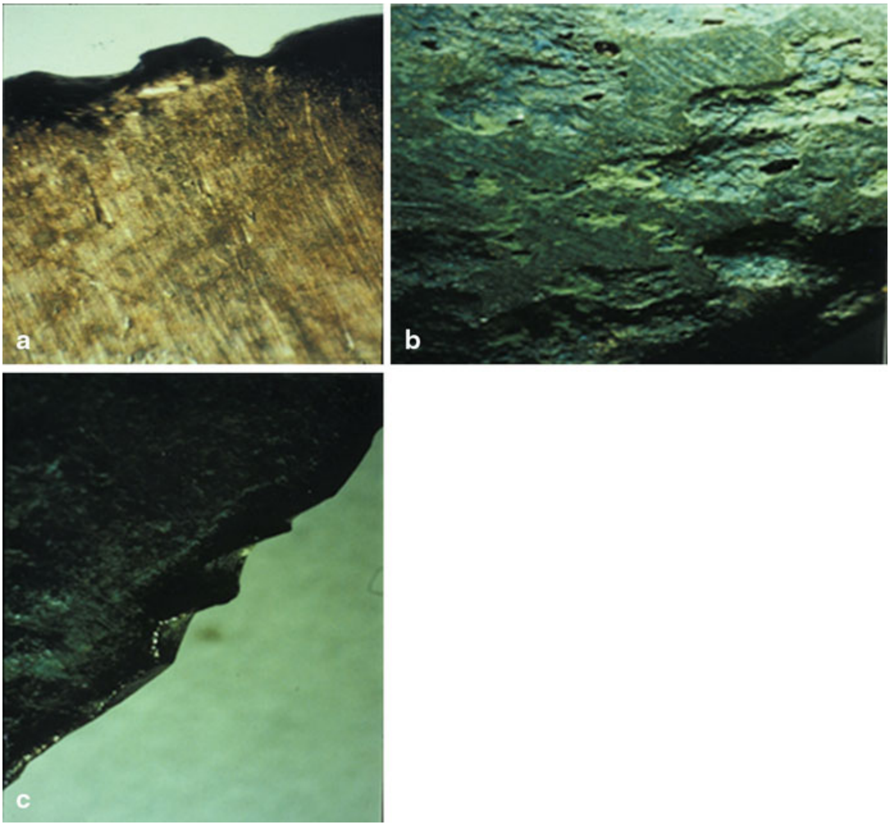


Fig. 8.31 **a** The experimental axe showing inclined parallel striations and nicks. **b** A prehistoric axe showing similar striations to experimental axe. **c** A prehistoric axe showing similar nicks to experimental axe. (Author's (BSO) photographs)

may explain some of the unevenness in the spatial and technical progression of metal working processes. The following graphics attempt to summarise the main topics of discussion in this paper, namely mining, beneficiation, smelting, alloying, production of the metal artefacts and their use wear.

The graphic summarising mining (Fig. 8.32) tries to show that almost all aspects of mining are a mixture of technical considerations and social aspects and knowledge.

The graphic summarising beneficiation (Fig. 8.33) indicates the interrelation between effort taken in hand sorting or water separation and fuel consumption, but it is also trying to give an idea that social time, i.e. time spent together while carrying out these activities can have a very important influence.

In Fig. 8.34, the overall scheme of smelting, the four squares surrounding the middle circle represent data which have been scientifically obtained. The circle in the middle contains non-quantifiable data, which is equally important to the success of this particular stage of the process.

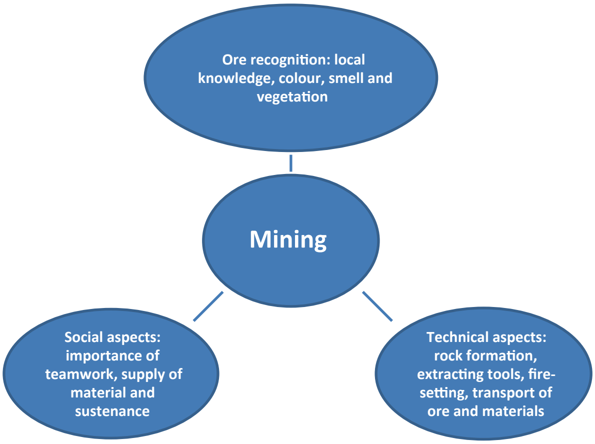


Fig. 8.32 Schematic diagram summarising mining

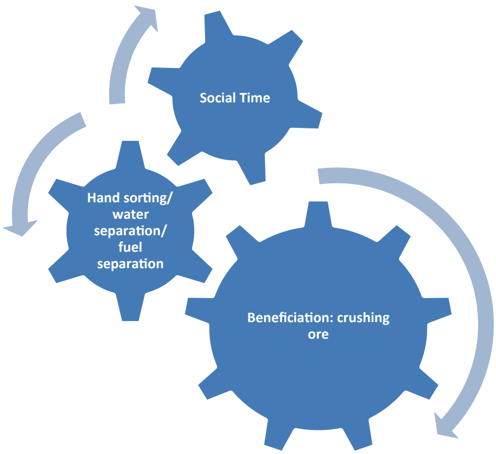


Fig. 8.33 Schematic diagram summarising beneficiation

When discussing alloying, it can be seen that there are more questions than firm answers, although of course, a great increase in our knowledge about the actual composition has been made (Fig. 8.35).

When summarising the production of metal artefacts (Fig. 8.36), again the squares indicate scientific data that have or can be obtained by analysis, whereas the middle circle contains questions which are not easily measurable. For instance, it can be noted that metal tools have been carefully polished all over, even if only a fraction of the artefact is visible.

Finally, the scheme representing use wear (Fig. 8.37) clearly shows that there are more questions than answers, as befits a branch of investigation which is in its infancy.

Experimental archaeometallurgy has been shown to be an invaluable research tool, reaching questions and topics which would otherwise remain unanswered or

Fig. 8.34 Schematic diagram summarising smelting

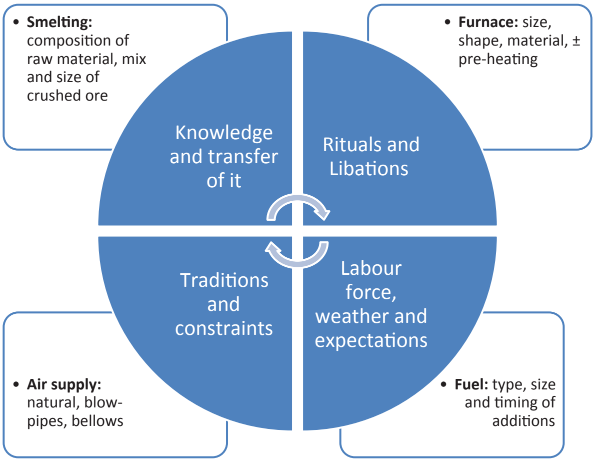


Fig. 8.35 Schematic diagram summarising the alloying choices

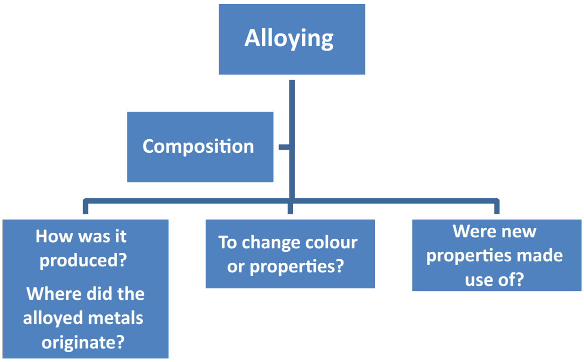
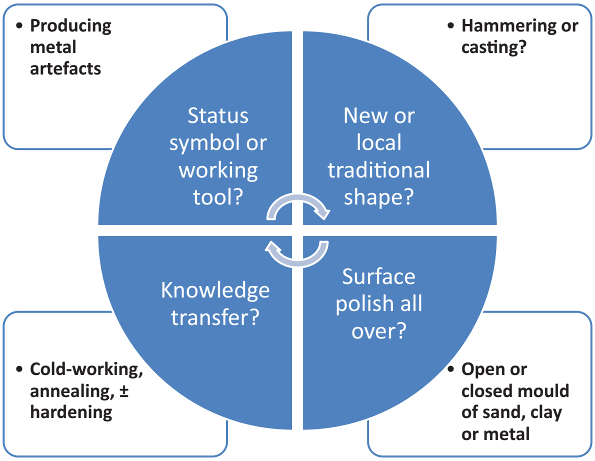


Fig. 8.36 Schematic diagram summarising the production of metal artefacts



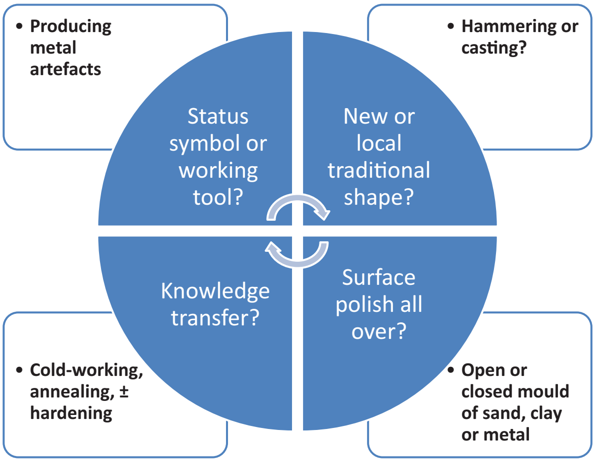


Fig. 8.37 Schematic diagram for investigating use wear

unconsidered. The great variety in experimental projects is a direct reflection of the multitude of choices and techniques used by the people in the past. The case studies used here represent only a small proportion of the vast body of experimental work carried out, which is both published and, unfortunately all too often, unpublished. The debate on what constitutes experimental archaeology is probably a reflection of the great diversity of people who are involved with experimental archaeology, which of course is a positive circumstance. Whatever activities one might consider part of experimental archaeology or indeed archaeometallurgy, the most important aspect of any project should always be the answering of specific questions in direct connection with the archaeological record.

Bibliography

Ambert, P., Figeroa-Larre, V., Guendon, J. L., Klemm, V., Laroche, M., Rovira, S., & Strahm, C. (2009). The Copper Mines of Cabrières (Hérault) in Southern France and the Chalcolithic Metallurgy. In T. L. Kienlin, & B. W. Roberts (Eds.), *Metals and societies. Studies in honour of Barbara S. Ottaway* (pp. 246–257). Bonn: Habelt.

Ascher, R. (1961). Experimental archaeology. *American Anthropologist, 63,* 793–816.

Betancourt, P. P. (2005). *The Chrysokamino Metallurgy Workshop and its territory. Hesperia Supplement 36*. Princeton: ASCSA Publications.

Bourgarit, D., Mille, B., Prange, M., Hauptmann. A., & Ambert, P. (2003). *Chalcolithic fahlore smelting at Cabrières: reconstruction of smelting processes by archaeometallurgical finds. Archaeometallurgy in Europe* (pp. 431–440). Milan: Associazione Italiana di Metallurgia

Boroffka, N. (2009). Simple technology: Casting moulds for axe-adzes. In T. L. Kienlin, & B. W. Roberts (Eds.), *Metals and societies. Studies in honour of Barbara S. Ottaway* (pp. 246–257). Bonn: Habelt.

Cierny, J., Marzatico, F., Perini, R., & Weisgerber, G. (2004). Der spätbronzezeitliche Verhüttungsplatz Acqua Fredda am Passo Redebus (Trentino). In G. Weisgerber, & G. Goldenberg (Eds.), *Alpenkupfer: Rame delle Alpi (pp. 155–164). Der Anschnitt Beiheft 17*. Bochum: Deutsches Bergbau Museum.

Coles, J. M. (1967). Experimental archaeology. *Proceedings of the Society of Antiquaries of Scotland*, *49*, 1–20

Craddock, B. R. (1990). The experimental hafting of stone mining hammers. In P. Crew & S. Crew (Eds.), *Early mining in the British Isles* (p. 58). Gwynedd: Snowdonia National Park Studie Centre, Plas Tan y Bwlch

Craddock, P. T. (1990). Copper smelting in the Bronze Age Britain: Problems and possibilities. In P. Crew & S. Crew (Ed.), *Early mining in the British Isles* (pp. 69–71). Gwynedd: Snowdonia National Park Studie Centre, Plas Tan y Bwlch

Craddock, P. T. (2001). From hearth to furnace: Evidences for the earliest metal smelting technologies in the eastern Mediterranean. *Palaeorient, 26,* 151–165.

Craddock, B. R., Cartwright, C. R., Craddock, P. T., & Wray, W. B. (2003). Hafted Stone Mining Hammer from Chuquicamata, Chile. In P. Craddock, & J. Lang (Eds.), *Mining and metal production through the ages* (pp. 52–68). London: British Museum Press.

Crew, P. (1990). Firesetting experiment at Rhiw Goch, 1989. In P. Crew & S. Crew (Eds.), *Early mining in the British Isles* (pp. 53–54). Gwynedd: Snowdonia National Park Studie Centre, Plas Tan y Bwlch

Cunningham, P., Heeb, J., & Paardekooper, R. (2008a). *Experiencing archaeology by experiment*. Oxford: Oxbow Books.

Cunningham, P., Heeb, J., & Paardekooper, R. (2008b). Introduction. In P. Cunningham, J. Heeb, & R. Paardekooper (Eds.), *Experiencing archaeology by experiment (pp. v–ix)*. Oxford: Oxbow Books.

Doonan, R. C. P. (1994). Sweat, fire and brimstone: pre-treatment of copper ore and the effects on smelting techniques. *Journal of the Historical Metallurgy Society, 28*(2), 211–258.

Earl, B. (1994).*Cornish mining. The technique of metal mining in the West of England, past and present* (2nd ed). St. Austell: Cornish Hillside Publications

Earl, B., & Özbal, H. (1996). Early bronze age tin processing at Kestel/Göltepe, Anatolia. *Archaeometry*, *38*(2), 289–303 (1996)

Eccleston, M., & Ottaway, B. S. (2002). Experimental casting of copper and bronze in sand moulds. In J. Jerem, & K. T. Biro (Eds.), *Archaeometry, 98* (pp. 185–189). Oxford: BAR.

Fasnacht, W. (1995). Die Schaftlochaxt von Parpan im Gussexperiment. In B. Schmid-Sikimić, & P. Della Casa (Eds.), *Trans Europam—Festschrift für Margarita Primas* (pp. 23–28). Bonn: Dr. Rudolf Habelt GMBH.

Fasnacht, W. (2009). 7000 years of trial and error in copper metallurgy—in one experimental life. In T. L. Kienlin, & B. W. Roberts (Eds.), *Metals and societies. Studies in honour of Barbara S. Ottaway* (pp. 395–399). Bonn: Habelt.

Goldenberg, G., & Rieser, B. (2004). Die Fahlerzlagerstätten von Schwaz/Brixlegg (Nordtirol). Ein weiteres Zentrum urgeschichtlicher Kupferproduktion in den österreichischen Alpen. In G. Weisgerber, G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 37–52). Der Anschnitt, Beiheft 17

Hauptmann, A. (2007). *The archaeometallurgy of copper: Evidence from Faynan, Jordan*. New York: Springer.

Hanning, E. (2010). Metal for Zambujal: Experimentally reconstructing a 5000-year-old technology. *Trabajos de Prehistoria, 67*(2), 287–304.

Hanning, E. (2011). *Smelting of sulfidic ore during the Bronze Age in the Eastern Alpine Region: An experimental approach*. Metalla International Conference Archaeometry in Europe III (Abstracts). Germany: Deutsches Bergbaumuseum Bochum (139)

Heeb, J. (2010). Rohling einer kreuzschneidigen Kupferaxt – Des Rätsels Lösung? *Acta Praehistorica et Archaeologica, 43*, 99–108.

Heeb, J. (2009) Thinking Through Technology – An experimental Approach to the Copper Axes from Southeastern Europe. In T. L. Kienlin and B. W. Roberts (eds.) *Metals and Societies – Studies in honour of Barbara S. Ottaway*. Bonn, Verlag Dr. Rudolf Habelt GmbH, 415–420.

Heeb, J. in preparation: *Copper shaft-hole axes and early metallurgy in south-eastern Europe: an integrated approach*. British Archaeological Reports.

Hoover, H. C., & Hoover, L. H. (Eds & trans.) (1912). *Agricola: De Re Metallica*. London: The Mining Magazine.
Jackson, C. (2009). Experimental archaeology and education: Theory without practice is empty; Practice without theory is blind. In T. L. Kienlin, & B. W. Roberts (Eds.), *Metals and societies. Studies in honour of Barbara S. Ottaway* (pp. 400–406). Bonn: Habelt.
Jantzen, D. (1993). Auf den Spuren bronzezeitlicher Gießer. *Archäologie in Deutschland, 1,* 24–27.
Jochum Zimmerman, E., Künstler-Wagner, N., & Kunnert, U. (2002). Zurück zur Gussform! Zum Einfluss des Gussformmaterials auf die Mikrostruktur eines gegossenen Bronzeobjektes. In M. Fansa (Ed.), *Experimentelle Archäologie in Europa, Bilanz 2002* (pp. 60–63). Isensee Verlag: Oldenburg.
Juleff, G. (1996). An ancient wind-powered iron smelting technology in Sri Lanka. *Nature, 379,* 60–63.
Kelterborn, P. (2005). Principles of experimental research in archaeology. *EuroREA, 2,* 120–122.
Kienlin, T. L., & Ottaway, B. S. (1998). Flanged axes of the North-Alpine Region: An assessment of the possibilities of use wear analysis on metal artifacts. In C. Mordant, M. Pernot, & V. Rychner (Eds.), *L'Atelier du bronzier en Europe* (pp. 271–286). Paris: CTHS.
Kienlin, T. L. (2008). Tradition and Innovation in Copper Age Metallurgy: Results of a Metallographic Examination of Flat Axes from Eastern Central Europe and the Carpathian Basin. *Proceedings of the Prehistoric Society* (pp. 79–107). 74(2008)
Kucera, M. (2004). Das Experiment in der Archäologie. In M. Fansa (Ed.), *Experimentelle Archäologie in Europa, Bilanz 2004*. Isensee Verlag: Oldenburg.
Lammers-Keijsers, Y. (2005). Scientific experiments: A possibility? Presenting a general cyclical script for experiments in archaeology. *EuroREA, 2,* 18–24.
Lechtman, H. (1999). The production of copper-arsenic alloys (arsenic bronze) by cosmelting: modern experiment, ancient practice. *Journal of Archaeological Science, 26,* 497–526.
Lewis, A. (1990). Firesetting experiments on the Great Orme's Head, 1989. In P. Crew & S. Crew (Eds.), *Early mining in the British Isles* (pp. 55–56). Gwynedd: Snowdonia National Park Studies Centre, Plas Tan y Bwlch
Long, S. (1964). Cire perdue copper casting in pre-columbian Mexico: An experimental approach. *American Antiquity, 30,* 189–192.
Lorscheider, F., Mass, A., & Steiniger, D. (2003). Frühe Kupferproduktion—archäologischer Befund und Experiment: Versuche zur Fahlerzverhüttung in einem einzigen Ofengang. In T. Stöllner, G. Körlin, G. Steffens, & J. Cierny (Eds.), *Man and Mining—Mensch und Bergbau—Studies in honour of Gerd Weisgerber* (pp. 301–308). Bochum: Deutsches Bergbau Museum Bochum
Lyngstrøm, H. S. (1997). In the borderland of Archaeology—Experimental forging. In L. Norbach (Ed.), *Early iron production—Archaeology, technology and experiments* (pp. 27–35). Lejre: Historisk-Archaeologisk Forgoscenter Lejre
Merkel, J. (1990). A reconstruction of copper smelting at Timna. In B. Rothenberg (Ed.), *The ancient metallurgy of copper, researches in the Arabah, 1959–1984*, *2* (pp. 78–122). London: Institute for Archaeo-Metallurgical Studies.
Merkel, J., & Shimada, I. (1988). *Investigation of prehistoric copper smelting at Batan Grande*. Peru: IAMS Newsletter (12, 4–7)
O'Brien, W. (2004). *Ross Island (Bronze Age Studies 5)*. Galway: National University of Ireland
Okafor, E. E. (1998). Lejja: bloom bank revisited. *Nigerian Heritage, 7,* 48–61.
Ottaway, B. S. (1994). *Prähistorische Archäometallurgie*. Espelkamp: Verlag Marie L. Leidorf
Ottaway, B. S. (2003). Experimental Archaeometallurgy. In T. Stöllner, G. Koerlin, J. Steffens, & J. Cierny (Eds.), *Man and mining—Mensch und Bergbau. Studies in honour of Gerd Weisgerber on occasion of his 65th birthday* (pp. 341–348). Bochum: Der Anschnitt.
Ottaway, B. S., & Seibel, S. (1998). Dust in the wind: experimental casting of bronze in sand moulds. In M. C. Frere-Sautot (Ed.), *Paleometallurgie de cuivres—Actes du colloque de Bourg-en-Bresse et Beaune 1997* (pp. 59–63). Montagnac: Editions Monique Mergoil

Outram, A. K. (2005). Publishing archaeological experiments: A quick guide for the uninitiated. *EuroREA, 2,* 107–110.

Outram, A. K. (2008). Introduction to experimental archaeology. *World Archaeology, 40,* 1–6.

Pazuchin, V. A. (1964). O proischoždenii drevnej myš'jakovistoj medi (on the origin of ancient copper containing arsenic). *Izvestija Akademii Nauk SSSR—Metallurgija i Gorneo Delo* (Transactions of the Academy of Sciences of the USSR—Metallurgy and Mining), (1):151–165

Radivojević, M. (2012). On the origins of metallurgy in Europe. Metal Production in the Vinca Culture, *Unpublished PhD Thesis UCL London*.

Radivojević, M., Rehren, Th., Pernicka, E., Sljivar, D., Brauns, M., and Boric, D. (2010). On the origins of extractive metallurgy: new evidence from Europe. *Journal of Archaeological Science, 37*, 2775–2787.

Reynolds, P. (1999). The Nature of Experiment in Archaeology. In A. F. Harding (Ed.), *Experiment and Design: Archaeological Studies in Honour of John Coles* (pp. 156–162). Oxford: Oxbow.

Rieser, B., & Schrattenthaler, H. (2004). Prähistorischer Kupferbergbau im Raum Schwaz/Brixlegg (Nordtirol). Geländebefunde und experimentelle Untersuchungen zur Schlägelschäftung. In G. Weisgerber, G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 75–94). Bochum: Der Anschnitt, Beiheft 17

Roberts, B. W., & Ottaway, B. S. (2003). The use and significance of socketed axes during the Late Bronze Age. *European Journal of Archaeology, 6,* 119–140.

Rostoker, W., Pigott, V., & Dvorak, J. (1989). Direct reduction of copper metal by oxide-sulphide mineral interaction. *Archaeomaterials, 3,* 69–87.

Rostoker, W., & Dvorak, J. (1991). Some experiments with co-smelting to copper alloys. *Archaeomaterials, 5,* 5–20.

Rothenberg, B. (Ed.). (1990). *The ancient metallurgy of copper, researches in the Arabah, 1959–1984*, *2* (pp. 78–122). London: Institute for Archaeo-Metallurgical Studies.

Rovira, S., Montero-Ruiz, J., and Renzi, M. (2009). Experimental co-smelting of copper-tin alloys. In T. L. Kienlin and B. W. Roberts (Eds.), *Metals and Societies. Studies in honour of Barbara S. Ottaway* (pp. 407–414), Bonn: Habelt.

Schroeder, E. (2006). *The use of hammer stones as Blacksmith hammers in the early iron age. MA in Experimental archaeology*. UK: University of Exeter.

Swiss and Ottaway. (in press). Investment or investment: casting and using a bronze mould. In P. Northover, & C. Salter (Eds.), *Founders, Smiths and Platers*. Oxford.

Tabor, G. R., Molinari D., & Juleff, G. (2005). Computational Simulation of Air Flows through a Sri Lankan Wind-Driven Furnace, *Journal of Archaeological Science*, 32, 753–766.

Timberlake, S. (1990). Firesetting and primitive mining experiments, Cwmystwyth, 1989. In P. Crew & S. Crew (Eds.), *Early mining in the British Isles* (pp. 53–54). Gwynedd: Snowdonia National Park Study Centre, Plas Tan y Bwlch

Timberlake, S. (2005). Experimental mining on Alderley Edge part 1: A firesetting and mining experiment at Church Quarry in 1997. In S. Timberlake & A. J. N. W. Prag (Eds.), *The archaeology of Alderley Edge survey, excavation and experiment, in an ancient mining landscape* (pp. 188–192). Archaeopress: British Archaeological Reports (British Series) 396

Timberlake, S. (2007). The use of experimental archaeology/archaeometallurgy for the understanding and reconstruction of Early Bronze Age mining and smelting technologies. In D. Hook, S. La Niece, & P. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 27–36). London: Archetype/British Museum.

Tylecote, R. F., Ghaznavi, H. A., & Boydell, P. J. (1977). Partitioning of trace elements between the ores, fluxes, slags and metal during the smelting of copper.; *305–333.*

Tylecote, R. F. (1982). Smelting copper ore from Rudna Glava, Yugoslavia. *Proceedings of the Prehistoric Society*, *48*, 459–465

Wager, E. C. (1997). Ffynnon Rufeinig. *Great Orme Exploration Society*, 15–9

Wager, E. C. (2009). Mining ore and making people: Re-thinking notions of gender and age in bronze age mining communities. In T. L. Kienlin, & B. W. Roberts (Eds.), *Metals and societies. Studies in honour of Barbara S. Ottaway* (pp. 105–115). Bonn: Habelt.

Wang, K., & Ottaway, B. S. (2004). *Casting experiments and microstructure of archaeologically relevant bronzes. British Archaeological Reports (International Series 1331)*. Oxford: Archaeopress.

Yener, K. A., Adriaens, A., Earl, B., & Özbal, H. (2003). Analyses of metalliferous residues, crucible fragments, experimental smelts, and ores from Kestel Tin Mine and the tin processing site of Göltepe, Turkey. In P. Craddock, & J. Lang (Eds.), *Mining and metal production through the ages* (pp. 181–187). London: British Museum Press.

Chapter 9
Ethnoarchaeological and Historical Methods

Louise Iles and S. Terry Childs

Introduction

Reference to ethnographic information, both explicitly and implicitly, formally and informally, plays a significant role in the formulation of our understanding of how people lived in the past. The essence of modern anthropological archaeology centres primarily upon the interpretation of material remains through an examination of likely parallels witnessed in the present. As others have stated before us, such inherent analogical reasoning underpins *all* archaeological interpretation (Johnson 2010; David and Kramer 2001; Wylie 2002). Interpretations of the past are developed within the context of the researcher's social and cultural background, and are governed by personal knowledge of how individuals and communities relate to and interact with material culture.

Ethnoarchaeology seeks to formalise these systems of inference and interpretation of the archaeological record. Through the observation of living relationships between culture and material culture in modern populations, it endeavours to bridge the gap between "past and present, 'data' and 'interpretation'" (Johnson 2010, p. 50). Ethnoarchaeology aims to draw these dichotomies closer together by developing firmer methodologies and more reliable theoretical structuring in order to generate reliable evidence that can inform and, hopefully, enhance archaeological interpretations. In this way, and despite the relatively few number of current dedicated practitioners,

---

The views expressed here are the author's and do not necessarily reflect the view of the Department of the Interior.

L. Iles (✉)
University of York, Department of Archaeology,
King's Manor, York, YO1 7EP, UK
e-mail: louise.iles@gmail.com

S. T. Childs
Department of the Interior, 1849 C Street NW, MS 4026,
20240 Washington, DC, USA
e-mail: Terry_Childs@ios.doi.gov

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_9,

ethnoarchaeology as a sub-discipline has made a great impact on theoretical and methodological approaches within contemporary archaeology (David and Kramer 2001).

In this chapter, we provide a brief introduction to the history and development of ethnoarchaeological approaches to past metallurgies. We address the use of linked data sets from ethnographic, anthropological and historical resources, and the impact these have had upon the study of early metallurgy. We then discuss the benefits and shortfalls of the application of such methods and data in ancient metallurgical contexts and follow with two case studies to illustrate some of the many ways that ethnoarchaeological approaches have been applied in practice. We conclude with thoughts on how these approaches can best be refined and utilised in the future in order to generate the most appropriate and informative understanding of past metallurgical practices.

Introducing Ethnoarchaeology: Data and Methods

Those interested in uncovering the past have long used analogies drawn from ethnographic and anthropological accounts. Scholars in the nineteenth and early twentieth centuries, famously Lubbock (1865) and Childe (e.g., 1930, 1940), alongside others who embraced popularist ideas of unilineal social evolution (e.g., Spenser 1863) were content to draw explicit parallels between contemporary, small-scale, so-called 'primitive' societies and those of Eurasian prehistory. Observations of indigenous communities in, for example, sub-Saharan Africa were often fed into interpretations of prehistoric remains in Britain, a trend that continues to influence modern research (e.g., Renfrew 1973; Giles 2007). Such an uncritical application of ethnographic analogy, whilst fortunately not commonplace now, certainly prompted and paved the way for the development of more sophisticated archaeological theories of inference and interpretation that sought to apply ethnological information in a more accountable manner.

From the 1930s onwards, anthropological studies with expressly ethnoarchaeological objectives and methodologies began to appear (e.g., Thompson 1939; Wauchope 1938), heralding a shift in theoretical emphasis towards developing robust, testable analogies for the interpretation of the past (Lane 2006). A few decades later, ethnoarchaeology was evolving into a distinct discipline in its own right, promising "more focused and complete analogies for archaeological application" (David 1992, p. 330). Binford (1983, p. 24) saw it as a 'Rosetta Stone,' capable of accurately translating the language of the archaeological record across time and space.

Modern ethnoarchaeology has developed from these roots into a discipline with a methodology drawn directly from archaeology and cultural anthropology. Ethnoarchaeological field research combines participant observation with a detailed recording of features and artefacts. Distinct from the data drawn from ethnographic and other sources, which sometimes omit material culture and technology entirely, ethnoarchaeological research openly aims to observe behaviours and generate data sets that are more readily applicable to the material remains encountered in the archaeological record. It directs attention towards the social and physical contexts of production technologies, artefact manufacture, use and distribution, stylistic variation, structuring of space and deposition and post-deposition processes (see Stiles 1977; David and Kramer 2001; Lane 2006).

Ethnoarchaeology of Metallurgy

Explorations of technology and technological processes form a significant corpus of ethnoarchaeological research. Studies of ceramic manufacture (*cf.* Costin 2000) and lithic production (*cf.* Sillitoe and Hardy 2003) are followed closely in volume by studies of metal production, especially iron. From as early as the start of the twentieth century, ethnographic accounts began to be used together with archaeological and analytical data to influence interpretations of archaeometallurgical remains (Thornton 2009), setting a precedent for later, more systematic ethnoarchaeological investigations of early metallurgy.

Somewhat unique to the archaeology and ethnoarchaeology of technology is the necessity to give due consideration to the technical, social and cognitive-symbolic elements of the processes involved. The merging of these factors is nowhere more apparent as in the examination of metallurgical processes (David and Kramer 2001, David 2001), as highlighted, for example, in the 'science versus magic' debate that drew inspiration from ethnographies of iron production from sub-Saharan Africa. Within this body of work (e.g., van der Merwe and Avery 1987; Rowlands and Warnier 1993; Barndon 1996, 2004, amongst many others), the premise of the 'mind' (magic) and 'matter' (science) as separate entities—as they are generally construed in modern western systems of thought (Horton 1993, p. 227)—was challenged. Instead, these researchers emphasised that within the cultural contexts studied, the correct application of social and ritual functions was as critical to the successful outcome of an iron smelt as the fulfilment of purely technical requirements.

This Africa-based research influenced archaeometallurgical studies throughout the world. It opposed the dominant western-based perspectives of technology, stressing "the importance of magic as a science," and thereby warning of the dangers of transposing modernvalue systems onto historical and archaeological scenarios (Haaland 2004, p. 11). The western ideological distinction between science and magic was demonstrated to be neither universal nor definitive, yet it had already had a significant impact on the shaping of ethnoarchaeological and archaeological research agendas, methodologies and hypotheses. An awareness of being confined by such theoretical limitations is of paramount importance in avoiding important information being overlooked or dismissed. In this regard, the lessons learnt from the study of nineteenth- and twentieth-century African iron production have gone on to influence the study of other materials and technologies in a global arena (e.g., Gosselain 1992; Costin 2000; Dobres and Hoffman 1994).

There have been various balances in ethnoarchaeological approaches to the social and technical aspects of metallurgy over the decades. Some researchers have focussed primarily on the documentation of the physical and technical processes of production technologies—how furnaces were constructed, what raw materials were used, what temperatures were achieved and so on (e.g., Todd 1985). Others have emphasised the social and symbolic aspects of the process (e.g., Reid and MacLean 1995). How the study of these seemingly disparate elements is conceptualised (and integrated) is key to the extent to which a technology as a whole can be understood (e.g., Lemonnier 1986; Pfaffenberger 1992).

The explicit intention now is to move away from a "lack of integration between metallurgical research and anthropologically informed archaeology" (Budd and Taylor 1995, p. 134) and to consolidate all aspects of the processes under examination—social, technical and ideological (David and Kramer 2001). In recent research, the holistic integration of ethnoarchaeology, materials science, ethnohistory, experimental archaeology and archaeological excavation (e.g., Schmidt 1997; Dupré and Pinçon 1997; Killick 1990; Hosler 1994; David et al. 1989) has enabled wider-reaching questions to be addressed of archaeometallurgical remains. These include examinations of the movement of metal items and raw materials through cultural landscapes, the relationship of stylistic patterns to sociocultural entities, the sociopolitical context of technology or the transmission of technical knowledge and know-how and how this manifests itself within different technologies (David and Kramer 2001). Such an interdisciplinary approach can contribute to building a more complete picture of the past, revealing metallurgy in its wider social context.

The science–magic debate certainly raised the profile of the ethnoarchaeology of African iron production, but metallurgy in other regions of the world and other metallurgical processes have been less extensively studied (David and Kramer 2001). Traditional metalsmiths producing and working with gold, silver, copper alloys and lead are known to still operate in parts of Asia and the Americas, but as yet there have been comparatively few ethnoarchaeological studies of these technologies. Exceptions include work in East Asia on the production of iron and, to a lesser extent, other metals (e.g., Juleff 1998; Juleff et al. 2009; Rijal 1995, 1998; Wagner 1984; Hai 2005; see also Bronson and Charoenwongsa 1986), lead and silver production in South America (e.g., van Buren and Mills 2005; Cohen 2008) and bloomery iron production in North America (e.g., Gordon and Killick 1993). There are also far fewer assessments of smiths, miners and the use and significance of metal objects, although exceptions include Larick (1985, 1986), de Maret (1980, 1985), Dewey and Childs (1996), Childs and Dewey (1996), Childs (1998), Brown (1995); Kusimba (1996) in Africa, as well as Horne (1983, 1994), Nash (1979) and Ascher (1962) in Asia and the Americas. Unfortunately, time is running out to be able to interact with many of those who have memories of living 'traditional' metallurgical practices, as these industries retreat into a more and more distant past and the practitioners pass away (Childs and Killick 1993; David 2001; see also Schmidt 2010). We urge that the most must be made of this valuable resource whilst it still exists.

Historical and Ethnohistorical Resources

There is a wide range of non-archaeological resources available to an archaeometallurgist to assist in the interpretation of metallurgical remains (*cf.* Stiles 1977). These include primary ethnohistorical, ethnographical, historical, art- and artefact-based sources, which sometimes incorporate useful descriptions and depictions of technological processes or objects, in addition to ethnoarchaeological and anthropological resources that focus chiefly on metallurgy.

Some of the earliest texts of value are the ancient encyclopaedias and compendiums of knowledge that covered subjects such as industry, technology and mineralogy from all over the Old World. A large variety of these resources exist from as early as the first millennium BC. Examples include the Greek *On Stones* by Theophrastus and *Indica* by Megasthenes (Caley and Richards 1956; McCrindle 1926), the Sanskrit *The Arthashstra* by Kautilya (Craddock 2009) and the Chinese records of Sima Qian and others (Watson 1993; see also extensive bibliographies in Wagner 2008). Later texts include Pliny's *Naturalis Historia*, and the Arabic *Kitab al-Jamahir fi Ma'rifat al-Jawahir* (*The Book Most Comprehensive in Knowledge of Precious Stones*) by Al-Beruni (Abu Rayhan Biruni) and *Kitab al-Suyuf* (*The Book of the Swords*) by Al-Kindi.

These sources can—with careful interpretation and contextualisation—reveal the extent of chemical, geological and mineralogical knowledge at the time when they were written. They also offer much information about the practicalities of various metallurgical processes, such as ore prospection, mining, reduction processes and the development of new methods and techniques concerning mercury, lead, silver, gold, copper, iron and tin. Detailed descriptions of trade links throughout Europe, Asia and northern Africa, and the locations of resources critical to metal production are also provided. Furthermore, these sources often supply useful eyewitness accounts regarding the organisation of production as well as descriptions of the cultural values attributed to various metals.

Moving later in time, one of the most frequently cited texts is Georgius Agricola's *De Re Metallica*, published in 1556. The book outlines the state of knowledge of European metallurgy at the beginning of the Reformation and makes extensive references to classical texts (Hoover and Hoover 1950). The primary focus of the work is on mining, but it also covers a multitude of processes and methods concerning silver, gold, tin, iron, lead and copper, as well as depicting many of these technologies in detailed woodcarvings. Agricola's tome has been referenced in archaeometallurgical papers of many wide-ranging topics (*cf.* Craddock 1994; e.g., Martinón-Torres and Rehren 2002; Heimann et al. 1998; Martin 1999).

The colonisation of the Americas was beginning at around this same time, as European empires expanded overseas. Colonial powers, often with the dubious intention of maximising their profits from local resources, began to make intricate records of metallurgical processes. The production (or control of production) of valuable metals, such as gold and silver, was a primary concern related to their acquisition of wealth. As such, a wide range of written resources exist that document the metallurgy of the region at this time, including Sahagún's 12-volume *Florentine Codex: General History of the Things of New Spain* (Dibble and Anderson 1950–1982). Some of the writers of these texts had a working knowledge of metallurgical industry (*cf.* Bray 1971, p. 25), including Benzoni, a Milanese silversmith, Oviedo, a master smelter of King Ferdinand and Alvaro Alonzo Barba, who worked as a mine supervisor.

Early explorers of North America, such as Giovanni de Verranzano (Wroth 1970) and Sir Richard Grenville (Hakluyt 1904), and of Africa, such as Emin Pasha (Schweinfurth et al. 1888) and Samuel Baker (1867), wrote personal and official accounts of the people they encountered, frequently referring to metal production. These explorers sometimes sought out mines to determine their possible economic benefits. This was followed in the nineteenth and twentieth centuries by more academic accounts by specialist engineers, geologists and prospectors (e.g., Foster and Whitney 1850; Percy 1970; Ball 1881; Stephens 1901–1902). Missionaries and early settlers also often wrote about the daily lives of those amongst whom they lived, including accounts of traditional metal working and uses of metal (e.g., Roscoe 1911, 1915, 1923; Fisher 1911 in eastern Africa; Fr. Allouez in North America (Kellogg 1917; Thwaites 1896–1901)). Unfortunately, such accounts were often marred by the agendas of the authors, who either were sometimes keen to promote the 'exotic' (and/or 'savage') nature of their subjects or would sensitively omit 'un-Christianly' behaviour. However, all of these sources can be useful to the archaeologist if their contexts are critically considered.

Another source of information about past metallurgies stems from transcriptions of traditional mythology and oral histories. Haaland (2004, p. 11) tells us that European cultural traditions include largely unexploited myths, legends and folktales that deal with "the magic and rituals of the smith, iron and ironworking." Norse, Celtic/Irish, African, Nordic, Roman, Greek and many other mythologies contain references to smith gods, the exploits and undertakings of whom have prompted discussion as to how smiths were perceived and regarded within these various societies (e.g., Eliade 1962; Haaland 2006; Barndon 2006; Blakely 2006).

Other sources that may provide valuable information for the archaeometallurgist include inscriptions, codices and images found on ceramics, walls, in mosaics, metalwork or paintings. Examples of the application of such resources include the interpretation of European brass clothing tags found in archaeological contexts in Cuba, which utilised metallurgical analysis alongside information from literature and pictorial sources (Martinón-Torres et al. 2007, see especially Fig. 12); the use of Egyptian wall paintings of bowl-furnace smelting from the second millennium BC to reconstruct copper smelting technology (Tholander 1987) or the depiction of a 'masked' furnace on a classical Greek vase from Vulci to infer the magical elements of metallurgical processes (Haaland 2004, 2006).

Brought together, this extensive body of work offers a panoply of valuable information to assist in the interpretation of archaeological remains. Together with anthropological and ethnoarchaeological resources, they can strengthen our understanding of how and why metallurgical processes in the past were undertaken in the way that they were.

The Application, Issues and Impact of Ethnoarchaeological Approaches to Metallurgy

The development of ethnoarchaeological research has resulted in several major impacts on our approaches to the study of early metallurgy. Firstly, it has influenced (and most would agree that it has improved) the interpretation of archaeometallurgical remains. Secondly, it has shaped research questions and agendas. Lastly, it has demonstrated the potential for imparting a tangible positive effect on local cultural heritage in the regions where it has been implemented.

Ethnographic Analogy in Archaeometallurgical Contexts: Interpretations Through Space and Time

Whereas the major aim of ethnoarchaeology has been to improve and strengthen archaeological interpretation of material remains, achieving this goal has proven to be a complicated task. Much theoretical discussion has been published to define the most effective and responsible way to apply ethnoarchaeological data to archaeological remains in order to maximise our understanding of the past (David and Kramer 2001; Lane 2006). Ethnohistorical, ethnoarchaeological and ethnographic sources are situated within complex historical, social, economic and political contexts. The data derived from these contexts are unable to provide 'timeless' technological analogies for past metallurgical practice (Killick 2009). This raises a poignant, overarching question: does ethnoarchaeology provide valuable clues as to how metallurgical processes were undertaken and organised in the past, or does it encourage us to make overly simplified assumptions regarding what were undoubtedly multifaceted technologies far removed from the societies that we live in today?

This question leads us to consider the two major ways in which ethnoarchaeology can be integrated into archaeometallurgical interpretation, 'direct analogy' and 'relational analogy', approaches which address different research questions and require different methodologies (*cf.* Parker-Pearson and Ramilisonina 1998 and responses for further discussion of analogy and materiality). Direct analogy uses observable ethnographic data that can be directly applied to past cultures. With regard to archaeometallurgy, specifically because "the physical properties of metals remain constant regardless of the historical or cultural setting" (Muhly 1988, p. 2), this can include information that is more technical in nature that can be applied regardless of the social or cultural affiliations of the remains under examination. Such data might be applied to metallurgical scenarios of all time periods and across all regions as long as observable and measurable differences in geology, geography, botany and so on are accounted for.

However, this type of analogy is generally restricted to observations of limited complexity, particularly with regard to the social aspects of technology. Examples include: confirming the technical feasibility of a posited hypothesis of metal working in antiquity by demonstrating its successful application in modern or historical metallurgical practice (which can also go hand-in-hand with experimental archaeology; see Ottaway and Heeb, this volume); providing inspiration for the interpretation of unknown archaeometallurgical features or aspects of metallurgical processes; demonstrating the range of potential interpretations of certain configurations of remains or challenging underlying and fundamental assumptions held by archaeologists. Killick (1991) illustrates several examples in his article discussing the relevance of modern African iron smelting to archaeometallurgical reconstruction. He notes that Clough (1984) used recent African bloomery smelting to demonstrate the plausibility that early European smelters used high-grade iron ores in bowl furnaces and, in particular, that this method of smelting would result in very little residual slag. Killick also observes similarities between fields of archaeological slag-pits in Poland and remains left by recent Hausa ironworkers in Nigeria. The strong material parallels between the two technologies enabled the archaeological remains in Poland to be identified as resulting from a comparable Hausa technique, the use of a portable shaft or a chimney. The rather obvious lack of a historical connection between the two regions did not diminish the conclusions made in this instance.

In some cases, direct analogies may also be made to more socially oriented features of a technology, such as decorative motifs, if a demonstrable connection and continuity can be established between the past and modern communities under examination. Killick mentions the practice of depositing finger bones underneath twentieth-century furnaces in the Lowveld of South Africa to ensure a successful smelt; the presence of comparable bones under prehistoric furnaces in the same region suggests that a similar interpretation can be made of these older remains based on the available ethnohistoric evidence (Killick 2009; Miller et al. 2003). However, although such analogies become more robust if the living population under examination is demonstrably contiguous with the past populations connected to the archaeological remains, this is not foolproof, since "every living community is in the process of continuous change with respect to the materials which it utilizes" (Ascher 1961, p. 324).

Nevertheless, as we have already stated, a holistic picture of past metallurgy can only emerge if archaeometallurgists also consider the somewhat more elusive evidence for these social, cultural, ideological and economic aspects of technology. This may include information regarding raw material access, trade, organisation of metalworkers, subsistence economy, settlement patterns and symbolism and ritual that surround and support metalworking technologies. Unfortunately, in many situations, direct analogies with related modern cultures are not possible, so analogies are sometimes then drawn from a wider pool of information. Relational analogy refers to such data used to create generalisations that are applied cross-culturally: a much more problematic scenario. Because these scenarios tend to deal with data that are socially and culturally oriented, they can only provide suggestions about past practice, not conclusive statements. The challenge lies in making these links and suggestions as relevant as possible, whilst not implying a tangible connection. A wider range of caveats needs to be taken into consideration when applying these types of data to archaeological interpretations, along with increased interpretative caution. It is a difficult task to ensure that the interpretations from ethnoarchaeological studies are as reliable, responsible and meaningful as possible.

Ethnoarchaeology has proved key in demonstrating just how much variation is possible within metallurgy as a whole and even within a single technological process (*cf.* for example, Cline 1937), and warns against projecting any one single example of metalworking method onto the past (e.g., Rowlands 1971). However, there still remains a temptation to seek wider, global parallels that aim to unite disparate technological approaches through the identification of common cultural themes (e.g., Eliade 1962; Hingley 1997; Haaland 2004, 2006; see also Blakely 2006). If "the past is a foreign country: they do things differently there" (Hartley 1953, p. 1), how best can archaeologists or ethnoarchaeologists identify the most appropriate analogue in any given archaeological situation, whether it is linked via a cultural continuum or not?

Reliability of Resources

An assessment of the reliability of ethnoarchaeological sources must be undertaken before those sources can be utilised. A number of potential shortcomings, originating both from the researchers and the informants, need to be taken into account.

Examples of iron smelting make up by far the largest component of the body of ethnoarchaeological work regarding metallurgy, yet very few ethnoarchaeologists have been able to observe an iron smelt "carried out in earnest to obtain iron" (David and Kramer 2001, p. 335; David 2001). The assumption must be that the smelters' methodologies in those instances may not be exactly the same as if the smelt was undertaken for local economic production. Furthermore, many of the studies mentioned in this chapter involve re-enactments or reconstructions of smelting processes that were abandoned decades before (e.g., Echard 1968; David et al. 1988; Saltman et al. 1986; Huysecom and Agustoni 1997), which introduces limitations due to the potentially waning memories of the smelters and their use of trial and error that might not be clear to the researcher. Herbert (1993, pp. 16–17) reminds us that smelters may choose not to reveal all of the rituals and secret knowledge that would otherwise be included in the smelting process. The iron workers may not have known all of them in the first place, particularly depending on their age and social status when they last participated in iron working. The process of filming and recording communities who are not accustomed to such technology may introduce additional complications during reconstructions.

However, such reconstructions enable the recording and viewing of a wide range of valuable data: the timing and sequencing of activities, the choices made by the smelters, scientific data such as temperature and atmosphere, spontaneous explanations about the meanings of activities and equipment, the vocabulary used for all aspects of the process and the drama of the noises, movements, songs, dances, etc. This information can be built upon through repeated re-enactments (e.g., Schmidt 1996, 1997; David et al. 1989), and can also be documented scientifically through the application of laboratory techniques, such as metallography, or through experiments that control different variables indicated during the re-enactments (Schmidt and Avery 1978; Killick 1991).

There are further factors that may influence the reliability of ethnoarchaeological data. Value-laden agendas and inherent biases of some researchers may influence what ethnoarchaeological questions are asked, as well as how they are asked and to whom they are directed. Yet, the unspoken agendas of informants are also relevant, and may in the same way affect the answers that are given and the information that is imparted. Whether a researcher is foreign or local, male or female, old or young can influence exactly what the informant chooses to disclose. Informants are also getting older and fewer as time passes. How reliable are the memories of events that are getting more and more distant, and presumably more indistinct? In a world where globalisation has taken full hold, we have to assume that present-day memories are not devoid of influences from external sources.

As such, ethnoarchaeologists must remain aware that information is unlikely to be ‘complete,’ and they must seek ways to validate that the information gained is as accurate as memory allows (David 2001). The best way is to triangulate data by using as many informants as possible to corroborate information. This can be difficult when there are only one or two people who remember the old ways or when potential informants defer to the memory of just one person. Further issues include problems with translating interviews, such as accuracy, identifying key vocabulary and identifying underlying symbolic meaning, especially if interviews are carried out by someone with little metallurgical experience. The age, gender and social status of a translator may also initiate additional complications that may not be visible to the researcher.

There has also tended to be unrepresentative coverage of particular social groups in ethnoarchaeological projects, most especially with regard to metal industries. Generally, informants have been male and from social groups already known to be associated with metalworking. This has led to the repeated confirmation of certain ideas that may not hold true if interviews are extended to include other segments of society (*cf.* Iles 2013). Women may have had different experiences than men, older generations may attribute different values than younger generations, informants with different social status may have had different access to the processes or objects being studied (*cf.* Schmidt 2010, especially pages 272–273). Historical documents have tended also to be written by men, directed towards a male audience and disproportionately address certain, often elite, sectors of society.

There are ways in which to minimise these effects. The quality of the resulting data may be improved by ensuring that researchers are sufficiently prepared to undertake ethnoarchaeological work using well-established theory and methods. Making this theory and methodology explicit when the research is presented to a wider audience enables readers to contextualise and assess the work to a far higher degree than is often currently possible (David and Kramer 2001). This would critically enrich the data and inform further discussion.

The Wider Contribution of the Ethnoarchaeology of Metallurgy

One benefit of drawing from ethnoarchaeological resources is the (at least partial) dilution of the inherent ethnocentric preconceptions of an individual researcher (Gould 1978). The archaeometallurgist often draws upon his or her personal experience of metallurgical techniques from that person’s country or region of origin. His or her perspective will be broadened, however, by interacting with a variety of modern practitioners and historical sources to understand alternative experiences and knowledge of techniques and technologies from across the globe. As Bray (197 1, p. 29) asks, “how many archaeologists would immediately think of metallurgy if they encountered alligator dung in a Panamanian excavation"? Yet, according to the sixteenth-century writings of Oviedo (Fernandez 1959), contemporary local metallurgists used sun-dried alligator faeces to polish metal.

Not only is ethnoarchaeology, as well as ethnohistory, able to provide alternative (and sometimes unusual) interpretations of archaeological remains, they have also acted to highlight the full *chaînes opératoires* of production that are involved in metalworking (*cf.* Lemonnier 1992). Certain aspects of production systems, such as charcoal production, the provision of water, the supply of food for metalworkers, the construction of furnace superstructures and so on, are not necessarily visible in the archaeological record. These stages are crucial for the successful outcome of metal production (Childs 1991), yet gaining information about them, and how they were carried out in the past, is notoriously difficult. Observing metallurgical processes in action, or referring to those detailed in ethnohistorical texts has reminded archaeometallurgists (and indeed anyone examining the archaeology of technology) that all these aspects need to be taken into consideration if a holistic picture of past metallurgical practice is to be realised.

The growth of ethnoarchaeology has strongly influenced the research questions of recent archaeometallurgists. The insights into the less tangible sociocultural and economic aspects of metal technologies—ritual, symbolism, social organisation, trade, specialisation and so on—have encouraged a more inclusive approach to the study of technology. Ethnoarchaeology provides alternative ways to approach technology and metallurgy in contrast to those that respond solely to dominant Euro-American perspectives and values, approaches that are religious, social and political in emphasis rather than 'economically deterministic' (Haaland 2004). This trend has influenced research agendas even where it has not been possible to carry out primary ethnographic or ethnoarchaeological work, bringing a new awareness of questions regarding technological organisation and participation.

Finally, an important but often overlooked impact of ethnoarchaeological research is the tangible contribution it can make to local cultural heritage. The act of carrying out interviews and commissioning reconstructions can maintain and/or reinvigorate local interest and pride in indigenous crafts and technologies (Childs 2000, p. 199). David and Kramer (2001, p. 335) note:

> The Dogon smelters . . . were motivated less by money than by the opportunity to demonstrate their skills to a generation ignorant of their past achievements.

Ethnoarchaeology can generate material for local museums and actively involve and intrigue local schoolchildren in accessing their past. It can be harnessed to direct cultural tourism and thereby generate local income, a significant consideration in many regions of the world where ethnoarchaeology is carried out. For example, David's informant Dokwaza occasionally undertook reconstructions for tourists (David et al. 1989) and reconstructions of Fipa iron smelting were conducted at the Village Museum in Dar es Salaam, Tanzania, as part of the Saba Saba National Festival (Wembah-Rashid 1969). Making ethnoarchaeological investigations relevant to the host communities should be an integral part of any planned research.

Case Studies

We have introduced the major concepts involved in the application of ethnoarchaeology in archaeometallurgical contexts. Now we offer two case studies to demonstrate how these methods have been and can be applied in practice. As we emphasised in the preceding sections, a holistic examination of metallurgy must involve both the technical process and the sociocultural context in which it occurs. One of the powerful advantages of ethnoarchaeology is the ability to look more closely at the cultural and ideological influences on a technology than is possible through archaeology alone. Done well, the information yielded can then inform archaeological method and interpretation in significant ways.

The following case studies focus on two aspects of the sociocultural context of technology that have become increasingly apparent through ethnographic, ethnoarchaeological and ethnohistorical research. The first explores the issue of gender in African iron working systems, which is almost, but not completely, invisible in the archaeological record of the continent. The second case study examines the values of metal objects produced from several metal technologies in Central and South America, based primarily on ethnohistorical records and archaeometallurgical findings.

Gender in African Iron Smelting

Iron smelting is a transformative, creative process that changes raw ore into functional metal through the use and control of fire by skilled iron workers (de Maret 1980; Childs 1991; Herbert 1993). In sub-Saharan Africa, the danger and uncertainty of this process has sometimes been controlled through ideological associations with the act of procreation that require specialised technical and ritual knowledge. Relationships between the processes of iron smelting, becoming pregnant and giving birth and restraining the potentially harmful ancestral and spirit world became evident in an array of African ethnographic studies from the late 1800s through the late 1900s (e.g., Cline 1937; Kense 1983). These studies highlighted the various roles the iron workers take on in preparation for and during a smelt: the names and features of the furnaces, resources and other paraphernalia used, the songs sung, prayers said and actions taken prior to and during the smelt, and the selection of the smelting site.

In many of these reports the roles of the iron smelters, particularly the head smelter, were seen to be carefully orchestrated. Strict sexual abstinence during smelting was frequently practiced (at least in many of these recorded examples) due to the perceived dangers it could pose to the iron being created (Cline 1937; Herbert 1993). Among the Chisinga of Zambia, the smelter was the ‘husband’ of the furnace ‘wife.’ He could not have sexual relations with his human wife during a smelt because the adultery would jeopardise the success of the smelt by ‘killing’ the iron child (the bloom) in the furnace (Brelsford 1949). Song, chants, dance and the careful use of various medicines were seamlessly combined with the building and charging of the furnace, as well as the smelt itself, to ensure success. Many of the songs and chants were expressly about sexual intercourse or the birthing process, depending upon the timing during the smelt, such as among the Hausa of Nigeria (Echard 1983) and the Ila of Zambia (Smith and Dale 1968).

The equipment and resources used to smelt iron were sometimes explicitly anthropomorphised and genderised, often through the naming of tools and apparatus. The We/Isu in Cameroon mixed two types of ore during smelting, a hard, dry and male ore that had the power of semen, and a wet ore "like a woman" (Rowlands and Warnier 1993, p. 524). In Zimbabwe, the Shona (Cooke 1959; Robinson 1961) and the Chazi (Housden and Armor 1959) configured their forced draft furnaces as women with breasts and incisions to represent female scarification. The Malinke, far to the west on the Ivory Coast, also prominently placed breasts above the tuyère holes of the furnace (Célis 1991). The Fipa smelters in Tanzania built a tall, natural draft furnace as a fecund bride by decorating it with red *nkulu* powder (Wise 1958b). Once the furnace was erected, Fipa smelters performed a wedding ceremony and later decorated the furnace in black to veil the young, hopefully pregnant, wife after they fully charged the furnace (Wyckaert 1914; Wise 1958a, b). The Tshokwe in the Democratic Republic of the Congo (DRC) used the same term for the rake hole at the base of the furnace, where the resulting slag and iron was pulled out, as the birth canal of a mother in delivery (de Maret 1980). The Banyoro in Uganda used two clay bellows to force a draft into their furnaces, one the moulded genitalia of a man and the other of a woman (Lanning 1954).

Women who were menstruating or men and women who were adulterous were seen as particularly dangerous to the smelt. Menstruation is a temporary state of sterility that could affect the productivity of the smelt, while adultery could cause a pregnant mother (i.e., the furnace in this case) to miscarry or have a difficult labour (Herbert 1993). Women were therefore sometimes forbidden from attending an iron smelt, and to ensure that restrictions in access could be followed, furnaces were often located away from villages, such as among the Sakata in the DRC (Maes 1930). Nevertheless, there are some recorded instances where women did participate in the wider smelting technology, whether mining, providing food and drink to the smelters, making some of the smelting equipment, such as bellows and tuyères or even participating in the smelting itself (e.g., Baumann 1891; Cline 1937; Herbert 1993; Chirikure 2007; also *cf.* Iles 2013). The contributions of these women should not be overlooked.

This very brief summary of the ethnographic and ethnoarchaeological literature provides a glimpse into the many ways that gender and, in particular, female fertility and reproduction played an integral role in many iron smelting technologies in sub-Saharan Africa. Specific contextual details and patterns have been chronicled about the shifting roles and identities of the smelters during a smelt, the interrelationships of the smelters with women before, during and after a smelt, the use and meaning of the smelting ingredients, including the ore, charcoal, fluxes and medicines, sexual prohibitions before, during and after smelting, and the use of space, among others. Some of these factors might be visible in the archaeological record; others may be less tangible. They can, however, provide archaeologists with better insights into their excavations through both direct and relational analogy, such as possible social organisation at a smelting site, choices that influenced the location of a furnace site, decoration on the material remains found and the identity and locations of medicines used.

Although data from these specific and complex socio-technical scenarios cannot be directly applied outside of the cultural or temporal contexts within which they were originally identified (*cf.* Killick 2009), they have shown some of the many ways in which gender might be embodied within technology and metallurgy. In doing so, they point to many questions that have tended to be inadequately considered, often due to insufficient time being allotted to the research. For example, more information is needed on women's roles in iron smelting and the social, economic and ideological variables that permit some women to be involved and not others (David 2001; Herbert 1993). Also, a better understanding of the manufacture of medicines, the variety of types used, the sequence of their use during the smelting process and their potential ideological linkages to the procreation metaphor is needed, particularly since they could have visible remains in the archaeological record. Furthermore, social and cultural practices and ideological paradigms may be manifest in other technologies (Lechtman 1984; Childs 1991; Collett 1993; Herbert 1993; David 2001). To test the efficacy of their findings on patterns such as decorations, spatial layouts of activity areas, naming conventions and social organisation, ethnoarchaeologists need to study analogous activities, particularly those that involve fire and transformative processes.

Symbolic Meaning of Metals in South and Central America

The archaeology of pre-Hispanic metallurgy in Central and South America is centred on the production of gold, silver, copper and their alloys. A long-term project involving excavations of copper–arsenic production sites in northern Peru, alongside replicative experiments and archaeometallurgical analyses, have provided important insights into the technical and ritual sequencing of that technology (Shimada et al. 1982; Shimada and Merkel 1991; Shimada 1994). In the southern Andes of Bolivia, ethnoarchaeological studies of silver production furnaces, called huayrachinas and tocochimbos, have provided critical data for understanding the specifics of Inka-period silver production in the archaeological record (Van Buren and Mills 2005; Cohen 2008).

Much of what is known about pre-Hispanic metallurgy, however, is based on the study of metal objects. Although some metal objects, particularly of copper, were made for utilitarian purposes, silver and gold operated in the realm of the elite to signal wealth, power and control. Some of these gold, silver and copper objects have been subjected to archaeometallurgical analyses, both metallographic and chemical, which provided an important window into their production histories. Importantly, however, ethnohistoric sources have been used in conjunction with archaeometallurgical data to better understand pre-Hispanic metal technologies and the use, meaning and values of the objects produced.

Lechtman's work (1979, 1981, 1984) demonstrates this particularly well. She used archaeometallurgical methods to detail the sophisticated techniques of depletion gilding of copper alloy objects to make them seem like something they were not entirely. Many of the objects studied are *tumbaga*, an alloy of gold and copper, often with silver as well. Although the major constituent of the alloy may have been copper, the surfaces of many objects that performed in the social, political and ideological sphere of the elite were intentionally depleted of their copper components, leaving the surfaces enriched with gold or silver.

Lechtman used the rich ethnohistoric record about the Inka to provide context for her findings. Gold and silver functioned to convey social status, political power and religious force throughout the prehistory of the Andes (Lechtman 1984; Shimada 1994). By the time of the Inka, the sweat of the sun was linked to gold and the sweat of the moon was linked to silver in their cosmological system. The Inka took control over the production and use of gold and silver because the first Inka were the children of the sun and the moon. The colours and reflectivity of these metals were visible and concrete manifestations of political and religious belief systems that legitimised the Inka elite.

But if this is the case, why were *tumbaga* alloys used in these elite contexts? Lechtman surmises, based on the ethnohistoric record and comparative analysis of the production of cloth, that there was an ideological foundation to the development and spread of *tumbaga*:

> The basis of [these] systems is the incorporation of the essential ingredient—the gold or the silver—into the very body of the object. The essence of the object, that which appears superficially to be true of it, must also be inside it . . . even if the essence is only minimally present. (1984, p. 30)

Thus, the messages of power and status displayed on the surface of the golden or silver objects came also from within them. This ethnoarchaeological approach, combining the ethnohistoric record with archaeometallurgical data, was able to indicate a significant sociocultural (rather than economic or metallurgical) influence over technological choice, based upon a complex interplay of religion, value systems and materiality.

Similar value systems are apparent in the metallurgical histories of other regions of Latin America. *Tumbaga* also had prominent use in the highlands of Columbia for many centuries. Falchetti (2003) analysed the cosmological systems of local cultural groups using ethnohistorical and ethnographic sources to elucidate the intimate linkages between the alloy and the lifecycle and regeneration of human beings. Gold is yellow and odourless and related to the male, procreative powers of the sun; copper is reddish and has a distinctive smell, which are linked to feminine, transformative and mortal properties related to the moon. Once the sun 'fertilises' the moon, it goes through a cycle of transformations, the monthly lunar phases, which are paralleled with the development of an embryo and the transformative process of making *tumbaga*. The use of metal objects by religious practitioners, as well as common people, carried the attributes (colour and odour) and symbolic association of supernatural regeneration to ensure their birth, life and perpetuation on earth.

Similarly, in Cuba, excavations at El Chorro de Maíta revealed a cemetery within a long-term settlement that dates until after the arrival of early explorers to the region (Martinón-Torres et al. 2007; Cooper et al. 2008). Archaeometallurgical analysis of the metal grave goods showed that they were made of pure gold, imported *tumbaga* (*guanín* in the language of the Taíno) and imported brass (*turey*) (Martinón-Torres et al. 2007; Cooper et al. 2008). Again, ethnohistoric and linguistic sources were used to offer insights regarding variations in the metal grave goods and their possible meanings and values.

For the purposes here, we will only focus on the objects of *guanín. Guanín* refers to a variety of objects with certain essential attributes: a reddish colour, a sweet smell and a shiny quality. Not only did this include ternary alloys of copper, gold and silver, it also incorporated certain types of feathers, plants and turtles (Oliver 2000). These were valued more highly than gold by the political and religious elite in the Caribbean area. Oliver (2000) analysed Taíno mythology, as recorded by early Spanish explorers, to postulate on the symbolic associations of the *guanín* objects for the Taíno elite. He summarised his findings to suggest that *guanín* "relate[s] to the quest for civilization, the separation of sexes, exogamy, incest rules and the achievement of the ultimate social order: the establishment (justification) of a society ruled by *caciques* or chiefs" (2000, p. 214). Again, the value of this alloy has been highlighted through an examination of ethnohistorical records.

These three examples of the interpretation of *tumbaga* in various parts of South America and the Caribbean show how careful use of ethnohistorical and ethnographic sources, in conjunction with archaeometallurgical as well as linguistic analysis, can elucidate the values and meanings of metal. Falchetti (2003) notes that members of extant Indian societies, such as those in Columbia, still pass down centuries-old mythologies and belief systems. An ethnoarchaeological exploration of these systems of understanding and explaining the world may offer important additional understandings of the use and meaning of *tumbaga* found in the archaeological record. Enquiries into the qualities (i.e., colour, tone, smell and reflectivity) of various types of metal, the context in which different types of metal objects are used, why and by whom (i.e., religious, funerary, marriage, birth and trade) and anything that might be known about the production of metal objects could provide important clues to understanding the archaeological record of South and Central America.

Concluding Thoughts, Future Directions and Emphases

The many ways that ethnoarchaeological approaches have contributed to archaeometallurgy have been outlined in this chapter. We sought to explain how ethnographic data are used to inform archaeometallurgical interpretation. Is it only a stimulus for understanding the range of technological phenomena that are possible, providing a "store of ideas" for the archaeometallurgist to dip into (Killick 1991, p. 52)? Or, can it reliably be used to provide direct analogies in certain circumstances? The answer lies in a combination of the above, since there will always be multiple potential analogies for any given situation (Ascher 1961). Nevertheless, we hope to have demonstrated that an ethnoarchaeological approach can be a valid and useful methodology for interpreting the remains of past metalworking, and for stimulating future research.

David (2001) provided a critical review of ethnoarchaeological work related to African metallurgy and suggested how the discipline can effectively move forward in an African context. These directions include pursuing the ethnobotany of smelting medicines and the need for "longer-term fieldwork" (David 2001, p. 67). The quality of ethnoarchaeological data produced could also be improved. There is a need for more thorough training to prepare archaeometallurgists planning to undertake primary fieldwork. An improvement in methodological and theoretical awareness, including methods to validate the findings from informants, would be beneficial. Training in the local language(s) to be used during fieldwork, and in interview technique, is also critical, both to improve relationships in the field and to broaden the ability to identify linguistic data that may be relevant. Nevertheless, Tringham (1978, p. 171) calls for even the most amateur research to be fully published, as long as the methodology is made explicit. This ensures that valuable primary data are not lost and are available for considered use by future researchers.

On a global scale, we believe that there are several ways in which the ethnoarchaeology of metallurgy can and should grow. In particular, one of the most striking shortcomings of the discipline is the comparative paucity of studies that deal with technologies outside of sub-Saharan Africa. We hope that this lack will soon be redressed, especially given the increasing age and decreasing numbers of potential informants worldwide. As David (2001) exhorts, we must also encourage local researchers to conduct ethnoarchaeological research in their region in order to take advantage of linguistic aptitude and cultural connections that can assist the research. Digitisation of historical records and the increased availability of archival material, especially in those regions from where it originated, will hopefully facilitate and encourage a greater use of these resources. Furthermore, ethnoarchaeological research should also not be limited to technologies that are perceived as 'traditional' or 'non-industrial' (Schiffer 1978, p. 231). By widening the scope of technologies studied, it will be possible to learn about the wide-ranging relationships between materials, processes, organisational structures and people.

Finally, we emphasise that there is also a need to make fieldwork more relevant to local populations, rather than communicating only to a mostly western academic audience. Ethnoarchaeological research offers many opportunities to do this. Local translators, interpreters, field practitioners and academics can be trained in an arena whereby ethnoarchaeological funding can be used to make a positive contribution to local communities. Incorporating a greater number of people from a wider range of backgrounds into the practicing discipline will greatly enrich the quality and range of the body of research that is generated in the future. In summary, we believe that the best ethnoarchaeological work is as hands-on as possible, engages a wide range of informants and remains aware of responsibilities to the host communities. Most importantly, however, ethnoarchaeological work must be as open and unambiguous as possible in how the methods, data and results are communicated so it can provide a rich and reliable resource for those seeking to better understand the nuances of early metallurgy.

References

Ascher, R. (1961). Analogy in Archaeological Interpretation. *Southwestern Journal of Anthropology*, *17*, 317–325.

Ascher, R. (1962). Ethnography for Archaeology: A case from the Seri Indians. *Ethnology*, *1*, 360–369.

Baker, S. (1867). *The Albert N'yanza: Great basin of the Nile and explorations of the Nile Sources*. London: Macmillan.

Ball, V. (1881). *A manual of geology of India III: Economic geology*. Geological Survey of India: Calcutta.

Barndon, R. (1996). Fipa ironworking and its technological style. In P. R. Schmidt (Ed.), *The culture and technology of African iron production* (pp. 58–73). Gainesville: University Press of Florida.

Barndon, R. (2004). *An ethnoarchaeological study of iron-smelting practices among the Pangwa and Fipa in Tanzania*. Oxford: Archaeopress.

Barndon, R. (2006). Myth and metallurgy: Some cross-cultural reflections on the social identity of smiths. In A. Andrén, K. Jennbert, & C. Raudvere (Eds.), *Old Norse religion in long-term perspectives: origins, changes, and interactions: An international conference in Lund, Sweden, June 3–7, 2004* (pp. 99–103). Lund: Nordic Academic Press.

Baumann, O. (1891). *Usambara und seine Nachbargebiete: Allgemeine darstellung des Nordoestlichen Deutsch-Ostafrika und seiner bewohner auf grund einer im auftrage Deutsch-Ostafrikanischen gesellschaft ausgefuehrten reise*. Berlin: Dietrich Reimer.

Binford, L. R. (1983). *In pursuit of the past: Decoding the archaeological record*. New York: Academic Press.

Blakely, S. (2006). *Myth, ritual and metallurgy in ancient Greece and recent Africa*. Cambridge: Cambridge University Press.

Bray, W. (1971). Ancient American Metal-Smiths. Proceedings of the Royal Anthropological Institute of Great Britain and Ireland 1971, 25–43.

Brelsford, W. V. (1949). Rituals and medicines of Chisinga iron-workers. *Man*, *49*, 27–29.

Bronson, B., & Charoenwongsa, P. (1986). Eyewitness accounts of the early mining and smelting of metals in Mainland Southeast Asia. *SPAFA Journal*, *4*, 4–17.

Brown, J. (1995). *Traditional metalworking in Kenya*. Oxbow: Oxford.

Budd, P. D., & Taylor, T. (1995). The Faerie Smith meets the bronze industry: Magic versus science in the interpretation of prehistoric metal-making. *World Archaeology*, *27*, 133–143.

Caley, E., & Richards, J. (1956). *Theophrastus on stones*. Columbus: Ohio State University.

Célis, G. (1991). *Les fonderies africaines du fer*. Frankfurt a. M: Museum für Völkerkunde.

Childe, V. G. (1930). *The Bronze Age*. New York: Biblo & Tannen.

Childe, V. G. (1940). *Prehistoric communities of the British Isles*. London: Chambers.

Childs, S. T. (1991). Style, technology and iron-smelting furnaces in Bantu-speaking Africa. *Journal of Anthropological Archaeology*, *10*, 332–359.

Childs, S. T. (1998). 'Find the ekijunjumira': Iron mine discovery, ownership and power among the Toro of Uganda. In A. B. Knapp, V. C. Pigott, & E. W. Herbert (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 123–137). London: Routledge.

Childs, S. T. (2000). Traditional iron working: A narrated ethnoarchaeological example. In M. Bisson, S. T. Childs, P. de Barros, & A. Holl (Eds.), *Ancient African metallurgy: The socio-cultural context* (pp. 199–253). Walnut Creek: Altamira.

Childs, S. T., & W. J. Dewey. (1996). Forging symbolic meaning in Zaire and Zimbabwe. In P. R. Schmidt (Ed.),*The culture and technology of African iron production* (pp. 145–71). Gainesville: University Press of Florida.

Childs, S. T., & D. J. Killick. (1993). Indigenous African metallurgy: Nature and culture. *Annual Review of Anthropology*, *22*, 317–337.

Chirikure, S. (2007). Metals in Society: Iron production and its position in Iron Age communities of southern Africa. *Journal of Social Anthropology*, *7*, 72–100.

Cline, W. (1937). *Mining and metallurgy in Negro Africa*. Wisconsin: George Banta.

Clough, R. (1984). The bloomery process—Observations on the use of rich ores and the production of natural steel. In B. Scott & C. Cleere (Eds.) *The crafts of the Blacksmith* (pp. 19–27). Belfast: Ulster Museum.

Cohen, C. (2008). The winds of change: An archaeometallurgical study of siver production in the Porco-Potosí region, southern Bolivia AD 1500–2000. PhD thesis. London: University College London.

Collett, D. (1993). Metaphors and representations associated with precolonial iron-smelting in eastern and southern Africa. In T. Shaw, P. Sinclair, B. Andah, & A. Okpoko (Eds.), *The archaeology of Africa: Food, metals and towns* (pp. 499–511). London: Routledge.

Cooke, C. K. (1959). An iron smelting site in the Matopo Hills, Southern Rhodesia. *South African Archaeological Bulletin*, *14*, 118–120.

Cooper, J., Martinón-Torres, M., & Valcárcel Rojas, R. (2008). American gold and European brass: Metal objects and indigenous values in the cemetery of El Chorro de Maíta, Cuba. In C. Hofman, M. Hoogland, & A. Van Gijn (Eds.), *Crossing the borders: New methods and techniques in the study of material culture in the Caribbean (pp. 34–42)*. Alabama: University of Alabama Press.

Costin, C. L. (2000). The use of ethnoarchaeology for the archaeological study of ceramic production. *Journal of Archaeological Method and Theory*, *7*(4), 377–403.

Craddock, P. T. (1994). Agricola and the study of early metallurgy. *Historical Metallurgy*, *28*, 1–6.

Craddock, P. T. (2009). Perceptions and reality: The fall and rise of the Indian mining and metal industry. In T. K. Kienlin & B. W. Roberts (Eds.), *Metals and Societies. Studies in honour of Barbara S. Ottaway* (pp. 453–464). Universitätsforschungen zur prähistorischen Archäologie. Bonn: Habelt.

David, N. (1992). Integrating ethnoarchaeology: A subtle realist perspective. *Journal of Anthropological Research*, *11*, 330–359.

David, N. (2001). Lost in the third hermeneutic? Theory and methodology, objects and representations in the ethnoarchaeology of African metallurgy. *Mediterranean Archaeology*, *14*, 49–72.

David, N., & Kramer, C. (2001). *Ethnoarchaeology in action*. Cambridge: Cambridge University Press.

David, N., Heimann, R., Killick, D., & Wayman, M. L. (1989). Between bloomery and blast furnace: Mafa iron-smelting technology in North Cameroon. *African Archaeological Review*, *7*, 183–208.

de Maret, P. (1980). Ceux qui jouent avec le feu: La place du forgeron en Afrique Centrale. *Africa*, *50*, 263–79.

de Maret, P. (1985). The smith's myth and the origin of leadership in Central Africa. In R. Haaland & P. Shinnie (Eds.), *African iron working* (pp. 142–63). Oslo: Norwegian University Press.

Dewey, W., & Childs, S. T. (1996). Forging memory. In M. N. Roberts & A. F. Roberts (Eds.), *Luba art and the making of history*. (pp. 61–83). New York: Museum for African Art.

Dibble, C., & Anderson, C. (1950–1982). *General history of the things of New Spain: Florentine codex/Bernardino de Sahagún*. Utah: University of Utah Press.

Dobres, M.-A., & C. R. Hoffman. (1994). Social agency and the dynamics of prehistoric technology. *Journal of Archaeological Method and Theory*, *1*, 211–58.

Dupré, M.-C., & Pinçon, B. (1997). Métallurgie et politique en Afrique: Deux mille ans sur les Plateaux Bateké. Paris: Harmattan.

Echard, N. (1983). Scories et symbols: remarques sur la métallurgie hausa du fer au Niger. In N. Echard (Ed.), *Métallurgies Africaines*: *Nouvelles contributions* (pp. 209–224). Paris: Société des africanistes.

Eliade, M. (1962). *The forge and the crucible* (Trans: S. Corrin). New York: Harper & Brothers.

Falchetti, A. M. (2003). The seed of life: The symbolic power of gold-copper alloys and metallurgical transformations. In J. Quilter & J. Hoopes (Eds.), *Gold and power in ancient Costa Rica, Panama, and Colombia* (pp. 345–374). Washington: Dumbarton Oaks Research Library and Collection.

Fernández de Oviedo y Valdés, G. (1959). *Historia general y natural de las Indias*, 5 vols. Madrid: Ediciones Atlas.

Fisher, A. (1911). *Twilight tales of the black Baganda*. London: Marshall Brothers Ltd.

Foster, J. W., & Whitney, J. D. (1850). Report on the geology and topography of a portion of the Lake Superior land district in the state of Michigan Part I: Copper Lands. 31st Congress, 1st Session, H. Doc. 69.

Giles, M. (2007). Making metal and forging relations: Ironworking in the British iron age. *Oxford Journal of Archaeology*, *26*, 395–413.

Gordon, R., & Killick, D. (1993). Adaptation of technology to culture and environment: Bloomery iron smelting in America and Africa. *Technology and Culture*, *34*, 243–270.

Gosselain, O. P. (1992). Technology and style: Potters and pottery among Bafia of Cameroon. *Man*, *27*(3), 559–86.

Gould, R. (1978). Beyond analogy in ethnoarchaeology. In Gould, R. (Ed.), *Explorations in Ethnoarchaeology* (pp. 249–294). Albuquerque: University of New Mexico Press.

Haaland, R. (2004). Technology, transformation and symbolism: Ethnographic perspectives on European iron working. *Norwegian Archaeological Review*, *37*, 1–19.

Haaland, R. (2006). Iron in the making—technology and symbolism. Ethnographic perspectives on European iron working. In A. Andrén, K. Jennbert, & C. Raudvere (Eds.), *Old Norse religion in long-term perspectives: origins, changes, and interactions: An international conference in Lund, Sweden, June 3–7, 2004* (pp. 79–85). Lund: Nordic Academic Press.

Hai, N. G. (2005). Ancient metallurgy in Vietnam: An ethnoarchaeological investigation. *Bulletin of the Indo-Pacific Prehistory Association*, *25*, 121–123.

Hakluyt, R. (1904). *The principal navigations, voyages, traffiques, and discoveries of the english nation*: *Vol. 8*. Glasgow: James MacLehose and Sons.

Hartley, L. P. (1953). *The Go-Between*. London: Hamish Hamilton.

Heimann, R., Kreher, U., Oexle, J., Hirsekorn, O., Ullrich, O., Janke, D., Lychatz, B., Ullrich, B., Lindner, H., & Wagenbreth, W. (1998). Archaeometallurgical investigations into the iron production technology in Upper Lusatia, Saxony, from the early Iron Age (Billendorf period) to the 12th century A.D. *European Journal of Mineralogy*, *10*, 1015–1035.

Herbert, E. W. (1993). *Iron, gender and power: Rituals of transformation in African societies*. Bloomington: Indiana University Press.

Hingley, R. (1997). Iron, ironworking and regeneration: A study of the symbolic meaning of metalwork in Iron Age Britain. In A. Gwilt & C. Haselgrove (Eds.), *Reconstructing iron age societies: New approaches to the British iron age* (pp. 9–18). Oxford: Oxbow Books.

Hoover, H. C., & Hoover, L. H. (trans.). (1950). *De Re Metallica*. New York: Dover

Horne, L. (1983). The brasscasters of Dariapur, West Bengal. *Expedition*, *29*(3), 39–46.

Horne, L. (1994). Itinerant brasscasters of eastern India. In B. Allchin (Ed.), *Living traditions: Studies in the ethnoarchaeology of South Asia* (pp. 265–80). New Delhi: Oxford and IBH Publishing Co.

Horton, R. (1993). *Patterns of thought in African and the West: Essays on magic, religion and science.* Cambridge: Cambridge University Press.

Hosler, D. (1994). *The sounds and colors of power: The sacred metallurgical technology of ancient West Mexico.* Cambridge: MIT Press.

Housden, J., & Armor, M. (1959). Indigenous iron smelters at Kalabo. *The Northern Rhodesia Journal*, *4*, 135–138.

Iles, L. (2013). Applying ethnographic presents to archaeological pasts: The relevance of memories of iron production in western Uganda In J. Humphris & Th. Rehren (Eds.), *The World of Iron* (pp. 281–287). London: Archetype.

Iles, L. (In press, b). Iron production in Uganda: memories of a near-forgotten industry. In H. Orange (Ed.), *Reanimating industrial heritage*. Walnut Creek: Left Coast Press.
Johnson, M. (2010). *Archaeological theory: An introduction*. Oxford: Wiley-Blackwell.
Juleff, G. (1998). *Early iron and steel in Sri Lanka. A study of the Samanalawewa Area.* Philipp von Zabern: Verlag.
Juleff, G., Craddock, P. T., Malim, T. (2009). In the footsteps of Ananda Coomaraswamy: Veralugasmankada and the archaeology and oral history of traditional iron smelting in Sri Lanka. *Historical Metallurgy*, *43*, 109–134.
Kellogg, L. P. (1917). *Early Narratives of the Northwest, 1634–1699*. New York: Charles Schribner's Sons.
Kense, F. (1983). *Traditional African iron working*. Calgary: African Occasional Papers 1.
Killick, D. (1990). *Technology in its social setting bloomery iron-smelting at Kasungu, Malawi;* 1860–1940. PhD thesis, Ann Arbor, Michigan.
Killick, D. (1991). The relevance of recent African iron-smelting practice to reconstructions of prehistoric smelting technology. In P. D. Glumac (Ed.), *Recent trends in archaeometallurgical research*. (pp. 47–54). MASCA Research Papers in Science and Archaeology.
Killick, D. (2009). Cairo to Cape: The spread of metallurgy through Eastern and Southern Africa. *Journal of World Prehistory*, *22*, 399–414.
Kusimba, C. M. (1996). Social context of iron forging on the Kenya coast. *Africa*, *66*, 386–410.
Lane, P. J. (2006). Present to past: Ethnoarchaeology. In C. Tilley, et al. (Eds.), *Handbook of Material Culture*. London: Sage.
Lanning, E. (1954). Genital symbols on smiths' bellows in Uganda. *Man*, *54*, 167–169.
Larick, R. (1985). Spears, style and time among Maa-speaking pastoralists. *Journal of Anthropological Archaeology*, *4*, 206–220.
Larick, R. (1986). Age grading and ethnicity in the style of Loikop (Samburu) spears. *World Archaeology*, *18*, 269–283.
Lechtman, H. (1979). A pre-Columbian technique for electrochemical replacement plating of gold and silver on copper objects. *Journal of Metals*, *31*, 154–160.
Lechtman, H. (1981). Copper-arsenic bronzes from the north coast of Peru. *Annals of the New York Academy of Sciences*, *376*, 77–122.
Lechtman, H. (1984). Andean value systems and the development of prehistoric metallurgy. *Technology and Culture*, *25*, 1–36.
Lemonnier, P. (1986). The study of material culture today: Towards an anthropology of technical systems. *Journal of Anthropological Archaeology*, *5*, 147–186.
Lemonnier, P. (1992). *Elements for an anthropology of technology*. Michigan: Ann Arbor.
Lubbock, J. (1865). *Pre-Historic times: As Illustrated by ancient remains, and the manners and customs of modern savages*. London: Williams & Norgate.
Maes, J. (1930). La métallurgie chez les populations du lac Leapold II-Lukenie. *Ethnologica*, *4*, 68–101.
Martin, S. R. (1999). *Wonderful Power: The story of ancient copper working in the Lake Superior basin*. Detroit: Wayne State University Press.
Martinón-Torres, M., & Rehren, Th. (2002). Agricola and Zwickau: Theory and practice of Renaissance brass production in SE Germany. *Historical Metallurgy*, *36*, 95–111.
Martinón-Torres, M., Valcárcel Rojas, R., Cooper, J., & Rehren, Th. (2007). Metals, microanalysis and meaning: A study of metal objects excavated from the indigenous cemetery of El Chorro de Maíta, Cuba. *Journal of Archaeological Science*, *34*, 194–204.
McCrindle, J. (1926). *Ancient India as described by Megasthenês and Arrian: being a translation of the fragments of the Indika of Megasthenês collected by Dr. Schwanbeck, and of the first part of the Indika of Arrian*. Calcutta: Chuckervertty, Chatterjee.
Miller, D., Mulaudzi, M., & Killick, D. (2003). An historical account of bloomery iron working in the Lowveld, South Africa. *Historical Metallurgy*, *36*, 112–121.

Muhly, J. D. (1988). The beginnings of metallurgy in the old world. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 2–20). Cambridge: MIT Press.
Nash, J. (1979). *We eat the mines and the mines eat us*. New York: Columbia University Press.
Oliver, J. R. (2000). Gold symbolism among Caribbean chiefdoms: Of feathers, Çibas and Guanín power among Taíno Elites. In C. McEwan (Ed.), *Pre-Columbian gold in South America: Technology, style and iconography* (pp. 196–219). London: British Museum Press.
Parker Pearson, M., & Ramilisonina. (1998). Stonehenge for the ancestors: The stones pass on the message. *Antiquity*, *72*, 308–326.
Percy, J. (1970). *The Metallurgy of Lead: Including Desilverisation and Cupellation*. London: John Murray.
Pfaffenberger, B. (1992). Social anthropology of technology. *Annual Review of Anthropology*, *21*, 491–516.
Reid, A., & MacLean, R. (1995). Symbolism and the social context of iron production in Karagwe. *World Archaeology*, *27*, 144–161.
Renfrew, C. (1973). *Before civilisation, the radiocarbon revolution and prehistoric Europe*. London: Cape.
Rijal, S. (1995). *The indigenous methods of iron production: A case study of the Khamis of Rokaya VDC from Jajarkot District.* MA thesis. Khatmandu: University of Tribhuvan.
Rijal, S. (1998). *The traditional system of iron-working: The technology, social context and rituals of transformation.* MA thesis. Bergen: University of Bergen.
Robinson, K. R. (1961). Two iron-smelting furnaces from the Chibi Native Reserve, Southern Rhodesia. *South African Archaeological Bulletin*, *16*, 20–22.
Roscoe, J. (1911). *The Baganda*. London: Macmillan and Co.
Roscoe, J. (1915). *The Northern Bantu: An account of some central African tribes of the Uganda Protectorate*. Cambridge: Cambridge University Press.
Roscoe, J. (1923). *The Bakitara or Banyoro*. Cambridge: Cambridge University Press.
Rowlands, M. J. (1971). The archaeological interpretation of prehistoric metalworking. *World Archaeology*, *3*, 210–224.
Rowlands, M.J., & Warnier, J.-P. (1993). The magical production of iron in the Cameroon Grassfields. In T. Shaw, P. Sinclair, B. Andah, & I. Okpoko (Eds.), *The archaeology of Africa: Food, metals and towns* (pp. 512–50). London: Routledge.
Schiffer, M. B. (1978). Methodological issues in ethnoarchaeology. In R. Gould (Ed.), *Explorations in Ethnoarchaeology*. Albuquerque: University of New Mexico Press.
Schmidt, P. R. (1996). *The culture and technology of African iron production*. Gainesville: University Press of Florida.
Schmidt, P. R. (1997). *Iron technology in East Africa: Symbolism, science and archaeology*. Bloomington: University of Indiana Press.
Schmidt, P. R. (2010). Social memory and trauma in northwestern Tanzania: Organic, spontaneous community collaboration. *Journal of Social Archaeology*, *10*, 255–279.
Schmidt, P. R., & Avery, D. (1978). Complex iron smelting and prehistoric culture in Tanzania. *Science*, *201*, 1085–1089.
Schweinfurth, G., Ratzel, F., Felkin, R. W., & Hartlaub, G. (Eds.). (1888). *Emin Pasha in Central Africa: Being a collection of his letters and journals* (trans: Mrs. R. W. Felkin). London: George Philip & Son.
Sillitoe, P., & Hardy, K. (2003). Living lithics: Ethnoarchaeology in highland Papua New Guinea. *Antiquity*, *77*, 555–566.
Shimada, I. (1994). Pre-Hispanic metallurgy and mining in the Andes: Recent advances and future tasks. In A. Craig & R. West (Eds.), *In quest of mineral wealth: Aboriginal and colonial mining and metallurgy in Spanish America* (Vol. 33, pp. 37–73). Los Angeles: Louisiana State University.
Shimada, I. & Merkel, J. (1991). Copper alloy metallurgy in ancient Peru. *Scientific American*, *265*, 80–86.
Shimada, I., Epstein, S., & Craig, A. (1982). Batan Grande: A prehistoric metallurgical center in Peru. *Science*, *216*, 952–959.
Smith, E., & Dale, A. (1968). *The Ila-speaking peoples of Northern Rhodesia,* Vol I. and II 1920. New York: University Books.

Spenser, H. (1863). *First Principles*. London: Willams & Norgate.
Stephens, F. (1901–1902). Geology and mineral resources of Kumaon and Garwhal. *Transactions of the Institute of Mining and Metallurgy*, *10*, 393–414.
Stiles, D. (1977). Ethnoarchaeology: A discussion of methods and applications. *Man*, *12*, 87–103.
Tholander, E. (1987). *Experimental studies on early iron-making*. Unpublished dissertation, The Royal Institute of Technology, Department of Process Metallurgy, Stockholm.
Thompson, D. (1939). The seasonal factor in human culture, illustrated from the life of a contemporary nomadic group. *Proceedings of the Prehistoric Society*, *5*, 209–21.
Thornton, C. P. (2009). Archaeometallurgy: Evidence of a paradigm shift. In T. K. Kienlin & B. W. Roberts (Eds.), *Metals and societies*. *Studies in honour of Barbara S. Ottaway* (pp. 25–33). Universitätsforschungen zur prähistorischen Archäologie. Bonn: Habelt.
Thwaites, Rueben G. (Ed). (1896–1901). *The Jesuit relations and allied documents*. 73 vols. Cleveland: Burrows Brothers Co.
Todd, J. (1985). Iron production by the Dimi of Ethiopia. In R. Haaland & P. Shinnie (eds.) *African iron working: Ancient and traditional* (pp. 88–101). Oslo: Norwegian University Press.
Tringham, R. (1978). Experimentation, Ethnoarchaeology, and the Leapfrogs in Archaeological Methodology. In R. Gould (Ed.), *Explorations in ethnoarchaeology* (pp. 169–199). Albuquerque: University of New Mexico Press.
van Buren, M., & Mills, B. (2005). Huayrachinas and tocochimbos: Traditional smelting technology of the southern Andes. *Latin American Antiquity 16*, 3–25.
van der Merwe, N. J., & Avery, D. H. (1987). Science and magic in African technology: Traditional iron smelting in Malawi. *Africa*, *57*, 143–172.
Wagner, D. (1984). Some traditional chinese iron production techniques practiced in the 20th century. *Journal of the Historical Metallurgy Society*, *18*, 95–104.
Wagner, D. (2008). *Science and civilisation in China. Volume 5: Chemistry and chemical technology, Part II: Ferrous metallurgy*. Cambridge: Cambridge University Press.
Watson, B. (trans.). (1993). *Records of the grand historian: Han Dynasty I, by Sima Qian*. New York: Columbia University Press.
Wauchope, R. (1938). *Modern Maya Houses*. Publication No. 50. Carnegie Institution: Washington.
Wembah-Rashid, J. (1969). Iron workers of Ufipa. *Bulletin of the International Committee on Anthropological and Ethnological Research*, *11*, 65–72.
Wise, R. (1958a). Iron smelting in Ufipa. *Tanganyika Notes and Records*, *50*, 106–111.
Wise, R. (1958b). Some rituals of iron-making in Ufipa. *Tanganyika Notes and Records*, *51*, 232–238.
Wroth, L. C. (1970). *The Voyages of Giovanni de Verranzano: 1524–1528*. Yale University Press, New Haven.
Wyckaert, P. (1914). Forgerons païens et forgerons chrétiens au Tanganyika. *Anthropos*, *9*, 367–380.
Wylie, A. (2002). *Thinking from Things: Essays in the philosophy of Archaeology*. Berkeley: University of California Press.

Films

David, N., Augé H., & Le Bleis. (1988). *Dokwasa: Last of the African iron masters*.
Echard, N. (1968). *Noces de feu*.
Huysecom, E., & Agustoni, B. (1997). *Inagina, the last house of iron*. University of Geneva, Department of Anthropology.
O'Neill, P., & Muhly, F. (1988). *Tree of iron*. Documentary Educational Resources: Watertown.
Saltman, C., Goucher, C., & Herbert, E. W. (1986). *The blooms of Banjeli: Technology and gender in African iron making, Ghana*.

Websites

For an extensive online bibliography http://people.ucalgary.ca/~ndavid/Homepage/#Eabib

Chapter 10
Chemical and Isotopic Studies of Ancient Metals

A. Mark Pollard and Peter Bray

Introduction to Chemical and Isotopic Analysis of Metals

It is not the intention of this chapter to give a thorough introduction to the many and varied methods which have been used to analyze archaeological metals. Some of these can be found in the selected bibliography at the end of this chapter. The aim of this section is to guide and advise the student about the different sorts of analyses which can be done, and which ones might be appropriate under what circumstances.

When embarking upon an analytical study of ancient metalwork, the researcher must start with a single fundamental question: 'what is the purpose of the analysis?' or, perhaps more precisely, 'to what purpose will the analytical data be put?' Answers to this question might range from the apparently trivial 'I want to know what it is made of' to the 'I need to know from which particular ore deposit this metal was ultimately derived'. Another key question, and not unrelated, is 'how destructive can my analysis be?' Increasingly, museums and collection managers are asking for completely nondestructive (preferably 'noninvasive') analyses, which might make sense from a curatorial point of view but not necessarily from an academic perspective. It calls into question the reason why we are collecting these things at all—simply to preserve them as 'objects' in perpetuity, or as an archive of information which can help us understand the human past? In many ways, this is a false dichotomy. On the one hand, analytical methods are tending toward being more-or-less nondestructive (but not noninvasive!), and so it might be seen as prudent to restrict sampling access for as long as possible. On the other hand, one might argue that if the information is worth having, then it is worth a small sacrifice. We are back to the quality of the question again.

A. M. Pollard (✉)
Research Laboratory for Archaeology and the History of Art, University of Oxford,
Dyson Perrins Building, South Parks Rd, OX1 3QY Oxford, UK
e-mail: mark.pollard@rlaha.ox.ac.uk

P. Bray
e-mail: peter.bray@rlaha.ox.ac.uk

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_10,

In addition to the rise of 'nondestructive' methods, museums are beginning to prefer analyses that bring the instrument to the collection rather than the objects to the instrument. Handheld instruments that can be taken into the field or to a museum have varying strengths and weaknesses in comparison to standard laboratory-based equipment, or large international facilities such as synchrotrons or neutron sources, which require the object to be taken to the facility. As many countries are increasingly taking control of the export of antiquities even for research purposes, a student of the metalwork may have to visit the country to look at recently excavated material, and either take the portable analytical tools with them, or make arrangements to have the work done with local partners.

In terms of the choice of analytical tools, let us be quite clear—there is no universal panacea for the analysis (chemical or isotopic) of metals. No one technique has all the answers, although some may now seem to approach it. No one technique is 'best'. Nor can the analysis be carried out from a recipe book. Each case is different. Different forms of ores and mineral deposits mean that, in some studies, one particular element or suite of elements may be the critical distinguishing factor, but in others, it may be irrelevant. In some cases, isotopic measurements may be diagnostic, while in others they may be completely ambiguous. What is 'right' depends on the nature of the question. Of course, as professionals we would always claim that the choice of analytical tool is made calmly and logically, to reflect the nature of the question. At one level this is true, but in many cases the choice is severely influenced by levels of availability and access, cost, and what is actually working at the time. Most graduate students know this from firsthand experience!

One issue to deal with is cost. All analyses cost money, even if no money changes hands. The true cost of some analyses can be enormous—consider the full cost of studying a metal object using a multimillion dollar synchrotron radiation source, or even just the marginal cost of doing so (i.e., not contributing to the cost of building the machine itself, but paying for the running costs). Somebody is paying for the capital investment and infrastructure that support these facilities. Archaeologists, and particularly (but by no means exclusively) commercial archaeologists (salvage or rescue archaeology), have a habit of considering some technical approaches as 'too expensive' to consider. Often there is no money in the budget to pay for any post-excavation analysis, and thus a lot of important work never gets done. However, there is no such thing as 'too expensive'. There is only a rational cost/benefit analysis, which balances the cost of obtaining the information against the intellectual value of that information. A cheap analysis which concludes that Roman nails contain iron, or that, in another context, pottery is made of clay, is poor value. An analysis (expensive or not) that rewrites our views on the role of copper alloys in the Early Bronze Age is good value. Again, it is the quality of the question that counts. There is a clear onus on the analyst to be able to explain to managers and finance officers what their work can deliver intellectually, above and beyond an appendix to a site report.

There is also a need to take into account the different levels of analysis that are possible, and what might be necessary for the question asked. A key differentiation is between destructive and nondestructive analysis, as described in more detail below. Although these categories appear to be mutually exclusive, the distinction between them is not always clear-cut. A second distinction to be made is between *qualitative*, *semiquantitative*, and *quantitative* analyses. Crudely speaking, *qualitative* is simply asking whether a particular element is present or not. This might be sufficient to identify a metal as gold rather than something else, or an alloy as bronze rather than brass, and may be all that is required. *Semiquantitative* can mean either an approximate analysis or that the amount of a particular element is categorized into broad groups, such as 'major' (a lot), 'minor' (a bit), or 'trace' (just enough to detect), or perhaps into bands such as '1–5 %'.[1] Again, this might be sufficient to answer the question 'is the major alloying element tin or zinc?' A *quantitative* analysis (sometimes referred to somewhat tautologically as 'fully quantitative'), on the other hand, is an attempt to quantify to some specified level of precision all of the components present in an alloy above a certain level.[2] Ideally, we should aim at quantitative analysis of as many elements as possible, validated by accompanying data on internationally accepted standard materials. In the end, quantitative data will have lasting value, and will mean that future analysts will not need to go back to the object and take more samples. Mostly, however, we compromise.

Nondestructive Chemical Analysis

Nondestructive methods are increasingly important in the study of archaeological and museum objects. First and foremost, among these techniques is X-ray fluorescence (XRF), which is now increasingly available as a handheld portable system. XRF uses a source of X-ray (usually an X-ray tube, but occasionally a sealed radioactive source) to irradiate the sample. The incoming ('primary') X-rays interact with the atoms that make up the sample and cause them to emit secondary ('characteristic') X-rays of a very specific energy. In the majority of XRF systems (the so-called energy dispersive systems), these secondary X-rays are captured in a solid-state detector, which both measures their energy and counts their number By knowing the energy of the secondary X-ray, we can identify which atom (i.e., element) it has come from, and from the number, we can estimate how much of that particular element is present in the sample. If the analysis is done in air (i.e., without the need to enclose the sample in an evacuated chamber), then the whole device can be made portable and the machine can be taken to the object, although the sensitivity and precision of the analysis is somewhat compromised. Some portable devices now come with 'skirts' that fit over the object and allow at least a partial vacuum, which improves the performance somewhat.

[1] It is important to note whether results are expressed in atomic or weight %. Atomic % denotes the percentage of the total number of atoms in a sample that are of a particular element. Weight % denotes what percentage of the mass of the sample each element contributes. If an archaeometallurgy paper does not explicitly state which system has been used, with caution, it can be assumed the results are in weight %.

[2] Bear in mind that, with at least 93 naturally occurring elements in the Periodic Table, no analysis containing fewer elements can truly claim to be 'fully quantitative'!

The advantages of XRF are many. It can give a rapid analysis, typically done in a few minutes or so. For metals, it can analyze most elements of interest, but if an air path is used (as described above), it cannot detect any element below calcium (Ca, atomic number 20) in the Periodic Table. Even under vacuum, the lightest element which can be seen by XRF is sodium (Na, atomic number 11). Thus, if using an air path, modern alloys containing magnesium or aluminum will show no sign of these components. Of the metals known in antiquity, however, this is only a problem for iron, where the main alloying elements (e.g., carbon and phosphorus) are too light to be seen by XRF, even under vacuum. Nevertheless, XRF is particularly well suited to metal alloy identification and quantification, as the majority of alloys used in antiquity (gold–silver/electrum and the bronzes and brasses) are primarily made up of heavy metals which show up well under XRF.

The disadvantages of XRF are also numerous. It is not a particularly *sensitive* method—sensitivity here is taken to mean the smallest amount of a particular element that can be measured accurately. For most elements in XRF, this is typically around 0.1 wt%, but the exact value will depend on the element being detected and nature of the other elements present. This is more than adequate if the nature of the question is ‘what alloy am I dealing with?’ Or, indeed, ‘what are the major impurities present in this metal?’, but it is nowhere near as sensitive as many of the techniques that involve sampling. More significantly, it is also a surface-sensitive technique due to absorption of the secondary X-rays by the metal matrix as they leave the sample. The degree to which these secondary X-rays are absorbed depends on the energy of the secondary X-ray and the nature of the material(s) through which it needs to pass in order to get to the detector. Typically, information is only obtainable from the top few tenths of a millimeter below the surface. Thus, if the surface is corroded, dirty, or unrepresentative of the bulk composition for any reason (see below), then the analysis given may be completely misleading. Sometimes this problem can be reduced by judicious mechanical cleaning of the surface (or preferably an edge) to reveal bright, uncorroded metal, but this may be curatorially unacceptable. This may be a particularly serious problem with handheld instruments, because often the primary X-ray beam diameter is a centimeter wide (to compensate for the relatively low intensity of the source); thus, the area needing to be cleaned may be too big for most museum curators. Other nondestructive analytical tools are available to the archaeometallurgist, provided he/she is prepared to transport the object to the facility. These include synchrotron XRF (sXRF), which is identical to other forms of XRF apart from the source of the X-rays, which in this case is a huge circular electron accelerator called a synchrotron. Accelerated to almost the speed of light, these electrons give off electromagnetic radiation of all frequencies from high-energy X-rays to long-wavelength radio waves. By harnessing the X-ray emission, the synchrotron can provide a highly intense collimated beam of monochromatic X-rays, which provide an excellent source of primary X-rays for XRF. Because they are so intense, it is normal to carry out sXRF in air, so that large objects of any shape can be accommodated in front of the beam, although the secondary X-rays are still attenuated by passage through air as described above.

In a similar vein, other forms of particle accelerator can be used to provide the primary beam for analytical use. Perhaps the most common is proton-induced X-ray emission (PIXE). In this case, a beam of protons is accelerated to high energies in a linear accelerator and extracted as a fine beam, which then strikes the object being analyzed. The protons interact with the atoms in the sample, causing them to emit secondary X-rays, as in XRF. Because the beam is external to the accelerator, objects of any shape can be analyzed in air, with the same advantages and disadvantages as above. The analytical sensitivity of PIXE is generally better than XRF, because proton impact causes a lower background X-ray signal than is the case with primary X-rays or electrons, so sensitivities on the order of a few parts per million (ppm) are possible.

Recent instrumental developments in PIXE have resulted in highly focused proton beams (down to a few microns) that allow chemical analysis and elemental mapping on the microscopic scale. This technique is called microPIXE, or μ-PIXE. Variants of PIXE include particle- (or proton-)induced gamma-ray emission (PIGE) in which the elements in the sample are identified by the gamma rays they emit as a result of proton beam irradiation (rather than by secondary X-rays). This method can be used to detect some of the lighter elements that XRF or other methods cannot detect.

(Mildly) Destructive Chemical Analysis

Where at all possible, it is usually better from an analytical point of view to remove a small sample from the metal object, polish it, and mount it for analysis. This also allows physical examination of the artifact (e.g., metallography, hardness, etc., as described in Chapter x) before any chemical analysis is carried out. Sampling also allows for spatially resolved chemical analysis—i.e., how does the composition of the sample vary from the surface to the interior of the artifact? When combined with information on the phase structure provided by optical microscopy, chemical analyses of this kind are an extremely valuable entry point into understanding the manufacture and use—the ‘biography’—of the object.

Once a sample has been taken, there are a very large number of choices of analytical instrumentation available. The two most common ones used today are based on either electron microscopy (EM) or inductively coupled plasma spectrometry (ICP).

Electron Microscopy

EM has been the workhorse of the chemical study of metals for more than 40 years. It is important to realize that although the microscopy side of the instrument is dependent upon a beam of electrons, the actual chemical analysis is still primarily dependent upon the detection of X-rays. EM has many advantages. It is widely available and can produce high-resolution images of the physical structures present, as well as micro-point chemical analyses and two-dimensional (2D) chemical maps of the exposed surface. As a technique, it has had many pseudonyms over the years, based upon the particular configuration available—electron microprobe analysis (EMPA), scanning electron microscopy (SEM), scanning electron microprobe with energy dispersive spectrometry (SEM-EDS), SEM with wavelength dispersive spectrometry (SEM-WDS), and probably more.

As an analytical tool (as opposed to a high-powered imaging device), the key aspect to understand about EM is how the chemical analysis is actually achieved, which in effect means: how are the secondary X-rays detected? In an EDS system, the process is almost identical to that described above for XRF, except that the primary beam in this case is made up of electrons rather than X-rays. These primary electrons have the advantage over X-rays of being steerable and focusable using electrostatic devices, and having more controllable energies. The electrons strike the sample and interact with the atoms to produce characteristic X-rays, which are collected and counted using solid-state detectors as before. Because such an analysis usually takes place in a high-vacuum chamber on a prepared and polished flat sample, many of the problems inherent with XRF are reduced. The sensitivity to lighter elements is much better than XRF, even to the extent that some systems can measure carbon in iron. Furthermore, the problem of surface sensitivity can be controlled by cleaning and/or preparing the sample in such a way that it provides a cross section of the artifact. One big advantage of energy dispersive analysis combined with SEM is that the speed of the analysis is such that 2D chemical maps of the prepared surface can be readily produced, showing just how and where the elemental inhomogeneities are distributed within the metallographic structures (i.e., are certain elements within the grains or between the grains, near the surface or near the core, etc.).

Less widely available (not only because of higher cost but also because of the expertise required to produce good data), but regarded by many as the 'gold standard' for metals analysis, is wavelength dispersive X-ray detection (WDS) in EM. This method differs from EDS only in the way that the X-rays are detected. However, it tends to make the machine much more suited to analytical rather than imaging applications, making it rather more specialized and less flexible than the 'all purpose' machines that use (energy dispersive) ED detection. In practice, many of the larger and more expensive machines have multiple wavelength detectors and an ED detector, giving multiple functionality. In WDS machines, the X-rays emitted from the sample are considered to be waves in the X-ray region of the electromagnetic spectrum, rather than particles of a particular energy. The nature of the parent atom is defined by the characteristic wavelength of the X-rays produced, and the number of atoms present is defined by the intensity of this wavelength. This is a graphic illustration of the quantum mechanical principle of particle–wave duality! The wavelength of the X-rays is measured using a crystal as a diffraction grating, which resolves the X-rays into their component wavelengths (in the same way as water droplets produce a rainbow), and the intensity of each wavelength is measured via a solid-state detector.

Without going into too much detail, WDS analysis in EM gives better sensitivity than EDS (typically detecting elements down to 0.001–0.01 %, rather than 0.1 % by EDS), but it is slower, which makes 2D mapping more cumbersome. In both forms of detection, however, because the primary irradiation is by electrons rather than X-rays, the beam can be focused down to a few microns in diameter, giving a spatial resolution for the chemical analysis in the order of a few tens of microns. This is necessary when looking at phenomena such as age embrittlement in alloys, where microscopic phases are precipitated at grain boundaries, or when attempting to characterize small inclusions in slag or metal that can tell us about the ore sources used and the metalworking processes applied.

It is worth pointing out that much more can now be achieved through EM without sampling than was possible just a few years ago. Environmental chambers, operating at near-atmospheric pressure, are available which can accommodate large objects (up to 30 cm in diameter and 8 cm high). Such equipment can produce images and analyses without the need for applying a conducting coat of gold or carbon to prevent charging. Software developments include 'hypermapping', where the data are collected and stored as a series of superimposed elemental maps. This allows the analyst to go back to the data at any time and generate a point analysis or a 2D map without needing to reanalyze the sample. The advantage of this is that it is feasible to collect all the data that might be conceivably needed now and in the future, and thus limit the analysis of an object to a one-off event. The downside of this method is the same as for nondestructive XRF: surface-only analysis and lowered sensitivity.

Inductively Coupled Plasma Spectroscopy/Spectrometry

ICP in various formats is now the method-of-choice for chemical analysis in a wide range of applications across research and industry. In its current form, it represents the refinement of a long line of optical spectroscopy techniques for chemical analysis, going back to optical emission spectroscopy that was developed in the 1930s. The principle is simple—when an atom is 'excited' (i.e., given a lot of energy), it reorganizes itself, but almost instantaneously de-excites back to its original state with the emission of a pulse of electromagnetic radiation, which is often in the visible part of the spectrum. In other words, it gives off light. The wavelength of this light is characteristic of the atom from which it came, and the intensity (amount) of light is proportional to the number of atoms of that particular element in the sample. Measurement of the wavelength and intensity of the light given off from a sample therefore forms the basis of a quantitative analytical tool of great sensitivity. In ICP, the sample is introduced into an extremely hot plasma at around 10,000 °C, which causes the atoms to emit characteristic frequencies. This emitted light is resolved into its component wavelengths using a diffraction grating, and the intensity of each line of interest measured. In this form, the instrument is known as an inductively coupled plasma optical emission spectrometer (ICP-OES), or sometimes as an ICP atomic emission spectrometer (ICP-AES). The use of ICP as an ion source for mass spectrometry (inductively coupled plasma mass spectrometer (ICP-MS)) is discussed in more detail below.

ICP is an extremely sensitive means of measuring elemental composition. Depending on the element to be measured and the matrix it is in, it can usually detect many elements down to levels of ‘parts per billion’ (ppb, equal to 1 atom in 10^9) from a very small sample (which varies depending on the particular needs of the experiment). The sample can be introduced into the spectrometer as a liquid (i.e., dissolved in acid), but more recently attention has switched to a device which uses a pulsed laser to vaporize (ablate) a small volume from a solid sample into a gas stream which then enters the plasma torch. This is known as laser ablation ICP (LA-ICP-OES). Laser ablation has several advantages over solution analysis, not least of which is simplicity of sample preparation and the potential to produce spatially resolved chemical analyses of complex samples (including 2D elemental maps, line scans, etc., as described above). The disadvantages include somewhat lower levels of sensitivity and a much more complex procedure for producing quantitative data. However, the fine scale of the ablation technique (the crater produced by the laser can be typically 10–15 microns in diameter and depth) means that for all intents and purposes, the analysis can be regarded as ‘nondestructive’. This assumes, of course, that the object is small enough (perhaps up to 10 cm across) to fit into the laser ablation chamber (and, of course, that clean metal can be obtained to give a non-biased sample). It is therefore now possible to analyze small metal objects without cutting a sample, in which up to 20 or 30 elements are quantified, covering the concentration range of the major and minor alloying elements, down to sub-ppm levels (or 1 in 10^6) of trace elements. As discussed below, in some circumstances isotopic ratios for particular elements can also be measured if a mass spectrometric detector is used.

The elemental analytical capability of most ICP methods is comparable to or better than the data previously produced by neutron activation analysis (NAA), which is historically the preferred means of analyzing trace and ultra-trace elements in archaeological and geological sciences. NAA is not discussed in detail here because it is rapidly becoming obsolete as a result of increasing difficulties in obtaining neutron irradiation facilities. However, it is described in most standard texts on analytical and archaeological chemistry and is an important method to understand due to its prevalence in earlier research. Suffice it to say that the archaeological science literature (including archaeometallurgical literature) contains a good deal of high-quality NAA data, which raises the question of how we should use this legacy data—a matter discussed in more detail below.

Analyzing Metals with Surface Treatments

One important feature of the analysis of ancient metals (which is much less common in other branches of inorganic archaeological chemistry) is the fact that the surfaces of ancient metals are usually different in chemical composition from the bulk of the metal. This provides a challenge to the analyst. For example, a simple handheld XRF scan of an archaeological metal surface will almost certainly produce an analysis that is not representative of the entire artifact. This may not be a major problem if the purpose of the analysis is to simply categorize the object into a class of metal—arsenical copper, brass (copper–zinc), bronze (copper–tin), leaded bronze, etc., or to decide if the object contains gold or silver (essentially, a qualitative analysis). If the purpose of the analysis is to be more precise than this (e.g., to talk in terms finer than percentage points), then handheld XRF on unprepared surfaces is not particularly useful.

Metal surfaces can differ from bulk composition for two main reasons, described in detail below. One is that they were made that way, either deliberately or accidentally. The second is that the long-term interaction of the metal with the depositional environment has altered the surface, sometimes but not always resulting in a mineralized surface known as corrosion or patina.

Deliberate surface treatments are well known from antiquity, and come in a wide variety of forms. These include the deliberate tinning of a bronze surface to give a silvery appearance, and the surface enrichment of gold objects to remove base metals to give a richer gold appearance. These come under the category of deliberately applied surface finishes, and they may be the result of either chemical or physical treatment, or both. Some treatments are highly sophisticated and still poorly understood, such as the use of niello (a black mixture of sulfides of copper and silver, used as a decorative inlay), or shakudo (a gold and copper alloy which is chemically treated to give dark blue–purple patina on decorative Japanese metalwork), or even the enigmatic Corinthian Bronze ('aes'), which may have had either a black or golden appearance.

This area of research opens up the knotty question of 'how was an object or statue expected to look in antiquity?' We are today most familiar with bronze statues looking either green from copper corrosion or bronze-colored if 'cleaned'. However, it is highly likely that in certain periods of antiquity at least some statues were intended to look very different—they may have been gilded, or surface-treated to give black–purple colors, or even painted. The careful detection through chemical analysis of any remnants of surface finishes is crucial to understanding how these objects were intended to look, and what might have been their social function. It also leads into the fascinating area of deception, either for sheer fakery (e.g., making gold coinage look finer than it actually is), or into the mystical world of alchemy, where base metals can be given the appearance of gold. There is much serious archaeological research to be done on the metallurgical underpinnings and consequences of alchemy.

Accidental surface treatments include various segregation phenomena, such as 'tin sweat' on bronzes, in which the casting conditions are such that the tin-rich phases preferentially freeze at the surface of the mould, giving a silvery appearance. It is sometimes difficult to decide whether a particular effect was deliberately intended, or purely accidental.

The long-term interaction of a metal with its burial environment (or, in rarer or more recent cases, with its atmospheric environment if it has never been buried) is essentially the story of the attack of metal by water, and is often electrochemically mediated. For many years, aesthetics dictated that metal corrosion products should be scrubbed or stripped away to leave the bare metal, in search of the 'original appearance' of the object. Thankfully, this barbaric approach has diminished. In fact, if one ever wants to provoke an 'old-school' metal conservator into a frenzy, it is worth simply injecting into the conversation that the most interesting bit of a metal object is the corrosion products, which historically at least used to be thrown away. Most modern conservators would probably not entirely agree with this statement, but would concede that the corrosion products are part of the object's biography. In theory at least, the metal corrosion contains encoded within it the whole environmental history of the object, including evidence for manufacturing, use, discard, and deposition. Not only does this have implications for the materiality of the object, but it could also have implications for authenticity studies. Decoding this history is, however, another story.

In the light of all of this, it should be clear that when approaching a metal archaeological object for the purposes of chemical or isotopic analysis, the analyst must *expect* to find surface anomalies that may be vital to the biography of the object, or which will at least, if not identified and countered, render any analyses quantitatively unreliable. Each object is in this sense at least unique. The best advice to the analyst is to start with a careful optical microscopic examination, and then work upward!

Isotopic Analysis of Metallic Objects

In addition to the chemical composition of an object, another key attribute that can be measured is the isotopic composition of some, or all, of the elements in that object. Isotopes are different versions of the same element, which differ only in their mass. The chemical identity of an element is determined solely by the number of protons in the nucleus, though the number of neutrons can be variable. Thus copper (proton number 29) has two naturally occurring isotopes, indicated as ^{63}Cu and ^{65}Cu, meaning that one isotope has 29 protons plus 34 neutrons in the nucleus (i.e., 63 particles in the nucleus in total) and the other has 29 protons plus 36 neutrons (65 in total). The 'natural abundance' of these two isotopes is roughly 75 % and 25 %, respectively, meaning that the average atomic weight of naturally occurring copper is approximately 63.546.

Chemically speaking, the isotopes of an element behave identically, but sometimes they take part in chemical reactions or physical transformations (e.g., evaporation) at slightly different rates. This is because the difference in mass of the isotopes means that bond energies between one isotope and, for example, oxygen will be slightly different from that of another isotope and oxygen. Thus, in the course of various chemical reactions or transport phenomena, the ratio of one isotope to another of the same element may change. In the case of chemical reactions, this is termed *fractionation*, and means that the environmental or geological history of certain metals can be reconstructed by measurements of isotopic ratios.

Some stable isotopes are formed as the result of the radioactive decay of another element. For example, strontium has four stable naturally occurring isotopes: ^{84}Sr (natural abundance 0.56 % of the total Sr), ^{86}Sr (9.86 %), ^{87}Sr (7.0 %), and ^{88}Sr (82.58 %). Of these, ^{87}Sr is produced by the decay of the radioactive alkali metal ^{87}Rb, and is therefore termed *radiogenic*. Thus, the isotope ratio ^{87}Sr/^{86}Sr in a rock is related to the original isotopic composition of the rock, but will also change with time as the ^{87}Rb originally present turns into ^{87}Sr.

Almost all metals of interest to the archaeometallurgist have more than one naturally occurring isotope. In fact, elements with only one isotope are exceptional in nature, and the ones of most relevance here are gold, which occurs naturally only as ^{197}Au, and arsenic (^{75}As). Many, such as Cu (with the two isotopes listed above) and silver (^{107}Ag and ^{109}Ag) have a couple, but a significant proportion has several stable isotopes, including iron (with 4), lead (4), Ni (5), Zn (5), and, champion of them all, tin (10). There is thus plenty of scope for measuring isotopic ratios among the metals of interest to archaeologists.

Foremost and by far, the most intensively studied is lead. It has four stable isotopes, ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb, the latter three of which are the stable end members of the three long natural radioactive decay chains found in nature (starting with uranium (^{235}U and ^{238}U) and thorium (^{232}Th)). The approximate natural abundances of these four isotopes of lead are 1.4, 24.1, 22.1, and 52.4 %, respectively, but the precise abundances in any particular mineral or geological deposit depend on the geological age of that deposit, and the initial concentrations of uranium and thorium. Because of the large range of possible starting conditions and the differing geological ages of mineral deposits, there is large variability in the measured abundance of geological lead isotope ratios—much larger than in any other metal of interest here. For reasons of measurement discussed below, it is conventional in the study of heavy metal isotopes to deal with ratios of one isotope to another rather than absolute values of abundance. Thus, in archaeological discussions of lead isotope data, it is conventional to deal with three sets of ratios (^{208}Pb/^{206}Pb, ^{207}Pb/^{206}Pb, and ^{206}Pb/^{204}Pb) which can be plotted together as a pair of diagrams.

Measurement of Isotopic Ratios in Metals

Measurement of the isotopic ratios of metals requires some form of mass spectrometry, in which the numbers of constituent atoms in the sample are directly measured after being separated according to weight. Conventionally, this has been achieved using thermal ionization mass spectrometry (TIMS), in which the sample to be measured is chemically deposited from a solution onto a fine wire, mounted in a mass spectrometer, and heated to evaporate and ionize the sample. The ions are then extracted into the spectrometer electrostatically, and ions of different mass are steered into a bank of detectors—one for each mass of interest (this is called a 'multicollector' or 'MC' instrument). Rather than measure each isotope independently, however, it is better to report the results as ratios of one isotope to another, as the data can be directly recorded as the ratio of the electric current flowing through each of the two detectors. This means that any fluctuation in ionization efficiency at the source is seen as an equal fluctuation in both detectors. The potential inaccuracy is therefore canceled out, making the ratio more precise than a single measurement. The main drawback of TIMS is the time taken to prepare the sample. It needs to be dissolved into high-purity acids, often concentrated by passing through an exchange column, and then deposited on the wire. The number of samples that can be analyzed in this way is relatively slow.

The preeminent position of TIMS for isotopic studies was vastly altered in the late 1990s, when it was realized that an ICP torch is also an extremely efficient source of ions. Rather than using optical techniques to measure the concentration of atoms in the sample (as in ICP-OES, described above), it was realized that if the plasma containing the ionized sample could be fed into a mass spectrometer, then a new instrument was possible—ICP-MS. The technical trick is to interface an extremely hot gas from the plasma source with a mass spectrometer under vacuum in such a way that the mass spectrometer does not melt and the vacuum in the mass spectrometer is not destroyed. This was achieved in the 1980s, and such instruments became commercially available through the 1990s. Early systems of this type used a low-resolution quadrupole mass spectrometer as the detector, because it is fast, cheap, and efficient. It is very effective for trace element abundance analysis, but the isotopic ratio measurement precision of a quadrupole is typically 100 times poorer than can be achieved by TIMS, and so the instrument saw limited use as an isotopic measurement tool. The next generation of ICP instruments used much more sophisticated mass spectrometers—either bigger systems with much higher resolution, or (more effective still) feeding the output from one mass spectrometer into a second mass spectrometer to give much improved resolution—combined with multi-collector detectors. Such instruments, termed 'HR-MC-ICP-MS' (high-resolution multi-collector ICP-MS) or 'ICP-MS-MS' (ICP with two mass spectrometers), are capable of measuring isotopic ratios with precisions at least as good as TIMS (if not better), but with much simpler sample preparation. TIMS instruments are quoted as giving 95 % confidence levels in precision (i.e., measurement reproducibility) of $\pm 0.05\,\%$ for the $^{207}Pb/^{206}Pb$ ratio, and $\pm 0.01\,\%$ for $^{208}Pb/^{206}Pb$ and $^{206}Pb/^{204}Pb$: a modern high-resolution multi-collector will do at least as well as this, if not an order of magnitude better.

Initially, ICP-MS instruments were designed for solution input, but as described above, the addition of a laser ablation 'front end' for spatially analyzing solid samples has just about revolutionized the practice of isotopic ratio mass spectrometry for heavy metals such as lead. As long as a solid sample can fit into the ablation chamber, such analyses can be carried out without sampling and with virtually no visible damage. That is not to say such measurements are cheap or easy, but it does mean that large numbers of measurements can now be made quickly and at high precision, reopening the potential for large-scale studies of ancient metals.

What Can Chemical and Isotopic Data Tell Us?

There is a long history of the chemical analysis of ancient metalwork, going back at least to the late eighteenth century in Europe, with Martin Heinrich Klaproth's investigation in 1795 of the composition of ancient copper coins and Pearson's 1796 paper analyzing Bronze Age tin-bronze. Until the mid-twentieth century, the question was primarily one of 'what is it made from?—that is, which metals and alloys were used by 'the ancients', and what was the sequence of their development? Interestingly, from this simple question, systematic patterns of behavior appeared to emerge over much of the Old World, although at different times. The large-scale chemical analysis of metal artifacts from known archaeological contexts during the twentieth century allowed scholars to propose a model for the ‘development of metallurgy in the Old World’ from an early use of ‘native’ metals (i.e., metals like copper, gold, silver, or iron which can occur naturally in the metallic state), to the smelting of ‘pure’ copper, followed by arsenical copper alloys, followed by tin bronzes, followed by leaded tin bronzes, and then eventually an Iron Age. This developmental sequence often provided a framework for archaeometallurgical research, which, as the rest of this volume demonstrates, has increasingly been superseded by detailed regional studies.

Since the 1950s, the dominant driver in the chemical analysis of metals has been the quest for provenance—i.e., can metal artifacts be traced back to a particular ore deposit? Given that the dominant model of technological evolution at this time was one of diffusion, it was plainly logical to use the artifacts themselves to see if tracing metal back to ore source could identify the source whence the knowledge of metals diffused. It quickly became apparent that matching the trace elements in a particular copper alloy object with those of its parent ore deposit was a tall order. Indeed, there are many potential sources of copper ores in the ancient world, and broadly speaking, ores from similar genetic and geochemical environments are likely to have similar patterns of trace elements. Nevertheless, from the tens of thousands of analyses that have been done on European Bronze Age objects, it is certainly true to say that particular combinations of trace element patterns are discernible within the data, which many think are inevitably linked with particular regional ore sources. Given that typological approaches to European Bronze Age copper alloy artifacts have defined particular assemblages of objects as ‘industries’, then it is clear that analytical and typological analyses were moving in the same direction. Hence the obsession with ‘groups’ of trace elements which has permeated much of the twentieth-century thinking on European Bronze Age metallurgy.

The general failure of this approach has been well documented. It is certainly true that particular types of copper ore deposits are likely to give rise to specific combinations of trace element impurities in the smelted copper (or, in some cases, to the absence of specific impurities). These impurity patterns may well have regional or even specific locality significance, but only in the simplest (and rarest) of cases—that is, when the metal is ‘primary’ (i.e., made directly from smelted copper from a single ore source) and not mixed with copper from other sources or recycled and remelted. In other words, if a metal artifact has received the minimum of manipulation, consistent with that required to convert an ore to metal, then this approach may be suitable. In all other cases, which represent the vast majority of ancient metalwork that has come down to us, a more sophisticated model is required.

A fundamental problem with this standard model of metallic provenance is that the dominant factor which is thought to affect the trace element pattern in the metal artifact is the original trace element composition of the primary ore. Although all authors engaged in this work have recognized that issues such as recycling and remelting are also certain to perturb this standard model, in practice most authors then proceed to interpret the data by ignoring these factors. Another factor to be

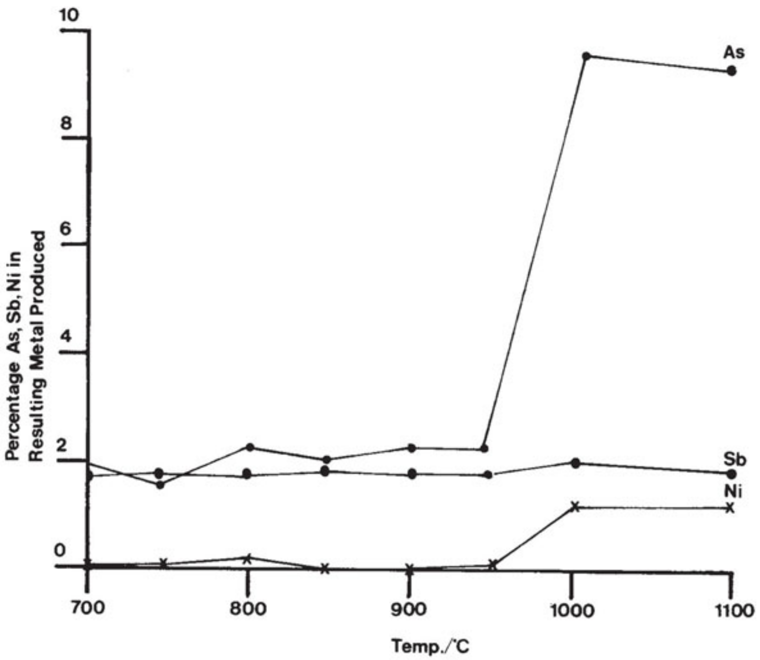


Fig. 10.1 Impurity content of copper alloy produced as a function of smelting temperature for charges containing 10 % As, 2 % Sb, and 2 % Ni

considered is that there is not necessarily a one-to-one relationship between the trace element pattern in the ore and the same pattern in the smelted metal. Not only do some trace elements preferentially concentrate in the slag (if there is any) as opposed to the liquid metal (called 'partitioning'), but there is even variation in this partitioning behavior as a function of temperature and 'redox' conditions (i.e., the degree of oxidation or reduction) in the furnace. It has been shown from laboratory experimentation, for example, that if a copper ore contains nickel, arsenic, and antimony, then all the antimony (Sb) in the charge is transferred to the metal at all temperatures between 700 and 1,100 °C. In contrast, the nickel (Ni) will not appear in the smelted metal at all unless the temperature is above 950 °C, while only low percentages of the original arsenic (As) content will be transferred at temperatures below 950 °C (see Fig. 10.1). Thus, if the 'impurity pattern' of interest consisted of the presence or absence of As, Sb, and Ni (all important elements in early copper-base metallurgy), then the impurity pattern for metal smelted from the same charge changes dramatically if the furnace temperature goes above 950–1000 °C. Under the standard model of provenance, such an observation would be taken as indicating a switch in ore source. This is not to say that all conclusions about provenance based upon changes in trace element pattern are wrong; it does, however, council caution if considering only one possible explanation for such a change.

Partly in response to these problems with the many large chemical analysis programs carried out in the 1960s and later, archaeometallurgists turned with glee to the new technique of lead isotope analysis (LIA). Much has been written about the value and limitations of LIA in archaeology as it has the potential to be an invaluable tool for provenance studies. LIA is based upon the fact that different ore bodies will contain varying initial amounts of thorium, uranium, and primogenic lead. Over varying amounts of time (depending of course on when the ore body was formed) radiogenic decay produces distinct lead isotope signatures that are dependent on the starting parameters of the ore body. This method proved to have importance not only for ancient metals that contain lead (i.e., copper alloys, silver alloys, as well as lead and lead/tin alloys) but also for glass, ceramics, and even human bone. The fact that LIA has yet to fully achieve this potential (at least as far as ancient metals are concerned) is probably also due to a lack of sophistication in the way that the provenance model has been applied, in much the same way as chemical provenancing discussed above.

One key issue that has yet to be fully addressed is the degree to which different ore deposits within a particular region can be expected to have distinctly different lead isotope signals. Clearly, this primarily depends upon the geological nature of the deposits, but it is worth recalling that much of the 1990s was taken up with a polarized debate between two key groups of LIA practitioners. One group stated that the various metalliferous outcrops on the Aegean islands could largely be distinguished from each other, while the other group (using much the same data) felt that they could not and preferred to use a single ‘Aegean field’. This debate, as much about philosophy as about ore geology and mathematics, is not dissimilar to the debates in evolutionary biology between ‘lumpers’ and ‘splitters’.

The most definitive recent statement using British data has come from the work of Brenda Rohl and Stuart Needham who have shown that the lead isotope fields for the four main mineralized regions of England and Wales effectively overlap and are therefore indistinguishable. They coined the term EWLIO—the England and Wales Lead Isotope Outline—to signify the lack of resolution between these sources. Moreover, the ore fields of the neighboring countries (Ireland, Western France, Germany, and Belgium) are also shown to be considerably overlapping with EWLIO. In other words, lead isotope data on their own are clearly not sufficient to distinguish between ore sources in northwestern Europe. Their research did, however, indicate a possible way forward by combining trace element patterns with lead isotope signatures and archaeological typologies, in a manner which has subsequently been built on elsewhere, as described below.

One interesting outcome of this discussion of the use of lead isotope data as a technique for provenancing has been the investigation of the conditions under which anthropogenic processing might affect the value of the isotopic ratio. It is well known elsewhere in isotope systematics that for the light elements (hydrogen, carbon, nitrogen, etc.), fractionation (changing of the isotopic ratio) is an inevitable consequence of many natural processes—indeed, it is this very fact that makes carbon isotopes such a powerful tool in tracing carbon cycling through the ecosystem. The question is: do heavy metal isotopes (Pb, Cu, Zn, etc.) undergo similar fractionation, especially as a result of anthropogenic processes such as smelting? Orthodoxy would say no. It is, however, possible to show that under certain conditions, such as nonequilibrium evaporation from a liquid phase, it is theoretically plausible that fractionation would occur. Such conditions might easily occur during the processing of metals in antiquity. All that is required is that the vapor phase above a liquid metal is constantly removed during evaporation. As light isotopes preferentially enter the vapor phase, the remaining liquid is gradually enriched in the heavier isotope. It is not difficult to conceive of some stages of metal processing which approximate to these conditions.

Unfortunately, at the time these processes were being investigated (1990s), measurement techniques were too imprecise to detect what, for all practical metallurgical processes, were likely to be small effects. Certainly, the attempts of the time failed to measure significant fractionation as a result of anthropogenic processing of lead or tin. Zinc, the major component of brass, and an extremely volatile element, showed much more promise. Unfortunately, none of these experiments have been repeated using the much more sensitive analytical equipment available today. We know relatively little about the natural variation in copper, tin, and zinc isotopes between different types of deposit. More interestingly, perhaps, it is possible that anthropogenically induced fractionation in these isotopes might offer an opportunity to observe smelting and melting processes. It would not be surprising, for example, if measurement of zinc isotopes allowed a distinction to be made between brass made by the direct process (adding zinc metal to copper metal) and that made by the calamine process (vaporizing zinc to form zinc-oxide and then adding this to copper). Similarly, does the tin isotope ratio in a bronze change systematically in proportion to the length of time the metal is molten? Does it therefore change measurably each time a bronze object is recycled? There is clearly a need for a series of careful laboratory experiments, leading to a program of experimental archaeology.Working with Legacy Data

The world of archaeometallurgy is blessed with a plethora of data on the chemical composition of ancient copper alloys (and, to a much lesser extent, other alloys including iron), and also with a corpus of lead isotope data from ancient mine sites and from copper, lead, and silver objects from the ancient world. In theory, this dataset is of immense value, and provides a basis upon which all scholars should be able to build their research. Apart from the usual problems of non-publication of some key data, the frequent lack of sufficient descriptive or contextual detail, and the occasional erroneous values, these data (particularly the chemical data) suffer from one major problem: they were measured using the best techniques of their time, which were (usually) not as good as those we have now. It would, however, be wrong to assume that all data collected in the past are inferior to that obtained now. For example, gravimetric determinations of major elements in copper or iron alloys carried out during the nineteenth and early twentieth centuries will almost always bear comparison with—indeed, may be marginally better than—instrumental measurements carried out today. Obviously, there was no way these pioneers could have determined the minute levels of trace elements that can be done today, but in terms of major element analysis, these data should be good enough to use today.

What is perhaps more of a problem is data collected through the major analytical campaigns of the 1930s and later, using now obsolete instrumental methods of analysis, such as optical emission spectrometry (OES) and subsequently atomic absorption spectrometry (AAS). OES in particular has well-known limitations, such as relatively poor reproducibility and a tendency to underestimate some elements in the alloy when they get to high concentrations. The key question for modern researchers is to what extent could or should we use this large database of 'legacy data'? Some limitations are obvious. Many historical analyses lack data on certain key elements, which can only be remedied by reanalyzing the original sample, if it can be traced, and if it can be resampled. Archives of old samples taken from known objects, where they can be tracked down and properly identified, are priceless to modern researchers and must be curated at all costs—the size of the samples taken from precious objects as late as the 1980s would make most modern museum curators' eyes water from pain!

Even if data on all the elements of interest are present, it is still difficult to imagine how to combine old and new datasets in a meaningful way—particularly if there are known deficiencies in the data for some elements. One approach is to say 'don't do it'. Indeed, major analytical projects on British metal objects from the 1970s onward were designed to create an entirely new dataset that excluded previous work. This is inherently cautious, but is probably a reflection of the tendency of most analysts only to trust their own data. However, is this simply wasting a vast archive of potential information, much of which, for financial or ethical reasons, we are unlikely to ever get again? This is the dilemma posed by legacy data.

In many ways, the existing scientific archaeometallurgical archive falls between two stools as it is often considered to lack sufficient scientific and archaeological information. The use of outdated analytical techniques and poor publication standards mean that modern archaeologists often have a stark list of numbers with little scientific context. The standards of modern chemistry require that analytical data are published alongside a number of measures of data quality. These include for each element the *limits of detection* (LoD, or *minimum detectable level*, MDL) of the analytical instrument, the *precision* of the measurements (how closely an analysis can be reproduced), and the *accuracy* of the data (how far the analysis deviates from the known true value of an internationally agreed laboratory standard). The large legacy dataset rarely provides this information and new research has to essentially trust the scientific proficiency and integrity of previous generations.

The large chemical legacy dataset has also been tarnished by the archaeological conclusions that were initially drawn from them. It was common for the chemical results to be interpreted solely by chemists (or mathematicians) who were relatively unfamiliar with the archaeological context of the metal objects. Baldly statistical interpretations of data often led to models of metal provenance and trade that clashed directly with the typologies, theories, and traditions of other archaeological specialists. An archetypal example of this was the Studien zu den Anfängen der Metallurgie (SAM) project, which relied on mathematically derived decision trees to assign provenance groups that were roundly attacked in the 1960s and 1970s. From a modern viewpoint, various statistical interpretative models of metallurgical data have been rightly ignored, but this has been at the expense of ignoring important raw data. Popular academic opinion has tended to confuse the notes with the tune; as Eric

Morecambe famously never said ‘we (probably) have all the right analyses, but not necessarily in the right order’.

Discussions of the future of chemical and isotopic archaeometallurgy commonly stress the two foci of research described in the first section of this chapter. First, gathering new scientific data using modern techniques and standards is essential. This must of course be undertaken within a framework of a well-designed set of scientific and archaeological questions. This will hopefully ensure that scarce funds are efficiently applied and that in the future more money will be available. The second research strand is the continuing development and application of new interpretative methods. It is hard to overplay the revolutionary impact of metallography and cheap quantitative chemical analysis on archaeometallurgy in previous centuries. The more widespread application of, for example, tin isotopic work and synchrotron radiation may have similar era-defining effects in the future.

The collation, confirmation, and reinterpretation of the legacy dataset form a potential third facet of archaeometallurgy’s future. A purely pragmatic viewpoint would stress that financial and conservational constraints demand that we focus on existing datasets. While often true, there is no need to see the use of legacy data as a kind of scientific crisis cannibalism—a choice of last resort. Of course, a new interpretative and theoretical approach would need to be developed for working with legacy data. In the traditional model of interpreting analytical data, the individual artifact’s chemical signature is given primacy. The uncertainties of legacy data require that we now develop a more robust, ‘fuzzy’, methodology. Rather than setting arbitrary but firm thresholds within our numerical data to define the difference between metals from different sources, a much more reasonable approach is to look at averages of archaeological groups. Coherent sets of artifacts can be proposed using the traditional combination of typological or chronological schemes and geological insights. It is important to remember that this is also a very powerful way of interpreting *new* scientific data collected by recent methods. As touched upon above, the precise level of individual chemical elements within an archaeological object is affected by conditions in the smelt, losses through oxidation under melting, heterogeneity caused by differing levels of solubility (e.g., lead will not dissolve into copper), and variability within ore deposits. Even where the quality of the scientific data available is extremely good, the usefulness of going beyond the peculiarities of individual objects and exploring broad archaeological trends is increasingly being recognized.

Archaeometallurgists are becoming ever more sophisticated in using scientific data to engage with wider archaeological problems than merely provenance and ‘compositional industries’. The last 20 years have seen several new interpretative concepts come to the fore such as the artifact biography, material agency, and the interaction of human choice with underlying material properties. Creating a history for an individual artifact obviously requires the integration of a wide range of archaeological datasets. Therefore, some archaeometallurgists stress the importance of applying a wide range of new analytical techniques on a few key artifacts. However, the large database of legacy data is actually an ideal tool to answer many of the modern questions of archaeomaterials, if we use an appropriate scale of analysis.

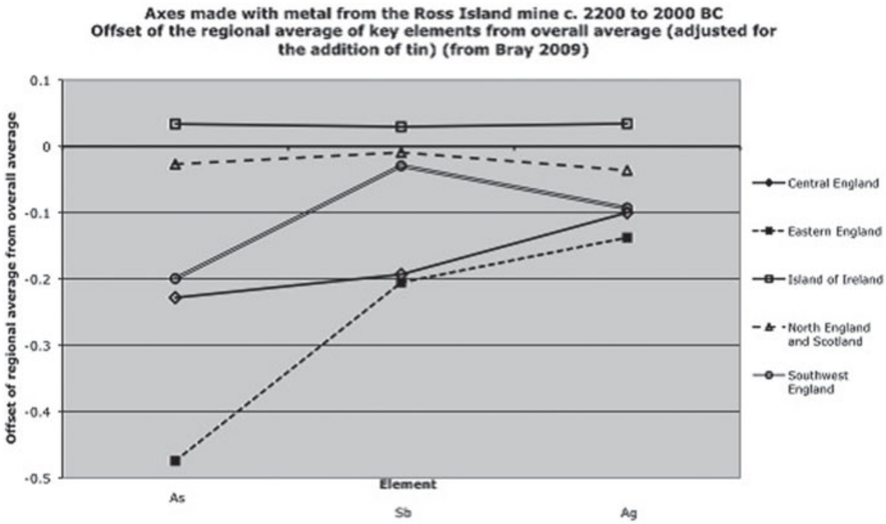


Fig. 10.2 The average level of key diagnostic elements can be a powerful way of interpreting chemical composition data; here showing the slow flow of metal away from an Early Bronze Age source in Ireland. As metal is remelted its composition alters in predictable ways. Eastern England is farthest from the source and, on average, uses copper that has been remelted the greatest number of times

Approximately half of all known Western European Early Bronze Age copper-alloy objects have been analyzed to find their chemical composition. This wealth of data allows averages to skip over individual weaknesses to create a strong regional picture that can be grounded in wider archaeological frameworks. Systematic *average*trends of the loss of elements such as arsenic and antimony under heating reveal regional patterns of recycling, curation, alloying, smithing, and exchange. A clear example is the relationship between Ireland and Scotland in the late second millennium BC The simple fact that arsenic is lost from a melt due to oxidation explains clear trends in the average composition of copper axes from the two regions. Scottish axes consistently show lower average levels of arsenic at this time. This can be simply explained by arguing that Ireland was a center of extractive metallurgy at this time, while melting and casting Irish axes into new forms produced local Scottish axe types. Beyond Scotland there are further losses of arsenic and antimony caused by the reworking of objects and slow movement of the metal away from the ore source at Ross Island, County Kerry (see Fig. 10.2). Focusing on individual objects without creating a broader regional picture misses these important archaeological trends. A preliminary re-interpretation of the archival data from the western European Early Bronze Age using these ideas has been published by Bray and Pollard (in press).

Though only in its preliminary stages, the correct use of legacy data must stand alongside new analytical programs and techniques as a third strand for the future of scientific archaeometallurgy. Work on new data mining techniques and theoretical frameworks is necessary to combat the concern that old datasets are neither scientific nor archaeological enough. The view must become not ‘they are wrong, what can replace them?’ but instead ‘how wrong are they, how can we incorporate them?’ They are simply too large, useful, and hard-won to ignore.

Summary

Although each case is unique, it is essential to anchor the chemical and isotopic study of metal around a systematic question and methodology. Due to the perennial difficulties of securing access, time, and money, it is important that any scientific intervention is carefully planned. Figure 3 summarizes the wide range of factors that typically affect such planning.

When archaeometallurgists ask themselves ‘What are we trying to learn from the analysis?’, the traditional response is one of the following:

‘*What is it made from?*’ can simply be answered from a qualitative analysis (perhaps by XRF) of the surface without too much cleaning—but is this the best approach? If it is a rare object, and/or something that is unlikely to be available again for analysis, then would it not be better to do a ‘proper job’ and produce a quantitative analysis which will have more lasting value (this assumes that any such analyses will then be properly published!).

‘Where does it come from?’ is the provenance question, and requires the usual set of considerations to be taken into account, including:

- Are we dealing with a single object, or a coherent group of objects?
- What do we know about possible ore sources?
- What do we know about mixing/recycling of ores and metals?
- Can we sample the object and get original metal?
- Do we need isotopes or trace elements, or both?
- Do we have access to sufficient comparative data to answer this question?
- How narrowly defined (geographically) does the answer have to be to be useful archaeologically—do we need a particular mine, or a region, or a geological unit?

How was it made is the technology question. If the object(s) can be sampled, then traditionally this is approached through metallography and physical testing (hardness, etc.), but if the samples come from a metalworking site then there may be additional evidence provided by the associated debris (slag, furnace remains, etc.). Again, we may not require a quantitative chemical analysis to answer this particular question, but it must always be worth considering doing it anyway, if only so that the object need not be ‘disturbed’ again. It is very likely that the sample taken for metallography can be used for chemical analysis, so if it is not analyzed at the time (or even if it is), it is vital that the sample taken is properly curated—preferably with the original object.

These three questions are likely to remain as important concerns. However, recent developments in archaeometallurgy have widened the range of our influences and

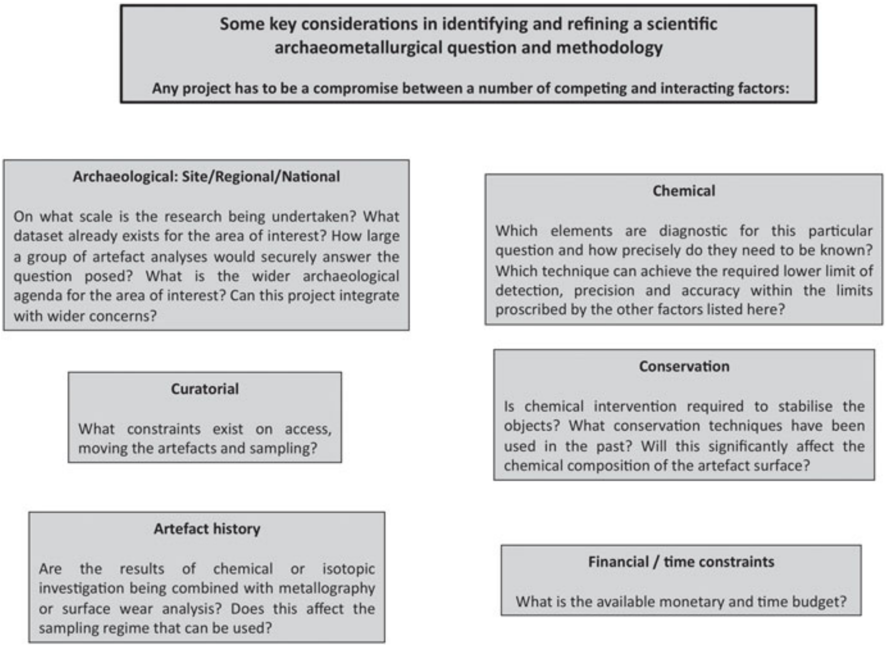


Fig. 10.3 Key considerations when choosing and refining a scientific archaeometallurgical question and methodology

sources (Fig. 10.3). Integration with other specialists must now be the primary concern of archaeologists of every flavor. When posing archaeometallurgical questions, we must consider the wider archaeological questions of that site, region, or time period. This can lead to our datasets being used to tackle social questions that at first seem to have very little connection to the chemistry of metalwork. In addition, it must be remembered that a chemistry-based approach to metallurgy need not include fresh analyses. Free and nondestructive legacy data can lead to radical new archaeological theories being produced from data originally intended for another purpose. In conclusion, we are beginning to recognize that a rigorous, scientific approach to composition, alteration, manufacturing technology, and source can tell us about the objects we excavate and the societies behind them in *equal* measure.

Bibliography

Bray, P. (2009). Exploring the social basis of technology: Reanalysing regional archaeometric studies of the first copper and tin-bronze use in Great Britain and Ireland. Unpublished D.Phil. Thesis, University of Oxford.

Bray, P., & Pollard, A. M. (2012). A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology. Antiquity *86*, 853–867.

Brothwell, D. R., & Pollard, A. M. (Eds.). (2001). *Handbook of Archaeological Sciences*. Chichester: John Wiley and Sons.

Junghans, S., Sangmeister, E., & Schröder, M. (1960). *Metallanalysen kuperzeitlicher und fühbronzezeitlicher Bodenfunde aus Europa. Studien zu den Anfängen der Metallurgie 1*. Berlin: Gebr. Mann.

Junghans, S., Sangmeister, E., & Schröder, M. (1968). Kupfer und Bronze in der frühen Metallzeit Europas. Studien zu den Anfängen der Metallurgie 2 Berlin: Gebr. Mann

Pernicka, E. (1998). Whither metal analysis in archaeology? In C. Mordant, M. Peront, & V. Rychner (Eds.), *L'Atelier du Bronzier en Europe du xxe au viiie siècle avant notre ère; vol 1: 259–267*. Paris: Edition du CTHS.

Pollard, A. M., & Heron, C. (2008). Archaeological Chemistry. Cambridge, Royal Society of Chemistry (2nd revised ed).

Pollard, A. M., Thomas, R. G., Ware, D. P., & Williams, P. A. (1991). Experimental smelting of secondary copper minerals: implications for Early Bronze Age metallurgy in Britain. In E. Pernicka, & G.A. Wagner (Eds.) Archaeometry '90:127–136. Basel: Birkhauser Verlag

Pollard, M., Batt, C., Stern, B., & Young, S. M. M. (2007). *Analytical Chemistry in Archaeology*. Cambridge: Cambridge University Press.

Rehren, Th., & Pernicka, E. (2008). Coins, artefacts and isotopes – archaeometallurgy and archaeometry. *Archaeometry, 50*(2), 232–248.

Rohl, B., & Needham, S. (1998). The Circulation of Metal in the British Bronze Age: the Application of Lead Isotope Analysis. Occasional Paper 102, British Museum, London

Rowlands, M. J. (1971). The archaeological interpretation of prehistoric metalworking. *World Archaeology, 3,* 210–224.

Shortland, A. J., Freestone, I. C., & Rehren, Th. (Eds.). (2009). From Mine to Microscope – Advances in the Study of Ancient Technology. Oxford, Oxbow Books.

Tylecote, R. F. (1976). A History of Metallurgy. Metals Society, London (2nd ed., Institute of Materials, London, 1992).

Tylecote, R. F. (1987). *The Early History of Metallurgy in Europe*. London: Longman.

Young, S. M. M., Pollard, A. M., Budd, P. D., & Ixer, R. A. (Eds.). (1999). *Metals in Antiquity. BAR International Series 792*. Oxford: Archaeopress.

Chapter 11
Provenance Determination of Archaeological Metal Objects

Ernst Pernicka

A Short History of Provenance Analysis of Archaeological Metal Objects

The application of scientific methods to the analysis of metals goes back to the very beginnings of analytical chemistry in the modern sense, as the first quantitative analysis of any metal alloy was performed on a Roman coin and published by Martin Heinrich Klaproth in the late eighteenth century. In this study, he mainly addressed the question of material composition. However, within a few decades the idea of provenance determination was formulated, for example by Göbel (1842), who published an article entitled: "On the impact of chemistry on the tracing of prehistoric peoples, or results of the chemical investigations of ancient metal objects, especially of those from the Baltic region, to determine the peoples from whom they derive" (my own translation). He suggested from the geographical distribution of about 120 analysed objects that they represented well-defined ethnic groups as was normal during that time.

It should be remembered that the three-age system had been proposed only a few years before (by C. J. Thomsen in 1836) and that an additional motivation for the analyses was the hope that metal objects could be dated based on their compositions. However, already in the nineteenth century it was discovered that this was a moot point and the interest of researchers concentrated on the question of provenance. Soon thereafter, it was proposed that minor elements were more useful in determining the nature of the ore from which the metal came and perhaps even its geographical origin (von Fellenberg 1860–1867; von Bibra 1869). Furthermore, it was found that compositional differences between copper metals were to be expected when native copper, oxide or sulphide ores were used for smelting (Wibel 1863), an idea

E. Pernicka (✉)
Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters,
Abteilung für Jüngere Urgeschichte und Frühgeschichte, Schloß Hohentübingen,
Eberhard-Karls-Universität Tübingen, 72070 Tübingen, Germany
e-mail: ernst.pernicka@cez-archaeometrie.de

University of Tübingen and Curt-Engelhorn-Zentrum Archäometrie, Mannheim, Germany

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_11,

repeated almost exactly a hundred years later by Friedman et al. (1966). However, the analytical methods available then did not allow further progress because of the large sample requirements and a small sample throughput.

Although most scholars agreed that trace elements were most indicative of the ore sources, the limited analytical means of that time did not allow them to make use of this knowledge. Accordingly, there was little further progress until the late 1920s, when instrumental analytical techniques became available. They were almost immediately applied to the concept of provenance studies of ancient metals. As an example, the Sumerian Metals Committee, inspired by the exceptional finds at the Royal Cemetery at Ur in Mesopotamia (Woolley 1931), was appointed by the Royal Anthropological Institute to investigate the origins of Mesopotamian metals. The committee reported on the origin of Sumerian copper, assuming that its nickel content could be indicative of an ore source in Oman (Desch 1928–1938). Oman was suggested as a possible region of origin because it was known that the basic and ultrabasic rocks there (so-called ophiolites) are enriched in nickel. The problem is that there are also ophiolites on Cyprus and in eastern Turkey, so that without field work the problem cannot be resolved. From these interim reports, it is obvious that the original objective was not really achieved, but they resulted in the creation of a further unit, the Ancient Metal Objects Committee, in 1939.

Halle

With the advent of atomic emission spectrometry around 1930 (Gerlach and Schweitzer 1930), it became possible to determine many trace elements in reasonably small samples of a few milligrams with sufficient sensitivity (in the range of 0.001–0.01 %) and in a short time. This opened the door to systematic studies of ancient metals, beginning in 1931 by W. Witter, a prehistoric archaeologist based in Halle with a background in mining engineering. Witter was later joined by H. Otto and together they began to systematically analyse all available metal objects in Germany from the Neolithic to the Early Bronze Age (Otto and Witter 1952). They were motivated by two aims: to determine whether there was Bronze Age copper mining in Germany and to develop a methodology for relating archaeological objects back to specific ore deposits. They refined their method to allow for the analysis of ten elements (Fe, Co, Ni, Cu, As, Sn, Ag, Sb, Pb, Bi and S) in some 1,300 objects within a few years—much more than had been accomplished over the preceding 100 years.

Otto and Witter then classified the objects according to their compositions into six groups that were based on the general knowledge of copper ore mineralogy. These groups were (in chronological order): (1) very pure copper; (2) unalloyed copper with minor impurities; (3) arsenical copper; (4) fahlore metal with high concentrations of arsenic, antimony and silver; (5) copper with nickel and arsenic as major impurities and (6) copper–tin alloys. This is the beginning of the concept of "Leitlegierungen" (major alloy types), which is generally still valid with the exception of the last group. As was later shown by the Stuttgart group (see below), very pure copper is typical of the fifth and early fourth millennia BC in southeast and central Europe, and arsenical copper dominates in the fourth and early third millennium. At the beginning of the Early Bronze Age, fahlore metal is most abundant in central Europe, which is later replaced by copper with arsenic and nickel as major impurities. As will be shown below, some of these copper types can indeed be related to certain mineralised regions, although it is usually difficult to pinpoint the exact mine.

A major deficiency of this study was the lack of an equal number of analyses of copper ores from deposits that were considered to be likely sources for the analysed artefacts. Although in their publication, Otto and Witter (1952) explicitly emphasised the necessity to analyse also ores and slag from ancient smelting sites, only a few examples from the geological literature were used for comparison. Furthermore, the ore deposits were implicitly considered to be homogenous and to be differentiated in their compositions. For the comparison of artefact and ore analyses, they did not consider the changes in chemical composition during smelting and used all measured elements including tin, which is obviously an alloying element as tin and copper ores rarely occur together. Using this approach, they concluded that 97 % of all prehistoric metal objects found in Germany were produced from copper ores in Saxony. Although this conclusion cannot be supported today, and was most likely influenced by nationalistic preoccupations, it is nevertheless a pioneering study, both from the methodological view and from the archaeological scope. It was the first large-scale attempt to determine the provenance of prehistoric metals with an appropriate analytical method, based on a large number of analyses and a classification method that was governed by substantial knowledge in economic geology. The importance of field work was also clearly expressed as well as the idea that chemical analyses could provide evidence for ancient exploitation of mines that do not have any visible remains of ancient mining due to modern activities.

Vienna

Parallel with the investigations in Halle, another group in Vienna under the direction of Richard Pittioni and Ernst Preuschen worked along similar lines. They specifically set out to determine "from which production area a specific object would derive" (Preuschen and Pittioni 1937). Their emphasis was on field work and mining archaeology, both having been educated as mining engineers. Accordingly, they not only had a more realistic view of the problems of characterising ore deposits geochemically, but they actually performed a large number of analyses on ore samples, mainly from prehistoric mining districts in Austria. More than 2,000 ore analyses formed the database on which they attempted to establish a clear relationship between "ore deposits and finished objects". Unlike the Halle group, the Vienna group was aware of the fact that trace element concentrations in ore deposits can be quite variable and that the concentrations are further altered during the production of copper metal. Using this knowledge they decided that the sensitivity of the analytical method should be more important than its reproducibility, because only the presence or absence of a certain element should be used to determine the trace element pattern as a whole. While this is generally true, it was an unfortunate decision, because they did not attempt to actually quantify the spectra but estimated the concentrations by visual inspection of the spectral lines on a film detector. This resulted in semi-quantitative analyses without numerical values for the concentrations so that they are hardly usable today. They also used the objects and ores directly as electrodes to avoid any alteration of the chemical composition during sample preparation. This, however, meant that only the surfaces of the objects were analysed, which are often not representative of the whole composition.

The Vienna group classified more than 6,000 analyses of artefacts, from the central European Bronze Age, into five groups that they assigned to different ore deposits in the eastern Alps and in Slovakia. There was much dispute between the two groups about the correct methodological approach, which continued when the methodology that was developed in Halle was continued in an even larger project in Stuttgart. However, the Vienna group is credited with the insight that provenance analysis of metal artefacts has to be accompanied by field work in ancient mining districts. Indeed, the results of their mining archaeological research have long remained without parallel.

Stuttgart

Considering the problems of relating metal artefacts to specific ore deposits, a new group in Stuttgart and Freiburg directed by Siegfried Junghans and Edward Sangmeister decided not to search for the origin of the raw metals, but simply use the chemical analyses of metal objects as an independent criterion for classification in addition to conventional typologies. They assumed that prehistoric metal workers would receive their raw metal primarily from the same source(s), similar to potters, and that they also applied similar processes to produce copper. If this assumption holds, then one would try to identify workshops rather than to identify the mines where the ore would have come from. By preparing distribution maps of copper types that were identified based on their chemical composition, it was hoped that one would obtain insight into the production and distribution of metals in Europe. For this purpose, more than 22,000 objects from all over Europe (Junghans et al. 1960, 1968, 1974) were sampled and analysed with practically the same method as in Halle.

In order to identify workshops, the analytical results were grouped according to their chemical similarity: first into 12 (Junghans et al. 1960) and later into 29 groups (Fig. 11.1). The grouping method used statistical methods of variance analysis (Junghans et al. 1954) based on histograms of the elemental concentrations. It was found that five elements contributed most of the variance of the data, namely Ag, Ni, As, Sb and Bi. In the histograms of these elements, several peaks were observed. The minima between such peaks were defined as limits between different groups. This is

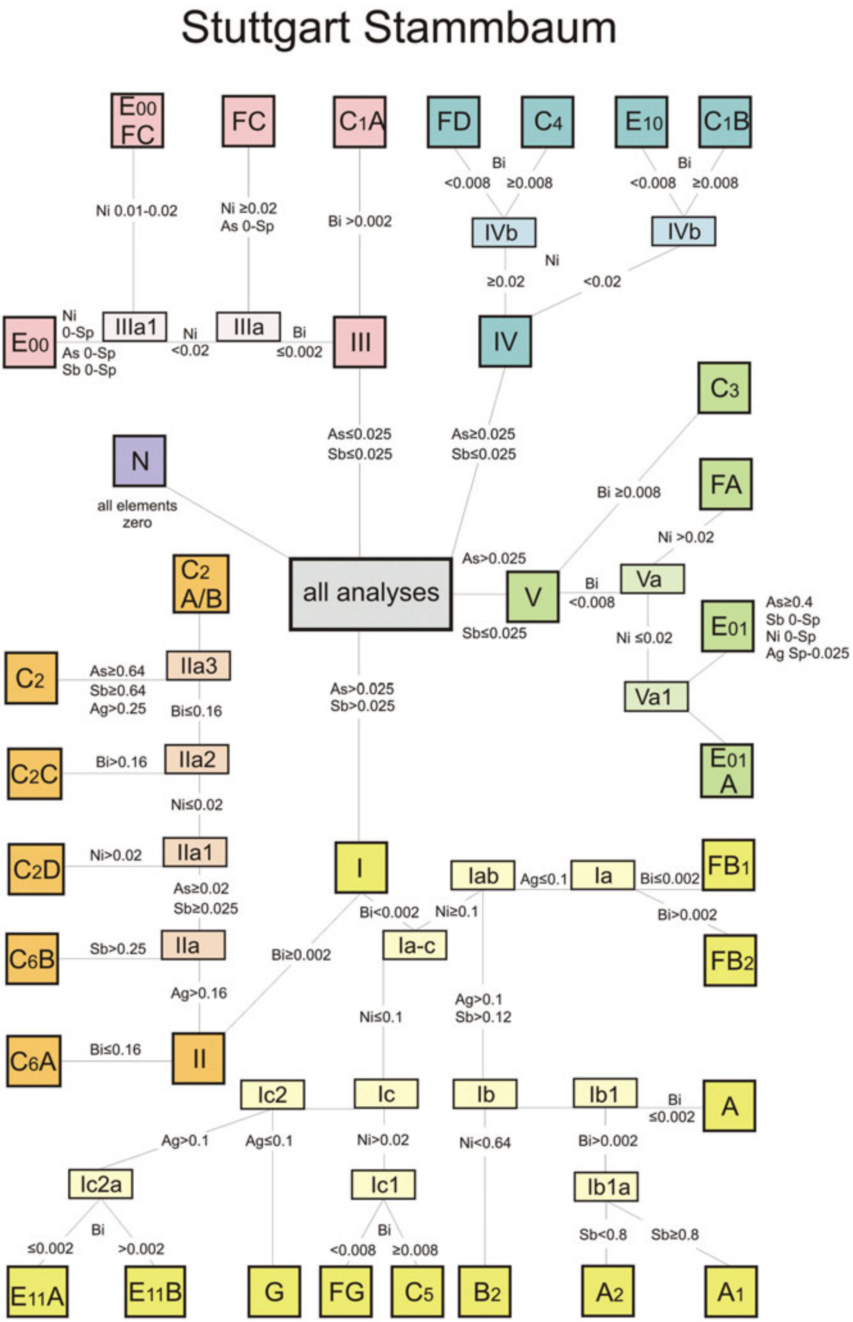


Fig. 11.1 The classification scheme developed and used by the Stuttgart team to find chemically similar prehistoric copper objects

certainly a reasonable procedure, but for many archaeologists it lacked the clearness of the groups defined in Halle and Vienna by their “Leitlegierungen” based on the general knowledge of ore deposits. The Stuttgart team then went on to study the distribution of these metal groups in time and space, and inferred from these patterns the production centres and socioeconomic relationships in the early metal-using periods of Europe.

Similar programs were established in other European countries, such as in Sweden (Oldeberg 1942), France (Maréchal 1963; Briard and Giot 1956) and in Britain (Coghlan and Case 1957; Blin-Stoyle 1959; Britton 1961). However, by far the largest programs of systematic analyses were established in the former Soviet Union by Selimkhanov (1960) in Baku and Evgeny Chernykh (1966) in Moscow, which resulted in well over 50,000 analyses of ancient metal objects mainly from Eurasia.

With so many data at hand, one may well ask what these exercises have yielded and what additional information could be gained by them. This is not the place to evaluate the achievements and possible failures of all these studies. It may suffice to remark that we have a profound knowledge of the alloy compositions used in prehistoric times in Europe and in northern Asia. It has been established beyond doubt that metallurgy began with the use of native copper and that extractive metallurgy does not appear to have been significant before the fifth millennium BCE. Even then, copper remained rather pure, probably deriving from very rich ores. In the fourth millennium, arsenical copper dominated over a large area and it has been suggested that this may be due to common metallurgical practices that would imply rapid technological exchange over wide distances (Chernykh 1992). It has also become clear that all over Europe, the compositions of metal objects changed significantly with the beginning of the Bronze Age, not only concerning the major composition but also the minor elements. This means that either very little of the Chalcolithic metal survived and was reused in the Early Bronze Age or that the amount of metal in the system increased substantially so that any reuse would be insignificant. It has also been established that certain metal groups are not equally distributed but are rather concentrated in restricted areas and periods that suggests the occurrence of one or several ore sources within those areas.

Nevertheless, the results of these large analytical programs were received with scepticism among non-specialists and a general opinion gained ground that metal analyses would not be able to make any significant contribution to the question of the provenance of metals (Hall 1970; Coles 1982). Major points of criticism, especially of the Stuttgart project, were: (1) the representativeness and accuracy of the analyses; (2) the methods of classification; (3) possible changes during metal production (and thus the difficulty in relating a metal object to a specific ore deposit) and (4) the chronological framework used for the evaluation of the analyses.

The first point is certainly justified. There were at this time no inter-laboratory comparisons and no internationally recognised reference materials available with which laboratories could compare their results. This is standard laboratory practice today, but was not applied in the early days of spectral analysis. Indeed, two programs (Chase 1974; Northover 1996) to compare the analyses of different laboratories indicated that there were many problems and that some seriously deviating results were produced and published. At least for the two largest series of metal analyses (in Stuttgart and Moscow), the accuracy of the data could be confirmed even though the precision of the spectroscopic method applied was rather low (Pernicka 1984; Pernicka et al. 1997).

On the other hand, the assertion that small samples taken from heterogeneous copper alloys would not be representative (e.g. Slater and Charles 1970) can now be rejected. The sample mass of 40 mg is more than sufficient for representative analyses (Pernicka 1984), if it is taken from the interior, usually by drilling with a steel drill. However, this does not exclude the possibility that some analyses may still be grossly wrong (e.g. Barker and Slater 1971) as was demonstrated by Pernicka (1990). It rather turns out that especially the large analytical programs in Stuttgart and Moscow produced essentially accurate analyses but with low precision of about 30 % relative (Fig. 11.2), while modern methods usually range between 2 and 5 %. It is difficult and requires much effort to obtain better precisions. Nevertheless, one frequently finds published data with four or more significant digits which are meaningless and only demonstrate lack of a sense of reality by the authors. For classification and provenance very high precision is actually not needed, since the variation of elemental concentrations in most ore deposits ranges over an order of magnitude or two. More important is the elemental pattern (e.g. Radivojević et al. 2010). This argument has also been used by Pittioni (1957) and overstrained at the same time, because he maintained that semi-quantitative analyses should be sufficient. As a consequence the large dataset produced by the group in Vienna cannot be used for comparison with modern analyses. On the other hand, high precision is required to answer questions of the type, if two or more objects may belong to the same casting. Nowadays, there is a tendency to exaggerate the damage induced by sampling and non-invasive analytical methods like X-ray fluorescence techniques are advocated. This neglects the problem that with these methods only the surface of an object is analysed which is often not representative of the metal composition, especially of corroded objects. With the new mobile X-ray fluorescence spectrometers, there is a definite danger that untrained personnel will propagate the idea that non-destructive analysis is fully quantitative and that again series of incomparable or even wrong (and thus unusable) analyses will make it into the literature.

The classification procedure of the Stuttgart team has mainly been criticised by Dutch archaeologists (Butler and van der Waals 1964; Waterbolk and Butler 1965) but it soon became clear that they were simply overstrained with the large data set. They suggest a graphical method of grouping of smaller subsets of the data which uses essentially the same reasoning as the Stuttgart team and, not surprisingly, comes to similar results (Härke 1978). Later, cluster analysis was introduced to deal with the same problem (Hodson 1969) and, again, the Stuttgart groups were largely confirmed when some 25,000 analyses were treated (Pernicka 1990).

Changes in chemical composition during metal production were actually of no concern as long as workshops were sought and not the geological origin of the copper. Some confusion and reluctance to accept the conclusions of the Stuttgart team may well be due to the chronological system used at the time for the archaeological interpretation, which adhered to “conventional” dates, especially for the southeast

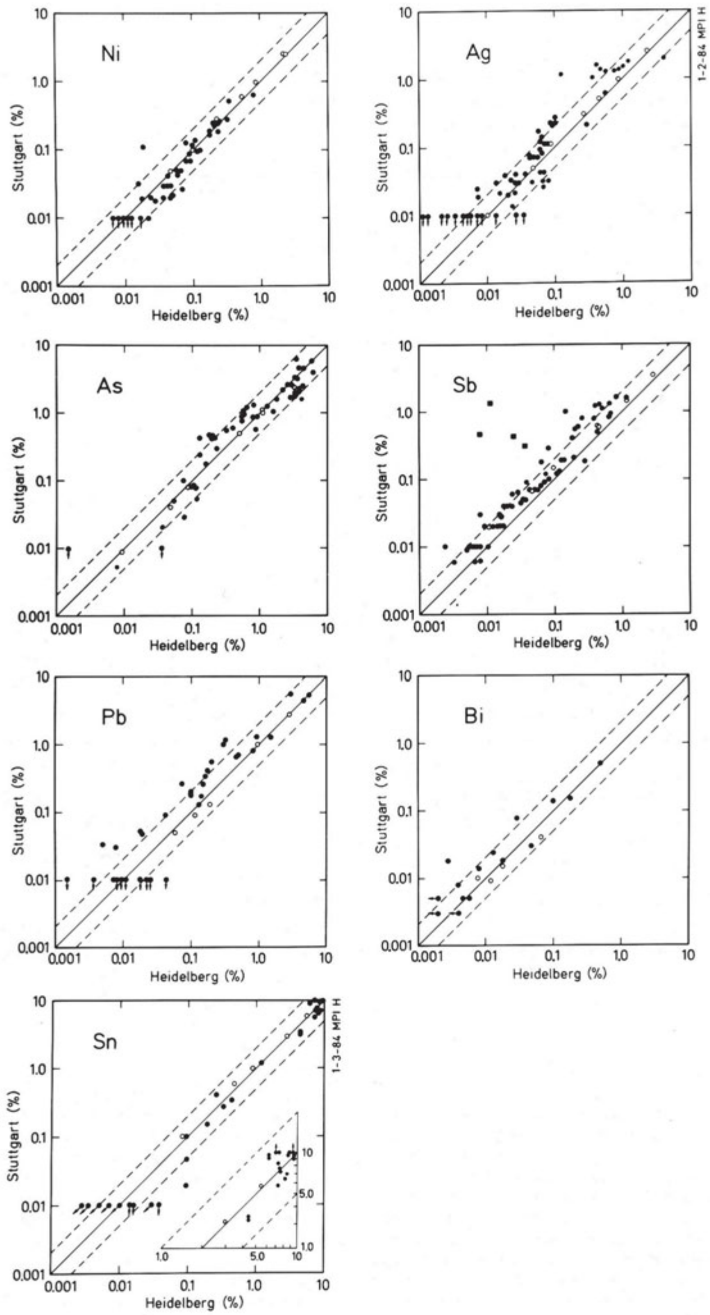


Fig. 11.2 Comparison of analyses obtained with atomic emission spectrometry at the Württembergisches Landesmuseum in Stuttgart ("Studien zu den Anfängen der Metallurgie" analyses) with results obtained with neutron activation analysis (*As, Sb, Ni, Ag* and *Sn*) and atomic absorption spectrometry (*Pb* and *Bi*) at the Max-Planck-Institute for Nuclear Physics in Heidelberg (from Pernicka 1990). The four outliers in the Sb diagram (indicated as *squares*) are due to an interference from Fe. (Pemicka 1984)

European Copper Age. However, it has to be remembered that the Radiocarbon Revolution (Renfrew 1973) had not yet occurred in European prehistory. A re-evaluation of the Stuttgart data based on the material classification by Pernicka (1990) has been attempted by Krause (2003). In summary, the very large analytical programs seem to have been ahead of their time despite the lack of a consistent chronological framework for all of Europe, a computer technology that could deal with such large datasets, or the analytical stringency that nowadays is a standard practice in professional laboratories. The high hopes that were originally connected with the analysis of metal objects to determine their provenance were seemingly disappointed.

The Revival of Metal Provenance Through Isotope Analyses

Some fifty years ago, new methods seemed to open a way out of this somewhat depressing situation. The earliest method was the introduction of lead isotope analysis, first applied to lead (Brill and Wampler 1965; Grögler et al. 1966) and silver (Gale et al. 1980) and later extended to copper and copper-based alloys (Gale and Stos-Gale 1981; Pernicka et al. 1984). The second method was the application of new analytical techniques that were more sensitive and more precise than the previously prevailing optical emission spectrometry. Most elements consist of different isotopes, i.e. atoms with very similar chemical characteristics but varying in weight. Compounds of elements of low atomic number can thus differ significantly in their molecular weight.

For example, H_2O exists in the form of nine different isotopic varieties ranging from 16 to 22 amu (atomic mass units). The differences in the molecular weights affect the way these molecules respond to certain kinds of physical processes that are mass dependent. This leads to slightly varying isotopic compositions in different reservoirs. For example, seawater and rainwater differ in their isotopic composition, as does rainwater collected at different geographical latitudes. The study of these subtle effects (referred to as *isotope fractionation*) has become very important not only for the Earth sciences, but also for provenance studies of materials that contain elements of low atomic number (such as marble) or for the study of prehistoric diet. The application of this method requires that the raw material of the artefact has not undergone any change of chemical or physical state, because such processes could induce additional isotopic fractionations that could delete the original differences of the geological sources. Thus, elements of low atomic numbers are generally of little value for the study of meta1 artefacts.

Elements of high atomic number, on the other hand, generally show no measurable isotope fractionation in the natural environment. However, some elements such as lead consist partly of isotopes that are products of radioactive decay. For example, uranium and thorium decay with half-lives of several billion years into the lead isotopes ^{206}Pb, ^{207}Pb and ^{208}Pb. Lead consists of these three isotopes and a fourth, ^{204}Pb, that is not produced by radioactive decay. It is evident that the lead isotope composition of the Earth will change through geologic time scales. It is also evident

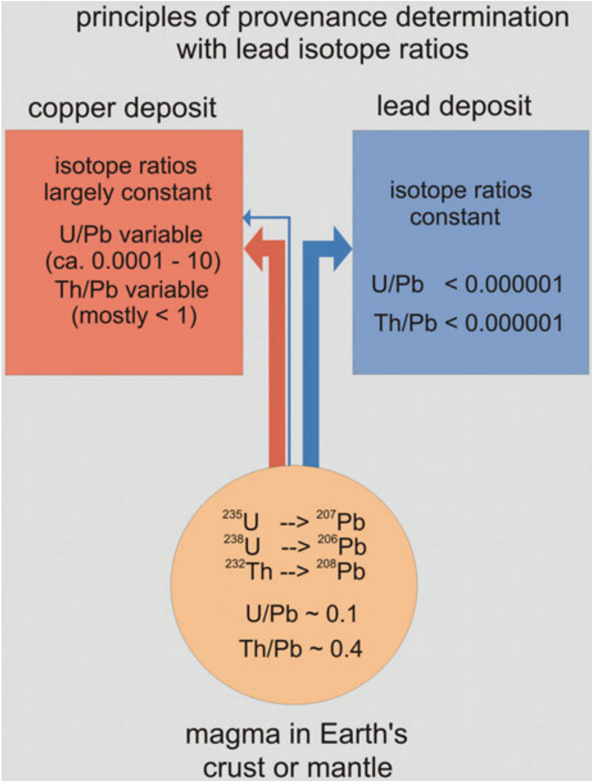


Fig. 11.3 Basic principles of provenance determination of ancient metal objects with lead isotope ratios

that lead deposits in the Earth's crust can vary in their isotope composition, depending on their geological age and the U/Pb and Th/Pb ratios of the geological reservoir that supplied the lead. By the formation of a lead deposit, these elemental ratios are changed by many orders of magnitude so that any further contribution by the decay of uranium and thorium becomes insignificant and the lead isotope composition becomes fixed. It is also then extremely unlikely that the lead isotope ratios will be altered by any of the physical and chemical processes that occur during the metallurgical process from ore to finished artefact, save for the mixing of lead of different origins. By and large the same arguments apply to lead in copper deposits; thus, lead isotope analysis can also be applied to copper-based metal objects (Fig. 11.3).

The advantage of looking at the isotopic composition of an element, rather than at abundances (or the abundance pattern) of minor and trace elements, is that the isotopic composition of a heavy element like lead does not change on the way from ore to artefact. Regardless of the processes involved in the treatment of ores or metal—whether it is roasting or smelting, cupellation or melting, alloying, dissolution or corrosion—the isotopic composition remains constant. Most of these processes are diffusion controlled and from physical laws one can deduce that measurable (i.e. in the permille range) effects can only be expected when the mass difference between two species or isotopes is larger than 10 %. The largest mass difference of the stable lead isotopes is 4 amu, just about 2 %. Isotope fractionation of lead can be induced in the laboratory, if lead is volatilised (e.g. by converting it into hydride) and almost completely removed from the sample. This has been observed (Pernicka, unpublished) but there is no similar process in copper metallurgy. It would certainly have to be considered with volatile elements such as mercury and zinc, if one would like to use their isotope ratios for provenance studies. This has two important consequences. First, neither the exact pathway from ore to artefact, nor the metallurgical techniques employed, need to be known. While both processes affect the behaviour of trace elements and govern how the elemental abundance pattern in ores relates to that in the metal, they have no bearing on the isotopic composition.

Second, the isotopic composition is not dependent on how lead is distributed between different phases. That is, different segregated phases in artefacts may have grossly different lead contents, but the lead will have the same isotopic composition. Similarly, there are no noticeable differences in the isotope abundances between the lead in slags and that in the complementary metal. Thus, sample heterogeneity (which is notorious for making many chemical analyses difficult to interpret) is of no relevance for the isotopic composition. Of course, a prerequisite for even attempting to utilise isotope abundance measurements for provenance studies is that the isotopic composition of lead from different parts of the world must vary. This is indeed the case, and the variations found in nature are many times larger than the analytical precision with which the composition can be determined.

Once there are a sufficient number of isotope measurements of an ore deposit available, it can be considered to be isotopically characterised. The question of how many measurements are required cannot be answered in a general way. Some deposits show a small variation in their lead isotope ratios and those are the ones that can best be used for provenance discussions. It is often found that lead ore deposits show this behaviour. In such cases, five to ten analyses may be sufficient for their charactersiation. On the other hand, there are lead deposits with large variations (e.g. the so-called Mississippi Valley Type deposits or MVT deposits) and then even 50 analyses may not be sufficient. It is now increasingly recognised that many copper deposits with low lead concentrations exhibit large variations in their lead isotope ratios. In such deposits, the assumption described above that the lead isotope ratios do not change after their formation does not apply, because the U/Pb and Th/Pb ratios may not be reduced to insignificant values. Accordingly, radiogenic lead will alter the lead isotope ratios even after the formation of the deposit. Since uranium and thorium are bound to be heterogeneously distributed in minerals on a small (mm to cm) scale, a large range of lead isotope ratios can develop since the formation of the deposit. This was first recognised in the Chalcolithic copper mine at Rudna Glava in Serbia (Pernicka et al. 1993) and later in many other copper deposits like Feinan in Jordan, the Erzgebirge in Saxony and in the greywacke zone of the eastern Alps. But even under these circumstances one can come to reasonable conclusions, if larger groups of ore and artefact samples are compared (e.g. Höppner et al. (2005).

Nevertheless, also lead isotope ratios of single artefacts can be compared with those of an ore deposit. If they are different, then it can be concluded that the artefacts do not derive from that specific ore source. Conversely, it is not possible to regard the provenance of an artefact as proven, even if it shares the same isotopic signature as an ore deposit. The reason for this is that although the variation of lead isotope ratios in ore deposits is much smaller than that of trace element concentrations, there exists the possibility that another deposit has the same lead isotope ratios. This is indeed increasingly being recognised as more deposits become characterised.

In the early days of lead isotope analysis in archaeology, neglecting this simple logic sometimes led to affirmative statements concerning the provenance of copper artefacts that did not stand up to later results. Thus, the general pattern of overoptimistic expectations followed by disappointment (as with trace element studies) seems to have been repeated with isotope analysis. It has also been stated that only lead isotope ratios are useful for provenance studies, while chemical analyses cannot match copper-alloy artefacts to their parent copper ores. Although this is often correct, there are cases where the trace element pattern may be more indicative of an ore source than lead isotope ratios. At Feinan (Jordan), for example, the ore deposit is chemically homogeneous but shows wide variations in its lead isotope ratios (Hauptmann et al. 1992).

With four stable lead isotopes, one has a maximum of three independent variables (i.e. lead isotope ratios). These could be plotted in a three-dimensional space but usually one uses two diagrams, in which the same lead isotope ratio is plotted on the abscissa and the two others on the ordinate (Fig. 11.4). As is obvious from the diagrams, lead isotope ratios are strongly correlated, which results in their alignment along a straight line, which further reduces their discrimination power, because they occupy only a minor part of the theoretically possible space, resulting in a tendency for different ore deposits to overlap. In such a situation, it is common sense that a combination of both sets of data—lead isotope ratios and trace element concentrations—will provide better discrimination between different sources.

The Information from Trace Elements

In provenance studies, only those elements that follow copper during smelting are useful, which means that the element/copper ratio largely remains the same between the ore and the final product. Five major complications and misconceptions have to be considered at this point. First, ores are generally inhomogeneous on all scales. The opinion has often prevailed that this precludes any correlation between artefacts and ores. However, this need not be so as the prehistoric mining region of the Mitterberg in Salzburg (Austria) shows. Here, trace element concentrations in chalcopyrite-rich ores vary over two orders of magnitude, yet this variation is not a random one. It is known, for example, that nickel in this region occurs mainly in the form of Ni–As minerals such as gersdorffite (NiAsS), so that copper produced from Mitterberg ores is characterised by a combination of about equal concentrations of nickel and arsenic as major impurities at variable concentrations combined with relatively low contents

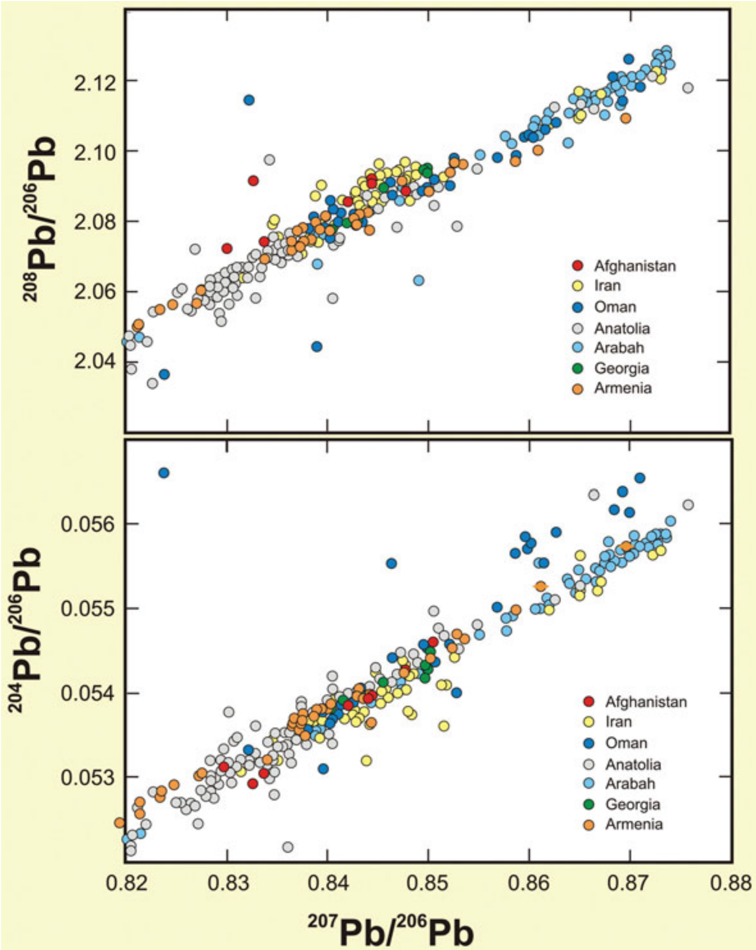


Fig. 11.4 Lead isotope ratios in copper ores, copper slag and native copper from some 170 occurrences in Southwest Asia (Afghanistan, Iran, southern Caucasus, Anatolia, Arabah valley and Oman). The analytical uncertainties are comparable with the size of the symbols. Although there is some separation between the (presently analysed) copper ores from various regions visible, it is obvious that it would be impossible to determine the provenance of a metal object from Mesopotamia, for example, with lead isotope ratios alone. (Data are from: Begemann and Schmitt-Strecker 2009; Seeliger et al. 1985; Wagner et al. 1986, 1989, 2007; Hauptmann et al. 1992, 2003; Begemann et al. 2003; Begemann and Schmitt-Strecker 2009, Yener et al. (1991); Hirao et al. (1995); Sayre et al. (2001); Nezafati et al. (2009); Pernicka et al. (2011) and Meliksetian and Pernicka (2010))

of antimony, silver and bismuth (Fig. 11.5). In a study of some 1,200 Bronze Age copper artefacts from the adjacent area, it was found that about 80 % of the copper alloys conformed to this general pattern. Knowing that the peak production period at the Mitterberg was during the Late Bronze Age Urnfield culture (about 1,300–800 BCE),

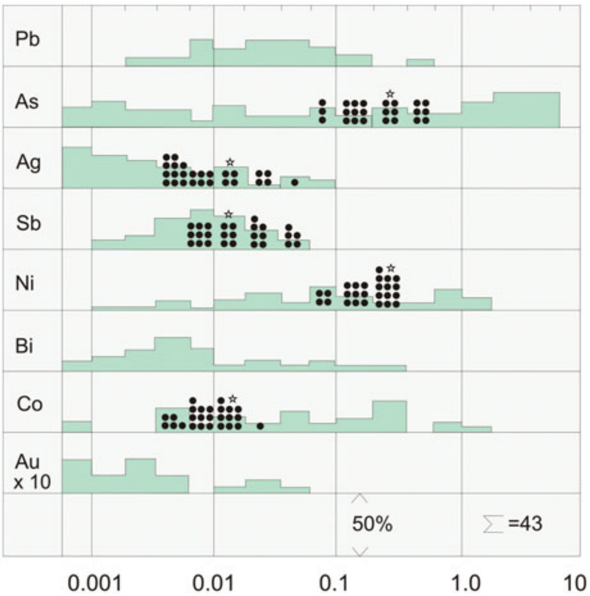


Fig. 11.5 Variation of trace element concentrations in the Bronze Age copper mine of Mitterberg (Austria). Although arsenic and nickel concentrations vary over several orders of magnitude, they are tightly related so that in copper metal there are always roughly equal concentrations of arsenic and nickel. The *star* indicates the concentrations in the sky disc of Nebra and the *dots* the metal objects that were found with it

it is only reasonable to assume that a correlation between ores and artefacts does exist.

A second complication arises from the behaviour of minor and trace elements during the smelting process, as this will differ depending on the type of ore being used. Reduction of oxide ores is quite straightforward compared with the processing of sulphide ores. Although it cannot be expected that reduction happened under chemical equilibrium conditions, it is possible to use thermodynamic data for equilibrium reactions to predict the general behaviour of certain trace elements during smelting (Pernicka 1987; Table 11.1). Using a similar approach and stressing non-equilibrium conditions, it was suggested that the concentration of some elements (notably nickel and arsenic) strongly depends on the smelting temperature and that copper (with or without nickel) could be produced from the same ore (Pollard et al. 1991). This is, however, a very theoretical possibility and requires the assumption that high and low impurity coppers were being produced intermittently due to different smelting temperatures. It is hard to imagine that ancient smelters did not know what they were doing and so sometimes smelted with low efficiency and without slag formation below the melting point of copper and at other times at very high temperatures above 1,200 °C. It is far more likely that people who were able to cast copper and thus achieve temperatures above 1,100 °C would strive to smelt at the maximum temperature obtainable with charcoal (between 1,200 and 1,300 °C). Under these circumstances, both slag and metal are liquid and the smelting process is easier to control and much more efficient. Consequently, it is most likely that the reduction smelting of ores containing nickel and arsenic would produce copper rich in both elements.

Table 11.1 Classification of elements reported in analyses of ancient copper-based objects concerning their bearing on provenance and/or smelting technology

Copper and copper alloys

Production technology	Provenance and/or production technology	Provenance
Al[a], B, Be, Ba, Ca, Cr, Cs, Fe, Ga, Ge, Hf, K, Li, Mg[a], Mn[a], Mo, Na, Nb, P[a], Pb, Rb, S, Sc, REE[c], Si[a], Sn, Sr, Ta, Ti[a], Th, U, V, W, Y, Zn, Zr	As, Co, In, Pb, Re, Sb, Sn, Se, Te, Zn	Ag, Au, Bi, Ir, Ni Os, Pd, Pt, Rh, Ru Cd[b], Hg[b], Tl[b]
Sn > ca. 1% Pb > ca. 5% Zn > ca. 2%	Sn < ca. 1% Pb < ca. 5% Zn < ca. 2%	routinely analyzed routinely analyzed

[a] only for authenticity investigations
[b] only for native copper
[c] Rare Earth Elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu)

Sulphide ores are more difficult to smelt because they cannot be reduced directly, but must be oxidised (roasted) before reduction in order to remove most of the sulphur. This is usually accomplished at around 700 °C, well below the melting point of copper and most ore minerals. However, it is possible that elements that are volatile or form volatile compounds like zinc, arsenic, antimony and (presumably) selenium and tellurium are lost during roasting (Tylecote et al. 1977). As a result, these elements are of limited use to relating copper artefacts to ore deposits, although it has been shown that the fahlore signature (high arsenic, antimony and silver concentrations) is at least partly preserved in the metal (Pernicka 1999).

A third complication in relating trace elements in ores to those in finished artefacts is the fact that early metallurgy is often envisaged as a two-step process, which may leave little or no slag—the so-called slagless process. According to this model, there is first the reduction of copper ore to copper metal in a solid-state reaction, which requires reducing conditions and temperatures from 700 °C upwards (Budd 1991), and second there is the actual melting of copper metal, which requires temperatures in excess of 1,080 °C. In this two-step model, the reducing stage is characterised by the necessarily incomplete burning of charcoal, which results in limited heat generation and may lead to the reduction of some copper oxide to copper metal. This metal would form in a finely dispersed form within any gangue components (such as iron oxides or silicates) that come together with the copper mineral. Any copper formed in this hypothetical process would then have to be melted in order to collect it and cast it into an artefact shape. To do this, one would have to raise the temperature above 1,084 °C, the melting point of copper.

This hypothetical scenario is rather unrealistic. There are several physical–chemical and practical arguments against it:

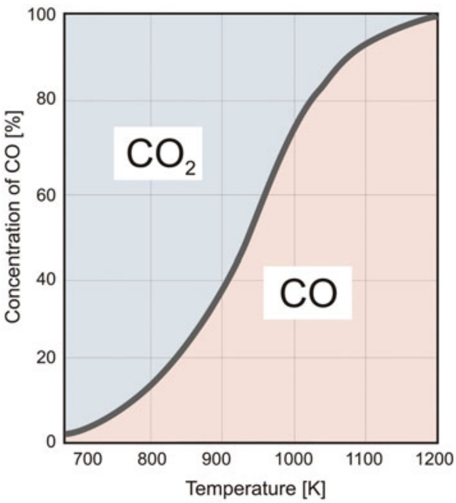


Fig. 11.6 *Curve 1* in the figure shows the equilibrium relationship for the reaction $CO_2 + C = 2\,CO$, which is called Boudouard's equilibrium. In the neighbourhood of 1,200 K, carbon dioxide that has been formed by burning of charcoal is changed into carbon monoxide by this reaction, making it possible to maintain the reducing capability of the gas. It is evident that below 1,000 K the reducing capability of the gas decreases rapidly

1. Reduction of copper to metal is much more efficient in the liquid phase due to much higher diffusion rates.
2. The reducing agent is gaseous carbon monoxide (CO) in all cases, which is produced when there is an excess of charcoal in contact with the burning charcoal. This so-called Boudouard equilibrium of the reaction $CO_2 + C = 2\,CO$ favours the CO side only above ca. 800 °C (Fig. 11.6). Below this temperature, the reduction efficiency (i.e. the amount of CO present) would be very low, so that the postulated solid-state reduction at such a moderate temperature would be very slow.
3. Finally, it would be very difficult for the ancient smelter to keep the temperature relatively low throughout the reaction vessel, due to inevitable temperature gradients from the tip of the blow pipe to areas further away. In effect, it would be difficult to control the temperature in the region between 800 and 900 °C if one were determined to reduce copper at such a low temperature. Therefore, it is highly unlikely that the early smelters consciously aimed at such a two-step process. It is much more likely that the two discrete aspects of copper smelting—chemical reduction and physical melting—may well have been combined in one process. The suggestion of a purely solid-state and "slagless" copper production remains hypothetical at best, even for the earliest periods of metallurgy.

The fourth complication arises from the treatment of smelted copper to produce the finished object. Nowadays, black (the first product of a smelting furnace) or "dirty" copper is generally refined to remove sulphur, iron and other impurities and this may also have been true in prehistoric times. This is an easy process because all that is required is to re-melt the copper under mildly oxidising conditions. Iron and other easily oxidised impurities are then removed as dross. It has been suggested that the refining of copper erases most of the chemical characteristics that survived from the ore (Merkel 1983, 1990). However, using Merkel's experimental data it can be shown that this is not the case for elements like silver, nickel and antimony (Fig. 11.7).

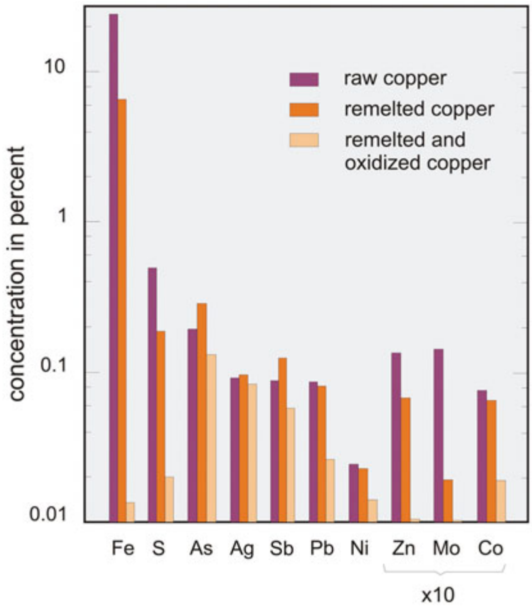


Fig. 11.7 Summary of refining experiments performed by Merkel (1983, 1990). It is evident that the concentrations of most elements relative to copper do not significantly change on simple re-melting, except for Fe, S and Mo, all of which are irrelevant for provenance studies. It is unlikely that molten copper was regularly exposed to a blast of air for extended time as indicated in the *third column* (*re-melted and oxidised copper*). But even then, only Co, Ni and Pb are reduced by a factor of 2, which is of little significance when ores are compared with artefacts. (After Pernicka 1987)

A final consideration is that some elements were deliberately alloyed to copper. In antiquity these were mainly arsenic, tin, lead and zinc. Copper–arsenic alloys have long been seen as accidental products of arsenic-rich copper ores and this may still be true in many cases. However, only recently it has been shown that speiss (an iron arsenide of variable composition) produced from arsenopyrite without copper may have been added to molten copper to enhance its arsenic content (Thornton et al. 2009; Rehren et al.). The effect on the trace element pattern of the copper is as yet unclear, but arsenopyrites are known to often contain gold so that the content of at least this element and possibly others as well may be altered compared with the copper ore. On the other hand, alloying with tin most likely produces little change in the trace element pattern of the copper as most cassiterites (SnO_2) are rather pure and the alloy usually contains an order of magnitude less tin than copper. Addition of lead to copper or bronze can alter the silver and antimony concentrations but not those of nickel, cobalt and gold. The effect of the addition of zinc to copper is difficult to assess, because this could only be achieved by the so-called cementation process, in which zinc metal in the vapour phase is taken up by the copper. Most likely there will be little change of the trace element pattern but some experimental research on this question would be helpful.

Since arsenopyrites and cassiterites usually contain very little lead, the effect on the lead isotope ratios of the copper should be minimal and is usually neglected. The opposite is true for the addition of lead. If it is assumed that lead was added intentionally to an alloy then the lead isotope ratios can only be used to discuss the provenance of the lead and not the copper. How can the intentional addition of lead be detected? This is not straightforward, because many copper deposits also contain lead minerals and substantial amounts of lead could accidentally be included in the

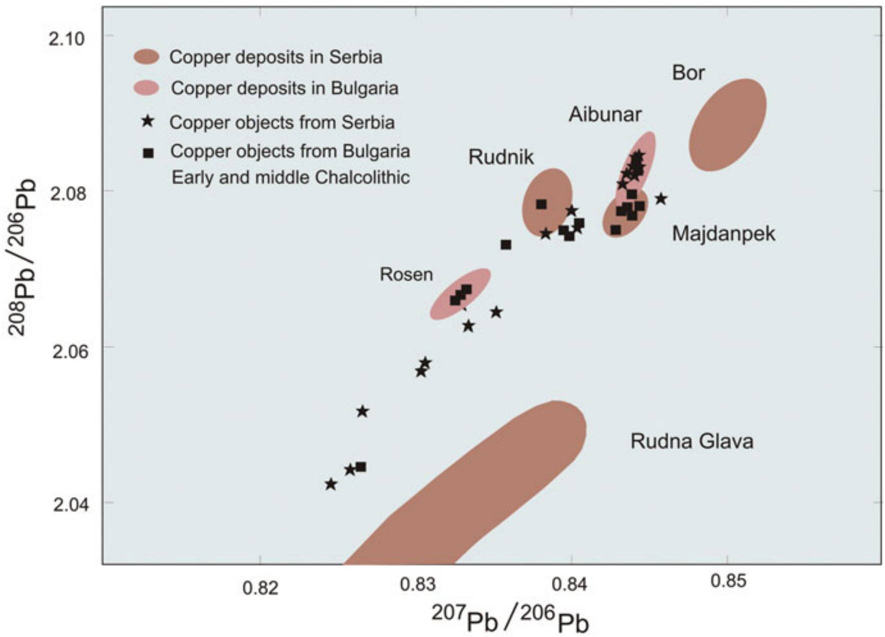


Fig. 11.8 Lead isotope ratios in various copper deposits in southeast Europe and in Chalcolithic copper artefacts (Pernicka et al. 1993, 1997). This shows that the major copper sources in this period, namely Ai Bunar in Bulgaria and Majdanpek in Serbia, partly overlap in their lead isotope ratios

copper. It is usually assumed that lead concentrations above 5 % most likely indicate intentional addition of lead and that below 1 % it is almost certain that there was no intentional addition. The region in between is a matter of discussion, depending on the date of the objects, their context and so on.

Table 1 contains a summary of the information provided by various elements that, in principle, can be found in ancient copper. There are few elements that are solely indicators of provenance. However, in very early times, when deliberate alloying did not occur, a whole suite of elements are available that can be useful in helping to determine provenance. The provenance of Chalcolithic copper in the Balkans (Pernicka et al. 1993, 1997) may serve as an example. Two of the earliest copper mines presently known, Ai Bunar in Bulgaria and Majdanpek in Serbia (only indirectly shown to have been exploited in the fifth millennium BC), have partly overlapping lead isotope signatures (Fig. 11.8) but can be differentiated by their trace element pattern (Fig. 11.9).

Finally, one of the most frequent questions relating to provenance analysis of copper alloys deals with mixing either of ores or of metal, for example recycling of scrap metal. In the earlier literature it was sometimes maintained that this can be recognised and taken into account. Today we realise that mixing of metals from different sources destroys the information on provenance of each component completely. This would be the case if many different metal pieces from random sources

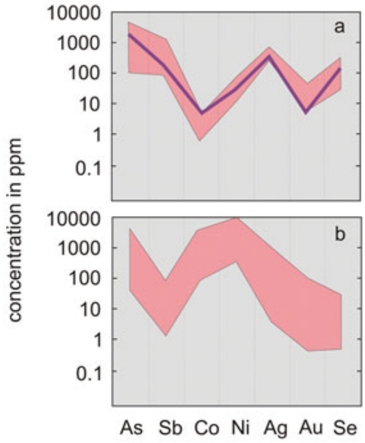


Fig. 11.9 Trace element patterns of Chalcolithic copper objects that are attributed to **a** Ai Bunar (Bulgaria) and **b** Majdanpek (Serbia) based on lead isotope ratios and their chemical compositions. The richest ore sample from Ai Bunar (*solid line*) is entirely consistent with this pattern

were mixed. But how realistic is this model? Mixing and recycling did occur, of course, but often within a certain region and period of time. An example is the Late Bronze Age of western Switzerland, where bun-shaped ingots were found that contained semi-molten pieces of identifiable metal objects. This is the best evidence for recycling that one can ask for. Nevertheless, Rychner and Kläntschi (1995) were able to identify local groups of metal objects of identical composition so that at least their classification was possible. It seems that in this case, recycling occurred within a pool of metal that was available and came from one source only. Thus, it is apparent that mixing did not obscure all information on provenance.

Another case that is often encountered when metal analyses are discussed is the question of whether a certain metal composition can be explained as a mixture of two other compositions. This problem was tackled in a systematic way by Pernicka (1987), who investigated whether any of the 46 metal objects could be derived from a mixture of any other two objects from the same suite. For this purpose, he compared lead isotope ratios and trace element concentrations (Fig. 11.10). The result was negative, at least for this limited problem. If one has to assume that more than two metal compositions were mixed, then there is no chance to calculate a mixing model, because the boundary conditions are not known. However, if mixing and reuse of metal would regularly occur, then there would be a tendency towards a homogenisation of the composition and no metal groups would be identifiable at all. As the opposite is observed (i.e. metal artefacts do group meaningfully), one can conclude that mixing and recycling was not important, at least in the early metal ages. Generally, one can state that the concentration of any element in an object on the extreme end on either side of the frequency distribution should indicate the absence of mixing. If, for example, an object shows a very low concentration of gold (e.g. less than a factor of ten below the average value of about 10 mg/kg), then its overall composition cannot be derived from mixing, unless one assumes the utterly improbable case that only copper scrap with unusually low gold concentrations was mixed. The same applies for very high concentrations of elements such as antimony or nickel, which are often found in the Early Bronze Age of central Europe and the Middle East/Caucasus.

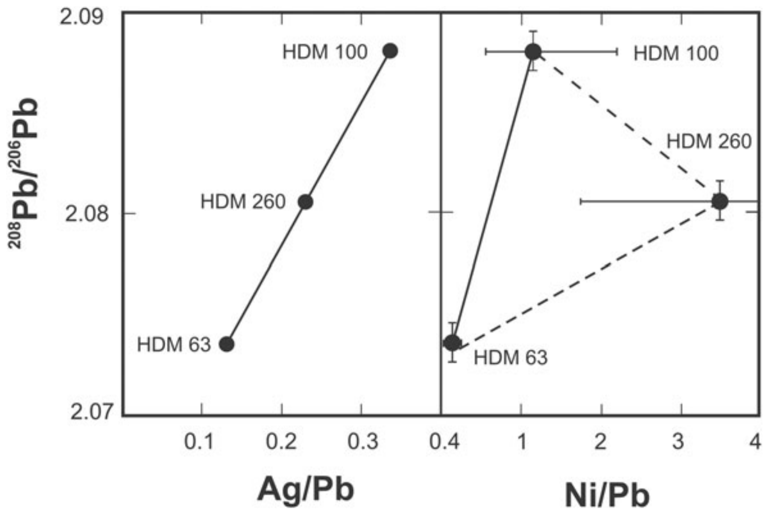


Fig. 11.10 Mixed diagram of one lead isotope radio and two element/lead ratios to demonstrate the method to identify mixing between two metal compositions. Plotted are the compositions of two metal objects from Troy (*HDM 100* and *HDM 260*) and one from the Troad (*HDM 63*) published by Pernicka et al. (1984). From the *left diagram* one could conclude that sample HDM 260 could be a mixture of HDM 100 and HDM 63, because it plots exactly on the mixing line between the two concerning the lead isotope ratio and the Ag/Pb ratio. Note that simply plotting the silver concentration would not be correct, because the position of a sample on the mixing line of lead isotope ratios depends on the lead concentrations of the mixed components. However, in the case of mixing, similar lines must be obtained with all other element/Pb ratios. In this example, this is obviously not the case as shown in the *right part of the diagram*. Even if one allows for the possibility of a concentration change of a factor of 2 on melting (indicated by the *horizontal error bar*, the *vertical error bar* is the uncertainty of the lead isotope measurement), then sample 260 cannot be explained as a mixture of samples HDM 100 and HDM 63.

The question of recycling is so obvious because we are living in an era where the resources of some metals are becoming scarce and recycling is an economic necessity. The modern recycling rate of copper is the highest among all engineering metals and well above 50 %. But was this always so? The answer is most probably no, but this depends again on the period considered and the region. In Europe, one can identify certain compositional groups of copper-based objects that are restricted in time and space. This would not be possible if recycling of metal from widely distributed sources were the rule. Note that recycling of copper from one source within a limited area would not have the same effect. On the other hand, in metal-poor regions like Mesopotamia, recycling was probably more important than in others. There is textual evidence of recycling and, indeed, low tin concentrations up to 2 % begin to become more abundant towards the end of the third millennium BCE (Hauptmann and Pernicka 2004). Such low tin concentrations do not alter the properties of the alloy significantly and are usually interpreted as indication for recycling scrap metal. Generally, one can assume that in expanding economies, the recycling rate should be small, because fresh metal must come into the system. If metal objects were removed from the system in the same period, either by loss or by intentional deposition, then this metal had little chance to be recycled. On the other hand, in declining cultures, the recycling rate should increase, because the economic structures become obsolete or are destroyed so that the metal supply is interrupted. A good example is the late Roman Empire and the Migration period. It is known that all kinds of old metal was actively sought and reused, be it lead pipes or iron clamps from buildings.

Other Metals

Attempts to elucidate provenance was not restricted to copper and its alloys. Already in the nineteenth century, series of analyses of silver and iron objects were performed (von Bibra 1873). The problems were the same as with the copper alloys. The analytical methods were not yet developed to achieve results that were useful for archaeology. After 1950, ancient silver was frequently analysed but concentrated on a narrow artefact group, namely coins (e.g. Gordus 1967), and it was often not the provenance of the silver that was sought but rather the alloy composition, especially the silver content. More focussed on provenance was the study of trace elements in Roman lead (Wyttenbach and Schubiger 1973) that could and should have been complemented by lead isotope analysis, which had already been introduced to the investigation of archaeological material (Brill and Wampler 1965; Grögler et al. 1966).

The pioneering work on the provenance of ancient silver was performed at the Max-Planck-Institut für Kernphysik in Heidelberg, where extensive field surveys for lead and silver deposits in the Aegean were combined with trace element and lead isotope analysis of ancient silver coins (Gale et al. 1980). Until the Middle Ages, silver was almost exclusively produced from argentiferous lead ores by a two-stage process, whereby lead ores were first smelted to produce lead metal that was then selectively oxidised in the molten condition to produce lead oxide until a small amount of silver remained (a process known as “cupellation”). The remaining lead in the silver is an ideal tracer for the provenance of the metal as has been shown by later work on Early Bronze Age finds (for a summary of the research in the Aegean, see Gale and Stos-Gale 1981; Pernicka 1990). In later periods, one has to take into account that cupellation was also used to purify the noble metals silver and gold. The lead used for this process may derive from a different source than the silver and be irrelevant for the provenance thus be irrelevant for the provenance of the silver. There is circumstantial textual evidence for this practice in the second millennium BCE. In the Roman period it is likely that debased silver coinage was purified this way and, beginning in the fifteenth century CE, lead metal was used to extract silver from argentiferous copper ores. In the Middle Ages, silver coinage was frequently recalled and re-minted so that provenance studies with this group of artefacts are fraught with problems.

For provenance investigations of lead, its isotope ratios are clearly the most valuable parameter. Trace element concentrations can be useful, if it can be assumed that the metal is the product of primary smelting. This is usually indicated by its silver content. Below a certain silver concentration it was not practical or economical to extract the silver, and lead was then used for other purposes. In the Bronze Age, this limit of silver extractability seems to have fallen from somewhere between 500 and 800 mg/kg to 200–300 mg/kg until it reached around 100 mg/kg in the Roman period, where it remained so until the eighteenth century CE. However, lead that has been desilvered through cupellation carries no memory of the trace element pattern of the original ore.

In principle, the problems associated with provenance studies of base metals and silver should not apply to gold, because this element mainly occurs in the metallic form in nature. Therefore, one would think that the analytical problem should be similar to rocks (e.g. obsidian, marble etc.) and that there would be no compositional change between the natural occurrence and the finished product. Unfortunately, this is not the case. There are several reasons why provenance determination of gold is even trickier than with base metals:

1. Gold is relatively pure in nature, although usually admixed with substantial silver contents (leading to natural electrum). This requires a very sensitive analytical method. Combined with the exceptional value that is always ascribed to ancient gold objects, the analytical task is formidable, because sampling is either not allowed or restricted to extremely small sample masses. The best method today is certainly mass spectrometry with inductivelycoupled plasma excitation combined with laser ablation sampling (LA-ICP-MS).
2. Silver as the major "impurity" in native gold exhibits a wide range of variation within gold occurrences so that it is of little use to discriminate between gold sources.
3. The majority of gold occurs in the form of small flakes either as alluvial gold or in rocks, which are usually powdered and the gold is extracted from the powder by some sort of panning. For manufacture, the gold was most certainly melted and this process induces significant changes in the trace element pattern of the gold (Hauptmann et al. 1995).
4. Many of the gold sources exploited in the past are geochemically insufficiently explored so that it is difficult to define characteristic elements for their discrimination. However, a pilot study has indicated that this may be possible (Schmiderer 2008). It has been found that many prehistoric gold objects contain more copper than is on average found in native gold. This means that copper may have been added to gold either intentionally or as a kind of contamination. This will certainly alter the trace element pattern of the alloy.
5. Native gold, especially alluvial gold, tends to have very low lead concentrations so that lead isotope analysis is either not possible (see 1) or difficult to interpret, because the source of the lead may not be always clear. In a study of Celtic gold coins, the question of provenance was not addressed because of evidence for recycling and alloying with copper (Bendall et al. 2009).
6. The hopes connected with the observation of inclusions of platinum group minerals (PGM) in ancient gold (Young 1972) concerning provenance analysis quickly evaporated when it was discovered that even within a single object the compositional (Meeks and Tite 1980) as well as the osmium isotopic (Junk and Pernicka 2003) variations were as large as found in nature. Therefore, discrimination of sources was not possible.

In this situation, the only realistic chance for gold provenance is the trace element pattern, concentrating on trace elements like Pd and Pt that are characteristic of the gold, do not change on melting and are not introduced by alloying with copper (Guerra 2004, Ehser et al. 2011). The most comprehensive analytical study of prehistoric gold objects was performed at the Württembergisches Landesmuseum by Hartmann (1970, 1982). He used optical emission spectroscopy and published some 5,000 analyses. This study has also been received with scepticism but it showed that, similar to copper and copper alloys, certain compositional groups could be identified that showed a restricted distribution in time and space.

For a long time, provenance discussions of ancient iron were largely based on conjecture rather than objective facts. In most cases it was simply assumed that the geographically nearest iron deposit was the source sought. This was hardly disputed as there are many iron ore occurrences known compared with copper and other base metals. However, recent studies have shown that even with iron, matters are not so simple. Iron was traded in the form of bipyramidal ingots that were often welded from two heterogeneously carburised halves. In a pilot study, a series of middle and late Iron Age iron finds from the Celtic oppidum of Manching in southern Bavaria were analysed in order to determine their possible provenance by combining trace element patterns of slag inclusions. Lead isotopic analysis, well established in non-ferrous archaeometallurgy but hardly employed for iron, was introduced as a new approach (Schwab et al. 2006). The methods applied provided valuable information but each is limited in some aspects. Small-scale variations within the ores are thus reflected in the iron artefacts and even large variations cannot be separated by the methods employed. Nevertheless, it was possible to distinguish various iron ore occurrences near the settlement, and bog ores have been generally identified as most likely sources for iron smelting in the nearby of Manching. Actually, only one local bog ore deposit matches the characteristics of the iron artefacts examined in all aspects (Schwab et al. 2006). Degryse et al. (2007) proposed to adapt the combination of lead isotope with strontium isotope ratios for the provenance study of iron objects as it has already been introduced for ancient glass.

In a different and complementary approach, slag inclusions in ancient iron artefacts were analysed also with the view to obtain information on their provenance (Hedges and Salter 1979). Similar to copper, it is important to understand the chemical heritage (major and trace elements) from the ore into the iron artefacts. Much work has been invested in this direction by a French group (Coustures et al. 2003; Desaulty et al. 2009). It was demonstrated that the study of major elements in the slag inclusions allows the identification of ore groups characterised by high levels of certain elements such as P or Mn. In a first step, a group of artefacts with potentially common provenance was found and, more important, some provenance hypotheses could be rejected. By including rare earth elements in the study, it was found that their respective ratios remain constant from the original ore to the slag inclusions. Thus, if the chemical signature of a given area is known, it is possible to verify its compatibility with an artefact by performing trace element analyses of slag inclusions. This was verified by the French team for the Pays de Bray region using archaeological ore and experimental smelting. With many elements at hand, one can add multivariate methods of data analysis (as with pottery) to compare ores with slag inclusions in iron artefacts.

Conclusion

To summarise, in this contribution the view is held that the scientific analysis of archaeological metal objects is not only a valuable contribution to archaeological research, but is necessary to correctly describe the archaeological material at the basic level. In many cases, metal finds that originally were described by the excavator as "bronze" turned out to be unalloyed copper or another copper alloy or even a different metal (e.g. silver). Analyses can also be used to classify metal objects according to their composition. This classification can be compared with the typological groups, and in the case of congruency, one may be able to identify the products of a particular workshop.

The most demanding and most difficult question relates to the provenance of the metal, especially in regions where no metallic ore deposits are known. It has been suggested that it may only be possible to identify the type of ore that has been used for primary smelting (Friedman et al. 1966; Budd et al. 1992). While it is possible to identify native copper rather securely by its trace element pattern (Pernicka 1990), despite assertions to the contrary (Maddin et al. 1980), it is more difficult to distinguish between oxidic and sulphidic ores post-smelting. The sulphur content is not a reliable indicator, as sulphur is concentrated in the metal phase and most oxidic ores contain small amounts of the primary sulphidic ore. The most reliable indicator seems to be the iron content (Craddock and Meeks 1987).

However, the key question remains to determine the geological source (or at least the original workshop) of a metal object. One may well ask why bother? Should we give up reaching for the stars and "rethink the quest for provenance" (Budd et al. 1996)? The answer is simple: we study provenance of metals because metal ores are unevenly distributed over large areas, so that some kind of long-distance transport naturally has to be assumed. Furthermore, metals are a new commodity that—much more than agricultural wealth—can be accumulated and hoarded. Accordingly, it has an influence on social dynamics that cannot be overestimated. Since metals are rare, their intrinsic value is high, so that small pieces of metal are equivalent in value of larger volumes or masses of other commodities, which made them ideal as exchange tokens. At least from the third millennium onwards, most values of all kind of merchandise were calculated in equivalent weights of metal, usually silver.

What is the Future of Provenance Studies?

These are just a few examples to show that provenance studies are important, especially for the reappraisal of hypotheses concerning contacts and relations of different regions and cultures on the basis of excavated materials and their distribution. It has taken a long time for the different strands of knowledge to be brought together that really promote our understanding of the unrecorded history of metallurgical production and exchange. The basis is, of course, a broad knowledge of the archaeological period under investigation to tackle the archaeologically relevant problems, select the appropriate material for this task and finally translate the analytical results into the cultural historical perspective. This applies to work in museum as well as in the field. Archaeologists are usually not trained to excavate and interpret metallurgical installations and know even less about ancient mining. Only when archaeological field surveys are combined with expert knowledge in mineralogy and economic geology can the metallurgical potential of a given region be correctly assessed. It requires a deep understanding of metallurgical practices and physical chemistry to understand the processes of metal production and the consequences for the chemical and isotopic composition of the metallic products. Last but not least, it requires a fair deal of experience in analytical chemistry to produce reliable data that do not lead us astray, as it has sometimes happened in the past.

Where do we go from here? Although a fairly good coverage of the geochemical characteristics of base metal deposits in the Mediterranean and in central and western Europe are now available, we will never reach a position as in provenance studies of obsidian where it is usually possible to pinpoint a certain geological obsidian source for every single artefact (at least in the eastern Mediterranean). Ore deposits are simply too heterogeneous, so that overlap between different sources is unavoidable. Actually, we are in the uncomfortable position that the more data we produce, the less (apparent) clarity we have. The way to escape this vice is the combination of parameters such as trace element patterns and lead isotope ratios. This may still not be successful in all cases, but important questions have been resolved in this way (such as the provenance of the Late Bronze Age oxhide ingots and Chalcolithic copper production and distribution in southeastern Europe). Furthermore, field studies will have to continue, because the most convincing relation between an ore deposit and archaeological metal artefacts is a match of the trace element patterns, lead isotope ratios and metal mining and production in the period in question, as was also demonstrated in southeastern Europe (Pernicka et al. 1997).

New parameters will be added in future and have already been tested, such as isotope ratios of copper (Klein et al. 2010), zinc (Budd et al. 1999), osmium (Junk and Pernicka 2003, Brauns et al. 2013) and recently also tin (Haustein et al. 2010). Of these, osmium may be most useful for the provenance of iron and still possibly of gold. Tin isotope ratios have already yielded a very surprising result in that it was found that the tin of the famous sky disc of Nebra most likely derives from Cornwall and not from the relatively nearby Erzgebirge, corroborating Pare's (2000) scenario of Early Bronze Age tin trade in central Europe. Provenance studies of all kinds of metal will certainly form an important component of archaeometallurgy also in the foreseeable future.

References

Barker, G., & Slater, E. (1971). The first metallurgy in Italy in the light of the metal analyses from the Pigorini Museum. *Bullettino di Paletnologia Italiana*, *80,* 183–212

Begemann, F., & Schmitt-Strecker, S. (2009). Über das frühe Kupfer Mesopotamiens. *Iranica Antiqua, 54,* 1–45

Begemann, F., Schmitt-Strecker, S., & Pernicka, E. (2003). On the composition and provenance of metal finds from Beşiktepe (Troia). In Wagner G. A. Pernicka E, & Uerpmann H.-P. (eds.) *Troia and the Troad—Scientific approaches* (pp. 173–201). Springer, Heidelberg

Bendall, C., Wigg-Wolf, D., Lahaye, Y., von Kaenel, H.-M., & Brey, G. P. (2009) Detecting changes of Celtic gold sources through the application of trace element and Pb isotope laser ablation analysis of Celtic gold coins. *Archaeometry, 51,*598–625

Blin-Stoyle, A. (1959) Chemical composition of the bronzes. *Archaeometry, 2*,1–17

Brauns, M., Schwab, R., Gassmann, G., Wieland, G., & Pernicka, E. (2013). Provenance of Iron Age iron in southern Germany: A new approach. *Journal of Archaeological Science*, 40, 841–849.

Briard, J., & Giot, P. R. (1956). Analyses des objets métalliques du chalcolithique et de l'age de bronze ancien et du bronze moyen de Bretagne. *L'Anthropolgie, 60,* 495–500.

Brill, R. H., & Wampler, J. M. (1965). *Isotope ratios in archaeological objects of lead. Application of science in the examination of works of art* (pp. 155–166). Boston: Museum of Fine Arts.

Britton, D. (1961). A study of the composition of Wessex culture bronzes. Based on spectroscopic analyses by E. E. Richards. *Archaeometry, 4,* 39–52.

Budd, P. D. (1991). Eneolithic arsenical copper—Heat-treatment and the metallographic interpretation of manufacturing processes. In E. Pernicka, & G. A. Wagner (Eds.), *Archaeometry '90: International symposium in archaeometry* (pp. 35–44). Basel: Birkhäuser Verlag.

Budd, P. D., Gale, D., Pollard, A. M., Thomas, R. G., & Williams, P. A. (1992). The early development of metallurgy in the British Isles. *Antiquity, 66,* 677–686

Budd, P. D., Haggerty, A., Pollard, A. M., Scaife, B., & Thomas, R. G. (1996). Rethinking the quest for provenance. *Antiquity, 70,* 168–174

Budd, P. D., Lythgoe, P., McGill, R. A. R., Pollard, A. M., & Scaife, B. (1999). Zinc fractionation in liquid brass (Cu/Zn) alloy: Potential environmental and archaeological applications. In A. M. Pollard (Ed.), *Geoarchaeology: Exploration, environments, resources* (pp. 147–153). London: Special Publication 165, Geological Society.

Butler, J. J., & van der Waals, J. D. (1964). Metal analysis, Studien zu den Anfängen der Metallurgie (SAM) I, and the European prehistory. A review article. *Helinium, 4*,1–39.

Chernykh, E. N. (1966). *Istorija drevnejšej metallurgii Vostočnoj Evropy*. Moskau-Leningrad: MIA 132.

Chase, W. T. (1974). Comparative analysis of archaeological bronzes. In C. W. Beck (Ed.), Archaeological chemistry (Advances in Chemistry Series No. 138), 148–185.

Chernykh, E. N. (1992). *Ancient metallurgy in the USSR*. Cambridge: Cambridge University Press

Coghlan, H. H., & Case, H. (1957). Early metallurgy of copper in Ireland and Britain. *Proceedings of the Prehistoric Society, 23*, 91–123.

Coles, J. M. (1982). The Bronze Age in northwestern Europe: Problems and advances. In: F. Wendorf and A.E. Close (eds.): Advances in World Archaeology 1, New York, 265–321.

Coustures, M.-P., Béziat, D., & Tollon, F. (2003). The use of trace element analysis of entrapped slag inclusions to establish ore-bar iron links: examples from two gallo-roman iron-making sites in France (Les Martys, Montagne Noire, and Les Ferrys, Loiret). *Archaeometry, 45,* 599–613.

Craddock, P. T., & Meeks, N. D. (1987). Iron in ancient copper. *Archaeometry, 29,* 187–204.

Degryse, P., Schneider, J., Kellens, N., Waelkens, M., & Muchez, P. H. (2007). Tracing the resources of iron working at ancient Sagalassos (South-west Turkey): A combined lead and strontium isotope study on iron artefacts and ores. *Archaeometry, 49*(1), 75–86.

Desaulty, A.-M., Dillmann, P., L'Héritier, M., Mariet, C., Gratuze, B., Joron J-L, & Fluzin P (2009) Does it come from the Pays de Bray? Examination of an origin hypothesis for the ferrous reinforcements used in French medieval churches using major and trace element analyses. *Journal of Archaelogical Science, 36,* 2445–2462

Desch, C. H. (1928–1938). Sumerian copper—reports of committee appointed to report on the probable source of the supply of copper used by the Sumerians, British Association for the Advancement of Science Reports: 1928, pp. 437–441; 1929, pp. 264–265; 1930, pp. 267–268; 1931, pp. 269–272; 1933, pp. 302–305; 1935, pp. 340–344; 1936, pp. 308–310; 1938, pp. 345–346.

Ehser, A., Borg, G., & Pernicka, E. (2011). Provenance of the gold of the early bronze age nebra sky disk, central Germany: Geochemical characterization of natural gold from Cornwall. *European Journal of Mineralogy, 23*(6), 895–910.

Friedman, A. M., Conway, M., Kastner, M., Milsted, J., Metta, D., Fields, P. R., & Olsen, E. (1966). Copper artifacts: correlation with some types of copper ores. Science 152:1504–1506

Gale, N. H., & Stos-Gale, Z. A. (1981). Cycladic lead and silver metallurgy. *Annual of British School at Athens, 76,* 169–224

Gale, N. H., Gentner, W., & Wagner, G. A. (1980). Mineralogical and geographical sources of Archaic Greek coinage. *Metallurgy in Numismatics, 1,* 3–49.

Gerlach, W., & Schweitzer, E. (1930). Die chemische Emissionsspektralanalyse. Teil I. Leopold Voß, Leipzig.

Göbel, F. (1842). Über den Einfluß der Chemie auf die Ermittlung der Völker der Vorzeit oder Resultate der chemischen Untersuchung metallischer Alterthümer, insbesondere der in den Ostseegouvernements vorkommenden, behufs der Ermittlung der Völker, von welchen sie abstammen. Enke Verlag, Erlangen.

Gordus A. A. (1967). Quantitative non-destructive neutron activation analysis of silver in coins. *Archaeometry, 10,* 78–86.

Grögler, N., Geiss, J., Grünenfelder, M., & Houtermans, F. G. (1966). Isotopenuntersuchungen zur Bestimmung der Herkunft römischer Bleirohre und Bleibarren. *Zeitschr. f. Naturforsch, 21a,* 1167–1172.

Guerra, M. F. (2004). Fingerprinting ancient gold with proton beams of different energies. *Nuclear Instruments and Methods in Physics Research Section B, 226,*185–198.

Härke, H. (1978). Probleme der optischen Emissionsspektralanalyse in der Urgeschichtsforschung. Prähist. *Zeitschr, 53,* 165–276.

Hall, E. T. (1970). Analytical techniques used in archaeometry. In: T. E. Allibone (Ed.), *The impact of natural sciences on archaeology* (pp. 135–141). Oxford University Press, London.

Hartmann, A. (1970). Prähistorische Goldfunde aus Europa. Studien zu den Anfängen der Metallurgie (SAM), Vol. 3. Gebr. Mann Verlag: Berlin.

Hartmann, A. (1982). Prähistorische Goldfunde aus Europa II. Studien zu den Anfängen der Metallurgie (SAM), Vol. 5. Gebr. Mann Verlag: Berlin.

Hauptmann, H., & Pernicka, E. (Hrsg). (2004). Die Metallindustrie Mesopotamiens von den Anfängen bis zum 2. Jahrtausend v. Chr. *Orient-Archäologie Band 3, Katalog, Tabellen, Tafeln*. Rahden: Leidorf.

Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E., & Schmitt-Strecker S (1992). Early copper produced at Feinan, Wadi Araba, Jordan: The composition of ores and copper. Archeomaterials 6:1–33

Hauptmann, A., Rehren, Th., & Pernicka, E. (1995). The composition of gold from the ancient mining district of Verespatak/Rošia Montana, Romania. In G. Morteani, & J. P. Northover (Eds.), *Prehistoric Gold in Europe* (pp 369–381). Amsterdam: Kluwer Academic Publishers.

Hauptmann, A., Rehren, Th., & Schmitt-Strecker, S. (2003). Early Bronze Age copper metallurgy at Shahr-i Sokhta (Iran), reconsidered. In Th. Stöllner, G. Körlin, G. Steffens, & J. Cierny (Eds.), Man and Mining—Mensch und Bergbau. Der Anschnitt, Beiheft 16: 197–213. Deutsches Berbgau-Museum, Bochum.

Haustein, M., Gillis, C., & Pernicka, E. (2010). Tin isotopy—A new method for solving old questions. *Archaeometry, 52,* 816–832.

Hedges, R. E. M., & Salter, C. (1979). Source determination of iron currency bars through the analysis of slag inclusions. *Archaeometry, 21,* 161–175.

Hirao, Y., Enomoto, J., & Tachikawa, H. (1995). Lead isotope ratios of copper, zinc and lead minerals in Turkey—In relation to the provenance study of artifacts. In H. I. H. Prince, & T. Mikasa (Ed.), *Essays on ancient Anatolia and its surrounding civilizations*, pp. 89–114. Wiesbaden: Harrassowitz.

Hodson, F. R. (1969). Searching for structure within multivariate archaeological data. *World Archaeology, 1,* 90–105.

Höppner, B., Bartelheim, M., Huijsmans, M., Krauss, R., Martinek, K.-P., Pernicka, E., & Schwab, R. (2005). Prehistoric copper production in the Inn valley, Austria, and the earliest copper in central Europe. *Archaeometry, 47,* 293–315.

Junghans, S., Klein, H., & Scheufele, E. (1954). Untersuchungen zur Kupfer- und Frühbronzezeit Süddeutschlands. *Ber. RGK, 34,* 77–114

Junghans, S., Sangmeister, E., & Schröder, M. (1960). Metallanalysen kupferzeitlicher und frühbronzezeitlicher Bodenfunde aus Europa, Gebr. Mann Verlag, Berlin.

Junghans, S., Sangmeister, E., & Schröder, M. (1968). Kupfer und Bronze in der frühen Metallzeit Europas 1–3, Berlin.

Junghans, S., Sangmeister, E., & Schröder, M. (1974). Kupfer und Bronze in der frühen Metallzeit Europas 4, Gebr. Mann Verlag, Berlin.

Junk, S. A., & Pernicka, E. (2003). An assessment of osmium isotope ratios as a new tool to determine the provenance of gold with platinum group metal inclusions. *Archaeometry, 45,* 313–331.

Klein, S., Brey, G. P., Durali-Müller, S., & Lahaye, Y. (2010). Characterisation of the raw metal sources used for the production of copper and copper-based objects with copper isotopes. *Archaeological and Anthropological Sciences, 2,* 45–56.

Krause, R. (2003). *Studien zur kupfer- und frühbronzezeitlichen Metallurgie zwischen Karpatenbecken und Ostsee*. Rahden: VML Verlag.

Maddin, R., Stech Wheeler, T., & Muhly, J. D. (1980). Distinguishing artifacts made of native copper. *Journal of Archaeological Science, 7,* 211–225.

Maréchal, J.-R. (1963). *Reflections upon prehistoric metallurgy. A research based upon scientific methods*. Lammersdorf: Junker.

Meeks, N. D., Tite, M. S. (1980). The analyses of platinum-group element inclusions in gold antiquities. *Journal of Archaeological Science, 7,* 267–275.

Meliksetian, K., & Pernicka, E. (2010). Geochemical characterisation of Armenian early bronze age metal artefacts and their relation to copper ores. In S. Hansen, A. Hauptmann, I. Motzenbäcker, & E. Pernicka (eds.), Von Maikop bis Trialeti. Gewinnung und Verbreitung von Metallen und Obsidian in Kaukasien im 4.-2. Jt. v. Chr. Beiträge des Internationalen Symposiums in Berlin vom 1.-3. Juni 2006. Kolloquien zur Vor- und Frühgeschichte, (Vol. 13, pp. 41–58). Habelt Verlag: Bonn.

Merkel, J. (1983). Summary of experimental results for Late Bronze Age copper smelting and refining. *Museum Applied Science Center Journal, 2/6,* 173–179.

Merkel, J. (1990). Experimental reconstruction of Bronze Age copper smelting based on archaeological evidence from Timna. In B. Rothenberg (Ed.), *The ancient metallurgy of copper*. London: Institute of Archaeo-Metallurgical Studies.

Nezafati, N., Pernicka, E., & Momenzadeh, M. (2009). Introduction of the Deh Hosein Ancient Tin-Copper Mine, Western Iran: Evidence from geology, archaeology, geochemistry and lead isotope data. *TÜBA-AR* (*Turkish Academy of Sciences Journal of Archaeology*)*, 12,* 223–236.

Northover, J. P. (1996). Comparison of metal analyses by different laboratories and methods, Appenidx II. In H. Vandkilde (Ed.), *From stone to bronze: the metalwork of the Late Neolithic and earliest Bronze Age in Denmark* (pp. 359–368). Moesgård: Jutland Archaeological Society/Jutland Archaeological Society Publications, 32.

Oldeberg, A. (1942). Metallteknik under förhistorisk tid. Part I. Otto Harrassowitz, Lund/Leipzig.

Otto, H., & Witter, W. (1952). *Handbuch der ältesten vorgeschichtlichen Metallurgie in Mitteleuropa*. Leipzig: Barth Verlag.

Pare, C. F. E. (2000). Bronze and the Bronze Age. In C. F. E. Pare (Ed.), *Metals make the world go round. The supply and circulation of metals in Bronze Age Europe* (pp. 1–38). Oxbow, Oxford.

Pernicka, E. (1984). Instrumentelle Multi-Elementanalyse archäologischer Kupfer- und Bronzeartefakte Ein Methodenvergleich *Jahrbuch Römisch-Germanisches Zentralmuseum 31,* 517–531.

Pernicka, E. (1987). Erzlagerstätten in der Ägäis und ihre Ausbeutung im Altertum: Geochemische Untersuchungen zur Herkunftsbestimmung archäologischer Metallobjekte. *Jahrbuch Römisch-Germanisches Zentralmuseum 34,* 607–714.

Pernicka, E. (1990) Entstehung und Ausbreitung der Metallurgie in prähistorischer Zeit. *Jahrb. Röm.-Germ. Zentralmus, 37,* 21–129.

Pernicka, E. (1999). Trace element fingerprinting of ancient Copper: A guide to technology or provenance?. In S. M. M. Young, A. M. Pollard, P. Budd, & R. A. Ixer (Eds.), *Metals in antiquity. BAR International Series, 792* (pp. 163–171). Oxford: Archaeopress.

Pernicka, E., Adam, K., Böhme, M., Hezarkhani, Z., Nezafati, N., Schreiner, M., Winterholler, B., Momenzadeh, M., & Vatandoust, A. (2011). Archaeometallurgical researches at Arisman in central Iran. In A. Vatandoust, H. Parzinger, & B. Helwing (eds.), Early mining and metallurgy on the Central Iranian Plateau. Report on the first five years of research of the Joint Iranian-German Research Project. *Archäologie in Iran und Turan 9,* 633–705, Philipp von Zabern, Mainz.

Pernicka, E., Begemann, F., Schmitt-Strecker, S., & Wagner, G. A. (1993). Eneolithic and Early Bronze Age copper artefacts from the Balkans and their relation to Serbian copper ores. *Praehistorische Zeitschrift, 68,* 1–54.

Pernicka, E., Begemann, F., Schmitt-Strecker, S., Todorova, H., & Kuleff, I. (1997). Prehistoric copper in Bulgaria: Its composition and provenance. *Eurasia Antiqua, 3,* 41–180.

Pittioni, R. (1957). Urzeitlicher Bergbau auf Kupfererz und Spurenanalyse. Beiträge zum Problem der Relation Lagerstätte-Fertigobjekt. Arch. Austriaca. Beih. 1, Wien.

Pollard, A. M., Thomas, R. G., Ware, D. P., & Williams, P. A. (1991). Experimental smelting of secondary copper minerals: Implications for Early Bronze Age metallurgy in Britain. In E. Pernicka, G. A. Wagner (Eds.), *Archaeometry '90* (pp. 127–136). Basel: Birkhäuser Verlag.

Preuschen, E., & Pittioni, R. (1937). Untersuchungen im Bergbaugebiete Kelchalpe bei Kitzbühel, Tirol. Erster Bericht über die Arbeiten 1931–1936 zur Urgeschichte des Kupferbergwesens in Tirol. Mitt. Prähist. Komm. Volume 3.

Radivojević, M., Rehren, Th., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the origins of extractive metallurgy: new evidence from Europe. *Journal of Archaeological Science, 37,* 2775–2787.

Rehren, Th., Boscher, L., & Pernicka, E. (2012). Large scale smelting of speiss and arsenical copper at Early Bronze Age Arisman, Iran. *Journal of Archaeological Science, 39*(6), 1717–1727.

Renfrew, C. (1973). Before civilization, Penguin, London.

Rychner, V., Kläntschi, N. (1995). Arsenic, Nickel et Antimoine. Cahiers d'Archéologie Romande, No. 63 and 64, Lausanne.

Sayre, E. V., Joel, E. C., Blackman, M. J., Yener, K. A., & Özbal, H. (2001). Stable lead isotope studies of Black Sea Anatolian ore sources and related Bronze Age and Phrygian artefacts from nearby archaeological sites. Appendix:New Central Taurus ore data. *Archaeometry, 43,* 77–115.

Schmiderer A. (2008) Geochemische Charakterisierung von Goldvorkommen in Europa. Diss. Martin-Luther-Universität Halle-Wittenberg.

Schwab, R., Heger, D., Höppner, B., & Pernicka, E. (2006). The provenance of iron artefacts from Manching: a multi-technique approach. *Archaeometry, 48,* 433–452.

Seeliger, T. C., Pernicka, E., Wagner, G. A., Begemann, F., Schmitt-Strecker, S., Eibner, C., Öztunali, Ö., & Baranyi, I. (1985). Archäometallurgische Untersuchungen in Nord- und Ostanatolien. *Jahrbuch Römisch-Germanisches Zentralmuseum, 32,* 597–659.

Selimchanov, I. R. (1960). Spektralanalytische Untersuchungen von Metallfunden des 3. und 2. Jahrtausends aus dem östlichen Transkaukasien—Azerbeidshan. *Archaeologia Austriaca, 28,* 71–79.

Slater, E. A., & Charles, J. A. (1970). Archaeological classification by metal analysis. *Antiquity, 44,* 207–213.

Thornton, C. P., Rehren, Th. H., & Pigott, V. C. (2009). The production of speiss (iron arsenide) during the Early Bronze Age in Iran. *Journal of Archaeological Science, 36,* 308–316.

Tylecote, R. F., Ghaznavi, H. A., & Boydell, P. J. (1977). Partitioning of trace elements between the ores, fluxes, slags and metal during the smelting of copper. *Journal of Archaeological Science, 4,* 305–333.

von Bibra, E. (1869). Die Bronzen und Kupferlegierungen der alten und ältesten Völker, mit Rücksichtnahme auf jene der Neuzeit. Erlangen.

von Bibra, E. (1873). Über alte Eisen- und Silberfunde. Nürnberg and Leipzig.

von Fellenberg, L. R. (1860–1867). Analysen von antiken Bronzen. Mitt. D. naturf. Ges. Bern.

Wagner, G. A., Pernicka, E., Seeliger, T. C., Lorenz, I. B., Begemann, F., Schmitt-Strecker, S., Eibner, C., & Öztunali, Ö. (1986). Geochemische und isotopische Charakteristika früher Rohstoffquellen für Kupfer, Blei, Silber und Gold in der Türkei. *Jahrbuch Römisch-Germanisches Zentralmuseum, 33,* 723–752.

Wagner, G. A., Begemann, F., Eibner, C., Lutz, J., Öztunali, Ö., Pernicka, E., & Schmitt-Strecker, S. (1989). Archäometallurgische Untersuchungen an Rohstoffquellen des frühen Kupfers Ostanatoliens. *Jahrbuch Römisch-Germanisches Zentralmuseum, 36,* 637–686.

Wagner, G. A., Wagner, I., Öztunali, Ö., Schmitt-Strecker, S., Begemann, F. (2003). Archäometallurgischer Bericht über Feldforschung in Anatolienund bleiisotopische Studien an Erzen und Schlacken. In: Stöllner, T., Körlin, G. Steffens G. & Cierny J. (Eds.), Man and Mining—Mensch und Bergbau. Der Anschnitt, Beiheft 16: 475–494, Deutsches Bergbau-Museum, Bochum.

Waterbolk, H. T., & Butler, J. J. (1965). Comments on the use of metallurgical analysis in prehistoric studies. *Helinium, 5,* 227–251.

Wibel, F. (1863). Beitrag zur Kenntnis antiker Bronzen vom chemischen Standpunkte. Hamburg.

Woolley, C. L. (1931). Excavations at Ur, 1930–1. *The Antiquaries Journal, 11,* 344.

Wyttenbach, A., & Schubiger, P. A. (1973). Trace element content of Roman lead by neutron activation analysis. *Archaeometry, 15,* 199–207.

Yener, K. A., Sayre, E. V., Joel, E. C., Özbal, H., Barnes, I. L., & Brill, R. H. (1991). Stable lead isotope studies of Central Taurus ore sources and related artifacts from Eastern Mediterranean Chalcolithic and Bronze Age sites. *Journal of Archaeological Science, 18,* 541–577.

Young, W. J. (1972). The fabulous gold of the Pactolus valley. *Bull.- Boston Museum of Fine Arts, 70/359,* 4–13.

Chapter 12
A Conservator's Perspective on Ancient Metallurgy

Deborah Schorsch

Introduction

Modes of deterioration

Virtually all physical matter, whether manipulated by human industry or left untouched in a natural environment, is subject to steady or periodic degradation. Most metals are unstable in their native state and must be extracted from ores. When buried in ritual contexts or discarded after use, metals endeavor to reach equilibrium with their subterranean (or aqueous) environment, bringing rise to chemical reactions that eventually convert them to a more stable mineral species (Figs. 12.1a, b).

The physical condition of an artifact removed from its archaeological context is the consequence of multiple factors that vary in origin but act in concert. These factors may include inherent qualities of the material(s) employed, manufacturing methods, burial conditions, previous treatments, and environmental conditions since retrieval. Metals decay and suffer from erosion during burial and may be less or more stable after they have been excavated. Similarly, removal of corrosion products can initiate or catalyze destructive processes. Metallic properties, and therefore physical integrity, are often compromised by long-term burial, and conservators must address issues of structural as well as chemical instability.

In addition to conservation treatments intended to achieve a stable condition, the removal of archaeological corrosion, accretions, post-retrieval accumulations of grime and dust, or disfiguring and/or deceptive restoration materials is frequently undertaken in order to reveal original contours and surface features (Fig. 12.1b). A degree of reconstruction may be required for structural stability, but is also used to

D. Schorsch (✉)
Sherman Fairchild Center for Objects Conservation
The Metropolitan Museum of Art, 1000 Fifth Avenue
New York, NY 10028-0198 United States of America
e-mail: Deborah.Schorsch@metmuseum.org

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_12,

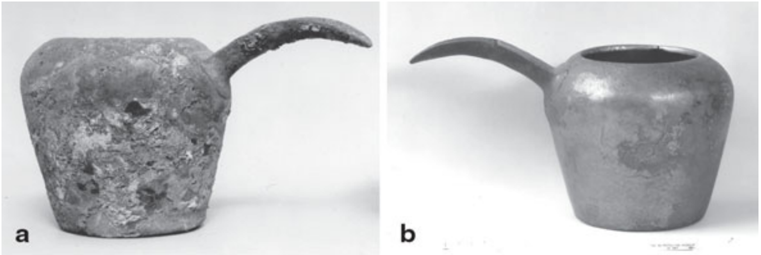


Fig. 12.1 Ewer, Egyptian, Old Kingdom (ca. 2641–2100 B.C.). Hammered arsenical copper sheet with arsenical-enriched surface, H. 11.0 cm. The Metropolitan Museum of Art; Gift of Edward Harkness, 1926 (26.9.13). **a** Condition in 1926 when acquired. **b** Condition in 1932 after electrochemical treatment. (Images © The Metropolitan Museum of Art)

establish visual integrity. Decisions concerning the extent and appearance of such restorations ensue from an ongoing dialogue between conservator and curator.

A condition known as *bronze disease* presents a major threat to objects made from copper and its various alloys. Ultimately the result of burial in a saline environment, bronze disease is a self-catalyzing reaction that occurs when an unstable copper chloride corrosion product analogous to the mineral nantokite is exposed to atmospheric oxygen and high humidity. Not only is bronze disease disfiguring, if left untreated, but it can also result in the complete disintegration of a cupreous artifact. Even after objects have received treatment, long-term success often depends on displaying and storing them in a suitably dry environment, and even under such conditions, chronic cases may still flourish.

In the past, acid baths and electrochemical reduction processes were used to reveal surface features and to treat bronze disease. These procedures generally led to the nonselective removal of both stable and unstable corrosion products and often left reactive chemicals on exposed surfaces and in cracks in the remnant core, leading to further corrosion. Newly exposed metal surfaces were often then artificially patinated (Fig. 12.2), painted, or waxed, and have tarnished over the intervening years, leaving the conservator to contend with surfaces that are unstable, disfiguring, or misleading. In fact, without resorting to destructive analysis, it can sometimes be difficult to distinguish between ancient copper alloy artifacts that have been stripped and repatinated, and objects made in modern times with the intention to deceive.

Iron and steel artifacts from most archaeological environments tend to be poorly preserved and highly unstable. Over time, conservation interventions are often ineffectual, and of necessity, much emphasis is placed on careful in situ documentation and appropriate environmental controls after retrieval. Ancient lead, as much as it survives intact, and its corrosion products, are generally stable, but unalloyed lead and leaded bronzes can be greatly affected by organic acid vapors generated by several wood species, which therefore should be avoided in storage and display environments. In addition, the toxicity of lead and copper is a consideration in handling. Like lead, tin from archaeological contexts is rarely cleaned, other than to remove soil accretions, and although relatively stable, it also can be adversely affected by organic acids.

Fig. 12.2 Osiris, Egyptian, el-Hiba, Third Intermediate Period, 21st–24th Dyn. (ca. 1070–712 B.C.). Solid cast bronze, traces of gilding, wood. H. 35.0 cm. The Metropolitan Museum of Art; Gift of the Egyptian Exploration Fund, 1903 (03.4.11a–d) The black surface is the result of a modern artificial patination process carried out after figure was cleaned of archaeological corrosion. (Image © The Metropolitan Museum of Art)

Silver buried in saline environments is greatly affected and even gold, under certain conditions, may develop thin corrosion layers. Fragile precious-metal objects frequently suffer mechanical damage during handling. In the past, silver artifacts entirely converted to corrosion products during burial were reconverted to silver electrolytically, just as works with a surviving metal core were routinely overcleaned using mechanical or other chemical methods. In such cases, resultant surfaces are usually overpolished, or pitted, and lacking fine detail (Fig. 12.3). Newly cleaned surfaces are particularly reactive and, if not protected, are subject to rapid tarnishing. In the past, to facilitate reforming, silver and gold and occasionally cupreous artifacts made from hammered sheet were annealed, a process that obscures their history by destroying the potential of subsequent metallurgical examination. The use of

Fig. 12.3 Long-necked Jar, Egyptian, from Tell Basta, Third Intermediate Period (ca. 1070–712 B.C.) Hammered silver sheet. H. 14.0 cm. The Metropolitan Museum of Art; Rogers Fund, 1907 (07.228.181); Department of Egyptian Art accession cards, showing condition when acquired in 1907 (*left*) and after treatment in 1919–20. (Images © The Metropolitan Museum of Art)

solder to reassemble components that have become separated can produce the same unfortunate results.

Preventive conservation is practiced in museums and in the field to minimize further deterioration of cultural materials so that (re)treatment does not become necessary in the future. Precautionary activities include the introduction of guidelines for safe handling, display, storage, and transport, and surveying collections for the purpose of establishing conservation priorities. Conservators, often in close collaboration with conservation scientists (see below), also devote research time to the development of new treatments, which includes testing and adapting commercial products for conservation applications.

Environmental conditions, specifically temperature, relative humidity, light, vibration, and air quality all play a decisive role in the preservation of cultural materials. It is essential that display and storage environments are regularly monitored and that emergency procedures for system failures have been established. As a rule, cool environments slow the rate of deterioration processes and are preferable. Optimal relative humidity levels vary from material to material, with inorganic media generally requiring drier environments. Displays are rarely organized by materials, necessitating the design of vitrines and galleries that can accommodate a range of environmental requirements. Maintaining low-light levels is more critical for organic materials, while both gaseous and particulate pollution, as well as vibration caused by seismic activity, construction, or footfalls and knocking, can affect all types of fragile artifacts.

On-site Preservation

Modern standards of archaeological practice dictate that any excavation team should include a conservator. Well-intentioned procedures by untrained field and museum personnel should be avoided. If there is no skilled conservation staff on site, excavators should follow two basic precautions to protect newly excavated metal finds from damage and further decay until such time when they can be properly examined and treated.

1. Excessive handling should be avoided. When metal corrodes, it loses its malleability and strength. Even gold, which may seem relatively unaltered to the naked eye, becomes embrittled over time due to stress corrosion. Archaeologists should resist the temptation of picking at metal artifacts with the aim of revealing original surfaces or contours. This is a task that requires training and experience, and if done improperly, can lead to the further disintegration of the metal as well as loss of valuable information that may be preserved in the corrosion layers. Similarly, chemical or electrochemical treatments to reduce or remove corrosion should not be undertaken.
2. Newly excavated metal artifacts should be stored in a stable, dry environment, avoiding wooden shelves or cupboards. Similarly, many common products containing plastics, textiles, rubber, and other organic materials, or that are painted or lacquered, emit deleterious fumes. Bags and containers used for artifact storage, unless made of preservation-grade materials, should not be tightly sealed, and measures for appropriate long-term housing should be instituted as soon as possible.

Conservation History and Training

During the nineteenth and early twentieth centuries, preservation treatments and technical study in museums and in the field were carried out by practitioners with a wide range of skills and training, drawn from the ranks of curators, field archaeologists, scientists, and craftsmen (Figs. 12.4a, b). In 1888, Friedrich Rathgen established the first scientific laboratory for the treatment and study of antiquities in the Königliche Museen zu Berlin, followed in 1920 and in 1928 by laboratories in the British Museum and in the Fogg Art Museum (Harvard University), respectively. *Technical Studies in the Field of the Fine Arts*, published from 1932 to 1942, was the first technical periodical dedicated to the field of conservation. The International Institute for the Conservation of Museum Objects, now known as the International Institute for

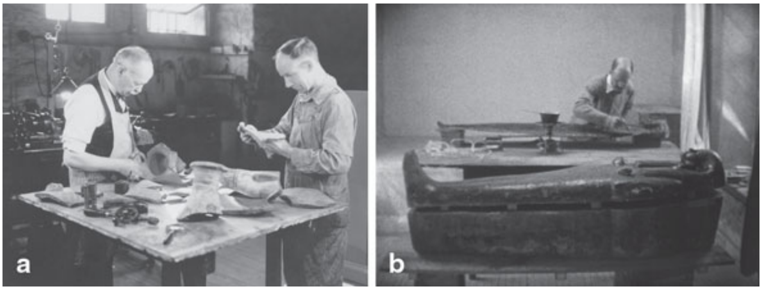


Fig. 12.4 **a** "Repair Shop Wing B Room 135 Basement Floor," The Metropolitan Museum of Art, 1926. **b** Herbert E. Winlock, Egyptologist and later Director of the Metropolitan Museum, at the Museum's expedition house in Thebes, consolidating a newly excavated coffin with wax. Still from archival film footage, 1924. (Images © The Metropolitan Museum of Art)

Conservation, was incorporated in London in 1950, and the establishment of national organizations followed quickly. The earliest international code of ethics governing conservation practice was ratified in 1963.

The first academic training programs for the conservation of works of art and other cultural materials were established in the USA and Europe during the 1950s and 1960s. Following a course of study based on these early curricula, professional conservators nowadays generally receive a multidisciplinary education that includes the study of art history and/or archaeology, material and laboratory sciences, the history of technology, and studio art, as well as practical experience during supervised internships. Quite often, conservators function as a bridge between specialists in the humanities, the social and natural sciences, and traditional crafts, thereby reflecting the diverse strengths of the earliest conservation practitioners.

Traditionally, scientists working in museums were classically trained as chemists or physicists, and sometimes had little prior exposure to cultural materials. This has changed in recent years as many pursue natural science degrees after conservation studies or simply enter the field by design rather than by accident. In the USA, there are now several graduate programs that train conservation scientists, paralleled by the establishment of new technical laboratories in many smaller, previously underserved, museums.

Conservation Practice and Technical Research

Like all materials, metals exhibit a range of physical, mechanical, optical, and chemical properties, and each culture exploits the strengths and wrestles with the limitations they confer, developing culture-specific technological solutions. Most metals, for example, are soft and malleable, and all display an inherent color and melt at a fixed temperature. Alloying may lower or raise the melting point, increase hardness, reduce malleability, and alter coloration. Furthermore, materials may develop social values based on their physical nature. For example, metals (and the ores from which they derive) are relatively rare and thus have inherent worth—witness the widespread use of metal coinage—and they can be remelted indefinitely for reuse, another physical trait that lends value.

Just as art historians ascribe visual style to works of art, ***technological style*** can be recognized in manufacture. Technological style is the unique combination of choices in materials and techniques associated with a specific culture, a specific time period, or a specific place. This perspective was pioneered in the 1960s at the Massachusetts Institute of Technology by Cyril Stanley Smith (1903–1992), an industrial metallurgist by profession, and further developed there by Heather Lechtman, a conservator by training, in her research on pre-Columbian Andean metallurgy. Over the last 10 years, "technical art history," a term perhaps originally coined by Norman Brommelle in 1963, is increasingly cited in art historical literature, but it is thought by many conservators to be disingenuous.

The ability of a conservator to devise and carry out effective strategies for the preservation of specific artifacts is based, therefore, not just on an understanding of modes of deterioration and familiarity with procedures and products used in treatments, but also on the knowledge of ancient and historic technological processes and the physical properties of materials. All works require an initial visual examination, which may be supplemented with instrumental procedures for imaging, such as radiography, and elemental or structural analysis, as well as consultation of pertinent scholarly literature. Just as an archaeological excavation destroys primary sources of information in the pursuit of studying them, some treatments, even when essential for preservation, may destroy evidence of an object's manufacture or subsequent history. Any treatments undertaken merely for aesthetic purposes should therefore be carefully considered. Although the goal of complete reversibility is sometimes unattainable, it is an issue that cannot be ignored. In every case, the importance of documentation is paramount.

Virtually all museums that collect antiquities and other archaeological objects, even if directly associated with a scientific excavation, have among their holdings works lacking documentation of their exact find spot or the circumstances of their discovery and retrieval. A few of these objects are outright forgeries, devised with the intention to deceive. Others may have begun their lives as legitimate copies and later came to be misinterpreted or represented fraudulently. Ill-advised treatments and overenthusiastic restoration, usually poorly documented, may have altered or obscured original appearance and workmanship, sometimes to the extent that the artifact in no way reflects the maker's intentions. Curators and conservators periodically revisit existing holdings as new discoveries reshape our perceptions of the past, and when an institution considers acquisition of a new work, conservators undertake technical examinations to ascertain its condition and determine if there are any material reasons to doubt its authenticity. Anachronistic stylistic and iconographic features, the use of an inappropriate material or manufacturing process, or a state of preservation incompatible with long-term burial may all lead to the determination that the work is a forgery. Doubt, once established, is difficult to dispel, because it is far more difficult to demonstrate authenticity than to disprove it.

The Study of Ancient Metal Artifacts

The study of ancient metalwork in the field of conservation usually focuses on three modes of manufacture: fabrication, joining, and surface finish. Nearly all preindustrial metal artifacts were fabricated by casting and hammering. Hammered sheet almost always originates with some form of cast metal, just as casts are sometimes hammered during manufacture, and works may combine cast and hammered components. Once they are identified as such, investigations of cast artifacts continue with a determination of whether they are solid or hollow, and if rigid mono- or bivalve molds, a direct or indirect lost-wax method, or multiple-sectioned piece molds were employed. All casts can be characterized by features such as the occurrence of porosity and other casting flaws, incorporation of separately fabricated components, and the fineness of surface detail. In the case of hollow casts, the relative thickness of the walls, whether or not the core cavity is conformal, and the system employed for supporting the core, for example, may be considered as well. The thickness and evenness of the sheet, the appearance of hammer marks, the presence of cracks that occurred during manufacture, as well as those that appeared later but reflect original workmanship, and the use of joins to assemble the object are among the features evaluated in technical examinations of artifacts made from hammered sheet.

Joining is generally effected using metallurgical or mechanical methods, and very occasionally with an adhesive. Metallurgical joins are achieved through the interdiffusion of metal atoms between the components to be joined that occurs at elevated temperatures. Methods most commonly observed on ancient metalwork include soft and hard soldering, colloidal hard soldering, and welding (for iron). Mechanical methods involve physical engagement of adjacent elements, such as crimping and riveting. Strictly speaking, "casting-on," an agglomerative process achieved by pouring molten metal onto independently prefabricated components, results in mechanical joins, because the added metal engages the contours of the substrate, and interdiffusion, as a rule, does not occur (see Fig. 12.24b).

Most metal *surface finishing* involves grinding, polishing, or burnishing. Other methods such as chasing, engraving, and perforation by drilling or chiseling may be used to add relief, texture, and detail. *Plating* is used to describe a range of metallurgical, mechanical, electrochemical, or adhesive techniques for applying an adherent layer of metal to a metal substrate (see Figs. 12.1b, 12.8a). Metal surfaces are sometimes inlaid, artificially patinated, or painted. Inlays are made from a wide range of materials, including metal; glass and other vitreous materials; minerals and stone; bone and ivory; and other synthetic products such as *niello,* a shiny, black paste made by dissolving silver and other metals in molten sulfur.

The primary source of information concerning any artifact is, of course, the artifact itself, as revealed through direct examination and analysis. This is complemented by data derived from a variety of interrelated sources and resources—ancient texts and images, archaeological investigation, ethnographic parallels, replication experiments, and the material sciences—that contribute to our understanding of ancient technology.

Ancient Textual and Visual Sources

Ancient textual sources, limited to literate cultures or cultures described by literate outsiders, provide information about manufacturing processes and materials, although actual metalworking treatises are rare. More common are visual representations of ancient workshops with artisans at their tasks. Interpretation of both written and visual sources is hindered by the fact that they are the products of artists and authors who themselves did not necessarily have firsthand knowledge of the processes they describe or illustrate, or whose primary purpose was not to communicate technologically accurate information. For example, manufactured goods seen in Egyptian tomb paintings, which are rich in representations of workers of all kinds, are often shown as finished products, even as they are being fabricated. Metal workshops are sometimes represented, also somewhat fancifully, on Greek black- and red-figure vases, the most famous of which is a *kylix* in the Antikenmuseum in Berlin attributed to the Foundry Painter.

Naturalis Historia, dating relatively late in antiquity, is surely the literary source in the Mediterranean region most often cited in relation to ancient metalworking. Written by the Roman philosopher, naturalist, and author Pliny the Elder (AD 23–79), who famously died at Pompeii during the eruption of Mount Vesuvius, it is an encyclopedic work encompassing the breadth of the natural world. Pliny's section on metal considers also the human dimension, chronicling greediness for precious metals in addition to more practical information on mining and manufacture. The latter has been applied extensively to studies of ancient manufacture, including alloying practices and techniques of casting, gilding, joining, and artificial patination.

Economic, political, and literary texts can be useful in gauging the social significance of metals and artifacts made of metal (see the Chapter by Iles and Childs, this volume). Our understanding of the changing relative values of gold and silver in Egypt in pre-Ptolemaic times, for example, is based on interpretations of lists inscribed on temple walls enumerating offers received from royal patrons. Similarly, it is possible to trace the evolution of precious-metal terminology in ancient Egypt from texts, starting from a single word to denote gold and silver in earliest times, to the gradual differentiation of gold, electrum, and silver, with the latter still known as "white precious-metal" or "white gold." During the New Kingdom (ca. 1550–1070 BC), terms emerge referring to golds of different colors, with different working qualities, and from different sources. Ancient Roman texts have been used as the basis for a study that considers whether the use of gold and silver was restricted to representations of deities and emperors. The legend of the "Nine Bronze Tripods," a fourth century AD commentary on a seventh century BC text, provides a more nuanced understanding of the obviously great value accorded bronze vessels, musical instruments, and weapons in ancient China by identifying their role in maintaining the political authority of the ruling dynasty. In the New World, both textual and visual sources come to us primarily through the chronicles of European observers. Indigenous representations of metalworkers are extremely rare; often illustrated is an ancient Peruvian ceramic vessel with a group of foundry workers using blowpipes.

Additional Secondary Sources

Other sources of information relevant to technological study are discussed in depth elsewhere in this volume. For example, the potential for information on ancient metalworking extracted from archaeological sites is unlimited. Habitation and ritual sites provide insight into function, but clearly of greatest interest to us are sites that relate to metallurgical production. These may include mines where ores were collected, workshops where metals were refined, and, of course, sites where manufacture took place—especially if raw materials, tools, or articles left unfinished or rejected by their maker were left behind.

Hands-on experience in metal smithing and foundry techniques can inform interpretation and facilitate further experimentation to reconstruct ancient manufacturing processes. Replication experiments and reenactments allow researchers to better understand the challenges faced by ancient metalworkers, and to test the feasibility of the methods they conjecture. Granulation and other joining and smithing techniques, for example, have received attention from skilled jewelers, whereas studies of amalgam, depletion, and electrochemical deposition gilding are less dependent on craft training and more on laboratory techniques. Craft traditions in contemporary pre- or early-industrial cultures can also provide valuable perspectives. Of particular interest, in addition to consideration of the processes themselves, is the way artisans feel about their work: how and why they have chosen specific materials and techniques, when they have moved away from tradition, and how the finished products are viewed and used in their society.

Conservators often refer to scientific literature that describes the physical properties of materials and how they can be altered and exploited in manufacture. Phase diagrams and metallography atlases provide data on the behavior of metals and alloys allowed to reach equilibrium, which is rarely the case for archaeological metals. Nevertheless, these are valuable resources that help researchers interpret or predict the behavior of metals under nonequilibrium conditions.

Technical Examination

Visual Examination

The most important tool of the conservator is his or her eyes, trained by innumerable hours spent scrutinizing artifacts. The varying degrees of magnification obtainable using hand-held and head loops, and binocular, stereoscopic, digital, and scanning electron microscopes (SEMs), all provide opportunities for making significant observations. Because it is so basic, and a skill learned largely through experience, "looking" is most difficult to illustrate with citations to scholarly studies.

Often visible on metal surfaces are tool marks left by hammers, chisels, chasing tools, etc., seemingly mundane details that collectively may help define the hand of an individual artist or the preferred manufacturing technique of a culture. Ornament produced by chasing and engraving may be distinguished from each other and from details executed in a wax model or piece mold during the casting process (Figs. 12.5a, b, c). On hammered sheet surfaces, tool marks associated with campaigns of raising or planishing may be visible (Figs. 12.6a, b, c, 12.7a, b). The edges of sheet metal may reveal whether they were finished using a hammer (Fig. 16.6c) or cut with a chisel (Figs. 12.8a, b, 12.13b), just as the size, placement, and execution of holes and other perforations, which may be drilled, punched, or cut (Fig. 12.8c), can be characteristic of a specific work or culture. Similarities and variations observed in fine details often help to distinguish original manufacture from ancient or modern alterations, explain the function of an object, or facilitate reconstruction of artifacts excavated in a disassembled state.

Raking visible light is useful for enhancing subtle surface detail. New developments in reflectance enhancement imaging allow systematic observation and documentation of surfaces using an integrated image obtained from photos taken sequentially using a standard dose of illumination delivered from 40–70 different fixed locations. Ultraviolet light is rarely applied to the study of ancient metalworking technologies, although it can be used for recognizing modern joins, fills, or inpaint.

The imaging capabilities of the SEM allow for the locating of features designated for chemical analysis, but it is also a powerful tool for direct observation (Figs. 12.9a, c). Because metals are conductive, no surface coatings are required, permitting the examination to be carried out directly on the artifact. A significant limitation is the size of the SEM chamber, although custom-built systems used in some museums can accommodate small- to medium-sized objects for in situ examination. The use of synthetic resins to take impressions of surface features, including tool marks, greatly expands the SEM's utility.

During the technical investigation, visual examination continues as other methods of study expand, confirm, or confound initial observations. By correlating features observed on the surface with data obtained by other means, in particular radiography, the conservator comes to recognize more obscure visual clues, which are helpful in the examination of objects in the field or in museums where instrumental means are limited or nonexistent.

Radiography

X-ray radiography is essentially a nondestructive imaging technique that reveals internal structural features, and it is undoubtedly the instrumental method most frequently used in museums for technological studies. The largest industrial units,

Fig. 12.5 **a** Kneeling figure of Amasis. Egyptian, Late Period, 26th Dyn, reign of Amasis (570–526 B.C.). Solid cast bronze with precious metal inlay and leaf. H. 11.0 cm. The Metropolitan Museum of Art; Gift of Edward S. Harkness, 1935 (35.9.3). **b** Channels for the inlaid inscription on the front of the king's kilt were chased in the wax model. **c** Channels for a second inscription applied later to the reverse of the figure on the belt were cut directly into the metal surface. **d** Computed radiograph. (Images © The Metropolitan Museum of Art)

delivering radiation up to 420 kV, are beyond the financial and logistical reach of most museum laboratories; 320 kV is generally adequate for routine as well as in-depth research of archaeological metalwork. Traditionally, radiographs are produced using silver-based emulsions on film, but recent advances in digital capture technology are transforming the process. Conventional radiographs can be scanned and

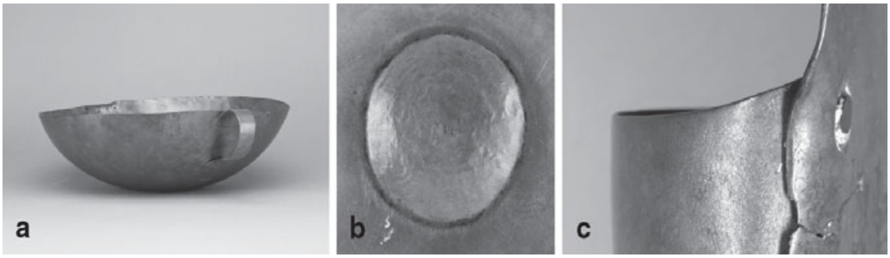


Fig. 12.6 **a** Basin, Egyptian, Thebes, Assasif, New Kingdom, early 18th Dyn. (ca. 1550–1458 B.C.). Hammered bronze sheet, copper rivets. Dia. 44.6 cm. The Metropolitan Museum of Art, Rogers Fund, 1916 (16.10.436). **b** Detail with hammer blows associated with raising process. **c** Detail showing undulating edges associated with hammering. (Images © The Metropolitan Museum of Art)

Fig. 12.7 **a** Situla, Egyptian, Thebes, Asasif, New Kingdom, early 18th Dyn. (ca. 1550–1458 B.C.). Hammered unalloyed copper and bronze sheet, copper rivets, cast bronze handles. H. 25.3 cm. The Metropolitan Museum of Art, Rogers Fund, 1916 (16.10.435). **b** Detail with riveted seam between copper (*below*) and bronze sheets, showing hammer blows associated with the planishing process. (Images © The Metropolitan Museum of Art)

visually enhanced for study and publication. Industrial material-testing firms offer gamma radiography using isotopic sources, which may be helpful for examinations of truly massive works in bronze (see Figs. 12.23a, b) or solid-cast precious-metal statuary. Computed tomography (CT) scans provide sophisticated three-dimensional information, but facilities with industrial-strength units suitable for high-atomic-weight materials such as metals are scarce.

X-rays lie on the electromagnetic spectrum to the right of visible light; by virtue of their shorter wavelengths and higher energies, they are capable of penetrating matter.

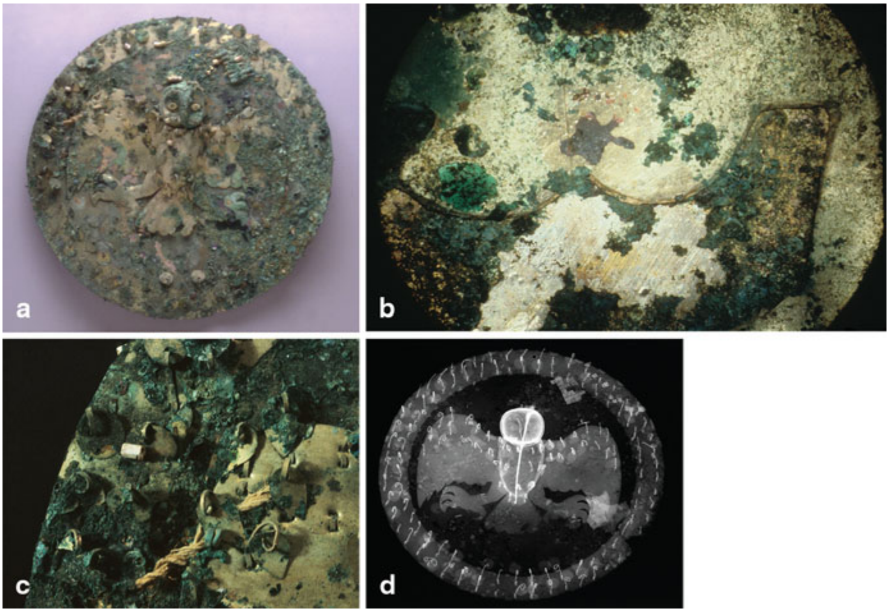


Fig. 12.8 **a** Disk, Moche, from Loma Negra, Peru, 3rd cen. A.D. Hammered copper sheet with precious-metal plating. Dia. 28.2 cm. The Metropolitan Museum of Art, Bequest of Jane Costello Goldberg, from the collection of Arnold I. Goldberg, 1986 (1987.394.56). **b** Detail showing juxtaposed sheets of owl (**a**) and back plate (**b**), with precious-metal surface layers containing 79.8 gold and 20.2 % silver and 56.3 % gold and 43.7 % silver, respectively; the edges of copper sheet bearing the more gold-rich alloy were cut with a chisel. **c** Detail showing rectangular perforations characteristically used on Moche metalwork to suspend dangles from flat wires. **d** X-ray radiograph; tabs are used to attach body and legs of owl to the back plate (*arrows*), but the wings were left unsecured and flapped freely when the disk was moved. The three-dimensional head, suspended on a rod mounted mechanically to the lower part of the owl's body, also had free movement from side to side. (Images © The Metropolitan Museum of Art)

The degree of penetration at any specific dose of voltage, amperage, distance, and exposure time is directly proportional to the subject's density and volume. Materials of greater density (i.e., higher atomic weight) or of greater volume can better resist penetration and will appear white or light gray on the resulting radiograph. Conversely, materials of lighter atomic weight or objects with relatively less volume appear a darker shade of gray or black. As a rule, without the aid of the newest digital technologies, radiography does not offer absolutes: the images reflect differences in density or volume only in relative terms.

These concepts are easily illustrated with the following examples. The various sections of an integrally solid-cast Egyptian bronze figure of a king (Figs. 12.5a, d) are of the same material but vary somewhat in thickness—the torso in this view, for example, is thicker than the arms or the face—which is reflected in the radiograph as differences in gray tones. The particularly radiopaque blaze on the arms is lead solder, applied in modern times to repair the right wrist which was broken off in

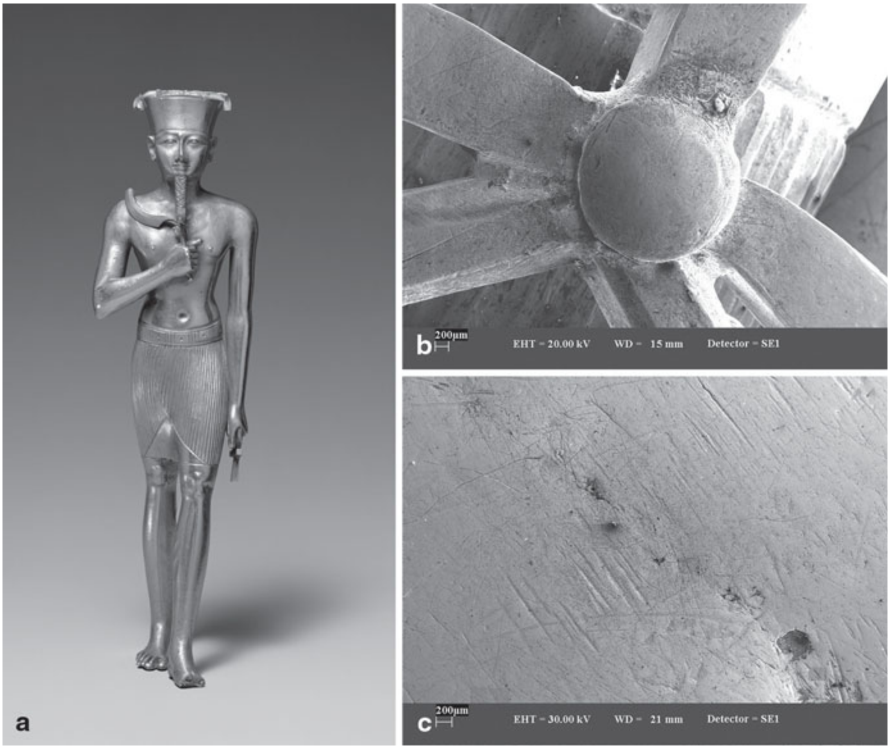


Fig. 12.9 **a** Amun. Egyptian, Third Intermediate Period, early 8th cen. Solid-cast gold, with separately cast components. H. 17.5 cm. The Metropolitan Museum of Art, Gift of Edward S. Harkness, 1926 (26.7.1412). **b** SEM photomicrograph showing solder join (photo by Mark T. Wypyski). **c** SEM photomicrograph with showing porosity in solder (photo by Mark T. Wypyski). (Images © The Metropolitan Museum of Art)

antiquity. This type of damage is observed frequently on Egyptian bronze kneeling figures of kings, which were removed apparently with substantial force from their bases when relieved of active duty and placed in storage.

A hollow-cast bronze cat sarcophagus from Egypt displays a range in radiopacity varying in direct proportion to the thickness of the metal walls (Figs. 12.10a, b). Therefore, the most radiopaque, solid-cast sections are white. Large dark flecks that correspond to internal voids can be seen in the radiograph of an extremely porous solid-cast unalloyed copper figure from southern Lebanon (Figs. 12.11a, b); conversely, a phase of lead globules in the copper–tin matrix of an Egyptian leaded bronze falcon sarcophagus causes the radiograph to appear hazy (Figs. 12.12a, b).

In a radiograph of a Peruvian gold-and-silver-sheet nose ornament with hammer-welded joins, differences in opacity are dependent upon the vast difference in atomic weight of the two metals as well as variations in sheet thickness, which could be confirmed with a caliper (Figs. 12.13a, c, d). Except for the serpent heads, which

Fig. 12.10 **a** Cat sarcophagus, Egyptian, Macedonian-Ptolemaic Period (332–30 B.C.). Hollow cast bronze. H. with tangs 32.0 cm. New York, The Metropolitan Museum of Art, Harris Brisbane Dick Fund, 1956 (56.16.1). **b** X-ray radiograph of bronze cat sarcophagus; the hollow body, head, and legs appear more radiotransparent than the solid ears, paws, tail, and tangs. Radiopaque bands along the top of the legs (**a**) indicate where wax, now reproduced in cast metal, was used to join separate cores. Small rectangular radiotransparent spot indicate original locations of now-rusted iron core supports (**b**) Two cast-in repairs are proportionately more radiopaque than the surrounding walls. (**c**) sarcophagus placed directly over microscope objective to avoid sampling during metallurgical examination. **d** Polished section viewed under conventional light showing dendritic structure; superficial and intergranular cuprite corrosion appears red. The latter, when present, is considered a highly reliable indicator of an extended period of burial. (Images © The Metropolitan Museum of Art)

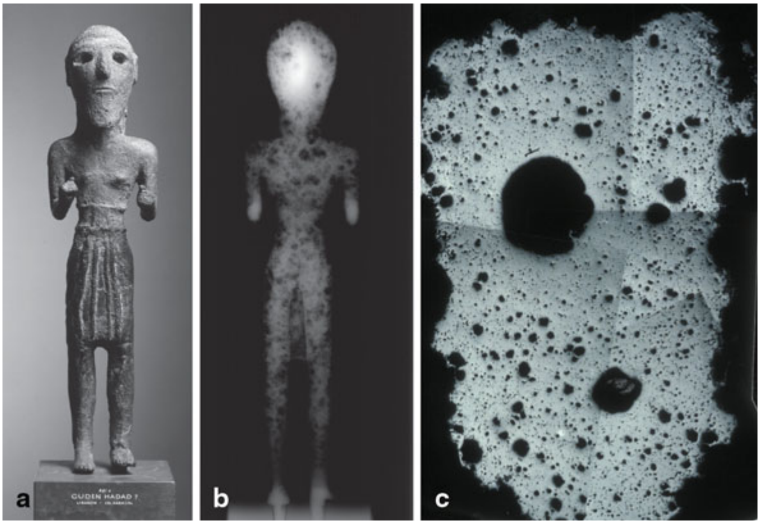


Fig. 12.11 **a** "Lebanese Mountain" figure said to be Syria. beg. 2nd mil. B.C. Solid cast, unalloyed copper. H. 39.5 cm (with tangs). Ny Carlsberg Glyptotek, Copenhagen (2836). **b** X-ray radiograph, showing highly porous internal structure Images: Ny Carlsberg Glyptotek. **c** Composite archival photomicrograph of polished section. (Image © The Metropolitan Museum of Art)

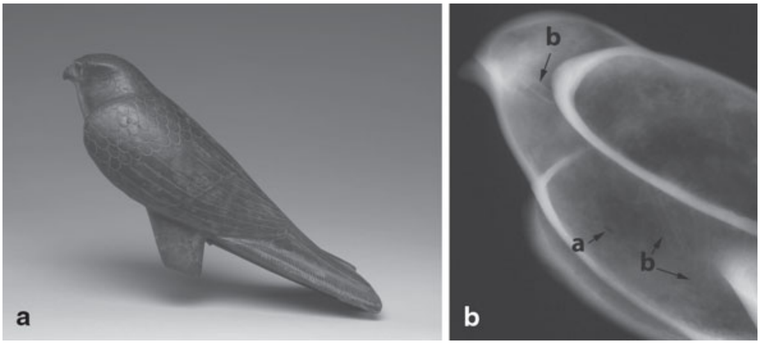


Fig. 12.12 **a** Falcon sarcophagus. Egyptian, Macedonian-Ptolemaic Period (332–30 B.C.). Hollow cast leaded bronze, with falcon remains. H. 18.1 cm. The Metropolitan Museum of Art, Rogers Fund, 1925 (25.2.11). **b** Detail of X-ray radiograph, showing mottled texture associated with segregated lead phase, locations of core supports (**a**) and falcon bones (**b**). (Images © The Metropolitan Museum of Art)

are substantially thinner than their bodies, the gold sheet in the middle register is more radiopaque than the silver sheets of greater thickness above and below. Cracks, breaks, and small losses in the thinnest, highly embrittled silver band of trophy heads on the bottom appear black in the radiograph; modern restorations made of silver sheet that is thicker than the original (and uncorroded) are white.

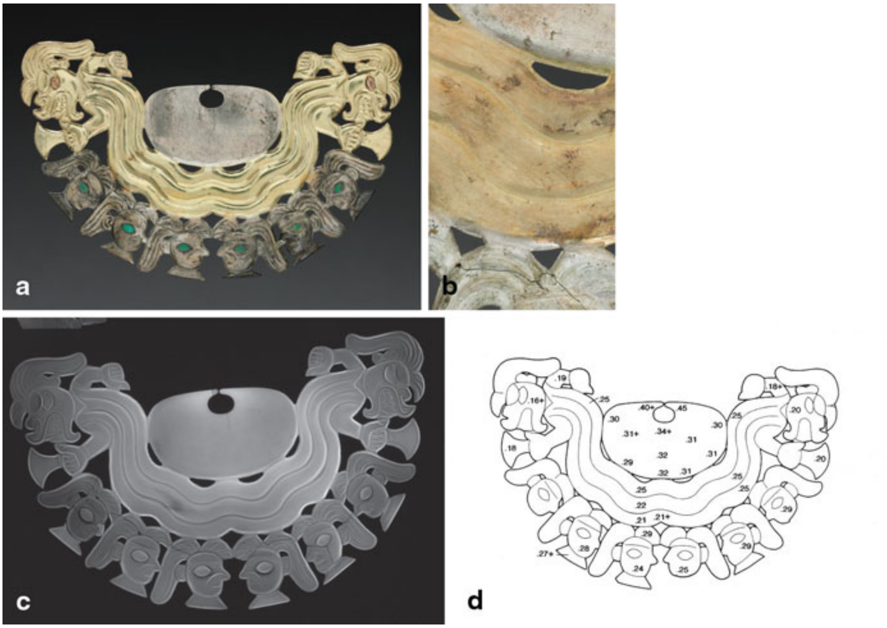


Fig. 12.13 **a** Nose ornament with Decapitators and Human Heads, Peru, Moche, ca. A.D. 100–300. Hammer-welded gold and silver sheet, H. 8.8 cm, L. 14.0 cm. The Cleveland Museum of Art. Severance and Greta Millikin Purchase Fund 2005.176 Photo: The Cleveland Museum of Art. **b** detail of cut-outs; note gold along edges of silver sheet and silver along edges of gold sheet as well as evidence of cutting using a chisel. **c** X-ray radiograph of nose ornament, with radiotransparent cracks in silver sheet (**a**) and radiopaque restorations (**b**). **d** Sketch plotting caliper measurements of sheet thickness. (Images © The Metropolitan Museum of Art)

Visual and radiographic examinations carried out during the first phases of a technical study allow researchers to formulate questions and consider appropriate paths for investigation. This may include identifying locations for in situ analyses and sites that might be profitably sampled. In some analytical contexts, destructive analysis refers to procedures that alter or degrade a sample, making it unsuitable for additional testing. When considering cultural artifacts—each a unique reflection of its manufacture and history—the removal of any original material, regardless of the amount, is destructive, even if the sample itself is not destroyed during the analysis. Under certain circumstances, the removal of corrosion products or even accretions may be judged invasive. Therefore, the potential for obtaining answers to well-formulated questions is balanced with the impact of removing a sample from the object, taking into consideration its relative rarity and size, and its overall state of preservation (as well as the size, location, and means of removing the requisite sample) (Fig. 12.10c).

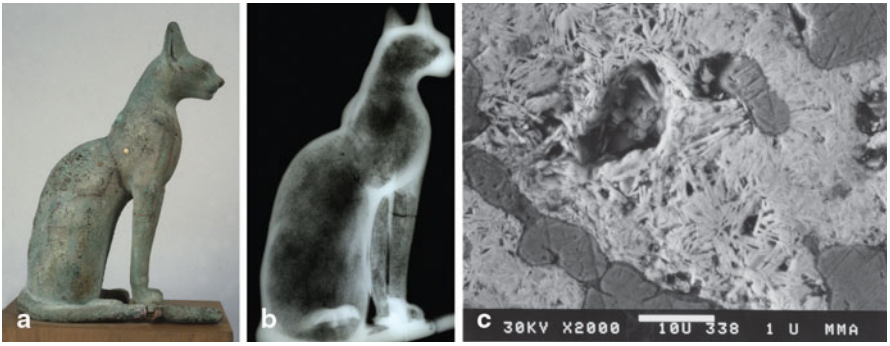


Fig. 12.14 **a** "Cat sarcophagus." 19th–20th cen. Hollow cast copper. H. 38.1 cm. The Metropolitan Museum of Art, Funds from various donors, 1958 (58.38). The figure, believed to be a forgery, seen after the removal of paint intended to disguise an unattractive, blistered surface and screw heads relating to major structural repairs. **b** SEM microphotograph showing acicular lead oxide crystals within copper dendrite matrix (photograph by Mark T. Wypyski). **c** X-ray radiograph showing coarse, angular, radiopaque flecks associated with an interdendritic lead-rich phase. (Images © The Metropolitan Museum of Art)

Metallography

Because metals retain their history in their internal structure, metallurgical investigation of polished and etched sections can be extremely useful for understanding manufacture. Evidence of mechanical deformation and exposure to elevated temperatures is recorded in the disposition of the metal grains. Metallography is discussed elsewhere in this volume (see the chapter by Scott, this volume), and is thus presented here only as some basic observations derived from the examination of two "related" works.

In cases when the authenticity of a cupreous metal alloy object is contested, metallographic examination can be quite helpful. Even if archaeological corrosion products have been altered or removed, the penetration of cuprite along intergranular boundaries is considered compelling evidence of great age and long-term burial, just as its absence strongly supports modern origins. The dendritic structure observed on an in situ polished surface of a bronze cat sarcophagus confirms the obvious: the figure was cast (Fig. 12.10d). The healthy formation of intergranular corrosion supports the authenticity of the sarcophagus, whereas the angular lines of cross-granular attack near the surface suggest that mechanical deformation—to a degree greater than usually observed on the surfaces of cast statuary—was carried out (Fig. 12.10d). A second cat sarcophagus was identified as a modern forgery (Fig. 12.14a). In that case, a crystalline lead-rich, nonmetallic phase within a dendritic matrix of relatively pure copper explained some puzzling features (Fig. 12.14b): the coarse texture observed in the radiographs (Fig. 12.14c); the many structural repairs of damages ensuing from extreme brittleness of the figure; and its unattractive surface, scarred by heat treatment. This surface was revealed after the removal of modern paint as well as nonadherent corrosion products not generally associated with archaeological cupreous-metal artifacts.

Instrumental Analysis

Once reserved for the largest and wealthiest institutions, scientific facilities with instrumental analytical capabilities are increasingly common in smaller museums. Over the last half century, various instrumental methods have been used for compositional analyses of ancient metal, including X-ray fluorescence (XRF), energy-dispersive and wavelength-dispersive spectrometry in an SEM (EDS–WDS–SEM), particle-induced X-ray emission spectroscopy (PIXE), atomic absorption spectroscopy (AAS), neutron activation analysis (NAA), and inductively coupled plasma mass spectrometry (ICP-MS). In all but the largest laboratories dedicated to the study of cultural materials, considerations of space and expense generally limit instrumentation to XRF and EDS–WDS–SEM. Fast and often portable, XRF can be quite useful for certain determinations as long as its limitations are kept in mind. Newest models allow the precise selection and documentation of the area analyzed, but the resultant data rarely reflect the original formulation, since archaeological metals generally have corrosion products on their surfaces, even if they have been cleaned. Similarly, aged surfaces are often selectively depleted of one or more alloying components. Furthermore, ancient alloys, even in single-phase systems, tend to be heterogeneous. In fact, data from any surface analyses must be treated as qualitative or semiquantitative at best.

EDS–WDS analyses may be carried out in situ, but internal standards are used to quantify the data, which is more commonly derived from analyses of surface scrapings, drilled samples, or polished sections. The latter format is most useful for locating and analyzing surface and substrate features, including specific phases in a multiphase system, nonmetallic inclusions, and plated surfaces. EDS is used for more gross compositional analyses, supplemented by WDS for minor or trace elements.

Conservation studies of archaeological artifacts generally focus on each individual work in its entirety, and other methods may be used to characterize nonmetallic components and to trace an artifact's history before, during, and after burial. X-ray diffraction (XRD) is used for the identification of crystalline materials that make up massive corrosion and tarnish layers, including artificially patinated surfaces. Crystalline materials are also present in casting cores, and were used for inlays or applied in paints or as unbound pigments. Cameras loaded with X-ray film and goniometers with sample chambers are suitable for crystalline materials removed from artifacts. Newer, open-architecture XRD units now allow for rapid, nondestructive analyses.

Another analytical method commonly found in conservation research laboratories in the study of ancient metalwork is Fourier transform infrared spectroscopy (FTIR). This method is increasingly used to identify inorganic materials such as corrosion products and pigments, although its traditional application has been for resins and other organics. Organic materials are found occasionally on ancient metalwork, and, now, with the advent of smaller sample sizes and more in situ analyses, the possibility of oil-based binding media having been used to adhere precious-metal leaf to ancient bronzes, for example, can be addressed.

The study of ceramic casting cores, usually a refractory conglomerate of sand and clay (or loess) often with an organic component, is generally carried out using a transmitted light microscope on samples prepared as petrographic thin sections. Major and minor components are identified and characterized in terms of size, shape, and frequency, with instrumental methods such as EDS–WDS and XRD to supplement visual observation. Thermoluminescence analysis is occasionally employed to date hollow-cast objects using samples of quartz particles obtained from their cores.

Case Studies

The following four case studies describe in brief typical investigations of archaeological metal artifacts carried out in The Metropolitan Museum of Art using the methodology outlined above. Each study integrates several means of visual and instrumental analyses, replication experiments, and significant input from textual, archaeological, or ethnographic sources. In each case, the research was undertaken with the aim of describing aspects of manufacture and considering them within a broader context of art historical, historical, or archaeological thought.

Precious-metal Technologies in Northern Peru During the Early Intermediate Period

The ancient Moche, a people that populated the oases dotting a coastal strip of desert in northern Peru during the Early Intermediate Period (ca. AD 100–800), can be counted as one of the world's most innovative ancient cultures with respect to precious-metal technology. Several interrelated studies of artifacts in the Metropolitan Museum attributed to Loma Negra, a Moche outpost in the far north Piura Valley, have highlighted the ingenious adaptation and development of joining techniques by ancient smiths seeking to juxtapose gold and silver surfaces. These studies have expanded our understanding of Moche aesthetics and documented the technologies shared by the "northern" Moche and their nearly contemporaneous but culturally distinct Vicús neighbors. These insights are based on visual examination augmented with caliper measurements, radiography, metallography, elemental analysis, and replications of the proposed technologies.

Moche metal manufacture involves almost exclusively hammered sheets of gold, silver, and copper, joined mechanically using tabs and slots or other forms of crimping. Two- and three-dimensional works of gold and silver sheet, mostly recognizable

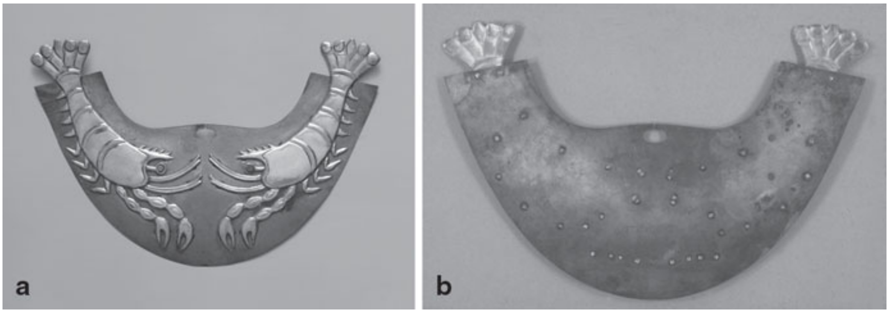


Fig. 12.15 **a** Nose ornament, Moche, from Loma Negra, Peru, 2nd–3rd cen. A.D. Silver and gold sheet, W. 18.7 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1236). A gold lobster was applied to the silver substrate using tabs and slots. DT 9245.tif. **b** Reverse (Images © The Metropolitan Museum of Art)

as personal ornaments, were produced in this way (Figs. 12.15a, b), as were complex assemblages of copper sheet. Precious-metal surface layers found on Moche cupreous metalwork from the other oases in the Sechura Desert located more to the south were produced by depletion. At Loma Negra, by contrast, copper sheet was plated with extremely thin gold–silver layers spanning a broad compositional range that were applied using a revolutionary electrochemical replacement process unique to the Piura Valley. Supplemented by punched and scored textures, and the motion of hinged or suspended elements (Figs. 12.8a, c, d), these shimmering ornaments were animated through the juxtaposition of subtle variations in surface color (Fig. 12.8b).

To combine gold and silver, Moche craftsmen also used metallurgical methods such as hammer welding, hard soldering, and partial silver plating on gold substrates. The use of solder in Peru for this purpose appears to predate Moche times; it appears only rarely on Vicús artifacts. As a rule, ancient solder appears in radiographs as an irregular mass, radiopaque and spotted with porosity. This is not the case on a Loma Negra nose ornament, where most of the poorly executed solder joins were intended to attach silver back plates to a spider's web of gold (Figs. 12.16a, b). Some of the rectangular solder pallions did not melt at all; in other instances, they melted but the metal did not flow. Apparently, the components were actually held together by several tab-and-slot joins, which are also visible in the radiographs.

Hammer welding was already used to join gold and silver sheets in Peru during the Early Horizon (ca. 1000–200 BC), but the most sophisticated use of the process is seen in the elaborate Moche ornaments made from multiple sheets of gold and silver decorated with images executed in repoussé and *ajouré* (see Fig. 12.13a). Evidence from radiographs and from polished sections from several works sections suggests that the sheets were overlapped and then heated and hammered repeatedly to achieve the join and simultaneously form the artifact. The interdiffusion that took place is demonstrated in the section from one of a pair of Lambayeque gold and silver ear flares, in which fingers of gold are seen reaching into the silver sheet

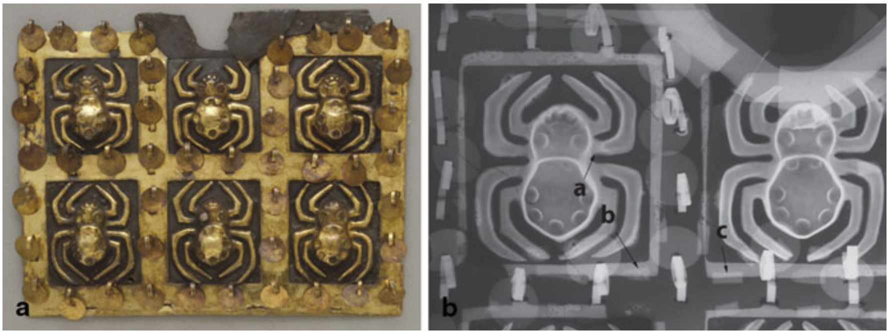


Fig. 12.16 **a** Nose ornament, Moche, from Loma Negra, Peru, 2nd–3rd cen. A.D. Silver and gold sheet, W. 8.6 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1230). Gold spiders were applied to silver back plates set within a gold web. **b** Detail of X-ray radiograph showing sites of successful soldering (**a**), intact solder pallions (**b**), and solder paillions that melted in place (**c**). (Images © The Metropolitan Museum of Art)

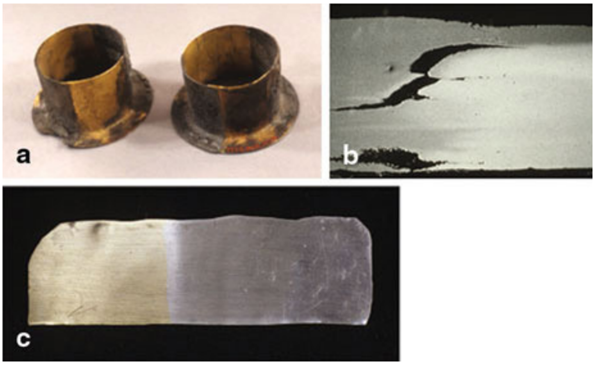


Fig. 12.17 **a** Ear flares, North Coast, Peru, 1st cen. B.C.–7th cen. A.D. Silver and gold sheet, Dia. of plugs (*left* and *center*), 5.2 & 5.3 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1175–1177). **b** Back-scatter electron photomicrograph of hammer-welded join between gold and silver sheet seen in polished section (photo by Mark T. Wypyski). **c** Modern hammer welded gold-to-silver join (courtesy of Robert Baines, RMIT University, Melbourne). (Images © The Metropolitan Museum of Art)

and vice versa (Figs. 12.17a, b). A replica of the join was produced with ease by a skilled goldsmith in a "low-tech" environment (Fig. 12.17c). On the elaborate *ajouré* hammered welded ornament, it is possible to see rims of gold around the interior edges of the silver sheet. This indicates that the entire shaping and welding process was carried out before the negative spaces, which, in fact, are only nominally located at the interfaces, were cut away (see Fig. 12.13b).

The Moche used two different processes for applying thick and thin silver layers onto gold substrates (Figs. 12.18a, b). As yet, no examples of artifacts produced in

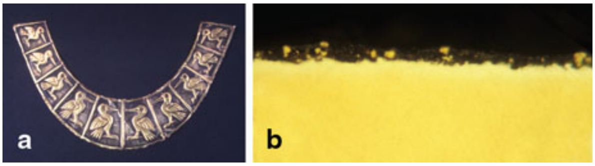


Fig. 12.18 **a** Nose ornament frontal, Peru, Moche, from Loma Negra, 1st-3rd cen. A.D. Partially silvered gold, W. 21.0 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1226). An extremely thin layer of silver overlies the gold substrate in the fields surrounding the birds. **b** Photomicrograph of a polished section. (Images © The Metropolitan Museum of Art)

either manner have been securely provenienced to a site outside the Piura Valley, nor do any date other than to the Early Intermediate Period. However, silvered-gold nose ornaments do form a significant subset within the extant corpus of Vicús metalwork. The techniques used to apply silver to gold substrates remain unexplained; the fact that this practice is observed only in the same small region where an electrochemical replacement gilding process developed and also flourished in isolation may prove significant in future investigations.

Red Surface Colorations on Ancient Gold

An examination of red surface films on ancient Egyptian gold raised the question of whether they represent an ancient artificial patination process or are the result of a previously uncharacterized form of corrosion (Fig. 12.19). For many years, a famous text sent by a Mitanni ruler in northwestern Mesopotamia to the Egyptian king Amenhotep III (reigned ca. 1390–1352 BC), with mention of "gold through which blood shines," has been the starting point for this discussion. Research carried out in the 1930s demonstrated that hematite dissolved in molten gold could produce cherry-red surfaces comparable in appearance to "red gold" sequins from the tomb of Tutankhamun (reigned ca. 1336–1327 BC), which clearly had been used coloristically, in alternation with conventional gold sequins. In most instances, however, red films on Egyptian gold are irregular in expanse, varied in hue, and have no discernible stylistic or iconographic function.

Subsequent to examination under the binocular microscope and infrared spectroscopy to eliminate the possibility of an organic coating, EDS analyses were carried out on typical Egyptian "red gold" surfaces. These analyses established that the surface films contain a substantial amount of sulfur. Analyses of corresponding polished sections demonstrated that the gold substrates were rich in silver. XRD analysis carried out on small leaf samples was used to identify the red tarnish as silver–gold sulfide (AgAuS), which proved to be the archaeological analogue of a compound known only in a modern synthetic form, and to a then newly discovered mineral, petrovskaite [AgAu(S, Se)]. It was possible to remove samples from red layers more

Fig. 12.19 Mummy of Ukhhotep. Egypt, from Meir, Middle Kingdom (ca. 1981–1802 B.C.) Wood, gold leaf, alabaster, obsidian, and various organic materials. The Metropolitan Museum of Art; Rogers Fund, 1912 (12.182.132c). Detail showing gilded mummy mask. The red surface film identified by XRD and SEM as a silver-gold sulfide is fortuitous. (Image © The Metropolitan Museum of Art)

granular in texture, and these were also identified using Debye–Sherrer cameras as AgAuS (Fig. 12.20). Gray particles within the red layers as well as gray tarnish films on electrum substrates were identified as Ag_3AuS_2 (analogous to uytenbogaardtite), also previously unknown in archaeological contexts. Heating gold–silver coupons with elemental sulfur in a low-oxygen environment produced red tarnishes also identified with XRD analysis as AgAuS (Fig. 12.21). Similar tarnish films, also clearly fortuitous, were found on silver-rich gold artifacts from other ancient contexts. In addition, it was noted that red silver–gold sulfide tarnishes sometimes reformed in ambient display and storage conditions on gold surfaces from which archaeological sulfide corrosion had been removed earlier.

Still, not all Egyptian red gold can be attributed to this corrosion process. A subsequent study of the gold jewelry of Tutankhamun and his predecessor, Akhenaton, confirmed that hematite was used intentionally to produce red surfaces and demonstrated the purposeful formulation of ruddy copper-rich gold alloys. Both processes were apparently intended to evoke a red aspect believed to be inherent in gold by the ancient Egyptians.

Fig. 12.20 Detail of tubular beads, Egypt, Thebes, Deir el Bahri, temple of Hatshepsut foundation deposit, New Kingdom, 18th Dyn., joint reign of Thutmose III and Hatshepsut (ca. 1373–1358 B.C.). Hammered gold sheet, L. 12–15 mm. The Metropolitan Museum of Art, Rogers Fund, 1927 (27.3.444). (Image © The Metropolitan Museum of Art)

Fig. 12.21 Gold-silver alloy coupons with induced silver-gold sulfide tarnishes. Clockwise from *upper left*: 9.3 w/o Ag; 9.0 w/o Ag; 15 w/o Ag; 20 w/o Ag. (Image © The Metropolitan Museum of Art)

This study is significant for its contribution to a more nuanced understanding of Egyptian manufacture and aesthetics and for the characterization of a previously unrecognized form of archaeological gold corrosion. By distinguishing several different mechanisms for both intentional and unintentional red surface colorations, it is particularly valuable for conservators considering whether to remove tarnish films or other reddish layers from gold antiquities.

Cast Metal Statuary from Ancient Egypt

A hollow-cast bronze figure of Pedubaste (reigned ca. 818–793 BC), an obscure king of the Twenty-third Egyptian dynasty, was examined as part of an ongoing study of Egyptian casting technology and the role of precious and cupreous metal statuary in

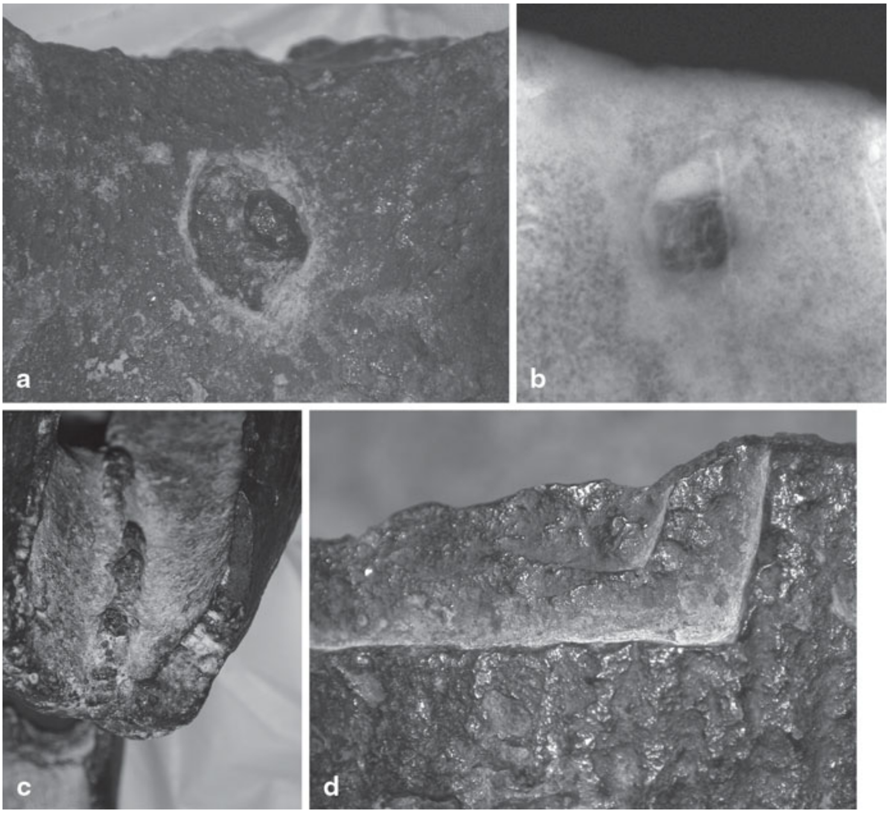


Fig. 12.22 **a** Torso of King Pedubaste. Egypt, Third Intermediate Period, 23rd Dyn., reign of Pedubaste (ca. 818–793 B.C.). Museu Calouste Gulbenkian, Lisbon (52). **b** Detail of an iron core support, seen on interior of abdomen wall and corresponding radiograph. **c** X-ray radiograph showing core support. **d** Detail of interior, showing iron armature imbedded in right leg. **e** Detail of patch on the reverse. (Images © The Metropolitan Museum of Art, courtesy of the Museu Calouste Gulbenkian, Lisbon)

ancient Egyptian ritual. The torso in the Calouste Gulbenkian Museu in Lisbon is all that survives of a figure that once measured in height between 74 and 78 cm, exclusive of the king's headdress (Fig. 12.22a); notable, even in its diminished state, are the torsion of the body and the implicit shift in weight that signal the king's movement forward. In Egypt, for the most part, solid and hollow metal statuary was were made using a direct lost-wax process. The Third Intermediate Period (ca. 1070–664 BC) is distinguished by an active metalworking industry that produced highly decorated, large- and small-scale statues of gods, kings, and other high-status individuals as well as ritual implements. This development in production parallels changes in the structuring of political power and religious practices—inseparable in ancient Egypt—since the statuary and ritual equipment were used during religious ceremonies in temples and in public processions. Still, compared with the truly monumental stone statuary so closely associated with ancient Egypt, even the largest metal statues were relatively small and portable. Whereas the stone monoliths were emphatically static, in posture as well as literally, the tendency during the Third Intermediate Period to infuse metal figures such as this one, with a greater sense of movement, of urgency, is facilitated by the medium. Craftsmen working in metal have greater freedom than their counterparts carving stone or wood: when molten, metal can take any form. After solidification, it supports its own weight, allowing negative spaces to open up and limbs and other elements to extend freely.

Furthermore, metal substrates offer a different palette and a different range of surface texture and luster than stone or wood. Unlike the latter, which are generally painted, metal surfaces are "embellished," made jewel-like with a miniaturist's attention to detail. Compositional data obtained from EDS analysis indicates that the inlays on Pedubaste's belt and apron were made from three different metals each with a different hue: pink unalloyed copper, yellow gold of conventional composition, and a reddish copper-rich gold similar to the gold–copper alloy mentioned in the discussion of "red gold" above. Through creative positioning, the inlays on the figure's apron amplify the movement inherent in its stance: arranged in rows by color, the inlays on the proper right side of the apron are larger than those on the left, creating a sense of perspective that underscores the forward thrust of the left leg, effectively forcing the right leg backward.

Until well into the Third Intermediate Period, hollow-cast statues had open cavities or other, still unexplained, strategies for supporting their cores during casting. To their detriment on the battlefield, the ancient Egyptians were slow to adopt iron, which had come into widespread use in western Asia in the second half of the second millennium BC. Earliest evidence of iron smelting and surviving iron implements date well into the second half of the first millennium, though iron and iron tools were used in bronze manufacture somewhat earlier. The Pedubaste torso is of special interest because it is the earliest securely dated Egyptian bronze with iron core supports (Figs. 12.22b, c) and an iron armature (Figure 12.22d). Egyptian craftsmen typically left the cores intact inside the castings, with the core supports and armatures in place. In the case of the Pedubaste torso, almost the entire core is gone, either eroded during burial or intentionally scratched out in modern times. Still, part of the armature survives, embedded in the front wall of the right leg. For, in spite of having been secured by both core supports and an armature, the core slipped during casting, creating a large opening in the back of the figure.

To accommodate a patch, now lost (Fig. 12.22e), metal around the loss was cut away and squared off. Attempts at replication have shown that even work-hardened bronze would not have been adequate for this job, leading to the strong supposition that it was executed using an iron tool. If this were correct, the figure would be the earliest Egyptian bronze to have been reworked in this way. Iron tools were used occasionally on later bronze works for repairs or surface alterations (see Fig. 12.5c), but apparently never as part of the original manufacturing process: surface details seem invariably to have been produced in the wax model. Of interest in this context is the fact that this type of repair, employing a square or rectangular patch hammered in place, is seen seldom on ancient Egyptian bronzes, especially when contrasted with Greek and Roman castings of comparable size. It is unclear if this is because Egyptian founders achieved greater mastery of their craft, because they or their patrons were

Fig. 12.23 a Four-armed Avalokiteshvara, the Bodhisattva of Infinite Compassion, Thailand Prakhon Chai, Buriram Province, 2nd quarter of 8th cen. Hollow cast high-tin bronze, silver, and black glass or obsidian inlays, H. 142.2 cm. Rogers Fund, 1967 (67.234). **b** Gamma-ray radiograph of left leg showing armature embedded in casting core; irregular radiopaque patches at and above ankle can be attributed to fins formed on wall interior(s) where molten metal penetrated the core during casting. (Images © The Metropolitan Museum of Art)

less willing to accept flawed or repaired works, or because the requisite iron tools were not generally available.

Small square or rectangular core supports, usually only a few millimeters in section, became the norm for Egyptian hollow-cast statuary made later in the first millennium BC. They quite often survive as iron corrosion products that fill the small openings in the bronze walls where the core supports had been pushed through the wax model, appearing in radiographs, therefore, as dark, angular spots (Figs. 12.10b, 12.12b). Armatures were used relatively infrequently in ancient Egypt but are common, for example, in Southeast Asian bronzes. Made of round- or rectangular-section iron rods, usually large in proportion to the core they support, the armatures can be easily recognized in radiographs, even though they tend to rust in situ (Figs. 12.23a, b).

“Replication” Casting in Bronze Age Cyprus

Lost-wax casting technology came to Cyprus during the second half of the Late Bronze Age (ca. 1330–1150 BC), probably under the influence of Egypt and the Levant. A group of artifacts excavated in Cyprus, Crete, and the Greek mainland,

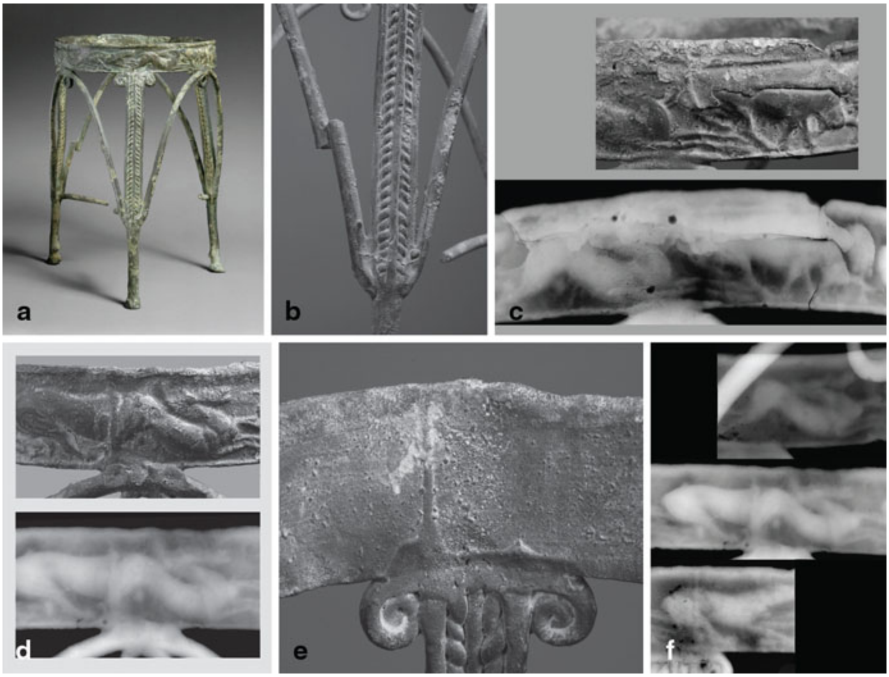


Fig. 12.24 **a** Tripod, Cyprus, Late Bronze Age, ca. 13th-12th cen. B.C. Cast bronze, H. 37.5 cm. The Metropolitan Museum of Art, The Cesnola Collection, Purchased by subscription, 1874–76 (74.51.5684). **b** Cold shut, and fins on surface reflecting lack of surface finishing after casting. **c** Cast-on repair, with corresponding radiograph. **d** Conflation of animal motifs, with corresponding radiograph. **e** Join with drip mark between band and strut in wax model reproduced in cast metal. **f** Details of radiographs of band; contours of relief motifs indicate that bands of wax model were produced using a replicative process; variation in thicknesses of the backgrounds reflects the use of a monovalve mold. (Images © The Metropolitan Museum of Art)

including tripods (Fig. 12.24), four-sided stands, and rims and handles mounted onto hammered-sheet amphorae (see Fig. 26a), fill out the otherwise meager corpus of lost-wax-cast copper-alloy Cypriot artifacts dating to that time. An investigation was initiated to evaluate claims by several archaeologists that these ritual implements had been cast in pieces and then hammered to shape and joined by brazing. This assertion is unlikely to be accurate, if only because high-temperature soldering of cupreous metals is virtually unknown in the Mediterranean region until Roman times. In earlier studies, the artisans responsible were praised for their "technical achievements," even though the mediocre quality of the works is amply demonstrated by casting porosity, cold shuts, cast-on repairs, and the lack of surface finish (Figs. 12.24a, b). Incongruously, an innovative process unknown elsewhere in the region was used to replicate the relief decoration, though neither the craftsmen nor their patrons seemed to mind that the resultant imagery was sometimes conflated (Fig. 12.24c) or misoriented. Radiography, elemental analysis, metallography, and replication castings supplemented the initial visual examinations.

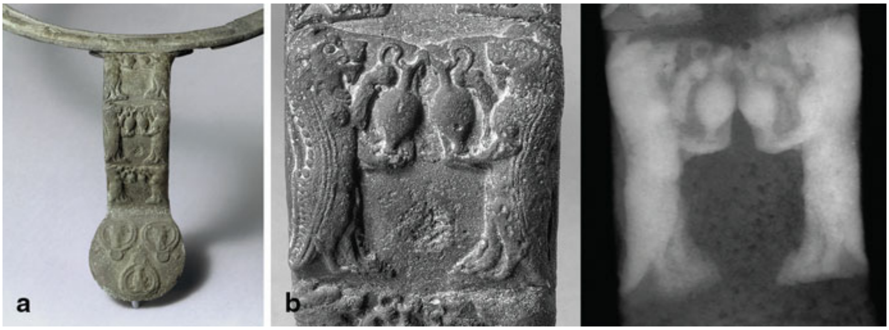


Fig. 12.25 **a** Amphora handle, Late Bronze Age, ca. 13th–12th cen. B.C. Cast bronze, H. 37.5 cm. The Metropolitan Museum of Art, The Cesnola Collection, Purchased by subscription, 1874–76 (74.51.5685). **b** Detail showing untrimmed edges of appliqués that were produced in wax in molds and applied to a wax model, with corresponding radiograph. (Images © The Metropolitan Museum of Art)

It is now clear that irregular masses of metal at interfaces between the band and the legs and struts on a large tripod in the Metropolitan Museum, once interpreted as brazing compound, actually indicate where wax softened and shaped by kneading was used to reinforce the joins in the wax model. Drip marks, now preserved in metal, are visible in places where heating of the wax was necessary. The orientation of the drips confirms that the wax legs and struts were added to the circular band while the model was upside down (Fig. 12.24e). The necessity of this was demonstrated when wax models were made to cast half-scale tripod replicas: the delicate limbs were simply not strong enough to support their own weight or that of the band.

The relief imagery on the tripod band comprises two complete, identical sequences of six motifs and one sequence with only the first two. In the radiographs, each individual motif can be seen to match in contour, outline, and interval its counterparts in the other sections. The thickness of the backgrounds around the motifs varies from section to section, indicating that the cast sequences derive from wax strips made by a replication process, which presumably involved pouring or pressing the wax into open stone molds (Fig. 12.25e). Molds were used in a similar way to produce small wax plaques that were applied to wax models used to cast handles for a no-longer extant amphora. The edges of wax elements representing genii were not trimmed, as seen in the radiographs (Figs. 26a, b), unlike the bucrania below. Still, the bottommost bucranium of the three on each handle was placed upside down. As observed on the tripod, missteps in design are coupled with clumsy manufacture and great ambition.

Final Words

These cases studies serve to demonstrate the methodology and research strategy of conservators carrying out technological research in museums, where artifacts are often also works of art valued for their beauty or unique features. The primary role of conservators is to preserve these works of artistic or historical importance, but it is not possible to carry out this task in an effective or ethical manner without a clear understanding of the materials and manufacturing methods used to create these works and an appreciation of the societies in which they find their inspiration. The true strength of conservators—their professional forte, so to speak—is their ability to combine experiential and intellectual understanding of an artifact's physical nature, a skill that develops over the course of many years engaged in the handling, examination, and preservation of cultural artifacts.

References

Benner, L. (1987). SEM-identification and documentation of tool marks and surface textures on the Gundestrup Cauldron. In J. Black (Ed.), *Recent advances in the conservation and analysis of artifacts.* Jubilee Conservation Conference (pp. 393–408). London, 6–10 July 1987. London: Summer Schools Press. (Innovative study on the use of silicon molds to replicate tool marks for SEM examination).

Bray, W. (1985). Ancient American metallurgy: Five hundred years of study. In *The Art of Precolumbian Gold, The Jan Mitchell Collection*, exhib. cat (pp. 76–84). New York: The Metropolitan Museum of Art. (Visual and textual sources for New World metallurgy).

Chase, W. T. (1991). *Ancient Chinese bronze art, casting the precious sacral vessel*. New York: Chinese Institute in America. (Describes replication casting; with essay by K. C. Chang on textual sources).

Cronyn, J. M. (1990). *The elements of archaeological conservation*. London and New York: Routledge.

Cultural Heritage Imaging. (http://culturalheritageimaging.org/). (Non-profit corporation dedicated to developing reflectance enhancement imaging technology and other digital documentation techniques).

Fröhlich, M. (1996). Zur Technik des Goldgusses bei den Ashanti (Ghana). *Das Gold in der Kunst Westafrikas* (pp. 43–57). Zurich: Museum Rietberg Zürich. (Investigation of traditional practices by goldsmith).

Gänsicke, S. (2008). Artifact conservation and Egyptology. In R. H. Wilkinson (Ed.), *Egyptology Today* (pp. 163-185). New York: Cambridge University Press.

Gilbert, M., & Vivian, D. (2001). The rise of conservation science in archaeology. In A. Oddy & S. Smith (Eds.), *Past practice—Future prospects*, British Museum Occasional Paper 145 (pp. 87–94). London.

Hill, M., & Schorsch, D. (2005). King Pedubaste from the Gulbenkian Museum. Lisbon: Investigations into the art of ancient Egyptian large bronze statuary. *Metropolitan Museum Journal*, *40*, 163–195. (Hollow-cast bronze figure presented in text as case study).

Lang, J. R. S., & Middleton, A. (Eds.). (2005). *Radiography of Cultural Materials*, Oxford and Boston, Mass.: Butterworth-Heinemann 2nd ed. London.

La Niece, S., & Craddock, P. T. (Eds.) (1993). *Metal plating and patination*. London: Butterworth-Heinemann. (A useful volume illustrating a multidisciplinary approach to surface decoration).

Lefferts, K. C., Majewski, L. J., Sayre, E. V., & Meyers, P. (1981). Technical examination of the classical bronze horse from The Metropolitan Museum of Art. *Journal of the American Institute of Conservation, 21,* 1–42. (Landmark technical rehabilitation of Greek bronze erroneously condemned as forgery).

Levy, T. E., & Levy, A. M., Radhakrishna Sthapathy, D., Srikanda Sthapathy, D., & Swaminatha Sthapathy D. (2008). *Masters of fire: Hereditary bronzes casters of south India*, Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum 162. Bochum: Selbstverlag des

Deutschen Bergbau-Museum Bochum. (Investigation of traditional workshop practices by an ethnoarchaeologist).

Mattusch, C. C. (1996). *The fire of Hephaistos: Large classical bronzes from North American collections*. Cambridge: Harvard Art Museum. (Interdisciplinary study with important technical contributions by conservator Henry Lie).

Oddy, A. W., & Meeks, N. D. (1982). Unusual phenomena in the corrosion of ancient bronzes. In N. S. Brommelle & G. Thomson (Eds.), *Science and technology in the service of conservation: Preprints of the contributions to the Washington Congress, 3–9 Sept 1982* (pp. 119–124). London: International Institute for Conservation of Historic and Artistic Works. (Interpretation of corrosion structures that reflect manufacturing processes).

Oddy, A. W. (1996). Jewelry under the microscope. In A. Calinescu (Ed.), *Ancient Jewelry & Archaeology* (pp. 185–197). Bloomington & Indianapolis: Indiana University Press.

Scheel, B. (1989). *Egyptian metalworking and tools*. Aylesbury: Shire Publications Ltd. (A summary of studies based on representations in ancient Egyptian tombs with textual annotations).

Schorsch, D. (1998). Silver-and-Gold Moche artifacts from Loma Negra. *Metropolitan Museum Journal, 33,* 109–136. (Research on Moche joining methods presented in text as case study).

Schorsch, D. (2001). Precious-metal polychromy in Egypt during the time of Tutankhamum. *Journal of Egyptian Archaeology, 87,* 55–71. (Considers significance of texts in establishing relative values of precious metals and terminology, and the question of Egyptian "red gold.").

Schorsch, D., & Hendrix, E. (2003). Ambition and competence in late bronze age Cyprus. *Report of the Antiquities Organization, Cyprus* (pp. 53–77). (Casting techniques presented in text as case study).

Smith, C. S. (1981). *A search for structure: Selected essays on science, art and history*. Cambridge (Mass.): MIT Press. (Pioneering work in the development of the concept of technological style).

Ward, P. R. (1986). *The nature of conservation, a race against time*. Marina del Rey: The Getty Conservation Institute. (Useful introduction to general principles and philosophy).

Chapter 13
Copper Working Technologies, Contexts of Use, and Social Complexity in the Eastern Woodlands of Native North America

Kathleen L. Ehrhardt

Introduction

The following contribution reviews recent archaeological approaches to the ways in which native peoples of the Eastern Woodlands of North America utilized metals throughout prehistory and suggests directions for future research. It will undoubtedly present a marked and provocative contrast to the models of New and Old World metallurgical development presented by other authors. There are two important reasons for this, both worth stating at the outset. First, until Europeans arrived on North America's shores in the sixteenth century, the history of metals use among Eastern Woodlands peoples centers on the exploitation of one particular metallic resource—native copper. This is not to say that the archaeological record does not contain evidence for the manipulation of other metals, like gold (Halsey 1996, pp. 3–5), silver (Brose and Greber 1979a, p. 253; Spence and Fryer 2005), lead (primarily in the form of galena) (Walthall et al. 1979; Walthall 1981) and meteoric iron (Halsey 1996, p. 3), it simply means that copper overwhelmingly predominates the metallurgical landscape.

Second, there is no reliable evidence that prehistoric native American copper workers ever melted, smelted, alloyed, or cast the metal (Clark and Purdy 1982, p. 45). "Producing" the raw material and forming it into finished objects never went beyond procuring it in its native form from nearby or far-away sources, then cold hammering (with some hot hammering), and annealing it into shape. Yet, despite this apparent absence of innovation and given the limitations of these primary techniques, skilled copper workers developed extraordinarily refined repertoires of secondary forming techniques to produce some of the most technologically sophisticated, symbolically powerful, and artistically breathtaking objects ever found in prehistoric native North America.

Kathleen L. Ehrhardt (✉)
Illinois State Museum, Springfield, IL, USA
e-mail: kathy@eclipse.net

930 S. Rangeline Road, 65201 Columbia, MO, USA

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_13,

In the Eastern Woodlands, indigenous copper working goes back well over 7,000 years, and has been known to archaeologists for well over 150 years (Martin 1999). Scholars have long known that copper use was hardly ubiquitous throughout prehistory; some native groups never used copper at all. In others, adoption is scanty or sporadic at best. In yet others, copper assumed an especially important, even paramount role as a valued, symbolically powerful raw material and as an even more spectacularly important and meaningful finished product. Native copper was used by prehistoric Eastern Woodlands peoples for utilitarian tools, art objects, items of ceremonial or symbolic importance, and personal or ritual adornment. Some artifacts were manufactured to be used in life, whereas many, both used and unused, appear in burial contexts as adornments or burial furniture.

Largely because it has traditionally been interpreted as an "exotic" and "valuable" raw material and as an important medium in exchange, mortuary practice, self-expression, and ritual, and because such spectacular artifacts have been fashioned from it, native copper's appearance in indigenous material culture assemblages has long intrigued archaeologists. In the Eastern Woodlands, approaches to its study have taken many forms. Some of the earliest were experimental in nature, conducted for the purpose of replicating indigenous copper working techniques and for controverting early claims that North American Indians could not have produced the copper artifacts recovered in nineteenth century mound investigations (Cushing 1894; Willoughby 1903). In culture history studies, copper and copper artifacts were listed as important "traits" in spatio-temporal ordering schemes. At the same time, copper artifacts have also been the subject of innumerable formal, stylistic, and technological analyses. Other studies have been directed toward understanding how copper was procured and distributed within and among native groups, how artifacts were manufactured and used, and what the raw material and the finished products "meant" in the social, political, economic, ideological, and technological contexts in which they functioned (see Griffin 1961 for a classic study).

While modern researchers may still be asking some of the same kinds of questions about the relationships among material culture, technology, and meaning, new approaches have emerged that are opening the door for new interpretations. Advances in materials science analysis and in scholarship (material culture studies, symbolic anthropology) are pushing our interpretive envelopes to unprecedented levels. The increased application of archaeometric (laboratory) methods to questions of material composition and sourcing, manufacturing history, and *chaîne opératoire* studies has begun to yield information that goes beyond that which formal, stylistic, and contextual analyses alone can reveal. This new knowledge adds solidity and confidence to our inferences (Kingery 1996a, p. 12). It has already shattered long-held beliefs in many realms of inquiry, and is opening our minds to new avenues of interpretation.

These new bodies of scientifically derived evidence, combined with the adoption of important ideas from the anthropology of technology and the social aspects of materials use, have resulted in the development of interdisciplinary approaches that emphasize the importance of illuminating the technical, ideational, and contextual details of production and use processes at local and supralocal levels (see Childs 1994). More importantly, they have stimulated interest among archaeologists in integrating these archaeometallurgical findings into analyses that consider both material and nonmaterial aspects of technological and sociopolitical systems (after Kingery 1996a, 1996b). Increasingly, scholars are working from the premise that copper working, like all native technology (and all technology, for that matter), is inextricably woven into the very fabric of culture. They recognize that it is indeed a "social" phenomenon—the material, its products, its procurers, its crafters, and its consumers operate within culturally meaningful sets of symbols, meanings, intentions, and actions with regard to its acquisition and use. All play multilayered roles on complex and dynamic social, political, technological, and ideological stage(s) (Ehrhardt 2005; Kingery 1996b; Lemonnier 1993, pp. 6–9). One of my arguments here is that understanding how both culturally ascribed attributes and physical properties of materials like native copper affect performance in all these domains should now be a critical aspect of our interpretations (after Kingery 1996a, p. 12; see also Charles et al. 2004). These perspectives and approaches are entirely compatible with materiality approaches in archaeology (Meskell 2005).

Most significantly, archaeologists are beginning to take the results of these studies to even higher levels of social inquiry. Questions concerning the role of copper in such areas as craft specialization, ritual and ceremonial practice, long-distance exchange, the rise and maintenance of social inequality, and technological and social change within prehistoric societies and at contact are some of the research issues that occupy the minds of researchers today.

Copper working is found (to a greater or lesser degree) in many prehistoric cultures of the Eastern Woodlands. However, archaeologists have identified three major prehistoric copper-consuming cultural traditions: the "Old Copper" complexes of the Middle and Late Archaic period, centered in the Upper Great Lakes and upper Midwest (c. 4000–1000 BC); the Hopewellian horizon of the Ohio Valley, midcontinent, and Gulf Coast (c. 100 BC–400 AD); and the Mississippian systems of the midcontinent and southeast (c. 900 AD to European contact in the southeast) (see Figs. 1, 3, 5). These manifestations are not temporally or culturally contiguous, nor do they exhibit the same level of organizational complexity. Copper use within them is not unchanging; because there are both distinct and subtle shifts over time in terms of production technique, form, function, and intended use of artifacts crafted, it cannot be said that there is one all-inclusive native "style." However, certain social threads are common to all three of these systems: (1) copper appears frequently in mortuary contexts; (2) it is identified as a "valued" good; (3) it was traded among groups, often long-distance; and (4) some form of specialization was likely present (Leader 1988). Even so, the door must remain open to recognize potential differences in the way the material was viewed, how it was worked and for what purpose, how production may have been organized, and in the "life histories" of various copper artifacts that were created. For this reason, there is no single developmental or interpretive "paradigm" that is now or has been applied to the whole of copper working in the Eastern Woodlands. In each area, researchers have developed their own suites of research questions (domains of inquiry can and often do overlap) based on the data at hand and the historical trajectory of scholarly inquiry.

The purpose of this work, then, is to review the major copper working traditions of the Eastern Woodlands, with an eye toward elucidating some of the ways that archaeologists are currently approaching the study of copper and copper working in their regions and in their respective cultural traditions. I emphasize contributions by those who have integrated scientific (archaeometric/archaeometallurgical) analyses into attempts to address larger anthropological problems. First, I present a very brief introduction to the Eastern Woodlands and its peoples. I then move to a discussion of native copper, its availability, and how archaeologists have shattered long-held beliefs about the source(s) of the material. A short and necessarily non-exhaustive review of what is known about metal working and the contexts of copper use in each of the three major prehistoric traditions follows; incorporated into each review is a discussion of the predominant paradigms and/or theoretical approaches that currently drive thinking. I end by offering suggestions as to the direction of future interdisciplinary research in copper working studies.

The Eastern Woodlands

Geographical Setting

The Eastern Woodlands of native North America is a vast geographically and culturally diverse region of indigenous peoples stretching from the Atlantic Ocean to the Mississippi River and from the Great Lakes to the Gulf of Mexico. It is generally divided into two subareas: the Northeastern Woodlands and the Southeast.

Native Peoples

It is impossible to enumerate here the myriad archaeological cultures identified in the Eastern Woodlands or to describe their diverse adaptations through time. Broadly speaking however, in the coastal or in often deeply forested or mixed grassland/forest areas of the Northeast subarea, native peoples exploited lands full of rich and varied local resources through hunting, fishing, gathering, and harvesting. Later, in zones where habitats were amenable, they practiced horticulture or a mixed economy (Tuck 1978, p. 28; Levine et al. 1999). Hunting–gathering groups were generally small and largely egalitarian in structure, maintaining relatively low population densities across local landscapes. Groups tended to be mobile according to seasonal or resource availability. Some populations, however, became seasonally sedentary or completely sedentary due to resource abundance and intensified exploitation patterns, or the adoption of and ultimate dependence on horticulture. Burial ceremonialism has a long trajectory in the Northeast (Tuck 1978, p. 43).

In the Southeast, where climatic conditions are temperate to subtropical, social and economic adaptations also varied broadly according to habitat. Small populations of mobile hunters and gatherers tended to gravitate along waterways, exploiting a wide spectrum of seasonal resources. Early on in many areas, populations increased and became residentially stable. In some places, small-to-very-large settlements arose concomitant with population increase and the intensive collection and tending of starchy seed plants and seasonal resources, such as nuts. Along coasts, peoples continued to follow a seasonal round of hunting and gathering, exploiting shellfish, mammal, and plant resources. Plant domestication (subsistence intensification), sedentism, long-distance exchanges, and the rise of political inequalities are features of southeastern cultural development.

At major points in the prehistory of the Eastern Woodlands, widespread cultural manifestations, namely Hopewellian and Mississippian traditions and their local variants, appeared over large geographical areas of the Eastern Woodlands. Within their respective spheres of influence, distinctive types of material culture and suites of ideas became elaborated and flourished to varying degrees. These were often accompanied by sweeping but not ubiquitous social, political, economic, and religious changes at the local level– among them intensification of cultivation practices, change in community organization and distribution, heightened symbolic and artistic expression, elaboration of mortuary practices and ceremonial ritual, and construction of monumental earthworks and mounds. In both cases, some form of social complexity emerged. Materially, both are marked by the widespread exchange and consumption of exotic goods.

The material repertoires that represent (and often serve to distinguish) Eastern Woodlands cultures in the archaeological record are utilitarian, non-utilitarian, or both. They consist mainly of implements relating to the procurement and processing of resources, weapons, personal adornment items, art objects, and ritual/ceremonial paraphernalia. Technologically, artifacts range from simple to very complex. They are made of a wide variety of natural resources (which may be local or nonlocal to their makers and/or users), including but not limited to stone, bone (and antler), shell, clay, teeth, wood, crystals, metals, minerals, fibers, and bark. Certain types of artifacts, particularly stone tools and pottery vessels, are frequently quite localized temporally, geographically, functionally, and stylistically: “tool kits” may be specialized and vary widely according to the range of activities for which they were manufactured.

Native Copper in the Eastern Woodlands—Multiple Sources for Prehistoric Metalworkers?

Copper Sources in the Eastern Woodlands

Native or metallic copper deposits occur in many locations in North America. In the Eastern Woodlands, deposits are found in the Lake Superior region, along the Appalachian mountains, and in Nova Scotia (Lattanzi 2007; Levine 1999; Rapp et al. 2000, p. 7, pp. 20–26). Copper can occur as masses, chunks, lumps, sheets, and in arborescent forms; it may be found in buried deposits, in near-surface pockets or veins, or as outcrops (Maddin et al. 1980, p. 212; Ries 1916, pp. 603–609). Of these occurrences, the deposits in the Lake Superior basin are the largest, richest, and best known. Indeed, they are the largest native copper deposits in the world (Rapp et al. 2000,, p. 9; Fig. 13.1). Significant outcrop and near-surface sources are found on the Keweenaw Peninsula and on Isle Royale, Michigan, and along the Brule River in northwestern Wisconsin (Martin 1999). "Drift" or "float" copper also occurs for hundreds of miles around these deposits in the form of nuggets/boulders of enormously varying size and weight, having been dropped on the landscape as a result of four episodes of glacial advance over the bedrock deposits (Halsey 1996, p. 6; Rapp et al. 2000, 11–12).

Native Copper Procurement in Prehistory—Old Questions, New Answers

Native copper from the Lake Superior region is thought to have been heavily exploited by indigenous peoples from about 6,000 BP to European contact. Abandoned mine pits are still visible on the ground surface, and mining tools have been found in and around the pits themselves (Martin 1999, p. 108; Mason 1981, p. 181). Generations of investigators (Griffin 1961; Martin 1999, pp. 84–110) have researched prehistoric mining activities there, documenting locations of mine pits, identifying processing stations, and conducting excavations. Researchers estimate that there are over 5,000 mines in the area (Rapp et al. 2000, p. 10), but they have been hesitant to provide estimates as to the exact amount of copper removed in these operations. Wayman (1989, p. 4), however, suggests that it may well have exceeded tons Rapp et al. (2000, p. 10) comment that production must have been "tremendous, far exceeding any other source."

This dramatic and unequivocal evidence for extensive prehistoric copper exploitation became the basis for the development of a source procurement model centering on the Lake Superior deposits as the single source for copper artifacts recovered in the "northern" copper region (see Levine 1996, 1996, 1999). The idea was given voice as early as 1855 (Wilson 1855, p. 204 cited in Levine 1996, p. 183). Despite some well-reasoned objections and solid geological evidence to the contrary, by the first decades of the twentieth century, it had become "fact" (Levine 2007). For interpreters of prehistoric economic and technological life, the implications of accepting this view were profound. If, as most researchers believed with apparent certitude, *all* the native copper used to make *all* of the copper artifacts found in Northeastern Woodlands came exclusively from the Great Lakes, then copper found in contexts far from this source would have to have been obtained either by trade or by direct procurement (often over long distances).

Importantly, copper artifacts found far from their sources were recognized as "exotic" (Seeman 1979, pp. 291–292; Streuver and Houart 1972). According to

Winters (1968, p. 181, italics mine), copper's exotic nature "may have added an intrinsic *value* to these [finished] items beyond their basic utilitarian properties (1968, p. 181, italics mine)." Value can be seen in a number of ways (Bernardini and Carr 2005, pp. 634–635; Cooper 2006, p. 152). In an economic sense, value has to do with "cost" to procure as a function of distance from the source (Seeman 1979, p. 292). In a technological sense, "value" may stem from the mechanical advantages of the material and its properties and the uses to which it could be put. It may also arise out of special regard for the specialized, transformative skills of the crafter, or the "powers" with which the material itself is thought to be imbued or invested (Helms 1993, p. 108, 115, pp. 149–150). It is also clear that copper has an intrinsic "worth" or value that transcends either economic or technological considerations. "Value" in a symbolic, ideational, or even aesthetic sense was undoubtedly culture-specific, but its distributional abundance throughout prehistory in "special" contexts, primarily in burials as status- or prestige-type gifts, elements of regalia, or as bodily adornment placed with the favored dead attests to its importance in mortuary and ritual ceremonialism (see Helms 1993). While it is imprudent to push historic meanings too deeply into prehistory, in the historic period, copper was esteemed by native peoples for its life-affirming and restorative qualities. It was associated with the "other world," specifically the Underworld and the Underwater Panther, whose tail was made of copper. Copper from the Panther's tail was thought to be a powerful healing medium (Bradley and Childs 1991, p. 16).

Thus, copper has been built into scenarios of long-distance trade and exchange as a desired "exotic" and "valued" material. Trade in copper had been established from Late Archaic times (Pleger 2000; Winters 1968), with a trend toward increased local control of the material's consumption and redistribution. It became a major prestige commodity in the complex, formalized trade systems that have been devised for the Middle Woodland (Hopewellian) and Mississippian eras (Seeman 1979). At the same time, copper has been deeply woven into hypotheses concerning the development of social complexity (the rise of elites/rank societies) based on local or regional control of access to or use and display of rare exchange goods (Brown et al. 1990; Goad 1979, p. 240; Lattanzi 2007; Pleger 2000).

But, to what extent is copper really an *exotic* material? What sources besides outcrops may have been exploited? While largely passed over, several researchers have pointed to the role that "float" or "drift" copper may have played in the rise of local copper working industries (Gibbon 1998; Halsey 2004; Rapp et al. 2000, pp. 11–12, Wayman 1989). Float copper is found as far south as the confluence of the Ohio and Mississippi Rivers, and as far east as New York. Throughout prehistory, nuggets of usable size could be picked off the ground or gathered from streambeds and used, arguing for a more "localized" pattern of copper procurement. Wayman (1989, p. 3) has called it a "prime source of native copper for ancient peoples," while John Halsey (2004) maintains that most of the copper used in the prehistoric period probably came from "float" sources.

Although compositional testing for sourcing prehistoric copper artifacts was reported as early as 1848 (Bastian 1961), application of modern systematic trace element analysis for the express purpose of linking copper artifacts to their geographic/geologic sources in order to assess the movement of copper in interregional trade began in earnest in the late 1970s (see Veakis 1979). One of the most influential studies was that of Goad (1978, 1979, 1980). Through optical emission spectrography and neutron activation analysis of copper ores and artifact samples from diverse locations and temporal periods, she determined that in addition to Lake Superior sources, Middle Woodland peoples of the southeast also exploited local sources, namely those deposits in northwest North Carolina and in the Ducktown triangle area of northeast Georgia–southeastern Tennessee–southwestern North Carolina. This led her to reevaluate Middle Woodland trade systems in that region (Goad 1979), finding that they were actually more "regional" in structure than "interregional." Goad also discovered that in certain cases, individual artifact types and archaeological sites correlated with particular material sources (Goad 1979; Brose and Greber 1979a, p. 252). Importantly, she noted a trend through time away from Lake Superior sources (which in some of her cases, were several hundreds of miles away) toward greater use of "local" resources in the Mississippian southeast.

Meanwhile, Rapp et al. (1980, 2000) from the University of Minnesota-Duluth were amassing a large database of chemical "fingerprints" of North American ore sources and archaeological artifacts (Rapp et al. 1980, 2000). Archaeologist Mary Ann Levine contributed geological and artifact samples from various locations in the Eastern Woodlands to enhance the data set (Levine 2007). Using neutron activation analysis (NAA), they chemically fingerprinted thirteen Eastern Woodlands sources. Of these, seven are in the Lake Superior region and the remaining six (two in New Jersey, two in Nova Scotia, and two in Pennsylvania) are found east of Lake Superior (Levine 2007; Rapp et al. 2000, p. 64).

Levine's (1996, 1999, 2007) interest in such a project was to test the "dominant model" privileging Lake Superior copper procurement throughout prehistory. Testing 65 native copper artifact samples from 19 sites in the northeast against fingerprinted sources, she found that her results varied by period; virtually all of the Late Archaic (c. 5000–3000 BP) specimens she tested were traced to Lake Superior sources, while sources for Early Woodland (c. 3000–2000 BP) artifacts centered on deposits from Nova Scotia.

While Levine's findings are extremely significant, she did not delve into what impact they might have on models of native copper distribution in northeastern prehistory. Lattanzi (2007), however, takes up this problem. He tests long-debated suggestions that the presence of copper in the Delaware Valley resulted either from the migration into the area of peoples who brought copper artifacts from elsewhere, or from local participation in far-flung trade networks centered outside the region. Although preliminary, results of his LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) sourcing of Late Archaic and Early Woodland artifacts from the Delaware Valley concur with Levine's: in the Late Archaic, native copper came from Lake Superior sources. Later, in the Early Woodland, a shift occurred to exploitation of local sources in New Jersey and Pennsylvania. He (2007, p. 9) concludes that "a more focused [geographically?] pattern of local copper procurement, manufacture, and exchange" prevailed in the Delaware Valley during the Early Woodland, indicating a change in procurement practices. Lattanzi (2007, p. 133) also suggests that copper and other exotic artifacts found in Early Woodland burials may also signal a move toward social complexity there.

McKnight (2007) looks at the problem in yet another way. Also using LA-ICP-MS, he sourced multiple artifacts from several Early and Middle Woodland caches only to find that these caches are not homogeneous sourcewise; in some cases, he found that up to three different source areas in the Upper Great Lakes and elsewhere are identified in a single cache.

Copper Consumption in the Eastern Woodlands

The results of these recent investigations broaden our interpretive vistas as to the potential sources of native copper in the Eastern Woodlands and challenge us to continue to revisit some long-held assumptions about how and from what source(s) the major copper working cultures of the Eastern Woodlands acquired and distributed it. At the same time, they set the stage for relating what we are now learning about the technological and contextual aspects of its consumption. As will be shown, crafters from the three traditions discussed here worked copper into different kinds of artifacts for somewhat different purposes, ranging from the strictly utilitarian to ritual. From a technological perspective, artifacts of all periods are generally complex in form and involved significant technical proficiency and knowledge on the part of the artisans of both the behavior and limitations of the material and of manufacturing techniques. Also, in each of these situations, it is clear that for indigenous peoples, native copper had qualities that lent it an "aura of exceptionality" as Helms (1993 p. 101) has termed it, for the people who were using it.

The "Old Copper Complex" (ca. 4000–1000 BC)

Not surprisingly, the oldest firm evidence for copper working in the Eastern Woodlands is found in the Lake Superior region (South Fowl Lake, Minnesota) and dates to 6800 BP (Martin 1999). Radiocarbon dates from pits on Isle Royale indicate that native peoples were removing copper from that locale by c. 3500 BC.

The single outstanding copper-using tradition in the region with roots in this era is the Old Copper Complex, or Industry (formerly known as the Old Copper 'Culture'), which flourished in the Mid-to-Late Archaic period (4000–1000 BC) (Martin and Pleger 1999; Pleger 2000, 2003; Pleger and Stoltman 2008). Centered in eastern Wisconsin, the Old Copper Complex is found throughout the western Great Lakes drainage, radiating both westward and eastward from that core (Gibbon 1998, p. 27, 36) (Fig. 13.1). The complex takes in a number of discrete, largely egalitarian, mobile hunting and gathering societies with their own characteristic tool kits of lithic and osseous materials. However, these cultures also shared "... in varying degree a common [copper] metallurgical technology and a set of style concepts" (Gibbon 1998, p. 40; Mason 1981, p. 186). Material evidence of the complex consists of distinctive types of copper implements, weaponry, and ornaments that were frequently but not always found in mortuary contexts. These artifacts include socketed

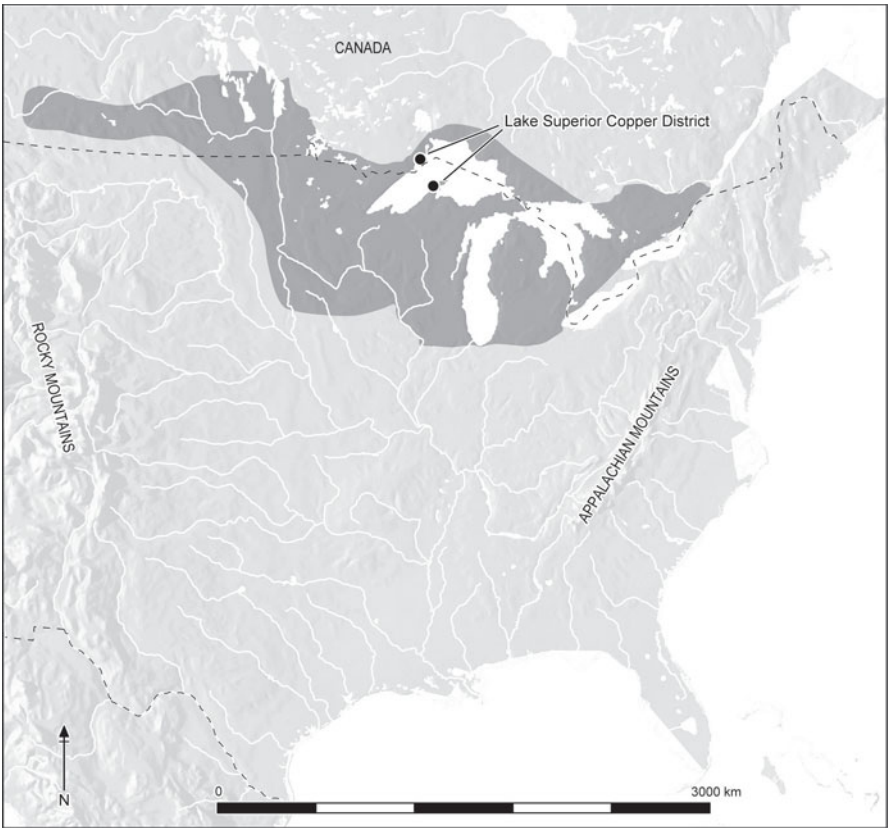


Fig. 13.1 Map showing the major copper-bearing zones of the Lake Superior Copper District and the approximate areal extent of the Old Copper Complex (after Gibbon 1998)

or tanged spear points, knives, straight, or "crescent" type blades (ulus), awls, perforators, spuds, celts, chisels/wedges/axes (some also socketed), harpoons, fish hooks, needles, gorges, crescent-shaped ornaments, bracelets, pendants, rings, and beads (Fig. 13.2; Pleger and Stoltman 2008, pp. 787-839)). Artifacts tended to be large, heavy, bulky, and primarily utilitarian in form (Leader 1988, p. 73). The origin of the raw material is assumed to be the Lake Superior deposits or the abundant float copper available in the region.

Important work has been done to elucidate Old Copper metalworking techniques. Leader (1988) (xeroradiography), William Vernon (1985, 1990), and Schroeder and Ruhl (1968) (metallography) are among those who have performed laboratory tests on Old Copper materials, while LaRonge (2001) has performed important experimental replication work. These investigations revealed that artifacts were fabricated either directly from nuggets or laminar plates or from prepared copper blanks that were hammered, flattened, and repeatedly folded over and bent into shape (Vernon 1990). Sheets were also produced. Alternate cold hammering and annealing processes were employed in manufacture. While hot hammering is suspected, it has

Fig. 13.2 Examples of Old Copper Complex copper artifacts from various locales in Wisconsin. Left to right:chisel (#11836/1571), socketed spud (#2147), small celt, socketed spearpoint, crescent knife, beads, stemless point (#1876), tanged point, 'rat tailed' tanged point (#1908). Courtesy of the Milwaukee Public Museum, Milwaukee, Wisconsin. Photograph by Kathleen L. Ehrhardt

not been demonstrated through laboratory analysis. These primary techniques were accompanied by differential, often combined use of abrading (grinding), riveting, perforation (by drilling or punching), bending, or molding (often around mandrels), and polishing (LaRonge 2001; Leader 1988, p. 71; Vernon 1985, 1990; see also Martin 1999). Researchers have found no evidence of casting, melting, or smelting of the metal (Smith 1968, p. 242).

Archaeologists have long sought to resolve a larger set of social questions with regard to the function of Old Copper artifacts, first by Lewis Binford (1962) more than 40 years ago: If these objects were recognizably utilitarian in form but are found primarily in mortuary contexts, were they ever actually used, or were they manufactured strictly as grave furniture or personal accouterments? Can some form of status recognition in an otherwise egalitarian society be inferred by their placement in burials? Looking into these questions, Penman (1977) used microscopic use wear analysis (examination of edge angles and wear marks from e.g. battering, blunting, smoothing, and reworking) to conclude that most of the over 1,000 Old Copper artifacts he examined had indeed been employed for various utilitarian purpose(s). In his visual examination and xeroradiographic testing, Leader (1988) also found signs of use and resharpening on many objects. While Schroeder and Ruhl's (1968, p. 162) metallographic revealed that four of the five objects they tested had been left cold worked, Vernon's (1985, 1990) showed that points, knives, and celts left annealed outnumbered their coldworked counterparts, 4:1. However, 80 % of the awls were finished by cold working.

Thus, Binford's questions have no firm resolution to date (see Childs 1994, pp. 234–235). However, as Gibbon (1998, p. 42) points out, the fact that these objects had functioned in the everyday world "… is not inconsistent with their placement with the dead or their use as social markers," and is probably connected with achieved status in otherwise egalitarian societies. Recent research has shown that as early as the Late Archaic, copper may have already held important social and symbolic meaning that may have rendered its placement with the dead of great significance to Old Copper peoples, particularly when placed with the dead. Pleger (2000, 2003) argues that while evidence for social complexity (in the form of

Fig. 13.3 Map showing sites mentioned in the text, and the approximate areal extent of Hopewell

achieved status) is indeed found in some Old Copper burial contexts, social differentiation begins to appear with greater intensity at about the time Old Copper merges (about 1000 BC) with the Red Ochre Culture. It is during this time that Pleger (2003, p. 16) sees a significant uptrend in the production of copper ornamentation versus copper implements, and a similar increase in the occurrence of prestige-type goods of nonlocal (exotic) manufacture in particular burials within area cemeteries. He also adds that it may well have been during this time that copper emerges as a valuable trade item.

Hopewell (ca. 100 BC–400 AD)

Hopewell is a Middle Woodland cultural phenomenon that covered vast, but noncontiguous territories of the Eastern Woodlands and whose influence was local, regional, and interregional (Fig. 13.3). While most researchers agree that its cores are in the Scioto Tradition of the Scioto River Valley, Ohio, and the Havana Hopewell of the Illinois River Valley in west central Illinois, its overall cultural expressions were extremely variable according to local or regional tradition and practice. Hopewell is known primarily for increased social complexity, elaborate mortuary ceremonialism, which included mound construction and the consumption of prestige goods, and the development of widespread, long-distance trade networks dealing in exotic materials and finished objects (Seeman 1979, pp. 237, 240, 254) commonly known as the "Hopewell Interaction Sphere."

Native copper is known to have played important roles in all of these domains. Seeman (1979, pp. 303–304) ranked copper first in "cultural importance" on his list of major Interaction Sphere raw materials, and McKnight's (2007) impressive inventory of the material's distribution throughout the Hopewellian world is dramatic testimony to its significance. Copper is thought to have circulated in both raw and finished form. Seeman (1979, p. 251) further argues that the Hopewell site, the major center of the Scioto Tradition (in Ross County Ohio), was copper's point of entry into the interaction system, and that the Hopewell and Trempealeau (western Wisconsin) sites were centers for the manufacture of finished copper artifacts. In view of recent studies arguing for local production, the latter supposition is now in question (Carr 2005; Ruhl 2005, p. 705).

New work has shed light on copper acquisition during this time. Until Sharon Goad's (1978, 1979) work, direct acquisition from Great Lakes sources had been the preferred procurement model (see Bernardini and Carr2005, pp. 631–634 for recent supporting arguments). However, McKnight offers new insights. Based on his recent LA-ICP-MS provenance findings, McKnight (2007, 224) concludes that 'copper deposits from Lake Superior were not the exclusive source for native copper, but were by far the most important'. He found, however, that beads from two burials caches at the Hester site in the Copena area of the southern Appalachians (northern Alabama) come from multiple sources in the Lake Superior district. He argues that these results, he claims, shed doubt on the notion that procurement was direct. McKnight further points out that, several of the major northern centers were located well within, or in reasonable distance of, the Lake Superior float copper cachement zone, making drift copper accessible for local consumption.

During this period, copper is thought to have been consumed and distributed by persons who controlled its movement and/or desired to communicate symbolically and materially their social (leadership? shamanic?) role in life, and more frequently, in death (Carr 2005, pp. 280–281; Charles et al. 2004, p. 63; Seeman 2004, pp. 59, 61; Winters 1981, pp. 19-22). Both finished and unfinished objects are documented primarily from mortuary contexts, appearing there as personal belongings or as gifts/offerings (Ruhl 2005). Katherine Ruhl (2005s, p. 707; see also Carr 2005, p. 280) has also noted their occurrence in other ritual settings.

Hopewellian artifacts differ significantly in form and manufacturing technique from the solid, largely utilitarian forms found in Old Copper contexts. A wide range of primarily ornamental forms, some quite spectacular, are featured in the industry. These include earspools (Fig. 13.4c), gorgets (Fig. 13.4b), bracelets, beads, arm rings/bracelets, and headdresses. Panpipes and platform pipes also occur, while relatively fewer implements (Fig. 13.4a), including awls, copper axes), adzes, and gouges are recovered.

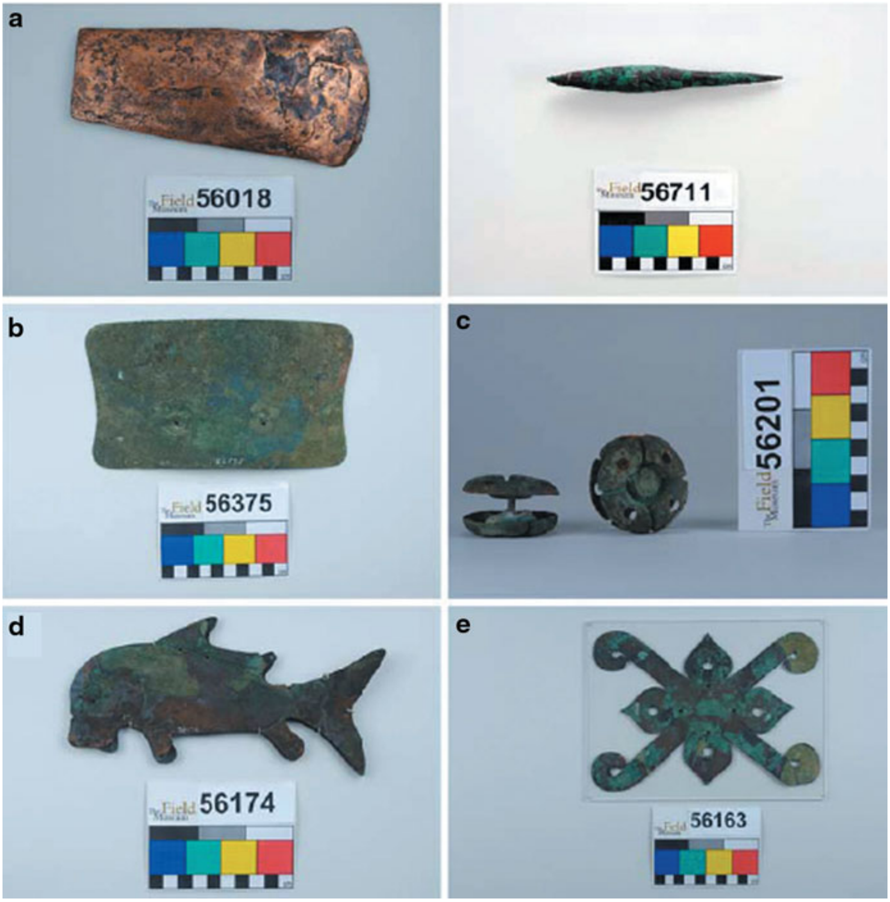


Fig. 13.4 Examples of Hopewellian copper artifacts from the Hopewell site, Ross County, Ohio. **a** Celt (left, #56018) and large awl or piercer (right, #56711); **b** rectangular gorget (#56375); **c** earspools with cut-out design (#56201); **d** sea mammal effigy (#56174); **e** geometric cut-out (#56163). All images ©2009 Field Museum, Chicago, Illinois. Reproduced with their permission

Several innovations are noted in Hopewellian metalworking technology. Hopewellian copper artifacts were manufactured by hammering copper nuggets or prepared blanks into solid forms and into sheet stock, the use of which becomes much more widespread. Rods and blanks were formed by hammering, annealing, and grinding into shape (Leader 1988, p. 78). Metallographic analysis by Wayman et al. (1992) revealed that the heads of two of the solid adzes they examined were formed using either hot forging and/or cold hammering and annealing. Final forms, such as solid bracelets and adze heads, were then achieved using various combinations of bending, folding, rolling, and grinding actions (Leader 1988; Wayman et al. 1992, p. 107,113). Sockets were formed by hammering over an anvil (Smith 1968, p. 242). Holes were created by punching or drilling.

Metalworkers also cold worked, annealed, and ground pieces of copper into flat sheets of various thicknesses (0.18–1.25 mm inclusively), which were then used alone or hammered together. Sheets were then used to produce finished artifacts that were mainly ornamental (Leader 1988; Wayman et al. 1992, p. 102; Willoughby cited in Greber and Ruhl 1989, p. 122). Breastplates and perforated rectangular ornaments were fashioned (Fig. 13.4b). Sheets were also cut into two-dimensional geometric and/or zoomorphic shapes (Fig. 13.4d, e). Openwork "cut-outs" are often features of the geometric cut sheets (Fig. 13.4e). Many animal "effigy sheets" are embossed or repousséed to enhance the design (see Fig. 13.4d). Sheet is also used to sheath or "clad" wooden or shell forms, perhaps to give the appearance of solid copper. Hollow beads and hollow bracelets were also produced. Beads were made of strips either wound around a cylindrical mandrel or free-formed. Bracelets were formed by "sinking" the sheet into concave molds, then hammering the protruding edges inward to form a c-shaped cross section (Leader 1988, p. 86). Sheets and ornaments were repaired using rolled strip copper rivets (Willoughby cited in Greber and Ruhl 1989, p. 122).

One of the most distinctive artifacts in the Hopewellian ornamental and ritual repertoire was the copper earspool (Fig. 13.4c). Bicymbal or "yo–yo" shaped examples are probably the most complex copper artifacts manufactured in native northeastern North America (Ehrhardt 2005, p. 67; see Greber and Ruhl 1989 for discussion). Earspools often exhibit exquisite craftsmanship; some are even made with an overlay of iron or native silver. Essentially, earspools are made of sheet hammered into two disks or plates. The inner and outer disks are joined centrally by a stem or other mechanism. In some cases, construction involved the use of nonmetal adhesives or twine (Ruhl 2005, Ruhl and Seeman 1998). Using optical microscopy of several prepared earspool cross sections, Wayman and colleagues (1992, pp. 101–103, p. 131) discovered that a number of the disks comprising the obverse and reverse of the finished spools were actually made up of at least three or four layers of copper sheet hammered tightly together. Importantly, the disks were riveted together at the midsection and joined at the outside edge through the use of mechanical, rather than metal welding or bonding techniques. The variability Ruhl (2005, p. 703) notes in earspool construction and decorative style within and across regions has led her to conclude that production and consumption were local in scale.

Thus, Hopewellian metalworkers produced solid objects and also manufactured and manipulated sheet stock. Embossing, cladding, and sinking techniques were added to the technological repertoire of earlier times. First evidenced in Archaic traditions, the use of rolled rivets for joining and repair becomes more frequent. Twine wrapping and adhesives are now also used as joins (Ruhl and Seeman 1998, p. 659). Several types of finished artifacts appear to exhibit standardization in form and design. The use of templates to achieve that consistency has not been demonstrated conclusively (Greber and Ruhl 1989, p. 141; Ruhl and Seeman 1998). Also, the purposeful selection of high arsenic copper (Wayman et al. 1992, p. 130) and the intentional use of copper and silver cladding techniques point to the importance of color and visual effect of the finished product (see Ruhl and Seeman 1998, p. 655, 657, 659). Overall, the impressive quality and complexity of the metalworking found

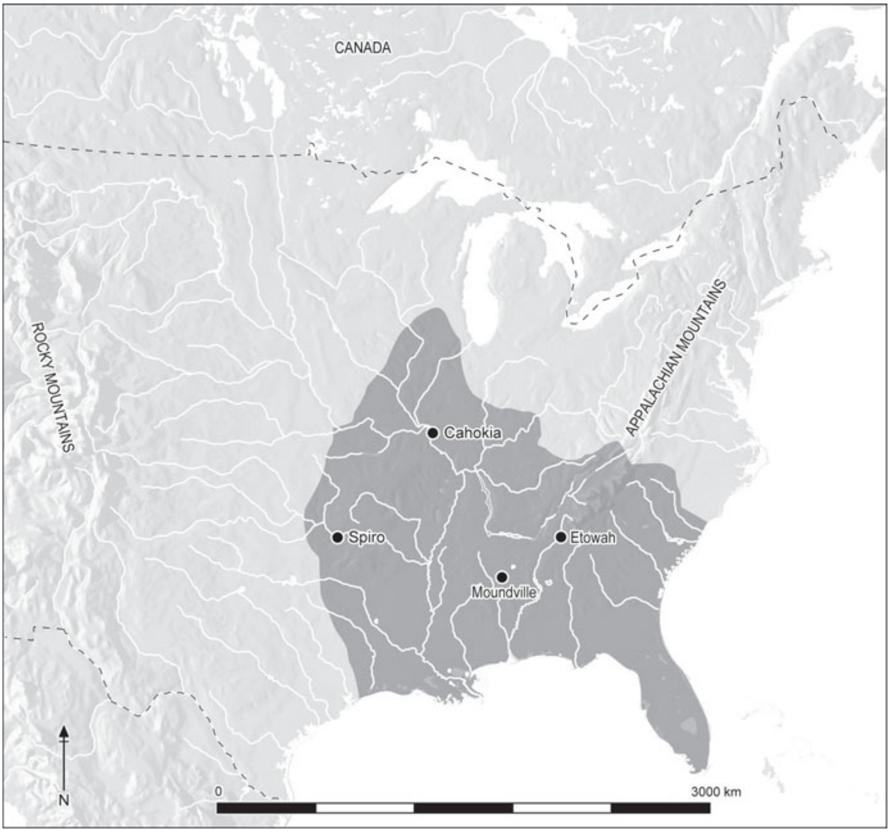


Fig. 13.5 Map showing sites mentioned in the text, and the approximate areal extent of the Mississippian

among Ohio Hopewellian peoples has prompted Leader (1988, p. 198) and Halsey (1996, p. 15) to suggest that metalworking specialists worked at manufacturing copper items, possibly on a full-time basis (Leader 1988, p. 198).

The Mississippian (c. 900 AD–European contact in the Southeast)

The Mississippian way of life is marked by the intensification of maize-based farming within a mixed subsistence economy, the emergence of local systems in which linked settlements ranged in size from farmsteads to large ceremonial temple/burial mound centers, the standardization of art styles over vast distances, participation in long-distance trade in exotic and "elite" goods, and an unprecedented level of legitimized sociopolitical authority (Brown 2004, p. 106; Griffin 1990; Pauketat 2004, pp. 7–9, 40–41) (Fig. 13.5). It was also a time of elaborate mortuary ritual, ritual ceremonialism, and complex ideological expression.

There is little doubt that native North American copper working technology reached an expressive high point in this period. As among Hopewell peoples, copper was a primary "prestige good" of the time; it was exploited by Mississippian peoples for internal and external consumption and was traded over long distances. It was used for fashioning a range of ceremonial artifacts and implements thought to be markers of high social status, authority, and wealth. This is demonstrated in the copper-rich elite gravesites found in mounds of the period.

Particular types of elaborate, well-finished, status/ritual-related objects made of copper, especially copper repoussé plates, are the preeminent components of the Southeast Ceremonial Complex (SECC), a hallmark of the Mississippian period (see Fig. 13.6c). The SECC is defined as "a set of specialized ritual imagery... in which thematically important animal and human figures are rendered according to specific stylistic conventions of representation" (Brown 2004, p. 105; Brown and Kelly 2000, p. 476). The SECC flourished throughout the Southeast from c. 1300–1500 AD; (Leader 1988, pp. 198–199; Sampson and Esarey 1993, p. 452). The large ceremonial center sites of Etowah (northwest Georgia), Spiro (eastern Oklahoma), and Moundville (western Alabama) have been identified as SECC copper working centers (Leader 1988; Sampson and Esarey 1993). Artistic "styles" (based primarily on variation in the artistic style of copper repoussé plates) of copper prestige goods have been identified with technological and artistic industries there (Brown 1989, 2004, pp. 120–121). Cahokia (southwest Illinois), the fourth and earliest of the major Mississippian ceremonial centers, has not yielded much in the way of copper or classic SECC-related copper artifacts. However, it is argued to have been a major pre-classic center, trading copper and producing particular types of copper artifacts in an early stage of SECC classical development (Brown 2004; Brown and Kelly 2000, pp. 473–474).

Copper artifacts, some very impressive in form and design, are also found in smaller quantities at various other sites throughout the Mississippian sphere (see Goodman 1984). Some of the copper for Mississippian artifacts is thought to have originated from Great Lakes sources, however, a shift is noted to the use of primarily southeastern resources (Goad 1978, 1980 p. 271; Hurst and Larsen 1958).

Copper working during this period is heavily directed toward production of ritual regalia, accessories, and adornment (Fig. 13.6). Artifacts include hair ornaments, gorgets, beads, headdresses, large perforated plates (plaques) (Fig. 13.6c), earspools, "long-nosed god" maskettes (Fig. 13.6a), ear ornaments, and copper-covered masks and other items. Ritual items are found in the form of zoomorphic and anthropomorphic rattles and effigies (Fig. 13.6d). Spear heads and other ceremonial implements such as celts, maces, large axes, bipointed needles, and pins are also found in the industries (Hamilton et al. 1974).

Mississippian crafters fabricated solid implements and sheets in the manner of earlier metalworkers. Refinements of the period center on the further thinning of sheet into foil [defined by Leader (1988) as sheet thinner than 0.05 mm] and the extensive use of repoussé technique in executing design motifs (Fig. 13.6b, c). Use of cutouts is also documented. Leader (1988) also notes the continued use of perforation,

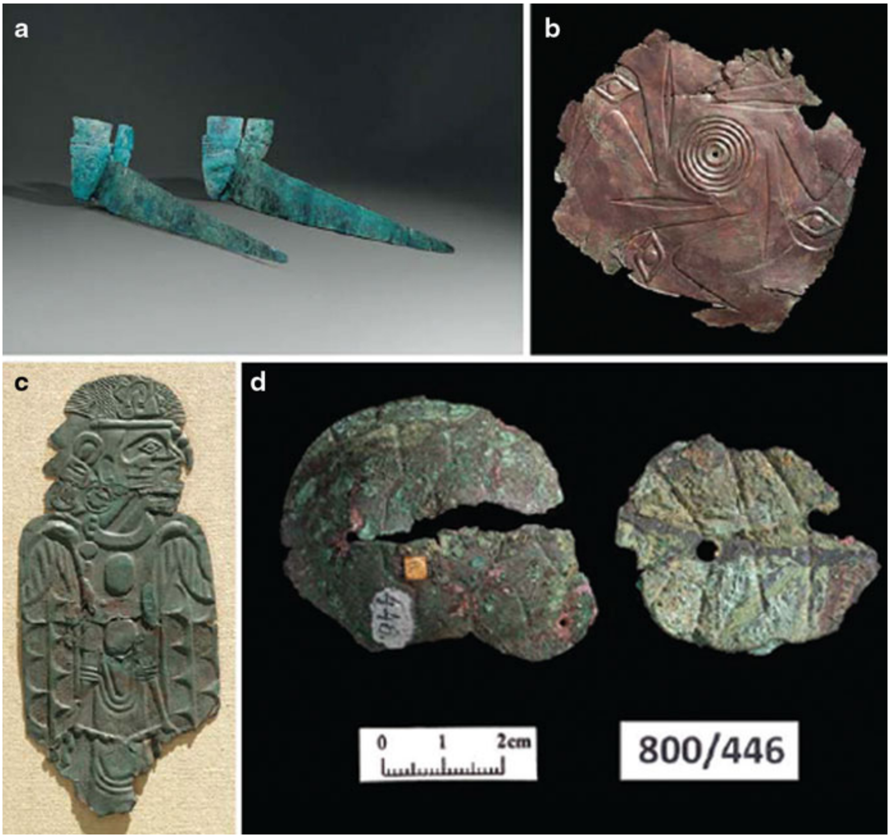


Fig. 13.6 Examples of Mississippian copper artifacts: a long-nosed god maskette ear ornaments, Meppen Mound site, Calhoun County, Illinois; b repousse´ plate with forked-eye surrounds, Craig Mound, Spiro site, LeFlore County, Oklahoma; c repousse´ plate depicting Birdman, Late Braden style. Wulfing group, Dunklin County, Missouri; d turtle-shell effigy rattles: carapace (left), plastron (right). Mitchell site, Madison County, Illinois. a Photograph by David H. Dye, courtesy of the Art Institute of Chicago. b Photo © John Bigelow Taylor, courtesy of the Art Institute of Chicago. c Artist unknown, repousse´ plaque, c. 1200 –1400. Copper, 119 500 . Mildred Lane Kemper Art Museum, Washington University in St. Louis. Gift of J. Max Wulfing, 1937. d Photograph by Doug Carr, courtesy of the Illinois State Museum

shearing, grinding, molding, and burnishing. The practice of covering objects made of materials such as wood and stone with thin copper sheathing intensifies during this period, and becomes a significant feature of Mississippian metalworking. Human and animal effigies, rattles, earspools, bodkins, finials, beads, bladelike objects, and sun gorgets are examples of clad objects (Leader 1988, pp. 129–135, p. 198; Hamilton et al. 1974, pp. 176–177).

Elaborate ceremonial, symbolic, and status-related ornamental artifacts such as highly decorated plates and symbol badges are manufactured of copper sheets and foils. Sheet artifacts are now larger due to the use of delicate riveting to join multiple hammered sheets. Plates are elaborately embossed with iconographic motifs reflecting important themes associated with the cult complexes they represented (Brown 1985, p. 114). More complex methods of attachment and repair are also in use (see Fig 13.6c for examples). Some artifacts, including headdresses and plates, are thought to have been used heavily and were even patched with new pieces or with pieces of other plates (Brown et al. 1990, p. 265; Hamilton et al. 1974, p. 187; Leader 1988, p. 184; Watson 1950).

During this period, designs became more standardized through use of templates; like plate styles are found widely distributed over long distances across the southeast (Brown 1989). Mixed styles at individual sites indicate trade in these prestige objects (Brown et al. 1990, p. 265). These and other considerations have led scholars to hypothesize that highly skilled and specialized artisan crafters, possibly under court sponsorship, were producing these objects full time in workshop settings (Brown 2004, Figure 25; Leader (1988). New findings of a copper working area and associated artifacts beneath Mound 34 at Cahokia should test these ideas on the ground, and further flesh out some new thoughts about the nature and intensity of copper production, craft specialization, and the location of dedicated precincts for ritual-related production there (see Ehrhardt 2007; Kelly 2006; Kelly and Kelly 2007). They will also provide new sets of well-provenienced data for technological studies of production.

Aside from Leader's (1988) careful examination of materials from Etowah and from Mississippian collections in Florida, Watson's (1950) detailed descriptive treatment of the Wulfing Plates (Dunklin County, Missouri), and Hamilton et al.'s (1974) work on the copper from Spiro, it appears that little large-scale archaeometric investigation has been done on Mississippian copper materials. Sourcing information comes primarily from Goad's (1978, 1980) influential NAA and optical emission spectroscopy work Schroeder and Ruhl (1968) conducted a very small-scale metallographic investigation on two copper sheets, finding that one had been cold worked and the other had been left annealed. Recently, two gorgets from Moundville were tested instrumentally and metallographically. Results indicate that they were cold worked, then left in an annealed state (Springer 2007, p. 5). Compositional analysis by XRF (X-ray fluorescence spectrometry) was inconclusive.

Discussion

It has not been possible to recognize here all of the fine research that has been conducted by scholars on the very kinds of anthropological questions we are looking to answer (see Brose and Greber 1979b; Carr and Case 2005a; Charles and Buikstra 2006; Clark and Purdy 1982; Galloway 1989; Goodman 1984; Leader 1988; Sharp 2004; Martin 1999). But, as this review demonstrates, there are lifetimes of work left to be done. From an anthropology of technology perspective, our goal is, of course, to understand the role(s) of copper and copper working in the lives of the people who consumed it. Using multiple lines of evidence, we seek to characterize and determine the source(s) of the materials themselves and to identify design and manufacturing techniques. We build these findings into a production technology, the material and social relations of which are then tied to procurement strategies and to the social, political, economic, and symbolic aspects of distribution, use, reuse, deposition, even discard. This comprises the technological system and situates it as a social project within a dynamic and changing universe of social and ideological action (after Kingery 1996a, b p. 227). At the same time, we must keep in mind that in all facets of the work, copper manipulation is but one aspect of a much larger material, social, and symbolic matrix.

As I prepared this review, I could not fail to recognize again how much potential continued, large-scale systematic archaeometallurgical research holds to expand upon, enrich, even recast the work that has gone before. Research on sourcing, manufacturing history, and on identifying the suites of techniques that make up these metalworking traditions has already brought new understandings and new interpretive possibilities. Identifying alternative sources of copper material and realizing the implications of those determinations for models of acquisition, manufacture, and exchange is one example. Another related theme involves working through the question of "regionalized" or "localized" copper production and consumption both inside and outside the "heartlands" of these traditions and how these processes might fit into larger schemes of intergroup (panregional) interaction and cohesion (Brown and Kelly 2000, p. 476; Carr and Case 2005a; Carr and Case 2005, pp. 22–28; Gibbon 1998).

One important way to address these questions (and other new inquiries as well) is to combine relevant material and contextual data with appropriate laboratory techniques to discern local technological "styles" (after Lechtman 1977, 1994). According to Lechtman (1977, p. 6), elucidating technological "style" means getting a grasp on 'technical modes of operation, attitudes towards materials, some specific organization of labor, ritual observances—elements which are unified nonrandomly in a complex of formal relationships'. This is accomplished, in part, by using materials science and materials engineering approaches to bring to light physiochemical and working properties of artifacts and materials, as well as their procurement and manipulation histories. Incorporating this information into our intellectual "tool kits" and placing the results within the contexts of many of the social questions we are asking, provides for an enhanced, yet more culture-specific reading of the particular choices, attitudes, perceptions, and activities involved in acquiring, crafting, using, and even disposing of copper as material and object within the larger cultural system(s) of which both individuals and objects are a part (Kingery 1996b). As we have seen, there is much more to be learned about the potential variations in the ways in which native peoples, whether separated or close in time, space, tradition, and/or social position interacted with this material. Identifying and isolating particular technological "styles" allows us to then turn our attention to understanding the interrelationships within and among prehistoric societies, in terms both of their copper use and in larger spheres of interaction.

Lastly, the question remains whether indigenous native copper working systems in Eastern Woodlands prehistory actually constituted "true" metallurgy. As has become amply clear to researchers, native American copper workers did not melt, smelt, cast, or alloy copper. Many authors argue that they did not need to—the high quality of the material available to them obviated the need for the kinds of manipulations associated with true metallurgy (Clark and Purdy 1982, p. 45; Craddock 1995, pp. 98–100; Martin 1999, pp. 28–29). Yet, through the use of simple techniques commonly attributed to the very earliest stages of native metalworking rather than to true metallurgy, crafters manipulated and improved copper's properties by heating and hammering it with a great deal of control and a "fairly sophisticated use of fire" (Clark and Purdy 1982, p. 56). Their specialized knowledge and skill in forming and shaping it into useful items and extraordinary pieces of functional, portable art in a range of iconographic styles is without question (Craddock 1995, p. 100; Wayman et al. 1992, pp. 133–134; but see Bernardini and Carr 2005, pp. 626–627). Regarding Old Copper artifacts, no less respected an archaeometallurgist than Cyril Stanley Smith asserts that "the skill with which the North American artifacts were made is impressive" and that they are "far larger and better shaped than any known native copper objects from the Middle East" (Smith 1968, p. 242). Craddock (1995, p. 122) comments that North American metallurgical practice "was the true summit of achievement in the fashioning of native metals."

In view of the many ways in which copper was manipulated by native North American peoples and the complex roles it played in social life, it appears to be of little overall consequence whether the technology itself can be labeled "true" metallurgy. It is provocative and useful to think about why North American metal working technology did not follow the same developmental paths documented for other New World metalworking industries (see Clark and Purdy 1982, p. 52). However, more immediate questions about the use of native copper and its roles in prehistoric material and ideological repertoires, in technological innovation, in mortuary ritual, in conspicuous display, and in the development and maintenance of social stratification appear to have taken center stage. I have argued here that materials science approaches provide important lines of evidence in these inquiries and that an integrated approach to technological "style" will help us elucidate these ideas. It is an exciting time to be in native North American copper studies. The "kinks" involved with "soft" social scientists trying to navigate the world of "hard" physical science and scientists are largely ironed out; it remains for us to build on the work of our predecessors and to operationalize larger-scale projects which will not only enlarge our data base but also respond to important questions touched on here and in the growing literature.

Acknowledgments I wish to thank sincerely Ben Roberts and Chris Thornton for inviting me to join the symposium, and for their support throughout the presentation and publication processes. Dorothy Hosler's comments are much appreciated. I also thank John Halsey, Greg Lattanzi, Lisa Anselmi, and MattMcKnight for sharing their ideas and their soon-to-be-published work with me, and Tom Pleger for technical advice on Old Copper. I am also indebted to the Field Museum, the Illinois State Museum, the Milwaukee Public Museum, and the Mildred Lane Kemper Art Museum for their help with the images, and to all of the institutions and photographers who allowed their photographs to be reproduced here. Larry Grantham helped with the maps. Tim Taylor's and Sarah Wright's editorial and organizational assistance is gratefully acknowledged. John Kelly and Jim Brown's enthusiasm for the ongoing work at Cahokia has been a great inspiration.

References

Bastian, T. (1961). Trace element and metallographic studies of prehistoric copper artifacts in North America: A review. In J. B. Griffin (Ed.), *Lake Superior copper and the Indians: Miscellaneous studies of Great Lakes prehistory* (pp. 150–175). Ann Arbor: University of Michigan.

Bernardini, W., & Carr, C. (2005). Hopewellian copper celts from Eastern North America. In C. Carr, & D. T. Case (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 624–647). New York: Kluwer Academic/Plenum Publishers.

Binford, L. R. (1962). Archaeology as anthropology. *American Antiquity, 28,* 217–225.

Bradley, J., & Childs, S. T. (1991). Basque earrings and panther's tails: The form of cross-cultural contact in sixteenth century Iroquoia. In R. Ehrenreich (Ed.), *Metals in society: MASCA Research Papers in Science and Archaeology* (vol 8(II), pp. 8–24

Brose, D. S., & Greber, N. (1979a). Discussion summary of topical papers. In D. S. Brose, N. Greber (Eds.), *Hopewell archaeology: The Chillicothe Conference* (pp. 251–253). Kent: The Kent State University Press

Brose, D. S., & Greber, N. (Eds.). (1979b). *Hopewell archaeology: The Chillicothe Conference*. Kent: The Kent State University Press

Brown, J. A. (1985). The Mississippian period. In D. Brose, J. Brown, & D. Penney (Eds.), *Ancient art of the American Woodland Indians* (pp. 93–140). New York: Harry Abrams.

Brown, J. A. (1989). On style divisions of the Southeastern Ceremonial Complex: A revisionist perspective. In P. Gallaway (Ed.), *The Southeastern Ceremonial Complex: Artifacts and analysis* (pp. 183–204). Lincoln: University of Nebraska Press

Brown, J. A. (2004). The Cahokian expression. In R. Sharp (Ed.), *Hero, hawk, and open hand: Ancient art of the ancient Midwest and South* (pp. 105–123). New Haven: The Art Institute of Chicago and Yale University Press.

Brown, J. A., & Kelly, J. (2000). Cahokia and the Southeastern Ceremonial Complex. In S. R. Ahler (Ed.), *Mounds, Modoc, and Mesoamerica*. [ISM Scientific Papers XXVIII] (pp. 469 –510). Springfield, Illinois State Museum.

Brown, J. A., Kreber, R. A., & Winters, H. D. (1990). Trade and the evolution of exchange relations at the beginning of the Mississippian period. In B. D. Smith (Ed.), *The Mississippian emergence* (pp. 251–280). Washington: Smithsonian Institution Press.

Carr, C. (2005a). Tripartite ceremonial alliance among Scioto Hopewellian communities. In C. Carr, & D. T. Case (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 258–338). New York: Kluwer Academic/Plenum Publishers.

Carr, C. (2005b). Rethinking interregional Hopewellian 'interaction'. In C. Carr, & D. T. Case (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 575–623). New York: Kluwer Academic/Plenum Publishers.

Carr, C., & Case, D. T. (2005). (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 19–50). New York: Kluwer Academic/Plenum Publishers.

Charles, D., & Buiksta, J., (Eds.). (2006). *Recreating Hopewell*. Gainsville: University Press of Florida

Charles, D., Van Nest, J., & Buikstra, J. E. (2004). From the earth: Minerals and meaning in the Hopewellian world. In N. Boivin, & M. A. Owoc (Eds.), *Soils, stones, and symbols*. London: UCL Press.

Childs, S. T. (1994). Native copper technology and society in eastern North America. In D. A. Scott, & P. Meyers (Eds.), *Archaeometry of pre-Columbian sites and artifacts* (pp. 229–253). Los Angeles: The Getty Conservation Institute.

Clark, D. E., & Purdy, B. (1982). Early metallurgy in North America. In T. A. Wertime, & S. F. Wertime (Eds.), *The evolution of the first fire-using industries* (pp. 45–58). Washington: Smithsonian Institution Press.

Cooper, H. K. (2006). Copper and social complexity: Frederica de Laguna's contribution to our understanding of the role of metals in native Alaskan society. *Arctic Anthropology, 43*(2), 148–163.

Craddock, P. (1995). *Early metal mining and production*. Washington: Smithsonian Institution Press.

Cushing, F. (1894). Primitive copper working: An experimental study. *American Anthropologist (Old Series), VII*, 93–117

Ehrhardt, K. L. (2005). *European metals in native hands: Rethinking technological change 1640–1683*. Tuscaloosa: University of Alabama Press

Ehrhardt, K. L. (2007). Technological perspectives on copper production at Cahokia. Paper presented at the 64th Annual Meeting of the Southeastern Archaeological Conference, Knoxville, November 1

Galloway, P. (Ed). (1989). *The Southeastern Ceremonial Complex: Artifacts and analysis*. Lincoln: University of Nebraska Press

Gibbon, G. (1998). Old copper in Minnesota: A review. *Plains Anthropologist, 43*(163), 27–50.

Goad. S. (1978). *Exchange networks of the prehistoric southeastern United States*. Unpublished Ph.D. dissertation, Department of Anthropology, University of Georgia, Athens. University Microfilms, Ann Arbor

Goad, S. (1979). Middle Woodland exchange in the prehistoric southeastern United States. In D. S. Brose & N. Greber (Eds.), *Hopewell archaeology: The Chillicothe Conference* (pp. 239–246). Kent: The Kent State University Press.

Goad, S. (1980). Chemical analysis of native copper artifacts from the southeastern United States. *Current Anthropology, 21*(2), 270–271.

Goodman, C. (1984). *Copper artifacts in late Eastern Woodlands prehistory*. Evanston: Center for American Archaeology

Greber, N., & Ruhl, K. (1989). *The Hopewell site: A contemporary analysis based on the work of* Charles C. Willoughby. Boulder: Westview Press.

Griffin, J. B. (1990). Comments on the late prehistoric societies in the southeast. In D. Dye, C. A. Cox (Eds.), *Towns and temples along the Mississippi* (pp. 5–15). Tuscaloosa: University of Alabama Press

Griffin, J. B. (Ed.). (1961). *Lake Superior copper and the Indians: Miscellaneous studies of Great Lakes prehistory*. Anthropological Papers 17, Museum of Anthropology, University of Michigan, Ann Arbor

Halsey, J. (1996). Without forge or crucible: Aboriginal native American use of metals and metallic ores in the Eastern Woodlands. *The Michigan Archaeologist, 14*(1), 1–58.

Halsey, J. (2004). Copper from the drift. Paper presented at the Joint 50th Midwest Archaeological Conference and the 61st Annual Meeting of the Southeastern Archaeological Conference. St. Louis, Missouri, October 21

Hamilton, H. W., Hamilton, J. T., & Chapman, E. F. (1974). *Spiro Mound copper*. [Missouri Archaeological Society Memoir no. 11]. Columbia: Missouri Archaeological Society.

Helms, M. W. (1993). *Craft and the kingly ideal: Art, trade, and power*. Austin: University of Texas Press.

Hurst, V. J., & Larson, L. H. (1958). On the source of copper at the Etowah site, Georgia. *American Antiquity, 24,* 177–181.

Kelly, J. (2006). The ritualization of Cahokia. In B. M. Butler, P. D. Welch (Eds.), *Leadership and polity in Mississippian societies* [Southern Illinois University Carbondale Occasional Paper No. 33.] (pp. 236–263). Carbondale: Center for Archaeological Investigations

Kelly, J., & Kelly, L. (2007). Cahokia mound 34: In pursuit of the copper workshop. Paper presented at the 64th Annual meeting of the Southeastern Archaeological Conference, Knoxville, November 1

Kingery, W. D. (1996a). Introduction. In W. D. Kingery (Ed.), *Learning from things: Method and theory of material culture studies* (pp. 1–15). Washington: Smithsonian Institution Press.

Kingery. W. D. (1996b). Materials science and material culture. In W. D. Kingery (Ed.), *Learning from things: Method and theory of material culture studies* (pp. 181–203). Washington: Smithsonian Institution Press.

LaRonge, M. (2001). An experimental analysis of Great Lakes archaic copper smithing. *North American Archaeologist,* 22, 371–385.

Lattanzi, G. (2007). The provenance of pre-contact copper artifacts: Social complexity and trade in the Delaware Valley. *Archaeology of Eastern North America, 35,* 125–138.

Leader, J. (1988). *Technological continuities and specialization in prehistoric metalwork in the Eastern United States*. Unpublished Ph.D. dissertation, University of Florida, University Microfilms, Ann Arbor

Lechtman, H. (1977). Style in technology—Some early thoughts. In H. Lechtman, R. Merrill (Eds.), *Material culture: Styles, organization, and dynamics of technology* (pp. 3–20). St. Paul: West Publishing Company

Lechtman, H. (1994). The materials science of material culture: Examples from the Andean past. In D. A. Scott, & P. Meyers (Eds.), *Archaeometry of pre-Columbian sites and artifacts* (pp. 3–12). Los Angeles: The Getty Conservation Institute.

Lemonnier, P. (1993). Introduction. In P. Lemonnier (Ed.), *Technological choices: Transformation in material cultures since the Neolithic* (pp. 1–35). London: Routledge.

Levine, M. A. (1996). *Native copper, hunter-gatherers, and northeastern prehistory*. Unpublished Ph.D. dissertation, University of Massachusetts, Amherst, University Microfilms, Ann Arbor

Levine, M. A. (1999). Native copper in the Northeast: An overview of potential sources available to indigenous peoples. In M. A. Levine, K. Sassaman, & M. S. Nassaney (Eds.), *The archaeological Northeast* (pp. 183–199). Westport: Bergin and Garvey.

Levine, M. A. (2007). Determining the provenance of native copper artifacts from northeastern North America: Evidence from instrumental neutron activation analysis. *Journal of Archaeological Science, 34*(4), 572–587.

Levine, M. A., Sassaman, K. E., & Nassaney, M. S. (Eds.) (1999). *The archaeological Northeast*. Westport: Bergin and Garvey.

Maddin, R., Wheeler, T.S., & Muhly, J. D. (1980). Distinguishing artifacts made of native copper. *Journal of Archaeological Science, 7,* 211–225.

Martin, S. (1999). *Wonderful power: The story of ancient copper working in the Lake Superior Basin*. Detroit: Wayne State University Press

Martin, S., & Pleger, T. C. (1999). The complex formerly known as a culture: The taxonomic puzzle of Old Copper. In R. F. Williamson, & C. M. Watts (Eds.), *Taming the taxonomy: Toward a new understanding of Great Lakes archaeology* (pp. 61–70). Toronto: Eastend Books.

Mason, R. (1981). *Great Lakes archaeology*. New York: Academic Press.

McKnight, M. (2007). The copper cache in early and middle Woodland North America. Doctoral thesis submitted to the Department of Anthropology, Pennsylvania State University. Available on the World Wide Web at https://etda.libraries.psu.edu/paper/8016/

Meskell, L. (2005). Introduction: Object orientations. In L. Meskell (Ed.), *Archaeologies of materiality* (pp. 1–16). Malden (MA): Blackwell Publishing

Pauketat, T. (2004). *Ancient Cahokia and the Mississipians*. Cambridge: Cambridge University Press.

Penman, J. (1977). The Old Copper Culture: An analysis of Old Copper artifacts. *The Wisconsin Archeologist (New Series), 58*(4), 3–23.

Pleger, T. C. (2000). Old Copper and Red Ocher social complexity. *Midcontinental Journal of Archaeology, 25*(2), 169–190.

Pleger, T. C. (2003). A brief introduction to the Old Copper Complex of the western Great Lakes: 4000 - 1000 BC. *In The Historic Oconto Area: Proceedings of the 27th Annual meeting of the Forest History Association of Wisconsin, Inc., October 4-5, 2002, Oconto, Wisconsin* (pp. 10 – 18). Wasau,Wis: Forest History Association.

Pleger, T. C., & Stoltman, J. (2008). The Archaic Tradition in Wisconsin. In T. E. Emerson, A. C. Fortier, & D. McElrath (Eds.), *Archaic societies: Diversity and complexity across the midcontinent* (pp. 787–839). Albany: State University of New York Press.

Rapp, G., Allert, J., Vitali, V., Jing, Z., & Henrickson, E. (2000). *Determining geologic sources of artifact copper: Source characterization using trace element patterns*. Lanham: University Press of America.

Rapp, G., Henrickson, E., Miller, M., & Aschenbrenner, S. (1980). Trace-element fingerprinting as a guide to the geographic sources of native copper. *Journal of Metals, 32*(1), 35–44.

Ries, H. (1916). *Economic geology*. New York: John Wiley and Sons.

Ruhl, L. (1992). Copper earspools from Ohio Hopewell sites. *Midcontinental Journal of Archaeology*, 17(1), 46–72

Ruhl, K. (2005). Hopewellian earspools from eastern North America: The social, ritual, and symbolic significance of their contexts and distribution. In C. Carr, & D. T. Case (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 696–713). New York: Kluwer Academic/Plenum Publishers.

Ruhl, K., & Seeman, M. F. (1998). Temporal and social implications of Ohio Hopewell copper ear spool design. *American Antiquity, 63*(4), 651–662.

Sampson, K., & Esarey, D. (1993). A survey of elaborate Mississippian copper artifacts from Illinois. In T. E. Emerson, A. C. Fortier, & D. L. McElrath (Eds.), *Highways to the past: Essays on illinois archaeology in honor of Charles J. Bareis*. *Illinois Archaeology*, Kampsville, Illinois: Center for American Archeology *5*(1–2), 452–480.

Schroeder, D., & Ruhl, K. (1968). Metallurgical characteristics of North American prehistoric copper work. *American Antiquity, 33*(2), 162–169.

Seeman, M.F. (2004). Hopewell art in Hopewell places. In R. Sharp (Ed.), *Hero, hawk, and open hand: American Indian art of the ancient Midwest and South* (pp. 57–71). New Haven: The Art Institute of Chicago and Yale University Press.

Seeman, M. F. (1979). *The Hopewell Interaction Sphere: The evidence for interregional trade and structural complexity. Prehistory Research Series V(2)*. Indianapolis: Indiana Historical Society.

Sharp, R. (Ed.) (2004). *Hero, hawk, and open hand: American Indian art of the ancient Midwest and South*. New Haven: Art Institute of Chicago and Yale University Press.

Smith, C. S. (1968). *Metallographic study of early artifacts made from native copper* (pp. 237–252). Warsaw: Actes du XI^{e}Congres International d'Histoire des Sciences VI

Spence, M. W., & Fryer, B. J. (2005). Hopewellian silver and silver artifacts from eastern North America: Their sources, procurement, distribution, and meanings. In C. Carr, & D. T. Case (Eds.), *Gathering Hopewell: Society, ritual, and ritual interaction* (pp. 714–733). New York: Kluwer Academic/Plenum Publishers.

Springer, S. (2007). An examination of alterations to Mississippian period native copper artifacts from the collection of the National Museum of the American Indian. ANAGPIC 2007. Available from World Wide Web: https://pacer.ischool.utexas.edu/dspace/bitstream/2081/9101/3/Springer_text.doc. Accessed 14th Feb 2008

Streuver, S., & Houart, G. (1972). An analysis of the Hopewell Interaction Sphere. In E. Wilmsen (Ed.), *Social exchange and interaction* (pp. 47 – 79). Ann Arbor: Anthropological Papers no. 46, Museum of Anthropology, University of Michigan.

Tuck, J. (1978). Regional cultural development 3000 to 300 B.C. In B. G. Trigger (Ed.), *Handbook of North American Indians, volume 15 Northeast* (pp. 28 – 43). Washington: Smithsonian Institution Press.

Veakis, E. (1979). Archaeometric study of native copper in prehistoric North America. Unpublished Ph.D. dissertation, Department of Anthropology, State University of New York at Stony Brook, University Microfilms, Ann Arbor.

Vernon, W. W. (1985). New perspectives on the archaeometallurgy of the Old Copper Industry. *MASCA Journal, 3*(5), 154–163.

Vernon, W. W. (1990). New archaeometallurgical perspectives on the old copper industry of North America. In N. P. Lasca, & J. Donahue (Eds.), *Archaeological geology of North America,* *Centennial Special* Volume 4 (pp. 499–512). Boulder: Geological Society of America. (Vol. 4, pp. 499–512). Boulder: Geological Society of America.

Walthall, J. A. (1981). *Galena and aboriginal trade in eastern north America*. Springfield: Illinois state museum scientific papers 17

Walthall, J. A., Stowe, S. H., & Karson, M. J. (1979). Ohio Hopewell trade: Galena procurement and exchange. In D. S. Brose, & N. Greber (Eds.), *Hopewell archaeology: The Chillicothe Conference* (pp. 247–250). Kent: The Kent State University Press

Watson, V. (1950). The Wulfing plates. Washington University Studies, Social and Philosophical Sciences New Series No. 8, St. Louis

Wayman, M. L. (1989). Native copper: Humanity's introduction to metallurgy? In M. Wayman (Ed.), *All that glitters: Readings in historical metallurgy* (pp. 3–12). Montreal: Metallurgical Society of the Canadian Institute of Mining and Metallurgy

Wayman, M. L., King, J. C. H., & Craddock, P. T. (1992). *Aspects of early North American metallurgy*. London: British Museum Occasional Paper 79, Departments of Scientific Research and Ethnography

Whittlesey, C. (1863). *Ancient mining on the shores of Lake Superior*. Washington, DC: Smithsonian Institution. Smithsonian Contributions to Knowledge 155, 1–29.

Willoughby, C. (1903). Primitive metal working. *American Anthropologist N.S.*, *5*, 54–57

Wilson, D. (1855). Antiquaries of the copper region of the North American lakes. *Proceedings of the Antiquaries of Scotland*, *2*, 203–212

Winters, H. D. (1968). Value systems and trade cycles of the Late Archaic in the Midwest. In L. R. Binford, & S. R. Binford (Eds.), *New perspectives in archeology* (pp. 175–221). Chicago: Aldine.

Winters, H. D. (1981) Excavations in museums: Notes on Mississippian hoes and Middle Woodland copper gouges and celts. In A. Cantwell, J. B. Griffin, and N. A. Rothschild (Eds.), *The research potential of anthropological museum collections* (pp. 17–34). New York: The New York Academy of Sciences.

Chapter 14
Mesoamerican Metallurgy: the Perspective from the West

Dorothy Hosler

Topic Overview

Mesoamerica provides an unusual and intellectually challenging case in the development of metallurgy when compared to other world areas we examine in this volume. The major challenge lies in complex events surrounding the introduction of this copper-based technology from South America to western Mesoamerica around 650 C.E. and its subsequent development there, long after state-level societies had become firmly established in the Central Highlands (Teotihuacan), the Southeastern Lowlands (Maya), and elsewhere. Here, we will synthesize our knowledge of Mesoamerican metallurgy at this point in time, focusing in particular on the west Mexican metalworking zone (Fig. 14.1) where the technology initially took root, developed, and flourished through 900 years, identifying those questions where answers are reasonably firmly established and those questions where the most productive work still lies ahead.

The earliest dates for metal artifacts in Mesoamerica come from the west Mexican metalworking zone, from sites along the west coast, in particular Tomatlán, Jalisco; Amapa, Nayarit; and from settlements located along the lower Balsas river between Michoacan and Guerrero in the Infiernillo region (Fig. 14.2), map showing Mesoamerica and site locations). They date to around 650–700 C.E. All objects are made from copper and represent two production traditions: some are lost-wax cast (bells and small ornaments) and others are cold-worked from an initial cast blank and comprise ornaments such as rings and small work tools (Hosler 1986, 1994). These sites are on the Pacific coast or have riverine access to the Pacific coast. This copper-based technology and/or its practitioners moved to the higher-elevation inland basins of Jalisco and Michoacan, where archaeologists recovered copper objects at sites such as Cojumatlan, Michoacan and Tizapan, Jalisco—both located on the shores of Jalisco's Lake Chapala (Hosler 1994).

D. Hosler (✉)
Department of Materials Science and Engineering,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
e-mail: hosler@mit.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_14,

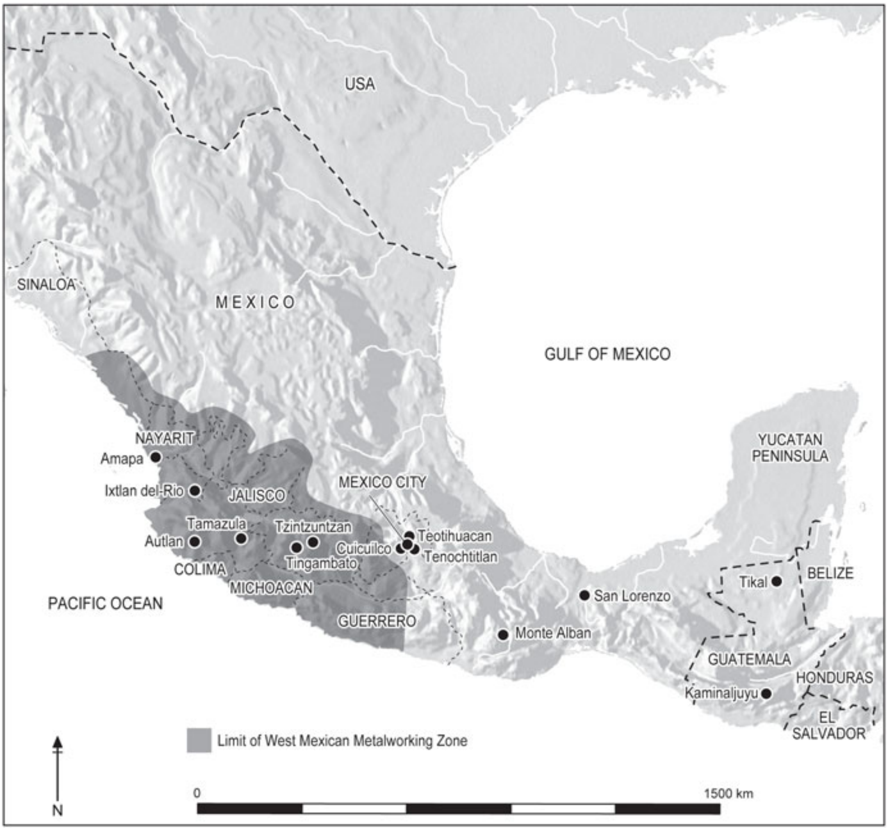


Fig. 14.1 Map showing major Mesoamerican archaeological sites and regions, the west Mexican metalworking zone, and archaeological sites within the metalworking zone

The copper artifacts from coastal and inland sites range from 650 to 1100/1200 C.E and comprise what Hosler has designated as Period 1 (Hosler 1994). At La Pena (Garcia 2007, 2008), a recently excavated site located in Cuenca de Sayula adjacent to Lake Chapala, copper objects date to between 800 and 1100 C.E (Garcia 2007). The La Peña artifacts also fit into the Period 1 types (Fig. 14.2), and consist of small cast copper bells, and copper objects shaped by cold work: open rings, pointed eye needles, and beam design tweezers. In fact, thus far, all artifacts analyzed from this period, except for one low-arsenic copper–arsenic figurine excavated from the Atetelco complex at Teotihuacan in 1998 (Hosler and Cabrera 2011), were made from copper. The artifact assemblages I have described provide the bulk of our earliest dated evidence. Unfortunately, the west Mexican metalworking zone, Mesoamerica's earliest locus for metalworking, still lacks studies of mining sites, smelting sites, and production-workshop sites dating to this period.

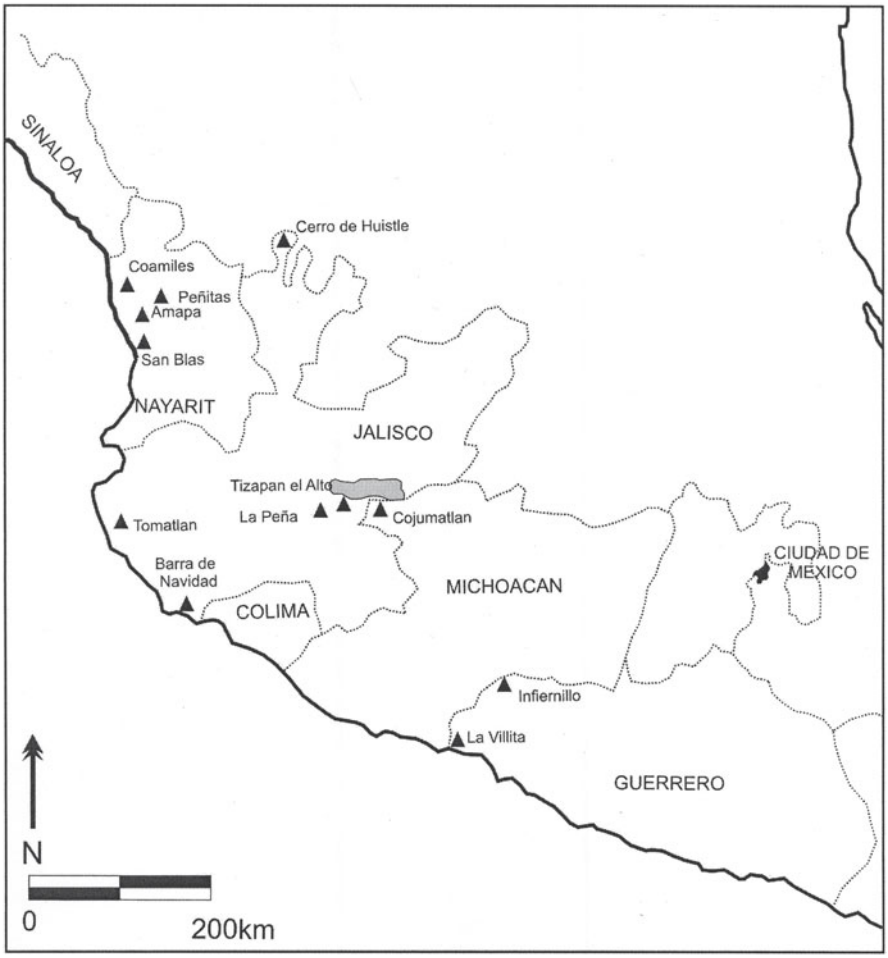


Fig. 14.2 Map showing locations of Period 1 archaeological sites where copper objects have been recovered

The Introduction of Metallurgy to Western Mexico and Period 1 Characteristics

There has been little argument concerning the origins of Mesoamerican metallurgy. Virtually all investigators since the pioneering research of Arsandaux and Rivet (1921, 1923) through the work in the 1960s and 1970s by Meighan (1969), Mountjoy (1969), Pendergast (1962), Willey (1966), Marcos (1978), and others have maintained that metallurgy was introduced to Mesoamerica either from Central America, South America, or from both regions most possibly via a maritime route. That hypothesis has been greatly strengthened and clarified in the last several decades by

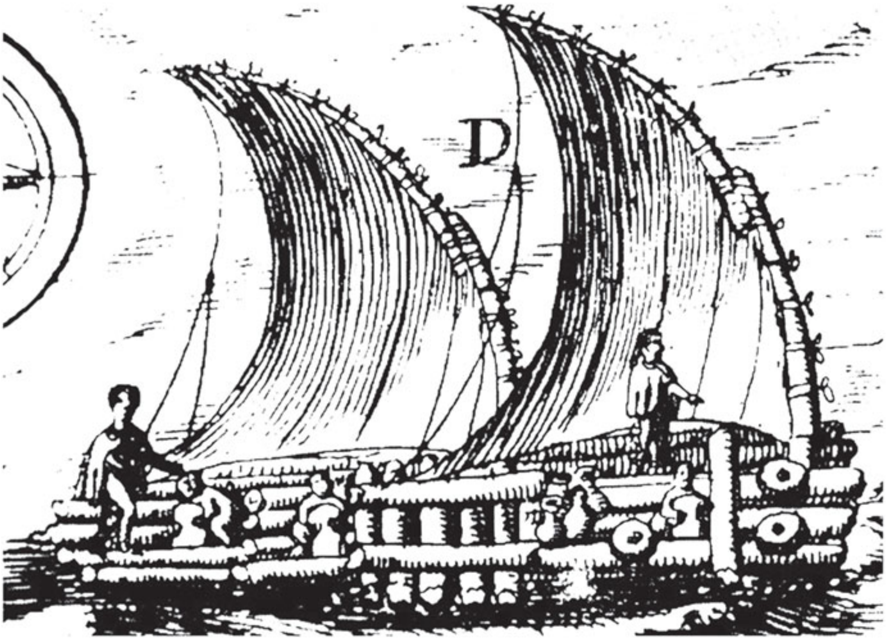


Fig. 14.3 Drawing of sixteenth-century balsa-wood watercraft drawn from Joris Van Spilbergen. (from Edwards 1965)

Hosler (1988a, b, 1994) and Dewan and Hosler (2008), whose research strongly supports the idea that knowledge of metallurgy was introduced by Ecuadorian voyagers to peoples living in west Mexican ports. The support for these conclusions derives from Hosler's comparative analyses of lower Central American and South American artifact chemistries, fabrication techniques, and design characteristics, with those of artifacts from west Mexico (Hosler 1986, 1988b, 1994, 1996) and from recent engineering studies of the design and performance of Ecuadorian balsawood sailing rafts (Dewan and Hosler 2008). Both lines of evidence strongly suggest that knowledge of metalworking techniques and a few prototype artifacts was carried to the shores of western Mexico by the seagoing maritime peoples of coastal Ecuador, whose balsawood trading rafts were still in evidence at the time of the European invasion (Hosler 1988b, 1994; Dewan and Hosler 2008). The comparative metallurgical studies, facets of which I discuss in subsequent sections, have identified specific Andean metallurgical traditions from which certain west Mexican artifact design types/fabrication methods and alloy systems originated (Hosler 1986, 1988b, 1994).

To reassess whether such seagoing voyages were feasible given Ecuadorian sailing technology, Dewan and Hosler (2008) carried out engineering studies of ancient Ecuadorian balsa-wood rafts. The engineering models were based on drawings of the sixteenth-century Ecuadorian watercraft (Fig. 14.3). The models reveal that these vessels, to navigate successfully, could measure between 6 and 11 m in length and would require two masts, measuring between 5 and 7.5 m in height. The cargo

Fig. 14.4 Spondylus oyster. (photo courtesy of HenryDomke.com)

capacity of balsa rafts in this size range varied between 10 and 30 metric tons, which replicates the cargo capacity of nineteenth-century Erie Canal barges. Further, these balsa rafts were capable of making two round-trip voyages between coastal Ecuador to the coasts of west Mexico (Guerrero or Michoacan) before deteriorating sufficiently to become inoperable. Dewan and Hosler (2011, p. 36) calculated that the raft could make the 3,000-km voyage between these two regions in 6–8 weeks, when traveling 12 h per day at 4 knots/h with eight crewmembers aboard. Analysis of Pacific weather conditions and currents suggests that these rafts could have most easily launched from coastal Ecuador in December and arrive in west Mexican ports in late January. The return trip could have been undertaken in March, at the earliest. At least one document, written by the royal accountant Rodrigo de Albornoz, describes native accounts from western Mexico of "Indians from certain islands to the south [who] brought exquisite things which they would trade for local products [and] those who had come would stay for 5 or 6 months until good weather occurred" (Dewan and Hosler 2008).

Hosler (1988b) has argued that long layovers were essential to the process of introducing this complex technology, metallurgy, to peoples who were unfamiliar with it. That enterprise requires that local west Mexican peoples at some point during these contacts—which probably occurred sporadically over hundreds of years—learn to identify key copper ore types (malachite, azurite, and chalcopyrite), tin (cassiterite), ores of arsenic (arsenopyrite), arsenic-bearing copper ores (tennantite and others), and the other parent materials Hosler has identified in previous studies of ore types used in the west Mexican metalworking zone (Hosler 1994, Chap. 2).

If Ecuadorian sailing technology indeed allowed these long-distance, round-trip voyages, another fundamental question has concerned what Ecuadorian voyagers were seeking in west Mexican coastal settlements. We have no new data since the last discussion of this particular topic (Hosler 1994), but those data merit recapitulation in view of the objectives of this special issue of this journal. Various authors, but most notably Jorge Marcos (1978), have posited that seagoing traders voyaged north from Ecuador along the Pacific coast to harvest sypondylus oysters which live in dispersed deep-water pockets from coastal Ecuador to southern Sinaloa, Mexico (Fig. 14.4). Spondylus' shell was sacred to Central and Southern Andean peoples.

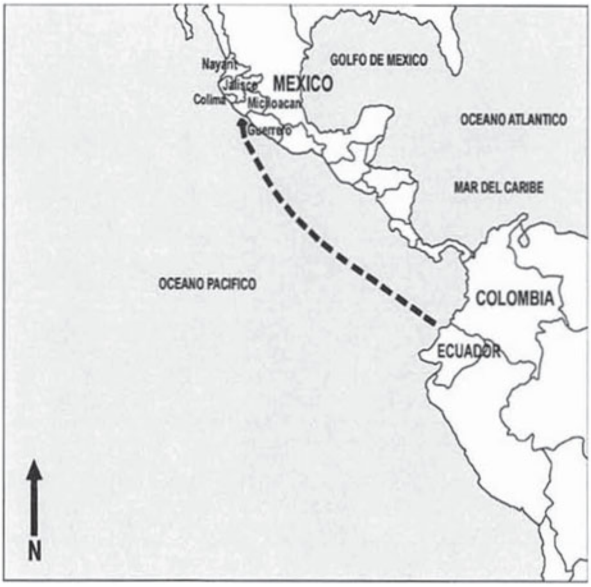


Fig. 14.5 Map showing possible maritime route from coastal Ecuador to west Mexico

Since spondylus oyster requires a warm-water habitat and cannot survive in the cold waters of the Chile–Peru current, the shell became an item of critical value in the Ecuador-based maritime trade along the coast of Peru. The observations of Bartolemé Ruíz de Estrada, Francisco Pizarro's chief pilot who captured one of these rafts as it sailed northward along the Ecuadorian coast (Hosler citing Samano Xerez 1937, pp. 66–67) are particularly germane to this discussion. Ruíz describes a raft with 20 men aboard carrying trade goods that included metal (silver) objects: tiaras, crowns, bands, tweezers and bells—all of which, he reports, they brought to exchange for some shells (Hosler 1994, p. 103 citing Samano Xerez 1937, pp. 65–66). These Ecuador-based traders thus also voyaged north. I have argued elsewhere (Hosler 1988b, 1994) that they offered metal objects, and metalworking knowledge and techniques to their west Mexican partners in exchange for spondylus shell (Fig. 14.4), which grows and was harvested along the west coast of Mexico (Fig. 14.5).

The argument that west Mexican metallurgy was introduced from the south becomes particularly convincing when we assess the laboratory and archaeological data comparing lower Central American and South American metallurgy to the metal objects excavated in the west Mexican metalworking zone. Those data show that copper objects recovered at the west Mexican metalworking zone sites mentioned previously—lost–wax-cast bells and cold worked needles, tweezers, and rings—are virtually identical in design parameters and fabrication techniques to Colombian and to Ecuadorian/Northern Peruvian artifacts (Hosler 1986, 1988a, 1994). Colombian and Ecuadorian/Peruvian peoples treated metal in very different ways. In Colombia, metal was treated as a liquid and objects were cast in open molds, in one- or two-piece molds or by the lost-wax method. Bells, cast using the lost-wax method,

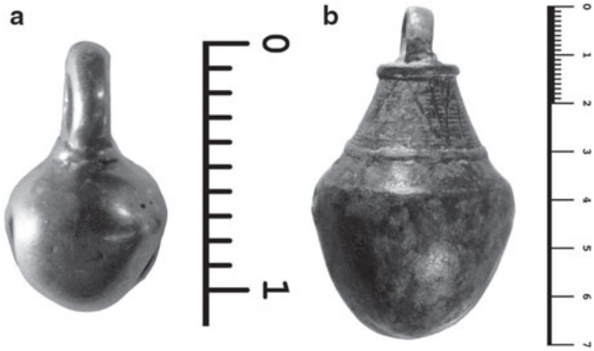


Fig. 14.6 **a** Costa Rican lost-wax-cast bell. **b** West Mexican lost-wax-cast bell

occur in Colombia and Costa Rica by 100 C.E. (Hosler 1994, p. 99) predating their appearance in the west Mexican metalworking zone by at least 500 years (Figs. 14.6 and 14.7. In Ecuador, Peru, and parts of the south-central Andes, metal was treated as a solid, and objects were formed by hammering them to shape from an original cast blank. Counterparts of the cold-worked Period 1 west Mexican items—copper-pointed eye needles, beam design tweezers, open rings, and small chisels—have been excavated in Ecuador and Northern Peru, and date to between 100 and 500 C.E. or earlier (Hosler 1994, Chap. 4), hundreds of years earlier than the west Mexican examples. (Hosler 1986, 1988b, 1994) (Figs. 14.8 and 14.9). In both Ecuador and west Mexico, the objects are made from copper, and the design parameters, fabrication techniques, and even burial contexts in some cases (the rings) are the same.

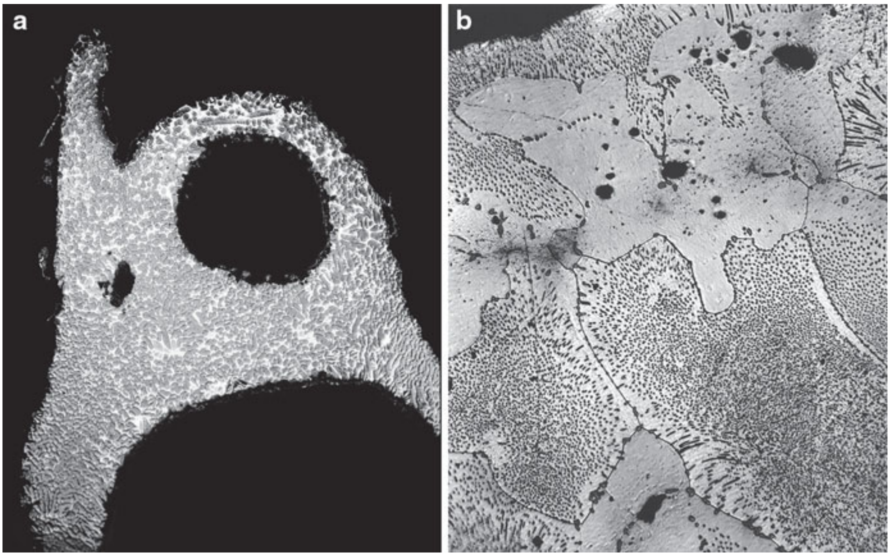


Fig. 14.7 **a** Cast microstructure of Costa Rican bell. **b** Cast microstructure of west Mexican bell

Fig. 14.8 **a** Ecuadorian pointed-eye needle. **b** West Mexican pointed-eye needle

Minor differences in the presence and concentrations of trace elements, and in the ratios of certain artifact dimensions to one another, distinguish the Andean material from the west Mexican objects. Thus, the objects excavated at Amapa and other sites were not imports from Colombia/Ecuador but were second-generation items, made

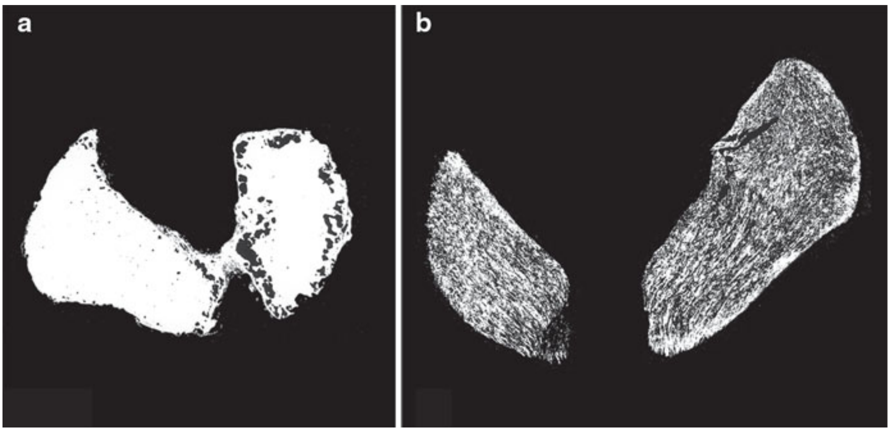


Fig. 14.9 **a** As-polished section through eye of Ecuadorian pointed-eye needle. **b** Etched section of west Mexican pointed-eye needle

from prototype exchange items introduced by seagoing Ecuadorian traders (Hosler 1988b, 1994) (Figs. 14.5, 14.6 and 14.7).

A significant piece of evidence supporting the introduction of these metalworking techniques through maritime contact is that the geographical distribution of these assemblages of cold-worked and cast objects is discontinuous. They are absent in the Intermediate area (Southern Mexico to Nicaragua) between 200 and 600 C.E, the time period we are discussing (Figs. 14.8 and 14.9).

The west Mexican metalworking zone contains the largest copper deposits in Mesoamerica (Hosler 1994). The metalworking zone (Fig. 14.1) comprises the area encompassed by the modern states of Guerrero, Michoacan, the southern part of the state of Mexico, Jalisco, Colima, and Nayarit. The Mexican copper belt runs through Michoacan and Guerrero and exhibits a series of massive sulfide deposits and innumerable smaller copper outcrops. The most common copper ores are chalcopyrite, malachite, and azurite (Fig. 14.10). Arsenopyrite is the major ore of arsenic; deposits of tennantite and enargite also appear, as well as deposits of gold (not shown) metallic silver, argentite, and silver sulfosalts. Small deposits of cassiterite, the oxide ore of tin, are dispersed sporadically in the metalworking zone particularly along the northeastern boundary, but most cassiterite occurs along the eastern edge of the Sierra Madre Occidental. That region is known as the Zacatecas tin belt.

People living in the metalworking zone thus had access to the raw materials for metal extraction and production, and in many cases lived in complex village settlements by 600–700 C.E, when the technology was introduced. In Guerrero's and Michoacan's middle Balsas region, for example, these settlements, which date to this and later periods, display residential sectors as well as extensive public and ceremonial architecture (Hosler 2000; Meanwell 2001, 2008; Moguel and Pulido 2005; Reyna 1997). Similar polities flourished in Michoacan, Jalisco, Colima, and Nayarit. Archaeological data show that peoples living in these areas understood and had been managing the properties of stone, clay, and other materials for hundreds of years and that they also were at least familiar with certain copper ore minerals such as malachite, which they polished and used for ornaments. It is not surprising that people living in these settlements could have learned and incorporated the techniques and practices required by the copper-based technologies introduced from the South (Fig. 14.10).

Evidence for Mining, Extractive Metallurgy (Smelting), and Object Fabrication

The laboratory analyses of artifacts show that, during the period between about 650 C.E. and 1100–1200 C.E., metalworkers across this broad geographical region were making the same kinds of objects from similar materials and using the same techniques. As I mentioned, no significant evidence exists for mining smelting and metal production. At Amapa several small objects appear which William Root, the chemist who analyzed them, has identified as slag (Root in Meighan 1976). Archaeologists

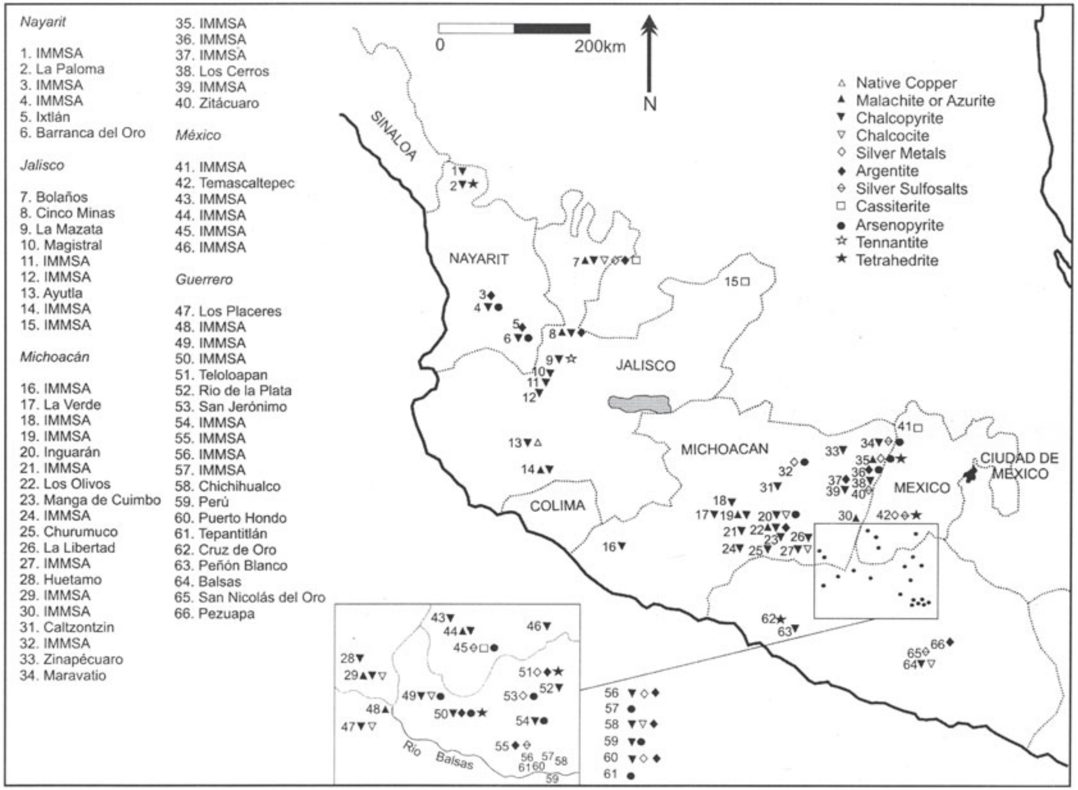


Fig. 14.10 Map showing the location of metallic ore deposits in the west Mexican metalworking zone. IMMSA represents unpublished archival data; the place names are taken from geological reports. (see Hosler 1994, 2003, Chap. 2)

report slag-like materials adhering to a potsherd at Peñitas, Nayarit (Carriveau 1978) but do not provide analyses of those materials. The strongest evidence comes from Ruben Cabrera, who identified amorphous metal adhering to stone-crucible fragments where he argues melting or smelting took place (Cabrera 1976, Hosler 1994). Joseph Mountjoy reported what he believes are metalworkers' tools at Tomatlan Jalisco. At Cojumatlán, Meighan and Foot (1968) excavated what they call "slugs" of metal: these, they think, were ingots (Hosler 1994, 2003) (Fig. 14.2). It is likely that some facet of metal production occurred at at least some of the Period 1 sites where copper artifacts were excavated but the data so far remain sparse.

Thus, the sum total of the direct evidence of production activities is small. However, the data indicate strongly that artifacts recovered from sites in this zone were produced somewhere within the region. Artifact distribution is confined to the metalworking zone during this period. Further, this region is one of Mexico's richest in copper ore minerals, and it also displayed the social prerequisites of metal production: the existence of complex societies (Hosler 1996). What is more, the lead isotope ratios of west Mexican artifacts match those of west Mexican copper ores we have sampled and distinguish those ores from other (i.e., eastern Mexican) copper sources (Hosler 2003, Hosler and Macfarlane 1996).

The paucity of archaeological information concerning extraction and smelting activities illustrates one of the major gaps in our understanding of west Mexican metallurgy and Mesoamerican metallurgy as a whole. This leaves another major question unanswered. What social entities participated in the incorporation of the technology from South America and initiated mining, ore processing, and metal production in the west Mexican metalworking zone? What are the dates? How did they organize extraction and production activities?

Pottery Clues

We do have evidence, while unrelated to processing, which may be useful from some (but not all) Period 1 sites concerning the social affiliations of the groups using these copper artifacts. A polychrome pottery type known as Aztatlan appears at Tomatlan, Amapa, Cojumatlan, and Tizapan associated with the copper artifacts excavated at those sites. Hosler (1994) reviewed this evidence and commented that the meaning of these associations is unclear but worth noting.Garcia (2007, 2008) found this same pottery type at La Peña (Fig. 14.11), which dates to approximately the same period. Unfortunately, the origins and social affiliations of peoples associated with this pottery complex are one of most contentious issues in Mesoamerican archaeology (Smith and Heath Smith 1980; Mountjoy 1990; Nicholson and Quiñones Keber 1994; Kelley 2000), and its discussion is far beyond the scope of this paper. This pottery cannot be associated with a particular social or ethnic group or region, and temporal controls are far from established. The data for the association of copper objects and Aztatlan pottery nonetheless continue to accumulate and at some point should provide some insights into the incorporation and dissemination of metal technology and/or of objects during Period 1.

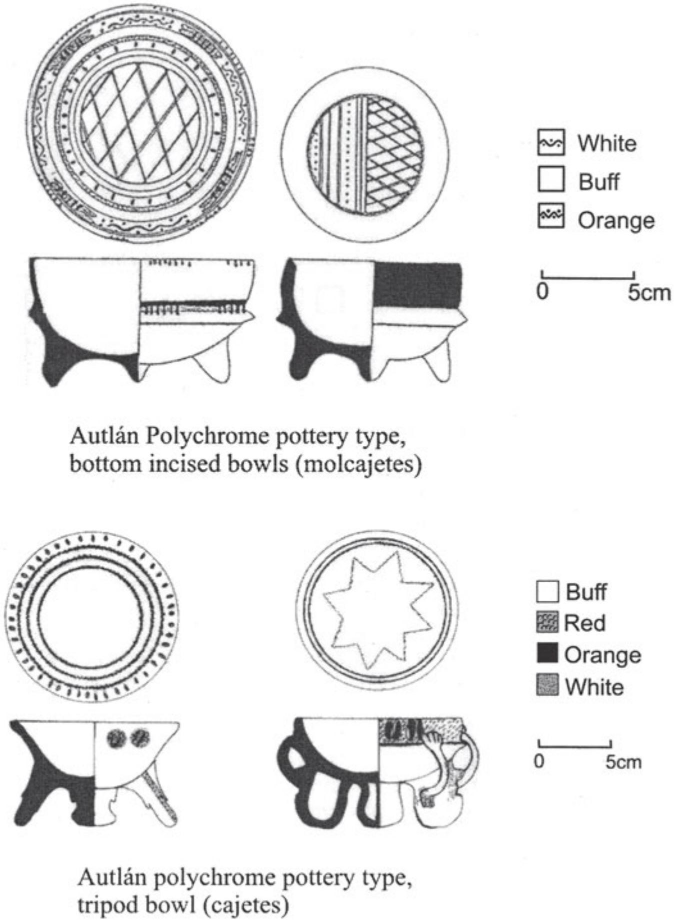


Fig. 14.11 Autlan pottery recovered at la Peña

Sound and Cosmology

Apart from the origins and characteristics of this new technology, one of the broad issues that we have been able to confront concerns the vital question of what people living in complex societies, who have already solved problems of daily and ritual life using other materials, choose to do with metal, a completely new material. Copper, when cold worked, lends itself to a variety of applications which, in some cases (for example, needles) produces an implement whose physical and mechanical properties (strength and toughness) are far superior to those of bone needles that Mesoamerican peoples produced in large quantities (Hosler 1994). Yet, the primary concern of these metalworkers was metal's acoustical properties, its sound. Bells, cast using the lost-wax method, by far outnumber any other artifact class. Bells comprise some 60 % of all items made from metal in the west Mexican repertoire. These peoples were particularly interested in producing a range of pitches, casting bells that varied in those design parameters (internal volume and width of resonator opening) crucial to pitch. Data from burials show that different-sized bells (i.e., bells whose pitches varied) were worn together on the wrists or ankles, attached to waistbands, and sewn onto clothing. (Hosler 1994, 1995).

Linguistic, lexical, ethnohistoric, and ethnographic evidence (Hosler 1994) reveals that metallic bell sounds and the sounds of composite instruments containing bells were highly significant in Mesoamerican cosmology. Bells and bell instruments were essential in rainmaking ceremonies: they reproduced the sounds of thunder, rain, and the roar of the jaguar, a progenitor of Mesoamerican peoples. Bell sounds also engendered agricultural and human fertility. Bell sounds could precipitate trance, in ritual, drawing the participants into altered states of consciousness, in which they directly experienced the supernatural (Hosler 1994).[1] In the metalworking zone, metal bells came to replace the seed pods, gourd rattles, and rattles made from other materials traditionally used in shamanistic curing ceremonies, in rainmaking ceremonies, and dance (Hosler 1994). As I discuss elsewhere (Hosler 1994), lexical evidence from several Mesoamerican languages indicates that the words for "metal" and for "bell" are the same, so that metal and bells can be considered culturally synonymous. Thus, the sounds of metal in bells and in composite bell instruments was the property of this new material that most interested these west Mexican people and which, from the outset, guided their production choices.

Metal bells and their sounds were also significant in Colombia, where bells were lost-wax cast, and in Ecuador where they were cold worked to shape. However, metal bells constituted minor elements in the technologies of those two Andean regions.

I have argued previously that metalworkers' interest in fashioning objects evoking sacred and supernatural spheres of experience through sound may respond to the particular circumstances surrounding the introduction of metallurgy from Andean South America. This foreign material and the sounds that it made may have been especially compelling to chiefs and other elites in consolidating power and attracting followers through associations with the supernatural (Hosler 1994). The timing $\sim$700 C.E. coincides was the collapse of Teotihuacan, Mesoamerica's most powerful state, and with the formation of smaller polities in many Mesoamerican areas. These events reconfigured loyalties, alliances, and trade networks and may have provided a particularly propitious moment for the introduction of a new and exotic material.

The Florescence of West Mexican Metallurgy: Period 2

Around or somewhat before 1100–1200 C.E,[2] the technical expertise of metalsmiths in the metalworking zone expanded greatly. They developed copper–tin and

[1] There has been some ethnographic work documenting trance states brought on by the repetitive sounds of rattles and bells.

[2] Garcia (2007) dates a copper–arsenic alloy bell to 1040 C.E. from Caseta where the numerous copper–tin and copper–arsenic bronze artifacts recovered fall between 1040 and 1300 C.E., making

copper–arsenic bronze and copper–silver alloys, which they primarily used—with the alloying element present in the bronzes to 23 weight percent—for the color of these alloys in elite status objects and in ritual paraphernalia. These objects consist of bells and other sounding instruments, rings, pendants, assorted body ornaments, ornamental tweezers, sheet metal breastplates, large disks, ornamental shields, and crowns. What is so striking about the trajectory of this metallurgy is that metalworkers took advantage of the increased strength, ductility, fluidity, and other properties of copper–tin bronze, copper–arsenic bronze, and sometimes copper–silver alloys, to refine, redesign, and sometimes alter the color of the same artifact classes they had previously made in copper.

These artifacts also include new tools and implement designs in which metalworkers capitalized on the increased hardness and toughness of the bronze alloys to improve functionality (Hosler 1994, 2003). In tools, they added the alloying element, tin or arsenic, only in concentrations (2–5 wgt %) sufficient when cold-worked to produce thinner and harder chisels, punches, axes, and awls. They produced these items in relatively small numbers when compared to status and ritual objects (Hosler 1994, 2003). These west Mexican peoples elected to define tin and arsenic bronze as sacred materials, particularly appropriate for elite and status purposes, rather than to use them either for the utilitarian ends common to other world metallurgies (for armor and weapons) or to undertake production of bronze tools and work implements on a large scale, thus altering the course of this technology.

Metalworking zone artisans cast vast numbers of bells of different sizes from these bronze alloys. By doing so, they were able to greatly expand the range of pitches the bells could produce. The physical and mechanical properties of tin and arsenic bronze alloys facilitate larger bell castings, and pitch, as noted, is a function of the internal volume of the bell resonator chamber. Their concern with metallic sound persisted, resulting in technical choices which disallowed the use of metal for other cultural objectives. They also became intensely interested in metallic colors, most notably of silver and gold. In the west Mexican case, metalworkers used the bronze alloys, especially copper–tin and sometimes copper–arsenic in concentrations to 23 % by weight in lost-wax castings to produce golden and silvery colors in objects, such as certain intricate thin-walled bell designs (Fig. 14.12) whose design parameters precluded the use of gold or silver metal. These bronze alloys are highly fluid; they flow easily into an extremely thin-walled mold cavity, and they do not solidify or freeze at a single temperature but over a range of temperatures, which allows time for the liquid metal to fill in design detail. These alloy concentrations are far higher than necessary to produce the fluidity and strength required by the design of the casting. High-tin bronze bells look golden. High-arsenic bronze bells look silvery. Gold and silver colors are associated in the Mesoamerican pantheon with the solar and lunar deities, respectively (Hosler 1994, 1995).

dates for the copper–tin and copper–arsenic alloys earlier than the (very general) 1200–1300 C.E. dates available previously (see Hosler 1994). Some Milpillas bronze artifacts dated lightly earlier than 1200 C.E., which is why Garcia's findings make the earliest dates about 100 years earlier than previously estimated.

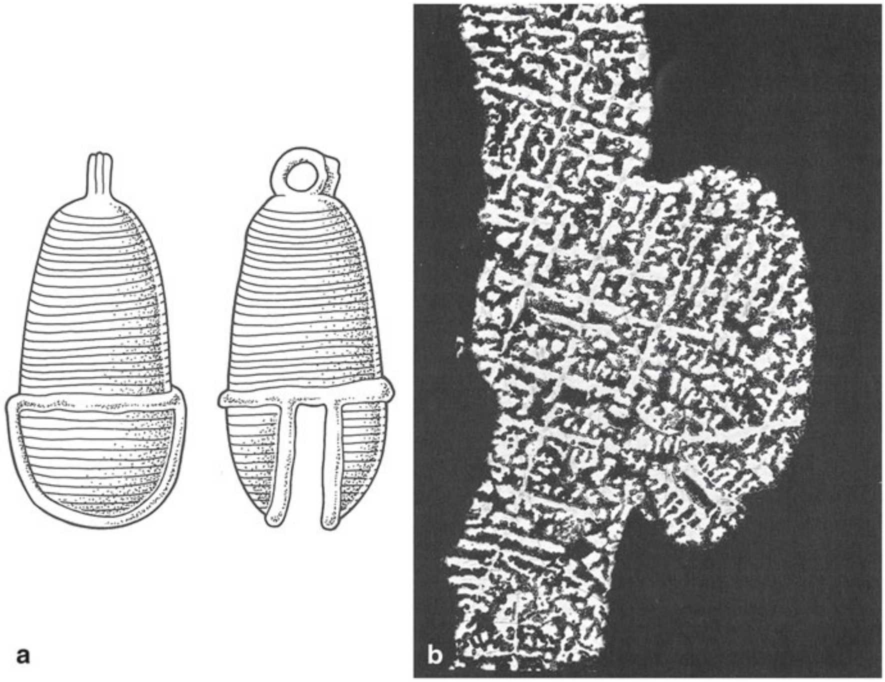


Fig. 14.12 **a** Copper arsenic bell. **b** Photomicrograph of longitudinal section of bell wall. The bell contains 23 % arsenic by weight

West Mexican smiths also used copper–tin bronze, and sometimes, copper–silver alloys, for worked objects. They crafted large, elaborate, thin, shell-shaped golden and silvery looking tweezers through cold and hot work (Fig. 14.13) (Hosler 1994). These tweezers became symbols of the state in the Tarascan empire (Hosler 1986, 1994). Tarascan priests donned large multispiralled versions of these tweezers as symbols of office. Ethnographic accounts concerning the meaning of body hair in Amerindian cultures (Hosler 1994) are useful in explaining how this pedestrian Andean and Period 1 west Mexican copper implement used to remove facial hair, became transformed in the Tarascan zone into a symbol of power. Body hair among indigenous American groups is identified with the animal realm rather than with socialized human groups. Hosler (1994) has argued that these large Tarascan tweezers symbolically separated the priests who wore them from that animal realm, reinforcing the priest's social and supernatural power and moral authority (Figs. 14.12 and 14.13).

Our studies have shown that the tweezer design itself, which in mechanical engineering parlance is known as a shell, can be realized only by using these bronze alloys due to their toughness and strength. Tin regularly appears in Period 2 shell tweezers in concentrations up to 10 % by weight, giving the metal a golden color that identified the priests and elites who wore them with the solar deities.

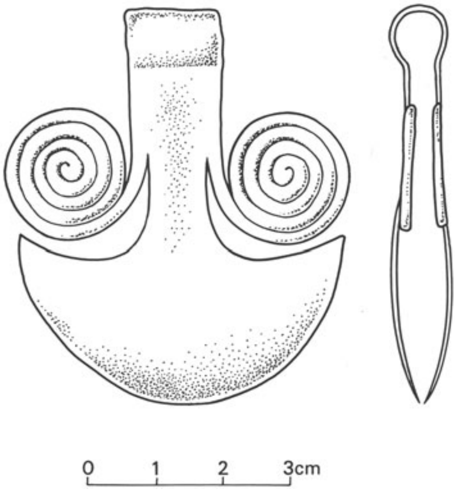


Fig. 14.13 West Mexican spiral tweezer design. These tweezers frequently contain to 10 % tin by weight

Other Period 2 object classes, such as the worked circular rings worn as earrings or hair braid holders, contain up to 18 % tin by weight (Hosler 1986, 1994), again giving the metal a golden color. Cold-hammered copper–silver alloys, which are extremely ductile, were shaped into the large pieces of silvery looking, highly reflective, sheet-metal ritual objects—for example, the breast plates, disks and shields, and other items just mentioned. Documentary and pictoral sources from the Tarascan state indicate that these items were worn and used by elites and nobility.

In other publications, I have assessed the extent to which aspects of this Period 2 technology, particularly the use of copper–tin, and copper–arsenic bronze and copper–silver alloys, were stimulated by the metallurgies of Ecuador and Peru where these alloys and some artifact classes (needle designs, certain tweezer designs) were also developed, but earlier. The similarities and differences in the use of these alloys in Ecuador and Peru and western Mexico are documented in Hosler 1994 (Chap. 6). In some cases, the object classes and alloy systems are identical: copper–silver alloy rings, for example, have a long, early history in Ecuador. The copper–silver alloy (and copper–silver rings) was so common in the State of Michoacan that the Spaniards called this alloy "the metal of Michoacan" (Hosler 1994). Although beyond the geographical scope of this paper, copper–arsenic alloy axe monies (Hosler 1986; Hosler et al. 1990) abound on the coast and in inland areas of Ecuador and these same items—thin, stackable, T- shaped Cu–As objects—were used as a medium of exchange in Guerrero and Oaxaca, located on the southern border of the west Mexican metalworking zone.

I have maintained that knowledge of the Cu–Sn, Cu–As, and Cu–Ag alloy systems and some prototype artifacts were introduced to western Mexico through the same Ecuador-based maritime trading system responsible for introducing knowledge and techniques that stimulated the initial development of metallurgy in the metalworking zone. Yet what stands out, as we compare these Mesoamerican and Andean metallurgical traditions, are the original and innovative ways in which west Mexican

Fig. 14.14 Map showing large west Mexican mines and/or archaeological sites, and the smelting sites referred to in the text

metalworkers reinterpreted and transformed the bronze alloys for their own social objectives. They principally were interested in these alloys for large golden and silvery looking bells they could cast, in keeping with their cultural interest in sound, and for the golden and silvery colors they could produce in the other elite and status items they fashioned that associated the wearers with the supernatural, particularly the solar and lunar deities.

These new artifact designs, made using tin-bronze, arsenic-bronze, and copper–silver alloys, have been recovered in burials and household debris at sites throughout the metalworking zone (Figs. 14.14 and 14.15). Ethnic affiliations are clear in only two cases: in Jalisco's Cuenca de Sayula and in the highland areas of the State of

Fig. 14.15 Map showing Period 2 archaeological sites where metal artifacts were recovered

Michoacan. The powerful Tarascan state dominated Michoacan between 1350 C.E. and the Spanish invasion in 1530 C.E. (Pollard 1994). The dates from excavations in the Cuenca de Sayula are earlier, and I will treat them first.

The Cuenca de Sayula project in Jalisco provides the single most significant new contribution to our understanding of the social affiliations of the peoples using objects made from copper–tin and copper–arsenic bronze in the metalworking zone. The Sayula project sites are located within 50 km of each other in a highland basin of Jalisco. This region lacks significant ore mineral deposits although such deposits are abundant to the south, in the Ayutla and Ayutlan area, and were exploited at the time of the Spanish invasion (Hosler and Macfarlane 1996) (Fig. 14.14).

Johan Garcia's research has focused on metal objects from Sayula sites (Garcia 2007, 2008). Since the investigation is multiyear and multidisciplinary, many other researchers have made signal contributions as well (for example, Acosta Nieva 1994; Valdez et al. 2005; Acosta Nieva et al. 1996; Liot et al. 2006). I have already commented on Garcia's work at La Peña (800–1100 C.E.), where archaeologists excavated Period 1 copper objects. Metal objects from the other three sites, Tasajillo, Caseta, and Atoyac, provide new insights into the dates for the bronze alloys in the metalworking zone and, on the basis of the associated pottery, about the social affiliations of the peoples using these metal objects. All data come from well-dated artifacts excavated chiefly from burials.

One significant contribution made by Garcia's work concerns the social affiliations of the metal-using groups in the metalworking zone. Several authors have argued that the Tarascan state (1350 C.E. through the Spanish conquest) controlled metal production over a broad area, and that, in fact, control of metal production was a critical element in the rise of the state (Pollard 1987, 1994; Maldonado 2006[3]) (Fig. 14.15). At the site of Caseta, in the Sayula basin, Garcia and others recovered 30 objects, 28 of which were from burial contexts. All are made from copper–tin and copper–arsenic alloys and the artifact designs (shell tweezers, for example) conform to the artifact designs Hosler has identified as Period 2. What is most compelling is that these copper–tin and copper–arsenic bronze artifacts date to between 1040 and 1300 C.E., prior to the emergence of the Tarascan state (1350 C.E.). On the basis of the pottery, and other material remains, they show no affiliations with that political entity. In fact, based on pottery (Autlan polychrome), these Caseta peoples are linked to groups in the Autlan area of southern Jalisco (Garcia 2007, 2008) where, as mentioned previously, copper deposits are plentiful. Garcia's work definitively puts the argument to rest concerning the control of metal production by the Tarascan state in this area of the metalworking zone. Hosler had long argued on the basis of artifact distribution and artifact chemical compositions that there is no evidence for the standardization implied by such state-level control of metallurgy in west Mexico (see, for example, Hosler 2002, p. 166).

The Cuenca de Sayula dates for the bronze alloys are also highly significant, because they make clear that the first use of these alloys in the west Mexican metalworking zone is earlier (Garcia 2007, 2008) by about 100 years than previous data allowed. The earlier dates also make sense. West Mexican bronze alloy objects have been identified outside of the metalworking zone dating to 1200–1300 C.E. (Hosler 1994, Chap. 7). Bronze production within the zone logically should have taken place earlier, but until Garcia's studies, we lacked the data to demonstrate this. Although we do not yet know who (what peoples) were first responsible for ore extraction, processing, and producing the bronze alloy objects excavated at Caseta, the pottery data from the site (Garcia 2007, 2008) (Figs. 14.14 and 14.15) indicate that archaeologists should be looking south to the Autlan area of Jalisco.

Atoyac (1350 C.E. to the Spanish invasion) also located in the Sayula basin (Fig. 14.15) produced approximately 200 artifacts, all from burials. Chemical analyses of 30 of these show copper–tin, copper–arsenic, and copper–silver alloys. The

[3] I was able to read the abstract of Dr. Maldonado's thesis (2006) but did not have access to the text at the time of the writing of this paper.

lower levels of the deposit contain some 50 metal artifacts (Garcia, personal communication 2008) associated with local pottery (Amacueca) produced by people living in the Sayula basin. Archaeologists recovered copper–tin and copper–arsenic bronze artifacts from these levels. The artifact types correspond to Hosler's Period 2. According to Garcia (2007), local Sayula (Amacueca) elites had been wearing and using these bronze objects prior to their contacts with the Tarascan traders who settled there. The later occupational phases of Atoyac display a distinct Tarascan presence based on pottery and other items. Copper–tin, copper–arsenic, and copper–silver objects were recovered, including examples of the Tarascan symbol of state, the spiral tweezer. Garcia maintains that (2007, 2008), the archaeological data indicate that Amacueca and Tarascan people were engaged in commercial rather than bellicose interactions, in which Amacueca and Tarascan elites were intermarrying and interacting. There are no data indicating a Tarascan conquest of these Amacueca people.

The only other area in the metalworking zone where there is clear evidence of the social affiliations of people using copper–tin, copper–arsenic, and copper–silver objects are sites in the modern state of Michoacan (Fig. 14.1), which was dominated by the Tarascan state from 1350 C.E. up to the Spanish invasion. Tin and arsenic bronze artifacts and copper–silver alloys have been excavated at the Tarascan capital, Tzintzuntzan in Michoacan (Cabrera 1988; Grinberg 1989; Hosler 1986; Rubin de la Borbolla 1944), and at Huandacareo, Tres Cerritos (Macias Goytia 1990; Hosler 1994), Orichu (Hosler and Macfarlane 1996), and Huetamo (Hosler 1986).

Unlike the clear-cut situation in the Cuenca de Sayula and in highland Michoacan, these bronze artifact types also appear at metalworking zone sites where the social affiliations of the people using these objects are problematic. At Apatzingan, Michoacan, Kelly (1947) recovered archaeological material she argues is unrelated to the Tarascan state, and this includes some of the metal artifact designs that characterize Period 1 (Cu, Cu–As alloys). Cultural affiliations are similarly unclear at Milpillas, Michoacan (Hosler 1994), at lo Arado, Jalisco (Hosler n. d.), at El Chanal, Colima (Kelly 1985; Hosler 1986 and field notes), at San Miguel Ixtapan in the state of Mexico (Ruben Nieto, personal communication 2000), and at Bernard in coastal Guerrero (Brush 1962); but copper–tin bronze artifacts are common at all of these sites. Moreover, hundreds of high-tin, tin-bronze artifacts (open rings) were recovered in the salvage operation in the Infiernillo region of the Rio Balsas, and social affiliations in these cases are likewise uncertain (Hosler 2002).

Discussion

Taken as a whole, we can point to significant contributions to understanding the South and Central American origins of west Mexican metallurgy, the characteristics of that technology, its chronological trajectory, and the ways in which west Mexican peoples incorporated, transformed, and defined the new material, using it for their own cultural objectives. The feasibility studies of the success of the Ecuadorian seagoing rafts in introducing the technology to western Mexico greatly strengthen that argument. Garcia's work at the Cuenca de Sayula has refined Hosler's chronology (1994) for the first use of the Cu–As and Cu–Sn alloys in the metalworking zone. By identifying the social affiliations of the Sayula groups' first use of these Cu–Sn and Cu–As alloys through the pottery analysis (Autlan polychrome), Garcia's work also makes southern Jalisco a key area for future studies of extraction, and perhaps initial production of these bronze alloys. The Sayula project also provides the first recent data allowing us to identify the social affiliations, interactions, and relations of two metal-using groups: the Amacueca and Tarascan peoples.

The most fundamental and serious lacunae in our data concern extractive technologies—identifying mines, smelting sites, and smelting regimes—and centers of production and distribution together with the social affiliations of the groups that did produce the Cu–As, Cu–Sn, and Cu–Ag alloys that developed in the west Mexican metalworking zone after 1100 C.E. I address this issue in the subsequent section.

Archaeological, Chemical Analytical, and Historical Evidence for Mining, Extractive Metallurgy, and Object Fabrication

Data for mining and ore processing in the metalworking zone are scant during and after the bronze and copper–silver alloys were introduced. Archaeologists have reported occasional evidence for metal production activities at widely dispersed sites and regions in Colima, Jalisco, Michoacan, and Guerrero (Hosler 1994). Only two possible prehispanic metal smelting sites, at la Barranca de Las Fundiciones de El Manchon, Guerrero (Hosler 2002, 2003) and Itziparatzico, Michoacan (Maldonado et al. 2005; Maldonado 2006[4]), have been systematically excavated (Fig. 14.14). La Barranca de Las Fundiciones was identified in a metallurgical site survey of the *tierra caliente* area of Guerrero and the adjacent Sierra Madre del Sur (Hosler 2000). Substantial evidence exists for preconquest and Colonial mining, ore processing, and metal production in this area of Guerrero. Thirty-two archaeological sites were located: all but two are situated within 1 km of a copper mine. Six of these sites display evidence for some facet of extractive metallurgy and metal production (e.g., ore, furnaces, processing tools, and slag) (Hosler 2002). Well-defined smelting areas distinguish five of these sites, all containing substantial slag accumulations. Three sites (La Barranca de Las Fundiciones, Cerro del Chivo, and Agua Fria) seemed the most promising for excavation (Hosler 2000, 2002, 2003). I elected to work at La Barranca de las Fundiciones, the largest of the three and the only site that did not exhibit some evidence[5] of Colonial or subsequent occupation.

[4] See footnote 3.

[5] Agua Fria was identified in a document referring to eighteenth century and subsequent mining activities, and thus was exploited after the conquest and from the pottery and prehispanic house mounds and house foundations likely before (Personal communication, RocuiColegio Mexiquense 2006).

La Barranca de las Fundiciones de El Manchon is located in the Sierra Madre del Sur in the State of Guerrero at 1,400 m (Hosler 2002, 2003). The site, which is badly eroded, consists of three distinct subareas distributed linearly across approximately 1 km—two of the three areas are habitation sites, marked by long, rectangular, house foundations. The surface collections of all three areas produced prehispanic potsherds and obsidian and both materials appear in the excavations of the two habitation areas. Pottery types have not been identified definitively, but the pottery is made from local clays (Reitzel 2007) and shows no particular association with the well-defined pottery traditions in other Mesoamerican areas (Aztec, Tarascan, Oaxaca, and Jalisco). Some of the potsherds have been provisionally linked to Yestla-Naranjo and Cuitlateca peoples, who were living in the State of Guerrero at the time of the Spanish invasion. Between the two habitation areas, and separated by a year-round arroyo, is a smelting area containing large volumes of slag and extremely disturbed and destroyed furnace structures (Hosler 2003).

Project members were able to recover copper ore and metallurgical slags from excavations of several of these furnace structures, and the ore and slag samples were extensively analyzed by Rachael Sharp (2003) in her comprehensive, laboratory-based, undergraduate thesis work. Sharp determined that metalworkers were smelting copper oxides and carbonates such as cuprite and malachite to produce copper metal. The ore originated from a weathered complex copper sulfide–iron sulfide deposit. The ore contains copper and iron oxides and, as a result, was self-fluxing. Sharp concludes that the furnaces did not have to operate at temperatures higher than 1,150 °C to smelt effectively. Most of the copper was consolidated within the furnace; only about 2 % of the copper was retained in the slag in the form of prills (Sharp 2003). We are not sure how metalworkers achieved these temperatures, but Sharp speculates that the furnaces may have operated through a natural draft mechanism. Unfortunately, the project has not yet located an intact furnace. Copper deposits are common throughout the area and one potential candidate, located approximately 1 km to the south of the site, has been completely exhausted. We recovered only three pieces of smelted copper metal from our excavations of the smelting area. I suspect that the copper metal may have been exported as ingots to the large, adjacent site of Los Cimientos, although we have no direct evidence for this contention. Local people do report occasionally recovering copper rings and a few other copper items from Los Cimientos. Social conflict and violence related to drug trafficking in this highland Guerrero area have precluded continued work at this site during the last several years.

Dates for La Barranca de las Fundiciones are problematic. The two habitation areas have produced calibrated radiocarbon dates ranging from 1250 to 1650 C.E.

The Spanish invasion took place around 1530 C.E. in this area. Although no evidence exists for Colonial or recent occupation in any portion of the site (no pottery, iron artifacts, etc.), radiocarbon dates from wood charcoal from the smelting area are equivocal and range from 1350–1850 C.E. and later. These dates are perplexing. I am currently working with geochemists to try to determine what may have contributed to these disparate results. Sixteenth-century documents referring to this area of Guerrero provide another line of investigation to determine whether this particular mine and smelting area may have been exploited after the invasion by the Spainards. For now, I suspect that Las Fundiciones peoples were smelting copper shortly before the Spanish invasion and that these activities continued after the invasion—perhaps by indigenous peoples under Spanish control or perhaps by Spanish miners themselves. To reiterate, our most confounding observation from this site is that virtually no colonial artifacts or artifacts representing later periods have been recovered either at the site of Las Fundiciones, or at the adjacent sites of La Nueva and Los Cimientos.

Blanca Maldonado has undertaken a study of the slags at the highland Tarascan site of Itziparatzico Michoacan (Maldonado et al. 2005). The authors have identified chalcopyrite as the copper ore that was smelted, present in a silica-rich matrix. They found that furnace temperatures must have been about 1,100 °C. Maldonado speculates that the copper ore was brought to Itziparatzico for smelting, then exported as ingots. She was unable to determine definitively whether the smelting activities represented prehispanic- or later-conquest period activities.

Archaeologists working in the metalworking zone have reported evidence for processing at various other sites in Jalisco, Michoacan, and Guerrero. Isabel Kelly (1949) identified slag in the Autlan area of Jalisco, and she also recovered copper ore as well as artifacts (already noted) at Apatzingan in Michoacan. Apatzingan lies in the Mexican copper belt and is very close to La Verde, one of Mexico's very large copper-belt mines. Grinberg (1989) has identified slag at Churumuco and at the La Verde (Michoacan) mines, but the slag was not associated with archaeological material and thus may correspond to more recent mining activities. These two mines have been subject to small-scale and commercial exploitation from the Spanish invasion into the twentieth century. Brush (1962) excavated slag at Bernard, Guerrero, which, from his description, may be a by-product of tin smelting. This is especially significant because he also identified tin-bronze alloys at that site. Weitlaner (1947) identified slag at Naranjo, Guerrero. Two ingots were excavated at El Chanal, Colima, neither of which has been analyzed.

Chemical analytical data also support the archaeological evidence (albeit scant) that metal processing and production were carried out in many regions of the metalworking zone. The hundreds of artifacts analyzed dating to Period 2 when the bronze alloys were used show little evidence for standardization in alloy composition or design (Hosler 2003). Metalworkers did not follow strict technical recipes; that is, they did not adhere to strict norms for alloy compositions. Artifact chemical compositions, whose suite of trace elements varies greatly, suggest that metal was smelted from quite different parent materials.

Perhaps most crucial to this argument are the results of our most recent lead isotope analyses of copper ores from the *tierra caliente* area and Sierra Madre del Sur in Guerrero (Lopez et al. 1999), which greatly expand the number of potential artifact ore sources we analyzed and published in *Science* (Hosler and Macfarlane 1996). At that time, the ore and artifact data pointed to several large Michoacan mines (Inguaran and Bastan) as major sources of copper ore for some 170 artifacts analyzed from sites in Jalisco, Michoacan, Morelos, Chiapas, Belize, and Tamaulipas. The Guerrero lead isotope ratios (from 21 mines) overlap with those of Michoacan (Inguaran and Bastan mines) and occasionally with ore lead isotope ratios from Jalisco deposits. These data and data gained from other geochemical studies of Mexican ores now indicate convincingly that ore lead isotopic values alone will not allow us to distinguish copper ore fields that are located along a north–south axis (for example, among the states of Jalisco, Michoacan, and Guerrero). We can sometimes make positive identifications when the lead isotope ratios for the deposits and the artifacts coincide precisely. Nevertheless, the data do confirm the evidence presented in the article published in *Science* that Mexico exhibits a west–east trend in lead isotopic ratios, making it possible to distinguish, for example, artifacts made from Jalisco ores from those made from copper deposits to the east, from San Luis Potosi or Veracruz. The lead isotope evidence from Guerrero, coupled with archaeological evidence for processing in the *tierra caliente* area, suggests that a variety of ore sources were exploited during Period 2.

Ethnohistoric sources from many Mesoamerican regions also have provided insights concerning metal production prior to the Spanish invasion. The Relaciones Geograficas report copper and silver deposits in the modern State of Jalisco in the province of Tenazmatlan, Jalisco (Acuña 1988, p. 290), where, in the last several decades, many copper artifacts have been recovered by looters. The region is classified as a mining district by Mexico's Instituto Nacional de Geografía e Estadistica (INEGI). In Michoacan, the Relaciones Geograficas also describe a copper mine at Sinagua (Acuña 1987, p. 254). Sinagua is located in Michoacan's *tierra caliente* region and is within about 25 km of the Inguaran, Churumuco, and Cocian mines, three of Mesoamerica's richest copper deposits. The historian Elinore Barrett (1981) argues that all three mines were subject to Sinagua prior to the invasion and were mined by local peoples. She cites *Legajo 1204*, a document written in 1533 C.E. and first published by J. Warren (1968) to support this contention, but she relies on other sources as well. Apart from identifying these mines, the *Legajo* reports that half of the metal was rendered as tribute to the Spanish Crown. It also describes copper smelting, but fails to do so in sufficient detail to facilitate useful reconstructions (Hosler 1986). In Guerrero, the Relaciones Geograficas from Tetela del Rio (Hosler 1986, 2003; Paso y Troncoso 1905, p. 36) mention two copper deposits and note that they had been mined prior to the invasion.

Technical Choices: Color, Sound, and Cosmology

Thus, the metalworking zone object designs that characterize the period after 1100–1200 C.E. have been recovered at many sites throughout the area. The properties of bronze facilitate a range of new applications. In general, rather than expanding the range of artifact classes, and for example, using bronze for tools weapons or armor, artisans continued to produce sacred and status items altering and refining design to take advantage of alloy properties. It is clear that the sound and color of this material were the two key physical properties that shaped the technical choices concerning objects they designed and the metals and alloys they used. Metalworkers used high tin and high arsenic bronzes for large, thin-walled, golden and silvery looking bells cast with intricate, complex, external zigzag design motifs. They redesigned their tweezers, making them thinner and wider, cold- and hot-working the blade portion into delicate concave shapes. From copper–silver alloys, they produced highly reflective silvery looking metal sheet, crafting it into ornamental shields and other items. I have observed elsewhere (Hosler 1994, 1995) that Tarascan nobility and the other elites in the metalworking zone wore and used these objects, as well as objects made from gold and copper–gold alloys, in ritual and by doing so affiliated themselves with the solar (gold) and lunar (silver) deities. The metallurgy that emerged in western Mexico functioned as a visual and auditory system that symbolically defined elite and sacred spheres of activity.

The central question to consider again concerns why metalworkers elected to develop these two properties of metal: its sound in bells and its golden and silvery colors in bells and an array of other objects. In previous discussions, I have pointed to sixteenth-century Nahuatl texts and linguistic evidence in which bell sounds and rattling sounds are related to song and associated with speech. Nahuatl texts and lexical and linguistic evidence (Hosler 1995) disclose that bell sounds regenerate, protect, and metaphorically create the Aztec sacred garden or paradise described by Louise Burkhart (1992) and treated subsequently. Bells and composite instruments containing them are associated particularly with three Mesoamerican deities in sixteenth-century Aztec texts and illustrations, all connected to ideas of fertility and regeneration: Tlaloc, the god of rain, Xipe Totec the god of the metalsmiths, regeneration, and new vegetation (Hosler 1994, 1995), and Quetzalcoatl who represents aspects of the wind and storm deity (Broda 1971). Quetzalcoatl (the plumed serpent) is often depicted as a rattlesnake, and in some illustrations the rattles are replaced by metal bells (Hosler 1995).

In the west Mexican metalworking zone, particularly in the Tarascan state, the evidence shows that deities responsible for these same forces and events exist, but in different guises. Tarascan ideology shares basic principles with other Mesoamerican groups, including autosacrifice, the ball game, flaying, and heart sacrifice (Pollard 1993). Xaranga the moon deity, was the wife of Curicaueri, the sky god, and the sun's messenger. Xaranga was the daughter of Cuerauperi. Cuerauperi controlled birth, death, rain, and fertility. Flaying rites were dedicated to her, and she, like Xipe Totec, was also associated with renewal (fertility) and regeneration. Xaratanga, the moon deity, is depicted in various ways, of which one is a snake. Xaratanga was associated with childbirth and also with fertility. The association between snakes, which make rattling sounds, and fertility seems also to prevail among Tarascan peoples. Linguistic evidence, while limited, suggests that the terms for copper and rattlesnakes are related (Prof. Kenneth Hale personal communication 1994). In addition, the Tarascan word *Tiamu* translates both as *Hierro* (iron or metal) and as *Campana* (bell), which, as I have emphasized elsewhere (Hosler 1994, Chap. 8), indicates that for these peoples the purpose of metal was to make bells: "bell" and "metal" became cultural synonyms. Stanford (1966) has observed that the musical cultures of the Aztec, Tarascan, and Mixtec cultures are fundamentally similar, so that sounding instruments, including bells and the meanings ascribed to them, should also resemble one another.

Documentary evidence from the Tarascan state is particularly helpful concerning the meaning of metals and of metallic color. Tarascan peoples considered golden and silvery objects divine, they associated them with the sun and with the moon deities, and nobility wore them to reify their status. One of the three brothers, Hiripan, who participated in the Tarascan state expansion expresses the following in declaring his intent to recover gold, silver, and other items from conquered peoples:

"The people in the villages run away and carry off the plumes and jewels which made them nobles in the villages we have conquered. Go get them so the gods (the golden and silvery objects} come back to their villages." Seeing that yellow gold and white silver Hiripan said: "Look brothers, this yellow metal must be the substances the sun excretes and that white metal must be the substances excreted by the moon." (Tudela 1977, p. 152)

The citation makes explicit that the nobility defined itself by possessing golden and silvery plumes and jewels. The association of gold with the sun is reinforced by linguistic data: the root *titipeti* means gold in Tarascan and Tiripiti was also the name of gods who were individual manifestations of the sun (Brand 1951). State treasuries stored golden diadems and disks in chests to honor the sun and disks of silver to honor the moon (Hosler 1994). The information from Central Mexican (Aztec) sources for similar associations, of gold with the sun and silver with the moon, are equally strong and have been cited elsewhere (Hosler 1994, 1995).

Perhaps the key to west Mexican and Mesoamerican interest in the golden and silvery colors of metal, whether achieved by alloying or by other means, is in the quality of brilliance that defined the Aztec paradise. Termed a "cult of brilliance" by Burkhart (1992) in Nahuatl devotional literature, this paradise is conceived as a shimmering sacred garden:

> In this symbolic garden one came into direct contact with the creative life-giving forces of the universe and with the timeless world of deities and ancestors. The garden is a shimmering place filled with divine fire, the light of the sun reflects from the petals of flowers and the iridescent feathers of birds—human beings the souls the dead or the ritually transformed living are themselves flowers, birds and shimmering gems [this garden] is a metaphor for life on earth, a metaphor that ritual transforms into reality by asserting that in fact this is the way that the world is. (Burkhart 1992, p. 89)

We presume that the concept of a brilliant, shimmering garden may also have existed in the Tarascan ideas of paradise, particularly given the quantities of copper–silver metal artifacts, gold and silver artifacts, and artifacts that looked golden or silvery produced by using the bronze alloys. The concept of a brilliant shimmering garden was probably held by other Uto-Aztecan speakers and possibly also by the Maya (Burkhart, personal communication 1993). Some evidence exists that these same concepts were held in Andean South America as well.

Stanzas from *Cantares Mexicanos* (Biehorst 1985)[6] show that a shimmering iridescent garden is created through song, represented by bell sounds, bird sounds, and the sounds of human voices singing, and that the Aztec paradise is replete with birds, flowers, trees, and golden colors (Hosler 1994, p. 241, 242). The idea that metallic sound can create metallic color also appears in these texts. As the following stanza

[6] Cantares Mexicanos was composed in Nahuatl between 1550 and 1580 C.E. and deals with the conquest and its aftermath.

from *Cantares Mexicanos* shows, it is precisely through sound and song that the sacred shimmering garden comes into being:

> As colors I devise them, I strew them in the Palace of Good Song. As jewel maps shot with jade and emerald sunray the Green Place flower songs are radiating green. A flower incense flaming all around spreads sky aroma filled with sunshot mist as I, the singer in this gentle rain of flowers sing before the ever present ever near. (Bierhorst 1985, p. 141)

Other metaphors in this poetry present the same idea. What is most compelling however is that sound and metallic colors can come into being through a metallurgical process:

> I drill my songs as though they were jades, I smelt them as gold. I mount these songs of mine as if they were jades. (Bierhorst 1985, p. 207)

This links sound, singing, smelting, and metallic colors. Producing song is analogous to the process of producing metal. Songs are smelted, a process of transformation from musical thought to musical production. Metal is smelted from the rocky ore to produce the liquid metal. This extraordinary conception of creative activity reveals that in Aztec thought, the processing technologies devised for creating objects, and including metal objects, and the cognitive processes involved in creating song require precisely the same coordination of thought and activity.

These sounds and colors helped define the Aztec paradise (Hosler 1994) described by Burkhart (1992) as a realm populated by deceased warriors and deified ancestors, and conceived as a shimmering, iridescent, golden and silvery garden filled with the creative, generative sounds and songs of bells, birds, and human voices singing.

The cultural interest in bell sounds arose from their association with thunder, rain, fertility, and regeneration, and that these sounds and the sounds of human voices singing could create the sacred paradise. This may explain the lexical evidence which indicates that "metal" and "bells" were cultural synonyms in three Mesoamerican languages. The experience of hearing metallic sounds for the first time, also must have deeply affected the west Mexican peoples. The highly reflective metallic colors were also a new, powerful, visual experience for these people, particularly the golden and silvery colors of metal sheet whose closest counterparts were in the silvery colors of the moon and the golden colors of the rays of the sun, reflecting off of lakes and streams. The sounds of metal bells and the golden and silvery metallic colors became fundamental to and integrated into these peoples' concepts of the sacred, and were associated with supernatural forces. The paradise was a garden filled with shimmering beings, reflective dewdrops, and the iridescent colors of insects, butterflies, dragonflies, and the feathers of certain multicolored birds that populated the tropical paradise. These conceptions of divinity and paradise may already have been in place when metal was first introduced to western Mexico. If this was so it helps explain the technical choices that resulted in the focus on lost-wax-cast bells. Pottery bells preceded them. If the idea of a shimmering paradise also holds for South America, the South American concern with producing the reflective colors through the production of golden and silvery sheet metal may also become explicable.

These topics merit further research, and one the most fruitful means of doing so in the Mesoamerican case may be through lexical and linguistic studies of the Tarascan and Nahuatl languages, and the meticulous exploration of Colonial-period religious texts.

The most interesting aspect of the information presented here is that metalworking zone smiths from across a very broad region, and representing many social groups, elected to use these new materials to produce religious and status-bearing paraphernalia to strengthen, consolidate, and reify religious and social power, and to express the cosmological precepts just discussed. This ritual use of metal distinguishes the technology of this metalworking zone. Linguistic and other evidence indicates that the metalworking zone peoples shared beliefs concerning the meaning of bell sounds and of golden and silvery metallic colors with other Mesoamerican groups. The remarkable implication of these findings is that although metalworkers differed in cultural affiliations (based on other aspects of their material repertoire, pottery, for example) and thus probably social affiliations and language, they nonetheless shared the highly specialized metallurgical knowledge of ores, smelting regimes, fabrication methods, and design options. We know nothing about how this information was transmitted from one generation to another or how it was disseminated to other metalworking zone peoples. What is clear is that the level of technical expertise required for smelting the complex ores used to produce the high arsenic copper–arsenic alloys, the specialized knowledge required to produce lost-wax castings, and the expertise required for many other facets of this extraordinary metallurgical tradition can only be compared to those of other highly skilled specialists: for example, individuals in the Maya realm who could write and read hieroglyphic script. Another implication of these findings is that metalworkers in the large and socially diverse west Mexican metalworking zone shared fundamental cosmological precepts regarding the sacred nature and the meaning of this new material.

What makes the West Mexican development of metallurgy so challenging to archaeologists is to determine how we identify the social mechanisms through which this highly specialized technical knowledge was initially transmitted and subsequently transformed by west Mexican peoples for their own social objectives. The larger question, that of documenting "technology transfer" or the introduction of technology by one non-literate ancient people to another, has to be one of the most complex issues an archaeologist can face.

References

Acosta Nieva, R. (1994). Los entierros del fraccionamiento San Juan, Atoyac, Jalisco. In E. Williams (Ed.), *Contribuciones a la Arqueología y Etnohistoria del Occidente de México* (pp. 93–114). Michoacán: El Colegio de Michoacán, Zamora

Acosta Nieva, R., Ramírez, S., & Emphoux, y J.-P. (1996). El sur de la Cuenca de Sayula, Jalisco: el sitio Caseta, un ejemplo. In E. Williams, P. C. Weigand (Eds.), *Las Cuencas del Occidente de México* (*Época Prehispánica*) pp. 367–394. ORSTOM, CEMCA. Michoacán: El Colegio de Michoacán, Zamora

Acuña, R. (1987). *Relaciones geográficas del siglo XVI: Michoacán*. México: UNAM

Acuña, R. (1988). *Nueva Galicia, relaciones geográficas siglo XVI*. México: UNAM

Arsandaux, H., & Rivet, P. (1921). Contribution à I'étude de la métallurgie mexicaine. *Journal de la Société des Americanistes de Paris, 13,* 261–280.

Arsandaux, H., & Rivet, P. (1923). Nouvelle note sur la métallurgie mexicaine. *L'Antropologie, 33,* 63–85.

Barrett, E. M. (1981). The King's Copper Mine: Inguarán in New Spain. *The Americas, 38*(1), 1–29.

Bierhorst, J. (1985). *Cantares Mexicanos: Songs of the Aztecs*. Standford: Stanford University Press.

Brand, D. (1951). *Quiroga: A Mexican Municipio*. Washington, D.C.: United States Government Printing Office.

Broda, J. (1971). Las fiestas aztecas de los dioses de la lluvia. *Revista Española de Antropología Americana, 5,* 245–327.

Brush, C. F. (1962). Precolumbian alloy objects from Guerrero, Mexico. *Science, 138,* 1336–1337.

Burkhart, L. (1992). Flowery heaven: The aesthetic of paradise in Nahuatl Devotional Literature. *Res, 21,* 89–109.

Cabrera, C. R. (1976). *Arqueología en el bajo Río Balsas, Guerrero y Michoacán: presa La Villita*. México: Tesis de maestría, Escuela Nacional de Antropología e Historia

Cabrera Castro, R. (1988). Nuevos resultados de Tzintzuntzan, Michoacán, en su décima temporada de excavaciones. In *Primera reunión sobre las sociedades prehispánicas en el centro-occidente de México* (pp. 193–218). México: INAH

Carriveau, G. (1978). Application of thermoluminescence dating techniques to prehistoric metallurgy. In W. J. Young (Ed.), *Application of science to the examination of works of art* (pp. 59–67). Boston: Museum of Fine Arts.

Dewan, L., & Hosler, D. (2008). Ancient Maritime trade on Balsa Rafts: An engineering analysis. *Journal of Anthropological Research, 64,* 19–40.

Edwards, C. (1965). *Aboriginal watercraft on the Pacific Coast of South America*. FInal report: National Academy of Sciences. DTIC online.

García, J. (2007). *Arqueometalurgia del Occidente de México: la Cuenca de Sayula, Jalisco como punto de conjunción de tradiciones metalúrgicas precolombinas*. Tesis de Licenciatura en Arqueología. Escuela de Literatura, Lenguas y Antropología. México: UAG

García, J. (2008). *Nuevos conocimientos sobre la metalurgia antigua del Occidente de México: filiación cultural y cronología en la Cuenca de Sayula, Jalisco. Manuscript on file*. Cambridge: Center for Materials Research on Archaeology and Ethnology, MIT.

Grinberg, D. M. (1989). Tecnologías metalúrgicas tarascas. *Ciencia y Desarrollo, 15*(89), 37–52.

Hosler, D. (1986). *The origins, technology and social construction of ancient west Mexican metallurgy*. Ph.D. dissertation, University of California, Santa Barbara. Ann Arbor: University Microfilms

Hosler, D. (1988a). Ancient West mexican metallurgy: A technological chronology. *Journal of Field Archaeology, 15,* 191–217.

Hosler, D. (1988b). Ancient west Mexican metallurgy: South and central american origins and west mexican transformations. *American Anthropologist, 90,* 832–55.

Hosler, D. (1994). *The sounds and colors of power: The sacred metallurgical technology of ancient west Mexico*. Cambridge: MIT Press.

Hosler, D. (1995). Sound, color and meaning in the metallurgy of ancient west Mexico. *World Archaeology, 27*(1), 100–115.

Hosler, D. (1996). Bells, shells, bees and boats: Metallurgy in ancient Mesoamerica. *Science Spectra, 4,* 38–45.

Hosler, D. (2000). Informe final: Reconocimiento de la superficie para localizar sitios de producción de cobre en la región sureste del cinturón de cobre mexicano Report, submitted and accepted by ei Instituto Nacional de Antropología e Historia, México.

Hosler, D. (2002). Nuevos hallazgos sobre la metalurgia antigua de Guerrero. In *El pasado arqueológico de Guerrero* (pp. 225–241). Christine Niederberger and Rosa Reyna Robles (coord). INAH: CEMCA, Gobierno del Estado de Guerrero

Hosler, D. (2003). Metal production. In M. Smith, F. Berdan (Eds.), *The postclassic mesoamerican world* (pp. 159–171). The University of Utah press
Hosler, D., & Cabrera, R. (2011). A Mazapa Phase Copper Figurine from Atetelco Teotihuacán: Data and Speculations. *Ancient Mesoamirica 21(2),* 249–260.
Hosler, D., & MacFarlane, A. (1996). Copper sources, metal production and metals trade in late postclassic mesoamerica. *Science*, 1819–1824
Hosler, D., Lechtman, H., & Holm, O. (1990). *Axe Monies and their relatives*. Washington D.C.: Dumbarton Oaks.
Kelley, C. (2000). The Aztatlán Mercantile System: Mobile traders and the northwestward expansion of Mesoamerican Civilization. In M. Foster, S. Gorestein (Eds.), *Greater Mesoamerica: The Archaeology of West and Northwest Mexico* (pp. 137–154). Salt Lake City: Utah State University.
Kelly, I. (1947). *Excavations at Apatzingan, Michoacán*. New York: Viking Fund.
Kelly, I. (1949). *The Archaeology of the Autlan-Tuxcacuesco Area of Jalisco (Vol. 2)*. Berkely: University of California Press.
Kelly, I. (1985). Some gold and silver artifacts from Colima. In M. Foster, & P. Weigand (Eds.), *The archaeology of west and northwest Mesoamerica* (pp. 153–179). Boulder: Westview Press.
Liot, C., Susana, R., Javier, R., & Otto, S. (2006). *Transformaciones socioculturales y tecnológicas en el sitio de La Peña, Cuenca de Sayula, Jalisco*. INAH: Universidad de Guadalajara
Lopez, R., Hosler, D., Pantoja, J., Martiny, B., Morales, J. J., Solis, G., & Moran-Zenteno, D. (1999). Inland Pb Isotope Groups of Paleocene Cu Ores from the Rio Balsas Basin, Guerrero State, Mexico, EOS Trans, AGU Fall Meeting, #5459
Macías Goytia, A. (1990). *Huandacareo: lugar de juicios, tribunal*. INAH, México
Maldonado, B. (2006). *Preindustrial Copper Production at the Archaeological Zone of Itziparátzico, a Tarascan Location in Michoacán, México*. Ph.D. thesis, Graduate School, College of the Liberal Arts, Pennsilvania State University
Maldonado, B., Rehren, Th., & Howell, P. (2005). Archaeological Copper Smelting at Itziparátzico, Michoacan, Mexico. In P. B. Vandiver, J. L. Mass, & A. Murray (Eds.), *Materials issues in art and archaeology VII* (Vol. 852, pp. 231–240). Warrendale: MRS Proceedings
Marcos, J. (1978). Cruising to Acapulco and back with the Thorny Oyster Set: A model for a lineal exchange system. *Journal of the Steward Anthropological Society, 9,* 99–132.
Meanwell, J. (2001). *Technical choice in pottery production: A west Mexican example*. Unpublished S.B. thesis, Department of Materials Science and Engineering, MIT
Meanwell, J. (2008). *Ancient engineering: Selective ceramic processing in the middle balsas region of Guerrero, Mexico*. Unpublished Ph.D. thesis, Department of Materials Science and Engineering, MIT
Meighan, C. W. (1969). Cultural similarities between western Mexico and Andean regions. In C. Kelley & C. Riley (Eds.), *Precolumbian contact within nuclear America: Mesoamerican studies 4* (pp. 11–25). Southern Illinois University, Carbondale University Museum
Meighan, C. W., & Foot, L. J. (1968). *Excavations at Tizapan el Alto, Jalisco*. Los Angeles: Latin American Center, University of California.
Moguel, A., & Pulido, S. (2005). Rasgos culturales de la tierra caliente de Michoacán. *Diario de Campo, 33,* 70–80.
Mountjoy, J. B. (1969). On the origin of west Mexican metallurgy. In C. Kelley, & C. Riley (Eds.), *Precolumbian contact within nuclear America: Mesoamerican studies 4* (pp. 26–42). Carbondale, University Museum: Southern Illinois University.
Mountjoy, J. B. (1990). El desarrollo de la cultura Aztatlán visto desde su frontera suroeste. In *Mesoamérica y Norte de México: siglo IX-XII, tomo 2* (pp. 541–564). México: Federica Sodi Miranda (coord)
Nicholson, H. B., Quiñones Keber, y E. (Eds.) (1994). *Introduction. In Mixteca-Puebla. Discoveries and research in Mesoamerican art and archaeology. Labyrinthos*. California: Culver City.
Pasoy Troncoso, F. (1905–1906). *Papeles de Nueva España*. Madrid: Sucesores de Rivadeneyra.
Pendergast, D. (1962). Metal artifacts in prehispanic Mesoamerica. *American Antiquity, 27,* 520–545.

Pollard, H. P. (1987). The political economy of prehispanic tarascan metallurgy. *American Antiquity, 52*(4), 741–752.
Pollard, H. P. (1993). *Tariacuri's legacy: The prehispanic Tarascan State*. Norman: University of Oklahoma Press
Pollard, H. P. (1994). Factores de desarrollo en la formación del estado Tarasco. In B. B. de Lameiras (Ed.), *El Michoacán Antiguo* (pp. 187–246). Zamora: El Colegio de Michoacán and Gobierno del estado de Michoacán
Reitzel, H. L. (2007). *Pottery engineering in ancient Guerrero, Mexico: The site of Las Fundiciones*. Unpublished S. B. thesis, Department of Materials Science and Engineering, MIT
Reyna, R. (1997). *La cultura arqueológica Mezcala*. Tésis de Doctorado en Antropología. Facultad de Filosofía y Letras. México: UNAM
Root, W. C. (1976). Metallurgical analysis. In C. C. Meighan (Ed.), *The archaeology of Amapa, Nayarit* (Vol. 2). *Monumenta archaeologica* (pp. 115–121). Los Angeles: The Institute of Archaeology. The University of California
Rubin de la Borbolla, D. (1944). Orfebrería Tarasca. *Cuadernos Americanos, 3*(4), 127–138.
Sámano-Xerez (1937). Relación. In R. Porras (Ed.), *Cuadernos de Historia del Perú* (pp. 63–68). París: Imprimeries les Presses Modernes (cited in Hosler 1994)
Sharp, R. (2003). *Analysis of Copper Slags from the archaeological site of El Manchon, Guerrero, Mexico*. Unpublished S.B. thesis. Department of Materials Science and Engineering, MIT
Smith, M., & Heath-Smith, C. M. (1980). Waves of influence in postclassic Mesoamerica? A Critique of the Mixteca-Puebla Concept. *Anthropology, 4*(2), 15–50.
Stanford, E. T. (1966). A linguistic analysis of music and dance terms for three sixteenth-century dictionaries of mexican indian languages. In *Yearbook II of the Inter-American Institute for Musical Research* (pp. 101–159). New Orleans: Tulane University Press
Tudela, J. (trad.). (1977). *Relación de las ceremonias y ritos y población y gobierno de los indios de la provincia de Michoacán* (*1545*). Morelia: Balsal Editores
Valdez, F., Schöndube, O., Emphoux, J. P. (coord.). (2005) *Arqueología de la Cuenca de Sayula*. México: Universidad de Guadalajara, Institut de Recherche Pour le Développement
Warren, B. J. (1968). Minas de cobre de Michoacán, 1533. *Anales del Museo Michoacano 6*, (2da. Época) *6*, 35–52
Weitlaner, R. (1947). Exploración arqueológica en Guerrero. In *El Occidente de México* Mesa Redonda, cuarta reunión de la Sociedad Mexicana de Antropología, México, pp. 77–85
Willey, G. R. (1966). *An introduction to American archaeology. Vol. I: North and Middle America*. Englewood Cliffs: Prentice Hall

Chapter 15
Andean Metallurgy in Prehistory

Heather Lechtman

Heartlands of Metallurgy

Scholars agree that Southwest Asia and the Andean zone of South America were unique heartlands of metallurgy in prehistory. Anatolia, Iran, and Palestine, in the Old World, Peru, Bolivia, and Northwest Argentina in the New were regions in which technologies of metallurgy nucleated independently and developed rapidly. With time, these regions became the sources from which metallurgical technologies were accessible to societies throughout Europe and Asia on the one hand and throughout Andean America, Central America, and Mesoamerica on the other.

In comparison with the archaeologically defined Chalcolithic and Bronze Age during which the early metallurgies of Southwest Asia appeared and matured, the Andes were long considered a backwater with respect to the development of metallurgical technologies on the world stage. What appeared to be an Andean emphasis on working almost exclusively with gold and silver supported a widely held view, even among Andean archaeologists, that pyrotechnology—the backbone of sophisticated metallurgy—was absent in the Andes.

The pioneering work of the early twentieth century by Ambrosetti (1904); Boman (1908); Nordenskiøld (1921, 1931), and Latcham (1938) presented Andean metallurgical technologies in their social contexts. Mathewson (1915) carried out the first metallographic studies of Andean artifacts in his remarkable analyses of items from Machu Picchu. These early studies were followed by the work of investigators such as Rivet and Arsandaux (1946); Root (1949, 1951); Caley and Easby (1959) who initiated systematic laboratory analyses of the chemical composition and metallurgical microstructures of Andean metal artifacts. Nevertheless, from the late 1960s forward, it took dedicated, anthropologically motivated field and laboratory investigations of Andean metallurgy to provide the data on which the current recognition of an Andean metallurgical heartland rests.

H. Lechtman (✉)
Department of Materials Science and Engineering,
Massachusetts Institute of Technology,
77 Massachusetts Avenue, Rm. 8-437, Cambridge, MA 02139, USA
e-mail: lechtman@mit.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_15,

Anthropology and archaeology are comparative sciences. The entrance of American metallurgy, both Andean and Mesoamerican (see Hosler, this volume), on the scene of archaeological scholarship has enhanced greatly our ability to draw comparisons between major heartlands of metallurgy in prehistory. We can now discard the Southwest Asian yardstick as the one against which we measure all other metallurgical developments.

The discussion of prehistoric Andean metallurgy presented here derives from a perspective that explores and emphasizes the cultural foundations of production technologies. From this perspective, a core question must be: What makes Andean metallurgy Andean; what is metallurgy like in Andean hands?

The Andean Region

A Vertical Environment

Following Murra (1974), this discussion considers the 'Andean region' in prehistory as delimited by those territories that were integrated politically into *Tawantinsuyu*, the Inka state. Between about CE 1438 and 1525, the Inka established an empire that included some 4,200 linear kilometers (2,600 miles) of rugged highlands and both moist and desert Pacific coastal terrain. At its apogee, *Tawantinsuyu* extended from what is today Ecuador, just north of the Equator (0° S latitude) at the current border between Ecuador and Colombia, to the city Santiago de Chile (33° S latitude) in the south, including the western portions of the modern nations of Ecuador, Peru, Bolivia, Chile, and Argentina (Fig. 15.1).

The Andean topography in these tropical latitudes produces a high-stress environment of extremes. Andean peoples are sometimes said to live in a vertical environment. The Andes mountain chain dominates the entire western limit of South America (Fig. 15.2). The range is high, narrow, and thus extremely steep. It is rugged, often inhospitable, and isolating. The narrow Pacific littoral, rarely exceeding about 30 km in width from west to east, hosts one of the driest deserts in the world along much of its length. Rivers flowing down the western slopes of the mountains cross the desert to discharge into the Pacific Ocean. Many rivers are without water during the 6-month dry season in the highlands.

The net result of this challenging environment has been to isolate communities from one another. Movement, communication, and exchange through mountain passes along a west–east trajectory, critical to the subsistence viability of highland populations and to their economic wealth, were the norm and practiced traditionally. The impediment to expansion, of whatever kind, lay in the near-insurmountable obstacle presented by the north–south axis of the Andes chain.

The Andes Mountains consist of three distinct massifs, the Cordillera Occidental (western), the Cordillera Central (center), and the Cordillera Oriental (eastern). Their

Fig. 15.1 Geographic extent of *Tawantinsuyu*, the Inka empire, at its apogee. The Late Horizon corresponds to the period of Inka territorial expansion and political sway. (After Lechtman 1996d, Fig. 3)

directional trend is generally north–south, but at the northern tip of Lake Titicaca, which today lies across the political border between Peru and Bolivia, the Cordillera Oriental bulges eastward, forming a high, intermontane plateau, the *altiplano*. The high, cold, and arid, tundra-like *altiplano* extends from the southern tip of Lake

Fig. 15.2 Map of the Central Andean area indicating major geographic features and archaeological sites mentioned in the text. (After Boone 1996, p. 12)

Titicaca for a distance of 965 km (600 miles) to the southwest corner of Bolivia, grading into high sierra (*puna*) at the Bolivian border with Northwest Argentina. At its widest, the *altiplano* measures about 150 km (93 miles), occupying portions of southern Peru, Bolivia, northern Chile, and Northwest Argentina.

Andean Metallic Mineral Deposits: Copper Ore and Tin Ore

This discussion of the primary metallic ore resources accessible to Andean metalworkers focuses on ores of copper and ores of tin. Copper was the matrix constituent of all the major alloys Andean metalworkers developed, including copper–silver, copper–gold, copper–arsenic, and copper–tin. Copper was never replaced as the foundation for all Andean metallurgical experiment and change, because its alloys generated the physical properties, such as color, and the mechanical properties required for the appropriate social and cultural functioning of the items those alloys produced.

The Central Andean and South Central Andean zones host some of the largest and richest deposits of copper ore in the world. These copper ores have been exploited heavily from prehistory to the present. The Central Andean zone is particularly rich in the tetrahedrite–tennantite [$Cu_{12}Sb_4S_{13}$–$Cu_{12}As_4S_{13}$] copper sulfarsenide ore solid solution series, sometimes referred to as fahlerz or grey ores. These ores of copper, arsenic, antimony, and sulfur and their weathered products are abundant from southern Ecuador to northern Bolivia and are also represented in significant deposits in Northwest Argentina and central Chile (Fig. 15.3). Enargite [Cu_3AsS_4], one of the purest mineral types in the series, occurs in an important group of deposits stretching the length of the Central Andes, from Pilzhum in northern Ecuador to Laurani in northern Bolivia (U. Petersen 1989). The largest and richest of these deposits are in central Peru (Fig. 15.3). Other sulfarsenide ores that are far less abundant in the Andes but were likely used in prehistoric smelting operations (Merkel et al. 1994; Shimada and Merkel 1991) include arsenopyrite [FeAsS], the primary metallic ore mineral West Mexican metalworkers smelted in the production of copper–arsenic alloys (Hosler 1986, 1994, this volume).

The presence of these abundant and accessible deposits of arsenic-bearing copper sulfide or iron sulfide ores in the Central Andes facilitated the production of copper–arsenic alloys there, either by direct smelting or by cosmelting procedures (Lechtman and Klein 1999; Lechtman 1991a; Shimada 1985). Depending upon the concentration of arsenic in the smelted metal, these alloys may be considered arsenical copper or arsenic bronze (Lechtman 1996a, 1997, 2005)[1].

By contrast, peoples living on the Bolivian *altiplano* and in the high sierras of Northwest Argentina exploited the rich cassiterite [SnO_2] deposits located in an extensive ore field that runs from the far southern *puna* of present-day Peru, on the southwestern shores of Lake Titicaca, through the *altiplano* and well into Northwest Argentina (Fig. 15.3). These cassiterite ores constitute the only significant source of tin anywhere in the Andes, and they are some of the richest cassiterite deposits in the world. They supplied the tin necessary for the production of tin bronze in the South Central Andes during the Middle Horizon and the Late Intermediate Period

[1] Given the experimentally measured changes in the mechanical properties of copper–arsenic alloys in which the arsenic concentration is 0.5 wt % or higher, I consider all such alloys bronzes (Lechtman 1996a). Binary alloys of copper and arsenic in which the arsenic concentration is below 0.5 wt % are arsenical coppers.

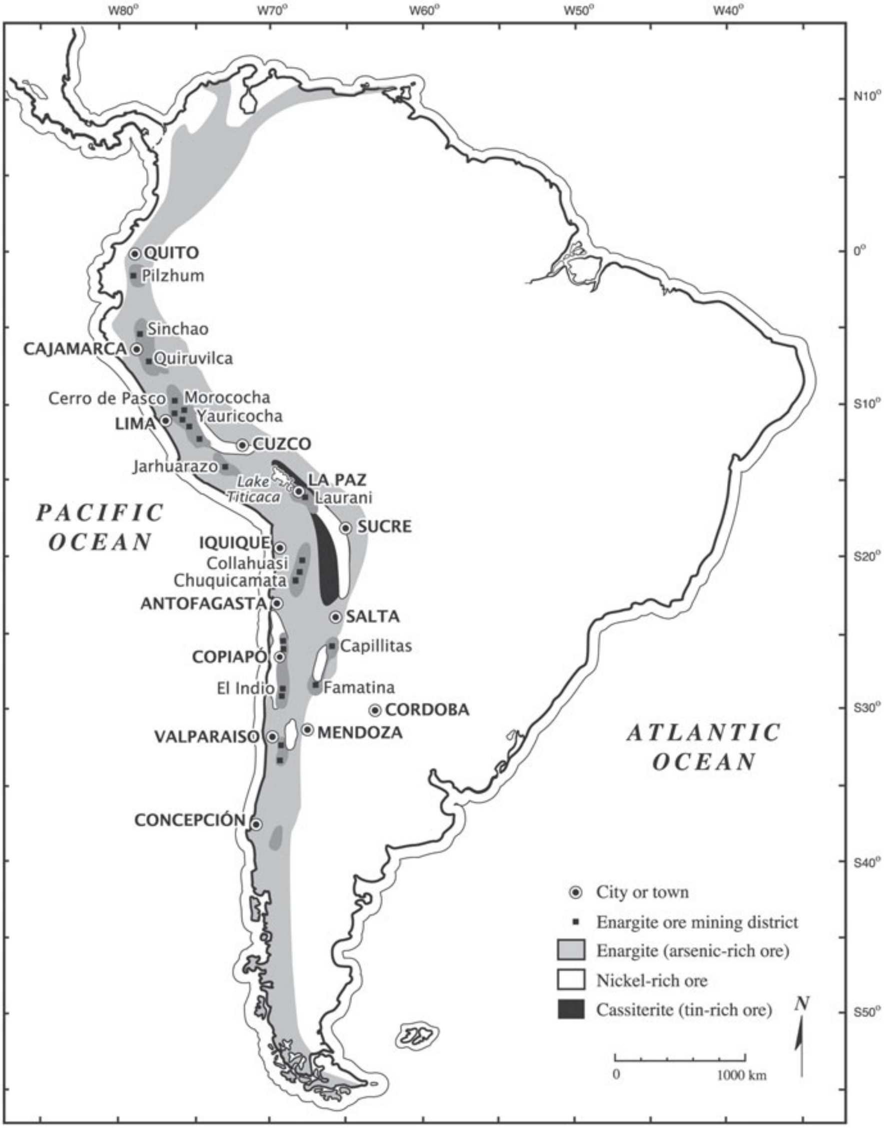


Fig. 15.3 Location of major ore deposits of enargite, cassiterite, and nickel-bearing minerals in the Central and South Central Andean region. (After Lechtman 2003b, Fig. 3)

(Fig. 15.4), and for the heightened scale of production and widespread use of tin bronze as the emblematic imperial alloy by the Inka state (Lechtman 1979, 2007; L. R. González 2004).

Prehistoric Andean metallurgy was never impeded by a lack of mineral resources. Gold and silver ores were and are abundant in the Central Andes, though they are much more regionally distributed than the copper deposits. The expansion of the

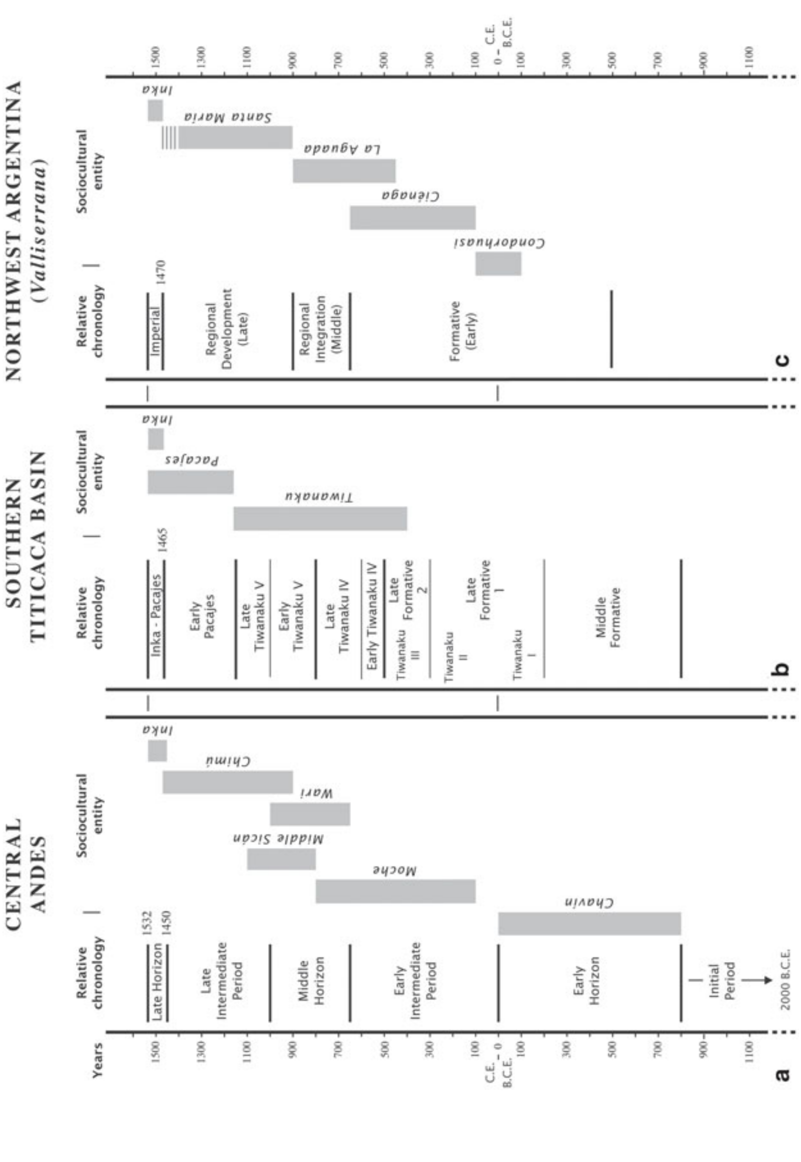


Fig. 15.4 Relative cultural chronologies for **a** the Central Andes, **b** the southern Titicaca Basin, and **c** the *valliserrana* of Northwest Argentina. (After Janusek 2003, Fig. 3.1; L. R. González 2004, p. 153; Leoni and Acuto 2008, Fig. 30.2)

Inka state into *Collasuyu*, the South Central Andes, was largely stimulated by the presence of silver deposits, especially in the Potosí region of southern Bolivia (Van Buren and Mills 2005; Platt et al. 2006) and in the northern reaches of Northwest Argentina (Pablo Cruz personal communication 2009).

Horizons and Periods: An Andean Archaeological Chronology

Figure 15.4 presents a broadly outlined, chronological scheme Andean archaeologists find useful in reckoning large-scale developments that occurred during Andean prehistory. The structure of the chronology, which divides major blocks of time into 'horizons' and 'periods', is related to the ability of peoples to overcome the dominant topographic realities of the Andean region.

The features that define a horizon include archaeological evidence for a considerable movement of ideas, people, and things in a north–south trajectory across, and in defiance of, the formidable natural barriers presented by the Andean mountain chain. Horizons were times of contact and exchange among peoples of different and often far-flung regions and from a variety of political contexts. They invariably suggest a preponderant concern for the intellectual or political handling of large, new groups of people (Willey 1991). Within this chronological framework, periods of time that do not manifest horizon features in the archaeological record are referred to as 'periods' or 'intermediate periods'. These exhibit a much higher degree of isolation between polities, when attention turned to local or regional affairs.

The chronological scheme provided in Fig. 15.4 records the dynamics of Andean prehistory essentially as a function of regionalism on the one hand and of contact, movement, and the assault on north–south physical barriers on the other. Figure 15.4a delimits and names interludes that characterize Central Andean prehistory. Archaeologists of the South Central Andes use similar chronological structures with different labels, but, as Figs. 15.4b and c indicate, the concordance among the three schemes is close, especially during the Common Era.

Whereas we consider horizon phenomena in the Central Andean zone as occasioned by highland peoples, coastal populations were responsible for many technological innovations that took place during the intermediate periods, including the development of sophisticated metallurgical technologies.

Central Andean Metallurgy: A Three-component System

The Central Andes, a geographic division defined by Andean archaeologists, comprises the region that stretches from the political limit of Ecuador with Colombia, in the north, to the borders of Peru with Bolivia and Chile, in the south (Fig. 15.2). The present political border between Peru and Bolivia bisects Lake Titicaca at roughly 69° W longitude. Figure 15.4a presents the chronological limits of the major Central

Andean intermediate periods and horizons as currently estimated from radiocarbon dates and ethnohistoric evidence. It also indicates the prominence, through time, of certain religious cults (e.g., Chavín), societies (e.g., Moche), and political entities (e.g., Inka) that are mentioned in the text.

Central Andean metallurgy was a three-component system. The elemental or material components are copper, silver, and gold. The system was set in place early in the Early Intermediate Period, as soon as these three metals were identified and used commonly by Andean metalworkers. The triad remained a physical and cultural reality up to and through the Late Horizon.

The three metals and their alloys, together with the Central Andean commitment to fabricating objects from them by processes of plastic deformation, comprised a technological style (Lechtman 1977, 1979, 1996c). The Inka inherited a metallurgical system that was already an entrenched Andean ideal. They used it in the service of the state.

Early Precursors: The Initial Period

Archaeological evidence for the use of metal in the Central Andes prior to the Early Horizon is scarce. In all cases reported, the metals are small, hammered pieces of gold or native copper. At the Terminal Archaic (2155–1936 BCE) site Jiskairumoko, Aldenderfer et al. (2008) excavated a group of cylindrical beads hammered to shape from fairly thick (0.5–1 mm) pieces of gold. Together with several greenstone beads, these formed a necklace associated with a human burial. The site, located in the Ilave River drainage of the southwest Lake Titicaca Basin in southern Peru, was inhabited by transhumant, hunting, and gathering people: a "society of low-level food producers" (Aldenderfer et al. 2008, p. 5002). The authors argue that the social context of this find suggests the use of gold for status-display purposes, long before the appearance of more complex societies in the region.

Two other examples of the early use of native metals date to the Late Initial Period. Richard Burger excavated examples of hammered gold foil and hammered native copper foil at Mina Perdida, a Late Initial Period site (1410–1090 BCE) in the lower Lurín valley of the central Peruvian coast (Burger and Gordon 1998). Mina Perdida is a large, civic-ceremonial center built by a settled, pottery-using village of farmers with a mixed subsistence base including irrigation agriculture, fishing, and shellfish collecting. Burger remarks that "despite the impressive scale of the public constructions, there is little suggestion of sharp economic inequalities or a strongly stratified society" (Burger and Gordon 1998, p. 1108). The metal foils (thicknesses range from 0.01 to 0.14 mm, with a single copper foil of 0.7mm thickness) were excavated on the summit of the main pyramid which, together with other monumental structures, was used for religious rituals and other community activities. The copper foils are especially interesting. One exhibits microstructural evidence of having been hammered and annealed. Another maintains bits of gold foil attached to the copper foil with an adhesive, apparently an early attempt at gilding copper, though not through metallurgical processes.

Joel Grossman (1972) excavated loose flakes of hammered gold foil and several lapis lazuli beads, placed in the hands of a male individual, from a burial at Waywaka (Fig. 15.2), a Late Initial Period Central Andean site in Andahuaylas Province, south-central Peru. This pottery-producing, habitation site also yielded a metalworker's toolkit in the form of a ceramic vessel that contained three small stone hammers and a stone anvil. The metalworker's toolkit was excavated from within refuse located at the same level as the burial, and it seems evident that such tools were used to hammer the foil produced at Waywaka. Grossman's single published radiocarbon date for the site is 1490 BCE, but in 2013 he analyzed 3 additional Waywaka charcoal samples by accelerator mass spectrometry (AMS) that yielded calibrated radiocarbon dates between 1680 and 1410 BCE (Grossman, *Andean Past*, in press).

The hammered native metals from all three of these sites occur in contexts of ritual activity or of burials, in some way distinguishing the individuals at death. The Mina Perdida metals are especially noteworthy for their early association of copper and gold.

Chavín Cult Media: The Early Horizon

The topographic challenge to mobility and intellectual exchange along the north–south axis of the Andean cordilleras, at anything more than a local level, was overcome for the first time by a religious cult movement with its principal temple and pilgrimage center at the highland site of Chavín de Huántar, in the north-central Peruvian sierra (Fig. 15.2).

The religious precepts at the center of the cult and iconographic emblems that bore Chavín ideological message spread unevenly but rapidly throughout most of the northern and central Peruvian highlands and coast from the latitudes of Cuzco and the Chillón Valley in the south roughly to Morropón and Paita in the north (see Fig. 191 in Burger 1992). This first Central Andean horizon episode lasted for about 800 years (800–0 BCE; R. Burger personal communication 2009).

Although the Chavín phenomenon may have been only partially successful in stimulating radical restructuring of earlier, coastal or highland societies (Burger 1988), the technologies responsible for the primary, portable cult media of Chavín—cloth and metal—underwent dramatic development. Cloth production, based on cotton as the major raw material and on twining and some loom weaving for web fabrication, already had at least 12 centuries of nonelite social and technological history when the Chavín cult appropriated cloth as a major carrier of its religious messages, at least in the central and south coast.

Metallurgy had neither history nor tradition at the onset of the Early Horizon. The occasional archaeological evidence available to date—the hammering of gold and of native copper, and perhaps the annealing of hammered copper during the Initial Period—indicates the tentative, experimental exploration of what is perhaps the most

Fig. 15.5 Chavín gold and silver effigy spoon, front and side views: Dumbarton Oaks No. B-440. (Photo: ©Dumbarton Oaks, Pre-Columbian Collection, Washington, DC)

evident and accessible mechanical property of native metals: their plasticity. When relatively pure, they are highly malleable and easy to shape.

Some scholars qualify the seemingly abrupt production of large, impressive, hammered gold objects by and for the Chavín cult as evidence of a technological revolution. Metallurgy was revolutionized in the service of religious ideology. Just as cloth seems to have been the preferred medium for disseminating Chavín emblems to communities to the south, gold became a primary medium chosen for its message-bearing qualities in the northern coast and highlands.

Does the technical handling of gold by Chavín smiths satisfy the presumption of a metallurgical revolution? The data available to address the question come from several technical laboratory studies of only a few examples from the small corpus of extant Chavín and Chavín-style gold artifacts. Almost all Chavín metal artifacts appear to be made entirely of gold. There are three published exceptions. The gold snuff spoon or dipper in the Dumbarton Oaks collection (Fig. 15.5) (Boone 1996, Vol. I, Plate 3) features a small gold figure crouched atop a stool, blowing into a silver trumpet that appears to represent a *Strombus galeatus* conch shell. Such shells, presumably of Ecuadorian Pacific coast origin, were carefully engraved and curated at Chavín de Huántar (Rick 2008; Burger 1992, Fig. 216). The figure-and-spoon, assembled from individual pieces of hammered gold sheet, is said to have been found at Chavín de Huántar (Burger and Lechtman 1996, pp. 55–66, Plate 3, Figs.17, 18 and 19). A second artifact was part of an undisturbed burial encountered near the town of Chongoyape, Peru, in the upper Lambayeque drainage (Figs. 4 and 6) (Lothrop

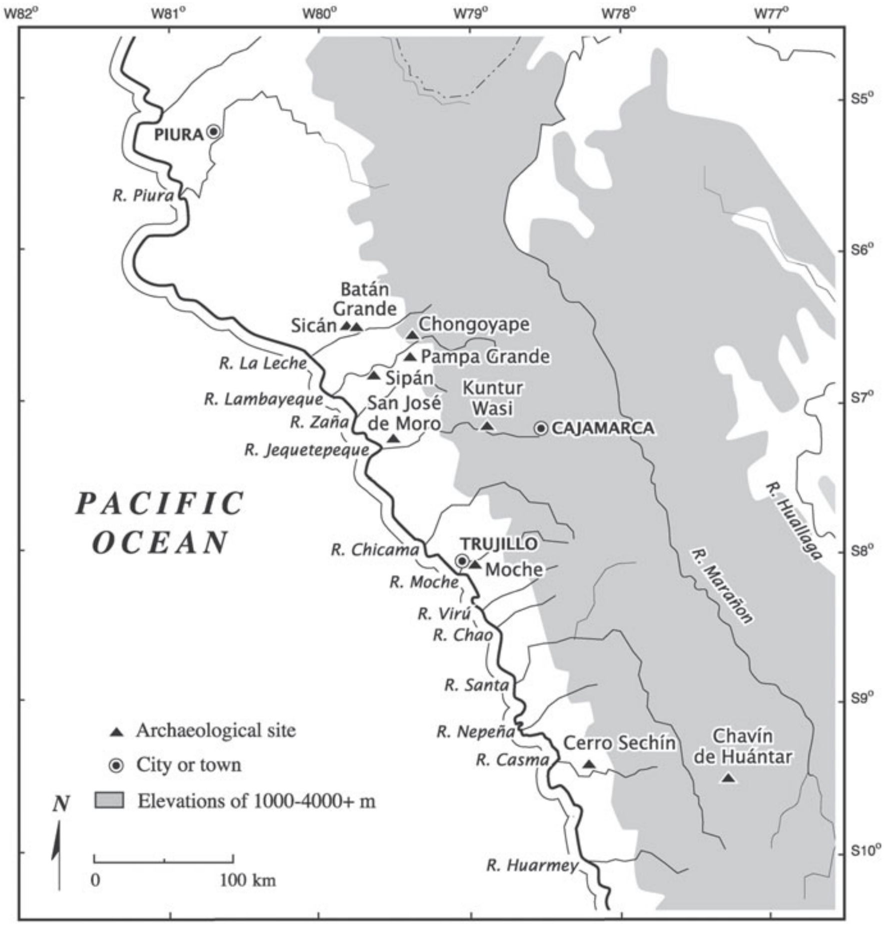


Fig. 15.6 Map of the Central Andean area, north; a detail of the inset outlined on the map of Fig. 15.2. (After Boone 1996, p. 13)

1941). Among the gold grave lot items that carry motifs similar to those found at Chavín de Huántar was a single pin made of a thin shaft of silver with a hollow, spherical gold head (Lothrop 1941, Plate XX-c). A Chavín-style pendant made of gold and silver, excavated at Kuntur Wasi (Cajamarca) (Fig. 15.6), provides the third example (Hirao et al. 1992; Kato 1993).

Lechtman (1996b, pp. 52–75) has compiled, published, and discussed the results of compositional analyses carried out on Chavín and Chavín-style gold and gold-and-silver artifacts that were reported in the literature as of the mid-1990s. The composition of a Janabarriu Phase gold ornament that Burger excavated at Chavín de Huántar and that serves as a reference analysis was determined to be 70.4 wt% Au, 26.3 wt% Ag, and 2.9 wt% Cu (Lechtman 1984, pp. 271–276, Figs. 436–445).

It forms a tight cluster with the analyses of five other gold artifacts, including the Dumbarton Oaks snuff spoon figure, that Burger has singled out as likely to have been uncovered at the Chavín de Huántar site (Lechtman in Burger and Lechtman 1996, pp. 60–61)

The average composition of the five other artifacts comprising this group is 72.4 wt% Au, 23.4 wt% Ag, and 4.2 wt% Cu. The uniformity in composition among these six artifacts is striking. They could have been made from the same batch of metal or similar batches of metal from a common source. The ternary gold–silver–copper alloy represents native gold, retrieved from placer deposits and melted to form ingots large enough for the fabrication of sheet metal, from which all of these items are constructed. Central Andean placer gold is high in silver and may contain minor amounts of copper (G. Petersen 1970).

The compositions of the silver *Strombus* shell held by the gold spoon figure and of the silver pin shaft from Chongoyape are extremely close: *Strombus shell* 72.2 wt% Ag, 25.6 wt% Au, 2.0 wt% Cu, and 0.2 wt% Pb; *pin shaft* 74.0 wt% Ag, 26.0 wt% Au, and 0 wt% Cu. These are intentional alloys probably made by melting together metallic silver with native gold. The proportion of silver to gold ensures a silver-colored metal that contrasts vividly with the rich golden color of the placer alloy.

The placer gold alloys from which many Chavín artifacts are made are the equivalent of about 17.5–18 karat gold. These placer alloys are far less malleable than the Initial Period pure gold foils. Hammering them to shape likely required intermittent low-temperature anneals. The microstructure of a thin-walled fragment of the Janabarriu Phase ornament Burger excavated exhibits large, equiaxed grains with annealing twins (Lechtman 1984, Figs. 436–445). If this thin sheet of metal required annealing, the far thicker sheets used in forming Chavín gorgets, plaques, and perhaps breastplates would also have undergone frequent anneals.

Two edges of the Janabarriu sheet ornament were bent so as to overlap slightly, then joined metallurgically at the seam. Electron microanalysis of the sheet and of the filler or solder along the seam indicated that both sheet and solder are ternary alloys of gold, silver, and copper. The concentration of copper in the solder alloy—almost three times its value in the sheet—depresses the melting point of the solder (930 °C) by 70° below the melting temperature of the sheet (1,000 °C) (Lechtman 1984). The great advantage of utilizing a solder of similar composition to that of the sheet is that the color of the solder and sheet are similar, thus masking the seam. Needless to say, a metallurgical join of this kind not only presupposes knowledge of the mechanisms of alloying and the dynamics of a soldered join, but also demands the unfailing ability to control the amount of heat brought to bear on an artifact at a precise location for a requisite period of time.

The composite snuff spoon and figure is constructed of 22 individual pieces of thin, pre-shaped placer gold (Lechtman 1996b, pp. 59–66). Each of the primary anatomical parts of the figure—head, torso, arms, and legs—is made of two pieces joined by sweat welding along a butt or overlap seam. The completed arms and legs were fitted mechanically into sockets in the torso, and the areas around each joint built up with metal that appears spongy or granular, in the form of tiny bits resembling a coarse powder. These local zones were heated until the metal particles sintered and began to fuse, but the packing was never allowed to reach a temperature at which it melted and ran freely. The stool and spoon were constructed similarly. The figure was joined to the stool with thick pallions of a silver-colored metal, likely a silver-based solder with a low concentration of copper and perhaps some gold.

Chavín smithing was entirely gold centered. The cult took advantage of the relative availability of the native metal: its color and its brilliance. Chavín smiths, many of whom must have been retainers of the cult, managed gold's plasticity and developed sophistication in annealing and in control of heat to achieve degrees of soldering and welding. Most important, gold was a new, resplendent material associated with and presumably controlled by the cult. It was elite in its social distribution and in its priestly and supernatural associations. Silver is scarcely present in Chavín smithing. We do not know if the silver used occasionally was native silver, but the combination of gold and silver in a few objects later became a central visual and symbolic theme of Moche metallurgy. Copper appears to be absent from Chavín technological and ritual domains.[2] Thus far, we have no archaeological evidence of extractive metallurgy, such as the smelting of metallic ores, having been practiced during the Early Horizon.

It is difficult to assess the impact that Chavín goldsmithing, as a technology, had on communities that incorporated the cult as a religious ideology, because we do not know how the production of cult items in metal was organized or regulated. We assume that the gold artifacts attributed to Chavín de Huántar were made at the sacred precinct. Nevertheless, the impact of Chavín on the development of Central Andean metallurgy was pronounced, in two respects. Chavín set the stage for what became a Central Andean commitment to the elaboration of form in metals: the shaping of metal in the solid state through plastic deformation, and the forming of objects—through either mechanical or metallurgical means—from a single or joined assembly of thin metal sheets. Metallurgical joins were accomplished by sweat welding, sintered welding, and soldering procedures.

Chavín incorporation of metal as a conveyor of cult iconography and ideology ascribed to metal the cultural property of a message-containing and message-providing material. Messages were communicated not only through the powerful Chavín imagery an object carried but also by the powerful physical properties of the material itself: metallic color and shininess. Above all, metal operated through priestly intervention and control, in the realm of the sacred and supernatural. The cultural association of metal with religious ideology was a Chavín stamp that persisted and was thoroughly exploited even by the politics of the Inka state.

---

[2] I have not included in this discussion, the breastplates uncovered near Huarmey, on the south coast of Peru, that are made of alternating color bands comprised of gold-silver-copper ternary alloys. Several of these items are in the collections of the American Museum of Natural History, New York. One of them, together with a compositional analysis of the component alloys, is illustrated and described by Burger and Lechtman (1996, pp. 71–75, Fig. 20). Given the absence of any context for this cache of gold-rich artifacts, I am reluctant to include the breastplates as definitively of Chavín or Early Horizon manufacture.

The Florescence of Central Andean Metallurgy: Moche

Chavín has been called the first civilization in the Central Andes (Burger, in Burger and Lechtman 1996). Moche may represent the earliest archaic Andean state. Moche was entirely a coastal polity. Its territory, centered on the north coast of Peru, extended from the Piura River valley in the north to the Nepeña valley in the south (Fig. 15.6). The Chicama and Moche valleys comprised the nuclear zone of the Moche polity.

The geopolitics of Moche administration are still in question. Scholars debate whether Moche was a single state administered by an elite group located at the Moche site; whether the Moche realm can be interpreted as being divided into distinct northern and southern regions, each of which likely corresponded to a different political entity; or whether Moche polities were small, centered in individual valleys, each of which was dominated by a single Moche lord (Castillo and Uceda 2008; Quilter 2002). Certainly, construction of the Huaca del Sol at the site of Moche, the largest adobe brick structure in the ancient Americas, was administered by members of the Moche elite and built by work parties that must have been recruited from adjacent valleys to supplement the labor available locally (Moseley 1975; Hastings and Moseley 1975).

Although the geographic extent of Moche was small, Moche society relied on a rich, diverse subsistence base, with a sophisticated network of agricultural irrigation canals, some of which were fed by intervalley canal systems, and an ocean fish, mollusk, and marine bird population that could be harvested year-round except during El Niño events. Exotic materials were brought from distant sources: *Spondylus princeps* shell and turquoise from Ecuador and lapis lazuli from Chile. Food surpluses supported specialists retained by local lords or by the state in what became a highly stratified social system run by a small, wealthy, and powerful elite.

Uncertainty concerning the nature of the Moche state, whether it was theocratic or bureaucratic, stems in part from archaeological evidence that suggests a dual profile and role for the highest members of Moche society, both men and women. The men were priests and lords, sometimes referred to by current archaeologists as warrior-priests, and some of the women were priestesses (Alva and Donnan 1993; Donnan and Castillo 1994; Alva 2001). Regardless of where they were buried, these individuals belonged to the same "ritual class" (Bourget 2008, p. 266). The principal individuals buried in the Moche III (ca. CE 300–450) cemetery alongside the Huaca del Sol as well as those buried at Sipán (Fig. 15.6), a large Moche III (ca. CE 300) burial and habitation site in the Lambayeque River drainage, were accompanied by a wide variety and large number of objects in many media: cloth, feathers, shell, pottery, and metal. "Moche visual culture and regalia are the conspicuous display of political and religious authority" (Bourget 2008, p. 284). The uniformly exceptional quality of these manufactured goods identifies the makers as specialists.

The male lord-priests or priest-warriors buried at Sipán are literally covered with metal objects. Jones (2001, p. 211) remarks that in the Moche belief system, metals must have had a protective or empowering role or quality, so that burying principal Moche lords completely covered with metal accorded them maximum authority and protection in death. Even for individuals of far lower status, it was common Moche burial practice to place copper ingots or pieces of folded, thin copper sheet in the mouth of the individual (Strong and Evans 1952; Donnan and Cock 1997). Copper especially protected. The stout wooden planks used to construct the coffin of the most noble warrior-priest buried in Tomb 1 at Sipán were lashed together and secured with thick copper straps (Alva and Donnan 1993). Ethnographic evidence (Cobo 1964, Vol. 2, Bk. 12, Chap. 5, p. 68) suggests that the mummies of later, Inka kings were wrapped in webs of cabuya fiber that secured small bars of copper (Lechtman 2007). There appears to have been a continuity of burial practice in the highlands and the coast, initiated by the Moche, by which the body of the paramount lord or lords was ultimately secured or enclosed by copper (Lechtman 2007).

The Moche innovated copper metallurgy in the Central Andes, including the smelting of copper from its ores (Lechtman 1980). With the introduction of copper, the Andean three-component metallurgical system was in place. Copper came to serve as the backbone of the system. It was the basis for all the major Andean alloys developed in both the Central and South Central Andes: copper–silver, copper–gold, copper–silver–gold, copper–arsenic, and copper–tin. It was partly responsible for all the physical and most of the mechanical properties of these alloys. Copper enabled the realization of the range of *cultural* qualities these alloys expressed through their design (Lechtman 1996c).

Moche metallurgy and the Central Andean metallurgies that followed Moche throughout the prehistoric era were color oriented. The manufacture of metal objects by thin-smithing techniques relied heavily on the plastic deformation of metal to provide thin sheets of uniform thickness that could be joined to produce three-dimensional forms. The first intentional alloys for use as solders—gold–silver–copper, copper–silver, copper–gold, and copper–arsenic alloys (Lechtman 1984, 1988)— fulfilled the need to accomplish high-quality metallurgical joins between metal sheets. The purpose of the objects Moche metalworkers made was to display and communicate messages, through form and color, about social status, political power, religious authority, and awe-inspiring ideology. Moche craftspeople designed their management of metal so that they would achieve metallic form and color regularly as dual and interdependent features of the procedures they followed. The plastic deformation of a selected range of copper-based alloys by thin-smithing techniques allowed for the message-bearing functions of the objects to inhere in the technologies by which they were made. Cultural messages were conveyed by metallurgical process as well as by the metal product.

A striking pattern in the disposition of Sipán tomb furnishings in metal is the occurrence of pairs of objects—one in sliver, the other in gold—placed in intimate association with the body of the male lord/priest: a soldier's backflap armor, ritual *tumi* knives, rattles that were worn by soldiers in battle, nose rings, and others.[3] Frequently unpaired objects are constructed partly in silver, partly in gold: e.g., a hand-held scepter, a necklace strung with peanut-shaped beads, half of which are

[3] The discussion here of the cultural significance of gold, silver, and copper as represented in Moche burial paraphernalia follows arguments presented in Lechtman 2007.

Fig. 15.7 Moche necklace of gold and silver, peanut-shaped beads from Tomb 1 at Sipán, Peru. Museo Tumbas Reales de Sipán, Lambayeque, Peru. (Photo: courtesy of C. B. Donnan)

silver and half are gold (Fig. 15.7), a soldier's backflap, and others. The pairing and juxtaposition of these two metals and their consistent relative placement on the right and left side of the male body suggest gender associations: gold/right side/male, silver/left side/female. This interpretation is based on ample ethnohistoric evidence that recalls beliefs among Andean peoples at the time of the European invasion concerning the male and female aspects of the lateral halves of the body and the association of each half with one of these two metals (Alva and Donnan 1993; Classen 1993).

In the Sipán royal tombs, copper objects such as elaborate headdresses, crowns, disc-shaped pectorals, bowls, bells, and slippers are most frequently associated with women, children, and high-status male attendants to the principal lords. At the much later (ca. CE 550), major Moche ceremonial center San José de Moro, in the lower Jequetepeque valley (Fig. 15.6), Donnan and Castillo (1992, 1994) excavated a group of burials of high-status Moche women two of whom they have identified as priestesses. The Moro burials are related closely to those at Sipán through the iconography of their contents.

The rectangular coffins of both women were made of cane, covered with cloth. On the vertical sides of the better-preserved coffin the cloth was adorned with large, hammered, copper-sheet renderings of the woman's head in the form of a mask (Fig. 15.8), her arms and legs (Fig. 15.9), and her distinctive headdress (Alva and Donnan 1993, Fig. 247). Both coffins were trimmed with hundreds of copper discs. Other copper and ceramic objects found in both burials allowed the excavators to identify these women as priestesses, the real-life counterparts of one (Fig. 15.10c) of the four most prominent actors in the Moche Presentation Scene (Fig. 15.10), also referred to as the Sacrifice Ceremony, depicted in fineline drawings on Moche ceramic vessels (Donnan 1978; Donnan and Castillo 1992, 1994; Bourget 2008). Donnan and Castillo (1992, 1994) and Bourget (2008) point to two other of the prime

Fig. 15.8 Copper burial mask from the cane coffin of a Moche priestess, San José de Moro, Jequetepeque Valley, Peru. (Lechtman 2007, Fig. 4)

actors in the Presentation Scene as corresponding to the prominent lords buried in Tomb 1 (Fig. 15.10a) and Tomb 2 (Fig. 15.10b) at Sipán (Donnan 1978, pp. 158–165; Alva and Donnan 1993, pp. 223–226). Bourget (2008, p. 266) attests that the Presentation Theme—the ritual sacrifice of Moche prisoners, the taking of their blood, and the presentation of their blood to the Moche paramount lord—is the most prominent theme in Moche iconography. Consequently, it depicts the most important Moche subjects. Gold and silver were not the exclusive conveyors in metal of high

Fig. 15.9 San José de Moro priestess burial. Hammered copper sheet metal arms and legs originally affixed to the exterior, vertical sides of the cane coffin. (Lechtman 2007, Fig. 5)

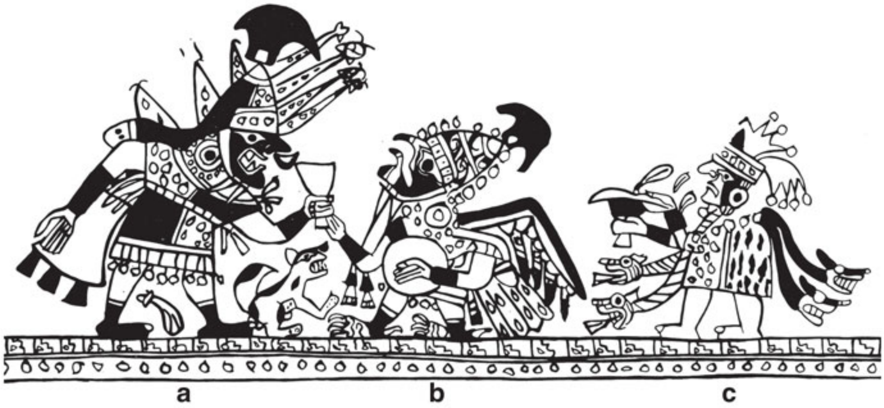


Fig. 15.10 Detail of a ceramic, fineline drawing of the Moche Presentation Scene. Figure **a** represents a Moche warrior-priest such as the individual buried in Tomb 1 at Sipán; figure **b** represents the bird priest, part bird and part human; figure **c** represents a Moche priestess such as the woman buried at San José de Moro (see Figs. 15.8 and 15.9). (After Donnan 1978, Fig. 239b)

rank and ritual command in Moche society. In particular, copper was associated closely with elite and powerful women.

Laboratory investigations have determined that with a few exceptions the gold- and silver-appearing artifacts from Tomb 1 at Sipán are made of binary alloys of copper and silver or copper and gold or of ternary alloys of copper with silver and gold (Eckmann n.d.; Hörz and Kallfass 2000). Copper is a deliberate addition to these alloys. It was added to improve their mechanical properties by increasing toughness (resistance to fracture) and stiffness, so that large, thin sheets of metal hammered to specific shapes would maintain their form.

Copper was also added to provide the mechanisms by which the original color of the alloy ingot could be transformed in the fabrication and shaping of a metal sheet. During the sequence of hammering and annealing required by the thin-smithing regime practiced by Moche smiths, copper that oxidized at the surface of a sheet was removed by intermittent pickling as the sheet was shaped. The cycles of hammering, annealing, and pickling depleted copper from the surface of the sheet, thereby enriching the surface in the remaining components: gold, silver, or an alloy of these two metals (Lechtman 1988). The final surface of the fully formed object, enriched in gold or silver through loss of surface copper, displayed a rich golden or silvery color (Lechtman 1973; Hörz and Kallfass 2000).

Objects in the Sipán tombs and many elite Moche metal artifacts appear in various hues of gold and silver as a result of the presence of copper in the alloys from which they were made. For example, the silver-looking sandals worn by the lord of Sipán (Tomb 1) were made of a binary alloy containing 50 wt% Ag, 45 wt% Cu, 2.55 wt% Pb, and 2.5 wt% Au. An ingot from the same tomb, cast from an almost identical alloy (50 wt% Ag, 47 wt% Cu, and 2.5 wt% Au), exhibits a pale coppery-pink surface color (Hörz and Kallfass 2000). Similarly, a large, golden-colored sheet metal headdress in Tomb 1 was hammered to shape from a copper-rich *tumbaga*[4] alloy containing approximately 60 wt% Cu, 34 wt% Au, and 6 wt% Ag (Hörz and Kallfass 2000). The color of the original ingot would have been a deep pink. Copper transforms metals from one color to another.

With regard to producing the culturally required colors metal objects were meant to display, the component of the metal essential to its final color—gold or silver—was made to alloy with copper. In this manner, the essence of the final object—the component that would impart its message-bearing property—was literally inside the object and would be transformed to emerge enhanced at the surface. "Copper was the mother of Andean metals in the sense that it generated the properties Andean peoples sought in metal—most especially the property of color. Copper was the source of those properties, the instrument of transformation" (Lechtman 1999, p. 226). Recalling the brilliant, golden surfaces of Chavín cult objects in metal and the clear association of these objects and metallic colors with the religious precepts and authority of the cult and its religious leaders, Moche took this configuration a step farther. They added silver, but most importantly copper, to the metalworkers' stock, they continued to refine smithing techniques and to develop a range of sophisticated metallurgical joining procedures, and they added new metallic colors to the symbolic field.

Moche utilitarian objects in copper included needles, spindle whorls, small knives and chisels, fishhooks, tweezers, and other items that appear in burial and habitation contexts. Only two or three Moche metal workshops have been excavated and published, two in an urbanized zone near the Huaca del Sol that operated towards the end of the occupation of the site (Rengifo and Rojas 2008; Bernier 2008, 2010) and another at Pampa Grande (Fig. 15.6), the late northern Moche site in the Lambayeque drainage that became an important center when the southern capital at Moche had already declined (Shimada 1994).

The workshops at Moche yielded a large amount of metal slag, copper prills, ceramic sherds (possibly from crucibles) with copper adhering to their surfaces, and various metal-processing or metalworking tools including a *yunque* (a type of grinding stone often associated with ore crushing), ceramic blowtube tips (*toberas*), stone hammers, and polishing tools (Bernier 2008, 2010). The excavators report traces of copper littered on the floor around the grinding stone. Nevertheless, to date no smelting installations have been identified with these workshops. This is not surprising, since the workshops are located in the urban center of the site.

Izumi Shimada (1994) describes the metal workshop he excavated at Pampa Grande as being equipped to handle the stages of metalworking subsequent to the processes of extractive metallurgy (i.e., ore smelting). The smelting that provided the ingots or metal blanks used by the smiths of Pampa Grande was carried out elsewhere, presumably near the mines where the ores were exploited. The tools recovered at the workshop were sufficient for fabrication of small, simple utilitarian objects like pins,

[4] *Tumbaga* is a term that refers to copper–gold alloys used predominantly in Colombia and in the Central Andean region. The term also often includes ternary alloys of copper, gold, and silver. For a discussion of the uses of this term see Lechtman (2007, pp. 344–345, endnote 4).

tweezers, and needles, but chisels, punches, and other tools normally associated with the finishing of more elaborate or finer forms were absent. Shimada (1994, p. 206) remarks that items made of copper and available to the city's residents appear to have been limited to small, utilitarian implements.

Utilitarian items of copper were not scarce during the Moche presence on Peru's north coast. Nevertheless, the need for metals of utility was not the driving force behind the explosive, highly inventive, and exuberant metallurgical technologies that developed in the Central Andes during the Early Intermediate Period. The scope, sophistication, and quality of Moche metallurgy were never surpassed during the prehistoric era, not even by the Inka.

The Middle Horizon

Bronze is the single alloy type with which the Moche experimented but never developed.[5] The production of a suite of bronze alloys in the Central and South Central Andes was a metallurgical phenomenon of the Middle Horizon (ca. CE 600–1000). Bronze metallurgy might even be considered a technological marker of that horizon.

Laboratory analyses of Middle Horizon bronzes demonstrate a high correlation between the types of bronze alloys produced in a given region of the Andes and the kinds of metallic ore minerals accessible in the region (Lechtman 2003a, b, 2005, 2007). Arsenic bronze—the alloy of copper and arsenic—was the only bronze alloy type manufactured in the Central Andes during the Middle Horizon, and it continued its singular role there until the Inka conquest and even somewhat later (Shimada and Merkel 1991; Costin et al. 1989; Howe and Petersen 1994). By contrast, tin bronze—the alloy of copper and tin—was the alloy favored in the South Central Andes among the *altiplano* peoples of Bolivia and communities from northern Chile through Northwest Argentina. A third bronze—the ternary alloy of copper, arsenic, and nickel— developed and was used briefly in a circumscribed region that included Tiwanaku, the urban pilgrimage center on the Bolivian *altiplano* at the southern limit of Lake Titicaca, and San Pedro de Atacama, the desert oasis on the western slopes of the north Chilean Andes (Fig. 15.11).

The ore distribution map in Fig. 15.3 clarifies why archaeologists find a high concentration of arsenic bronze artifacts in the Central Andean region. Rich, abundant, and accessible deposits of enargite occur throughout this zone, as do the copper arsenates that form as weathering products of the primary copper sulfarsenide ores. Smelting copper arsenate ores produces copper–arsenic alloys directly and automatically within the furnace. Alternatively, cosmelting a copper oxide ore with a copper sulfarsenide ore, such as enargite, will also produce a copper–arsenic alloy directly (Lechtman and Klein 1999). Arsenopyrite may also have contributed arsenic

[5] For examples of Moche III (ca. CE 300) artifacts and solder made from copper-arsenic alloys, see Lechtman (1979, pp. 3–4, 1988, pp. 363–365, 2007, pp. 317–318, endnote 3, Fig. 6); Hörz and Kallfass (2000, p. 400).

Fig. 15.11 Map of the Central Andes and South Central Andes indicating the Wari and Tiwanaku spheres of influence during the Middle Horizon. (After Lechtman and Macfarlane 2006, Fig. 1)

to bronzes produced on the far north coast of Peru (Merkel et al. 1994). On the other hand, communities living on the Bolivian *altiplano* and in the high sierra of Northwest Argentina exploited the rich cassiterite (SnO_2) deposits unique to that zone, as indicated in Fig. 15.3. The bronzes known archaeologically from the South Central Andes are primarily tin bronzes. Nickel minerals are extremely rare anywhere in the Andes range.

In both the Central and South Central Andes, the production of bronze meant exploitation of new ore types that had rarely been mined or smelted previously. What is notable and still requires explanation, however, is that there was no exchange of bronze alloys, for example, in the form of ingots or of bronze objects, between the two primary production spheres prior to the Inka conquest of both regions. To my knowledge, not a single tin bronze artifact has been retrieved archaeologically from sites in the Central Andes that date to before the Late Horizon, the period of Inka hegemony.

The political, religious, and military dynamics that characterized the Middle Horizon are complex and still far from understood and agreed upon (Isbell and McEwan 1991). By the close of the Early Intermediate Period, the decline of Moche in the sixth and seventh centuries followed on a series of ecological crises, both long-term droughts and severe floods, some of them associated with El Niño events (Shimada 1994; Moseley et al. 2008). During the widespread social unrest that ensued throughout the Andes in the wake of these cataclysmic environmental circumstances, two political states emerged: one with an urban center at Wari in the Central Andean highlands and the other with an urban, religious, and pilgrimage center at Tiwanaku, in the north Bolvian *altiplano* (Fig. 15.11). "The two capitals certainly interacted and exchanged information, but it is unlikely that one ever controlled the other, or that one resulted from a critical religious stimulus originating at the other" (Isbell and McEwan 1991, p. 7). Each state also sent colonists to settle regions that became incorporated into its sphere of influence.

Bronze in the Central Andes

Arsenic Bronze and Its Uses

Pikillacta, a large and complex, imperial administrative center located in the Lucre Basin at the eastern end of the valley of Cuzco (Fig. 15.11) (McEwan 2005), is the southernmost of the highland Wari provincial administrative centers. From an inventory of approximately 50 metal artifacts excavated at Pikillacta in 1989, Gordon McEwan submitted 30 for analysis to the Laboratory for Research on Archaeological Materials at the Massachusetts Institute of Technology (MIT). Twenty-six (86.7 %) artifacts are made from arsenic bronze with arsenic present in the concentration range of 0.57–3.5 wt%.

In 2005, Denise Pozzi-Escot and William Isbell submitted to the MIT laboratory 23 metal artifacts they had excavated individually between 1982 and 2005 at Conchopata, the second largest Wari highland site, located approximately 9 km south of the capital at Wari (Pozzi-Escot 1991; Isbell and Cook 2002). Unlike Pikillacta, Conchopata is an urban center at the geographic core of the Wari sphere. Of 19 artifacts analyzed for their chemical composition, 16 (89 %) are made of arsenic bronze. The arsenic concentration in the alloys ranges from 0.51 to 3.75 wt%, a range of compositions almost identical with that determined for the Pikillacta artifacts (Lechtman unpublished laboratory report).

That close to 90 % of metal artifacts excavated at Pikillacta and Conchopata are made from arsenic bronze is not surprising, as both sites lie along the major highland enargite belt of the central cordillera (Fig. 15.3). Wari is located just east of the large and rich enargite deposit at Julcani (U. Petersen 1989; Lechtman 1991a). Lead isotope analyses of 20 of the Conchopata arsenic bronzes suggest strongly that the ores used to produce the bronzes came from Julcani, a highland, copper-bearing, arsenical polymetallic deposit located approximately 68 line-of-flight kilometers northwest of Conchopata (Lechtman and Macfarlane unpublished laboratory report). None of the bronzes yielded lead isotope signatures that correspond to any known ore source in the South Central Andes. Wari bronzes were made from Central Andean ore bodies in the regions under Wari influence.

The Pikillacta bronze inventory presents a narrow range of object types. Half of these are personal items, primarily *tupus* (womens' shawl pins). Small tools, such as needles and spatulas, constitute 35 % of the corpus, and 15 % represent assorted fragmentary items (Lechtman 2003b, 2005). The Conchopata assemblage is similar. Of 24 bronzes analyzed from Sectors A and B, 14 are personal items (*tupus*) and eight represent small tools (needles, hand tools, nail, mace head); two were unidentifiable as to type. The proportion of personal items to tools at Conchopta (58.3 %:33.3 %) is close to that at Pikillacta (50 %:35 %).

The inventory of tool types made from the new bronze appears not to have broadened significantly from the range of small tools the Moche manufactured in copper: e.g., heavy needles, *tumis* (small knives), lightweight chisels, star-shaped mace heads or insignia. The toolkit was not redesigned to include more massive implements, such as heavy axes or agricultural tools. Significantly, the preponderance of personal items over tools did not alter in spite of the mechanical and physical properties the new bronze alloy could provide.

The presence of Sicán peoples in the mid-La Leche River valley on the far north coast of Peru (Fig. 15.11) appears archaeologically at about CE 750/800-900, after the abandonment of Pampa Grande and the end of the Moche state in the north. The onset of the Middle Sicán period (ca. CE 900) coincided with the decline of the Wari state which, on the far north coast, appears to "have generated . . . a rapid resurgence of local political identity and autonomy" (Shimada 2000, p. 52). Among the striking characteristics of what Shimada (2000, p. 52) considers the Sicán "theocratic state" are "innovative and large-scale pyrotechnologies and elite shaft tombs of unprecedented dimension and material wealth" which, together, constitute evidence of a highly productive economy and marked social stratification (Shimada et al. 1999). The Middle Sicán polity, with its base at Sicán, dominated 400 km of the Peruvian north coast up to and beyond the Piura River (Figs. 15.6 and 15.11) from about CE 900 to 1100 (Shimada and Merkel 1991), the beginning of the archaeological Late Intermediate Period in the Central Andes.

Fig. 15.12 Sicán-style "points" made of arsenic bronze. (**a**) Serpentine motifs on several points. (**b**) illustrates the method of hafting. Collections of the Museo Brüning, Lambayeque, Peru. (After Lechtman and Macfarlane 2006, Fig. 5a, b)

Middle Sicán metallurgy followed the traditions of the north coast in its emphasis on the production of large expanses of sheet metal in gold and in a variety of *tumbaga* (Cu–Ag–Au) alloys. To this inventory Middle Sicán smiths added arsenic bronze, and Shimada has excavated a large-scale production site at Batán Grande, in the La Leche valley (Fig. 15.11), where ores were smelted to yield arsenic bronze (Shimada et al. 1982; Shimada and Merkel 1991). In general, the use of metal of many alloy types permeated Sicán society, not only as expressions of power and religious authority but as markers of social status. Based on the contents of both single and elite multiple burials at Sicán, Shimada remarks that "access to different metals was clearly demarcated: The commoner had arsenical copper, lower elite arsenical copper and *tumbaga* and upper nobility, all metals including high karat gold alloys" (Shimada 2000, p. 56).

One of the most impressive Middle Sicán elite tombs, located at the Huaca Loro East, held five individuals accompanied by 1.2 tons of grave goods, "over 2/3 of which, by weight, were arsenical copper, *tumbaga*, and high karat gold objects" (Shimada 2000, p. 56). The gold objects, hammered from sheet metal, are primarily items of personal adornment, some striking in size and elaborateness. They include masks, fancy headdresses (incorporating crowns, feathers, and head bands), ear spools, a backflap, and ritual paraphernalia such as rattles and *tumi* knives.

An unusual feature of certain of the tomb's artifacts made of arsenic bronze is their packaging in bundles. The Huaca Loro East tomb included 15 bundles of cast-and-hammered, arsenic bronze 'points' (Fig. 15.12). Each bundle, tied with plant fiber cords, contained about 30 of these heavy items, for a total of 489, weighing about 200 kg (Shimada et al. 2000). Many points appear not to have been finished or used (see also Lechtman 1979, 1981) and may have been made expressly for burial. They resemble digging stick or spear points, but their function, apart from tomb offerings, thus far has not been ascertained.

Anikó Bezúr analyzed 85 points from four bundles. Their arsenic concentration ranges, in a normal distribution, from 1.06 to 5.23 wt%, with a mean of 3.03 wt% (Bezúr 2003, p. 314). These values agree with analyses carried out by Lechtman (1979, 1981) on points from the Lambayeque drainage and with analyses of 12 points from the Huaca Loro East tomb determined by Vetter et al. (1997). In addition to the unfinished and unused condition of the points, Bezúr found that the differences in arsenic concentration among the points do not correlate with differences in their design.

Points of the Huaca Loro East type are known from the far north coast of Peru between the Zaña and Motupe valleys. Many have not been excavated scientifically, but when found they are said to be buried in large hoards (Lechtman 1981). It is likely that they were manufactured at Batán Grande. We have no prototype for these points in any other material or in any context other than burials, but the bundling and careful wrapping sets them apart as especially valuable implements that concentrated masses of arsenic bronze at a level available only to the powerful elite.

Bezúr also describes what she calls “sheet points,” thin arsenic–bronze leaves hammered to the general shape of the heavy points (see also Hosler et al. 1990). These were also stacked and bundled. Bezúr’s study of this category of bundled items showed that the mean value of arsenic concentration in a total of 55 sheet points is generally higher than the mean for the solid points: mean values of each of four bundles were 2.30, 4.36, 4.53, and 4.69 wt% As (Bezúr 2003, Table 9.1). Sheet points made from a copper–arsenic alloy with an arsenic concentration of 4 wt% would have a decidedly light pink color, and this alloy range may have been chosen for its color properties.

Naipes, small and thin sheet metal leaves of arsenic bronze (Fig. 15.13), hammered into standard I-shapes and to a small range of sizes, were also buried in bundles in the Huaca Loro East tomb (see also Hosler et al. 1990). The Huaca Loro *naipes* measure approximately 5 $\times$ 3 cm. The excavators found approximately 1,500 individual bundles of *naipes* (Shimada et al. 2000, p. 42), representing about 21,000 single leaves, tied together carefully with plant fiber cord. The entire cache weighed close to 2.5 kg.

Considerable speculation surrounds the function of *naipes*, especially since their shape has not been identified with respect to Sicán objects in metal or any other material. They have been referred to as “primitive money” (Shimada 1985; Merkel and Velarde 2000). *Naipes* have also been compared to other extremely thin leaves of arsenic bronze, hammered to the shape of an axe blade, bundled and tied in multiples, and buried in hoards—the so-called Ecuadorian “axe-monies” (Hosler et al. 1990; Pedersen 1976; Holm 1978). There is ethnohistoric and archaeological evidence in

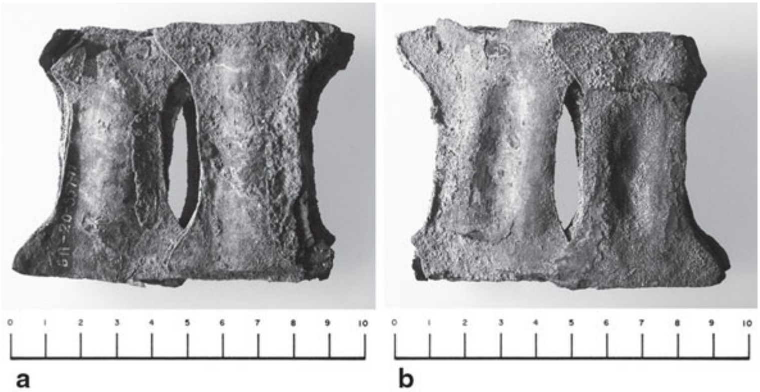


Fig. 15.13 Sicán-style *naipes*, showing obverse (**a**) and reverse (**b**) of two stacks of individual leaves. Collections of the Museo Antropológico del Banco Central del Ecuador, Guayaquil, Ecuador. (After Hosler et al. 1990, Fig. 5)

Ecuador to suggest that axe-monies may have served in prehistory as tribute or as a medium of exchange throughout large regions of coastal Ecuador. On the other hand, the geographic restriction of *naipes* essentially to the Lambayeque valley during the Middle Horizon (barring a few examples) argues against their use as primitive money or as items of exchange with Ecuador (Hosler et al. 1990).

Naipes appear to have been a special form of wealth among the Middle Sicán, an important status symbol, perhaps amassed in life for burial at death. Like axe-monies, *naipes* represented the quintessential phenomenon of copper–arsenic alloy thin smithing, and stack packeting/bundling that characterized the entire Central Andean far north coast, from Lambayeque to Manta in Ecuador (Fig. 15.2). What we see in the Central Andean sheet metal tradition as expressed at Sicán and in coastal Ecuador is a focus that accorded special place to thinness; thinness in and of itself had value. The bulk form of thinness is the packet or bundle. Since wealth in metal was reckoned by weight or mass, hundreds, thousands, or tens of thousands of individual leaves, too thin by themselves to maintain their integrity, were packeted to assume a new form. Such a system is entirely different from one in which wealth is concentrated in a few or unique items (Hosler et al. 1990).

The thin design required a metal strong and tough enough to survive thinness (Lechtman 1996a). In the selection and production of arsenic bronze, Middle Sicán smiths stimulated the widespread development and use of thin-style smithing and the range of objects that issued from it along the far north coast of Peru and probably into Ecuador. Thin smithing, as equivalent to value, was a Middle Sicán export (Hosler et al. 1990, p. 68).

The elite, sumptuous tomb furniture in arsenic bronze at Sicán represents the hoarding of metal made in specific sizes and shapes, in large quantity, and amounting to high weights in metal (Lechtman 1981; Bezúr 2003). The primary purpose of these hoards was as concentrators of metal that constituted real wealth. Bundles may also have served as a method of accounting, since the bundles normally contain some regular number of items in any given category (Shimada 2000, p. 43). Sicán selection of burial hoards in arsenic bronze for the highest-status individuals reflects the cultural ascription of value to the material as well as to the form.

Production of Arsenic Bronze

Shimada found evidence of Middle Sicán intensive smelting technology that produced copper–arsenic alloys at the Huaca del Pueblo Batán Grande, in the modern village of Batán Grande, La Leche valley (Fig. 15.11) (Shimada et al.1983; Shimada and Merkel 1991). Excavations uncovered many sets of three to five closely spaced, bowl-type furnaces dug into the floor of individual workshop areas. The excavators estimated the presence of about 100 such furnaces in the sector they examined. They uncovered similar furnaces at the Huaca and at other smelting sites close by. Some of them are late Chimú constructions, and still others were installed by the Inka.

A typical Middle Sicán furnace measured about 30 cm long, 25 cm high, 25 cm wide and held a charge of between 1.25 and 3.50 liters of ore and charcoal (Shimada and Merkel 1991). Shimada et al. (1983) remark that the Batán Grande area may likely have been selected for intensive smelting because of the nearby dense and extensive tropical thorn forest that could have been the source for charcoal, in addition to the presence of copper and mixed metallic mineral deposits within a 10km distance of the site. These deposits supplied the primary furnace ore charge of malachite [$Cu_2(OH)_2CO_3$] and presumably scorodite [$FeAsO_4 \cdot 2H_2O$], a weathered product of arsenopyrite [FeAsS], that would have supplied arsenic to the alloy, as well as iron oxides that comprised the flux (Shimada and Merkel 1991; Merkel et al. 1994). The arsenic concentration John Merkel analyzed (Merkel et al. 1994; Shimada and Merkel 1991) in smelted copper–arsenic prills retrieved at Batán Grande ranges from 1 to 10 wt%, with an average of about 6 wt%. Metalworkers introduced air into the furnace to accelerate combustion and to raise the temperature of the furnace chamber by blowing through long blowtubes, likely made of cane, outfitted with ceramic tips (*toberas*) at the distal end. Many of these ceramic tips, often scoriated from exposure to heat, remain at the site (Shimada et al. 1982; Shimada and Merkel 1991). The volume of air introduced into the furnace together with the highly localized concentration of heat with each successive blow were insufficient to raise the chamber temperature high enough to melt the slag and to maintain the growing volume of slag in the liquid state. As a result, metallic alloy prills became trapped in the thick, viscous slag where they remained when the furnace cooled and the slag solidified (Shimada and Merkel 1991). The large *batanes*, or grinding stones, at this and other nearby smelting sites were used to crush the brittle slag, releasing the prills that were later melted in crucibles to produce ingots of arsenic bronze (Shimada and Merkel 1991). Large mounds of finely crushed slag, once associated with *batanes*, measure 7 m in diameter and 1.5 m in height (Shimada et al. 1983; Shimada and Merkel 1991), attesting to both the volume of production and the nearly 400 years of extractive metallurgy that took place at these Batán Grande sites during the Middle Sicán period.

The Batán Grande region was unequivocally a primary north coast center of arsenic bronze production in the Central Andes during the end of the Middle Horizon and the early Late Intermediate Period. We have not yet determined, however, the center or centers of production that provided either arsenic bronze or objects made from the alloy to the Wari highland sites at Conchopta and Pikillacta. The inhabitants of these large urban, administrative centers were using personal and utilitarian objects made of arsenic bronze 200–300 years prior to the Middle Sicán production of the alloy on the far north coast of Peru. Lead isotope analyses, mentioned previously, indicate that the ores used to produce the bronze metal from which Conchopata objects were made were definitely Central Andean ores, likely from the highland deposit at Julcani.

Bronze in the South Central Andes

Andean archaeologists define the South Central Andes as an extensive zone that covers coastal and highland territory roughly from the latitude of the Moquegua River valley in southern Peru and the southernmost tip of Lake Titicaca in Bolivia (approx. 16.3° S) to approximately 30° S, just beyond the city of La Rioja in Northwest Argentina. The high and steep Andean topography typical of Peru continues into northern Chile, but to the east the mountain range becomes a high, flat plateau—the *altiplano*—that dominates the western half of Bolivia from the Lake to the political border of Bolivia with Argentina. Northwest Argentina comprises the region from the Bolivian–Argentine border to slightly south of the latitude of La Rioja (approx. 29° S: Figs. 15.11 and 15.16). Throughout this terrain—in northern Chile, on the Bolivian *altiplano*, in the high intermontane valleys (the *valliserrana*) of Northwest Argentina—people mined and smelted metallic ores, produced a variety of bronze alloys, and moved metal objects via caravans of llamas among coastal and highland communities. Figure 15.3b presents a chronology for the southern Titicaca Basin and the site of Tiwanaku, the large *altiplano* pilgrimage center at the southern tip of Lake Titicaca. Figure 15.3c sets out the sequence of major archaeologically defined periods and social entities that characterize the prehistory of Northwest Argentina.

Tiwanaku and Its Sphere of Influence

Between 1986 and 1991, approximately 208 metal artifacts were excavated at Tiwanaku and a nearby satellite community, Lukurmata, located at the southeastern tip of Lake Titicaca, on the Bolivian *altiplano* (Fig. 15.11). Based solely on field identification, 84.6 % of the corpus ($N = 176$) was deemed to be made of copper or copper alloys. Of these artifacts, 75.6 % ($N = 133$) were excavated at Tiwanaku and 24.4 % ($N = 43$) at Lukurmata (Lechtman. 2003a).

In spite of the distance between Pikillacta—the Wari Cuzco valley administrative site—and Tiwanaku, their political affiliations, and their use of distinctly different

Table 15.1 Chronology of Titicaca Basin bronze alloys determined by artifact analyses. (Lechtman 2003a, Table 17.6)

Phase	Number analyzed [$N = 31$]	Alloy type									
		Cu		Cu–As		Cu–As–Ni		Cu–Sn		Cu–As–Ni–Sn	
		No.	% Total	No.	% Total	No.	% Total	No.	% Total	No.	% Total
LF2–E. Tiw IV	11	–	–	1	9.1	9	81.8	1	9.1	–	–
L. Tiw IV–E. Tiw V	11	1	9.1	–	–	6	54.6	3	27.3	1	9.1
Tiw V	6	–	–	–	–	1	16.7	5	83.3	–	–
Post Tiw	3	1	33.3	–	–	–	–	2	66.6	–	–

bronze alloy types, these major urban centers exhibit a remarkable similarity in the functional distribution of the bronze objects people used regularly. At both sites personal items account for half of all the bronze artifacts in the collection studied: womens' shawl pins or *tupu*s, finger rings, figurines, and ornaments. Small tools represent about 30 % of the bronze inventory: pins, needles, spoons and spatulas, knives, nails, hand tools, axes, and architectural cramps (Lechtman 2003a, b). The preponderance of items of personal use over tools (a 1.7:1 ratio) in the metal inventories of both these large, Middle Horizon cities perpetuated what had become a pan-Andean bias, set in place by the Moche, with regard to the appropriate uses of metal. In the north, the Sicán continued the same tradition at the end of the Middle Horizon and into the Late Intermediate Period.

Except for the architectural cramps used in monumental constructions at Tiwanaku, metal objects in copper and copper alloys there and in Lukurmata were small in size and light in weight. Most were worked to shape, but some were cast, and the overall volume of metal entailed in their production was small (Lechtman 2003b). There are no examples of the heavy axes, crow bars, mace heads, bells, or other massive metal objects typical of Late Horizon artifacts from Bolivia and Northwest Argentina. Although there is a wide variety of small tools, there are few items in any single tool category. Knives and needles are the most abundant.

Thirty-seven copper artifacts excavated at Tiwanaku and Lukurmata were sampled at MIT for chemical analysis. In addition, samples were removed from two I-shaped architectural cramps located at the butt joints between upright sandstone blocks that form the southern canal walls of the Pumapunku temple at Tiwanaku (Lechtman 2003a, b, 1998, 1997). The analytical results (Table 15.1) (Lechtman 2003a, Table 17.2) indicate that three different copper alloys were in use at Tiwanaku during the middle-to-late Tiwanaku IV phase through the Tiwanku V phase (see Fig. 15.3). As much as 64 % of all Tiwanaku artifacts analyzed ($N = 18$) are made from a ternary copper–arsenic–nickel (Cu–As–Ni) alloy; 28.6 % are made from tin bronze ($N = 8$); 3.6 % are made from arsenic bronze ($N = 1$); and 3.6 % ($N = 1$) are made from impure copper. The two architectural cramps from the Pumapunku temple are also made from a ternary Cu–As–Ni alloy.

Lukurmata presents a somewhat different picture (Lechtman 2003a, Table 17.3). The preponderant alloy there is tin bronze ($N = 5$), representing 62.5 % of the Lukurmata artifacts analyzed. Two artifacts are made of the ternary Cu–As–Ni alloy, and one is made of impure copper. The two Cu–As–Ni alloy artifacts from Lukurmata, a pin and a *tupu*, are considerably earlier than any of the Tiwanaku items made from this alloy. These two artifacts represent the earliest appearance of the ternary alloy in the Lake Titicaca Basin, coming from excavation levels that date to the Late Formative 2 (Tiwanaku III) and Early Tiwanaku IV phases. At both Tiwanaku and Lukurmata, tin bronze appears for the first time in Late Tiwanaku IV contexts. Tin bronze continued in use through Tiwanaku V and, at Lukurmata, into the Late Intermediate Period (Lechtman 2003a).

During the period of Tiwanaku sway, inhabitants of the Lake Titicaca Basin experimented with a variety of copper alloys, all of them in the category of bronzes: copper–arsenic, copper–arsenic–nickel, and copper–tin. All three bronzes were in use by CE 600. At Lukurmata, the Cu–As–Ni bronze may have been available as early as CE 100–400. The ternary bronze appears to have preceded tin bronze (Lechtman 2003a) (Table 15.1). In contrast to the metalworking style of Central Andean smiths, for whom stock metal was prepared in the form of thin sheets, many of the artifacts examined metallographically from Tiwanaku and Lukurmata were fabricated from stock metal that was available in the form of cast rod. Needles, *tupus*, nails, and hand tools were hammered to shape directly from solid rods that had been cast to a range of thicknesses. The use of cast as opposed to hammered stock represents a major difference between Central and South Central Andean metalworking traditions (Lechtman 2003a).

With regard to tools, all needles, nails, or chisels as well as the architectural cramps are made from the ternary bronze alloy (Lechtman 1998, 2003a), while the hand tools and axes are fashioned from low-tin bronze. The carefully shaped working end of a hand tool, hammered from tin bronze containing only 5.6 wt% tin, was work-hardened to a Vickers Hardness Number (VHN) of 199. This is not as hard, however, as the tip of a nail ($\text{VHN} = 220$) work-hardened from a Cu–As–Ni alloy whose combined (As + Ni) concentration is 5.34 wt% (Lechtman 2003a). Small knives were made from either the ternary bonze or tin bronze.

The two axes in the collection are cast from low-tin bronze, and their working edges were subsequently hardened through cold work. Both contain casting flaws, and one axe would hardly have been serviceable as a result. In general, the artifacts studied give the impression of artisans experimenting with tin bronze metallurgy. The casting of tin bronze appears to have presented technical difficulties not yet resolved. Cast tin bronze axes exhibit centerline porosity and fissures that would have reduced severely the useful life of the tool. A finger ring cast from a high-tin bronze containing 9.95 wt% tin, undoubtedly golden in color, is replete with macropores that occupy a considerable volume fraction of the metal. The decorative details have been rendered faithfully, but the casting is not sound (Lechtman 2003a).

A review of the development and use of bronze metallurgy in the Lake Titicaca Basin, as outlined in Table 15.1, corroborates the impression that only by Late Tiwanaku V was tin bronze used almost exclusively at Tiwanaku from among the bronzes that were current earlier. By the middle period at Tiwanaku, between Late Tiwanaku IV and Early Tiwanaku V phases (CE 600–900) almost one-third of all objects were made from tin bronze, though the majority (55 %) continued to be fabricated from the ternary bronze alloy. This marked change took place at the apogee of Tiwanaku's influence among *altiplano* and north Chilean communities, and it represents the deliberate prospecting for and exploitation of cassiterite ores that were abundant within the Tiwanaku sphere in the South Central Andes. By Late Tiwanaku V (CE 800–1100), tin bronze assumed the place that the Cu–As–Ni alloy had occupied earlier: 83 % of all copper-based objects from this later period were made from tin bronze, whereas only 17 % were made of the ternary bronze alloy (Table 15.1) (Lechtman 2003a, Table 17.6).

Subsequent to the decline of Tiwanaku, during the Late Intermediate Period, the production of tin bronze accelerated, and the size, weight, and variety of objects made from this alloy increased (Mayer 1994). The Late Horizon saw a major exploitation of Bolivian tin fields by the Inka as tin bronze became an imperial metal disseminated throughout *Tawantinsuyu*.

The Middle Horizon provided the social context that stimulated remarkable developments in metallurgical technologies centered in the Titicaca Basin and the *altiplano* to the south. The change in bronze alloy type from copper–arsenic–nickel to copper–tin appears to have been associated with a change in access to the mineral resources necessary for the production of each of the two bronzes. Both bronzes were used interchangeably for a wide variety of object types, and the mechanical properties of the Cu–As–Ni variety, such as the capacity to develop high degrees of work hardening without becoming brittle, were controlled and used systematically long before the production of tin bronze. The presence of nickel in high concentrations in Middle Horizon bronzes is remarkable, however, because nickel minerals occur rarely in the Andean range (Lechtman 2003a). The decline in production of Cu–As–Ni bronze may signal the gradual dwindling of a scarce and special ore supply, whether from Bolivia or Chile, where small deposits of nickel minerals have been identified and exploited in the twentieth century. Alternatively, the change may indicate the state's decision to utilize ores that were nearby and whose availability it could regulate and control easily.

During the florescence of the Tiwanaku state in the South Central Andes, architects and builders used the ternary Cu–As–Ni alloy to facilitate the phased construction of buildings in the capital city. At around CE 600, Tiwanaku underwent a transformation that altered its residential and monumental quarters dramatically (Vranich 2006). Two new, towering pyramids, the Akapana in the northern half of Tiwanku and the Puma Punku temple complex in the southern half, dominated the civic and ceremonial core of the city. Both temples were constructed from what sixteenth- and seventeenth-century Spanish chroniclers described as "cyclopean" stone slabs (Vranich 2006, p. 122), assembled as successive horizontal platforms, each layer resting on the one below. Large, often massive bronze architectural cramps (*grapas*), fitted across the common joint or interface between abutting stone slabs, stabilized the slabs during construction (Vranich 2006). Over the centuries, most of the cramps have been removed from the temple ruins, but the sockets carved in the sandstone attest to

Fig. 15.14 Puma Punku pyramid at Tiwanaku, Bolivia. Detail of a side wall of the southwest water channel. At the *left*, a bronze cramp remains in situ within an I-shaped socket carved into the upper faces of abutting sandstone blocks

Fig. 15.15 An intact I-cramp, removed from the Puma Punku canal. The upper surface of the ternary bronze alloy cramp exhibits the highly textured features of molten metal that has solidified in an open "mold"

their dimensions and volume. Protzen and Nair (1997) illustrate a typical slab stone socket. The channel measures 42 cm in length and 9 cm at its widest opening.

Both the Akapana and Puma Punku temples were outfitted with wide, stone-lined canals that carried water through the building and discharged it below ground into a major city drainage system (Kolata 1993). Portions of the side walls of these canals preserve cramps in situ between the faces of abutting vertical stones (Fig. 15.14). In 1995, Lechtman (1998) analyzed a cramp from one wall of the south canal (Fig. 15.15) where the canal exits from the Puma Punku pyramid. The I-shaped metal cramp is made from a ternary Cu–As–Ni bronze containing 6.00 wt% As, 5.85 wt% Ni, and 0.27 wt% Sb. The microstructure of a sample removed from the cramp showed it to be a two-phase, coarse-grained, highly cored casting. During construction of the canal wall, molten bronze was cast directly into a socket previously prepared on the upper faces of two abutting sandstone canal blocks, at their common joint (Fig. 15.14) (Lechtman 1998).

A mechanical and materials analysis of the cramp (David Parks, in Lechtman 1998, pp. 890–891) indicates that, as the molten bronze solidified and shrank in the mechanically constrained geometry, the clamping force developed in the bar portion of the cramp was sufficient to pull the stone blocks together to a tight fit. David Parks' calculations of the clamping force of the canal *grapa* show that it could sustain a suspended load of approximately 4,490 kg (Parks, in Lechtman 1998). The Puma Punku *grapas* were engineered both mechanically and through control of alloy composition to clamp together the stone blocks in a tight fit—a requirement for a canal that would handle large volumes of water.

The use of bronze architectural cramps in the monumental buildings at Tiwanaku is the only example to date of this technique in Andean prehistoric constructions (Protzen 1993; Protzen and Nair 1997). That the ternary bronze alloy accomplished an important special function in the construction of the primary sacred buildings at Tiwanaku suggests that the reasons for which use of this bronze type lessened with time had little to do with its performance capabilities.

A second concentration of Middle Horizon artifacts made from the ternary bronze alloy occurs at San Pedro de Atacama (Fig. 15.11), an oasis on the northern edge of the Salar de Atacama, in the arid western sierra foothills (2,400 masl) of the north Chilean Andes. San Pedro was an entrepôt in a network of exchange routes through which goods and llama caravans passed, connecting Tiwanaku with the southern Bolivian *puna*, Northwest Argentina, and the north Chilean coast. Large numbers of metal artifacts have been uncovered from burial grounds in the vicinity of San Pedro, including a group of Middle Horizon axes, at least one of which is identical to an axe excavated at Lukurmata. These artifacts form part of the collections of the Museo Arqueológico R.P. Gustavo Le Paige at San Pedro. Lechtman (Lechtman and Macfarlane 2005, 2006) analyzed 80 % ($N = 36$) of the museum's metal axes, 61 % of which are made from Cu–As–Ni bronze. The remainder are primarily tin bronzes.

Archaeologists (Núez 1987; Núez and Dillehay 1995 [1979]) have long held that during the Middle Horizon, llama caravans supplied Tiwanaku with arsenical copper processed from ore extracted at Chuquicamata (Fig. 15.2), the large and rich deposit of copper sulfarsenide mineral located about 100 km north of San Pedro. The source of nickel, indispensable for the production of Cu–As–Ni bronze, remains undetermined.

That both Tiwanaku and San Pedro were using objects made from the rare ternary bronze raises questions about whether there may have been multiple centers producing this bronze, perhaps located on the *puna* or on the dry, western mountain slopes at much lower elevations. Lechtman and Macfarlane (2005, 2006) carried out lead isotope analyses of 14 ternary bronze artifacts excavated at Tiwanaku and 16 ternary bronze axes from the Museo Arqueológico collections at San Pedro and compared these determinations with the lead isotope signatures of copper ores they had field collected in the South Central Andes (Lechtman and Macfarlane 2005, 2006).

Of the 14 Tiwanaku artifacts studied by lead isotope analysis, the metal from nine derives without doubt from local ores in the geographic vicinity of Tiwanaku.

Of the 16 San Pedro axes, 13 have isotopic signatures that coincide unequivocally with highland ore lead isotope ratios. These axes could not have been made from metal smelted from Chilean coastal or low sierra ores, such as those at Chuquicamata. Half of the axes with *puna* lead isotopic signatures coincide with ores located in the geographic region of Tiwanaku.

These results challenge Andean scholars to readdress the system of far-flung, South Central Andean exchange networks that were an economic mainstay of the Tiwanaku state. With regard to the movement of metal or metal objects, knowing how much of bronze production was state sponsored and how much depended on the local exploitation and smelting of ores that were then transferred out via the caravan networks is critical to interpreting the interdependence between Tiwanaku and the Andean communities that sent pilgrims to the ritual architecture of the sacred city.

The Middle Horizon and the Bronze Divide

During the Middle Horizon the appearance of new bronze metallurgical technologies coincided with the north–south, long-distance movement of goods and religious iconographies and with development of innovative highland agricultural systems. All of these changes facilitated the exchange of technological experience over vast distances and across the semi-permeable Wari–Tiwanaku interface between the two states' respective spheres of influence. Nevertheless, a 'bronze divide' (Lechtman and Macfarlane 2006)—located roughly between the latitude of the southern tip of Lake Titicaca and that of the Moquegua valley in south coastal Peru (Fig. 15.11)—was not breached. The bronzes that developed on either side of the divide were not among the items of material culture that moved across what seems to have been a cultural barrier.

The Wari and Tiwanaku colonies at Cerro Baúl and Omo, respectively (Fig. 15.11), are located mid-valley along the Osmore River drainage (often referred to as the Moquegua valley) in the southernmost reaches of Peru. The sites are situated 20 km from each other. Cerro Baúl was an elaborately fortified Wari outlier established and maintained by Wari deep within Tiwanaku territory. The Omo complex was settled by *altiplano* peoples to the east and grew to become something akin to a Tiwanaku province under the direct control of the capital, some 300 km away (Lechtman 2003b).

In 1995, the copper metal inventory from Cerro Baúl included 12 artifacts, six of which were analyzed for their chemical composition. Of the 18 metal artifacts in the Omo corpus, four of the larger, intact artifacts underwent chemical analysis (Lechtman 2003b). In general, the artifact alloys represented at the Cerro Baúl and Omo colonies fit the patterns that had been established previously for metal artifacts from Pikillacta, the large, highland Wari administrative center, and from Tiwanaku (Lechtman 2003a, b). Of the six Cerro Baúl artifacts, four are arsenic bronzes typical of Middle Horizon bronzes in the Central Andean zone. Two are made of a ternary copper–arsenic–nickel bronze alloy and are almost certainly Tiwanaku items introduced to Baúl, likely from Omo. The Omo material is close in analytical profile to the compositions of copper and bronze artifacts from the Tiwanaku site. One artifact is an arsenic bronze, two are made from a Cu–As–Ni bronze alloy, and one is a tin bronze with minor amounts of arsenic and nickel (Lechtman 2003b). Not only are the bronze alloys at each of the two Moquegua valley colonies consistent with the metallurgies of their respective imperial centers, but the types of metal artifacts excavated at each outlier are also typical, respectively, of Wari or Tiwanaku material culture in metal.

Cerro Baúl and Omo present a well-documented example of the Middle Horizon bronze divide, as they were outliers along a major political frontier between two extensive Middle Horizon states. We might interpret the close commitment of each outlier to its own metallurgical repertoire as indicative of a technological and cultural frontier coincident with the political limit. At the same time, the horizon character of bronze metallurgy throughout the Andes suggests a pan-Andean interest in exploiting new types of ore, reaching farther afield for resources, and experimenting with the products of extractive metallurgical technologies, all of which contributed to the manufacture of a variety of bronzes in an uncommonly mineral-rich geological environment.

The Burger et al. (2000) exhaustive study of pre-Hispanic obsidian procurement and exchange in the Central Andes and northern Bolivia from the Preceramic Period to the Late Horizon offers a comparative perspective on patterns of resource utilization between obsidian and metal, especially in the highland zone that comprises southern Peru and the Lake Titicaca Basin. High-quality obsidian deposits are rare in the Central Andes, but two varieties located in the province of Arequipa of the southern Peruvian highlands were exploited continuously: the Alca source in the Cotahuasi valley and the Chivay source in the Colca valley (Fig. 15.11). Unlike bronzes, obsidian traveled widely from the source deposits. The pattern of exploitation and use of these two obsidians indicates that people in the Cuzco Basin of highland Peru exploited the Alca source, while the Chivay source was utilized predominantly by inhabitants of the Lake Titicaca Basin. Groups in the intermediate area obtained obsidian from both sources.

This pattern of obsidian distribution obtained in the southern highlands of Peru can be seen throughout most of its prehistory, but the pattern changed markedly during the Middle Horizon. "... The obsidian evidence suggests that the previous, long-standing tradition of south highland interaction was now disrupted by two powerful imperial forces [Huari and Tiahuanaco]. The obsidian distribution in what is now southern Peru reflects the impact of the territorial expansion and influence of the Huari empire and its frontier with the Tiahuanaco polity in the south" (Burger et al. 2000, p. 324). Wari and Tiwanaku territories overlapped only in the southern Peruvian valleys at sites such as Cerro Baúl and Omo (Fig. 15.11). Richard Burger's data show that at the Wari colony Cerro Baúl, obsidian was being brought in primarily from distant sources far to the north that were favored by and located within Wari territory.

In the highlands, there was a buffer zone between the two imperial borders.

Burger points out that the Chivay obsidian source, in the Colca River valley, appears to have been located just within the southern frontier of Wari expansion "... and thus its location must have created special problems for the altiplano populations dependent on this rare natural resource" (Burger et al. 2000, p. 325). Yet the sample of obsidian that Burger analyzed from the northern Lake Titicaca Basin indicates that these communities, including Tiwanaku, continued to utilize only Chivay obsidian during the Middle Horizon, as they had prior to the Wari expansion (Burger et al. 2000, p. 326). Burger offers one possible explanation for this apparent anomaly.

> Perhaps as a result of the difficult situation posed by Chivay's location, obsidian may have been channeled directly into the Tiahuanaco heartland through formalized state-controlled

> mechanisms and/or agreements worked out with Huari authorities. Such a hypothesis would help to explain why this obsidian is absent in the rest of Huari territory and why it failed to reach the Tiahuanaco population in Moquegua [at Omo] in significant amounts. (Burger et al. 2000, p. 342)
>
> For the southern highlands of Peru, the obsidian data present unambiguous evidence of a radical shift in distribution strategies that reinforces the perception that the Middle Horizon Huari profoundly transformed the relations between Andean regions and, as a result, modified their respective developmental trajectories. (Burger et al. 2000, p. 351)

Following the collapse of the Wari state, during the ensuing Late Intermediate Period, preliminary data indicate reemergence of the pre-Middle Horizon obsidian procurement and distribution pattern (Burger et al. 2000, p. 344), although the use of obsidian generally declined throughout the Central Andean zone. To the contrary, the bronze divide remained firmly fixed until the Inka hegemony.

The considerable difference in resource exploitation patterns that characterize Middle Horizon metallic ores and Middle Horizon obsidian resulted, in part, from the ubiquity of the former and the scarcity of the latter. The ores required to make good bronzes in the Central and South Central Andes were generally abundant, widely distributed, and accessible, though compositionally varied. High-quality obsidian, by contrast, is rare and occurs in discrete locations. Burger cites only eight known sources in the Central Andean zone with perhaps an equal number in Bolivia and into Northwest Argentina and Chile.

We also need to recognize the nature of the cultural arenas in which these materials and objects functioned. Obsidian, particularly from certain prized sources, had ritual uses and associations in the Andes as well as in Mesoamerica. In Northwest Argentina, one of the paramount features of certain objects made from tin bronze was their symbolic efficacy in the performance of religious rituals, some of which involved human sacrifice (González 1992). Understanding the associations Andean peoples held with respect to bronze is essential in order to interpret the unusually fixed set of boundaries that characterized bronze production and use during and subsequent to the Middle Horizon, especially since bronze technologies developed throughout the Andes almost at the same time and precisely during a period of heightened interchange.

Northwest Argentina: Aguada and the Regional Development Period

Societies of Northwest Argentina, principally those located in the *valliserrana* (Fig. 15.16)—the high, intermontane valleys bordered on the north and west by *puna* and on the east by the low plains of the *chaco*—produced both arsenic bronze and tin bronze with mineral resources common to the region. The sulfarsenide deposits in Northwest Argentina are not nearly as extensive or as rich as those in the Central Andes (Fig. 15.2), but certain polymetallic deposits, such as those at the large Capillitas mine near the Hualfín valley, are known for their enargite, tetrahedrite, and tennantite mineralization (Fester 1962).

Analyses of 13 artifacts from the Formative (500 BCE to CE 450) Condorhuasi and Ciénega cultures (Table 15.2) (González 2004, p. 170) of the *valliserrana* region

Fig. 15.16 Map of Northwest Argentina, indicating the *valliserrana* region and archaeological sites mentioned in the text. (After González 2004, p. 151, 154; Acuto 2008, Fig. 42.1)

(Fig. 15.16) do not provide evidence for a well-developed or widespread bronze metallurgy that was shared among the early agricultural and pastoral societies of Northwest Argentina. They do provide strong evidence, however, that prior to the Middle Horizon smelting technologies required to produce arsenic bronze from arsenic-bearing ores were already in place. They also demonstrate the likelihood that tin was extracted from cassiterite and alloyed with copper to produce tin bronze[6], or alloyed with arsenic bronze to produce ternary alloys of the three metals.

[6] In view of the fact, that the ore mineral stannite (Cu_2FeSnS_4) has not been reported to be present in the metallic ore deposits of the *valliserrana* region, we can argue with some confidence that early bronze alloys were made by melting together copper and tin (González 2004) or by smelting a mixed charge of copper ore and tin ore.

Table 15.2 Compositions of Condorhuasi and Ciénaga copper alloy artifacts from the *valliserrana*, Northwest Argentina. (After González 2004, p. 170)

	Object	Cu	As	Sn
			[wt%]	
Condorhuasi	Bracelet	90.73	3.81	1.57
	Bracelet	97.15	2.16	0.70
	Plaque fragment	92.33	3.40	2.05
Ciénaga	Axe fragment	85.07	–	3.54
	Axe fragment	98.11	1.29	0.71
	Axe fragment	96.72	1.46	1.90
	Chisel	94.10	3.31	0.28
	Chisel	84.20	–	5.90
	Chisel	96.26	3.43	0.09
	Chisel	84.61	–	4.34
	Punch	93.80	1.96	0.32
	Punch	96.67	3.16	0.30
	Punch	97.59	2.00	0.21

– unknown

The first instances of social, political, and ideological integration of agropastoral communities inhabiting small but sometimes densely populated groups of hamlets in Northwest Argentina took place in what Myriam Tarragó (1999) calls the first regional integration. Between about CE 400 and 900—the Middle Period (Fig. 15.3c)—two culturally independent economic and social interaction spheres developed, coincident with the Middle Horizon in the Central and South Central Andes. Yavi and Isla inhabitants of the Quebrada de Humahuaca (Fig. 15.16) and the *puna* north of that valley looked to the north—to Tiwanaku and San Pedro de Atacama—for their long-distance exchanges (González 2004, p. 181–183). The metal artifacts associated with this interaction sphere are almost entirely gold and silver items recovered in burials (González 1979). Many of these artifacts appear to have come from Tiwanaku.

The other socioeconomic interaction sphere developed in the central valleys of Catamarca Province, the heart of the *valliserrana* area (Fig. 15.16), and involved many small hamlets that became integrated into what archaeologists refer to as the La Aguada culture. Growing out of the earlier Condorhuasi-Alamito and Ciénega populations, and including the inhabitants of the Ambato valley, Aguada achieved a unique synthesis of political and religious expression that was dominant in the region until the beginning of the tenth century CE (González 2004, p. 184). Myriam Tarragó (2000) refers to the theocratic character manifested by the societies that were linked to the Aguada religious complex. This complex centered around a cult of the feline and on severed heads, reminiscent of north Andean cults, such as Chavín, and of Moche iconography that displays trophy heads. The cult constructed large ceremonial complexes and produced objects in ceramic and metal that were ritually associated with these monumental structures.

> The Aguada culture of northwest Argentina was one of the first to utilize [tin] bronze in South America. But the practical-utilitarian applica tions of this alloy held little significance for this culture. Almost all bronze objects or the large majority were purely sumptuary or

> related to ritual and to ceremonialism. They were designated to satisfy the demand of an elite, not to serve the practical needs of the majority. (González 1998, p. 367; the author's translation)

At the same time, Alberto Rex González characterizes the Middle Period as representing "... the cultural climax of northwest Argentina" (González 1979, p. 162) and the Aguada culture as best exemplifying that period.

Luis González (2004) identifies the two overriding characteristics of Aguada metallurgy. First, the casting of metal, including use of lost wax casting, greatly predominated over processes of plastic deformation for realizing form. Second, tin bronze was the alloy of choice for objects that functioned in religious and political arenas as well as for utilitarian purposes. The large majority of tin bronze objects was produced for and used by religious and political elites. The high quality and complexity of cast tin bronze plaques and axes—all of which had ritual connotations—indicate that these objects were made by specialists. The power of religious and political elites was expressed and broadcast by their use of tin bronze, not through devices of gold or silver. Over time, the more complex the sociopolitical systems became and the larger and denser the populations within the Aguada ritual field, the greater the volume of tin bronze objects produced.

There is abundant archaeological evidence for a rich inventory of utilitarian objects in Northwest Argentina: needles, tweezers, simple axes, knives, chisels, awls, and punches (González 1979). In the earlier periods, these objects were made from a variety of metals, including copper, arsenic bronze, tin bronze, and ternary alloys of copper, arsenic, and tin. Nevertheless, Geraldine Gluzman's (2008) chemical and metallographic study of a group of Regional Development Period (CE 900–1400) tin bronze knives, chisels, and punches from the Yocavil valley indicates that few of the tools appear to have been used. In addition, tools that were presumably destined for different functions often contain similar concentrations of tin. The author suggests that the bronze metal itself held cultural value, and owning bronze tools was a sign of prestige that contributed to the social status of the owner, commonly members of nonelite groups within a community.

Tin Bronze and Its Uses

The two most salient characteristics of Aguada metallurgy that distinguish it from Wari and Tiwanaku technologies of metal production are the choice of tin bronze for the most ritual-laden objects and use of the lost wax process to cast them. A. R. González (1992) identifies three classes of tin bronze objects in Northwest Argentina that performed singly or together in the context of sacrificial rites: discs or plaques, heavy axes in stylized forms, and large, oval bells (*tan tanes*).

The earliest discs and stylized axes are considered Aguada manufactures (but see Cruz, in press, for an alternative chronology).[7] Only about 30 Aguada discs

[7] In a manuscript Pablo Cruz submitted for publication to *Mundo de Antes*, Tucumán, Argentina (Cruz personal communication, 2011), he argues that the corpus of discs regularly ascribed to

Fig. 15.17 Lafone Quevedo disc. Length of longest axis: 16 cm. Museo de La Plata, La Plata, Argentina. (Photo: courtesy of L. R. González)

are known (González 2004), distinctive for their elaborate iconography rendered in high relief. The circular plaques (discs) rarely exceed 15 cm in diameter (González 2004, p. 196). Six Aguada discs have been analyzed for their chemical composition and, in some cases, to determine their microstructures (Biloni et al. 1990; Lechtman 1991b; Scott 1998; Cabanillas et al. 2002). All are made of tin bronze and were cast by the lost wax process. The well known, most ornate and complex of these—the Lafone Quevedo disc (Fig. 15.17) made around CE 600—contains about 2.5 wt% Sn (Biloni et al. 1990); the tin concentration in the other five plaques ranges from 1.31 to 14.58 wt% (González 2004, p. 209). When cast, the three discs made from alloys containing 5.81, 8.0, and 14.58 wt% Sn, respectively, would have appeared light yellow to golden in color.

Luis González (2004, p. 210) discusses the wide range of variation in the tin content of these six Aguada disc alloys, pointing out that deposits of cassiterite in Northwest Argentina are far scarcer than deposits of copper ores. Some of the variation in tin content of the disc alloys may derive from a scarcity of tin sources and a consequent effort to economize on the amount of tin added to copper in the production of bronze. Clearly, adding two or three weight percent of tin to copper

---

La Aguada was produced during the ensuing Regional Development Period (CE 900–1400). In his analysis of the complex iconography carried in high relief on each disc, Cruz has identified motifs that represent a variety of bronze axes and a unique style of bronze knife produced during the Regional Development Period but that are not known archaeologically as items of La Aguada material culture. González (1979, charts II and IV) provides helpful charts that distinguish La Aguada-style axes from Regional Development Period axes.

Fig. 15.18 Aguada axe. A handle would be hafted at the central, narrow bridge between the blade and heel. The heel represents a feline. Length: 38 cm. Museo de La Plata, La Plata, Argentina. (Photo: courtesy of L. R. González)

would have little effect on the resulting color of the alloy, but these concentration levels would lower the melting point of the alloy, thereby increasing the amount of superheat[8] available to achieve a successful casting. Unlike the discs, Aguada tin bronze axes were cast in piece molds. L. R. González and H. Buono (2007a) examined an axe similar to the example in Fig. 15.18 that was cast in a two-piece mold, although the decorative motifs were engraved later. The alloy contains 6.31 wt% Sn.

In the tenth century CE, the collapse of the societies that concentrated the religious and political power of La Aguada in the *valliserrana* region and the concurrent inability of Tiwanaku to maintain its sphere of influence in the larger orbit of the South Central Andes brought about profound changes in Northwest Argentina (Tarragó 2000, p. 259). The ensuing Regional Development Period (CE 900–1400) saw a dramatic demographic rise with the establishment of a number of densely populated, almost urban centers. Powerful, hierarchically ordered societies emerged that held large, highly productive agricultural and pastoral territories, well controlled and well defended by hilltop forts (*pukara*) that were also social, political, and religious centers. These social entities were often in competition for resources with other, similarly organized communities (Acuto 2008; Leoni and Acuto 2008). As their sizes continued to increase, social inequalities were accentuated not only in the

[8] Superheating: Heating molten metal above the normal casting temperature so as to obtain greater fluidity (American Society for Metals 1985).

Fig. 15.19 Santamariana disc depicting a pair of warriors. Diameter: 19.5 cm. Collection of the Ministerio de Relaciones Exteriores, Buenos Aires, Argentina. (Photo: courtesy of L. R. González)

organization of labor but also in the distribution and consumption of sumptuary and prestige goods (Tarragó 2000).

The establishment of workshops with specialist artisans for the production of objects of high social and symbolic value was closely tied to the reinforcement and consolidation of elites within these societies (Tarragó 2000, pp. 259–260). As A. R. González states (in Tarragó 2000, p. 282), "These societies placed the crafts at the service of warlike ritual and religious ritual" (the author's translation). Tarragó (2000, pp. 287–288) argues that it was precisely the strong links between these goods "and the phenomenon of social complexity . . . that served the interests of the dominant elites, contributing to the consolidation of political power within the large social entities" (the author's translation).

Production of Tin Bronze

Tin bronze continued as the high-prestige alloy for sumptuary and ritual goods during the Regional Development Period, and these items were cast in molds. Discs and plaques were made simpler in design (Fig. 15.19) than previously but were larger in size and heavier. New varieties of heavy axes included those with handles cast integrally with the blades (Fig. 15.20). Large, oval bells (*tan tanes*) (Fig. 15.21) added to the complex of the three, highly ritually symbolic paraphernalia. Most, though not all, of these items were cast in piece molds.

Luis González compiled a table (2004, p. 247) that presents published analyses of the composition of 36 discs/plaques, primarily from the *valliserrana,* that date to the Late Period. Table 15.3 reproduces those data with the addition of analyses of two discs: one from Tafí, Province of Tucumán (L. R. González personal communication 2009) and another from Chuscha (Cabanillas et al. 2007). Twenty-nine discs (80.5 % of the group) are made of tin bronze, 25 of which contain tin in a concentration range between 1.57 and 8.03 wt%. The average composition of 18 binary copper–tin bronze discs reported in Table 15.3 whose tin concentration is below 10 wt% is Cu, 3.73 wt% Sn. In four high-tin bronze discs, the tin concentration ranges from 15.51 to

Fig. 15.20 Santamariana axe, with the metal handle cast integrally with the blade. Length: 24.5 cm. Museo Adán Quiroga Catamarca, Argentina. (Photo: courtesy of L. R. González)

Fig. 15.21 Large bell with oval cross section and pairs of heads cast in relief on both of the principal sides. Height: 23 cm. Museo Adán Quiroga Catamarca, Argentina. (Photo: courtesy of L. R. González)

23.47 wt%, with three compositions that cluster around an average tin concentration of 16.14 wt%. Two discs are arsenic bronzes, one is made from a copper–silver alloy, one is made of copper, and three are copper–zinc alloys, or brasses.[9]

In his exhaustive 1992 volume on the metal plaques of the Southern Andes, Alberto Rex González cites two discs that are considerably larger and heavier than any of the others: one, from Cachi, weighs 23.78 kg; the other, from Tafí, weighs 32.43 kg. No analyses have been carried out to determine the compositions of these two discs.

[9] Cabanillas et al. (2007) mention that such high-zinc discs are associated with hispano-colonial contexts. Brass alloys were introduced to the Andean zone by the invading Spaniards in the sixteenth century, therefore these discs were likely made by metalworkers indigenous to Northwest Argentina who utilized the new material.

Table 15.3 Compositions of Late Period *valliserrana* bronze discs/plaques. (After L. R. González personal communication 2009, 2004, p. 247)

No.	Provenience	Cu	As	Sn	Zn	Fe	Pb	Ag	Au	Cr
		[wt%]								
1	Averías	91.84	–	5.26	–	2.55	–	–	–	–
2	Chilca Pozo	97.42	–	2.54	–	–	–	–	–	–
3	Sequía Vieja	97.12	–	2.83	–	–	–	–	–	–
4	Sequía Vieja	94.08	–	4.04	–	–	–	–	–	–
5	Las Conchas	91.08	–	8.03	–	0.44	0.32	–	–	–
6	La Rioja	80.55	–	16.53	–	–	–	–	–	–
7	Tolombón	90.06	tr	6.87	–	0.28	–	–	–	–
8	Pampa Gde.	97.25	–	2.52	–	–	0.22	–	–	–
9	Luracatao	94.95	–	3.03	0.94	0.37	–	–	–	–
10	Pampa Gde.	97.41	–	2.00	–	0.56	–	–	–	–
11	Salta	91.80	–	5.66	–	0.50	–	–	–	–
12	Calchaquí V.	96.00	–	2.43	–	1.54	tr	–	–	–
13	Calchaquí V.	96.42	–	1.57	–	–	tr	–	–	–
14	Calchaquí V.	97.40	tr	2.12	–	0.46	–	–	–	–
15	Calchaquí V.	96.85	–	3.14	–	–	–	–	–	–
16	Calchaquí V.	97.25	–	2.90	–	–	–	–	–	–
17	Calchaquí V.	93.55	–	3.46	1.01	0.75	0.18	–	–	–
18	Calchaquí V.	94.57	–	5.43	–	–	tr	–	–	–
19	Calchaquí V.	91.79	–	6.64	0.81	0.50	0.14	–	–	–
20	Chicoana	95.49	–	2.43	–	1.79	–	–	–	–
21	Calchaquí V.	94.98	–	2.58	1.65	0.11	0.29	–	–	–
22	Calchaquí V.	94.00	–	3.07	1.15	0.08	–	–	–	–
23	NWA	93.50	–	0.80	0.25	–	0.50	1.70	–	–
24	NWA	80.40	–	7.70	2.14	0.17	3.25	3.60	–	–
25	Guandacol	69.39	–	–	25.07	0.49	1.32	–	–	–
26	NWA	84.80	–	7.80	0.24	0.10	0.22	3.82	–	–
27	Baradero	66.00	–	0.59	27.58	tr	1.01	–	–	–
28	Baradero	68.24	25.77	0.15	–	–	3.17	–	0.73	–
29	Sta. Fe La Vieja	84.15	1.34	10.50	–	–	1.26	–	–	–
30	Yocavil V.	83.62	–	16.37	–	–	–	–	–	–
31	Yocavil V.	92.15	–	4.82	–	–	–	–	–	–
32	Yocavil V.	98.07	–	–	–	–	–	–	–	–
33	Yocavil V.	94.01	–	–	–	–	–	4.66	–	–
34	Yocavil V.	90.45	–	–	9.54	–	–	–	–	–
35	Yocavil V.	83.74	–	15.51	–	–	–	–	–	–
36	Yocavil V.	94.98	–	2.47	–	2.54	–	–	–	–
37	Tafí	69.92	–	23.47	–	–	–	–	–	–
38	Chuscha	93.0	1.5	4.0	–	–	1.1	–	–	0.28

tr trace element, – unknown, *NWA* Northwest Argentina

Years later, Cabanillas et al. (2007) examined and analyzed a third bronze disc, supposedly from an Inka burial located in the Nevado de Chuscha, near Quilmes (Fig. 15.16), at the border between the provinces of Salta and Catamarca. This disc is also exceptional for its size and weight: 58.34 cm average diameter, thickness varies from 0.7 cm at the perimeter to 2.2 cm at the center, and 32.7 kg in weight. In all three discs, both faces are without decoration.

X-ray fluorescence analysis of the body of the metal in the Chuscha disc provided the alloy composition: 93.0 wt% Cu, 4.0 wt% Sn, 1.5 wt% As, 1.1 wt% Pb, 0.28 wt% Cr (Cabanillas et al. 2005). The investigators concluded that the composition of the Chuscha disc is congruent with alloy compositions provided by wet chemical analysis of many other discs and that the Chuscha disc is prehistoric. Given its size, the authors suspect that the molten metal was poured into a cavity prepared in the ground whose surfaces were covered with a fine clay paste prior to the pour.

Reconstruction of the arrangement for casting 33 kg of bronze in a single pour is less certain. Cabanillas et al. (2007) suggest that natural draft furnaces of the *huayra* type (Van Buren and Mills 2005) were capable of smelting the large volume of bronze required for the disc if several furnaces operated simultaneously. The Inka built *huayras* at the metalworking site Rincón Chcio 15, discussed below, and L. R. González (2004) suggests the possibility that the Chuscha disc may have been cast there. These three oversize, cast discs discussed here represent the largest and heaviest tin bronze objects known to date to have been produced anywhere in the prehistoric Andes.

Regional Development Period axes tend to be larger, heavier, and not as finely designed or executed as the La Aguada examples. Two new types appeared. In one, the handle is cast integrally with the blade (Fig. 15.20). In the other, the blade is socketed, to accept a handle. The relief designs on these axes are often in a style associated with communities in the Santa María valley, and the motifis usually include a face or severed head which are also typical icons of the large, oval Santamariana bells (Fig. 15.21).

Table 15.4 (González and Buono 2007a, b) presents published analyses of axes made in Northwest Argentina, with determinations of the chemical composition of a single La Aguada axe (González and Buono 2007a), 36 Regional Development Period axes, and six Inka axes (González and Buono b). Five of the axes are made of copper, the rest are tin bronzes. Two of the bronze alloys have compositions well above the solid solubility limit of tin in copper (13.5 wt%), and these are brittle alloys. Those with tin concentrations at or above 10 wt% would be yellow to golden in color. The average alloy composition of 22 Regional Development Period axes with a tin concentration below 10 wt% is Cu, 5.3 wt% Sn.

Large, oval, tin bronze bells (Fig. 15.21) constitute the third member of the Northwest Argentine disc–axe–bell set of ritual paraphernalia. Only slightly more than thirty bells are known, none of them with secure provenience, although many have been found in the *valliserrana.* Their broad distribution implies a symbolic content in their iconography, in their form, and in their metallic, two-tone sounds that transcended ethnicities and were shared within a common religious tradition (González 2004; González and Cabanillas 2004). The predominance of cephalic representations on these bells, as well as on the Regional Development Period plaques and axes, suggests the importance of the severed head—perhaps first human, then animal—in ceremonial activities (González 1992, 2004).

Table 15.5, compiled by Luis González (personal communication 2009; L. R. González and Cabanillas 2004), presents the alloy compositions determined and published for seven intact bells or bell fragments together with two unpublished laboratory analyses for the Cafayate and Northwest Argentine bells. All are tin bronzes.

Table 15.4 Compositions of axes from Northwest Argentina: Aguada, Regional Development Period, and Inka. (After L. R. González and Buono 2007a, b, Table 1)

Period	No.	Provenience	Cu	As	Sn	Zn	Fe	Pb	Ni	Ag
			[wt%]							
Middle (Aguada)	1	NWA	91.00	–	6.31	–	0.92	–	–	–
	2	NWA	96.53	–	3.21	–	–	–	–	–
	3	NWA	91.98	–	7.53	–	–	–	–	–
	4	NWA	93.19	–	6.31	–	–	–	–	–
	5	Santa María	94.26	–	5.73	–	–	tr	–	–
	6	San Carlos	94.66	–	3.86	–	0.45	tr	0.90	–
	7	Averías	94.82	–	4.64	–	–	–	–	–
	8	Sequía Vieja	91.84	–	5.94	–	–	tr	–	–
	9	Sequía Vieja	89.32	–	10.60	–	tr	–	–	–
	10	Chilca Pozo	94.96	–	2.82	–	1.24	–	0.66	–
	11	Mutquin	92.44	–	6.57	–	–	–	–	–
	12	Averías	93.23	–	6.37	–	–	–	–	–
	13	Sequía Vieja	94.80	–	5.18	–	–	–	–	–
	14	Tolombón	92.49	–	6.72	–	0.52	tr	–	–
	15	Mendoza	87.05	0.28	7.53	–	–	8.14	–	–
	16	NWA	89.50	–	10.30	–	–	–	–	–
	17	NWA	92.83	–	2.68	–	0.35	–	–	–
	18	NWA	99.60	–	0.30	–	–	–	–	–
Late Regional Development [lines 2–37]	19	NWA	83.50	–	6.00	0.20	0.33	0.41	0.10	3.65
	20	NWA	89.98	–	0.15	–	0.78	–	–	–
	21	NWA	86.70	–	8.30	–	–	–	–	4.30
	22	Santa María	94.22	–	1.96	–	–	–	–	–
	23	Santa María	93.87	–	6.12	–	–	–	–	–
	24	La Toma	99.84	–	–	–	0.07	–	–	–
	25	NWA	85.41	tr	12.87	–	tr	–	–	–
	26	La Paya	99.10	–	–	–	0.46	0.30	–	–
	27	NWA	98.45	–	–	–	tr	–	–	–
	28	NWA	97.19	–	1.92	–	0.42	tr	–	–
	29	Andalgalá	93.02	–	6.45	–	–	–	–	–
	30	Belén	98.43	–	0.72	–	–	0.42	–	–
	31	NWA	86.87	–	11.44	–	0.64	–	–	–
	32	La Paya	87.72	–	6.40	–	–	–	–	–
	33	Londres	75.77	–	15.96	–	1.78	–	–	–
	34	Luracatao	93.66	–	4.73	–	–	–	–	–
	35	La Paya	98.01	–	–	–	–	–	–	–
	36	NWA	90.82	–	7.88	–	1.29	–	–	–
	37	NWA	81.27	–	12.98	1.60	1.94	–	–	–
	38	Sequía Vieja	96.12	–	3.58	–	–	–	–	–
	39	Jujuy	92.03	–	8.04	–	tr	–	–	–
Imperial (Inka) [lines 38–43]	40	NWA	92.48	–	0.09	–	0.32	–	–	–
	41	NWA	91.50	–	4.00	0.17	0.15	tr	–	3.58
	42	NWA	89.6	–	10.10	–	–	–	–	–
	43	NWA	77.86	–	17.83	–	1.34	–	–	–

tr trace element, – unknown, *NWA* Northwest Argentina

Table 15.5 Compositions of Late Period tin bronze oval bells (tan tanes) from Northwest Argentina. (After González personal communication 2009; González and Cabanillas 2004, Table 15.1)

Provenience	Cu	As	Sn	Fe	Pb
			[wt%]		
Cachi[a]	91.2	–	6.0	tr	tr
Molinos	93.7	–	6.0	0.27	tr
La Paya	95.6	–	3.9	0.29	0.14
NW Argentina	95.0	0.01	4.9	0.02	0.01
Calchaquí Valley	96.9	–	2.5	0.13	tr
Cafayate	96.6	nd	3.4	nd	nd
Rincón Chico[b]	96.7	nd	2.5	nd	nd
Cafayate[c]	84.80	nd	11.01	nd	nd
NW Argentina[c]	87.58	nd	10.02	tr	nd

tr trace element, – unknown, *nd* not detected, *NWA* Northwest Argentina
[a]a large bell fragment
[b]fragment of bell mouth
[c]previously unpublished

Seven fall in the composition range of 2.5–6 wt% Sn, with an average tin concentration of 4.2 wt%. This low tin concentration is expected in a bell that sounds through percussive action, either by an interior clapper or a blow to the exterior surface. Brittleness is to be avoided in bells. Each of these bells was cast in a mold with a solid ceramic core. Two careful studies of such bells (Lechtman and González 1991; González and Cabanillas 2004) have been published, but the investigators have not reached consensus about the design and construction of the mold or on the stage at which the interior surface of the mold was engraved with the motifs that appear in raised relief on the bell surfaces. A few *tan tanes* have been found with wooden clappers, but most were struck on the surface and could produce two different tones: one when struck on the flat faces and a second when struck on the narrow sides (González and Cabanillas 2004). The *tan tanes* are the product of a sophisticated mold-making and foundry technique. Large volumes of bronze metal were involved in their production.

As the size of social entities grew and with that growth the needs of elites to broadcast their religious and political sway, bronzes became larger and heavier. More metal was entailed in each casting event. Production sequences, the technologies of ceramic mold making, the number and scale of operations required to smelt prodigious volumes of metal—all increased in complexity and sophistication. What remained constant was the disc–axe–bell triad of ritual equipment and the alloy type from which these items were made: tin bronze. As Tables 15.3, 15.4, and 15.5 indicate, except for a few outliers among the disc and axe alloy compositions, alloy design remained invariant for all three artifact types. The average tin content of bronze alloys for discs was 3.73 wt%; for axes, 5.3 wt%; and for bells, 4.2 wt%.

There must have been a number of significant metallurgical sites in Northwest Argentina for the smelting, alloying, and casting of tin bronze at the production level suggested by the archaeological artifacts. Nevertheless, Site 15 at Rincón Chico, in the southern sector of the Yocavil (or Santa María) valley (Fig. 15.16), is the only bronze production site to have been excavated intensively, by Luis González and Myriam Tarragó (Tarragó and González 1996; González 2001, 2004). The metallurgical Site 15 at Rincón Chico covers approximately 1,500 m^2. Radiocarbon analyses determined that the workshop operated between the tenth and seventeenth centuries. Activities began there during the Regional Development Period, and the site was reoccupied later by Inka administrators (González 2002, 2004).

Rincón Chico 15 is especially significant, because the archaeological evidence indicates that both the smelting of metallic ores and the casting of bronze artifacts took place there. Ceramic mold and crucible fragments, metallurgical slags, remains of copper mineral, metal discards, and stone tools are abundant at the site. Most mold fragments were for casting discs of small-to-medium size (less than 20 cm in diameter), but larger pieces indicate that approximately 2 kg of metal were required to fill them. The bell mold fragments also fall within a medium-size range. These molds correspond to the classic Santamariana type of discs and bells (Fig. 15.21) (González 2004).

Prior to the Inka administration of the site, ore smelting was carried out in ceramic crucibles (10–15 cm in diameter) placed in shallow, bowl-shaped hearths dug out of the ground. The hearths measure between 50 and 70 cm in diameter. The fire was ventilated by forced draft, likely from some form of blowtube, and analyses of slags and of the thermoalteration of the ceramic refractory materials determined that the temperature achieved within the crucibles was at least 1150 °C (González 2004). Luis González suspects that the product of the smelting operations was prills that were later consolidated and melted in crucibles (González personal communication 2009).

The high-grade copper mineral found at the site (30 wt% Cu in a silicious gangue) is of a type consistent with the copper mineralization at the Las Capillitas (Fig. 15.2) and Cerro Atajo deposits (60–80 km south) as well as with deposits at the extreme southern end of the Yocavil valley, approximately 30 km from the site. The closest tin deposits are between 140 and 170 km to the southeast, in the sierra of Belén (Fig. 15.16) and Fiambalá (González 2004). The remains of 31 bits of metal—both prills and burrs—were analyzed for their composition: 11 were tin bronzes with an average tin concentration of 9.24 wt%; zinc was detected in seven fragments, six of which were brasses with zinc concentrations ranging from 1.42 to 14.84 wt% (González 2002, 2004). Since the mineralization at Las Capillitas includes significant deposits of zinc minerals (Fester 1962), the binary alloys with zinc were likely the result of processing copper ores and ores with a high zinc mineral content.

At about CE 1200, accompanying the growing complexity of social organization at Rincón Chico, the scale of production at the metal workshop increased dramatically, as did the social recognition of the workers who operated it. Luis González argues (2004, pp. 273–274) that these changes were occasioned primarily by two factors: first, a need on the part of the political elite to possess materials of social distinction that were valued in terms of their connections to religious belief structures and for the level of technical knowledge and labor invested in their manufacture; second, an ability of the elites to direct regional and macro-regional interaction networks through the distribution of metal, which translated into an increase in the economic and political power of these elites. In fact, several tin bronze discs of this period have been found in Chile and in Bolivia.

Introduction of Tin Bronze Metallurgy to Northwest Argentina

Northwest Argentina must be considered the center of tin bronze production in the prehistoric Andes. Whereas ceramic molds have been uncovered there for small chisel blanks and simple axes (González 2004), the overwhelming majority of tin bronze objects in this region were large, complex castings. Tin bronze and casting—the alloy and its translation into cultural items—were coupled, and it was this union of material and mode of production that the Inka encountered and incorporated. The technology and its products had been developed to a high level of sophistication and of economic import by political units that were not organized as states nor were they affiliated with states.

Nevertheless, Alberto Rex González argues (1992) that metallurgy as a materials technology must have been introduced to Northwest Argentina during the late Formative or the early Regional Integration Period, because thus far we have no evidence for any prior, indigenous experience with metallurgical activities having developed there. That may be so. Several issues need clarification when considering arguments about the transfer of metallurgical technologies to Northwest Argentina. First, which specific metallurgical technologies or techniques were introduced; second, what group(s) of people provided the metallurgical knowledge and skills, and through what mechanisms was that expertise transmitted; and third, when were specific metallurgical technologies introduced to Northwest Argentina. To date, none of these issues has been resolved on the basis of sufficient archaeological or laboratory-analytical data.

The most unusual aspect of the first florescence of metallurgy in Northwest Argentina, during the Early Integration (or Middle) Period, is the use of the lost wax casting technique to produce complex, circular and rectangular plaques with elaborate motifs rendered in high relief (see Fig. 15.17). Evidence for the lost wax casting of metal objects is rare anywhere in the Central Andes, in the Titicaca Basin, and in the South Central Andes except in Northwest Argentina, when Aguada craftspeople used the technique to cast what González (2004) considers the most elaborate discs of greatest aesthetic and symbolic value. Thereafter, Northwest Argentine discs, axes, and large bells were cast primarily in ceramic piece molds.

Lost wax casting of metal objects was the technique of choice in Colombia (the Northern Andes) and in Central America (Easby 1955; Plazas and Falchetti 1979; Howe 1986). There it developed as a highly sophisticated production process for objects made primarily of gold or *tumbaga*: binary copper–gold alloys or ternary alloys of copper, gold, and silver. The material essential to this casting technology was wax from the stingless honeybee (members of the family *Meliponidae*), the bee that even today provides a bountiful source of beeswax for Colombia as well as for Central America and the eastern lowland (*ceja de selva*) slopes of the Andes (Bird 1979). Alberto Rex González (1979, 1992) suggests that the technique of lost wax casting may have reached Northwest Argentina from Colombia by way of the eastern, lowland zone of the Andes. He sees similarities in certain ritual features common to Colombia that appear in Aguada ritual, such as the "sacrificer" figure depicted on Aguada discs. Another shared feature was the use of the fruit of the cebil tree (*Anadenanthera*) that was ground and smoked as a hallucinogen in a Colombian type of clay pipe found in Northwest Argentina as early as the preceramic period, at least 1,000 years before Aguada.

At the site of Rincón Chico, Luis González (2004) has excavated dozens of small ceramic fragments of molds used in lost wax casting, many of them dating to the CE 1400s (González personal communication 2010). He points out (1994) that the habitat of the stingless honeybee does not extend to the *valliserrana* of Northwest Argentina. On the other hand, González reports (1994) that the retamo plant (*Bulnesia retama*), common to semiarid regions of the *valliserrana*, exudes large quantities of "wax." On the basis of what we know about pre-Columbian methods of lost wax casting (see, e.g., Easby 1955; Plazas and Falchetti 1979), González cast an 85 wt% Pb–15 wt% Sn, low-melting alloy[10] into a ceramic mold made from a lost retamo wax model (1994). The experiment was successful.

With respect to the religious iconography of Aguada, Alberto Rex González (1992, p. 196) maintains that one of the primary figures on Aguada discs, the sun god motif, derives from similar symbolic images emanating from the circum-Titicaca region, most especially from Tiwanaku. He cites archaeological evidence that these influences likely reached Aguada from the Chilean desert oasis of San Pedro de Atacama which, as mentioned earlier, was an important node on the heavily trafficked route between Tiwanku and points south. After about CE 600, González (1992, p. 196) concludes, it must have been influences from Tiwanaku that brought both the religious cult and the technique of bronze casting to Aguada, giving rise to the plaques that exhibit the sun deity prominently, such as the Lafone Quevedo disc (Fig. 15.17).

The evidence provided by Lechtman's investigations of Middle Horizon, copper-based metal artifacts at Tiwanaku (2003a) and San Pedro de Atacama (Lechtman and Macfarlane 2005) is illuminating. Referring to Table 15.1, between the Late Formative 2 Phase and the Early Tiwanaku IV Phase (CE 250–600), 82 % of the 11 artifacts Lechtman analyzed from Tiwanaku and Lukurmata were made from the ternary alloy of copper, arsenic, and nickel; 9 % are copper–arsenic bronzes; 9 % are copper–tin bronzes (Lechtman 2003a, Table 17.6). Of an additional 11 artifacts dated to between Late Tiwanaku IV and Early Tiwanaku V (CE 800–1000), 55 % continued to be made from the ternary bronze alloy and 27 % were made of tin bronze. With regard to 36 bronze axes from San Pedro de Atacama attributed to the Middle Horizon, Lechtman determined that 61 % are made from the ternary Cu–As–Ni bronze alloy and the remainder are made of tin bronze (Lechtman and Macfarlane 2005, Table 15.4).

The binary tin bronze Ciénaga artifacts (Table 15.2) made during the Formative Period in Northwest Argentina (500 BCE to CE 450) were produced at a time when

[10] Lead–tin alloys are used commonly today as solders. This particular alloy begins to melt at a temperature of about 290 °C.

Tiwanaku was just beginning to experiment with the production and use of tin bronze. Even at the height of Tiwanaku's expansion, between about CE 600 and 800, which occurred towards the end of the Regional Integration Period (La Aguada) in Northwest Argentina (CE 450–900), only about 27 % of the artifacts at Tiwanaku were made of tin bronze; 55 % were still being made of the ternary Cu–As–Ni bronze alloy (Table 15.1) (Lechtman 2003a, Table 17.6). These analytical data were not available at the time A. R. González (1992) offered his interpretation of the relationships between the metallurgies of Tiwanaku and of the *valliserrana*, but they need to be taken into serious consideration now. In addition, there are no definitive examples of large, heavy castings of tin bronze having been produced in the circum-Titicaca region until the occupation of that zone by the Inka during the Late Horizon. Northwest Argentine communities were masters of tin bronze casting, and their castings were symbolic emblems that served religion and the heads of political domains.

The Inka: Tin Bronze and the Central Andean Three-component Metallurgy System

The Inka conquered territories far to the north and even farther to the south of their Central Andean highland base at Cuzco (Fig. 15.1). The push to their southern, frontier regions was prompted, in part, by an interest in the rich metallic mineral resources at the southeastern reaches of Lake Titicaca (gold), on the Bolivian *puna* (silver and tin), and ultimately in Northwest Argentina (copper and tin). Their overthrow of the extensive Chimú kingdom on the Peruvian north coast (ca. CE 1476) gave the Inka access to the smelting site at Batán Grande where production of arsenic bronze had continued since Sicán establishment of that facility. Under Inka direction, the ore grinding sectors were separated from the smelting furnaces (Epstein and Shimada 1983; Shimada 1985), but Batán Grande does not appear to have operated for long under imperial administration.

On the other hand, in the *valliserrana* of Northwest Argentina the production of tin bronze at Rincón Chico 15 increased dramatically under Inka management (González 2002, 2004). The area of the workshop expanded, the Inka installed *huayra*-like ore smelting furnaces to increase the yield of metal produced, and the rate at which smelting events occurred accelerated. Local metalworkers who had traditionally operated the workshop continued to do so, but the earlier crucible–hearth complex was relegated primarily to refining smelted metal and to melting metals and alloys prior to casting. The volume of refractory ceramic sherds from crucibles and molds attests to the significant increase in bronze production at Rincón Chico 15 under imperial reorganization. Fragments of molds for lost wax casting indicate the conservation of that technique and its use during the Inka presence (González 2002, 2004).

The Inka management style Luis González reports for Rincón Chico 15—expansion of the scale of production for state purposes while allowing indigenous

	Tumi	Mace	Axe	Axe-mace
ECUADOR	✓	✓	few	✓
BOLIVIA	✓	✓	✓	✓
CHILE	few	few	few	few
ARGENTINA	✓	✓	✓	--

Fig. 15.22 Inka standard tin bronze tools, arms, and insignia found widely dispersed throughout *Tawantinsuyu*. (Lechtman 2007, Fig. 15.17)

activities to continue—is similar to that recorded at other Inka mining and ore processing sites in the frontier regions, such as the gold mining operation at Chuquiabo (Berthelot 1978), at the extreme southeastern border of Lake Titicaca. In the case of Rincón Chico 15, metalworkers continued to make large bronze discs and bells for the religious and political purposes of local elites.

The Inka repertoire in cast bronze was different, however. Their products were literally tools of the state: fancy *tumi* knives, star-lobed maces, T-shaped axes, and a combination axe–mace head (Fig. 15.22; Lechtman 2007, Fig. 15.18). Except for some items that may have been used locally, few of these objects were intended for utilitarian purposes or as weapons. They were disseminated widely throughout *Tawantinsuyu* as imperial insignia, symbols of Inka dynastic rule but also of membership in the state.

The evidence from Northwest Argentina is clear. The Inka appropriated a metallurgical complex entirely new to them and that had been perfected in the *valliserrana* for centuries. This complex combined tin bronze alloys with intricate mold casting techniques to confine and shape the molten metal. The technology was founded on the expertise and production organizational skills of a local body of metalworkers. The Inka eschewed any local religious connotations for their imperial products, concentrating instead on enhancing their political symbolism.

Moreover, tin bronze became the imperial metal throughout *Tawantinsuyu* in the sense that the Inka controlled the cassiterite sources in Bolivia and Northwest Argentina. Tin bronze was an exotic material everywhere in the empire except in the South Central Andes where communities had produced the alloy since at least the early years of the Middle Horizon. Luis González (2002, 2004) comments that, on the basis of analyses carried out on Inka tin bronze artifacts from La Paya, Calchaquí valley (Fig. 15.16), there was no attempt by the Inka there to standardize alloy design. The average tin concentration characteristic of Regional Development Period disc and bell bronzes did not change in those same object types that were produced during the Inka occupation of the region. A large ingot mold uncovered at Rincón Chico 15 as well as several similar molds excavated at Valdéz (Fig. 15.16), in the Calchaquí Valley, Salta Province (González 2004, p. 306; Earle 1994, Fig. 15.3), appear to have been used for casting copper ingots, which suggests that bronze alloys may have been made by melting copper and tin together.

The Inka contribution to Andean metallurgy lay in the large-scale production and widespread distribution of tin bronze. When tin bronze was associated physically with other metals on a single object, whether as an inlay or as the matrix material that carried the inlay, the association was always with two or frequently all three of the Central Andean triad metals: copper, silver, and gold. It may be that high-tin bronze, with its yellow-gold color, took the part of gold in objects that represented tool-like items (knives, axes, finials), even if they did not function as tools (Lechtman 2007, p. 330–332, Figs. 15.11 and 15.12).

Inka use of the metal triad went much deeper, however, than the assignment of these metals to objects, together or in specific patterns, to evoke cultural associations familiar to Andean peoples. They assigned the metals to social groups within the empire, relying upon specific relationships among the three metals as those relationships were recounted in an Andean coastal creation myth. Vichama, a son of the Sun, seeing that the world is without people and that the shrines and the Sun have no one to worship them, begs his father to create a new set of human beings. The Sun sends three eggs: one of gold, one of silver, and one of copper. From the golden egg issued the nobles and "principals"; from the silver egg the wives of the latter; and from the copper egg the common people (Duviols 1983; Lechtman 2007).

Lechtman (2007, p. 323) has suggested that in *Tawantinsuyu*, the metals of the myth—the three-component Central Andean system—were related within a structural hierarchy established by the Inka in which each metal represented or was emblematic of a social group: gold = *collana*, silver = *payan*, copper = *cayao* (Bauer 1998). Zuidema (1977) renders the terms *collana* as signifying principal or first; *payan*, second or middle; and *cayao*, origin or source. These terms appear to apply to an Inka conquest hierarchy in which *collana* stands for the conquerors (the Inka) or insiders, *cayao* for the conquered (the groups incorporated into the empire) or outsiders, and *payan* for the intermarriages of the first two, resulting in those "in the middle" (Lechtman 2007, p. 323). The Inka appropriated the traditional Andean gender and transformational associations of the three metals, associations already in place and manifest in Moche metallurgical practice, and fitted them onto an organizational framework in which each material represented a social segment within the empire.

In this scheme, copper remained the female source or origin metal (*cayao*) which, in combination with the other two, retained its primary quality or power of transformation. *Cayao* represented fertility. It was the social group from which the Inka (*collana*) took secondary wives. *Cayao* was the source of the real strength of the empire, for its ranks ensured the vitality and continuity of the royal lineages. *Cayao* was copper.

> These metals provided ideological tools, not mechanical tools, to the state. Even tin bronze, which the Inka clearly intended for widespread distribution, had not seen significant innovative use by the time of the Spanish invasion. (Lechtman 2007, p. 342)

Metallurgy in Andean Hands

The metallurgies that developed in the Andean region in prehistory were pan-Andean in the materials they used, in the inventories they produced, and in the social and cultural domains in which they functioned. They were copper-based, tool-poor, information-bearing technologies. They depended upon Andean metallic ore deposits that, except for tin-bearing ores such as cassiterite, were local, abundant, rich, and accessible. Similar societal preoccupations and needs stimulated the production of metal objects everywhere. For example, major metal object types throughout the Andes, such as the axe, were symbolic cultural elements, not primarily utilitarian tools, regardless of the alloys from which they were made or how they were fashioned.

Given the major social arenas in which metal objects played a significant role and in which metal served to communicate social status, political power, and religious authority and awe, metalworkers throughout the Andes sought and developed those properties of metal that served these purposes. At the same time, Andean societies generated two distinct traditions for the rendering of metal objects. Each tradition was devoted to what appears to be a cultural attitude towards metal as a material (Lechtman 1993). Central Andean metalworkers focused entirely on metal as a solid. An essential property of solid metal—plasticity—enabled form to be realized through plastic deformation. South Central Andean metalworkers concentrated on metal as a liquid, enabling form to be realized through casting the molten material into a variety of mold types.

These two traditions shared an overriding emphasis on the physical properties—as distinct from the mechanical properties—of metal. Metallic colors, together with specific mechanisms for generating culturally required colors, preoccupied Central Andean smiths. Color but more emphatically metallic sounds generated by large tin bronze bells were critical to ritual enactments sponsored by religious and political elites in Northwest Argentina. It was precisely these two metallic properties—color and sound—that West Mexican societies appropriated from pan-Andean metallurgies (including those practiced in Colombia) and which they then emphasized and tailored to their own social and cultural dictates (Hosler 1988, 1995, 1994, this volume). Dorothy Hosler recognizes them as "the sounds and colors of power" (Hosler 1994).

References

Acuto, F. A. (2008). Experiencing Inca domination in Northwestern Argentina. In H. Silverman & W. H. Isbell (Eds.), *Handbook of South American Archaeology* (pp. 845–861). New York: Springer.

Aldenderfer, M. S., Craig, N. M., Speakman, R. J., & Popelka-Filcoff, R. (2008). Four-thousand-year-old gold artifacts from the Lake Titicaca basin, southern Peru. *Proceedings of the National Academy of Science*, *105*(13), 5002–5005.

Alva, W. (2001). The royal tombs of Sipán: art and power. In J. Pillsbury (Ed.), *Moche Art and Archaeology in Ancient Peru* (pp. 223–245). Washington, D.C.: Dumbarton Oaks Research Library and Collection.

Alva, W., & Donnan, C. B. (1993). Royal Tombs of Sipán, Fowler Museum of Cultural History. Los Angeles: University or California.

Ambrosetti, J. B. (1904). El bronce en la región Calchaquí. *Anales del Museo Nacional de Buenos Aires T.*, *11*, 163–314.

American Society for Metals. (1985). Metals Handbook. In H. E. Boyer & T. L. Gall (Eds.), Section 1.3.8, ASM. Ohio: Metals Park.

Bauer, B. S. (1998). The sacred landscape of the Inca. Austin: University of Texas Press.

Bernier, H. (2008). Especialización artesanal en el sitio Huacas de Moche. In L. J. Castillo, H. Bernier, G. Lockard, & Y. J. Rucabado (Eds.), *Fondo Editorial* (pp. 33–51). Lima: Pontificia Universidad Católica del Perú.

Bernier, H. (2010). Craft specialists at Moche: Organization, affiliations, and identities. *Latin American Antiquity*, *21*(1), 22–43.

Berthelot, J. (1978). L'exploitation des métaux précieux au temps des Incas. *Annales: Économies, Sociétés, Civilisations 33*(5–6), 948–966.

Bezúr, A. (2003). Variability in Sicán copper alloy artifacts: Its relation to material flow patterns during the middle Sicán period in Peru, AD 900–1100, UMI Dissertation Services, Ann Arbor.

Biloni, H., Kiss, F., Palacios, T., & Vasallo, D. (1990). Análisis metalográfico de la placa de Lafone Quevedo. Serie Difusión 7, Comisión de Investigaciones Científicas, La Plata.

Bird, J. (1979). Legacy of the stingless bee. *Natural History*, *88*(9), 49–51.

Boman, É. (1908). *Antiquités de la Région Andine de la République d'Atacama*. Paris: Imprimerie Nacionale.

Boone, E. H. (Ed.). (1996). Andean art at Dumbarton Oaks, Vol. 1, Dumbarton Oaks Research Library and Collection, Washington, D.C.

Bourget, S. (2008). The third man: Identity and rulership in Moche archaeology and visual culture. In S. Bourget & K. L. Jones (Eds.), *The art and archaeology of the Moche* (pp. 263–288). Austin: University of Texas Press.

Burger, R. L. (1988). Unity and heterogeneity within the Chavín horizon. In R. W. Keatinge (Ed.), *Peruvian Prehistory* (pp. 99–144). Cambridge: Cambridge University Press.

Burger, R. L. (1992). *Chavin and the origins of Andean civilization*. London: Thames and Hudson.

Burger, R. L., & Gordon, R. B. (1998). Early central Andean metalworking from Mina Perdida, Peru. *Science 282*, 1108–1111.

Burger, R. L., & Lechtman, H. (1996). Chavín. In E. H. Boone (Ed.), *Andean art at Dumbarton Oaks* (pp. 45–75). Washington, D.C.: Dumbarton Oaks Research Library and Collection.

Burger, R. L., Mohr Chávez, K. L., & Chávez, S. L. (2000). Through the glass darkly: Prehispanic obsidian procurement and exchange in southern Peru and northern Bolivia. *Journal of World Prehistory*, *14*(3), 267–362.

Cabanillas, E., González, L. R., & Palacios, T. A. (2002). Three new Aguada bronze plaques from Northwest Argentina. *Bulletin, Institute for Archaeo-Metallurgical Studies*, *22*, 12–14.

Cabanillas, E., González, L. R., Palacios, T. A., & Eppis, M. R. (2007). Estudios sobre un disco de bronce prehispánico del Noroeste argentino. In A. Pifferetti & R. Bolmaro (Eds.), Actas, Primer Congreso Argentino de Arqueometría, Humanidades y Artes Ediciones, Rosario, pp. 59–69.

Caley, E. R., & Easby, D. T. Jr. (1959). The smelting of sulfide ores of copper in preconquest Peru. *American Antiquity*, *25*(1), 59–65.

Castillo, L. J., & Uceda, S. (2008). The Mochicas. In H. Silverman & W. H. Isbell (Eds.), *Handbook of south American archaeology* (pp. 707–730). New York: Springer.

Classen, C. (1993). *Inca cosmology and the human body*. Salt Lake City: University of Utah Press.

Cobo, B. (1964) [1653]. Historia del Nuevo Mundo. In P. F. Mateos (Ed.), *Obras, Biblioteca de Autores Españoles 92*. Madrid: Atlas.

Costin, C. L., Earle, T. K., & Owen, B. (1989). The impact of Inca conquest on local technology in the upper Mantaro valley, Peru. In S. Van der Leeuw & R. Torrence (Eds.), *What's new? A closer look at the process of innovation* (pp. 107–139). London: Unwin Hyman.

Cruz, P. (in press). El brillo del señor sonriente: Miradas alternativas sobre las placas metálicas surandinas. *Journal de la Société des Américanistes*, Paris.

Donnan, C. B. (1978). *Moche art of Peru, museum of cultural history*. Los Angeles: University of California.

Donnan, C. B., & Castillo, B. L. J. (1992). Finding the tomb of a Moche Princess. *Archaeology*, *45*(6), 38–42.

Donnan, C. B., & Castillo, B. L. J. (1994). Excavaciones de tumbas de sacerdotistas Moche en San José de Moro, Jequetepeque. In C. S. Uceda & B. E. Mujica (Eds.), *Moche: Propuestas y Perspectivas, Travaux de l'Institut Français D'Études Andines, T. 79* (pp. 415–424). Trujillo: Universidad Nacional de La Libertad.

Donnan, C. B., & Cock, G. A. (Eds). (1997). *The Pacatnamu Papers. Vol. 2, Museum of Cultural History*. Los Angeles: University of California.

Duviols, P. (1983). El *Contra idolatrium* de Luis de Teruel y una versión primeriza del mito de Pachacamac-Vichama. *Revista Andina*, *1*(2), 385–392.

Earle, T. K. (1994). Wealth finance in the Inka empire: evidence from the Calchaquí valley, Argentina. *American Antiquity*, *59*(3), 443–460.

Easby, D. T. Jr. (1955). Sahagún y los orfebres precolombinos de México. *Anales del Instituto Nacional de Antropología e Historia*, *9*, 85–117.

Eckmann, C. (n.d.). Technologische untersuchungen zu vergoldungstechniken der Moche kultur an objekten aus dem fürstengrab von Sipan. In Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz, author's manuscript.

Epstein, S. M., & Shimada, I. (1983). Metalurgia de Sicán: una reconstrucción de la producción de la aleación de cobre en el Cerro de los Cementerios, Perú. *Beiträge zur Allgemeinen und Vergleichenden Archäologie*, *5*, 379–430.

Fester, G. A. (1962). Copper and copper alloys in ancient Argentina. *Chymia*, *8*, 21–31.

Gluzman, G. (2008). Producción metalúrgica de bienes utilitarios en el noroeste argentino prehispáncio. In M. Tarragó & L. R. González (Eds.), *Estudios Arqueológicos en Yocavil* (pp. 177–224). Buenos Aires: Museo Etnográfico.

González, A. R. (1979). Pre-Columbian metallurgy of Northwest Argentina. In E. P. Benson (Ed.), *Pre-Columbian Metallurgy of South America* (pp. 133–202). Washington, D.C.: Dumbarton Oaks Research Library and Collection.

González, A. R. (1992). *Las Placas Metálicas de los Andes del Sur*. Mainz: Verlag Philipp von Zabern.

González, L. R. (1994). El caso de la cera perdida. Metalurgia prehispánica y recursos en el valle de Yocavil. *Relaciones de la Sociedad Argentina de Antropología*, *19*, 171–190.

González, A. R. (1998). Cultura La Aguada. Arqueología y Diseños. Buenos Aires: Filmediciones Valero.

González, L. R. (2001). Tecnología y dinámica social. La producción metalúrgica prehispánica en el Noroeste argentino. Tesis Doctoral, Facultad de Filosofía y Letras, Universidad de Buenos Aires, Buenos Aires.

González, L. R. (2002). Heredarás el bronce. Incas y metalurgias en el Noroeste argentino. *Intersecciones en Antropología*, *3*, 55–68. (Olavarvía, Argentina).

González, L. R. (2004). *Bronces Sin Nombre*. Buenos Aires: Ediciones Fundación CEPPA.

González, L. R., & Buono, H. (2007a). La metalurgia del Período de Integración en el Noroeste argentino. Estudios técnicos sobre un hacha Aguada. In E. Néspolo, M. Ramos, & B. Goldwaser (Eds.), *Signos en el Tiempo y Rastros en la Tierra, T. 2* (pp. 37–43). Luján: Universidad Nacional de Luján.

González, L. R., & Buono, H. (2007b). Hachas y cetros de metal del Noroeste argentino prehispánico. *Revista Andina*, *44*, 175–195.

González, L. R., & Cabanillas, E. D. (2004). Las campanas ovales de bronce del Noroeste argentino prehispáncio. *Revista Andina*, *38*, 225–251.

Grossman, J. W. (1972). An ancient goldworker's tool kit. *Archaeology*, *25*(4), 270–275.

Hastings, C. M., & Moseley, M. E. (1975). The adobes of Huaca del Sol and Huaca de la Luna. *American Antiquity*, *40*(2), 196–203.

Hirao, Y., Ohnishi, J., Ohnuki, Y., & Kato, Y. (1992). Chemical composition of samples excavated from Kuntur Wasi archaeological site, Peru. *Archaeology and Natural Science*, *25*, 13–30.

Holm, O. (1978). Hachas monedas del Ecuador. In R. Matos (Ed.), *Actas y Trabajos del 3° Congreso Peruano, El Hombre y la Cultura Andina I* (pp. 347–361). Lima: Editora Lasontay.

Hörz, G., & Kallfass, M. (2000). The treasure of gold and silver artifacts from the royal tombs of Sipán, Peru—A study on the Moche metalworking techniques. *Materials Characterization*, *45*, 391–420.

Hosler, D. (1986). *The origins, technology, and social construction of ancient west Mexican metallurgy*. PhD. Dissertation, University of California, Santa Barbara.

Hosler, D. (1988). Ancient west Mexican metallurgy: South and central American origins and west Mexican transformations. *American Anthropologist*, *90*(4), 832–855.

Hosler, D. (1994). *The sounds and colors of power*. Cambridge: MIT Press.

Hosler, D. (1995). Sound, color and meaning in the metallurgy of ancient west Mexico. *World Archaeology*, *27*(1), 100–115.

Hosler, D., Lechtman, H., & Holm, O. (1990). Axe-Monies and their relatives. *Studies in Pre-Columbian art and archaeology 30*. Washington, D.C: Dumbarton Oaks Research Library and Collections.

Howe, E. G. (1986). Estudio radiográfico de colgantes de oro fundidos al vacío de Sitio Conte. In C. Plazas (Ed.), *Metalurgia de América Precolombina*, (pp. 169–200). Bogotá: Banco de la República.

Howe, E. G., & Petersen, U. (1994). Silver and lead in the late prehistory of the Mantaro Valley, Peru. In D. Scott & P. Meyers (Eds.), *Archaeometry of Pre-Columbian sites and artifacts* (pp. 183–198). Los Angeles: The Getty Conservation Institute.

Isbell, W. H., & McEwan, G. F. (1991). A history of Huari studies and introduction to current interpretations. In W. Isbell & G. McEwan (Eds.), *Huari administrative structure* (pp. 1–17). Washington, D.C.: Dumbarton Oaks Research Library and Collections.

Isbell, W. H., & Cook, A. G. (2002). A new perspective on Conchopata and the Middle Horizon. In H. Silverman & W. Isbell (Eds.), *Andean Archaeology II* (pp. 249–305). New York: Kluwer Academic.

Janusek, J. W. (2003). Vessels, time, and society: toward a ceramic chronology in the Tiwanaku heartland. In A. L. Kolata (Ed.), *Tiwanaku and Its Hinterland 2* (pp. 30–91). Washington, D.C.: Smithsonian Institution Press.

Jones, J. (2001). Innovation and resplendence: Metalwork for Moche lords. In J. Pillsbury (Ed.), *Moche art and archaeology in ancient Peru* (pp. 207–221). Washington, D.C.: Dumbarton Oaks Research Library and Collections.

Kato, Y. (1993). Resultados de las excavaciones en Kuntur Wasi, Cajamarca. In L. Millones & Y. Onuki (Eds.), *El Mundo Ceremonial Andino, Senri Ethnological Studies 37* (pp. 203–228). Osaka: National Museum of Ethnology.

Kolata, A. L. (1993). *The Tiwanaku: Portrait of an Andean civilization*. Oxford: Blackwell.

Latcham, R. E. (1938). *Arqueología de la Región Atacameña*. Santiago: Prensas de la Universidad de Chile.

Lechtman, H. (1973). The gilding of metals in Pre-Columbian Peru. In W. Young (Ed.), *Application of science in examination of works of art* (pp. 38–52). Boston: Boston Museum of Fine Arts.

Lechtman, H. (1977). Style in technology—Some early thoughts. In H. Lechtman & R. S. Merrill (Eds.), *Material culture: Styles, organization, and dynamics of technology* (pp. 3–20). St. Paul: West Publishing Co.

Lechtman, H. (1979). Issues in Andean metallurgy. In E. Benson (Ed.), *Pre-Columbian metallurgy of South America* (pp. 1–40). Washington, D.C: Dumbarton Oaks Research Library and Collections.

Lechtman, H. (1980). The central Andes—metallurgy without iron. In T. Wertime & J. Muhly (Eds.), *The coming of the age of iron* (pp. 267–334). New Haven: Yale University Press.

Lechtman, H. (1981). Copper-arsenic bronzes from the north coast of Peru. *Annals of the New York Academy of Sciences*, *376*, 77–122.
Lechtman, H. (1984). Technical examination of a gold-alloy object from Chavín de Huántar, Peru. In R. L. Burger (Ed.), *The Prehistoric Occupation of Chavín de Huántar, Peru* (pp. 271–276, figs. 436–445). Berkeley: University of California Press.
Lechtman, H. (1988). Traditions and styles in Central Andean metalworking. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 344–378). Cambridge: MIT Press.
Lechtman, H. (1991a). The production of copper-arsenic alloys in the Central Andean culture area: Highland ores and coastal smelters? *Journal of Field Archaeology*, *18*, 43–76.
Lechtman, H. (1991b). Pre-Columbian metallurgy: Values and technology. In *America's Vanished Metalsmiths* (pp. 9–18, 36). Santiago de Chile: Museo Chileno de Arte Precolombino.
Lechtman, H. (1993). Technologies of power: The Andean case. In J. S. Henderson & P. J. Netherly (Eds.), *Configurations of power* (pp. 244–280). Ithaca: Cornell University Press.
Lechtman. H. (1996a). Arsenic bronze: Dirty copper or chosen alloy? *Journal of Field Archaeology*, *23*, 477–514.
Lechtman, H. (1996b). Chavín, technical discussions. In E. H. Boone (Ed.), *Andean Art at Dumbarton Oaks, Burger, R. and Lechtman, H. chapter on Chavín* (pp. 52–75). Washington, D.C.: Dumbarton Oaks Research Library and Collections.
Lechtman, H. (1996c). Cloth and metal: The culture of technology. In E. Boone (Ed.), *Andean art at Dumbarton Oaks* (pp. 33–43) Washington, D.C: Dumbarton Oaks Research Library and Collections.
Lechtman, H. (1996d). The Andean world. In E. Boone (Ed.), *Andean Art at Dumbarton Oaks* (pp. 15–32). Washington, D.C.: Dumbarton Oaks Research Library and Collections.
Lechtman, H. (1997). El bronce arsenical y el Horizonte Medio. In R. Varón & E. J. Flores (Eds.), *Arqueología, Antropología e Historia en los Andes* (pp. 153–186). Lima: Instituto de Estudios Peruanos.
Lechtman, H. (1998). Architectural cramps at Tiwanaku: Copper-arsenic-nickel bronze. In Th. Rehren, A. Hauptmann, & J. Muhly (Eds.), *Metallurgica Antiqua, Der Anschnitt 8* (pp. 77–92). Bochum: Bergbau-Museum.
Lechtman, H. (1999). Afterword. In M.-A. Dobres & C. Hoffman (Eds.), *The social dynamics of technology* (pp. 223–232). Washington, D.C.: Smithsonian Institution Press.
Lechtman, H. (2003a). Tiwanaku period (Middle Horizon) bronze metallurgy in the lake Titicaca basin: A preliminary assessment. In A. L. Kolata (Ed.), *Tiwanaku and its hinterland 2* (pp. 404–434). Washington, D.C.: Smithsonian Institution Press.
Lechtman, H. (2003b). Middle Horizon bronze: Centers and outliers. In L. van Zelst (Ed.), *Patterns and process* (pp. 248–268).Washington, D.C.Smithsonian Center for Materials Research and Education.
Lechtman, H. (2005). Arsenic bronze at Pikillacta. In G. McEwan (Ed.), *The Wari Occupation of Cuzco* (pp. 131–146). Iowa City: University of Iowa Press.
Lechtman, H. (2007). The Inka, and Andean metallurgical tradition. In R. Burger, C. Morris, & R. Matos (Eds.), *Variations in the Expression of Inka Power* (pp. 323–365). Washington, D.C.: Dumbarton Oaks Research Library and Collections.
Lechtman, H., & González, A. R. (1991). Análisis técnico de una campana de bronce estañífero de la cultura Santa María, Noroeste argentino. *Boletín del Museo Chileno de Arte Precolombino*, *5*, 81–85.
Lechtman, H., & Klein, S. (1999). The production of copper-arsenic alloys (arsenic bronze) by cosmelting: Modern experiment and ancient practice. *Journal of Archaeological Science*, *26*(5), 497–526.
Lechtman, H. N., & Macfarlane, A. (2005). La metalurgia del bronce en los Andes Sur Centrales: Tiwanaku y San Pedro de Atacama. *Estudios Atacameños*, *30*, 7–27.
Lechtman, H., & Macfarlane, A. (2006). Bronce y redes de intercambio andino durante el Horizonte Medio: Tiwanaku y San Pedro de Atacama. In H. Lechtman (Ed.), *Esferas de Interacción*

Prehistóricas y Fronteras Nacionales Modernas: Los Andes Sur Centrales (pp. 503–539). Lima: Instituto de Estudios Peruanos.

Leoni, J. B., & Acuto, F. A. (2008). Social landscapes in Pre-Inka Northwestern Argentina. In H. Silverman & W. H. Isbell (Eds.), *Handbook of south American archaeology* (pp. 587–603). New York: Springer.

Lothrop, S. K. (1941). Gold ornaments of Chavín style from Chongoyape, Peru. *American Antiquity*, *6*(3), 250–262.

Mathewson, C. H. (1915). A metallographic description of some ancient Peruvian bronzes from Machu Picchu. *American Journal of Science*, *190*(240), 525–616.

Mayer, E. F. (1994). *Armas y Herramientas de Metal Prehispánicas en Bolivia, Materialien zur Allgemeinen und Vergleichenden Archäologie* (*53*). Mainz: Verlag Philipp von Zabern.

McEwan, G. F. (Ed.). (2005). *Pikillacta: The Wari empire in Cuzco*. Iowa City: University of Iowa Press.

Merkel, J. F., & Velarde, M. I. (2000). Naipes: Pre-Hispanic axe money currency of Peru. *Minerva*, *11*(1), 52–55.

Merkel, J. F., Shimada, I., Swann, C. P., & Doonan, R. C. P. (1994). Pre-Hispanic copper alloy production at Batán Grande, Peru: Interpretation of the analytical data for ore samples. In D. Scott & P. Meyers (Eds.), *Archaeometry of Pre-Columbian sites and artifacts* (pp. 199–227). Los Angeles: Getty Conservation Institute.

Moseley, M. E. (1975). Prehistoric principles of labor organization in the Moche Valley, Peru. *American Antiquity*, *40*(2), 191–196.

Moseley, M. E., Donnan, C. B., & Keefer, D. K. (2008). Convergent catastrophe and the demise of Dos Cabezas: Environmental change and regime change in ancient Peru. In S. Bourget & K. Jones (Eds.), *The art and archaeology of the Moche* (pp. 81–91). Austin: University of Texas Press.

Murra, J. V. (1974). Andean cultures. *Encyclopedia Britannica* (15) (pp. 854–856). Chicago: Helen Hemingway Benton.

Nordenskiöld, E. (1921). *The Copper and Bronze Ages in south America. Comparative Ethnographical Studies* (*4*). Göteborg: Elanders Boktryckeri Aktiebolag.

Nordenskiöld, E. (1931). *Ancient Colombian tools of Gold alloy* (*Au-Ag-Cu*). *Comparative Ethnographical Studies* (*9*), *Appendix 3a*. Göteborg: Elanders Boktryckeri Aktiebolag.

Núñez, A. L. (1987). El tráfico de metales en el área centro-sur andina: Factos y expectativas. *Cuadernos Instituto Nacional de Antropología*, *12*, 73–105.

Núñez, A. L., & Dillehay, T. S. (1995) [1979]. *Movilidad Giratoria, Armonía Social y Desarrollo en los Andes Meridionales: Patrones de Tráfico e Interacción Económica*. Antofagasta: Universidad Católica del Norte.

Parks, D. M. (1998). Mechanics and materials analysis of the Tiwanaku architectural cramps. In H. Lechtman(Ed.), Architectural cramps at Tiwanaku. *Der Anschnitt*, *8*, 89–91.

Pedersen, A. (1976). El ajuar funerario de la Tumba de la Huaca Menor de Batán Grande, Lambayeque, Perú. Actas del 41°. *Congreso Internacional de Americanistas*, *2*, 60–73.

Petersen, G. G. (1970). *Minería y Metalurgia en el Antiguo Perú. Arqueológicas 12*. Lima: Museo Nacional de Antropología y Arqueología.

Petersen, U. (1989). Geological framework of Andean mineral resources. In G. E. Ericksen, M. T. P. Cañas, & J. A. Reinemund (Eds.), *Geology of the Andes and its relation to hydrocarbon and mineral resources* (pp. 213–232). Houston: Circum-Pacific Council for Energy and Mineral Resources.

Platt, T., Bouysse-Cassagne, T., & Harris, O. (2006). *Qaraqara-Charka: Mallku, Inka y Rey en la Provincia de Charcas* (*Siglos XV-XVII*). La Paz: Instituto Francés de Estudios Andinos, Plural Editores, and University of St Andrews.

Plazas, C., & Falchetti, A. M. (1979). Technology of ancient Colombian gold. *Natural History*, *88*(9), 36–46.

Pozzi-Escot, B. D. (1991). Conchopata: A community of potters. In W. H. Isbell & G. F. McEwan (Eds.), *Huari administrative structure* (pp. 81–92). Washington, DC: Dumbarton Oaks Research Library and Collections.

Protzen, J. P. (1993). *Inca Architecture and Construction at Ollantaytambo*. Oxford: Oxford University Press.

Protzen, J. P., & Nair, S. (1997). Who taught the Inca stonemasons their skills? *Journal of the Society of Architectural Historians*, *56*, 146–167.

Quilter, J. (2002). Moche politics, religion, and warfare. *Journal of World Prehistory*, *16*(2), 145–195.

Rengifo, C. C., & Rojas, V. C. (2008). Talleres especializados en el conjunto arqueológico Huacas de Moche. In L. J. Castillo, H. Bernier, G. Lockard, & Y. J. Rucabado (Eds.), *Arqueología Mochica: Nuevos Enfoques, Fondo Editorialv* (pp. 325–339). Lima: Pontificia Universidad Católica del Perú.

Rick, J. W. (2008). Context, construction, and ritual in the development of authority at Chavín de Huántar. In W. J. Conklin & J. Quilter (Eds.), *Chavín art, architecture and culture, Cotsen Institute of Archaeology* (pp. 3–34)., Los Angeles: University of California.

Rivet, P., & Arsandaux, H. (1946). La Métallurgie en Amérique Précolombienne. Université de Paris, Travaux et Mémoires de l'Institut d'Ethnologie (39), Musée de l'Homme, Paris.

Root, W. C. (1949). The metallurgy of the southern coast of Peru. *American Antiquity*, *15*(1), 10–37.

Root, W. C. (1951). Gold-copper alloys in ancient America. *Journal of Chemical Education*, *28*, 76–78.

Scott, D. (1998). Technical examination of South American metals: Some examples from Colombia, Peru, and Argentina. *Boletín del Museo del Oro, 44–45*, 78–105.

Shimada, I. (1985). Perception, procurement, and management of resources: Archaeological perspective. In S. Masuda, I. Shimada, & C. Morris (Eds.), *Andean ecology and civilization* (pp. 357–399). Tokyo: University of Tokyo Press.

Shimada, I. (1994). *Pampa Grande and the Mochica Culture*. Austin: University of Texas Press.

Shimada, I. (2000). The late Prehispanic coastal states. In L. L. Minelli (Ed.), *The Inca World* (pp. 49–64, 97–110). Norman: University of Oklahoma Press.

Shimada, I., & Merkel, J. (1991). Copper-alloy metallurgy in ancient Peru. *Scientific American*, *265*, 80–86.

Shimada, I., Epstein, S. M., & Craig, A. K. (1982). Batán Grande: A prehistoric metallurgical center in Peru. *Science*, *216*, 952–959.

Shimada, I., Epstein, S. M., & Craig, A. K. (1983). The metallurgical process in ancient north Peru. *Archaeology*, *36*, 38–45.

Shimada, I., Gordus, A., Griffin, J., & Merkel, J. F. (1999). Sicán alloying, working and use of precious metals: an interdisciplinary perspective. In S. Young, A. M. Pollard, P. Budd, & R. Ixer (Eds.), *Metals in antiquity, BAR International Series 792* (pp. 301–309). Oxford: Archeopress.

Shimada, I., Griffin J., & Gordus, A. (2000). The technology, iconography and social significance of metals: A multi-dimensional analysis of Middle Sicán objects. In C. McEwan (Ed.), *Precolumbian gold: technology, style and iconography* (pp. 28–61). London: British Museum Press.

Strong, W. D., & Evans, C. (1952). Cultural Stratigraphy in the Virú Valley. *Northern Peru: The formative and florescent epochs. Columbia studies in archeology and ethnology 4*. New York: Columbia University Press.

Tarragó, M. N. (1999). Las sociedades del Sudeste andino. In R. T. Rojas & J. V. Murra (Eds.), *Las Sociedades Originarias. Historia General de América Latina, T.1, Ediciones UNESCO* (pp. 465–480). Paris: Editorial Trotta.

Tarragó, M. N. (2000). Chacras y pukara: desarrollos sociales tardíos. In M. N. Tarragó (Ed.), *Los Pueblos Originarios y la Conquista* (pp. 257–300). Buenos Aires: Editorial Sudamericana.

Tarragó, M. N., & González, L. R. (1996). Producción especializada y diferenciación social en el sur del valle de Yocavil. *Anales de Arqueología y Etnología*, *50/51*, 85–108. (Argentina: Universidad Nacional de Cuyo, Cuyo).

Van Buren, M., & Mills, B. H. (2005). Huayrachinas and tocochimbos: Traditional smelting technology of the southern Andes. *Latin American Antiquity*, *16*(1), 3–25.
Vetter, L., Carcedo, P., Cutipa, S., & Montoya, E. (1997). Estudio descriptivo, metalográfico y químico de las puntas de aleación de cobre de la tumba de un señor de la Élite Sicán, Lambayeque-Perú. *Revista Española de Antropología Americana*, *27*, 23–38.
Vranich, A. (2006). The construction and reconstruction of ritual space at Tiwanaku, Bolivia (A.D. 500–1000). *Journal of Field Archaeology*, *31*(2), 121–136.
Willey, G. R. (1991). Horizontal integration and regional diversity: An alternating process in the rise of civilizations. *American Antiquity*, *56*(2), 197–215.
Zuidema, R. T. (1977). The Inca calendar. In A. Aveni (Ed.), *Native American Astronomy* (pp. 219–259). Austin: University of Texas Press.

Chapter 16
Production Networks and Consumer Choice in the Earliest Metal of Western Europe

Benjamin W. Roberts

Introduction

The dating, transmission and role of the earliest metal objects and metallurgy in western Europe remain the subject of considerable debate, arguably out of proportion to the importance attached to the new material and production practices by communities during the fourth and third millennia BC. In seeking to assess the current evidence for copper, arsenical copper, gold, silver, lead and tin bronze in the modern countries of Spain, Portugal, France, Belgium, Holland, Britain and Ireland, it is necessary to understand the influence of past ideas, techniques and projects. Debates surrounding the earliest metal in western Europe began in earnest with the excavation of prehistoric sites containing copper and occasionally gold, but crucially not bronze, objects during the nineteenth century (e.g. Wilson 1851; Wilde 1862; Evans 1881), whether as chance finds or during antiquarian excavations as at Los Millares, Southeast Spain (Siret and Siret 1887). Incorporating a copper-using period into the Stone–Bronze–Iron chronological framework (Rowley-Conwy 2007) proved a challenge to scholars, whose revised proposals ranged from a distinct Copper Age or Chalcolithic—as in Iberia (e.g. Cartailhac 1886; Veiga 1889), central Europe (Von Pulsky 1884) and Europe (Much 1886)—to an earliest stage in the Bronze Age where only copper was used—as in Britain and Ireland (e.g. Montelius 1909; Coffey 1913). As a consequence, the earliest period of metal use signified both a new archaeological age and an apparent continuity throughout western Europe, which had consequences for its subsequent treatment (Childe 1944; Lichardus and Echt 1991; Lichardus-Itten 2006; Roberts and Frieman 2012). However, the appearance of copper objects and metallurgy heralded a technological milestone, as it was self-evidently superior to stone and was therefore inherently desirable to prehistoric communities. Despite the allure of metals, virtually all scholars felt that there was no possibility of an independent invention, and that metal had to have been brought in by advanced colonisers,

B. W. Roberts (✉)
Department of Archaeology, South Road Durham,
Durham, DH1 3LE UK
e-mail: benjamin.roberts@durham.ac.uk

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_16,

generally in search of new ore sources, in a manner not entirely dissimilar to contemporary colonial powers (see Roberts 2008b).

The large expansion in archaeological activity, together with a shift towards a framework of archaeological cultures, during the first half of the twentieth century did little to alter the interpretations of migrating, invading or diffusing metallurgists pouring into western Europe, whose technical expertise in creating a revolutionary new material provided them with special status (Roberts 2008b). This interpretation was articulated most influentially by V. Gordon Childe (1930), who made itinerant metalsmiths primary agents of social change in European societies, due to their mobility and perceived lack of tribal affiliations (see Rowlands 1971; Wailes 1996). This elevation of metal production did not coincide with any growth in the understanding of the past technology, which was limited to assumptions regarding its complexity and the observations of stone tools associated with 'primitive mines' at copper ore deposits (e.g. Domergue 1987). The attribution of metal to an archaeological culture (e.g. Beaker culture), interpreted as representing a past people (e.g. Beaker folk), meant that early metal object types were also given cultural identities (e.g. Beaker metallurgy) (see Vander Linden 2006 for a review).

The challenge to these narratives came from the application of scientific techniques during the second half of the twentieth century. The use of radiocarbon dating enabled the first independent chronology for early metal objects and metal production in western Europe. It was used by Colin Renfrew to challenge the established Childean orthodoxy by arguing for the independent discovery of metallurgy in southern Iberia, rather than its appearance through colonists from the East Mediterranean (e.g. Renfrew 1967, 1973; contra Blance 1961). Despite the relatively few dates available, southern Iberia could be shown to be earlier than its neighbouring regions. Basic assumptions regarding the technology of the early metal objects were addressed by measuring their composition, most prolifically through the vast Stuttgart-based *Studien zu den Anfängen der Metallurgie* (S.A.M.) that encompassed the earliest copper, copper alloys and gold throughout Europe (Junghans et al. 1960, 1968, 1974; Hartmann 1970, 1979, 1982). Unfortunately, the inability to reliably match many metal object compositions to ore sources as originally intended meant that the projects were unable to fulfil their original purpose (see Tylecote 1970). However, researchers sought to use the data to address whether there were distinctive composition groupings in space (cf. Butler and Van der Waals 1964; Waterbolk and Butler 1965) and whether these could be equated with defined archaeological groupings. For western Europe, the third millennium BC Beaker culture, which was thought to define the period of metal adoption in Northwest Europe and metal transformation in Southwest Europe, and thus Beaker metallurgy, provided the focus for debate (e.g. Case 1966; Butler and Van der Waals 1967; Harrison 1974). However, conspicuous by their absence in these investigations were the proven metal production sites. It was during the 1970s that archaeological fieldwork and archaeometallurgical analysis were integrated in projects that were specifically directed towards the investigation, recording and dating of metal production to investigate where and how ores were mined and smelted, as in the Huelva area of Southwest Spain (Rothenberg and Blanco-Freijeiro 1981).

The data that this and subsequent projects in ore-rich areas in Southwest Ireland (e.g. O'Brien 2004), Wales (e.g. Timberlake 2003), Southeast France (e.g. Ambert et al. 2005; Mille and Carozza 2009), South Portugal (e.g. Müller et al. 2007) and Spain (e.g. Montero-Ruiz 1994; Delibes de Castro and Montero-Ruiz 1999; Hunt-Ortiz 2003; Nocete 2006; Bayona 2008; Costa Caramé 2010; Soriano 2013) generated allowed experimental replications of mining and smelting techniques that could be informed by, and compared to, archaeological evidence and archaeometallurgical data through the regions under consideration (e.g. Happ et al. 1994; Rovira and Guttierez 2005; Timberlake 2005, 2007; Hanning et al. 2010). The widespread application of lead isotope analysis in an attempt to provenance copper objects to ores reinvigorated, though did not entirely resolve, questions of provenance (e.g. Buikstra et al. 1991; Hunt-Ortiz 2003; Prange and Ambert 2005; Müller et al. 2007). Many of these projects tended to address primarily the technological questions surrounding metal objects that had originally stimulated geologists and materials scientists to delve into archaeometallurgy (e.g. Tylecote 1987; Craddock 1995).

However, neither radiocarbon dating nor archaeometallurgy provided an intellectual framework within which to address the appearance of metal in western Europe, the diverse nature of early metal forms, production techniques and sites or the role of metal in prehistoric communities. This requires the ability to analyse early metal within the dynamics of the societies involved in its production, use and consumption. The influence of archaeological theory on early metal has not been nearly as substantial as that of archaeological science. This is despite the fact that the adoption of metal attracted the early attention of two of the most influential practitioners of archaeological theory: Lewis Binford (Binford 1962) and Colin Renfrew (Renfrew 1967, 1973). The main shift is the reduction in the causal role ascribed to metal and metallurgical specialists in models of social change. However, it can be argued that this reflects the impact of archaeometallurgy, which demonstrated to scholars of all stripes that early metallurgy was on a very small scale compared to other contemporary practices (e.g. contrast Chapman 1975 with Chapman 1990). Interpretations tend to follow the idea that metal symbolised elite power and was possibly subject to elite control (e.g. Gilman 1996; O'Brien 2004) and, when placed in a broader material context, was only one of several rare and visually striking prestige materials in circulation (e.g. Pétrequin et al. 2002; Roberts and Frieman in press). Where the impact of archaeological theory has been most keenly felt is in the scale of research orientated towards understanding locales and regions in the pursuit of a more detailed, systematic or contextual archaeology. The consequence has been that the broader temporal and spatial perspective that encompasses western Europe in its entirety has been either ignored or simply left as background description. Thus, the proposal of the independent invention of copper metallurgy in southern Iberia has gone unchallenged (Renfrew 1967, 1973) and there are few models (e.g. Pétrequin 1993; Brodie 1997, 2001; Roberts and Frieman 2012) exploring the mechanisms by which metallurgy was adopted, beyond vague and unhelpful notions of diffusion and spread. Even discussions relating to the role of metal have been restricted to regional assessments of metallurgy surrounding the Beaker culture (e.g. Ambert 2001; Needham 2002; Rovira and Delibes de Castro 2005). This stands in contrast to northern Europe (Klassen 2000, 2004), central and eastern Europe (e.g. Strahm 1994; Krause 2003; Kienlin 2008; Borić 2009; Radivojević et al. 2010; Kienlin 2011; the chapter by Kienlin, this volume) and the Mediterranean (e.g. Kassianidou and Knapp 2005; the chapter by Dolfini, this volume).

This has meant that the three major issues regarding early metal in western Europe have not been properly addressed—namely the validity of the independent invention model, the transmission of metal objects and metallurgical practices and the role of metal objects. In order to analyse whether there is the independent invention of metallurgy in western Europe, it is necessary to review the earliest dates for metal objects and production practices throughout Europe. To analyse the transmission and role of metal objects and practices requires an analytical framework that encompasses the stages in the lifecycle of a metal object from the selection of an ore or ore source to the deposition of the object (Ottaway 2001; Ottaway and Roberts 2008; see the chapter by Heeb and Ottaway, this volume). The knowledge, skills and tools that would be required to perform each identifiable transformation can be assessed in the broader material and social context in which they occurred. This is a biographical perspective (cf. Gosden and Marshall 1999), but one that is general rather than individual (e.g. Lechtman 1977, 1996; Hosler 1995; Ottaway 1994, 2001; Killick 2001; Fontijn 2002/3; Needham 2004; Ehrhardt 2005; Roberts 2008a). Whilst linear sequences are undoubtedly present, it is important to stress the many different interrelationships within such a system (see Kingery 1993, 1996; Knappet 2005). It is the implications of the actions underlying the analytical patterns of early metal that allow a greater understanding of the dynamics of prehistoric societies and represent the main contribution of archaeometallurgy to broader debates (Thornton 2009).

Dating the Earliest Metallurgy

The earliest evidence for the exploitation of native copper and copper oxide in Europe occurred in the southeast of the continent during the mid-sixth millennium BC (see the chapter by Kienlin, this volume), on settlement sites such as Divostin in Serbia and maybe even earlier at the copper mine of Rudna Glava, Serbia (Borić 2009) (Fig. 16.1), reflecting broader patterns stretching as far east as Pakistan (Roberts et al. 2009).

By the late sixth millennium BC, there is plentiful evidence for native copper or copper oxide beads, hooks, needles and awls at sites confirming relatively extensive exploitation in Southeast Europe during this time (see Thornton 2002; Krause 2003; Zachos 2007; Borić 2009; Kienlin 2011 for reviews). The earliest copper smelting is less clear due to the ephemeral nature of the evidence, the relative lack of analyses and difficulties in distinguishing smelted copper objects from native copper (see Wayman and Duke 1999). However, recent research at Belovode, Serbia has demonstrated the presence of copper-smelting slag dating to BC (Radivojević et al. 2010). Given that this date is comparable to sites throughout Southwest Asia, a single central region of invention, possibly in Anatolia, is far more probable than many parallel independent discoveries (Roberts et al. 2009). The earliest gold exploitation dates from the

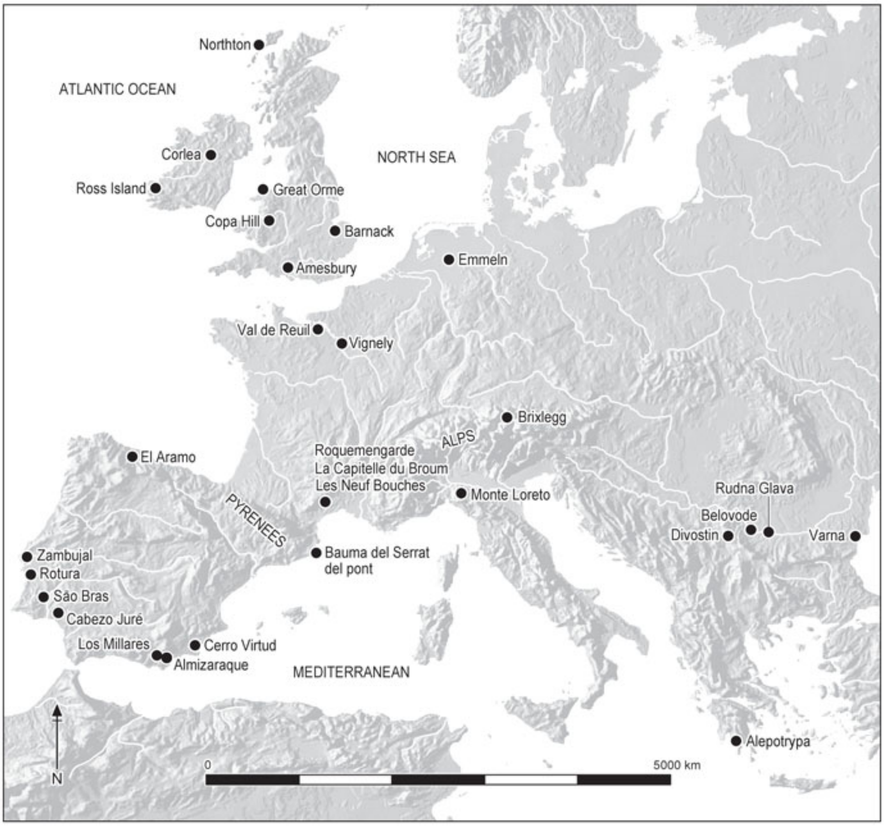


Fig. 16.1 Map of the sites featured in the text

mid-fifth millennium BC and adorns the burials at Varna in eastern Bulgaria (Renfrew 1986; Makkay 1991; Higham et al. 2007), whilst the earliest silver is found in a hoard at Alepotrypa Cave in southern Greece and is dated to the mid-fifth—early fourth millennium BC (Muhly 2002). Moving further west to into central Europe and the central Mediterranean, there is evidence of copper fahlore smelting from the later fifth millennium BC at Brixlegg, Austria (Höppner et al. 2005; see the chapter by Kienlin, this volume for discussion of the dating), reflecting practices further east during this time (Ryndina et al. 1999). There are also copper flat axes and ornaments from Switzerland, and possibly the surrounding regions, dating to the second half of the fifth millennium BC (Matuschik 1997; Krause 2003; the chapter by Kienlin, this volume), though the evidence for copper smelting is not currently supported even over a millennium later (see Fasnacht 1991, 1995; Rehren 2009). Copper axes and ornaments are found throughout the plains north of the Alpine region as far as Scandinavia from the fourth millennium BC and, in the absence of any copper ores, would have represented the long-distance movement of ores or, more probably, copper metal (Ottaway 1982; Klassen 2000, 2004; Roberts and Frieman in press). To the south of the Alps, copper objects are present in northern Italy from the early–mid-fifth millennium BC (Skeates 1994; Pearce 2007, pp. 48–52; see the chapter by Dolfini, this volume) and there is extensive copper ore extraction at Monte Loreto in Northwest Italy from the mid-fourth millennium cal BC (Maggi and Pearce 2005). Copper and silver production occurs on Sardinia from the late fifth–later fourth millennium BC (Lo Schiavo et al. 2005), though is rarely found in the broader central and western Mediterranean region until the end of the third millennium BC (Primas 1995). The identification and dating of lead objects and the smelting of lead ores, whether intentionally or as a by-product of the production of silver, has attracted relatively little attention, though it occurs in Greece as well as Sardinia from the early fourth millennium BC (McGeehan-Liritzis 1983; Lo Schiavo 2005)

The earliest reliable radiocarbon dates for metal objects in western Europe occur in northern France, where the dating of the collective burials at Vignely revealed that a child aged around 5 years had a necklace of nine copper beads with a date range of 3517–3357 cal BC (Mille and Bouquet 2004), comparable to beads found across northern Europe (e.g. Ottaway 1973, 1982) but not in southern France (Barge-Mathieu 1995). This can be contrasted with Southeast France, where rich copper ores and connections to the communities in the central Mediterranean might imply an earlier metallurgical presence—this is suggested, but not proven, by a gold repoussé diadem whose closest parallels are in the Balkans (Guilaine and Eluère 1997, p. 176). The earliest radiocarbon dates are for copper awls, dagger and awl fragments and lead beads, found in contexts at the site of Roquemengarde and radiocarbon dated to the later fourth millennium BC (Guilaine 1991). These sites are both still older than the earliest copper mining at Les Neuf Bouches and earliest copper smelting at the nearby La Capitelle du Broum which date to the end of the fourth millennium BC (Ambert et al. 2005; Mille and Carozza 2009).

In Iberia, defining the earliest metal objects is problematic, in the absence of secure contexts for the late fifth and fourth millennia BC where they might be expected given the dates in nearby countries such as France, Sardinia and Italy though as yet not the Balearic islands (e.g. Alcover 2008). There is fragmentary evidence of copper oxide-smelting slag at Cerro Virtud, Southeast Spain, which has been radiocarbon dated to the first half of the fifth millennium BC (Delibes and Montero-Ruiz 1997; Montero-Ruiz et al. 1999; Ruíz Taboada and Montero-Ruíz 1999). However, this is at least a millennium older than any other evidence of smelting or anything metallurgical in Iberia (e.g. Montero-Ruiz 1994, 2005; Delibes de Castro and Montero-Ruiz 1999). The evidence itself is not unproblematic; it consists of copper slag on a ceramic fragment that was excavated under rescue conditions and was then dated to a layer rather than by an associated organic material or feature. It was reported as having remained untouched despite the widespread evidence of mining disturbance at the site (see response to criticisms of the dating of Cerro Virtud by this author and others in Murillo-Barroso and Montero-Ruiz 2012). Several other sites in southern Spain have been cited as potential evidence for fourth millennium BC copper smelting, though their contexts are not secure (Montero-Ruiz 2005). To the west, potentially late fourth millennium BC smelting evidence at the sites such as Rotura and São Bras 1 in southern Portugal still remains unanalysed (Gonçalves 1989; Monge Soares et al. 1994). The metal production activities at the third millennium BC sites of Zambujal (Müller et al. 2007), Cabezo Juré (Nocete 2006), Almizaraque (Müller et al. 2004) and Los Millares (Montero-Ruiz 1994) in southern Iberia remain the most comprehensively dated and analysed, though these sites represent the later establishment of metallurgical practices rather than their inception. No contemporary copper mine has yet been found within this region, perhaps because rich surface deposits required only small-scale working (Rovira 2002), with the earliest dating to the mid-third millennium BC at El Aramo in northern Spain (Hunt-Ortiz 2003; Blas-Cortina 2005). The recent discovery of a gold bead at Tossal Gros, Northeast Spain dating to c. 3000 BC makes it the earliest confirmed evidence for gold in western Europe (Soriano et al. 2012). It is therefore at least a millennium earlier than the earliest silver in western Europe (Bartelheim et al. 2012).

Traces of metal use in Belgium, Netherlands and Northwest Germany prior to the mid-third millennium BC (cf. Cauwe et al. 2001; Warmenbol 2004) are sparse and consist of small copper ornaments, as at the Emmeln-2 megalithic tomb, Germany (Schlicht 1968). Unfortunately, the earliest potential objects in Atlantic France have only been typologically dated (Briard and Roussot-Larroque 2002; Roussot-Larroque 2005) and the earliest potential production site inland at Val-de-Reuil dates only to the late third millennium BC (Billard et al. 1991). Surveys and excavations of the copper ore sources in Wales have revealed extraction activities beginning in earnest c. 2100/2000 cal BC as at Copa Hill (Timberlake 2002, 2003), whilst copper ore extraction and possibly smelting in Southwest Ireland occur at Ross Island c. 2400 BC (O'Brien 2004). Beyond typologies, the metal axe marks in the Corlea 6 wooden trackway in the Irish Midlands dendro-dated to 2259 ± 9 BC (O'Sullivan 1996), whilst across the sea there are several mid–late third-millennium BC radiocarbon dates in southern Britain for copper and gold objects found in the Beaker burial sites such as at Amesbury and Barnack (Needham 1996; Fitzpatrick 2011) and a droplet of arsenical copper in a midden at Northton, Isle of Harris (Simpson et al. 2006).

Analysing Metallurgical Transmission

Scholars analysing the 'spread' of metallurgy have tended to rely either on the migration of a people as represented by an archaeological culture or in the absence of a widespread change in the material record, the all-encompassing and vague concept of diffusion as mechanisms for the movement of objects or technology (Roberts 2008b). The transmission of metallurgy can be addressed more systematically by analysing the metallurgical knowledge, skills and equipment that would be required to perform each identifiable transformation from ore to metal—encompassing the prospecting, extraction, processing, smelting and casting and comparing them to pre-existing technologies, providing insights into the origins and role of metal in western Europe.

Metallurgical ores and naturally occurring metals would have been abundant and visible in Southeast France, Wales, southern Ireland and especially in Iberia. Yet there is no evidence of copper ores or native copper being exploited during the pre-metallurgical period in western Europe, as occurs from Serbia to Pakistan (Roberts et al. 2009). Prospecting might not have been easy, as there were plenty of other similarly coloured mineral sources that could have been a source of confusion to any potential smelter, and there needs to be the initial motivation to experiment. It seems likely that the discovery of a metallurgical source would have led to further surveys in the vicinity, but that the initial identification would have required either prior experience or a process of trial and error. The direct evidence for ore extraction is limited to mining, as neither surface collection nor placer deposits are archaeologically traceable (Weisgerber and Pernicka 1995), and represents the transferral of earlier flint and stone-mining practices (e.g. Bosch 2005; Korlin and Weisgerber 2006). When ore veins are followed underground, as at copper-mining sites such as El Aramo, northern Spain (Blas Cortina 2005) and Ross Island, Southwest Ireland (O'Brien 2004), expertise would have been needed to facilitate the movement of miners, their equipment and the ore, and to provide them with adequate ventilation, illumination and drainage, all whilst ensuring that the underground structures did not collapse. Organisation was necessary to source, make and transport the mining tools and equipment such as stone hammers and antler picks (e.g. Pascale 2003; Timberlake 2003), the large quantities of fuel for fire setting (cf. Weisgerber and Willies 2001), and food for the miners. Whether close to the settlements or not, the implication is that there would have been dedicated mining expeditions containing several individuals with relevant expertise that had access to the ore. The subsequent processing or beneficiation of the ore would have been very familiar to people used to preparing and grinding wheat and barley.

It is the smelting of the ore that potentially provided the greatest challenge to a metallurgical novice. By modern standards, the earliest smelting in western Europe can be characterised as relatively simple—small scale, relatively low-temperature processes carried out under poorly reducing conditions on oxidic and/or sulphidic ores in small stone and clay structures and/or ceramic crucibles with no intentional addition of fluxes and little consequent slag (Craddock 1999; Bourgarit 2007). The smelting would have yielded only small quantities of copper that would then have to be refined in a separate process. How straightforward the smelting of copper ores would have been depends on the sophistication of the pre-existing pyrotechnologies such as the firing of ceramics. Unfortunately, this is not easy to ascertain, as there are no known Neolithic ceramic firing sites in western Europe that would reveal the techniques involved (Gheorghiu 2008). It is therefore left to inferences from analysing the existing pottery and subsequent experimental replications to provide insights. It seems probable that ceramic firings took place in an open bonfire, which would render the process virtually invisible archaeologically (see Orton et al. 1997, pp. 127–130). In replicating these bonfire-type firings, it is evident that there is a lack of control, rapid changes in temperature, an oxidizing atmosphere and a duration varying from several minutes to several hours. Though temperatures of c. 1,000 °C can occasionally be reached, this is only for a very short duration and cannot be maintained before dropping back to c. 600–800 °C or lower (e.g. Gosselain 1992; Livingstone-Smith 2001; McDonnell 2001). It is possible that more control could have been achieved, as shown by the recent analysis of Neolithic red ochre decorated pottery from Southeast Spain (Capel et al. 2006), but even this would not have been sufficient in terms of temperature, atmosphere or control to smelt oxidic and/or sulphidic ores according to experimental reconstructions (e.g. Rovira and Guttierez 2005; Timberlake 2005, 2007; Bourgarit 2007; see the chapter by Heeb and Ottaway, this volume). The presence or role of charcoal before metal production is hard to establish, as neither the surviving evidence nor the necessity can be found. However, charcoal would have been of fundamental importance in smelting not simply due to its ability to create high temperatures using relatively small quantities in a small space, but as a source of highly reducing carbon monoxide gas (see Horne 1982; Craddock 2001). The transmission of copper smelting represented a significantly different practice to existing pyrotechnologies and would have to have been learnt in one place and applied elsewhere. This could therefore apparently only occur through either the movement of individuals or groups possessing the smelting skills. The excavation of equipment relating to the creation of copper and gold objects, such as moulds, hammers, tongs and anvils, is very sparse, indeed relative to the number of objects that have been recovered. This is partially due to the difficulty in identifying the specific tools that would have been employed, but more probably related to the rapid degradation of sand moulds (e.g. Ottaway and Seibel 1998; Eccleston and Ottaway 2002), the fragmentation of clay moulds (e.g. Ottaway 2003) and the decomposition of any wooden objects such as patterns, models and containers. The earliest dated objects, such as the copper beads from Vignely, northern France, were created through rolling sheet metal, while other early types found throughout western Europe, such as copper flat axes, were cast, and where metallographic analysis has been performed, occasionally cold and hot worked (e.g. Rovira and Gómez-Ramos 2004; Murillo-Barroso and Montero-Ruiz 2012). Neither the making of the moulds nor the working of the metal in its earliest form would have required a major transition for individuals used to manipulating clay and wood. However, while the technical aspects of casting and working metal would perhaps not have been a barrier to the adoption of the new material, there is no evidence to imply that simply any objects were made or that a uniform standard prevailed across western Europe. The extraction and smelting of copper ores may have been fundamentally comparable at a technological level, but the way in which these techniques were applied is not entirely uniform. It is through understanding the role of metal objects and metallurgy within the societies involved that such similarities and variations can be explained.

Exploring the Roles of Early Metal and Metallurgy

The roles of metal objects and metal production practices in western Europe during the late fourth–third millennium BC can be explored through the patterning in the metal production practices and object types, through the archaeological contexts of metal-related activity and through discussing their relationship to broader societal trends. The prehistoric archaeologist or archaeometallurgist will never rival the ethnographer in capturing the social minutiae of metal in a community, but the data are present to allow analysis of aspects of the early development of metal and how it was shaped by past communities (cf. Budd and Taylor 1995). This analysis will concentrate on the organisation of metal production and the consumption of metal objects.

Metal production throughout western Europe during the fourth–third millennium BC was small scale, required simple facilities and equipment and only part-time specialisation, and there is no evidence for any fundamental changes during this time. The proposal that Cabezo Juré, Southwest Spain, possessed copper-smelting furnaces dating from the early third millennium BC is unconvincing from the published data (Nocete 2004; Nocete 2006). It is comparable to metallurgical features at other sites in southern Iberia, which have been demonstrated not to be furnaces. Furthermore, if true, these furnaces would be contemporary with the earliest use in the East Mediterranean and Near East (Craddock 2001; Hauptmann 2007), and substantially predate those furnaces in the central Mediterranean and Alpine regions that appeared during the later second millennium BC (Craddock 1999). Where it is possible to identify sites where the extraction, processing and smelting of copper ore took place, they tend to be very close to one another, as at Les Neufs Bouches and La Capitelle du Broum in Southeast France (Maas 2005; Mille and Carozza 2009), Ross Island, Southwest Ireland (O'Brien 2004), and from the end of the third millennium BC the Great Orme, Northwest Wales (Dutton and Fasham 1994; Chapman 1997; Wager 1997). For each production site, the range of radiocarbon dates indicates a long-term commitment over centuries, even if opening new ore sources nearby would have required substantially less effort and expertise. Despite this concentration in production activities, the abundance of copper ore in those areas where primary metal production occurred, especially in the landscapes such as southern Iberia, would militate against centralised elite control (cf. Rovira 2002).

This is reflected in the diverse nature of the places even within the same region. In southern Iberia, copper smelting has been found in large, walled enclosures such as Los Millares (Molina et al. 2004), smaller fortified sites such as Cabezo Juré (Nocete 2004; Nocete 2006) and unfortified sites such as Almizaraque (Müller et al. 2004). In Southeast France there are extensive double-walled structures at La Capitelle du Broum (Ambert et al. 2002, 2005), as well as open settlement sites such as Al Claus (Mille and Carozza 2009), while in Southwest Ireland, the architecture at the only known potential smelting site of Ross Island consisted of temporary huts (O'Brien 2004). The smelting equipment found at these sites mainly comprises thick-walled, open-mouthed ceramic vessels as in Iberia and Southeast France (Rovira and Ambert 2002), though clay-lined hearths have been excavated at Los Millares (Molina et al. 2004) and Zambujal (Müller et al. 2007). Analysis of the slag and slagged ceramics revealed the smelting of mainly oxidic ores in Iberia, but both oxidic and sulphidic ores, with the probability that co-smelting or mixed smelting occurred, in Southeast France (Rovira and Ambert 2002; Bourgarit 2007). The evidence in Ireland and Britain is far more ephemeral, as at Ross Island, Southwest Ireland (O'Brien 2004) and the Great Orme, Wales (Chapman 1997), implying a simpler and archaeologically lessvisible technique (cf. Timberlake 2005). Furthermore, experimental replications of the co-smelting further south have struggled, possibly as a result of the environment, suggesting that our understanding of the processes involved throughout western Europe is far from complete (Timberlake 2007). The virtual absence of ceramic or stone tuyère fragments throughout western Europe and beyond during the fourth and third millennia BC (Roden 1988) has led to suggestions of wind potentially having played a greater role than previously acknowledged (e.g. Happ 2005; Nocete 2004; Nocete 2006; Bourgarit 2007, pp. 7–8).

Perceptions of the consumption of the metal objects being made, whether of quantity, type or composition, are inevitably highly influenced by past practices of deposition or discard, as well as recycling or re-melting (e.g. Taylor 1999; Needham 2001). Many aspects of a metal object's life remain elusive, such as where an object was taken, how it was used, how it changed possession, the ideas that surrounded it and whether it was recycled, re-melted or recast, which may all be more important to understanding its presence than production or depositional practices. However, recent research on early metal in Britain and Ireland has demonstrated that further insights can be gained, especially in the re-analysis of older datasets (Bray and Pollard 2012; the chapter by Bray and Pollard, this volume). The dating of early metal objects is invariably typological, with a chronological resolution of centuries. As a consequence, it is only through analysing the broader patterning in the distribution and deposition of recovered metal objects that patterns of consumption can be discerned.

The ability to provenance early copper and gold objects through trace element and lead isotope analysis remains problematic, especially for the identification of multiple contributing ore sources. Where it is possible to make inferences, it would seem that single copper ore sources provided the copper objects in a broad region for at least several centuries, as appears to have occurred in Southeast France (Prange and Ambert 2005; Mille and Carozza 2009) and Southwest Ireland (O'Brien 2004), although it is perfectly possible that any patterning indicates several mines in the same geological area, rather than simply those that have been excavated. The changing use of metallurgical sources in regions over time and the recycling of early metal has recently been explored for Britain and Ireland (Bray and Pollard 2012; the chapter by Bray and Pollard, this volume). Perhaps more interestingly, compositional data in regions lacking copper ores, such as eastern Britain and continental Northwest Europe, have revealed very different yet coherent patterning, originally termed Bell Beaker metal (Butler and Van der Waals 1964; Butler and Waterbolk 1965), which may have originated from several obviously distant geological sources, though it is currently impossible to define exactly where (Needham 2002). This apparent selection of a particular metal composition is also seen in regional copper–arsenic alloying practices in certain object types during the mid–late third millennium BC, such as elongated awls and sheet metal at Zambujal, south-central Portugal (e.g. Müller et al. 2007) and possibly halberds and daggers in Ireland (e.g. Northover 1989). In these instances, the smelting of copper ores rich in arsenic may have been accompanied by an awareness of how this harder silver-coloured metal could be reproduced, though whether copper–arsenic objects can be defined as deliberate and therefore alloys is not always straightforward, as in southern Iberia (Montero-Ruiz 1994, pp. 247–263;

Hunt-Ortiz 2003, though contra Hook et al. 1991; Keesman et al. 1991/2). Nevertheless, there appears to be a strong element of choice in the use of copper–arsenic that is more pronounced in the later adoption of alloying copper with tin throughout Europe, where the first half of the third millennium BC witnessed the creation of low tin bronzes (Fernandez Miranda et al. 1995; Primas 2002; Müller 2002; Krause 2003), but there is no evidence of more consistent and higher tin bronzes in western Europe until the late third–early second millennium BC (Pare 2000; Fernandez Miranda et al. 1995), albeit at widely varying rates that do not appear to relate to the distance from tin ores (Pernicka 1998; Guimlia-Mair and Lo Schiavo 2003). However, this curiosity and eventual institutionalisation of new and distinctive metals do not seem to have extended to mixing gold, copper or lead together.

The metal object forms being deposited or discarded in copper, copper arsenic and gold reveal distinctive designs that are spatially and temporally, and occasionally compositionally, specific. The objects involved encompass copper flat axes, beads, needles, fishhooks, awls, knives, daggers, saws, sickles, spatulas and chisels in Iberia (Delibes de Castro and Montero-Ruiz 1999), in contrast to a restricted range with virtually no copper objects beyond flat axes, daggers and halberds in Ireland (Harbison 1969a, b). Where exhaustive typological research has been conducted on an object type, such as beads and copper flat axes in Southeast France (Chardenoux and Courtois 1979; Barge 1982), flat axes, halberds and daggers in Ireland (Harbison 1969a, b), or gold lunula and discs in Northwest Europe (Taylor 1980; Eogan 1994; see front cover), it has revealed extensive morphological micro-variations based on several distinctive designs. It appears that the replication of specific objects occurred far less frequently than the creation of subtly new ones. The implication for the production of copper objects is that only slight alterations on accepted norms occurred. Rather than re-use stone moulds or wooden patterns for shaping clay and sand moulds, new moulds would therefore have had to be made or the metal would have to have been manipulated in a different way.

When placed against their chronological range, the quantities of metal objects involved we have found are relatively small, even for well-studied areas known for primary metal production, as shown by only c. 600 objects for Southeast Spain over a period of c. 800–1,000 years (Perea 1991; Pingel 1992; Montero-Ruiz 1994). The number of metal objects being produced is therefore more indicative of an occasional rather than continuous production process, with a relatively low level of circulation. The placing of metal throughout burial traditions in western Europe during the late fourth and the third millennium BC indicates its role as a visually striking and valued material. However, metal probably did not quite carry the prestige for prehistoric communities as is frequently imagined. The small scale of metal production suggests that it was undertaken by part-time smiths, while the regionally specific object forms imply that they made objects that reflected certain standards. Furthermore, early metal tools did not provide an advantage over existing materials in performing everyday tasks—they were less effective than stone, bone or flint counterparts (Mathieu and Mayer 1997), and may not even have been hardened or used.

The choices of forms and uses of metal objects that created the patterning in the metal consumption were far from arbitrary (Sofaer-Derevenski and Sørensen 2002;

Roberts 2008a)—whether in Ireland, where copper flat axes imitated in form and depositional context the polished stone axes in circulation in preceding centuries (e.g. Cooney and Mandal 1998), or in Southeast France where copper, gold and lead beads were made when beads in other materials such as horn, bone, variscite and shell adorned the dead (Barge 1982). This ability to smelt different ores, create different metals or increase metal production did not increase in any linear evolutionary fashion, but was dictated by the desires and demands of those consuming the metal. This is shown not only by the subsequent change in the inhumation practices in Southeast France to the Beaker burial rite, which actually led to fewer metal objects in more restricted range (Ambert 2001; Vander Linden 2006), but also in the absence of metal objects in regions where they had been introduced—as occurred in Northwest Continental Europe during the first half of the third millennium BC.

Discussion

There is no clear evidence to imply the independent invention of metallurgy in western Europe. The radiocarbon dates, the technological requirements and the archaeometallurgical data do not provide a convincing challenge to the idea that skilled metalsmiths from the east introduced metallurgy to the region by exploiting its ore sources (Roberts 2008a; Roberts et al. 2009 but see Murillo-Barroso and Montero-Ruiz 2012 for an opposing perspective). Analysing the origins of these metalsmiths is only going to be feasible in exceptional circumstances, such as the 'Amesbury Archer', who may well have spent his formative years in the foothills of the Swiss Alps before making the vast journey to southern England where he was buried (Fitzpatrick 2011). It is more difficult to assess how the technology itself travelled. It would require a process of learning at an exploitable ore source to communicate the various stages of metal production through visual demonstrations and verbal explanations. It is certainly possible that aspects of this crucial knowledge could be restricted. For the 'spread' of metallurgy to occur, a sufficiently skilled individual or group would have to move to a new ore source. This is a process that can be seen not only throughout Europe (Ottaway and Roberts 2008) but also throughout Eurasia (Roberts et al. 2009), and would have created an extensive yet fragile network of metallurgical expertise over substantial distances. Yet the emphasis on metal producers is perhaps misplaced. It is argued that the desires of the communities who supported the acquisition of metallurgical skills, assisted with the collective aspects of metal production (e.g. ore prospection, extraction and processing), and circulated and used the metal objects, were more influential than the smiths. Rather than a uniform standard, early metal objects in western Europe were a mosaic of frequently diverse metallurgical traditions distinguished by form, composition and production techniques constrained by cultural rather than technological boundaries (Roberts 2008a). There was no inherent functional reason why metal objects or metal production should be adopted by local communities or introduced by non-local communities. The distinctive colours, lustre and malleability can be proposed as attractive qualities. The ability to recycle meant that object forms created elsewhere could be melted down and converted into more familiar shapes, even in regions far from ore deposits or primary production centres.

The earliest presence of metal objects in western Europe, during the fourth millennium BC, did not immediately provoke a significant material or technological transformation. The division of European prehistory into a Stone Age and Metal Age still encourages the idea of a highly significant technological event accompanied by broader societal changes, as is shown by the ongoing visions of distinctly Chalcolithic societies (Guilaine 2006). Copper and gold objects continue to be ascribed high, yet frequently unspecified, value for prehistoric communities, and are interpreted as a consequence in terms of elites and prestige (see Bartleheim 2007). In reality, metallurgy in western Europe in the fourth and third millennia BC was not a dynamic or innovative technology, but was practiced sporadically and at a smallscale, to specifications outlined by consumers whose requirements were highly conservative. This is not sufficient to propose metal as a major stimulus for the creation of new societal structures. Even the argument that metal played a role in enhancing social status can be partially disingenuous if not accompanied by a consideration of the other materials. For instance, the burial of an individual in the Beaker rite involved a thin-walled, elaborately decorated pottery vessel potentially together with polished stone bracers, finely made flint arrowheads, v-perforated buttons, possibly in amber or jet, daggers in flint or copper and earrings in gold or copper. The ability to acquire these materials or craft the desired objects required similar processes of gaining specific knowledge and skills—none of which can easily be used to elevate metal in the overall interpretation. Instead, all the materials are made to reflect a desired standard and are not rigorously demarcated (Frieman 2012). The appearance of metal objects and metallurgy in western Europe therefore represents a single material that has survived through the millennia that has been elevated in importance by the modern values ascribed to it. Metal remains an exceptionally valuable source of data for understanding prehistoric dynamics during the fourth–third millennia, but it should be regarded not in glorious isolation, but as one of many materials being exploited at the time.

Acknowledgments This is a slightly revised paper from the paper of the same title in the *Journal of World Prehistory* (2009). The errors and opinions remain my own.

References

Alcover, J. A. (2008). The first Mallorcans: Prehistoric colonization in the western mediterranean. *Journal of World Prehistory, 21,* 19–84.

Ambert, P. (2001). La place de la métallurgie campaniforme dans la première métallurgie française. Etat de la question. In F. Nicolis (Ed.), *Bell beakers today: Pottery, people, culture and symbols in prehistoric Europe* (pp. 387–409).Trento: Ufficio Beni Culturali. (International Colloquium Riva del Garda (Trento, Italy), 11–16 May 1998).

Ambert, P., Coularou, J., Cert, C., Guendon, J.-L., Bourgarit, D., Mille, B., Houlès, N., & Baumes, B. (2002). Le plus vieil établissement de metallurgistes de France (III[e] millénaire av J.-C.: Péret (Hérault). *Comptes Rendu Palevol, 1,* 67–74.
Ambert, P., Bouquet, L., Guendon, J. L., & Mischka, D. (2005). La Capitelle du Broum (district minier de Cabrières-Péret, Hérault): établissement industriel de l'aurore de la métallurgie française (3100–2400 BC). In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 83–96). Mémoires de la Société Préhistorique Française 37.
Barge, H. (1982). *Les Parures du Neolithique Ancien au debut de l'Âge des Métaux en Languedoc*. Paris: CNRS.
Barge-Mahieu, H. (1995). Les premiers objets métalliques du Chalcolithique provençal. In L'homme méditerranéen: mélanges offerts à Gabriel Camps (pp. 359–373). Nimes: Université de Provence.
Bartelheim, M. (2007). *Die Rolle der Metallurgie in vorgeschichtlichen Gesellschaften: Sozioökonomische und kulturhistorische Aspekte der Ressourcennutzung. Ein Vergleich zwischen Andalusien, Zypern und dem Nordalpenraum*. Rahden: Verlag Marie Leidorf.
Bartelheim, M., Contreras Cortés, F., Moreno Onorato, A., Murillo-Barroso, M., & Pernicka, E. (2012). The silver of the south Iberian El Argar culture: A first look at production and distribution. *Trabajos de Prehistoria, 69*(2), 293–309.
Bayona, M. (2008). *2008 La investigación de la actividad metalśrgica durante el III Milenio A.N.E. en el Suroeste de la Península Ibérica: la arqueometalurgia y la aplicación de análisis metalográficos y composicionales en el estudio de la producción de objetos de Metal*. British Archaeological Reports, International Series 1769. Oxford: Archaeopress.
Billard, C., Bourhis, J.-R., Desfosses, Y., Evin, J., Huault, M., Lefebvre, D., & Paulet-Locard, M.-A. (1991). L'habitat des Florentins à Val-de-Reuil (Eure). *Gallia préhistoire, 33,* 140–171.
Binford, L. R. (1962). Archaeology as anthropology. *American Antiquity, 28,* 217–225.
Blance, B. (1961). Early bronze age colonists in Iberia. *Antiquity, 35,* 192–202.
Blas-Cortina, M., (2005). Un témoignage probant de l'exploitation préhistorique du cuivre dans le nord de la Péninsule Ibérique: le complexe minier d'El Aramo (Asturias). In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 195–206). Mémoires de la Société Préhistorique Française 37.
Borić, D. (2009). Absolute Dating of Metallurgical Innovations in the Vinča Culture of the Balkans. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and Societies: Papers in honour of Barbara S. Ottaway, (*pp. 191–245). *Universitätsforschungen zur prähistorischen Archäologie*. Bonn: Habelt.
Bosch, J. (2005). Les techniques d'exploitation des plus anciennes mines d'Europe méditerranéennes: l'example de Gavà, Barcelone. In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 207–210). Mémoires de la Société Préhistorique Française 37.
Bourgarit, D. (2007). Chalcolithic Copper Smelting. In Susan La Niece, H. Duncan & C. Paul (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 3–14). London: Archetype and British Museum.
Bray, P. J., & Pollard, A. M. (2012). A new interpretative approach to the chemistry of copper-alloy objects: Source, recycling and technology. *Antiquity, 86,* 853–867.
Briard, J., & Roussot-Larroque, J. (2002). Les Débuts de la Métallurgie dans la France Atlantique. In M. Bartelheim, E. Pernicka & R. Krause (Ed.) *The beginnings of metallurgy in the old world* (pp. 135–160). Rahden: Verlag Marie Leidorf.
Brodie, N. (1997). New perspectives on the Bell Beaker culture. *Oxford Journal of Archaeology, 16,* 297–314.
Brodie, N. (2001). Technological frontiers and the emergence of the beaker culture. In F. Nicolis (Ed.), *Bell beakers today: Pottery, people, culture and symbols in prehistoric Europe* (pp. 487–496). Trento: Ufficio Beni Culturali. (International Colloquium Riva del Garda (Trento, Italy), 11–16 May 1998).

Budd, P. D., & Taylor, T. (1995). The faerie smith meets the bronze industry: Magic versus science in the interpretation of prehistoric metal-making. *World Archaeology, 27,* 133–43.

Buikstra, J. E., Castro, P., Chapman, R., Gale, N., Gonzalez Marcen, P., Grant, A., V, L., Jones, M. K., Picazo, M., Risch, R., Sanahuja, M., & Stos Gale, S. (1991). Proyecto gatas, ii fase: Informe preliminar del estudio de los materiales. *Annuario Arqueologicao de Andalucia para 1989*, 214–218

Butler, J. J., & Van der Waals, J. D. (1964). Metal analysis: SAM 1 and European prehistory. *Helenium, 4,* 3–39.

Butler, J. J., & van der Waals, J. D. (1967). Bell beakers and early metal-working in the Netherlands. *Palaeohistoria, 12,* 41–139.

Capel, J., Huertas, F., Pozzuoli, A., & Linares, J. (2006). Red ochre decorations in Spanish Neolithic ceramics: A mineralogical and technological study. *Journal of Archaeological Science, 33,* 1157–1166.

Cartihallac, E. (1886). *Les âges préhistoriques de l'Espagne et du Portugal*. Paris: C. Reinwald.

Case, H. (1966). Were beaker people the first metallurgists in Ireland? *Palaeohistoria, 12,* 141–177.

Cauwe, N., Vander Linden, M., & Vanmontfort, B. (2001). The middle and late neolithic. In N. Cauwe, A. Hauzeur & P.-L. van Berg (Eds.), *Prehistory in Belgium—Préhistoire en Belgique* (pp. 77–89). Bruxelles: Société Royale Belge d'Anthropologie et de Préhistoire (Anthropologica et Praehistorica 112, n° spécial à l'occasion du XIV[e] congrès de l'Union Internationale des Sciences Pré- et Protohistoriques).

Chapman, D. (1997). Great Orme, smelting site, Llandudno. *Archaeology Wales, 37,* 56–57.

Chapman, R. W. (1975). *Economy and society within late prehistoric Iberia: A new framework*. Unpublished PhD thesis: Cambridge University.

Chapman, R. W. (1990). *Emerging complexity: The later prehistory of south-east Spain, Iberia and the west Mediterranean*. Cambridge: Cambridge University Press.

Chardenoux, M.-B., & Courtois, J. (1979). *Les haches dans la France méridionale. Prähistorische Bronzefunde*. Abteilung IX, II Munich

Childe, V. G. (1930). *The Bronze Age.* Cambridge: Cambridge University Press.

Childe, V. G. (1944). Archaeological ages as technological stages. *Journal of the Anthropological Institute of Great Britain and Ireland, 74,* 7–24.

Coffey, G. (1913). *The Bronze Age in Ireland*. London: Dublin: Hodges, Figgis, & Co.

Cooney, G., & Mandal, S. (1998). *Irish stone axe project I*. Dublin: Worldwell

Costa Caramé, M.E. (2010). Las Producciones Metálicas del III y II Milenio Cal ANE en el Suroeste de la Península Ibérica. British Archaeopress (International Series) 2106. Oxford: Archaeopress.

Craddock, P. T. (1995). *Early mining and metal production*. Edinburgh: Edinburgh University Press.

Craddock, P. T. (1999). Paradigms of metallurgical innovation in prehistoric Europe. In A. Hauptmann, E. Pernicka, Th. Rehren & Ü. Yalçin (Eds.), *The beginnings of metallurgy* (pp. 175–192). Der Anschnitt, Beiheft 9. Bochum: Bergbau-Museum.

Craddock, P. T. (2001). From hearth to furnace: Evidences for the earliest metal smelting technologies in the eastern Mediterranean. *Paléorient, 26,* 151–165.

Delibes de Castro, G., & Montero-Ruiz, I. (1999). *Las Primeras Etapas Metalurgicas en la Peninsula Ibérica. II. Estudios Regionales*. Madrid: Instituto Universitario Ortega y Gasset y Ministerio de Educacion, Cultura y Deporte.

Domergue, C. (1987). *Catalogue des mines et des fonderies antiques de la Péninsule Ibérique*. Madrid: Publications de la Casa de Velázquez.

Dutton, A., & Fasham, P. (1994). Prehistoric copper mining on the Great Orme, Llandudno, Gwynedd. *Proceedings of the Prehistoric Society, 60,* 245–286.

Eccleston, M., & Ottaway, B. S. (2002). Experimental casting of copper and bronze in sand moulds. In E. Jerem & K. T. Biro (Eds.), *Archaeometry 1998 (British Archaeological Reports (pp. 185–189) 1043)*. Oxford: BAR.

Ehrhardt, K. L. (2005). *European metals in native hands: Rethinking the dynamics of technological change (1640–1683)*. Tuscaloosa: University of Alabama Press.

Eogan, G., (1994). *The accomplished art: Gold and goldworking in Britain and Ireland during the Bronze Age (c. 2300–650 BC)*. Oxford: Oxbow Monograph 42.

Evans, J. (1881). *Ancient bronze implements, weapons, and ornaments of Great Britain and Ireland*. London: Longmans.
Fasnacht, W. (1991). Analyses d'objets en cuivre du Néolithique récent du bassin zürichois. In C. Eluère & J. P. Mohen (Eds.), *Découverte du métal* (pp. 157–166). Paris: Picard.
Fasnacht, W. (1995). Metallurgie. In W. Stöckli (Ed.), *Die Schweiz vom Paläolithikum bis zum frühen Mittelalte. Volume II. Neolithikum* (pp. 183–187). Basel: Verlag Schweizerische Gesellschaft für Ur-und Frühgeschichte.
Fernández Miranda, M., Montero-Ruíz, I., & Rovira, S. (1995). Los Primeros Objetos de Bronce en el occidente del Europa. *Trabajos de Prehistoria, 52*(1), 57–69.
Fitzpatrick, A. P. (2011). *The Amesbury Archer and the Boscombe Bowmen. Bell Beaker burials at Boscombe Down, Amesbury, Wiltshire*. Salisbury: Wessex Archaeology Reports 27.
Fontijn, D. (2002/3). Sacrificial landscapes: Cultural biographies of persons, objects and natural places in the bronze age of southern Netherlands, c. 2300–600 cal BC. *Annalecta Praehistoria Leidensia* 33–34.
Frieman, C. J. (2012). *Innovation and imitation: Stone skeuomorphs of metal from 4th–2nd millennia BC northwest Europe*. Oxford: Archaeopress. University of Oxford
Gheorghiu, D. (2008). The emergence of pottery. In A. Jones (Ed.), *Prehistoric Europe: Theory and practice* (pp. 164–192). London: Blackwell.
Gilman, A. (1996). Craft specialization in late prehistoric mediterranean Europe. In B. Wailes (Ed.), *Craft specialization and cultural evolution: In memory of V. Gordon Childe* (pp. 67–71). Philadelphia: The University Museum of Archaeology and Anthropology. (University of Pennsylvania Museum Monograph 93).
Giumlia-Mair, A. & Schiavo, F. Lo. (Eds.) (2003). *Le problème de l'étain à l'origine de la métallurgie/The Problem of Early Tin*. Colloque/Symposium. Acts of the XIVth UISPP Congress, University of Liège, Belgium (2–8 September 2001) [British Archaeological Reports (International Series) 1199]. Oxford: Archaeopress.
Gonçalves, V. (1989). *Megalitismo e metalurgia no Alto Algarve Oriental: uma aproximaçãointegrada*. Lisbon: INIC.
Gosden, C., & Marshall, Y. (Eds.) (1999). The cultural biographies of objects. *World Archaeology* 31.
Gosselain, O. P. (1992). Bonfire of the Enquiries. Pottery firing temperatures in archaeology: What for? *Journal of Archaeological Science, 19,* 243–59.
Guilaine, J. (1991). Roquemengarde et les débuts de la métallurgie en France méditerranéenne. In C. Eluère, & J. P. Mohen (Eds.), *Découverte du métal* (pp. 279–294). Paris: Picard.
Guilaine, J. (Ed.). (2006). *Le Chalcolithique et la Construction des Inégalités*. Paris: Errance.
Guilaine, J., & Elèure, C. (1997). Sur les origines de la métallurgie de l'or dans les Corbières. In B. Fritsch, M. Maute, I. Matuschik, J. Müller & C. Wolf (Eds.), *Tradition und Innovation. Prähistorische Archäologie als historische Wissenschaft. Festschrift für Christian Strahm* (pp. 175–182). Rhaden: Verlag Marie Leidorf.
Happ, J. (2005). Comment j'ai enterré ma tuyère et mon soufflet à la Capitelle du Broum. *Cu* + 29–31.
Hanning, E., Gauß, R., & Goldenberg, G. (2010). Metal para Zambujal: reconstrucción experimental de una tecnología de 5.000 años. Trabajos de Prehistoria *67*(2), 287–304.
Happ, J., Ambert, P., Bourhis, J. R., & Briard, J. (1994). Premiers essais de métallurgie expérimentale à l'Archéodrome de Beaune à partir de minerais chalcolithiques de Cabrières (Hérault). *Bulletin de la Société Préhistorique Française, 91*(6), 429–434.
Harbison, P. (1969a). *The Daggers and the Halberds of the Early Bronze Age in Ireland*. Munich: Prähistorische Bronzefunde VI, 1.
Harbison, P. (1969b). *The axes of the Early Bronze Age in Ireland*. Munich: Prähistorische Bronzefunde VI, 2.
Harrison, R. J. (1974). A reconsideration of the Iberian background to Beaker metallurgy. *Palaeohistoria, 16,* 63–105.
Hartmann, A. (1970). *Prähistorische Goldfunde aus Europa: Spektralanalytische Untersuchungen und deren Auswertung. Studien zu den Anfängen der Metallurgie 3*. Berlin: Mann.

Hartmann, A. (1979). Irish and British gold types and their West European counterparts. In M. Ryan (Ed.), *The origins of metallurgy in Atlantic Europe* (pp. 215–228). Dublin: Stationary Office.

Hartmann, A. (1982). *Prähistorische Goldfunde aus Europa: Spektralanalytische Untersuchungen und deren Auswertung. Studien zu den Anfängen der Metallurgie 5*. Berlin: Mann.

Hauptmann, A. (2007). *Archaeometallurgy of Copper: evidence from Faynan, Jordan*. New York: Springer.

Higham, T., Chapman, J., Gaydarska, B., Slavchev, V., Honch, N., Yordanov, Y., & Dimitrova, B. (2007). New perspectives on the Varna cemetery (Bulgaria)—AMS dates and social implications. *Antiquity, 81,* 640–654.

Hook, D., Freestone, I., Meeks, N., Craddock, P. T., & Moreno Onorato, A. (1991). The early production of copper-alloys in South-East Spain. In E. Pernicka & G. Wagner (Eds.), *Archaeometry'90* (pp. 65–76). Basle: Birkhauser

Höppner, B., Bartelheim, M., Husijmans, M., Krauss, R., Martinek, K., Pernicka, E., & Schwab, R. (2005). Prehistoric copper production in the Inn Valley, Austria, and the earliest copper production in central Europe. *Archaeometry, 47*(2), 293–315.

Horne, L. (1982). Fuel for the metal worker. The role of charcoal and charcoal production in ancient metallurgy. *Expedition, 25,* 6–13.

Hosler, D. (1995). Sound, colour and meaning in the metallurgy of ancient west Mexico. *World Archaeology, 27,* 100–115.

Hunt-Ortiz, M. A. (2003). *Prehistoric mining and metallurgy in South West Iberia* [British Archaeological Reports (International Series) 1188]. Oxford: Archaeopress

Junghans, S., Sangmeister, E., & Schröder, M. (1960). *Studien zu den Anfängen der Metallurgie*. Berlin: Gebr. Mann.

Junghans, S., Sangmeister, E., & Schröder, M. (1968). *Studien zu den Anfängen der Metallurgie*. Berlin: Gebr. Mann.

Junghans, S., Sangmeister, E., & Schröder, M. (1974). *Studien zu den Anfängen der Metallurgie*. Berlin: Gebr. Mann.

Kassianidou, V., & Knapp, A. B. (2005). Archaeometallurgy in the mediterranean: The social context of mining, technology and trade. In A. Bernard Knapp & E. Blake (Eds.), *The archaeology of mediterranean prehistory* (pp. 215–251). London: Blackwell.

Keesman, I., Moreno-Onorato, A., Kronz, A. (1991/2). Investigaciones cientificas de la metalurgia de El Malagon y Los Millares, en el Sureste de Espana. *Cuadernos de Prehistoria de la Universidad de Granada* (pp. 16–17, 247–302).

Kienlin, T. L. (2008). Tradition and innovation in copper metallurgy: Results of a metallographic examination of flat axes from eastern central Europe and the Carpathian Basin. *Proceedings of the Prehistoric Society, 74,* 79–108.

Kienlin, T. L. (2011). *Traditions and transformations: Approaches to eneolithic (copper age) and bronze age metalworking and society in Eastern Central Europe and the Carpathian Basin*. British Archaeological Reports (International Series) 2184: Archaeopress.

Killick, D. (2001). Science, speculation and the origins of extractive metallurgy. In D. R. Brothwell & A. M. Pollard (Eds.), *Handbook of archaeological sciences* (pp. 483–492). Chichester: John Wiley and Sons.

Kingery, W. D. (1993). Technological systems and some implications with regard to continuity and change. In S. Lubar & D. W. Kingery (Ed.), *History from things* (pp. 215–230). Washington: Smithsonian Institution Press.

Kingery, W. D. (1996). Introduction. In D. W. Kingery (Ed.), *Learning from things: Method and theory of material culture studies* (pp. 1–15). Washington, DC: Smithsonian Institution Press.

Klassen, L. (2000). *Frühes Kupfer im Norden*. Århus: Århus Archaeology Monograph.

Klassen, L. (2004). *Jade and Kupfer*. Århus: Århus Archaeology Monograph

Knappett, C. (2005). *Thinking through material culture: An interdisciplinary perspective*. Philadelphia: University of Pennsylvania Press.

Korlin, G., & Weisgerber, G. (2006). *Stone Age—Mining Age, Der Anschitt: Beiheft 19*. Bochum: Deutsches-Bergbau Museum.

Krause, R. (2003). *Studien zur kupfer- und frühbronzezeitlichen Metallurgie zwischen Karpatenbecken und Ostsee*. Leidorf: Rahden/Westf.

Lechtman, H. (1996). Cloth and metal: The culture of technology. In E. Boone (Ed.), *Andean art at Dumbarton Oaks* (pp. 33–43). Washington DC: Dumbarton Oaks Research Library and Collection.

Lechtman, H., (1977). Style in technology: Some early thoughts. In H. Lechtman & R. Merrill (Ed.), *Material culture: Styles, organization, and dynamics of technology* (pp. 3–20). St. Paul: West Publishing Co.

Lichardus, J., & Echt, R. (1991). *Die Kupferzeit Als Historische Epoche*. Symposium Saarbrucken Und Otzenhausen.

Lichardus-Itten, M. (2006). Le Chalcolithique: une époque historique de l'Europe. In J. Guilaine (Ed.), *Le; et la Construction des Inégalités* (pp. 11–22). Paris: Errance.

Livingstone-Smith, A. (2001). Bonfire II: The return of pottery firing temperatures. *Journal of Archaeological Science, 28,* 991–1003.

Lo Schiavo, F., Giumlia-Mair, A., & Valera, R. (2005). *Archaeometallurgy in Sardinia: From the origin to the beginning of early iron age*. Monographies Instrumentum 30. Montagnac: Monique Mergoil.

Maass, A. (2005). Quelques réflexions concernant les structures minières chalcolithiques de la region de Cabrières. In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 63–70). Mémoires de la Société Préhistorique Française 37.

Maggi, R., & Pearce, M. (2005). Mid fourth-millennium copper mining in Liguria, north-west Italy: The earliest known copper mines in Western Europe. *Antiquity, 79,* 66–77.

Makkay, J. (1991). The most ancient gold and silver in Central and South-East Europe. In C. Eluère & J. P. Mohen (Eds.), *Découverte du métal* (pp. 119–130). Paris: Picard.

Mathieu, J. R., & Mayer, D. A. (1997). Comparing axe heads of stone, bronze, and steel: Studies in experimental archaeology. *Journal of Field Archaeology, 24,* 333–351.

McDonnell, J. G. (2001). Pyrotechnology. In D. Brothwell & M. Pollard (Eds.), *Handbook of archaeological sciences* (pp. 493–506). London: Wiley.

McGeehan-Liritzis, V. (1983). The relationship between metalwork, copper sources, and the evidence for settlement in the Greek Late Neolithic and early bronze age. *Oxford Journal of Archaeology,* 2(2), 147–180.

Mille, B., & Bouquet, L. (2004). Le métal au 3e millénaire avant notre ère dans le Centre-Nord de la France. In M. Vander Linden & L. Salanova (Eds.), *Le troisième millénaire dans le nord de la France et en Belgique. Actes de la journée d'études SRBAP—SPF*. 8 mars 2003, Lille. Mémoires de la Société Préhistorique Française, XXXV. *Anthropologica et Praehistorica*, 115, 197–215.

Mille, B., & Carozza, L. (2009). Moving into the metal ages: The social importance of metal at the end of the neolithic period in France. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and societies: Papers in honour of Barbara S. Ottaway* (pp. 143–171). Universitätsforschungen zur prähistorischen Archäologie. Bonn: Habelt.

Molina, F., Cámara, J. A., Capel, J., Nájera, T., & Sáez, L. (2004). Los Millares y la periodización de la prehistoria reciente del sureste (pp. 142–148). *Simposos de Prehistoria Cueva de Nerja*. Nerja: Fundacion Cueva de Nerja.

Monge Soares, A., Araujo, M de F., & Peixoto Cabral, J. (1994). Vestígos da Práctica de Metalurgia em povoados Calcolíticos da Bacia do Guadiana, entre Ardila e o Chança. In J. Campos, J. Perez & F. Gomez (Eds.), *Arqueologia en el entorno delBajo Guadiana* (pp. 165–200). University de Huelva: Grupo de Investigacion Arqueológica del Património del Suroeste.

Montelius, O. (1909). The chronology of the British Bronze Age. *Archaeologia, 61,* 97–162.

Montero Ruiz, I. (1994). *El origen de la Metalurgia en el Sureste Peninsula*: Instituto de Estudios Almerienses.

Montero Ruiz, I. (2005). Métallurgie ancienne dans la Péninsule Ibérique. In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 187–194). *Mémoires de laSociété Préhistorique Française* 37.

Montero Ruiz, I., Rihuete, C., & Ruiz Taboada, A. (1999). Precisones sobre el enterramiento colectivo neolítico del Cerro Virtud (Cuevas de Almanzora, Almería). *Trabajos de Prehistoria, 56*(1), 119–130.

Much, M. (1886). *Die Kupferzeit in Europa*. Vienna.

Muhly, J. D., (2002). Early metallurgy in Greece and Cyprus. In Ü. Yalçin (Ed.), *Anatolian Metal II* (pp. 77–82). Der Anschnitt, Beiheft 15. Bochum: Deutches Bergbau- Museum.

Müller, J. (2002). Modelle zur Einführung der Zinnbronzetechnologie und zur sozialen Differenzierung der mitteleuropäischen Frühbronzezeit. In J. Müller (Ed.), *Vom Endneolithikum zur Frühbronzezeit: Muster sozialen Wandels?* (pp. 267–289). Universitätsforschung zur prähistorischen Archäologie 90. Bonn: Habelt.

Müller, R., Rehren, Th., & Rovira, S. (2004). Almizaraque and the early metallurgy of southeast Spain: New data. *Madrider Mitteilungen, 45,* 33–56.

Müller, R., Goldenberg, G., Bartleheim, M., Kunst, M., & Pernicka, E. (2007). Zambujal and the beginnings of metallurgy in southern Portugal. In S. La Niece, D. Hook, & P. Craddock (Eds.), *Metals and Mines: Studies in archaeometallurgy* (pp. 15–26). London: Archetype.

Murillo-Barroso, M., & Montero-Ruiz, I. (2012). Copper ornaments in the iberian chalcolithic: Technology versus social demand. *Journal of Mediterranean Archaeology, 25*(1), 53–73.

Needham, S. (1996). Chronology and periodisation in the British bronze age. *Acta Archaeologica, 67,* 121–40.

Needham, S. (2001). When expediency broaches ritual intention: The flow of metal between systemic and buried domains. *Royal Anthropological Institute, 7,* 275–298.

Needham, S., (2002). Analytical implications for beaker metallurgy in North-West Europe. In E. Pernicka & M. Bartelheim (Ed.), *The beginnings of metallurgy in the old world* (pp. 99–133). Rahden: Verlag Marie Leidorf.

Needham, S. (2004). Migdale-Marnoch: Sunburst of Scottish metallurgy. In I. Shepherd & G. Barclay (Eds.), *The Neolithic and Early Bronze age of Scotland in their European context* (pp. 217–245). Edinburgh: Royal Society of Antiquaries of Scotland.

Nocete, F. (2006). The first specialised copper industry in the Iberian peninsula: Cabezo Juré (2900–2200 BC). *Antiquity, 80,* 646–657.

Nocete, F. (Ed.). (2004). *Odiel: Projecto de Investigación Arqueológia para el análisis de la desigualidad social en el Suroeste de la Península Ibérica*. Seville: Monografias de Arqueologia 19.

Northover, J. P. (1989). Properties and use of arsenic-copper alloys. In E. Pernicka & G. Wagner (Eds.), *Old world archaeometallurgy, andreas hauptmann* (pp. 111–118). Der Anschnitt Beiheft 7. Bochum: Deutsches Bergbau Museum.

O'Brien, W. (2004). *Ross Island* (bronze age studies 5). Galway: National University of Ireland.

O'Sullivan, A. (1996). Neolithic, bronze age and iron age woodworking techniques. In B. Raftery (Ed.), *Trackway excavations in the mountdillon bogs, co. longford, 1985–1991* (pp. 291–342). Dublin: Irish Archaeological Wetland Unit.

Orton, C., Tyers, P., & Vince, A. (1997). *Pottery in archaeology*. Cambridge: Cambridge University Press.

Ottaway, B. S. (1973). The earliest copper ornaments in northern Europe. *Proceedings of the Prehistoric Society, 39,* 294–331.

Ottaway, B. S. (1982). *Earliest copper artifacts in the Northalpine. Region: Their analysis and evaluation*. Bern: Schriften des Seminars fuÌr Urgeschichte der UniversitaÌt Bern.

Ottaway, B. S. & Seibel, S. (1998). Dust in the wind: Experimental casting of bronze in sand moulds. In M.-C. Frère-Sautot (Ed.), *Paléométallurgie des cuivres: Actes du colloque de Bourg-en-Bresse et Beaune, 17–18 oct. 1997* (pp. 59–63). Monographies Intrumentum 5. Montagnac: Monique Mergoil.

Ottaway, B. S. (1994). *Prähistorische Archäometallurgie*. Espelkamp: Verlag Marie L. Leidorf.

Ottaway, B. S. (2001). Innovation, production and specialisation in early prehistoric copper metallurgy. *European Journal of Archaeology, 4*(1), 87–112.

Ottaway, B. S. (2003). Experimental archaeometallurgy. In T. Stöllner, G. Steffens & J. Cierny (Eds.), *Man and mining—Mensch und Bergbau: Studies in honour of Gerd Weisgerber on occasion of his 65th birthday* (pp. 341–348). Der Anschnitt Beiheft 9. Bochum: Bergbau-Museum.

Ottaway, B. S., & Roberts, B. W. (2008). The emergence of metalworking. In A. Jones (Ed.), *Prehistoric Europe: Theory and practice* (pp. 193–225). London: Blackwell.

Pare, C. F. E., (2000). Bronze and the bronze age. In C. Pare (Ed.), *Metals make the world go round* (pp. 1–38). Oxford: Oxbow Books.

Pascale De, A. (2003). 'Hammerstones from early copper mines' sintesi dei ritrovamenti nell' Europa e mel Mediterraneo orientale e prime considerazioni sui mazzuoli di Monte Loreto (IV millennio BC—Liguria). *Rivista di Studi Liguri, 69,* 5–42).

Pearce, M. (2007). *Bright blades and red metal: Essays on north Italian prehistoric metalwork.* London: Accordia Research Institute.

Perea, A. (1991). *Orfebrería Prerromana: Arqueologia de Oro*. Madrid: Caja de Madrid0

Pernicka, E. (1998). Die Ausbreitung der Zinnbronze im 3. Jahrtausend. In B. Hänsel (Ed.), *Mensch und Umwelt in der Bronzezeit Europas* (pp. 135–147). Kiel: Oetker-Voges Verlag.

Pétrequin, P. (1993). North wind, south wind. Neolithic technical choices in the Jura mountains, 3700–2400 BC. In P. Lemonnier (Ed.), *Technological choices. Transformation in material cultures since the Neolithic* (pp. 36–76). London: Routledge.

Pétrequin, P., Cassen, S., Croutsch, C., & Errera, M. (2002). La valorisation sociale des longues haches de l'Europe néolithique. In J. Guilaine (Ed.), *Matériaux, productions, circulations du Néolithique à l'Âge du Bronze* (pp. 67–98). Paris: Editions Errance.

Pingel, V. (1992). *Die vorgeschichtlichen Goldfunde der Iberischen Halbinsel: Eine archäeologische Untersuchung zur Auswertung der Spektranalysen. Deutsches Archäologisches Institut. Madrider Forschungen* (Bd. 17). Berlin: Walter de Gruyter und Co.

Prange, M., & Ambert, P. (2005). Caractérisation géochimique et isotopique des minerais et des métaux base cuivre de Cabrières (Hérault). In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 71–81). Mémoires de la Société Préhistorique Française 37.

Primas, M., (1995). Gold and silver during the 3rd mill cal BC. In G. Morteani & J. P. Northover (Eds.), *Prehistoric gold in Europe* (pp. 77–93). Dortrecht: NATO ASI Series.

Primas, M., (2002). Early tin bronze in central and southern Europe. In M. Bartelheim, E. Pernicka, & R. Krause (Eds.,) *The beginnings of metallurgy in the old world* (pp. 303–314). Rahden: Marie Leidorf.

Radivojević, M., Rehren, Th., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the origins of extractive metallurgy: New evidence from Europe. *Journal of Archaeological Science, 37,* 2775–87.

Rehren, Th. (2009). From mine to microbe: The neolithic copper melting crucibles from Switzerland. In Th. Rehren, I. Freestone & A. Shortland (Eds.), *From mine to microscope: Advances in the study of ancient technology* (pp. 223–233). Oxford: Oxbow.

Renfrew, C. (1967). Colonialism and megalithismus. *Antiquity, 41,* 276–288.

Renfrew, C. (1973). *Before civilization: The radiocarbon revolution and prehistoric Europe*. Cambridge: Cambridge University Press.

Renfrew, C. (1986). Varna and the emergence of wealth in prehistoric Europe. In A. Appadurai (Ed.), *Social life of things: Commodities in a cultural perspective* (pp. 141–68). Cambridge: Cambridge University Press.

Roberts, B. W. (2008a). Creating traditions and shaping technologies: Understanding the earliest metal objects and metal production in Western Europe. *World Archaeology, 40*(3), 354–372.

Roberts, B. W., (2008b). Migration, craft expertise and metallurgy: Analysing the 'spread' of metal in Europe. *Archaeological Review from Cambridge, 23*(2), 27–45.

Roberts, B. W., & Frieman, C. J. (2012). Drawing boundaries and building models: Investigating the concept of the 'Chalcolithic frontier' in Northwest Europe. In M. Allen, J. Gardiner & A. O. Sheridan (Eds.), *Is there a British Chalcolithic: People, place and polity in the later 3rd millennium* (pp. 27–39).

Roberts, B. W., Thornton, C. P., & Pigott, V. (2009). Development of metallurgy in Eurasia. *Antiquity, 83,* 1012–22.

Roberts, B. W., & Frieman, C. J. (in press). Early metal in Western and Northern Europe. In C. Fowler, J. Harding & D. Hoffman (Eds.), *The Oxford handbook of Neolithic Europe*. Oxford: Oxford University Press.

Roden, C. (1988). Blasrohrdüsen: Ein archäologischer Exkurs zur Pyrotechnologie des Chalkolithikums und der Bronzezeit. *Der Anschnitt, 40,* 62–82.

Rothenberg, B., & Blanco-Freijeiro, A. (1981). *Ancient mining and metallurgy in South-west Spain*. London: I.A.M.S.

Roussot-Larroque, J. (2005). Première métallurgie du Sud-Ouest Atlantique de la France. In P. Ambert & J. Vaquer (Eds.), *La première métallurgie en France et dans les pays limitrophes* (pp. 159–174). Mémoires de la Société Préhistorique Française 37.

Rovira, S. (2002). Metallurgy and society in Prehistoric Spain. In B. S. Ottaway & E. C. Wager (Eds.), *Metals and society: Papers from a session held at the European association of archaeologists sixth annual meeting in Lisbon 2000* (pp. 5–20). Oxford: Archaeopress. (British Archaeological Reports (International Series) 1061).

Rovira, S., & Ambert, P. (2002). Les céramiques à réduire le minerai de cuivre: une technique métallurgique utilisée en Ibérie, son extension en France méridonale. *Bulletin de la Société Préhistorique Française, 99*(1), 105–126.

Rovira, S., & Delibes de Castro, G. (2005). Beaker metallurgical technology in the Iberian Peninsula: Pouring, moulding and post-smelting treatments. In M. A. Rojo Guerra, R. Garrido Pena, & I. García-Martínez de Lagrán (Eds.), *El Campaniforme en la Península Ibérica y Su Contexto Europeo* (pp. 513–521). Valladolid: Universidad de Valladolid.

Rovira, S., & Gómez-Ramos, P. (2004). *Las Primeras Etapas Metalurgicas en la Peninsula Ibérica. III. Estudios Metalográficos*. Madrid: Instituto Universitario Ortega y Gasset y Ministerio de Educacion, Cultura y Deporte.

Rovira, S., & Guttierez, A. (2005). Utilisation expérimentale d'un four primitif pour fonder du minerai de cuivre. In P. Ambert & J. Vaquer (Eds.), *La première métallurgie France et dans les pays limitrophes* (pp. 241–246). Mémoires de la Société PréhistoriqueFrançaise 37.

Rowlands, M. J. (1971). The archaeological interpretation of metalworking. *World Archaeology, 3,* 210–223.

Rowley-Conwy, P. (2007). *From genesis to prehistory. The archaeological three age system and its contested reception in Denmark, Britain and Ireland*. Oxford: Oxford University Press.

Ruíz Taboada, A., & Montero-Ruíz, I. (1999). The oldest metallurgy in western Europe. *Antiquity, 73,* 897–903.

Ryndina, N. V., Indenbaum, G., & Kolosova, V. (1999). Copper production from polymetallic sulphide ores in the northeastern Balkan Eneolithic culture. *Journal of Archaeological Science, 26,* 1059–1068.

Schlicht, E. (1968). *Die Funde aus dem Megalithgrab 2 von Emmeln, Kreis Meppen: Studien zur Keramik der Trichterbecherkulturim Gebiet zwischen Weser und Zuidersee*. Neumünster: K. Wachholtz.

Siret, E., & Siret, L. (1887). *Les Premiers ℜges du Metal dans le sud-est de l' Espagne*. Antwerp.

Skeates, R. (1994). Early metal use in the central mediterranean region. *Accordia Research Papers, 4,* 5–47.

Sofaer-Derevenski, J., & Sørensen, M.-L. S. (2002). Becoming cultural: Society and the incorporation of bronze. In B. S. Ottaway & E. C. Wager (Eds.), *Metals and society: Papers from a session held at the European association of archaeologists sixth annual meeting in Lisbon 2000* (pp. 117–122). [British Archaeological Reports (International Series) 1061]. Oxford: Archaeopress.

Soriano, I., Soler Subils, J., & Soler Masferrer, N. (2012). ¿La primera orfebrería del nordeste de la Península Ibérica? Nuevas aportaciones a partir de la cuenta áurea de Cau del Tossal Gros (Torroella del Montgrí, Baix Empordà, Girona). *Trabajos de Prehistoria, 69*(1), 149–161.

Soriano, I. (2013). Metalurgia y Sociedad en el Nordeste de la Peninsula Ibérica (finales del IV-II milenio cal ANE). British Archaeological Reports (International Series) 2502. Oxford: Archaeopress.
Strahm, C. (1994). Die Anfänge der Metallurgie in Mitteleuropa. *Helvetia Archaeologica, 25,* 2–39.
Strahm, C. (2005). L'introduction et la diffusion de la métallurgie en France. In P. Ambert & J. Vaquer (Eds.) *La première métallurgie en France et dans les pays limitrophes* (pp. 27–36). Mémoires de la Société Préhistorique Française 37.
Taylor, T. (1999). Envaluing metal: Theorizing the Eneolithic 'hiatus'. In S. Young, M. Pollard, P. Budd, & R. Ixer (Eds.), *Metals in antiquity* (pp. 22–32) [British Archaeological Reports (International series) 792]. Oxford: Archaeopress.
Thornton, C. P. (2009). Archaeometallurgy: Evidence of a paradigm shift? In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and societies: Papers in honour of Barbara S. Ottaway* (pp. 25–33). Universitätsforschungen zur prähistorischen Archäologie. Bonn: Habelt.
Timberlake, S. (2002). Ancient prospection for metals and modern prospection for ancient mines: The evidence for bronze age mining within the British Isles. In M. Bartelheim, E. Pernicka, & R. Krause (Eds.), *The beginnings of metallurgy in the old world* (pp. 327–357). Rahden: Verlag Marie Leidorf.
Timberlake, S. (2005). In search of the first melting pot. *British Archaeology, 82,* 32–33.
Timberlake, S. (2007). The use of experimental archaeology/archaeometallurgy for understanding and reconstructing early bronze age mining and smelting. In S. La Niece, D. Hook, & P. Craddock (Eds.) *Metals and mines: Studies in archaeometallurgy* (pp. 27–36). London: Archetype and British Museum.
Timberlake, S. (2003). *Excavations on Copa Hill, Cwmystwyth (1986–1999); An Early Bronze Age copper mine within the uplands of Central Wales. British archaeological reports (British Series) 348*. Oxford: Archaeopress.
Tylecote, R. F. (1970). The composition of metal artifacts: A guide to provenance? *Antiquity, 44,* 19–25.
Tylecote, R. F. (1987). *Early history of metallurgy in Europe*. London: Longman.
Van der Linden, M. (2006). *Le phénomène campaniforme dans l'Europe du 3ème millénaire avant notre ère: Synthèse et nouvelles perspectives* [British Archaeological Reports (International Series) 1470]. Oxford: Archaeopress.
Veiga da, S. P. M. E. (1889). *Antiguidades monumentaes do Algarve: tempos prehistoricos*. Lisboa: Imprensa nacional.
Von Pulsky de, F. (1884). *Die Kupferzeit in Ungarn*. Budapest.
Wager, E. C. (1997). Ffynnon Rufeinig. *Great Orme Exploration Society, 1,* 6–9.
Wailes, B. (Ed.). (1996). *Craft specialization and social evolution: In memory of V. Gordon Childe*. University Museum Monograph 93, Philadelphia: University Museum of Archaeology and Anthropology, University of Pennsylvania.
Warmenbol, E., (2004). Le début des âges des Métaux en Belgique. In M. Vander Linden & L. Salanova (Eds) *Le troisième millénaire dans le nord de la France et en Belgique. Actes de la journée d'études SRBAP—SPF*. 8 mars 2003, Lille. Mémoires de la Société Préhistorique Française, XXXV, *Anthropologica et Praehistorica*, 115, 27–48.
Waterbolk, H. T., & Butler, J. J. (1965). Comments on the use of metallurgical analysis in prehistoric studies. *Helenium, 5,* 227–241.
Wayman, M. L., & Duke, J. (1999). The effects of melting on native copper. In A. Hauptmann, E. Pernicka, Th. Rehren, & Ü. Yalçin (Eds.). *The beginnings of metallurgy* (pp. 55–63). Bochum: Der Anschnitt.
Weisgerber, G., & Pernicka, E. (1995). Ore mining in prehistoric Europe: An overview. In G. Morteani & J. P. Northover (Eds.), *Prehistoric gold in Europe* (pp. 159–182). Netherlands: Kluwer Academic Publishers.
Weisgerber, G., & Willies, L. (2001). The use of fire in prehistoric and ancient mining: Firesetting. *Paleorient, 26*(2), 131–149.

Wilde, W. (1862). *A descriptive catalogue of the antiquities of gold in the museum of the Royal Irish academy*. Dublin

Wilson, D. (1851). *Prehistoric annals of Scotland*. Edinburgh: Sutherland & Knox.

Zachos, K. (2007). The neolithic background: A reassessment. In P. M. Day & R. C. P. Doonan (Eds.), *Metallurgy in the Early Bronze Age Aegean* (pp. 168–206). Sheffield: Sheffield Studies in Aegean Archaeology 7.

Chapter 17
Aspects of Metalworking and Society from the Black Sea to the Baltic Sea from the Fifth to the Second Millennium BC

Tobias L. Kienlin

Introduction

In this contribution a review is given of the early evidence of metallurgy in south-eastern and central Europe. Starting from the Eneolithic or Copper Age and extending into the Bronze Age, an attempt is made to follow the development of mining for copper minerals and ores, the origins of extractive metallurgy (smelting), the working of copper and the succession of different types of copper and copper-based alloys. From the fifth to the second millennium BC, early metalworking communities between the Baltic and the Black Sea are designated as anything from (Late) Neolithic, via Eneolithic, Chalcolithic or Copper Age to (Early) Bronze Age. Such terminology not only describes technological advances but also carries broader social and cultural implications that tend to go unstated. For example, in the Carpathian Basin the term 'Copper Age' refers to a period when a large number of heavy copper implements first made their appearance. 'Copper Age' in this tradition denotes a technological stage that is not necessarily coeval throughout south-eastern Europe. In contrast, other scholars would seek to correlate this technological change with perceived progress in wider economic and cultural domains. In this academic tradition, metallurgy is thought to have experienced a rapid rise in complexity that necessitated exchange and specialised production, triggered new social hierarchies and invited attempts by higher-ranking individuals to increase the efficiency and stability of their power. Broadly speaking these are evolutionist notions—both in terms of technology and society—that are not supported here. The nature of changes in economy, society and ideology—if any—is subject to debate and, across the vast area from the Black Sea to central Europe, may not occur at the same time and can take different forms.

The study of metallurgy is entangled with the wider intellectual development of prehistoric archaeology. Hence, apart from a mere review of the evidence for early metalworking and related scientific data, the second aim of this contribution is to challenge evolutionist assumptions in our notions of technological 'progress'. An attempt

T. L. Kienlin (✉)
Institut für Ur- und Frühgeschichte, Universität zu Köln, Weyertal 125 D-50923 Köln
e-mail: tkienlin@uni-koeln.de

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_17,

is made to deconstruct some commonly held perceptions regarding the social context of early metallurgy. It will become clear that sharply defined technological stages tend to become blurred by new discoveries. We cannot rely on inevitable 'progress' and geological conditions as a guide to the development of early metallurgy anymore. The early use of copper and the subsequent development of metallurgy was the result of technological choices drawing upon and embedded in the respective groups' cultural and social texture. These choices were taken by actors firmly integrated in kinship-based networks of communication and decision-taking. They were neither determined in their action by the laws of chemistry or physics alone nor by any 'political' authority manipulating the production and circulation of 'prestigious' metal objects.

The Earliest Use of Copper and the Beginnings of Metallurgy

The origins of metallurgy are hotly debated. Some opt for single invention in Southwest Asia (e.g. Roberts et al. 2009), while others are ready to consider the autonomous invention of metallurgy in south-eastern Europe depending on evidence that might still come to light (e.g. Parzinger 1993). A great number of syntheses integrate the evidence at hand into a coherent culture-historical picture that typically involves the spread of metallurgy ultimately from the Near East via south-eastern to central and northern Europe (e.g. Pernicka 1990; Klassen 2000; Krause 2003). Recent scientific evidence, on the other hand, suggests the independent development of extractive metallurgy on the Balkans (Radivojević et al. 2010).

New finds still have the potential to significantly alter the overall picture. However, such discussions also touch upon questions of world view. The notion of eastern origins goes back to V. G. Childe. In his influential work, the emergence of metallurgy is located in the urban centres of the Near East (e.g. Childe 1930). From there, Childe claimed the knowledge of copper and bronze had spread to Europe, where—in a distinctly Childean turn—it was thought to have taken on a new quality whereby the specific freedom and creativity of itinerant Bronze Age craftsmen started a trajectory that led right up to modern western civilisation. When C. Renfrew (1969) used radiocarbon dates to defy diffusionist claims, this vision of European creativity was no longer employed. But with the cemetery of Varna providing the social background to Eneolithic/Copper Age metallurgy (Renfrew 1986), he clearly remained in a Childean tradition of linking metalwork to the emergence of sociopolitical elites. Not everyone would share this Childe–Renfrew view of causality. Still, Renfrew's call to move archaeology beyond concepts of 'spread', 'influence' or 'diffusion' clearly stands since these do not significantly add to our knowledge of early metallurgy. Instead, we have to aim towards an understanding of innovation in a local or regional context. Early metalworking from the fifth to the second millennium BC took place in groups widely different in their cultural and organisational complexity. This prompts questions as to the different strategies for incorporating copper and bronze into existing cultural schemes and as well as the impact of metalworking and metal objects on the societies in question. Beyond the call for additional archaeological and scientific data and to re-evaluate the assumption that prestigious copper and bronze objects caused culture change, this involves a discussion of the role of technology in society and of the social context of early metalworking, its meaning and symbolic implications.

The use of native copper and attractively coloured copper carbonate minerals (azurite and malachite) for symbolic purposes, such as ornaments, has been declared a feature of the original Neolithic package. In Anatolia and the Levant, there is evidence for the use of copper minerals as pigments and native copper for small artefacts such as beads, rings and awls at least from the mid-ninth millennium BC pre-pottery Neolithic onwards. The technology involved the grinding of copper minerals as well as hammering and applying heat (annealing) to restore the deformability of native copper once the material became brittle (e.g. Maddin et al. 1999). Heating to modify the mechanical properties of matter and also its colour can be traced back to the working of flint and wood. Once pottery was introduced this possibility would have been a widespread notion in Neolithic groups. The concept of 'pyrotechnology' refers to this technological background, and a comparison of the different *chaînes opératoires* involved may improve our understanding of the early use of copper (e.g. Ottaway 2001). There are controversial debates whether the working of native copper and copper minerals at this stage involved strategies and knowledge not otherwise applied in the contemporaneous production of tools and ornaments from other materials. Generally speaking, the earliest interest in native copper and copper minerals falls into the wider field of Neolithic communities' involvement with their natural surroundings and their attempts at the manipulation of matter. It must not be seen as purposive experimentation in a modern sense, leading up to the 'science' of metallurgy. Rather it referred to the aesthetic values and broader symbolic concerns expressed and negotiated through material culture. This development predates proper metallurgy, which apart from working native copper and copper minerals should include mining for the deliberate production of copper ore, smelting and casting. These are somewhat later developments.

In the Carpathian Basin and the Balkans, the earliest artefacts made of native copper and copper minerals during this pre-metallurgy phase include beads, fish-hooks and awls. They are known from Early to Middle Neolithic contexts (e.g. from Starčevo/Criş culture sites; Pernicka 1990; Parzinger 1993). Reflecting the spread of the Neolithic way of life, they are younger than the earliest corresponding evidence from Anatolia and date from the mid-sixth millennium BC onwards.

A significant increase in the number of such finds and an expansion of the copper artefact types in use occurred during the early fifth millennium BC in the north-central Balkans during the later phases of the Late Neolithic/Eneolithic Vinča culture. Recent radiocarbon dating shows that the copper mining site of Rudna Glava in Serbia was most likely exploited from at least 5400 cal BC, i.e. right from the beginning of Vinča culture (Borić 2009). In addition, the settlement of Belovode now has evidence of copper smelting from about 5000 cal BC onwards (Radivojević et al. 2010). Driven by cultural and social preferences, the earliest mining was directed towards copper minerals desirable for their colour and maybe native copper that was worked into ornaments. This tradition formed the background to attempts at the

Fig. 17.1 Map of the sites mentioned in the text

thermal alteration of copper minerals, possibly with a transformation of colour or mechanical properties in mind. This eventually led to the transformation of matter from stone/mineral to copper, i.e. the discovery of smelting. This may have happened in the pyrotechnological context of dark-burnished Vinča ware that combined high temperatures with a reducing atmosphere (Bailey 2000; Borić 2009). The earlier technological tradition persisted parallel to the new ability to produce copper from its ores, and both traditions remained distinct. Recent lead-isotope analyses (LIA) imply that different copper outcrops were used to obtain ore for smelting and for the procurement of pigments. In addition, from the excavations at Belovode there is evidence to suggest that both activities were spatially separated (Radivojević et al. 2010). For the time being, the smelting at Belovode predates anything comparable in the Near East. It may well suggest the autonomous invention of extractive metallurgy in south-eastern Europe. Irrespective of single or multiple origins, however, the Vinča path to metallurgy, which is now quite well established, may help us understand some of the desires and motivations underlying the gradual building up of a potential for proper metallurgy in a Neolithic context. (Fig. 17.1)

In the course of time, larger amounts of copper became available and with the introduction of casting there was a shift in aesthetic values and in the perception of matter. The earlier concern, that also motivated the beginnings of mining at Rudna Glava, had been with the colour of native copper or copper minerals, ground or hammered and annealed into ornaments or pigments. With the adoption of smelting and casting there was an increase in the size and in the variety of shapes that copper objects could take. We enter the domain of what D. Bailey (2000) aptly called "expressive material culture". The large number of copper shaft-hole implements, which initially gave rise to the definition of a Copper Age period in south-eastern Europe, feature prominently under this heading. Among them, there is a variety of different types of hammer axes (e.g. Pločnik and Vidra) and axe-adzes (e.g. Jászladány). All of these forms, as well as contemporaneous flat axes and chisels, consist of pure copper. It is likely that they were cast in closed moulds and finished by hot working (Kienlin 2010). Hence their hardness was low and their potential for practical use was limited when compared to contemporaneous stone or flint implements. By their sheer size and weight some shaft-hole axes were unusable. They shared the characteristic shiny appearance of earlier (native) copper ornaments, but they existed in greater numbers and increased the potential of symbolic expression. The same is true for the growing number of gold ornaments of this period as in the famous Varna cemetery on the Black Sea coast.

Grave finds and hoards testify to the symbolic dimension copper and gold artefacts had acquired in the Tiszapolgár and Bodrogkeresztúr culture contexts of the Early and Middle Copper Age (in Hungarian terminology) during the late fifth and early fourth millennium cal BC. However, this should not only be conceptualised in terms of abstract 'wealth', and it should not be taken to imply that metallurgy was under the control of some kind of hereditary political elite. Varna, which is now dated to c. 4560–4450 cal BC (Higham et al. 2007), is unparalleled even in Bulgaria, and there is no comparable evidence from other cemeteries of status inherited beyond prestigious objects apparently derived from age and/or personal achievement. In the somewhat later Tiszapolgár and Bodrogkeresztúr culture graves from the Carpathian Basin, for example, we find different kinds of personal identities and levels of authority that hardly extended beyond the co-residential unit or the limits of the individual's lifespan (Lichter 2001). There are occasional shaft-hole axes in the (male) graves of both groups, but it is not possible to translate variation in the expression of personal identities and possibly 'economic' success into differential access to status or power. Instead, we see a complex web of individual and corporate identities that were negotiated on various levels from the household, kin-groupings to the village or the tribe (Whittle 1996; Bailey 2000).

In his review of the earliest use of copper in south-eastern Europe, H. Parzinger (1993) lists a total number of just 54 (native) copper artefacts from Neolithic contexts (including Anatolia) compared to, for example, 55 Pločnik- and Vidra-type hammer axes and some 227 Jászladány-type axe-adzes from the Eneolithic/Copper Age. This gives an impression of just how much metal was in circulation during this period. Shaft-hole axes were a widespread phenomenon, and they were 'understood' throughout south-eastern Europe. There are many different 'variants' of these implements that point to distinct traditions in their production. Clearly, these also offered the potential to be involved in the negotiation of local identities that are well attested in contemporaneous pottery production (e.g. Parkinson 2006). It should also be noted that at least some of the axes have traces of use-wear. Use in this sense may include occasional conflict. Use was certainly of limited intensity and restricted to just certain practical activities, and does not correspond to our modern use of steel axes. It is likely that such implements were present in people's daily life on a more regular basis than our interest in their role in a formalised social display, ceremonies and burial ritual implies. Rather than focusing on their conspicuous deposition during burial ceremonies, it is apparent that it was precisely their presence in more mundane situations and activities that substantiated the axes' suitability as markers of male habitus and—in more general terms—the potential of copper to play a role in the expression of a person's identity and social standing.

In the North Alpine region of central Europe, there was only a weak reflection of this development. From Neolithic contexts of the late fifth and the early fourth millennium BC, no more than about 10–20 copper objects are known. Among them, there are the well-known disc from the lakeside settlement of Hornstaad-Hörnle on Lake Constance (Klassen 2010), two shaft-hole axes and one flat axe from Linz-St. Peter, Austria, and Überlingen on Lake Constance, awls as well as some small copper beads and rings. Until the recent discovery of smelting slag supposedly dating to this horizon at Brixlegg in Austria (c. 4400–4200 cal BC; Bartelheim et al. 2002), these early copper finds were thought to be imported from south-eastern Europe. This would imply a rapid spread of smelting to central Europe and/or roughly contemporaneous local experimentation. There is a problem, however, with the dating of the metallurgical remains from Brixlegg, which might also belong to a younger horizon on this site (Gleirscher 2007; Turck 2010). It may be safer to maintain that copper came from the East (see also Höppner et al. 2005), for the shaft-hole axes mentioned clearly originate from the Carpathian Basin. Even if some experimentation with smelting was going on, it is quite clear that this did not immediately result in the widespread use of copper objects or in the practice of metallurgy.

It is only somewhat later after about 3900/3800 cal BC with the Late Neolithic Cortaillod, Pfyn, Altheim and Mondsee cultures that the number of copper artefacts increases. There are numerous flat axes, daggers, awls and ornaments such as spirals and beads mainly from the wetland sites along the Alpine foothills (Krause 2003; Turck 2010). In this context there is also good evidence of metalworking with numerous crucibles and copper prills relating to the casting process (Matuschik 1998). Extractive metallurgy, on the other hand, has been suggested but is still not entirely proven. Hence copper is thought either to have been derived from nearby Alpine ore deposits or to have been imported from south-eastern Europe. In particular, the East Alpine mining district is thought to have been exploited by the population of the Mondsee culture, although related evidence of extractive metallurgy (smelting) from the Götschenberg settlement in the Alpine Salzach valley is disputed (Bartelheim et al. 2002). Copper composition may point towards ongoing exchange with the Carpathian Basin instead and indicate the exploitation of ore deposits in the Slovakian Ore Mountains (Schreiner 2007).

Neither the Eneolithic/Copper Age metallurgy of south-eastern Europe nor its western counterpart during the local Late Neolithic developed continuously into the Bronze Age. Rather, any apparent metallurgical 'progress' turned out to be reversible. With the end of Kodžadermen-Gumelniţa-Karanovo VI in Bulgaria and somewhat later of Bodrogkeresztúr etc. in the Carpathian Basin, there was a change in many aspects of this cultural world. Metallurgy—in particular the production of heavy copper implements—lost much of its attraction in the Late Eneolithic/Copper Age period characterised by the Baden culture. Similarly, although the existence of at least some crucibles indicates that knowledge of metallurgy was not entirely lost, after the Pfyn, Altheim and Mondsee cultures there is a significant decrease in the intensity of metalworking during the subsequent Horgen culture and related cultures. Traditionally, this is explained by the exhaustion of oxide ore deposits exploited at this early stage, i.e. by technological incapability vis-à-vis changing external parameters. However, since there is increasing evidence for the early use of sulphidic copper ores (see below), it is more likely that a shift in depositional practices and in the role of material culture in the social reproduction of these 'hiatus' or 'transition period' communities is responsible (e.g. Taylor 1999; Bailey 2000).

Finally, in northern central Europe and southern Scandinavia, there is evidence of imported copper artefacts in various Neolithic groups such as Jordanów in Silesia, Brześć-Kujawski in central Poland and from the various sub-groups of the Funnel Beaker culture from about 4000 cal BC onwards (Klassen 2000; Müller 2001). There is disagreement on precisely which route the earliest copper imports took and part of this discussion still relies on ill-conceived diffusionist concepts (e.g. 'Metallurgiedrift', 'Hauptachse' and 'Abzweig'; Krause 2003). In southern Scandinavia, the earliest copper imports may even date back to the local Late Mesolithic Ertebølle culture of the second half of the fifth millennium BC. These copper objects are used in current models to explain the spread of the Neolithic to the northern coastal areas. It has been proposed that the acceptance of a Copper Age ideology encompassed large parts of south-eastern and central Europe (e.g. Michelsberg culture) before extending into the Ertebølle territory (Klassen 2004). With systems of elite exchange supposedly stretching as far as from Brittany to Varna, this involves considerable extrapolation from the archaeological data. Both the social dynamics supposedly caused by foreign prestige goods and emergent hierarchies have to be demonstrated rather than assumed. The same holds true for more conventional attempts to link early metal objects and metallurgy to an increase in social complexity, in what fundamentally remained an agrarian, kinship-based society far beyond the end of the Neolithic.

Bronze and the Bronze Age

As with the differing understandings of 'Eneolithic' or 'Copper Age', the term 'Early Bronze Age' encompasses subsequent developments throughout south-eastern and central Europe but denotes quite different phenomena in this region. Typically it is culturally, rather than metallurgically, defined as its earliest stage refers to groups that did not yet use tin bronze. This is most marked in the Balkans and in the Carpathian Basin where cultures such as Ezero (from c. 3100/3000 cal BC), late Vučedol and Makó (from c. 2600/2400 cal BC) constitute the beginnings of the Bronze Age. These cultures mark the end of the so-called Eneolithic hiatus and there was a renewed increase in metallurgy after 3000/2800 cal BC. However, this was based on a different metal in arsenical copper, which was used for new types of axes (e.g. Baniabic and Fajsz types; Bátora 2003) and daggers. In addition, new types of precious metal ornaments were introduced (also axes and daggers in silver and gold: Velika and Mala Gruda in Montenegro; Primas 1996).

In central Europe, the re-emergence of metallurgy is linked to various regional groups of the Corded Ware and Bell Beaker cultures that were replaced later on by Únětice culture and the Early Bronze Age communities of the North Alpine area. In the Carpathian Basin, Makó culture gave way to a variety of EBA II/III and MBA cultures such as Nagyrév, Hatvan or Maros. Drawing on earlier beginnings in the Beaker period all of these groups, which are distinguished by differences in artefact spectrum, burial customs and settlement patterns, are distinctly 'metal age' because copper artefacts became increasingly widespread in burial ritual and hoarding. In some areas at least mining and metal production became of some importance. The precise way, however, in which tin bronze entered this system is subject to debate.

Tin most likely was won from alluvial stream deposits carrying tin oxide minerals. These might have been used directly to produce bronze by co-smelting with copper ores or by adding tin oxide to molten copper under reducing conditions. This process might account for highly variable tin contents at beginning of the Bronze Age. But when tin contents stabilized in the 8–12 % range (10 % typically given in the literature is an idealized value, hardly achieved in practice) it is more likely that metallic tin was produced and added to the liquid copper (Pernicka 1998). Metallic tin is apt to decompose at low temperatures. This is why very few tin artefacts or ingots are known from prehistoric Europe. Notable exceptions are the tin ingots from the famous shipwreck of Ulu Burun off the Turkish coast and recently at Salcombe off the coast of Southwest England.

Unlike arsenical copper, tin bronze with tin contents in excess of about 2–3 % is a proper alloy because in the Old World there are few occurrences of both copper and tin minerals which upon co-smelting could have produced an unintentional copper–tin 'alloy' (among the few exceptions are Iberia and central Asia). Copper ore deposits are far more common in fact than occurrences of tin, the most well known of which are located in Cornwall and in the German–Czech as well as in the Slovakian Ore Mountains (*Erzgebirge*). Additional ones are known from the Iberian peninsula, Brittany and the French Massif Central, Tuscany and Sardinia, but their prehistoric exploitation is even more controversial than in the Cornwall and *Erzgebirge* case (Muhly 1985; Penhallurick 1986; Bartelheim and Niederschlag 1998; Giumlia-Mair and Lo Schiavo 2003; Haustein et al. 2010).

Many debates, therefore, on Bronze Age trade go back to the question of tin supply for what was to become the standard alloy of this period and to the amazing fact that the earliest tin bronzes after c. 3000 cal BC appeared in northern Mesopotamia and Anatolia–the former devoid of tin sources (Weeks 2004; Pernicka et al. 2003). Only somewhat later by the middle of the third millennium BC was a more regular use made of bronze in the Near East and the Aegean, typically for prestige objects first. Traditionally, the ancient civilisations of this area were thought to have drawn upon tin deposits either in the British Isles or in the German Ore Mountains. Radiocarbon dating necessitated a review of these far-reaching contacts (e.g. Gerloff 2007). The result is a more nuanced picture of pre-Bronze Age and Early Bronze Age exchange systems extending along the river Danube or the Adriatic Sea and across the Balkans towards the Carpathian Basin and central Europe (Maran 1998). While authors working in Anatolia and the Near East consider western tin sources to be one of the possible causes of contact and exchange, LIA show that at least the mid-third millennium BC increase in Aegean tin bronze metallurgy was probably due to copper and tin ultimately imported from as far east as central Asia (Boroffka et al. 2002).

This finding might explain why apart from some early finds such as Velika Gruda, the regular use of tin bronze in south-eastern Europe is a relatively late phenomenon (Liversage 1994; Pare 2000). Since there is better evidence for early low-tin bronzes in Beaker contexts than in local Early Bronze Age ones, it has been suggested that this technology might reflect western influences instead of a transmission along the Danube route. In Bulgaria, Romania and the former Yugoslavia, the regular use of high-tin bronze is only attested from the local Middle to Late Bronze Age (after 1700/1600 cal BC). Similarly, in the Carpathian Basin in early cemeteries such as Mokrin or Branč there is little evidence for the use of tin bronze prior to 1900/1800 cal BC. In the Slovakian cemetery of Jelšovce it is only in the later graves that tin bronze became the standard alloy and the same is true for the North Alpine region where bronze was widely used only in EBA A2 after about 1900/1800 cal BC. The move to tin bronze was a gradual process which only came to end well into the second millennium cal BC. In north-western Europe, on the other hand, tin bronze is well attested somewhat earlier at about 2200–2000 cal BC, and its introduction took place in a rather short period of time drawing on local placer deposits in south-western Britain. Given the evidence of early contact between the British Isles and the continent it is possible that the knowledge of tin bronze was in fact a western European innovation that spread east—perhaps meeting the older eastern tin bronze practices which were influenced by traditions in the Near East and in the Aegean.

Mining and the Social Organisation of ‘Mining Communities’

There is ample evidence throughout Europe of mining for flint and stone already in the Neolithic (e. g. Körlin and Weisgerber 2006). While some of these workings were aimed at superior raw material, there are examples where deep mining was unnecessary in strictly functional terms of the mechanical properties of the stone or flint exploited and/or the raw materials obtained by mining apparently were set apart for special socially motivated needs. Symbolism clearly was involved in the Mesolithic and Neolithic use of haematite as well and in the early mining for this reddish iron oxide mineral. The attention paid to social and symbolic aspects of early mining, both in the operation of mining activities and in the uses of its products, is a relatively recent phenomenon (e.g. Knapp et al. 1998; Topping and Lynott 2005), but is a development with important implications on the early history of metallurgy as well. The mines of Rudna Glava in Serbia and Ai Bunar in Bulgaria are an excellent example as they give an impression of the complexity of the early mining for copper minerals, their working and distribution in south-eastern Europe.

Unlike many other copper ore deposits potentially exploited in prehistory, Rudna Glava and Ai Bunar yielded direct archaeological evidence of Late Neolithic and Eneolithic and Copper Age mining in the form of Vinča and Karanovo VI-Gumelniţa pottery recovered from the mines themselves (Jovanović 1982; Chernykh 1978). Radiocarbon dates confirm this chronology and allow us to be more precise about the duration of mining activities. In both Rudna Glava and Ai Bunar there are indications that small-scale mining activities may have begun much earlier than the Eneolithic and Copper Age, although this period certainly saw the most intense mining activity (Gale et al. 2003; Borić 2009). Mining was done by following ore veins down from the surface. Typically, miners went down a few metres only but occasionally a depth of 20–30 m was reached, resulting in irregular cavities (Rudna Glava) and *Pingen*-like structures of up to 100 m length (Ai Bunar). Mining tools included (grooved) hammer stones and antler picks, and there is evidence of fire setting. Several copper shaft-hole axes found at Ai Bunar were interpreted as mining tools as well but their low hardness would certainly have limited practical use. From Rudna Glava, in particular, there is evidence of (ritual) hoarding in the mines with pottery, stone and bone tools as well as ore left behind by the miners (Jovanović 1998). In both Rudna Glava and Ai Bunar the trenches were backfilled—perhaps in an attempt to appease supernatural powers after the removal of the earth's wealth. Some crushing and beneficiation of the ore was carried out but there is no evidence of further processing in the vicinity of the mines themselves. This finding, which is in line with other early mining districts throughout the Old World (e.g. Chalcolithic Feinan, Jordan: Weisgerber 2003; Early Bronze Age Aegean: Catapotis 2007), has been interpreted in terms of redistribution (Ottaway 1981). Alternative explanations have explored technical, cultural and symbolic reasons for a spatial separation of mining, smelting and metalworking (Weisgerber 2004; Catapotis 2007: 'conspicuous production').

This finding requires a close look at contemporaneous settlements from which both copper minerals/ores and copper objects are known and extractive metallurgy is more or less convincingly demonstrated (e.g. Belovode close to Rudna Glava or Stara Zagora near Ai Bunar; Gale et al. 2003; Radivojević et al. 2010). The overall picture turns out to be much more complex than simply a spatial extension of the *chaîne opératoire* from mine (exploitation/beneficiation) to settlement (smelting/working). Firstly, mining at both Rudna Glava and Ai Bunar in part predates the earliest production of massive copper implements. At least initially copper minerals came to the settlements for use as ornaments and pigments (see above). More importantly, however, LIA indicate that copper minerals from Vinča settlements in Serbia did not originate from Rudna Glava at all (Pernicka et al. 1993). In addition, since hardly any copper objects are consistent with having been made of copper from Rudna Glava, it is quite clear that there was more than one mine in operation (e.g. Majdanpek or Ždrelo; Šljivar et al. 2006). In Bulgaria, on the other hand, there may be a match between the minerals/ores recovered from settlement sites and Ai Bunar (Gale et al. 2003), although in this area as well the use of additional ore sources is likely, and they are as yet unidentified (Pernicka et al. 1997). The way copper minerals were used as pigments or for smelting was more complex than simply 'down-the-line' from the mine to the nearest settlement, and it was regionally specific. At Belovode at least there even was a distinction made between different deposits used to procure pigments and ore for smelting (see above).

In both areas a range of different ore sources were exploited, and the exchange networks for copper minerals and copper were complex. Some settlements can be shown to have drawn on a number of different ore deposits, as can also be seen at the Varna cemetery, and this is thought to have carried ritual connotations for the inhabitants of a wider territory. Variability in compositional and LIA data and therefore probably in the origin of the copper used can be found throughout the Copper and Early Bronze Ages. It may be taken to support the notion that early mining for copper minerals and ores for smelting was small scale and seasonal, not an elite-driven effort but most likely carried out in a communal or kinship-based mode of operation.

Subsequent Early Bronze Age metallurgy is characterised not only by the incipient use of tin bronze but also by a shift in copper production from oxide ores to sulphidic ones that yielded a variety of new copper types. In the broadest terms, this sequence reflects the structure of ore deposits with oxide ores on top and sulphidic ones underneath (but see below). Unlike western Europe, however, with its well-attested exploitation of mining districts such as Ross Island, Mount Gabriel or the Great Orme on the British Isles and Cabrières in southern France (e.g. O'Brien 1994, 2004; Ambert et al. 2009; Roberts this volume), in central Europe the evidence of third and early second millennium BC copper mining is for its most part circumstantial. The Alps as well as the German and Slovakian Ore Mountains traditionally received most attention due to their substantial copper ore deposits known to have been exploited in medieval and early modern times. Early Bronze Age cultural groups more or less rich in copper and bronze objects are situated in both the Alpine foreland and in the vicinity of the Ore Mountains. This coincidence has been taken to imply both the Bronze Age exploitation of adjacent ore deposits as well as wealth and power derived from metallurgy and exchange of its products. In addition, at some stage for each of these mining areas analytical evidence of Bronze Age exploitation has been claimed, but not universally accepted. H. Otto and W. Witter (1952), for example, drew attention to the so-called fahlore type copper, which they claimed was mined in the German *Erzgebirge* and distributed widely throughout Bronze Age central Europe. A comparable approach relating copper objects and ore deposits was conducted by R. Pittioni and E. Preuschen. In their case, however, it was the Bronze Age exploitation of East Alpine copper sources, especially in the Mitterberg area, which they thought could be proven (e.g. Preuschen and Pittioni 1937).

A substantial increase in the number of analyses—still mainly on the artefact side—was achieved by the SAM-project (Junghans et al. 1968). Somewhat more careful in the question of relating artefacts to specific mining areas, the collaborators in this project relied on the mapping of different types of copper based on the assumption that spatial patterning would emerge and hint towards the origin of the copper types used in the Neolithic and Bronze Age periods. For the Early Bronze Age, two large groups of fahlore metal were distinguished according to whether nickel is present among the characteristic trace elements or not, and the differences in their distributions were noted. In the debate that followed the nickel-containing variant was named *Singen* copper after the eponymous EBA A1 cemetery (c. 2200–2000 cal BC) close to the western part of Lake Constance which produced numerous artefacts consisting of this type of (mostly unalloyed) fahlore copper (Waterbolk and Butler 1965). Fahlore copper with little or no nickel, on the other hand, was frequently found in neck rings (*Ösenringe*) and rib ingots (*Spangenbarren*) from large hoards in Bavaria and further east. It became known under the name of *Ösenringkupfer* (Butler 1978).

It was only in the 1990s with a statistical re-evaluation of the older SAM-groups and an increasing number of analyses from eastern central Europe that it became possible to differentiate a truly North Alpine Singen copper from similar fahlore type copper that was circulating in the Únětice culture area. These are closely related copper types that originated from the exploitation of similar ore deposits in different mining areas and used comparable smelting techniques (Krause 2003). Currently, such issues are being re-examined by large-scale LIA projects. However, systematic work on ore deposits was neglected for a long time, and sufficient chemical and LIA data from the Alpine deposits as well as from the German and Slovakian Ore Mountains are still lacking. Most attempts, therefore, at provenancing the different types of fahlore copper mentioned may still be seen as an informed guess based mainly on the distribution of various types of copper artefacts (see, however, recent studies, for example, by Höppner et al. 2005; Schreiner 2007).

Much the same is true for the organisation of copper mining and the distribution of copper, which are often modelled along modernist notions of managerial elites, craft specialisation and trade in valuable or prestigious copper objects. This situation differs markedly from research into Neolithic mining and its social organisation which tends to draw on anthropological approaches and often favours seasonal mining activities. In contrast, in Bronze Age research there is a tendency to see the European Bronze Age as a historically unique development. Consequently, Bronze Age society and the organisation of its metallurgical activities is conceptualised as somehow distinct from both what anthropology tells us about technology in traditional societies and the evidence from earlier Neolithic societies. Mining and metallurgy are seen as an exceedingly complex undertaking discussed in the context of full-time craft specialisation and emerging social hierarchies. Only recently a more reluctant view has been expressed by reference to the fertile soils and salt springs of the German Únětice culture area that suggest alternative avenues to 'wealth' and—if so—to related 'power' (Bartelheim 2007).

We are not equally well informed on early mining and copper production in the western and the eastern Alps, and most unequivocal evidence of extractive metallurgy comes from later periods. In Switzerland there is so far no evidence at all of Bronze

Age copper mining or smelting furnaces, with radiocarbon dated slag heaps relating to Late Bronze Age and Iron Age activities only (Fasnacht 2004). The same is still true of the Alpine Rhine valley and Montafon area in Austria where the search of Bronze Age mines has recently been intensified. In the eastern Alps, on the other hand, there are for instance the famous Mitterberg area and the Paltental mining district with extensive evidence of Middle to Late Bronze Age mining (e.g. Stöllner et al. 2004). Both elaborate deep-mining and *Pingenbau* were practiced, typically exploiting sulphidic chalcopyrite copper ores—resulting in the so-called East Alpine copper (*ostalpines Kupfer*) that from the second half of the Early Bronze Age onwards replaced the earlier fahlore-type copper.

The evidence of Early Bronze Age mining and metallurgy is much less clear. Often it comes from the earliest settlements established towards the end of the Early Bronze Age and during the early Middle Bronze Age after c. 1800/1700 cal BC when permanent settlement started to extend well into the Alps. The well-known site of St. Veit-Klinglberg in the inner Alpine part of the Salzach valley is one of these (Shennan 1995). Other examples include the Buchberg near Wiesing in the lower Tyrolean Inn valley (Martinek and Sydow 2004), Savognin-Padnal and Savognin-Rudnal in the western Alps in the Swiss canton Graubünden (Rageth 1986) and—with the most recent excavations—the Bartholomäberg in the central Alpine Montafon region (Krause 2005). In organisational terms unlike later metallurgy—both copper production and working—was still practiced in the settlements or their immediate surroundings.

Typically, these sites are rather small, but situated on hilltops and some of them show signs of fortification. Some, but by no means all, were drawing upon neighbouring ore deposits, for example St. Veit-Klinglberg, where there is evidence of food brought in from outside to support a mining population. For this reason in the standard model of Early Bronze Age settlement such sites are interpreted as central places in control of smaller neighbouring sites in what is conceived of as a hierarchical settlement system (Krause 2005). Although, for instance from Bartholomäberg there is no evidence of metallurgical activities at all, it is supposed that power was derived from control over the exploitation of copper ore deposits in the vicinity and the exchange of copper. Early mining and metal production in this perspective is a complex technology that required organisation and control exercised by emergent Bronze Age elites. The move into the Alps itself is seen as a consequence of the growing need for copper.

An alternative approach was suggested in S. Shennan's (1995) study on St. Veit-Klinglberg, conceptualised as a mining settlement operating largely autonomously without centralised control. From a formalist perspective this usefully deconstructs the controversial emphasis on elites and metallurgy of the standard model—Shennan's (1993) "myth of control". It is unclear, however, if the notion that mining offered hitherto unknown potential for individual ambition and ways to break through traditional social boundaries by acquiring metal and wealth in fact applies to traditional (prehistoric) societies. Instead, we have to ask if copper was the main economic reason for the colonisation of the Alps. A review of the earliest settlement evidence suggests a much more nuanced picture. It is likely that different Alpine areas and valleys followed different trajectories with regard to early mining and metal production (Kienlin and Stöllner 2009). Much of the earliest mining after c. 2200 cal BC was driven forward by lowland communities on a seasonal basis—expeditions to copper ore deposits carried out in connection with pastoral activities that may well have been organised in a communal or kinship-based mode of operation. When the first inner Alpine communities became established somewhat later (see above), most of them were subsistence based. Mining was continued on a seasonal basis or not depending on the local occurrence of scheduling conflicts with agriculture and cattle breeding. In the long run, it was only in those areas with more abundant and sustainable ore deposits that mining and metallurgy increased in scale, and some communities could establish intensive copper production from the sixteenth to fourteenth centuries BC like the Middle Bronze Age Mitterberg area.

The Transformation of Matter (Smelting): Geology-derived 'Stages' and Prehistoric Reality

At the beginning of metallurgy, high-purity copper was used that was derived from either native copper or the smelting of oxidic copper ores (copper carbonate minerals). Later on this *Reinkupfer* was increasingly replaced by arsenical copper thought to be easier to work and to offer superior mechanical properties (but see below). With typically rather low arsenic contents up to about 2 % arsenical copper—in a central and south-eastern European context—this metal is not an alloy, but derives from the smelting of copper ores associated with arsenic bearing minerals (for summaries of this debate see Lechtman 1996; Kienlin 2008a). As far as central Europe is concerned it is only during the Early Bronze Age that arsenical copper was replaced—on a large scale—by fahlore copper and other copper varieties derived from sulphidic ores. This sequence is usually interpreted in terms of geology (see above) and technological progress by the earliest miners and smelters who are thought to have worked the upper, oxidized regions of their mines with relatively simple technology while the exploitation of the deeper, sulphidic ore bodies required advances both in mining and smelting techniques.

This standard model is derived from a simplified geological view of the ore bodies in question and from early modern sources such as G. Agricola's 1556 description of the smelting of sulphidic copper ores in a multi-stage process that involves the roasting of the ore prior to smelting (e.g. Bachmann 2003). It is this process we encounter in the Late Bronze Age eastern Alps. Copper production in substantial furnaces increasingly was standardised, resulting in the specific eastern Alpine tradition of multi-stage roasting and smelting. There is evidence of this so-called Mitterberg process from a large number of Middle to Late Bronze Age copper production sites often situated in the vicinity of potential ore outcrops (e.g. Cierny et al. 2004; Giumlia-Mair 2005). From the Early Bronze Age site at Buchberg, on the other hand, there is evidence of on-site smelting of fahlore minerals from neighbouring ore deposits in a one-step process without roasting. Smelting was carried out in open hearths that left behind few archaeological traces apart from some slag (Martinek and Sydow 2004). This may explain why from some other sites evidence of smelting is controversial and not easily distinguished from the remains of casting and metalworking also attested in some of these settlements. However, at least in the eastern Alps smelting slag was widely used as a temper in pottery thus providing indirect evidence of extractive metallurgy. In technological terms the processes involved were simple and had not yet reached the standardisation apparent somewhat later in the Middle and Late Bronze Age.

So during the Bronze Age there was undoubtedly some kind of progress in smelting techniques and changes in organisational patterns. Nonetheless, the standard model is simplistic, and there is increasing evidence for a more nuanced picture with the earliest working of sulphidic ores reaching back far into the Eneolithic. Early Bronze Age fahlore copper typically has high impurity levels indicating the use of this specific type of sulphidic ore. Compositional data imply the early use of such copper prior to the Early Bronze Age in some parts of central Europe (e.g. 'diluted' fahlore copper in the Final Neolithic of eastern Germany; Krause 2003). Furthermore, although sulphur is not routinely analysed for in many projects, it can be shown by metallography that Eneolithic/Copper Age objects occasionally contain sulphide inclusions that point towards the early use of (mixed oxidic and) sulphidic ores. In western Europe the early pre-Bronze Age use of sulphidic ore deposits is well attested (Bourgarit 2007). For the earliest metalworking horizon of central and south-eastern Europe the evidence of smelting is more ambiguous and often disputed. But even so there is some information to be gained from the (potential) mines themselves and the scientific analysis of installations and residues related to the smelting process.

From the fifth millennium BC Vinča sites of Belovode, Pločnik and Selevac in Serbia, there is evidence of thermally altered copper carbonate minerals or 'slags' thought to relate to smelting activities (e.g. Glumac and Tringham 1990; Šljivar et al. 2006). Typically, these are small pieces and it is difficult to distinguish proper slag from thermally altered ore/minerals, heated for whatever reason other than the smelting of copper. Interpretation is also often unclear in terms of smelting slags versus slags from casting copper and forging activities (see, for example, Bartelheim et al. 2002 on the Selevac evidence). Similarly, related installations such as small 'melting pots' or bottomless vessels thought to have served as furnaces (Šljivar et al. 2006) often have unclear signs of actual heating. It is only with a careful re-examination of the archaeometallurgical remains that proper evidence for copper smelting in Vinča contexts becomes available. Thus, from 5000 cal BC onwards from the Vinča site of Belovode there is secure evidence of smelting (Radivojević et al. 2010). Copper production was apparently carried out in ephemeral installations that left no archaeological traces. The technique involved relied upon the careful selection and processing of specific copper oxide ores rich in manganese that facilitated the reduction and formation of slag.

By a combination of metallography and the analysis of refractory ceramics this 'hole in the ground' or crucible-type smelting technique can be shown to have worked equally well on sulphidic copper ores as early as the second half of the fifth millennium BC in the Bulgarian Gumelniţa and Varna groups (Ryndina et al. 1999). At about the same time in the Münchhöfen culture (c. 4500–3900 cal BC) from the site of Brixlegg what is thought to be the earliest evidence of smelting in the North Alpine region has been recorded (Bartelheim et al. 2002). There may be problems with such an early date (see above). Yet even if the metallurgical activities observed in fact belong to the somewhat younger Pfyn, Altheim and Mondsee cultural horizon (c. 3900–3600 cal BC), it is remarkable that at Brixlegg the nearby fahlore deposits of sulphidic copper ore were already being drawn upon at this early stage. On the other hand, previously accepted evidence of Mondsee period oxide ore smelting at the Alpine Götschenberg site is now debated by the authors of the Brixlegg study. So the overall situation is not yet clear.

Smelting evidence from the (late) fifth and fourth millennium BC tends to be problematic because of the bad archaeological visibility of the processes and installations involved. But early experimentation with both oxidic and sulphidic ores clearly has to be taken into consideration. The smelting of both types of ore are not clear-cut technological stages. Hardly any mine follows the ideal of oxide ores on top and sulphidic ones underneath. This is why early miners found different types of copper minerals which typically but by no means universally could be distinguished and sorted by colour etc. Experimental work shows why this did not pose fundamental problems for subsequent smelting. It is exactly the ‘primitive’ nature of early oxide ore smelting under rather oxidizing conditions that allowed for the incorporation of sulphidic ores as well without causing the failure of the entire process (Timberlake 2007). Throughout the Old World, approaches to early smelting relied on highly concentrated, self-fluxing ores to produce small copper prills embedded in a matrix of partially smelted ore and slag (Hauptmann 2007; 2008). Knowledge of advanced medieval and modern smelting techniques alone is a poor guide to the earliest stages of the development of this process.

Casting and Working: The ‘Evolution’ of Material Properties?

Information on the basic production parameters of metal artefacts can be obtained from metallographic analyses, i.e. from the examination of an object’s microstructure under the optical microscope and by relating these findings to composition (Scott 1991; this volume). In a long-term perspective there is clear patterning and the development of methods of casting and forging can be outlined.

In general terms one would expect the production of copper-based weapons or tools to involve the following steps: casting, cold working the as-cast object, annealing, and final cold hammering. This procedure has a twofold aim: some degree of deformation is required to finish the as-cast object, a smooth surface needs to be achieved and feeders or casting seams may need to be removed, which is done by hammering and subsequent grinding and polishing. If a stronger deformation is required, such as for shaping an axe’s body or blade, this may necessitate more than one annealing process. Final cold working, on the other hand, increases hardness and adds to the strength and durability of a weapon or tool. Late Neolithic Altheim-type axes and related forms clearly follow this procedure and their microstructures show traces of cold working of the as-cast object, followed by annealing and final cold hammering. Their producers fell short of recognizing the differential work hardening of pure copper and arsenical copper. However, they clearly operated on the basis of an empirically gained knowledge of the cold-working properties of their copper with low arsenic contents, and they certainly were interested in the hardness of their axes (Kienlin 2008b). The tradition they established can be traced right up to the Early Bronze Age, when a two-step working of flanged axes is the rule (Kienlin 2008a). Profiting from the new fahlore-type copper and tin bronze at this stage a considerable increase in hardness was achieved by a relatively strong final cold working.

Metallography, however, can also be used to examine the knowledge gained by prehistoric metalworkers of their raw materials and to deconstruct modernist assumptions on the properties of the different types of copper and copper alloys they were working. Tin bronze, for example, is thought to be superior to copper for a number of reasons: among them its lower casting temperature, its better casting properties and its higher hardness both in the as-cast state and after working. However, often such arguments fall short of the actual compositions used or the approach to metalworking taken. There are strong evolutionist notions involved in our conception of technological progress and the interpretation of changing compositional patterns. Thus, early low-tin bronzes in the 2–6 % range tend to be seen as a result of poor initial control over the alloying process or problems with access to tin. However, the overall direction is thought obvious and directed towards the superior alloy—high-tin bronze. This certainly is true in retrospect, and eventually tin bronze became the standard alloy of the Bronze Age. But in many parts of the Old World bronze did not replace copper for a considerable period of time indicating that its adoption was "a cultural choice, not a product of technological determinism" (Pare 2000). In particular this is true wherever arsenical or fahlore copper was in widespread use offering a serious alternative to tin bronze, for example not only in parts of central Europe, but also in the Aegean or Iran, where arsenical copper and bronze coexisted for a long time. The British Isles and Ireland, where tin bronze replaced arsenical copper rather quickly, provide an example to the contrary. These are technological choices informed, on the one hand, by the rapid spread of metallurgical knowledge among metalworkers in a wider area and on the other by the availability of different sorts of copper and tin. But they were taken against a local or regional background that must not be subsumed to our modern knowledge of long-term trends in Copper to Bronze Age metallurgy.

Starting with the first step in metalworking, namely casting, it has been argued that along the sequence from pure copper via arsenical copper to fahlore copper and tin bronze the presence of trace elements and the addition of tin allows for a reduction of the casting temperature. This is the first in a series of modernist assumptions related to the properties of different types of copper and copper alloys used in prehistory. It is easily refuted by a look at the actual evidence (Kienlin 2008a): copper containing 'impurities' such as arsenic or tin solidifies over a wider temperature range between the so-called liquidus and solidus lines of the phase diagram. But for this interval to drop significantly below the melting point of pure copper (1,084 °C) impurity contents in the plus 10 % range are required. Such concentrations are rarely found in Late Neolithic arsenical copper. Most of the earliest bronzes remain well below 10 % tin, so that during the early stages of metallurgy, composition would have had little effect on casting temperature as suggested by many reviews of early metalworking. Moreover, even with higher trace-element contents in Early Bronze Age fahlore copper and the advent of high-tin bronze in the second half of the Early Bronze Age, casting temperature did not drop. There are copper sulphide inclusions in many objects that solidified at around 1,100 °C and provide evidence that casting still took place at high temperatures—which at this stage meant superheating the molten copper with beneficial effects on the success of the casting process. Our interest in lower casting temperatures does not adequately reflect the concerns of prehistoric metalworkers.

A related point concerns the supposed effect of impurities such as arsenic and the alloying element tin on porosity and oxide content. It is possible that the wider solidification interval of impure or alloyed copper facilitated the casting of more complex objects because part of the molten copper remained liquid somewhat longer and a complete fill of the casting mould was more easily achieved. This may apply, for example, to some Early Bronze Age pins and solid-hilted daggers. A differentiated approach to the production of different kinds of ornaments and weapons or tools is required. It is not, however, an argument in favour of tin bronze alone, since much of the Early Bronze Age fahlore copper would have offered the same advantage. Complex objects, on the other hand, are also known in rather pure copper. It is quite obvious that complex shapes such as Copper Age shaft-hole axes could be cast to a high standard using pure copper. Generally speaking, the success of casting was not dependent on composition alone but upon the care taken and the expertise acquired in various steps of the casting process.

As far as weapons and tools are concerned it is likely that advantages of new types of copper and copper alloys would have been most obvious and most readily taken up in the wider field of mechanical properties. But again, we must be wary of transferring our knowledge derived from a reading of modern materials science to traditional prehistoric metalworking. The presence of arsenic and somewhat more so of tin increases the as-cast hardness of the resulting (natural or artificial) copper alloy by a mechanism called solid solution hardening. But with arsenic contents up to around 3–4 % this effect is limited, and even for tin contents of around 10 % are required for an increase in hardness to twice the value of pure copper at 50 HV. A minor increase in hardness and strength at lower concentrations may or may not have been noticed. It may have been relevant in the production of copper objects, such as ornaments, that could not be cold-worked or whenever mechanical properties were of little interest. In the case of ornaments (or prestigious weaponry etc.) colour also has to be taken into consideration to account for the presence of trace and alloying elements. But for all proper weapons and tools it is a modernist misconception that prehistoric metalworkers should have relied on manipulating as-cast hardness via composition. From the Late Neolithic onwards, hardness was a function of (composition and) at times substantial cold working. As-cast hardness (i.e. solid solution hardening) was certainly a concept familiar to the metalworkers themselves in this period. But whenever an axe or any other weapon or tool entered the sphere of exchange and use, its mechanical properties were determined by previous cold working. They would have been attributed to the effort involved in forging and to the expertise of the smith.

Here, too, composition is thought to play an important role and different types of copper and copper alloys are aligned in terms of progress because of assumed differences in deformability and work hardening of arsenical copper and tin bronze in particular. These differences, however, are comparatively slight when compared in the light of more recent experimental data. Often they occur under circumstances not directly relevant to prehistoric metalworking. Arsenical copper, for example, is more ductile than pure copper and can be worked to a very high reduction in thickness with a considerable increase in hardness. Bronze may achieve even higher hardness values, but this requires tin concentrations in excess of 10 % not reached in a majority of early tin bronzes. In addition, unrealistically high deformation rates are involved from a Copper or Bronze Age perspective. Metallographic analyses show that cold work typically was in the 20–50 % range of reduction in thickness, and working was not done with the highest possible hardness of the respective copper or copper alloy in mind. Rather, it was carried out to profit from the strong initial increase in hardness at lower deformation which for various concentrations of arsenic and tin is very similar. Because of this initial closeness and parallelism in cold-working behaviour arsenical copper, fahlore copper and tin bronzes reached comparable hardness values. For the same reason the alleged brittleness of copper compared with arsenical copper or tin bronze may not have been as relevant as modern expectations have us believe. Irrespective of composition, working simply was not strong enough to cause intolerable brittleness.

Metalworking and Society: Kinship and the Transmission of Metallurgical Knowledge

Early metalworking is a fascinating field of study, both in its more technical aspects that attract the application of scientific methods and with regard to its wider cultural implications. There are, however, a number of problems some of which were highlighted in the previous sections. On the more technical side the application of ever more sophisticated scientific methods tends to conceal that 'hard' scientific data also are in need of interpretation. Specialist studies tend to dominate the field to a neglect of an integration of this scientific perspective with wider culture-historical concerns. In particular, there are interpretative problems with the notion of technological 'progress' and increasingly better control obtained over nature. The early evidence for copper mining and smelting is discussed in terms of evolution, and the succession of different types of copper and copper alloys is interpreted as an improvement in operational and functional terms that do not adequately reflect prehistoric reality. The field of craft specialisation is another area that still awaits a true integration of the science-based reconstruction of technological choices with an anthropologically informed discussion of their social and ideological context.

Typically, however, this still takes the form of evolutionist grand narratives linking perceived technological progress to the emergence of hierarchical society.

Starting in the Eneolithic/Copper Age and throughout the Bronze Age metalworkers excelled not only in the production of weapons or tools. In the course of time an amazing array of quite sophisticated techniques became available for the production of elaborately crafted and lavishly decorated metal objects. The Nebra disc comes to mind in this context and inlays of gold and silver may also be found on late Early Bronze Apa swords from the Carpathian Basin or on the famous daggers recovered from the Late Bronze Age shaft graves at Mycenae (Meller and Bertemes 2010). The Late Bronze Age also saw the production of vessels of bronze or precious metals, and both weapons and defensive arms such as amply decorated shields put great demands on the skills of craftsmen.

At some later stage there was obviously a two-tier system of metalworking, for it is unlikely that every metalworker was able to apply all techniques known or to work both in copper and gold, nor was there a demand for such objects in every community. Surprisingly little is known, however, on the actual organisation of metalworking, and maybe it is in consequence of the sheer impressiveness of some of its more elaborate remains that metallurgy tends to become enmeshed in narratives of elite control over production and exchange so readily. We are confronted with highly elaborate material culture, which we cannot imagine ‘ordinary’ people were capable of crafting or why anyone should have bothered without aggrandizement in mind or pressure put upon him. We are concerned then with elites and their display of wealth, when in fact during most of the Eneolithic/Copper Age and the Bronze Age and in most areas we are dealing with a segmentary society very much in a Neolithic tradition and dependent mainly on agriculture and animal husbandry. There is a centralisation bias in our approaches, and we should consider that institutionalised social ranking was less stable and not as common throughout Copper and Bronze Age Europe as we tend to expect. We are entitled then to ask by what mechanisms other than elite control the practice of metallurgy and the transmission of metallurgical knowledge from one generation to the next may have been organised.

An alternative model may refer to the essentially kinship-based organisation of traditional society. Apart from structuring traditional groups as a whole, kinship is of particular importance for any kind of specialised tasks extending beyond everyday household-based production. For the right and the ability to carry out such activities often depend on affiliation to a particular segment of society. One does not become a founder or smith in the same way we decide to study archaeology but by descent from a particular lineage. The individual is not only taught the knowledge and practical skills required for his future ‘profession’ but also picks up the norms and values, the habitus, of his descent group. By socialisation he (or she) not only becomes a metalworker but also finds his position in a particular kinship group and in society as a whole.

The ethnographic evidence of craft specialisation was reviewed many years ago by M. Rowlands (1971), and in such kinship-based groups there is great variability with regard to craft specialisation, organisation of production, social position of (metal-) craftsmen, the activities carried out and objects produced. We find specialised full-time metalworkers attached to an elite alongside those producing for a village community which derive most of their living from agriculture, metalworkers firmly integrated in local groups alongside ethnic differences and high mobility, smiths held in high esteem and those subject to superstition and segregation. But clearly metallurgy cannot be said in any way to be tied to elites. Part-time metalworkers may have been able to produce the most complex objects and the communication of metallurgical knowledge does not have to rely on the presence of strong leadership and political control to be efficient.

It is suggested that the practice of metallurgy was kind of 'self-organising' among particular segments of society and metallurgical knowledge was passed along kinship lines. Command of such (ritually framed?) knowledge would have set apart those involved from their neighbours, etc. This is true to the extent that—ethnographically—in oral societies some kind of 'secrecy' seems to be a precondition for the transmission and stability of such 'special' knowledge and related practical skills. It should not be taken to imply, however, that metallurgists were foreigners to their supporting communities, the notorious itinerant craftsmen. Ethnography implies that metalworkers operating in a foreign-cultural context are rare. Typically mobility if any is restricted to an area with some kind of previously established contact and affinity in terms of communication, exchange and/or a broadly similar sociocultural background. We should expect, then, that metalworkers were conceived as more or less firmly integrated in local communities (see also Kuijpers 2008 on the problem of 'detribalisation'). Demand initially was low, the amount of copper won and worked was small, and metal only gradually replaced other materials such as flint or stone in the large-scale production of weapons and implements. This implies some kind of part-time specialisation and parallel involvement of metalworkers in subsistence activities. Thus, metalworkers were not that much 'special' or foreign, and pressure put on local communities to support metallurgy would have been low. It is another matter whether mining and/or smelting were communal events or involved 'secret' knowledge, and attempts were made to restrict access to such activities. The latter has been suggested, for example, for stone and copper mining on the British Isles and smelting in the Bronze Age Aegean (e.g. O'Brien 2007; Catapotis 2007). In any case, people may not have been working *for* their metallurgist or have been obliged to keep the provision of a valued commodity going, but they may have been engaging *with* him (her?) in some communally sanctioned raw material-procurement activity among others.

Even more so the casting and working of copper should be seen in the context of already existing 'technologies' and intra-community 'specialisation'. It is likely that the knowledge and skills involved were 'special' or complex enough to be handed down in particular families or lineages or clans only. So not every community member was able to cast and work copper, and possibly metalworkers' knowledge of and ties with segments of far-off communities were closer than normally was the case, particularly so if they had to procure copper from abroad themselves. However, to a certain extent this may reflect the situation of working other materials such as stone, flint, wood or bone some of which were obtained from abroad as well and also provide early indications of intra-community 'specialisation'. So initially metalworking may have been just one ‘specialisation’ or rather a preference among others, albeit one that developed into firm traditions and had a long-term tendency towards an increase in scale and a more full-time occupation.

Accordingly, for the Bronze Age tell at Százhalombatta, Hungary, it has been shown that the social boundaries between different ‘crafts’ such as pottery production and metalworking were fluid. Skills or knowledge were easily transferred between different domains of production, and cooperation was required (Sofaer 2006). Unfortunately, this finding is linked to the standard hierarchical model of Bronze Age society. In consequence a caste-like system of (specialised) craft production is suggested, and if anything one gets the impression that the aim is to improve the standing of those (females) involved in pottery making, wood working etc., vis-à-vis (male dominated) metallurgy in what is fundamentally conceived of as a stratified society along mainstream lines. Why not instead turn things upside down and take the close links between metallurgy (and those male and/or female activities involved) and other ‘specialised’ crafts that require experience and skill to scale down the importance traditionally attached to metallurgy?

References

Ambert, P., Figueroa-Larre, V., Guendon, J.-L., Klemm, V., Laroche, M., Rovira, S.,& Strahm, Ch. (2009). The Copper Mines of Cabrières (Hérault) in Southern France and the Chalcolithic Metallurgy. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and Societies. Studies in Honour of Barbara S. Ottaway* (pp. 285–295). Bonn: Habelt.

Bachmann, H.-G. (2003). Bunt- und Edelmetalle aus mitteleuropäischen Komplexerz-Lagerstätten: Fahlerz-Verhüttung von der Bronzezeit bis zur Renaissance. In Th. Stöllner, G. Körlin, G. Steffens, J. Cierny (Eds.), *Man and Mining—Mensch und Bergbau* (pp. 25–35). Bochum: Deutsches Bergbau-Museum.

Bailey, D. W. (2000). *Balkan Prehistory. Exclusion, Incorporation and Identity*. London: Routledge.

Bartelheim, M. (2007). Die Rolle der Metallurgie in vorgeschichtlichen Gesellschaften. Sozioökonomische und kulturhistorische Aspekte der Ressourcennutzung. Rahden, Westf.: VML.

Bartelheim, M., Eckstein, K., Huijsmans, M., Krauß, R., & Pernicka, E. (2002). Kupferzeitliche Metallgewinnung in Brixlegg, Österreich. In M. Bartelheim, E. Pernicka & R. Krause (Eds.), *Die Anfänge der Metallurgie in der Alten Welt* (pp. 33–82). Rahden, Westf.: VML.

Bartelheim, M. & Niederschlag, E. (1998). Untersuchungen zur Buntmetallurgie, insbesondere des Kupfers und Zinns, im sächsisch-böhmischen Erzgebirge und dessen Umland. *Arbeits- und Forschungsberichte zur sächsischen Bodendenkmalpflege*, *40*, 8–87.

Bátora, J. (2003). Kupferne Schaftlochäxte in Mittel-, Ost- und Südosteuropa. (Zu Kulturkontakten und Datierung—Äneolithikum, Frühbronzezeit). *Slovenská Archeológia*, *51*, 1–38.

Borić, D. (2009). Absolute Dating of Metallurgical Innovations in the Vinča Culture of the Balkans. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and Societies. Studies in Honour of Barbara S. Ottaway* (pp. 191–245). Bonn: Habelt.

Boroffka, N., Cierny, J., Lutz, J., Parzinger, H., Pernicka, E., & Weisgerber, G. (2002). Bronze Age Tin from Central Asia: Preliminary Notes. In K. Boyle, C. Renfrew & M. Levine (Eds.), *Ancient Interactions: East and West in Eurasia* (pp. 135–159). Cambridge: McDonald Institute for Archaeological Research.

Bourgarit, D. (2007). Chalcolithic Copper Smelting. In S. La Niece, D. Hook, P. Craddock (Eds.), *Metals and Mines* (pp. 3–14). London: Archetype Publications.

Butler, J. J. (1978). Rings and Ribs: The Copper Types of the "Ingot Hoards" of the Central European Early Bronze Age. In M. Ryan (Ed.), *The Origins of Metallurgy in Atlantic Europe* (pp 345–362). Dublin: Stationery Office.

Catapotis, M. (2007). On the Spatial Organisation of Copper Smelting Activities in the Southern Aegean during the Early Bronze Age. In P. M. Day & R. C. P. Doonan (Eds.), *Metallurgy in the Early Bronze Age Aegean* (pp. 207–223). Oxford: Oxbow.

Chernykh, E. N., & Bunar, Ai. (1978). A Balkan copper mine of the fourth millennium BC. *Proceedings of the Prehistoric Society*, *44*, 203–217.

Cierny, J., Marzatico, F., Perini, R., Weisgerber, G. (2004). Der spätbronzezeitliche Verhüttungsplatz Acqua Fredda am Passo Redebus (Trentino). Ergebnisse der Grabungen am Redebus-Pass. In G. Weisgerber & G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 155–164). Bochum: Deutsches Bergbau-Museum.

Fasnacht, W. (2004). Prähistorischer Kupferbergbau in den Schweizer Alpen I. In G. Weisgerber, G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 107–11). Bochum: Deutsches Bergbau-Museum.

Gale, N. H., Stos-Gale, Z. A., Raduncheva, A., Panayotov, I., Ivanov, I., Lilov, P., & Todorov, T. (2003). Early Metallurgy in Bulgaria. In P. Craddock, J. Lang (Eds.), *Mining and Metal Production Through the Ages* (pp. 122–173). London: British Museum Press.

Gerloff, S. (2007). Reinecke's ABC and the Chronology of the British Bronze Age. In Ch. Burgess, P. Topping, & F. Lynch (Eds.), *Beyond Stonehenge* (pp. 117–161). Oxford: Oxbow.

Giumlia-Mair, A. (2005). Copper and copper alloys in the southeastern Alps: An overview. *Archaeometry*, *47*, 275–292.

Giumlia-Mair, A., Lo Schiavo F. (2003). (Eds.), *The Problem of Early Tin*. Oxford: Archaeopress.

Gleirscher, P. (2007). Frühes Kupfer und früher Kupferbergbau im und um den Ostalpenraum. In M. Blečić, M. Črešnar, B. Hänsel, A. Hellmuth, E. Kaiser, & C. Metzner-Nebelsick (Eds.), *Scripta praehistorica in honorem Biba Teržan* (pp. 93–110). Ljubljana: Narodni Muzej Slovenije.

Glumac, P. D., & Tringham, R. (1990). The Exploitation of Copper Minerals. In R. Tringham & D. Krstić (Eds.), *Selevac. A Neolithic Village in Yugoslavia* (pp. 549–566). Los Angeles: Institute of Archaeology.

Hauptmann, A. (2007). Alten Berg- und Hüttenleuten auf die Finger geschaut: Zur Entschlüsselung berg- und hüttenmännischer Techniken. In G. A. Wagner (Ed.), *Einführung in die Archäometrie* (pp. 115–137). Berlin: Springer.

Hauptmann, A. (2008). Vom Erz zum Metall—naturwissenschaftliche Untersuchungen innerhalb der Metallurgiekette. In A. Hauptmann & V. Pingel (Eds.), *Archäometrie* (pp. 125–140). Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Haustein, M., Gillis, C., & Pernicka E. (2010). Tin Isotopy: A new method for solving old questions. *Archaeometry*, *52*(5), 816–832.

Higham, T., Chapman, J., Slavchev, V., Gaydarska, B., Honch, N., Yordanov, Y., & Dimitrova, B. (2007). New Perspectives on the Varna cemetery (Bulgaria)—AMS Dates and Social Implications. *Antiquity*, *81*, 640–654.

Höppner, B., Bartelheim, M., Huijsmans, M., Krauss, R., Martinek, K.-P., Pernicka, E., & Schwab, R. (2005). Prehistoric copper production in the Inn Valley (Austria), and the earliest copper in Central Europe. *Archaeometry*, *47*, 293–315.

Jovanović, B. (1982). *Rudna Glava. Najstarije rudarstvo bakra na Centralnom Balkanu*. Bor-Beograd: Muzej rudarstva i metalurgije & Arheološki institut.

Jovanović, B. (1998). Technological Significance of Hoards from Rudna Glava, the Copper Mine of the Vinča culture. *Starinar*, *49*, 179–183.

Junghans, S., Sangmeister, E., Schröder, M. (1968). *Kupfer und Bronze in der frühen Metallzeit Europas. Studien zu den Anfängen der Metallurgie 2*. Berlin: Mann.

Kienlin, T. L. (2008a). *Frühes Metall im nordalpinen Raum. Eine Untersuchung zu technologischen und kognitiven Aspekten früher Metallurgie anhand der Gefüge frühbronzezeitlicher Beile*. Bonn: Habelt.

Kienlin, T. L. (2008b). Tradition and innovation in copper age metallurgy: Results of a metallographic examination of flat axes from Eastern Central Europe and the Carpathian Basin. *Proceedings of the Prehistoric Society*, *74*, 79–107.

Kienlin, T. L. (2010). *Traditions and Transformations: Aspects of Eneolithic (Copper Age) and Bronze Age Metallurgy*. Oxford: Archaeopress.

Kienlin, T. L., & Stöllner, T. (2009). Singen Copper, Alpine Settlement and Early Bronze Age Mining: Is There a Need for Elites and Strongholds? In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and Societies. Studies in honour of Barbara S. Ottaway* (pp. 67–104). Bonn: Habelt.

Klassen, L. (2000). *Frühes Kupfer im Norden*. Århus: Århus University Press.

Klassen, L. (2004). *Jade und Kupfer*. Højbjerg: Jutland Archaeological Society.

Klassen, L. (2010). Karpaten oder Alpen? Zur Herkunft der Kupferscheibe aus Hornstaad (Lkr. Konstanz) *Archäologisches Korrespondenzblatt* 40.

Knapp, A. B., Pigott, V. C., & Herbert, E. W. (1998). (Eds.), *Social Approaches to an Industrial Past*. New York: Routledge.

Körlin, G., & Weisgerber, G. (2006). (Eds.), *Stone Age—Mining Age*. Bochum: Deutsches Bergbau-Museum.

Krause, R. (2003). *Studien zur kupfer- und frühbronzezeitlichen Metallurgie zwischen Karpatenbecken und Ostsee*. Rahden: VML.

Krause, R. (2005). Bronzezeitliche Burgen in den Alpen. Befestigte Siedlungen der frühen bis mittleren Bronzezeit. In B. Horejs, R. Jung, E. Kaiser, & B. Teržan (Eds.), *Interpretationsraum Bronzezeit* (pp. 389–413). Bonn: Habelt.

Kuijpers, M. H. G. (2008). *Bronze Age Metalworking in the Netherlands (c. 2000–800 BC). A Research into the Preservation of Metallurgy Related Artefacts and the Social Position of the Smith*. Leiden: Sidestone Press.

Lechtman, H. (1996). Arsenic Bronze: Dirty Copper or Chosen Alloy? A View from the Americas. *Journal of Field Archaeology*, *23*, 477–514.

Lichter, C. (2001). *Untersuchungen zu den Bestattungssitten des südosteuropäischen Neolithikums und Chalkolithikums*. Mainz: v. Zabern.

Liversage, D. (1994). Interpreting composition patterns in ancient bronze: The Carpathian Basin. *Acta Archaeologica*, *65*, 57–134.

Maddin, R., Muhly, J. D., & Stech, T. (1999). Early Metalworking at Çayönü. In A. Hauptmann, E. Pernicka, & Th. Rehren Ü. (Eds.), *The Beginnings of Metallurgy* (pp. 37–44). Bochum: Deutsches Bergbau-Museum.

Maran, J. (1998). *Kulturwandel auf dem griechischen Festland und den Kykladen im späten 3*. Jahrtausend v. Chr. Bonn: Habelt.

Martinek, K.-P., & Sydow, W. (2004). Frühbronzezeitliche Kupfermetallurgie im Unterinntal (Nordtirol). Rohstoffbasis, archäologische und archäometallurgische Befunde. In G. Weisgerber & G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 199–211). Bochum: Deutsches Bergbau-Museum.

Matuschik, I. (1998). Kupferfunde und Metallurgie-Belege, zugleich ein Beitrag zur Geschichte der kupferzeitlichen Dolche Mittel-, Ost- und Südosteuropas. In M. Mainberger, *Das Moordorf von Reute* (pp. 207–261). Staufen i. Br.: Teraqua.

Muhly, J. D. (1985). Sources of tin and the beginnings of bronze metallurgy. *American Journal of Archaeology*, *89*, 275–291.

Müller, J. (2001). *Soziochronologische Studien zum Jung- und Spätneolithikum im Mittelelbe-Saale-Gebiet (4100–2700 v. Chr.)*. Rahden: VML.

O'Brien, W. (1994). *Mount Gabriel. Bronze Age Mining in Ireland*. Galway: Galway University Press.

O'Brien, W. (2004). *Ross Island. Mining, Metal and Society in Early Ireland*. Galway: National University of Ireland.

O'Brien, W. (2007). Miners and Farmers: Local Settlement Contexts for Bronze Age Mining. In Ch. Burgess, P. Topping, & F. Lynch (Eds.), *Beyond Stonehenge* (pp. 20–30). Oxford: Oxbow.

Ottaway, B. S. (1981). Modelle des Kupferhandels im Äneolithikum Europas. *Slovenska Archeologia*, *29*, 139–148.
Ottaway, B. S. (2001). Innovation, production and specialization in early prehistoric copper metallurgy. *European Journal of Archaeology*, *4*, 87–112.
Otto, H., Witter, W. (1952). *Handbuch der ältesten vorgeschichtlichen Metallurgie in Mitteleuropa*. Leipzig: Barth.
Meller, H. & Bertemes, F. (2010). (Eds.) *Der Griff nach den Sternen. Wie Europas Eliten zu Macht und Reichtum kamen. Internationales Symposium in Halle (Saale) 16.–21. Februar 2005*. Halle (Saale): Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt.
Pare, C. F. E. (2000). Bronze and the Bronze Age. In C. F. E. Pare, *Metals Make the World Go Round* (pp. 1–38). Oxford: Oxbow Books.
Parkinson, W. A. (2006). *The Social Organization of Early Copper Age Tribes on the Great Hungarian Plain*. Oxford: Archaeopress.
Parzinger, H. (1993). *Studien zur Chronologie und Kulturgeschichte der Jungstein-, Kupfer- und Frühbronzezeit zwischen Karpaten und Mittlerem Taurus*. Mainz: v. Zabern.
Penhallurick, R. D. (1986). *Tin in Antiquity*. London: Institute of Metals.
Pernicka, E. (1990). Gewinnung und Verbreitung der Metalle in prähistorischer Zeit. *Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz*, *37*, 21–129.
Pernicka, E. (1998). Die Ausbreitung der Zinnbronze im 3. Jahrtausend. In B. Hänsel (Ed.), *Mensch und Umwelt in der Bronzezeit Europas* (pp. 135–147). Kiel: Oetker-Voges.
Pernicka, E. C., Eibner, Ö. Öztunalı, & G., Wagner, A. (2003). Early Bronze Age Metallurgy in the North-East Aegean. In G. A. Wagner, E. Pernicka, & H.-P. Uerpmann (Eds.), *Troia and the Troad. Scientific Approaches* (pp. 143–172). Berlin: Springer.
Pernicka, E., F. Begemann, Schmitt-Strecker, S., & Wagner, G. A. (1993). Eneolithic and Early Bronze Age Copper Artefacts from the Balkans and their Relation to Serbian Copper Ores. *Prähistorische Zeitschrift*, *68*, 1–54.
Pernicka, E., Begemann, F., Schmitt-Strecker, S., Todorova, H., & Kuleff, I. (1997). Prehistoric Copper in Bulgaria. Its Composition and Provenance. *Eurasia Antiqua*, *3*, 41–180.
Preuschen, E., & Pittioni, R. (1937). Untersuchungen im Bergbaugebiete Kelchalpe bei Kitzbühel, Tirol. *Mitteilungen der Prähistorischen Kommission der Akademie der Wissenschaften*, *3*, 1–160.
Primas, M. (1996). *Velika Gruda I. Hügelgräber des frühen 3. Jahrtausends v. Chr. im Adriagebiet—Velika Gruda, Mala Gruda und ihr Kontext*. Bonn: Habelt.
Radivojević, M., Rehren, Th., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the Origins of Extractive Metallurgy: New Evidence from Europe. *Journal of Archaeological Science*, *37*, 2775–2787.
Rageth, J. (1986). Die wichtigsten Resultate der Ausgrabungen in der bronzezeitlichen Siedlung auf dem Padnal bei Savognin (Oberhalbstein GR). *Jahrbuch der Schweizerischen Gesellschaft für Ur- und Frühgeschichte, 69,* 63–103.
Renfrew, C. (1969). The Autonomy of the South-east European Copper Age. *Proceedings of the Prehistoric Society*, *35*, 12–47.
Renfrew, C. (1986). Varna and the Emergence of Wealth in Prehistoric Europe. In A. Appadurai (Ed.), *The Social Life of Things* (pp. 141–168). Cambridge: Cambridge University Press.
Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity*, *83*, 1012–1022.
Rowlands, M. J. (1971). The Archaeological Interpretation of Prehistoric Metalworking. *World Archaeology*, *3*, 210–224.
Ryndina, N. V., Indenbaum, G., & Kolosova, V. (1999). Copper Production from Polymetallic Sulphide Ores in the Northeastern Balkan Eneolithic Culture. *Journal of Archaeological Science*, *26*, 1059–1068.
Schreiner, M. (2007). *Erzlagerstätten im Hrontal, Slowakei*. Rahden: VML.
Scott, D. A. (1991). *Metallography and Microstructure of Ancient and Historic Metals*. Marina del Rey: Getty Conservation Institute.

Shennan, S. J. (1993). Commodities, Transactions, and Growth in the Central-European Early Bronze Age. *Journal of European Archaeology*, *1*, 59–72.
Shennan, S. J. (1995). *Bronze Age Copper Producers of the Eastern Alps: Excavations at St. Veit-Klinglberg*. Bonn: Habelt.
Šljivar, D., & Kuzmanović-Cvetković, J. D. (2006). Jacanović, Belovode—Pločnik. New Contributions Regarding the Copper Metallurgy in the Vinča Culture. In N. Tasić & C. Grozdanov (Eds.), *Homage to Milutin Garašanin. Belgrade: Serbian Academy of Sciences and Arts and Macedonian Academy of Sciences and Arts* (pp. 251–266).
Sofaer, J. (2006). Pots, houses and metal: Technological relations at the Bronze Age Tell at Százhalombatta, Hungary. *Oxford Journal of Archaeology*, *25*, 127–147.
Stöllner, T., Eibner, C., & Cierny, J. (2004). Prähistorischer Kupferbergbau Arthurstollen. Ein neues Projekt im Südrevier des Mitterberg-Gebietes (Salzburg). In G. Weisgerber & G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 95–106). Bochum: Deutsches Bergbau-Museum.
Taylor, T. (1999). Envaluing Metal: Theorizing the Eneolithic 'Hiatus'. In S. M. M. Young, A. M. Pollard, P. Budd, & R. A. Ixer (Eds.), *Metals in Antiquity* (pp. 22–32). Oxford: Archaeopress.
Timberlake, S. (2007). The Use of Experimental Archaeology, Archaeometallurgy for the Understanding and Reconstruction of Early Bronze Age Mining and Smelting Technologies. In S. La Niece, D. Hook, & P. Craddock (Eds.), *Metals and Mines* (pp. 27–36). London: Archetype Publications.
Topping, P., & Lynott, M. (2005). (Eds.) *The Cultural Landscape of Prehistoric Mines*. Oxford: Oxbow.
Turck, R. (2010). *Die Metalle zur Zeit des Jungneolithikums in Mitteleuropa. Eine sozialarchäologische Untersuchung*. Bonn: Habelt.
Waterbolk, H. T., & Butler, J. J. (1965). Comments on the Use of Metallurgical Analysis in Prehistoric Studies. *Helinium*, *5*, 227–251.
Weeks, L. R. (2004). *Early Metallurgy of the Persian Gulf*. Boston: Brill.
Weisgerber, G. (2003). Spatial Organisation of Mining and Smelting at Feinan, Jordan. In P. Craddock & J. Lang (Eds.) *Mining and Metal Production Through the Ages* (pp. 76–89). London: British Museum Press.
Weisgerber, G. (2004). Schmelzanlagen früher Kupfergewinnung—ein Blick über die Alpen. In G. Weisgerber & G. Goldenberg (Eds.) *Alpenkupfer—Rame delle Alpi* (pp. 15–36). Bochum: Deutsches Bergbau-Museum.
Whittle, A. (1996). *Europe in the Neolithic*. Cambridge: Cambridge University Press.

Chapter 18
Early Metallurgy in the Central Mediterranean

Andrea Dolfini

Introduction

The central Mediterranean is the area encompassing the Italian peninsula, its adjacent islands and the coasts of Dalmatia and Albania in the eastern Adriatic Sea. It is naturally bordered to the north by the Alpine chain, to the east by the Dinaric Alps, to the west by an imaginary line linking the Maritime Alps to Corsica and Sardinia, and to the south by Sicily and the Maltese archipelago. Stretching from the heart of the Mediterranean to the fringes of central Europe and from the western Balkans to southern France, the Italian peninsula—the principal feature of this macro-region—is especially important from an archaeological perspective as it provided a natural channel of communication for peoples, ideas and goods in prehistory (Fig. 18.1).

Interest in prehistoric metal working and using in this region dates back to the nineteenth century, when pioneering prehistorians and collectors of antiquities first classified metallic artefacts according to the Three Ages System (Thornton and Giardino 2008). Scientific studies into early metallurgy commenced at the turn of the twentieth century and frequently focused on explaining the evidence according to *ex Oriente lux* models (Colini 1898–1902; Mosso 1906; Peet 1909). In line with this tendency, the appearance of metalwork in the Italian peninsula was often ascribed to raiding hordes of nomadic *pastori-guerrieri* (warrior-shepherds) coming from the eastern Mediterranean or the Balkans, who would have subjugated the local Neolithic population due to their mastery of the superior copper technology (Laviosa Zambotti 1943; Puglisi 1959; Trump 1966).

Barker (1971, 1981) and Renfrew and Whitehouse (1974), among others, reacted against earlier migrationist models. Barker, in particular, stressed the local character of early metalworking in northern and central Italy, whose impressive florescence was credited to the indigenous Remedello and Rinaldone cultures (Barker 1971) or to a combination of local developments and information exchange with the eastern

A. Dolfini (✉)
School of History, Classics and Archaeology, Newcastle University,
Armstrong Building, Newcastle upon Tyne, NE1 7RU, United Kingdom
e-mail: andrea.dolfini@newcastle.ac.uk

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_18,

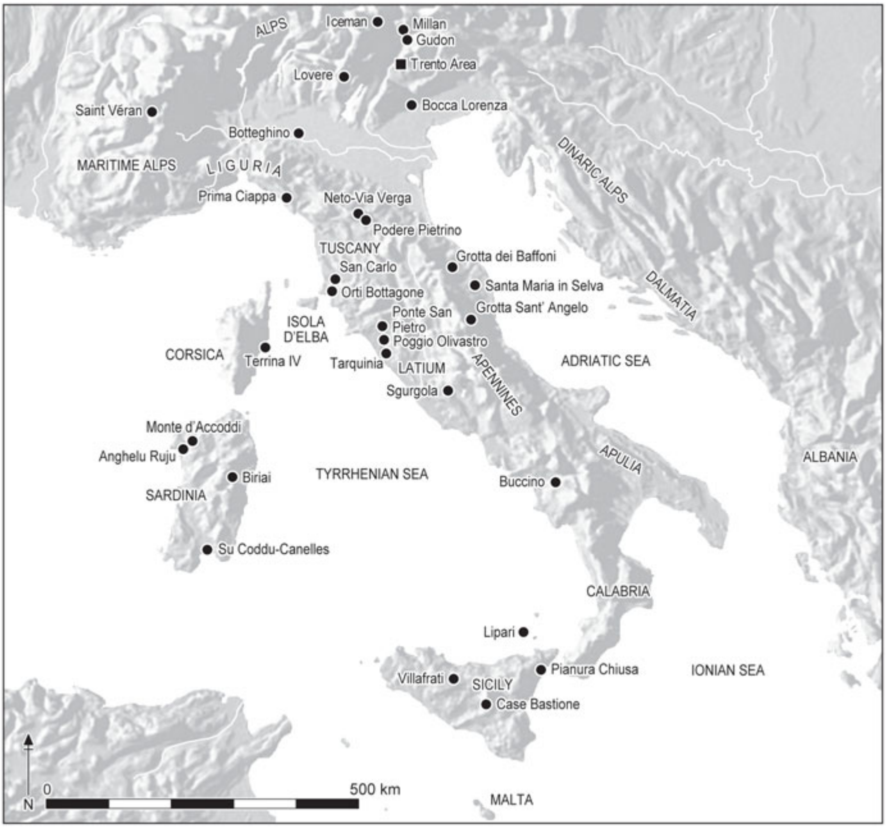


Fig. 18.1 Map of the archaeological and metalworking sites mentioned in this work (prehistoric mines are shown at Fig. 18.3). Sites in the area of Trento: Acquaviva di Besnello, Croz del Cius, La Vela di Valbusa, Montesei di Serso, Riparo Gaban, Riparo Marchi, and Romagnano Loch

Mediterranean (Barker 1981). In a similar vein, Renfrew and Whitehouse (1974) argued for a blend of independent inventions and cultural contacts with the Balkans to explain the emergence of metallurgy in Italy.

Recent research has mainly focused on the social contexts of metalworking and metal using (e.g. Pearce 1998, 2007; Skeates 1993). However, new proposals concerning the origins of metallurgy have also been put forward, based on finer-grained chronological data and more sophisticated theoretical perspectives. Skeates (1993), in particular, proposed a complex three-route scenario whereby metallurgy would have reached Italy from the eastern Alps, the Adriatic coast and western Switzerland, and perhaps would have been invented independently in Sardinia. Derivation from the eastern Mediterranean was also re-proposed by Strahm (1994, 2007), while Barfield (1996) and Cazzella (1994) revived earlier suggestions of a Balkan influx, the former positing technology transfer through the eastern Alps and the latter from across the Adriatic. Finally, Pearce (2007) maintained that metalworking appeared

Table 18.1 Chronology of the period of time from the fifth to the third millennium BC. Metal using and metalworking emerged and developed in the central Mediterranean during this time period, but the exact phasing of the process is still debated

Archaeological phase	Absolute chronology (cal. BC)
Middle Neolithic	*c*. 5000–4500
Late Neolithic	*c*. 4500–3800
Final Neolithic	*c*. 3800–3600
Early Copper Age	*c*. 3600–3300
Middle Copper Age	*c*. 3300–2700
Late Copper Age	*c*. 2700–2200
Early Bronze Age, phase 1	*c*. 2200–2000

earlier in western Italy than in eastern Italy. Building on Renfrew's proposal (1970, 1973), he suggested that metallurgical knowledge would have spread into Italy from the Iberian Peninsula "perhaps via the Balearics, Sardinia and Corsica, perhaps via southern France" (Pearce 2007, 47).

In this chapter, I shall review the evidence of early metalworking and metal using in the central Mediterranean based on the most recent research. First, I will focus on the controversial chronology of this evidence. Contrasting scholarly views will be discussed and new data will be presented, which contribute to solving this long-standing problem. Furthermore, the archaeological and metallurgical evidence concerning the *chaîne opératoire* of prehistoric copper metallurgy (*sensu* Ottaway 2001; Ottaway and Roberts 2008) will be expounded. Given that some of its stages are archaeologically unknown in this region, the discussion will concentrate on mining and ore processing; smelting; casting and smithing; and the finished objects. Based on this evidence, technological and social changes related to the emergence of metallurgy will be discussed in the final section.

Chronology

In the central Mediterranean, the period of time from the fifth to the third millennium BC is conventionally divided into three major phases: Middle Neolithic, Late/Final Neolithic and Copper Age (or Eneolithic), the latter being further broken into three sub-phases (De Marinis 1997; Dolfini 2010; Skeates 1993, 1996). The Copper Age is followed by the first phase of the Early Bronze Age, in which tin-bronze technology made its appearance. Local sequences are normally used for Dalmatia, Albania and the major islands of the central Mediterranean (Camps 1988; Guilaine and Prendi 1991; Melis et al. 2007; Trump 2004; Žeravica 1993), but they will not be considered here for the sake of consistency. The absolute chronology of this period is summarised in Table 18.1.

The earliest metal objects made their appearance in the central Mediterranean region during the Late/Final Neolithic (*c*. 4500–3600 cal. BC). Pearce (2007, 47), Skeates (1993, 8), and Dolfini (2013; in press) have summarised the evidence, which encompasses some 20 objects from Italy and Sardinia, all dated by radiocarbon or

Fig. 18.2 Early copper axe from Sgurgola, Latium. Copper axes whose shapes and features are still reminiscent of groundstone implements were manufactured in the central Mediterranean during the Late/Final Neolithic. (By kind permission of the 'Pigorini' Museum, Rome)

associated pottery. Findings include copper awls, ornaments and unclassifiable fragments, and also two silver rings from Sardinia. A good deal of Neolithic metalwork is also found along the eastern Adriatic coast, but this is not discussed in this chapter as these objects display unmistakable eastern European traits, thus suggesting origins within the Balkan metallurgical sphere (Žeravica 1993, *passim*). The highest concentration of Neolithic metalwork is found in northern Italy, where the oldest objects are dated to the third quarter of the fifth millennium BC (Mazzieri and Dal Santo 2007; Visentini 2005). Interestingly, a fragmentary crucible and unanalysed 'slag' recently found at Botteghino, a Late Neolithic open settlement in northern Italy, hint at the precocious inception of metal production in this area. A radiocarbon date taken from the same context as the crucible calibrates at 4501–4365 2sigma cal. BC (Hd-25298; 5619±25 BP), while another from a different context is slightly later (Hd-25297; 5456±25 BP; 4351–4259 2sigma cal. BC: Mazzieri and Dal Santo 2007). *In situ* pottery seems fully consistent with these dates, thus ruling out any 'old wood' effect for the charcoal samples (Schiffer 1986). Neolithic metalworking might also be suggested by a much-discussed fragmentary crucible from Lipari in the Aeolian archipelago, which is dated by associated pottery to the early fourth millennium BC (Bernabò Brea and Cavalier 1980; Skeates 1993).

It has long been debated whether Neolithic metal production was limited to small tools such as awls and rings or whether axes were also manufactured. A while ago, Barfield (1966) suggested that a handful of copper axes from poorly known contexts in northern Italy could be as old as the Middle Neolithic (*c*. 5000–4500 cal. BC), but this chronology is now generally ruled out (Barfield 1996; Dolfini in press; Skeates 1993; *contra* Pearce 2007). Such axes, all of which feature archaic traits including rounded profiles, pointed butts and rough surfaces due to poor casting, could be best assigned to the Late/Final Neolithic, when copper production commenced south of the Alps (Dolfini 2013). This proposal seems to be supported by an archaic tool found with two obsidian cores in a trench grave at Sgurgola, west-central Italy (Carboni 2002, 243) (Fig. 18.2). In spite of the uncertainties surrounding this early twentieth-century finding, the context can probably be dated to the late fifth or early fourth millennium BC on the grounds that this was the time when the central Mediterranean obsidian trade reached its peak, only to dramatically decrease in the mid-late fourth millennium BC (Cazzella 1994; Melis 2009; Robb and Farr 2005; Vaquer

2006). Moreover, axes of the Bocca Lorenza type, which were previously thought to be of the Copper Age, are now firmly assigned to the early fourth millennium BC, thus further corroborating the great antiquity of copper metallurgy south of the Alps (Klassen 2010; Pearce 2007, 42–46).

Metalworking and metal using increased dramatically during the Copper Age (*c*. 3600–2200 cal. BC). Traditionally, this period is identified in Italy with four archaeological cultures: Remedello in the north, Rinaldone in the centre, Gaudo in the southwest and Laterza in the southeast (Trump 1966). Although it is now clear that these 'cultures' are nothing but formalised burial traditions (Barfield 1985; Dolfini 2004, 2006; Giardino 2000), this general subdivision maintains some analytical value as early metalwork is mostly found at burial sites belonging to these regional groupings. Copper Age metal artefacts are most numerous in northern Italy, west-central Italy and Sardinia, while their number sharply declines as one moves to the western Adriatic, the southern peninsula, and Corsica (Camps 1988; Dolfini 2008; Melis 2009; Skeates 1993). In line with this trend, metalwork is extremely rare in Sicily for the entire Copper Age and altogether absent in Malta until the 'Tarxien cemetery' period (*c*. 2500–1500 cal. BC), except for a stone bead inlaid in gold from a disturbed layer possibly dating to the Chalcolithic 'Temple' period (Giardino 1997; Trump 2004, 233).

A major area of controversy concerns the overall chronology of Copper Age metalwork in the Italian peninsula. It is debated, in particular, whether metalworking emerged in full swing at the onset of the Copper Age (mid-fourth millennium BC) or whether it developed more gradually during the mid/late Copper Age, in the third millennium BC. Authoritative proposals posited that copper and arsenical-copper technology would have developed during the latter period, and would have been carried on until an advanced phase of the Early Bronze Age. The implication of this reading is that tin-bronze metallurgy would not have appeared until *c*. 2000 cal. BC, a few centuries later than in the north-Alpine area (Bianco Peroni 1994; Carancini 2001, 2006; De Marinis 2006; Peroni 1971, 1996). Critics of this proposal pointed out that all stages of the metallurgical *chaîne opératoire* including mining and smelting are documented from the mid-fourth millennium BC (Barfield 1996; Maggi and Pearce 2005; Pearce 2007; Skeates 1993). However, the lack of radiocarbon dates from metalwork-rich sites prevented, until recently, any independent assessment of the evidence.

This long-standing problem has now been solved by a targeted programme of radiocarbon dating (Dolfini 2010). Although all dated sites lie in central Italy, it seems probable that the results of this research can be extended to neighbouring northern and perhaps southern Italy, where Copper Age metallurgy displays similar technological and cultural traits. The new dates, which are presented and discussed elsewhere (Dolfini 2010), show unambiguously that a local tradition of copper and arsenical-copper working emerged in central Italy in the Early Copper Age (*c*. 3600–3300 cal. BC), presumably following a short but momentous intensification period in the Final Neolithic (*c*. 3800–3600 cal. BC). Clustering as they do around an early and middle phase of the Copper Age, these dates do not lend themselves to considerations regarding the later developments of this craftsmanship. Based on

Table 18.2 Semi-quantitative analyses of Copper Age tin-bronzes from Prima Ciappa (Campana et al. 1996) and Poggio Olivastro (Bulgarelli and Giumlia-Mair 2008). Results are given as weight percentages. The high quantity of tin in the bead from Prima Ciappa is probably indicative of the surface segregation of this element

Site	Item	Analysis	Cu	Sn	As	Sb	Ag	Pb	Fe	Ni	Zn	Co
Poggio Olivastro	Ring	XRF, SEM-EDS	92.5	6.2	1.3	1.2	1.2	–	0.2	1.4	–	0.1
Prima Ciappa	Bead	XRF, SEM-EDS	82	16.4	<0.4	–	–	1.6	<0.5	–	<0.5	–

the current evidence, however, it seems unlikely that any of the artefacts found in Rinaldone-style and coeval burial sites could be ascribed to the Early Bronze Age, if not exceptionally. Indeed, dozens of radiocarbon dates are now available for such sites and all but a handful consistently calibrate before 2200 cal. BC (Anzidei et al. 2011; Cazzella and Silvestrini 2005; Conti et al. 1997; Manfredini et al. 2009; Petitti et al. 2002, 2011).

The last area of chronological controversy regards the shift from copper and arsenical-copper technology to the earliest tin-bronze alloys. Eaton (1977) suggested that a handful of Copper Age implements would contain more than 1% tin, but this seems based on an incorrect discrimination of Copper Age and Early Bronze Age artefacts. A recent in-depth survey of the central Italian evidence does not confirm this reading (Dolfini 2008), and the same holds true for the northern and southern peninsula (De Marinis 1992, 2006; Giardino 2000). In contrast, De Marinis (2006) suggested that arsenical and arsenical/antimonal alloys were still exclusively manufactured during the first phase of the Early Bronze Age (*c*. 2200–2000 cal. BC) and that the earliest tin-bronzes would not have appeared prior to the second millennium BC. This claim, however, was based on a chronological framework that has now been disproved (see above).

Despite the lack of tailored research on this problem, the current data seem to suggest that the first tin-bronze alloys appeared in Italy at the turn of the Bronze Age *circa* 2300/2200 cal. BC. This would be in line with the general backdating of Copper Age metalwork discussed above, and would notably agree with the chronology of early tin-bronze technology now established for central and western Europe (Ottaway and Roberts 2008; Pare 2000). Significantly, the sporadic appearance of small ornaments with high amounts of tin at Late Copper Age sites would support this working hypothesis (Table 18.2). However, it is presently unclear whether the alloy was naturally obtained from the smelting of a tin–copper ore such as stannite or was deliberately achieved by adding metallic tin to the melt.

Mining and ore Processing

The central Mediterranean region features three major ore-mineral districts in the Alps, west-central Italy, and Sardinia. These are complemented by a plethora of relatively minor deposits and outcrops scattered across the region, with special foci

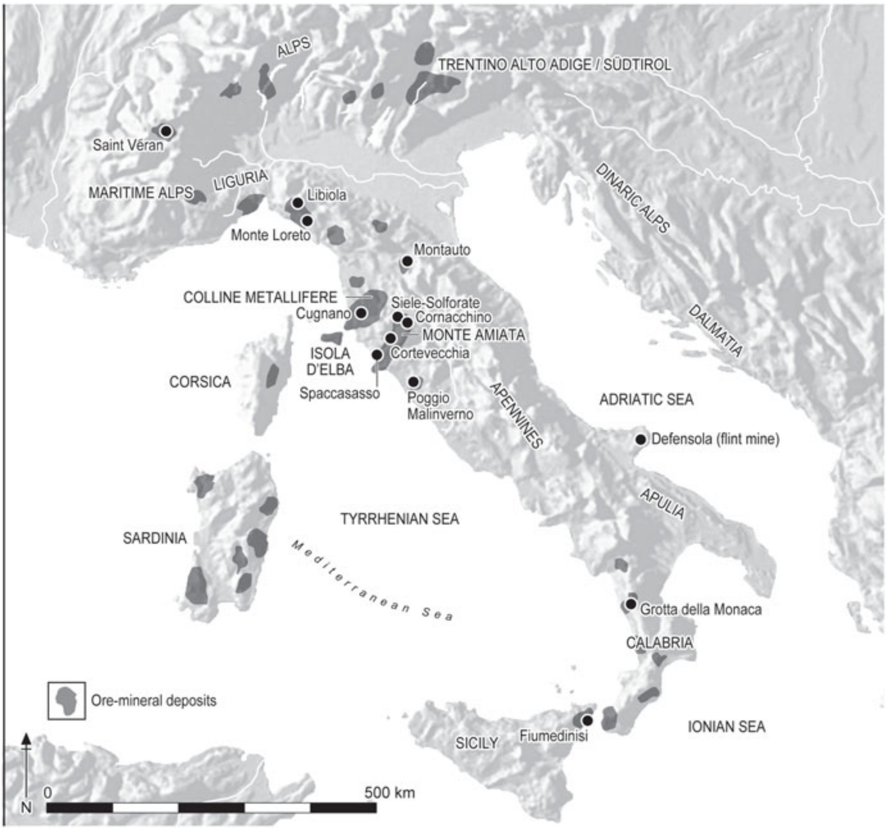


Fig. 18.3 Ore-mineral deposits and early mining sites from the central Mediterranean region (location and size of the deposits are approximate)

in Calabria, northeast Sicily, and Corsica. The present discussion will concentrate on the copper and lead deposits, many of which were first exploited prior to the Bronze Age, and will also consider antimony, tin and cinnabar (mercury sulphide) mineralizations (Fig. 18.3).

It is long known that some of the richest copper deposits in Europe are located in the eastern Alps including the Trentino-Alto Adige/Südtirol region in Italy (Baumgarten et al. 1998; Preuschen 1973). However, conspicuous ore bodies are also found in the central and western Alps as well as the Ligurian Alps east of Genoa (Bourgarit et al. 2008; Giardino 2003–2006; Pearce 2007). The Alpine deposits encompass copper and iron–copper sulphides, fahlores (i.e. polymetallic sulphides), and occasionally galena (Oxburgh 1968; Zuffardi 1989). Abundant and varied ore sources are also found throughout west-central Italy, namely in the northern Apennines, central Apennines, and the Tyrrhenian coast north of Rome, with a major concentration in the Tuscan Colline Metallifi hate ere (or 'Metalliferous Hills'). Ore bodies encompass copper, iron–copper and polymetallic sulphides occasionally rich in arsenic and antimony, and also silver-bearing galena. Stibnite (antimony sulphide) and cinnabar (mercury sulphide) are also found in west-central Italy, the former presumably exploited as a source of metallic antimony and the latter as an ochre-red pigment used in burial and other ritual practices during the Copper Age (Carobbi and Rodolico 1976; Cavinato 1964; Giardino et al. 2011). Tin-bearing cassiterite was also historically mined at Monte Valerio in western Tuscany, but its prehistoric exploitation is currently debated (Tanelli 1989).

In Sardinia, ore-mineral deposits are mainly concentrated in the southwest, the eastern coast, and, to a lesser extent, the northwest (Valera and Valera 2005; Valera et al. 2005). These include copper and iron–copper sulphides as well as polymetallic fahlores. Argentiferous galena is also widespread on the island and was certainly exploited in prehistoric times, as shown by the numerous silver and lead objects (Usai 2005). A gold-alloy necklace is also known from a Late Copper Age site, but the nature of the local deposits suggests that these were not exploited in prehistory, and the object must have been imported (Atzeni et al. 2005). Minor metalliferous deposits and outcrops also occur in Calabria, northeast Sicily and eastern Corsica (Skeates 1993).

Despite such a wide array of ore-mineral sources, evidence of prehistoric mining and ore processing is scarce. The reason seems to lie in the impact that continued working until modern times has had on the ephemeral traces left by early activities (Giardino 2008). Modern large-scale workings, though destroying ancient shafts and mines, have occasionally led to the discovery of prehistoric artefacts. Radiocarbon dating from Spaccasasso, a small cinnabar mine in Tuscany, testifies to the Copper Age beginnings of some of these workings (Cavanna and Pellegrini 2007). More detailed information on prehistoric ore procurement comes from Liguria, where remains of prehistoric workings have been recently excavated at Monte Loreto. Explorations brought to light narrow artificial galleries dug in prehistory to follow cupriferous veins, which were subsequently backfilled (Fig. 18.4). Basalt hammerstones sourced some miles away from the mine were employed to extract the ore and fire-setting was also used to facilitate the task. Evidence of ore beneficiation has also been unearthed near the mouth of a prehistoric mineshaft in the form of extensive dumps of graded and sorted debris; this would have been performed by hand-sorting as the nearest water source lies some distance below the site. A sequence of working floors used for grinding and sieving the ore, but not for its smelting, was found within and alongside these dumps. Radiocarbon dates show that prehistoric mining was mainly conducted in two periods: the middle of the fourth millennium BC and the first half of the third millennium BC (Maggi and Pearce 2005; Pearce 2007).

Substantial traces of prehistoric ore exploitation have been brought to light at Saint Véran in the western Alps, at an altitude exceeding 2400 m above the sea level. Seasonal mining concentrated here on two subvertical strata of bornite (iron-copper sulphide), which were dug to a depth of over 80 m. Undoubtedly, early mining aimed at the rich primary ore, since copper oxides and carbonates are absent; native copper is also occasionally found there in the form of sizeable lenses intermingled with the main ore body. Smelting was carried out at a short distance from the mine, and its evidence is discussed below. Radiocarbon dates from both the mine and the smelting

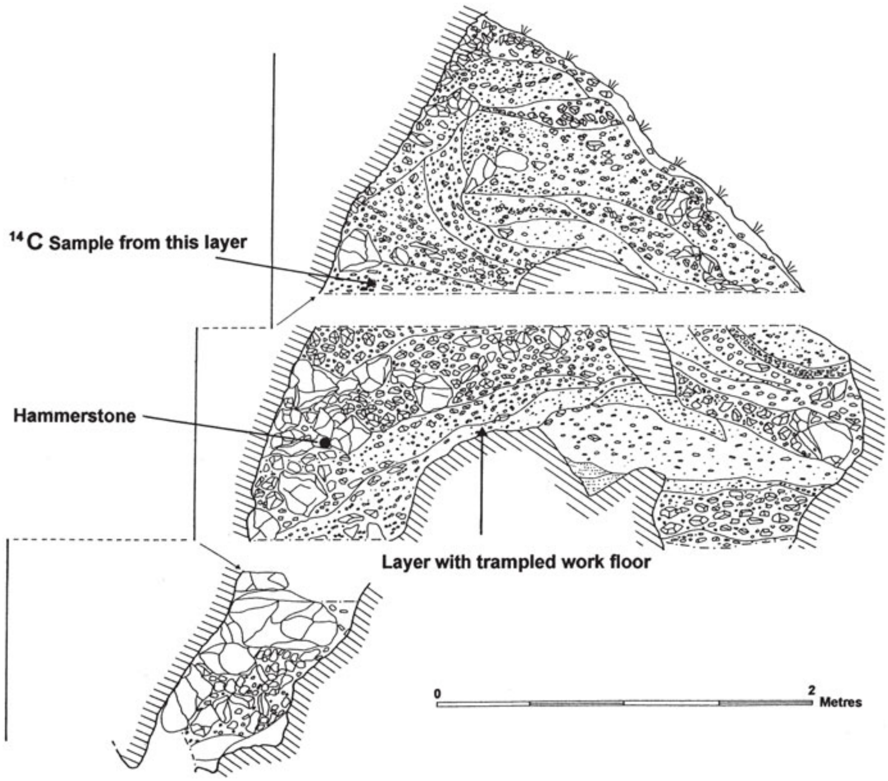


Fig. 18.4 Section across a prehistoric gallery at Monte Loreto, the earliest copper mine in the central Mediterranean region. Radiocarbon dates from this site calibrate from mid-fourth to mid-third millennium BC. (Maggi and Pearce 2005)

site calibrate from about 2500 to 1800 BC, the highest probability falling *circa* 2400–2000 cal. BC (Bourgarit et al. 2008, 2010). The evidence concerning early ore-mineral extraction in the central Mediterranean region is outlined in Table 18.3.

Smelting

In contrast with the scarce data available on early copper smelting in much of Europe, Copper Age and Early Bronze Age smelting sites are particularly abundant in the eastern Alps. Therefore, research has frequently concentrated on this region at the expense of other areas. This situation has started being rectified only recently, but the yawning gap of knowledge regarding the rest of the central Mediterranean is still far from filled. Smelting evidence from the eastern Alps has been summarised by Cierny et al. (1998), Pearce (2007) and Perini (2001). Physico-chemical analyses of an increasingly high number of slags have also been undertaken in the last two

Table 18.3 Evidence of prehistoric ore mining from the central Mediterranean region. The ephemeral traces of most early workings have been destroyed by later underground and open-cast mining

Site	Commune (Province)	Main ore body	Evidence	Bibliography
Saint Véran	Saint Véran (Hautes Alpes)	Bornite	Prehistoric workings	Bourgarit et al. 2008, 2010
Libiola	Sestri Levante (Genoa)	Chalcopyrite	Prehistoric workings, hammerstones and wooden artefacts	Maggi and Pearce 2005; Pearce 2007
Monte Loreto	Castiglione Chiavarese (Genoa)	Chalcopyrite	Hammerstones and prehistoric workings including firesetting	Maggi and Pearce 2005; Pearce 2007
Montauto	Anghiari (Arezzo)	Chalcopyrite	Flat axe	Colini 1898–1902
Siele-Solforate	Piancastagnaio (Siena)	Cinnabar	Hammerstone, deer antler pick and 'ancient timberwork'	Mochi 1915
Cugnano	Massa Marittima (Grosseto)	Mixed sulphides (chalcopyrite, galena and tetrahedrite)	Copper ingot	Colini 1898–1902
Spaccasasso	Alberese (Grosseto)	Cinnabar	Hammerstones, prehistoric workings and burials	Cavanna and Pellegrini 2007
Cornacchino	Castell'Azzara (Grosseto)	Cinnabar	Hammerstones and deer antler pick	Mochi 1915
Cortevecchia	Semproniano (Grosseto)	Cinnabar	Deer antler pick, groundstone axe and prehistoric workings (60 m long gallery)	Mochi 1915
Poggio Malinverno	Allumiere (Rome)	Galena?	Hammerstones	Giardino and Steiniger 2011
Grotta della Monaca	Sant'Agata di Esaro (Cosenza)	Goethite, malachite and azurite	Prehistoric workings and hammerstones	Geniola et al. 2006; Larocca 2005
Fiumedinisi (San Carlo)	Fiumedinisi (Messina)	Mixed sulphides (chalcopyrite, galena and tetrahedrite)	Prehistoric workings?	Leighton 1999

decades, leading to a better understanding of early metallurgy in this area (Anguilano et al. 2002; Artioli et al. 2007; Colpani et al. 2009; D'Amico et al. 1998; Storti 1990–1991).

Eastern Alpine smelting sites cluster around Trento in the middle Adige valley, and also further north in the province of Bolzano/Bozen; they are frequently located under rock shelters away from villages, at altitudes not exceeding 700 m above the sea level. Late Bronze Age sites, in contrast, are found at higher altitudes and at longer distances from valley-bottom settlements. The reason of this remarkable change across the whole region is at present unclear, but could depend on underlying transformations of Bronze Age society rather than on modifications in the metal technology per se (Doonan 1999; Krause 2009; Ottaway 2001). Notably, burials are occasionally found at early smelting sites in this area, and the two practices seem too frequently associated for this to be a mere coincidence. It could perhaps be suggested that both mortuary and smelting performances were grounded in secret knowledge to be solely unfolded at liminal places away from domestic sites (Budd and Taylor 1995; Pearce 2007).

A great deal of analytical work has been undertaken on early slags from the eastern Alps, which was predictably followed by some debate concerning their interpretation (e.g. Doonan 1999; Doonan et al. 1996). Overall, early smelting slags seem to fall into two groupings (Artioli et al. 2007): (1) coarse, viscous, highly heterogeneous slags containing abundant unreacted or partially reacted material; these slags were normally broken into small pieces to recover the entrapped copper prills, but are also occasionally found in the form of unbroken sub-circular 'cakes' up to 20 cm in diameter (*Schlackenkuchen*); and (2) flat slags featuring a mature fayalitic composition that testifies to a more complete reaction of the copper ore in a strongly reducing atmosphere (*Plattenschlacke*). Slags of this type are first encountered at Saint Véran (western Alps) in the late third millennium BC, only to become widespread in the developed Bronze Age (Bourgarit et al. 2008, 2010; Cierny et al. 2004; Goldenberg 2004; Metten 2003).

The interpretation of both types of slag is still debated and focuses in particular on the technological processes that led to their formation (Bourgarit 2007; Doonan 1999). A consensus, however, seems to have been reached amongst most scholars concerning two aspects of early smelting practices in this area: the widespread use of sulphidic ores and the long-term technological change witnessed by the shift from coarse to flat slags. Long-standing doubts have now been dispelled regarding the early exploitation of sulphidic ores, not only in the eastern Alps but also elsewhere in Europe (Bourgarit 2007; Ryndina et al. 1999). This is now demonstrated by evidence as old as the late fifth millennium BC from Brixlegg in Austria (Höppner et al. 2005; *contra* Gleirscher 2007) and is indeed true for most, if not all, Copper Age and Early Bronze Age sites from the Italian Alps. Based on archaeological, analytical and experimental data, the ores sourced in this period seemingly included iron–copper sulphides (mainly chalcopyrite and bornite, which may be locally associated with other ores) and polymetallic fahlores of the tetrahedrite-tennantite group (Anguilano et al. 2002; Artioli et al. 2007; D'Amico et al. 1998; Krause 2003).

As for the shift from coarse to flat slag, a broad technological trajectory seems apparent in the archaeological record starting with the earliest coarse slag, which had to be crushed to recover the metallic copper, to third millennium BC *Schlackenkuchen*, in which molten matte was probably first produced, to the *Plattenschlacke* found at Saint Véran and other Early Bronze Age sites, which testify to increasingly sophisticated mastering of slagging techniques (Artioli et al. 2007; Bourgarit 2007; Bourgarit et al. 2008, 2010). This trajectory, however, should not be understood as a sequence of clear-cut phases (*sensu* Strahm and Hauptmann 2009), but one that depended on context-specific conditions including, crucially, the nature of the ore and the technological *savoir-faire* of the smelters. Centuries-long overlaps between stages seem also attested in the record, but the relatively small number of radiocarbon dates available does not lend itself to a detailed understanding of the process.

Evidence of smelting and metalworking from the rest of the central Mediterranean is mainly concentrated in Tuscany, Corsica, Sardinia, and Sicily. Although potentially crucial for assessing early copper technology in areas other than the Alps, this evidence is still poorly understood due to a dearth of targeted archaeometallurgical research. The recent discoveries from Botteghino, a Late Neolithic site in northern Italy, have been discussed above. If confirmed by further analysis and radiocarbon dating, these would testify to the inception of copper smelting south of the Alps in the third quarter of the fifth millennium BC (Mazzieri and Dal Santo 2007). In Sardinia, metallurgical residues including a spoon-shaped crucible were discovered at Su Coddu-Canelles. Until recently, this settlement site held special importance for the early history of Mediterranean metallurgy due to the alleged finding of Late Neolithic copper and silver slags (Lo Schiavo 1989; Usai 2005). However, analysis has shown that these 'slags' might not be metallurgical by-products, but residues of ceramic pyrotechnology. Moreover, radiocarbon dating now assigns *in situ* metalworking to the Early–Middle Copper Age rather than the Neolithic (Manunza et al. 2005–2006; Melis 2005; Melis et al. 2007).

The reassessment of the evidence from Su Coddu acts as a cautionary tale against over-assertive interpretations of a Neolithic fragmentary crucible from Lipari (Bernabò Brea and Cavalier 1980, 490). Lacking any analysis, it is doubtful whether this potsherd containing a lump of greenish substance would document the precocious smelting of (Sicilian?) ores, the melting of (native?) copper, or the refining of previously processed metal. As for the copper slag and processed ore found at Orti Bottagone, a Late Neolithic site in Tuscany, it must be borne in mind that this is a surface assemblage, and it is far from clear whether slag and pottery are coeval (Fedeli 1999). Trial petrographic and chemical analysis highlighted the presence of well-reacted copper and iron minerals in the slag, thus raising doubts as to whether such an evolved reduction process could have been mastered at the very earliest stages of metal production (Artioli et al. 2007).

Evidence of Copper Age smelting has been brought to light at a number of sites south of the Alps. Amongst the most significant is San Carlo, a now-destroyed domestic site at the heart of the Tuscan *Colline Metallifere* (Fedeli 1995). There, rescue excavations unearthed abundant remains of processed ore, slags and crucibles, which were especially concentrated near open-air hearths interpreted as roasting platforms

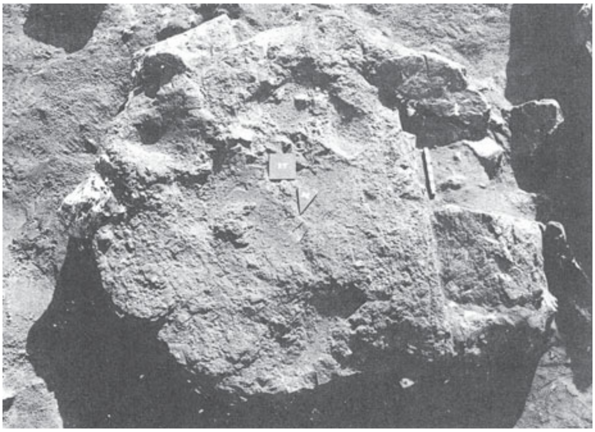


Fig. 18.5 Circular hearth from San Carlo, a Copper Age smelting and metalworking site in Tuscany. It has been suggested that this and similar open-air installations were used for roasting and perhaps smelting the copper ore. (Fedeli 1995)

Fig. 18.6 Possible smelting installation from Case Bastione, a domestic site in central Sicily. Associated pottery assigns this feature to the mid/late third millennium BC. (Courtesy of Enrico Giannitrapani)

and perhaps smelting installations (Fig. 18.5). Preliminary slag analysis highlighted the use of sulphidic ores (possibly the polymetallic compounds widespread in the area), while also revealing that copper extraction was efficient enough to allow for the almost complete separation of the slag from the molten matte (Artioli et al. 2007). Although no radiocarbon dates are available for this site, diagnostic pottery seems indicative of third millennium BC chronology.

Furthermore, substantial traces of smelting and metalworking including socketed crucibles, slags, a tuyère and a copper awl were brought to light at Terrina IV in Corsica. Comprehensive examination of the metallurgical residues and artefacts indicates that locally sourced copper ores were smelted at this site from the mid-fourth millennium BC (Camps 1988). More recently, possible clay-lined smelting pits (Fig. 18.6) were found at Case Bastione, a Late Copper Age domestic site in central Sicily (Giannitrapani and Iannì 2011). If confirmed by further research, these findings would provide much-needed evidence. Smelting and metalworking evidence from the Central Mediterranean region is summarised in Table 18.4.

Casting and Smithing

Information regarding casting and smithing is provided by scientific methods of analysis including metallography, optical microscopy and neutron diffraction (Artioli 2007; Roberts and Ottaway 2003; Scott this volume). Metallography has been performed on an elongated copper bead and a small rod from Isera La Torretta, a Late Neolithic site near Trento (Artioli et al. 2003; Pedrotti 2001). The analysis suggests that these objects may have been obtained from nuggets of native copper mechanically worked at room temperature; this seems especially probable for the elongated bead, which was clearly rolled into shape from a small copper sheet (Artioli et al. 2003, Fig. 1). Two Late Neolithic axes from Bocca Lorenza were also analysed by Matteoli and Storti (1982), who claimed that they had been hot-hammered and subsequently forged to improve their working properties. However, subsequent analysis by neutron diffraction did not confirm these early results (see below). Finally, metallography was performed on a halberd and two daggers from Buccino, a Copper Age cemetery in southern Italy (Avery et al. 1973). The researchers were puzzled by the inconsistent smithing pattern displayed by these artefacts, two of which were left in the soft annealed state while the third was work-hardened thoroughly after a cycle of cold- and hot-working. Based on these data, Avery et al. (1973, 114) noted that "these blades reflect utilitarian techniques and design without being adequate themselves" and suggested that they would have been manufactured for funerary consumption.

Recently, neutron diffraction was performed on a sample of 20 early axes from northern Italy including the Iceman's axe (Artioli 2007). It was observed that most of the tools had been slightly mechanically worked after casting and then partially annealed. Of the remainder, two axes displayed nearly complete thermal recrystallisation, two specimens including the Iceman's tool had been left in the soft as-cast state and three items showed peculiar textures that may be produced by extremely slow cooling after casting. Interestingly, most axes fall into similar parameters as the earliest tools from the northern Alps, which underwent a cycle of cold-working and annealing but were almost never work-hardened (Kienlin 2007; Kienlin et al. 2006). However, most of the north-Alpine axes display full recrystallisation due to prolonged hot-working at high temperatures, while recrystallisation is only partial in most Italian tools. According to Artioli (2007), this feature indicates that smithing was not aimed at hardening the metal, but just at shaping tools after casting or reshaping them after use.

A sample of flat axes, daggers and halberds from various Copper Age sites in central Italy were also examined for wear traces by using low-power optical microscopy (Dolfini 2011). Although the analysis was chiefly aimed at identifying use marks, valuable insights into manufacturing techniques were also obtained. Some objects

Table 18.4 Late Neolithic to Early Bronze Age smelting and metalworking sites from the central Mediterranean region

Site	Commune (province)	Features	Artefacts	Chronology	Lab. code	Date BP	Date 2σ cal. BC	Notes	References
Northern Italy and Alps									
Botteghino	Parma (Parma)	–	Slag, crucible, Cu awls	Late Neolithic	Hd-25298	5619±25	4501–4365	Slag not analysed	Mazzieri and Dal Santo 2007
Romagnano Loch III	Trento (Trento)	–	Crucible	Middle Copper Age	R-775	4810±50	3697–3383	Date from layer below the crucible	Cierny et al. 1998; Pearce 2007; Perini 2001
					R-769	3720±50	2285–1965	Date from layer above the crucible	Cierny et al. 1998; Pearce 2007; Perini 2001
Acquaviva di Besnello	Besnello (Trento)	Open furnace, burial	Slag, tuyère	Middle–late Copper Age	ETH-12497	4410±70	3337–2904	Date from burial below the furnace	Cierny et al. 1998; Pearce 2007; Perini 2001
Riparo Gaban	Martignano (Trento)	Open furnace	Slag, tuyères, crucibles	Middle–late Copper Age	Bln-1776	3985±50	2831–2310	Date from layer above the furnace	Cierny et al. 1998; Pearce 2007; Perini 2001
Romagnano Tof de la Val	Trento (Trento)	Open furnace	Slag heap, tuyère	Middle–late Copper Age	–	–	–	Pottery dating	Cierny et al. 1998; Pearce 2007; Perini 2001
Millan	Bressanone/ Brixen (Bolzano)	–	Slag heap, tuyères	Middle–late Copper Age	ETH-26698	4090±55	2872–2490	–	Dal Ri et al. 2005

Table 18.4 (continued)

Site	Commune (province)	Features	Artefacts	Chronology	Lab. code	Date BP	Date 2σ cal. BC	Notes	References
Gudon	Chiusa/Klausen (Bolzano)	–	Slag heap, tuyères	Late Copper Age	ETH-31825	3950±50	2576–2295	–	Dal Ri et al. 2005
Montesei di Serso	Pergine Valsugana (Trento)	Stone furnace	Shaft-axe mould, Cu awls	Late Copper Age	–	–	–	Pottery dating	Cierny et al. 1998; Pearce 2007; Perini 2001
Croz del Cius	Pergine Valsugana (Trento)	Stone furnace	Slag	Late Copper Age	–	–	–	Pottery dating	Cierny et al. 1998; Pearce 2007; Perini 2001
Riparo Marchi	Trento (Trento)	Seven open furnaces, burial	Slag, tuyères	Late Copper Age	–	–	–	Pottery dating	Mottes et al. 2011
Lovere	Lovere (Bergamo)	–	Slag	Middle Copper Age to Early Bronze Age	–	–	–	Pottery dating	Giardino 2003–2006
Saint Véran	Saint Véran (Hautes Alpes)	Bornite mine	Slag heap, tuyères, crucibles	Late Copper Age to Early Bronze Age	See Bourgarit et al. 2008 for 14C dates			–	Bourgarit et al. 2008, 2010
Romagnano Loch IV	Trento (Trento)	Stone furnace, burial	Slag, tuyères, crucible	Early bronze age	–	–	–	Pottery dating	Cierny et al. 1998; Pearce 2007; Perini 2001
La Vela di Valbusa	Trento (Trento)	Open furnace, burial	Slag heap, tuyère	Early Bronze Age	–	–	–	Pottery dating	Cierny et al. 1998; Pearce 2007; Perini 2001

Table 18.4 (continued)

Site	Commune (province)	Features	Artefacts	Chronology	Lab. code	Date BP	Date 2σ cal. BC	Notes	References
Central Italy									
Orti Bottagone	Campiglia Marittima (Livorno)	–	Slag	Late Neolithic?	–	–	-	Surface assemblage	Fedeli 1999
Santa Maria in Selva	Treia (Macerata)	-	Slag?	Late–final Neolithic	–	–	–	Slag not analysed	Lollini 1965; Silvestrini et al. 2002
Neto-via Verga	Sesto Fiorentino (Florence)	–	Slag, crucibles, Cu objects	Early Copper Age	Beta-63296	4790±80	3709–3371	–	Sarti 1998; Volante 2003
Podere Pietrino	Sesto Fiorentino (Florence)	–	Slag, crucibles, Cu objects	Early Copper Age				Pottery dating	Sarti 1998
San Carlo	San Vincenzo (Livorno)	Open-air hearths	Slag, crucibles, Cu objects	Middle–late Copper Age	–	–	–	Pottery dating	Fedeli 1995
Grotta Sant'Angelo	Cetona (Siena)	–	Tuyère?	Copper Age	–	–	–	Pottery dating	Grifoni Cremonesi and Di Fraia 1996
Grotta dei Baffoni	Genga (Ancona)	–	Mould, casting residue	Late Copper Age or Early Bronze Age	–	–	–	Pottery dating	Skeates 1997
Corsica									
Terrina IV	Aléria (Haute-Corse)	Open-air hearths	Slag, crucibles, tuyère, Cu awl	Early–Middle Copper Age	See Camps 1988 for 14C dates			–	Camps 1988

Table 18.4 (continued)

Site	Commune (province)	Features	Artefacts	Chronology	Lab. code	Date BP	Date 2σ cal. BC	Notes	References
Sardinia									
Su Coddu-Canelles	Selargius (Cagliari)	–	Crucible, Cu awls	Early–Middle Copper Age	LTL-295A	4554±45	3493–3097		Melis 2005; Melis et al. 2007
				LTL-1104A LTL-1105A	4512±50 4345±40	3365–3029 3090–2891			
Monte d'Accoddi	Sassari (Sassari)	–	Crucibles, several Cu objects	Copper Age	–	–	–	Pottery dating	Lo Schiavo 1989; Usai 2005
Biriai	Oliena (Nuoro)	–	Tuyères? Cu awl	Copper Age	–	–	–	Pottery dating	Lo Schiavo 1989; Usai 2005
Anghelu Ruju, tomb 14	Alghero (Sassari)	–	Tuyère	Copper Age?	–	–	–	Pottery dating, multi-phase site	Melis 2000; Usai 2005
Sicily									
Case Bastione	Villarosa (Enna)	Open furnace?	clay mould?	Late Copper Age	–	–	–	Pottery dating	Giannitrapani and Iannì 2011
Villafrati	Villafrati (Palermo)	–	Crucible?	Late Copper Age	–	–	–	Pottery dating	Leighton 1999
Pianura Chiusa	Fiumenidisi (Messina)	–	Slag?	Copper Age?	–	–	–	Surface assemblage	Villari 1981
Aeolian Archipelago									
Lipari	Lipari (Messina)	–	Crucible	Late-Final Neolithic	–	–	–	Pottery dating	Bernabò Brea and Cavalier 1980

Cu copper or copper alloy

Fig. 18.7 Copper axe from Tarquinia, west-central Italy. The v-shaped shrinkage in the butt of the axe indicates use of bivalve moulds during the Italian Copper Age. (Author's photograph, by kind permission of The Trustees of the British Museum)

display features that strongly suggest casting in bivalve moulds. These include v-shaped shrinkages on the butts of axes, which can only develop in two-piece moulds standing upright (Fig. 18.7), dashed and rough faces caused by gases trapped in close moulds during the cast, and conspicuous midribs on both faces of daggers and halberds. These features strikingly contrast with the negligible number of moulds known from Copper Age and Early Bronze Age sites in the central Mediterranean—a situation occurring in much of Europe at this time. Ottaway and Seibel (1998) maintain that this was due to the widespread use of sand and clay moulds, which rarely survive in the archaeological record. Although these materials are often assumed to be solely suitable for one-piece moulds, experiments show that two-piece moulds can also be made from them (Ottaway and Seibel 1998; Wang and Ottaway 2004). That bivalve moulds were used from the Early Copper Age is also shown by X-ray diffraction performed on antimony beads from Ponte San Pietro (Pallecchi et al. 2002).

Hammer marks are visible on a number of axes in the form of thickened or flattened margins, raised flanges, and bevels near the cutting edge; these indicate that axes were frequently worked after casting. However, it is impossible to determine by optical microscopy whether tools were only hammered into shape after casting or whether smithing was also carried out at later stages in their technological history. Metallography is being performed on a number of early Italian axes to address this question (by I. Angelini and A. Polla, Padua University), but the results are not yet available. The last type of manufacturing traces detected are polishing and sharpening marks. Previous research shows that surface polishing generates a clear pattern of long striations on both faces of the object, while sharpening is suggested

Fig. 18.8 Early copper-alloy dagger from Ponte San Pietro, a burial site in west-central Italy. Metal daggers made their appearance in the mid-fourth millennium BC, at the inception of the Copper Age. (Courtesy of Museo delle Origini)

by shorter striations parallel to the cutting edge (Kienlin and Ottaway 1998; Roberts and Ottaway 2003). Both features are relatively common on early Italian axes, daggers and halberds (Dolfini 2011). Irrespective of whether and to what extent these objects were used to perform practical tasks, these traces indicate that prehistoric smiths carefully finished their artefacts before parting from them.

The finished artefacts: shape and composition

A relatively restricted spectrum of artefacts was manufactured in the central Mediterranean during the early stages of metallurgy. Whilst only small tools, ornaments and axes reminiscent of groundstone implements were normally made in the Late Neolithic, the Copper Age saw the establishment of new classes and types of artefacts, which were exclusively designed for metal production. These include quadrangular and trapezoidal axes with flat or hammered margins, triangular daggers with tangs or rounded heels, and elongated halberds originally riveted at right angles to wooden shafts (Fig. 18.8). New types of metal ornaments were also introduced such as necklace beads and pinheads. However, Neolithic copper technology was also carried forward for the manufacturing of awls (possibly used for flint pressure-flaking: Pearce 2000) and rings.

Barfield (1996, 65) pointed out that the difficulties with classifying metalwork are more acute in the Copper Age than in later periods since shapes are simpler and standardisation is not rigid. He maintained that this was due to a number of reasons including the use of sand or clay moulds, the production of cast blanks that required substantial hammering to be finished, and great variation in the thickness of flat axes. He concluded that, under these circumstances, the classification of early metalwork cannot be too subtle. Although this viewpoint led him and other scholars to develop coarse-grained classifications of early Italian metalwork (Barfield 1996; Bianco Peroni 1994; De Marinis 1992, 1994), other authors have proposed much finer typological schemes. For example, Carancini (1993) suggested subdividing early Italian axes into no less than 47 distinct types, and this classification is now used by most Italian prehistorians.

It is noteworthy that the observations put forward by Barfield over a decade ago are now systematically confirmed by analysis and experimental work. Casting experiments suggest that sand and clay moulds prevented smiths from using the same mould more than once. Inevitably, this must have led to greater shape variation than in later periods, when stone and bronze moulds were frequently employed (Ottaway 2003; Ottaway and Seibel 1998; Wang and Ottaway 2004). Moreover, we now know that early metal axes were often hammered into shape after casting, thus causing modifications of the original casting blanks and reduction in their thickness to a degree that is neither predictable nor uniform throughout the record (Artioli 2007; Budd and Ottaway 1995; Kienlin 2007; Kienlin et al. 2006). Not taking these factors into account, Carancini (1993) might have paradoxically classified similar axes that underwent different post-casting treatments, or conversely dissimilar casting blanks made alike by hammering, under distinct types. Therefore, his classification cannot be accepted.

The Stuttgart programme of metallurgical analysis has long revealed the chemical composition of prehistoric metalwork (Junghans et al. 1960, 1968, 1974). Based on these data, it has been pointed out that three main compositional groupings are discernible in the early Italian record: pure copper, which characterises early axes all over the peninsula; arsenical copper, which normally occurs in daggers and halberds in the north and the south; and a rather peculiar copper alloy featuring high amounts of both arsenic and antimony (plus occasionally silver), which is typically found in daggers and halberds from central Italy (Barker 1971, 1981; De Marinis 2006; Giardino 2000). This pattern seemingly reflects three distinct metalworking traditions, each of which would have been characterised by the exploitation of local ores (Renfrew and Whitehouse 1974; Skeates 1993). A fourth metalworking tradition could arguably be discerned in Sardinia as indicated by the distinctive typology of the local copper artefacts as well as the extensive use of lead and silver extracted from Sardinian galena (Lo Schiavo et al. 2005, *passim*). In contrast, the situation in Corsica and Sicily is less clear due to the insufficient number of objects analysed.

A recent reassessment of the evidence from central Italy has nuanced this picture, leading to conclusions that can partially be extended to the rest of the central Mediterranean region (Dolfini 2008). This research has confirmed that pure copper was normally employed in the manufacture of axes, although the prehistoric understanding of a 'pure' metal was seemingly based on empirical parameters that led to noticeable variations in chemical composition. Indeed, several axes display detectable amounts of impurity including arsenic, antimony and silver, which are occasionally higher than 1%. On the other hand, daggers and halberds can be divided into two clear-cut groupings, the first featuring a copper–arsenic alloy similar to the one encountered in northern and southern Italy, and the second characterised by a copper–arsenic–antimony alloy that is solely found in central Italy. The two alloys were apparently used rather randomly, for no distinctions based on provenance, typology or chronology can be discerned in the record (*pace* De Marinis 2006). With regard to ornaments, silver and metallic antimony were often employed in their making.

These compositional patterns give insights into the manufacturing technology and cultural understanding of early metalwork. Most students of Italian metallurgy agree that arsenical and antimonal copper alloys were intentionally sought through the selection of fahlores naturally rich in these elements rather than by adding metallic alloyants to the melt (Barker 1971, 1981; De Marinis 2006; Northover 1989; Pare 2000). This is indicated by the varying arsenic and antimony content in the finished objects as well as by the presence of recurrent impurities including silver, nickel and bismuth, which are typically found in fahlores. Ore selection is also hinted at by compositional differences between the arsenical alloys found in northern and southern Italy and the arsenical/antimonal alloys occurring in central Italy, the latter seemingly depending on the specific make-up of Tuscan fahlores (Carobbi & Rodolico, 1976).

Interestingly, it would appear that technological constraints played a limited role in the establishment of these compositional groupings. It is sometimes suggested that axes had to be made from a softer material to withstand repeated blows and subsequent mechanical reshaping, whilst daggers and halberds needed primarily to keep their edge, hence their making from stronger arsenical and antimonal alloys. However, this claim seems untenable given that, indeed, early axes were made of arsenical copper in other regions of Europe including the British Isles (Northover 1999; O'Brien 1999). Experiments have also shown that tensile strength, resiliency and other mechanical properties of copper are not significantly altered by arsenic contents below 8% (Lechtman 1996).

Rather, the reason underlying this compositional pattern seems to lie in a sharp principle of cultural categorisation, which would have dictated the appropriate materials to be used for each class of artefacts (Lahiri 1995). Colour, luminosity, and the context-specific conceptualisation of metallic substances may have played a far greater role than functional preoccupations in the establishment of these categories (Hosler 1995; Keates 2002; Morphy 2006; Roberts et al. 2009). This is further suggested by the prehistoric use of both silver and antimony in the making of Italian necklace beads. Although silver and antimony are dissimilar metals obtained from quite different ores, both share the same dazzling silvery colour. Their appearance, rather than their manufacturing technology, would have triggered an understanding of these metals as similar substances, either of which was deemed suitable for casting the shiny jewellery used by Italian prehistoric communities for bodily ornamentation.

Understanding Early Metallurgy in the Central Mediterranean

The chronological data discussed in this article suggest that the early stages of metal-using and metalworking in the central Mediterranean can be divided into two distinct horizons: the Late/Final Neolithic (*c*. 4500–3600 cal. BC) and the Copper Age (*c*. 3600–2200 cal. BC). It was tentatively proposed to date a handful of archaic-looking axes to the preceding Middle Neolithic period (Barfield 1966; Pearce 2007), but this proposal has been ruled out as it stands on inconclusive evidence (Dolfini in press). It is also suspicious that these artefacts would be assigned to a time span predating the emergence of metallurgy in much of west-central Europe, with the possible exception of southeast Iberia (Ottaway and Roberts 2008; Roberts 2008; Roberts et al. 2009; Strahm and Hauptmann 2009).

The Late Neolithic saw the appearance of copper metallurgy in all main ore-mineral districts of the central Mediterranean region, and the first experiments with silver making in Sardinia. Objects include awls/points, small ornaments and copper axes that are still reminiscent of groundstone tools in their shapes and technological features. Fragmentary crucibles possibly containing lumps of greenish copper, and perhaps slag, were also found at Botteghino and Lipari (Bernabò Brea and Cavalier 1980; Mazzieri and Dal Santo 2007). If analysis confirms the metallurgical nature of the slag and crucibles, this would backdate the inception of metalworking to the third quarter of the fifth millennium BC, a time when the first experiments with copper smelting were conducted in the northeast Alps (Höppner et al. 2005). Importantly, these findings are contributing to bring to an end the long-standing debate as to whether Neolithic metallurgy south of the Alps consisted exclusively of imported objects, or whether copper casting was locally practised (Barfield 1996; Cazzella 1994; Klassen 2010; Pessina and Tiné 2008; Skeates 1993). The debate seems now resolved in favour of the latter hypothesis, although the exact timescale of early copper working cannot be ascertained until further radiocarbon dating is carried out.

A further problem is posed by whether the earliest production entailed the smelting of the ore, as the unanalysed evidence from Botteghino would imply, or whether smiths simply hammered native copper and silver into shape. Metallography showed that two small artefacts from the southeast Alps were probably obtained from native copper mechanically worked at room temperature (Artioli et al. 2003). It seems unlikely, however, that this applied to all contemporary objects including large implements. Recent research shows that copper technology was relatively developed in the northern Alps during the late fifth and early fourth millennium BC. In this area, early metal production featured the smelting of sulphidic ore, casting in monovalve and possibly bivalve moulds, and the cold-working and annealing of the finished objects (Höppner et al. 2005; Kienlin 2007, 2010; Kienlin et al. 2006). Compared to such complex technology, Neolithic metallurgy south of the Alps looks fairly basic. However, given the limited number of sites securely dated to this period and the scarcity of analytical work, this impression might be overturned by future research.

In contrast, Copper Age evidence stands out for its richness and complexity in all major and indeed some minor ore-mineral districts of the central Mediterranean region. Radiocarbon dates indicate that full-fledged metal technology was practised at several sites in west-central Italy, Corsica and probably Sardinia during the Early Copper Age (*c*. 3600–3300 cal. BC). Puzzlingly, most radiocarbon dates from the southeast Alps calibrate in the third and early second millennium BC, in the advanced Copper Age and Early Bonze Age. It is unclear, however, if this reflects a real historical process or a sample bias. On balance, one would be inclined to favour the latter hypothesis considering the importance of the local copper sources and the fact that metal technology fully developed both north and south of this area from the late fifth millennium BC (Dolfini 2013; Klassen 2010). It should be noted that some key contexts from the southeast Alps still lack radiocarbon dating, and it seems likely that future research will prove the present picture incorrect.

All stages of the *chaîne opératoire* of metal production were fully developed during the Early Copper Age. The ore was sourced using techniques of underground mining presumably developed during the Neolithic at flint mines such as Defensola in Apulia (Galiberti 2005). Sulphidic ores were routinely smelted including fahlores, from which arsenical and arsenical/antimonal alloys were obtained. Large implements such as axes, daggers and halberds were cast in bivalve moulds and were subsequently worked by complex (though somewhat incomplete) cycles of cold-hammering and annealing. Metals other than copper were also exploited based on locally available sources. These encompassed silver, either smelted from galena or argentiferous fahlores, lead, and antimony, the latter probably smelted from Tuscan stibnite (Giardino et al. 2011). Moreover, imported gold artefacts and the earliest tin-bronzes (either naturally obtained from stannite or deliberately alloyed) made their appearance in the third millennium BC (Atzeni et al. 2005; Bulgarelli and Giumlia-Mair 2008; Campana et al. 1996; Trump 2004).

A notable characteristic of central Mediterranean metalworking and metal using is the appearance of regional traditions within a broader techno-cultural framework (Skeates 1993). Shared metallurgical practices encompassed the exploitation of sulphidic ores, the use of bivalve moulds, the selection of different metals and alloys for the making of different artefacts, and the manufacture of the same classes and sometimes even the same types of artefacts across the whole region (e.g. the iconic Remedello daggers). At the same time, however, local technological choices (*sensu* Lemonnier 1993) can be noticed in the preference for certain ores and metals (e.g. antimony in Tuscany and lead in Sardinia), which would have required adapting the extractive technology and smelting methods to context-specific conditions, and in the morphology of certain daggers and halberds, which reflects local manufacture and circulation (Bianco Peroni 1994; Lo Schiavo et al. 2005, *passim*).

Adaptation and reworking of metallurgical knowledge is also hinted at by the wide variety of slag found across the central Mediterranean, which range from poorly reacted material that had to be crushed to recover the copper prills, to immature slag ‘cakes’ testifying to a partial separation of the molten matte, up to the fayalitic *Plattenschlacke* that are sporadically found in the Alps from the late third millennium BC. Interestingly, not only was smelting carried out according to locally adapted reduction technology, but it was also enacted according to dissimilar social practices. Secluded and liminal settings where burial was also performed were *de rigueur* in the southeast Alps during the third millennium BC; this would suggest that smelting was shrouded in secret knowledge, taboos and magic among these communities, not unlike iron smelting in modern sub-Saharan Africa (Herbert 1993; Reid and MacLean 1995). In contrast, ore reduction was carried out at domestic sites in west-central Italy and Corsica, thus implying that seclusion, initiation and magic would have played a negligible role, if any, in the metallurgical knowledge of these communities. Unlike either area, Sardinian society would have practised copper smelting during periodical inter-community gatherings. This seems indicated by the crucibles and tuyères found at the megalithic ‘temple’ of Monte d’Accoddi as well as the ‘village-sanctuary’ at Biriai, although metalworking is also attested at settlement sites such as Su Coddu-Canelles (Melis 2000; Usai 2005).

Conclusions

This research has led to three main conclusions regarding the chronology, technology, and social interpretation of early metallurgical practices in the central Mediterranean region. As regards chronology, it has been ascertained that the first copper artefacts, and probably the technology to make them, appeared south of the Alps in the late fifth millennium BC and had fully developed by mid-fourth millennium BC. This is significantly later than the emergence of copper metallurgy in the Balkans and the Carpathian basin, but concomitant to the first smelting experiments north of the Alps (Borić 2009; Höppner et al. 2005; Radivojević et al. 2010). Therefore, it could be suggested that metallurgical knowledge, coming from eastern Europe, was simultaneously introduced into both the northern and the southern Alpine region, whence it would have rapidly spread to the central Italian peninsula, Sardinia, and later to the remainder of the central Mediterranean (Dolfini 2013). Notably, this scenario ties in with the proposal that metal technology would have spread throughout Europe in a north-westerly direction, following either a single invention event in Anatolia or independent rediscovery in the central Balkans (Radivojević et al. 2010; Roberts et al. 2009; Strahm and Hauptmann 2009). On the contrary, claims for Aegean origins seem far less probable given the lack of early evidence from southern Italy and Sicily, while the Iberian transmission hypothesis aired by Pearce (2007, 47) does not stand in the light of the later developments of metalworking west of the central Mediterranean (Cerro Virtud notwithstanding: Ruiz Taboada and Montero Ruiz 1999). Similar claims for the independent invention of metallurgy in Sardinia (Skeates 1993) can also be dismissed, since early smelting and metalworking on this island are not appreciably older than in Italy, and might be later.

In technological terms, the evidence suggests that metallurgical practices were brought about during a three-stage process in which two long periods of fairly slow-paced change—the sporadic introduction of copper technology in the Late Neolithic and the impressive but rather unchanging metal production of the Copper Age—were separated by a relatively short but momentous intensification phase in the Final Neolithic *circa* 3800–3600 cal. BC. Although data are frustratingly scanty, it would appear that all the principal technological and cultural traits of Copper Age metallurgy were elaborated upon in this period, and did not change significantly until the introduction of tin bronze in the late third millennium BC (Dolfini 2013). This 'punctuated evolution' scenario (*sensu* Sherratt 1997) rules out previous claims for the gradual and late development of metallurgy in the Italian peninsula (Carancini 2001, 2006; Peroni 1971, 1996).

As for the social interpretation of this evidence, it could be argued that, during the Final Neolithic intensification phase, metal technology underwent a process of cultural adaptation whereby not only technological traits, but also meanings, agency, and social practices relating to the working and using of metal objects were negotiated and agreed upon (Dobres 2000; Ehrhardt 2005; Sofaer and Sørensen 2002; Sørensen 1989). This can be seen, for example, in the use of metal artefacts for mortuary practices and ancestor rituals, in which new concepts of gender and personhood were brought about (Dolfini 2008; Robb 2008, 2009; Whitehouse 1992). Interestingly, technological and cultural variation within the central Mediterranean region suggests that meanings and practices were further reworked at the local level. Arguably, this indicates that the incorporation of metallurgy into prehistoric society was not a monolithic process, but one that rested upon context-specific strategies of negotiation performed by knowledgeable social actors. Thus, by performing such strategies region by region and perhaps village by village, prehistoric communities turned a potentially meaningless new technology into a socially understandable set of practices worth adopting.

Note For the sake of consistency, all radiocarbon dates referred to in this work have been newly calibrated with OxCal 4.1 using IntCal 09 as a calibration curve (Bronk Ramsey 2009). Two-sigma confidence is in excess of 95% for all dates.

Acknowledgments I am grateful to Ben Roberts and Chris Thornton for inviting me to contribute to this volume, and for their insightful comments on earlier versions of this chapter. Invaluable feedback was also provided by Gilberto Artioli, Claudio Giardino and Daniel Steiniger, while Paola Mazzieri, Annaluisa Pedrotti and Umberto Tecchiati drew my attention to relevant publications and data. It is understood that all opinions and errors are mine.

References

Anguilano, L., Angelini, I., Artioli, G., Moroni, M., Baumgarten, B., & Oberrauch, H. (2002). Smelting slags from Copper and Bronze Age archaeological sites in Trentino and Alto Adige. In C. D'Amico (Ed.), *Atti del Secondo Congresso Nazionale di Archeometria* (pp. 627–638). Bologna: Patron.

Anzidei, A. P., Carboni, G., Carboni, L., Castagna, M. A., Catalano, P., Egidi, R., Malvone, M., & Spadoni, D. (2011). Il gruppo Roma-Colli Albani della facies di Rinaldone: organizzazione spaziale, rituali e cultura materiale nelle necropoli di Lucrezia Romana e Romanina (Roma). In Atti della XLIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria IIPP (pp. 297–307). Florence.

Artioli, G. (2007). Crystallographic texture analysis of archaeological metals: Interpretation of manufacturing techniques. *Applied Physics A, 89,* 899–908.

Artioli, G., Angelini, I., Burger, D., Bougarit, E., & Colpani, F. (2007). Petrographic and chemical investigations of the earliest copper smelting slags in Italy: Towards a reconstruction of the beginning of copper metallurgy. In Archaeometallurgy in Europe 2007, Papers of the 2nd International Conference (CD issue, slag session) (pp. 1–9).

Artioli, G., Dugnani, M., Angelini, I., Lutterotti, L., Pedrotti, A., & Fleckinger, A. (2003). Early copper alpine metallurgy. In Archaeometallurgy in Europe. Proceedings of the International Conference (pp. 19–27). Associazione Italiana di Metallurgia, Milano.

Atzeni, C., Massidda, L., & Sanna, U. (2005). Investigations and results. In F. Lo Schiavo, A. Giumlia-Mair, U. Sanna, & R. Valera (Eds.), *Archaeometallurgy in Sardinia from the origin to the Early Iron Age* (pp. 115–183). Montagnac: Monique Mergoil.

Avery, D. H., Grossman, V. V., & Eaton, E. R. (1973). Metallurgical analysis of copper and bronze objects. In R. Ross Holloway (Ed.), *Buccino: The Eneolithic Necropolis of S. Antonio and other discoveries made in 1968 and 1969 by Brown University* (pp. 113–114). Roma: De Luca.

Barfield, L. H. (1966). Excavations on the Rocca di Rivoli (Verona) 1963 and the prehistoric sequence in the Rivoli basin. *Memorie del Museo Civico di Storia Naturale di Verona, 14,* 1–100.

Barfield, L. H. (1985). Burials and boundaries in Chalcolitic Italy. In Malone, C. & Stoddart, S. (Eds.), Papers in Italian Archaeology IV. BAR Int. Ser. 244, (pp. 152–176, vol. II).

Barfield, L. H. (1996). The chalcolithic in Italy: Considerations of metal typology and cultural interaction. In B. Bagolini & F. Lo Schiavo (Eds.), *The Copper Age in the Near East and Europe* (pp. 65–74). Abaco, Forlì: XIX Colloquium of the XIII UISPP Congress.

Barker, G. (1971). The first metallurgy in Italy in the light of the metal analyses from the Pigorini Museum. *Bullettino di Paletnologia Italiana, 80,* 183–212.

Barker, G. (1981). *Landscape and society: Prehistoric central Italy*. London: Academic Press.

Baumgarten, B., Folie, K., & Stedingt, K. (1998). *Auf den Spuren der Knappen: Bergbau und Mineralien aus Südtirol*. Lana: Tappeiner.

Bernabò Brea, L., & Cavalier, M. (1980). *Meligunìs Lipàra IV. L'acropoli di Lipari nella preistoria*. Palermo: Flaccovio.

Bianco Peroni, V. (1994). *I pugnali nell'Italia continentale (Prähistorische Bronzefunde VI.10).* Stuttgart: Franz Steiner Verlag.

Borić, D. (2009). Absolute dating of metallurgical innovation in the Vinča culture of the Balkans. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and societies: Studies in honour of Barbara S. Ottaway* (pp. 191–245). Bonn: Rudolf Habelt.

Bourgarit, D. (2007). Chalcolithic copper smelting. In S. La Niece, D. Hook, & P. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 3–14). London: The British Museum.

Bourgarit, D., Rostan, P., Burger, E., Carozza, L., Mille, B., & Artioli, G. (2008). The beginning of copper mass production in the western Alps: The Saint Véran mining area reconsidered. *Historical Metallurgy, 42*(1), 1–11.

Bourgarit, D., Rostan, P., Carozza, L., Mille, B., & Artioli, G. (2010). Vingt ans de recherches à Saint-Véran, Hautes Alpes: état des connaissances de l'activité de production de cuivre à l'â ge du Bronze ancien. *Trabajos de Prehistoria, 67*(2), 269–285.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. *Radiocarbon, 51*(1), 337–360.

Budd, P. D., & Ottaway, B. S. (1995). Eneolithic arsenical copper: chance or choice? In B. Jovanovi (Ed.), *Ancient mining and metallurgy in Southeast Europe*. Bor, Belgrade, 95–102.

Budd, P., & Taylor, T. (1995). The faerie smith meets the bronze industry: magic versus science in the interpretation of prehistoric metal-making. *World Archaeology, 27*(1), 133–143.

Bulgarelli, M. G., & Giumlia-Mair, A. (2008). Un anellino metallico dal sito Neo-Eneolitico di Poggio Olivastro (Canino, Viterbo). In P. Petitti & F. Rossi (Eds.), *Aes: Metalli Preistorici dalla Tuscia* (pp. 12–13). Valentano: Museo della Preistoria della Tuscia.

Campana, N., Franceschi, E., Maggi, R., & Stos-Gale, Z. A. (1996). Grotticella sepolcrale di Val Frascarese (Genova): Nuove analisi dei reperti metallici. In D. Cocchi Genick (Ed.), *L'antica età del Bronzo in Italia* (pp. 556–557). Firenze: Octavo.

Camps, G. (1988). *Terrina et le Terrinien: recherches sur le Chalcolithique de la Corse (Collection de l'École Française de Rome 109)*. Rome: École Française de Rome.

Carancini, G. L. (1993). Primi sviluppi della metallurgia nell'area medio-tirrenica nel quadro della protostoria peninsulare. In P. Petitti (Ed.), *Vulcano a Mezzano: insediamento e produzioni artigianali nella media valle del Fiora durante l'età del Bronzo* (pp. 125–150). Comune di Valentano: Valentano.

Carancini, G. L. (2001). Origini e sviluppi della metallurgia in Toscana nell'ambito delle fasi più antiche della protostoria. In Atti della XXXIV Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence (pp. 235–249).

Carancini, G. L. (2006). Note relative ai primi sviluppi della metallurgia nella penisola italiana alla luce della sequenza cronologica dell'Eneolitico di Grotta Pavolella (Cassano allo Jonio, Cosenza). In G. L. Carancini (Ed.), *Miscellanea Protostorica 2006*(pp. 189–195). Perugia: Alieno.

Carboni, G. (2002). Territorio aperto o di frontiera? Nuove prospettive di ricerca per lo studio della distribuzione spaziale delle facies del Gaudo e di Rinaldone nel Lazio centro-meridionale. *Origini, 24,* 235–301.

Carobbi, G., & Rodolico, F. (1976). *I minerali della Toscana: saggio di mineralogia regionale*. Firenze: Olschki.

Cavanna, C., & Pellegrini, E. (2007). La Buca di Spaccasasso: ricerche 2000–2004. In C. Cavanna (Ed.), *La preistoria nelle grotte del parco naturale della Maremma* (pp. 117–136). Grosseto: Museo di Storia Naturale della Maremma.

Cavinato, A. (1964). *Giacimenti minerari*. Torino: UTET.

Cazzella, A. (1994). Dating the Copper Age in the Italian Peninsula and adjacent islands. *Journal of European Archaeology, 2*(1), 1–19.

Cazzella, A., & Silvestrini, M. (2005). L'Eneolitico delle Marche nel contesto degli sviluppi culturali dell'Italia centrale. In Atti della XXXVIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, vol. I, IIPP, Florence, 371–386.

Cierny, J., Marzatico, F., Perini, R., & Weisgerber, G. (1998). Prehistoric copper metallurgy in the southern Alpine region. In C. Mordant, M. Perno, & V. Rychner (Eds.), *L'Atelier du bronzier en Europe du XX au VIII siècle avant notre ère* (pp. 25–34). Paris: Comité des travaux historiques et scientifique.

Cierny, J., Marzatico, F., Perini, R., & Weisgerber, G. (2004). La riduzione del rame in località Acqua Fredda del Redebus (Trentino) nell'età del Bronzo Recente e Finale. In G. Weisgerber & G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 125–154). Bochum: Deutsches Bergbau-Museum.

Colini, G. A. (1898–1902). Il sepolcreto di Remedello Sotto nel Bresciano e il periodo eneolitico in Italia. *Bullettino di Paletnologia Italiana, 24,* 1–27, 88–110, 206–260, 280–295; *Bullettino di Paletnologia Italiana, 25,* 1–32, 218–295; *Bullettino di Paletnologia Italiana, 26,* 57–101, 202–267; *Bullettino di Paletnologia Italiana, 27,* 73–132; *Bullettino di Paletnologia Italiana, 28,* 5–43, 66–103.

Colpani, F., Angelini, I., Artioli, G., & Tecchiati, U. (2009). Copper smelting at the Millan and Gudon Chalcolithic sites (Bolzano, Italy): Chemical and mineralogical investigations of the archaeometallurgical finds. In J.-F. Moureau, R. Auger, J. Chabot, & A. Herzog (Eds.), Proceedings of the 36th International Symposium of Archaeometry, Université Laval, Quebec City (pp. 367–374).

Conti, A. M., Persiani, C., & Petitti, P. (1997). I riti della morte nella necropoli eneolitica della Selvicciola (Ischia di Castro, Viterbo). *Origini, 21,* 169–185.

D'Amico, C., Gasparotto, G., & Pedrotti, A. (1998). Scorie eneolitiche di Gaban e Acquaviva (Trento): caratteri, provenienza ed estrazione del metallo. In C. D'Amico & C. Albore Livadie (Eds.), *Le Scienze della Terra e l'Archeometria* (pp. 31–38). Naples: CUEN.

Dal Ri, L., Rizzi, G., & Tecchiati, U. (2005). Lo scavo di una struttura della tarda età del Rame connessa a processi estrattivi e di estrazione del minerale di Rame a Millan presso Bressanone. In L. Ri Dal & U. Tecchiati (Eds.), *Abstracts of the International Conference 'Il sito fusorio dell'età del Rame di Millan presso Bressanone nel quadro della prima metallurgia dell'area alpina'* (pp. 4–12). Bolzano: Provincia Autonoma di Bolzano.

De Marinis, R. C. (1992). La più antica metallurgia in Italia settentrionale. In F. Höpfel, W. Platzer, & K. Spindler (Eds.), *Der Mann im Eis: Bericht über das Internationale Symposium 1992 in Innsbruck* (Bd. 1, pp. 389–409). Innsbruck: Eigenverlag der Universität.

De Marinis, R. C. (1994). La datazione dello stile IIIA. In S. Casini (Ed.), *Le pietre degli dei: menhir e stele dell'età del Rame in Valcamonica e Valtellina* (pp. 69–87). Comune di Bergamo.

De Marinis, R. C. (1997). The Eneolithic cemetery of Remedello Sotto (BS) and the relative and absolute chronology of the Copper Age in Northern Italy. *Notizie Archeologiche Bergomensi, 5,* 33–51.

De Marinis, R. C. (2006). Aspetti della metallurgia dell'età del Rame e dell'antica età del Bronzo in Toscana. *Rivista di Scienze Preistoriche, 56,* 211–272.

Dobres, M.-A. (2000). *Technology and Social Agency*. Oxford: Blackwell.

Dolfini, A. (In press). The Neolithic beginnings of metallurgy in the central Mediterranean region. Accordia Research Papers 13.

Dolfini, A. (2013). The emergence of metallurgy in the central Mediterranean region: A new model. *European Journal of Archaeology 16*(1), 21–62.

Dolfini, A. (2004). La necropoli di Rinaldone (Montefiascone, Viterbo): Rituale funerario e dinamiche sociali di una comunità eneolitica in Italia centrale. *Bullettino di Paletnologia Italiana, 95,* 127–278.

Dolfini, A. (2006). Embodied inequalities: Burial and social differentiation in Copper Age central Italy. *Archaeological Review from Cambridge, 21*(2), 58–77.

Dolfini, A. (2008). *Making sense of technological innovation: The adoption of metallurgy in prehistoric central Italy*. University of Cambridge, Unpublished PhD Thesis.

Dolfini, A. (2010). The origins of metallurgy in central Italy: New radiometric evidence. *Antiquity, 84,* 707–723.

Dolfini, A. (2011). The function of Chalcolithic metalwork in Italy: An assessment based on use-wear analysis. *Journal of Archaeological Science, 38*(5), 1037–1049.

Doonan, R. C. P. (1999). Copper production in the eastern Alps during the Bronze Age: Technological change and the unintended consequences of social reorganization. In S. M. M. Young, A. M. Pollard, P. Budd, & R. A. Ixer (Eds.), *Metals in Antiquity*. BAR Int. Ser. 792 (pp. 72–77).

Doonan, R. C. P., Klemm, S., Ottaway, B. S., Sperl, G., & Weinek, H. (1996). The east Alpine Bronze Age copper smelting process: Evidence from the Ramsau valley, Eisenertz, Austria. In S. Demerci, A. M. Özer, & G. D. Summers (Eds.), *Archaeometry '94*. Ankara: Tübitak.

Eaton, E. R. (1977). Early metallurgy in Italy. In W. A. Oddy (Ed.), *Aspects of early metallurgy (British Museum Occasional Paper 17)* (pp. 159–168). London: The British Museum.

Ehrhardt, K. L. (2005). *European metals in native hands: Rethinking technological change 1640–1683*. Tuscaloosa: University of Alabama Press.

Fedeli, F. (1995). Scavo di un insediamento eneolitico nel distretto minerario del Campigliese. In N. Negroni Catacchio (Ed.), *Preistoria e Protostoria in Etruria: Atti del II Incontro di Studi* (pp. 73–81, Vol. 2). Milan: Centro Studi di Preistoria.

Fedeli, F. (1999). Il sito preistorico degli Orti Bottagone (Piombino, Livorno): comunicazione preliminare. *Rassegna di Archeologia, 19,* 115–127.

Galiberti, A. (2005). *Defensola: una miniera di selce di 7000 anni fa*. Siena: Protagon.

Geniola, A., Larocca, F., & Vurro, F. (2006). Approvvigionamento di risorse minerarie nella Grotta della Monaca (Sant'Agata di Esaro, Cosenza). In Atti della XXXIX Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence (pp. 1349–1359, Vol. III).

Giannitrapani, E. (forthcoming) Modi di produzione, complessità sociale e la produzione metallurgica nella Sicilia del III mill. cal. a.C. In M. Cultraro (Ed.), *L'Eneolitico in Sicilia: stato degli studi e prospettive di ricerca*.

Giannitrapani, E., & Iannì, F. (2011). La tarda età del Rame nella Sicilia centrale. In Atti della XLIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence (pp. 271–278).

Giardino, C. (1997). La metallotecnica nella Sicilia pre-protostorica. In S. Tusa (Ed.), *Prima Sicilia: alle origini della società siciliana* (pp. 404–414). Palermo: Ediprint.

Giardino, C. (2000). The beginning of metallurgy in Tyrrhenian south-central Italy. In D. Ridgway, F. R. Serra Ridgway, M. Pearce, E. Herring, R. Whitehouse, & J. Wilkins (Eds.), *Ancient Italy in its Mediterranean Settings: Studies in Honour of Ellen Macnamara* (pp. 49–73). London: Accordia Research Institute.

Giardino, C. (2003–2006). Le prime attestazioni di estrazione del rame dai suoi minerali nell'area prealpina: le evidenze di Lovere (Bergamo). *Annali del Museo della Valle Sabbia, 20,* 53–59.

Giardino, C. (2008). Paesaggi minerari dell'Etruria pre-protostorica. In N. Negroni Catacchio (Ed.), *Preistoria e Protostoria in Etruria: Atti dell'VIII Incontro di Studi* (pp. 73–89, Vol. I). Milan: Centro Studi di Preistoria e Archeologia.

Giardino, C., & Steiniger, D. (2011). Evidenze di miniere preistoriche nell'Etruria meridionale. In C. Giardino (Ed.), *Archeometallurgia: dalla conoscenza alla fruizione* (pp. 289–292). Bari: Edipuglia.

Giardino, C., Guida, G., & Occhini, G. (2011). La prima metallurgia dell'Italia centrale tirrenica e lo sviluppo tecnologico della facies di Rinaldone: evidenze archeologiche e sperimentazione. In Atti della XLIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence (pp. 181–186).

Gleirscher, P. (2007). Frühes Kupfer und früher Kupferbergbau im und um den Ostalpenraum. In M. Blečić, M. rešnar, B. Hänsel, A. Hellmuth, E. Kaiser, & C. Metzner-Nebelsick (Eds.), *Scripta Praehistorica in Honorem Biba Teržan (Situla 44)* (pp. 93–110). Ljubljana: Narodni Muzej Slovenije.

Goldenberg, G. (2004). Ein Verhüttungsplatz der mittleren Bronzezeit bei Jochberg (Nordtirol). In G. Weisgerber & G. Goldenberg (Eds.), *Alpenkupfer—Rame delle Alpi* (pp. 199–211). Bochum: Deutsches Bergbau-Museum.

Grifoni Cremonesi, R., & Di Fraia, T. (1996). *La Grotta Sant'Angelo sulla Montagna dei Fiori*. Pisa: Istituti Editoriali e Poligrafici Internazionali.

Guilaine, J., & Prendi, F. (1991). Dating the Copper Age in Albania. *Antiquity, 65,* 574–578.

Herbert, E. W. (1993). *Iron, gender and power: Rituals of transformation in African societies*. Bloomington and Indianapolis: Indiana University Press.

Höppner, B., Bartelheim, M., Husijmans, M., Krauss, R., Martinek, K., Pernicka, E., & Schwab, R. (2005). Prehistoric copper production in the Inn Valley, Austria, and the earliest copper production in central Europe. *Archaeometry, 47*(2), 293–315.

Hosler, D. (1995). Sound, color and meaning in the metallurgy of ancient West Mexico. *World Archaeology, 27*(1), 100–115.

Junghans, S., Sangmeister, E., & Schröder, M. (1960). *Metallanalysen kupferzeitlicher und frühbronzezeitlicher Bodenfunde aus Europa (Studien zu den Anfängen der Metallurgie-SAM 1).* Berlin: Gebr. Mann Verlag.

Junghans, S., Sangmeister, E., & Schröder, M. (1968). *Kupfer und Bronze in der frühen Metallzeit Europas (Studien zu den Anfängen der Metallurgie-SAM 2.1–3)*. Berlin: Gebr. Mann Verlag.

Junghans, S., Sangmeister, E., & Schröder, M. (1974). *Kupfer und Bronze in der frühen Metallzeit Europas (Studien zu den Anfängen der Metallurgie-SAM 2.4)*. Berlin: Gebr. Mann Verlag.

Keates, S. (2002). The flashing blade: Copper, colour and luminosity in north Italian Copper Age society. In A. Jones & G. MacGregor (Eds.), *Colouring the past: The significance of colour in archaeological research* (pp. 109–126). Oxford: Berg.

Kienlin, T. L. (2007). Results of a metallographic examination of Copper Age flat axes from Eastern Central Europe and the Carpathian basin. In Archaeometallurgy in Europe 2007, Papers of the 2nd International Conference (CD issue, copper section) (pp. 1–15).

Kienlin, T. L. (2010). *Traditions and Transformations: Approaches to Eneolithic (Copper Age) and Bronze Age Metalworking and Society in Eastern Central Europe and the Carpathian Basin (BAR Int. Ser. 2184)*. Oxford: Archaeopress.

Kienlin, T. L., & Ottaway, B. S. (1998). Flanged axes of the north-alpine region: An assessment of the possibilities of use-wear analysis on metal artefacts. In C. Mordant, M. Perno, & V. Rychner (Eds.), *L'Atelier du bronzier en Europe du XX au VIII siècle avant notre ère* (pp. 271–286, Vol. II). Paris: Comité des travaux historiques et scientifique.

Kienlin, T. L., Bischoff, E., & Opielka, H. (2006). Copper and bronze during the Eneolithic and Early Bronze Age: A metallographic examination of axes from the Northalpine region. *Archaeometry, 48*(3), 453–468.

Klassen, L. (2010). Karpaten oder Alpen? Zur Herkunft der Kupferscheibe aus Hornstaad (Lkr. Konstanz). Archäologisches Korrespondenzblatt*,* 40*,* 29–48.

Krause, R. (2003). *Studien zur kupfer- und frühbronzezeitlichen Metallurgie zwischen Karpatenbecken und Ostsee*. Rahden: Marie Leidorf Verlag.

Krause, R. (2009). Bronze Age copper production in the Alps: Organisation and social hierarchies in mining communities. In T. L. Kienlin & B. W. Roberts (Eds.), *Metals and societies: Studies in Honour of Barbara S. Ottaway* (pp. 47–66). Bonn: Rudolf Habelt.

Lahiri, N. (1995). Indian metal and metal-related artefacts as cultural signifiers: An ethnographic perspective. *World Archaeology, 27*(1), 116–132.

Larocca, F. (Ed.). (2005) *La miniera preistorica di Grotta della Monaca (Sant'Agata di Esaro, Cosenza)*. Roseto Capo Spulico Stazione: Centro Regionale di Speleologia 'E. dei Medici'.

Laviosa Zambotti, P. (1943). *Le più antiche culture agricole europee*. Milan: Principato.

Lechtman, H. (1996). Arsenic bronze: Dirty copper or chosen alloy? A view from the Americas. *Journal of Field Archaeology, 23*(4), 477–514.

Leighton, R. (1999). *Sicily before history*. Ithaca: Cornell University Press.

Lemonnier, P. (Ed.). (1993) *Technological choices: Transformations in material cultures since the Neolithic*. London: Routledge.

Lollini, D. G. (1965). Il Neolitico delle Marche alla luce delle recenti scoperte. In Atti del VI Congresso Internazionale delle Scienze Preistoriche e Protostoriche (Vol. II, pp. 309–315). Florence: Union Internationale des Sciences Préhistoriques et Protohistoriques.

Lo Schiavo, F. (1989). Le origini della metallurgia e il problema della metallurgia nella cultura di Ozieri. In L. Dettori Campus (Ed.), *La cultura di Ozieri: problematiche e nuove acquisizioni* (pp. 279–293). Ozieri: Il Torchietto.

Lo Schiavo, F., Giumlia-Mair, A., Sanna, U., & Valera, R. (2005) (Eds.). *Archaeometallurgy in Sardinia from the Origin to the Early Iron Age*. Montagnac: Monique Mergoil.

Maggi, R., & Pearce, M. (2005). Mid fourth-millennium copper mining in Liguria, north-west Italy: The earliest known copper mines in Western Europe. *Antiquity, 79,* 66–77.

Manfredini, A., Fugazzola Delpino, M. A., Sarti, L., Silvestrini, M., Martini, F., Conati Barbaro, C., Muntoni, I. M., Pizziolo, G., & Volante, N. (2009). Adriatico e Tirreno a confronto. *Rivista di Scienze Preistoriche, 59,* 115–180.

Manunza, M. R., Lecca, A., Atzeni, C., & Massidda, L. (2005–2006). Lo scavo del lotto Deiana nel villaggio di Su Coddu-Selargius (Cagliari). *Quaderni della Soprintendenza per i Beni Archeologici per le province di Cagliari e Oristano, 22*(1), 3–17.

Matteoli, L., & Storti, C. (1982). Metallographic research on four pure copper flat axes and one related metallic from an Eneolithic Italian cave. *Historical Metallurgy, 16*(2), 65–69.

Mazzieri, P., & Dal Santo, N. (2007). Il sito del Neolitico Recente di Botteghino (Parma). *Rivista di Scienze Preistoriche, 57,* 113–138.

Melis, M. G. (2000). *L'Età del Rame in Sardegna: origine ed evoluzione degli aspetti autoctoni*. Villanova Monteleone: Soter Editrice.

Melis, M. G. (2005). Nuovi dati dall'insediamento preistorico di Su Coddu-Canelles (Selargius, Cagliari). In P. Attema, A. Njiboer, & A. Zifferero (Eds.), Communities and settlements from the Bronze Age to the Early Medieval Period. BAR Int. Ser. 1452, (pp. 554–560, Vol. II).

Melis, M. G. (2009). L'Eneolitico antico, medio ed evoluto in Sardegna: dalla fine dell'Ozieri all'Abealzu. In Atti della XLIV Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence (pp. 81–109, Vol. I).

Melis, M. G., Quarta, G., Calcagnile, L., & D'Elia, M. (2007). L'inizio dell'età del Rame in Sardegna: nuovi contributi cronologici. *Rivista di Scienze Preistoriche, 57,* 185–200.

Metten, B. (2003). Beitrag zur spätbronzezeitlichen Kupfermetallurgie im Trentino (Südalpen) im Vergleich mit anderen prähistorischen Kupferschlacken aus dem Alpenraum. *Metalla, 10,* 1–122.

Mochi, A. (1915). Indizi di miniere preistoriche di cinabro nella regione dell'Amiata. *Bullettino di Paletnologia Italiana, 41,* 5–12.

Morphy, H. (2006). From dull to brilliant: The aesthetics of spiritual power among the Yolngu. In H. Morphy & M. Perkins (Eds.), *The anthropology of art* (pp. 302–320). Oxford: Blackwell.

Mosso, A. (1906). Le armi più antiche di rame e di bronzo. Memorie dell'Accademia dei Lincei, Series V, XII: 479–582.

Mottes, E., Bassetti, M., Silvestri, E., & Stefan, L. (2011). The Copper Age archaeometallurgical site of 'Riparo Marchi' in the Adige Valley (Trento, Italy). Poster presented at the conference 'Archaeometallurgy in Europe' 2011, Bochum, Deutsches Bergbau-Museum.

Northover, J. P. (1989). Properties and use of arsenic-copper alloys. In A. Hauptmann, E. Pernicka, & G. Wagner (Eds.), *Old world archaeometallurgy* (pp. 111–118). Bochum: Deutsches Bergbau-Museum.

Northover, J. P. (1999). The earliest metalworking in southern Britain. In A. Hauptmann, E. Pernicka, Th. Rehren, & Ü. Yalçin (Eds.), *The beginnings of metallurgy* (pp. 211–225). Bochum: Deutsches Bergbau-Museum.

O'Brien, W. (1999). Arsenical copper in early Irish metallurgy. In P. Budd, R. Ixer, & S. Young (Eds.). Metals in Antiquity. BAR Int. Ser. 792 (pp. 33–42).

Ottaway, B. S. (2001). Innovation, production and specialization in early prehistoric copper metallurgy. *European Journal of Archaeology, 4*(1), 87–112.

Ottaway, B. S. (2003). Experimental archaeometallurgy. In T. Stöllner, G. Steffens, & J. Cierny (Eds), *Man and mining—Mensch and Bergbau: Studies in honour of Gerd Weisgerber on occasion of his 65th birthday* (pp. 341–348). Bochum: Deutsches Bergbau-Museum.

Ottaway, B. S., & Roberts, B. W. (2008). The emergence of metallurgy in Europe. In A. Jones (Ed.), *Prehistoric Europe: Theory and practice* (pp. 193–224). Oxford: Blackwell.

Ottaway, B. S., & Seibel, S. (1998). Dust in the wind: experimental casting of bronze in sand moulds. In M.-C. Frère-Sautot (Ed.), *Paléométallurgie des cuivres. Actes du colloque de Bourg-en-Bresse et Beaune* (pp. 59–63). Montagnac: Monique Mergoil.

Oxburgh, E. R. (1968). *The geology of the eastern Alps*. London: The Geologists Association.

Pallecchi, P., Pecchioli, R., & Tocci, A. M. (2002). La necropoli eneolitica della Selvicciola (Ischia di Castro, Viterbo): i vaghi della tomba 23. In N. Negroni Catacchio (Ed.), *Preistoria e Protostoria in Etruria: Atti del V Incontro di Studi* (pp. 539–543, Vol. II). Milano: Centro Studi di Preistoria.

Pare, C. F. E. (2000). Bronze and the Bronze Age. In C. F. E. Pare (Ed.), *Metals Make the World Go Round: The Supply and Circulation of Metals in Bronze Age Europe* (pp. 1–38). Oxford: Oxbow.

Pearce, M. (1998). Reconstructing prehistoric metallurgical knowledge: the northern Italian Copper and Bronze Ages. *European Journal of Archaeology, 1,* 51–70.

Pearce, M. (2000). What this awl means: understanding the earliest Italian metalwork. In D. Ridgway, F. R. Serra Ridgway, M. Pearce, E. Herring, R. Whitehouse, & J. Wilkins (Eds.), *Ancient Italy in its mediterranean settings: Studies in honour of Ellen Macnamara* (pp. 67–73). London: Accordia Research Institute.

Pearce, M. (2007). *Bright blades and red metal: Essays on north italian prehistoric metalwork*. London: Accordia Research Institute.

Pedrotti, A. (2001). L'Età del Rame. In M. Lanzinger, F. Marzatico, & A. Pedrotti (Eds.), *Storia del Trentino: La Preistoria e Protostoria* (pp. 183–253). Bologna: Il Mulino.

Peet, T. E. (1909). *The Stone and Bronze Ages in Italy*. Oxford: Oxford University Press.

Perini, R. (2001). L'età del Bronzo Antico e Medio. In M. Lanzinger, F. Marzatico, & A. Pedrotti (Eds.), *Storia del Trentino: La Preistoria e Protostoria* (pp. 287–335). Bologna: Il Mulino.
Peroni, R. (1971). *L'età del Bronzo nella penisola italiana I. L'antica età del Bronzo*. Florence: Accademia Toscana di Scienze e Lettere 'La Colombaria'.
Peroni, R. (1996). *L'Italia alle soglie della Storia*. Rome: Laterza.
Pessina, A., & Tiné, V. (2008). *Archeologia del Neolitico*. Rome: Carocci.
Petitti, P., Bondioli, L., Conti, A. M., Macchiarelli, R., Persiani, C., & Salvadei, L. (2002). La tomba 23 della necropoli della Selvicciola (Ischia di Castro, Viterbo): analisi archeologica e aspetti tafonomici e antropologici. In N. Negroni Catacchio (Ed.), *Preistoria e Protostoria in Etruria: Atti del V Incontro di Studi* (Vol. II, pp. 523–537) Milano: Centro Studi di Preistoria.
Petitti, P., Persiani, C., & Pallecchi, P. (2011). Reperti metallici dalla necropoli della Selvicciola (Ischia di Castro—Viterbo). In Atti della XLIII Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, IIPP, Florence, pp. 187–194.
Preuschen, E. (1973). Estrazione mineraria dell'età del bronzo in Trentino. *Preistoria Alpina, 9,* 113–150.
Puglisi, S. M. (1959). *La civiltà appenninica: origine delle comunità pastorali in Italia*. Florence: Sansoni.
Radivojević, M., Rehren, Th., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the origins of extractive metallurgy: New evidence from Europe. *Journal of Archaeological Science, 37,* 2775–2787.
Reid, A., & MacLean, R. (1995). Symbolism and the social contexts of iron production in Karagwe. *World Archaeology, 27*(1), 144–161.
Renfrew, C. (1970). The tree-ring calibration of radiocarbon: An archaeological evaluation. *Proceedings of the Prehistoric Society, 36,* 280–311.
Renfrew, C. (1973). *Before civilization: The radiocarbon revolution and prehistoric europe*. London: Jonathan Cape.
Renfrew, C., & Whitehouse, R. (1974). The Copper Age of peninsular Italy and the Aegean. *The Annual of the British School at Athens, 69,* 343–390.
Roberts, B. W. (2008). Migration, craft expertise and metallurgy: Analysing the 'spread' of metal in Western Europe. *Archaeological Review from Cambridge, 23*(2), 27–45.
Roberts, B. W., & Ottaway, B. S. (2003). The use and significance of socketed axes during the Late Bronze Age. *European Journal of Archaeology, 6*(2), 119–140.
Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity, 83,* 1012–1022.
Robb, J. E. (2008). Tradition and agency: Human body representations in later prehistoric Europe. *World Archaeology, 40*(3), 332–353.
Robb, J. E. (2009). People of stone: stelae, personhood and society in prehistoric Europe. *Journal of Archaeological Method and Theory, 16,* 162–183.
Robb, J. E., & Farr, H. (2005). Substances in motion: Neolithic Mediterranean 'trade'. In E. Blake & A. B. Knapp (Eds.), *The archaeology of mediterranean prehistory* (pp. 24–45). Oxford: Blackwell.
Ruiz Taboada, A., & Montero Ruiz, I. (1999). The oldest metallurgy in western Europe. *Antiquity, 73,* 897–903.
Ryndina, N. V., Indenbaum, G., & Kolosova, V. (1999). Copper production from polymetallic sulphide ores in the northeastern Balkan Eneolithic culture. *Journal of Archaeological Science, 26,* 1059–1068.
Sarti, L. (1998). Aspetti della ceramica eneolitica pre-campaniforme in area fiorentina. *Rivista di Scienze Preistoriche, 49,* 411–429.
Schiffer, M. B. (1986). Radiocarbon dating and the "old wood" problem: the case of the Hohokam chronology. *Journal of Archaeological Science, 13,* 13–30.
Sherratt, A. (1997). Climatic cycles and behavioural revolutions: the emergence of modern humans and the beginning of farming. *Antiquity, 71,* 271–287.
Skeates, R. (1993). Early metal-use in the central Mediterranean region. *Accordia Research Papers, 4,* 5–48.

Skeates, R. (1996). Towards an absolute chronology for the Copper Age in central Italy: A note based on the Conelle site and culture. *Papers of the British School at Rome, 64,* 273–282.
Skeates, R. (1997). Copper Age settlement and economy in Marche, central Italy: A social perspective. *Journal of Mediterranean Archaeology, 10*(1), 49–72.
Silvestrini, M., Baglioni, L., Carlini, C., Casciarri, S., Frediani, A., Freguglia, M., Martini, F., Sarti, L., & Volante, N. (2002). Il neolitico tardo-finale delle Marche: primi dati su S. Maria in Selva. In. A. Ferrari & P. Visentini (Eds.), *Il declino del mondo neolitico* (pp. 453–459). Pordenone: Museo Archeologico del Friuli Occidentale.
Sofaer, J., & Sørensen, M. L. (2002). Becoming cultural: Society and the incorporation of bronze. In B. S. Ottaway & E. C. Wager (Eds.), *Metals and society* (pp. 117–121). BAR Int. Ser. 1061.
Sørensen, M. L. (1989). Ignoring innovation—denying change: The role of iron and the impact of external influences on the transformation of Scandinavian societies 800–500 BC. In S. E. van der Leeuw & R. Torrence (Eds.), *What's new? A closer look at the process of innovation* (pp. 182–202). London: Unwin Hyman.
Storti, C. (1990–1991). Esame delle scorie del forno di fusione de 'La Vela' di Valbusa (Trento). *Sibrium, 21,* 349–361.
Strahm, C. (1994). Die Anfänge der Metallurgie in Mitteleuropa. *Helvetia Archaeologica, 25,* 2–39.
Strahm, C. (2007). L'introduction de la métallurgie en Europe. In J. Guilaine (Ed.), *Le Chalcolithique et la construction des inégalités* (pp. 49–71). Paris: Errance.
Strahm, C., & Hauptmann, A. (2009). The metallurgical developmental phases in the old world. In T. L. Kienlin & B. Roberts (Eds.), *Metals and societies: Studies in honour of Barbara S. Ottaway* (pp. 116–128). Bonn: Rudolf Habelt.
Tanelli, G. (1989). I depositi metalliferi dell'Etruria e le attività estrattive degli Etruschi. In Atti del Secondo Congresso Internazionale Etrusco (Vol. III pp. 1409–1417). Bretschneider, Rome.
Thornton, C. P., & Giardino, C. (2008). Alla ricerca di un paradigma archeometallurgico. *Rivista di Scienze Preistoriche, 58,* 385–404.
Trump, D. H. (1966). *Central and Southern Italy before Rome*. London: Thames and Hudson.
Trump, D. H. (2004). *Malta: Prehistory and temples*. Malta: Midsea Books.
Usai, L. (2005). Pre-nuragic metallurgical records. In F. Lo Schiavo, A. Giumlia-Mair, U. Sanna, & R. Valera (Eds.), *Archaeometallurgy in Sardinia from the origin to the Early Iron Age* (pp. 257–277). Montagnac: Monique Mergoil.
Valera, P. G., & Valera, R. G. (2005). Outline of geology and mineral deposits of Sardinia. In F. Lo Schiavo, A. Giumlia-Mair, U. Sanna, & R. Valera, (Eds.), *Archaeometallurgy in Sardinia from the origin to the Early Iron Age* (pp. 35–42). Montagnac: Monique Mergoil.
Valera, R. G., Valera, P. G., & Rivoldini, A. (2005). Sardinian ore deposits and metals in the Bronze Age. In F. Lo Schiavo, A. Giumlia-Mair, U. Sanna, & R. Valera (Eds.), *Archaeometallurgy in Sardinia from the origin to the Early Iron Age* (pp. 43–87). Montagnac: Monique Mergoil.
Vaquer, J. (2006). La diffusion de l'obsidienne dans le Néolitique de Corse, du Midi de la France et de la Catalogne. In Atti della XXXIX Riunione Scientifica dell'Istituto Italiano di Preistoria e Protostoria, (Vol. I, pp. 483–498), IIPP, Florence.
Villari, P. (1981). I giacimenti preistorici del Monte Belvedere e della Pianura Chiusa di Fiumedinisi (Messina): successione delle culture nella Sicilia nordorientale. *Sicilia Archeologica, 46–47*, 111–121.
Visentini, P. (2005). Bannia-Palazzine di Sopra: una comunità preistorica del V millennio a.C., Museo Archeologico del Friuli Occidentale, Pordenone.
Volante, N. (2003). Neto-Via Verga (Sesto Fiorentino): la produzione vascolare dell'area 1. *Rivista di Scienze Preistoriche, 53,* 375–504.
Wang, Q., & Ottaway, B. S. (2004). *Casting Experiments and Microstructure of Archaeologically Relevant Bronzes*. BAR Int. Ser. 1331.
Whitehouse, R. D. (1992). Tools the manmaker: The cultural construction of gender in Italian prehistory. *Accordia Research Papers, 3,* 41–53.
Žeravica, Z. (1993). *Äxte und Beile aus Dalmatien und anderen Teilen Kroatiens, Montenegro, Bosniens und Herzegowina (Prähistorische Bronzefunde, IX.18)*. Stuttgart: Steiner.
Zuffardi, P. (1989). Italy. In F. W. Dunning, P. Garrard, H. W. Haslam, & R. A. Ixer (Eds.), *Mineral deposits of europethe mineralogical society* (pp. 221–277, Vol 4/5). London.

Chapter 19
Cairo to Cape: The Spread of Metallurgy through Eastern and Southern Africa

David Killick

Introduction

This review is structured differently from the other contributions to this volume. My assigned task is to review the evidence for the social contexts of the earliest metallurgy in the eastern half of the African continent. This presents two practical problems. The first of these is that the target (the earliest metallurgy) keeps moving through time and space. The earliest metallurgy in Egypt dates to the fifth millennium cal BCE; in the Great Lakes region of Central Africa it dates somewhere in the first millennium cal BCE, while at the southernmost terminus before European colonization—at the Great Fish River in the Eastern Cape province of South Africa—metals were not used before about 300 cal CE. My review of the earliest metallurgy must therefore span a linear distance of some 11,000 km and nearly five millennia. I have chosen to expand it to six millennia so that I can discuss the first use of gold and bronze in southern Africa, which on present evidence was more than a thousand years after the first production of iron and copper in this region.

The sheer size of the area assigned also makes it impossible for me to discuss the social contexts of metallurgy in each of these areas, as there are gross disparities in our knowledge of the early history and archaeology of these various regions. Egypt has 5,000 years of written records; Nubia at least 3,000; Ethiopia a little less than 2,000; and parts of the Sahel and the East African Coast 1,000 years (though most of these are not eyewitness accounts). In the rest of Africa the historical record extends back barely 200 years, and in some regions less. Similar caveats apply to the archaeological record. Egypt and Nubia have attracted the attention of large numbers of European and American archaeologists over the last two centuries, but their attention has been focussed almost entirely upon tomb and temple. Oddly, we actually know much less about the history of metallurgy in Egypt than in sub-Saharan Africa, in which (as David O'Connor once said, with pardonable exaggeration) a teaspoon of soil has been excavated for every ton on the Nile. Paleolithic archaeology

D. Killick (✉)
Department of Anthropology, University of Arizona, 85721-0030 Tucson, AZ, USA
e-mail: killick@email.arizona.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective*,
DOI 10.1007/978-1-4614-9017-3_19,

has been undertaken over most of the African continent for a century, as have attempts to locate the towns in the Sahel mentioned by Muslim travelers in the first and second millennia CE. But until the late 1960s the total number of archaeologists working in all of sub-Saharan Africa were never more than 30, and often much smaller (Robertshaw 1990). Even this overstates the extent of research, for there was no satisfactory means of dating prehistoric sites in sub-Saharan Africa until the advent of radiocarbon dating, which did not become widely used until the late 1960s. Even today there are fewer archaeologists (both resident and foreign) working in the whole of sub-Saharan Africa than in my home state of Arizona. There are only three radiocarbon laboratories on the entire African continent (in Cairo, Dakar and Pretoria), and only one laboratory for archaeometallurgy (at the University of Cape Town). Most archaeology in sub-Saharan Africa has been on a small scale, focussed on the excavation of test pits, trenches or near-surface features (e.g., furnaces) rather than lateral decoupage, so at present it is rarely possible to situate metallurgical practices in their spatial contexts. Given these constraints, it is hardly surprising that the history of technology in sub-Saharan Africa has barely begun to be written. There have been only two review articles on the topic (Austen and Headrick 1983; Killick 2005) and these are necessarily brief.

Under these circumstances, it is impossible to address many of the questions posed by the organizers. We simply do not have the primary data that we would need to address questions about the social contexts of metal production and use in Africa, about transmission of technical knowledge between generations or about the varying uses of metals by elites and commoners. What little we do know about the prehistory of metallurgy in Africa is however so interesting, and so different from the course of early metallurgy in other regions of the world, that some account of it must be given in this volume.

On the Use of Ethnographic Analogy

My statement that we can say little about the social contexts of early metallurgy in Africa will undoubtedly raise some eyebrows. Most students of archaeometallurgy know that in the late nineteenth and twentieth centuries, iron smelting in many areas of sub-Saharan Africa was viewed by its practitioners as exactly equivalent to human gestation and childbirth. More broadly, iron workers in many areas were recognized as masters of the transformation of both substances and persons. Thus, in some West African societies, ironworkers were also entrusted with circumcision and burial, while their spouses were potters and midwives. Both might be feared (and shunned) as sorcerers. In some central African kingdoms royal investiture involved symbolic appropriation of the occult powers of the ironworker, with kings being symbolically “forged” into their new roles (Childs and Killick 1993; Herbert 1993). These are perhaps the best-known examples of the social construction of technology, and obviously they must have had prehistoric antecedents. Many African archaeologists in the southern half of the continent still assume that these same beliefs can be inferred for any prehistoric iron-smelting site (e.g., Huffman 2007). So why am I so reluctant to allow these ethnographic analogies in the interpretation of early African metallurgy?

It is by no means illegitimate to use analogy in the interpretation of prehistoric archaeological remains; indeed it would be impossible to function as an archaeologist without analogy (David and Kramer 2001; Wylie 2002). For example, we employ analogy every time that we identify an archaeological feature as a smelting furnace. The act of identifying a prehistoric furnace involves—or should involve—a systematic comparison of attributes noted in excavation with attributes that we (or others) have recorded on modern or historic smelting furnaces. It is however much more difficult to make secure inferences about the beliefs of prehistoric metalworkers because these rarely have material correlates. Such inferences are most secure where there is good reason to argue for an unbroken line of descent from a particular prehistoric society. For example, it seems quite likely that the isolated human finger bones buried beneath prehistoric furnace bases in the Lowveld of eastern South Africa were put there to harness occult powers to ensure a successful smelt, as the same practice is recorded in an early twentieth-century ethnography of this same region (Miller et al. 2003). But we cannot make a secure argument that smelters thought of a furnace as a woman unless the furnace is so marked, whether explicitly (with molded breasts, etc.) or with symbols that are unambiguously linked in other contexts with sexually mature women (on which see Childs 1991). Unmarked prehistoric furnaces may well have been seen as female, but to claim this is just speculation.

Nor is it appropriate to export this analogy to a distant context where there is no direct link to historically recorded beliefs. Structuralists like Eliade and Delcourt did so in the late 1950s and 1960s by claiming a conceptual link between metallurgy and procreation for pre-industrial societies in Europe and Greece. Sandra Blakely's comprehensive restudy of Greek *daimones* finds absolutely no support for this claim (Blakely 2006). She shows that the surviving myths are fragments of several distinct regional traditions, only some of which can be identified with metallurgy, and that there is no clear conceptual link in any of these between metallurgy and procreation. In this case, as so often in structuralist analyses, the urge to identify the "deep structures" of human thought has led its proponents to grossly misrepresent the underlying data. The lesson that we should draw from Blakely's reassessment is that interpretations of the social context of early metallurgy should be grounded in the soil of the region under consideration, rather than in analogies to other times and places.

Copper, Silver and Gold in Early Egypt and Nubia

The extent of excavation and publication of archaeological sites in Egypt and Nubia dwarfs that for the rest of continent. It is therefore a curious fact that we know more about the development of extractive metallurgy in sub-Saharan Africa than in Egypt, where archaeometallurgy has barely begun. Most of what we currently know about

Egyptian metallurgy derives from historical inscriptions, finds of metal objects in graves and field studies of mines (mostly Dynastic); there has been very little study indeed of smelting or alloying (Ogden 2000).

There are no sources of copper, lead, silver or gold near the lower Nile Valley (Fig. 19.1). Copper objects first appeared in the Maadi culture near the Nile delta between 4000 and 3200 BCE, and in the later part of this period partially replaced flint for many tool forms. Midant-Reynes (2000, p. 59) notes that the same transition occurred in the southern Levant at about the same time, though there is no parallel in Egypt for the elaborate lost-wax castings in copper–arsenic–antimony alloys, such as those in the Nahal Mishmar hoard, in the Levant (see Golden, this volume). The sources of copper ore may have been the same for both for both regions—namely those of the Sinai peninsula and/or Feinan in southern Jordan—but this has yet to be tested by lead isotope analysis. The green copper carbonate malachite is also quite common in Maadi culture sites, but was not necessarily imported for metallurgical purposes, as no evidence of reduction of the ore has yet been reported from Lower Egypt. The possibility that copper was imported as already-smelted metal must therefore be kept in mind. The well-known obsession of Dynastic Egypt with bright colors has its origin in Predynastic times, and copper and malachite were just parts of a whole spectrum of desirable color and lusters that also included turquoise (from Sinai?), lapis lazuli (from Afghanistan?) and amazonite (Aston et al. 2000).

On the middle Nile, malachite has been recovered graves of the Badarian period (ca. 4400–4000 cal BCE), which is the period when agriculture was first practiced in Egypt. It was ground to powder (for eye shadow?) and possibly derived from the copper deposits of the Eastern Desert, which begins at the longitude of Luxor and continues south into Nubia (Aston et al. 2000). Badarian tools were made of flint, but rare ornaments and implements of copper metal have been recovered. It is not known whether these were made from native or smelted copper.

Copper oxides were a necessary component of the blue and green glazes used on carved stone objects found in Naqada I cemeteries (4000–3500 cal BCE), which developed into faience. By the Naqada II phase (3500–3200 cal BCE) larger copper objects—axes, blades bracelets—were used in the middle Nile, though flint tools were still dominant. Gold and silver also appear at low frequency appearance in Naqada II graves (Midant-Renes 2000). The nearest gold deposits to the middle Nile are in the eastern desert, but the major sources lie to the south-east in Nubia (Fig. 19.1). The uncertainties regarding the sources of copper for the middle and lower Nile may potentially be resolvable by lead isotope analysis, which has been little used so far in Egypt and Nubia.

Copper and gold items first appeared in lower Nubia (the region between the First and Second Cataracts) in graves of the Middle A-Group, which are dated from ca. 3600–3300 cal BCE. These occur with Naqada pottery and other imports of Egyptian origin, so it seems probable that the copper was also imported. By 3000 cal BCE copper beads, awls and pins were reaching as far south as the Third Cataract. Almost all cutting implements were however still made of stone. Edwards (2004, pp. 68–74) suggests that the A-Group settlements were collecting products from the savannah

Fig. 19.1 Locations of sites in Egypt and Nubia, and potential sources of metals and other materials (Shaw 2000, p. 319. Reprinted by permission of Oxford University Press)

margins, such as ivory and ostrich feathers, and trading them north to present Egypt. The earliest evidence of the production of metals in Nubia is from Old Kingdom context (ca. 2600 BCE) at Buhen (Emery 1963) and within the temple precinct further upstream at Kerma, in contexts dated by radiocarbon to 2200–2000 cal BCE

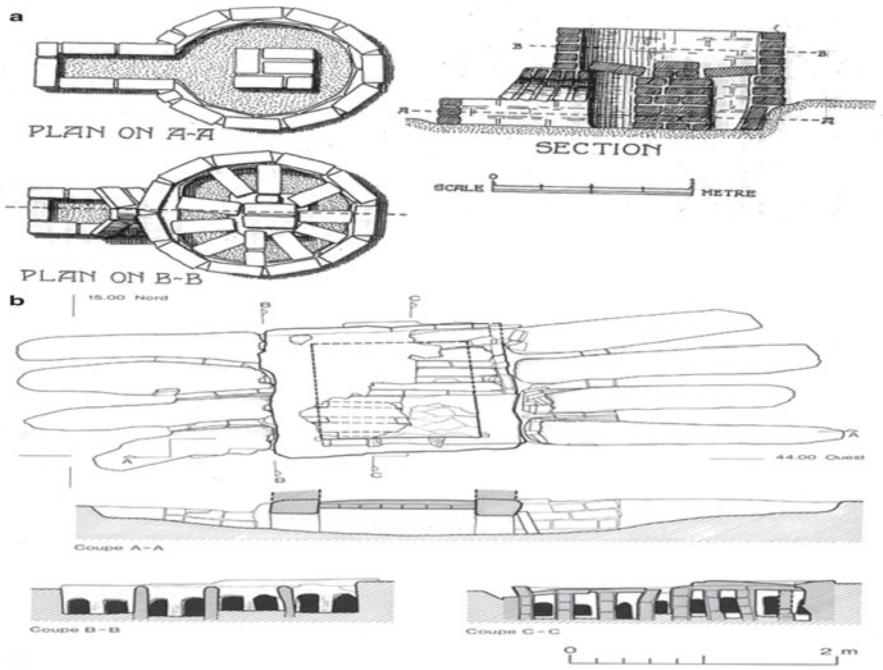


Fig. 19.2 **a** Furnace excavated at Buhen, ca. 2600 BCE (Emery 1963, Fig. 19.1); **b** furnace excavated at Kerma, 2200–2000 cal BCE. (Bonnet 1986, Fig. 19.1)

(Bonnet 1986). The Buhen finds (which long predate the famous Middle Kingdom fortress at that site) relate to the reduction of malachite ore to copper metal. There is some uncertainty about the nature of the smelting process; the supposed crucible-smelting furnace (Fig. 19.2a) is identical to the usual Nubian pottery kilns (Bonnet 1986), but a study of pieces of furnace lining (El Gayar and Jones 1989) suggests the use of a conventional smelting furnace with iron oxide flux. The later Kerma furnace (Fig. 19.2b) is a rectangular platform, originally covered by a vault, and heated from below. This was used for melting bronze in crucibles. No evidence of smelting has yet been found at Kerma, and the sources of the copper and tin used are unknown. Both sites require more substantial archaeometallurgical study, and it can be expected that evidence of even earlier metalworking will emerge in due course (Edwards 2004, p. 86).

Although the major sources of gold lie within present Sudan, in the eastern desert between the First and Second Cataracts, there is no evidence that Nubians attempted to contest Egyptian control of these deposits—not even during the Second Intermediate Period (1650–1550 BCE), when the Kerma state drove the Egyptians back past the First Cataract. Edwards (2004, pp. 96 and 137–138) suggests that the Kerman and later Napatan elites much preferred copper to gold, and that the highly polished red-slipped pottery of the Classic Kerma period is meant to evoke the redness of polished copper. Here he is extending the argument of Eugenia Herbert, in *Red Gold of Africa* (1984), that there was a strong cultural preference for the redness of copper over the yellow of gold throughout sub-Saharan Africa before the Islamic era.

Taking a wider view, it is clear that the adoption of metal in Egypt and Nubia was a very slow process. Knowledge of metals seems to have diffused to Egypt from the Levant, with groups along the middle and lower Nile adopting the high valuation placed by contemporary Near Eastern groups on gold and brightly colored stones. The adoption of metals in Egypt had little effect on agricultural production; peasant farmers were still using flint for cutting tools well into the first millennium BCE. Metal objects were traded into Nubia within 500 years of their first appearance on the Middle Nile, but even after a century of large-scale excavation we still do not know when metallurgy was first practiced in Nubia.

What is certain, however, is that copper metallurgy was not transmitted along the upper Nile to the Great Lakes area during the third millennium BCE, as pottery and domestic animals had been a millennium before (Edwards 2004, pp. 38–65). This long hiatus in the southwards movement of metallurgy has attracted curiously little comment. I suggest that it is probably related to climatic constraints upon agriculture based on wheat and barley. These crops formed the basis of the first agriculture in the middle and lower Nile, and appear from stable isotope ratios of human bone collagen (summarized in Thompson et al. 2008) to have been the staple cereals at Kerma. But wheat and barley are winter-rainfall domesticates from the Near East, and cannot be grown under in the lowland summer-rainfall regimes of the upper Nile and the Great Lakes. Since the earliest metallurgy on the middle and lower Nile was in the context of agricultural societies, I suggest that its southern expansion halted at the southern limit for wheat and barley agriculture. The most recent synthesis of research on the domestication of the African summer-rainfall cereals (sorghum, finger millet and bulrush millet) suggests that these were domesticated no earlier than the third millennium BCE (Neumann 2005), but there is no evidence for their cultivation in the southern half of present Sudan at this time. The Nile headwaters south of present Khartoum appear to have populated in the third millennium by highly mobile cattle pastoralists who also fished and gathered wild grains (Edwards 2004, pp. 60–64). These mobile populations evidently had little inclination to adopt the practice of metallurgy from the sedentary farmers further downstream.

Holl (2009) argues that in sub-Saharan West Africa the earliest evidence of metallurgy was among mobile pastoralists. It is too early to be sure about this, as almost none of the sites containing early metallurgy in West Africa have also received the attention of an archaeobotanist, though certainly the earliest metallurgical sites in Mauretania and Niger lie north of the probable limit of rainfed agriculture at that time. In the Nile Valley, only agricultural societies produced metals between the fifth and second millennia BCE.

As is well known, Egyptian vessels sailed down the Red Sea to the land of Punt (modern Eritrea?) to trade for ebony, animal skins and incense. The earliest voyages were during the Middle Kingdom, but they became more frequent in New Kingdom times (after 1500 BCE), as recorded in the famous panels on the temple of Queen Hatshepsut (Kitchen 1993). But the Egyptians never established any colonies there, and do not appear to have given the inhabitants of that region the gift of metallurgy. As noted below, metallurgy was probably not practiced in Eritrea until the first millennium BCE.

Fig. 19.3 East Africa, showing location of the Great Lakes

The Origins of Ironworking in East-Central Africa

In sharp contrast to the Nile Valley, the Great Lakes area of East Africa (modern Uganda, Tanzania, Rwanda and Burundi) has provided us with a wealth of evidence for the first smelting of metal in the region, backed by some first-rate archaeometallurgical investigation (Fig. 19.3). Unfortunately, the age of many of these smelting sites is very uncertain, and few are connected to habitation sites that might allow some inference about the social context.

All of these early smelting sites relate to the smelting of iron. No early copper smelting sites have been found, but then there are very few sources of copper in the Great Lakes region. The origin of iron smelting in sub-Saharan Africa has been the subject of intense controversy over the last 60 years, with proponents of independent invention battling with those who favor diffusion of the technology from various other regions (Egypt, Phoenician North Africa, Arabia or all of these). This literature has been comprehensively reviewed by Alpern (2005).

No evidence for the antiquity of metallurgy in this region was available until the 1960s, when radiocarbon dating first began to be widely applied in Africa. Prior to this time most scholars had assumed that iron working technology had diffused into the Great Lakes region from the Meroitic state on the upper Nile (ca. 300 BCE–ca. 350 CE). There are massive mounds of iron slag at the capital city of Meroe (Fig. 19.1) itself, representing, by a rough calculation, the production of about 5000 tons of iron bloom (Rehren 2001). In the late 1960s, however, a number of surprisingly early radiocarbon dates (between 2500 and 3600 BP) were announced for ironworking sites in Buhaya, north-western Tanzania (by Peter Schmidt) and in Rwanda and Burundi (by Jean Hiernaux and Francis van Noten). Although the field evidence was not yet published, these dates were immediately accepted by many Africanists. Bruce Trigger (who was at this point still a specialist in Nubian archaeology) wrote a highly influential review entitled “The Myth of Meroe and the African Iron Age” (Trigger 1969). He concluded that iron working in central Africa was earlier than that at Meroe, and must therefore have been independently invented. This fuelled a debate that is still without resolution.

The evidence for early ironworking in the Great Lakes region was greatly expanded during the 1970s and 1980s through archaeological fieldwork in Buhaya (directed by Schmidt), Rwanda and Burundi (by Van Noten and by Marie-Claude van Grunderbeek). The cumulative result of all of these projects is a corpus of about 30 iron-smelting furnaces, dated by radiocarbon to between ca. 1500 BP and 3600 BP (van Grunderbeek et al. 1982, 2001; Schmidt and Childs 1985; Schmidt 1997). All of these are slag-pit furnaces with truncated conical shafts made of clay (Fig. 19.4), the deliberately broken remains of which are often found within the slag pit, sometimes with tuyères. These furnaces certainly used multiple tuyères, but it is difficult to say how many. The slag pits vary in diameter from ca. 80 to ca. 130 cm; in the rare cases where the original shaft height can be estimated from fragments, it appears to have been between 78 and 130 cm from the top of the slag pits, which were between 20 and 77 cm deep. In both Buhaya and Rwanda/Burundi the slag pits were often stuffed with reeds or grass before charging, as impressions of these are preserved in the slags (van Grunderbeek et al. 1982, 2001; Schmidt and Childs 1985).

Exemplary archaeometallurgical studies (by Donald Avery and Terry Childs) of the Buhaya materials dating to the early first millennium cal CE show that they were capable of producing steel blooms and highly fluid slags that drained efficiently from the iron, producing clean blooms (Childs 1996). A recent study of the slags from

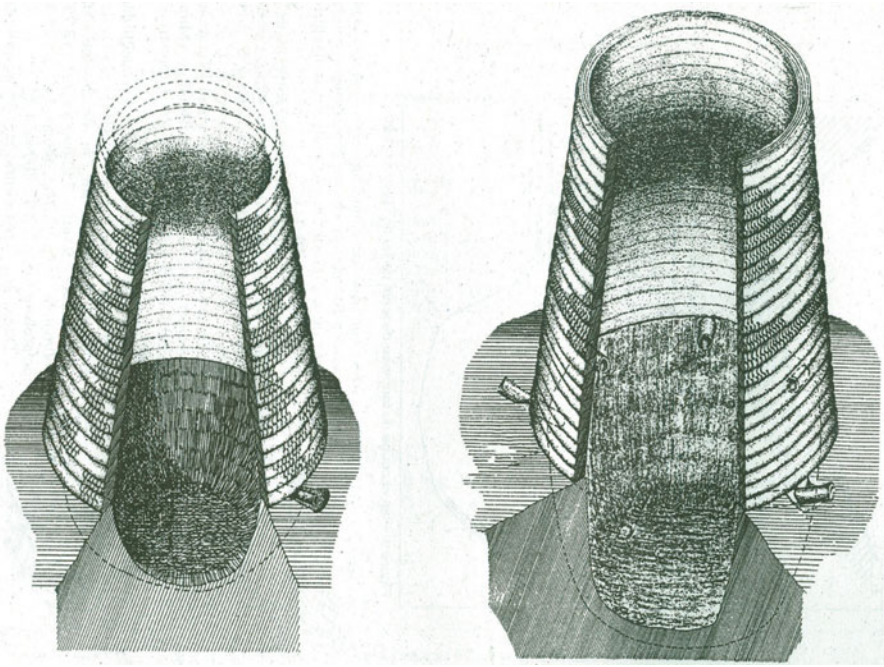


Fig. 19.4 Reconstruction of an early slag-pit iron-smelting furnace from Rwanda. (van Grunderbeeck et al. 2001, Figure 7)

van Grunderbeek's Rwanda and Burundi furnaces (Craddock et al. 2007) shows that they are very similar to those from Buhaya and were capable of reaching at least 1,250 °C.

How do these compare with iron-smelting technology at Meroe? The earliest radiocarbon date associated with iron slag at Meroe is 2514 ± 73 BP (Shinnie 1985), but only fragments of the bases of shallow bowl bases were found in deposits of the first millennium BCE. It is not clear whether these are from forging or smelting. Five complete furnaces were excavated and dated by radiocarbon in the interval 0–600 cal CE. These are slag-tapping furnaces built of fired brick with a shaft 100 cm tall, lined with a sandy clay; in one case four pot-bellows were found still in place (Shinnie 1985). Since most of the huge slag heaps at Meroe are of tapped slag (Rehren 2001), this type of furnace seems to have been responsible for the bulk of iron production there. Obviously these furnaces are of completely different design than contemporary slag-pit furnaces from the Great Lakes region; Shinnie considers them to be derived from Roman prototypes. It is frustrating that we do not have any firm evidence for smelting furnace construction from the first millennium BCE at Meroe.

Paul Craddock's wealth of comparative knowledge has brought some much-needed external perspective to the overheated debate about the origins of African iron smelting. A decade ago he noted that it is difficult to derive these large, efficient

African furnaces of the first millennium BCE from anything in the Near East (Craddock 1997, pp. 261–264). It is true that almost no iron-smelting furnaces of any kind are known from the Levant or Mesopotamia but, as Craddock points out, slag pits are highly distinctive and preserve very well, so it is hard to imagine that they would not have been noted had they ever been employed in these areas. The only remaining candidate for an extra-continental source for Great Lakes iron metallurgy is South Arabia, via the pre-Axumite culture of present Eritrea and lowland Ethiopia. There is a hint of a north-eastern origin for Great Lakes iron in historical linguistics; Ehret (1998) and Schoenbrun (1998) both derive the words for iron working in Eastern Bantu languages from Central Sudanic languages. But there is no published work at all on ancient iron metallurgy in south Arabia, and the director of a large archaeological survey project in Yemen informs me that she has never even seen an iron-smelting site in that nation (Joy McCorriston, personal communication, March 2008).

Could iron smelting have been independently invented in the Great Lakes region? The many supporters of an independent invention of metallurgy continue to cite the published radiocarbon dates of 2800–3600 BP in the Great Lakes region, but ignore the fact that the archaeologists who are most familiar with these dates no longer have confidence in them. Schmidt (1997, p. 14) has disavowed the three oldest dates (> 3000 BP) from Buhaya, while van Grunderbeek et al. (2001) have backed away from the dates > 2800 BP from Rwanda and Burundi. One cannot prove that these dates are not contemporary with the furnaces, but the most likely explanation for these dates is that they are on old charcoal from forest fires, which were present in the soils into which the slag pits were dug.

There remain, however, at least four radiocarbon dates between ca. 2350 BP and ca. 2650 BP, each in good association with furnaces and on charcoal of small diameter, which should eliminate the possibility of an "old wood" error (Marie-Claude van Grunderbeek, personal communication, February 2006). Unfortunately these all fall within a well-known "black hole" in the radiocarbon calibration curve, and thus all calibrate at two sigma to a calendar range of approximately 800–400 cal BCE. This is exactly the same range of calibrated age as for the earliest radiocarbon dates for iron slag at Meroe (Shinnie 1985; Rehren 2001)— and indeed almost all of the earliest dates for iron smelting in West Africa also fall in this range (Alpern 2005; Holl 2009). Clearly we cannot progress as long as we rely solely upon radiocarbon dating for chronology. For more than 25 years I have urged African archaeologists to use thermoluminescence dating to date potentially early furnaces (Killlick 1987, 2004) and it is currently being used to date slag heaps around Meroe (Dana Drake Rosenstein, personal communication, 2012).

I have gone into the evidence in some depth to make it clear that the origins and timing of the first metallurgy of the Great Lakes area are still quite unclear. If we accept, for the sake of argument, that ironworking began here somewhere in the interval 800–400 cal BCE, let us see what else was happening in the Great Lakes region in this interval. Pollen cores show little evidence for widespread forest clearance during the first millennium cal BCE (Taylor and Marchant 1995; Schmidt 1997, pp. 268–280; Lejju et al. 2006), but there are nevertheless hints of agricultural activity. The domesticated cereal *Eleusine coracana* (finger millet), whose wild ancestors are in the Great Lakes region, has been found in secure archaeological contexts at the end of the second millennium BCE in South Asia (Fuller 2003). It must therefore have been cultivated in the Great Lakes area for some time before this. Conversely, phytoliths of banana (*Musa* spp.), which is an Indonesian domesticate, have been reported in a swamp core from Uganda in levels below a radiocarbon date of 4560 ± 40 BP (Lejju et al. 2006), and also from charred residue in a pot from Nkang, Cameroon, dated in the range 850–350 cal BCE (Mbida et al. 2000). So there is good reason to believe that when ironworking began in the Great Lakes area, it was in an agricultural context, though there do not appear to have been very many people on the landscape. This is not much to go on, but at present it is all that we have.

There is some contextual evidence from Buhaya for iron smelting in the first few centuries cal CE. Clusters of several slag-pit furnaces at this time were situated between and within village sites around small bays and swamps within a few kilometers of the western shore of Lake Victoria (Schmidt and Childs 1985). Little faunal or botanical evidence has yet been recovered, and the scale of iron production appears to have been small. Charcoal analysis implies that in the initial centuries cal CE mature gallery forest was still close to the lake, but by ca. 1100 CE much of this appears to have been cleared, and the region was abandoned for several centuries (Schmidt 1997).

Ironworking spread south from the forested regions of the Great Lakes into the savannas of present Kenya and Tanzania, and had reached the coast in the region of present Dar-es-Salaam by the first century BCE. The near-coastal site of Limbo, dated in the first centuries CE, is of interest because it contains at least 3 t of iron slag (Chami 1992). This is the earliest known evidence of the production of metals on a substantial scale in regions south of the Meroitic and Axumite states.

Iron- and Copper-Working in Southern Africa

The southwards expansion of iron-producing agricultural peoples brought them, by the second century BCE, to the northern edge of the vast belt of *miombo* woodlands that covers Angola, southern Tanzania, Zambia, Malawi and northern Mozambique. These woodlands, dominated by the genera *Brachystegia* and *Julbenardia*, evolved on an old stable continental craton covered with deeply leached, very infertile soils. Before the advent of chemical fertilizers, agriculture within the *miombo* was only possible because of the invention of a number of truly ingenious crop rotations, employed for a few years on fields temporarily fertilized by the felling, stacking and burning of large volumes of wood, and subsequently abandoned to long periods of fallow (Allan 1965). These systems of agriculture would not be possible without a constant supply of metal axes. I have suggested (Killick 2005) that there may have been a hiatus in the expansion of agricultural populations at the northern margin of the *miombo* while these swidden systems were invented, but there are as yet too few radiocarbon dates to confirm this.

In the Great Lakes region it appears that agriculture, ironworking, cattle keeping and Bantu languages have different time depths (Schoenbrun 1998). There can however be little doubt that all of these came into southern Africa as a package, together with the first evidence for settled village life. The immigrants settled among hunter-gatherers, but did not wholly displace them. Excavations in rock shelters in many parts of east-central Africa have shown that microlithic technologies persisted in many areas until at least the middle of the second millennium CE. Two separate "streams" of migrants can be traced archaeologically—a western stream from Angola into Namibia and Botswana, and an eastern stream from Tanzania south through Mozambique, Zambia and Zimbabwe (Phillipson 2005; Huffman 2007). Expansion of the eastern stream continued down the fertile eastern coastal plain of South Africa, reaching the Fish River by the fourth century cal CE. South of this lies the winter rainfall region, in which the African cereals (millets and sorghum) cannot be grown. For the next 1,000 years, metals were traded in small quantities from the agricultural communities to the pastoralist and hunter-gatherers of the eastern and southern Cape; after 1500 CE this supply was supplemented by metals scavenged from European shipwrecks. But there was never enough metal circulating to replace microlithic stone tool technologies, which were still being used in these regions in the mid-nineteenth century CE (Mitchell 2002).

On the drier western side of the continent agriculture was similarly restricted, and hunter-gatherers, pastoralists and agriculturalists were linked in complex webs of exchange at the margins of the arable regions. The complexity of these relationships is well illustrated at the Tsodilo hills, deep in the Kalahari Desert at the north-west corner of Botswana (Fig. 19.5). Archaeological research has shown that between ca. 550 and ca. 1100 CE these hills were occupied by both stone-tool makers (presumably hunter-gathers) and later arrivals (presumably agro-pastoralists) who smelted iron and copper (Denbow and Wilmsen 1986; Miller 1996; Reid 2005). Both groups were attracted to the hills by specularite, a glittering form of the iron ore haematite. This had been mined at Tsodilo—and at many other locations in southern Africa—for many thousands of years before metallurgists entered the area, and was used as a pigment in rock art and as a cosmetic. Metal-using populations appear to have adopted the latter practice, and the glittering powder (known in Tswana as *sebilo*) was still widely traded and used by hunter-gatherers, pastoralists and agriculturalists alike in the early twentieth century CE. The image of the isolated Kalahari hunter-gatherer, painstakingly constructed by social anthropologists from the 1950s to the 1980s, has been exposed by archaeologists as a romantic fiction. In fact, agriculturalists, pastoralists and hunter-gatherers have been sharing spaces and exchanging metals, *sebilo*, pottery, hunted products and imported materials (glass beads) in the northern Kalahari since the first millennium cal CE (Denbow and Wilmsen 1986; Wilmsen 1989; Reid 2005).

Iron and unalloyed copper were the only two metals used in southern Africa before ca. 1100 cal CE. Unalloyed copper was employed exclusively for items of personal adornment, in the form of pendants, rings, bangles and wire. Iron was also used for jewelry, but its main inferred use was in hunting and agriculture, as spears, axes, knives and hoes. (Large iron items have rarely been found in archaeological

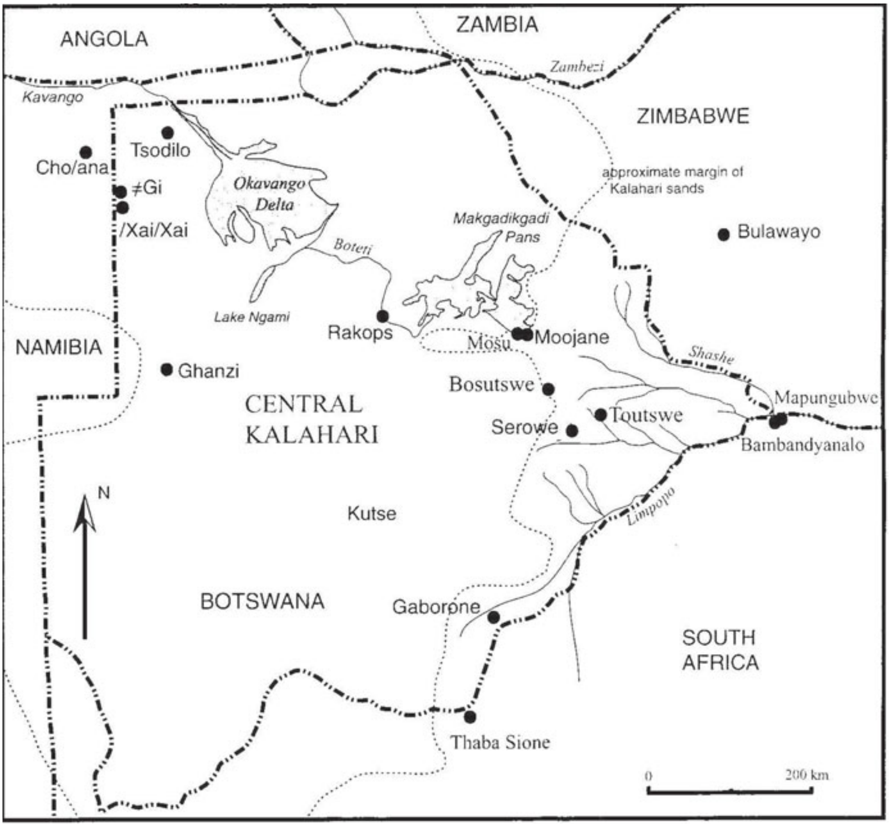


Fig. 19.5 The Kalahari Desert and adjacent regions, showing archaeological sites mentioned in the text. (Reid 2005, Figure 14.1. Reproduced by permission of Blackwell Publishing)

excavations and are presumed to have been intensively recycled). Little evidence for the smelting, casting or forging of copper has been reported for this early period (Miller 2002), but there is abundant evidence of iron smelting. There has been recent controversy in southern African archaeology over the location of early iron-smelting sites. As I noted above, historical and ethnographic accounts of African iron smelting show that in many regions of Africa the formation of the iron bloom was understood through the metaphor of pregnancy and childbirth (Herbert 1993; Schmidt 1997). In smelting iron, men were symbolically appropriating the reproductive powers of women, who were excluded from the vicinity of the furnace while the smelt was under way. The archaeologically visible correlate of this social construction of technology is that smelting furnaces were usually situated well outside villages, beyond the gaze of women. Forges were generally not assigned a gender, and thus forging was often done within the confines of the village.

There has been much argument over the time depth of this distinctive practice. In the Great Lakes area, there is no doubt that smelting was carried out within villages during the early first millennium cal CE (Schmidt and Childs 1985; Schmidt 1997), but southern African archaeologists have tended to interpret early ironworking through the ethnographic model of smelting as reproduction. This position has recently been challenged by archaeologists working in Zimbabwe, who have produced evidence of iron smelting within villages of the first millennium cal CE (Chirikure and Rehren 2006; Swan 2007). This debate can only be resolved with further evidence, but it serves as a reminder of the potential dangers of uncritical application of ethnographic analogy.

Gold, Silver, Lead and Tin in Eastern and Southern Africa

Perhaps the most striking feature of the early metallurgy of the vast region from the Great Lakes to the southern Cape is the absolute lack of evidence for metals other than copper and iron until maritime trade with the Islamic world commenced in the eighth or ninth century CE. On present evidence there was no tin or bronze, no silver, no gold and no lead in southern Africa before then. Yet all of these metals are present in archaeological sites of the last centuries BCE and early centuries CE in Nubia and Ethiopia. Their absence in contemporary sites in the Great Lakes region and Kenya must surely be telling us that there was essentially no interaction between these regions and the contemporary Meroitic and Axumite states to the north.

Silver deposits are very rare in Africa, but there is abundant tin (as cassiterite) in the pegmatites of southwest Uganda, Rwanda, eastern Congo and Zimbabwe (von Knorring and Condliffe 1987). Tin deposits are also found in many locations around and within the Upper Granite of the enormous Bushveld Igneous Complex in northern South Africa. Yet there is no evidence at all that any of these deposits were exploited in the first millennium CE. There is not even much evidence of arsenical copper in artifacts analyzed to date, though admittedly the available data are geographically skewed—almost all chemical analyses for copper alloys of the first millennium CE have been generated in South Africa by Duncan Miller (e.g., Miller 1996, 2002). The scarcity of arsenical copper presumably means that only the surficial copper carbonate ores were smelted by early metallurgists in southern Africa. Lead is also quite common (as galena) in the subcontinent south of the Great Lakes region, but neither lead metal nor leaded copper has been noted in archaeological contexts of the first millennium BCE and the first millennium CE.

One might argue that it is not obvious that cassiterite, which is a heavy dark brown or black mineral, contains a metal, but this argument will not hold for galena, which has a metallic luster. It is not even very convincing for cassiterite—magnetite, which is also dull, heavy and black, was certainly smelted to iron in Zimbabwe during the first millennium CE (Swan 2007), so there is no good reason why alluvial cassiterite should have been ignored. The temperatures and furnace atmospheres needed to reduce cassiterite to tin are comparable to those for reducing iron oxide to iron metal (Killick 2001, Fig. 39.1) so early African ironworkers would have no difficulty in producing metallic tin. It is even harder to account for the absence of

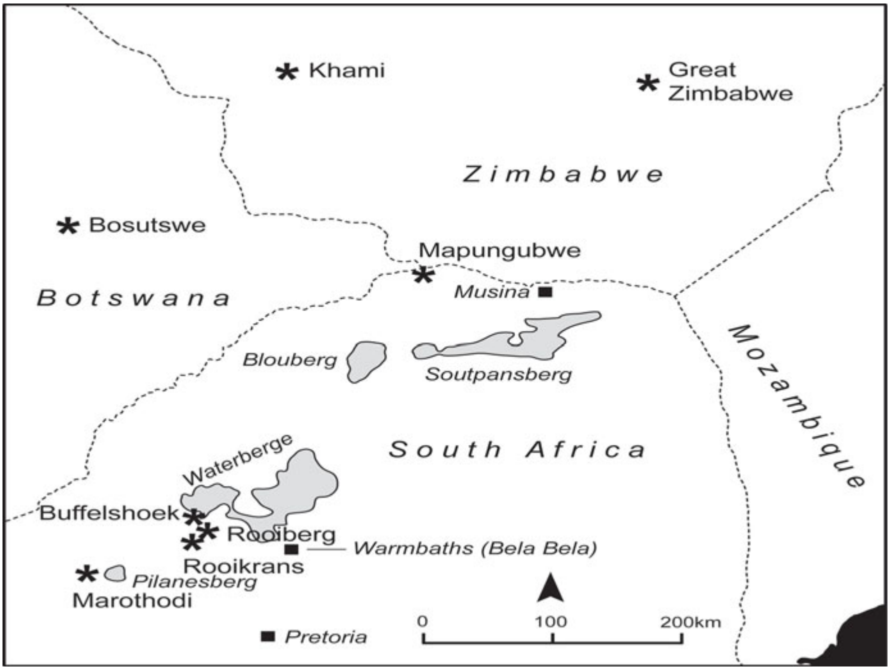


Fig. 19.6 Archaeological finds of tin and bronze in southern Africa (*stars*) modern towns (*squares*) and major mountain ranges (irregular *grey areas*). *Dotted lines* are modern national boundaries. (Figure supplied by Simon Hall)

gold, which only occurs as the bright shiny metal. Gold deposits of Africa are mostly in Precambrian rocks on the old stable continental cratons of west and southern Africa, which between them supplied most of the gold circulating in the western half of Eurasia from the tenth through the fifteenth centuries. Alluvial gold could be found in the streams draining these cratons, and it is simply impossible to believe that the inhabitants of the regions between the Great Lakes and the Cape of Good Hope were not aware of its presence.

The only satisfactory solution to these paradoxes is that proposed by Eugenia Herbert (1984). She argued that prior to trade contacts with the Muslim world, the populations of sub-Saharan Africa valued the redness of unalloyed copper much more than the yellow of gold or bronze. A quarter of a century later, with much more archaeological and archaeometallurgical data in hand, her argument looks even stronger. The most telling evidence in support of her thesis is the change that occurred when the external trade with the Muslim world became established (Miller 2002; Killick 2009). Before the eighth or ninth century cal CE there was no external trade, and unalloyed red copper was the metal of choice for personal adornment (Miller 1996, 2002). In the ninth century imported glass beads first appear in the Limpopo river valley, the present border between South Africa, Zimbabwe and Botswana (Fig. 19.6). Beads, and probably Indian cotton cloth, were traded for ivory, and the struggle for local control of this trade led to political centralization in the Limpopo valley, leading to formation of the first state in southern Africa at Mapungubwe in the thirteenth century cal CE (Leslie and Maggs 2000).

The impetus behind state formation in the Limpopo valley was in large part the trade in alluvial gold (Huffman 2007; Killick 2009). The earliest mention in Arabic documents of trade in gold from southern Africa is in the eleventh century, but it is not yet known when the alluvial gold of the middle Limpopo valley began to be exported. By the thirteenth century cal CE, the high cultural value of gold in the Muslim world had evidently been adopted by the emerging African elites of the region, as the royal burials on Mapungubwe Hill contained gold jewelry and other objects—the earliest objects of gold yet found in southern Africa. It is definitely not a coincidence that the earliest bronze objects known from southern Africa also come from twelfth- and thirteenth-century Mapungubwe (Miller 2002). What we are seeing in this sequence is the adoption by the new southern African elites of an alien value system, in which the golden color of gold and bronze supplanted the red of copper for personal ornamentation among an emerging elite. In Bourdieu's terms, this is a new form of distinction created to differentiate the new royal stratum from lower strata of the elite.

There is an interesting coda to this story. The Mapungubwe bronzes are assumed to have been imported, as no tin or evidence for bronze working has been found in sites of this period. A further two centuries pass before there is actual evidence of manufacture of tin and bronze in southern Africa. At the site of Bosutswe in eastern Botswana, a lead–tin object and a spill from bronze casting are dated in the range 1450–1550 cal CE (Denbow and Miller 2007), while at Great Zimbabwe a tin ingot and a lead-tin object are dated in the same range (Thomas Huffman, personal communication, 2006). My collaborators Lisa Molofsky and John Chesley have established by lead isotope ratio analysis that both the lead-tin objects and the Zimbabwe tin ingot derive from the Rooiberg tin mines in north-western South Africa, where hard-rock mining of cassiterite is implied at roughly the same time by dates of 1436–1650 cal CE on charcoal embedded in a tin ingot and 1426–1633 cal CE on a wooden pit prop from a prehistoric mine (Grant 1990; Chirikure et al. 2007; Molofsky et al. in prep.).

What these findings suggest is that a tin mining industry began at Rooiberg in the fifteenth or sixteenth century to supply an indigenous bronze industry over a wide area of southern Africa (Chirikure et al. 2007). This is contemporary with the late Zimbabwe state, which by this time was centered at Khami. Sites with Khami pottery are found in northern Botswana at this time, and Reid (2005) suggests that these are connected with the procurement of distant resources (particularly salt) for the state. Though no Khami pottery has yet been found at Rooiberg, it is conceivable that the start of tin mining here was also the result of a widening network of resource exploitation by the late Zimbabwe state. Although there is no mention of tin from southern Africa in Islamic sources, we should also be aware of the possibility that Rooiberg tin was exported through Swahili intermediaries into the Indian Ocean trading network. This may explain some very puzzling passages in Portuguese documents from the early 1500s. Portuguese sailors reported that some inhabitants of coastal Mozambique were wearing silver, and that some captured Swahili vessels were also bearing it (Axelson 1973, passim). The Portuguese spent another two centuries desperately searching for silver mines in present Mozambique and Zimbabwe, but the fact is that there are no sources of silver in southern Africa that would have been exploitable by pre-industrial miners. My guess is that what the first Portuguese sailors actually saw was Rooiberg tin.

Conclusion

I make no apology for stretching out my examination of "early" metallurgy over six millennia. As I noted in the introduction to this paper, Africa is a very large continent indeed. The earliest metallurgy in Egypt, in the fifth millennium BCE, was clearly acquired from adjacent regions of the Levant, as is seen by the parallelism in the value accorded to copper, gold and particular colored stones in both regions. It is not yet clear when metals were first smelted in Nubia (as opposed to imported from Egypt) but bronze metallurgy was definitely well established at Kerma towards the end of the third millennium BCE. It appears, on present evidence, that there was then a long hiatus in the further expansion of metallurgy. Copper, bronze and iron technology probably first appeared in Ethiopia and Eritrea in the early first millennium BCE, but we must await publication of ongoing archeometallurgical work from that region. The origins of iron smelting in the Great Lakes region are still a complete mystery. If we accept for the moment that iron smelting began here somewhere in the range 800–400 cal BCE, then it took between 800 and 1,200 years for the technique to be transported to its southernmost terminus at the Fish River. To put this whole process in perspective, the earliest metallurgy in Africa is contemporary with the first agriculture in Egypt; by time that metallurgy reached present South Africa, Egypt was a province of the late Roman Empire.

We can as yet say very little about the social contexts of early African metallurgy. The main conclusion to be drawn from my very brief review is that the relative social valuation of metals in early Egypt (gold > silver > bronze > copper) did not necessarily apply in Nubia, and was most certainly not shared by the inhabitants of Africa south of present Sudan. The only metals used—and thus valued—in the long trek of metallurgy from the Great Lakes region to southern Africa were copper and iron. Gold, lead and tin ores are quite common in eastern and southern Africa, but appear to have been completely ignored until the early second millennium CE. At that time Muslim traders, sailing south along the east African coast, and penetrating up its major rivers, noted alluvial gold and induced African societies to pan and mine it for exchange against imported beads and cloth (Leslie and Maggs 2000; Huffman 2007; Killick 2009). The struggle to control the African end of this trade produced southern Africa's first state, the rulers of which chose to mark their distinction from their subjects by wearing gold.

In conclusion, it must be noted that the interpretations offered here are made on the basic of data that are clearly inadequate. Indeed, it has been difficult to find any relevant data on the social contexts of metallurgy for regions north of southern Africa, which was the last region of the continent to acquire the capacity to make metal. Given the slow pace at which archaeological research proceeds in sub-Saharan Africa—a consequence of the low level of funding and the dearth of specialist technical expertise—it will be many years before Africanists can address the very detailed questions posed by the editors of this volume.

References

Allan, W. (1965). *The African husbandman*. New York: Barnes and Noble.

Alpern, S. B. (2005). Did they or didn't they invent it? Iron in sub-Saharan Africa. *History in Africa*, *32*, 41–94.

Aston, B., Harrell, J., & Shaw, I. (2000). Stone. In Nicholson, P. and Shaw, I. (eds.), *Ancient Egyptian materials and technology* (pp. 5–77). Cambridge: Cambridge University Press

Austen, R. A., & Headrick, D. (1983). The role of technology in the African past. *African Studies Review*, *26*, 163–184.

Axelson, E. (1973). *Portuguese in South-East Africa, 1488–1600*. Johannesburg: Struik.

Blakely, S. (2006). *Myth, ritual and metallurgy in Ancient Greece and recent Africa*. New York: Cambridge University Press.

Bonnet, C. (1986). Un atelier de bronziers à Kerma. In M. Krause (Ed.), *Nubische Studien* (pp. 19–23). Mainz: von Zabern.

Chami, F. (1992). Limbo: Early iron working in southern Tanzania. *Azania*, *27*, 45–52.

Childs, S. T. (1991). Style, technology and iron-smelting furnaces in Bantu-speaking Africa. *Journal of Anthropological Archaeology*, *10*, 332–359.

Childs, S. T. (1996). Technological history and culture in western Tanzania. In P. R. Schmidt (Ed.), *The culture and technology of African iron production* (pp. 277–320). Gainesville: University of Florida Press.

Childs, S.T., & Killick, D. J. (1993). Indigenous African metallurgy: Nature and culture. *Annual Review of Anthropology*, *22*, 317–337.

Chirikure, S., & Rehren, Th. (2006). Iron smelting in precolonial Zimbabwe: Evidence for diachronic change from Swart Village and Baranda, northern Zimbabwe. *Journal of African Archaeology*, *4*, 37–54.

Chirikure, S., Hall, S. L., & Miller, D. (2007). One hundred years on: What do we know about tin and bronze production in southern Africa? In S. La Niece, D. Hook, & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 112–118). London: Archetype Press.

Craddock, P. T. (1995). *Early metal mining and production*. Washington: Smithsonian Institution Press.

Craddock, P. T., Freestone, I., Middleton, A., & van Grunderbeek, M.-C. (2007). Early Iron Age iron-smelting debris from Rwanda and Burundi, East Africa. *Historical Metallurgy*, *41*, 1–14.

David, N., & Kramer, C. (2001). *Ethnoarchaeology in action*. Cambridge: Cambridge Unversity Press.

Denbow, J., & Miller, D. M. (2007). Metal working at Bosutswe, Botswana. *Journal of African Archaeology*, *5*, 271–313.

Denbow, J., & Wilmsen, E. N. (1986). Advent and course of pastoralism in the Kalahari. *Science*, *234*, 1509–1515.

Edwards, D. N. (2004). *The Nubian past: An archaeology of the Sudan*. London: Routledge.

Ehret, C. (1998). *An African Classical Age: Eastern and Southern Africa in world history, 1000 BC to AD 400*. Charlottesville: University Press of Virginia.

El Gayar, E. S., & Jones, M. P. (1989). Old Kingdom copper smelting artifacts from Buhen in Upper Egypt. *Historical Metallurgy*, *23*, 16–24.

Emery, W. B. (1963). Egypt Exploration Society preliminary report on the excavations at Buhen, 1962. *Kush, 11*, 116–120.

Fuller, D. (2003). African crops in prehistoric South Asia: a critical review. In K. Neumann, A. Butler, & S. Kahlheber (Eds.), *Food, fuel and fields: Progress in African archaeobotany* (pp. 239–271). Köln: Heinrich Barth Institut.

Grant, M. R. (1990). A radiocarbon date on a tin artefact from Rooiberg. *South African Journal of Science*, *86*, 83.

Herbert, E. W. (1984). *Red gold of Africa: Copper in precolonial history and culture*. Madison: University of Wisconsin Press.

Herbert, E. W. (1993). *Iron, gender and power: Rituals of transformation in African societies*. Bloomington: University of Indiana Press.

Holl, A. (2009). Early West African metallurgies: new data and old orthodoxy. *Journal of World Prehistory*, *22*, 415–438.

Huffman, T. N. (2007). *Handbook to the Iron Age: The Archaeology of pre-colonial farming societies in Southern Africa*. Durban: University of Kwazulu-Natal Press.

Killick, D. J. (1987). On the dating of African metallurgical sites. *Nyame Akuma*, *28*, 29–30.

Killick, D. (2001). Science, speculation and the origins of extractive metallurgy. In D. R. Brothwell & A. M. Pollard (Eds.), *Handbook of Archaeological Sciences* (pp. 479–488). London: Wiley.

Killick, D. J. (2004). What do we know about African iron working? *Journal of African Archaeology*, *2*, 97–112.

Killick, D. J. (2005). Sub-Saharan Africa. In W. B. Carlson (Ed.), *Technology in World History* (Vol 4, pp. 8–35). New York: Oxford University Press.

Killick, D. J. (2009). Agency, dependency and long-distance trade: East Africa and the Islamic World, ca. 700–1500 C.E. In S. Falconer & C. Redman (Eds.), *Polities and power: Archaeological perspectives on the landscapes of early states* (pp. 179–207). Tucson: University of Arizona Press.

Kitchen, K. A. (1993). The land of Punt. In T. Shaw, P. Sinclair, B. Andah, & A. Okpopo (Eds.), *The archaeology of Africa: Food, metals and towns* (pp. 587–608). London: Routledge.

Lejju, B. J., Robertshaw, P. M., & Taylor, D. (2006). Africa's earliest bananas? *Journal of Archaeological Science*, *33*, 102–113.

Leslie, M., & Maggs, T. (Eds.) (2000). *African naissance: The Limpopo valley 1000 years ago, South African Archaeological Society*, Goodwin Series 8, Claremont.

Mbida, C., van Neer, W., Doutrelpont, H., & Vrydaghs, L. (2000). Evidence for banana cultivation and animal husbandry during the first millennium BC in the forest of southern Cameroon. *Journal of Archaeological Science*, *27*, 151–162.

Midant-Renes, B. (2000). The Naqada Period (c. 4000–3200 BC). In I. Shaw (Ed.), *The Oxford history of ancient Egypt* (pp. 44–60). Oxford: Oxford University Press.

Miller, D. M. (1996). *The Tsodilo jewellery: Metalwork from Northern Botswana*. Cape Town: University of Cape Town Press.

Miller, D. M. (2002). Smelter and smith: Iron Age metal fabrication technology in southern Africa. *Journal of Archaeological Science*, *29*, 1083–1131.

Miller, D. M., Mulaudzi, M., & Killick, D. J. (2003). An historical account of bloomery iron working in the Lowveld, South Africa. *Historical Metallurgy*, *36*, 112–121.

Mitchell, P. (2005). *The archaeology of Southern Africa*. Cambridge: Cambridge University Press.

Molofsky, L. J., Chesley, J. T., Killick, D. J., Ruiz, J., & Thibodeau, A. M., unpublished. *A novel approach utilizing lead isotopes to unravel the sources of tin in prehistoric bronzes*.

Neumann, K. (2005). The romance of farming: plant cultivation and domestication in Africa. In A. B. Stahl (Ed.), *African archaeology* (pp. 225–248). Oxford: Blackwell.

Ogden, J. (2000). Metals. In P. Nicholson & I. Shaw. *Ancient Egyptian materials and technology* (pp. 148–176). Cambridge: Cambridge University Press.

Phillipson, D. W. (2005). *African archaeology*, 3rd edn. Cambridge: Cambridge University Press.

Rehren, Th. (2001). Meroe, iron and Africa. *Der Antike Sudan*, *12*, 102–109.

Reid, A. (2005). The archaeology of the Kalahari. In A. B. Stahl (Ed.), *African archaeology* (pp. 353–377). Oxford: Blackwell.

Robertshaw, P. (Ed.) (1990). *A history of African archaeology*. London: James Curry.

Schmidt, P. R. (1997). *Iron technology in East Africa*. Bloomington: Indiana University Press.

Schmidt, P. R., & Childs, S. T. (1985). Innovation and industry during the Early Iron Age in East Africa: the KM2 and KM3 sites of northwest Tanzania. *The African Archaeological Review*, *3*, 53–94.

Schoenbrun, D. (1998). *A green place, a good place: Agrarian change, gender and social identity in the Great Lakes Area to 1500*. Portsmouth: Heineman.

Shaw, I. (2000). Egypt and the outside World. In I. Shaw (Ed.), *The Oxford history of ancient Egypt* (pp. 314–329). Oxford: Oxford University Press.

Shinnie, P. M. (1985). Iron working at Meroe. In R. Haaland & P. M. Shinnie (Eds.), *African iron working: Ancient and traditional* (pp. 28–35). Oslo: Norwegian University Press.

Swan, L. (2007). Early iron manufacturiing industries in semi-arid, south-eastern Zimbabwe. *Journal of African Archaeology*, *5*, 315–338.

Thompson, A. H., Chaix, L., & Richards, M. P. (2008). Stable isotopes and diet at ancient Kerma, Upper Nubia, Sudan. *Journal of Archaeological Science*, *35*, 376–387.

Taylor, D., & Marchant, R. (1995). Human impact in the interlacustrine region: long-term pollen records from the Rukiga highlands. *Azania, 29/30*, 283–295.

Trigger, B. G. (1969). The myth of Meroe and the African Iron Age. *African Historical Studies*, *2*, 23–50.

van Grunderbeek, M.-C., Roche, E., & Doutrelepont, H. (1982). L'Âge du Fer Ancien au Rwanda et au Burundi: Archéologie et environnement. *Journal des Africanistes*, *52*, 5–58.

van Grunderbeek, M.-C., Roche, E., & Doutrelepont, H. (2001) Un type de fourneau de fonte de fer associé à la culture Urewe (Âge du Fer Ancien) au Rwanda et au Burundi. *Mediterranean Archaeology*, *14*, 291–297.

von Knorring, O., & Condliffe, E. (1987). Mineralized pegmatites in Africa. *Geological Journal*, *22*, 253–270.

Wilmsen, E. N. (1989). *Land filled with flies: A political history of the Kalahari*. Chicago: University of Chicago Press.

Wylie, A. (2002). *Thinking from things: Essays in the philosophy of archaeology*. Berkeley: University of California Press.

Chapter 20
Organization and Specialization of Early Mining and Metal Technologies in Anatolia

Joseph W. Lehner and K. Aslıhan Yener

Introduction

This chapter is a retrospective of current developments in the field of Anatolian archaeometallurgy. Since the 2000 publication of *The Domestication of Metals* (Yener 2000), a number of new field- and laboratory-based projects and international conferences have provided new data that challenge old assumptions about the development of metallurgy and other complex pyrotechnologies. Frequent conference proceedings dedicated to mining and metallurgy in Anatolia (Yalçın 2000a, 2002, 2005, 2008; Yalçın et al. 2008) demonstrate the diversity and importance of this craft. Perhaps the most salient theme is the role of localized processes in the development of early complex metallurgy and ore extraction, both as a cascade of technological innovation (Schiffer 2005) and as an understanding of the organization of production and trade (see, for example, Hauptmann et al. 2002; Ramage and Craddock 2000).

Archaeologists are now becoming increasingly aware that these highland zones were areas of intense technological and social innovation. For example, excavations at Göbekli Tepe (Schmidt 2000, 2006), located on the southern plains directly adjacent to the Taurus Mountains, have revealed at least two phases of monumental architecture dating to the tenth and ninth millennium BC. These structures with richly adorned monolithic pillars demonstrate the presence of specialized institutions and societal inequality before the regional adoption of agriculture and increasingly sedentary lifeways. The development of complex technologies like metallurgy may also follow a similar trajectory, where technological innovation and adoption correlate to socioeconomic and political structures.

J. W. Lehner (✉)
Cotsen Institute of Archaeology, University of California,
A210 Fowler Bldg., Los Angeles, CA 90095, USA
e-mail: jwlehner@ucla.edu

K. A. Yener
The Department of Archaeology and History of Art,
Koç University, RumelifeneriYolu, 34450 Sariyer, Istanbul, Turkey
e-mail: akyener12@gmail.com

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_20,

When past scholars assumed that the development of social complexity and the demand for metal raw materials was a lowland Mesopotamian causation (e.g., Childe 1930), they did not take into account the potential for autonomous social institutions and cultural development in the periphery of powerful states and empires (Stein 1999). In addition, the discovery of production debris in the Balkans dating to before 5000 cal. BC (Radivojević et al. 2010) suggests that the development of metallurgy is likely unrelated to the emergence of complex political economy in Syro-Mesopotamia. The emergence of early complex technologies must take into account the potential for indigenous developments and the structure of interregional interaction.

Today, Anatolia is known to be one of the earliest regions where communities participated in complex metallurgical traditions (see Bachmann 2008 for a history of early research; de Jesus 1980; Muhly 2011; Müller-Karpe 1994; Nieling 2009; Pernicka 1990; Przeworski 1939; Yener 2000). With access to a diverse material base, Anatolia was witness to the early production of a wide variety of nonferrous alloys, surface treatments, and intricate cast/hammered forms. While the time and place of these innovations lack a high degree of chronological and spatial precision, early Anatolian metallurgy shares broad technological developments with the Near East and southeastern Europe. That being said, recent research in prehistoric archaeology over the past 20 years has generated a body of data which indicates that developmental trajectories of complex technologies occurred at varied rates and in regional contexts, with a probable origin in Southwest Asia (Roberts et al. 2009). Research in this region, therefore, has the potential to evaluate longstanding assumptions about not only the origins of metallurgy but also the relationships among social complexity, technology, and long-distance trade.

Regional traditions of metal production and consumption seem to emerge in areas where mineral and native metal resources were relatively abundant (Hauptmann 2007, p. 255; Roberts et al. 2009, pp. 1013–1014; Yener 2000, pp. 18–25). However, geographic proximity to resources and technological proficiency alone cannot generate interest in producing and developing costly materials. There must also be social and economic incentives. Social differentiation and inequality often necessitated the use of scarce resources and complex technologies to display and communicate social heterogeneity or homogeneity (Vidale and Miller 2000). Metal production, a unique pyrotechnological development involving both rare materials and complex technologies, provides a way for some groups to manage access to wealth, which was used to differentiate social groups (Brumfiel and Earle 1987; Helms 1993). Once metal became an indicator of wealth, disparities in access to raw materials and production technologies promoted varying degrees of cooperation and competition among producer and consumer groups. Empirical evidence, especially from textual sources and modern frameworks of urban growth, suggests that interregional cooperative alliances develop out of the potential to increase wealth and surplus, where scale economies promote specialization and economic expansion promotes diversification (see Algaze 2008: 30–39). It is therefore likely that well adapted economic strategies often helped integrate a heterogenous cultural and natural geography between the highlands and lowlands.

Through the assessment of archaeological materials from Anatolia, with a particular focus on data from central and eastern Anatolia, we reexamine some of the main theoretical facets posed in earlier work. After discussing important issues in the heterogeneous distribution and variation in ore resources across Anatolia, we formulate a geographically salient theoretical framework, which is used to explore long-term changes in the metallurgy of the region. Here, we also focus on how a technological organization is socially networked and indivisible from local culture-historical developments.

Highland Geography in Anatolia and the Distribution of Raw Materials

The landscape of Anatolia, modern-day Turkey, is extraordinarily complex. Anatolia is a large peninsular landmass that is surrounded by three seas: the Black Sea to the north, the Aegean to the west, and the Mediterranean to the southwest. The landmass is primarily composed of a series of high mountain ranges and steppes as a result of relict continental agglomeration, tectonic activity, and volcanism that took place during most of the Phanerozoic (Okay 2008). Turkey is composed geologically of three main tectonic units including the Pontide, the Anatolide-Tauride Block, and the Arabian Platform. Resting in between the Pontide and Anatolide-Tauride Block, the central Anatolian crystalline complex stretches from modern Kırıkkale to Sivas, and is composed of mostly metamorphic and plutonic rocks dating to the Cretaceous. Anatolia is also highly varied in terms of climate, with arid regions to the south and southeast along the Syro-Mesopotamian plains and subtropical rainforests in the northeast along the Black Sea. Many of the mountainous regions are heavily wooded, including most of the Pontide belt and western Anatolia. Relict forests that have survived several different periods of deforestation can be found in different areas of the central Anatolian plateau (Miller 1999; Willcox 1974, 2002).

The highlands of Anatolia, a varied mountainous and steppe landscape, are endowed with pockets rich in metal-bearing mineral concentrations (Fig. 20.1). As part of a larger metallogenic belt within the Alpine–Himalayan orogenic system (Okay 2008), Anatolia has extensive polymetallic deposits of copper, iron, lead, silver (often in the form of argentiferous lead), and zinc, in addition to rarer deposits of antimony, arsenic, nickel, gold, and tin (Bayburtoğlu and Yıldırım 2008; Çağatay et al. 1979, 1989; Çağatay and Pehlivan 1988; de Jesus 1980; Maden Tetkik ve Arama Enstitüsü 1970, 1971, 1972; Öztürk and Hanilçi 2009; Sarp and Cerny 2005). The three largest massive sulfide ore bodies include the metallogenic zones of Ergani in the eastern Taurus and Küre and Murgul/GöktaşŸ along the central and eastern Pontide belt (Wagner and Öztunalı 2000). The geological history of the Anatolian landmass resulted in mineralizations of different ages, which is a decisive factor in the success of extensive lead isotope research conducted in Anatolia (Begemann and Schmitt-Strecker 2008).

The geographic distribution of ore bodies roughly follows the contours of the Pontide and Tauride orogenic belts in northern and southern Turkey. Polymetallic

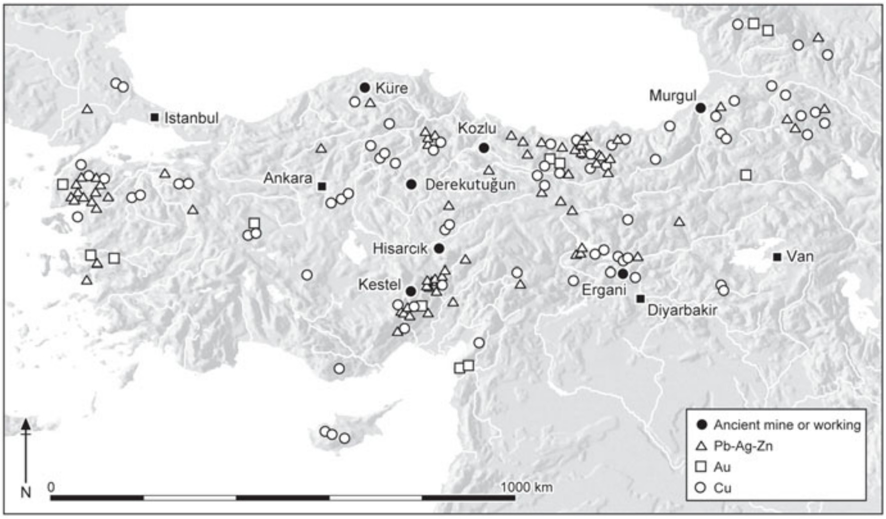


Fig. 20.1 Known major ore sources. Important ancient mining or old working sites noted

copper and lead–zinc–silver ores are particularly abundant in the eastern sectors of these regions (Seeliger et al. 1985; Wagner et al. 1989). Arsenic and antimony-rich ores of the fahlerz-type are evident in both Pontide and Tauride sources (Özbal et al. 1999; Özbal et al. 2002a, b; Özbal et al. 2001; Özbal et al. 2008) and from fourth-millennium BC archaeological deposits at Norşuntepe (Seeliger et al. 1985; Zwicker 1980) and Arslantepe (Palmieri et al. 1993) along the Upper Euphrates. A major copper–nickel sulfide deposit near modern Bitlis in eastern Turkey has also been reported (Çağatay 1987). The Bolkardağ mining district of the central Taurus and immediately north of Cilicia includes mostly iron, argentiferous lead, copper-lead-zinc ores, and smaller occurrences of gold and tin (Pehlivan and Alpan 1986; Yener and Özbal 1986; Yener et al. 1991). More specifically, cassiterite, a tin-oxide, has been observed in floor debris at the ancient mining site of Kestel and also nearby alluvial deposits (Yener et al. 1989). Cassiterite has also been observed together with oxides of iron, arsenic, and antimony north of the Bolkardağ on the northeastern slopes of Erciyes Dağ at Hisarcık (Yazgan 2005; Sarp and Cerny 2005). In the northwest, the Troad sources reveal a diverse array of complex ore deposits, including copper, lead, silver, and gold (Pernicka et al. 2003; Pernicka et al. 1984; Wagner et al. 1985). Arsenic-bearing ore bodies are unknown in this metallogenic zone. The central Anatolian highland, an arid steppe environment bounded to the north and south by high mountains, is less abundant in copper resources. Exceptions include the polymetallic copper–lead–silver ores located near Akdağmadeni, small oxidic and native copper deposits near Sungurlu, and secondary copper ore deposits near Karaali, south of Ankara.

A key pattern in the distribution of raw materials and environments in highland regions like Anatolia, Transcaucasia, and Iran is their heterogeneous and uneven characters (Wilkinson 2003). Despite a relative abundance of ore sources, their spotty

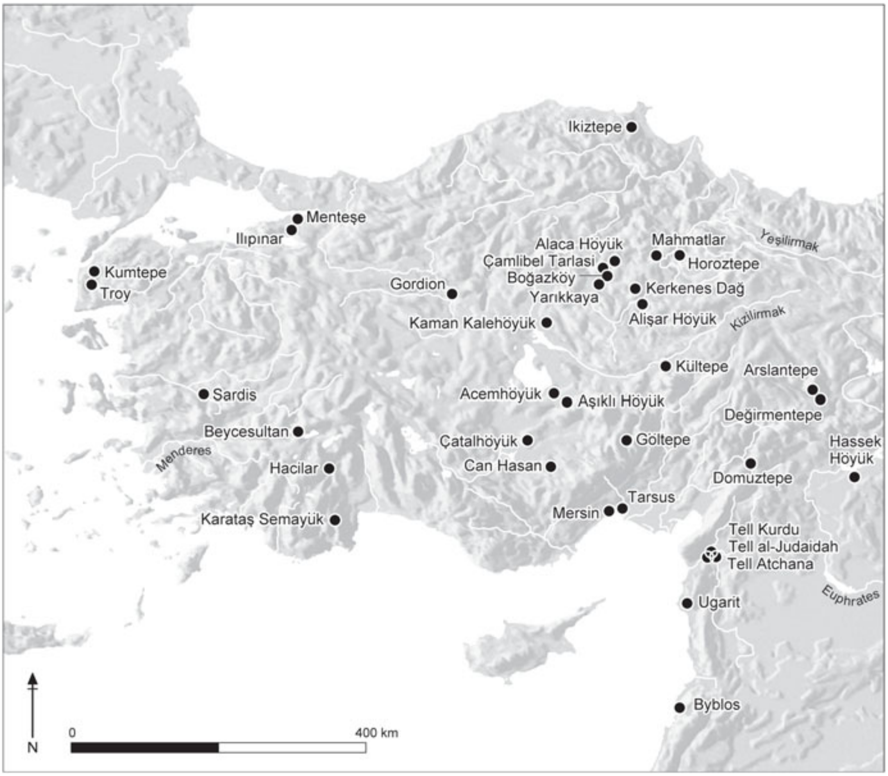


Fig. 20.2 Map of **w**estern and **c**entral Anatolia with sites mentioned in this text

distribution created special stresses that influenced how they were extracted, refined, smelted, and transported (Craddock 1995). In other words, geographic and social parameters of mining regions had significant influence on technological organization and socioeconomic process (Knapp 1998). Distance from the raw materials to fuel and food supplies, as well as seasonal weather conditions, were key factors in how they were utilized. The dynamic and costly ventures of mining and smelting activities often had considerable impact on the environment, leading to deforestation, alterations of drainage routes, and other problems (Monna et al. 2004). Transportation is often limited to navigable rivers and wide intermontane valleys, and even then it was largely a seasonal enterprise. As the Kültepe-Kanesh texts tell us, movement of goods across central Anatolia was often abruptly postponed due to poor weather, and this likely had significant effects on trade relations and the exchange rates of metal types (Dercksen 1996).

The clustered distribution and diverse mineralogical characteristics of these metal resources no doubt influenced their availability over time. Disparities in proximate access to these resources and regional competition for material use created incentives for long-distance cooperation among some individuals and communities, while

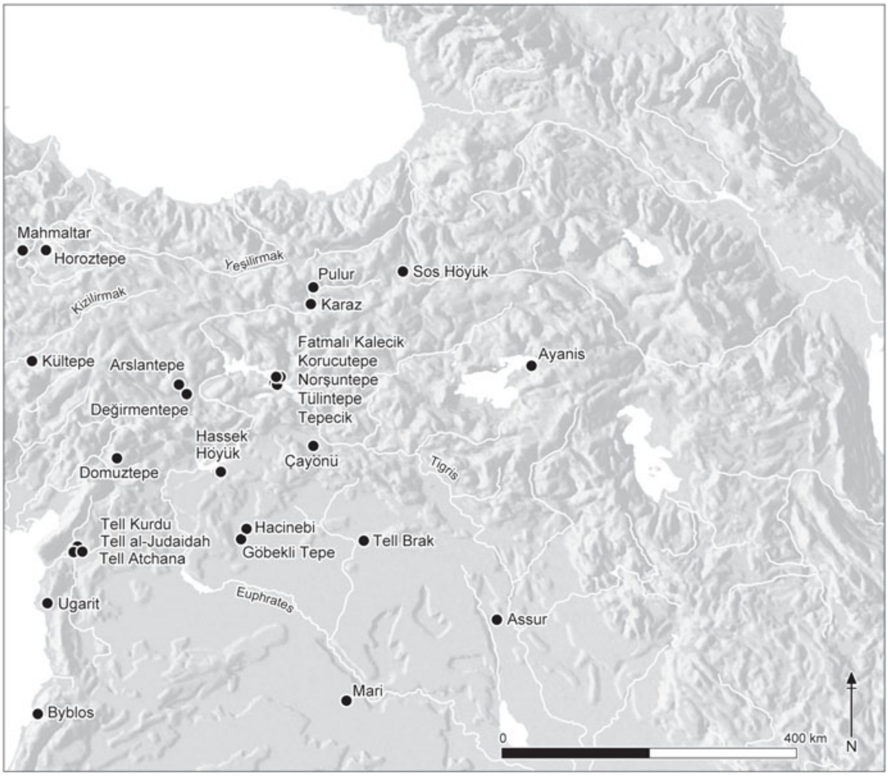


Fig. 20.3 Map of **e**astern Anatolia with sites mentioned in this text

providing leveraging power to others. As will be argued later in this chapter, economic specialization and diversification in mining, and extraction technologies and strategies, were not only the result of an increased demand for metals and finished forms but also the result of innovations in labor organization. Increased sophistication in technological organization ensured a predictable supply of important materials necessary for the regular maintenance of social relations while at the same time generating potential for significant social inequality. Diverse alloys and technologies are well represented in many fourth- and third-millennium BC burial contexts in Anatolia. For example, the well-known collections of decorated copper alloy swords and spearheads from the Early Bronze Age "Royal Tomb" at Arslantepe (Hauptmann et al. 2002; Palmieri and Di Nocera 2000), and the elaborate Alacahöyük, Kalınkaya, and Horoztepe cast tin bronze standards and figurines (Arik 1937; Koşay 1938; Özgüç 1964; Yıldırım and Zimmermann 2006; Zimmermann and Yıldırım 2007), indicate metal resources and technologies were associated with disparities among social groups.

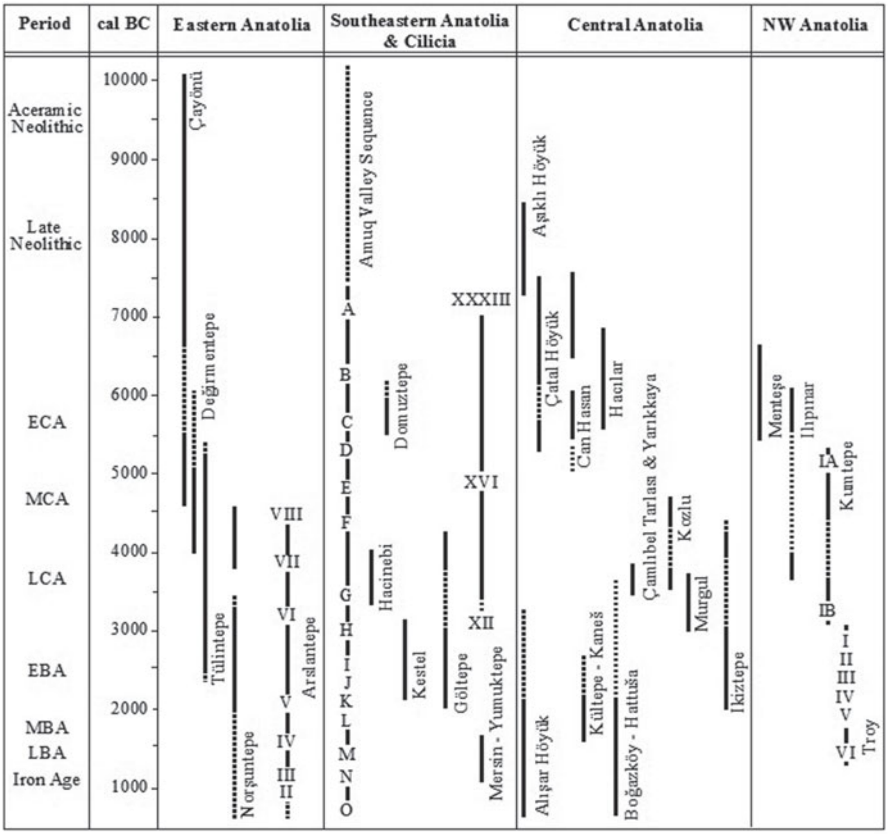


Fig. 20.4 Calibrated radiocarbon dates and relative chronology of important sites mentioned in this text. *Solid lines* are C14 dated sequences. *Dotted lines* are inferred occupations without absolute chronological control

Intellectual Framework

The model of highland Anatolia and lowland Syro-Mesopotamia as a core–periphery relationship in which lowland predominantly urban cultures extract highland raw materials is of course simplistic. While archaeologists continue to refer to Anatolia as a highland region, it should be stressed that the dichotomy between highland and lowland regions is somewhat problematic because, as Yener (2000) and Thornton (2009, p. 305) point out, the Near Eastern highland regions are internally highly variable. They constitute a series of interlocked highland intermontane and lowland valleys and plateaus. Nevertheless, Anatolia is a distinct region that warrants discussion of both broad diachronic changes in the organization metal technologies and localized traditions of metallurgical practice.

The framework for this discussion is divided into two parts. First, we will discuss how perceptions of the role of ancient Anatolia in the Near East are changing with respect to complex technologies. As a corollary to this and in agreement with Thornton (2009), we will then offer an alternative view which suggests that Anatolia and other resource-rich regions in the Near East were regions of indigenous technological and social innovation. This is apparent because organized mining and metal production exist before apparent large-scale Mesopotamian involvement in Anatolia. Second, we discuss how metal production is coordinated over long distances to mitigate disparities in access to rare materials and technologies. Changes in the organization of metal technology coordinate with socioeconomic shifts in the way metal resources are acquired and distributed, which results in the emergence of a multi-tier hierarchy of mining and metal production.

Anatolia as a Region of Innovation

An increasingly sophisticated understanding of cultural and historical process in Anatolia is changing our conceptualization of this region as a focus of analysis (Düring 2011; Mathews 2011; Sagona and Zimansky 2009). Past researchers tend to view archaeological problems in terms of the regions that surround Anatolia, including Greece and Mesopotamia. It is usually assumed that novel social, political, and technological forms originated elsewhere, outside the frontier highlands of the Anatolian peninsula.

In a review of the intellectual history and rhetorical devices used to describe the Anatolian peninsula, Yazıcıoğlu (2007) examines the origins and pitfalls of the conception of Anatolia as a "land bridge," most notably as a conduit of knowledge rather than a landscape of innovation unto itself. Yazıcıoğlu argues against the conceptualization of Anatolia as a land bridge because this metaphorical simplification "hampers a thorough understanding of the material culture of Anatolia and skews our perspective, especially in analyzing trade and exchange relations or processes of diffusion and/or migration" (Yazıcıoğlu 2007, p. 219). In effect, she argues that this perspective generates an emphasis on the movement of people, things, and ideas through the region, while downplaying the significance of several millennia of regional traditions and cultural practices. As Yener (1995, p. 119) has pointed out, "Anatolia is often presented as a cultural frontier in which it is seen as passive receiver of innovations that emanated from more sophisticated centers." The common metaphor is of Anatolia embodying a land bridge from Mesopotamia to Europe—from the East to the West.

The suggestion that highland regions promote diversity is not a novel concept. Aldenderfer (1998), Ehlers and Kreutzmann (2000), and Körner (2003) all argue that various challenges inherent in highland environments promote behavioral specialization. Human communities adapted to these local environments to facilitate predictable access to their unique resources, including pastureland, food sources, and raw materials used in the manufacture of tools and ornaments. Highland regions, rather than impeding transportation, guided trade and exchange routes by way of valleys and mountain passes. Central to the question of Anatolia as a region of innovation are the resources of its diverse natural environments and the close proximity of its ecotones that were the necessary preconditions for the emergence of metallurgy and its rapid success in the region.

Regional environments and resource distributions in the Anatolian highlands influenced diverse institutions of production and specialization that otherwise would not be feasible in the lowland plains of Mesopotamia. Highland mining communities are one subset of these specialized institutions. These communities seemed to emerge with the greater demand for resources used in the creation of utilitarian and wealth objects, during the mid-fourth millennium BC.

Technological Organization as Social Organization

The procedural stages to metal technology need not be repeated here; see Craddock (1995), Miller (2007a, pp. 144–166), and Rehren and Pernicka (2008) for detailed descriptions of production and manufacturing techniques. Key steps in these procedures allow for a wide variety of variations in smelting techniques, alloy recipes, and final forms and shapes. For the purposes of this chapter, we argue that production and manufacturing strategies have clear spatial components that are necessary to grasp in the understanding of technological organization (e.g., Stöllner 2003). In this sense, technologies are theorized to track and focus on these various elements of the production chain (Earle 2010), from the acquisition of raw materials and smelting to the melting, casting, and manufacturing of finished products.

To define how we approach the technological organization of metal production, it is important to embrace a holistic perspective of craft production in the context of mutual technological developments across regions and assemblages (Shimada 2007). In this aspect, we try to view metal working regions and specialized production activities in terms of their technological, socioeconomic, spatial, and ideological dimensions (Hanks and Doonan 2009; Knapp 1998; Levy 1993; Linduff 2004; Linduff and Mei 2009; Topping and Lynott 2005). Sites across the highlands of Anatolia demonstrate unique adaptations to highland environments; thus, it is essential to view specialized technological process "in concert with the social coordination of labor" (Pfaffenberger 1992, p. 497). Labor specialization, either part time or full time, occurred as a series of cooperative social arrangements among an economically diversified demographic. Following Costin (1991, p. 43), we define specialization as "differential participation in specific economic activities," where metallurgical activities necessitated at least part-time dedication to production.

The precise location and context of change are intrinsic components to long-term changes in the organization of activities (Miller 2007b). Depending on the social and spatial infrastructure in which ancient communities interacted, whether in urban or interregional contexts, many crafts were located in specific areas to regulate relations among associated technologies, materials, and socioeconomic outcomes. The emergent pattern is that technological organization often maps onto social organization (Nelson 1991).

The degree to which metal technological organization in Anatolia was controlled during different periods of time is debatable. The evidence is inconclusive whether lowland centers cooperated in reciprocal networks of exchange with highland production zones or whether they effectively controlled these regions by politically integrating them. While it is clear that some finished forms were signifiers of status, including alloy vessels, swords, and spearheads, there is very little evidence for the systematic control of their production and distribution without evidence from texts. Elite control of trade does seem to be exercised to some degree during the Middle Bronze Age 2000–1750 BC, as is evident from numerous Akkadian texts known from Anatolia (Dercksen 1996, pp. 162–178). The emerging picture from these texts is that Mesopotamian and Anatolian merchants were actively vying for control of trade in a competition of merchant coalitions and palatial bureaucracies.

Artifacts of Wealth and Prestige—Metal During the Anatolian Neolithic

The use of native metals and metalliferous minerals (e.g., malachite $Cu_2CO_3(OH)_2$, hematite Fe_2O_3, and galena PbS), during the Anatolian Neolithic demonstrates a high degree of technological sophistication and familiarity before the development of formal smelting techniques (Schoop 1995, 1999; Pernicka 1990). In addition, access to raw materials during formative periods of emergent complexity helped generate temporally resilient acquisition networks important to many later complex technologies. As early as the eleventh millennium BC, metalliferous minerals were used as raw materials for pigments and ornaments, such as a perforated pendant possibly made of malachite from Shanidar in Iraq and green stone beads from Rosh Horesha in Israel (Bar-Yosef Mayer and Porat 2008; Solecki 1969; Solecki et al. 2004). Evidence for the regional occurrence of cold-worked native copper begins during the ninth to seventh millennium BC in the form of ornaments (Schoop 1995).

Substantial evidence for the working of native copper comes from the Neolithic site of Çayönü in southeastern Turkey (Özdoğan and Özdoğan 1999). Dating from the ninth to seventh millennium BC, successive occupational strata at Çayönü provide key evidence for the emergence of complex societies that partake in agricultural economies and specialized technologies in the Near East (Özdoğan 1999). Located in a highland setting, near to the Tigris river valley and approximately 20 km from Ergani Maden, one of the largest copper sources in Turkey, materials from all occupation layers demonstrate the use of native copper metal and minerals. Parallel traditions in working lithic and metal minerals include the production of perforated stone beads and cold-hammered and annealed metal beads rolled into small tubes (Maddin et al. 1999). Similar use of metal minerals and annealed and hammered native copper beads has been noted in central Anatolia at the sites of Aşıklı Höyük (Esin 1995, 1999; Yalçın and Pernicka 1999) and Çatalhöyük (Mellaart 1964; Birch et al. 2013). Two native silver tube beads from Domuztepe in modern Kahramanmaraş date to the mid-sixth millennium BC and show evidence of annealing and hammering (Carter et al. 2003; Yener et al. in prep.).

The production and consumption patterns related to these materials indicate that they were used to demarcate social boundaries and were also likely indicators of social status. These scarce materials were naturally circumscribed by rugged highland terrain and their technological alteration into ornaments required sufficient specialized knowledge. Later metallurgical traditions correspond to two important patterns that emerge during the Neolithic. First, the establishment of metal materials and technologies as a source of wealth developed alongside the emergence of increasingly complex social institutions. This is best evinced by the presence of scarce materials associated with early monumental architecture at many important Neolithic sites along the Taurus such as Çayönü, Nevalı Çori, and Hallan Çemi (Lichter 2007). Second, the emergence of long-distance trade patterns created path-dependent economies that influenced the way materials were exchanged and distributed. Economic interaction patterns between highland source areas and adjacent lowland agricultural villages established a successful way of accessing and distributing these materials that would have dramatic network effects.

Site-centered Production: Centralization, Nucleation, and Balkanization

Significant socioeconomic reorganization during the Early and Middle Chalcolithic (ca. 6000–4000 BC) created a mosaic of complex cultural regions across Anatolia (Düring 2011; Schoop 2005). Regionalized political affiliations and exchange networks focused largely on local materials, although certain materials (e.g., obsidian) are known to have been transported over very long distances (e.g., Carter et al. 2008; Healey 2007). Important developments in extractive metallurgy occur during this crucial time period in lowland regions that are proximate to highland resource areas such as in the Altınova, in Cilicia, and in the Amuq Valley. As Yener et al. note (1996), these regions are set apart from other sites in northern Mesopotamia by virtue of their direct access to scarce materials, while at the same time sharing similar highly productive agricultural conditions. Interregional patterns of competition and cooperation, and the management of access to lowland centers, are identified by the possible innovation of city walls or enclosures at sites like Hacılar, Kuruçay, Mersin, and Değirmentepe. In addition, the repertoire of metal objects drastically increases during this time period. Ornaments and jewelry were produced with tools and weapons by the Late Chalcolithic period, which provides sound evidence for the diversification of the technology as it was variably adopted in different parts of Anatolia.

Dating to the beginning of the fifth millennium BC, a series of metal axes, chisels, and other tools from Mersin (XVI–XIV) in Cilicia (Garstang 1953) demonstrate the development of casting technologies and the possible smelting of ores into metal (Caneva 2000; Esin 1969; Yalçın 2000b). Unlike objects made from native copper, which is relatively pure, the metal objects from Mersin show significant amounts of antimony (0.032–0.748 wt%), arsenic ($<$ 0.006–0.604 wt%), and tin ($<$ 0.005–0.010 wt%) (Yalçın 2000b, p. 114). The presence of these elements indicates that the metals were derived from the smelting of polymetallic ores, several sources of which have been documented to the north in the central Taurus Mountains (Yener et al. 1991). Problematically, no production debris (e.g., slags, crucibles, and furnace

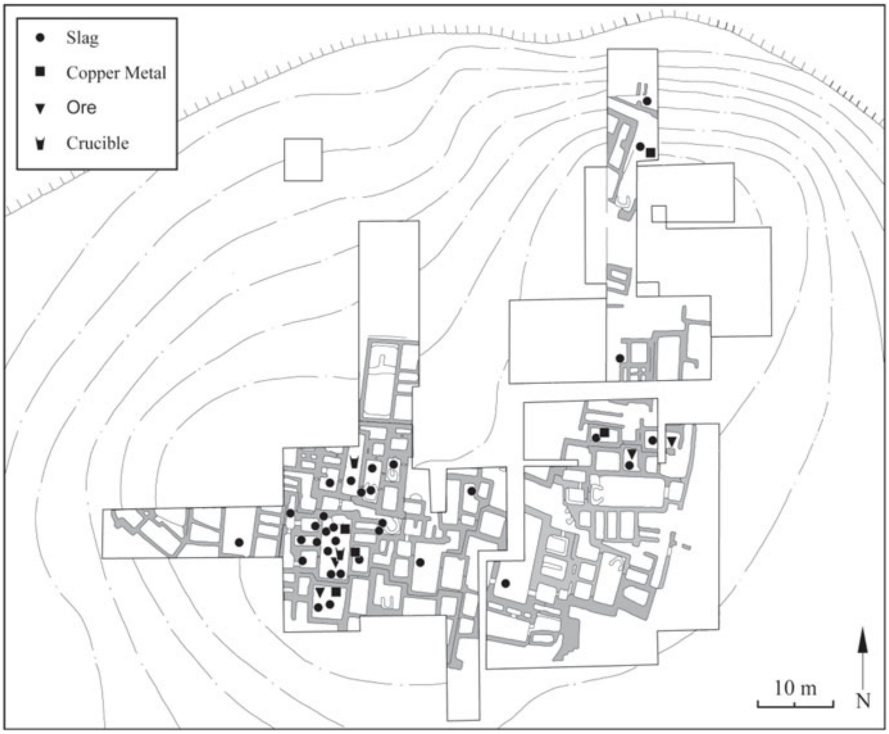


Fig. 20.5 Değirmentepe with metallurgical remains. (Adapted from Müller-Karpe 1994, Fig. 4)

installations) has been discovered at Mersin dating to this early period, so the actual characteristics of extractive metallurgy can only be inferred from these finished products.

Some of the first evidence for the organization of extractive metallurgy comes from the site of Değirmentepe and dates to the end of the fifth and beginning of the fourth millennium BC (Esin and Harmankaya 1988; Yener 2000, pp. 33–44). Değirmentepe is a multi-period village along the Upper Euphrates with a significant Middle and Late Chalcolithic occupation sharing cultural affinities with Ubaid Mesopotamia. Several houses were excavated to reveal that many of the households were involved with many metallurgical activities from ore processing, smelting, and possibly melting and casting (Fig. 20.5). Importantly, many of the households also had evidence of administrative activities, including seals, sealings, tokens, and bullae of local and foreign styles (Esin 1990), and their production (Arsebük 1986).

Several different polymetallic ore sources are known in the region and their use has a long history that starts during this period. Metallurgical debris from the site indicates that the organization of production relied heavily on nearby ore sources. However, it is not clear whether or not mining sites that date to this period took part in smelting activities. The presence of several furnaces and some raw ore materials indicates that primary production was a village activity and that ores could have been transported directly from the source areas and consumed at the village. Parallels for these activities are noted at the nearby sites of Norşuntepe (Hauptmann 1982) and Tepecik (Esin 1982). The analyses of slag debris and slaggy encrustations on crucibles, however, suggest that much of the production may have been the further refinement of copper-rich slags and copper metal in a secondary or final production stage to produce arsenical copper alloys (Kunç and Çukur 1988; Özbal 1985). It is entirely possible that ores and slags were smelted elsewhere and then brought into the village for further working and refinement. Metallurgical production debris is evenly distributed across the site, which suggests that the organization of production may be characterized as an independent household or nucleated workshop-level production.

The Late Chalcolithic site of Arslantepe, near to modern Malatya along the Upper Euphrates, provides an excellent contrast to the organization of metal production at Değirmentepe. Arslantepe was the center of a large network of Late Chalcolithic villages during the so-called Uruk period of Mesopotamia. This period is particularly known for the intrusive activities of Mesopotamian communities into regions outside their political and cultural core in southern Iraq. Algaze (2005), Stein (1999), Rothman (2001), and Frangipane (2001a) have argued for different forms of interaction among communities in Anatolia and Mesopotamia during this period. It is clear that Mesopotamian communities, at this time, sourced metal materials and finished products from the Taurus and Zagros, although the nature of those interactions, as based on symmetrical or asymmetrical relations, is hotly debated. Excavations at Arslantepe indicate a certain degree of interaction with Uruk Mesopotamia, but there was also a local elite presence independent of Uruk control. A large monumental structure in the Late Chalcolithic (period VIA) contained several rooms for storage which together suggest that the building was the seat of a local power or a redistributive center (Frangipane 1997).

Frangipane (2001b) notes two opposing forms of power at Arslantepe in this period—a local kingdom and a later intrusive power related to Transcaucasian migrations into southeastern Anatolia and Syro-Palestine—both of which correspond to developments in Mesopotamia. Metallurgical traditions and the economic networks inferred from the analyses of the raw materials, production debris, and finished goods differ significantly between these two periods. Palmieri et al. (1999) notes a significant relationship among successive periods (VII ca. 3700–3400 BC, VIA ca. 3400–3000 BC, and VIB 3000–2900 BC) and the types of alloys and ores. During the Late Chalcolithic (period VIA), communities used polymetallic ores with varying quantities of arsenic, antimony, silver, bismuth, and nickel. Ore selection changes to the predominant use of copper–iron sulfides during the Early Bronze Age (period VIB), which indicates possible shifts in trade networks and metallurgical traditions. Finished artifacts also reflect these variations with a predominance of copper–arsenic alloys but also alloys of copper–silver and copper–arsenic–nickel (Hauptmann et al. 2002).

A hoard of 21 metal alloy weapons dating to the VIA period contain almost predominantly copper–arsenic alloys, ranging from 2.57 to 6.08 wt% arsenic. Intriguingly, lead isotope analysis (LIA) of the objects suggests they originate from several likely sources in the northeastern Pontides near to the Black Sea (Hauptmann et al. 2002, pp. 61–62). In contrast, metals from a large tomb dating to the VIB period, contemporary with large-scale changes in material culture related to the Kura–Araxes culture of Transcaucasia, demonstrate a change in alloy preference and provenance. In addition to copper–arsenic alloys, several nonutilitarian objects made of a silver–copper alloy and objects made of a copper–arsenic–nickel alloy reflect gross changes in ore consumption and alloy preferences. LIA of the copper–arsenic alloys from Period VIB suggest a similar provenience to those from the earlier period VIA, but the copper–arsenic–nickel alloys may reflect a more local source or one potentially to the north-east in Transcaucasia or the central Taurus. The copper–silver alloys have a unique isotopic signature that does not allow their identification with any known ore source, but does match with other artifacts from central Anatolia (Hauptmann et al. 2002; Sayre et al. 2001).

Slag analyses from the site suggest a wide-ranging technological variety of extractive metallurgy. Perhaps most significantly, a class of slags, containing prills of an arsenic–nickel–iron speiss (Palmieri et al. 2000, p. 145), indicate that alloying strategies may have involved the production and trade of this special co-smelting product used to produce early copper–arsenic alloys (Thornton et al. 2009). It may also have been a by-product of smelting copper–nickel–arsenic ores. However, the use of speiss as an ingredient in the production of arsenic alloys, as suggested by Thornton et al. (2009) and Rehren et al. (2012), may help explain the emergence of high-arsenic copper alloys. At the sites of Habuba Kabira and Fatmalı-Kalecik, both dating to the Late Chalcolithic, the presence of lead-rich litharge provides the earliest evidence for the reduction of argentiferous lead ores into refined silver metal through cupellation (Hess et al. 1998; Pernicka et al. 1998).

Recent excavations at Çamlıbel Tarlası have explored in detail the activities of a small Chalcolithic village in central Anatolia that thrived ca. 3590–3470 cal. BC (Schoop 2008, 2009, 2010). Four occupational phases (CBT I–IV) of rectangular architecture with stone foundations and rammed earth revealed a range of activities, including different stages of stone tool and metal production. All phases show the presence of metallurgical slags, ores, pounding stones, crucible fragments, a diagnostic ring-idol mold, and finished metal objects. Analyses of the slags by Rehren and Radivojević (2010) demonstrated that the primary reduction of sulfide and oxide ores into pure copper metal was an activity on site. This explains the presence of pounding stones, which were used in the benefaction of ore materials for their preparation in a smelt. Fieldwork within the vicinity of the site discovered a large outcropping of sulfide and oxide ore minerals (Marsh 2010) that seem to correlate with the slag analyses. Near to Çamlıbel Tarlası, the Late Chalcolithic site of Yarıkkaya demonstrates a similar household-level production of metal (Hauptmann 1969; Schoop 2005). Production debris, including several crucibles with a thin layer of encrusted metalliferous residues (Fig. 20.6), indicates that producer communities in north-central Anatolia lived in small household aggregates composed of part-time specialists.

Analyses of a few finished artifacts from Çamlıbel Tarlası by Rehren and Radivojević (2010, p. 215) demonstrate that the metals used are arsenical copper alloys.

Fig. 20.6 Crucible from Yarıkkaya, north-central Anatolia. (See Schoop 2005, Plate 30.1)

As the current analyses of slags from the site do not show any presence of arsenic in the copper nor iron–arsenic–nickel speiss, it is not clear whence the arsenic derived. Recent surveys by Özbal and his colleagues (Özbal et al. 2008) discovered a range of arsenical minerals to the north of Çamlıbel along the Pontide belt. These resources may have been used in the production of the arsenical copper found at Çamlıbel, although direct evidence for this has yet to be demonstrated.

The emergence of complex metallurgy, as highlighted above, is clearly a reflection of the availability of necessary resources, appropriate technologies, and the ability to free up labor for specialized production. The regionalism and localization of political entities that occur with urbanism, as highlighted with the administrative technologies and monumental architecture of Arslantepe, allowed for constrained networks of production. It is not clear how groups acquired the necessary raw materials for the various technologies examined above. During these periods along the Upper Euphrates, it is clear that many stages of metal production occurred perhaps simultaneously and in the same location. The sites in this region can be characterized as having in-site production with nucleated production areas. Similar patterns are recognized for other regions in regard to finished materials with the caveat that local alloying traditions likely remained a conservative tradition often unique to the area in which it was produced (Yakar 1984, 1985; Yener 2000). Ores were purposely chosen for their properties and alloys were produced from a range of complex and divergent traditions that likely reflected the local socioeconomic and political networks of production. The presence of arsenical copper alloys across Anatolia, for example, at Ilıpınar in northwestern Anatolia (Begemann et al. 1994) and Ikiztepe near to the Black Sea (Bilgi 1984, 1990; Özbal et al. 2008; Özbal et al. 2002a, b), means that while divergent patterns of metal production were localized, some metallurgical techniques, perhaps utilizing speiss, were shared across very long distances.

Specialized Mining Communities and the Development of Tin Bronze

During the Early Bronze Age (ca. 3000–2000 BC), several regional polities across central Anatolia and regions south of the Taurus began to participate in long-distance trade for materials like lapis lazuli and tin that extended as far east as modern Afghanistan (Delmas and Casanova 1990; Muhly 1973a, b). Two major innovations in copper metallurgy during this time period altered the way metal technology was organized. First is the advent of an intentional copper–tin alloy (i.e., tin bronze). The alloying of tin and copper hardens the metal, alters casting properties, and changes its color to yellowy–gold if the correct amount of tin is incorporated (Scott 2011, pp. 109–173). The earliest tin bronzes in Anatolia occur in the northeastern bend of the Mediterranean Sea near to the Taurus, specifically in Cilicia and the Amuq during the Late Chalcolithic ca. 3000 BC (Yener 2009).

This pivotal area, linking the coastal Mediterranean with the cultures of Syro-Anatolia, has immediate relevance to the early production of tin metal from Tauride sources such as Kestel, Bolkardağ, and Hisarcık. The site of Tell Judaidah in the northeastern passes of the Amuq valley in southern Turkey yielded an assemblage of tin bronze artifacts that were found to contain up to 9.74 wt% tin content from Phase G levels (Braidwood et al. 1951). The highest quantity of tin measured was from a crucible fragment encrusted with a green slag from Phase G. Bronze droplets entrapped in the crucible slag yielded multiple phases of Cu–Sn metal rich in tin (35–75 wt% Sn, 15–60 wt% Cu), with the noted presence of 1.49 wt% Ni and 1.80 wt% As (Adriaens et al. 2002: 275). The heterogeneity of the crucible slag led the authors of the study to conclude that this crucible was not used for the re-melting of scrap tin bronzes, but that it was used to prepare a copper–tin alloy from raw materials. From the same context at Judaidah came ten tin bronze pins, chisels, and awl fragments, which had been previously tested, and new analyses again confirmed that they contained appreciable tin content. Copper alloy figurines from Tell Judaidah, which were excavated from sounding TT20 in a well documented context just above floor XIV-3 and dated to Phase G, were analyzed by Friedman et al. (1999) who confirmed that the figurines contained up to 10 wt% tin. Lead isotope analysis of the silver helmet of one of these figurines, as well as other materials from the Amuq, linked the materials to the central Taurus ore sources (Yener et al. 1991).

Further evidence of an early technological breakthrough in bronze alloys comes from Gaziantep in southeastern Turkey, during the Early Bronze (EB) II period (Duru 2006, p. 206). Level III radiocarbon dates range 3090–2500 cal. BC. The analyses of 96 copper-based objects (mostly pins) from burials at the site of Gedikli were determined to be tin bronzes, with an average tin content of 6.33 wt% (Bengliyan 1985). Tell Qara Quzaq, situated in the north Syrian Euphrates region, yielded tin bronzes dating to ca. 2900–2750 BC, contemporary to Phase G in the Amuq. Two chisels and 14 pins had tin contents from 1.47 to 19.07 wt%, the latter of which is an exceptionally high level of tin which indicates the actual alloying of tin and copper metal and not mixed ore smelting (Montero Fenollós 1996). Other sites in northern Syria also show a preponderance of copper–tin alloys dating to the same period (Montero Fenollós 1995, 1997, 2000). Throughout the third millennium BC, during the florescence of Kestel mine operations, Tell Tayinat (Snow 2005) and Tell Judaidah in the Amuq valley, Tarsus in Cilicia southern Turkey (Kuruçayırlı and Özbal 2005), northern Syrian sites, as well as central Anatolian settlements (see summaries in Kuruçayırlı 2007) continued to use tin in the production of bronzes. Further east, early tin bronze spear-points from Tülintepe near to modern Elaziğ date to the Arslantepe VIA-B period (Yalçın and Yalçın 2009).

The second major innovation in the Early Bronze Age is the development of second-tier processing sites in mining regions. Increased urbanization and a diversified means of acquiring important subsistence resources, through pastoralism and improved agricultural practices, helped create a social environment in which economically specialized settlements emerged to mediate access to metal resources. The development of second-tier processing sites occurred as economic alliances grew larger and more complex, effectively networking multiple regions together to hedge against the uncertainty of access. This uncertainty was derived from several variables, including seasonality, finite availability, and sudden shifts in political and economic networks.

Yener and her colleagues began a survey of the Bolkardağ mining district in the early 1980s to examine the economic and technological components of one of the earliest known mining regions (Yener 1986; Yener and Özbal 1986; Yener et al. 1989). Several small sites along the valley suggested that much of the activity in this region was the seasonal extraction of ores. Excavations at the Early Bronze Age mining village of Göltepe and the Kestel mining complex demonstrated that these communities were actively involved in the intensive and sophisticated extraction of polymetallic ores and the reduction of these ores into raw metal.

The site of Göltepe was a mining village situated on top of a large natural hill facing the Kestel mine complex. The hill measures close to 60 hectares and is fortified at the summit with a circuit wall. Excavations from 1990 to 1993 uncovered a total of 1,500 m^2 of the settlement dating to the Late Chalcolithic through to the EB III phase (from ca. 4375–3750 BC to 2880–2175 BC). Habitation structures in period 3 (EBII) are semi-subterranean to fully subterranean and would have had superstructures of wattle and daub (Fig. 20.7). One house in particular had a full range of metallurgical production paraphernalia including crushers, mortars, a crucible, and kilos of ground ore and ore nodules. The house contained large EBA burnished orange-ware jars full

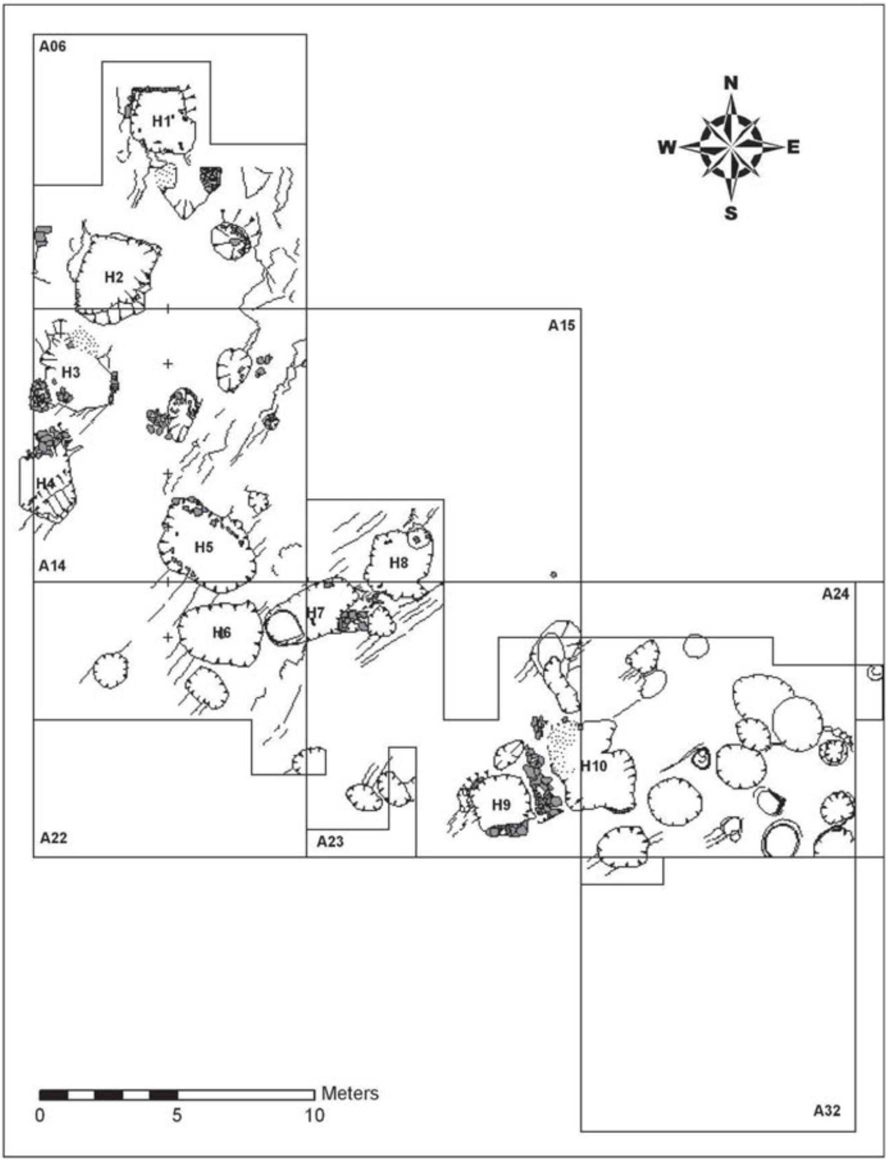


Fig. 20.7 Göltepe site plan, Area A

of ground and refined ore and processed waste materials containing 0.28–3.65 wt% tin, 6.90–41.00 wt% iron, plus minor amounts of arsenic (Adriaens et al. 1999a, b; Vandiver et al. 1992). The relatively high concentration of tin in the prepared ore is evidence that one of the primary activities of the metalsmiths at Göltepe was the preparation of tin metal. The single most significant find at Göltepe relating to the processing of tin has been discovery of over one ton of vitrified earthenware bowl furnaces or crucibles with a glassy slag accretion rich in tin. Constructed with a coarse straw- and grit-tempered ware, they range in rim size from 6 to 50 cm in diameter and have vitrified surfaces containing between 30 and 90 wt% tin content (Adriaens et al. 1996, 1997, 1999a, b). Activities involved the intentional production of tin metal by reduction firing of tin oxide in crucibles in a labor-intensive, multistep process carried out between 800° and 950°C (Yener and Vandiver 1993a, Özbal 2009; Earl and Özbal 1996). Lead isotope analysis of one of the Göltepe crucibles provided complimentary evidence that tin ores from the central Taurus were being processed (Lehner et al. 2009). Metal artifacts from the site, including copper–tin, copper–tin–arsenic, and copper–tin–silver alloys, range from 4.75 to 12.3 wt% tin and some have traces of gold (1.23–52.1 ppm), which are comparable with the Kestel ore analyses (Yener et al. 2003).

Prior to the identification of Anatolian tin, scholars hypothesized that tin was necessarily traded in from Central Asia, Egypt, or Europe for consumption in the Near East (see Muhly 1985; 1993; Stöllner 2011; Yener 1993a, b). Rather than explaining the early presence of copper–tin alloys as a product of long-distance exchange, these new alloys were being produced locally by innovations in technological organization that focused on the primary extraction of tin ores (Yener 2009), but also through regional trade networks that linked these regions to other areas of production. Polymetallic ore deposits near modern Hisarcık in central Anatolia (Sarp and Cerny 2005; Yalçın and Özbal 2009; Yazgan 2005), and in the Astaneh-Sarband area in Iran (Nezafati 2006), also show pronounced concentrations of tin that may have been utilized for the production of early tin alloys (Nezafati et al. 2008, 2009).

The early adoption of copper–tin alloys in central Anatolia is also documented at the Early Bronze Age cemetery of Resuloğlu where copper–tin and copper–tin–silver alloys are attested (Yıldırım and Zimmermann 2006; Zimmermann and Yıldırım 2007). Curiously, the Early Bronze Age settlements and mining activities in the Bolkardağ, and elsewhere in the Pontides (Lutz 1990; Lutz et al. 1994), witness a decline in use during the very end of the Early Bronze Age or beginning of the Middle Bronze Age (ca. 2000 BC). During this period, Old Assyrian texts found at Kültepe testify to the presence of a highly organized and sophisticated metals trade that possibly linked tin resources from central Asia (see Boroffka et al. 2002; Parzinger 2002) to central Anatolia by way of Babylonia and Assyria (Dercksen 1996, 2005; Larsen 1976). Interestingly, lead isotope analyses of a silver bracelet from Grave 20 at Assur point to the continuation of Taurus silver sources (Yener et al. 1991), despite the preference for eastern tin supplies as confirmed by the information in the Assyrian tablets.

Conclusion

As a retrospective on Anatolian metallurgical research over the last 10 years, we have argued for two major points in line with *The Domestication of Metals*. First, we argued that Anatolian metal industries and their organization must be seen in light of local developments and patterns. Past views of the organization of production, such as those imported from the southern Levant (see Thornton 2009), do not fit the data in Anatolia. Rather, we see the development of what has been called the "balkanized technological horizon" during the mid-late Chalcolithic (Yener 2000). These developments occurred *before* formal interaction began with Mesopotamian communities south of the Taurus. The effect of these regionalized traditions is the production of many different types of metal products by many, likely yet unidentified, means of production. Not until the Early Bronze Age do we witness the effects of larger-scale interaction networks on technological traditions.

Second, we argue for the development of specialized settlement hierarchies based on a cooperative model that sees production specialization as a way to mitigate uncertainty of access to crucial raw materials and finished goods. The beginnings of this can be seen at the site of Göltepe in the central Taurus, although indications of long-distance exchange have been demonstrated to exist earlier despite a more constrained, site-centered mode of production. These sites demonstrate how the intensive production of locally available materials creates incentives for long-distance exchange of other scarce materials necessary for the production of socially desirable materials, such as copper–arsenic or copper–tin alloys.

The rise of metal industries in the Near East and Anatolia provides an ideal case study into how human societies organize and develop exchange relations over long distances and difficult terrains. The use of metals and their production in these regions demonstrate clearly how these societies constructed economies in relation to changes in urban and political structure. Most importantly, we can see how technological organization is effectively related to social organization, both spatially and structurally.

Acknowledgments We would like to sincerely thank the editors of this volume for their unending patience and flexibility. Many thanks also go to Ulf-Dietrich Schoop for the many conversations and comments about this work, especially on the central Anatolian Chalcolithic. We would also like to thank Elizabeth Carter, Jeanne Arnold, and David Scott for comments on this draft and for innumerable discussions on the prehistory of the Near East, craft specialization, and of metal technologies. Thanks are also due to Scott Branting, John Marston, Andreas Schachner, and Fikri Kulakoğlu for countless discussions over Anatolian metallurgy and cultural history. Finally, the authors would like to thank Brett Kaufmann, Stephanie Salwen, Hannah Lau, Lyssa Stapleton, and Néhémie Strupler for their comments and various edits.

References

Adriaens, A., Yener K. A., & Adams. F. (1996). Surface analysis of Early Bronze Age ceramic crucibles from Göltepe, Turkey. In H. J. Mathieu, B. Reihl, & D. Briggs (Eds.), *The Proceedings of the 6th European Conference on Applications of Surface and Interface Analysis* (pp. 123–126). Chichester: Wiley.

Adriaens, A., Yener K. A., Adams F., & Levi-Setti R. (1997). SIMS Analyses of ancient ceramic crucibles and slags from Turkey. In A. Benninghoven, B. Hagenhoff, & H. W. Werner (Eds.), *Tenth International Conference on Secondary Ion Mass Spectrometry SIMS X*, (pp. 877–880). Chichester: Wiley.

Adriaens, A., Yener, K. A. & Adams, F. (1999a). An analytical study using electron and ion microscopy of thin-walled crucibles from Göltepe, Turkey. *Journal of Archaeological Science*, *26*(8), 1069–1073.

Adriaens, A., Veny, P., Adams, F., Sporken, R., Louette, P., Earl, B., Özbal, H., & Yener, K. A. (1999b). Analytical investigation of archaeological powders from Göltepe, Turkey. *Archaeometry 41*(1), 81–89.

Adriaens, A., Earl, B., Özbal, H., & Yener, K. A. (2002). Tin bronze metallurgy in transformation: analytical investigation of crucible fragments from Tell al-Judaidah, Amuq (Turkey) Dating to Circa 3000–2900 BC. In E. Jerem & K. T. Biro (Eds.), *Archaeometry 98*. BAR International Series 1043 (pp. 273–277). Oxford: Archaeopress.

Aldenderfer, M. S. (1998). *Montane Foragers: Asana and the south-central Andean Archaic*. Iowa City: University of Iowa Press.

Algaze, G. (2005). *The Uruk World System: The dynamics of expansion of early mesopotamian civilization*. Chicago: The University of Chicago Press.

Algaze, G., (2008). *Ancient Mesopotamia at the dawn of civilization: The evolution of an urban landscape*. Chicago: University of Chicago Press.

Arik, R. O. (1937). *Alaca Höyük Hafriyatı. 1935 deki Çalışmalara ve Keşiflere ait İlk Rapor*. Ankara: Türk Tarih Kurumu.

Arsebük, G. (1986). An assemblage of microlithic engravers from the chalcolithic levels of Değirmentepe (Malatya). *Jahrbuch für Kleinasiatische Forschungen*, *10*, 132–142.

Bachmann, H.-G. (2008). Beginnings of archaeometallurgical research in Turkey: A personal retrospect. In Ü. Yalçın, H. Özbal, & A. G. Paşamehmetoğlu (Eds.), *Ancient mining in Turkey and The Eastern Mediterranean*, (pp. 3–14). Ankara: Atılım University.

Bar-Yosef Mayer, D. E., & Porat, N. (2008). Green stone beads at the dawn of agriculture. *Proceedings of the National Academy of Sciences*, *105*, 8548–8551.

Bayburtoğlu, B., & Yıldırım, S. (2008). Gold and silver in Anatolia. In Ü. Yalçın (Eds.), *Anatolian metal IV* (pp. 43–51). Der Anschnitt 21. Bochum: Deutsches Bergbau-Museum.

Begemann, F., Pernicka, E., & Schmitt-Strecker, V. (1994). Metal finds from Ilıpınar and the advent of arsenical copper. *Anatolica*, *20*, 203–219.

Begemann, F., & Schmitt-Strecker, S. (2008). Bleiisotopie und die Provenienz von Metallen. In Ü. Yalçın (Ed.), *Anatolian Metal IV* (pp. 125–134). Bochum: Deutsches Bergbau-Museum.

Bengliyan, A. (1985). *Trace element analysis of metal artifacts from Gedikli Hoard by Atomic Absorption Spectroscopy. YayımlanmamışŸ Yüksek Lisans Tezi, Chemistry*. Istanbul: Boğaziçi University.

Bilgi, Ö. (1984). Metal objects from Ikiztepe—Turkey. *Beiträge zur Allgemeinen und Vergleichenden Archäologie*, *6*, 31–96.

Bilgi, Ö. (1990). Metal objects from Ikiztepe—Turkey. *Beiträge zur Allgemeinen und Vergleichenden Archäologie*, *9–10*, 119–219.

Birch, T., Rehren, Th., & Pernicka, E. (2013). The metallic finds from Çatalhöyük: A review and preliminary New Work. In I. Hodder (Ed.), *Substantive technologies at Çatalhöyük* (pp. 307–316). Los Angeles: Cotsen Institute of Archaeology Press.

Boroffka, N., Cierny, J., Lutz, J., Parzinger, H., Pernicka, E., & Weisgerber, G. (2002). Bronze age tin in Central Asia: Preliminary notes. In K. Boyle, C. Renfrew, & M. Levine (Eds.), *Ancient interactions: East and West in Eurasia*, (pp. 135–159). Cambridge: McDonald Institute of Archaeological Research.

Boroffka, N., et al. (2002). Bronze age tin in Central Asia. In K. Bole, C. Renfrew, & M. Levine (Eds.), *Ancient interactions: East and West in Eurasia* (pp. 135–159). Cambridge: Cambridge University Press.

Braidwood, R. J., Burke J. E., & Nachtrieb, N. H. (1951). Ancient Syrian coppers and bronzes. *Journal of Chemical Education*, 28, 87–96.

Brumfiel, E. M., & Earle, T. K. (1987). Specialization, exchange and complex societies: An introduction. In E. M. Brumfiel & T. K. Earle (Eds.), *Specialization, exchange and complex societies*, (pp. 1–9). Cambridge: Cambridge University Press.

Çağatay, M. N. (1987). The pancarli nickel-copper sulfide mineralization, Eastern Turkey. *Mineralium Deposita*, *22*(3), 163–171.
Çağatay, A., & Pehlivan, R. (1988). Celaller (Niğde-Çamardı) Kalay Cevherleşmesinin Mineralojisi. *Jeoloji Mühendisleri*, *32–33*, 27–31.
Çağatay, A., Altun, Y., & Arman, B. (1979). Madenbelenitepe (Soğukpınar-Bursa) Kalay Cevherleşmesinin Mineralojisi. *Maden Tetkik ve Arama Dergisi*, *92*, 40–48.
Çağatay, A., Altun, Y., & Arman, B. (1989). Bolkardağ Sulucadere (UlukışŸla-Niğde) Kalay Içerikli Çinko-Kurşun Cevherleşmesinin Mineralojisi. *Jeoloji Mühendisleri*, *32*, 15–20.
Caneva, I. (2000). Early metal production in Cilicia: A view from Mersin-Ymuktepe. In Ü. Yalçın (Ed.), *Anatolian Metal I* (pp. 69–74). *Der Anschnitt 13*. Bochum: Deutches Bergbau-Museum.
Carter, E., Campbell, S., & Gauld, S. (2003). Elusive complexity: New data from the late Halaf Domuztepe in South Central Turkey. *Paléorient*, *29*(2), 117–133.
Carter, T., Dubernet, S., King, R., Le Bourdonnec, F.-X., Milić, M., Poupeau, G., & Shackley, M. L. (2008). Eastern Anatolian Obsidians at Çatalhöyük and the Reconfiguration of Regional Interaction in the Early Ceramic Neolithic. *Antiquity*, *82*, 900–909.
Childe, V. G. (1930). *The Bronze Age*. Cambridge: Cambridge University Press.
Costin, C. L. (1991). Craft specialization: Issues in defining, documenting, and explaining the organization of production. In M. B. Schiffer (Ed.), *Archaeological method & theory* (pp. 1–56, Vol. 3). Tuscon: University of Arizona Press.
Craddock, P. T. (1995). *Early metal mining and production*. Edinburgh: University of Arizona Press.
de Jesus, P. S. (1980). *The development of prehistoric mining and metallurgy in Anatolia. BAR International Series 74*. Oxford: BAR.
Delmas, A. B., & Casanova, M. (1990). The Lapis Lazuli sources in the ancient East. In M. Taddei (Ed.), *South Asian archaeology 1987* (pp. 493–506). Rome: IsMEO.
Dercksen, J. G. (1996). *The old Assyrian copper trade in Anatolia*. Istanbul: Nederlands Historisch-Archaeologisch Instituut te Instanbul.
Dercksen, J. G. (2005). Metals according to documents from Kültepe-Kanish Dating to the old Assyrian Colony. Period. In Ü. Yalçın (Ed.), *Anatolian Metal III (pp. 17–34). Der Anschnitt 18*. Bochum: Deutsches Bergbau-Museum.
Düring, B. S. (2011). *The prehistory of Asia Minor: From complex hunter-gathers to early urban societies*. Cambridge: Cambridge University Press.
Duru, R. (2006). *Gedikli Karahöyük I. The results of excavations directed by Prof. U. Bahadır Alkım in the Years 1964–1967*. Ankara: Türk Tarih Kurumu.
Earl, B., & Özbal, H. (1996). Early Bronze Age tin processing at Kestel/Göltepe, Anatolia. *Archaeometry*, *38*, 289–303.
Earle, T. K. (2010). Exchange Systems in Prehistory. In C. D. Dillian & C. L. White (Eds.), *Trade and Exchange*, (pp. 205–217). New York: Springer.
Ehlers, E., & Kreutzmann H. (2000). High mountain ecology and economy: Potential and constraints. In E. Ehlers & K. Hermann (Eds.), *High mountain pastoralism in northern Pakistan* (pp. 9–36). Stuttgart: Franz Steiner Verlag.
Esin, U. (1969). *Kuantitatif Spektral Analiz Yardımıyla Anadolu'da Baslangıcından Asur Kolonileri Çağına Kadar Bakır ve TunçMadenciliği*, Istanbul: Taş Matbaası.
Esin, U. (1982). Tepecik excavations, 1974. *Keban Project 1974–75 activities*, (pp. 95–127). Ankara: METU Press.
Esin, U. (1990). Değirmentepe (Malatya) Kalkolitik Obeyd Evresi Damga Mühür ve Mühür Baskıları. *Türk Tarih Kongresi*, *10*, 47–56.
Esin, U. (1995). Early copper metallurgy at the pre-pottery site of Aşıklı. In *Readings in prehistory: Studies presented to Halet Cambel* (pp. 61–78). Istanbul: Prehistorya Yayınları.
Esin, U. (1999). Copper objects from the pre-pottery neolithic site of Aşıklı (Kızılkaya Village, Province of Aksaray, Turkey). In A. Hauptman, E. Pernicka, Th. Rehren and Ü. (Eds.), *The Beginnings of Metallurgy* (pp. 23–30). *Der Anschnitt 9*. Bochum: Deutsches Bergbau-Museum.
Esin, U., & Harmankaya, S. (1988). Değirmentepe (Malatya) Kurtarma Kazısı. *Kazı Sonuçları Toplantası*, *9*(1), 79–125.

Frangipane, M. (1997). Arslantepe-Malatya: External factors and local components in the development of an early state. In L. Manzanilla (Ed.), *Emergence and change in early urban societies* (pp. 43–58). New York: Plenum Press.

Frangipane, M. (2001a). Centralization processes in greater mesopotamia: Uruk "Expansion" as the climax of systemic interactions among areas of the greater mesopotamian region. In M. S. Rothman. (Ed.), *Uruk Mesopotamia and Its Neighbors* (pp. 307–348). Sante Fe: School of American Research Press.

Frangipane, M. (2001b). The transition between two opposing forms of power at Arslantepe (Malatya) at the beginning of the 3rd millenium. *TÜBA-AR*, *4*, 1–24.

Friedman, E. S., Yener, K. A., Stampfl, A. P. J., Sato, Y., Alp, E. E., Haeffner, D. R., Wilkinson, T. J., & Johnson, C. E. (1999). Archaeology at the APS: Illuminating the past. *Advanced Photon Source Research*, *2*(1), 12–16.

Garstang, J. (1953). *Prehistoric Mersin: Yümük Tepe in southern Turkey: the Neilson expedition in Cilicia*. Oxford: Clarendon Press.

Hanks, B. k., & Doonan, R. (2009). From scale to practice: A new agenda for the study of early metallurgy on the Eurasian Steppe. *Journal of World Prehistory*, *22*(4), 329–356.

Hauptmann, H. (1969). Die Grabungen in der prähistorischen Siedlung auf Yarıkkaya. In K. Bittel, H. G. Güterbock, H. Hauptmann, H. Kühne, & P. Neve (Eds.), *Boğazköy 4. Funde aus den Grabungen 1967 und 1968* (pp. 66–69). Berlin: Gebr. Mann Verlag.

Hauptmann, H. (1982). Die Grabungen auf dem Norşun Tepe, 1974. *Keban Project 1971 Activities* (pp. 41–70). Ankara: METU Press.

Hauptmann, A. (2007). *The Archaeometallurgy of copper*. Berlin: Springer-Verlag.

Hauptmann, A., Schmitt-Strecker, S., Begemann, F., & Palmieri, A. M. (2002). Chemical composition and lead isotopy of metal objects from the "Royal" tomb and other related finds at Arslantepe, Eastern Anatolia. *Paléorient*, *28*(2), 43–69.

Healey, E. (2007). Obsidian as an indicator of inter-regional contacts and exchange: Three case-studies from the Halaf Period. *Anatolian Studies*, *57*, 171–189.

Helms, M. W. (1993). *Craft and the kingly ideal: Art, trade, and power*. Austin: University of Texas Press.

Hess, K., Hauptman, A., Wright, H., & Whallon, R. J. (1998). Evidence of fourth millennium BC silver production at Fatmalı-Kalecik, East Anatolia. In Th. Rehren, A. Hauptman, & J. D. Muhly (Eds.), *Metallurgica antiqua: In honour of Hans-Gert Bachmann and Robert Maddin* (pp. 57–68). Bochum: Deutsches Bergbau-Museum.

Knapp, A. B. (1998). Social approaches to the archaeology and anthropology of mining. In A. B. Knapp, V. C. Pigott, & E. W. Herbert (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 1–23). London: Routledge.

Körner, C. (2003). *Alpine plant life* (2nd ed.). Berlin: Springer-Verlag.

Koşay, H. Z. (1938). *Alaca Höyük Hafriyatı. 1936 daki Çalışmalara ve KeşŸiflere ait İlk Rapor*. Ankara: Türk Tarih Kurumu.

Kunç, Ş., & Çukur, A. (1988). Bakır Buluntularda iz Element Dağılımı. *Arkeometri Sonuçları Toplantısı*, *3*, 97–105.

Kuruçayırlı, E. (2007). *Tin and tin-bronze in the Bronze Age: Their use, sources and trade from the Balkans to India*. Unpublished MA thesis, Bryn Mawr University.

Kuruçayırlı, E., & Özbal, H. (2005). New metal analysis from Tarsus-Gözlükule. In A. Özyar (Ed.), *Field Seasons 2001–2003 of the Tarsus- Gözlükule Interdisciplinary Research Project* (pp. 177–195). Istanbul: Ege Yayınları.

Larsen, M. T. (1976). *The old Assyrian city-state and its colonies*. Copenhagen: Akademisk Forlag.

Lehner, J. W., Yener, K. A., & Burton, J. H. (2009). Lead isotope analysis and chemical characterization of metallic residues of an early Bronze Age crucible from Göltepe Using ICP-MS. *TÜBA-AR*, *12*, 165–174.

Levy, T. E. (1993). Production, space and social change in protohistoric Palestine. In A. Holl & T. E. Levy (Eds.), *Spatial boundaries and social dynamics: Case studies from food-producing societies* (pp. 63–81). Ann Arbor: International monographs in prehistory.

Lichter, C. (Ed.). (2007). *Vor 12.000 Jahren in Anatolien. Die ältesten Monumente der Menschheit*. Stuttgart: Theiss Verlag.

Linduff, K. M. (2004). *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River*. New Haven: Edwin Mellon Press.

Linduff, K. M., & Mei, J. (2009). Metallurgy in ancient eastern Asia: Retrospect and prospects. *Journal of World Prehistory*, *22*(3), 265–281.

Lutz, J. (1990). *Geochemische und mineralogische Aspekte der frühen Kupferverhüttung in Murgul/Nordost-Türkei*. Unpublished PhD Dissertation, Universität Heidelberg, Heidelberg.

Lutz, J., Pernicka, E., & Wagner, G. A. (1994). Chalkolitische Kupferverhüttung in Murgul, Ostanatolien. In R. B. Wartke (Ed.), *Handwerk und Technologie im Alten Orient* (pp. 59–66). Mainz: Verlagg Philipp von Zabern.

Maddin, R., Muhly, J. D., & Stech, T. (1999). Early metal working at Çayönü. In Th. Rehren & Ü. Yalçın (Eds.), *The beginnings of metallurgy* (pp. 37–44). *Der Anschnitt 9*. Bochum: Deutsches Bergbau-Museum.

Maden Tetkik ve Arama Enstitüsü. (1970). *Arsenic, mercury, antimony and gold deposits of Turkey*. *MTA Yayınlarından No. 129*. Ankara: Maden Tetkik ve Arama Enstitüsü.

Maden Tetkik ve Arama Enstitüsü. (1971). *Iron ore deposits of Turkey*. *MTA Yayınlarından No. 133*. Ankara: Maden Tetkik ve Arama Enstitüsü.

Maden Tetkik ve Arama Enstitüsü. (1972). *Türkiye Bakır, Kurşun ve Çinko Yatakları*. *MTA Yayınlarından No. 133*. Ankara: Maden Tetkik ve Arama Enstitüsü.

Marsh, B. (2010). Geoarchaeology of the human landscape at Boğazköy-á¸ªattuša. *Archäologischer Anzeiger*, *2010*, 201–207.

Matthews, R. (2011). A history of preclassical archaeology in Anatolia. In S. R. Steadman & G. McMahon (Eds.), *The Oxford Handbook of Ancient Anatolia* (*10,000–323 BCBC*) (pp. 34–55). Oxford University Press: Oxford.

Mellaart, J. (1964). Excavations at Çatal Hüyük. Third preliminary report. *Anatolian studies*, *14*, 39–119.

Miller, N. F. (1999). Interpreting ancient environment and patterns of land use: Seeds, charcoal and archaeological context. *TÜBA-AR*, *2*, 15–29.

Miller, H. M.-L. (2007a). *Archaeological approaches to technology*. New York: Academic.

Miller, H. M.-L. (2007b). Associations and ideologies in the locations of urban craft production at Harappa, Pakistan (Indus Civilization). *Archaeological Papers Of The American Anthropological Association*, *17*(1), 37–51.

Monna, F., Galop, D., Carozza, L., Tual, M., Beyrie, A., Marembert, F., Chateau, C., Dominik, J., & Grousset, F. E. (2004). Environmental impact of early Basque mining and smelting recorded in a high ash minerogenic peat deposit. *Science of the Total Environment*, *327*(1–3), 197–214.

Montero Fenollós, J.-L. (1995). Estudio Provisional del Ajuar Metalico del Conjunto Funerario de los Loci 12 E y 12 W. Tell Qara Quzaq (Siria). Campagna 1992. *Aula Orientalis*, *13*, 25–30.

Montero Fenollós, J.-L. (1996). Metallurgia en el Proximo Oriente Antiguo. El Ejemplo de Siria. *Revista de Arqueología*, *178*, 14–23.

Montero Fenollós, J.-L. (1997). L'activité Métallurgique dans la Vallée du Haut-Euphrate Syrien (IIIe-IIe Millénaires av. J.C. *Akkadica*, *103*, 6–28.

Montero Fenollós, J.-L. (2000). La Métallurgie du Bronze dans le Bassin Syromésopotamien au Début du IIIe Millénaire Avant J.-C. In P. Matthiae, A. Enea, L. Peyronel, & F. Pinnock (Eds.), *Proceedings of the first international congress on the Archaeology of the Ancient Near East* (pp. 1093–1104). Rome: Universita degli Studi di Roma.

Muhly, J. D. (1973a). *Copper and tin: The distribution of mineral resources and the nature of the metals trade in the Bronze Age*. Transactions 43. New Haven: The Connecticut Academy of Arts and Sciences.

Muhly, J. D. (1973b). Tin trade routes of the Bronze Age. *American scientist*, *61*(4), 404–413.

Muhly, J. D. (1985). Sources of tin and the beginnings of bronze metallurgy. *American Journal of Archaeology, 89*, 275–291.

Muhly, J. D. (2011). Metals and metallurgy. In S. R. Steadman & G. McMahon (Eds.), *The Oxford handbook of ancient Anatolia* (*10,000–323 BC*), (pp. 858–876). Oxford: Oxford University Press.

Müller-Karpe, A. (1994). *Altanatolisches Metallhandwerk*. Neumünster: Wachholtz Verlag.
Nelson, M. C. (1991). The study of technological organization. In M. B. Schiffer (Ed.), *Archaeological method & theory* (pp. 57–101, Vol. 3). Tuscon: University of Arizona Press.
Nezafati, N. (2006). Au-Sn-W-Cu-mineralization in the Astaneh-Sarband area, west central Iran. Disseration, Geowissenschaftlichen Fakultät, Universität Tübingen, Tübingen.
Nezafati, N., Pernicka, E., & Momenzadeh, M. (2008). Iranian ore deposits and their role in the development of the ancient cultures. In Ü. Yalçın (Ed.), *Anatolian Metal IV* (pp. 77–90). Bochum: Deutsches Bergbau-Museum.
Nezafati, N., Pernicka, E, & Momenzadeh, M. (2009). Introduction of the Deh Hosein ancient tin-copper mine, western Iran: Evidence from geology, archaeology, geochemistry and lead isotope data. *TÜBA-AR*, *12*, 223–236.
Nieling, J. (2009). *Die Einführung der Eisentechnologie in Südkaukasien und Ostanatolien während der Spätbronzeund Früheisenzeit. Black Sea Studies 10*. Aarhus: Aarhus University Press.
Okay, A. I. (2008). Geology of Turkey: A synopsis. In Ü. Yalçın (Ed.), *Anatolian Metal IV* (pp. 19–42). Bochum: Deutsches Bergbau-Museum.
Özbal, H. (1985). Değirmentepe Metal, Cüruf ve Filiz Analizleri. *Arkeometri Ünitesi Bilimsel Toplantası Bildileri VI* (pp. 101–113). Ankara: TÜBITAK.
Özbal, H. (2009). New analytical data from Göltepe crucibles. *TÜBA-AR*, *12*, 155–163.
Özbal, H., Adriaens, A., Earl, B., & Gedik, B. (1999). Samsun, Amasya, Tokat Illeri Yüzey Araştırmaları. *Arkeometri Sonuçları Toplantısı*, *21*, 47–54.
Özbal, H., Pehlivan, H., & Earl, B. (2001). Durağan ve Bakırçay Arsenik Cevherleşmesinin Jeolojik, Mineralojik ve Kimyasal Incelenmesi. *Arkeometri Sonuçları Toplantısı*, *22*, 29–40.
Özbal, H., Adriaens, A., Earl, B., & Gedik, B. (2002a). Minor metallic components associated with Anatolian copper and bronze artifacts: Indications of the utilization of polymetallic ores. In E. Jerem & K. T. Biro (Eds.), *Archaeometry 98. BAR International Series 1043*. Oxford: Archaeopress.
Özbal, H., Pehlivan, N., Earl, B., & Gedik, B. (2002b). Metallurgy at Ikiztepe. In Ü. Yalçın (Ed.), *Anatolian metal II* (pp. 39–48). Bochum: Deutsches Bergbau-Museum.
Özbal, H., Pehlivan, N., Adriaens, M., Uluocak, B. G., & Earl, B. (2008). Metal technologies during the late chalcolithic and early Bronze Age in north central Anatolia: Ikiztepe A case study. In Ü. Yalçın, H. Özbal, & A. G. Paşamehmetoğlu (Eds.), *Ancient mining in Turkey and the eastern mediterranean* (pp. 65–85). Ankara: Atılım University.
Özdoğan, A. (1999). Çayönü. In M. Özdoğan & N. Başgelen (Eds.), *Neolithic in Turkey. The cradle of civilization: New discoveries* (pp. 35–63, 2 Vols.). Istanbul: Arkeoloji ve Sanat Yayinlari.
Özdoğan, M., & Özdoğan, A. (1999). Archaeological evidence on the early metallurgy at Çayönü Tepesi. In A. Hauptman, E. Pernicka, Th. Rehren, & Ü. Yalçın (Eds.), *The beginnings of metallurgy*, *Der Anschnitt 9*. Bochum: Deutsches Bergbau-Museum.
Özgüç, T. (1964). New finds from Horoztepe. *Anatolia*, *8*, 1–25.
Öztürk, H., & Hanilçi, N. (2009). Metallogenic evaluation of Turkey: Implications for tin sources of Bronze Age Anatolia. *TÜBA-AR*, *12*, 105–116.
Palmieri, A. M., & Di Nocera, G. M. (2000). The metal objects from the "Royal" tomb at Arslantepe (Malatya-Turkey) and the metalwork development in the early Bronze Age. In L. Milano, S. de Martino, F. M. Fales, & G. B. Lanfranchi (Eds.), *Landscapes: Territories, frontiers and horizons in the ancient near east* (pp. 179–190). Padova: Sargon.
Palmieri, A. M., Sertok, K., & Chernykh, E. (1993). From Arslantepe metalwork to arsenical copper technology in eastern Anatolia. In M. Frangipane, H. Hauptmann, M. Liverani, P. Matthiae, & M. Mellink (Eds.), *Between the rivers and over the mountains: Archaeologica Anatolica et Mesopoamica Alba Palmieri Dedicata* (pp. 573–599). *Dipartmento di Scienze Storiche Archaeologiche e Antropologiche dell'Antichità*. Rome: Università di Roma La Sapienza.
Palmieri, A. M., Frangipane, M., Hauptmann, A., & Hess, K. (1999). Early metallurgy at Arslantepe during the late chalcolithic and the early Bronze Age IA – IB periods. In A. Hauptmann, E. Pernicka, Th. Rehren & Ü. (Eds.), *The beginnings of metallurgy* (pp. 141–148). *Der Anschnitt 9*. Bochum: Deutsches Bergbau-Museum.

Parzinger, H. (2002). Das Zinn in der Bronzezeit Eurasiens. In Ü. Yalçın (Ed.), *Anatolian Metal II*. Bochum: Deutsches Bergbau-Museum.

Pehlivan, N. A., & Alpan, T. (1986). Niğde Masifi Altın-Kalay Cevherleşve Ağır Mineral Çalışmarları Ön Raporu. Maden Tetkik ve Arama Enstitüsü, unpublished report. Ankara.

Pernicka, E. (1990). Gewinnung und Verbreitung der Metalle in prähistorischer Zeit. *Jahrbuch des Römisch-Germanisches Zentralmuseum*, *37*, 21–129.

Pernicka, E., Seeliger, T. C., Wagner, G., Begemann, F., Schmitt-Strecker, S., Eibner, C., Öztunalı, Ö., & Baranyi, I. (1984). Archäometallurgische Unterschungen in Nordwestanatolien. *Jahrbuch des Römisch-Germanisches Zentralmuseum*, *31*, 533–599.

Pernicka, E., Rehren, Th., & Schmitt-Strecker, S. (1998). Late Uruk silver production by Cupellation at Habuba Kabira, Syria. In Th. Rehren, A. Hauptmann, & J. D. Muhly (Eds.), *Metallurgica Antiqua: In honour of Hans-Gert Bachmann and Robert Maddin* (pp. 123–134). *Der Anschnitt 8*. Bochum: Deutsches Bergbau-Museum.

Pernicka, E., Eibner, C., Öztunalı, Ö., & Wagner, G. A. (2003). Early Bronze Age metallurgy in the north-east Aegean. In G. A. Wagner, E. Pernicka, & H.-P. Uerpmann (Eds.), *Troia and the Troad* (pp. 143–172). Berlin: Springer-Verlag.

Pfaffenberger, B. (1992). Social anthropology of technology. *Annual Review of Anthropology*, *21*, 491–516.

Przeworski, S. (1939). Die Metallindustrie Anatoliens in der Zeit von 1500–700 vor Chr.: Rohstoffe, Technik, Produktion. Leiden: Brill.

Radivojević, M., Rehren, Th., Pernicka, E., Šljivar, D., Brauns, M., & Borić, D. (2010). On the origins of extractive metallurgy: New evidence from Europe. *Journal of Archaeological Science*, *37*(11), 2775–2787.

Ramage, A., & Craddock, P. T. (Eds.). (2000). King Croesus' Gold: Excavations at Sardis and the history of gold refining. London: British Museum Press.

Rehren, Th., & Pernicka, E. (2008). Coins, artefacts and isotopes—Archaeometallurgy and archaeometry. *Archaeometry*, *50*(2), 232–248.

Rehren, Th., & Radivojević, M. (2010). A preliminary report on the slag samples from Çamlıbel Tarlası. *Archäologischer Anzeiger*, *2010*, 207–216.

Rehren, Th., Boscher, L., & Pernicka, E. (2012). Large scale smelting of speiss and arsenical copper at Early Bronze Age Arisman, Iran. *Journal of Archaeological Science, 39*, 1717–1727.

Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity*, *83*, 1012–1022.

Rothman, M. S. (Eds.). (2001). *Uruk Mesopotamia and its neighbors*. Sante Fe: School of American Research Press.

Sagona, A., & Zimansky, P. (2009). *Ancient Turkey*. London: Routledge.

Sarp, H., & Cerny, R. (2005). Yazganite, NaFe3+2 (Mg, Mn)(As04)3.H20, a new mineral: Its description and crystal structure. *European Journal of Mineralogy*, *17*, 367–374.

Sayre, E. V., Joel, E. C., Blackman, M. J., Yener, K. A., & Özbal, H. (2001). Stable lead isotope studies of Black sea Anatolian ore sources and related Bronze Age and Phrygian artefacts from nearby archaeological sites: Appendix—New Taurus Ore Data. *Archaeometry*, *43*(1), 77–115.

Schiffer, M. B. (2005). The devil is in the details: The cascade model of invention processes. *American Antiquity*, *70*(3), 485–502.

Schmidt, K. (2000). Göbekli Tepe, Southeastern Turkey. A Preliminary Report on the 1995–1999 Excavations. *Paléorient*, *26*(1), 45–54.

Schmidt, K. (2006). *Sie bauten die ersten Tempel: das rätselhafte Heiligtum der Steinzeitjäger*. München: Beck.

Schoop, U.-D. (1995). *Die Geburt des Hephaistos: Technologie und Kulturgeschichte neolithischer Metallverwendung im Vorderen Orient. Internationale Archäologie 24*. Espelkamp: Verlag Marie L. Leidorf.

Schoop, U.-D. (1999). Aspects of early,metal use in neolithic mesopotamia. In A. Hauptman, E. Pernicka, Th. Rehren, & Ü. Yalçın (Eds.), *The beginnings of metallurgy* (pp. 31–36). *Der Anschnitt 9*. Bochum: Deutsches Bergbau Museum.

Schoop, U.-D. (2005). *Das anatolische Chalkolithikum. Eine chronologische Untersuchung zur vorbronzezeitlichen Kultursequenz im nördlichen Zentralanatolien und den angrenzenden Gebieten*. Remshalden: Verlag BA Greiner.

Schoop, U.-D. (2008). Ausgrabungen in Çamlıbel Tarlası 2007. In: A. Schachner (Ed.), Die Ausgrabungen in Bogazköy-Hattuša 2007. *Archäologischer Anzeiger*, *2008*(1), 148–157.

Schoop, U.-D. (2009). Ausgrabungen in Çamlıbel Tarlası 2008. In A. Schachner (Ed.), Die Ausgrabungen in Bogazköy-Hattuša 2008. *Archäologischer Anzeiger*, *2009*(1), 56–69.

Schoop, U.-D. (2010). Ausgrabungen in Çamlıbel Tarlası 2009. In A. Schachner (Ed.), Die Ausgrabungen in Bogazköy-Hattuša 2009. *Archäologischer Anzeiger*, *2010*(1), 191–216.

Scott, D. A. (2011). Ancient metals: Microstructure and metallurgy (Vol. 1). Los Angeles: Conservation Science Press.

Seeliger, T. C., Pernicka, E., Wagner, G. A., Begemann, F., Schmitt-Strecker, S., Eibner, C., Öztunalı,Ö., & Baranyi, I. (1985). Archäometallurgische Untersuchungen in Nord- und Ostanatolien. *Jahrbuch des Römisch-Germanisches Zentralmuseum*, *32*, 597–659.

Shimada, I. (Ed.). (2007). Craft production in complex societies: Multicraft and producer perspectives. Salt Lake City: University of Utah Press.

Solecki, R. L. (1969) A Copper mineral pendant from northern Iraq. *Antiquity*, *43*, 311–314.

Solecki, R. S., Solecki, R. L., & Agelarakis, A. P. (2004). *The Proto-neolithic Cemetary in Shanidar Cave*. Texas: Texas A & M University Press.

Snow, H. (2005). *The role of metals in the early Bronze Age economies of North Syria and Anatolia*. Unpublished dissertation, Department of Near and Middle Eastern Civilizations, University of Toronto.

Stein, G. J. (1999). *Rethinking world systems: Diasporas, colonies, and interaction in Uruk Mesopotamia*. Tucson: University of Arizona Press.

Stöllner, T. (2003). Mining and economy—A discussion of spatial organisations and structures of early raw material exploitation. In T. Stöllner, G. Korlin, G. Steffens, & J. Cierny (Eds.), *Man and mining—Studies in honour of Gerd Weisberger on occasion of His 65th birthda*y (pp. 415–446). Bochum: Veröffentlichungen aus dem Deutschen Bergbau-Museum.

Stöllner, T., Samaschev, Z., Berdenov, S., Cierny, J., Doll, M., Garner, J., Gontscharov, A., Gorelik, A., Hauptmann, A., Herd, R., Kusch, G. A., Merz, V., Riese, T., Sikorski, B., & Zickgraf, B. (2011). Tin from Kazakhstan—Steppe tin for the West? In Ü. Yalçın (Ed.), *Anatolian metal V* (pp. 231–252). Bochum: Deutsches Bergbau-Museum.

Thornton, C. P. (2009). The emergence of complex metallurgy on the Iranian plateau: Escaping the Levantine paradigm. *Journal of World Prehistory*, *22*, 301–327.

Thornton, C. P., Rehren, Th., & Pigott, V. C. (2009). The production of Speiss (Iron Arsenide) during the early Bronze Age in Iran. *Journal of Archaeological Science*, *26*(2), 308–316.

Topping, P., & Lynott, M. (Eds.). (2005). *The cultural landscapes of prehistoric mines*. Oxford: Oxbow Books.

Vandiver, P., Yener, K. A., & Leopold, M. (1992). Third millennium B.C. tin processing debris from Göltepe (Anatolia). *Materials Issues in Art and Archaeology III*, *267*, 545–569.

Vidale, M., & Miller, H. M.-L. (2000). On the development of Indus technical virtuosity and its relation to social structure. In M. Taddei & G. de Marco (Eds.), *South Asian archaeology 1997* (pp. 115–132). Naples: Istituto Italian per l'Africa e l'Oriente & Istituto Universitario Orientale.

Wagner, G. A., & Öztunalı, Ö. (2000). Prehistoric copper sources in Turkey. In Ü. Yalçın (Ed.), *Anatolian Metals I* (pp. 31–67). Bochum: Deutsches Bergbau-Museum.

Wagner, G. A., Pernicka, E., Seeliger, T. C., Öztunalı, Ö., Baranyi, I., Begemann, F., & Schmitt-Strecker, S. (1985). Geologische Untersuchungen zur Frühen Metallurgie in NW-Anatolien. *Bulletin of the Mineral Research and Exploration Institute of Turkey*, *101/102*, 45–81.

Wagner, G. A., Begemann, F., Eibner, C., Lutz, J., Öztunalı, Ö., Pernicka, E., & Schmitt-Strecker, S. (1989). Archäometallurgische Untersuchungen an Rohstoffquellen des Frühen Kupfers Ostanatoliens. *Jahrbuch des Römisch-Germanisches Zentralmuseum*, *36*, 637–686.

Wilkinson, T. J. (2003). *Archaeological Landscapes of the Near East*. Tucson: University of Arizona Press.

Willcox, G. H. (1974). A history of deforestation as indicated by charcoal analysis of four sites in eastern Anatolia. *Anatolian Studies*, *24*, 117–133.
Willcox, G. H. (2002). Evidence for ancient forest cover and deforestation from charcoal analysis of ten archaeological sites on the euphrates. In S. Thiébault (Ed.), *Charcoal analysis: Methodological approaches, paleoecological results and wood uses: Proceedings of the Second International Meeting of Anthropology, Paris, September 2000* (pp. 141–145). *BAR International Series 1063*. Oxford: Archaeopress.
Yakar, J. (1984). Regional and local schools of metalwork in early Bronze Age Anatolia: Part I. *Anatolian Studies*, *34*, 59–86.
Yakar, J. (1985). Regional and local schools of metalwork in early Bronze Age Anatolia: Part II. *Anatolian Studies*, *35*, 25–38.
Yalçın, Ü. (Ed.). (2000a). *Anatolian metal I*. Bochum: Deutsches Bergbau-Museum.
Yalçın, Ü. (2000b). Frühchalkolitische Metallfunde von Mersin-Yumuktepe: Beginn der extraktiven Metallurgie? *TÜBA-AR*, *3*, 111–130.
Yalçın, Ü. (Ed.). (2002). *Anatolian metal II*. Bochum: Deutsches Bergbau-Museum.
Yalçın, Ü. (Ed.). (2005). *Anatolian metal III*. Bochum: Deutsches Bergbau-Museum.
Yalçın, Ü. (Ed.). (2008). *Anatolian metal IV*. Bochum: Deutsches Bergbau-Museum.
Yalçın, Ü., & Pernicka, E. (1999). Frühneolithische Metallurgie von Aşıklı Höyük. In A. Hauptman, E. Pernicka, Th. Rehren, & Ü. Yalçın (Eds.), *The beginnings of metallurgy* (pp. 45–54). Der Anschnitt 9. Bochum: Deutsches Bergbau-Museum.
Yalçın, Ü., & Özbal, H. (2009). Ein Neues Zinnvorkommen in Kayseri-Hisarcık, Zentralanatolien: Ein Vorbericht. *TÜBA-AR*, *12*, 117–122.
Yalçın, Ü., & Yalçın, H. G. (2009). Evidence for early use of tin at Tülintepe in Eastern Anatolia. *TÜBA-AR*, *12*, 123–142.
Yalçın, Ü., Özbal, H., & Paşamehmetoğlu, A. G. (Eds.). (2008). *Ancient mining in Turkey and The Eastern Mediterranean*. Ankara: Atılım University.
Yazgan, E. (2005). Cassiterite (tin) mineralization related with Erciyes volcanic activities and the mode of formation of the magnetite-cassiterite-yazganite-tridymite paragenesis. 58th Geological Congress of Turkey, 11–17 April 2005 abstracts, 135–138. Ankara: MTA Kültür sitesi.
Yazıcıoğlu, G. B. (2007). Archaeological politics of Anatolia: Imaginative identity of an imaginative Geography. In L. M. Popova, C. W. Hartley, & A. T. Smith (Eds.), *Social orders and social landscapes* (pp. 218–250). Newcastle: Cambridge Scholars Publishing.
Yener, K. A. (1986). The archaeometry of silver in Anatolia: The Bolkardağ mining district. *American Journal of Archaeology*, *90*(4), 469–472.
Yener, K. A. (1995). The archaeology of empire in Anatolia: Comments. *Bulletin of the American Schools of Oriental Research*, *299/300*, 117–121.
Yener, K. A. (2000). *The domestication of metals: The rise of complex metal industries in Anatolia*. Leiden: Brill.
Yener, K. A. (2009). Strategic industries and tin in the ancient near East: Anatolia updated. *TÜBA-AR*, *12*, 143–154.
Yener, K. A., & Özbal, H. (1986). Bolkardag mining district survey of silver and lead in ancient Anatolia. In J. S. Olin & M. J. Blackman (Eds.), *Proceedings of the 24th International Archaeometry Symposium* (pp. 309–320). Washington: Smithsonian Institution Press.
Yener, K. A., & Vandiver, P. B. (1993a). Tin processing at Göltepe, an Early Bronze Age site in Anatolia. *American Journal of Archaeology*, *97*(2), 207–238.
Yener, K. A., & Vandiver, P. B. (1993b). Reply to J.D. Muhly, "Early Bronze Age Tin and the Taurus". *American Journal of Archaeology, 97*, 207–238.
Yener, K. A., Campbell, S., Belcher, E., Carter, E., Humayun, J. L., Humayun, M., Morey, E., & Lehner, J. W. (in prep.). Earliest known silver metal: Two sixth millennium BC rolled beads from Turkey, Ancient Anatolia. *Archaeometry*.
Yener, K. A., Özbal, H., Kaptan, D., Pehlivan, N., & Goodway, M. (1989). Kestel: An early Bronze Age source of tin ore in the Taurus mountains, Turkey. *Science*, *244*, 200–203.
Yener, K. A., Sayre, E. V., Joel, E. C., Özbal, H., Barnes, I. L., & Brill, R. H. (1991). Stable lead isotope studies of central taurus ore sources and related artifacts from eastern mediterrannean chalcolithic Bronze Age sites. *Journal of Archaeological Science*, *18*, 541–577.

Yener, K. A., Geçkinli, E., & Özbal, H. (1996). A brief survey of Anatolian metallurgy prior to 500 BC. In Ş. Demirci, A. M. Özer, & G. D. Summers (Eds.), *Archaeometry 94: The proceedings of the 29th international symposium on archaeometry*. Ankara: Türkiye Bilimsel ve Teknik Araştırma Kurumu.

Yener, K. A., Özbal, H., Earl, B., & Adriaens, A. (2003). The analyses of metalliferous residues, crucible fragments, experimental smelts, and ores from Kestel Tin mine and the Tin processing site of Göltepe. In P. T. Craddock, & J. Lang (Eds.), *Mining and metal production through the ages* (pp. 181–197). London: The British Museum Press.

Yıldırım, T., & Zimmermann, T. (2006). News from the Hatti Heartland—The early Bronze Age Necropoleis of Kalinkaya, Resuloglu, and Anatolian metalworking advances in the late 3rd Millennium BC. *Antiquity*, *80*(309).

Zimmermann, T., & Yıldırım,T. (2007). Land of plenty?—New archaeometric insights into central Anatolian early Bronze Age metal consumption in funeral contexts. *Antiquity*, *81*(314).

Zwicker, U. (1980). Investigations on the extractive metallurgy of Cu/Sb/As ore and excavated smelting products from Norsun-Tepe (Keban) on the upper Euphrates (3500–2800 B.C.). In W. A. Oddy (Ed.), *Aspects of early metallurgy*. London: British Museum Research Laboratory and The Historical Metallurgy Society.

Chapter 21
Who Dunnit? New Clues Concerning the Development of Chalcolithic Metal Technology in the Southern Levant

Jonathan Golden

Several decades after the discovery of the spectacular Nahal Mishmar Hoard—a collection of cast metal goods, some quite ornate, found in a cave high in the cliffs of the Judean Desert—many important questions about Chalcolithic metallurgy in the southern Levant still remain unanswered. What is the origin of the materials used? Where were the final goods produced? And what were the dynamics of production? In fact, not only do these questions persist, but new ones have also arisen, as recent discoveries are now forcing us to reconsider previous interpretations of Chalcolithic metallurgy and the societies within which it evolved. Such will be the focus of this chapter.

After a brief review of the current state of knowledge and an introduction to the major research problems, we will examine more closely the archaeological evidence for copper production in order to understand both the technical process and the organization of production in the southern Levant, and how these processes changed over time. We will also consider a set of research problems pertaining specifically to the production and use of complex metal castings, a subset of the Chalcolithic metal assemblage comprising a corpus of elegant and elaborate castings made from arsenic and/or antimony-rich copper. The form and function of the artifacts in this corpus are often enigmatic, and as their manufacture involves exotic, imported materials and advanced skills, they are usually treated as symbolic/luxury goods. The number of artifacts in this class has grown steadily over the past few years, yet direct evidence for their production is still not forthcoming and the archaeological contexts where they have been discovered can often be difficult to interpret. Fortunately, recent excavations have brought to light some new clues, offering new insights on this assemblage, and allowing us to tackle questions about where the metal came from, whether the goods were locally cast, who commissioned their manufacture, and what circumstances brought them to their final resting places (Fig. 21.1).

J. Golden (✉)
Departments of Comparative Religion and Anthropology, Drew University,
36 Madison Ave, Madison, NJ 07940, USA
e-mail: jgolden@drew.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective*,
DOI 10.1007/978-1-4614-9017-3_21,

Fig. 21.1 Map of sites mentioned in text. (Courtesy of Y. Rowan)

The Current State of Knowledge: A Brief Overview

Copper first appears in the southern Levant during the period known as the Chalcolithic (4500–3200). It is often taken for granted that copper first appears in the region during the Chalcolithic, though the question of precisely when is sometimes overlooked. It is probably toward the end of the fifth millennium, as the earliest copper finds in the region date to around 4200 BC. There has been some debate as to whether metallurgical technology evolved independently in the southern Levant or whether it was introduced from elsewhere. Copper metallurgy had been known in Iran and Anatolia since the Neolithic (8000–4500 BC), yet there is little evidence for diffusion of the technology to the southern Levant from either of those regions. Both of those areas also had a tradition of working in native copper as well as greenstones (un-smelted copper minerals) that preceded metallurgy. Native copper is not known from the southern Levant, but there is a tradition of working “greenstones” (e.g., malachite), either ground to a powder to make pigment or sculpted to make beads or pendants, going back to the Levantine Neolithic at sites, such as Nahal Hemar (Bar-Yosef and Alon 1988), and continuing into the Chalcolithic at early sites such as Gilat (Golden 2010). Yet, the implications of a "greenstone tradition" for understanding the evolution of metallurgy are not clear. It reflects a familiarity with ores, but not the necessary step of applying pyrotechnology to this material (see Hauptmann 2007, pp. 256–260). We know from evidence for the production of ceramics and lime plaster during the Neolithic that people had already achieved advanced levels of pyrotechnology; but apparently, it would be some centuries before this technology was applied to ore. Irrespective of how copper technology first emerged in the southern Levant, within a few centuries copper production in the region began to thrive, blossoming into an industry on a par with, if not surpassing, those of other contemporary peoples in terms of technology, craftsmanship, and creativity. In time, metal would come to hold a special place in the material culture of the Chalcolithic, not necessarily in terms of quantity and prevalence, but rather, as a rare and an exotic new medium that required considerable effort and resources to produce and obtain.

Chalcolithic metallurgy is typically seen as comprising two distinct industries. The first involves the use of relatively "pure" copper to make a limited range of forms, seemingly more utilitarian in nature, and employing a process that entailed open casting, hammering, and annealing. The second industry involves the production of unique and sometimes highly intricate forms made from a range of metals, often called "natural alloys" because they contain copper with arsenic, antimony, and, to a lesser extent, nickel and other trace metals. The origin of this material—referred to here as "complex metals"—is uncertain, but it seems likely that the admixture of materials occurs naturally in some mineralizations, rather than being the product of deliberate admixing of metals, i.e., alloying (Hauptmann 2007). Yet, there remain important questions about the relationship between these two industries: Was the manufacture of goods from complex metals a "secondary" industry, where more advanced technology evolved out of the more basic industry, or does this represent a new class of goods imported in finished form from outside the region?

Understanding the evolution of the metal industry is complicated by the fact that our knowledge of the time frame within which these developments unfolded, is still inadequate. It now seems clear that at least some Chalcolithic sites predate the local advent of copper metallurgy; while some sites have evidence for both production and finished goods, some had finished goods only, while others have no evidence for metal at all. Village sites such as Shiqmim and Abu Matar provide extensive evidence for the local smelting of copper ores in addition to examples of the finished products (Golden forthcoming; Golden et al. 2001; Shugar 2000). Yet, at sites such as Gilat (Levy 2006) and Grar (Gilead 1995, 1989), less than a day's journey away from Shiqmim and Abu Matar, neither copper goods nor evidence for metal production have been recovered. One of the largest and most impressive Chalcolithic sites, Teilelat Ghassul in Jordan, had just some few copper remains (Bourke 2002; Bourke and Lovell 2004; Hennessy 1982; Mallon et al. 1934). Thus, the straight correlation between "the Chalcolithic Period" and the presence of copper technology must be questioned. It is tempting, to infer that some of these sites were inhabited prior to the local advent of copper. A *mid*-Chalcolithic copper boom might even help explain why Gilat, considered an important cultic center (Levy 2006) declined: Could the lure of a younger town steeped in the production of a brand new material like copper have caused the older center to lose some of its luster? (Golden 2010). This notion of a "pre-metallic" explanation would appear to be supported by certain aspects of the material culture, yet radiocarbon dates and other evidence complicate the picture. For instance, radiocarbon dates from Gilat and Shiqmim overlap, suggesting the copper-less and copper-bearing sites could have been occupied simultaneously, and the absence of any copper artifacts at sites in the Golan, many dating to the latter part of the Chalcolithic, also indicates that a purely chronological explanation for the presence or absence of copper is inadequate. Another explanation for the uneven distribution of copper across the Chalcolithic landscape has been proposed by Levy and Shalev (1989), who outline a scenario in which there were contemporaneous haves and have-nots with regard to metal.

In order to understand the process whereby metal technology spread to the rest of the southern Levant, we must first establish the general time frame within which changes occurred, which in turn requires that we know something about when and by what means metal technology first arrived in the region. Chernykh (1992) has invoked the term "metallurgical provinces" to convey the idea that the evolution of metal technology in each respective region follows its own unique trajectory, despite certain commonalities. It is certainly true that the neighboring provinces of Iran and Anatolia had their own trajectories, characterized by long sequences of continuous development from the "cold/hot working" of "native" copper to full-blown smelting of ores (Thornton 2008; Schoop 1995), while in the southern Levant the first signs of metallurgy already involved the use of crucibles and smelting installations with no preliminary "native copper phase," the closest native copper artifact comes from Tel Ramad in Syria and was likely imported as a finished good from Anatolia.

As noted already, this raises many questions about the origins of metallurgy in the southern Levant; for example, whether it was first brought to the southern Levant as a developed technology and how much internal development took place. Thornton (2008) points out that copper smelting technology had been current in Iran at sites like Tal-I Iblis for some 1,000 years prior to its appearance in the southern Levant. There is also the problem of when the complex metals (e.g., Cu–As–Sb) first appear in the region and whether this is a secondary or subsequent development that evolves from an existing "pure" copper industry. Again, this technology is seen in Iran in advance of the Levant, yet there are no parallels, neither stylistic nor technological, that allow us to connect the two industries (Thornton 2008, p. 19). This is also true of Anatolia, Mesopotamia, and Egypt, all of which had metallurgy prior to or by roughly the same time as the southern Levant; contemporaneity can be established, but drawing connections between metal industries during the time period under discussion, however, is difficult. There is some evidence for trade with Anatolia during the earlier part of the Chalcolithic, for instance, obsidian discovered at Gilat (Levy 2006), but copper does not appear yet at this stage in the southern Levant. There also appears to be limited links between the southern Levant and Egypt during the Chalcolithic (Commenge and Alon 2002). It has been suggested that the people of Maadi in the Nile Delta, and the southern Levant may have exploited the same sources in the Sinai and/or Faynan for the green copper carbonate malachite (Midant-Reyes 2000; Killick 2008). It is noteworthy, however, that Maadi did not have any evidence for copper production, and the occupation of the site generally corresponds to rather late in the Levantine Chalcolithic.

As noted above, copper goods found at sites in the southern Levant have generally been grouped into two broad categories. One includes artifacts in forms that are "utilitarian" in appearance, mainly tools such as axes, adzes, chisels, and awls. These items are usually made from "pure" copper (i.e., copper with no significant levels of other metals), cast in open molds, and subsequently annealed and hammered to create the finished products. The second group includes artifacts manufactured by employing the lost-wax technique for casting complex metals, mainly copper with arsenic and/or antimony (Goren 2008). This group comprises the more elaborate or symbolic objects, such as standards, vessels, and large rings referred to as "crowns". Maceheads are also usually included in this category because of the material used (complex metals) and method of manufacture ("lost-wax" casting) employed; the "functionality" of the maceheads, however, is unclear (e.g., some contain residues suggesting they had at some point been hafted, meaning they were not necessarily just for show, but rather, were used as weapons).[1] This "dual industry" dichotomy was originally suggested by Potaszkin and Bar-Avi (1980) and Key (1980) and later confirmed by Shalev and Northover (1987) and though subsequent research has revealed important exceptions, the pattern of two distinct industries generally still holds true.

The Production of the "Pure" Copper

Just east of the 'Arava' in southern Jordan, lies the Faynan region, where copper-bearing mineralizations with structure and composition similar to ore samples found in the villages of the Negev have been known to researchers for some time (Hauptmann 1989; Hauptmann and Weisgerber 1990; Hauptmann et al. 1996). Investigations in and around the Faynan mines have yielded evidence for limited smelting of copper ore, perhaps representing test smelting (Hauptmann 1989). Understandably, the dating of activities at the mines is more difficult to determine than the more securely provenienced material from the villages. Copper mines have also been identified at Timna, but while there is evidence of copper exploitation from later times to the present (Rothenberg et al. 1978), evidence for Chalcolithic activity at these mines is limited (Khalil 1988, 1992; Rothenberg and Glass 1992). It is possible, that some of this material was used in the Negev villages; according to Hauptmann (2007), ores from Timna probably played an important role in the western trade toward Egypt, with some of the material appearing at the Aqaba Gulf site of Magass (Khalil 1992).

The evidence for copper smelting at Chalcolithic settlement sites in the southern Levant is substantial, especially at northern Negev settlements such as Shiqmim

[1] In previous publications (Golden 1998; Golden et al. 2001), I have used the term "complex metals," to convey the fact that multiple metals were present in widely varying proportions, while avoiding the word 'alloy' which implies an intentional admixture of these metals.

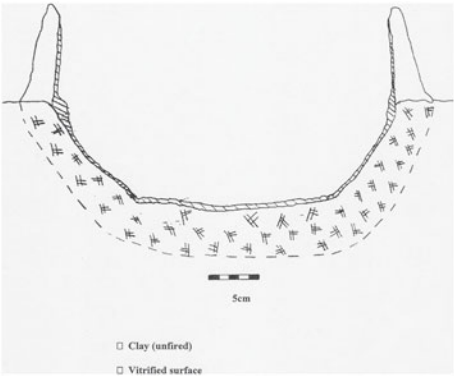


Fig. 21.2 Drawing based on what the section of a complete Chalcolithic furnace would have looked like. (Drawing by J. Golden)

and Abu Matar. Villagers at both sites used a variety of ores, mainly malachite and cuprite in various combinations, which closely match the chemical composition, structure, and texture of the material found at Faynan (Perrot 1955; Shalev and Northover 1987; Golden et al. 2001; Shugar 2000). Based on these similarities, we may infer that the "pure" copper used by these southern Levantine metalworkers derived from ores found at the Faynan mines (Hauptmann 1989; Hauptmann et al. 1992; Golden et al. 2001), and possibly from Timna as well (Hauptmann 2007; Rothenberg and Glass 1992). How the material made its way from the source to the production locales is another question, one which must take into account both cultural geography (Thornton 2008) and the logistics of transportation (Levy 2007).

The village at Abu Matar provides the most extensive and thoroughly documented evidence for Chalcolithic smelting in the southern Levant[2] (Perrot 1955; Golden 1998; Shugar 2000). Typical of this archaeometallurgical assemblage are the shards of ceramic crucibles found at production stations throughout the site. These crucibles are usually oblong in shape, roughly 8–12 cm in diameter, with the smaller end functioning as a simple spout. Less common, are the remnants of proto-furnaces, or smelting installations. These installations are represented by the remnants of thick ceramic rings, or "collars,"roughly 30 cm in diameter, which formed a "chimney" over a small clay-lined pit (see Fig. 21.2). Scatters of ash and charcoal were often found in the vicinity of crucibles and smelting installations. Raw, unused ore is found in small concentrations throughout the site. Excavations have also yielded ore in varying stages of reduction (i.e., partly reduced ore that is not completely smelted), some of this ore is so extensively burned, it is difficult to distinguish from slag. This material—partially reduced ore with a slag-like coating—sometimes contains sizable copper prills. Hammer stones used to break up ore and/or these partial slags are also sometimes found in association with the archaeometallurgical remains. In addition, small fragments of "raw" copper, probably in need of refining prior to use for casting, are also found. In two instances, there are small blocks of metal, akin to tiny "ingots,"

[2] This is especially true if Bir es-Safadi is also part of the same site, the two sites (Abu Matar and Safadi) becoming separated by geological activity.

one with a metallic composition similar to that of the fancy poly-metal castings (this will be discussed again below). The most recent excavations at Abu Matar (Gilead et al. 1993; Shugar 2000) have yielded a great deal of evidence for metal production, duplicating discoveries during Perrot's earlier excavations, while adding important new data (Perrot 1955, 1959, 1968, 1984). This is especially true of excavation of Area A, which produced an in situ furnace that contained charcoal radiocarbon dated to ca. 4200–4000 BC (Shugar 2000). In Area M of Abu Matar, excavations yielded substantial metallurgical remains including one dense concentration consisting of seven hammer stones, ore, crucible fragments, furnace fragments, and over 1 kg of slag, the highest concentration of slag at the site.

Our understanding of the dynamics of Chalcolithic copper production has advanced considerably in recent years. Earlier studies were useful in first establishing that production indeed took place at Chalcolithic settlements and provided but a narrow snapshot of the industry. Samples of artifacts were analyzed employing scientific methods in order to characterize the material itself and the chemical processes employed in their production. More recently, new techniques for recording and examining artifact distribution have been developed, and this, coupled with a concomitant interest in the study of craft specialization, has led to more exhaustive studies of archaeometallurgical assemblages in context. In addition to Abu Matar, the site of Shiqmim has also provided a rich assemblage of archaeometallurgical artifacts, allowing us to reconstruct the copper industry within a village context.

Metal Production as a Specialized Craft at Shiqmim

Archaeometallurgical materials from Shiqmim have recently been reanalyzed, providing a good case study for examining the organization of copper production at the village level and allowing us to address questions about the daily dynamics of copper production at the site. Precise information regarding the find-spot for each archaeometallurgical artifact, going back to the earliest phases of excavation at the site, has been carefully recorded, and the use of geographic information system (GIS) technology has enabled us to analyze the archaeological context for all metallurgical finds according to spatial distribution across the site grid and by stratum (Golden et al., no date). This in turn helps us to paint a more complete picture of the metallurgical craft within the broader setting of local village life, and, when correlated with stratigraphic data, how the various activities related to production and use of metals may have changed over time.

In many cases, the metal-related finds, including fragments of slag, "raw" copper, and, to a lesser extent, ore, were discovered in and around domestic contexts. A number of the houses at Shiqmim incorporated small courtyards, which in some instances may have employed part-time as areas for domestic production activities, such as metalworking, weaving, and flint knapping. Earlier studies on metallurgical evidence from Shiqmim suggest the existence of what Costin (1991) would call a cottage industry or community specialization. The recent study of Shiqmim material, synthesizing the metal-related finds from all seasons of research, indicates that metallurgical production activities, while found throughout most of the site, were generally concentrated in one centralized, nucleated production zone. In fact, a majority of the slag, "raw" copper, crucibles, and smelting installations discovered at Shiqmim derive from one area at the northwest end of the site. One example is the area adjacent to the subterranean structure known as Room 6 (Stratum I), where a concentration of slag, numerous fragments of "raw" copper, and a completed awl were found. Roughly 10 m to the south of Room 6, near Building 25 (Str. II), more fragments of copper and some stray pieces of ore were recovered. Subterranean Room 9 (Sq. K12), just a few meters to the southeast of Room 6, may have also functioned as a copper production station, as suggested by the fill (L. 3313) containing a concentration of slag and fragments of copper associated with the structure. It should be kept in mind, however, that the precise chronological association between contexts such as Room 9 and Room 6 is not certain.

Some 15–20 m away from the Room 6 production station, in the vicinity of Buildings 23–24 (Str. II), appears one of the densest concentrations of archaeometallurgical finds at the entire village of Shiqmim. Here, artifacts such as slag, fragments of copper, and refractory ceramics were found within the fill inside the Building 23–24 complex as well as the courtyard adjacent to the east side of the buildings, all of which indicates the presence of a metallurgical workshop. The fill associated with the buildings and courtyard (Loci 508, 512, 545, 551, 566) contained dense concentrations of black ash. The adjacent Locus 515 had a large, flat chalk block that was propped up, perhaps for use as some sort of ore-crushing device, in addition to a shallow pit with a limestone mortar. Still, questions about the chronological relations of these contexts remain.

Most of the archaeometallurgical remains, the crucibles and smelting installations, were discovered in one quarter of the village, suggesting that metallurgy was practiced by specialized craftspeople who focused their efforts in one area. It is difficult to say more about the specific nature of specialization (e.g., division of labor) within this trade. A precedent for the differentiation of tasks can be seen in evidence from nearby Abu Matar (Golden 2010). If we can presume that smelting and casting were the more complicated processes, might the roasting and crushing of ores have been left to an apprentice? In the case of the complex metal castings, it seems likely there was a breakdown in tasks. The designing of the molds, requiring the skills and talent of an artist, may have been a specialized task (Goren 2008). Modern artisans working with alloys observed by the present author typically design and construct the molds themselves. They also participate in the actual casting process as well, with help from people at the foundry; but the smelting of the ores to make the metal is usually the job of a different workshop altogether. In other words, mold design on the one hand and smelting of ores on the other require rather different skill sets. Molds are quite rare in the archaeological record from the Chalcolithic; Hauptmann (2007) notes a few examples from Wadi Fidan 100, while no examples used in the lost-wax process are known. Goren (2008) has recently advanced a convincing argument that the small fragments of ceramic often found inside of the complex metal castings are just that: the remains of molds used in the lost-wax process that remained trapped inside the finished product. The analysis of this ceramic material provides important

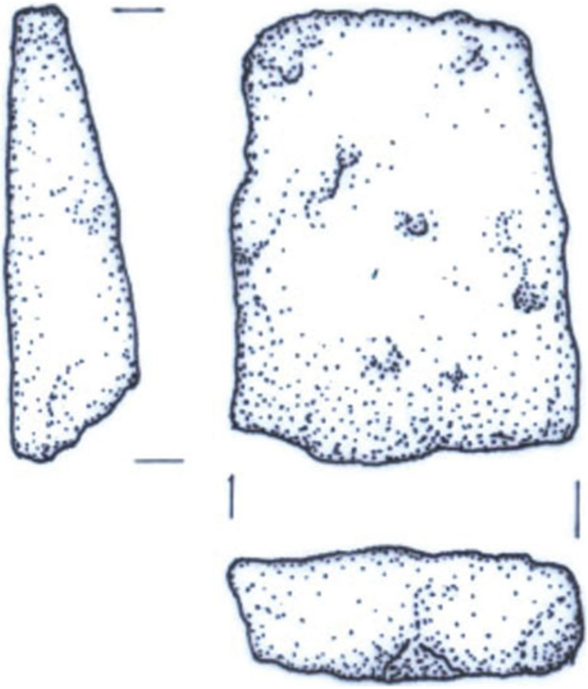


Fig. 21.3 Drawing of metal artifact from copper with arsenic and antimony, discovered at Abu Matar-Safadi. (Drawing by J. Golden)

data about the preparation of the molds, including the likelihood that all of the molds, and thereby the castings, were made in one single workshop, located somewhere in the southern Levant (see further discussion below).

Artisans engaged in casting metal can either work from ready-made ingots or "win" the metal themselves by smelting ores. In the case of the complex metals (involving some combination of Cu–As–Sb–Ni) that are found in the southern Levant, there are no comparable ores present, and thus the import of metal as opposed to ore is the likelier scenario. The possible "ingots" or copper blanks from Shiqmim and Safadi (Abu Matar) noted above (see Fig. 21.3), especially the latter with its polymetallic composition, would seem to indicate that the preparation of ingots to be used in casting was carried out as a distinct step in the production process, separate from the job of casting.

Excavations at a series of smaller, satellite sites surrounding Shiqmim have revealed that several of these sites, especially Mezad Aluf, were also host to metal-working activities (Golden et al. 2001). The evidence for metallurgy at Mezad Aluf, though limited, reflects an industry similar to that seen at Shiqmim. The ores are indistinguishable from the tile ores and brecciated ores found at Shiqmim. Chemical analysis has been conducted on one ore sample from Mezad Aluf, yielding a profile very similar to that ore from found at Shiqmim and Faynan. The virtually identical nature of the ore, slag, crucibles, and furnaces found at Abu Matar, Bir es-Safadi, Shiqmim, and Mezad Aluf demonstrates that a common technology was shared by

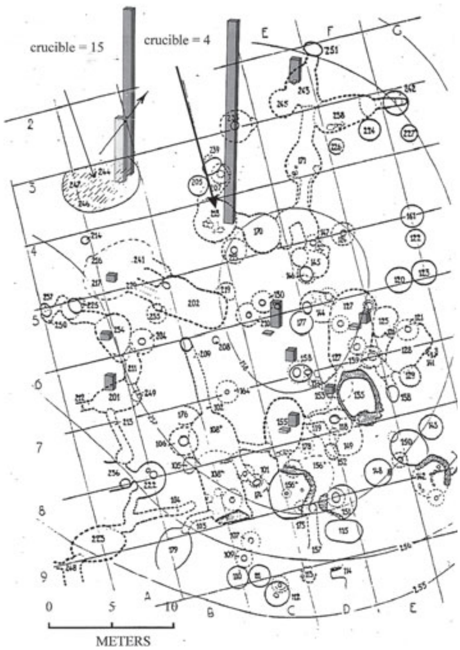


Fig. 21.4 Map of Abu Matar (Perrot excavations) showing the distribution of metal-related finds. (Original map courtesy of CNRS, reproduced by J. Golden)

the metalworkers at all of these sites. The comparable nature and composition of the slag and "raw" copper prills found at each site reflect a similar level of success among the various village workshops. All of this evidence suggests a certain common level of technology with regard to the "pure" copper industry. The converse negative evidence for complex metal usage may provide a clue regarding the production of the ornate "prestige" goods; in other words, were advanced metalsmiths who produced these fancy goods operating in workshops removed from the villages, leaving them all but invisible in the archaeological record?

The archaeometallurgical remains from Shiqmim and Abu Matar related to "pure" copper working display a pattern that may be expected for an "independent" industry. Although the village metalsmiths may have been producing primarily for a limited sector of society (i.e., the wealthy and elite), there is little to indicate that the elite had direct control over production (see Earle 1987; van der Leeuw 1989; Costin 1991). Initially, it was thought that the production of copper goods may have been practiced in the confines of closed courtyards, and while some metalworking does appear to have been carried out within partly enclosed places, new evidence suggests that this was just one part of a bigger picture. For example, the recent identification of a large work zone at the eastern end of Abu Matar village, away from significant architecture, suggests a large open-air workshop (see Fig. 21.4) though it should be kept in mind that many of the finds come from Stratum 1, where the surface is often poorly preserved.

Complex Metals

One of the great mysteries of Chalcolithic culture concerns the production of objects made from copper-based metals with variable levels of arsenic, antimony, and nickel, i.e., complex metals, usually produced through casting. The large majority of artifacts in this group are piriform maceheads with some few examples of other various ornamental goods. Questions persist about the origins of the ores used to produce them, the techniques employed in their manufacture, and the people who produced and where they were produced. Initially, researchers assumed that because no known sources of Cu–As–Sb and Cu–As–Ni exist in Palestine, the origin of the entire industry must reside in areas such as Anatolia or Azerbaijan, where these types of raw material are known to exist today (Bar-Adon 1980; Key 1980; Shugar 2000). Copper with arsenic, for instance, is known from Anatolia, Armenia, the Transcaucasus, and Azerbaijan (the latter over 1,000 km away) (Tadmor et al. 1995; Hauptmann 2007). Recent research also suggests possible sources of copper with arsenic and antimony in Syria (Ostanali, as cited in Shalev 1996, p. 161). There are even some hints of a more direct connection, as lead isotope analyses of a macehead from the Judean Desert show parallels with artifacts from Ugarit and Ras ibn Hanni in Syria (Stos-Gale 1991, as cited in Shalev 1996, p. 161). Evidence for long-distance trade in mineral resources, for example, turquoise from the Sinai (Beit-Arieh 1980) and obsidian from Anatolia (Yellin et al. 1996), also helps to establish contact with people that were exploiting these resources during the Chalcolithic. For now, the precise location of the source of this metal remains a mystery, but as our knowledge of Near Eastern mineral sources continues to grow and as data from lead isotope analysis accrue, we can hope to move closer to a more definitive answer.

Questions concerning the location of the source of this material are but one facet of a broader problem. There is as yet no direct evidence for the manufacture of the complex metal castings at any Chalcolithic settlement, leaving open the question of whether the material came in the form of ore or was imported in metallic form. Another important question concerns whether copper was deliberately alloyed with separate sources of arsenic or antimony, or if copper sources already containing higher levels of arsenic and antimony, i.e., “natural alloys” were utilized. Recently, several new findings have provided some small yet important clues about these questions. Most important, there are now some data that speak to the question of where the complex metal castings were actually manufactured, with new evidence indicating that the casting of complex metals was performed locally using imported materials.

One of the first clues came when a team of researchers examining a copper macehead from Shiqmim (Shalev et al. 1992) decided to look not only at the metal contained in the metallic portion of the object, but also at the stone core around which the metal was cast. Cores of stone or ceramic are often included in objects made by the lost-wax technique, presumably to reduce the amount of metal used. Analysis of the core indicated it was made of a glauconitic chalk originating somewhere in the region, perhaps from the ‘Arava’. This would suggest that while the metal used to make the item was probably imported, the final product was locally made. Similar findings were observed during the study of nonmetallic cores from Nahal Mishmar and Nahal Zeelim as well (Goren 1995). More recently, Goren (2008) has conducted detailed studies on 75 Chalcolithic copper implements from sites throughout the southern Levant, including Abu Matar, Bir es-Safadi, Givat Ha Oranim, Nahal Ashan, Nahal Ze'elim, Peqi'in, Shiqmim, and Nahal Mishmar, most coming from the latter. As noted above, the ceramic material seen inside the metal objects is assumed to be part of a deliberately placed core, and this material is now identified as residual fragments of the ceramic molds originally used to make the metal castings. By characterizing the ceramic material—mixtures of ferruginous clay with coarse quartzitic sand, sometimes with lime plaster or basalt—it is possible to locate the provenance of the ceramic material somewhere between the central hill country of Israel and the eastern part of the lower Jordan Valley (Goren 2008, p. 391). As clays are widely available in the region, it stands to reason that the source of the clays used to make the ceramic molds should reflect the general location of the workshop where the casting of the metal occurred; in other words, the exotic metal had to be imported but not the clay. Based on the petrographic data, Goren (2008, pp. 391, 392) suggests that such a workshop may have been located in the lower Jordan Valley or the Dead Sea basin, and perhaps even at the site of Ein Gedi (related finds from this site are currently under review).

There is additional evidence pointing to the possibility of local casting in the southern Levant, specifically the presence of what appears to be "raw" metal, imported into the region. From the Nahal Qanah cave tomb comes one "amorphous" lump of metal—often overlooked in the shadow of the impressive gold "rings"—with a composition of copper with 5 % Sb, 2 % As, and nearly 1 % Pb (Gopher and Tsuk 1991, 1996). This object could represent an unused piece of metal, either brought in this amorphous form or left somewhere midway through the production process that nonetheless had value as a result of its composition and thus was included in the tomb. There is also the aforementioned block of metal from Bir es-Safadi with a composition of roughly 92 % Cu, 2.5 % Sb, 1.5 % Pb, and 0.8 % As (Golden 2010). Is it possible that these artifacts represent metal imported to the southern Levant in ingot form for future casting? Artifacts of similar size and shape found at Magass in southern Jordan may provide evidence for a precedent (Khalil 1992). In a recent discussion of evidence for the lost-wax casting process in the southern Levant, Goren (2008, p. 375) suggests that arsenic–antimony-rich metals may have been brought to the region in the form of small bars via long-distance exchange.

In addition to this, some of the crucibles recovered during renewed excavations at Abu Matar have revealed traces of up to 1 % arsenic (Shugar, 2000). Whether this material could have been used to produce complex metal castings with the much higher concentrations of arsenic and antimony, observed in the Nahal Mishmar Hoard artifacts and the like, remains unclear. Ore found at Abu Matar may provide additional clues: out of four types of copper ore identified at Abu Matar by Shugar (2000), three were determined to come from the Faynan mining region, while the fourth, based on similarities in lead isotope ratio, geographical proximity, and evidence for regional contact, is believed to originate in Anatolia. Lead isotope analyses suggest this fourth ore type may derive from central and north central Anatolia, perhaps Kaman-Kalehoyuk and mines around the central Black Sea (Shugar 2000, p. 178).

Additional evidence indicating the local processing of complex metals comes from a seemingly unlikely source: human skeletal remains. A study of the assemblage of human remains from Shiqmim included chemical analysis (ICP) of the bones (Oakberg et al. 2000). The study revealed that within one burial context—Structure 101 of Shiqmim Cemetery V—the bones of several individuals buried in the Shiqmim cemetery had arsenic levels significantly higher than those observed in the rest of the site's population. One interpretation is that these remains represent people who were exposed to gaseous arsenic, i.e., the metalsmiths handling arsenical copper were from the area. The fact that they were all buried as a corporate group *could* suggest either a family trade or a small "guild," though the smaller tomb (Structure 101) with less grave goods suggests these were not people of higher status (Oakberg et al. 2000). Taken together, these discoveries all point to the conclusion that the complex metal castings, as exotic as they seem, may well have been manufactured by local metalworkers in the southern Levant, despite the fact that the precise location of their workshops remains unknown.

Of course, many important breakthroughs in the study of Chalcolithic metal industries come not from the chemical analysis of the artifacts, but rather from understanding context and from changes in the way we conceptualize these problems. For instance, our understanding of the archaeological contexts from which metal goods derive is paramount to our understanding of copper's overall meaning. Some of the earliest examples of complex metal castings were discovered in small caches, with groups of items numbering just a few, intentionally deposited in a small pit. Following the discovery of the Nahal Mishmar Hoard in 1960, and in a host of subsequent publications describing it, attention was focused on the fact that it was a large cache, or hoard of goods, stashed away in a remote cave in a desert cliff. Since that time, the number of sites with similar copper goods has grown considerably, and as many of these goods were found buried in caves, this seemingly lent further support to the "hoard hypothesis." Yet, as more complex metal goods associated with cave sites have come to light, we must now consider an alternative explanation. If one looks closely, several of the copper-bearing cave sites also include burials, and mounting evidence supports the interpretation that these groups of metal goods were not private stashes, buried on their own, but rather part of the contents of wealthy tombs. The most outstanding examples of this phenomenon are Nahal Qanah (Gopher and Tsuk 1996), Piqe'in (Gal et al.1996), and Givat Ha'oranim (Scheftelowitz and Oren 1997). In most cases, these were corporate graves involving multiple burials, and oftentimes, secondary burials associated with ossuaries. The metal artifacts, in fact, both the "pure" copper and complex metals, were but one form of valuable included as part of a burial kit that also included ivory, basalt, textiles, and fancy ceramics. In some cases (e.g., Nahal Qanah), the cave tombs were landscaped with stone walls. These tombs typically contained ceramic or stone ossuaries ("bone boxes," the most outstanding example being Piqe'in (Gal et al.1996, 1997)) with several hundred unique ceramic ossuaries. Other caves, such as the Cave of the Warrior (Schick 1998), do not have copper, but conform to the pattern of caves being used as tombs. Whether or not to include the famous Nahal Mishmar Cave in this group is an intriguing question. The kit of burial goods is there, as are several inhumations, but the relationship between the hoard of goods found in the cave and the burials is not entirely clear (Bar -Adon 1980; Goren 2008). As for who would be buried in these tombs, it would appear that certain members of society commanded greater status than others did. Levy (2006; Levy and Shalev 1989) has long argued for the presence of chiefs, suggesting that these were powerful individuals who "relied on a combination of staple and wealth finance to build and maintain their coalitions" (Levy 2007, p. 99). Evidence from corporate tombs such as Peqi'in (Gal et al. 1999) suggests that there may have been groups of elites, perhaps high-status kin groups, but all of this is difficult to know with certainty.

The "dual industry" pattern discussed earlier, still largely holds true, but is worth noting that significant exceptions have also been observed. Two maces from Nahal Mishmar, for example, were made of relatively pure copper (Tadmor et al. 1995), as was a disc-shaped macehead from the Cave of the Sandal site (Segal et al. 2002). This does not conform to the simple pattern of "pure" copper = utilitarian items, complex metal ("alloyed" copper) = nonutilitarian, symbolic objects. In addition, items such as standards and maceheads were manufactured using metals of widely varying composition and not just "arsenical copper" as the material was originally termed (Tadmor et al. 1995, p. 132). Antimony appears quite frequently as a significant component, along with silver and lead; Hautpmann (2007) points to the notable occurrence of a metal combining copper–arsenic–nickel. Finally, it is important to bear in mind that items from the two different artifact groups sometimes occur together. In fact, most of the cave assemblages (e.g., Peqi'in, Nahal Mishmar) have examples of both, while at the settlement of Neve Noy (Bir es-Safadi) "pure" copper and complex metal artifacts were found literally bound together with copper wire (Eldar and Baumgarten 1985a, b).

Moreover, in light of recent discoveries, the term "utilitarian" has itself been called into question: whether these objects were ever intended to actually function as tools is questionable. To begin, the "pure" copper lacks the hardness of the complex metals, which in items such as an axe-head or chisel would seriously limit their effectiveness in tasks such as cutting and chopping. Nor does it appear as if there was any attempt to intentionally harden any of these so-called tools, a fact that also raises doubts about their functionality (Tadmor et al. 1995; Hauptmann 2007). Furthermore, the general shape of some adzes and chisels seems awkward for use as real tools. It is also noteworthy that the flint corollaries for these forms (e.g., axes and chisels) are frequently found to be won or broken, underscoring their functional use, something typically lacking on copper examples. Rather, it is the "prestige" objects that were manufactured with the complex metals, suggesting the material may have been selected largely for its lower melting point and viscosity, which make them better suited for the lost-wax casting process. The pairing of the *cire perdue* ("lost wax") method with the complex metals underscored this fact when we consider the intricate forms produced (Levy and Shalev 1989; Moorey 1988; Shalev 1996; Shalev and Northover 1987, 1993; see Goren 2008 for a useful description of this process). One implication of this is that the copper chisels, axes, and adzes may have also served as prestige items, despite their less elaborate design. Kerner (2001) has suggested that these items may represent lower-level prestige goods, and there is an

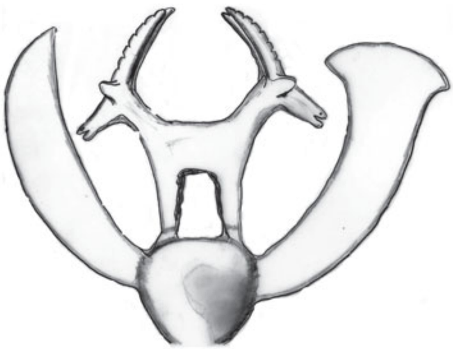


Fig. 21.5 Drawing of metal casting from Nahal Mishmar combining elements that are “utilitarian” (*the axe blades*) and a macehead, along with an animal. (Drawing by J. Golden, adopted from Bar-Adon 1980)

interesting parallel from early southern Africa (Killick, this volume) where it appears that copper, even the more readily available “pure” copper, could have served as a new way of expressing distinction between emerging social classes. In one more twist to the conventional dichotomy, it should be kept in mind that the maceheads, which are made from complex metals, could in fact have been functional weapons, while the “nonutilitarian” goods with more elaborate design sometimes incorporate the more “utilitarian” forms, e.g., note the combination of animal and axe-head motifs (see Fig. 21.5).

New evidence related to the distribution of copper-related finds throughout the southern Levant has also forced us to reconsider another model that has dominated the study of Chalcolithic metallurgy for some time. Levy and Shalev (1989; Levy 2003) suggested that access to metallurgical technology and copper goods, the prestige items in particular, was deliberately manipulated in an effort to maintain a monopoly on this new technology. The evidence for copper production is still limited to the northern Negev area, mainly two sites: Abu Matar-Safadi and Shiqmim. However, the last two decades has brought a series of newly discovered Chalcolithic sites, in particular, the aforementioned burial caves, such as Peqi’in, Givat Ha’Oranim and Nahal Qanah, each of which contain some combination of complex metal castings and “pure” metal goods. In addition to increasing the general corpus of metal products from the region, these finds have also expanded the area where copper is thought to have circulated during the Chalcolithic and finished copper goods may have moved more freely throughout the region. As discussed already, the locus of production for complex metal castings remains at large, but new data are bringing us closer to solving this mystery (Goren 2008; Shugar 2000; Golden 2010).

We must also take into account the temporal dimension, which has come into sharper view, and affords us a new glimpse of the evolution of Chalcolithic metallurgy over time. Within the southern Levant as a whole, a pattern has begun to emerge, where some sites seem to have little or no copper because they date to an early “Pre-Metallic” phase of the Chalcolithic, predating the local advent of copper. It is not yet clear though how sites like Shiqmim, with its long radiocarbon record, fit into this broader scheme. Most of the metal finds, for instance, derive from the final phase of occupation (Stratum IA). This seems consistent with the evidence for a copper "boom" in the northern Negev (e.g., Abu Matar) late in the fourth millennium, when the Shiqmim metal workshops were most active. Ideally, sites with a long sequence of occupation can contribute to the chronological picture.

By the end of the Chalcolithic, the metal industry sees significant changes. The tradition of working with complex metals, such as copper with arsenic and antimony, to produce elaborate castings virtually disappears. By the beginning of the Early Bronze Age, the manufacture of the more elaborate forms has ceased. Evidence for metal production has been identified at sites such as Arad (Ilan and Sebanne 1989) and Nahal Tillah (Golden 2002), but overall it appears as though the great florescence of copper production of the Chalcolithic was on the wane as craftsmanship and creativity declined. It is not clear why this was the case; it has been suggested that there was an interruption in the trade networks that brought the complex metals to the southern Levant (Hauptmann 2007). Indeed, the collapse of the Chalcolithic culture may be directly intertwined with this decline in the metal industry.

Conclusion

Our understanding of Chalcolithic metal production continues to advance today. Recent archaeological discoveries have yielded a great deal of new data related to metal production and use, and there is now a much broader and more varied assemblage of archaeometallurgical remains than there was even a decade ago. In addition, the development of ever more powerful and precise methods of analysis has produced more detailed and reliable data concerning these artifacts; both the newest discoveries and older assemblages continue to be restudied. At Shiqmim, the use of GIS technology has allowed archaeologists to produce detailed artifact distribution maps more rapidly and with greater precision than before (Golden et al., no date). Where the characterization of materials is concerned, archaeologists have increasingly sophisticated techniques in chemical profiling at their disposal. In particular, the application of lead isotope analysis to artifacts and other materials (e.g., ores) promises to help advance our knowledge about the sources of metallurgical materials.

In addition to employing new and improved methods of material analysis, we must persist in generating new ways of posing questions about ancient metallurgy and proposing alternative ways of addressing some of the persistent archaeological problems that remain unresolved. Overall, our task is threefold: consider all new evidence pertaining to metal production and use, recognizing that relevant information can come from a variety of places (e.g., ceramics and bones); extend the application of the most current methods of analysis (e.g., lead isotope analysis and GIS) to the widest possible range of artifacts; and, finally, continue to develop ever more creative ideas for explaining and synthesizing these data while subjecting them to rigorous standards of analysis.

There are a number of important questions that should guide future research. For one, we should continue to pursue the origins of Levantine metallurgy: when precisely did metal first appear in the region and how exactly did the technology make its way there are questions critical to our understanding of the origins and development of Levantine metallurgy. There is a whole set of questions surrounding the complex metal (i.e., copper "alloy") prestige goods, and we must be creative in our approach to studying these problems. How these goods were manufactured and who made them are questions that might be answered in nonconventional ways as petrographic and osteological studies have demonstrated. The source of the copper with arsenic and antimony continues to confound, but lead isotope analysis—of metal and ore—sheds increasing light on the problem. The question of how complex metals made their way into the Levantine production centers—in raw ore form or as ingots—also requires further investigation. Along the way, we should also take time to reconsider some of the basic working assumptions. In his paper for this volume, Thornton (2008) points to the Levantine "straw man" and suggests that explanatory models such as the "dual-industry" model distinguishing "pure" copper "utilitarian" goods and complex metal prestige goods should not be taken for granted without question, and in light of recent data, it would appear that this distinction is not so consistent as previously thought. Thus, we need continued excavation of archaeological sites and investigation of raw material sources in order to answer some of the outstanding problems, while new and improved methods of analysis will allow us to draw ever more information from these discoveries. Equally important is the development of new ideas and ways of thinking about the archaeological problems, and alternative models to be used for explaining the data as well as posing new questions.

References

Bar Adon, P. (1980). *The Cave of the Treasure*. Jerusalem: Israel Exploration Journal.

Bar-Yosef, O., & Alon, D. (1988). Excavations in the Nahal Hemar Cave. *Atiqot, 18,* 1–30.

Beit Arieh, I. (1980). A Chalcolithic site near Serabit el-Khadim. *Tel Aviv, 7,* 45–64.

Bourke, S. J. (2002). The origins of social complexity in the south Jordan Valley: New evidence from Teleilat Ghassul, Jordan. *Palestine Exploration Quarterly, 134,* 2–27.

Bourke, S. J., & Lovell, J. L. (2004). Ghassul, chronology and cultural sequencing. *Paléorient, 30,* 179–182.

Chernykh, E. N. (1992). *Ancient Metallurgy in the USSR: The early metal age* (Trans. S. Wright). Cambridge: Cambridge University Press.

Commenge, C., & Alon, D. (2002). Competitive involution and expanded horizons: Exploring the nature of interaction between northern Negev and Lower Egypt (ca. 4500–3600 B.C.E). In E. van den Brink, & T. E. Levy (Eds.), *Egypt and the Levant: interrelations from the 4th through the early 3rd millennium BCE* (pp. 139–153). London: Continuum.

Costin, C. L. (1991). Craft specialization: Issues in defining, documenting, and exploring the organization of production. In M. E. Schiffer (Ed.), *Archaeological method and theory* (pp. 1–56, Vol. 3). Tucson: University Of Arizona Press.

Earle, T. K. (1987). Specialization and the production of wealth: Hawaiian chiefdoms and the Inca Empire. In E. M. Brumfiel & T. K. Earle (Eds.), *Specialization, exchange, and complex societies* (pp. 64–75). Cambridge: Cambridge University Press.

Eldar, I., & Baumgarten, Y. (1985a). A Chalcolithic site of the Beer Sheva Culture. *Biblical Archaeologist, 48,* 134–139.

Eldar, I., & Baumgarten, Y. (1985b) Neve Noy. In R. Cohen (ed.), Notes and news. *Israel Exploration Journal*, *35,* 74.
Gal, Z., Smithline, H., & Shalem, D. (1996). A Chalcolithic burial cave in Peqi'in. *Qadmoniot, 111,* 19–24.
Gal, Z., Smithline, H., & Shalem, D. (1997). A Chalcolithic burial cave in Peqi'in, Upper Galilee. *Israel Exploration Journal, 47,* 145–154.
Gal, Z., Smithline, H., & Shalem, D. (1999). New iconographic aspects of Chalcolithic art: Preliminary observations on finds from the Peqi'in Cave. *Atiqot, 37,* 1–16.
Gilead, I. (1995). *Grar: A Chalcolithic site in the Northern Negev*. Beer Sheva: Ben Gurion University of the Negev Press.
Gilead, I. (1989) Grar: A Chalcolithic Site in the Northern Negev, Israel, *Journal of Field Archaeology, 16,* 377–394.
Gilead, I., Rosen, S., Fabian, P., & Rothenberg, B. (1993). New archaeo-metallurgical evidence for the beginnings of metallurgy in the southern Levant. Excavations at Tell Abu Matar, Beersheba (Israel) 1990/1. *Institute for Archaeo-Metallurgical Studies Newsletter, 19,* 11–5.
Golden, J. (1998). Dawn of the Metal Age. Doctoral dissertation, Department of Anthropology, University of Pennsylvania.
Golden, J. (2002). The origins of the copper trade in the eastern Mediterranean during the early Bronze Age. In E. van den Brink & T. Levy (Eds.), *Egyptian and Canaanite Interaction During the Fourth-Third Millennium BCE*. London: Leicester University Press.
Golden, J. (2010) *Dawn of the Metal Age*, Equinox, London.
Golden, J., Levy, T. E., Shalev, S., & Hauptmann, A. (No date). The production and use of metal at Shiqmim. In Levy, T. E. & Rowan, Y. (Eds.), *Shiqmim II*, Continuum, London.
Golden, J., Levy, T. E., & Hauptmann, A. (2001). Recent discoveries concerning ancient metallurgy at the Chalcolithic (ca.4000 BC) village of Shiqmim, Israel. *Journal of Archaeological Science, 9,* 951–63.
Gopher, A., & Tsuk, T. (1991). *Ancient gold: Rare finds from the Nahal Qanah cave*. Jerusalem: Israel Museum.
Gopher, A., & Tsuk, T. (1996). *The Nahal Qanah cave: Earliest gold in the Southern Levant*. Monograph Series of the Institute of Archaeology. Tel Aviv: Tel Aviv University.
Goren, Y. (1995). Shrines and ceramics in Chalcolithic Israel: The view through the petrographic microscope. *Archaeometry, 37,* 287–305.
Goren, Y. (2008). The Location of specialized copper production by the lost wax technique in the Chalcolithic southern Levant. *Geoarchaeology, 23,* 374–397.
Hauptmann, A. (1989). The earliest periods of copper metallurgy in Feinan, Jordan. In A. Hauptmann, E. Pernicka, & G. A. Wagner (Eds.), *Old world archaeometallurgy* (pp. 119–136). Bochum: Selbstverlag des Deutsches Bergbau-Museum.
Hauptmann, A. (2007). *Archaeometallurgy of copper: Evidence from Faynan, Jordan*. Berlin: Springer.
Hauptmann, A., & Weisgerber, G. (1990). Periods of ore exploitation and metal production in the area of Feinan, Wadi 'Arabah, Jordan. *Annual of the Department of Antiquities of Jordan, 34,* 61–66.
Hauptmann, A., Begemann, F., Heitkemper, E., Pernicka, E., Schmitt-Strecker, S. (1992). Early Copper produced at Feinan, Wadi Araba, Jordan: The composition of ores and Copper. *Archaeomaterials, 6*, 1–33.
Hauptmann, A., Bachmann, H.-G., & Maddin, R. (1996). Chalcolithic copper smelting: New evidence from excavations at Feinan, Jordan. In G. Summer, S. Demirci, & A. Özer (Eds.), *Archaeometry* (*1994*) (pp. 3–10). Ankara: Tubetak.
Hennessy, J. B. (1982). Teleilat Ghassul: Its place in the archaeology of Jordan. In A. Hadidi (Ed.), *Studies in the history and archaeology of Jordan* (pp. 55–88). Amman: Department of Antiquities.

Ilan, O., & Sebbane, M. (1989). Copper metallurgy, trade and the urbanization of southern Canaan in the Chalcolithic and Early Bronze Age. In P. de Miroschedji (Ed.), *L'Urbanisation de la Palestine a l'Age du Bronz Ancien* (pp. 139–162). Oxford: British Archaeological Reports.

Kerner, S. (2001). *Das Chackolithikum in der Südlichen Levante. Orient-Archäologie Bd. 8*. Westfalen: Leidorf Rahden.

Key, C. (1980). Trace element composition of the copper and copper alloys of the Nahal Mishmar Hoard. In P. Bar-Adon (Ed.), *The Cave of the Treasure* (pp. 238–243). Jerusalem: Israel Exploration Society.

Khalil, L. (1988). Excavations at Magass-Aqaba (1986). *Dirasat, 16,* 71–109.

Khalil, L. (1992). Some technological features from a Chalcolithic site at Maqass-Aqaba. In M. Zaghoul, K. Amr, F. Zayadine, & R. Nabeel (Eds.), *Studies in the history and archaeology of Jordan IV* (pp. 143–148). Amman: Department of Antiquities of Jordan.

Killick, D. (2008). Social contexts of the first uses of metals in Eastern and Southern Africa: Some preliminary notes. Paper presented at the Annual Meetings of the Society for American Archaeology, March 26, 2008.

Levy, T. E. (2003). Cult, metallurgy and rank societies - Chalcolithic period (ca. 4500–3500 BCE). In T. E. Levy (Ed.), *The Archaeology of Society in the Holy Land* (pp. 226–244). London: Leicester University Press.

Levy, T. E. (2006). Conclusion: The evolution of a Levantine prehistoric regional cult center. In T. E. Levy (Ed.), *Archaeology, anthropology and cult: The Sanctuary at Gilat, Israel* (pp. 831–846). London: Equinox.

Levy, T. E. (2007). *Journey to the Copper Age*. San Diego: San Diego Museum of Man.

Levy, T. E., & Shalev, S. (1989). Prehistoric metalworking in the southern Levant: Archaeometallurgical and social perspectives. *World Archaeology, 20,* 352–372.

Mallon, A., Koeppel, R., & Neuville, R. (1934). *Teleilat Ghassul I*, 1929–1932. Rome: Pontifical Biblical Institute.

Midant-Renes, B. (2000). The Naqada Period (c. 4000–3200 BC). In I. Shaw (Ed.), *The Oxford history of ancient Egypt* (pp. 44–60). Oxford: Oxford University Press.

Moorey, P. R. S. (1988). The Chalcolithic hoard from Nahal Mishmar, Israel, in context. *World Archaeology, 20,* 171–189.

Oakberg, K., Levy, T., & Smith, P. (2000). A method for skeletal arsenic analysis, applied to the Chalcolithic copper smelting site of Shiqmim, Israel. *Journal of Archaeological Science, 27,* 895–901.

Perrot, J. (1955). The excavations at Tell Abu Matar, Near Beersheba. *Israel Exploration Journal, 5,* 17–41, 73–84, 167–189.

Perrot, J. (1959). Bir es-Safadi. *Israel Exploration Journal,* 9, 141–142.

Perrot, J. (1968). La prehistoire Palestiniene. *Supplement au Dictionnaire de la Bible*. Letouzey and Ane, Paris, pp. 286–446.

Perrot, P. (1984). Structures d'habitat mode de vie et environnement. Les villages souterrains des pasteurs de Beersheva, dans le sud d'Israel, au IVe millenaire avant L'ere chretienne. *Paléorient, 10*(1), 75–96.

Potazkin, R., & Bar-Avi, K. (1980). A material investigation of metal objects from the Nahal Mishmar Hoard. In P. Bar Adon (Ed.), *The Cave of the Treasure* (pp. 235–237). Jerusalem: Israel Exploration Society.

Rothenberg, B., & Glass, J. (1992). The beginnings and the development of early metallurgy and the settlement and chronology of the western Arabah, from the Chalcolithic Period to Early Bronze Age IV. *Levant, 24,* 141–157.

Rothenberg, B., Tylecote, R. F., & Boydell, P.J. (1978). *Chalcolithic copper smelting, excavations and experiments*. London: Institute for Archaeo-Metallurgical Studies.

Scheftelowitz, B., & Oren, E., (1997). *Givat Ha'oranim (Nahal Barequet). New antiquities: Recent discoveries from archaeological excavations in Israel* (p. 20). Jerusalem: The Israel Museum.

Schick, T. (1998). *The cave of the warrior: A fourth millennium burial in the Judean Desert*. Jerusalem: Israel Antiquities Authority.

Schoop, U. D. (1995). *Die Geburt des Hephaistos. Technolgie und Kulturgeschichte neolithischer Metallvervendung im Vorderen Orient. Intern Archäologie* (Bd. 24). Rahden: Mrie Leidorf.

Segal, I., Kamenski, A., & Merkel, J. (2002). The cave of the Sandal, Ketef Jericho: New evidence from recent Chalcolithic copper finds. *Institute for Archaeo-Metallurgical Studies, 22,* 7–10.

Shalev, S. (1996). Metallurgical and metalographic studies. In A. Gopher (Ed.), *The Nahal Qanah cave: Earliest gold in the Southern Levant* (pp. 155–174). Monograph Series of the Institute of Archaeology. Tel Aviv: Tel Aviv University.

Shalev, S., & Northover, J. P. (1987). The Chalcolithic metal and metalworking from Shiqmim. In T. E. Levy (Ed.), *Shiqmim I* (pp. 357–371). Oxford: British Archaeological Reports.

Shalev, S., & Northover, J. P. (1993). The metallurgy of the Nahal Mishmar Hoard reconsidered. *Archaeometry, 35,* 35–46.

Shalev, S., Goren, Y., Levy, T. E., & Northover, J. P. (1992). A Chalcolithic mace head from the Negev, Israel: Technological aspects and cultural implications. *Archaeometry, 34,* 63–71.

Shugar, A. N. (2000). *Archaeometallurgical investigation of the Chalcolithic site of Abu Matar, Israel: A reassessment of technology and its implications for the Ghassulian culture*. Unpublished doctoral dissertation, University College London.

Stos-Gale, Z. A. (1991). Lead isotope studies—A bar ingot and a mace head from the Negev: Technological aspects and cultural implicaitons. *Archaeometry, 34,* 63–71.

Tadmor, M., Kedem, D., Begemann, F., Hauptmann, A., Pernicka, E., & Schmitt-Strecker, S. (1995). The Nahal Mishmar Hoard from the Judean Desert: Technology, composition, and provenance. *'Atiqot, 27,* 95–148.

Thornton, C. P. (2008) The emergence of complex metallurgy on the Iranian Plateau:escaping the Levantine paradigm. Paper presented at the Annual Meetings of the Society for American Archaeology, March 26, 2008.

van der Leeuw, S. (1989). Risk, perception, and innovation. In S. van der Leeuw & R. Torrence (Eds.), *What's new. A closer look at the process of innovation* (pp. 300–329). London: Unwin Hyman.

Yellin, J., Levy, T. E., & Rowan, Y. (1996). New evidence on prehistoric trade routes: The obsidian evidence from Gilat, Israel. *Journal of Field Archaeology, 23,* 361–368.

Chapter 22
Ancient Metallurgy in the Caucasus From the Sixth to the Third Millennium BCE

Antoine Courcier

Introduction

The region known as the Caucasus includes on its northern side several autonomous republics still within the Russian Federation, and on its southern side, three totally independent countries: Georgia, Armenia and Azerbaijan (including the semi-autonomous region of Nakhchivan). Several natural features characterize the Caucasus from north to south: the plains and plateau of Pre-Caucasia (or Ciscaucasia); the chain of the Greater Caucasus; the Colchedia River depression; the mountains of the Lesser Caucasus; the Kura and Araxes River depressions; and the Armenian knot (Frolova 2006, p. 18). The southern part of the Caucasus is also referred to as "Transcaucasia" based on the Russian literature. The Greater Caucasus region is defined by an axis with a general orientation NW–SE, and is 130 km wide on the Elbrus meridian and 170 km wide on that of Dagestan. The highest summits of the Caucasus are located between the Elbrus and the Kazbek mountains. Despite the mountainous terrain, the Caucasus is characterized by several passes that can be crossed seasonally (Freshfield 1896).

According to a recent global imaging systems (GIS) project (Cassard et al. 2009), the Caucasus is characterized by a diverse and complex metallogeny. The outcrops and deposits are numerous (more than 1,800) and present multiple metalliferous mineralizations in the form of mineralogical associations (e.g. fahlores), native metals (Cu, Au and Ag) and hydro-carbonated/oxide ores (e.g. malachite). These deposits were mineralized principally during the Precambrian, Variscian, Alpine and Eocene–Quaternary cycles. It should be underlined that ophiolitic formations were mineralized in the Caucasus (North and South) from the Middle Paleozoic until the Hauterivien. These particular host-rocks are linked to the evolution and the closing of the Thetys Ocean. Copper-bearing ophiolitic formations,

A. Courcier (✉)
CNRS - UMR 5060, Institut de Recherche sur les ArchéoMATériaux, Belfort, France
e-mail: courcier.antoine@laposte.net

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_22,

known in different areas of the Near East (Oman, western Iran, Turkey and Caucasus), are directly linked to nickel and cobalt mineralizations. In spite of a geology generally unfavourable (basic and ultrabasic rocks) to the mineralization of tin, there are some examples of cassiterite and stannite deposits. Several regions contain such tin-bearing deposits, including North Ossetia, Karachay-Cherkessia, Kabardino-Balkaria, Dagestan, Georgia, Armenia and Azerbaijan (Cassard et al. 2009). Unfortunately, we have no information about the concentration or the amount of tin. Furthermore, no recent field research has been done on these deposits. This explains why the existence of tin deposits in the Caucasus is still a matter of debate among archaeometallurgists.

To explain the development of metallurgy in the Caucasus, this chapter will first give a brief introduction to the history of research into early metallurgy of this region. After this, the rest of the chapter is organized chronologically—from the "Early Metallurgical stage" (from sixth to early fourth millennium BCE) to the "rise" of true metallurgy (from early fourth to third millennium BCE)—and then spatially (from north to south). In each stage, we will detail what is known of the metallurgy of each archaeological culture as well as the importance of metals both intra- and inter-regionally.

History of Research

Soviet Scholars

A. A. Iessen and B. E. Degen-Kovalevskij's 1935 publication was the first systematic research on ancient metallurgy in the Caucasus. In spite of chronological problems, the topic was approached through the combination of archaeological and geological/metallogenical data. Their synthetic work on the ancient extractive and manufacturing metallurgical sites of the northern Caucasus (and to a lesser degree of the southern Caucasus) have not yet been re-examined but nevertheless constitute an important reference for later works (e.g. Kuftin 1944, 1950; Formosov 1965).

Numerous studies appeared during the 1950s and 1960s, mainly concerned with Early Bronze Age metallurgy (ca. third millennium BCE) both in the northern Caucasus (Krupnov 1951, 1960; Iessen 1951) and in Transcaucasia (Dzhaparidze 1955; Abesadze et al. 1958; Khanzadjan 1964, 1967; Iessen 1959, 1965). This period also corresponds to the first use of spectrographic analyses on metal artefacts in the laboratories of Baku and Tbilisi. The results of this research allowed for the characterization of the metallurgical practices of each culture in the Caucasus, and became the basis of theories like that of E. N. Chernykh (1966; see below) and others (e.g. Khanzadjan 1967; Selimkhanov 1960a, b, 1962, 1964, 1966; Selimkhanov and Marechal 1968; Kushnareva and Chubinishvili 1970; Gevorkjan 1974, 1980; Korenevskij 1972, 1974, 1984). These analyses, which were certainly an important scientific contribution at the time, are currently the subject of great debate as to their accuracy. Thus, the theories that are built on their shoulders are worth re-examining.

In the 1960s, Chernykh first put forth his influential theory on the existence of "metallurgical provinces" (Chernykh 1966). This hypothesis was enlarged during the following years (Chernykh 1978a, b, 1988, 1991, 1992, 2005; Chernykh et al. 1991, 2000, 2002) and succeeded in establishing a hierarchical model of metallurgical practice from the Chalcolithic period until the end of the Bronze Age. A "metallurgical province" corresponds to an arborescent system of "provinces", "zones", "focuses/foci" and "nuclei". Each zone contains several "focuses" based essentially on dependant relations: "metallurgical foci" (extractive metallurgy) and "metalworking foci" (manufacturing metallurgy). Such "zones" can correspond to whole regions or just particular metallurgical centres, sometimes even to specific archaeological cultures. However, "foci" often contain several cultures in a defined area. Each focus is characterized by four criteria: (1) typological uniformity of the metal products; (2) similarities of the techniques used, as much in the tools (principally the moulds) as in the types of metalworking (according to metallographic investigations); (3) homogeneity of the alloy compounds (according to spectral analyses); and (4) specific social structure or organization in a metallurgical centre (Chernykh et al. 1991; Chernykh 1992, pp. 7–10).

The technological dynamism and the expansion of a metallurgical province are governed by the "nuclei" which are included in the focus and correspond to metallurgical centres (extractive or manufacture) of production or distribution. The influence of the technological traditions of these metallurgical centres is perceptible over a large area.

For example, according to a widely held theory (e.g. Kushnareva and Chubinishvili 1970, p. 113; Kavtaradze 1999, p. 71), reiterated principally by Chernykh (1966, pp. 48–49, 1992, p. 60), metallurgy appeared first in Transcaucasia owing to favourable metallogenical conditions (hydro-carbonate and oxide copper ores such as malachite, azurite, *etc.*) that were exclusively present in the southern Caucasus. However, this theory is not supported by recent metallogenical data (Cassard et al. 2009; see below). Indeed, numerous copper deposits are also present in the northern Caucasus in their hydro-carbonate and oxide ore state.

Chernykh (1966, 1972, 1978a, b), based on his research in south-eastern Europe, also proposed that only the copper deposits of the Carpatho-Balkan region were characterized by ores without impurities. On the basis of this assumption, he suggested that all objects of "pure copper" found in the Caucasus came from the Carpatho-Balkan region (Chernykh 1991, pp. 585–587, 1992, pp. 39–53). This hypothesis, which is one of the foundations of his metallurgical province theory, has now come into question, given the existence of copper deposits without notable impurities in the Caucasus (Cassard et al. 2009; see below).

Another point of Chernykh's paradigm that needs to be re-evaluated is the "historico-technical" scheme, according to which he considers the type of ore (e.g. nickel cuprous) or the nature of the ore (e.g. hydro-oxidized, sulphate) to be determining factors for ancient metallurgy (Chernykh 1966, pp. 44–49, 1992, p. 11). That is, the earliest metallurgy is supposed to be linked to the exploitation of the altered dissolution zone of a deposit (oxide, carbonated and hydro-carbonated ores). Only in later periods, he argues, were more elaborate processes developed (arbitrarily fixed to the Middle and Late Bronze Age) that allowed early metalworkers to exploit the sulphur ores of the deposit (Chernykh 1966, pp. 45–46 and 49, 1992, p. 5 and 60; Palmieri et al. 1993, pp. 594–598).

This theory of historico-technical determinism was widely adopted by Soviet researchers and still today affects our understanding of ancient metallurgy in the Caucasus (e.g. Pitskhelauri and Chernykh 2003; Korenevskij 2004; Markovin 2004; Rezepkin 2001; Ryndina 2003; Ryndina and Ravich 2000, 2001). In this article, we will underline the limits of Chernykh's paradigm and propose another schema for the development of ancient metallurgy in the Caucasus.

Western Scholars

At the turn of the twentieth century, several discussions on ancient metal productions in the Caucasus were put forth (e.g. Klaproth 1823, 1935; Morgan 1889a, b; Bapst 1885, 1886, 1887, 1898; Baye 1899a, b, c, 1900). These works, however, concern mainly the second and first millennium BCE (from Middle/Late Bronze Age to Iron Age). It was not until the 1950–1960s that studies on earlier metallurgy of the Caucasus were first carried out by Western scholars.

Until recently, the Caucasus was considered a "mysterious periphery" in the archaeological publications on the Near East (Chataigner 1995). Several studies refer to the Caucasus as an hypothetical origin for ores and metals found in different regions throughout the greater Near East (e.g. Field and Prostov 1938; Eaton and McKerrel 1976, p. 176; Penhallurick 1986, p. 19; Vatandoust 1999, p. 124; Yener 2000, p. 3; Berthoud et al. 1982, p. 40; Crawford 1974, pp. 242–244; Kelly-Buccelati 1990, p. 119; Potts 1993, pp. 391–392), Levant (Tadmor et al. 1995, p. 143) and the Aegean (Betancourt 1970, p. 355; Laffineur 1994, p. 633). More specifically, the question about possible tin deposits in the Caucasus fed the debate on the origins of tin for Anatolian and Mesopotamian metallurgy (e.g. Deshayes 1960, p. 14; Muhly 1973, pp. 260–261 and notes 155–157; Moorey 1982, p. 14, 1994, p. 300; Pare 2000, p. 7; Yener 2000, p. 72).

H. Frankfort (1928, pp. 231–233) was one of the first to note parallels in metal artefacts between Mesopotamia and the Caucasus. He argued for a relationship based on a trade in metal between the Caucasus and Anatolia during the Uruk period. He considered the Caucasus to be an important metallurgical centre linking central and eastern Europe with the greater Near East (Frankfort 1932, pp. 39–40). In his brilliant PhD thesis, some 30 years later, J. Deshayes (1960) underlined the typological parallels in the tools and weaponry between south-eastern Europe (Carpatho–Balkan region), the Caucasus, Anatolia and Iran.

Numerous studies carried out in Anatolia and Iran have confirmed prehistoric relationships with the Caucasus and the importance of metals in these exchanges. They propose the importation of ores or of technological know-how from Transcaucasia to Anatolian settlements like Arslantepe (Palmieri 1981, p. 111; Hauptmann and Palmieri 2000, p. 75; Hauptmann et al. 2002, p. 52; Frangipane et al. 2001, pp. 115–116). Relations between the Caucasus and north-western Iran, more specifically the

Urmia region, have also been noted (Burton-Brown 1955, p. 182; Burney and Lang 1971).

Since 1986, P. Kohl from Wellesley College has been studying Transcaucasia in relation to adjacent regions and the importance of metallurgy in these exchanges. His research at Velikent on the Caspian plain (Dagestan) confirms the high technical level of metallurgy reached in the Early Bronze Age and raises again the interesting question of the use of tin in the Caucasus (Kohl 2003; Kohl et al. 2002a, b). More recently, Kohl (2007) has presented an excellent synthesis of cultural relations and the role of metallurgy in the Bronze Age across the Balkans, the Steppes, the Caucasus and the Urals.

Beginning in 1998, A. T. Smith of the University of Chicago has directed a project named "*The Archaeology and Geography of Ancient Transcaucasian States Project (ArAGATS)*" (Smith et al. 2009). It is based on the survey and excavation of settlements in the Tsaghkahovit Valley, and aims to understand the Transcaucasian cultures of the area and the adjacent regions from the Early Bronze Age to the medieval period (ca. 3500 BCE–1200 CE). One of the members associated with the ArAGATS project, D. L. Peterson, recently finished a PhD dissertation on the evolution of metallurgy in the middle Volga and north-eastern Caucasus (ca. 3000–1500 BCE). Peterson (2007) approaches the question from a comparative point of view, noting how the value of metal objects (as imbued through the technical practice of metalworking) interrelates with the 'value' or social standing of individuals and societies.

Since 1999, a scientific team headed by A. Hauptmann of the Deutsches Bergbau-Museum (DBM) at Bochum has developed a project on ancient metallurgy in the Caucasus. Their archaeometallurgical research has focused mainly on Georgia (Gambaschidze et al. 2002) and attempts to demonstrate the exploitation and use of local ores by the Early and Middle Bronze Ages (Hauptmann et al. 2009). Similarly, another German team under E. Pernicka's direction began in 2002 an analytical program (compound and isotopic analyses) on metal artefacts dated to the third millennium BCE, as part of a cooperative program with the archaeological and ethnological institute of Erevan (Meliksetian et al. 2003).

In her PhD dissertation on metallurgy in Transcaucasia from the Late Chalcolithic to the Middle Bronze Age (ca. 3500–1500 BCE.), L. A. Tedesco (2006a) gives a different vision than the traditional scheme established by Chernykh. She argues for the absence of large-scale metal production from the Early Bronze Age to the beginnings of the Middle Bronze Age. On the contrary, she documents the existence of small-scale production on a community level. She also underlines a shared technological style between Transcaucasia and northern Caucasus during the Early Bronze Age and suggests a standardization of the products at this period (Tedesco 2006b).

Research on the relations between the Caucasus and the Near East conducted by B. Lyonnet since 2000 have also underlined the possible importance of metallurgy in the exchanges between these adjacent areas (e.g. Lyonnet 2004, p. 100, 2007b, p. 150; Lyonnet et al. 2009b). The recent chronological scheme proposed by Lyonnet (2007a, b), and her emphasis on the importance of metals in relations between the Caucasus and adjacent areas, led to my own dissertation on the beginning of metallurgy in the Caucasus from the end of Neolithic (sixth millennium BCE) to the

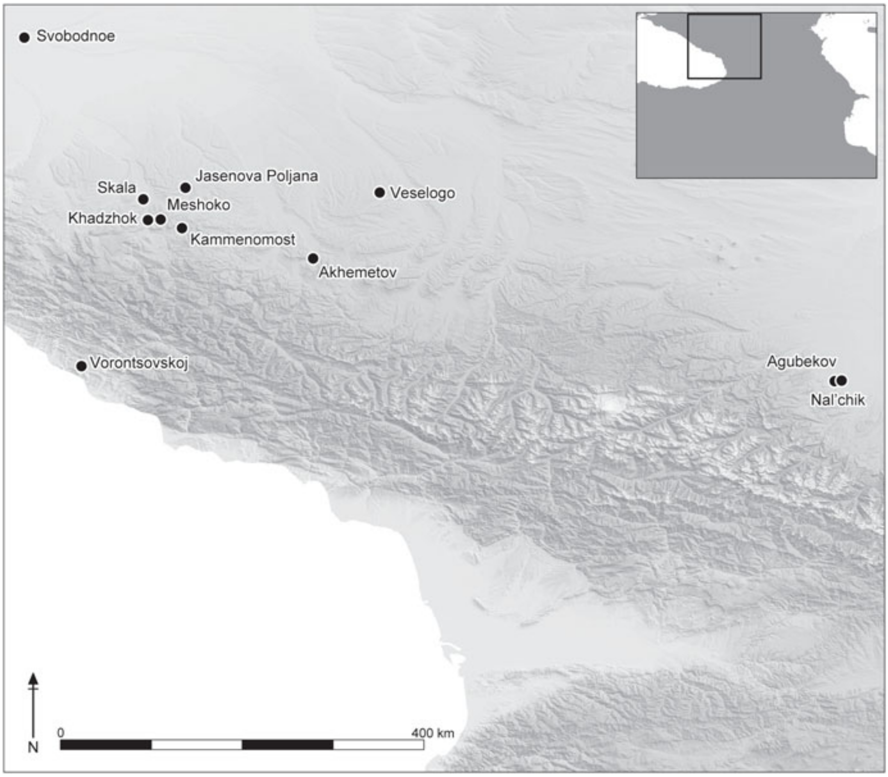


Fig. 22.1 Settlements attached to the Meshoko culture. (Cassard et al. 2009, GIS project)

Early Bronze Age (third millennium BCE) (Courcier 2010). This work combined archaeometrical analyses of metal objects coming from settlements related to different Chalcolithic cultures of the southern and northern Caucasus with a GIS project conducted by the BRGM (French Geological Institute) and CNRS (French National Scientific Research Center) in which geologic/metallogenic and archaeological data were combined to look for patterns of resource exploitation and trade.

The Early Metallurgical Stage (From Sixth to Early Fourth Millennium BCE)

Meshoko Culture

In the North-West Caucasus (Fig. 22.1), the Meshoko culture (including sites like Meshoko, Svobodnoe and Zamok) is dated between the middle of the fifth and the beginning of the fourth millennium BCE (Fig. 22.2). The end of the Meshoko culture

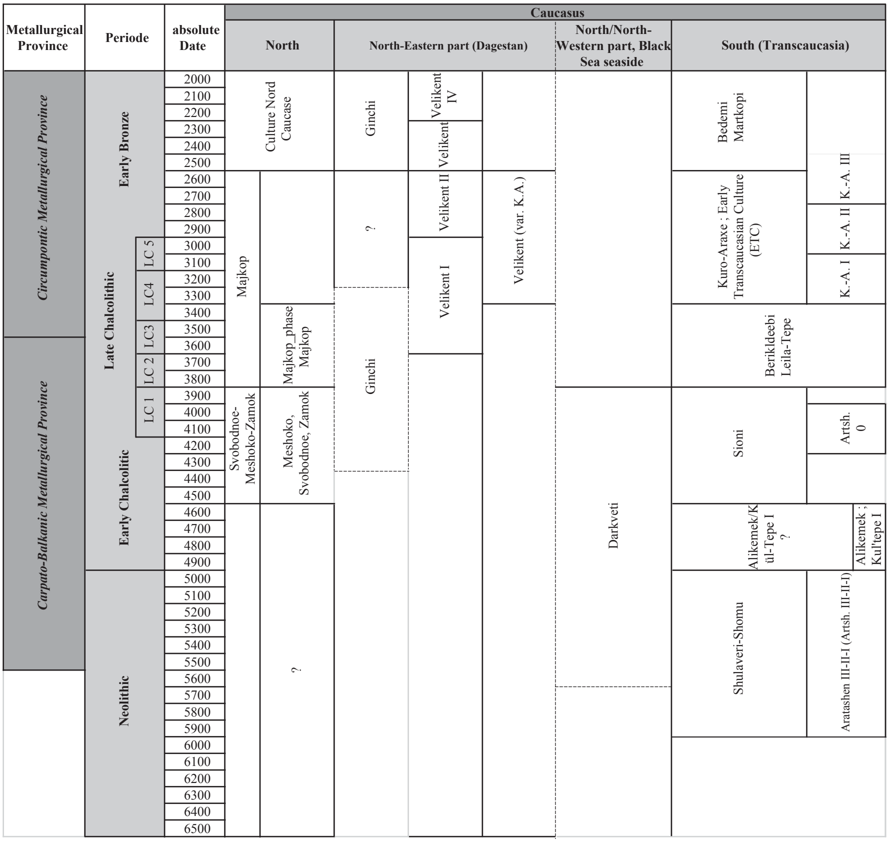


Fig. 22.2 Chronological scheme illustrating the chronological connections between the cultures of the Caucasus

seems to have overlapped with the Majkop culture, which started during the first half of the fourth millennium BCE. The type-site of the Meshoko culture, Svobodnoe, also contained some sherds considered to be related to the Skelya culture that developed in the steppes north of the Black Sea (Lyonnet 2004, pp. 93–94). A few other objects from this group of cultures suggest relations between the northern Caucasus, the Steppes and the Carpatho-Balkan area during the Karanovo VI–Tripol'e B1 period (ca. second half of the fifth millennium BCE) (ibid.).

The first metal objects discovered in the northern Caucasus come from settlements attached to this culture. They include an undetermined object[1] (Chernykh 1991, pp. 584–585) from the upper level 1 of Svobodnoe (Fig. 22.3), a small ring and a knife blade from Skala (Formozov 1965, pp. 70–71) and 11 fragments of tools and ornaments (awl, bracelet, pendant) from Meshoko (Chernykh 1966, pp. 101–102).

[1] It is not clear, according to the publication, if it is a curved band or a bead.

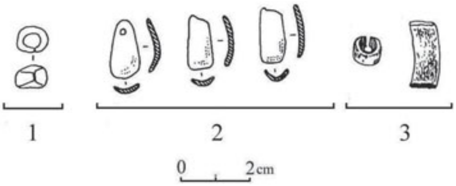


Fig. 22.3 Ornaments coming from settlements dated to the Late Chalcolithic: *1* Svobodnoe (Chernykh 1991, p. 585), *2* Vesjolaja Rošča II (Idem 1991, p. 585), *3* Kul'tepe I. (Chataigner 1995, p. 131)

At Veselogo, the presence of a crucible (Formozov 1965, p. 116) may suggest the local production of metal objects. According to I. R. Formozov, several traces of extractive and smelting activities have been identified upstream of the many rivers of this region, especially close to the Belorechensk Pass. Nevertheless, the date of these activities is not well established (Formozov 1965, p. 116).

Analysis of the metal artefact from Svobodnoe revealed that it was made of "pure" copper (Chernykh 1991, p. 591, n°40114). Chernykh considered this evidence for the use of copper ores free of impurities, argued to be typical of the copper deposits in the Carpatho-Balkan area (Chernykh 1992, p. 158.; Chernykh et al. 1991, pp. 600–601). Thus, he suggested that this object came from across the Black Sea (Chernykh 1991, pp. 585–587). Although we now know that copper deposits with few impurities also exist in the Caucasus (Cassard et al. 2009), Chernykh's hypothesis implied a west–east circulation that was later reinforced by the discovery of similar prestige objects over a vast area (including bone pearls, tusk pendants, very long flint blades, triangular stone arrowheads, bracelets and adzes in serpentine and zoomorphic sceptres) (Rassamakin 1999, p. 75 et seq.). In this exchange trade, the Skelya culture of the Pontic Steppe (north of the Black Sea) could have played an intermediary role. This culture does seem to have been a link between the entities of the Lower Danube (Suvorovo and Cernavoda I cultures), the Kuban region (including Svobodnoe, Meshoko, Myskhako and Zamok) and the wooded steppes of the Volga River (Khvalynsk). This vast territory coincides with the area of the Carpatho-Balkan metallurgical province (CBMP) as laid out by Chernykh et al. (1991, pp. 593–595, 2002, pp. 83–87). Furthermore, a certain chronological overlap exists between the period of these exchanges (ca. 4550–4100/4000 BCE) and the apogee of this CBMP, dated to ca. 4400–4100 BCE (Chernykh 1978a, pp. 263–265 and 274; 1992, pp. 51–53; see also Pernicka et al. 1997, pp. 51–56 and 131–136; Ryndina 1998, pp. 190–191).

However, the idea of local metallurgical production cannot be excluded from the northern Caucasus. The majority of the metal artefacts found at Meshoko were different from those of Svobodnoe and made of arsenical copper (1–1.2 % As [2]) (Chernykh 1966, pp. 98–99, Table I). Only the blade seems to be of "pure" copper (*ibid.*: 101–102, Table II). Numerous copper deposits in the northern Caucasus contain natural impurities of arsenic (Cassard et al. 2009). The evidence identified by Formozov and the crucible at Veselogo could confirm the hypothesis of extractive metallurgy in this region during the fifth millennium BCE. The transhumant lifestyle thought to

[2] It is assumed (although unclear) that this is wt%.

Table 22.1 Analysis of the undefined object found at Svobodnoe. (Chernykh 1991, p. 591, percent type not précised)

n°analyse	Type d'objet	Localisation	Composition percent										Reference
			Cu	Sn	Pb	Zn	Bi	Ag	As	Fe	Ni	Co	
40114	Perle	niv. I/Q 631		0.0024	0.002	0.0009	0.0003	0.0004	0.011	0.4	0.0047	0.0011	Chernykh 1991, p. 591

be typical of this region at this time could have encouraged an early identification of copper deposits by the local population, and the circulation of metallurgical techniques and/or metal artefacts between the cultures living on both sides of the Greater Caucasus.

Ginchi Culture

In the North-East Caucasus, in Dagestan, the first phase of the Ginchi culture is said to be contemporaneous with the end of the Meshoko and the Sioni cultures (Fig. 22.2). The transition between this first phase of Ginchi culture and the second is synchronous with the beginnings of the Majkop culture (see below). At present, no metal objects have been discovered in these settlements.

Shomu–Shulaveri Culture

In the southern Caucasus (Transcaucasia), the Neolithic is characterized by the Shomu–Shulaveri culture, which developed in the middle Kura River Valley during the sixth millennium BCE in five distinctive phases (22.2 and 22.4) (Kushnareva 1997, pp. 25–26). Metal artefacts are rare and occur only in some settlements dated to the end of this period (ca. end of sixth millennium BCE.). They mainly consist of ornaments like beads—e.g. at Gargalar-Tepesi (Arazova et al. 1973, p. 455) and Khramis Didi-Gora (Kiguradze 1986, p. 70 and 93)— and small tools like awls and bradawls—e.g. at Khramis Didi-Gora (Menabde et al. 1984, p. 34). The discovery of unstratified stone-grooved and cupula hammers at Arukhlo (Kushnareva and Chubinishvili 1970, p. 24; Chubinishvili 1971, pp. 31–33), which is close to copper deposits, may suggest extractive metallurgical activities in this region.

Recent survey and cleaning work at Göy Tepe (Lyonnet et al. 2009c) seems to confirm this suggestion, as a vitreous slag with several small copper prills was found by chance in levels dated to the middle of the sixth millennium BCE. This slag "cake", composed of ore gangue and some metal prills, appears to be an intermediate product of the smelting process. Analyses performed on this slag cake have shown that it has an alumino-silicate matrix with zinc impurities[3] (Table 22.2). According

[3] Unpublished data. Analyses carried out in the laboratory of the Deutsches Bergbau-Museum (Bochum), under the direction of A. Hauptmann and M. Prange.

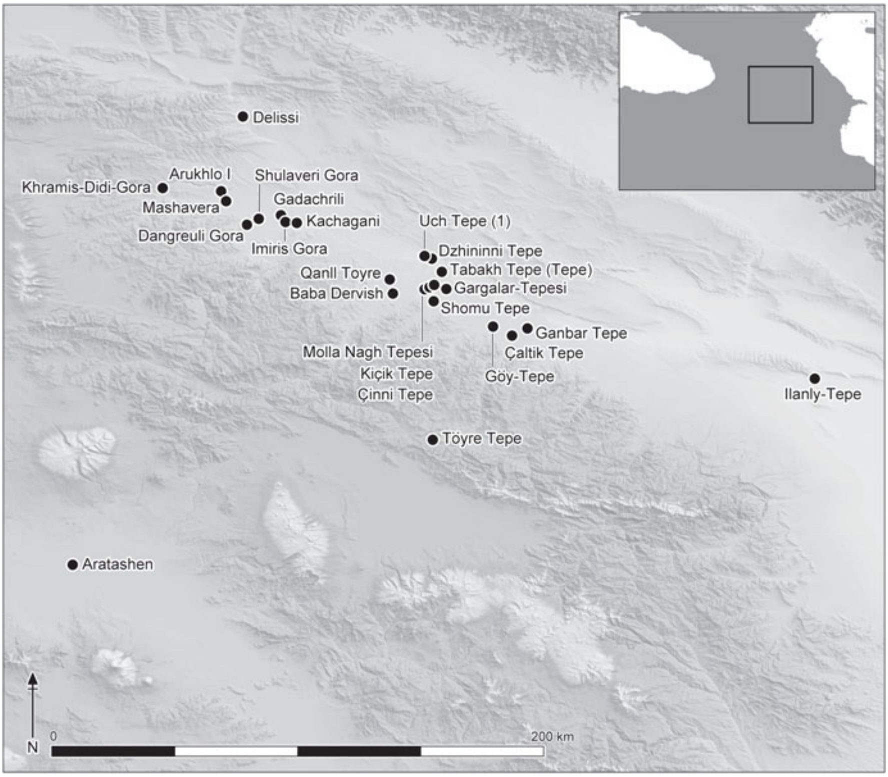


Fig. 22.4 Settlements attached to the Shomu–Shulaveri culture. (Cassard et al. 2009, GIS project)

to other analyses made on another part of the sample[4], the matrix also contained copper (2.36 wt%) and nickel (0.79 wt%). Nickel and zinc could originate from the copper ore, since these elements are often associated with copper in the deposits of the Caucasus (Cassard et al. 2009).

In contrast, the analysis performed on the artefacts coming from Gargalar-Tepesi (bead) and Khramis Didi-Gora (bradawl and beads) has shown that they were both made from "pure" copper (Narimanov 1990, pp. 8–9; Tavadze et al. 1987, p. 46). If we follow Chernykh's hypothesis, then these objects should be seen as imports from the Balkans. It is, however, more probable that they are local products.

Aratashen, Kul'tepe and Alikemek Cultures

Further south, in the Ararat plain (Armenia) (Fig. 22.4), the Aratashen culture (Fig. 22.2) began in the early sixth millennium BCE (Aratashen levels II and I) and

[4] XRF (ISP 28) analysis carried out in the laboratory of the Institute of Archaeology and Ethnology (Bakou), under the direction of A. Gazanova.

Table 22.2 Analyses of several objects coming from Kul'tepe I. (Abibullaev 1965b, p. 69; Selimkhanov 1966, p. 230, Table 1; Kushnareva and Chubinishvili 1970, p. 130–131; Kashkaj and Selimkhanov 1971, p. 53, percent type not précised)

n°analyse	Type d'objet	Localisation	Composition percent													References
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	P	Mo	
	frag. perle	niveau I	majoritaire			0.01		0.004			0.1	0.001				Selimkhanov 1966, p. 230, Table 1; Kashkaj and Selimkhanov 1971, p. 53; Kushnareva and Chubinishvili 1970, p. 130
	frag. perle	niveau I	majoritaire								0.1	0.0005			0.1	Kushnareva and Chubinishvili 1970, p. 130; Kashkaj and Selimkhanov 1971, p. 53
	frag. perle	niveau I	majoritaire								> 1	0.0005		0.1		Abibullaev 1965b, p. 69; Selimkhanov 1966, p. 230, Table 1
	frag. bracelet	niveau I	majoritaire	0.05	0.1	0.03	0.003	0.01			0.5	0.0005	0.001		0.002	Abibullaev 1965b, p. 69; Selimkhanov 1966, p. 230, Table 1
	frag. objet	niveau I	majoritaire			0.05		0.0s14			0.01					Selimkhanov 1966, p. 230, Table 1; Kashkaj and Selimkhanov 1971, p. 53
	frag. objet	niveau I	majoritaire	0.003	0.07			0.043	0.005	0.4	0.2	0.01		0.05		Selimkhanov 1966, p. 230, Table 1; Abibullaev 1965b, p. 69; Kashkaj and Selimkhanov 1971, p. 57; Kushnareva and Chubinishvili 1970, p. 130

Table 22.2 (continued)

n°an-alyse	Type d'objet	Locali-sation	Composition percent													References
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	P	Mo	
	alène	niveau I	majoritaire	0.002			0.003	0.01	0.02	1.15	0.2	1.6	0.2			Kashkaj and Selimkhanov 1971, p. 72; Abibullaev 1965b, p. 69; Selimkhanov 1966, p. 230, Table
	Alène	niveau I	majoritaire					0.018	0.2	1.15	0.02	1.6	0.02			Selimkhanov 1966, p. 224 (nanlyse de l'oxyde)
	alène	niveau I	majoritaire				0.001	0.002	0.05	0.7	0.2	0.5	0.002	0.15		Selimkhanov 1966, p. 224 (analyse de la patine)
	Alène	niveau I	majoritaire	0.002	0.002		0.01	0.002	0.05	0.7	0.2	0.05	0.002			Abibullaev 1965b, p. 69
	pointe de flèche	niveau I	majoritaire	0.003	0.15		0.02	0.1		1.14	0.001	0.005		1.05		Kushnareva and Chubinishvili 1970, pp. 130–131
	pointe de flèche	niveau I	majoritaire		0.05	0.02	0.003	0.002		0.3		0.002		1		Selimkhanov 1966, p. 230, Table 1

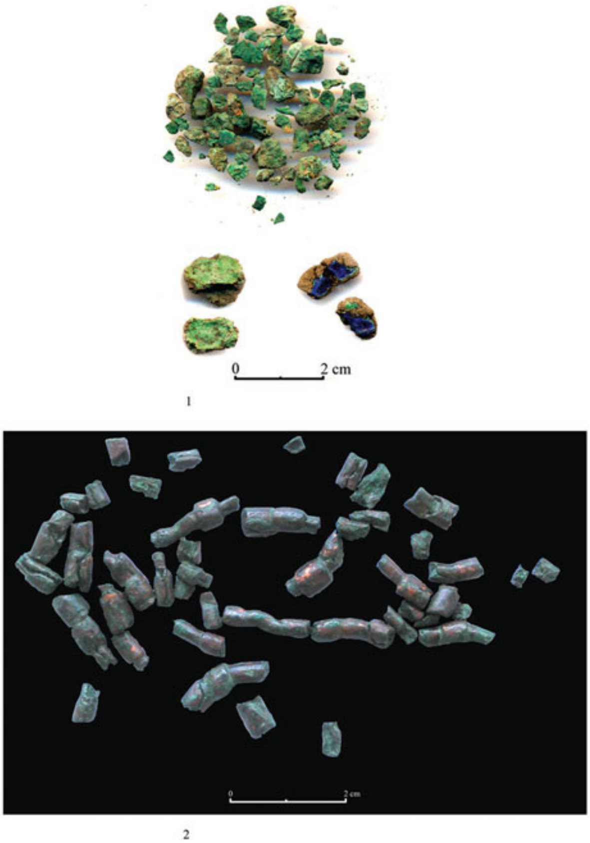


Fig. 22.5 Fragments of copper ores and beads in cuprous matrix found in the level IId of Aratashen. (Chataigner, personal communication, published in Badaljan et al. 2007, p. 53)

continued into the Chalcolithic period (Aratashen level 0). The material coming from the Neolithic levels presents similarities with those of the Shomu–Shulaveri culture, although local traditions are also noted. Moreover, a few Halaf sherds from northern Mesopotamia have been found, but their stratigraphic context is still unclear. These imported wares are similar to those known at Kul'tepe (Nakhchevan) and at Tilkitepe and Tüllintepe (eastern Turkey). Provenience studies carried out on obsidian also suggest contacts with eastern Anatolia and north-western Iran at that time (Badalyan et al. 2007, pp. 67–73). The Chalcolithic levels contain material considered local, although also presenting similarities with sites in northern Syria and northern Mesopotamia (Palumbi 2007, pp. 73–75).

In the Neolithic level IId of Aratashen, dated to the beginnings of the sixth millennium BCE, several fragments of copper ores (malachite and azurite) and 57 arsenical copper beads (Meliksetian 2009) were discovered (Badalyan et al. 2007, pp. 52–53) (Fig. 22.5). Close to Aratashen, at Khatunark, one fragment of copper ore (malachite) has been discovered in a level dated to the first half of the sixth millennium

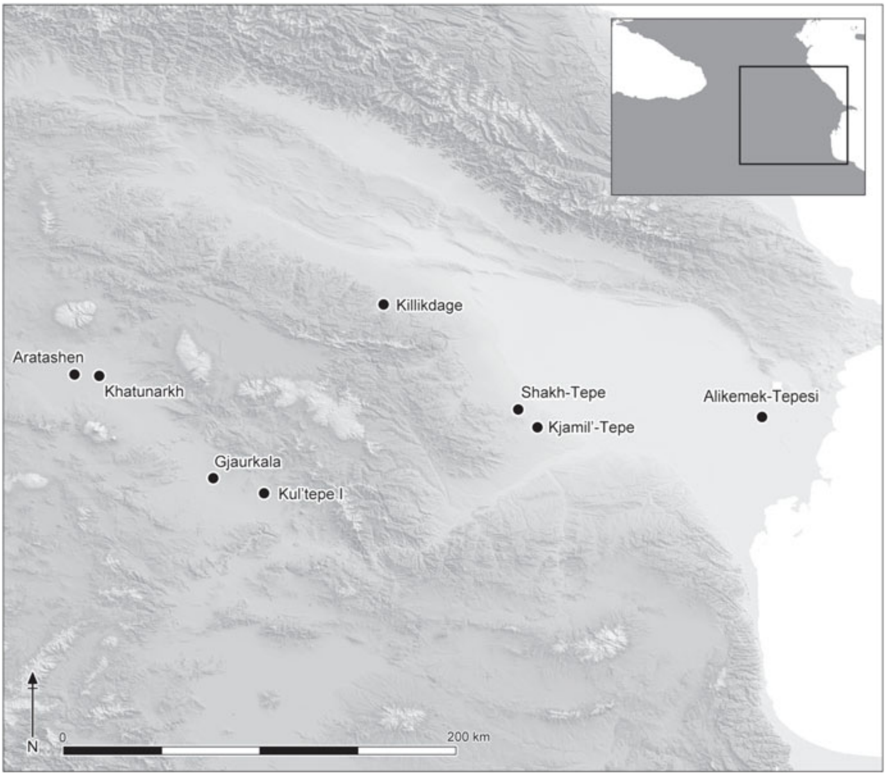
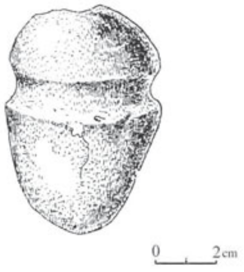


Fig. 22.6 Neolithic Sites of Aratashen and Khatunakh, settlements attached to the Alikemek/Kül-Tepe I culture (Cassard et al., 2009. GIS project)

BCE[5] (Badalyan and Harutyunyan 2008). This artefact, together with those found at Aratashen, suggest the nascent emergence of metallurgy in the Ararat region already during the Late Neolithic.

Following the Shomu–Shulaveri culture and Aratashen (levels I and II), the Alikemek–Kül'tepe culture of the south-eastern Caucasus covers the transition between the Neolithic and Chalcolithic periods (Kushnareva 1997, p. 25 and 30 *sq*.; Lyonnet 2007a, p. 12, 2008, p. 4) (Fig. 22.2). Situated respectively at the border of the Mugan Steppe and in Nakhichevan (Azerbaijan) (Fig. 22.6), the settlements of Alikemek and Kul'tepe I were excavated in the 1950s–1970s and are not dated with certainty. They probably represent a relatively long period and occupation seems to have started early (probably during the sixth millennium BCE) (Lyonnet 2008, pp. 4–6). The Alikemek–Kul'tepe culture covered the Ararat Plain, Nakhichevan, the Mil'skoj and Mugan Steppes and the region around Lake Urmia in north-western Iran (Kushnareva 1997, p. 33).

[5] I sincerely thank C. Chataigner for her authorization to report on this important discovery.



1

2

Fig. 22.7 *1* grooved hammer found at Kul'tepe I (Abibulaev 1963, p. 160), *2* grooved hammer coming from Duzdaği. (Bakhshaliyev et al. 2009, p. 49)

In a tomb of the upper level (Early Chalcolithic) at Alikemek Tepesi, three beads and an awl were discovered (Makhmudov et al. 1974, p. 455). At Kul'Tepe I, seven metal artefacts (Fig. 22.8; Table 22.2) were found in the upper part of level I and in tomb 33 (Abibullaev 1965b, p. 67; Selimkhanov 1966, p. 226). The date of these objects is unclear because level I contains material dating both to the Neolithic (including pottery of the Halaf culture of northern Mesopotamia) and to the beginning of the Chalcolithic (related to the Dalma culture of north-western Iran). A grooved hammer was also found in a tomb of level I at Kul'Tepe I (Fig. 22.7) that is close

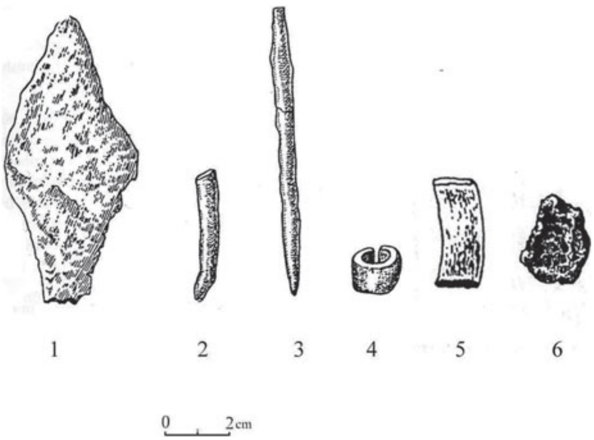


Fig. 22.8 Metal artefacts found in the level I of Kul'tepe I: *1* arrowhead, *2* fragment of object (awl?), *3* awl, *4* bead, *5* fragment of ring, *6* fragment of undefined object (metallurgical waste?). (Munchaev 1982a, pp. 19–22, Table XLII; Selimkhanov 1966, p. 226, Fig. 2)

to examples known at Gjaurkala (near Shakhtakhy in Azerbaijan) and at Killikdag (near Khanlar in Azerbaijan) (Abibullaev 1963, p. 160). This type of tool is generally associated with extractive metallurgical activities so we could propose that ore mining was being done at Kul'tepe. However, recent research at the salt mines of Duzdaği, close to Kul'Tepe, proves that similar grooved hammers were also used to extract salt (Fig. 22.7) (Bakhashaliyev and Marro 2009).

In addition to their mixed archaeological context, the analyses of the artefacts from Kul'tepe were done decades ago and thus must be considered with caution. However, they appear to be made of both "pure" and arsenical copper. Arsenic is naturally present in numerous copper ore deposits in the Greater and Lesser Caucasus (Cassard et al. 2009). The smelting of these ore types could have led to the presence of arsenic in the resulting objects.

Sioni Culture

During the fifth millennium BCE, the Sioni culture developed in the southern Caucasus, but this phenomenon is still not well characterized and consists of several different settlements over a relatively long period of time (Fig. 22.2). The Sioni culture covered a vast territory including eastern Georgia (Dzhavakhishvilla et al. 1987, p. 8; Kiguradze and Sagona 2003, pp. 40–42), north-western Iran (Lyonnet 2007b, p. 136, footnote 42), Armenia and eastern Turkey (down to Oylum Höyük, at the fringes of northern Mesopotamia) (Palumbi 2007, p. 73; Marro 2007, pp. 79–90). Moreover, some features of the Sioni culture have been discovered in Majkop settlements of the northern Caucasus (Korenevskij 2004, Figs. 4, 5, 12 and 15; Lyonnet 2007b, pp. 135–136), in the upper levels of Meshoko (Formosov 1965, p. 119; Lyonnet 2007b, p. 136) and in some later sites linked to Mesopotamia—e.g. Berikldeebi (Žavaxišvili, Fig. 3; Korenevskij 2004, Fig. 117; Lyonnet 2007b,

Fig. 22.9 Metal objects coming from Mentesh Tepe: *1* slag, *2* awl, *3* ring, *4* fragment of undefined object, *5* fragment of undefined object (awl?), *6–8* agglomerates of strongly corroded undefined objects, *9* mould, *10* awl. (Lyonnet et al. 2009c)

pp. 135–136), Leilatepe (Akhundov 2007, pp. 108–119) and Boyuk-Kesik (Lyonnet 2007b, p. 136). In some sites, the coexistence of characteristic elements attributed to the Meshoko, Majkop, Ginchi and Sioni cultures presumes a certain chronological overlap between them (Lyonnet 2007b, p. 137) (Fig. 2).

Recent research at Mentesh Tepe[6] (Lyonnet et al. 2009c), a site also associated with the Sioni culture and dated to the second half of the fifth millennium BCE, adds support to the idea of local metallurgy at this time. Indeed, a complete manufacturing process is illustrated at this site (Fig. 22.9), from slags to fragmentary

[6] Unpublished Data. I sincerely thank B. Lyonnet and F. Gulyev for their authorization to present here first these very interesting discoveries.

objects (recycling?), from a mould to the finished object (awl). Several metal objects were discovered at other Sioni culture sites such as Alazani III (Kiguradze 2000, p. 323), Tsiteli Gorebi (Varazashvili 1992, p. 32) and Chalagan Tepe (Narimanov 1985, p. 490). According to analysis, these objects were made of copper with traces of zinc (Tsiteli Gorebi: Varazashvili 1992, p. 69; Chalagan Tepe: Narimanov 1990, p. 5). Upstream of the Alazani River, several copper deposits contain zinc-bearing minerals were found (Cassard et al. 2009). Unfortunately, no research has ever been done on possible extractive activities at these deposits.

Archaeometallurgical studies have been performed at the Deutsches Bergbau Museum (Bochum) on artefacts from Mentesh Tepe[7]. Most of the objects from this site are completely corroded. Only two—an undetermined object (Fig. 22.9, no.°4) and an awl (Fig. 22.9, no.°10)—still contain metal in their centres. Metallographic analysis of the undetermined object reveals a dentritic and eutectoidal structure ($Cu + CuO_2$) (Fig. 22.10), which is characteristic of a cast object. Etching permitted the identification of a few hexagonal grains with annealing twins in the alpha dendrites. They prove that a soft hammering and an annealing step were executed. A rapid energy-dispersive X-ray spectroscopy (EDS) analysis confirms that this object is made of relatively "pure" copper (90.0–96.4 wt% Cu) with minor amounts of arsenic (0.8–3.8 wt% As).

Metallographic analysis done on the awl showed some distorted dendrites (Fig. 22.11), suggesting cold-working. Etching the section confirmed this hypothesis due to the presence of several hexagonal grains with annealing twins and thin strain lines within the grains (Figs. 22.11 and 22.12). In sum, this object was cast, cold-hammered, then annealed and finally cold-worked again. EDS analysis of this awl revealed that it was also made of relatively "pure" copper (91.5–97.9 wt% Cu), with traces of arsenic (0.7–1.4 wt% As) and sulphur (0.5–0.9 wt% S). EDS mapping shows a homogeneous repartition of sulphur, which may correspond with small inclusions seen within the grains. Arsenic is concentrated at the edge of the object, a consequence of the natural segregation of this element. The metal artefacts found at Mentesh Tepe demonstrate the capacity for casting and manufacturing objects in the Sioni culture.

Darkveti Culture

In the north-western Caucasus and along the Black Sea in Georgia (Fig. 22.13), several settlements (Darkveti, Tetramitsa, Samele-Klde and others) were excavated that are linked to a different archaeological group named the "Darkveti culture" (Fig. 22.2). There are no ^{14}C dates yet, but it seems that at some settlements occupation began in the Neolithic (perhaps even before) and continued till the end of the Chalcolithic (although not always continuously) (Lyonnet 2004, pp. 89–91, 2007b,

[7] I would like to acknowledge M. Prange, Ü. Yalcin and A. Hauptmann for their support and advice during these analyses.

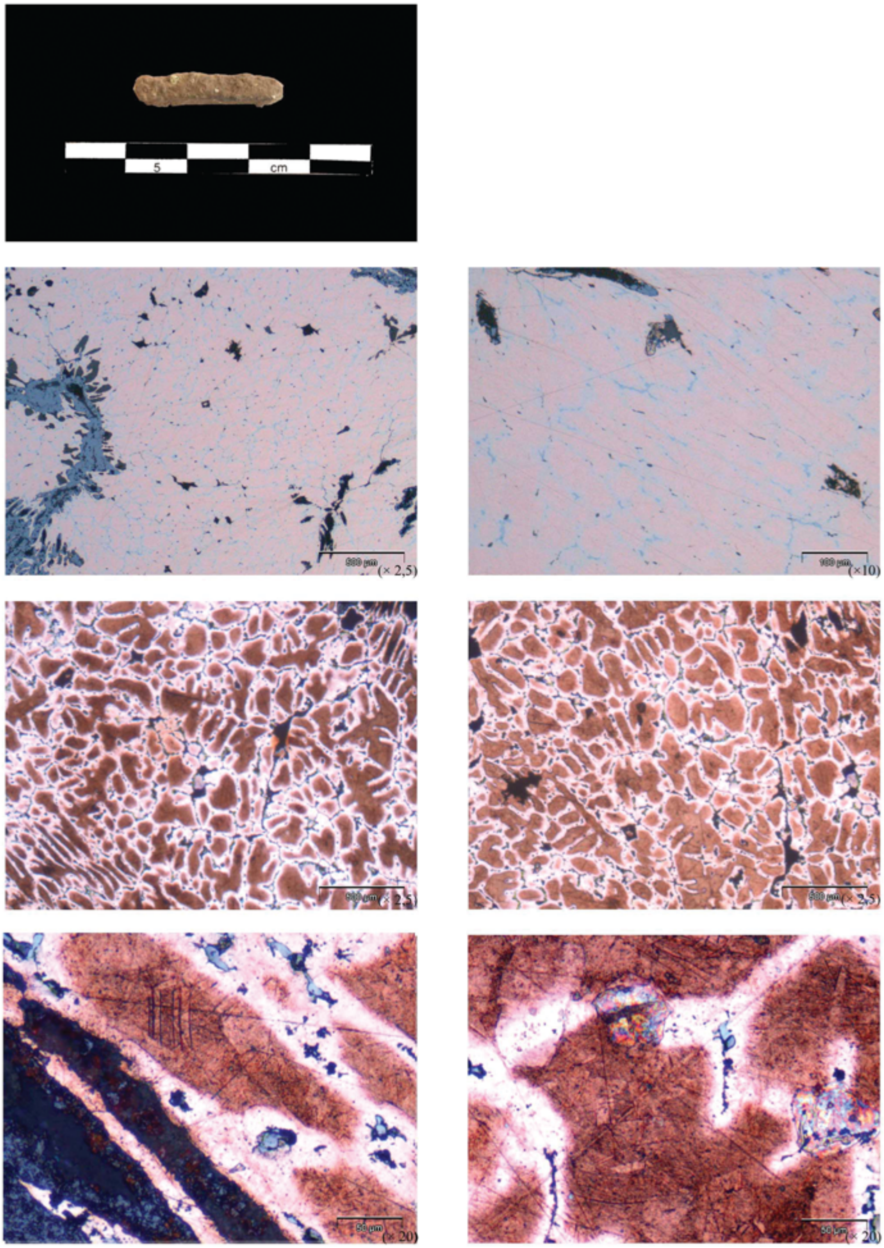


Fig. 22.10 Metallographies (non-etched and etched) of the fragment of the undefined object seen in Fig. 22.9, no. 4

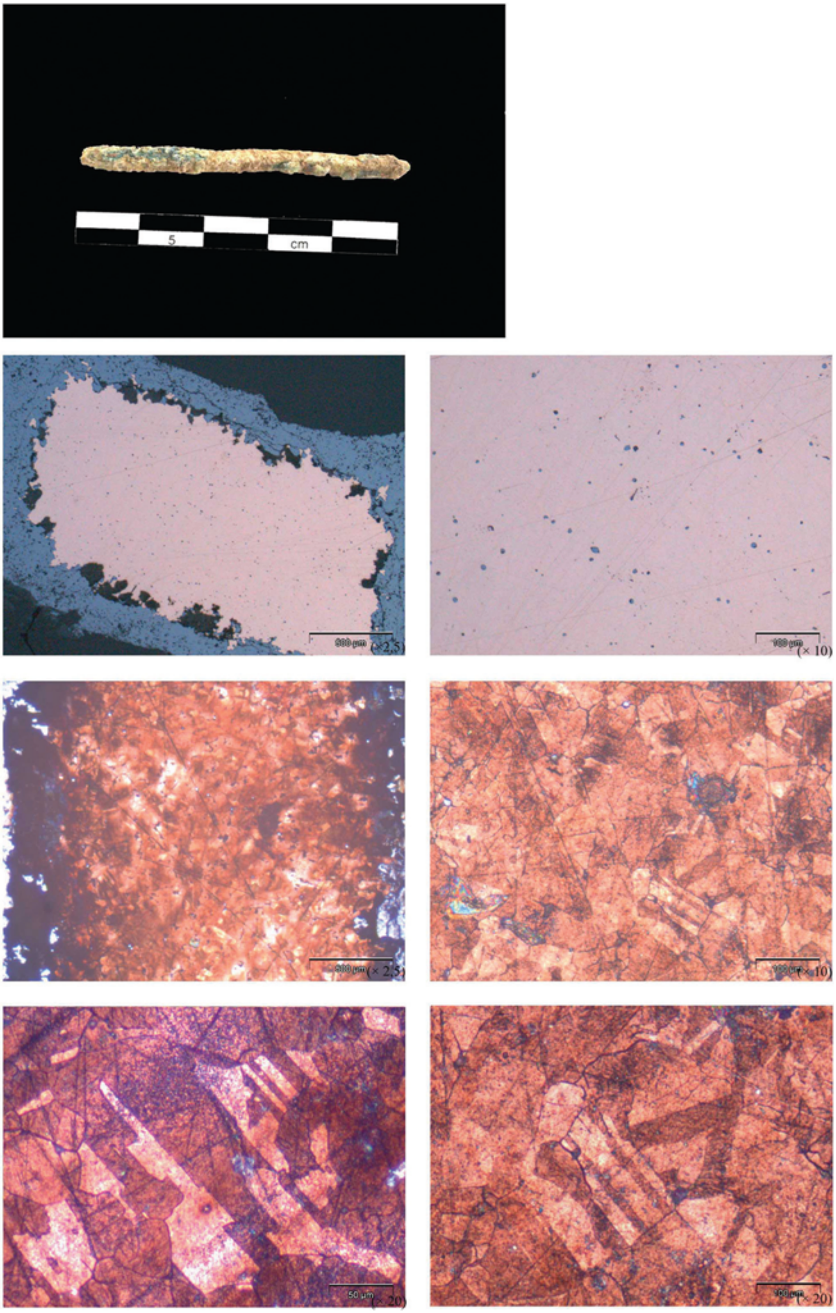


Fig. 22.11 Metallographies (non-etched and etched) of the awl seen in Fig. 22.9, no. 10

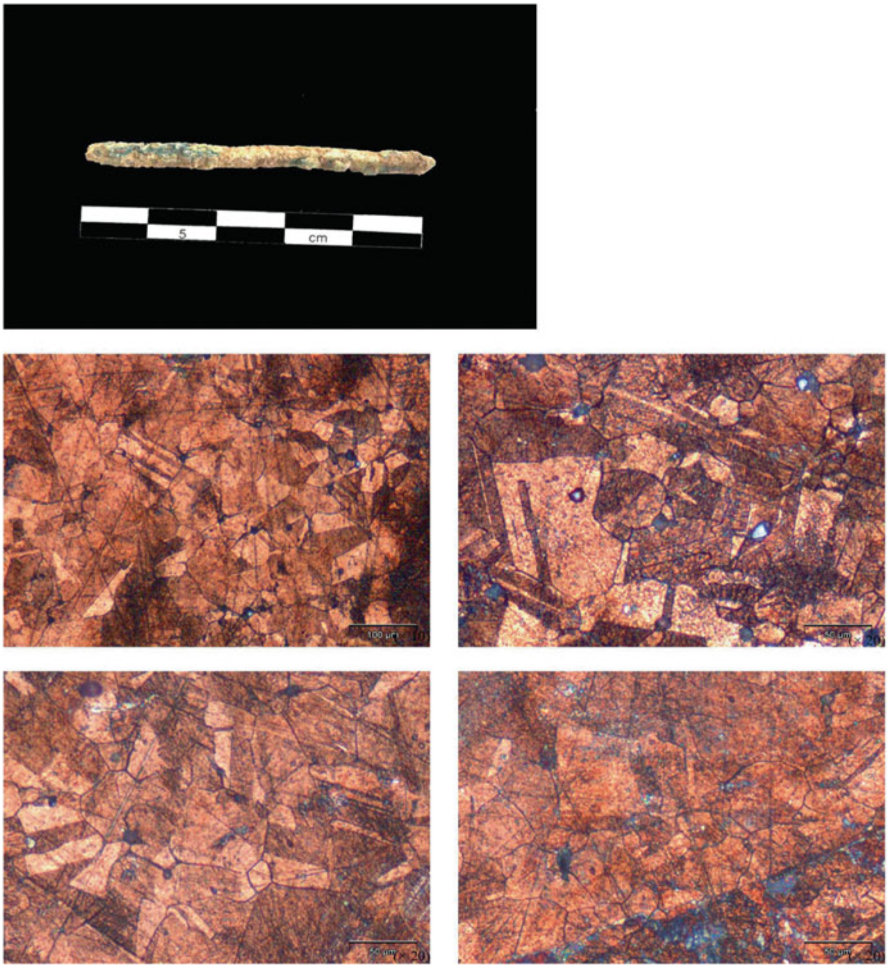


Fig. 22.12 Metallographies (etched) of the awl found at Mentesh in Fig. 22.9, no. 10

p. 19; Chataigner 1995, pp. 50–51; Kushnareva 1997, p. 19). The Darkveti culture is found principally in caves but open air settlements are also attested (Tetramitsa, Chikhori) with semi-buried oval or circular huts made of light structures (wattle and daub). A few stone bracelets characteristic of the Meshoko culture have been found in some of the Darkveti settlements, especially in caves along the basin of the Kvirila River and at Tetramitsa. These bracelets suggest relations between the two regions, maybe associated with transhumance between the two slopes of the Caucasus (Trifonov 2001; Lyonnet 2004, p. 91).

Early metallurgy is also attested on some settlements of this culture. Evidence mainly consists of artefacts that have been cold-worked and annealed. Some of these objects differ typologically from those discovered in other contemporary cultures. These unique types include rods at Samele-Klde (Formosov 1973, p. 37; Chataigner

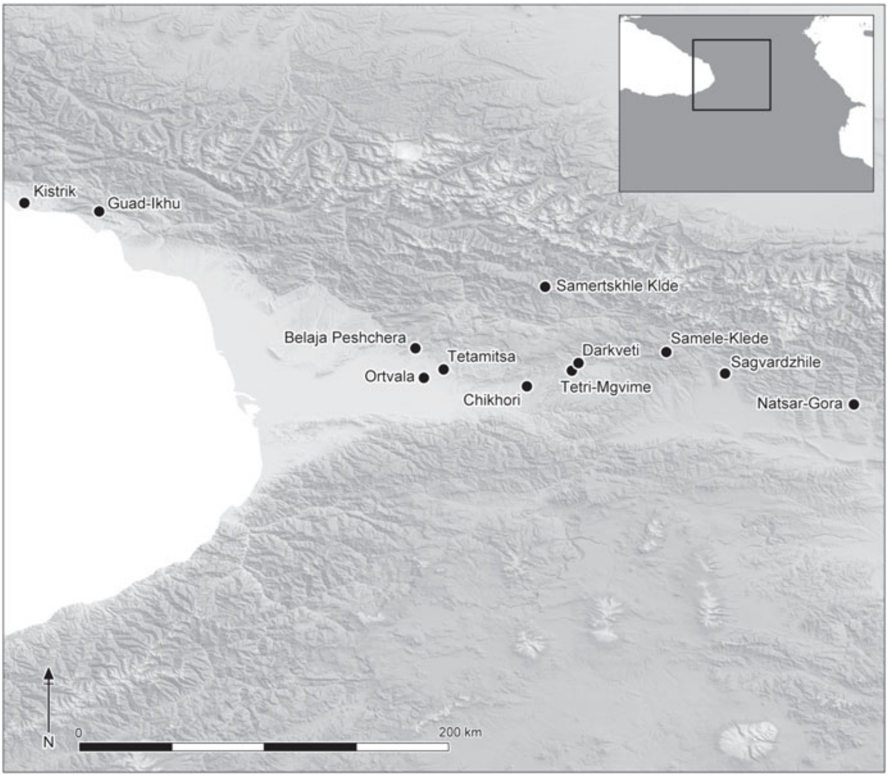


Fig. 22.13 Settlements attached to the Darkveti culture. (Cassard et al. 2009, GIS project)

Table 22.3 Analysis of the awl coming from Chikhori. (Tavadze et al. 1987, p. 46, percent type not précised)

n°analyse	Type d'objet	Localisation	Composition percent				Reference
			Cu	Ag	As	Ni	
	alène	Chikhori	majoritaire	0.001	0.8	0.001	Tvadze et al. 1987, p. 46

1995, p. 132) and Chikhori (Nebieridze 1985, p. 9; 1986, p. 10), wire at Natsar Gora (Gobedzhishvili 1951, pp. 242–243; Tekhov and Dzhaparidze 1971, p. 52), a hook at Sagvardzhile (Lordkipanidze 1989, p. 67.), ingots at Guad ikhu (Solov'ev 1967, p. 24.) and hoops at Kistrik (Lukin 1950, p. 282). More common are metal artefacts such as awls at Sagvardzhile (Lordkipanidze 1989, p. 67) and Chikhori (Nebieridze 1985, p. 9, 1986, p. 10), knife blades at Tetri-Mgvime (Kalandadze and Kalandadze 1982; Abesadze and Bakhtadze 1987, p. 51), arrowheads at Belaja-Peschera (Pkhakadze 1988, p. 209), pendants at Chikhori (Nebieridze 1985, p. 9, 1986, p. 10) and undetermined objects at Ortvala (Nioradze 1986, p. 11). The analyses done on these metal objects suggest that the majority were made of "pure" copper (Table 22.3), although we must be careful using older analyses which may not have detected important elements such as arsenic and sulphur. Only three objects (a knife blade, arrowhead and awl coming from Chikhori) contain traces of arsenic (0.7–0.8 %[8] As, Tab. 22.4) (Tavadze et al. 1987, P. 46; Abesadze and Bakhtadze 1987, p. 51). The ingots and the hoops may have been made of lead, according to the analysis (Bzhanija 1961, p. 109; Nebieridze 1985, p. 9, 1986, p. 10), but this has not been confirmed.

Understanding the Early Metallurgical stage (ca. Sixth to Early Fourth Millennia BCE)

To sum up, the beginnings of metallurgy in the Caucasus seem to be characterized by:

- Small objects
- Simple manufacturing techniques
- Non-alloyed copper or copper with minor amounts of arsenic (probably due to the types of ores being used)
- Possibly also lead metallurgy (based on the unconfirmed analyses from the Darkveti culture, above)

The lack of research on the exploitation of local deposits does not allow many conclusions about extractive metallurgy in the Caucasus during this period. Nevertheless, recent research on metal-related data suggests the possibility of local metallurgical activities. In fact, several local metallurgical traditions seem to develop in the different regions of the Caucasus, all of which are probably in close contact with transhumant or fully nomadic cultural groups (e.g. the Sioni). These connections could have encouraged the development of metallurgy through the wider circulation of techniques, metal-bearing ores and artefacts. The cultures of the Caucasus had probably also established long-distance relations with other regions such as the Carpatho-Balkan area, the Steppes, eastern Anatolia, northern Mesopotamia and northern Iran. Though we often cannot demonstrate these relations clearly, such cultural connections probably played a great role in the development of local metallurgies in the Caucasus, and may have even stimulated its growth from the very start.

The Rise of Metallurgy (Early Fourth to Third Millennium BCE)

Majkop and Novosvobodnaja Components

The Majkop (or "Maikop") culture, which spread over a vast territory (Figs. 22.14 and 22.15) from the Black Sea to the Terek River, from the spur of the Greater Caucasus to the Steppe, began in the second quarter of the fourth millennium BCE (Trifonov 1996;

[8] It is assumed although unclear that this is wt%.

Table 22.4 Analyses of metal artefacts found at Majkop. (Selimkhanov 1962, p. 74; Chernykh 1966, pp. 98–101; Korenevskij 1988, p. 94; percent type not précised)

n° analyse	Type d'objet	Localisation	Composition percent												Reference
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	Au	
34/7	lame plate d'outil	kourgane	majoritaire	0.002		0.015		0.035		0.5	0.01	1.05			Selimkhanov 1962, p. 74, Table I
34/9	Hache	kourgane	97.3	0.004	0.005			0.049		2.03	0.015	0.007		0.003	Selimkhanov 1962, p. 74, Table I
34/10	hache-houe	kourgane	92.8	0.001	0.01		0.01	0.5	0.007	4.55	0.05	1.6		0.005	Selimkhanov 1962, p. 74, Table I
34/11	Houe	kourgane	94.9	0.0005	0.04		0.01	0.052	0.015	3.57	0.06	0.85			Selimkhanov 1962, p. 74, Table I
34/12	hache plate	kourgane	85.7	0.0005	0.01	0.015		0.031	0.002	9.08	0.2	4.4	0.002		Selimkhanov 1962, p. 74, Table I
34/13	hache plate	kourgane	91.5	0.001	0.003	0.015	0.03	0.039	0.005	7.8	0.1	0.01	0.001		Selimkhanov 1962, p. 74, Table I
34/14	Ciseau	kourgane	97	0.001	0.02	0.005	0.002	0.05	0.006	2.37	0.05	0.001			Selimkhanov 1962, p. 74, Table I
34/15	ciseau	kourgane	93.3	0.001	0.02	0.004	0.002	0.035	0.008	6.08	0.1	0.001			Selimkhanov 1962, p. 74, Table I
34/16	alène	kourgane	93.2	0.001	0.01			0.012		6.06	0.2	0.01			Selimkhanov 1962, p. 74, Table I
29608	vase	kourgane	majoritaire		0.01			0.04	0.01	2.5	0.001	0.02		< 0.001	Korenevskij 1988, p. 94
29609	seau	kourgane	majoritaire		0.02			0.1	0.02	1.3	0.001	0.02		< 0.001	Korenevskij 1988, p. 94
29610	cruche	kourgane	majoritaire		0.02			0.04	0.01	5	0.002	0.02		< 0.001	Korenevskij 1988, p. 94
29611	Paroi de vase	kourgane	majoritaire		0.01			0.03	0.009	2.5	0.008	0.015		< 0.001	Korenevskij 1988, p. 94
29612	vase à corolle	kourgane	majoritaire		0.006			0.004		3	0.015	0.003		< 0.001	Korenevskij 1988, p. 94

Table 22.4 (continued)

n° analyse	Type d'objet	Localisation	Composition percent												Reference
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	Au	
29613	vase à corolle	kourgane	majoritaire					0.03	0.01	2.5	0.002	0.02		< 0.001	Korenevskij 1988, p. 94
29614	vase à corolle	kourgane	majoritaire		0.004			0.03		5	0.001	0.015		< 0.001	Korenevskij 1988, p. 94
29615	Coupe	kourgane	majoritaire	0.002	0.004	0.01		0.1	0.004	2.5	0.002	0.06		< 0.001	Korenevskij 1988, p. 94
29616	coupe à bord	kourgane	10	Traces	Traces	Traces	Traces	90							Korenevskij 1988, p. 94
29617	tige à baldaquin	kourgane	10	Traces	Traces		Traces	90			Traces	Traces		Traces	Korenevskij 1988, p. 94
29618	vase à nervures	kourgane	11	Traces	Traces		Traces	91			Traces	Traces		Traces	Korenevskij 1988, p. 94
	lame de couteau	kourgane	majoritaire	0.002		0.015		0.035		0.5	0.01	1.05			Chernykh 1966, pp. 98–99
	Hache-herminette	kourgane	94.1	0.001	0.01		0.01	0.5	0.007	4.55	0.05	1.6		≈ 0.005	Chernykh 1966, pp. 98–99
	herminette	kourgane	95.7	0.0005	0.04		0.01	0.052	0.015	3.57	0.06	0.85			Chernykh 1966, pp. 98–99
	herminette	kourgane	89.9	0.0005	0.01	0.015		0.031	0.002	9.08	0.2	4.4	0.002		Chernykh 1966, pp. 98–99
	hache	kourgane	97	0.004	0.005			0.049		2.03	0.15	0.007		0.003	Chernykh 1966, pp. 101–102
	hache	kourgane	91.5	0.001	0.003	0.015	0.03	0.039	0.005	7.8	0.1	0.001			Chernykh 1966, pp. 101–103
	gouge, burin	kourgane	97	0.001	0.02	0.005	0.002	0.05	0.006	2.37	0.05	0.001			Chernykh 1966, pp. 101–103
	gouge, burin	kourgane	93.3	0.001	0.02	0.004	0.002	0.035	0.008	6.08	0.1	0.001			Chernykh 1966, pp. 101–103
	alène.	kourgane	93.2	0.001	0.01			0.012		6.06	0.2	0.01			Chernykh 1966, pp. 101–103

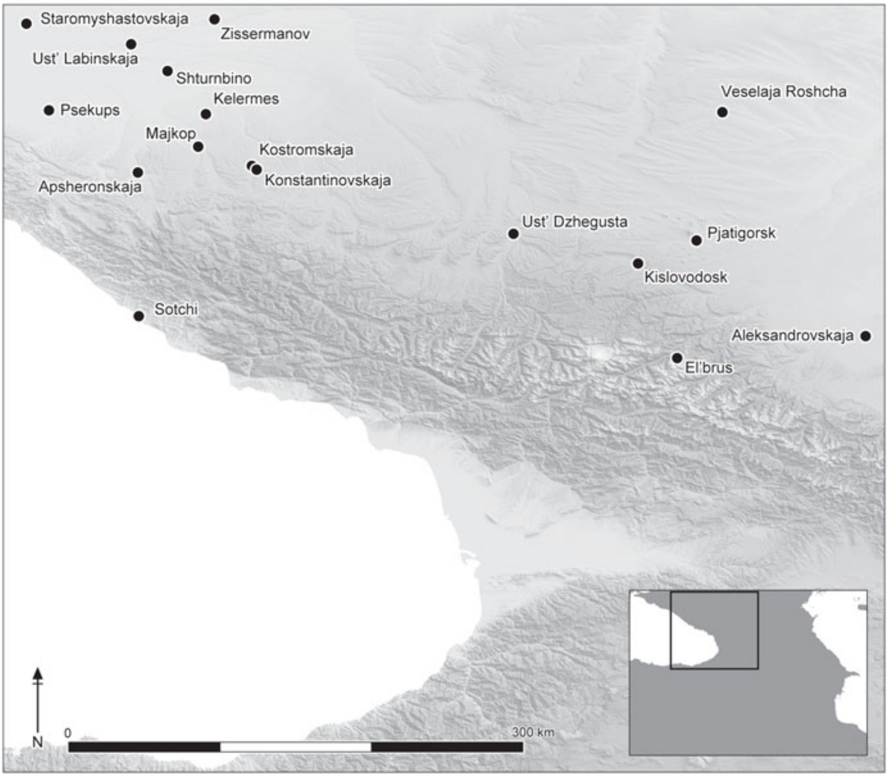


Fig. 22.14 Settlements attached to the Majkop culture—Majkop component. (Cassard et al. 2009, GIS project)

Lyonnet 2000, 2004) . Recent research by B. Lyonnet (2007a, b) has helped to distinguish two "components" of the Majkop culture: Majkop and Novosvobodnaja (Fig. 22.2). The end of the Meshoko and Sioni cultures in the late fifth/early fourth millennium BCE coincides with the beginnings of the "Majkop component" and a chronological overlap seems to have existed between these three cultural groups (Meshoko, Majkop and Sioni) (Fig. 22.2). The "Majkop component" was grafted onto the Meshoko cultural background but blended with foreign influences (Lyonnet 2007b, p. 134). Indeed, the Majkop component presents close similarities with material found in northern Mesopotamian settlements that are dated to the Late Chalcolithic (LC2-LC4) (ca. 3800–3500 cal. BCE). This period also corresponds to the final phase of the Early Uruk Period in Mesopotamia and the beginning of the Middle Uruk Period (Lyonnet 2007b, p. 148). Parallels have also been established between the Majkop ceramic material and that known from the contemporary Leilatepe–Berikleedebi culture of the southern Caucasus (Fig. 22.16).

As for the "Novosvobodnaja component" (Fig. 22.15), dated to ca. 3300–2600 BCE, part of its ceramic material presents affiliations with the preceding Majkop component. The rest of the pottery shows a number of similarities with the ceramic material of the Kura–Araxes culture of the southern Caucasus (Lyonnet 2007b,

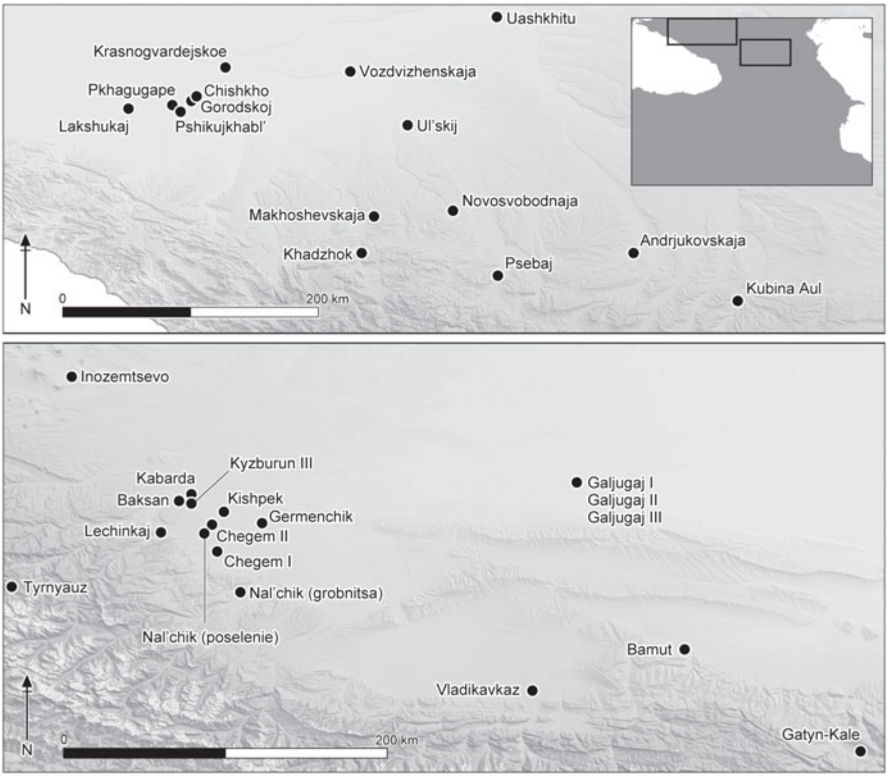


Fig. 22.15 Settlements attached to the Majkop culture—Novosvobodnaja component. (Cassard et al. 2009, GIS project)

p. 148; see below). By this time, the northern Mesopotamian features had begun to disappear.

It is thought that in the early fourth millennium BCE, the CBMP lost its importance in favour of the circumpontic metallurgical province (CMP), which covered, at its maximum geographical extent, a zone including the Caucasus, the Steppe area, the northern Balkans, the Carpathians, the Aegean, Anatolia and Mesopotamia (Chernykh et al. 2002, p. 83). As with the preceding province, the CMP corresponds to an arborescent scheme ("province", "zone", "focus", "nucleus") in which the different regions within it are seen as dependent upon one another. According to E. N. Chernykh (1978b, pp. 55–56), the beginning of the CMP coincides with the beginning of the Kura–Araxes culture—thought at that time to be more or less contemporary with the beginning of the Majkop culture, around the second half of the fourth millennium BCE (ca. 3500/3300 BCE) (Chernykh et al. 2002, p. 83). Chernykh based his argument upon the chronological framework that was then used by Soviet archaeologists. This framework has now been revised and confirmed by recent C14 dates. The beginning of the Majkop component (and thus the origins of his Circumpontic Metallurgic Province) should be dated back to the first half of the

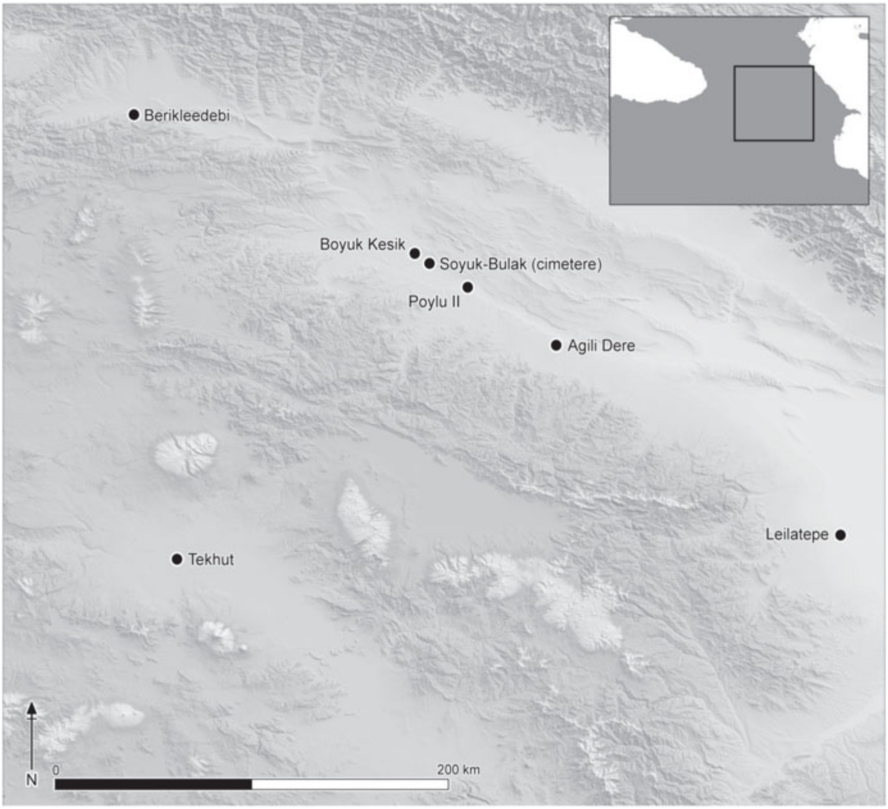


Fig. 22.16 Settlements attached to the Majkop culture – undefined component (Cassard et al., 2009. GIS project)

fourth millennium BCE (LC2) (Rassamakin 1999), earlier than the beginning of the Kura–Araxes culture.

Chernykh considered the metallurgy of the Majkop culture to be entirely dependent upon the southern Caucasus—principally the Kura–Araxes culture—due to a belief in migration theories, the hierarchical concept of the metallurgical province, the hypothesized lack of cupriferous hydrocarbonate (malachite, azurite, *etc.*) and cupronickelous ores in the northern Caucasus, as well as the apparent absence of furnaces in this region. Under this scheme, the Majkop culture is believed to have been a mere intermediary between the regions rich in ores (Anatolia, Iran, Transcaucasia) and those deprived of raw material for metallurgy (e.g. the Steppes) (Chernykh 1992, pp. 59–67). This theory was widely accepted by Soviet researchers (e.g. Abesadze et al. 1958; Korenevskij 1972, 1974).

Recent research in this region (Cassard et al. 2009; Courcier 2006, 2007, 2008; Courcier et al. 2009a, b), including the new chronological scheme proposed by B. Lyonnet (2004, 2007a, b, 2009), has led us to reconsider Chernykh's theory

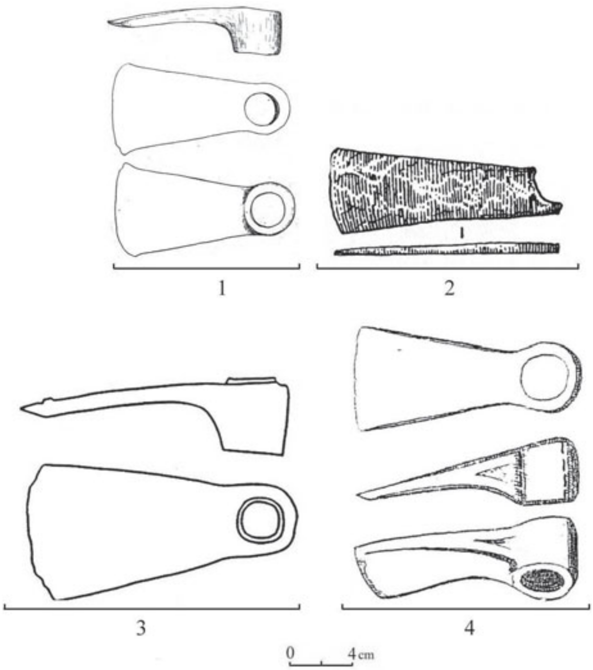


Fig. 22.17 Adzes coming from Majkop component settlements: *1* Galjugaj I (Korenevskij 1995, p. 170), *2* Konstantinovskaja (Markovin 1994a, p. 270), *3* Psekups (Lovpache 1985), *4* Maïkop (Chernykh 1966, p. 98)

on the northern Caucasus's dependence on the southern Caucasus. It is clear that metallurgy expanded significantly in both regions during the first half of the fourth millennium BCE. Two major categories of metallurgy can be distinguished: copper objects and precious metals (gold and silver). The former is characterized by a spread of technologies and a rise in the quantity and diversity of the objects made. The latter is notable for some of the most elegant and complex workings of gold and silver alloys anywhere in the Old World at this time. Due to the importance of this new research in overturning long-held theories about the technological dominance of the southern Caucasus over the northern Caucasus, the Majkop material is laid out in detail below.

Metallurgy of Copper Objects (Majkop and Novosvobodnaja)

Tools

Throughout the Majkop and Novosvobodnaja phases, there was continuity in certain types of metal objects—notably awls and bracelet even from the previous period (Meshoko culture). Some new tool types appeared in the Majkop phase and most continued into the Novosvobodnaja phase. These consist of hollow chisels, flat axes (Fig. 22.18), adzes (Fig. 22.17), axe-adzes and plain chisels (both types only known in the Majkop kurgan). These tools seem linked to woodworking rather than to

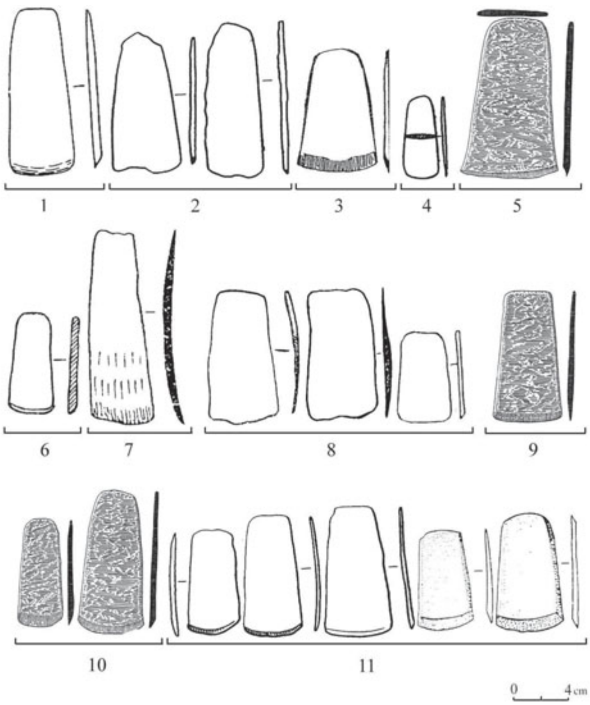


Fig. 22.18 Flat axes found in settlements attached to Majkop component and Novosvobodnaja component. **Majkop component:** *1* Apsheronskaja (Chernykh 1992, p. 75), *2* Majkop (*Idem* 1966, p. 98), *3* Psekups (Lovpache 1985), *4* Sturbino (Chernykh 1966, p. 98 and 100–101). **Novosvobodnaja component:** *5* Bamut (Ibidem; Munchae 1994, p. 206), *6* Chegem II (Betrozov and NaGoev 1984, p. 42), *7* Chirkejskogo (Makhmundov et al. 1968), *8* Kishpek (Miziev 1984, p. 92), *9* Kuban area (Chernykh 1966, p. 98 and 100–101), *10* Makhoshevskaja (Munchaev 1994, p. 206), *11* Novosvobodnaja (ibidem)

agricultural production or military activities as proposed by Korenevskij (2004, pp. 45–46). Similar adzes are known at Ordzhoshani (Georgia), which is linked to the Kura–Araxes culture (Dzhibladze 2005, pp. 100–101) and at Susa in southwestern Iran[9] (Deshayes 1960, p. 233; Tallon 1987, p. 174). Axe-adzes were present in the Carpatho-Balkan area since the first half of the fifth millennium BCE (Gernez 2007, p. 248) and moulds of this tool type have been discovered at Tepe Ghabristan (Period II) and Tepe Sialk (Period III, 4–5) in Iran, both dating to the fourth millennium BCE (Amiet 1986, p. 42; Gernez 2007, p. 248). Since the axe-adzes have only been discovered in the Majkop kurgan, their presence could confirm existing contacts between the northern Caucasus and the Carpatho-Balkan area, while also showing new relations with Iran. Interestingly, Deshayes (1960, p. 41 and 107) also suggested an Iranian influence for the flat axes and the hollow chisels. However, Mesopotamian contacts have also been attested during the Majkop phase (Lyonnet 2007b) and we cannot rule out the idea that Mesopotamia may have influenced a local production of metal artefacts in the northern Caucasus.

During the Majkop phase, the pickaxe (Fig. 22.19) appears for the first time at sites such as Ust'-Labinskaja and El'brus (Ryndina 2003, pp. 16–17). Similar stone and bone pickaxes were known in the previous Meshoko culture (e.g. at Jasenova Poljana, Veselogo and Svobodnoe) (Munchaev 1975, p. 191; Nekhaev 1992, p. 88), which, as

[9] Undated artefact.

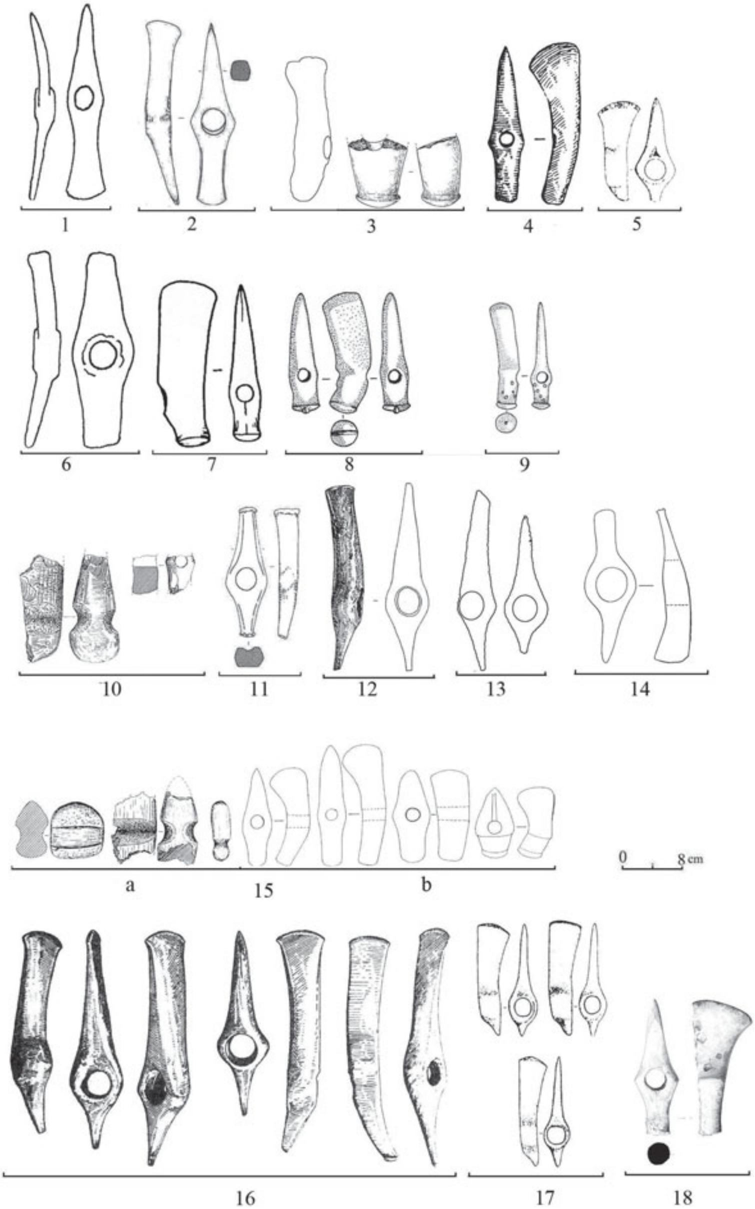


Fig. 22.19 Pickaxes discovered in settlements attached to the Majkop and Kura–Araxes cultures and in Iran. **Majkop component**: *1* Elbrus area (metal; Ryndina 2003, p. 17), *2* Ust'-Labinskaja (ibid.). **Novosvobodnaja component**: *3* Gatyn-Kale (stone; Markovin 1963, p. 92), *4* Mikhajlovskaja (stone; idem 1994a, p. 270), *5* Lenchinkaj (metal; Batchaev 1984, p. 131), *6* Vladikavkaz (metal; Ryndina 2003, ibid.), *7* Vodzdvizhenskaja (metal; Chernykh 1992, p. 75), *8* Novosvobodnaja (stone), *9* Klady (metal; Masson 1997, p. 69). **Kura–Araxes**: *10* Kabaz-Kutan (stone; Gadzhiev et al. 2000, p. 55), *11* Rugudzha (metal; Chernykh 1991, p. 585), *12* Alaverdi (metal; Martirosjan and Miatsakanjan 1973, p. 125), *13* Dmanisi (ibid.), *14* Leninakan (Martirosjan 1964, p. 32), *15a* Velikent tell II, *15b* Velikent tell III grave 11 (stone; Gadzhiev et al. 2000, p. 64 and 93). Other: *16* Dzhrashen (metal; Chernykh 1992, p. 64–65), *17* Sé Girdan (metal; Muscarella 2003, p. 126), *18* Suse (metal; Tallon 1987, p. 75)

shown earlier, was in contact with the Carpatho-Balkan area. The two metal pickaxes discovered in the northern Caucasus are indeed typologically close to models known in the Carpatho-Balkan area (Jászladány Devnja and Siria types) (Ryndina 2003, p. 15; Gernez 2007, pp. 249–251). Because of its composition in "pure copper", the undated pickaxe from Ust'-Labinskaja was considered by Chernykh (1991, pp. 585–590; 1992, p. 48) to be an import from the Carpatho-Balkan area. Since there is no real proof for that, and since pure copper objects are also known in the Caucasus, the label of "import" requires further evidence.

During the Novosvobodnaja phase, the pickaxes are still present alongside a new variant, the axe-hammer. It differs from the pickaxe by its convex and circular shoulder. These two types are known in several settlements (Fig. 22.16; Klady, Vozdvizhenskaja, Lenchinskaj and Vladikavkaz) and are close to stone models in the same or contemporary settlements (Fig. 22.19; Gatyn-Kale, Novosvobodnaja and Mikhajlovskaja). The diffusion of this tool (and its variant) in the northern Caucasus during the Novosvobodnaja component is concomitant with the appearance of pickaxes (in metal or stone) in many Kura–Araxes settlements. It should be underlined that Lyonnet (2007b) has already noted strong parallels between Novosvobodnaja and Kura–Araxes ceramics. Parallels made with pickaxes from Se-Girdan (Muscarella 2003, p. 124) and Susa[10] (Tallon 1987, pp. 97–99) also suggest continued contact with Iran.

New tools appeared during the Novosvobodnaja phase such as needles, hooks, forks and rolled rods[11]. Contrary to the tools of the Majkop phase, the tools of the later Novosvobodnaja phase have no real parallels with other contemporaneous cultures in the Caucasus or beyond, except with the Kura–Araxes (e.g. a fork found at Dag-Ogni in Dagestan; Gadzhiev 1991, p. 192). It seems likely that the metal artefacts of the Novosvobodnaja phase are mainly local productions.

The socketed axe appeared during the Majkop phase at a number of sites (Fig. 22.20). During the Novosvobodnaja phase, numerous socketed axes are characterized by different shapes of the blade. The exact function of the socketed axes is not clear—they could be either tools or weapons—but they are important for the first use of the socket. Socketing was probably mastered first in the Carpatho-Balkan area during the fifth millennium BCE (Gumelnitsa/Karanovo VI cultures) and suggests the use of bivalve moulds (Gernez 2007, p. 173 and 546). This technique could have come from the Carpatho-Balkan area, although it is surprising that no evidence of bivalve mould use is known from the previous culture (Meshoko), which was in contact with the Carpatho-Balkan area during the fifth millennium BC.

[10] Undated axe-hammer.

[11] Possibly parts of bits for horses according to Munchaev 1975: 209, although this has been contested.

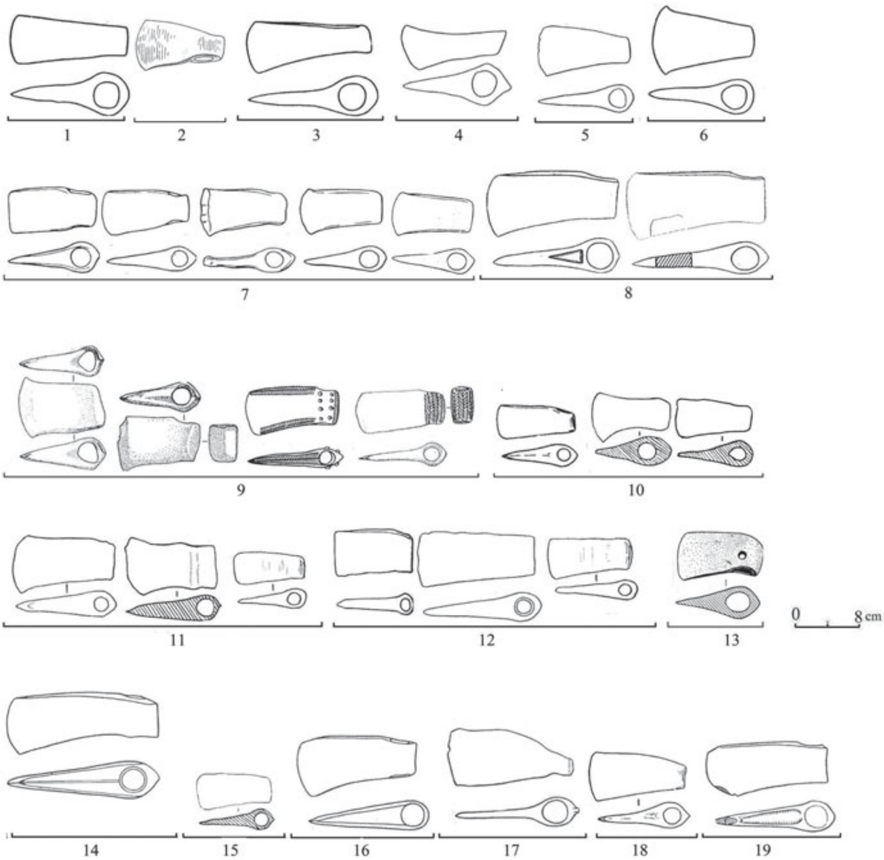


Fig. 22.20 Socketed axes coming from the Majkop culture. **Majkop component**: *1* Majkop (Chernykh 1992, p. 75), *2* Kostromskaja (Munchaev 1975, p. 259), *3* Ust'-Dzhegusta (Korenevskij 1974, p. 17), *4* Pjatigorsk (Korenevskij 1972, p. 336), *5* Apsheronskaja (Idem 1974, p. 20), *6* Balaklava (Idem, p. 17). **Novosvobodnaja component**: *7* Novosvobodnaja (Chernykh 1966, p. 98; Korenevskij 1974, p. 20; Munchaev 1975, p. 250; Chernykh 1992, p. 75), *8* Andrjukovskaja (Korenevskij 1974, p. 24), *9* Klady (Masson 1997, p. 270), *10* Chegem II (Betrozov 1984, p. 42; Chernykh 1992, p. 75), *11* Kishpek (Chechenov 1980, p. 21; Miziev 1984, p. 92), *12* Nal'chik (Chernykh 1966, p. 100; Korenevskij 1974, p. 20), *13* Bamut (Munchaev 1975, p. 259), *14* Dolinka (Korenevskij 1974, p. 22), *15* Kyzburun III (Miziev 1984, p. 101), *16* Lakshukaj (Korenevskij 1974, p. 24), *17* Psebaj (Ibidem). **Undefined component:** *18* Khashi (Chernykh 1992, p. 75), *19* Anatas'evskaja (Korenevskij 1974, p. 24)

Weapons

During the Majkop phase, new types of weapons appear: daggers with flat blades (Fig. 22.21) and tripartite spearheads (e.g. at Psekups). The dagger coming from the Majkop kurgan shows that the technique of riveting was known even in the early phase; during the next period (Novosvobodnaja) a similar technique was widely used.

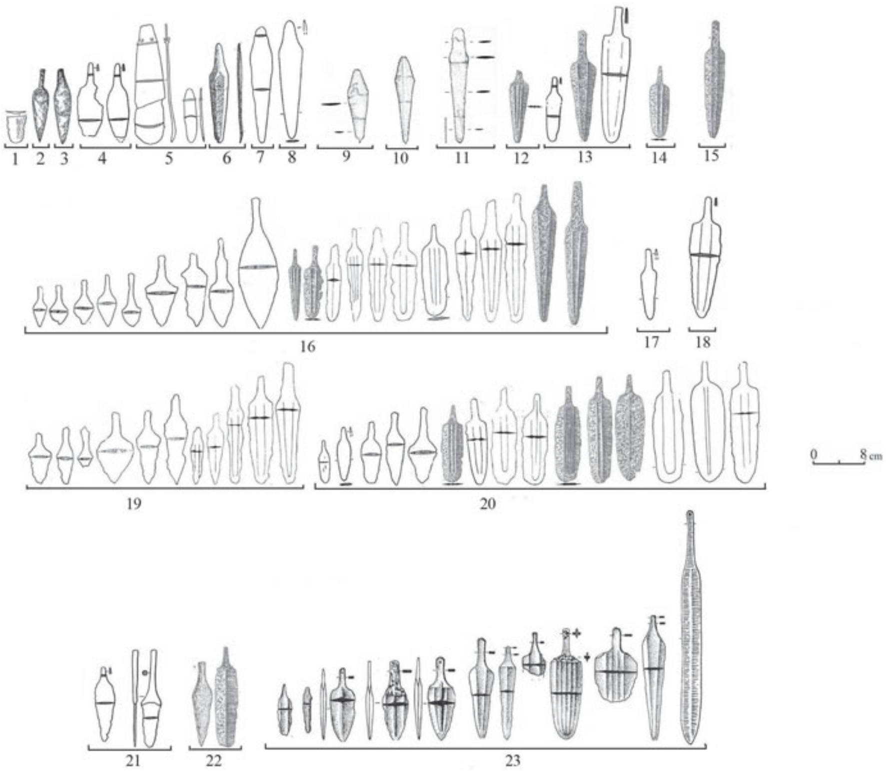


Fig. 22.21 Daggers found in settlements linked to the Majkop culture. **Majkop component:** *1* Galjugaj I (Korenevskij 1995, p. 170), *2* Kislovodsk (Markovin 1994a, p. 270), *3* Konstantinovskaja (ibid.), *4* Kostromskaja (Chernykh 1966, pp. 101–102), *5* Majkop (Chernykh 1966, p. 100, 1992, p. 75), *6* Psekups (Lovpache 1985, p. 32), *7* Zissermanov (Chernykh 1966, pp. 100–101), *8* Aleksandrovskaja (Chernykh 1992, p. 75), *9* Zunda-Tolga (Shishlina 2008, p. 30), *10* Chograj (ibidem), *11* Mandjikiny. **Novosvobodnaja component**: *12* Baksan (Munchaev 1994, p. 204), *13* Bamut (Chernykh 1992, ibidem), *14* Kyzburun III (Miziev 1984, p. 101), *15* Krasnogvardejskaja (Munchaev 1994: *idem*), *16* Chegem I (Betrozov and NaGoev 1984, p. 45 et 70), *17* Kubina Aul (Chernykh 1992, p. 75), *18* Timachevsk (Chernykh 1966, p. 98 et 100–101), *19* Chegem II (Chernykh 1966, p. 102; Betrozov and NaGoev 1984, p. 45 and 70; Munchaev 1994, p. 204), *20* Kishpek (Betrozov and NaGoev 1984, pp. 37–39 and 70; Munchaev 1994, p. 204), *21* Novosvobodnaja (Chernykh 1992, p. 75), *22* Nal'chik (Markovin 1994a, p. 264), *23* Klady (Masson 1997, p. 270)

Similar but narrower daggers are known in the Leilatepe–Berikldeebi culture (Boyuk-Kesik and Soyuq-Bulaq), which is contemporaneous with the Majkop component (Museibli 2007, p. 85, Fig. XL; Akhundov 2007, p. 106; Lyonnet 2007b, p. 150; Courcier et al. 2008a, p. 21). During the Novosvobodnaja phase, daggers with flat blades continue to exist while new types with ribbed blades appear (Fig. 22.21). This new type of dagger is characteristic of this period and seems to be a local production. Similar models are known later in the Near East during the Early Bronze Age III period (ca. 2600 BCE) at Tell Melebiya (phase 2), Tell Brak, Uruk and Mari (Gernez 2007, pp. 489–490).

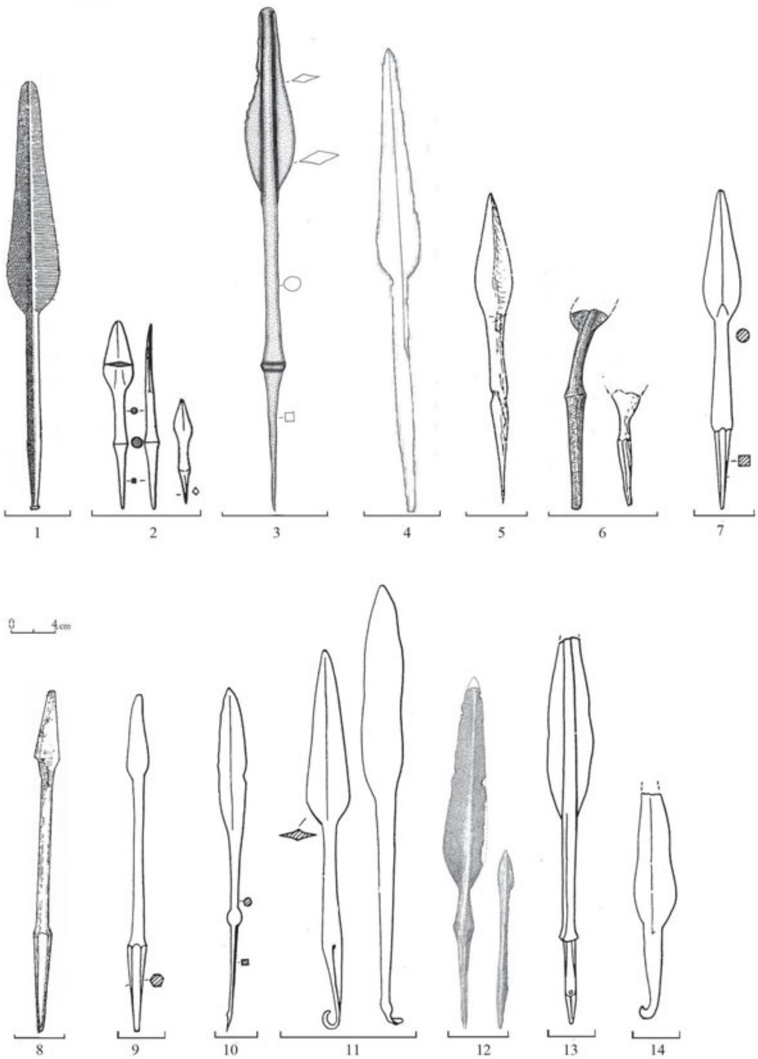


Fig. 22.22 Tripartite spearhead discovered in settlements of the Majkop culture (Novosvobodnaja component) and the Kura–Araxes culture. **Novosvobodnaja component**: *1* Psekups (Lovpache 1985, p. 33), *2* Novosvobodnaja (Chernykh 1966, p. 98; Idem, 1992, p. 75), *3* Klady (Rezpkin 2000, p. 12), *4* Psebaj (Museum of Saint-Petersburg). **Kura–Araxes**: *5* Chirkejskogo (Gadzhiev 1991, p. 140), *6* Sigitma (Gadzhiev 1991: *idem*; Markovin 1994b, p. 292), *7* Akhaltsikh (Kushnareva and Chubinishvili 1970, p. 124), *8* Tskhinvali (Tekhov and Dzhaparidze 1971, p. 66), *9* Osprisi (Kushnareva 1997, p. 199), *10* Sevan (*ibidem*), *11* Tbilisi (*ibidem*), *12* Telman-Kend (*ibidem*), *13* Tsartis-Gora (*ibidem*), *14* Zemo-Avchalskaja (*ibidem*)

The Novosvobodnaja phase is also characterized by the apparition and wide diffusion of the tripartite spearheads (Fig. 22.22). Spearheads similar to these are also known in Kura–Araxes settlements. A large diffusion of this weapon type seems to

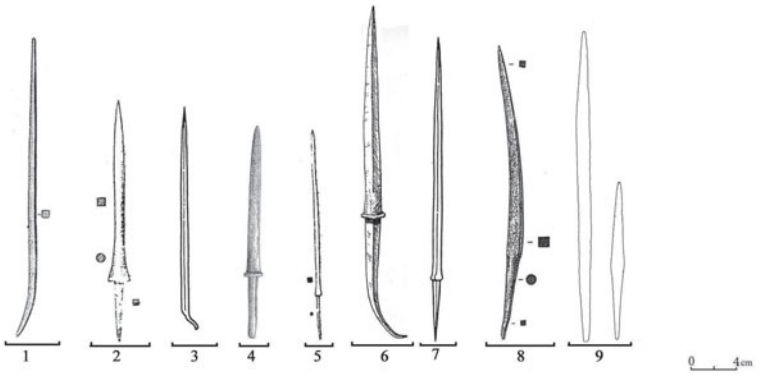


Fig. 22.23 Spearheads, whose head was prolonged with a sharp wedge-shaped blade and finished with a pike, in the Majkop culture (Novosvobodnaja component) and the Kura–Araxes culture. **Novosvobodnaja component**: *1* Bamut (Mnchaev 1975, p. 306). **Kura–Araxes**: *2* Akhalchihskogo grave (Amiranis-Gora) (Kushnareva et al. 1963, p. 15), *3* Khachbulag (Schachner 2002, p. 124), *4* Kul'tepe II (Kushnareva and Chubinishvili 1970, p. 124), *5* Kvatskhelebi (*ibidem*), *6* Tsartis Gora (*ibidem*), *7* Verkhnegunibskoe (Gadzhiev 1991, p. 192)

have occurred throughout the northern and southern Caucasus at the end of the fourth millennium BCE, spreading into eastern Anatolia, northern Syria and as far as Turkmenistan by the first half of the third millennium BCE (Gernez 2007, pp. 296–298; Courcier 2007, p. 215). A second type of spearhead appeared during the Novosvobodnaja phase—i.e. a pike with a square section (Fig. 22.23; Munchaev 1975, p. 306; Korenevskij 1986, p 7). This type is also close to examples known in the Kura–Araxes culture (Kushnareva and Chubinishvili 1963, 1970, p. 124 and 170; Schachner 2002, p. 124). This again underlines the strong parallels between these two cultures. Similar pikes are also known during the Early Bronze Age II/III (ca. 2800–2600 BCE) at Tell Kara Hassan (Woolley 1914, pl. 19), Jerablus-Tahtani and Carchemish (Woolley and Barney 1952, pl. 60–61; Gernez 2007, pp. 285–286).

Copper Vessels and Other Objects

The Majkop phase is also characterized by the appearance of copper vessels. Discoveries made in the Majkop kurgan and at Kislovodosk illustrate these metal types (Munchaev 1975, p. 213; 1994a, p. 199 and 209). They show that the techniques of cold-hammering, annealing and embossing were already fully mastered. During the next period (Novosvobodnaja), the copper vessels become more widespread (Munchaev 1994, p. 208; Shishlina 2008, p. 41).

Some particular metal objects confirm the diversity of metal production during the Majkop phase, including a square-section rod at Kelermes (Munchaev 1975, p. 225), a helix-shaped object at Majkop (Munchaev 1975, p. 213) and hoops at Majkop (Munchaev 1994, p. 199). This diversity is still attested during the Novosvobodnaja phase with the presence of discs at Klady and Chegem I (Bochkarev et al. 1980, p. 97;

Fig. 22.24 Silver and gold artefacts coming from the Majkop kurgan. (Korenevskij 2004, Plate VI)

Betrozov and NaGoev 1984, p. 11), a wheel with four spokes at Klady (Bochkarev et al. 1980, p. 97), metal sheet at Chegem I (Korenevskij 1984, p. 189) and metal plates at Chegem I (Betrozov and NaGoev 1984, p. 16).

Copper ornaments, already known in the Meshoko culture, are present in settlements linked to the Novosvobodnaja phase and represented by beads, pendants, earrings, rings, wristbands and cones at Chegem I, Chegem II and Kyzburun III (Betrozov and NaGoev 1984, p. 18, 30, 32, 36; Chechenov 1984, p. 209; Miziev 1984, p. 100).

Metallurgy of Precious Metals (Gold and Silver)

Precious metals had appeared in the northern Caucasus already by the Majkop phase in the first half of the fourth millennium BCE. Such finds are mainly illustrated by the treasures of the Majkop and Staromyshastovskaja kurgans (Figs. 22.24, 22.25 and 22.26). The number of precious metal artefacts found in the Majkop kurgan is extraordinary: 68 gold strips with stamped gold lions and bull figurines; 2 gold vases; 14 silver vases (2 of which were ornamented); many gold rivets and nails; a stone macehead with its upper part in gold; 10 gold rosettes; many silver and gold beads (often decorated in relief); numerous gold rings; and 6 long rods of silver on

Fig. 22.25 Gold and silver necklaces found at Majkop, arsenical copper and gold animal figurines coming from Staromyshastovskaja. (Korenevskij 2004, Plate VII)

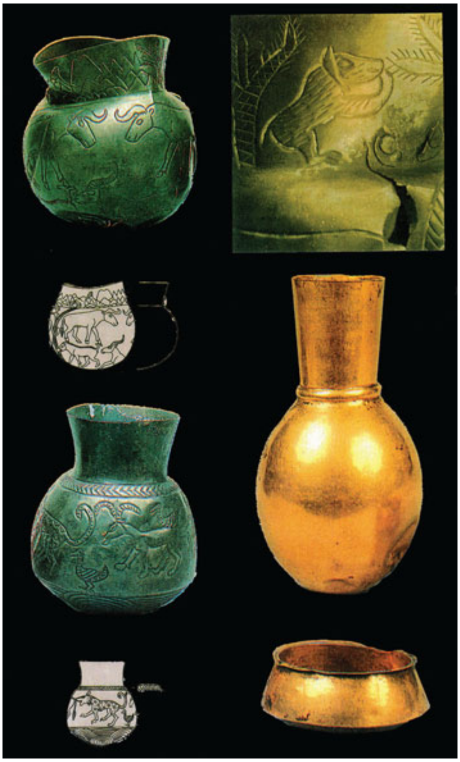


Fig. 22.26 Gold and arsenical copper wares coming from Galugaj I, Alikovovskoe and Majkop. (Korenevskij 2004, Plate III)

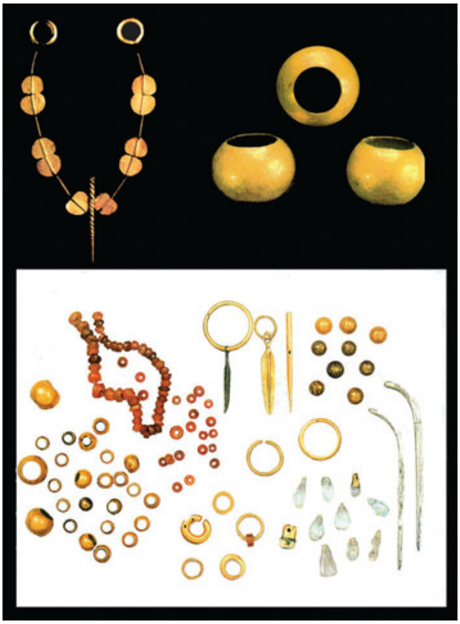


Fig. 22.27 Jewellery ornaments found at Novosvobodnaja. (Korenevskij 2004, Plate VIII)

which gold and silver bull figurines were attached (Munchaev 1975, p. 213 et seq.). Similarly, the Staromyshastovskaja Treasure included: 1 silver vase; 2 silver figurines of a bull and an antelope; 1 gold lion head figurine; 3 gold rosettes; 40 small rings; and over 2,500 gold and silver beads (Rostovtsev 1918, p. 8–25; Munchaev 1975, p. 213 *sqq*.; 1994a: 199). In both collections, all of this precious metal ornamentation was accompanied by numerous semi-precious stones including turquoise, carnelian and even lapis-lazuli.

In other kurgans linked to the Majkop phase, other precious metal artefacts were also discovered, like the silver vessel from Staryj Urukh (Munchaev 1975, p. 228) and the silver rings found in two kurgans in the north of the Stravropol hills (Kuma-Manych depression; Shishlina 2008, p. 28). These discoveries present some parallels with the 23 gold beads, 33 electrum beads, 2 electrum rings and numerous semi-precious stone beads coming from the kurgans of Soyuq-Bulaq in Azerbaijan, which are considered to be related to the Leilatepe–Berikldeebi culture and therefore contemporaneous with the Majkop phase (Lyonnet et al. 2008; Courcier et al. 2008a). Other parallels can be drawn with the material of kurgans III and IV at Se-Girdan in north-western Iran (Muscarella 1969, p. 20; 1971, pp. 11–12; see also 2003), at Tepe Gawra in north-eastern Iraq dating to levels XI, XA, X and IX, ca. 4000–3600 BCE (Rothman 2002, p. 105, 111–127, 282–285 and 366–381) and at Hacinebi in eastern Turkey, from an infant's tomb dated to the Late Chalcolithic A, ca. 4100–3800 BCE (Stein et al. 1997, p. 142; 1999a: 167). These parallels between the northern Caucasus (Majkop component), Transcaucasia (Leilatepe–Berikldeebi culture) and northern Mesopotamia present evidence for the pre-Uruk expansion which affected both slopes of the Caucasus at the same time (LC 2–4) (Lyonnet 2007b, p. 150; 2009, pp. 5–6).

During the next phase (Novosvobodnaja), starting around 3500/3400 BCE, the use of precious metals continued (Fig. 22.27). In many kurgans (e.g. Novosvobodnaja, Klady, Kubina Aul, Kishpek, Chegem I, Nal'chik and Bamut), prestigious objects in gold and silver were discovered including beads, rings, needles, awls, sheet fragments and wristbands associated with carnelian, rock crystal and lapis-lazuli beads (Chechenov 1973, pp. 119–120; Munchaev 1975, pp. 242–244, 273, 305). Some parallels seem also to exist with Tell Brak, level TW 16 (LC2) (Emberling and McDonald 2003) and Arslantepe (level VIB "Royal Tomb", ca. 3000–2900 BCE; Frangipane et al. 2001; Hauptmann et al. 2002; Norcera et al. 2004). Besides these examples, relations with the surrounding areas seem them to have been much reduced during the Novosvobodnaja phase.

Questions on the Composition of Metals (Majkop and Novosvobodnaja Phases)

The chemical composition of Majkop and Novosvobodnaja phase artefacts (Tables 22.4 and 22.5) constitutes the basis of Chernykh's theories about Majkop metallurgy (Chernykh 1966: 44–50; 1992: pp. 157–160). His analysis of 85 objects related to the Majkop culture[12] (4 coming from Meshoko, 15 from the Kuban area, 24 from kurgans related to Phase I and 42 to Phase II), led him to identify two groups of metal objects characterized either by a low percentage of nickel (< 0.1 % Ni) or by a high percentage of nickel (0.1 to 4.4 % Ni) (Chernykh 1966, p. 38). In these two groups, the percentage of arsenic is very similar: 0.5–9.08 % and 0.70–10 % As, respectively (Chernykh 1966, p. 43). Chernykh also considered that these two groups corresponded respectively with the two phases of the Majkop culture, and underlined the importance of high nickel concentrations for assigning artefacts to the later phase (*ibid.*).

On the basis of Selimkhanov's work (Selimkhanov 1960a, b, 1962, 1964), Chernykh (1966, pp. 44–46) further detailed the areas and settlements with metal objects containing nickel (i.e. Transcaucasia, Iran, Anatolia and Mesopotamia) and the copper deposits characterized by nickel ores in Transcaucasia and eastern Anatolia. In his discussion, he mentions that the copper deposits situated in the northern Caucasus contain many impurities but no nickel and are almost entirely sulphidic ores (Chernykh 1966, p. 49). As a proponent of the linear "historical–technical" scheme[13], he thus concluded that Majkop metallurgy was wholly dependent upon the metal products manufactured by the Kura–Araxes population in the South who could take advantage of more favourable metallogenical conditions (Chernykh 1966, pp. 49–50).

In order to characterize Majkop metallurgy, these results need to be reconsidered.

As we have seen, the analyses made in the 1960s do not allow us to characterize with certainty the metal composition of the objects related to the Majkop component. However, two alloys seem to have been used: Cu–As and Cu–As–Ni. The origin of the nickel depends on the ores but also on the possible recycling of objects. The

[12] As Chernykh (1966: 38) defined it, with Phase I corresponding more or less to the Majkop phase mentioned in this article and his Phase II to the Novosvobodnaja phase.

[13] According to which native copper was used first, then carbonaceous and oxides ores, and finally sulphidic copper ores.

Table 22.5 Analyses of metal artefacts found at Novosvobodnaja. (Selimkhanov 1962, p. 75; Chernykh 1966, p. 98–103; percent type not précised)

n° analyse	Type d'objet	Localisation	Composition percent												Reference
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	Au	
	fourche	kourgane 6	95.2	0.008	0.18		0.003	0.015	0.003	4.08	0.02	0.001		0.0005	Selimkhanov 1962, p. 75, Table I
	hache	kourgane 2	94.7	0.0005	0.01			0.004	0.005	4.73	0.01	0.001			Selimkhanov 1962, p. 75, Table I
	hache	kourgane 2	97.45	0.001	0.07		0.007	0.042	0.005	1.95	0.005	0.002		0.002	Selimkhanov 1962, p. 75, Table I
	hache	kourgane 1	90.8	0.001	0.04		0.001	0.022	0.015	6.68	0.02	1.9	0.002	0.001	Selimkhanov 1962, p. 75, Table I
	pointe de lance tripartite	kourgane 4	96.6	0.0005	0.002			0.013		2.7	0.15	0.001		0.0005	Selimkhanov 1962, p. 75, Table I
	ciseau muni d'une gouge	kourgane 5	96.3		0.1		0.002	0.005	0.005	3.16	0.02	0.007			Selimkhanov 1962, p. 75, Table I
	poignard	kourgane 7	92.9		0.08		0.005	0.025	0.005	6.49	0.05	0.001		0.001	Selimkhanov 1962, p. 75, Table I
	fragment d'objet	kourgane 7	majoritaire	0.001	0.1		0.003	0.023	0.015	0.7		0.003		0.002	Selimkhanov 1962, p. 75, Table I
	herminette	kourgane 8	89.4	0.001	0.001			0.003	0.007	10	0.01	0.001			Selimkhanov 1962, p. 75, Table I
	dague	kourgane 8	91.3		0.07	0.004	0.002	0.017		8.07	0.01	0.001		0.002	Selimkhanov 1962, p. 75, Table I
10	burin	kourgane 2, tombe 2	majoritaire		0.01		0.001	0.05	0.003	1.7	0.001	0.45			Chernykh 1966, pp. 98-99
959	couteau arc manche	kourgane 2, tombe 2	majoritaire		0.003		0.001	0.5	0.005	1.2	0.009	0.35			Chernykh 1966 pp. 98-99
963	puisoir	kourgane 1, tombe 1	majoritaire	un peu	0.016		0.006	0.025		0.8	0.001	0.004			Chernykh 1966, pp. 101–102
946	hache	kourgane 1, tombe 1	majoritaire		0.001		0.001	0.003		2	un peu	0.003			Chernykh 1966, pp. 101–102

Table 22.5 (continued)

n° analyse	Type d'objet	Localisation	Composition percent												Reference
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	Au	
948	hache	kourgane 1, tombe 1	94.7	0.0005	0.01			0.004	0.005	4.73	0.01	0.001			Chernykh 1966, pp. 101–102
947	hache	kourgane 1, tombe 1	majoritaire		0.005		0.002	0.01		0.65		0.007			Chernykh 1966, pp. 101–102
957	hache	kourgane 1, tombe 1	majoritaire		0.006		0.001	0.02		1.3	un peu	0.003			Chernykh 1966, pp. 101–102
960	hache plate	kourgane 2, tombe 2	majoritaire					0.006		4.5	0.001	0.003			Chernykh 1966, pp. 101–102
955	hache plate	kourgane 2, tombe 2	majoritaire					0.0007		3.4	un peu	0.001			Chernykh 1966, pp. 101–102
954	hache plate	kourgane 1, tombe 1	majoritaire				< 0.001	0.0005		2		0.001			Chernykh 1966, pp. 101–102
956	hache plate	kourgane 1, tombe 1	89.4	0.001	0.001			0.003	0.007	10	0.001	0.001			Chernykh 1966, pp. 101–102
962	fourche	kourgane 1, tombe 1	majoritaire	0.001	0.012		0.003	0.019		1.8	un peu	0.004			Chernykh 1966, pp. 101–102
953	pointe de lance	kourgane 1	96.6	0.0005	0.002			0.013		2.7	0.15	0.001		0.0005	Chernykh 1966, pp. 101–102
1060	couteau	kourgane 1	majoritaire				0.001	0.006		4	0.001	0.003			Chernykh 1966, pp. 101–102
951	ciseau	kourgane 1	majoritaire		0.02		0.004	0.016		0.8		0.003			Chernykh 1966, pp. 101–102
950	ciseau	kourgane 1	96.3		0.1		0.002	0.005	0.005	3.16	0.02	0.007			Chernykh 1966, pp. 101–102
952	ciseau	kourgane 1	majoritaire		0.001		0.002	0.01		2		0.003			Chernykh 1966, pp. 101–102
	poignard	kourgane 1	92.2		0.08		0.005	0.025	0.005	6.49	0.05	0.001		0.001	Chernykh 1966, pp. 101–103
	chaudron	kourgane 1	majoritaire	0.001	0.1		0.003	0.023	0.015	0.7	0.03	0.003		0.002	Chernykh 1966, pp. 101–103
	poignard	kourgane 1	91.3		0.07		0.002	0.017		8.07	0.01	0.001		0.002	Chernykh 1966, pp. 101–103

question of whether the ores used to make these alloys came from the south or the north must await further studies.

Questions on Metalworking (Majkop and Novosvobodnaja Phases)

Metallographic studies by N. V. Ryndina and I. G. Ravich of dagger blades from kurgans of the Novosvobodnaja phase have demonstrated the presence of two styles of metalworking (Ryndina and Ravich 1995). The first style involves casting the object and then carrying out an alternating series of cold-working and annealing steps in order to obtain a more homogenous microstructure. The second style consists of casting and cold-working the object, then annealing it once before cold-working it again. The blades made via the first method present fewer impurities, while blades made via the second method contain higher amounts of nickel. Both metalworking styles are probably local to the Caucasus (Ryndina and Ravich 2000). However, according to the authors of these studies, the existence of two metalworking styles may suggest the specialisation of a particular group of metalworkers. Therefore, these metallurgical "traditions" illustrate the manner in which metal production was locally organized and specialized at different sites (Ryndina and Ravich 1995, p. 12).

These conclusions are akin to Tedesco's research on metallurgy in Armenia during the Early Bronze Age. She identified close parallels between the microstructures of the Novosvobodnaja daggers and the metallography she performed on two blades found at Yerevan (Armenia) dated to the beginnings of the third millennium BCE (ca. 2800–2700 BCE). In spite of typological differences between her daggers and those studied by Ryndina and Ravich, the manufacturing sequences show close similarities, such as ghost dendritic structures with heavily strained and compressed grains along the cutting edges. However, the Yerevan daggers did not present the same degrees of segregation as in the Novosvobodnaja daggers (Tedesco 2006a, p. 207, pp. 235–236). Her studies led Tedesco to propose the absence of large-scale production in the Majkop phase. On the contrary, she argued for the existence of household-level production but following a standardized technical tradition, which could explain the widespread uniformity of metallurgy in Transcaucasia and the northern Caucasus (Tedesco 2006a, p. 205, pp. 315–322). Her hypothesis is in accordance with our own research, which demonstrates strong similarities between the Novosvobodnaja and the Kura–Araxes metallurgical styles (see Courcier 2010).

Questions on Extractive Metallurgy (Majkop and Novosvobodnaja Phases)

Among the 204 ore deposits known in the northern Caucasus, 57 contain copper, and 17 deposits, irrespective of the copper deposits, contain arsenic as the main element. Some of these deposits present natural associations of copper and arsenic. In addition, nickel is present in numerous ore deposits in the northern Caucasus (Cassard et al. 2009). An important metalliferous potential thus exists in this area.

These deposits would have been more than adequate for supplying the ores used in the production of metal objects of the Majkop component (Cu–As and Cu–As–Ni alloys). Furthermore, many gold and silver deposits are known from the northern Caucasus. Silver ores correspond to native formations or are linked with Pb–Zn ores. Gold is present in native form, often associated with copper or silver (Cassard et al. 2009).

No research concerning ancient extractive metallurgy has been done in the northern Caucasus for the Majkop component. Chernykh theory about the reliance of the Majkop culture upon Kura–Araxes metalworkers of the South has remained unchallenged until now, thus discouraging scholars from even exploring the possibility of local ore extraction in the northern Caucasus. However, thanks to local geological research carried out between 1920 and 1933 by A.A Iessen and B. E. Degen-Kovalevskij, we know of several settlements in the northern Caucasus which could be directly or indirectly connected with extractive metallurgy (Iessen and Degen-Kovalevskij 1935, pp. 36–41). Although the deposits remain undated, their descriptions constitute invaluable information. When combined with our recent survey data of the ore deposits of the region, it is clear that the deposits with noticeably ancient exploitation all contain either argentiferous ores associated with lead or cupriferous ores associated with some arsenic and even nickel. It is also important to note that recent research by C. Hamon (2007, pp. 192–196) on stone tools from Majkop sites has provided further evidence of extractive metalworking in this region.

The Origin of Majkop Metallurgy

There are a variety of theories on the origins of metallurgy in the Majkop culture. First, many authors have suggested that the metal objects discovered in the Majkop culture were imported from Mesopotamia based on typological and iconographic similarities (e.g. Rostovtsev 1918, pp. 24–25; Childe 1936; Betancourt 1970; Sulimirski 1970, pp. 123–125; Andreeva 1977, 1979; Nekhaev 1986). Chernykh, as we have already seen, has suggested that Majkop metallurgy was derived from highland cultures of the Middle East (Iran, Anatolia) via Transcaucasia (Kura–Araxes) (Chernykh 1966, pp. 45–50; Chernykh 1992, pp. 65–73 and 155–160). Such theories of "migration waves" from the Middle East also helped to explain Mesopotamian influence on the Majkop culture (Munchaev 1975, pp. 322–329; 1994a, pp. 169–170; Korenevskij 2004; Akhundov 2007).

Far rarer are arguments in favour of a local basis for Majkop metallurgy (e.g. Iessen 1950, p. 191; Munchaev 1975, pp. 322–335, 1994a, pp. 199–209, 2005, pp. 13–15). Such indigenous origins theories are based on the existence of deposits in the northern Caucasus with different metalliferous minerals that parallel the composition of metal objects of the Majkop culture. Other scholars underline the unique character of certain types of metal production which are only known in the northern Caucasus (e.g. Formozov 1965, p. 117; Korenevskij 1974, 1988a, pp. 93–95) as well as local styles of metalworking (e.g. Ryndina and Ravich 1995).

Our own research supports the idea of a local metal industry in the Majkop culture. The metallurgical processes, most likely originating in the Carpatho-Balkan area and already known during the preceding Meshoko culture, were probably further developed by the Majkop population. It seems that this western influence continued into the beginning of the Majkop phase, as suggested by the introduction of the socket and the metal pickaxe. We cannot exclude, however, that metallurgical technologies in the Majkop culture were also influenced by exchanges with the southern Caucasus, especially with the Sioni culture. As we saw above, the Majkop culture had relations with several areas (Transcaucasia, north-western Iran and eastern Anatolia) where metallurgy had already started, and its metallurgy shows close similarities with that of the Leilatepe–Berikldeebi culture (below).

Nevertheless, several types of objects (flat axes, tripartite spearhead, adzes, copper vessels, gold and silver vessels and gold and silver zoomorphic figurines) seem to be typical only of the Majkop culture, both during the Majkop phase and during the Novosvobodnaja phase. During this later phase, we see an intensification of local metal production and, except for the ornaments and some types of weapons (like tripartite spearheads), the parallels with the neighboring regions seem to disappear. Interestingly, contact is still apparent with the Kura–Araxes culture of Transcaucasia (below).

Metallurgy of the Leilatepe–Berikldeebi Culture

During the Late Chalcolithic 2–4, the "Pre-Uruk" expansion can be traced in Transcaucasia within several settlements (Fig. 22.16). We group these sites together under the name of the Leilatepe–Berikldeebi culture, which is contemporaneous with the early phase of the Majkop culture. Compared to the previous cultures known in this area (Shomu–Shulaveri and Aratashen), metallurgy shows a more similar development to that observed for the Majkop phase.

At Tekhut in Armenia, three metal objects (a small knife, an awl and an arrowhead) were discovered that were shown to have been made of arsenical copper (Selimkhanov and TorosJan 1969). Metallographic studies on these pieces suggest cold-hammering, although their results are difficult to utilize (Tedesco 2006a, p. 104). In level V1 of Berikldeebi in Georgia, the discovery of a copper wristband and of a copper flat axe (Žavaxišvili 1998) confirms the appearance of metallurgy during this period. This is even more noticeable at Leilatepe in Azerbaijan, where several metal artefacts have been discovered: awls, wire, fragment of a curved plate and extremity of a knife/dagger (Akhundov 2007, pp. 103–108). Moreover, in Building 4 at Leilatepe, prills and rest of melting mixed with ashes and slags suggest the manufacturing of metals. According to T. Akhundov (2007, p. 107), one of the 11 ovens discovered on site was probably associated with metallurgy given its proximity to where the metal artefacts were discovered. We cannot discuss here in detail the results of the analysis done on the metal artefacts, but we can nevertheless underline this paradox that copper prills come mainly from the slags (Aliev and Narimanov 2001, p. 135; Akhundov 2007, p. 106). The authors do not explain this fact which, for us, suggests an uncontrolled smelting process.

Recently, six awls, a plate, two daggers with rivets, metal slag and a stone axe mould were discovered (Table 22.6) at Boyuk-Kesik in Azerbaijan (Museibli 2007,

Table 22.6 Analyses of several artefacts coming from Boyuk-Kesik. (Museibli 2007, p. 86, percent type not précised)

n° analyse	Type d'objet	Localisation	Composition percent (massique)												Reference
			Cu	Sn	Pb	Zn	Bi	Ag	Sb	As	Fe	Ni	Co	Au	
25	lame poignard (analyse 1)	Boyuk Kesik	96.8	0.041	0.014	0.018	0.0006	0.00016	0.0027	0.0008	0.034	0.054	0.054	0.0005	Museibli 2007, p. 86
26	lame poignard (analyse 2)	Boyuk Kesik	97.86	0.012	0.006	0.0107	0.0008	0.00001	0.0006	0.0008	0.024	0.0005	0.0001	0.0005	Museibli 2007, p. 86
27	lame poignard (analyse 3)	Boyuk Kesik	96.9	0.008	0.005	0.0012	0.0007	0.00003	0.0006	0.0012	0.012	0.0024	0.0005	0.0005	Museibli 2007, p. 86
28	lame poignard (analyse 4)	Boyuk Kesik	96.42	0.012	0.0056	0.0018	0.0006	0.00002	0.0008	0.0019	0.016	0.0016	0.0009	0.0005	Museibli 2007, p. 86
29	lame poignard (analyse 4)	Boyuk Kesik	97.14	0.014	0.0048	0.0007	0.0012	0.00004	0.0005	0.0021	0.009	0.0015	0.0006	0.0005	Museibli 2007, p. 86
30	lame poignard (analyse 5)	Boyuk Kesik	96.15	0.016	0.0034	0.0012	0.0005	0.00003	0.0009	0.0012	0.008	0.0012	0.0012	0.0005	Museibli 2007, p. 86
31	lame poignard (analyse 6)	Boyuk Kesik	97.5	0.0024	0.003	0.0008	0.0007	0.00006	0.0007	0.002	0.012	0.0016	0.0005	0.0005	Museibli 2007, p. 86
32	lame poignard (analyse 7)	Boyuk Kesik	95.8	0.0018	0.0051	0.001	0.0004	0.00007	0.0012	0.0016	0.014	0.0017	0.0001	0.0005	Museibli 2007, p. 86
33	lame poignard (analyse 8)	Boyuk Kesik	97.54	0.012	0.006	0.008	0.0008	0.00002	0.0016	0.0008	0.016	0.0012	0.0002	0.0005	Museibli 2007, p. 86
34	fragment de poignard	Boyuk Kesik	96.44	0.064	0.086	0.0005	0.0005	0.00002	0.0008	0.0006	0.062	0.014	0.0003	0.0005	Museibli 2007, p. 86
35	fragment de poignard	Boyuk Kesik	96.9	0.0028	0.021	0.0007	0.0006	0.00001	0.0006	0.0005	0.057	0.009	0.0002	0.0005	Museibli 2007, p. 86
36	objet en forme de balle	Boyuk Kesik	93.6	0.046	0.096	0.024	0.0004	0.00003	0.0007	0.0008	0.012	0.0012	0.0001	0.0005	Museibli 2007, p. 86
37	fragment de couteau	Boyuk Kesik	96.14	0.016	0.063	0.096	0.0006	0.00001	0.0012	0.0004	0.021	0.014	0.0002	0.0005	Museibli 2007, p. 86
38	Fragment d'alène	Boyuk Kesik	97.5	0.024	0.0012	0.008	0.0007	0.00001	0.0008	0.0005	0.01	0.0006	0.0002	0.0005	Museibli 2007, p. 86
39	fragment de couteau	Boyuk Kesik	96.8	0.013	0.006	0.0008	0.0008	0.00001	0.0021	0.0008	0.01	0.0008	0.0001	0.0005	Museibli 2007, p. 86

Fig. 22.28 Dagger coming from kurgan 1 of Soyuq-Bulaq. (Lyonnet et al. 2008, p. 31)

pp. 85–87). The daggers are typologically close to those found at Majkop, which is more or less contemporaneous. Nearby, in kurgan 6 of Soyuq-Bulaq, another similar dagger (although without rivets) has also been found (Akhundov 2007, p. 106), and various other metal objects (bead, awl and fragment of blade) come from the same cemetery of kurgans. The excavations carried out on other kurgans of this cemetery by a French–Azerbaijani team, co-directed by B. Lyonnet and T. Akhundov, has confirmed the diversity of the Leilatepe–Berikldeebi metallurgy: 33 beads in silver–gold alloy (probably electrum), 23 gold beads, a copper knife/dagger, two copper rings and a copper awl have been unearthed (Lyonnet et al. 2008, pp. 30–34; Courcier et al. 2009a). A stone sceptre with an equid head and numerous semi-precious stone beads (e.g. cornaline, steatite, lapis-lazuli) were also found there. Recent analyses and metallographic studies (Figs. 22.28, 22.29, 22.30, 22.31 and 22.32; Tables. 22.7, 22.8, 22.9, 22.10, 22.11 and 22.12) performed on this material have demonstrated a high manufacturing level for the silver–gold beads (Figs. 22.33, 22.34, 22.35, 22.36, 22.37, 22.38, 22.39 and 22.40) (Courcier et al. 2009a). Preliminary proveniencing on these beads has suggested that the ores used could come from four close districts: Madneuli, Sakdrisi–Bolnissi (Georgia), Dagkesaman (Azerbaijan) or Alaverdi (Armenia). Only future research, in particular on the gold beads, could allow for a more precise origin to be proposed.

The metal objects from Soyuq-Bulaq present similarities with the Majkop component (Majkop and Staromyshastovskaja Kurgans) as well as with Se-Girdan, Tepe Gawra and Hacinebi as mentioned above. All of these examples demonstrate the rather widespread use of precious metals in combination with copper-base alloys at the very earliest stages of silver and gold use in the ancient Near East.

Fig. 22.29 Silver beads found in kurgan 1 of Soyuq-Bulaq. (Lyonnet et al. 2008, p. 34)

Fig. 22.30 Gold beads found in kurgan 1 of Soyuq-Bulaq. (Lyonnet et al. 2008, p. 34)

Fig. 22.31 Silver rings found in kurgan 4 of Soyuq-Bulaq. (Lyonnet et al. 2008, p. 38)

Metallurgy of the Kura–Araxes Culture

The Kura–Araxes culture (also called the Early Transcaucasian or Karaz culture) (Fig. 22.41) appeared in the second half of the fourth millennium BCE (ca. 3400/3300 BCE, at the end of LC4) and lasted until the end of the third millennium BCE. Its very long duration led to several divisions which are still a matter of debate (e.g.

Fig. 22.32 Awl found in kurgan 4 of Soyuk-Bulaq. (Lyonnet et al. 2008, p. 38)

Table 22.7 Results of analyses (EDS analyses) of the silver beads whose compound is characterized by silver-with little traces of copper. (Courcier et al. 2009a, p. 23)

Lab.	Artef.	Composition (weight percent)														
		O	Mg	Si	S	Cl	Ca	Cu	Ag	Br	Au	Sn	Pb	Zn	Sb	Fe
Bm	Bead 1	13.7	0.28	3.28	0.67	6.57	13.52		40.22	21.58						
Bm	Bead 1	7.47	0.25	2.47	0.17	6.81	8.29		49.25	25.29						
Bm	Bead 1	11.08	0.33	1.32	0.39	5.71	18.25		39.38	23.53						
Bm	Bead 1	7.39		2.44		7.04	8.3	0.41	49.09	25.34						
Bm	Bead 3	17.3		1.02	0.76	4.23	33.23	2	29.81	11.65						
Bm	Bead 3	15.88		2.21	0.82	5.33	26.41		34.15	15.21						
Bu	Bead 3							1.57	35.14		0.034	0.02	0.2	0.2	0.02	0.05

Table 22.8 Results of analyses (EDS analyses) of the silver beads whose compound is characterized by an alloy of silver-gold-copper. (Courcier et al. 2009a, p. 24)

Lab.	Artef.	Composition (weight percent)								
		O	Si	S	Cl	Ca	Cu	Ag	Br	Au
Bm	bead 2	8.75	1.93		7.59	5.86		46.01	24.01	5.86
Bm	bead 2	5.63	1.99		7.81	1.99		51.41	25.79	5.38
Bm	bead 2	5.52	0.66		7.7	1.78		46.38	16.59	21.36
Bm	bead 2	2.17	2.55		2.05	0.27	5.5	19.17	8.26	60.04
Bm	bead 2	0.72	0.34		6.75		0.6	56.03	30.52	
Bm	bead 2	0.18	0.31		6.54		0.04	57.23	30.76	
Bm	bead 2	3.08	1.35		8.26		2.77	50.24	15.96	18.34
Bm	bead 2	18.91	1.78		1.27	33.77	5.31	9.56	0.74	28.66
Bm	bead 2	8.27	1.48		6.88	10.11	0.87	43.27	22.4	6.71
Bm	bead 2	10.91	1.89		8.6		2.74	46.4	14.75	14.71
Bu	bead 2						5.32	50.02		41.03
Bm	bead 6	15.54	1.67	0.89	5.86	24.07		34.51	15.08	2.37
Bm	bead 6	5.55	1.36	0.5	10.11	1.08		57.44	23.5	0.47
Bm	bead 6	20.19	0.74	0.98	2.98	31.49	1.58	22.61	4.13	15.31
Bm	bead 6	21.69	1.71		2.19	36.25	3.96	17.66		15.51
Bm	bead 6	2.73	1.87	0.35	8.65	0.16		58.06	28.17	
Bm	bead 6	18.69	1.85		2.26	31.27	3.77	21.53	5.36	15.26
Bm	bead 6	16.33	1.41		3.35	30.48	2.7	29.51	8.95	10.88
Bm	bead 6	2.56	1.5	0.12	9.42	0.24		59.21	26.95	
Bu	bead 6						1.58	34.72		6.95

Table 22.9 Results of analyses (EDS analyses) of the silver beads whose compound is characterized by an alloy of silver–gold. (Courcier et al. 2009a, p. 24)

Lab.	Artef.	Composition (weight %)													
		O	Mg	Si	Cl	Ca	Cu	Ag	Br	Au	Sn	Pb	Zn	Sb	Fe
Bm	bead 4	4.23		1.6	7.26	4.45		48.24	20.21	14					
Bm	bead 4	3.22		0.75	6.17	2.02		48	11.16	27.89					
Bm	bead 4	4.63		1.33	7.72	4.55		52.67	16.99	11.68					
Bm	bead 4	8.27	0.3	2.51	6.5	6.38		42.94	15.62	17.29					
Bm	bead 4	4.2		0.75	6.91	4.08		45.37	15.45	9.51					
Bm	bead 5	19.18	7.23	13.61	5.8	2.73		32.78	18.12						
Bm	bead 5	20.83	8.32	16.18	5.59	1.78		30.94	16.35						
Bm	bead 5	21.93				36.33		21		21.04					
Bu	bead 5						0.72	30.45		8.12	0.02	0.05	0.2	0.2	0.15

Table 22.10 Results of analyses (EDS analyses) of the silver rings. (Courcier et al. 2009a, p. 27)

lab.	Artef.	Composition (weight percent)																
		O	Al	Si	Cl	Ca	Cu	As	Ag	Br	Au	Sn	Pb	Zn	Sb	Ni	Co	Fe
Bm	Ring 1	1.85	1.13	2.61	0.99	2.04	2.66		83.19		5.54							
Bm	Ring 1		0.9	3.52	0.57		2.69		87.85		4.49							
Bm	Ring 1	10.14		2.84	3.87	13.71	2.06	0.13	51.86	10.62	4.77							
Bm	Ring 1	0.87		3.38	0.7	0.18	2.53		87.96	0.23	4.15							
Bu	Ring 1						1.9	0.03	51.57		9.5	0.02	0.03	0.05	0.2	0.01	0.02	0.12
Bm	Ring 2	10.08		1.12	7.17	8.66			42.79	26.42	3.77							
Bm	Ring 2	2.79		0.6	9.14	1.53	0.58		56.23	28.6	0.54							
Bm	Ring 2	19.08		2.11	3.32	20.87	5.15		17.35	9.36	21.74							
Bu	Ring 2						1.5	0.03	51.85	9.7		0.02	0.05	0.02	0.05	0.005	0.02	0.12

Table 22.11 Results of analyses (EDS analyses) of the awl. (Courcier et al. 2009a, p. 28)

Sector	Artefact type	Composition (weight percent)																	
		O	Al	Si	S	Cl	Ca	Cu	As	Br	Ni	Sn	Pb	Zn	Sb	Au	Bi	Co	Fe
K. 1	awl	3.95		0.44		0.24		92.34	1.2	0.32	1.51								
K. 1	awl	4.07	0.52	0.53	0.14	0.75		91.87	0.72		1.39								
K. 1	awl	3.18	0.61	0.34				95.87											
K. 1	awl	4.2	0.54	0.44		2		90.01	2.83										
K. 1	awl	6.19	0.48	0.49	0.11	0.27		79.29	6.79		6.38								
K. 1	awl	4.14	0.35	0.26		2.89	0.26	88.94	2.36		0.79								
K. 1	awl							90.05	1.2		1.18	0.03	0.1	0.2	0.2	0.055	0.03	0.2	0.12

Table 22.12 Results of analyses (EDS analyses) of the dagger. (Courcier et al. 2009a, p. 29)

Sector	Artefact type	Composition (weight percent)																
		O	Al	Si	Cl	Ca	Cu	As	Sn	Pb	Zn	Sb	Ag	Au	Bi	Ni	Co	Fe
K. 1	Dagger	10.42	0.77	0.23	15.76	0.3	71.24	1.29										
K. 1	Dagger	15.78	0.53	0.13	22.67	0.22	62.67											
K. 1	Dagger	10.89	0.42	0.05	18.31	0.14	68.66	1.51										
K. 1	Dagger	11.67	0.61	17.52		0.19	68.59	1.42										
K. 1	Dagger	13.18	0.65	17.96		0.34	65.76	2.1										
K. 1	Dagger						70.21	1.17	0.37	0.05	0.21	0.25	0.005	0.05	0.03	0.01	0.3	0.2

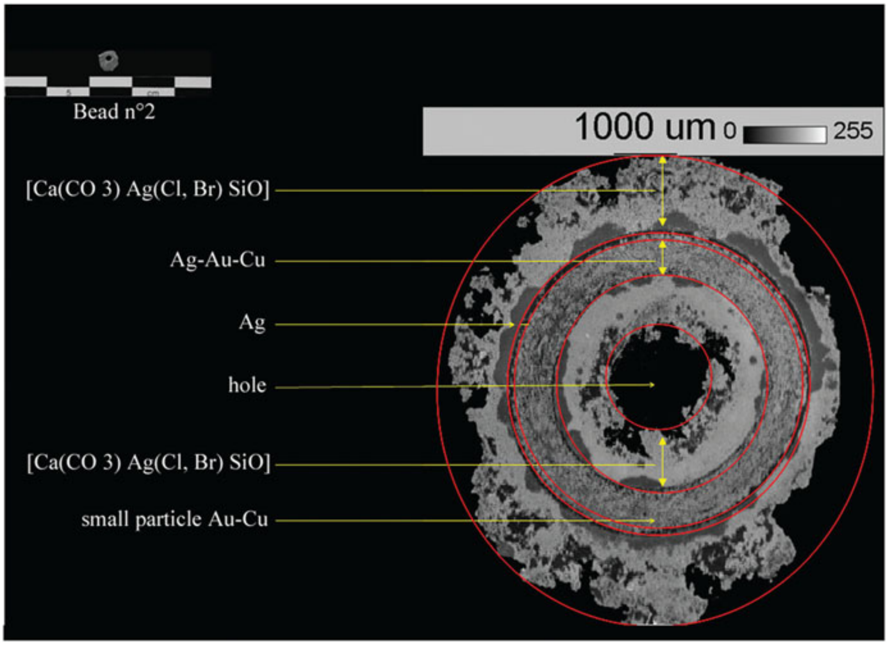


Fig. 22.33 Section of bead no.°2 with SEM observations. (Courcier et al. 2009a, p. 24)

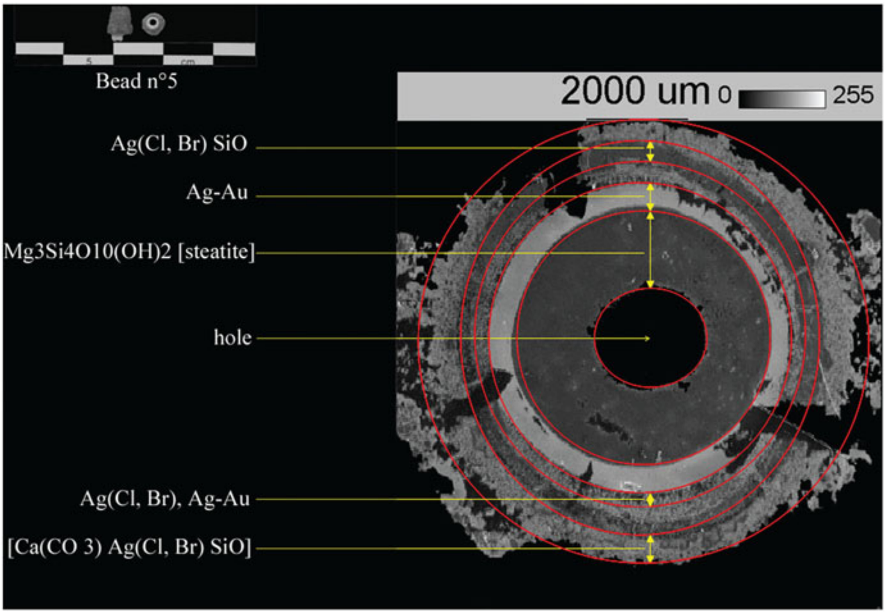


Fig. 22.34 Section of the bead no.°5 with SEM observations. (Courcier et al. 2009a, p. 24)

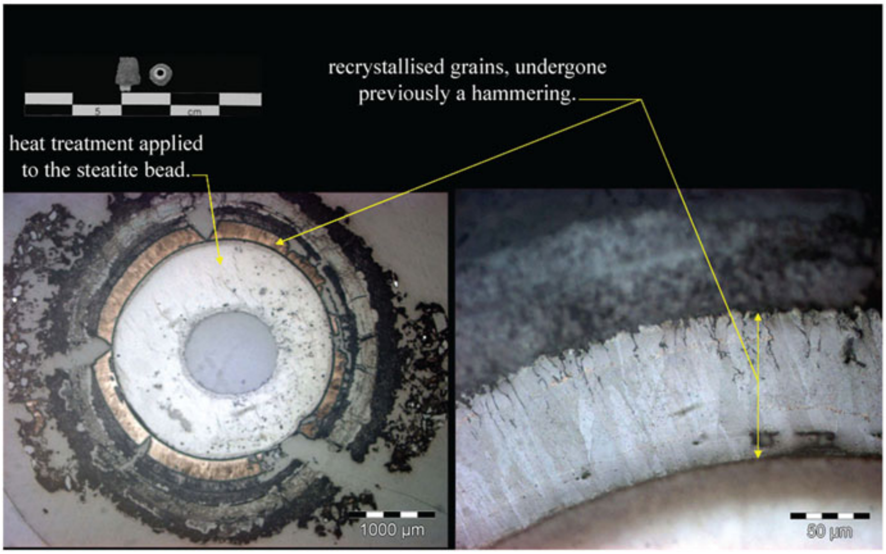


Fig. 22.35 Microstructure of bead no.°2, etched sample, magnifications 50 × and 100 × . (Courcier et al. 2009a, p. 25)

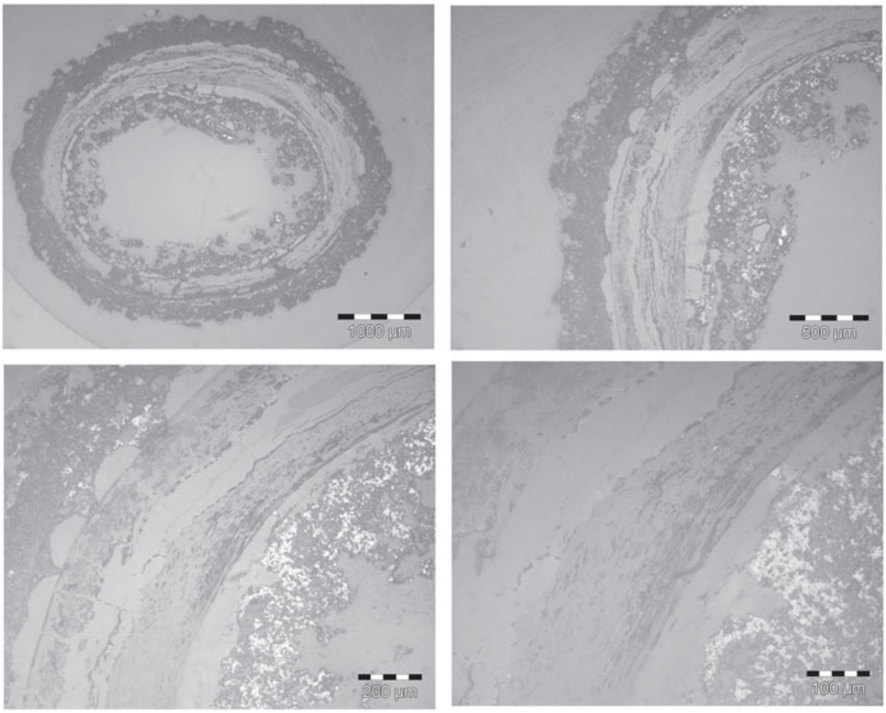


Fig. 22.36 Microstructure of bead no.°3, etched sample, magnifications 25 × , 50 × , 100 × and 200 × . (Courcier et al. 2009a, p. 26)

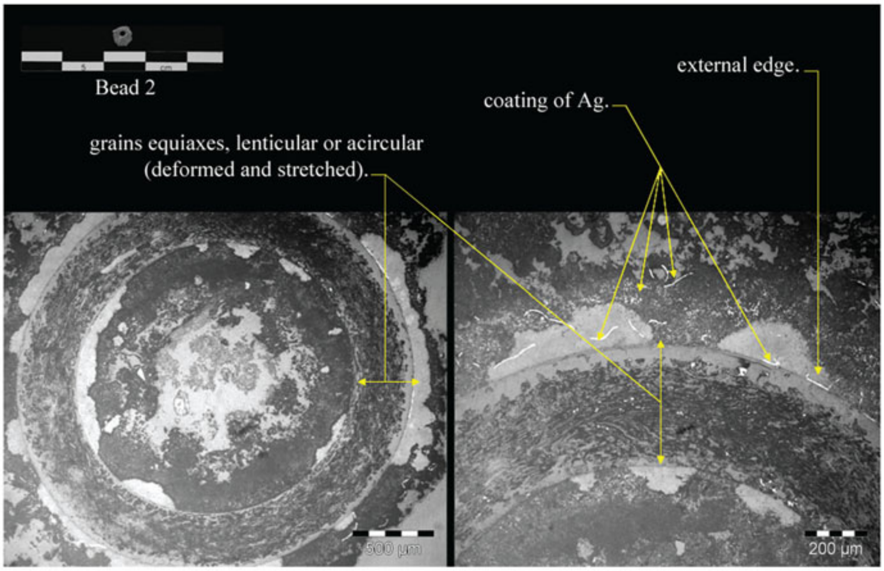


Fig. 22.37 Microstructure of bead no.°5, etched sample, magnifications 50 × and 100 × . (Courcier et al. 2009a, p. 26)

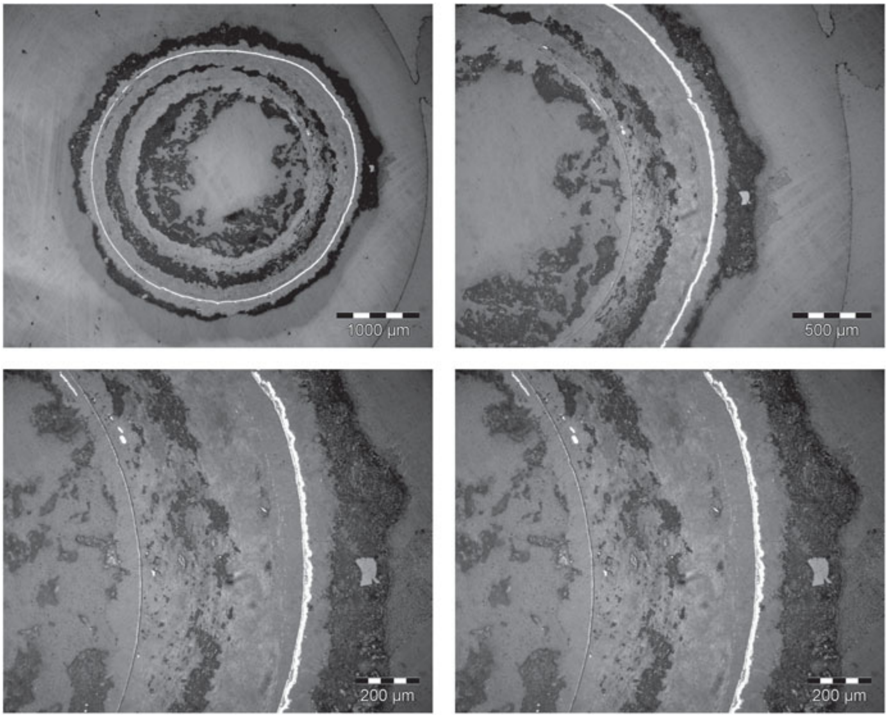


Fig. 22.38 Microstructure of bead no.°6, etched sample, magnifications 25 × , 50 × , 100 × and 200 × . (Courcier et al. 2009a, p. 27)

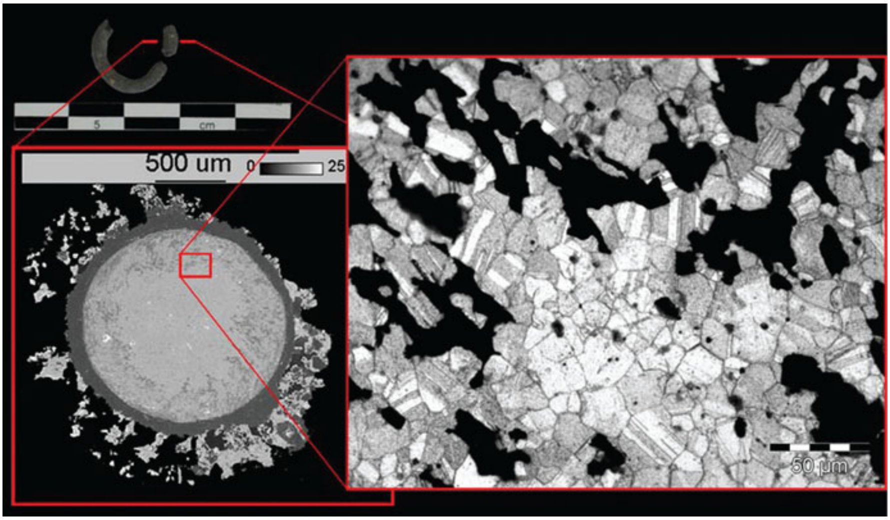


Fig. 22.39 Metallographic studies of ring no.°1, etched sample, magnifications 500 × . (Courcier et al. 2009a, p. 28)

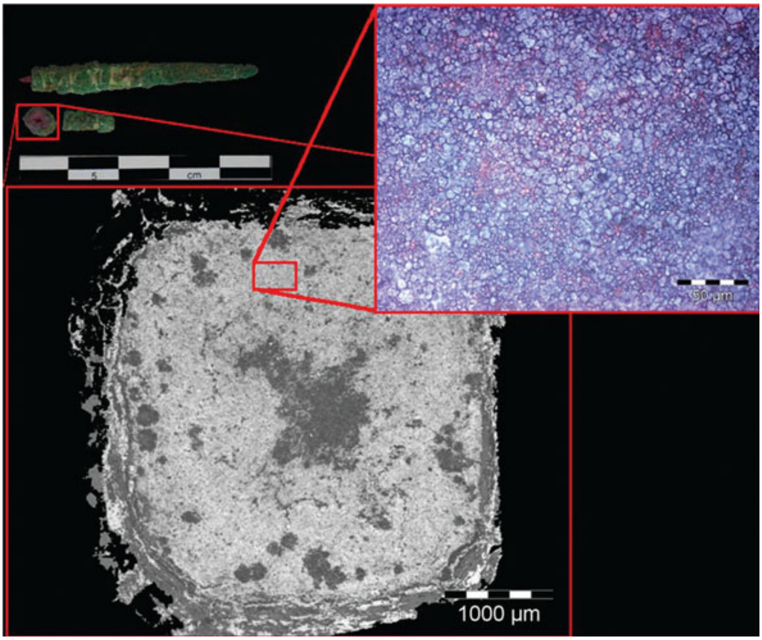


Fig. 22.40 Metallographic studies of the awl, etched sample, magnifications 500 × . (Courcier et al. 2009a, p. 29)

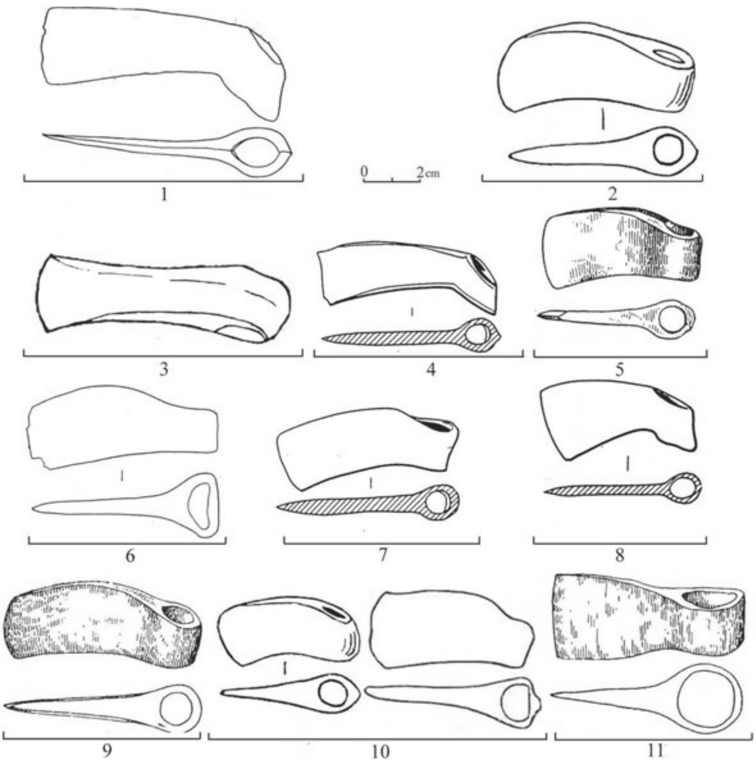


Fig. 22.41 Socketed axes coming from Kura–Araxes settlements. *1* Ararat region (Khanzadjan 1964), *2* Brdadzor (*Ibidem*), *3* Dzhrashen (Chernykh 1992, pp. 64–65), *4* Egmiadzin (Kushnareva 1997, p. 201), *5* Kulbakeli (*Ibidem*), *6* Leninakan (*Ibidem*), *7* Marneuli (*Ibidem*), *8* Medzhvriskhev (*Ibidem*), *9* Sadakhlo (*Ibidem*), *10* Jalbuzi (Korenevskij 1974; Kushnareva 1997, p. 201), *11* Zemo-Avchalskaja (*Ibidem*)

Kushnareva 1997; Kavtaradze 1999; Marro 2000; Sagona 2000). The earliest sites of this culture are found between the Kura and Araxe Rivers in Transcaucasia, but are unknown in the western part of Georgia (Fig. 22.41). P. L. Kohl (2007, p. 88) also includes south-eastern Dagestan in the early Kura–Araxes culture, although he specifies that Velikent is not a "Kura–Araxe variant" (Munchaev 1975, pp. 172–191) but rather a distinct culture of its own (Kohl 2007, p. 103).

Around 3000 BCE, the Kura–Araxes culture began to spread into eastern and central Anatolia and eventually into the northern Levant (Sagona 2000, p. 340; Frangipane and Palumbi 2007, p. 253). This phenomenon is documented through the diffusion of red-black-brown burnished ceramics characteristic of this culture (Frangipane 2000; Rothman 2003). Close relations between the Upper Euphrates, north-eastern Anatolia and Transcaucasia had begun in the preceding LC4 period and continued into the LC5/early Kura–Araxes period (Frangipane and Palumbi 2007, pp. 253–254). The Kura–Araxes phenomenon is, however, strongly regionalized, leading to distinct cultures such as Novosvobodnaja in the North-West Caucasus, Velikent in the North-East Caucasus and Kura–Araxes in the southern Caucasus and eastern Anatolia (Lyonnet 2007a, *idem*). An additional regional variant is known from north-western Iran (Summers 2004), north-central Iran (Thornton 2009, p. 18, 67) and in the central Zagros (Weiss and Young 1975; see Rothman 2005). The internal divisions of the Kura–Araxes chronology as well as its finale are still the subject of much debate (e.g. Muscarella 2003, p. 90; Sagona 2004, pp. 477–479; Magomedov 2006, pp. 153–155; Kohl 2007, pp. 86–88; Makharadze 2008, pp. 66–67).

One aspect of the Kura-AraxesKura–Araxes culture that remains undisputed is the strong evidence for local metallurgical production and metalworking. At Amiranis Gora in Armenia, in a level probably dated to the early phase[14], a furnace, charcoal and a tuyère were found (Chubinishvili 1963, pp. 94–103). Another "metallurgical workshop" was discovered at Baba-Dervish II in Azerbaijan, comprised of three furnaces (two of which were equipped with a ventilation system), tuyères, clay moulds and slags (Makhmundov et al. 1968, pp. 18–20). At Mokhra-Blur on the Ararat plain, some vestiges of casting/melting processes suggest local metalworking (Khanzadjan 1975, p. 477). In Mound II of Velikent in Dagestan, dated to ca. 3000 BCE (Kohl et al. 2002a, p. 115), fragmentary blades, a chisel or gouge, metal prills, hammer-stones and half of a two-part clay mould for casting a shaft-hole axe indicate local metallurgy also in the north-eastern Caucasus (see Peterson 2007, p. 193 and 198). At nearby Kabaz-Kutan, a crucible and a mould were found in a level probably contemporaneous with Velikent (Gadzhiev et al. 2000, pp. 49–51), which confirms the presence of metalworking in Dagestan at this time (Peterson 2007, pp. 178–179).

The discovery of furnaces, crucibles, ingots or slags from other Kura–Araxes settlements in Georgia, Azerbaijan and Armenia—all probably dated to ca. 3000 BCE[15]—as well as in later third millennium BCE sites such as Shortepe, Shengavit, Igdir and Pichori, firmly establish the importance of metallurgy in the Kura–Araxes culture (Makhmundov et al. 1968; Narimanov 1987). The practice of transhumance and other pastoralist activities in the Kura–Araxes culture (e.g. Kushnareva 1997, pp. 192–195; Piro 2008, p. 462) certainly played a role in the spreading of metallurgy across the wide realm of Kura–Araxes influence (e.g. Palmieri et al. 1999 for Arslantepe; Frame 2010 for Godin Tepe).

In contrast to the Majkop culture, most of the metal artefacts found at Kura–Araxes sites come from domestic contexts. Amiranis-Gora, Kvatskhelebi and Dzagina in Georgia; Khachbulag in Azerbaijan; and Elar in Armenia are the only sites where metal artefacts have been unearthed in funerary contexts (Kushnareva and Chubinishvili 1963; Glonti et al. 2008).

Copper Metallurgy

Most ornaments of the Kura–Araxes culture are copper-based. A few wristbands, spiralled rods and earrings were discovered at Dzagina, Amiranis-Gora and Akhaltsikh in Georgia (Kushnareva and Chubinishvili 1963, p. 16). Tombs 2 and 5 at

[14] The ^{14}C date proposed for this settlement varies by author. The sample (TB-4; 4835 ± 180 BP) provided a date of the metallurgical level, which Kavtaradze (1999: 73–74) calibrates to 3790–3373 cal. BCE (1σ). For Chernykh (CHERNYKH et al. 2000: 74–75) the same sample is a little earlier: 3900–3350 (1σ) and 4050–3100 (2σ) cal. BCE.

[15] According to ^{14}C dates, *cf.* Kushnavera, 1994: 52 and Chernykh et al. 2000: 74–75.

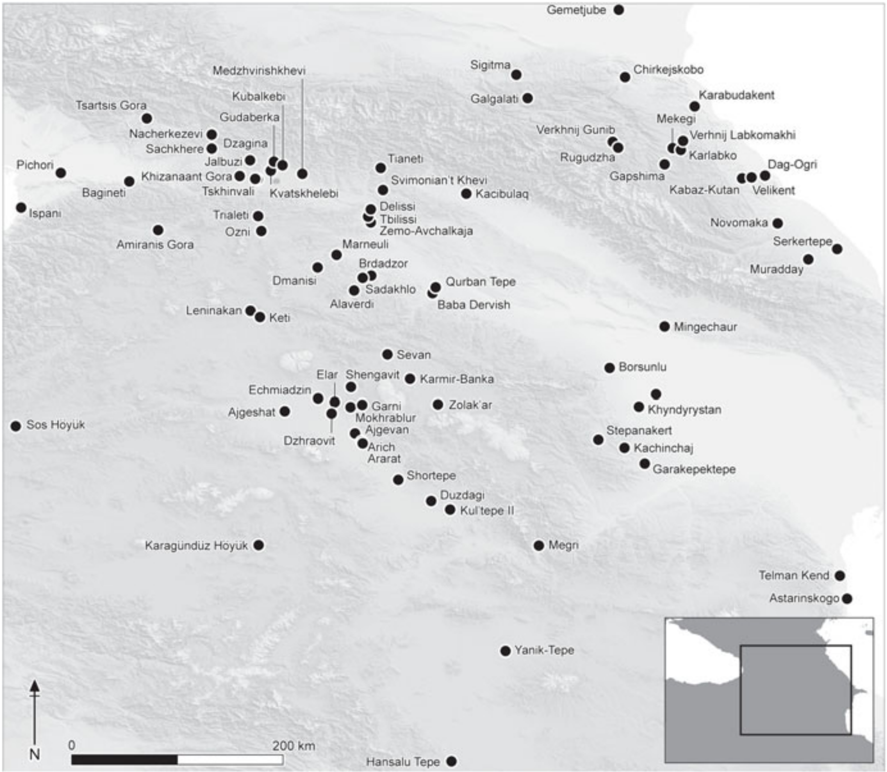


Fig. 22.42 Settlements attached to the Kura–Araxes culture. (Cassard et al. 2009. GIS project)

Kvatskhelebi contained the well-known diadem and others ornaments like wrist-bands, a double spiral-headed pin and various copper beads (Glonti et al. 2008). Some earrings and rings are also known at Serkertepe, which is dated probably to the end of the fourth millennium BCE.

Copper-base awls are found in most Kura–Araxes settlements, and their shape (i.e. generally quadrangular, straight or slightly curved) resembles those rare specimens known from earlier periods. In this later period, the first true needles were being made of metal (thin pins with a rounded, loop-like head). Needles from even later sites, like Serkertepe (Munchaev 1997, p. 152), have more elaborate shapes, such as the twisted bilateral wire involutions known at Kul'tepe II.

Several tool types are close to those known from the Novosvobodnaja phase of the Majkop culture, like flat axes (e.g. Makhmundov et al. 1968, p. 21; Kushnareva et al. 1971, p. 117) and some socketed axes (Fig. 22.42). The majority of the Kura–Araxes shaft-hole axes is characterized by a short shaft-hole and a rectangular or trapezoidal inclined blade (e.g. Khanzadjan 1964; Chernykh 1992, p. 65). According to the recent typology elaborated by Gernez (2007, pp. 159–160), these axes are principally localised in the southern part of the Caucasus and in north-eastern Anatolia (e.g.

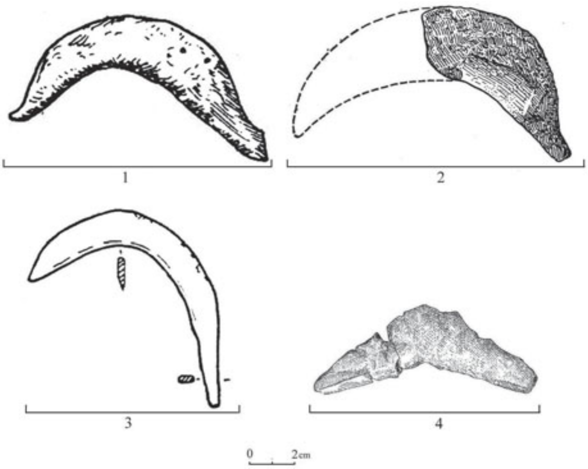


Fig. 22.43 Sickles found in Kura–Araxes settlements. *1* Amiranis-Gora grave (Kushnareva and Chubinishvili 1963), *2* Garni (Khanzadjan 1964), *3* Khizanaant-Gora (Kushnareva 1997, p. 197), *4* Kul'tepe II (Kushnareva and Chubinishvili 1970, p. 114)

at Norsuntepe level VIII). This geographical distribution demonstrates clearly the cultural connection between these two regions during the Kura–Araxes culture.

Pickaxes (Fig. 22.12) also illustrate existing connections between the northern Caucasus (Novosvobodnaja), Transcaucasia (Kura–Araxes) and the Near East (in particular Iran). Indeed, the Kura–Araxes metal and stone examples from Leninakan, Dmanisi, Alaverdi, Dzhrashen, Rugudzha and Velikent Mound II (Martirosjan 1964, p. 32; Martirosjan and Miatsakanjan 1973, p. 125; Chernykh 1992, pp. 64–65; Gadzhiev 1991, p. 55, 64 and 93, respectively) are close to pickaxes known in Novosvobodnaja sites (see above) and at Se-Girdan (Muscarella 2003, p. 126) and Suse (Tallon 1987, p. 75) in western Iran. On the contrary, metal sickles (Fig. 22.43) known from some settlements and tombs at Garni, Amiranis-Gora, Khizanaant-Gora and Kul'tepe II (Kushnareva and Chubinishvili 1963, 1970, p. 116) seem to be unique to the Kura–Araxes culture (Tedesco 2006a, p. 116).

The Kura–Araxes daggers present some similarities with those known in the Novosvobodnaja phase of the Majkop culture. This is especially true of the ribbed daggers found at Amiranis-Gora and Ajgevan (Kushnareva and Chubinishvili 1963, pp. 14–15; Kushnareva 1994b, pp. 93–94). These weapons are rather typical of Novosvobodnaja, since over 100 examples are known there (see above; Fig. 22.21). On the other hand, the flat blade with oblique shoulders from Elar, Kul'tepe II, Stepanakert and Yerevan (Kushnareva et al. 1971, pp. 116–119; Kushnareva 1994b, p. 110; Tedesco 2006a, p. 235) presents some parallels with north-eastern Anatolia (Arslantepe "Royal Tomb", Ikiztepe and Düdartepe) and with Tepe Sialk in north-central Iran (level IV) according to recent typological research (Gernez 2007, pp. 449–450). The daggers with biconvex blades from Ajgechat (Kushnareva 1994b, p. 94) are also known in later settlements of the Novosvobodnaja phase like Klady (Rezepkin 2000, pl. 54.9) and in Velikent Mound III, tomb 11 (Kohl et al. 2002a, pp. 123–124), as well as in the cultures following the Kura–Araxes culture like Martkopki and Bedeni (Gernez 2007, p. 451).

The tripartite spearheads (Fig. 22.22) found in a tomb from Amiranis-Gora as well as at various Kura–Araxes sites (Kushnareva et al. 1971, pp. 116–119) are similar to spearheads from the Novosvobodnaja phase (see above) and from the Near East. This weapon type illustrates clearly the expansion of the Kura–Araxes culture throughout the eastern part of Anatolia, North Mesopotamia and perhaps as far as Turkmenistan (see above).

The picks (Fig. 22.16) discovered at Kura–Araxes settlements such as Amiranis-Gora, Khachbulag, Kul'tepe II, Kvatskhelebi and Tsatsis-Gora (Kushnareva and Chubinishvili 1963, 1970, p. 124 and 170; Schachner 2002, p. 124) also confirm relationships between Transcaucasia and the northern Caucasus, where similar picks are known during the Novosvobodnaja phase (see above). Furthermore, these picks can also be compared to weapons from Tell Kara Hassan (Woolley 1914, pl. 19), Jerablus-Tahtani and Carchemish (Woolley and Barney 1952, pl. 60–61; Gernez 2007, pp. 285–286) dating to Early Bronze Age II/III transition (ca. 2800–2600 BCE).

Precious Metals of the Kura–Araxes Culture

Few objects in precious metals are known from the Kura–Araxes sites. A gold and silver earring comes from a tomb in Kachbulag (Narimanov 2004, p. 471), while three silver rings have been found in the cemetery of Amiranis-Gora (Chubinishvili 1963, p. 99). Tombs 2 and 5 of Kvatskhelebi[16] contained some silver spiralled rods (Glonti et al. 2008), while a gold bead has been discovered in a house at the settlement of Mingechaur (Chubinishvili 1971, pp. 105–106; Narimanov 2004, p. 470). More recently at Velikent, silver rings and a gold leaf were found in tomb 11 on Mound III, while a gold ringlet was discovered in tomb 1 on Mound IV, both dated to the first half of the third millennium BCE (Kohl et al. 2002a, p. 124).

These ornaments (in particular those which come from Kvatskhelebi) offer parallels with the jewellery found in the "Royal Tomb" at Arslantepe (end of level VIA/beginning of VIB2, dated to ca. 3000 BCE[17]; Norcera et al. 2004). Beyond the typological parallels, this tomb illustrates trade associated with pastoralist activities between Transcaucasia and the Malatya region at this time (Frangipane and Palumbi 2007, pp. 245–248). These exchanges probably included not only metal objects but also the ores, particularly in the period between 3350 and 3000 cal. BCE corresponding to level IVA (Palmieri et al. 1998, p. 42, Hauptmann and Palmieri 2000, p. 80).

[16] Tombs 1, 3, 4 and 5 are dated to the last quarter of the fourth millennium BCE; tomb 2 is not precisely dated but the excavators compared its material with those of the "Royal Tomb" at Arslantepe dated to 3000 BCE (Glonti et al. 2008: 154).

[17] 14C date: 3081–2897 (1 σ), 3308–2879 (2 σ); Palumbi 2004: 115.

The Composition and Manufacture of Kura–Araxes Artefacts

Most metal artefacts from the Kura–Araxes culture that have been analyzed derive from the latest phase of this culture and are made of arsenical copper (Schachner 2002, p. 120 and 124–125, Tables 1 and 2; Akhundov 2004, p. 427). Some objects coming from the sites of Ozni, Kul Tepe II and Karaköpek have low percentages of arsenic (Selimkhanov 1966, pp. 230–231; Kushnareva and Chubinishvili 1970, p. 132), while others have higher contents (Kushnareva and Chubinishvili 1970, pp. 130–135, Table II, Table III, Table IV, Kavtaradze 1999, pp. 89–97, Table 1). In general, most arsenic-bearing copper artefacts contain between 2 and 4 wt% As (Courcier 2007). A small minority of artefacts from Kvatskhelebi and Kul'tepe II have contents higher than 6 wt% As, some even as high as 22.7 % As[18] (Selimkhanov 1966, p. 130; Kushnareva and Chubinishvili 1970, pp. 130–135, Table II). Such a large percentage of arsenic improves the cast-ability of the copper while giving it a silvery aspect, but it also makes the object more brittle. For this reason, the use of high-arsenic copper alloys seems to have been reserved for jewellery (Kushnareva 1997, p. 203).

In addition to the presence of arsenic, objects from the Kura–Araxes culture often have minor amounts of zinc, ranging from 1 to 5 wt% Zn (Kushnareva and Chubinishvili 1970, p. 132, Table II; Chernykh 1992, p. 66). Lead content rarely exceeds 0.1 wt%, although for some artefacts it can be as high as 14.7 wt% Pb (Kushnareva and Chubinishvili 1970, p. 132, Table II). The earliest phase of the Kura–Araxes culture is characterized by very little antimony (0.005–1.15 wt% Sb) and most of the artefacts are low in nickel ($\leq$ 0.03 wt% Ni)—only slightly higher levels of nickel (0.04–1 wt% Ni) are found in a few rare objects (Chernykh 1992, p. 66; Gevorkjan 1980, pp. 49–52). Low nickel content has been determined for most artefacts from Georgia and Armenia, suggesting local ore deposits with similarly low nickel content (Kushnareva 1997, pp. 200–202). Recent archaeometallurgical studies carried out by L. A. Tedesco (2006a) have allowed a better characterization of the manufacturing techniques in Transcaucasia during the Early Bronze Age. The artefacts in arsenical-copper present several cycles (two or four) of cold-working/annealing steps, and for some daggers, strong work-hardening. She also identified a standardization of Kura–Araxes metalworking which seems similar to that argued previously for the Novosvobodnaja component (Ryndina and Ravich 1995, pp. 12–14). Tedesco (2006a, p 320) proposes metal production on a small-scale in individual households in Transcaucasia (and perhaps also in the northern Caucasus), while acknowledging a widespread uniformity in the way various classes of artefacts were made throughout the Early and early Middle Bronze Ages.

In another recent study, D. L. Peterson (2007, p. 237 and 280) analyzed 11 objects (rings and bracelets) coming from the tomb 1 on Mound III at Velikent. Previously, three metal groups had been identified at this site based on earlier spectral analyses (Gadzhiev and Korenevskij 1984, p. 19): unalloyed copper, arsenical copper and tin

[18] We ignore the analytical method used; this percentage could correspond to surface segregation.

bronze. However, Peterson (2007, p. 194) noted three exceptional types: one bracelet with 90 wt% Ag and two other bracelets cast in a copper–silver alloy with 70 wt% Cu and 30 wt% Ag. For the arsenical copper objects, the amount of arsenic ranged from 0.1 to 20.0 wt%, with the majority lying between 0.1 and 5 wt% (Gadzhiev and Korenevskij 1984, p. 19). The arsenical copper artefacts were further separated into two groups: arsenical bronze (1.5–20 wt% As)[19] and arsenical copper (0.1–0.9 wt% As), corresponding to intentional alloys and unalloyed metal (Gadzhiev and Korenevskij 1984). The intentionally alloyed pieces seem to be mostly ornaments and were excluded from tools and weapons (*ibid.*: 20).

From the same tomb 1 on Mound III at Velikent, 8 % of the total number of metal artefacts proved to be tin–bronze alloys. These tin bronzes are the earliest recorded for the Caucasus (Kohl et al. 2002a, pp. 126–127). According to lead isotopic analyses, these artefacts may have come from the same source as the early tin bronzes from Oman (Weeks in Kohl et al. 2002b, pp. 180–183). However, Peterson (2007, pp. 199–200) has underlined that this conclusion is based on a small number of analyses and that more analyses are needed in order to point out with more certainty the probable source. He adds that the extension of the Kura–Araxes culture may have provided numerous opportunities to acquire tin from a variety of sources. Peterson concludes by noting that metalworking at Velikent was "implicated in a social process of hierarchization involving both the production and use of metal objects, in which shifts in production and consumption were linked to changes in joint constructions of value and related technological and social practices" (Peterson 2007, p. 312).

Extractive Metallurgy in the Kura–Araxes Culture

In contrast to the impression given by Chernykh (1966, pp. 45–49, 1992, pp. 59–67), there is little evidence of exploitation of metalliferous deposits during the Kura–Araxes culture. Currently, research into early mining practices of the Kura–Araxes culture is barely more important than for the Majkop culture. The early research carried out by Iessen and Degen-Kovalevskij identified several sites where ancient extractive metallurgy was practiced in Transcaucasia (Iessen and Degen-Kovalevskij 1935, pp. 42–61). Unfortunately, in most cases, such mines were not dated; at best, a few mines were datable to the second or first millennium BCE. Others studies, mainly done in Georgia (Ratcha and Svanetia districts), have not securely proven extractive metallurgy during the Kura–Araxes culture, since most sites were dated to the second millennium BCE (e.g. Mudzhiri 1975, 1977, 1979, 1988a, b; Mudzhiri and Kvirikadze 1978, 1979). Nevertheless, some authors have argued that the deposits investigated (all situated in Transcaucasia) were probably exploited earlier and have conjectured exploitation during the Kura–Araxes period (e.g. Gevorkjan 1980,

[19] Most scholars would define arsenical bronze as containing above 4–5 wt% As, although this is still much debated (e.g. Northover 1988; Lechtman 1996).

pp. 21–33; Chernykh 1992, p. 60; Palmieri et al. 1993, pp. 594–595; Kushnareva 1997, p. 197).

The composition of the Kura–Araxes artefacts has also led scholars to the suggestion that polymetallic ores and arsenic-rich ores (e.g. orpiment and realgar—arsenious sulphides) had been used. Paradoxically, G. L. Kavtaradze rejects the idea that sulphur-based ores were used, pointing to the absence of sulphur[20] in most objects to support his view. He argues that towards the later phase of the Kura–Araxes culture (ca. the middle of the third millennium BCE), the extraction of copper–sulphur such as chalcopyrite became necessary due to the extinction of sources of copper oxides and hydrocarbonates (Kavtaradze 1999, p. 81). Thereafter, he argues, the principle of co-smelting was utilized consistently in Transcaucasia.

It should be noted that besides the recurring problem of trusting these early analyses, the issue of metal recycling has never been raised. It is highly probable that the practice of re-melting was carried out both by the Kura–Araxes and the Majkop cultures. It is well known that each stage of the recycling process involves a change in the composition of particular impurities (As, Ni, Sb, Pb, Zn, Bi, etc.). The presence of these elements is therefore not exclusively related to the type of ores used but also to the various phases of the metallurgical transformation. In addition, melting (or re-melting) of copper-base metal under even slightly oxidizing conditions can lead to the loss of sulphur (and other important elements, such as arsenic). Thus, the conclusions of Kavtaradze about the "shift" to copper sulphides in the third millennium BCE must be re-examined.

The recent research carried out by the Deutsches Bergbau-Museum on the Bolnisi–Madneuli copper–gold district in Georgia has shown that the Sakdrissi gold deposit was already exploited during the second half of the third millennium BCE, and it is proposed that extraction there began even before 3000 BCE (Stöllner et al. 2008; Hauptmann et al. in press). In our opinion, the Sakdrissi deposit was not the only one exploited by the Kura–Araxes population. Recent archaeometallurgical research in the Kedabeck district in Azerbaijan has identified a probable Kura–Araxes exploitation at Perizamenly, where Kura–Araxes ceramic sherds were discovered (Lyonnet et al. 2009b). We also identified many other sites with evidence for ancient extractive activities, but we found no way to date them.

Understanding the Rise of Metallurgy (ca. From Fourth to Third Millennium BCE)

From the beginnings of the fourth millennium BCE, metallurgy in the Caucasus underwent an important transformation characterized by technological developments in extractive metallurgy as well as in manufacturing techniques. This modification is not as clear for extractive metallurgy as for manufacturing techniques because of

[20] The lack of sulphur is most likely due to the analytical methods used, which were often unable to detect sulphur.

the lack of research in this field. However, based upon the admittedly limited data at hand, it would seem that local deposits were exploited often containing complex ores (e.g. copper sulphides interlaced with arsenic- and nickel-bearing minerals). An important rise in copper metallurgy is also noticeable, including the generalized production and use of copper alloys (e.g. Cu–As, Cu–As–Ni); diversification of tool and weapon types; and the rise in the sheer number of metal objects known from this period. The high technical level of metalworkers in this period is testified by the masterful production of objects in precious metals (silver, gold and electrum), although mostly this is true for the Majkop, Novosvobodnaja and the Leilatepe–Berikleedebi cultures. Although relations between the Caucasus and the Near East never ceased from the Neolithic until the Middle Bronze Age, they appear to have been especially important during the fourth millennium BCE. The role of metals and metallurgy was undoubtedly significant in these exchanges.

Conclusion

Between 5000 and 2000 BCE, metallurgy in the Caucasus underwent a tremendous development. The first appearance of metal in the northern Caucasus dates to the Meshoko culture, around the second half of the fifth millennium BCE, although it may have emerged earlier, given metal's early appearance in Transcaucasia by the end of the sixth millennium BCE in the Shomu–Shulaveri, Aratashen and Kul'tepe–Alikemek cultures. However, the lack of known Neolithic sites in the northern Caucasus limits our ability to say more about this hypothesis.

Both the Carpatho-Balkans region, characterized at this time by an apogee of metallurgy, and the Sioni culture may have stimulated the development of metallurgy in the northern Caucasus, as Chernykh has suggested. However, local deposits of copper ores could also have been exploited by the Meshoko and Sioni cultures from earlier periods. The way of life of these populations, probably nomadic and practising transhumance, could have allowed the diffusion of metallurgical activities, of technical principles, of raw material (ores, ingots), as well as of metal object between the northern and southern Caucasus. It has to be underlined that southern Transcaucasian cultures (Shomu–Shulaveri and others) were also closely connected with Anatolia, northern Iran and northern Mesopotamia, which had been using native metals since at least the seventh millennium BCE.

The beginnings of metallurgy in the Caucasus are characterized by smelting, melting, casting, cold-hammering, annealing and probably recycling of mainly "pure" copper and copper with minor (probably natural) impurities. The finished products were mainly implements (awls, bradawls, pins, knives, hooks, rods, wires, hoops, ingots), ornaments (rings, beads, pendants) and small weapons (daggers, arrowheads). Paradoxically, relatively little metallurgical waste (slags, fragments of crucibles or moulds) has been reported and no furnaces have been discovered. From the beginning of the fourth millennium BCE, metallurgy is connected to the rise of the Majkop and Leilatepe–Berikldeebi cultures, followed later by the Novosvobodnaja, Kura–Araxes and Velikent cultures. This cultural sequence is characterized by an intensification of extractive metallurgy (still poorly documented), a diversification of the types of metals being used (i.e. precious metals and copper alloys), the development of new technologies (e.g. smelting of complex ores, alloying, cladding, casting in bivalve moulds, copperware), the invention of new types of metal objects (e.g. forks, adzes, flat axes, gouges, pickaxes, socketed axes, spearheads, sickles, harness pieces, long daggers, swords) and the increase of the number of metal objects produced. Surprisingly, the only furnaces known come from Kura–Araxes settlements.

The increase in metallurgical activity by ca. 3000 BCE is concomitant with an intensification of relations north to south between the Caucasus and the Near East. The diffusion of some specific objects (like the tripartite spearheads) from the Caucasus (Novosvobodnaja and the Kura–Araxes c) to Anatolia, northern Mesopotamia and as far away as Turkmenistan, confirms the importance of metallurgy in the Caucasus during this period. Nevertheless, several features concerning metallurgy in the Caucasus remain unclear—in particular, the rise of extractive metallurgy and the processes used in manufacturing metals. We hope that future excavations, the use of modern analyses and new methods (e.g. the use of GIS), as well as an increased attention on the Caucasus will help to better understand these crucial points.

Acknowledgment I would like to express here my warmest acknowledgments to B. Lyonnet for her critical reading of this text. I would also like to express my thanks to A. Lepers for her help in the translation and structuring of this paper.

References

Abesadze, Ts. N. (1969). *Proizvodstvo Metalla v Zakavkaze v III tysjacheletii do. n.e (Kuro-Araksskaja kult'tura)*. Tbilissi: Izdatel'tvo akademija nauk Gruzinskoj.

Abesadze, Ts. N., & Bakhtadze, R. A. (1987). Iz istorii drevneishei metallurgii Gruzii. In K. N. Pitskhelauri & E. N. Chernykh (Eds.), *Kavkaz v Sisteme Paleometallicheshikh Kul'tur Evrazii, materialy i Simpoziuma "Kavkaz v Epokhu Rannego Metalla* (pp. 5–9). *(Telavi-Signakhi 1983)*. Tbilissi: Metsniereba.

Abesadze Ts. N., Bakhtadze, R., Bvali, T., & Dzhaparidze, O. (1958). *Istorii Medno-Bronzovoj Metallurgii v Gruzii*. Tbilissi: Gosudarstvennoe izdatel'stvo uchebno-pedagogicheskoj literatury "Tsodna".

Abibullayev, O. A. (1959). Raskopki kholma Kyul Tepe bliz Nakhichevan v 1955 g., *Materialy i isselovanija po arkheologii SSR*, 67, 431–452. Leningrad, Moscou: Nauka.

Abibullayev, O. A. (1963). Nekotorye itogi izuchenija kholma Kyul'-Tepe v Azerbajdzhane. *Sovetskaja Arkheologija*, *3*, 157–168.

Abibullayev, O. A. (1965a). Ostaki zhilishch vo vtorom sloe poselenija Kjul'-Tepe, okolo Nakhichevani. *Materialy i isselovanija po arkheologii SSR*, *125*, 40–64. Leningrad, Moscou: Nauka.

Abibullayev, O. A. (1965b). K voprosu o drevnej metallurgii Azerbajdzhana, *Materialy i isselovanija po arkheologii SSR*, 125, 65–73. Leningrad, Moscou: Nauka.

Abibullayev, O. A. (1982). *Eneolit i bronza na territorii Nakhichevanskoy ASSR*. Bakou: Nauka.

Akhundov, T. (2004). South Caucasus in the Neolithic and the Early Bronze Age: The question of epochs and periods. In A. Sagona (Ed.), *A View from the Highlands: archaeological studies in* *honour of Charles Burney* (pp. 12, pp. 421–434). Ancient Near Eastern Studies 12. Louvain: Peeters.

Akhundov, T. (2007). Sites de migrants venus du Proche-Orient en Transcaucasie. In B. Lyonnet (sous la direction). *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient*, 95–121. Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Aliev, V. (1980). Raskopki poselenija Kjul'tepe II. In B. A. Rubakov & N. V. Malinovskaja (Eds.), *Arkheologicheskie otkrytija 1979 g.*: 419. Moscou: Nauka.

Aliev, V. (1997). Kura-Araxes culture settlements of the Nakhichevan area. In O. D Lordkipanidze, B. A. Jorbenadze, & A. A. Tchanturia (Eds), *Archaeology of the Caucasus: New discoveries and perspectives* (pp. 9–10). Tbilissi: The Centre for Archaeological Studies of the Georgian Academy of Sciences.

Aliev, N. G., & Narimanov, G. I. (2001). *Kul'tura severnogo Azerbajdzhana v epokhi pozdnego eneolita*. Bakou: Agridag.

Andreeva, M. V. (1977). K voprosu o juzhnykh svazakh Majkopskoj kul'tury. *Sovetskaja Arkheologija*, *1*, 39–56.

Andreeva, M. V. (1979). Ob izobrazhenijakh na serebrjanykh majkopskikh sosudakh. *Sovetskaja Arkheologija*, *1*, 22–34.

Arazova, R. B., Makhmudov, F. R., & Narimanov, I. G. (1972). Eneoliticheskoe poselenie Gargalar Tepesi. *Arkheologicheskie otkrytija 1971 g.*, 478–479.

Arazova, R. B., Makhmudov, F. R., & Narimanov, I. G. (1973). Raskopki na eneoliticheskom poselenii Gargalar Tepesi. *Arkheologicheskie otkrytija 1972 g.*, 434–435.

Ataev, G. A. (1988). Metalloobrabotka prisulakskikh plemen Dagestana v epokhu srednej Bronzy. In V. V. Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 33–35). Sukhumi: Tezisy Dokladov.

Badalyan, R., & Harutyunyan, A. (2008). Fouilles d'Aknashen-Khatunarkh (mission 2008), *Rapport de la mission "Caucase" du MAEE* (pp. 27–40). Unpublished.

Badalyan, R., Lombard, P., Avetisjan, P., Chataigner, C., Chabot, J., Vila, E., Hovsepjan, Wilcox, G., & Pessin, H. (2007). New data on the late prehistory on the Southern Caucasus. The excavations at Aratashen (Armenia): Preliminary report. In B. Lyonnet (sous la direction) *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 37–62). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Bakhashaliyev, V., & Marro, C. (2009). *The archaeology of Nakhichevan, ten years of new discoveries*. Istanbul: Yayinlari.

Batiuk, S., & Rothman, M. S. (2007). Early Transcaucasian cultures and their neighbors: Unraveling migration, trade, and assimilation. *Expedition*, *49*(1), 7–17.

Baye, J. (1899a). Dolmens de la région nord du Caucase. *Bulletin de la Société d'Anthropologie de Paris*, 153–156.

Baye, J. (1899b). Au Nord de la chaîne du Caucase, souvenir d'une mission. Paris: Nilsson.

Baye, J. (1899c). Au Sud du Caucase, souvenir d'une mission. Paris: Nilsson.

Baye, J. (1900). Fouilles de kourganes au Kouban (Caucase). Paris: Nilsson.

Behm-Blancke, M. (1981). Hassek Höyük. Vorlaufiger Bericht über die Ausgrabungen der Jahre 1978–80. *Istanbuler Mittellungen*, *31*, 5–93.

Behm-Blancke, M. (1984). Hassek Höyük. Vorlaufiger Bericht über die Ausgrabungen der Jahre 1981–83. *Istanbuler Mittellungen*, *34*, 31–149.

Berthoud, Th., Cleuziou, S., Hurtel, L. P., Menu, M., & Volfovsky, C. (1982). Cuivres et alliages en Iran, Afghanistan, Oman au cours des IV^e^ et III^e^ millénaires. *Paléorient, 8/2*, 39–54.

Betancourt, P. P. (1970). The Majkop copper tools relationship to Cretan metallurgy. *American Journal of Archaeology*, *74/4*, 351–358.

Beucler, A. (1931). *Caucase*. Paris: Emile-Paul.

Betrozov, R. J., & NaGoev, A. Kh. (1984). Kurgany epokhi bronzy u selenij Chegem I, Chegem II i Kishpek (1ja i 3ja gruppy). In V. I. Markovin (Ed.), *Arkheologicheskie issledovanija na* *novostrojkakh Kabardino-Balkari v 1972–1979 gg.*, t. I, Pamjatniki epokhi bronzy (III-II tys. do n.e.) (pp. 7–87). Nal'chik: El'brus.

Bgdasarjan, A. T., Ezakjan, O. S., & Sargsjan, A. A. (2007). Prirodnye resurcye Armenii. *Gornyj Zhournal*, *10*, 20–23.

Bidzhev, Kh. Kh. (1980). Bolshoj kurgan u aula Kubina v Karachaevo-Cherkesii. In V. I. Markovin (Ed.), *Severnyj Kavkaz v drevnosti i v srednie veka* (pp. 33–43). Moscou: Nauka.

Bocharev, V. S., & Rezepkin, A. D. (1980). Raboty Kubanskoj ekspeditsii. *Arkheologicheskie otkrytija 1979 g.*, 97–98.

Burney, C. A., & Lang, D. M. (1971). *The peoples of the hills: Ancient Ararat and Caucasus*. Londres: Weidenfeld & Nicolson.

Burton-Brown, T. (1955). *Excavations in Azerbaijan*, *1948*. Londres: Murray J.

Bzhnaja, V. V. (1966). Macharskoe poselenie epokhi eneolita i bronzy v Abkhazii, *Sovetskaja Arkheologija*, *1*, 113–126.

Bzhnaja, V. V. (1967). Istorija arkheologicheskogo izuchenija pamjatnikov eneolita I rannej bronzy v Abkhazii. In M. M. Trapish (Ed.), *Materialy po arkheologii Abkhazii* (pp. 99–114). Tbilissi: Metsniereba.

Bzhnaja, V. V. (1979). Raskopki Macharskogo poselenija i kurgana Pskhu, *Arkheologicheskie otkrytija 1979 g.*, 497.

Bzhnaja, V. V. (1988). Drevnie rudyniki y prevala Akheng'. In V. V. Bzhanija, Ju. G. Argun, O. Kh Bgazhba, & T. G. (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 7–9). Sukhumi: Tezisy Dokladov.

Bzhanija, V. V., Argun, Ju. G., Bgazhba, O. Kh., & Alanija, T. G. (Eds.). (1988). Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija. Sukhumi: Tezisy Dokladov.

Caneva, C., & Palmieri, A. M. (1983). Metalwork at Arslantepe in Late Chalcolithic and Early Bronze I, the evidence from metal analysis. *Origini*, *12*(2), 637–654.

Cassard, D., Courcier, A., Billa, M., Gateau, C., Lafitte, A., Lyonnet, B., Maldan, F., & Mallon, J. F. (2009). SIG: Les cultures du Caucase et la métallurgie, 6^{e}–3^{e} millénaires (Sud Russie, Républiques du Nord Caucase, Géorgie, Arménie, Azerbaïdjan, Iran du NO, Turquie orientale). Projet CNRS–BRGM.

Chantre, E. (1881). Notes anthropologiques. Recherches paléoethnologiques dans la Russie méridionale et spécialement au Caucase et en Crimée. Lyon: Georg H.

Chantre, E. (1883). Rapport sur une mission scientifique dans l'Asie occidentale, et spécialement dans les régions de l'Ararat et du Caucase. Paris: Imprimerie Nationale.

Chantre, E. (1885). Recherches anthropologiques dans le Caucase, t. I, Période Préhistorique. Paris: Reinwald Ch.

Chantre, E. (1886a). Recherches anthropologiques dans le Caucase, t. II, Période Protohistorique, texte. Paris: Reinwald Ch.

Chantre, E. (1886b). Recherches anthropologiques dans le Caucase, t. II, Période Protohistorique, atlas. Paris: Reinwald Ch.

Chantre, E. (1887a). Recherches anthropologiques dans le Caucase, t. III, Période Historique. Paris: Reinwald Ch.

Chantre, E. (1887b). Recherches anthropologiques dans le Caucase, t. IV, Populations actuelles. Paris: Reinwald Ch.

Chartolani, SH. G. (1988). Mednye gornorudnye vyrabotki v Svanetii. In V. V. Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 15–16). Sukhumi: Tezisy Dokladov.

Chartolani, SH. G. (1989). K Istorii nagor'ja zapadnoj Gruzii doklassovoj epokhi. Tbilisii: Metsniereba.

Chartolani, SH. G. (1997). Newly discovered mining sites in Svaneti. In O. D. Lordkipanidze, B. A. Jorbenadze, & A. A. Tchanturia (Eds.), *Archaeology of the Caucasus: New discoveries*

and perspectives (pp. 20–21). Tbilissi: The Centre for Archaeological Studies of the Georgian Academy of Sciences.
Chartolani, SH. G. (2002). Alter bergbau in Swanetian. In I. Gambaschidze, A. Hauptmann, R. Slotta, & Ü. Yalcin (Eds.), Georgien. Schätze aus dem land des Golden Vlies, Katalog der Ausstellung des deutschen Bergbau-Museums Bochum in Verbindung mit dem Zentrum für Archäologische Forschungen der Georgishen akademie der Wissenschften Tbilisse von 28 Oktober 2001 bis 19 Mai 2002 (pp. 120–129). Bochum: Deutsches Bergbau Museum.
Chataigner, C. (1995). La Transcaucasie au Néolithique et au Chalcolithique, BAR International Series 624. Oxford: Archaeopress.
Chechenov, I. M. (1973). *Nal'chikskaja podkurgannaja grobnitsa*. Nal'chik: Nauka.
Chechenov, I. M. (1980). Bogatye zakoronenija v kurgane rannebronzovogo veka u sel. Kishpek v Kabardino-Balkarii. In V. I. Markovin (Ed.), *Severnij Kavkaz, v drevnosti i srednie veka* (pp. 15–32). Moscou: Nauka.
Chechenov, I. M. (1984). Vtorye kurgannye gruppy u selenij Kishpek i Chegem II. In V. I. Markovin (Ed.), *Arkheologicheskie issledovanija na novostrojkah Kabardino-Balkari v 1972–1979 gg*., t. I, pamjatniki epokhi bronzy (III-II tys. do n.e.) (pp. 164–253). Nal'chik: El'brus.
Chechenov, I. M. (1986). Kurgan 2 I selenija Kishpek v Kabardino-Balkarii. In V. I. Markovin (Ed.), *Novoe v arkheologii severnogo Kavkaza* (pp. 39–51). Moscou: Nauka.
Chernykh, E. N. (1963). Spektral'nye Issledovanija metallicheskikh izdelij iz mogil'nika Gatyn-Kale. In E. I. Krupnov, Drevnosti Checheno-Ingushtii, *Materialy i isselovanija po arkheologii SSR*, *116* (pp. 136–138). Moscou: Nauka.
Chernykh, E. N. (1966). Istorija drevnejshej metallurgii vostochnoj Evropy. *Materialy i isselovanija po arkheologii SSR*, 132. Leningrad, Moscou: Nauka.
Chernykh, E. N. (1972). *Metall chelovek vremja*. Moscou: Nauka.
Chernykh, E. N. (1978a). Gornoe delo i metallurgija v drevnejshej Bolgarii. Sofia: Nauka.
Chernykh, E. N. (1978b). Metallugicheskije provintsii periodizatsija epoki rannego metalla na territorii SSSR. *Sovetskaja Arkheologija*, *4*, 53–82.
Chernykh, E. N. (1988). Kavkaz v sisteme metallurgicheskikh provintsij broizovogo veka. In V. V. Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 4–6). Sukhumi: Tezisy Dokladov.
Chernykh, E. N. (1991). Früheste Kupfer in den Steppen und Waldsteppennkulturen Osteuropas. In J. Lichardus (Ed.), *Die Kupferzeit als Historische Epoche*, Saarbrücker Beitrage zur Altertumskunde, 55 (Vol. II, pp. 581–592). Bonn: Habelt R.
Chernykh, E. N. (1992) *Ancient metallurgy in the USSR. The Early Metal Age*. Cambridge: Cambridge University Press.
Chernykh, E. N. (2005). Puti i modeli razvitija arkheometallurgii (staryj i novyj svet), Ross. *Arkh.*, *4*, 49–60.
Chernykh, E. N., Avilova, L. I., Barcheva, T. B., OrlovskaJa, A., & Tenejshvili, T. O. (1991). The circumpontic metallurgical province as a system. In J. Lichardus (Ed.), *Die Kupferzeit als Historische Epoche*, Saarbrücker Beitrage zur Altertumskunde 55 (Vol. II, pp. 593–622). Bonn: Habelt R.
Chernykh, E. N., Avilova, L. I., & OrlovskaJa, A. (2000). *Metallurgical provinces and radiocarbon chronology*. Moscou: Rossijskaja Akademija Nauk; Institut Arkheologii.
Chernykh, E. N., Avilova, L. I., & OrlovskaJa, A. (2002). Metallurgy of the circumpontic area: From the unity to disintegration. In Ü. Yalçin (Ed.), *Anatolian Metal II, Der Anschnitt* 15, 83–100. Bochum: Deutsches Bergbau Museum.
Chikovani, G. (1998). Rannezemledel'cheskaja poselinija iz s. Chinti. In: *Trudy II* (pp. 72–84). Tbilissi: Universitet Legija I Kompanii.
Childe, V. G. (1936). The axes from Maikop and Caucasian metallurgy. Annual reports to the libraries, museums and art committee city of Liverpool, 23, 113.
Chubinishvili, T. N. (1963). *Amarinis-Gora: Materialy k Drevneyshej Istorii Meskheti-Dzhavakheti*. Tbilissi: Gsudarstvennoe izdatel'stvo "Sabchota Sakartvelo".

Chubinishvili, T. N. (1971). *K drevnej istorii juzhnogo Kavkaza*. Leningrad: Nauka.
Courcier, A. (2006). La métallurgie de la fin du VI[e] au milieu du III[e] millénaire—Chalcolithique, début de l'â ge du Bronze—au Caucase, *Orient Express*. In press.
Courcier, A. (2007). La métallurgie dans les pays du Caucase au Chalcolithique et au début de l'â ge du Bronze: bilan des études et perspectives nouvelles. In B. Lyonnet (sous la direction) *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 198–231). Paris: CNRS Editions/Editions Recherche sur les Civilisations.
Courcier, A. (2008). Metalliferous potential, metallogenous particularities and extractive metallurgy: Interdisciplinary researches for understanding the ancient metallurgy in the Caucasus during the Early Bronze Age. In I. Motzembäcker (dir.), *Von Majkop bis Trialeti—Gewinnung und Verbreitung von Metallen und Obsidian in Kaukasien im 4.–2. Jts. v. Chr* (symposium, 1.-3 Juni 2006, Ethnologisches Museum Berlin Dahlem). Berlin: DAI Crawford. Will be published.
Courcier, A., Gasanova, A. A., & Hauptmann, A. (2009a). Ancient metallurgy in the Caucasus during the Chalcolithic and Early Bronze Age: Recent results from excavations in Western Azerbaijan. *Metalla, 15/1*, 21–34.
Courcier, A., Kuparadze, D., & Pataridze, D. (2009b). Archaeometallurgical researches on the early beginnings of metallurgy (VIth–IIIrd millennia B. C.) in the Caucasus: an example of interdisciplinary studies. *Metalla, 15/1*, 35–50.
Crawford, H. E. W. (1974). The problem of tin in Mesopotamian bronze. *World Archaeology*, *8*, 242–247.
Dayton, J. E. (1971). The problem of tin in the Ancient World. *World Archaeology*, *3*, 49–104.
Dayton, J. E. (1973). The problem of tin in the Ancient World: A reply to Dr. Muhly and Dr. Wertime. *World Archaeology*, *5*, 123–124.
Dayton, J. E. (2003). The problem of tin in the ancient world. In A. Giumlia-Mair & F. Lo-Schavo (Eds.), *Le problème de l'étain à l'origine de la métallurgie, session 8; Acts of the UISPP Congress (2–8 september 2001)* (pp. 165–170). Oxford: Archaeopress.
Deshayes, J. (1960). Les outils de bronze de l'Indus au Danube (IV[e] au II[e] millénaire). Paris: Geuthner P.
Dzhaparidze, O. M. (1955). *Rannij Etap Drevnej Metallurgii v Gruzii*. Tbilissi: Tekhnika na shroma.
Dzhaparidze, O. M. (1975). Otchet Kvemo-Kartlijskoj arkheologicheskoj ekspeditsii (1965–1971). Tbilissi: Mesniereba.
Dzhaparidze, O. M. (1989). *Na zare etnokul'turnoj istorii Kavkaza*. Tbilissi: izdatel'stvo Tbilisskogo Universiteta.
Dzhaparidze, O. M. (1991). *Arkheologija Gruzii (Kamennyj vek i epokha bronzy)*. Tbilissi: Izdatel'stvo Tbilisiskogo Universiteta.
Dzhaparidze, O. M. (1993). Über die ethnokulturelle situation in Georgien gegen ende des 3. jahrtausends v.chr. In M. Frangipane, A. Hauptmann, M. Liverani, P. Matthiae, & M. Mellnick (Eds.), *Between the rivers and over the mountains, Archaeologica Anatolica et Mesopotamica Alba Palmieri Dedicata* (pp. 476–491). Rome: Dipartimento di Scienze Storiche Archeologiche e Antropologiche dell'Antichità, Università di Roma "La Sapienza".
Dzhaparidze, O. M. (1996). Kul'tura ranneikh kurganov na territorii Zakavkaz'ja. In Ju. Ju. Piotrovskij (Ed.), Mezhdu Aziej I Evropoj, Kavkaz v IV – I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena (pp. 76–78). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.
Dzhaparidze, O. M. (2002). Zur frühen Metallurgie Georgiens vom 3. bis zum 1. Jahrtausend v. Chr. In I. Gambaschidze, A. Hauptmann, R. Slotta, & Ü. Yalcin, *Georgien. Schätze aus dem land des Golden Vlies, Katalog der Ausstellung des deutschen Bergbau-Museums Bochum in Verbindung mit dem Zentrum für Archäologische Forschungen der Georgishen akademie der Wissenschften Tbilisse von 28 Oktober 2001 bis 19 Mai 2002* (pp. 92–118). Bochum: Deutsches Bergbau Museum.
Dzhaparidze, O. M. (2005). Frühe ethnokulturelle Geschichte der gerorgischen Stämme nach archäologischen Angaben. *Metalla*, *12*(1/2), 5–7.

Dzhavakhishvilla, A. I., Narimanov, N. G., & Kiguradze, T. V. (1987). Juzhnyj Kavkaz v VI—IV tys. do n.e. In K. N. Pitskhelauri & E. N. Chernykh (Eds.), *Kavkaz v Sisteme Paleometallicheshikh Kul'tur Evrazii, materialy i Simpoziuma "Kavkaz v Epokhu Rannego Metalla" (Telavi-Signakhi 1983)* (pp. 5–9). Tbilissi: Metsinereba.

Eaton, E. R., & McKerrel, H. (1976). Near-Eastern alloying and some textual evidence for the early use of arsenical copper, *World Archaeology*, *8*, 169–191.

Emberling, G. G., & McDonald, H. (2003). Excavations at Tell Brak 2001–2002: Preliminary report. *Iraq*, *65*, 1–75.

Esin, U. (1969). Kantitatif Spektral Analiz Yardimiyla Anadolu'da Baslangicandan Asur Kolonileri Cagina Kadar Bakir ve Tunç Madenciligi. Istanbul.

Field, H., & Prostov, E. (1938). Tin deposits in the Caucasus. *Antiquity*, 341–345.

Fleury, L. (1894). Les Tumuli du Caucase fouillés par M. le professeur Samokwassoff et leur rapport avec ceux du département de la Charente. Angoulê me: Coquemard L.

Formosov, A. A. (1961). Arkheologicheskije issledovanija peshcherv verkho'jarh r. Beloj v Krasnodarskom kraj. In N. V. Anfimov (Ed.), *Sbornik materialov po arkheologii Adygei*, t. II (pp. 39–72). Majkop.

Formosov, A. A. (1963). Novoe o juzhnykh svjzjakh majkop kul'tury,—-*Kratkije Soobshchesnija Instituta Arkheologija*, *93*, 35–45.

Formosov, A. A. (1965). *Kamennyj vek i eneolit Prikuban'ja*. Moscou: Nauka.

Formosov, A. A. (1973). O sootnioshenii neolitischeskikh i eneoliticheskikh kul'tur Kavkaz. *Kratkije Soobshchenija Instituta Arkheologija*, *137*, 36–41.

Formosov, A. A., & Chernykh, E. N. (1963). Novye poselenija Majkopskoj kul'tury v Prikubane. *Kratkije Soobshchenija Instituta Arkheologija*, *93*, 99–120.

Formosov, A. A. (2004). *Alle origini del potere, Arslantepe, la collina dei leoni*, catalogue de l'exposition, Rome 13 Octobre 2004–9 Janvier 2005. Electra Milan.

Frame, L. D. (2010). Metallurgical investigations at Godin Tepe, Iran, Part I: the metal finds. *Journal of Archaeological Science*, *37*, 1700–1715.

Frangipane, M. (2000). The late Chalcolithic/EB I Sequence at Arslantepe. Chronological and Cultural Remarks from a Frontier Site. In C. Marro & A. Hauptmann (Eds.), *Chronologies des pays du Caucase et de l'Euphrate aux IVe—IIIe millénaires, actes du colloque d'Istanbul (16–19 décembre 1999)*, *Varia Anatolica*, XI (pp. 439–471). Istanbul: IFEA, diffusion de Boccard.

Frangipane, M., & Palmieri, A. M. (1983). A Protourban Center of the Late Uruk Period. *Origini*, *12*, 287–409.

Frangipane, M., & Palumbi, G. (2007). Red-black ware, pastoralism, trade and Anatolian-transcaucasian interactions in the 4th–3rd millennium B. C. In B. Lyonnet (sous la direction) (Ed.), *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 233–255). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Frangipane, M., Di Norcera, G.M., Hauptmann, A., Morbidelli, P., Palmieri, A. M., Sadori, L., Schultz, M., & Schmidt-Schultz, T. (2001). New symbols of a new power in a "Royal" tomb from 3000 BC Arslantepe, Malatya (Turkey). *Paléorient*, *27*(2), 105–139.

Frankfort, H. (1928). Sumerian, Semites and the origins of copper working. *Antiquity*, *8*, 217–335.

Frankfort, H. (1932). Archaeology and the Sumerian problem. *Studies in ancient Oriental civilization*, *4*, 1–76.

Freshfield, D. W. (1896). *The exploration of the Caucasus*. Londres: Arnold E.

Frolova, M. (2000). Les paysages du Caucase, contribution géographique à l'étude des représentations et des modélisations d'une montagne. *Thèse environnement et paysage*. Toulouse: Université de Toulouse II.

Frolova, M. (2006). *Les paysages du Caucase: invention d'une montagne*. Paris: éditions du Comité des Travaux Historiques et Scientifiques.

Gadzhiev, M. G. (1991). Rannezemledel'cheskaja kultura Severo-Vostochnogo Kavkaza. *epokha Eneolita i rannej Bronzi*. Moscou: Nauka.

Gadzhiev, M. G., & Korenevskij, S. N. (1984). Metall Velikentskoj katakomby. In M. M. Mammaev (Ed.), *Drevnie promyshly, remeslo I torgovlja v Dagestane* (pp. 7–27). Makhachkala: Nauk.

Gadzhiev, M. G., Kohl, P. L., Magomedov, W. R. G., Stronach, D., Gadzhiev, B., & Gadzhiev S. M. (2000). Dagestan-American Archaeological Investigations in Dagestan Russia, 1997–1999. *Eurasia Antiqua*, *6*, 47–121.

Gale, N. H., & Stos-Gale, Z. A. (1981a) Ancient Egyptian Silver. *Journal of Egyptian Achaeology*, *67*, 103–115.

Gale, N. H., & Stos-Gale, Z. A. (1981b) Sources of Galena, Lead and Silver in Predynastic Egypt. *Revue d'Archéométrie*, *3*, 285–295.

Gambaschidze, I., Hauptmann, A., Slotta, R., & Yalcin, Ü. (Eds.) (2002). *Georgien. Schätze aus dem land des Golden Vlies*. Katalog der Ausstellung des deutschen Bergbau-Museums Bochum in Verbindung mit dem Zentrum für Archäologische Forschungen der Georgishen akademie der Wissenschften Tbilisse von 28 Oktober 2001 bis 19 Mai 2002. Bochum: Deutsches Bergbau Museum.

Gasan, N., Gamid, A. I., & Narimadov I. G. (2001). *Kul'tura severnogo Azerbajdzhana v epokhu pozdnego Eneolita*. Baku: Natsional'naja Akademija Nauk Azerbajdzhana Institut Arkheologii i Etnografii.

Gevorkjan, A. Ts. (1974). O drevnejshej mednorudnoj baze Armenii. *Sovetskaja Arkheologija*, *4*, 32–39.

Gevorkjan, A. Ts. (1980). *Iz istorii drevnejshej metallurgii Armjanskogo Nagor'ja*. Erevan: Akademija Nauk Armjanskoj SSR.

Glonti, L., Ketshoveli, M., & Palumbi, G. (2008). The cementery at Kvatshelebi. In A. Sagona & M. Abramishvili (Eds.), *Archaeology in Southern Caucasu: Perspectives from Georgia* (pp. 153–184). (Ancient Near Studies supplement 19). Louvain: Peeters.

Gobedzhishvili, G. F. (1951). *Kholm Natsar Gora bliz g. Staliniri*. Tbilissi: Metsniereba.

Gobedzhisivili, G. G., Inanishvili, G. V., & Mudzhiri, T. P. (1988). Oput komplekskogo issledovanija pamjatnikov gornogo dela I metallurgii v verkhnej Rachi epokhi bronzy. In V. V. Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija (Eds.) *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 27–28). Sukhumi: Tezisy Dokladov.

Gogelija, D. D., & Chelidze, L. M. (1985). Resul'taty rabot Kvemokartilijskoj arkheologicheskoj ekspeditsii, Polevje arkheologicheskije issledovanija v 1982 g. Tbilissi.

Graham, P. (1989). Metals Weapons of the Early and Middle Bronze Ages in Syria and Palestina. BAR International Series 526. Oxford: Archaeopress.

Greenberg, R. (2007). Transcaucasian collors: khirbet kerak ware at Kirbet Kerak (Tel Bet Yerah). In B. Lyonnet (Ed.), (sous la direction), *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 257–268). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Gzelishvili, I. A. (1967). K drevnej istorii dobychi I obrabotki medi v Bolnisskom rajone. *Soobshchneija Akademii nauk Gruzinskoj*, *17*(1), 247–251.

Hamon, C. (2007). Modes de subsistence et activités dans le Chalcolithique du Nord Caucase: etude fonctionnelle des outils en pierre dans la culture de Maïkop. In B. Lyonnet (sous la direction) (Ed.), *Les cultures du Caucase (VIe-IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 189–197). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Hauptmann, A., & Palmieri, A. M. (2000). Metal Production in the Eastern Mediterranean at the Transition of the 4th/3rd Millennium: Case Studies from Arslantepe. In Ü. Yalcin (Ed.), *Anatolian Metal I, Der Anschnitt*, *13*, 75–82. Bochum: Deutsches Bergbau Museum.

Hauptmann, A., Schmitt-Strecker, S., Begemann, F., & Palmieri, A. M. (2002). Chemical composition and lead isotopy of metal objects from the "Royal" Tomb and other related finds at Arslantepe, Eastern Anatolia. *Paléorient*, *28*(2), 43–70.

Hauptmann, A., Bendall, C., Brey, G., Dschaparidze, I., Gambaschidze, I., Klein, S., Prange, M., & Stöllner, T. (2009). (under press) Gold in Georgien, Analytische Untersuchubgen an Goldartefakten und an Naturgold aus dem Kaukasus und dem Transkaukasus. In I. Motzembäcker (Ed.) (dir.), *Von Majkop bis Trialeti– Gewinnung und Verbreitung von Metallen und Obsidian in*

Kaukasien im 4.–2. Jts. v. Chr (symposium, 1.–3 Juni 2006, Ethnologisches Museum Berlin Dahlem). Berlin: DAI Crawford.

Iessen, A. A. (1935). *Olovo Kavkaza*. Moscou: izdatel'stvo gosudarstvenaja akademija istorii materialnoj kul'tury.

Iessen, A. A. (1951). Prikubanskiy ochag metallurgii i metallo-obrabotki v kontse medno-bronzovogo veka. *Materialy i isselovanija po arkheologii SSR*, *23*, 75–124.

Iessen, A. A. (1959). *Trudy Azerbajdzhanskoj* (*Oren-Kalinskoj*) *arheologicheskoj ekspeditsii*, Materialy i isselovanija po arkheologii SSR, 67. Moscou: Nauka.

Iessen, A. A. (1963). Kavkaz i drevnij vostok v IV i III tysjacheletijakh do nashej ery. *Kratkije Soobshchenija Instituta Arkheologija*, *93*, 3–13.

Iessen, A. A. (1965b) Iz istoricheskogo proshlogo mil'skogo-Karakhskoj stepii. In A. A. Iessen & K. Kh. Kushnareva (Eds.), *Trudy Azerbajdzhanskoj (orenkaanskoj) ekspeditsii, Tom I (1956–1960 gg.)*, *Materialy i isselovanija po arkheologii SSR*, 125 (pp. 10–36). Moscou: Nauka.

Iessen, A. A., & Degen-Kovalevskij, B. E. (1935). *Iz istorii drevnej metallurgii Kavkaza*. Moscou: Gosudarstvennoe Sotsial'no Ekonomicheskoe Izdatel'stvo "Ogiz".

Iessen, A. A., & Kushnareva, K. Kh. (1965). Trudy Azerbajdzhanskoj arkheologicheskogo ekspeditsii, 1956–1960 gg. Materialy i isselovanija po arkheologii SSR, 125. Moscou: Nauka.

Inanishvili, G. V. (1988). Khimiko-teknologicheskie voprocy izuchenija metallurgii bronzy v drevnej Gruzii. In V. V Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 11–12). Sukhumi: Tezisy Dokladov.

Inanishvili, G. V. (2002). Metallurgische verfaren und kenntnisse im alten Georgien. In I. Gambaschidze, A. Hauptmann, R. Slotta, & Ü Yalcin (Eds.), *Georgien. Schätze aus dem land des Golden Vlies, Katalog der Ausstellung des deutschen Bergbau-Museums Bochum in Verbindung mit dem Zentrum für Archäologische Forschungen der Georgishen akademie der Wissenschften Tbilisse von 28 Oktober 2001 bis 19 Mai 2002* (pp. 142–149). Bochum: Deutsches Bergbau Museum.

Inanishvili, G. V., Maisuradze, V. G., Gobedzhisvili, G. G., & Mudzhiri, T.P. (2001). K istorii gorno-metallurgischeskogo bronzvodstva Kolkhidy. *Rossijskaja Arkheologija*, *3*, 18–24.

Ismailov, G. S., & Bakshliev, V. G. (1988). Gorno-metallurgicheskoe proizvodstvo epokhi paleometalla na territory Azerbajdzhana. In V. V. Bzhanija, Ju. G. Argun, O. Kh, Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 22–23). Sukhumi: Tezisy Dokladov.

Kalandadze, A. N., & Kalandadze, K. S. (1982). Drevnejshe metallicheskie oruzhija iz peshchery Tetri Mgvime. *Arkheologicheskije issledovanija na novostrojkakh Sovetskoj Gruzii*, t.2. Tbilissi: Metsniereba.

Kashkaj, M. A., & Selimkhanov, I. R. (1957). Issledovanie medno-myshjakovykh predmetov iz raskopok Kyl'-Tepe v Nakhichevanskoj ASSR. *Doklady Akademy nauk Azerbajdzhanskoj SSR*, *12*(4), 449–454.

Kashkaj, M. A., & Selimkhanov, I. R. (1971). *Iz istorii drevnej metallurgii Kavkaza*. Bakou: Elm.

Kavtaradze, G. L. (1999). The Importance of Metallurgical Data for the Formation of a Central Transcaucasian Chronology. In A. Hauptmann, E. Pernicka, Th. Rehem, & Ü Yalçin. (Eds.), *The beginnings of Metallurgy*, *Der Anschnitt*, *9*, 67–101. Bochum: Deutsches Bergbau Museum.

Kelly-Buccelati, M. (1990) Trade in metal in the thrid millenium: Northeastern Syria and Eastern Anatolia. In P. Matthiae, M. N. V. Loon, & H. Weiss (Eds.), *Resurrecting the Past: a Joint Tribute to Adam Bounni* (pp. 117–131). Istanbul: Nederlands Historische-Archaeologische Instituut te Istanbul.

Khanzadjan, E. V. (1964). O metallurgii drevnebronzovoj epokhi v Armenii. *Sovetskaja Arkheologija*, *2*, 92–101.

Khanzadjan, E. V. (1967). *Kultura Armjanskogo Nagor'ja v III tysjacheletii do n.e*. Erevan: Izdatel'stvo akademija nauk Armjanskoj SSR.

Khanzadjan, E. V. (1969) *Garni IV*. Erevan: Izdatel'stvo Akademii nauk Armjanskogo SSR.

Khanzadjan, E. V. (1975) Poselenije Dzhraovit. *Arkheologicheskie otkrytija 1974 goda* (pp. 475–478).

Khlopin, I. H. (1983). Jugo-zapadnaja Turkmenija v epokhu pozdenej bronzy po materialam sumbarskikh mogilnikov. Lemingrad: Nauka.

Kiguradze, T. V. (1976). Periodizatsija rannezemledel'cheskoj kul'tury vostochnogo Zakavkaja. Tbilissi: Metsniereba.

Kiguradze, T. V. (1986). *Neolitsche Siedlungen von Kvemo-Karteli, Georgian*. Materialien zur Allgemeinen und Vergleichenden Archäologies (coll.), 29. Munich: Beck C.H.

Kiguradze, T. V. (2000). The Chalcolithic—Early-Bronze age transition in the eastern Caucasus. In C. Marro & A. Hauptmann (Eds.), *Chronologie des pays du Caucase et de l'Euphrate au IV^{e}–III^{e} millénaires*, *Var. Anat. XI* (pp. 321–328). Istanbul/Paris: IFEA, de Boccard.

Kiguradze, T. V., & Menabe, M. (1981). Arkheologicheskie pamjatniki s. Sioni Marneulskogo rajona (itogi rabot 1974–1979 gg.). Tbilissi: Metsniereba.

Kiguradze, T. V., & Sagona, A. (2003). On the origins of the Kura-Araxes Cultural Complex. In A. T. Smith & K. S. Rubinson (Eds.), *Archaeology in the Borderlands: Investigations in Caucasia and Beyond* (pp. 38–94). Chicago: Cotsen Institute of Archaeology.

Kiladze, N. Z. (1951). Pamjatniki novogo kamennogo veka iz Tetramitsy, Vestnik Gosudarstvennogo Muzeja Gruzii, 29, 237–287.

Klaproth, J. (1823). *Voyage au mont Caucase et en Géorgie*. Paris: Gosselin C.

Klaproth, J. (1935). Magasin asiatique ou revue géographique et historique de l'Asie Centrale et Septentrionale. Paris: De Dondey T.

Kohl, P. L. (2002) Bronze production and utilization in Southeastern Daghestan, Russia: c. 3600–1900 BC. In M. Bartelheim, E. Pernicka, & R. Krause (Eds.), *Die Anfange der Metallurgie in der Alten Welt* (pp. 161–184). Rahden/Westf.: Verlag Marie Leidorf GmbH.

Kohl, P. L.(2003). Integrated interaction at the beginning of the Bronze age: new evidence from the Northeastern Caucasus and the advent of tin bronze in the third millennium BC. In A. T. Smith & K. S. Rubinson (Eds.), *Archaeology in the Borderlands: Investigations in Caucasia and Beyond* (pp. 9–21). Chicago: Cotsen Institute of Archaeology.

Kohl, P. L. (2007). *The Making of Bronze Age Eurasia*. Cambridge: Cambridge University Press.

Kohl P. L., Gadzhiev M. G., & Magomedov R. G. (2002a) Between the Steppe and the Sown: Cultural Developments on the Caspian Littoral Plain of the Southern Dagestan, c. 3600–1900 B. C. In K. Boyle, C. Renfrew, & M. Levine (Eds.), *Ancient Interactions: East and West in Eurasia* (pp. 113–128). Cambridge: McDonald Institute Monographs.

Kohl P. L., Gadzhiev M. G., & Magomedov R. G. (2002b). Investigations of Dagestan American Velikent (Dav) Expedition. In M. Bartelhein, E. Pernicka, & R. Krause (Eds.), *Die Anfänge des Metallurgie in der Alten Welt* (pp. 163–183). Berlin: M. Leidorf.

Korenevskij, S. N. (1972). Nakhodka bronzovogo topora u g. Pjatigorska. *Sovetskaja Arkheologija*, *3*, 337–338.

Korenevskij, S. N. (1974). O metallicheskikh toporakh majkopskoj kultury. *Sovetskaja Arkheologija*, *3*, 14–32.

Korenevskij, S. N. (1984). Novye dannye po metalloobrabotke dokobanskogo perioda v Kabardino-Balkarii. In V. I. Markovin (Ed.), *Arkheologicheskie issledovanija na novostrojkakh Kabardino-Balkari v 1972–1979 gg.*, t. I, pamjatniki epokhi bronzy (III-II tys. do n.e.) (pp. 254–299). Nal'chik: El'brus.

Korenevskij, S. N. (1986). O metalle epokhi srednej bronzy v gornoj zone severo-vostochnogo Kavkaza. *Sovetskaja Arkheologija.*, *3*, 5–15.

Korenevskij, S. N. (1988). Dva pogrebenija Mjkopskoy kul'tury iz Kislovodska. *Kratkie Soobshchenija*, *193*, 88–91.

Korenevskij, S. N. (1993). Radiokarbonnye daty Majkopskikh (Galjugaevskikh) poselenii. In: *Vtoraja Kubanskaja arkheologicheskaja conferentsija* (pp. 86–104). Majkop.

Korenevskij, S. N. (1995). Galjugaj I- poselenie Majkopskoj kul'tury (arkheologicheskie istochniki po probleme drevnejshikh zemledel'tsev i skotovodov na Kavkazskoj granitse Perednej Azii i Vostochnoj Evropy. Moscou: Institut etnologii i antropologii im. N.N. Miklukho-Maklaja, Rossijskaja AN.

Korenevskij, S. N. (1996). K voprosu o lokal’nykh razlichijakh i vnutrennej tipologii Majkopsko-Novosvobodnenskoj obshchnosti s uchetom dannykh ee poselenij. In Ju. Ju. Piotrovskij (Ed.), *Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena* (pp. 54–59). Sankt-Petersburg: Institut istorii material’noj ku’ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Korenevskij, S. N. (1997). The problem of the inner typology of Majkop in the reflection of its ceramic context. In O. D. Lordkipandze, B. A. Jorbenadze, & A. A. Tchanturia (Eds.) *Archaeology of the Caucasus: new discoveries and perspectives* (pp. 40–43). Tbilissi: The Centre for Archaeological Studies of the Georgian Academy of Sciences.

Korenevskij, S. N. (1998). Poselenie “Zamok” u goroda Kislovodska nizhnij sloj. In A. B. Belinskij (Ed.), *Materialy po izucheniju istoriko-kul’turnogo naseledija severnogo Kavkaza, Arkheologija* (pp. 96–147). Stravropol.

Korenevskij, S. N. (2004). Drevnejshie zemledel’tsy i skotovody Predkavkaz’ja, Majkopskogo-Novosvobodnenskaja obshchnost’, Problemy vnutrennej tipologii. Moscou: Nauka.

Koridze, D. L. (1958). Novye nakhodki mednikh orudij v Kvemo-Kartli. *Sovetskaja Arkheologija*, *1*, 134–140.

Krupnov, E. I. (1950). *arkheologicheskie issledovanija v Kabardinskoj ASSR v 1948 g*. Nal’chik: Uchenie Kabardinskij nauchno-issledovatelskij institut, 5.

Krupnov, E. I. (1951). Materialy po arkheologii severnoj Osetii dokabanskogo perioda. *Materialy i isselovanija po arkheologii SSR*, *23*, 3–74. Leningrad/Moscou: Nauka.

Krupnov, E. I. (1958). *Drevnija istorija i kul’tura Kabardy*. Moscou: Nauka.

Krupnov, E. I. (1960). *Drevnjaja istorija severnogo Kavkaza*. Moscou: Nauka.

Kuftin, B. A. (1936). *godov. Materialy k Arkheologii Kolkhidy*, vol. II. Tbilissi: Tekhnika da Shroma.

Kuftin, B. A. (1941). *Arkheologicheskie raskopki v Trialeti*. Tbilissi: Akademija Nauk SSR.

Kuftin, B. A. (1944). O drevnejshikh kornjakh Gruzinskoj kultury na Kavkaze po dannym arkheologii. Moskva: Akademija Nauk SSR.

Kuftin, B. A. (1950). *Arkheologicheskie izyskanija v Rionskoj nizmennosti i na chernomorskom poberezh’i 1935 i.*

Kushnareva, K. Kh. (1954). Pamjatniki mednogo veka v Nagorno-Karabakhe. *Sovetskaja Arkheologija*, *20*, 165–179.

Kushnareva, K. Kh. (1963a). Arkheologicheskie raboty 1954 g. v okrestnostjankh sel. Khodzhaly. In A. A. Iessen (Ed.), *Trudy Azerbajdzhanskoj (orenkaanskoj) ekspeditsii, Tom I (1953–1955 gg.)*, *Materialy i issledovanija po arkheologii SSSR*, 67 (pp. 371–386). Moscou: Nauka.

Kushnareva, K. Kh. (1963b). Poslednie epokhi bronzy na kholme Uzerlik-Tepe okolo Agdama. In A. A. Iessen (Ed.), *Trudy Azerbajdzhanskoj (orenkaanskoj) ekspeditsii, Tom I (1953–1955 gg.)*, *Materialy i issledovanija po arkheologii SSSR*, 67 (pp. 388–429). Moscou: Nauka.

Kushnareva, K. Kh. (1965). Novye dannye o poselenii Uzerlik-Tepe okolo Agdama. In A. A. Iessen & K. Kh. Kushnareva (Eds.), *Trudy Azerbajdzhanskoj (orenkaanskoj) ekspeditsii, Tom I (1956–1960 gg.)*, *Materialy i issledovanija po arkheologii SSSR*, 125 (pp. 74–101). Moscou: Nauka.

Kushnareva, K. Kh. (1993) *Juzhnyj Kavkazv IX-II tys. do n.e*. Sankt-Petersburg: Akademija-Nauk.

Kushnareva, K. Kh. (1994a). Pamjatniki Trialetskoj kul’tury na territorii Juzhnogo Zakavkaz’ja. In K. Kh. Kushnareva & V. I. Markovin (Eds.), *Epokha Bronzy Kavkaza i Srednej Azii. rannaja i srednjaja Kavkaza* (pp. 93–105). Moscou: Nauka.

Kushnareva, K. Kh. (1994b). Karmirberdskaja (tazakenskaja) kultura. In K. Kh. Kushnareva & V. I. Markovin (Eds.), *Epokha Bronzy Kavkaza i Srednej Azii. rannaja i srednjaja Kavkaza* (pp. 106–117). Moscou: Nauka.

Kushnareva, K. Kh. (1996). K probleme kul’turnykh I ekonomicheskikh svjazej Kavkaza v epokhi paleometalla. In Piotrovskij Ju.Ju. (Ed.), *Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e.*

Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena (pp. 40–43). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Kushnareva, K. Kh. (1997). The Southern Caucasus in Prehistory: Stages of Cultural and Socioeconomic Development from the Eight to the Second Millenium. Philadelphia: University of Pensylvania Museum.

Kushnareva, K.Kh., & Chubinishvili, T. N. (1963). Istoricheskoje mesto Juzhnogo Kavkaza v III tys. do n.e. *Sovetskaja Arkheologija*, *3*, 19–24.

Kushnareva, K.Kh., & Chubinishvili, T. N. (1970). *Drevnie kul'tury Juzhnogo Kavkaza*. Leningrad: Nauka.

Laffineur, R. (1994). Metals supply and metal trade in Bronze Age Eastern Mediterranean. In P. B. Vandiver, J. R. Druzik, J. L. Galvan Madrid, I. C. Freestone, & G. S. Wheeler (Eds.), *Material Issues in Art and Archaeology IV, Symposium held May 16–21, 1994, Cancum, Mexico* (pp. 631–638). Pittsburgh: Material Research Society.

Lordkipanidze, O. (1989) *Naseledie drevnei Gruzii*. Tbilissi: Metsniereba.

Lordkipanidze, O. (1991). *Archäologie in Georgien von der Alteinzeit zum Mittelalater*. Heidelbelg: VCH, Acta Humaniora.

Lechtman, H. (1977). Style in technology: some early thoughts. In H. Lechtman & R. S. Merrill (Eds.), *Material Culture: Styles, Organization, and Dynamics of the Technology* (pp. 3–20). St Paul: West Publishing.

Lechtman, H. (1996a). Cloth and metal: the culture of technology. In E. H. Boone (Ed.), *Andean Art at Dumbarton Oaks* (pp. 33–43). Washington D.C.: Dumbarton Oaks Research Library and Collection.

Lechtman, H. (1996b). Arsenic bronze: dirty copper or chosen alloy? A view from the Americas. *Journal of Field Archaeology*, *23*, 477–514.

Leemans, W. F. (1960). Foreign Trade in the Old Babylonian Period as revealed by texts from southern Mesopotamia. Leyde: Brill E.

Lovpache, H.G. (1985). Mogil'niki v ust'e reki Psekupsa. In: *Voprosy arkheologii Adygei*, pp. 15–64. Majkop.

Lucas, A. (1928). Notes on the early history of tin-bronze. *Journal of Egyptian Archaeology*, *14*, 97–108.

Lyonnet, B. (2000). La Mésopotamie et le Caucase du Nord au IVe et au début du IIIe millénaires av. n. è.: leurs rapports chronologiques et la culture de Maïkop. Etat de la question et nouvelles propositions. In C. Marro & A. Hauptmann (Eds.), *Chronologie des pays du Caucase et de l'Euphrate au IVe–IIIe millénaires*, Varia Anatolica, XI (pp. 299–320). Istanbul/Paris: IFEA, de Boccard.

Lyonnet, B. (2004). Les cultures anciennes du Caucase du nord et de l'ouest (du Néolithique au début de l'â ge du Bronze). In J. Guilaine (Ed.). *Aux marges des grands foyers du Néolithique. Périphéries, débitrices ou créatrices?* Séminaire du Collège de France (pp. 87–104). Paris: Errance.

Lyonnet, B. (2005). A new possible interpretation of the Bactro-Margiana culture (BMAC) of the Central Asia: the tin trade. In C. Jarrige & V. Lefèvre (Eds.), *South Asia Archaeology 2001* (pp. 191–200). Paris: Editions Recherche sur les Civilisations.

Lyonnet, B. (2006). *Mission ≪ Boyuk Kesik ≫, Azerbaidjan*, rapport fait au Ministère des Affaires Etrangères. Unpublished.

Lyonnet, B. (2007a). Les cultures du Caucase (VIème-IIIème millénaires avant notre ère). Leurs relations avec le Proche Orient. In B. Lyonnet (sous la direction), *Les cultures du Caucase (VIe–IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 11–19). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Lyonnet, B. (2007b). La culture de Majkop, la Transcaucasie, l'Anatolie orientale et le Proche-Orient: relations et chronologie. In B. Lyonnet (Ed.), (sous la direction), *Les cultures du Caucase (VIe–IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 133–161). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Lyonnet, B. (2008). L'Azerbaïdjan au Néolithique et au Chalcolithique (VIe–IVe millénaire avant notre ère), conférence du Louvre Décembre 2008.

Lyonnet, B. (2009). Périphérie de la Mésopotamie à la période d'Uruk (IVe millénaire): le cas des régions du Caucase. In J.-M. Durand & A. Jacquet (Eds.), *Centre et périphérie: approches nouvelles des Orientalistes. Actes du colloque organisé par l'Institut du Proche-Orient Ancien du Collège de France, La Société Asiatique et le CNRS (UMR 7192) les 31 Mai et 1er juin 2006 (Paris—Collège de France)* (pp. 1–28). Paris: Maisonneuve.

Lyonnet, B., & Marro, C. (2000). *Recherches archéologiques dans le Caucase nord-occidental et en Transcaucasie*. Rapport du Ministère des Affaires Etrangères. Unpublished.

Lyonnet, B., & Maisuradze, B. (2005). *Prospections archéométallurgiques dans le district de Ratcha*, rapport Ministère des Affaires Etrangères français. Unpublished.

Lyonnet, B., Akhundov, T., Almamedov, K., Bouquet, L., Courcier, A., Jellilov, B., Huseynov, F., Loute, S., Makharadze, Z., & Reynard, S. (2008). Late Chalcolithic Kurgans in Transcaucasia. The cemetery of Soyuq Bulaq (Azerbaijan). *Mitteilungen aus Iran und Turan*, *40*, 27–44.

Lyonnet, B., & Rezepkin, A. (2009a). Excavations and surveys on Majkop culture sites in Adygei, near Krasnodar (Russia) and their relations with the Uruk civilisation of Mesopotamia. In J.-C. Margueron, P. Miroschedji, & J.-P. Thalmann (Eds.), *actes du 3e Colloque International sur l'Archéologie du Proche-Orient (ICAANE)*, Paris, Avril 2002, Wiona Lake, Eisenbrauns. To be published.

Lyonnet, B., & Gulyev, F. (2009b). *Mission ≪ Boyuk Kesik ≫, Azerbaidjan (campagnes 2006–2008)*, rapport fait au Ministère des Affaires Etrangères. Unpublished.

Mactear, J. (1894–1895). Some notes on Persian mining and metallurgy. *Transactions of the Institution of Mining and Metallurgy*, *3*, 2–39.

Magomedov, R. (2006). The Kura-Araxe "Culture" in the North-Eastern Caucasus: problems in its identification and chronology. In D. L. Peterson, L. M. Popova, & A. T. Smith (Eds.), *Beyond the Steppe and the Sown, Proceedings of the 2002 University of Chicago Conference on Eurasian Archaeology* (pp. 142–159). Leide: Brill.

Magomedov, G., Gadzhiev, G., Kohl, P. L., Magomedov, R. G., Stronach, D., & Gadzhiev, S. M. (2000). Daghestan-American archaeological investigations in Daghestan, Russia 1997–99. *Eurasia Antiqua*, *6*, 47–121.

Maisuradze, B. & Gobedshchischvili, G. (2002). Alter Bergbau in Ratcha. In I. Gambaschize, A. Hauptmann, R. Slotta, & Ü Yalcin, Georgien (Eds.), *Schätze aus dem land des Golden Vlies*. Katalog der Ausstellung des deutschen Bergbau-Museums Bochum in Verbindung mit dem Zentrum für Archäologische Forschungen der Georgishen akademie der Wissenschften Tbilisse von 28 Oktober 2001 bis 19 Mai 2002 (pp. 130–135). Bochum: Deutsches Bergbau Museum.

Makharadze, Z. (2008). The settlement at Tsikhiagora the early brarrows at Kvatiskhevi. In A. Sagona & M. Abramishvili (Eds.), *Archaeology in Southern Caucasus: Perspectives from Georgia* (pp. 63–104). Ancient Near Studies supplement 19. Louvain: Peeters.

Makhmudov, F.R., Munchaev, R.M., & Narimanov, I. G. (1968). O drevnejshej metallurgii Kavkaza. *Sovetskaja Arkheologija*, *4*, 16–26.

Malfoy, J.-M., & Menu, M. (1987). la métallurgie du cuivre à Suse au IVe et IIIe millénaire: analyses en laboratoire. In F. Tallon (Ed.), *Metallurgie susienne I, de la fondation de Suse au XVIIIe avant J.C.* (pp. 355–373). Paris: Réunion des Musés Nationaux.

Markovin, V. I. (1963). Novy pamajtnik epokhi bronzy v gornoj Chechie (mogil'nik u s. Gatyn-Kale). In E. I. Krupnov (Ed.), *Drevnosti Checheno-Ingushtii*, *Materialy i isselovanija po arkheologii SSR*, 116 (pp. 49–135). Moscou: Nauka.

Markovin, V. I. (1994a). Severokavkazskaja kul'turno-istoricheskaja obshchnost'. In K. Kh. Kushnareva & V. I. Markovin (Eds.), *Epokha Bronzy Kavkaza i Srednej Azii. rannaja i srednjaja Kavkaza* (pp. 254–286). Moscou: Nauka.

Markovin, V. I. (1994b). Severo-Vostochnyj Kavkaz v epokhu bronzy. In K. Kh. Kushnareva & V. I. Markovin (Eds.), *Epokha Bronzy Kavkaza i Srednej Azii. Rannajai i Srednjaja Kavkaza* (pp. 287–333). Moscou: Nauka.

Markovin, V. I. (1994c). O Nekotorykh novykh tendentsijakh v arkheologicheskom izuchenii drevnostej Severnogo Kavkaza. *Rossijskaja Arkheologija.*, *4*, 25–43.

Markovin, V. I. (1999). Drevnosti Severnogo Kavkaza, 275 let rossijskaja Akademija nauk. Moscou: Nauka.

Markovin, V. I. (2004). O Nekotorykh novykh tendentsijakh v arkheologicheskom izuchenii drevnostej severnogo Kavkaza. *Rossijskaja Arkheologija.*, *4*, 25–43.

Marro, C. (2007). Upper-Mesopotamia and Transcaucasia in the late chlacolitthic period (4000–3500 B. C.). In B. Lyonnet (sous la direction) (Ed.), *Les cultures du Caucase (VIe–IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 77–94). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Martirosjan, A. A. (1964). O periodizatsii arkheologicheskikh pamjatnikov Armenii epokhi bronzy i rannego zheleza. *Sov. Arkh.*, *3*, 21–36.

Martirosjan, A. A., & Munchaev, R. M. (2003). *Severnyj Kavkaz, ocherki drevnej I srednevekoj istorii i kul'tury*. Rossijskaja Akademija nauk Institut Arkheologii: Moscou.

Martirosjan A. A., & Miatsakanjan A. O. (1973). Prierevanskij klad drevnej bronzy. *Kratkije Soobshchenija Instituta Arkheologija*, *134*, 122–127.

Martirosjan, A. A., & Torosjan, R. M. (1967). K voprosu ob interpretatatsii eneoliticheskoj kul'tury Armeni, Vestnik Obschestvennykh Nauk Armenij SSSR, 3, 52–62.

Mellaart, J. (1960). Excavation at Hacilar, 3rd preliminary report. *Anatolian Studies*, *10*, 87.

Mellaart, J. (1962). Excavations at Çatal Höyük. 1st preliminary Report. *Anatolian Studies*, *12*, 41–65.

Mellaart, J. (1963a). Early cultures of the south Anatolian plateau. *Anatolian Studies*, *13*, 199–236.

Mellaart, J. (1963b). Excavation at Çatal Höyük, 1962. Second preliminary report. *Anatolian Studies*, *13*, 43–103.

Mellaart, J. (1964). Excavations at Çatal Höyük. 3rd preliminary Report. *Anatolian Studies*, *14*, 39–119.

Mellaart, J. (1967). *Çatal Höyük*. London: Thames and Hudson.

Mellaart, J. (1968). Anatolian trade with Europe and Anatolian geography and cultures provinces in the late Bronze. *Anatolian Studies*, *18*, 187–202.

Meliksetian, Kh., Pernicka, E., Badaljan, R., & Avetissjan, P. (2003). Geochemichal characteristaion of Armenian early Bronze age metal artefacts and their relation to copper ore. In A. Giumlia-Mair, E. Pernicka, & R. Pleiner (Eds.), *Archaeometallurgy in Europe (24–26 September 2003)* (pp. 597–606). Milan: Associazione Italiana di Metallurgia.

Menabde, M. V., Kiguradze, T. V., & Kikodze, Z. V. (1980). Rezul'taty rabot Kvemokartlijskoj arkheologicheskoj ekspeditsii (1976–1977 gg.). *Arkheologicheskije ekspeditsii Gosudarstvenogo muzeja Gruzii*, *4*, 27–46.

Miroschedji, P. de (2000). La céramique de Khirbet Kerak en Syro-Palestine: état de la question. In C. Marro & A. Hauptmann (Eds.), *Chronologie des pays du Caucase et de l'Euphrate au IV*^{e}*–III*^{e} *millénaires*, *Varia Anatolica* XI (pp. 255–278). Istanbul/Paris: IFEA, de Boccard.

Miziev, I. M. (1984) Dva kurgana u selenij Kishpek i Kyzburun III. In V. I. Markovin (Ed.), *Arkheologicheskie issledovanija na novostrojkakh Kabardino-Balkari v 1972–1979 gg.*, t. I, Pamjatniki epokhi bronzy (III–II tys. do n.e.) (pp. 88–111). Nal'chik: El'brus.

Montero-Fenollos J.-L. (2001). Metalistería de la Edad del Bronce en Tell Qara Quzaq, estudio tipológico y technológico. In G. Del Olmo Lete, J.-L. Montero, & C. Valdes Pereiro (Eds.), *Tell Qara Quzaq II, campaas IV–VI (1992–1994)* (pp. 255–303). Barcelone: AUSA.

Moorey, P. R. S. (1982). The archaeological evidence for metallurgy and related technology in Mesopotamia C. 5500–2100 B. C. *Iraq*, *44*, 13–38.

Moorey, P. R. S. (1994). *Ancient mesopotamian materials and industry: The archaeological evidence*. Oxford: Clarenton Press.

Moorey, P. R. S. (1995). Metals ancient societies in old world, the emergence of copper and bronze working in the light of recent research. *Beer-Sheva*, *8*, 27–50.

Morgan, J. (1889a). Mission scientifique au Caucase, tome 1: les premiers âges des métaux dans l'Arménie russe: études archéologiques et historiques. Paris: Leroux E.

Morgan, J. (1889b). Mission scientifique au Caucase, tome 2: recherches sur les origines des peuples du Caucase: études archéologiques et historique. Paris: Leroux E.

Morgan, J. (1912). Observations sur les couches profondes de l'Acropole de Suse. *Mémoires de la Délégation en Perse*, *13*, 1–25.

Mudzhiri, T. P. (1975). Istoricheskie svedennja o dobbiche i pererabotke rud v drevnej Gruzii. In *tekhnologija dobychi i obogashchennja poleznykh iskopaemykh Gruzii* (pp. 69–78). Tbilissi: Metsniereba.

Mudzhiri, T. P. (1977). O tekhnike i tekhnologii drevnejshikh surmjahykh razrabotok Gruzii. In *tekhnologija dobychi i obogashchennja poleznykh iskopaemykh Gruzii* (pp. 104–116). Tbilissi: Metsniereba.

Mudzhiri, T. P. (1979). Polevye issledovanija drevnikh rudnikov gruzii epokhi bronzi (gornaja Racha, gornaja Abkhazia). In E. O. Mindeli, V. A. Bojarskij, I. I. Zurabishvili, V. F. Chanishvili, & T. P. Mudzhiri (Eds.), *Istorija gornoj nauki i tekhniki, materialy pervogo vsesojuznogo koordinatsionnogo soveshchija, Tbilisi 15–17 nojabrja 1976 goda* (pp. 67–83). Tbilissi: Metsniereba.

Mudzhiri, T. P. (1988a). Polevye metody Kompleksnogo issledovanija drevnikh rudnikov. In V. V. Bzhanija, Ju. G. Argun, O. Kh Bgazhba, & T. G. Alanija (Eds.), Mednye rudniki zapadnogo Kavkaza III–I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija (pp. 17–18). Sukhumi: Tezisy Dokladov.

Mudzhiri, T. P. (1988b). Drevnie rudniki gornoj Abkhazii v sisteme gorno-metallurgicheskogo proizvodstva Gruzii I Kavkaza epokhi bronza. In V. V. Bzhanija, Ju. G. Argun, O. Kh Bgazhba, & T. G. Alanija (Eds.), *Mednye rudniki zapadnogo Kavkaza III–I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 10–11). Sukhumi: Tezisy Dokladov.

Mudzhiri T. P., & Kvirikadze K. V. (1978). Polevye issledovanija tekhniki drevnikh mednikh razrabotok gruzii v verkhov'jakh reki Bzib'. In *tekhnologija dobychi i obogashchennja poleznykh iskopaemykh Gruzii* (pp. 130–142). Tbilissi: Metsniereba.

Mudzhiri T. P., & Kvirikadze K. V. (1979) Polevye issledovanija drevnikh rudnikhov Gruzii epokhi bronzy (Gornaya Racha, Gornaya Abkhazia. In *tekhnologija dobychi i obogashchennja poleznykh iskopaemykh Gruzii* (pp. 67–83). Tbilissi: Metsniereba.

Muhly, J. D. (1973). Copper and tin, the distribution of mineral resources and the nature of the metal trade in the Bronze Age. *Transactions of the Connecticut Academy of Art and Science*, *43*, 155–535.

Munchaev, R. M. (1975). Kavkaz na zare bronzovogo veke, Neolit, Eneolit, Rannaja Bronza. Moskva: Nauka.

Munchaev, R. M. (1982a). Pamjatniki kul'tury eneolita Kavkaza. In V. M. Masson & N. Ja Merpert (Eds.), *Eneolit SSSR, Archaeologija SSSR* (pp. 93–164). Moscou: Nauka.

Munchaev, R. M. (1982b) Eneolit Kavkaza. In V. M. Masson & N. Ja. Merpert (Eds.), *Eneolit SSSR, Archaeologija SSSR* (pp. 165–320). Moscou: Nauka.

Munchaev, R. M. (1994). Majkopskaja Kultura. In K. Kh. Kushnareva & V.I. Markovin (Eds.), *Epokha Bronzy Kavkaza i Srednej Azii. Rannaja i srednaja bronza Kavkaza* (pp. 158–225). Moskva: Nauka.

Munchaev, R. M. (1996a). Blizhnij vostok I Kavkaz: problema Kul'turnykh svjazej v VI—III tys. do nashej ery. In Ju. Ju. Piotrovskij (Ed.), *Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena* (pp. 35–36). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Munchaev, R. M. (1996b). Litejnoe proizvodstvo na severnom Kavkaze v epokhi rannej bronzy. In Ju. Ju. Piotrovskij (Ed.), Mezhdu Aziej I Evropoj, Kavkaz v IV – I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena (pp. 67–69). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Munchaev, R. M. (1997). K voprosu o drevnej metallurgii i metallo-obrotki na territorii Azerbaidzhanaja. *Tarih ve onun problemleri*, *1*, 149–152.

Munchaev, R. M. (2005) Mesopotamija, Kavkaz i Tsirkumpotijskaja metallurgicheskaja provintsija, *Rossijskaja Arkheologija*, *4*, 13–24.

Muscarella, O. W. (1969) The tumuli at Sé Girdan, a preliminary report. *Metropolitan Museum Journal*, *2*, 5–25.

Muscarella, O. W. (1971). The tumuli at Sé Girdan, second report. *Metropolitan Museum Journal*, *4*, 5–28.

Muscarella, O. W. (2003). The chronology and culture of Sé Girdan: Phase III. Ancient Civilizations from Scythia to Siberia, an International Journal of Comparative Studies in History and Archaeology, 117–131.

Museibli, N. (2007). *Chalcolithic settlement, Boyuk Kesik*. Bakou: Nafta-Press.

Narimanov, I. G. (1969). Raskopki eneoliticheskogo poselenija Ilanly-Tepe. *Arkheologicheskie otkrytija 1968 g*, 396–397.

Narimanov, I. G. (1970). Kjulli-Tepe I Geoj-Tepe. *Arkheologicheskie otkrytija, 1969 g*, 374–375).

Narimanov, I. G. (1977). K istorii drevnejshego skovodstva Kavkazaja, *Doklady Akademy nauk Azerbajdzhanskoj SSR*, *19*, 56–58.

Narimanov, I. G. (1985). Raskopki poselenja Chalagan Tepe. *Arkheologicheskie otkrytija 1983 goda*, 489–490.

Narimanov, I. G. (1987). Kul'tura drevnejshego zemledel'chesko-skotovodcheskogo naselenija Azerbajdzhana (epokha eneolita VI-IV tys. do n.e.). Bakou: Elm.

Narimanov, I. G. (1990). O drevnej metallurgii medi na territorii Azerbajzhana. *Sovetskaja Arkheologija*, *1*, 5–14.

Narimanov, I. G. (1996). O rannezemledel' cheskom poselenii Chalagantepe. In Ju. Ju. Piotrovskij (Ed.), Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena: 49–50. Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Narimanov, I. G. (2004). Archaeological sites of the Early Bronze Age in north Azerbaidjan: A gazetteer. In A. Sagona (Ed.), *A view from the highlands, archaeological studies in honour of Charles Burney*, *ancient near eastern studies*, 12, (pp. 467–473). Louvain: Peeters.

Narimanov, I. G., & Dzhafanov G. F. (1988). K istorii drevnej metallurgii Azerbajdzhana. In V. V. Bzhanija, Ju. G. Argun, O. Kh. Bgazhba, & T. G. Alanija, *Mednye rudniki zapadnogo Kavkaza III-I tys. do n.e. i ikh rol' v gorno-metallurgicheskom proidzvodstve drevnogo naselenija* (pp. 21–22). Sukhumi: Tezisy Dokladov.

Nebieridze, L. D. (1985). Arkheologicheskie issledovanija na poselenii Chirokhi. *Polevye arkheologicheskije issledevanija 1982 g*, 8–9.

Nebieridze, L. D. (1986). Arkheologicheskie issledovanija v Tverdzhol'skom rajone, *Polevye arkheologicheskije issledevanija 1983 g*, 8–10.

Nekhaev, A. A. (1984). Nekotorye voprosy izuchenija poselenija Svobodnoe. In *Voprosy arkheologii Adygei*, Majkop (pp. 69–79).

Nekhaev, A. A. (1986). Pogrebenie majkopskoj kult'ury iz kurgana u sela Krasnogvardejskoe, *Sovetskaja Arkheologija*, *1, 244–248.*

Nekhaev, A. A. (1990). Eneoliticheskie poselenija Zakuban'ja. In A. M. Zhdanovskij & I. I Marchenko (Eds.), *Drevnie pamjatniki Kubani* (pp. 5–22). Krasnodarskij Kraevoj Sovet, Vserossijskogo Obshchestva Okhrany Pamjatnikov Istorii i Kul'tury.

Nekhaev, A. A. (1992). Domajkopskaja Kul'tura Severnogo Kavkaza, *Arkheologicheskie Vesti*, *1*, 76–96.

Nioradze, M. G. (1986). Issledovanie peschery Ortvala. *Polevye arkheologicheskije issledevanija 1983 g*, 10–13.

Norcera, G. M. Di, Hauptmann, A., & Palmieri, A. M. (2004). I metallic della Toma Reale e la mettllurgia agli ablbori del III millennio. In M. Frangipane (Ed.), *Arslantepe, alle origini del potere, la collina dei leoni* (pp. 123–143). Milan: Electra.

Northover, J. P. (1989). Properties and use of arsenic-copper alloys. In A. Hauptmann, E. Pernicka, & G. A. Wagner (Eds.), *Old world archaeometallurgy* (pp. 111–118). Bochum: Deutsches Bergbau-Museum.

Oates, J., & Oates, D. (1997). An open gate: Cities of the fourth millennium B. C. (Tell Brak 1997). *Cambridge Archaeological Journal*, *7*(2), 287–307.

Ökse, A. T. (2003). Excavations at Gre Virike in 2000. In N. Tuna & J. Velibeyoglu (Dir.), *Salvage Project of the Archaeological Heritage of the Ilisu and Carchemish Dam Reservoirs. Activities in 2000* (pp 270–280). Ankara: Middle East Technical University.

Palmieri, A. M. (1967). Insediamento del bronzo antico a GelincikTepe (Malatya), *Origini*, *8*, 117–193.

Palmieri, A. M. (1969). Recenti dati sula stratigrafia di Arslantepe, *Origini*, *3*, 7–66.

Palmieri, A. M. (1974). Arslantepe (Malatya). Report on the excavations 1971–1972. *Türk Tarih, Arkeoloji ve Etnografya Dergisi*, *21*(1), 137–146.

Palmieri, A. M. (1978). Scavi ad Arslantepe (Malatya). *Quaderni de La Ricerca Scientifica*, *100*, 311–373.

Palmieri, A. M. (1981). Excavations at Arslantepe (Malatya). *Anatolian Studies*, *31*, 101–226.

Palmieri, A. M. (1985). 1984 Excavations at Arslantepe. *Kazi Sonuçlari Toplantisi*, *7*, 29–36.

Palmieri, A. M., & Sertok, K. (1993). Mineral in and around Arslantepe. *Arkeometry Sonuçlari Toplantisi*, *9*, 119–135.

Palmieri, A. M., Sertock, K., & Chernykh, E. N. (1993). From Arslantepe Metalwork to Arsenical Copper Technology in Eastern Anatolia. In M. Frangipane, A. Hauptmann, M. Liverani, P. Matthiae, & M. Mellinck (Eds.), *Between the Rivers and over the Mountains, Archaeologica Anatolica et Mesopotamica Alba Palmieri Dedicata* (pp. 573–599). Rome: Dipartimento di Scienze Storiche Archeologiche e Antropologiche dell'Antichità, Università di Roma "La Sapienza".

Palmieri, A. M., Hauptmann A., & Sertok, K. (1995). Additional data of ores from east-Anatolian metallurgy. *Arkeometry Sonuçlari Toplantisi*, *11*, 167–180.

Palmieri, A. M., Frangipane, M., Hauptmann, A., & Hess K. (1998). Early Metallurgy at Arslantepe during the late Chalcolithic and the Early Bronze Age IA–IB periods. In A. Hauptmann, E. Pernicka, Th. Rehem, & Ü. Yalçin (Eds.), *The beginnings of Metallurgy, Der Anschnitt*, 9 (pp. 141–148). Bochum: Deutsches Bergbau Museum.

Palmieri, A. M., Hauptmann, A., & Hess, K. (1998). Les objets en métal du tombeau monumental d'Arslantepe de 3000 av. J. C. (Malatya, Turquie). *Revue d'Archéométrie*, *22*, 39–43.

Palmieri, A. M., Frangipane, M., Hauptmann, A., & Hess, K. (1999). Early metallurgy at Arslantepe during the Late Chalcolithic and the Early Bronze Age IA–IB periods. In A. Hauptmann, E. Pernicka, Th. Rehren, & U. Yalcin (Eds.), *The Beginnings of Metallurgy*, *Der Anschnitt, Beiheft 9* (pp. 141–149). Bochum: Deutsches Bergbau-Museum.

Palumbi, G. (2004). La più antica Tomba "Reale". Dati archeologici e costruzione dele ipotesi. In M. Frangipane (Ed.), *Arslantepe, alle origini del potere, la collina dei leoni* (pp. 115–119). Milan: Electra.

Palumbi, G. (2007). A preliminary analysis of the prehistoric pottery from Aratashen (Armenia). In B. Lyonnet (sous la direction), *Les cultures du Caucase (VIe–IIIe millénaires avant notre ère). Leurs relations avec le Proche-Orient* (pp. 63–76). Paris: CNRS Editions/Editions Recherche sur les Civilisations.

Pare, C. F. E. (2000) Bronze and the Bronze Age. In C. F. E. Pare (Ed.), *Metals make the world go round, the supply and the circulation of metals in bronze age in Europe*, Proceedings of a Conference Held at The University of Birmingham in June 1997 (pp. 1–38). Oxford: Oxbow Books.

Penhallurick, R. D. (1986). *Tin in antiquity: Its minings and trade throughout the ancient world with a particular References to Cornwall*. London: The Institute of Metal.

Pernicka, E., Begemann, F., Schmitt, S., Todorova, S., & Kuleff, I. (1997). Prehistoric copper in Bulgaria. Its composition and provenance. *Eurasia Antiqua*, *3*, 41–180.

Peterson, D. L. (2003). Ancient metallurgy in the mountain kingdom: The technology and value of early bronze age metalwork from Velikent, Daghestan. In A. T. Smith & K. S. Rubinson (Eds.), *Archaeology in the Borderlands: Investigations in Caucasia and Beyond* (pp. 22–37). Chicago: Cotsen Institute of Archaeology.

Peterson, D. L. (2007). Changing technologies and transformations of the value in the middle Volga and the northeastern Caucasus, circa 3000–1500 B. C. PhD dissertation, Department of Anthropology. Chicago: UMI.

Philip, G. & Millard, R. (2000). Khirbet Kerak ware in the Levant: the implications of radiocarbon chronology and spatial distribution. In C. Marro & A. Hauptmann (Eds.), *Chronologie des pays du Caucase et de l'Euphrate au IV^{e}–III^{e} millénaires*, *Varia Anatolica* XI (pp. 279–291). Istanbul, Paris: IFEA, de Boccard.

Piro, J. (2008). Pastoral economies in early Transcaucasian communities from the mid 4th to 3rd millennium B. C. In E. Vila, L. Gourichon, A. M. Choyke, & H. Buitenhuis (Eds.), *Archaeozoology oft he Near East, VIII, Actes des huitièmes Rencontres internationales d'Archéozoologie de l'Asie du Sud-Ouest et des régions adjacentes (Lyon, 28 Juin—1er Juillet 2006)* (pp. 451–463). Lyon: Maison de l'Orient et de la Méditérranée.

Pitskhelauri, K. N., & Chernykh, E. N. (1987). Kavkaz v Sisteme Paleometallicheshikh Kultur Evrazii, materialy i Simpoziuma "Kavkaz v Epokhu Rannego Metalla" (Telavi-Signakhi 1983). Tbilisi: Metsniereba.

Pitskhelauri, K. N., & Chernykh, E. N. (1991). *Kavkaz v Sisteme Paleometallicheshikh Kultur Evrazi*. Tbilisi: Metsniereba.

Pitskhelauri, K. N., & Chernykh, E. N. (2003). Kavkaz v Sisteme Paleometallicheshikh Kultur Evrazii, III mezhdunarodnyj simpozium Sagaredzho,1989. Tbilisi: Metsniereba.

Pkhakadze, G. G. (1988). Nekotorye voprosy eneolita zapadnogo Zakavkaz'ja. *Soobschenija Akademii Nauk Gruzinskoj SSR*, *130*(1), 209–211.

Pkhakadze, G. G. & BAramidze, M. (2008). The settlement at Pichori and colchedian Bronze Age chronology. In A. Sagona & M. Abramishvilli (Eds.), *Archaeology in Southern Caucasus: Perspectives from Georgia* (pp. 249–267). Ancient Near Studies supplement 19. Louvain: Peeters.

Potts, P. F. (1993). Patterns of trade in the third millennium B. C. Mesopotamian and Iran. *World Archaeology*, *24*(3), 379–402.

Prag, K. (1978). Silver in the Levant in the fourth millennium B. C. In R. Moorey, P. Parr (Eds.), *Archaeology in the Levant, Essays for Kathleen Kenyon* (pp. 36–45). Aris and Phillips LTD, Warminster.

Rassamakin, Y. (1999). The Eneolithic of the Black Sea steppe: Dynamics of the cultural and economic development 4500–2300 B. C. In M. Levine, Y. Rassamakin, A. Kislenko, & N. Tatarinstseva (Eds.), *Late Prehistoric Exploration of the Eurasian Steppe*. McDonald Institute Monographs (pp. 59–182). Cambridge: McDonald Institute for Archaeological Research.

Rehren, Th., Hess, K., & Philip, G. (1996). Auriferous silver in Western Asia: ore or alloy? *The Journal of the Historical Metallurgy Society*, *30*(1), 1–10.

Rezepkin, A. D. (1981). Raboty bliz stanitsy Novosvobodnoj. *Arkheologicheskie otkrytija 1979 g.*, 115–116.

Rezepkin, A.D. (1991a). Kul'turno-khronologicheskie aspekty proiskhozdenija I razvitija Majkopskoj kul'tury. In V. A. Trivonov (Ed.), *Majkopskij fenomen v drevnej historii Kavkaza I vostochnoj Evropy, Symposium International de Novorossijsk Mars 1991* (pp. 20–21). Leningrad: Leningradskoe Otdelenie Instituta Arkheologii AN SSSR, Upravlenie Kul'tury Krasnodarskogo Krajispolkoma, Nauchno-Proizvodstvennyj Proektno-Konstruktorskij Tsentr po Okrane i Ispol'zovaniju Pamjatnikov Istorii i Kul'tury Krasnodarskogo Kraja, Maloe Predprijatie Arkhitektura, Restavratsija, Tekhnologija, Turizm.

Rezepkin, A. D. (1991b). Kurgan 31 mogil'nika Klady: problemy genezisa i khonologii majkopskoj kul'tury. In V. M Masson (Ed.), *Drevnie kul'tury Prikuba: po materialam arkheologicheskikh rabot v zonakh melioratsii KrasnodarskogoKraja*. Moscou: Nauka.

Rezepkin, A. D. (1996). K probleme sootnoshenija khronologija kul'tur epokhi eneolita—rannej bronzy severnogo Kavkaza I Tripol'ja. In Ju. Ju. Piotrovskij (Ed.), *Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena* (pp. 50–54). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Rezepkin, A. D. (2000). *Das frühbronzezeitliche Gräberfeld von Klady und die Majkop-Kultur in Nordwestkaukasien*, Arkhäologie in Eurasien, 10. Rahden/Westf: Marie Leidorf.

Rezepkin, A. D. (2001). Majkop-Novosvobodnaja. Etapy ili kul'tury. In I. I. Marchenko, T*re'ja Kubanskaja Arkheologicheskaja Konferentsija* (pp. 148–155). Krasnodar-Anapa: Krajbibkollektor.

Rostovtsev, M. I. (1918). *Ellistvo i iranstvo na jugy Rossij*. Petrograd: "Ogni".

Rothman, M. S. (2001). *Uruk Mesopotamia and ist Neighbors. Cross-Cultural Interactions in the Era of State Formation.* School of American Research Advanced Seminar Series. Santa-Fe: School of American research Press.

Rothman, M. S. (2002). *Tepe Gawra: the evolution of a small, prehistoric center in Northern Iraq*. University Museum Monograph 112. Philadelphia: University of Pennsylvania.

Rothman, M. S. (2003). Ripples in the Stream: Transcaucasia-Anatolia Interactions in the Murat/Euphrate basin at the beginnings of the third millennium B. C. In A. T. Smith & K. S Rubinson (Eds.), *Archaeology in the Borderlands: Investigations in Caucasia and Beyond* (pp. 95–110). Chicago: Cotsen Institute of Archaeology.

Rothman, M. S. (2005). Transcaucasians: Settlement, migration, and trade in the Kura-Araxes periods. *Archaeologische Mitteilung aus Iran und Turan*, *37*, 53–62.

Ryndina, N. V. (1998). Drevneishee metalloobratyvajushchee proizvodstvo Jugo-Jugo-Vostoschnoj Evropy (istoki i razvitie v neolite-eneolite). Moscou: editorial URSS.

Ryndina, N. V. (2003). Earliest copper axes of the eastern Europe: Centers of production and spreading ways. In A. Giumlia-Mair, E. Pernicka, & R. Pleiner (Eds.), *Archaeometallurgy in Europe (24–26 September 2003)* (pp. 11–18). Milan: Associazione Italiana di Metallurgia.

Ryndina, N. V., & Ravich, I. G. (1995). Early copper-arsenic alloys and the problems of their use in the bronze age in North Caucasus. *Bulletin of the Metals Museum*, *23*, 1–18.

Ryndina, N. V., & Ravich, I. G. (2000). Eneoliithic Balkan-Carpathian Metallurgical Province (BCMP) as an unique centre of the origin and development of the earliest metallurgical activity (part I). *Bulletin of the Metals Museum*, *32*, 6–28.

Ryndina, N. V., & Ravich, I. G. (2001). Eneoliithic Balkan-Carpathian Metallurgical Province (BCMP) as an unique centre of the origin and development of the earliest metallurgical activity (part II). *Bulletin of the Metals Museum*, *34*, 1–21.

Saintot, A. (2000). Reconstruction des champs de paléocontraintes de la Crimée au Caucase nord-occidental, relations avec le développement des structures majeures. Apport de la télédétection à l'analyse structurale. Paris: Université Pierre et Marie Curie.

Sagona, A. (1984). *The Caucasian region in the early bronze age*. BAR International Series 214. Oxford: Archaeopress.

Sagona, A. (1993). Settlement and society in late prehistoric Trans-Caucasus. In M. Frangipane, A. Hauptmann, M. Liverani, P. Matthiae, & M. Mellinck (Eds.), *Between the Rivers and over the Mountains, Archaeologica Anatolica et Mesopotamica Alba Palmieri Dedicata* (pp. 455–474). Rome: Dipartimento di Scienze Storiche Archeologiche e Antropologiche dell'Antichità, Università di Roma "La Sapienza".

Sagona, A. (2000). Sos Höyük and the Erzurum region in late Prehistory: a provisional chronology for northeast Anatolia. In C. Marro & A. Hauptmann (Eds.), *Chronologie des pays du Caucase et de l'Euphrate au IV^{e}–III^{e} millénaires, Varia Anatolica XI* (pp. 321–373). Istanbul: IFEA, diffusion de Boccard.

Sagona, A. (2004). Social boundaries and ritual landscapes in late prehistoric transcaucasian and highland Anatolia. In A. Sagona (Ed.), *A View from the Highlands, Archaeological Studies in Honour of Charles Burney*, *Ancient Near Eastern Studies*, 12, 478–538. Louvain: Peeters.

Selimkhanov, I. R. (1960a). K issledovaniju metallicheskikh predmetov iz “eneolticheskikh” pamjatnikov Azerbajdzhana i Severnogo Kavkaza, *Sovetskaja Arkheologija*, *2*, 89–102.
Selimkhanov, I. R. (1960b). Spektralanalytische Untersuchungen von Metallfunden des 3. und 2. Jahrtausends aus dem östlichen Trankaukasian-Azerbaidzhan, *Archaeologia Austriaca*, *28*, 71–79.
Selimkhanov, I. R. (1962). Spectral analysis of metal articles from archaeological monuments in the Caucasus. *Proceedings of the Prehistoric Society*, *28*, 68–79.
Selimkhanov, I. R. (1964). Was native copper used in transcaucasia in Eneolithic times? *Proceedings of the Prehistoric Society*, *30*, 66–74.
Selimkhanov, I. R. (1966). Ergebnisse von spektralanalytischen Untersuchungen an Metallgegenständen des vierten und dritten Jahrtausends aus Transkaukasien. *Germania*, *44*, 221–231.
Selimkhanov, I. R. (1973). Certains résultats des recherches archéochimiques du métal ancien datant des IV et III^{e} millénaires avant notre ère (Transcaucasie, Iran). In Ezat O. N.(Ed.), *Marlik I* (pp. 11–21). Tehran: Tehran University.
Selimkhanov, I. R. (1978). Ancient tin objects of the Caucasus and their results of their analyses. In A. D. Franklin, J. S. Olin, & T. A. Wertime (Ed.), *The Search of Ancient Tin* (pp. 53–58). Washington: Smithsonian Institute Press.
Selimkhanov, I. R., & Marechal, J. R. (1968). Frühetappen der vorgeschichtlichen kupfermetallurgie auf dem Gebiet Europas und des Kaukasus im Lichte neuer Erkenntnisse und analysenergebnisse. *Slovenska Archeolögia*, *16*, 461–472.
Selimkhanov I. R., & TorosJan R. M. (1966). K opredeleniju Eneolita na territorii Zakavkaz’ja po dannym analyza metallicheskikh predmetov. *Istoriko-Filologicheskij journal*, *1*, 304–308.
Selimkhanov I. R., & TorosJan R. M. (1969). Metallograficheskij analiz drevnejshikh metallov v Zakavkaz. *Sovetskaja Arkheologija*, *3*, 229–235.
Sertok, K., & Ergeç, R. (1999). A new Early Bronze Age cemetery: Excavation near the Bierecik Dam, southeastern Turkey, preliminary report (1997–1998). *Anatolia*, *25*, 87–106.
Seure, G. (1902). Notes d’archéologie russe. IX. Tumuli et poteries de l’â ge du bronze en Géorgie. *Extrait de la Revue archéologique* (pp. 62–78).
Shishlina, N. (2008). *Reconstruction of the Bronze Age of the Caspian Steppes*. BAR 1876. Oxford: Archaeopress.
Solov’ev, L. N. (1967). Neoliticheskie poselenija chernomor’skogo poberezhaja Kavkaza: Nizhne-Shilovskoe I Kistrik. In M. M. Trapish (Eds.), *Materialy po arkheologii Abkhazii* (pp. 3–38). Tbilissi: Metsniereba.
Squadrone, F. F. (2000). Metals for the dead. Metal finds from Birecik Dam EBA cemetery in the middle Euphrate area, near Carchemish (Turkey). In P. Matthiae, A. Enea, L. Peyronel, & F. Pinnock (Eds.), *Proceedings on the First International Congress on Archaeology of the Ancient Near East, Rome may 18th–23th 1988 vol. II*. (pp. 1541–1555). vol. II. Rome: Universita Degli Studi di Roma “la Sapienza”.
Squadrone, F. F. (2007). Regional culture and the metal objects in the area of Carchemish during the early bronze age. In E. Peltenburg (Ed.), *Euphrates River Valley Settlement. The Carchemish sector in the third millennium BC* (pp. 198–213). Levant Supplementary Series 5. Oxford: Oxbow Books.
Stein G. J., Edens, C., Edens, J. P., Keith, K., McMahon, A., & Özbal, H. (1997). Excavations at Hacinebi, Turkey—1996: Preliminary report. *Anatolia*, 23, 111–168.
Stein, G. J., & Edens, C. (1999a). Hacinebi and the Uruk expansion: additional comment. *Paléorient*, *25*(1), 167–171.
Stein, G. J., (1999b). Material culture and social identity: The evidence for a 4th millennium B. C. Mesopotamian Uruk Colony at Hacinebi, Turkey. *Paléorient*, *25*(1), 11–22.
Stöllner, T., Gambaschidze, I., & Hauptmann, A. (2008). The earliest gold mining of the ancient world? Research on an Early Bronze Age gold mine in Georgia. In Ü. Yalçin, H. Özbal, & A. G. Pasamehmetoglu (Eds.), *Ancient mining in Turkey and the Eastern Metirranean* (pp. 271–288). International Conference AMITEM 2008. Ankara: Atilim University.
Sulimirski, T. (1970). *Prehistoric Russia*. London: Baker J.

Summers, G. D. (2004). Yanik Tepe and the early Transcaucasian Culture: problems and perspectives. In A. Sagona (Ed.), *A View from the Highlands, Archaeological Studies in Honour of Charles Burney*, *Ancient Near Eastern Studies*, 12 (pp. 617–643). Louvain: Peeters.

Tavadze, F. N., Sakvarelidze, T. N., & Inanishvili, G. V. (1987). Etapy razvitija metallurgii v Gruzii. In K. N. Pitskhelauri & E. N. Chernykh (Eds.), *Kavkaz v Sisteme Paleometallicheshikh Kul'tur Evrazii, materialy i Simpoziuma "Kavkaz v Epokhu Rannego Metalla" (Telavi-Signakhi 1983)* (pp. 44–50). Tbilissi: Metsniereba.

Tedesco, L. A. (2006a). Redefining technology in Bronze Age Transcaucasia: copper-alloy metallurgy in Armenia in the 3rd—mid 2nd millennium B. C. PhD dissertation in the Department of Anthropology, New York University.

Tedesco, L. A. (2006b). Refining the definition of technology in the southern zone of the Circumpontic Metallurgical Province: copper alloy in Armenia during the early and the middle Bronze age. In D. L. Peterson, L. M. Popova, & A. T. Smith (Eds.), *Beyond the steppe and the sown, Proceedings of the 2002 University of Chicago Conference on Eurasian Archaeology* (pp. 310–321). Leide: Brill.

Tekhov, B. V., & Dzhaparidze, O. M. (1971). *Ocherki drevnej istorii I arkheologii Jugo-Osetii*. Tbilissi: Metsniereba.

Thornton, C. P. (2001). Tepe Yahya Revisited: a Reassessment of the Metallurgical Sequence of the Iranian Plateau from the Chalcolithic to the Iron Age through Chemical an Metallograpic Analyses of a "Trinket" technology. Masters dissertation. Harvard University.

Thornton, C. P. (2009). The Chalcolithic and Early Bronze Age Metallurgy of Tepe Hissar, Northeast Iran: A Challenge to the "Levantine Paradigm". PhD Dissertation in Anthropology. University of Pennsylvania.

Thornton C. P., & Lamberg-Karlovsky, C. C. (2004). A new look at the prehistoric metallurgy of southern Iran. *Iran*, *42*, 47–59.

Torosjan, R. M. (1976). *Rannezemledel'cheskoe poselenie Tekhuta*. Arkheologicheskie Raskopki v Armenii, 14. Erevan: Akademija nauk Armjanskoj S.S.R. Institut arkheologii i etnografii.

Trifonov, V. A. (1996). Popravki k absoljutnoj khonologii kul'tur epokhi eneolita—bronzy severnogo Kavkaza. In Ju. Ju. Piotrovskij (Ed.), *Mezhdu Aziej I Evropoj, Kavkaz v IV—I tys do n.e. Materialy konferntsii, posvjashchennoj 100-letiju so dnja rozhdenija Aleksandra Aleksandrovicha Iessena* (pp. 43–49). Sankt-Petersburg: Institut istorii material'noj ku'ltury, Rossijskoj akademii nauk, Gosudarstvennyj Ermitazh, Sankt-Petersburgskij gosudarstvennyj universitet.

Trifonov, V. A. (2001). Darkveti-Meshokovskaja kul'tura. In I. I. Marchenko (Ed.), *Tret'ja Kubanskaja Arkheologicheskaja Konferentsija* (pp. 190–194). Krasnodar-Anapa: Krajbibkollektor.

Trifonov, V. A. (2006). Transanatolia: Bridging the Gap Between East and West in the Archaeology of Ancient Anatolia, poster abstract. Conference held at the British Museum (Friday 31st March–Saturday 1st April 2006). *Bridging the Gap between East and West in the Archaeology of Ancient Anatolia*. London.

Tvalchrelidze, G. A. (2006). Poleznye iskopaemye I mineral'naja resursnaja baza Gruzi. In *Ruda I metally* (p. 319 ss). Moscou: Nauka.

Vatendoust, A. (1999). A view on prehistoric Iranian metalworking: elemental analysis and metallographic examinations. In A. Hauptmann, E. Pernicka, T. Rehem, & Yalçin, Ü (Eds.), *The beginnings of Metallurgy, Der Anschnitt* 9 (pp. 121–140). Bochum: Deutsches Bergbau Museum.

VarazasHvili, V. L. (1992). Rannezemledel'cheskaja kul'tura jugo-alazonskogo bassejna. Tbilisi: Metsniereba.

Verardi, V. (2006). Une tombe du IIIe millénaire à Tell Mohammed Diyab. *Revue d'Assyriologie*, *100*, 41–52.

Verardi, V. (2008). *L'introduction et la diffusion de la technologie du bronze en Syrie-Mésopotamie*. BAR International Series 1740. Oxford: Hadrian.

Watkins, T. (1974). Two Unfinished Spearheads in the Ashmolean Museum, Oxford. *Levant*, 6, 188–192.

Weiss, H., & Young, T. C. (1975). The merchants of Susa: Godin V and the plateau lowland relations in the late fourth millennium B. C. *Iran*, *13*, 1–18.
Woolley, C. L. (1914). Hittite burial customs. *Annals of Archaeology and Anthropology*, *6*(3), 87–98.
Woolley, C. L., & Barney, R. D. (1952). *Carchemih report on the excavations at Jerablus on Behalf of the British Museum Part III*. London: British Museum.
Yakar, J. (2002). East Anatolian metallurgy in the fourth and third millennium BC: some remarks. In Ü. Yalçin (Ed.), *Anatolian Metal II*, *Der Anschnitt 15*, 15–25. Bochum: Deutsches Bergbau Museum.
Yener, K. A. (2000). *The domestication of metals: The rise of complex metal industries in Anatolia*. Leiden: Brill.
ŽavaxiŠvili, A. I. (1988). Ausgrabungen in Berikledeebi (Shida Kartli). *Georgica*, *21*, 7–20.

Chapter 23
The Emergence of Complex Metallurgy on the Iranian Plateau

Christopher P. Thornton

Introduction

The early production and use of metals in Iran has been a topic of considerable interest since the 1960s, when the first synthetic overviews of the prehistoric metallurgy of this region were written (Lamberg-Karlovsky 1967; Moorey 1969) and when the first early metalworking sites were recognized (Caldwell and Shahmirzadi 1966; Caldwell 1968). This newfound interest in the ore-rich nation of Iran and its long history of metal use and exploitation led to the famous Wertime Pyrotechnological Expedition of 1968 (Wertime 1968; see also Arab and Rehren 2004a, b). This important survey project involved some of the most renowned twentieth-century scholars of ancient technology (including Cyril Stanley Smith, Ronald Tylecote, Frederick Matson, Radomir Pleiner, Beno Rothenberg, Robert Brill, and Theodore Wertime), who traveled from Turkey to Iran and Afghanistan in search of evidence for ancient mining and craft production (see papers in Caldwell 1967a). It was their supposition that the beginnings of Old World metallurgy must have occurred in the ore-rich Taurus-Zagros highlands (Wertime 1973). Thus, they argued that to understand the development of early metallurgy *in toto*, one must first understand the development of metallurgy in Turkey, in Transcaucasia, and in Iran.

Although interest in Iranian prehistoric metallurgy has continued since then, most notably in the synthetic writings of Moorey (1982) and Pigott (1999a, b), there have been few attempts to combine recent analytical data with changes in the archaeological understanding of Iranian prehistory since the fall of the Shah in 1978–1979 led to the expulsion of foreign archaeologists. This lacuna is due mainly to language barriers between pre-Revolution scholars (most of whom are Europeans or Americans publishing in English, French, German, and Italian) and post-Revolution scholars

C. P. Thornton (✉)
Asian Section, University of Pennsylvania,
3260 South St, Philadelphia, PA 19104, USA
e-mail: cpt2@sas.upenn.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_23,

(most of whom are Iranians publishing only in Persian). With the Reformist *glasnost* of the late 1990s, foreign scholars and Iranian scholars were reunited and Iranian prehistoric metallurgy quickly became a topic of considerable interest once again. Indeed, many of the international field projects and analytical programs begun in this period have specifically focused on ancient metallurgical production, including the Sialk Reconsideration Project (Shahmirzadi 2003), the Arisman Project (Chegini et al. 2000), the Malyan Archaeometallurgical Project (Pigott et al. 2003, a, b), the Shahr-i Sokhta Archaeometallurgical Project (Artioli et al. 2005), and many others (Thornton and Rehren 2007; Weeks 2008; see also papers in Stöllner et al. 2004). Needless to say, it has become obvious that the models for early metallurgy in Iran that have held sway since the early 1980s (e.g., Heskel 1982, 1983) require substantial updating.

Despite this recent attention to the question of early metal production and trade, Iranian prehistoric metallurgy remains relatively unknown outside of the few scholars who actively pursue it. It is here argued that the reason Iranian metallurgy is so poorly understood is because it defies the established sequence of metallurgical development for Southwest Asia first laid out by Wertime (1964) and then adjusted by numerous important scholars (e.g., Charles 1980; Muhly 1988; Hauptmann et al. 1993; Craddock 2001). That is, there is an almost mantric narrative on the development of metallurgy in the Old World taught to every student of archaeometallurgy, which explains how copper ore exploitation in the earliest Neolithic periods led to the simple working of native copper, which led to the small-scale smelting of oxidic copper ores in the Chalcolithic, followed by the mixing of ores to produce alloys in the Early Bronze Age, which all cumulated in the large-scale smelting of suldific ores by the Late Bronze Age. Although somewhat accurate when viewed over the long dureé, the development of metallurgy on the Iranian Plateau deviates from this model on many key points, and challenges the established notions of what early metalworkers could and could not do (cf. Bourgarit 2007). Since the Iranian data do not fit into this model,the data are usually either ignored, forced to fit into the established sequence by disregarding certain evidence, or altogether discredited.

In order to put Iran back onto the archaeometallurgical map in its rightful place as one of *the* early centers of metallurgical production and innovation, this paper will attempt to synthesize both old and recent data regarding the development of early metallurgy using the newfound archaeological appreciation of its Neolithic through Early Bronze Age societies (ca. 7000–2000 BCE). Special attention will be paid to specific sites that epitomize the metallurgical traditions of their region in particular time periods. Furthermore, this paper will challenge what the author calls the ‘Levantine Paradigm’—i.e., the stereotypical model for early metallurgy in the Old World, which in many ways developed out of the seminal archaeometallurgical projects of the Southern Levantine region. In contrast, this paper will follow Yener (2000) and others in proposing a separate ‘highland model’ for the metallurgical sequence of Southwest Asia.

What is the 'Levantine Paradigm'?

Thomas Kuhn (1962) famously brought attention to the fact that science is constructed of "paradigms" or established models agreed upon by a certain quorum of scholars. Although his work focused specifically upon the natural sciences, the social sciences (like archaeology) are inherently constructed of such paradigms and actually revel in their multiple competing paradigms in a way that 'real' scientists generally find appalling. The 'Levantine Paradigm' mentioned above is one such agreed-upon model, although it is in itself comprised of a multiplicity of competing paradigms that have been grouped here to serve as a 'straw man' for the sake of comparison. The big three Levantine models are: the 'Timna' school of Rothenberg (1990), Bachmann (1980), and others; the 'Feinan' school of Hauptmann (2000), Weisgerber (2006), and others (see also Weisgerber and Hauptmann 1988); and the 'Beersheva' school of Levy (1995), Shalev (1994), and others (see also Levy and Shalev 1989). While it is not the author's intention to go into any great detail on these differing perspectives (see *Golden this volume*), it is important here to delineate the main points that seem to comprise this so-called 'Levantine Paradigm'.

The general sequence of metal use and production in the Southern Levant is extremely well documented compared to neighboring regions and begins with the early exploitation of copper ores in the pre-pottery Neolithic for ornaments and pigments (Schoop 1995, 1999; Bar-Yosef and Porat 2008). Native copper use was extremely limited and simplistic, appearing only in the Early Chalcolithic (ca. 4500–4200 BCE) at sites in the Beersheva (Golden 1998, p. 108). The origin of copper smelting in the Southern Negev (i.e., around Timna), often argued to date to the fifth millennium BCE or even earlier (e.g., Rothenberg et al. 2003), is still one of the most contentious issues in Old World archaeometallurgy (e.g., Merkel and Rothenberg 1999; Craddock 2001, p. 156; Hauptmann and Wagner 2007). Less controversial is the argument for late fifth millennium smelting in the Beersheva Valley of the Northern Negev (Hauptmann 1991; Golden et al. 2001) utilizing ores mined in the Feinan district of western Jordan (Hauptmann 1989; Genz and Hauptmann 2002; Hauptmann 2007).

Chalcolithic copper smelting in the Levant (ca. 4200–3400 BCE) was carried out in numerous sites of the Beersheva Valley such as Abu Matar, Bir es-Safadi, and Shiqmim almost 200 km away from the Feinan deposits. Levy and Shalev (1989) suggest that ores from Feinan were collected by a restricted group of metalworkers who went to the mines themselves and brought high-grade ores and fuel back to the settlement. The actual smelting was done in small crucibles under low temperatures and low reducing conditions, which produces small amounts of highly viscous slag containing high levels of copper in the range of 10–50 wt% (Hauptmann et al. 1993, p. 568). This copper can be entrapped either in metallic form as prills, which require crushing of the slag for extraction, or in oxide form (usually as cuprite or delafossite), requiring a second stage of smelting to produce metal (Shugar 2003). The highly viscous (and thereby inefficient) nature of these early slags has led Hauptmann (2000, 2003) to argue strongly against the idea of 'intentional' fluxing in the Chalcolithic.

He suggested instead that metalworkers utilized "self-fluxing" ores such as the 'tile ores' from Feinan, which contain silica, iron oxides, and high-grade copper oxide ores. Given the similarities in the metalworking techniques and debris at multiple sites, Levy and Shalev (1989, p. 365) argued for a "shared knowledge" held by all metalworkers in the Southern Levant (see also Golden et al. 2001, p. 960).

The other major feature of the Chalcolithic metallurgy of the Southern Levant is the presence of two classes of metal artifacts: "elite" metals and "utilitarian" metals (Shalev and Northover 1987; Shalev 1991; Golden et al. 2001). "Elite" or "prestige" metals include lost-wax cast items that are generally made of copper-base alloys containing high levels of arsenic, nickel, and/or antimony. These objects are found mainly in hoards such as at Nahal Mishmar (Bar-Adon 1980; Tadmor et al. 1995) or at Nahal Qanah, where they were found in association with the earliest use of gold in the Near East (Gopher et al. 1990). It is argued that such 'natural' alloys are the product of smelting polymetallic ores, and not evidence of intentional mixing (Shalev and Northover 1993; Golden et al. 2001). The so-called "utilitarian" artifacts are more usually found on settlement sites (where they were both produced and used) and consist mainly of relatively pure copper with occasional impurities of arsenic, nickel, or antimony that are cast in simple, open-faced molds. General consensus among Levantine scholars is that the complex alloys were imported to the Levant and then worked locally (Shalev et al. 1992), while 'pure' copper was made locally for local or regional consumption (Golden et al. 2001).

In the Early Bronze I period (ca. 3400–3000 BCE), with the collapse of the Chalcolithic "chiefdoms" of the Beersheva Valley, independent settlements once again appeared in the fertile lowlands of the Mediterranean coast (i.e., twice as far from the mines as the Beersheva sites) and smelting was carried out both in the lowlands and at the ore sources of Timna and Feinan (Levy 1995; Genz and Hauptmann 2002; Levy et al. 2002). However, the technology did not change much from the Chalcolithic to the EB I, as demonstrated by the heterogeneous slags with 8–43 wt% copper found at Ashqelon-Afridar (Segal et al. 2002; Segal 2004) and contemporary sites near Feinan (Hauptmann 2000). Only in the EB II–III periods (ca. 3000–2300 BCE) was there a significant change in the metallurgical tradition of the Southern Levant, as metal production became large scale and centralized (Levy 1995), took place outside of habitation areas (Genz and Hauptmann 2002, p. 150), and settlements began importing metal ingots rather than ores (Golden et al. 2001, p. 961). These changes were paralleled in the metallurgical technology of the Southern Levant, including a shift from crucible-based smelting to furnace-based smelting (Craddock 2001) and a shift from iron-rich 'tile ores' to manganese-rich ores (Hauptmann et al. 1992, p. 7). These changes, as well as the addition of draft induction aids such as tuyeres and bellows and the first widely accepted use of 'intentional' fluxes, led to greater separation between slag and metal, as demonstrated by the presence of tap slags, plate slags, and primary ingots by the late third millennium BCE (Hauptmann 2003; Craddock 2001). These technological innovations allowed for the smelting conditions necessary for large-scale production of metal from complex, sulfidic ores, as well as the production of 'true' alloys such as tin bronze by importing tin metal and mixing it with local or imported copper metal.

Previous Highland Critiques

As argued previously, the model for metallurgical development in the Southern Levant has become paradigmatic in discussions of early metallurgy in the Middle East as a whole. The effects of this hegemony can be seen in casual references to the crushing of slag for the extraction of prills, even if there is no evidence for such behavior, or comments about the high copper content of early slags, even when the analytical results suggest otherwise. In a recent paper, David Bourgarit (2007) has challenged many of these paradigmatic notions about 'primitive' Chalcolithic smelting, and has suggested that many of the 'dramatic' changes seen in Early Bronze Age metallurgy (i.e., tap slags, low copper content, and improved furnaces) may in fact originate in the Chalcolithic, just on a smaller scale.

An extremely cogent argument against the "lowland model" for early metallurgical development in the Near East was put forth by Aslihan Yener (2000) in her synthetic book on Anatolian metallurgy. While a full review of this important volume is beyond the scope of this paper, a few key points are relevant to discussions of Iranian prehistoric metallurgy. First, she notes how early theorists focused exclusively on lowland 'core' regions (e.g., Mesopotamia) as the source of all technological advancements (Yener 2000, p. 6). Indeed, it was not until the mid-1980s that scholars began to discuss the highland 'peripheries' as centers of indigenous development and technological innovation (e.g., Trigger 1984; Kohl 1987). Even then, 'the highlands' were still perceived as a unified supplier of raw materials to the resource-poor lowlands. Yener (2000, p. 26) argues instead for a "balkanized technological horizon" in the Early Chalcolithic of the Anatolian highlands (ca. 4500–3500 BCE), in which "multiple centers of production" shared seals, ceramics, architecture, and other forms of material culture, yet practiced quite distinct metalworking traditions (contra the idea of "shared knowledge"). She also notes the fact that 'highland' vs. 'lowland' dichotomies break down when one considers that so-called 'highland' regions are themselves made up of highlands and relative lowlands or plateaus (Yener 2000, p. 6).

Second, Yener emphasizes the relatively advanced metallurgy of 'highland' regions, citing the low levels of entrapped copper in many early fourth millennium slags and the use of polymetallic ores to create complex copper-base alloys. Unlike the Levantine idea of 'natural' alloys in the Chalcolithic, Yener (Yener 2000, p. 29) states, "so called 'accidental' alloys may be the product of deliberate choice." Certainly by the EB I period (ca. 3500–3000 BCE), the intentional production of both 'pure' copper and more complex copper-base alloys at the same site is evident in Eastern Turkey (Palmieri et al. 1993, 1999) and in the Caucasus (Courcier 2007).

Finally, Yener (2000, p. 28) suggests that in the third millennium BCE, Anatolian metallurgical centers shifted from the relative lowland/plateau sites to the highlands near the mines themselves. This argument runs counter to the idea that in the third millennium BCE, much of Mesopotamia's prowess derived from its ability to import raw materials from its 'peripheries' and then convert them into luxury goods for export, as suggested by Moorey (1988) and others (see also Algaze 1993). The notion that metallurgy shifted to the lowlands in the Early Bronze Age is also present in Levantine archaeometallurgy, although the rise of large-scale smelting at the (relatively highland) ore sources (e.g., at Feinan and Timna) is also well attested.

As should be evident, these critiques of the dominant ‘lowland model’ for early metallurgy in the Near East are fundamentally based upon the different cultural geographies of the regions being debated. Anatolia is generally a ‘highland’ region, with plentiful and diverse mineral resources but relatively limited agricultural and demographic potential, while Mesopotamia is the exact opposite. The Southern Levant lies somewhere between these extremes: it has large but relatively homogeneous ore deposits, and abundant but by no means impressive agro-demographic capabilities. Of course, both the Levant and Anatolia have internal *and* external lowland–highland dynamics that play a role in the development and spread of technology, a situation that is even more extreme when one turns to Iran.

Geography of a Highland Zone: The Iranian Plateau

Generally speaking, the Iranian Plateau consists of two geographic regions: the Zagros Mountains to the west, and the high deserts and plains to the east (see Fig. 23.1). The Zagros Mountains are in many ways simply an extension of the Taurus Mountains of Anatolia, thrust up by the collision of the Arabian and Eurasian Plates (see Wilber 1963; Bates and Rassam 2001). This collision caused a folding of the Earth’s crust (much like an accordion), leaving innumerable parallel mountain valleys running northwest to southeast from Eastern Anatolia and the Southern Caucasus (“Transcaucasia”) down to the Straits of Hormuz in south-central Iran. The Zagros Mountains themselves are extremely rich in mineral resources, including all of the ores necessary for early metallurgy, and are well suited to small-scale agricultural and/or large-scale pastoral lifestyles. Although such a landscape lent itself to a great diversity of localized communities and cultures in the past (as well as the present), the overarching dynamic was between this general highland region and the resource-poor lowlands to the west in Mesopotamia and Southwestern Iran (modern-day Khuzistan or ancient Elam).

The eastern part of the Iranian Plateau is a little more complicated, as it consists of a series of relatively low drainage basins or ‘dashts’ (the largest of which are today salt deserts) separated by highland mountain ranges, and the whole region is bordered on the outer edges by lowland zones including the Gorgan and Halil river valleys, the Caspian littoral rainforest, and the Persian Gulf coastline. This geographic situation created a number of localized highland–lowland relationships of varying types, such as between extremely fertile lowlands and less-fertile (but relatively resource-rich) dashts, between extremely fertile lowlands and resource-rich highlands, and between relatively fertile dashts and resource-rich highlands. It is unfortunate that we know little about ancient communities of the extreme highlands (see Zagarell 1982), presumably because they were nomadic (or at least transhumant) populations who left little archaeological signature on the landscape. In most cases, it is unclear whether people from the dashts went up into the mountains to mine the

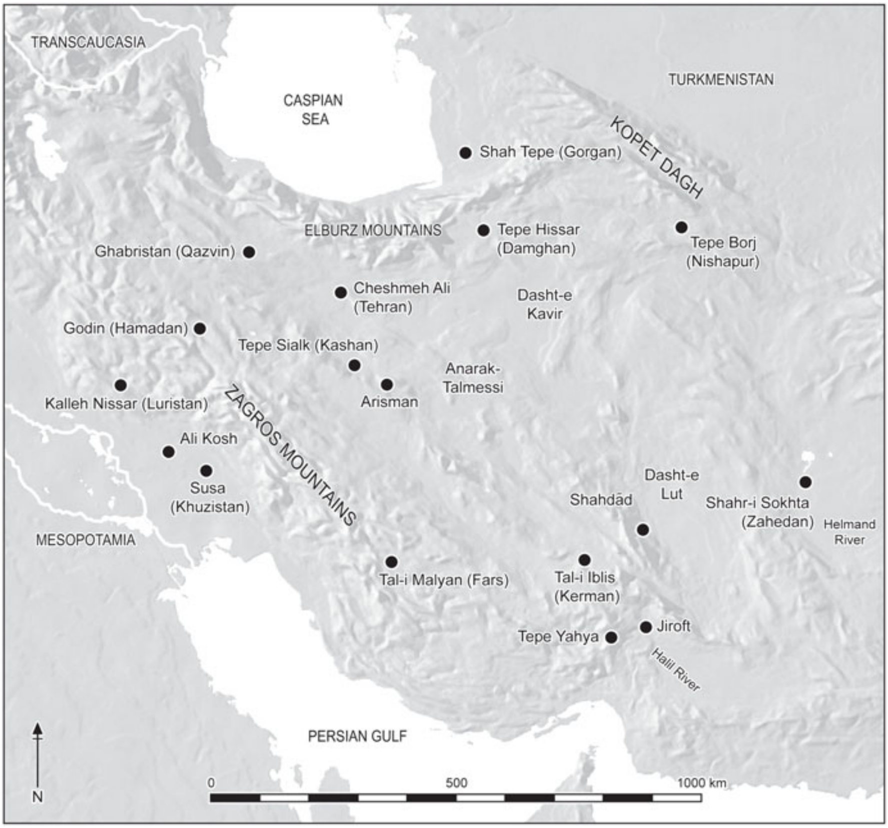


Fig. 23.1 Topographic map of Iran and sites mentioned in the text

ore, or whether they received the ore from local highland populations through trade and exchange.

Because the Iranian Plateau was such a daunting and unfamiliar landscape to peoples of the surrounding lowlands, most highland–lowland interactions happened on a fairly localized scale. Thus, ancient sites on the northeastern side of the Plateau (e.g., Tepe Hissar) were closely aligned with the alluvial settlements of the Gorgan Plain, while those on the southeastern side (e.g., Shahdad) were tied to sites of the Helmand River basin to the east and the Halil River basin to the south. Although for distinct periods of time the entire Iranian Plateau could be closely linked by shared economic and even political ties (e.g., during the 'Proto-Elamite' expansion of the late fourth millennium BCE; see Alden 1982), generally it was highly regionalized. Thus, plateau sites like Tepe Hissar were often more closely connected with lowland sites to the north (despite the imposing Elburz Mountains in between) than with other plateau sites to the southwest like Tepe Sialk near Kashan.

It is interesting to note that while the cultural geography of the Iranian Plateau and its neighbors played an important role in the adoption and transmission of materials and technologies, the overall development of metallurgy in Iran does not seem to have followed this pattern. For example, paralleling Yener's argument for a 'balkanized' technological horizon in the Taurus Mountains, metallurgical innovation in the central Zagros region had little effect upon the metallurgy of the northwest Zagros or the southeast Zagros regions, although this has long been a traditional corridor for trade and migrations. Similarly, despite great differences in the material culture between northeast Plateau and southeast Plateau sites, the metal technologies of both regions were at times astoundingly similar. It is this level of complexity, both in the social landscapes and in the mechanisms of cultural and technological transfer, that makes the 'Levantine Paradigm' so difficult to apply in this region.

Development of Metallurgy in Iran

The full sequence of metallurgical development in prehistoric Iran is beyond the scope of this paper (see Table 23.1). Instead, a brief outline of the evidence for early metal adoption and exploitation is presented, followed by a more in-depth look at the smelting and metalworking technologies employed on the Iranian Plateau from the late sixth to the early second millennium BCE. Finally, a general synthesis of the adoption and innovation of metallurgy on the Iranian Plateau will be attempted, in order to better understand the mechanisms of technological transfer and the socioeconomic systems in which such behavior was performed.

The earliest evidence for metal use in Iran is still the rolled bead of native copper from the lowland site of Ali Kosh in Southwestern Iran analyzed by Cyril Stanley Smith (1969) and recently redated to the late eighth/early seventh millennium BCE (Hole 2000). This simple bead is remarkable for a number of reasons. First, it appeared almost a millennium after native copper had become relatively widespread in Anatolia, although long before other lowland regions such as Mesopotamia began utilizing native copper (Moorey 1988, p. 29). Second, it occurred at a site far removed from any known native copper deposits, suggesting that this object may be related to the presence of obsidian at Ali Kosh, which originally derived from the Lake Van region of Eastern Anatolia (Renfrew et al. 1966). Finally, the bead appeared a millennium before native copper was found anywhere on the Iranian Plateau (i.e., close to local native copper resources). Thus, the true adoption of metal occurred much later in the early-mid sixth millennium BCE, when native copper artifacts were utilized consistently in various parts of the Plateau, such as in the Fars region of Southwestern Iran (Moorey 1982, p. 85; Bernbeck 2004, p. 144), in Southeastern Iran at Tepe Yahya (Heskel 1982; Thornton et al. 2002), and in North-Central Iran at Tepe Sialk (Ghirshman 1938: Pl. LII).[1]

---

[1] The isolated finds of native copper from late seventh/early sixth millennium contexts at Mehrgarh in Pakistan (Moulherat et al. 2002; Mille et al. forthcoming) along with other aspects of the 'Neolithic Package' suggest that native copper was probably known in Eastern Iran by the mid-late seventh millennium BCE. However, until sites in Eastern Iran earlier than Tepe Yahya VII (c. 5500–5000 BCE) are excavated, the adoption of metal in northwestern South Asia remains inconclusive (see *Hoffman & Miller paper*).

Table 23.1 Chronological periods and metallurgical advances in Iranian prehistory

	Southwestern Iran		Southeastern Iran		Northwestern Iran	
DATE (BC)	Sites/Periods	Metallurgy	Sites/Periods	Metallurgy	Sites/Periods	Metallurgy
7000	Ali Kosh	-native copper				
		appears				
6500						
	Mushki					
6000	(Tol-i Bashi)	-native copper				
		common	??	??	??	??
	Jari					
5500						
	Early Susiana		Yahya VII	-native copper	Hajji Firuz	
	Shamsabad			present	Tepe Sarab	
5000			Iblis I	-copper smelting		
	Middle Susiana			adopted	Godin X	
	Early Bakun					
					Dalma	
4500	Middle Bakun				Seh Gabi	-copper appears
			Iblis II			
			Yahya VIA	-copper-alloys	Pisdeli	
				appear	Godin VIII	
	Late Bakun	-smelted copper				
4000	Susa I	adopted			Godin VII	-casting appears
	(Lapui)		Yahya VC	-native copper	Geoy M	
				continues		
	late Susa I	-copper-alloys	Iblis II-III			
		appear			(Se Girdan)	-silver/gold
3500				-smelted copper/	Godin VI.2	appear
	Susa II	-copper-alloys	Yahya VB-VA	copper-alloys		
		common		common	Geoy K.1	
	Banesh Malyan	-lead, silver, gold	Iblis IV	-gold appears	Godin VI.1	-smelted copper
		adopted				adopted
3000	Susa III		Yahya IVC	-lost-wax cast	Godin V	
	(Kalleh Nissar)	-tin bronze		adopted?	Geoy K.2	
		appears	Shahr-i Sokhta II			
	(Jalyan)			-industrial-scale	Godin IV	-copper alloys
				workshops		adopted
2500	Susa IV		(Konar Sandal S)	appear		
		-tin bronze	Shahr-i Sokhta III		Godin III.6	
		common	Yahya IVB	-tin bronze	Geoy K.3	
	Susa VA	-stone moulds		appears	Godin III.5	
		adopted	(Shahdad)			
2000	Kaftari Malyan	-iron appears		-tin bronze	Godin III.4	-tin bronze
	Susa VB		Yahya IVA	common	Geoy G	adopted
	(Tal-i Nokhodi)		(Konar Sandal N)	-brass appears	Geoy D	-iron appears
					Godin III.2	

Table 23.1 (continued)

North-central Iran		Northeastern Iran		
Sites/Periods	**Metallurgy**	**Sites/Periods**	**Metallurgy**	**DATE (BC)**
				7000
		??		
		Aceramic Neolithic		**6500**
??	??		??	
		Sang-i Chakhmaq		
		West		
(Chahar Bone)		Ceramic Neolithic		**6000**
Early Sialk I				
		Djeitun Period		
(Ebrahimabad)	-native copper	Yarim I		
	present			**5500**
Late Sialk I		Sang-i Chakhmaq	-copper appears	
		East		
Early Sialk II		Sialk II Period		
				5000
(Zagheh)	-copper common	Tureng IB		
(Tepe Pardis)				
		(Shir-i Shian)		
Late Sialk II		Anau IA Period	-copper common	**4500**
	-smelting/casting			
Sialk III.1-3	appears	Hissar IA	-casting appears	
Ghabristan I			-copper alloys	
		Hissar IB	adopted	**4000**
Sialk III.4-5	-lead/silver appears			
Ghabristan II	-smelted copper/	Hissar IC-IIA	-gold appears	
	copper alloys	Tureng IIA		
Sialk III.6-7	adopted	Hissar IIA		
Arisman B	-gold appears		-lead/silver appears	**3500**
		early Hissar IIB		
Sialk IV.1	-industrial-scale	Tureng IIB	-industrial-scale	
Arisman C	workshops	middle Hissar IIB	workshops	
Ghabristan IV	appear	Shah III-IIB	-furnaces adopted	
Sialk IV.2				**3000**
Arisman A/D/E	-furnaces adopted	late Hissar IIB		
		Tureng IIIA		
		Hissar IIIA		
"Kura-Araxes"		Shah IIB		
				2500
		Hissar IIIB		
		Tureng IIIB		
Sagzabad	-stone moulds	Hissar IIIC		
(Qeytareh)	adopted	Shah IIA.1	-tin bronze	**2000**
		Tureng IIIC.1	appears	
		Tureng IIIC.2		

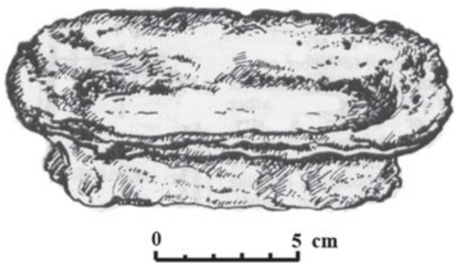


Fig. 23.2 Drawing of the Iblis-type crucibles as reconstructed by Joseph Caldwell and members of the 1968 Wertime Pyrotechnological Expedition. Note that the open form of these vessels suggests that the crucible was placed in a pit in the ground and then covered with charcoal (Frame 2004). (Image adapted from Caldwell 1968, Fig. 23.6)

The exploitation of native copper in Iran lasted over a thousand years and was not, as some scholars have argued, simply an extension of stone-working industries. From the earliest period, copper beads and other ornaments were made by rolling or cold working flattened sheets, which was a property unique to metal. Furthermore, unlike the Levant or Mesopotamia, native copper in Iran was often worked with great skill, such as the round-headed tack from Tepe Yahya VII (Thornton et al. 2002, p. 1456). Similar examples of skilled cold working and annealing of native copper are also known from Anatolia, such as the native copper macehead from Can Hasan dated to ca. 5000 BCE (Yalcin 1998).

The earliest evidence for metal smelting in Iran, and one of the earliest known smelting sites in the world, is the small mound of Tal-i Iblis located in a rich highland plain of Southeastern Iran roughly 50–100 km away from over 40 copper ore deposits (Fig. 23.2). Excavated in the 1960s by Joseph Caldwell (1967a; see also Caldwell and Shahmirzadi 1966), Tal-i Iblis has often been ignored in the archaeometallurgical literature due to confusion over the context of the metallurgical finds and a lack of technical analysis of the crucibles, copper artifacts, and other debris from the site. Indeed, important scholars such as Muhly (1988) and Craddock (2001) have gone so far as to suggest that the Iblis material may represent merely the melting of native copper, given what they see to be a lack of actual smelting sites in the Near East before the fourth millennium BCE. These assertions are currently being challenged.

Although the archaeological and chronological sequence of Tal-i Iblis is indeed confused (see Voigt and Dyson 1992, pp. 143–146), the important period for the purposes of this paper is Iblis I, which can be relatively dated by ceramic and architectural parallels to the Yahya VII–VI and Sialk II periods (ca. late sixth to late fifth millennium BCE). In one of the earliest levels of the Iblis I period, Caldwell's team excavated a number of well-made buildings with red-painted mud-brick walls, mat-covered floors, and numerous beads of semiprecious stones (Evett 1967; Caldwell and Sarraf 1967). In "Area G" (or "House G"), in a fill layer between a Period I floor and an early Period II floor, was found a "shallow firepit" filled with crucible fragments, malachite fragments, and charcoal (Evett 1967, pp. 252–254). The floor below this "firepit" and the floor of a different Period I building both gave a 2-sigma date range of 5430–4730 cal BC, while two other roughly contemporary buildings gave C14 date ranges of 5000–4330 and 4930–4240 cal BC (Voigt and Dyson 1992). A large dump (100 m long, 60 cm deep) containing "hundreds" of slagged crucible fragments and domestic refuse, called "Period II" but with C14 dates in the range of Periods I and early II (ca. 5200–4400 BCE), attests to the long-standing presence of cottage-level metalworking at this site (Caldwell 1967b, pp. 34–36).[2]

Recently, two projects at M.I.T. have sought to determine whether these crucibles represent smelting or melting processes. Pigott and Lechtman (2003) published metallographic and chemical analyses of a few copper-base artifacts from Iblis II contexts, but found it difficult to say whether the relatively pure copper used to make these artifacts was smelted from pure copper ores or melted from native copper. In an unpublished thesis, Frame (2004) studied a few of the "Period I–II" crucible fragments that had been given to Cyril Stanley Smith in the 1960s. Her results demonstrate fairly conclusively that at least some of the crucibles were heated from above to temperatures greater than 1,150 °C and with redox conditions reducing enough to turn the interior face of the crucible gray. Furthermore, analyses of the silicate phases and copper prills in the slag—the latter containing high traces of arsenic, sulfur, cobalt, nickel, and iron—confirm the presence of smelting at Tal-i Iblis at least in the early fifth millennium BCE if not earlier. Frame (pers. comm. 2008) is continuing to work on metallurgical material from the early levels at Tal-i Iblis for her dissertation research, and we must await her results to say more about this important site.

Besides Tal-i Iblis, the widespread appearance of artifacts that likely derived from smelted copper (due to the presence of notable impurities such as arsenic and lead) occurred toward the end of the fifth millennium, as at Susa I in Southwestern Iran (Benoit 2004), Tepe Hissar I in Northeastern Iran (Thornton 2009), and at Tepe Yahya VIA (Thornton et al. 2002, p. 1456; Thornton 2010). However, very few fifth millennium metal artifacts have actually been analyzed. For example, the large numbers of copper-base artifacts from Tepe Sialk II in North-central Iran (Ghirshman 1938: Pl. LII), as well as a recently reported slagged crucible from late fifth millennium levels at Cheshmeh Ali near Tehran (Matthews and Fazeli 2004, p. 65), remain entirely unstudied and may suggest that smelting activities took place in this region during this period (Fig. 23.3).

In some cases, the initial appearance of smelted copper did not necessitate the end of native copper exploitation, such as at Tepe Yahya where smelted copper–arsenic was not truly adopted until Period VB of the mid-fourth millennium BCE (Heskel and Lamberg-Karlovsky 1980; Thornton and Lamberg-Karlovsky 2004a). This lag in the acceptance of new materials may be due to a number of economic

[2] Crucible fragments described as "much larger and deeper" as well as pieces of malachite were also found in late fourth millennium Iblis IV contexts (Caldwell 1967b, p. 37), while Massimo Vidale (pers. comm. 2007) reports evidence of Iblis-style ceramics and metalworking debris at the late fifth to early third millennium site of Mahtoutabad near Jiroft.

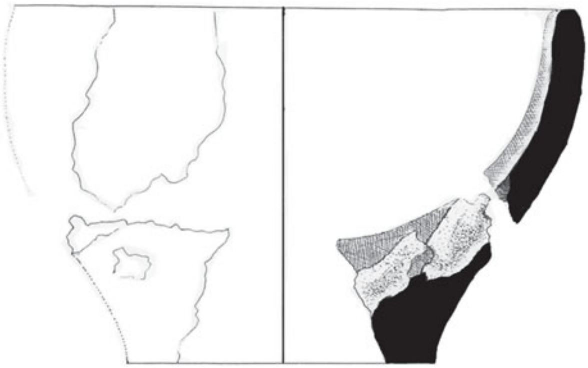


Fig. 23.3 Drawing of the slagged crucible from late fifth millennium BCE levels at Cheshmeh Ali near Tehran. The closed form of this vessel, so different from the earlier Iblis-style crucibles and the later Ghabristan-style crucibles, suggests an entirely different approach to smelting that was probably carried out on a much smaller (domestic?) scale. (Image courtesy of Dr. Hassan Fazeli, director of the Iranian Center for Archeological Research in Tehran)

and/or technical factors (e.g., distance from smelting sites and no demand for "better" materials), or may be related to more cultural factors such as conservatism or the ideological significance of certain materials. What is particularly notable, however, is that whenever smelted copper is adopted, it signals the end of the use of 'pure' copper in favor of copper-base alloys containing low levels (1–3 wt%) of arsenic, lead, and other elements. These are what Levantine scholars often refer to as 'natural' alloys (see above)—i.e., copper-base alloys created by the non-intentional mixing of polymetallic ores. However, given the abundance of pure copper ores and native copper in Iran (see Momenzadeh 2004, p. 12), the predominance of copper-base alloys in the Chalcolithic period of Iran suggests that polymetallic ores were deliberately chosen and perhaps even intentionally mixed. *Uncontrolled alloying is not the same as unintentional alloying*!

Although the crucial fifth millennium transition from native copper usage to smelting copper is basically unknown, fourth millennium metallurgy on the Iranian Plateau has recently been elucidated thanks to a number of current archaeological and archaeometallurgical projects focusing specifically on North-central and Northeastern Iran. Most significant has been the redating of the prehistoric sequence of this region thanks to a number of radiocarbon-based excavations by joint British–Iranian and German–Iranian teams (e.g., Fazeli et al. 2005; Fazeli Nashli and Sereshti 2005; Chegini et al. 2000, 2004). This reassessment of the traditional Sialk I–IV sequence established by Ghirshman (1938) allows for a fairly in-depth look at the development of large-scale metal production in the Chalcolithic period.

The site of Tepe Ghabristan, located in the Qazvin Plain of North-central Iran only $\sim$20 km from the nearest copper ore source, has been often cited in the archaeometallurgical literature as one of the earliest copper smelting sites in Southwest Asia based upon the well-preserved metallurgical workshops excavated by Majidzadeh (1979, 1989) and assigned by him to the early fifth millennium BCE (see Pigott 1999b, pp. 111–112; Matthews and Fazeli 2004, p. 64) . However, recent C14-dated

Fig. 23.4 Ghabristan-style crucibles found in one of the metallurgical workshops of Period II at Ghabristan. Note how one of the crucibles has been used (but not destroyed or discarded) while the other remains unused. (Image courtesy of Thomas Stöllner and Gero Steffens of the Deutsches Bergbau-Museum)

stratigraphic excavations at the site have confirmed archaeological suspicions (see Voigt and Dyson 1992, p. 167) that "Period II" at Ghabristan dates in fact to the early fourth millennium BCE (Fazeli et al. 2005). Regardless of the date, the large, walled compound, which contained copper smelting and ceramic workshops and was located in the center of the Ghabristan II town, provides some of the earliest evidence for centralized and perhaps specialized copper production in Iranian prehistory.

In the first copper workshop were found two small "hearths" (probably small pit furnaces) ~25 cm in diameter, near to which lay a complete smelting crucible of the "Ghabristan-type" (see Fig. 23.4). Such smelting crucibles are extremely diagnostic, being composed of a shallow dish on a low stand with a 2-cm-diameter hole through the stand to allow the heated crucible to be lifted with a stick and poured out. Also in or near the first workshop were found a large, deep bowl full of ~20 kg of nut-sized copper oxide ore fragments (i.e., prepared for smelting) and about ten molds or mold fragments. Most of the molds that were complete or could be reconstructed were for shaft-hole implements including two-headed picks, one-headed picks, axes, and adzes, although a multiple bar-ingot mold was also found. In the second workshop, which was badly rain-damaged, was found another hearth like in the first workshop, plus a crucible fragment, a mold fragment for a shaft-hole axe or adze, clay cylinders for creating the shaft hole during casting, and an ambiguous ceramic tube with evidence of interior burning, which is possibly a mold (Madjidzadeh 1979, p. 84) or a tuyere (Madjidzadeh 1989, p. 161). Unfortunately, none of the Ghabristan material has ever been analyzed (or even looked at) by an archaeometallurgist, so we must await future studies before saying too much about the early Chalcolithic metallurgy of the Iranian Plateau.

Ghabristan-style crucibles are found at a number of other sites in North-Central Iran, including at Tepe Sialk and most especially at the industrial site of Arisman, which is located ~60 km southeast of Kashan in the foothills of the ore-bearing Karkas Mountains[3] (Chegini et al. 2004). It is notable that these crucibles, as well as other items suggesting contact with Ghabristan such as bar-ingot molds, molds for

[3] Barbara Helwing (pers. comm. 2008) informs the author that although the Karkas Mountains do contain copper ores, there is some question as to their usefulness in crucible smelting and so far isotopic analysis has been unable to match these same ores with the slags and metal prills from the site.

flat and shaft-hole axes, and clay cylinders for forming the shafts, are only found at area B of the site of Arisman, which is well dated by ceramic finds and radiocarbon dates to the Sialk III_{6-7} period (ca. 3700–3400 BCE) (Helwing 2004, 2004). Prior to the establishment of "Ghabristan-style" workshops at Arisman, copper smelting took place in small, ephemeral sites along the rim of the desert near to Arisman (e.g., the site of Qaleh Gusheh)—i.e., even farther from the ore sources (see Chegini et al. 2004, p. 211; Stöllner 2005, p. 193). These small sites, dated by ceramics to the Sialk III_{4-5} period (i.e., contemporary with Ghabristan II; ca. 4000–3700 BCE), display a well-developed metallurgical technology utilizing a very different style of smelting crucible with a large handle—perhaps better suited to extramural smelting operations than the fenestrated-stand crucibles found at Ghabristan II and Arisman B (see Fig. 23.5).

The metallurgical production of Arisman B appears to have taken place on a relatively small scale in residential buildings, either as a 'cottage' industry or perhaps in small workshops also engaged in pottery production as at Ghabristan (Boroffka and Becker 2004). Found together with the crucibles and molds were fairly large amounts of slag, ore, litharge, hammer stones, a possible tuyere, and a few finished objects made of both copper and gold (Chegini et al. 2000, p. 294, 2004, p. 211). Although the material from this site awaits analysis, contemporary slags from nearby Tepe Sialk were analyzed by Marcus Schreiner (2002) and were found to be the result of a rather uncontrolled crucible smelt involving copper carbonate and sulfide ores with natural impurities of iron and arsenic, both of which appear in the resulting metal prills (see also Schreiner et al. 2003).[4] The high amount of entrapped copper in the Sialk slags (< 30 wt% Cu_2O) and the low levels of iron relative to silica (present as partially reacted quartz relicts) led Schreiner to suggest a rather poor understanding of the firing process and of the ore/gangue compositions necessary to produce a good separation between slag and metal.

Before holding up the Sialk slags as representative of early fourth millennium slags in general, it is important to remember that Tepe Sialk was a residential town that engaged in small-scale copper and lead/silver production (Nezafati and Pernicka 2006), while Arisman was an industrial town whose sole *raison d'ê tre* may have been copper and lead/silver production (Chegini et al. 2004). Given that the material culture at both sites is practically identical but the technology seems more specialized at Arisman, it could be suggested that Arisman represents an offshoot of the Sialk society—perhaps a community of skilled metalworkers (and potters) who preferred to work closer to the ore sources (or away from the main settlement). Alternatively, if future analysis of the Arisman material reveals few technical differences from Schreiner's Sialk slags[5], then it could be posited that the same craftspeople were migrating (seasonally?) between the two sites.

---

[4] Arsenic contents in the Sialk slag prills can be as high as 30 wt%, suggesting a crude but effective mixed ore smelting technique for the early production of arsenical copper.

[5] Barbara Helwing (pers. comm. 2008) notes that the Sialk slags and the Arisman slags do not carry the same isotopic signature, suggesting the use of different ore sources.

Fig. 23.5 Photograph of one of the handled smelting crucibles from Qaleh Gusheh found along the desert rim near Kashan along with pottery dating to the Sialk III_{4-5} period (ca. 4000–3700 BCE). (Image courtesy of Barbara Helwing and the Arisman Photographic Archive)

The relationship between these two sites requires further study before any conclusions can be reached, but comparison of the Sialk slags with contemporary slags from the 12-ha town of Tepe Hissar in Northeastern Iran reveals significant variation across the Plateau in the mid-fourth millennium BCE. Three pieces of slag and two slagged crucible fragments from the 1976 Hesar Restudy Project (see Dyson and Howard 1989) were analyzed, all from contexts C14-dated to ca. 3600 BCE (see Thornton 2009). Both of the crucible fragments and one of the slag pieces were suggestive of secondary smelting/melting processes, but the other two slags are unquestionably evidence of primary copper smelting. Like the Sialk slags analyzed by Schreiner, the two early smelting slags from Tepe Hissar are highly viscous, show evidence of either low temperatures or short smelting times (or both), and contain appreciable amounts of arsenic (< 3 wt%) and iron in the prills (see Thornton and Rehren 2009). However, unlike the Sialk slags, the two slags from Hissar contain very little entrapped copper (2–3 wt% Cu_2O), they are very iron-rich relative to silica ($FeO:SiO_2 = 1.3$) and are 'fayalitic' in their crystal structure. Partially reacted ore and gangue fragments suggest the direct smelting of copper–iron sulfides (e.g., bornite: Cu_5FeS_4) with significant impurities of lead and arsenic. These copper–iron sulfides, which appear to have entered the smelt with a gangue of iron-oxide, apatite, and steatite (i.e., talc-schist), were probably mixed with oxidic copper ores to increase the metal yield by removing the sulfur (i.e., 'co-smelting' *a la* Rostoker and Dvorak 1991).

The point is that the roughly contemporary slags from Sialk and from Hissar are entirely different in their microstructure and in the amount of copper that became entrapped in the slag phase (see Fig. 23.6).The Sialk slags follow the 'Levantine'

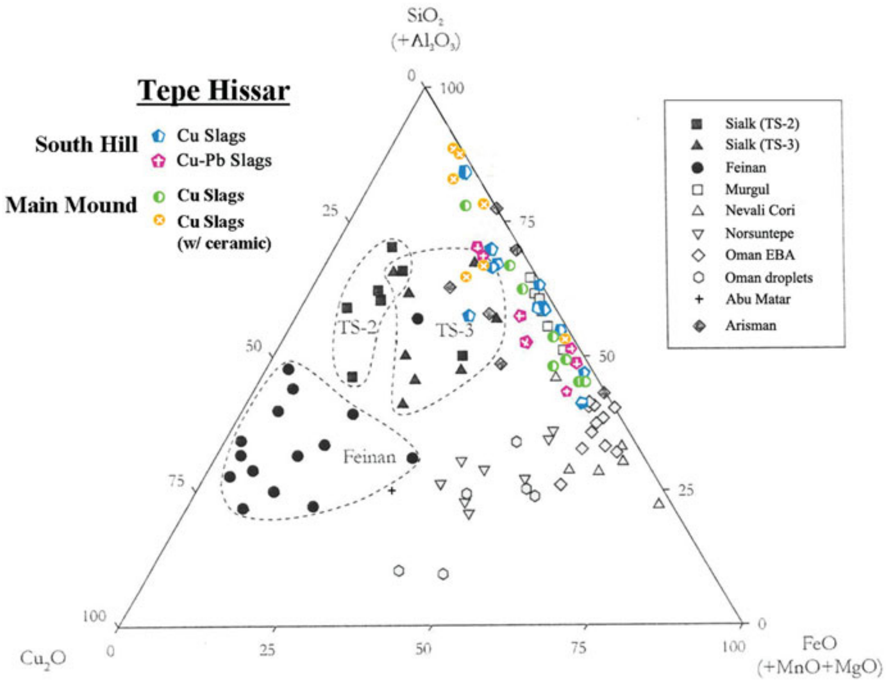


Fig. 23.6 Ternary scatterplot showing normalized values of SiO_2–FeO–Cu_2O for the slags from Tepe Hissar in comparison to roughly contemporary slags from Feinan, Tepe Sialk, and a number of other fourth and third millennium sites in Southwest Asia. Note how the Hissar slags cluster with other fourth millennium sites with 'industrial'-scale metallurgy, including Murgul and Arisman. (Image adapted from Schreiner 2002, p. 21)

model of poor slag–metal separation, while the Hissar slags (despite being quite viscous) parallel the iron-rich and copper-poor fourth millennium slags from Murgul in Northeastern Anatolia (see Hauptmann et al. 1993). The major similarity between the technologies of these two sites is the selection of arsenic-rich ores and the presence of iron (< 4 wt%) in the copper prills themselves. Such high levels of iron in copper prills have long been considered an indicator of furnace smelting as opposed to smelting in a crucible (see Craddock 2001, p. 154), but this too derives from study of the Levantine third millennium vs. fourth millennium material and cannot be applied to the Iranian situation. While Sialk and Hissar may have utilized crude pit furnaces for their smelts, we have no evidence for such at this early date.

By the late fourth millennium (i.e., "EB I" using Levantine terms), the metal-producing sites of North-central and Northeastern Iran discussed above display certain significant changes to their social and technological frameworks. First, certain production zones appear (e.g., the "Industrial Quarter" at Sialk, the "South Hill" at Hissar, and "Slag Heaps A, D, and E" at Arisman) that are entirely devoted to metalworking and other crafts (see Shahmirzadi 2003; Pigott 1989; Chegini

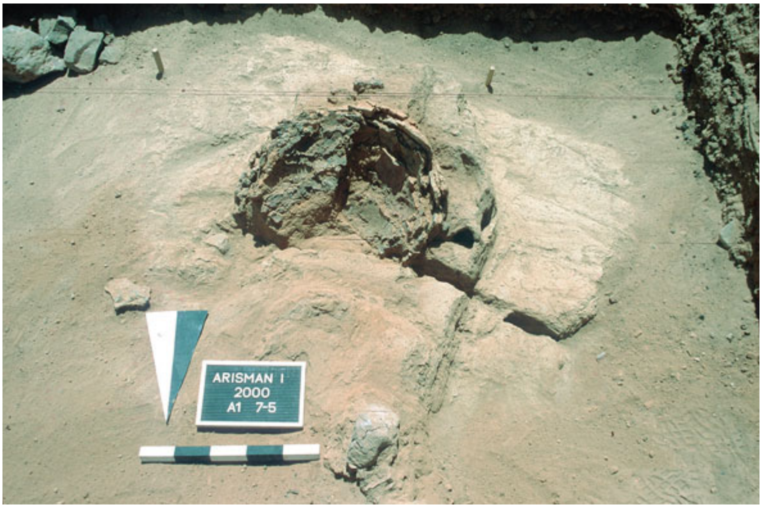


Fig. 23.7 The furnace from Arisman A dated ca. 3000 BCE. Set into a clay platform, the furnace consists of a *lower* bowl for collecting the metal and an *upper* ceramic chimney for holding the charge and charcoal and for regulating the conditions in the smelt. This furnace was reused at least 30 times. (Image courtesy of Barbara Helwing and the Arisman Photographic Archive)

et al. 2004). These areas feature complete furnaces, slag heaps, roasting pits, mold and crucible fragments, and other debris from metalworking. Unlike earlier such deposits, this debris is not mixed with mundane daily refuse and is not found in habitation contexts (see Fig. 23.7).[6] In the case of Tepe Hissar (see Pigott et al. 1982; Thornton 2009), the appearance of specialized metallurgical "workshops" removed from habitation contexts does not mean the cessation of smelting activities in residential contexts. Instead, smelting and casting continued both in residential contexts (the "Main Mound") and in 'industrial' contexts (the "South Hill"). The main difference between these technologies is the evidence for lead production (and possibly cupellation for silver extraction) and the production of copper–lead alloys (instead of copper–arsenic alloys) in the South Hill slags, and the complete absence of lead in almost all slags from the Main Mound but the intense focus on the production of copper–arsenic alloys in this area.[7] Intriguing also is the appearance of metal-casting debris (e.g., molds and melting crucibles) but no metallurgical slag at extreme lowland sites such as Shah Tepe in the Gorgan River valley (Arne 1945, p. 258), suggesting perhaps the local working of imported metal from plateau sites like Tepe Hissar, located about 50 km to the south.

[6] Although both Iblis and Ghabristan have metallurgical 'workshops', in both cases smelting was carried out in rooms that also served as domiciles.

[7] This divide between specialized and domestic metallurgy is also apparent in the contemporary metallurgical production at two areas ("elite" and "utilitarian") of Tal-i Malyan in South-central Iran (Pigott et al. 2003a).

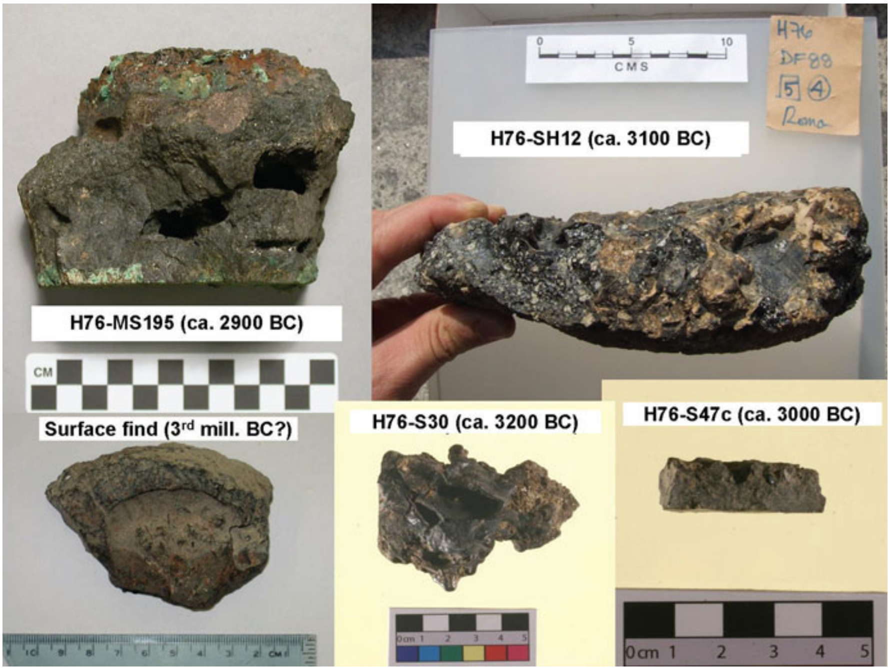


Fig. 23.8 Various slags from the late fourth and early third millennium levels at Tepe Hissar, including large slag cakes (H76-MS195), large furnace slags with possible evidence of quartz fluxing (H76–12), small plate slags (H76-S47c), and tap slags (H76-S30). The slag on the *bottom left* is a surface find from Hissar that can be compared stylistically to mid-third millennium slags from Shahr-i Sokhta in which the metal ingot separates completely from the overlying slag, thereby creating the round rim seen here. (Image of H76–12 provided by Claudio Giardino)

The rise of specialized metalworking areas (and the appearance of true furnaces) on the Iranian Plateau paralleled advancements in the smelting technology as shown by the Period IIB slags from Tepe Hissar (ca. 3400–3100 BCE). These advances include greater separation between slag and metal caused by higher temperatures and longer smelting times, better balance between iron and silica in the initial charge, and even the addition of fluxes (particularly the presence of regularly sized quartz grains in South Hill lead slags) (Thornton 2009). Furthermore, by the end of the fourth millennium we have the earliest true tap slags, plate slags, and large slag cakes (up to 10 cm thick) at Hissar (see Fig. 23.8). In the third millennium, these smelting improvements developed into the plano-convex ingots and round slag cakes documented from Shahr-i Sokhta in Eastern Iran (Hauptmann 1980; Hauptmann and Weisgerber 1980; Helmig 1986; Hauptmann et al. 2003), from Oman (Hauptmann 1985; Hauptmann et al. 1988; Prange 2001; Weeks 2003), and found on the surface of Tepe Hissar (see Fig. 23.8, bottom left). By this stage, metal production at certain key sites on the Iranian Plateau is standardized, of industrial scale, and probably controlled by central 'elite' authorities[8].

Finally, a point should be made about alloying practices in the early stages of Iranian metallurgy and how this fits with the Levantine notion of 'natural' alloys. Obviously, the Iranian Plateau is quite rich in polymetallic ores containing useful impurities like lead, arsenic, antimony, nickel, etc., in addition to (and often naturally mixed with) an abundance of high-grade copper ores. Thus, from the earliest stages of smelting on the Iranian Plateau (and even in some native copper artifacts; see Smith 1965), arsenic played an important role in copper metallurgy as a deoxidant (which improves casting), for hardening the metal, and for coloration. However, given the abundance of 'pure' copper ores (both oxidic and sulfidic) in the same contexts (see Bazin and Hubner 1969), it is clear that certain mixed or polymetallic ores were intentionally selected by prehistoric metalworkers of the fifth to fourth millennium BCE in order to take advantage of their physical and chemical differences.

By the end of the fourth millennium BCE, alloying techniques appear to change quite dramatically. First, there is evidence for direct mixing of different ores to create a single alloy, such as the tin-bronze artifacts from the Kalleh Nissar cemetery in Luristan (Western Iran), which were likely made by combining local copper and tin ores from the recently reported Deh Hosein deposit (Pigott 2004, p. 34; Fleming et al. 2005; Nezafati et al. 2006).[9] Some of the copper–lead slags from Hissar IIB contexts on the South Hill may also suggest direct mixing of ores for alloying purposes (Thornton 2009). Second, smelting slags at Hissar demonstrate a rise in the production of 'pure' copper (as opposed to arsenical copper or leaded copper) by ca. 3000 BCE, which parallels the early third millennium shift to 'pure' copper production at Kura-Araxes sites in Northwestern Iran such as Godin IV (Frame 2007) and in Eastern Turkey such as Arslantepe VIB2 (Palmieri et al. 1999; Yener 2000, pp. 48–57). Similarly, almost all of the round slag cakes and ingots from third millennium Shahr-i Sokhta also contain copper with no major impurities, which is surprising given the presence of arsenic and sometimes lead in almost all of the finished artifacts from the site (Hauptmann et al. 2003; Artioli et al. 2005).

The disparity in arsenic contents between primary prills/ingots and finished artifacts can only be explained by the direct addition of arsenic to the copper sometime after the initial smelt. Dennis Heskel (1982; see also Heskel and Lamberg-Karlovsky 1980) followed Smith (1968) in arguing for the use of copper arsenides from the Anarak-Talmessi region of central Iran, which could theoretically be added to molten copper to produce an alloy (see Pigott 1999a, p. 78). However, no evidence for the exploitation of this rare resource in central Iran has ever been found despite recent

[8] This situation contrasts sharply with contemporary production practices in western Iran at sites such as Godin tepe, where metallurgy remains rather small scale and decentralized well into the second millennium BCE (Frame pers. comm. 2008).

[9] The appearance of copper–tin alloys in Luristan c. 3200–2800 BCE is surprising given the complete lack of even minor amounts of tin at other Iranian sites until the end of the third millennium BCE (Stech and Pigott 1986; Thornton et al. 2005).

exploration of the region (Pernicka pers. comm. 2007), and no evidence of copper arsenides or their use has ever been documented from a third millennium site.

What *has* been found at Shahr-i Sokhta are examples of arsenic-rich speiss, an iron–arsenic pseudo-metal usually produced as an accidental and unwelcome by-product of iron or lead smelting (see Hauptmann et al. 2003). More recently, a handful of slags from Tepe Hissar dating to ca. 3000 BCE were found to contain no copper or lead, but only prills of iron–arsenic speiss and iron–arsenic sulfide (Thornton et al. 2009). While it could be argued that these slags represent the accidental smelting of iron–arsenic ores such as arsenopyrite, the presence of similar 'speiss slags' at Arslantepe (Hess 1998), at Arisman (Pernicka pers. comm. 2007), and the presence of actual speiss at Shahr-i Sokhta might also suggest the intentional production of arsenic-rich speiss, which was then used as a direct alloying agent in the production of arsenical copper (cf. Zwicker 1991, pp. 333–334). The production and use of direct alloying agents in the beginning of the third millennium preludes the large-scale production of and trade in tin ingots known from Mesopotamian texts of the early second millennium BCE (Reiter 1999; Dercksen 2005).

Discussion

Compared to Anatolia or the Levant, the amount of archaeometallurgical research carried out on Iranian prehistoric sites, mines, and artifacts is extremely limited. Thus, until recently, discussions of the early adoption and transformation of metal use and production in Iran have been forced to conform to the model for early metals in the Middle East as a whole—what is called here the "Levantine Paradigm." There is, of course, basis for some comparison. In both regions, native copper first appears as an import (from Anatolia?) in the late eighth millennium (e.g., at Tell Ramad and at Ali Kosh), long before the general adoption of metal. Smelting becomes widespread in both the Levant and Iran at the end of the fifth millennium, while other metals such as gold see their first usage in the early fourth millennium (e.g., at Nahal Qanah in Israel and at Tepe Borj in Northeastern Iran[10]). By the third millennium, both regions are engaged in a fairly large-scale production of and trade in metal ingots.

Although there are important synchronisms in the metallurgical development of the Levant and the Iranian Plateau, there are also significant chronological and technological differences. While native copper use appears in the Southern Levant for a few centuries leading up to the beginning of smelting, in Iran it is an entire craft spanning millennia that displays in some cases considerable artistry and skill. When smelting appears in the Levant at the end of the fifth millennium BCE, it had already been in practice on the Iranian Plateau for a thousand years (e.g., at Tal-i Iblis) as a cottage-level industry utilizing crucible-based "proto-furnaces" like

[10] Emran Garajian pers. comm. 2007.

those described from Shiqmim (Golden et al. 2001, p. 952). Chalcolithic metallurgy in the Levant is based upon the production of relatively ‘pure’ copper made from oxidic ores, while in Iran the product is almost invariably arsenical copper or leaded copper often made from a combination of oxide and sulfide ores (either naturally mixed or directly mixed, but always intentionally chosen). Despite the “advanced” nature of Iranian metallurgy relative to the Levant, the lost-wax cast, polymetallic alloys of the ‘prestige’ items from the Chalcolithic Levant have no parallel either stylistically or technologically in Iran; thus, their origin must lie elsewhere (Goren 2008).

In the early fourth millennium BCE, when the Levant experienced a florescence of metalworking ‘peer-polities’ in the Beersheva Valley all engaged in similar metal production practices due to “shared knowledge,” Ghabristan has a central, walled compound of specialized metalworkers and potters practicing a very different craft from the desert-fringe metalworkers of Qaleh Gusheh near Arisman despite great similarities in the overall material culture (cf. “balkanized” Anatolian metalworkers; Yener 2000, p. 26). This situation changes with the founding of the site of Arisman ca. 3700 BCE, when sites from Ghabristan to Sialk/Arisman (a distance of ~ 300 km) began to display the same types of crucibles, molds, and overall metalworking techniques utilizing (at least in the case of Sialk) arsenic- and iron-rich sulfidic and oxidic ores. In contrast, the contemporary site of Tepe Hissar (~ 300 km east of Ghabristan and ~ 300 km northeast of Sialk/Arisman) practiced an entirely different metallurgical tradition utilizing arsenic- and iron-rich sulfidic and oxidic ores smelted under much better conditions to produce slags with lower viscosity and thus higher metal yield. Interestingly, the sites near Kashan (i.e., Sialk and Arisman) as well as Hissar and sites in Southern Turkmenistan (e.g., Ilgynly-depe) were all engaged in lead smelting and silver extraction (through cupellation) by the early-mid-fourth millennium BCE, which suggests some level of ‘shared knowledge’ of this complicated technique within northern Iran and with contemporary silver-producing sites of Syro-Anatolia (Hess et al. 1998; Pernicka et al. 1998; Pernicka a, b).

By the EB I period (late fourth millennium BCE), metalworking sites on the Iranian Plateau often demonstrate two or more metalworking traditions within the same community, such as at Tepe Hissar near Damghan. Both Arisman and Sialk are engaged in metal production and metalworking in this period, and the relationship between these two sites requires archaeometallurgical and archaeological assessment. In all three cases, we may be witnessing segregation between ‘elite’-driven production and ‘utilitarian’ production. In the case of Tepe Hissar, the ‘elite’ lapis lazuli and metallurgical workshops of the South Hill are also engaged in lead smelting and possibly silver production, while the ‘utilitarian’ courtyard workshops of the Main Mound show no evidence of lead smelting but are engaged in the production of arsenic-rich speiss, probably for the production of arsenical copper. Although analysis of metal artifacts from these two areas awaits publication, the metal artifacts from ‘utilitarian’ area TUV at Tal-i Malyan in Fars differ significantly in their manufacturing techniques from those found in ‘elite’ area ABC, suggesting two totally different metalworking traditions within the same society (Pigott et al. 2003a).

The second half of the fourth millennium on the Iranian Plateau also brings most of the metallurgical techniques long thought to be representative of the end of the third millennium BCE. These include tap slags, plate slags, large slag cakes, fluxing, and eventually near-perfect separation between metal ingots and slag as seen at Shahr-i Sokhta and elsewhere in the early-mid-third millennium. All of these changes were related to the widespread adoption of furnaces in the fourth millennium BCE.[11] Furthermore, advances in alloying techniques such as mixed smelting (or co-smelting) and possibly even direct alloying (e.g., with speiss) led to the invention of new metals such as tin bronze and eventually brass in the third millennium (Thornton 2007). In other words, while the 'Levantine Paradigm' provides a framework for discussing early metallurgical development in the Near East over the long dureé, its use as a 'dating method' for metalworking sites in highland regions like Iran or Anatolia is entirely inaccurate and should henceforth be discontinued.

Conclusion

The concept called here the 'Levantine Paradigm' is of course an academic foil—a 'straw man' model used for comparative purposes—and not a model likely to be supported by a significant quorum of scholars either in the Levant or elsewhere. Instead, it is an amalgamation of various viewpoints and opinions by scholars who all work in the important and well-studied archaeometallurgical sites of the Southern Levant. Relative to this region, the Iranian Plateau is not only an extremely vast area of land (1.5 million km^2), but also an archaeometallurgical *terra incognita*. Scholars have not yet managed to even map all of the ore deposits to be found in Iran, let alone attempted to find metalworking sites in these same regions. Our understanding of this important highland zone remains limited to certain key sites that probably represent less than 1 % of all prehistoric archaeological sites that have ever been mapped, let alone the ones that exist and remain unsurveyed. For these reasons, recent research by scholars in both the Levant (e.g., Golden 1998; Shugar 2000) and Iran (e.g., Thornton 2009; Schreiner 2002; Frame 2004, 2007) will likely change the picture considerably by adding both new data and new perspectives.

However, as this paper hopefully begins to demonstrate, the Iranian Plateau served as one of *the* early 'heartlands' of metallurgy, and to understand its development is to tap into the earliest stages of human engagement with metals (Pigott 1999b). While it would be premature to predict a new 'model for early metallurgy' in Iran, certain key points can be raised that should form the basis of future research. First, the relationship between lowlands and highlands is complicated by the cultural geography of both landscapes, in which localized highland–lowland interactions (e.g., Feinan to Beersheva, or Hissar to the Gorgan Valley) often preempt more regional or

[11] Shugar 2003 reports on the presence of slagged furnace lining (as opposed to crucible fragments) from Chalcolithic levels at Abu Matar, which will require a reconfiguration of the Levantine model as it is stereotyped in this paper.

super-regional highland–lowland interaction (e.g., Levant to Syro-Anatolia, or Iran to Mesopotamia). Thus, metal production and metalworking must be understood at both local and regional levels.

Second, the initial appearance of new materials and techniques in Iran does not seem to have caused widespread changes to local metalworking traditions like in the Levant. Instead, there was often a lag of up to a millennium before true adoption occurred—for example, in the utilization of native copper, in the spread of smelting, and in the production and use of tin bronze.[12] The reasons for this technological conservatism are not immediately obvious. One could suggest that the abundance of local resources in Iran quenched demand for new materials or techniques to be adopted. Alternatively, the 'technological styles' evident in these conservative metalworking traditions may signify strong local identities that constructed and were constructed by material culture and technological performance. One could also suggest the presence of formalized and ritualized apprenticeship systems in which crafts were passed from generation to generation. Our data are simply too few at this stage to reach any conclusions to explain this phenomenon.

Finally, it is important to emphasize once again that the metallurgical technology of the Iranian Plateau does not conform to traditional models of early metal production and use in the ancient Near East. As a 'highland' region with plentiful mineral resources, Iran was able to carry out fairly large-scale production of a diverse repertoire of metals and metal objects by the beginning of the fourth millennium BCE. However, as a relatively fertile land for agriculture and pastoralism, Iran also provided the perfect setting for significant technological innovations, in that craft specialists could be supported by the community and given the time to experiment with different minerals and smelting/working techniques. Thus, the beginnings of direct alloying and the use of true furnaces and furnace techniques (e.g., tapping) in the late fourth millennium—almost a millennium before such advances were thought to occur elsewhere in the Middle East—is surely related to the presence of discrete metallurgical workshops and slagheaps separated from nearby habitation areas. It is this tension between Iran's social and technical conservatism on the one hand, and its precocious social and technological practices on the other, that will require further attention as archaeometallurgical research in this region continues over the next few decades.

Acknowledgments I would like to thank Lesley Frame, Jonathan Golden, Barbara Helwing, Vince Pigott, Ben Roberts, Lloyd Weeks, and the other authors in our 2008 SAA session in Vancouver for their helpful comments and criticisms. Special thanks to Lesley Frame, Emran Garajian, Ernst Pernicka, and other colleagues for allowing me to comment upon their unpublished data for this synthesis. I am also very grateful to Hassan Fazeli, Claudio Giardino, Barbara Helwing, Gero Steffens, and Thomas Stöllner for providing me with images.

[12] The long-standing metalworking techniques shown by metallographic analysis of numerous small utilitarian artifacts from a ca. 3000 year span at Tepe Yahya would seem to bolster the argument for technological conservatism on the Iranian Plateau (Thornton and Lamberg-Karlovsky 2004b).

References

Alden, J. R. (1982). Trade and politics in Proto-Elamite Iran. *Current Anthropology*, *23*(6), 613–640.

Algaze, G. (1993). *The Uruk world system*. Chicago: University of Chicago Press.

Arab, R., & Rehren, Th. (2004a). The Wertime pyrotechnological expedition of 1968. *IAMS*, *24*, 29–34.

Arab, R., & Rehren, Th. (2004b). The pyrotechnological expedition of 1968. In T. Stöllner, R. Slotta, & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 550–555). Bochum: Deutsches Bergbau-Museum.

Arne, T. J. (1945). *Excavations at Shah Tepe, Iran*. Stockholm: The Sino-Swedish Expedition (Pub. 27).

Artioli, D., Giardino C., Guida G., Lazzari A., & Vidale M. (2005). On the exploitation of copper ores at Shahr-i Sokhta (Sistan, Iran) in the 3rd millennium BC. In U. Franke-Vogt & H.-J. Weisshaar (Eds.), *South Asian archaeology 2003* (Vol. 1, pp. 179–184) (Forschungen zur Archäologie Außereuropäischer Kulturen FAAK). Bonn: Linden Soft.

Bachmann, H.-G. (1980). Early copper smelting techniques in Sinai and in the Negev as deduced from slag investigations. In P. T. Craddock (Ed.), *Scientific studies in early mining and extractive metallurgy* (pp. 103–134) (Occasional Paper No. 20). London: British Museum.

Bar-Adon, P. (1980). *The cave of the treasure: The finds from the caves of Nihal Mishmar*. Jerusalem: Israel Exploration Society.

Bar-Yosef Mayer, D. E., & Porat, N. (2008). Green stone beads at the dawn of agriculture. *Proceedings of the National Academy of Sciences*, *105*, 8548–8551.

Bates, D. G., & Rassam, A. (2001). *Peoples and cultures of the middle East*. Upper Saddle River: Prentice Hall.

Bazin, D., & Hübner, H. (1969). *Copper deposits in Iran* (Report 13). Tehran: Geological Survey of Iran.

Benoit, A. (2004). Susa. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 178–193). Bochum: Deutsches Bergbau-Museum.

Bernbeck, R. (2004). Iran im Neolithikum. In T. Stöllner, R. Slotta, & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 140–147). Bochum: Deutsches Bergbau-Museum.

Boroffka, N., & Becker, J. (2004). Töpferöfen in Arisman. In T. Stöllner, R. Slotta, & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 218–221). Bochum: Deutsches Bergbau-Museum.

Bourgarit, D. (2007). Chalcolithic copper smelting. In S. La Niece, D. Hook, & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 3–14). London: Archetype Publications Ltd.

Caldwell, J. R. (Ed). (1967a). *Investigations at Tal-i-Iblis* (Illinois State Museum Preliminary Reports No. 9). Springfield: Illinois State Museum Society.

Caldwell, J. R. (Ed.). (1967b). The setting and results of the Kerman Project. *Investigations at Tal-i Iblis* (pp. 21–40) (Illinois State Museum Preliminary Reports No. 9). Springfield: Illinois State Museum Society.

Caldwell, J. R. (1968). Tal-i-Iblis and the beginning of copper metallurgy at the fifth millennium. *Archaeologia viva*, *1*, 145–150.

Caldwell, J. R., & Sarraf, M. (1967). Exploration of excavation area B. In J. R. Caldwell (Ed.), *Investigations at Tal-i-Iblis* (pp. 272–308) (Illinois State Museum Preliminary Reports No. 9). Springfield: Illinois State Museum Society.

Caldwell, J. R., & Shahmirzadi, S. M. (1966). *Tal-i-Iblis: The Kerman range and the beginnings of smelting* (Illinois State Museum Preliminary Reports No. 7). Springfield: Illinois State Museum Society.

Charles, J. A. (1980). The coming of copper and copper-base alloys and iron: A metallurgical sequence. In T. A. Wertime & J. D. Muhly (Eds.), *The Coming of the Age of Iron* (pp. 151–182). New Haven: Yale University Press.

Chegini, N. N., Momenzadeh, M., Parzinger, H., Pernicka, E., Stöllner, T., Vatandoust A., & Weisgerber, G. (2000). Preliminary report on archaeometallurgical investigations around the prehistoric site of Arisman near Kashan, western Central Iran. *Archaeologische Mitteilungen aus Iran und Turan*, *32*, 281–318.

Chegini, N. N., Helwing, B., Parzinger, H., & Vatandoust, A. (2004). Eine prähistorische Industriesiedlung auf dem iranischen Plateau-Forschungen in Arisman. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 210–216). Bochum: Deutsches Bergbau-Museum.

Courcier, A. (2007). La metallurgie dans les pays du Caucase au Chalcolithique et au debut de l'age du Bronze: bilan des etudes et perspectives nouvelles. In B. Lyonnet (Ed.), *Les Cultures du Caucase (VIe-IIIe millenaires avant notre ere): Leurs Relations avec le Proche-Orient* (pp. 199–232). Paris: CNRS Editions Recherche sur les Civilisations.

Craddock, P. T. (2001). From hearth to furnace: Evidences for the earliest metal smelting technologies in the eastern Mediterranean. *Paleorient*, *26*, 151–165.

Dercksen, J. G. (2005). Metals according to the documents from Kultepe-Kanish dating to the Old Assyrian Colony Period. In U. Yalcin (Ed.), *Anatolian Metal III* (pp. 17–34) (Der Anschnitt, Beiheft 18). Bochum: Deutsches Bergbau Museum.

Dyson, R. H., & Howard S. M. (Eds.). (1989). *Tappeh Hesar: Reports of the Restudy Project*, *1976*. Reports of the Restudy Project of 1976. Firenze: Case Editrice le Lettere.

Evett, D. (1967). Artifacts and architecture of the Iblis I period: Areas D, F, and G. In J. R. Caldwell (Ed.), *Investigations at Tal-i-Iblis* (pp. 202–255) (Illinois State Museum Preliminary Reports No. 9). Springfield: Illinois State Museum Society.

Fazeli Nashli, H., & Sereshti, R. A. (2005). Social transformation and interregional interaction in the Qazvin Plain during the 5th, 4th, and 3rd millennia B.C. *Archaeologische Mitteilung aus Iran und Turan*, *37*, 7–26.

Fazeli, H., Wong, E. H., & Potts, D. T. (2005). The Qazvin Plain revisited: A reappraisal of the chronology of northwestern Central Plateau, Iran, in the 6th to the 4th millennium BC. *ANES*, *42*, 3–82.

Fleming, S. J., Pigott, V. C., Swann, C. P., & Nash, S. K. (2005). Bronze in Luristan: Preliminary analytical evidence from copper/bronze artifacts excavated by the Belgian Mission in Iran. *Iranica Antiqua*, *40*, 35–64.

Frame, L. D. (2004). *Investigations at Tal-i Iblis: Evidence for Copper Smelting during the Chalcolithic Period*. B.S. thesis. Department of Material Science and Engineering, Massachusetts Institute of Technology.

Frame, L. D. (2007). *Metal finds from Godin Tepe, Iran: Production, consumption, and trade*. M.S. Thesis. Department of Material Science and Engineering, University of Arizona.

Genz, H., & Hauptmann, A. (2002). Chalcolithic and EBA metallurgy in the Southern Levant. In U. Yalcin (Ed.), *Anatolian Metal II* (pp. 149–158) (Der Anschnitt, Beiheft 15). Bochum: Deutsches Bergbau Museum.

Ghirshman, R. (1938). *Fouilles de Sialk*. Paris: Librairie Orientaliste Paul Guenthner.

Golden, J. M. (1998). *The dawn of the metal age: Social complexity and the rise of copper metallurgy during the Chalcolithic of the Southern Levant, ca. 4500–3500 BC*. Ph.D. dissertation. Department of Anthropology, University of Pennsylvania.

Golden, J. M., Levy, T. E., & Hauptmann, A. (2001). Recent discoveries concerning chalcolithic metallurgy at Shiqmim, Israel. *Journal of Archaeological Science*, *28*(9), 951–963.

Gopher, A., Tsuk, T., Shalev, S., & Gophna, R. (1990). Earliest gold artifacts in the Levant. *Current Anthropology*, *31*, 436–443.

Goren, Y. (2008). The location of specialized copper production by the lost wax technique in the Chalcolithic Southern Levant. *Geoarchaeology*, *23*, 374–397.

Hauptmann, A. (1980). Zur frühbronzezeitlichen Metallurgie von Shahr-i Sokhta (Iran). *Der Anschnitt*, *2–3*, 55–61.

Hauptmann, A. (1985). *5000 Jahre Kupfer im Oman*. Der Anschnitt, Beiheft 4. Bochum.: Deutsches Bergbau Museum.

Hauptmann, A. (1989). The earliest periods of copper metallurgy in Feinan. In A. Hauptmann, E. Pernicka & G. A. Wagner (Eds.), *Old world archaeometallurgy* (pp. 119–135) (Der Anscnitt, Beiheft 7). Bochum: Deutsches Bergbau Museum.

Hauptmann, A. (1991). From the use of ore to the production of metal. In J.-P. Mohen & C. Eluere (Eds.), *Decouverte du Metal* (pp. 397–412). Paris: Picard.

Hauptmann, A. (2000). *Zur frühen Metallurgie des Kupfers in Fenan, Jordanien* (Der Anschnitt, Beiheft 11). Bochum: Deutsches Bergbau-Museum.

Hauptmann, A. (2003). Rationales of liquefaction and metal separation in earliest copper smelting: basics for reconstructing Chalcolithic and Early Bronze Age smelting processes. *Archaeometallurgy in Europe* (pp. 459–468). Milano: Proceedings of the International Conference.

Hauptmann, A. (2007). *The archaeometallurgy of copper: Evidence from Faynan, Jordan*. Berlin: Springer.

Hauptmann, A., & Wagner, I. (2007). Prehistoric copper production at Timna: Thermoluminescence (TL) dating and evidence from the east. In S. La Niece, D. Hook & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 67–75). London: Archetype Publications Ltd.

Hauptmann, A., & Weisgerber, G. (1980). The Early Bronze Age copper metallurgy of Shahr-i Sokhta (Iran). *Paleorient*, *6*, 120–127.

Hauptmann, A., Weisgerber, G., & Bachmann, H.-G. (1988). Early copper metallurgy in Oman. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 34–51). Cambridge: MIT Press.

Hauptmann, A., Begemann, F., Heitkemper, R., Pernicka, E., & Schmitt-Strecker, S. (1992). Early copper produced at Feinan, Wadi Arabah, Jordan: The composition of ores and copper. *Archaeomaterials*, *6*, 1–33.

Hauptmann, A., Lutz, J., Pernicka, E., & Yalcin, U. (1993). Zur Technologie der fruhesten Kupferverhuttung im ostlichen Mittelmeerraum. In M. Frangipane, H. Hauptmann, M. Liverani, P. Matthiae & M. J. Mellink (Eds.), *Between the rivers and over the mountains* (pp. 541–572). Roma: Dipartimento di Scienze Storiche Archeologiche e Antropologiche dell'Antichita.

Hauptmann, A., Rehren, Th., & Schmitt-Strecker, S. (2003). Early Bronze Age copper metallurgy at Shahr-i Sokhta (Iran), reconsidered. In Th. Stöllner, G. Koerlin, G. Steffens & J. Cierny (Eds.), *Man and Mining—Mensch und Bergbau. Studies in Honour of Gerd Weisgerber* (pp. 197–213) (Der Anschnitt, Beiheft 16). Bochum: Deutsches Bergbau-Museum.

Helmig, D. (1986). *Versuche zur analytisch-chemischen Charakterisierung frühbronzezeitlicher Techniken der Kupferverhüttung in Shahr-i Sokhta, Iran*. Bochum: Diplomarbeit (Faculty of Chemistry, Ruhr-University).

Helwing, B. (2004). Tracking the Proto-Elamite on the Central Iranian Plateau. In S. M. Shahmirzadi (Ed.), *The Potters of Sialk* (pp. 45–58). Tehran: Iranian Center for Archaeological Research.

Helwing, B. (2005). Early mining and metallurgy on the western Iranian Plateau: First results of the Iranian-German archaeological research at Arisman, 2000–2004. *Archaeologische Mitteilung aus Iran und Turan*, *37*, 425–434.

Heskel, D. L. (1982). *The development of pyrotechnology in Iran during the fourth and third millennia B.C*. PhD dissertation, Department of Anthropology, Harvard University.

Heskel, D. L. (1983). A model for the adoption of metallurgy in the ancient Middle East. *Current Anthropology*, *24*, 362–365.

Heskel, D. L., & Lamberg-Karlovsky, C. C. (1980). An alternative sequence for the development of metallurgy: Tepe Yahya, Iran. In T. Wertime & J. Muhly (Eds.), *The coming of the age of iron* (pp. 229–266). New Haven: Yale University Press.

Hess, K. (1998). *Frühe Metallurgie am Oberen Euphrat: Untersuchungen an archäometallurgischen Funden vom Arslantepe aus dem 4. und 3. Johrtausend v.Chr*. Dissertation, Universität Frankfurt.

Hess, K., Hauptmann, A., Wright, H. T., & Whallon, R. (1998). Evidence of fourth millennium BC silver production at Fatmali-Kalecik, East Anatolia. In Th. Rehren, A. Hauptmann & J. D. Muhly (Eds.), *Metallurgica Antiqua* (pp. 57–68) (Der Anschnitt, Beiheft. 8.) Bochum: Deutsches Bergbau-Museum.

Hole, F. (2000). New radiocarbon dates for Ali Kosh, Iran. *Neo-lithics*, *1*, 13.
Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
Kohl, P. L. (1987). The ancient economy, transferable technologies and the Bronze Age world-system: A view from the northeastern frontier of the ancient Near East. In M. Rowlands, M. Larsen & K. Kristiansen (Eds.), *Centre and Periphery in the Ancient World* (pp. 13–24). Cambridge: Cambridge University Press.
Lamberg-Karlovsky, C. C. (1967). Archaeology and metallurgical technology in prehistoric Afghanistan, India, and Pakistan. *American Anthropologist*, *69*, 145–162.
Levy, T. E. (1995). Cult, metallurgy and rank societies–Chalcolithic period (ca. 4500–3500 BCE). In T. E. Levy (Ed.), *The archaeology of society in the Holy Land* (pp. 226–244). London: Leicester University Press.
Levy, T. E., & Shalev, S. (1989). Prehistoric metalworking in the southern Levant: Archaeometallurgical and social perspectives. *World Archaeology*, *20*, 352–372.
Levy, T. E., Adams, R. B., Hauptmann, A., Prange, M., Schmitt-Strecker, S., & Najjar, M. (2002). Early Bronze Age metallurgy: A newly discovered copper manufactory in southern Jordan. *Antiquity*, *76*, 425–437.
Majidzadeh, Y. (1979). An early coppersmith workshop at Tepe Ghabristan. In *Akten des VII. Internationalen Kongresses für Iranische Kunst und Archäologie, München 7–10 September 1976* (pp. 82–92) (Archaeologische Mitteilungen aus Iran, suppl. 6). Berlin: Verlag Dietrich Reimer.
Majidzadeh, Y. (1989). An early industrial proto-urban center on the Central Plateau of Iran: Tepe Ghabristan. In A. Leonard & B. B. Williams (Eds.), *Essays in Ancient Civilization Presented to Helene J. Kantor* (pp. 157–166) (Studies in Ancient Oriental Civilization No. 47). Chicago: Oriental Institute of the University of Chicago.
Matthews, R., & Fazeli, H. (2004). Copper and complexity: Iran and Mesopotamia in the fourth millennium B.C. *Iran*, *42*, 61–75.
Merkel, J., & Rothenberg, B. (1999). The earliest steps to copper metallurgy in the western Arabah. In A. Hauptmann, E. Pernicka, Th. Rehren & U. Yalcin (Eds.), *The beginnings of metallurgy* (pp. 149–166) (Der Anschnitt, Beiheft. 9). Bochum: Deutsches Bergbau-Museum.
Mille, B., Bourgarit, D., Haquet, J.-F., & Besenval, R. (forthcoming). From the 7th to the 2nd millennium BC in Balochistan (Pakistan): The development of copper metallurgy before and during the Indus Civilisation. *South Asian Archaeology 2005*.
Momenzadeh, M. (2004). Metallische Bodenschätze in Iran in antiker Zeit. Ein kurzer Überblick. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 8–21). Bochum: Deutsches Bergbau-Museum.
Moorey, P. R. S. (1969). Prehistoric copper and bronze metallurgy in western Iran (with special reference to Luristan). *Iran*, *7*, 131–153.
Moorey, P. R. S. (1982). Archaeology and pre-Archaemenid metalworking in Iran: A fifteen year retrospective. *Iran*, *20*, 81–101.
Moorey, P. R. S. (1988). The Chalcolithic hoard from Nahal Mishmar, Israel, in context. *World Archaeology*, *20*, 171–189.
Moulherat, C., Tengberg, M., Haquet, J.-F., & Mille, B. (2002). First evidence of cotton at Neolithic Mehrgarh, Pakistan: Analysis of mineralized fibres from a copper bead. *Journal of Archaeological Science*, *29*(12), 1393–1401.
Muhly, J. D. (1988). The beginnings of metallurgy in the Old World. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 2–20). Cambridge: MIT Press.
Nezafati, N., & Pernicka, E. (2006). The smelters of Sialk: Outcomes of the first stage of archaeometallurgical researches at Tappeh Sialk. In S. M. Shahmirzadi (Ed.), *The Fishermen of Sialk* (pp. 79–102) (Archaeological Report Monograph Series 7). Tehran: Iranian Center for Archaeological Research.
Nezafati, N., Pernicka, E., & Momenzadeh, M. (2006). Ancient tin: Old question and a new answer. *Antiquity*, *80*, 308.

Palmieri, A. M., Sertok, K., & Chernykh, E. N. (1993). From Arslantepe metalwork to arsenical copper technology in eastern Anatolia. In M. Frangipane, H. Hauptmann & M. Liverani (Eds.), *Between the rivers and over the mountains. Archaeologica Anatolica et Mesopotamica Alba Palmieri Dedicata* (pp. 573–599). Rome: Universita 'La Sapienza'.

Palmieri, A. M., Frangipane, M., Hauptmann, A., & Hess, K. (1999). Early metallurgy at Arslantepe during the Late Chalcolithic and the Early Bronze Age IA-IB periods. In A. Hauptmann, E. Pernicka, Th. Rehren & U. Yalcin (Eds.), *The beginnings of metallurgy* (pp. 141–149) (Der Anschnitt, Beiheft. 9) Bochum: Deutsches Bergbau-Museum.

Pernicka, E. (2004a). Kupfer und Silber in Arisman und Tappeh Sialk und die frühe Metallurgie in Iran. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 232–239). Bochum: Deutsches Bergbau-Museum.

Pernicka, E. (2004b). Silver production by cupellation in the fourth millennium BC at Tepe Sialk. In S. M. Shahmirzadi (Ed.), *The potters of Sialk* (pp. 69–72) (Archaeological Report Monograph Series 5). Tehran: Iranian Center for Archaeological Research.

Pernicka, E., Rehren, Th., & Schmitt-Strecker, S. (1998). Late Uruk silver production by cupellation at Habuba Kabira, Syria. In Th. Rehren, A. Hauptmann & J. D. Muhly (Eds.), *Metallurgica Antiqua* (pp. 123–134) (Der Anschnitt, Beiheft. 8). Bochum: Deutsches Bergbau-Museum.

Pigott, V. C. (1989). Archaeo-metallurgical investigations at Bronze Age Tappeh Hesar, 1976. In R. H. Dyson & S. M. Howard (Eds.), *Tappeh Hesar: Reports of the restudy project*, *1976* (pp. 25–34). Firenze: Case Editrice le Lettere.

Pigott, V. C. (1999a). The development of metal production on the Iranian Plateau: an archaeometallurgical perspective. In V. C. Pigott (Ed.), *The Archaeometallurgy of the Asian Old World* (pp. 73–106). Philadelphia: University Museum Symposium Series.

Pigott, V. C. (1999b). A heartland of metallurgy. Neolithic/Chalcolithic metallurgical origins on the Iranian Plateau. In A. Hauptmann, E. Pernicka, Th. Rehren & U. Yalcin (Eds.), *The beginnings of metallurgy* (pp. 109–122) (Der Anschnitt, Beiheft. 9) Bochum: Deutsches Bergbau-Museum.

Pigott, V. C. (2004). Zur Bedeutung Irans für die Erforschung prähistorischer Kupfermetallurgie. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 28–43). Bochum: Deutsches Bergbau-Museum.

Pigott, V. C., & Lechtman, H. (2003). Chalcolithic copper-base metallurgy on the Iranian plateau: A new look at old evidence from Tal-i Iblis. In T. Potts, M. Roaf, & D. Stein (Eds.), *Culture through objects: Ancient near Eastern studies in honour of P.R.S. Moorey* (pp. 291–312). Oxford: Griffith Institute.

Pigott, V. C., Howard, S. M., & Epstein, S. M. (1982). Pyrotechnology and culture change at Bronze Age Tepe Hissar (Iran). In T. A. Wertime & S. F. Wertime (Eds.), *Early pyrotechnology: The evolution of the first fire-Using industries* (pp. 215–236). Washington: Smithsonian Institute Press.

Pigott, V. C., Rogers, H. C., & Nash, S. K. (2003a). Archaeometallurgical investigations at Tal-e Malyan: The Banesh Period. In W. M. Sumner (Ed.), *Early urban life in the land of Anshan: Excavations at Tal-e Malyan in the Highlands of Iran* (pp. 94–102, 149–159) (University Museum Monograph 117). Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology.

Pigott, V. C., Rogers, H. C., & Nash, S. K. (2003b). Archaeometallurgical investigations at Tal-e Malyan: The evidence for tin-bronze in the Kaftari phase. In N. F. Miller & K. Abdi (Eds.), *Yeki Bud, Yeki Nabud: Essays on the archaeology of Iran in honor of William M. Sumner* (pp. 161–175). Philadelphia: University of Pennsylvania Museum.

Prange, M. (2001). *5000 Jahre Kupfer im Oman, Band II* (vol. 8.5). Bochum: Metalla.

Reiter, K. (1999). Metals and metallurgy in the Old Babylonian period. In A. Hauptmann, E. Pernicka, Th. Rehren & U. Yalcin (Eds.), *The beginnings of metallurgy* (pp. 167–171) (Der Anschnitt, Beiheft. 9). Bochum: Deutsches Bergbau-Museum.

Renfrew, C., Dixon, J. E., & Cann, J. R. (1966). Obsidian and early cultural contact in the Near East. *Proceedings of the Prehistoric Society*, *32*, 30–72.

Rostoker, W., & Dvorak, J. (1991). Some experiments with co-smelting to copper alloys. *Archaeomaterials*, *5*, 5–20.

Rothenberg, B. (Ed.). (1990). *The ancient metallurgy of copper*. London: Institute of Archaeo-Metallurgical Studies.

Rothenberg, B., Segal, I., & Khalaily, H. (2003). Late Neolithic and Chalcolithic copper smelting at Yotvata oasis in the South Arabah. In *Archaeometallurgy in Europe* (pp. 577–586). Milano: Proceedings of the International Conference.

Schoop, U.-D. (1995). *Die Geburt des Hephaistos: Technologie und Kulturgeschichte neolithischer Metallverwendung in Vorderen Orient*. Espelkamp: Verlag Marie L. Leidorf.

Schoop, U.-D. (1999). Aspects of early metal use in Neolithic Mesopotamia. In A. Hauptmann, E. Pernicka, Th. Rehren, & U. Yalcin (Eds.), *The beginnings of metallurgy* (pp. 31–36) (Der Anschnitt, Beiheft 9). Bochum: Deutsches Bergbau Museum.

Schreiner, M. (2002). *Mineralogical and geochemical investigations into prehistoric smelting slags from Tepe Sialk/Central Iran*. Diplomarbeit. Institute für Minerologie, TU Bergakademie Freiberg.

Schreiner, M., Heimann, R. B., & Pernicka, E. (2003). Mineralogical and geochemical investigations into prehistoric smelting slags from Tepe Sialk/Central Iran. In *Archaeometallurgy in Europe, Proceedings of the International Conference 24–26 September 2003, Milan* (pp. 487–496): Associazione Italiana di Metallurgia.

Segal, I. L. (2004). The metallurgical remains from Ashqelon, Afridar—Areas E, G, and H. *Atiqot*, *45*, 311–330.

Segal, I., Halicz, L., & Kamenski, A. (2002). The metallurgical remains from Ashqelon-Afridar, Israel, and their source. In E. Jerem & K. T. Biro (Eds.), *Archaeometry 98: proceedings of the 31st Symposium, Budapest, April 26-May 3 1998* (pp. 461–473) (B.A.R. International Series 1043). Oxford: Archaeopress.

Shahmirzadi, S. M. (Ed.). (2003). The silversmiths of Sialk. *Sialk Reconsideration* (Project, No. 2). Tehran: Iranian Center for Archaeological Research.

Shalev, S. (1991). Two different copper industries in the chalcolithic cultures of Israel. In J.-P. Mohen & C. Eluere (Eds.), *Decouverte du Metal* (pp. 413–424). Paris: Picard.

Shalev, S. (1994). The change in metal production from the Chalcolithic period to the Early Bronze Age in Israel and Jordan. *Antiquity*, *68*, 630–637.

Shalev, S., & Northover, J. P. (1987). Chalcolithic metal and metalworking from Shiqmim. In T. E. Levy (Ed.), *ShiqmimI* (pp. 357–371) (B.A.R. International Series 365). Oxford: Archaeopress.

Shalev, S., & Northover, J. P. (1993). The metallurgy of the Nahal Mishmar hoard reconsidered. *Archaeometry*, *35*, 35–46.

Shalev, S., Goren, Y., Levy, T. E., & Northover, J. P. (1992). A Chalcolithic mace head from the Negev, Israel: technological aspects and cultural implications. *Archaeometry*, *34*(1), 63–71.

Shugar, A. N. (2000). *Archaeometallurgical investigation of the Chalcolithic site of Abu Matar, Israel: A reassessment of technology and its implications for the Ghassulian culture*. Ph.D. dissertation. Institute of Archaeology, University College London.

Shugar, A. N. (2003). Reconstructing the Chalcolithic metallurgical process at Abu Matar, Israel. *Archaeometallurgy in Europe* (pp. 449–458). Milano: Proceedings of the International Conference.

Smith, C. S. (1965). The interpretation of microstructures of metallic artifacts. In W. J. Young (Ed.), *Applications of science in the examination of works of art* (pp. 20–52). Boston: Museum of Fine Arts.

Smith, C. S. (1968). Metallographic study of early artifacts made from native copper. *Actes du XIe Congres International d'Histoires des Sciences, Warsaw*, *6*, 237–243.

Smith, C. S. (1969). Analysis of the copper bead from Ali Kosh. In F. Hole, K. V. Flannery & J. A. Neely (Eds.), *Prehistory and human ecology of the Deh Luran plain: An early village sequence from Khuzistan, Iran* (pp. 427–428). Ann Arbor: University of Michigan.

Stech, T., & Pigott, V. C. (1986). The metals trade in southwest Asia in the third millennium B.C. *Iraq*, *48*, 39–64.

Stöllner, T. (2005). Early mining and metallurgy on the Iranian Plateau. In U. Yalcin (Ed.), *Anatolian metal III* (pp. 17–34, 191–207) (Der Anschnitt, Beiheft 18). Bochum: Deutsches Bergbau-Museum.

Stöllner, T., Slotta, R., & Vatandoust, A. (Eds.). (2004). *Persiens Antike Pracht*. Bochum: Deutsches Bergbau-Museum.

Tadmor, M., Kedem, D., Begemann, F., Hauptmann, A., Pernicka, E., & Schmitt-Strecker, S. (1995). The Nahal Mishmar hoard from the Judean desert: Technology, composition, and provenance. *Atiqot*, *27*, 96–148.

Thornton, C. P. (2007). Of brass and bronze in prehistoric Southwest Asia. In S. La Niece, D. Hook & P. T. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 189–201). London: Archetype Publications.

Thornton, C. P. (2009). *The Chalcolithic and Early Bronze Age metallurgy of Tepe Hissar, Northeast Iran: A challenge to the 'Levantine Paradigm'*. Ph.D. dissertation. Department of Anthropology, University of Pennsylvania.

Thornton, C. P. (2010). The rise of arsenical copper in Southeastern Iran. *Iranica Antiqua*, *45*, 31–50.

Thornton, C. P., & Lamberg-Karlovsky, C. C. (2004a). Tappeh Yahya und die prähistorische Metallurgie in Südostiran. In T. Stöllner, R. Slotta & A. Vatandoust (Eds.), *Persiens Antike Pracht* (pp. 264–273). Bochum: Deutsches Bergbau-Museum.

Thornton, C. P., & Lamberg-Karlovsky, C. C. (2004b). A new look at the prehistoric metallurgy of Southeastern Iran. *Iran*, *42*, 61–76.

Thornton, C. P., & Rehren, Th. (2007). Report on the first Iranian prehistoric slag workshop. *Iran*, *45*, 315–318.

Thornton, C. P., & Rehren, Th. (2009). An unusual refractory crucible from fourth millennium Tepe Hissar, Northeast Iran. *Journal of Archaeological Science*, *36*(12), 2700–2712.

Thornton, C. P., Lamberg-Karlovsky, C. C., Liezers, M., & Young, S. M. M. (2002). On pins and needles: tracing the evolution of copper-base alloying at Tepe Yahya, Iran, via ICP-MS analysis of common-place items. *Journal of Archaeological Science*, *29*(12), 1451–1460.

Thornton, C. P., Lamberg-Karlovsky, C. C., Liezers, M., & Young, S. M. M. (2005). Stech and Pigott revisited: New evidence for the origin of tin bronze in light of chemical and metallographic analyses of the metal artifacts from Tepe Yahya, Iran. In H. Kars & E. Burke (Eds.), *Proceedings of the 33rd International Symposium on Archaeometry, 22–26 April 2002, Amsterdam* (pp. 395–398) (Geoarchaeological and Bioarchaeological Studies 3). Amsterdam: Vrije Universiteit.

Thornton, C. P., Rehren, Th., & Pigott, V. C. (2009). The intentional production of speiss (iron arsenide) during the Early Bronze Age in Iran. *Journal of Archaeological Science*, *36*(2), 308–316.

Trigger, B. G. (1984). Archaeology at the crossroads: What's new? *Annual Review of Anthropology*, *13*, 275–300.

Voigt, M. M., & Dyson, R. H. J. (1992). The chronology of Iran, ca. 8000–2000. In R. W. Ehrich (Ed.), *Chronologies in old world archaeology* (pp. 122–178). Chicago: University of Chicago Press.

Weeks, L. R. (2003). *Early metallurgy of the Persian Gulf*. Boston: Brill Academic Publishers, Inc.

Weeks, L. R. (2008). The 2007 early Iranian metallurgy workshop at the University of Nottingham. Iran 46.

Weisgerber, G. (2006). The mineral wealth of ancient Arabia and its use I: Copper mining and smelting at Feinan and Timna–Comparison and evaluation of techniques, production, and strategies. *Arabian Archaeology and Epigraphy*, *17*, 1–30.

Weisgerber, G., & Hauptmann, A. (1988). Early copper mining and smelting in Palestine. In R. Maddin (Ed.), *The beginning of the use of metals and alloys* (pp. 52–62). Cambridge: MIT.

Wertime, T. A. (1964). Man's first encounters with metallurgy. *Science*, *146*, 1257–1267.

Wertime, T. A. (1968). A metallurgical expedition through the Persian desert. *Science*, *159*, 927–935.

Wertime, T. A. (1973). The beginnings of metallurgy: A new look. *Science*, *182*, 875–887.

Wilber, D. N. (1963). *Iran: Past and present*. Princeton: PrincetonUniversity Press.

Yalcin, U. (1998). Der Keulenkopf von Can Hasan (TR): Naturwissenschaftliche Untersuchung und neue Interpretation. In Th. Rehren, A. Hauptmann & J. D. Muhly (Eds.), *Metallurgica Antiqua* (pp. 279–289) (Der Anschnitt, Beiheft. 8). Bochum: Deutsches Bergbau-Museum.

Yener, K. A. (2000). *Domestication of metals*. Leiden: Brill.

Zagarell, A. (1982). *The prehistory of the Northeast Bakhtiy-ar-i Mountains, Iran: The rise of a Highland way of life* (Beihefte zum Tuebinger Atlas des Vorderen Orients Nr. 42). Wiesbaden: Reichert.

Zwicker, U. (1991). Natural copper-arsenic alloy and smelted arsenic bronzes in early metal production. In J.-P. Mohen & C. Eluere (Eds.), *Decouverte du Metal* (pp. 331–340). Paris: Picard.

Chapter 24
Production and Consumption of Copper-Base Metals in the Indus Civilization

Brett C. Hoffman and Heather M.-L. Miller

Introduction

The organizers of this volume have posed an intriguing set of questions regarding the emergence, technological development, and adoption of copper metallurgy. Given the restricted nature of the current data available from the Indus Civilization, we were asked to summarize the approaches taken to date, the nature of production, and the style of Indus metal production and use, both within the Indus domain and beyond its regions of influence. We briefly review the data available for production, pointing readers to the publications available, and consider the case of Indus technological style for all stages of production. We then turn to consumption, reviewing typologies of Indus metal objects and past conclusions about use and distribution of copper-based artifacts. Finally, we discuss the relationships between metal consumption and social values.

There have been several major synthetic reviews of Indus copper metallurgy in the past two decades, including Chakrabarti and Lahiri (1996), Kenoyer and Miller (1999), Agrawal (2000), and Agrawal and Kharakwal (2003). These works provide comprehensive reviews of the nature of the evidence and the current state of interpretation up to the mid- to late 1990s (note that Kenoyer and Miller 1999 was submitted for publication in October 1996). The outline of copper production presented here is essentially the same as that presented in Kenoyer and Miller (1999), with additions and corrections from the few subsequent publications with new information on Indus metal production. Here we also summarize and expand the discussion of typology and the consumption of copper objects, particularly in Indus cities. Through an analysis of the types of forms that are fashioned from copper and the archaeological

H. M.-L. Miller (✉)
Anthropology Department, University of Toronto, 3359 Mississauga Rd N.,
Mississauga, ON L5L1C6, Canada
e-mail: heather.miller@utoronto.ca

B. C. Hoffman
Department of Anthropology, University of Wisconsin-Madison, Madison, WI, USA

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_24,

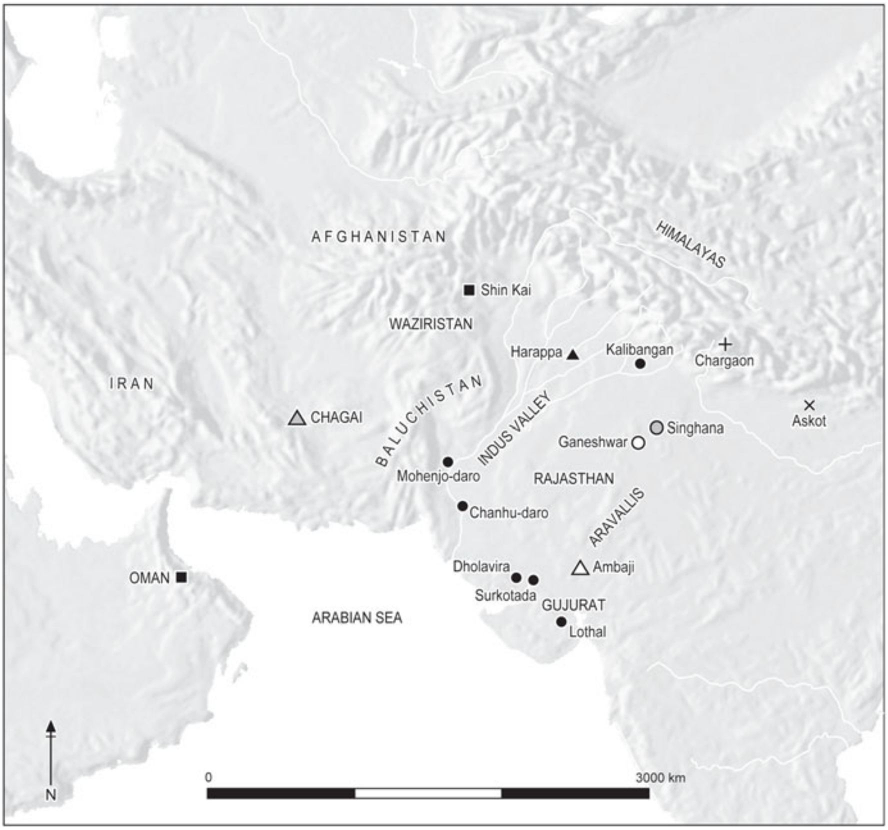


Fig. 24.1 Map of sites and copper ore locations discussed in text

contexts that they are found in, we propose some hypotheses for the role that copper played in the larger economic and social reality of Indus cities.

The Indus Civilization refers to the complex urban tradition that spread across the alluvial plains of northwestern South Asia (Fig. 24.1). Centered on the twin river systems of the Indus and the Ghaggar-Hakra, the Indus Civilization expanded to encompass vast stretches of modern-day Pakistan and northwestern India. During the Regionalization Era of the Indus Valley Tradition (Shaffer 1992), the latter portion of the fourth millennium and early third millennium BC, we can see the beginnings of the growth and development of the major Indus sites (Table 24.1). By 2600 BC, large urban centers, regional towns, and many smaller sites were found within the core area, especially along the river courses. Indus cities, and Indus sites in general, are marked by the presence of several types of diagnostic artifacts. These include chert weights; certain types of terracotta figurines and items of personal ornamentation such as stone beads; seals and tablets inscribed with the Indus script; and distinctive black on red pottery forms (Kenoyer 1998; Possehl 2002). Indus craftspeople produced

Table 24.1 Generalized chronology for the Indus Valley Tradition. (After Shaffer 1992; Kenoyer 1998; Meadow and Kenoyer 2005)

Early Food Producing Era		c. 6500–5000 BC
Regionalization Era		c. 5000–2600 BC
	Early Harappan—Ravi Phase	3300–2800 BC
	Early Harappan—Kot Diji Phase	2800–2600 BC
Integration Era	Harappan Phase	2600–1900 BC
Localization Era	Late Harappan Phase	1900–1300 BC

a variety of items in a diverse array of raw materials, including copper and copper alloys (Kenoyer 1998; Vidale 2000; Vidale and Miller 2000).

Metal objects have been recovered from each of the major excavated Indus cities (Marshall 1931; Mackay 1938, 1943; Vats 1940; Rao 1979; Bisht 1997; Kenoyer 1998; Lal et al. 2003) as well as smaller sites (Shaffer 1982; Agrawal 2000). Perhaps no other raw material besides clay was employed by Indus people to produce such a diversity of forms. Evidence from excavations indicates that copper and bronze were used to make tools, such as knives and saws; weapons, such as spears and arrow points; jewelry, such as beads, rings, and bangles; household materials, such as dishes and other vessels; and items of possible economic control or religious importance, such as scale pans and tablets. Despite the number of copper artifacts that crosscut all aspects of Indus life, the material remains critically understudied (Kenoyer and Miller 1999; Agrawal 2000; Bhan et al. 2002). This is not to say that analyses of copper and bronze objects have not been undertaken. Determining the sources of Indus copper has traditionally been the major focus of Indus metallurgical studies (Desch 1931; Sana Ullah 1931, 1940; Agrawal 1971; Rao 1979; Lal et al. 2003). However, there has been little work done regarding the specific uses of copper at Indus sites, and few detailed typological categorizations of changes over time in the copper and copper alloy assemblages. Notable exceptions to this include Yule's (1985a, b) typologies of copper objects from the major excavations at Mohenjo-daro, Harappa, Lothal, and other Indus sites; work on excavated material from Chanhudaro by Miller (2000); and a discussion of use and consumption at these sites by Mark Kenoyer and Miller (1999), which also includes a summary of catalogues of Indus and related metal objects published before 1996. Work is also ongoing on materials from the urban site of Dholavira (Bourgarit et al. 2005; Srinivasan 2007).

Work being undertaken on copper and copper alloy assemblages in the regions adjacent to the Indus Valley plains is essential for contextualizing the Indus copper metallurgical tradition. Such work includes summaries and typologies of materials from Baluchistan and what is now northwestern India, as well as the Indus Valley, dating from the fifth to second millennia BCE and spanning the range of the Indus Valley Tradition (Yule 1985c; Haquet 1994; Chakrabarti and Lahiri 1996; Agrawal 2000; Sharma 2002; Agrawal and Kharakwal 2003; Mille et al. 2005). The volumes by Chakrabarti and Lahiri, Agrawal, and Agrawal and Kharakwal provide large-scale syntheses of data from numerous excavation reports, covering all of the metallurgical traditions recognized to date within northwestern South Asia. All of this work will allow future examinations of regional variations in metallurgical traditions within the Indus world, as well as comparison of Indus traditions with neighboring traditions.

Overview of Production: Indus Copper Technology and Technological Style

Although there are some new publications on Indus copper, as noted above, the vast majority of these works focus on metal object descriptions, lists of compositional analyses (often reprints from older excavation reports), and discussion of sources of the metal ores. These are all useful, and the major new contributions of our paper also deal with consumption and sourcing. Very little new material on Indus copper production processes is available, partially due to research restrictions and the in-progress nature of current interesting work, but also apparently due to a general lack of interest in production-related questions (other than sourcing) by researchers. The majority of the data presented here is a brief summary of material found in Kenoyer and Miller (1999), updated in Miller (1999, 2005).

Figure 24.2 is a generalized model of the process of production for copper and its alloys. Metal production processes can be divided into raw material procurement, materials preparation, primary production of metal from ore (smelting), and secondary production (melting/casting and fabrication). Table 24.2 shows examples of assemblages characteristic of the most common types of smelting and melting, as well as nonmetallurgical pyrotechnologies (from Miller 1999, Fig. 3.2).

Smelting and Sourcing

There has been considerable confusion in the literature about evidence for the presence of copper smelting versus melting stages at Indus sites. In the hopes of preventing its spread farther through the secondary literature, we emphasize that, based on all information to date, only melting of copper took place at sites within the main Indus region, as might be expected for a floodplain region with no metal mineral deposits or much stone at all (see Law (2008) for the distribution of mineral deposits around the Indus Valley). To date, there is no evidence for the import and smelting of quantities of metalliferous ores at any of the Indus sites. In particular, only a small number of actual mineral fragments have been reported, and there is a significant lack of smelting slags. (We use the usual definition of an ore as a mineral with economic value for the production of metals, with the knowledge that copper-bearing minerals also had other values, especially as pigments for cosmetics and paintings. Therefore, we carefully reserve the use of the term "ore" to quantities of metallic minerals probably intended for metal production.) Mineral fragments that might possibly relate to metal working found at Indus sites include various cuprous minerals, hematite (iron), löllingite (arsenic and iron), antimony, cinnabar (sulfide of mercury), and several types of lead minerals, including cerussite, galena, and orpiment (see Miller 1999, pp. 192, 204–217 for full discussion). However, since the

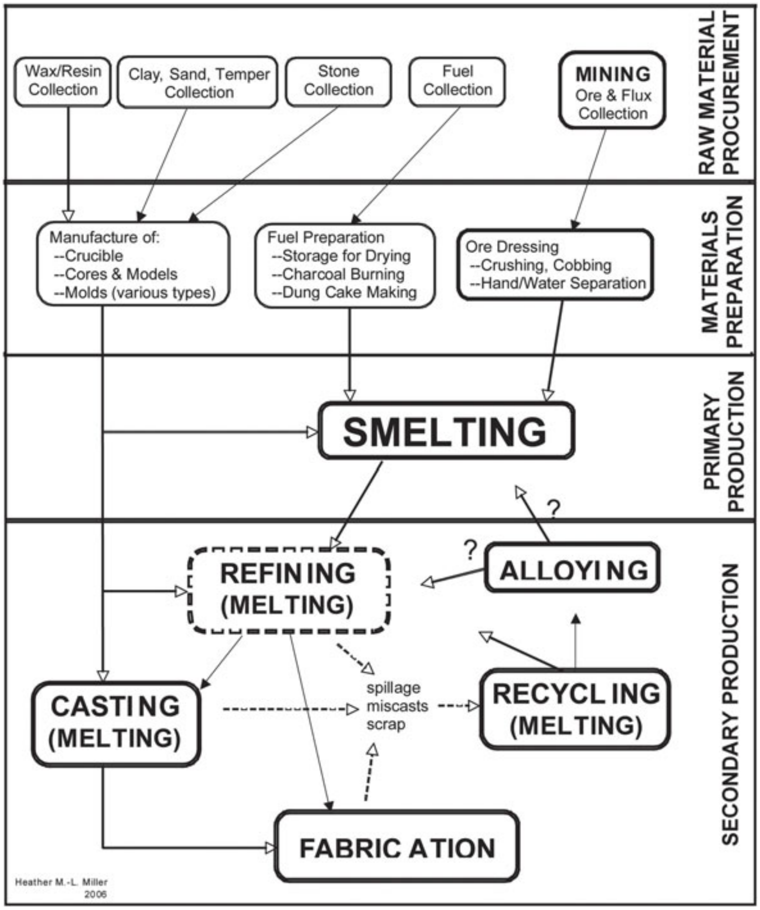


Fig. 24.2 Generalized diagram of copper production

great majority of these minerals were not found in association with metal processing debris, it is more likely that most of them were imported not for metal production or alloying, but for other purposes—as cosmetics, medicines, poisons, or pigments. An interesting contextual exception is a fragment of löllingite found at Harappa that was the only noncopper object in a copper vessel containing a hoard of more than 90 copper/alloy objects and scrap (Vats 1940, p. 90), which might be suggestive evidence for deliberate arsenical alloying; analytical testing might be interesting.

Furthermore, smelting of metal ore usually results in fairly conspicuous accumulations of manufacturing debris and broken firing structures, especially the weather-resistant vitrified masses of silica and other fused minerals that generally accumulate in conspicuous mounds near the smelting furnaces. On the basis of quantity and type of slag, the small amounts of copper metal slag found at Indus Civilization sites seem to be more representative of melting than of smelting (Miller

Table 24.2 Assemblage characteristics for nonferrous metal processing. (Compiled from Craddock 1989, p. 193, Fig. 8.2; Bayley 1985; Cooke and Nielsen 1978)

Material type	Smelting	Melting	Nonmetallurgical
Ore/Flux	Fragments usually found in association	Fragments rare/none	No associated ore/flux
	Proximity to ore source	Proximity to markets	
Installations (kilns/furnaces)	No Ash	Ash possible	Ash possible
	Diameter usually < 60 cm	Heavily vitrified, some slagging	Diameter may be large (> 60 cm possible)
	Heavily vitrified & slagged	Usually less poorly preserved (not destroyed to remove melt)	Tend to be unvitrified, but may be ash-glazed
	Usually poorly preserved (destroyed to remove smelt)		Usually better preserved
Kiln tools/furniture (crucibles, molds, tuyeres, *etc*.)	Heavily vitrified and slagged; crucibles possible; molds unlikely	Some vitrification and slagging or ash-glazing; crucibles and a variety of mold types possible	(Different types of kiln tools/furniture)
Other Slags (especially scoria/dross)	*Large quantities (many kg) of hard, dense scoria, dark in color with relatively uniform structure and fewer, larger bubbles*; includes both furnace bottoms and tap slags)	*Slags much more vesicular/porous; lighter weight; less homogeneous but inclusions distributed very heterogeneously; macroscopic metal inclusions possible/likely*	*Usually much lighter in color and density; also unhomogeneous*. (Glass slags more obviously glassy than most other slags.)

1994, 1999). Metal ingots must therefore have been imported into the Indus region, and a number of copper ingots have been found at several sites, as well as a possible lead ingot at Mohenjo-daro (detailed in Kenoyer and Miller 1999 and in Miller 1999, Fig. 3.4, 220–222; the latter includes a correction to the erroneous citation that an ingot was found by Sir Aurel Stein at a site in Cholistan).

In addition, if there were Indus settlements engaged in large-scale extraction of copper (smelting) at any of the source areas surrounding the Indus region in Rajasthan, Baluchistan, Afghanistan, or Oman, they have yet to be identified. It seems more likely that the Indus people were engaged in trade for copper ingots with local groups in one or more of these source areas. As this must have been an extremely important trade item, considering the apparent abundance of copper used by Indus people, it is not surprising that sourcing has been such a focus of interest, particularly given the possible Indus use of several source areas. It is noteworthy that there are mineralogical resources on all sides of the Indus region, making alternate sources of supply possible, and so sourcing gives us some idea about **actual** trading connections as opposed to simply **possible** connections. The inability to clearly distinguish between actual and possible connections has been another long-term problem with discussions of Indus copper, and indeed many Indus raw materials.

Law's (2008) current excellent work on many types of stone provides a model of how much such research might tell us about the direction and nature of such connections, and how they change over time.

The systematic pursuit of Indus ore sources has been difficult, due to a number of factors. The complexity of sourcing studies in general is compounded by the fact that the Indus Civilization had numerous likely source areas for metals, particularly for copper. Each of these source areas has their own geologically complex mineral deposits. Preservation of metals is extremely poor at most Indus sites. There are also potential problems with what appears to be a high degree of metal recycling at some Indus sites (Kenoyer and Miller 1999), which might be addressed if studies could be focused on copper slags ingots, and prills from remelting sites as well as finished objects. The location of some of the potential ore/ingot sources in border areas or tribal regions that are not easily accessible to modern researchers (e.g., Baluchistan and Afghanistan) is a major issue that has been a problem for several decades now. However, lead isotope analysis is slowly being carried out on Indus samples and regional ore sources by several projects; we present initial, preliminary work by Hoffman and law below.

Lead Isotope Case Study

The application of lead isotope analysis (LIA) is extremely complex for copper materials from the Indus Civilization. A primary obstacle is that, at present, there is no comparative database of geological isotopic values from the many potential sources surrounding the Indus, and there are potential logistical difficulties in obtaining the samples from several of these possible source areas. Additionally, the often highly corroded condition of the Indus archaeological materials may present difficulties for any analytical procedure. While these challenges may preclude the ready establishment of the specific source-provenance correlations that have traditionally been the result of LIA research programs in other regions, there are several broad statements regarding copper metals and the Indus that have been made and can be immediately tested through the application of LIA. While it may not be possible to identify the specific sources utilized by individual Indus sites, it is possible to discuss the likely and unlikely sources of copper metals present at sites during a given time period. This would provide important evidence for issues related to metal consumption, resource availability and access, and the operation of Indus metal acquisition. At present it is possible to make some tentative evaluations of the preliminary data emerging from ongoing research at the site of Harappa.

Hoffman and Law (see this article and Law 2008) conducted lead isotope analysis (LIA) at the Laboratory for Archaeological Chemistry (LARCH) at the University of Wisconsin-Madison to analyze the isotopic characteristics of seven archaeological copper mineral specimens from Harappa, and compared them to samples from potential source areas within and adjacent to northwestern South Asia (Tables 24.3 and 24.4). Wherever possible, minerals were obtained, but slags were also analyzed

Table 24.3 Regional ore deposits

Deposit	Location	Sample type
Ambaji	Northern Gujarat	Ore
Ganeshwar	Northern Rajasthan	Slag
Singhana	Northern Rajasthan	Slag
Chagai Hils	Baluchistan	Ore
Shin Kai	Waziristan	Ore
Chargaon	Himachal Pradesh	Ore
Askot	Uttaranchal	Ore
Various	Oman	Published Ore Data

Table 24.4 Copper minerals from Harappa

Sample	Mineral type	Location	Period
H94/4999–529	chalcocite	misc. surface find	Unknown
H90/3008–13	chalcocite	Mound E—survey	Harappan or Later
H90/2070–12	chalcocite	Mound E—survey	Harappan or Later
H90/3008–14	chalcocite	Mound E—survey	Harappan or Later
H90/3022–98	malachite	Mound E—Tr. 58	Harappan or Later
H95/4943–8	malachite	Mound ET—Tr. 28	Harappan or Later
H90/3126–1	malachite	Mound E—Tr. 56	Harappan

for some sites. Additionally the data from South Asia were compared to published LIA values for copper deposits in Oman (Calvez and Lescuyer 1991; Weeks 2003).

Lead isotope analysis was first developed to date geological deposits (Faure 1986; Dickin 1995). Three of the isotopes of lead (^{206}Pb,^{207}Pb, and ^{208}Pb) are the products of the decay of uranium and thorium, while the fourth (^{204}Pb) is taken to be a stable reference isotope (Faure 1986). Since there are only four isotopes of lead, three distinct ratios exist. Based on the principles of radiogenic decay and the known half-lives of the daughter products, geologists have used lead isotope abundance ratios to develop models for extrapolating the age of geological samples (Faure 1986; Dickin 1995). Over the past 30 years, archaeologists have adopted and applied this technique to the study of archaeological metal remains (Gale and Stos-Gale 2000). This is because Pb isotopes do not undergo fractionation during smelting or any subsequent manufacturing processes (Gale and Stos-Gale 2000). Therefore an artifact containing lead will retain the original isotopic composition of its parent deposit. As a result, lead isotopes have demonstrated a high degree of utility in establishing source provenance correlations for archaeological metals. Of course for copper artifacts this is a best-case scenario. It is always a problematic possibility that copper from two or more sources could be mixed and other metals or materials could be added during the manufacturing process, either of which could alter the isotopic characteristics of the finished object.

Some initial conclusions can be drawn from this research on the Harappa materials, through the analysis of a bivariate plot of the LIA results (Fig. 24.3a). The samples from both of the Himalayan sources are clearly distinct not only from each other, but also from all of the other sample regions as well. All seven of the archaeological copper minerals from Harappa that were analyzed clearly do not exhibit an isotopic

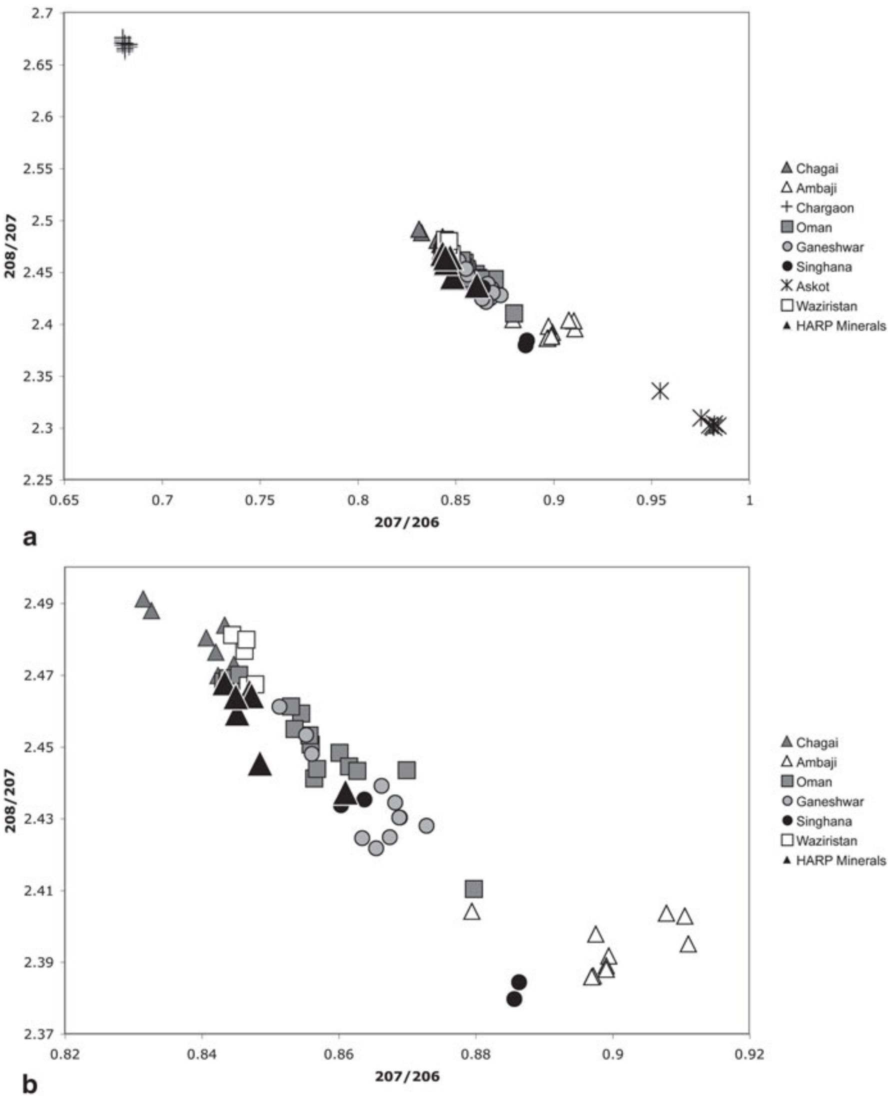


Fig. 24.3 **a** LIA results for regional ores sources and mineral fragments from Harappa. **b** The same in detail

relationship to the Himalayan sources. These samples can be eliminated from further analysis of this data set and the other samples can be examined in greater detail (Fig. 24.3b). None of the samples from Harappa are isotopically related to the modern ore samples from Amabaji. Five, or perhaps, six of the Harappan minerals do appear to be related to one of the sources to the west or south of Harappa, that is, Baluchistan, Waziristan, and Oman. Many of the copper mineral samples from the site fall in the area where the isotopic values for these three sources overlap. The overlap exhibited

Table 24.5 Copper or copper alloy artifacts from Harappa

Year	Lot	Rec.	Type	Feature	Trench	Mound	Phase
H2000	2102	1447	Sheet/Blade	1	54	E	Harappan
H2000	2226	40	Sheet/Blade	1	54	E	Harappan
H2000	2357	3	Bead	475	54	E	Harappan
H2001	2394	3	Bead	534	54	E	Harappan
H1996	6913	45	Bangle	686	11	E	Harappan
H1996	6958	61	Rod	730	11	E	Harappan
H1994	4343	3	Sheet/Blade	283	11	E	Harappan
H1995	4638	1	Bangle	538	10	ET	Harappan
H1995	4968	12	Bangle	174	28	ET	Harappan
H1996	7227	32	Rod	30	37	F	Harappan
H1996	7248	1	Rod	56	37	F	Harappan
H1998	8627	18	Rod	37	43	F	Harappan

by these sources is likely the result of the similarity in geologic age of these three ophiolitic metallogenic zones. One of the seven copper mineral samples from Harappa *may be* isotopically analogous to the slag samples from northern Rajasthan, specifically those from Ganeshwar (Fig. 24.3b). Based on these seven archaeological copper mineral samples from Harappa, the following conclusions can be advanced. It is unlikely that either Ambaji or the central Himalayan sources were supplying Harappa with copper minerals. Harappa *may have procured a small portion* of its copper minerals from sources in northern Rajasthan. However, at present, the data indicate that the majority of Harappa's copper minerals were obtained from sources to the west or south of the site. If mineral procurement parallels copper ingot procurement, sources to the west or south likely supplied the majority of Harappa's needs.

LIA has also been conducted on 12 copper or copper alloy artifacts from Harappa, although the compositional analysis of these artifacts has not yet been done, as discussed below. Examples of beads, bangles, rods, and sheets were analyzed. All artifacts were from the Harappan Phase (Integration Era) and from either mound E, ET, or F (Table 24.5). This analysis was conducted at the University of Michigan, Department of Geosciences on a Thermal Ionization Mass Spectrometer (TIMS). Recent archaeological applications of LIA have demonstrated the utility of using the technique to determine the number of potential source areas present even in the absence of geologic comparisons (see Weeks 2003 for further references). In order to determine if the results of these initial analyses indicated the potential for different source areas for the copper artifacts, cluster analysis was run on the data. The results strongly indicated the presence of three possible groups, or source areas, with perhaps two of the groups indicative of closely geologically related source areas (Hoffman 2007). It must also be noted that these objects may contain alloyed lead or other metals that might affect these results; compositional analysis has not yet been done, but given the compositional work to date at Harappa, it would be surprising if all of these samples were made only from unalloyed copper metal (see Kenoyer and Miller 1999 for tables of compositional analysis published up to 1995). As noted above, it is important to be aware that lead isotope ratios can be affected by mixing together lead from different sources, both the mixing of lead from two different

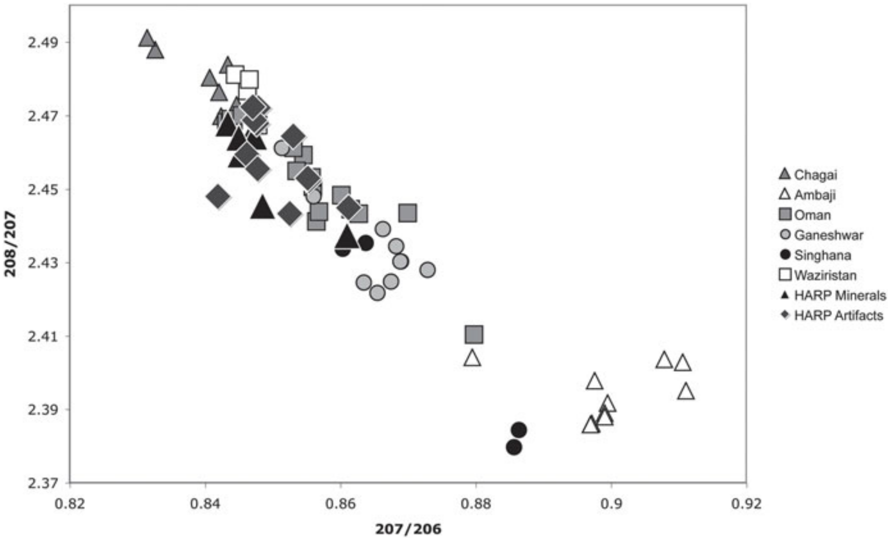


Fig. 24.4 LIA results for regional ore sources, mineral fragments, and artifacts from Harappa

copper ore sources, and the mixing of other metals containing lead impurities with copper. However, the match to patterning with mineral fragments is very interesting and bodes well for further research.

A final bivariate plot compares the results of the LIA on archaeological mineral samples and geological ores and slags with the results from LIA on these initial dozen artifacts (Fig. 24.4). Comparing the results from the analysis of the archaeological mineral samples to the artifacts, some preliminary conclusions can be drawn. The first is that the same broad pattern seen in the archaeological minerals, that of being primarily related to copper ore sources west or south of Harappa, is also evident in the data from the artifacts. Further, just as in the minerals, there is a potential isotopic correlation with slag samples from northern Rajasthan. However, this connection does appear to be very weak based on the data presently available. It is also important to note that the groups defined through cluster analysis on the archaeological data continue to correlate with one another when plotted alongside the data from geological ores/slags and archaeological minerals. The results from the beginning stages of analysis of the copper assemblage from Harappa indicate that during the Harappan Phase, the city was obtaining copper raw material primarily from sources to the west or south of the site in Oman, Baluchistan, and Waziristan. The artifacts from Harappa also demonstrate this pattern. While there is some evidence for the possible utilization of copper from northern Rajasthan at Harappa, it is neither firm nor indicative of a high degree of use, contrary to previous hypotheses regarding the source of Indus period copper (Agrawal 2000).

Recently some of the data and conclusions outlined above have been used to argue that the Indus city of Harappa obtained significant amounts of copper raw material and finished artifacts from sources and/or locations in the Aravalli Hills of Rajasthan

(Rizvi 2007). We cannot support such statements; in fact, our conclusions to date are quite different. While it is not possible to rule out sources in the Aravallis for either copper minerals or artifacts found at Harappa, it is also not possible to conclusively support this hypothesis. Even if supported, only a small proportion of objects and minerals could come from this source. The lead isotope work conducted to date is only on a sample set of nineteen archaeological objects and mineral fragments, and only a few dozen geologic samples. It is critical to note that due to the limitations regarding access to geologic samples from the Aravalli region, particularly critical areas in northern Rajasthan, slag samples were used as proxy data. Only future laboratory analysis will confirm the validity of these proxy data in regards to the actual isotopic signature of the region.

Again, as stressed in previous presentations by Hoffman, preliminary data from ongoing research conducted by Hoffman and others have demonstrated that there may be a limited degree of isotopic overlap of a single copper mineral and two, perhaps three artifacts from the site of Harappa with copper sources in northern Rajasthan. It must be stressed that this association is far weaker and more limited than the more definitive conclusion that the vast majority of copper (analyzed to date) has its source in regions to the west or south of Harappa in either Waziristan, Oman, or Baluchistan, and likely some combination of all three.

Melting and Alloying

As noted above, all of the data published for Indus sites to date are indicative of melting rather than smelting assemblages. The melting of original smelting ingots to produce secondary or refined ingots is a common intermediary stage between the production of the original smelting ingot and the final fabricated or cast object. This secondary ingot production is undertaken for one or more reasons: to remove slags or other undesired elements left in the original smelting ingots; to break up large smelting ingots into more workable or transportable ingots; to melt down metal scrap; and/or to form metal alloys. The production of alloys can take place at any one of a number of stages during the production process. For the Indus, not only is the place of alloying in the production sequence unknown, but also the very question of what alloys exist is difficult to answer. What constitutes an alloy and what a single metal with impurities? As detailed in Kenoyer and Miller (1999) and Miller (1999), different researchers have used different standards to define alloying, and in the lower percentages (less than 5 %) it is often not possible to determine if the "alloy" is the result of the intentional mixture of two separate metals or metal ores, or due to the natural metallic impurities in particular copper ores (Stech 1999). Thus, for the analyses of Indus copper objects to date, only tin is unequivocally an "alloy" with copper. Lead and arsenic are strong possibilities as deliberate "alloys", at least for some objects, but involve some complications as discussed in Miller (1999, pp. 222–228).

At this point it appears that Indus metalsmiths did not follow a rigid system of alloying related to specific artifact categories for copper and its alloys. For example, morphologically similar objects found at Indus sites are made from relatively pure copper, from arsenical copper, and from tin-alloyed copper (Kenoyer and Miller 1999). As detailed in Miller (1999, pp. 195–196), possible patterns of alloying are obscured by sampling and excavations problems, as well as the prevalence of Indus recycling as seen in the numerous caches of metal objects and scraps recovered from all of the major sites. Furthermore, patterns of alloying are likely obscured in these analyses because the Indus metalsmiths used alloying for a variety of purposes—functional, aesthetic, ritual, and/or simply expedient. Tin could be added to copper to increase strength and hardness for some objects, or used to produce particular colors or fulfill ritual requirements in others. Alternatively, the only material available for a smith to use may have been a mixture of alloyed scrap metals; expediency is too common ethnographically to ignore. (See Lahiri (1993, 1995) and Chakrabarti and Lahiri (1996) for excellent discussions of the variety of reasons for alloying in modern and historic South Asia.) When faced with the choice of desired characteristics, including hardness and color, the Indus metalsmiths may have chosen from a number of alternative means of producing a given result; in some cases they may have used physical modifications such as forging to harden metal, while in other situations they may have produced a harder metal by modifying the composition of the metal through alloying. These choices would depend on the manufacturing techniques used, the types of copper and alloys available, and the stage of metal production (smelting, melting, casting of blanks, *etc*.) at which the end product was first visualized (Miller 1999, pp. 196).

Casting and Fabrication

Production techniques for metal objects can be classified depending on the state of the metal during working. *Casting* refers to the manipulation of molten metal, while *fabrication* is the treatment of nonmolten metal, whether cold or hot. Fabrication involves the direct shaping of metal, while casting begins with the shaping of other materials into which the molten metal is poured. The tools and techniques of the two categories overlap to some degree, and ancient metalworking ateliers may have been involved in both fabrication and casting. Some objects, however, may have been cast by one group of artisans and finished or fabricated by another group in a separate workshop. The possible division of manufacturing stages into discrete and often exclusive activities practiced by different artisans is an important part of metal working that has not been investigated for the Indus Civilization, primarily because few metal production areas have been conclusively identified. At this point, in spite of Miller's excavations in the year 2000 in the most promising area of Harappa for metal workshops, we can say little about the nature of copper metal production organization. It was noteworthy that almost no inscribed material was found in this area, so that there is no evidence to date for any sort of centralized control of metal production, at least for Harappa (Miller 2005).

For all of the metals, all of the evidence to date for both casting and fabrication techniques has come from the examination of finished objects. Casting of copper objects appears to include both open face and bivalve casting, as well as lost wax techniques. Mille et al. (2005) discuss early casting methods at the Baluchistan sites of Mehrgarh and Shahi Tump; the latter case might be more related to eastern Iranian traditions than Indus traditions. Fabrication techniques include shaping by forging to manufacture both sheets and vessels, cutting, cold and hot joining, and finishing methods such as polishing, engraving, and inlay (see Miller 1999, pp. 228–241 for more details). The preserved Indus corpus of copper and copper alloy objects appears to be well made with a good standard of workmanship, but fabrication and casting techniques do not appear to be particularly complex or intricate, in contrast to contemporaneous metal traditions in eastern Iran or Central Asia (e.g., the repoussé work from Shadad (Hakemi 2000)). Although remelting for scrap was common, as indicated by both finds of hoards and (possibly) patterns of artifact composition, there is every reason to think that the work preserved is representative of the overall production abilities. However, more precise information on finishing, and on manufacturing techniques in general, might benefit greatly from the restudy of all objects in a standardized fashion, including radiography of the objects and selected metallography, particularly given the generally better preservation of those objects kept from the older, large-scale excavations. (This is optimistically assuming better research conditions than those that currently exist in many areas.)

Technological Style

Style of objects has been a major focus of archaeological thought for decades. Hegmon (1992, 1998) summarizes the three main archaeological approaches to style as: (1) choices made between functional equivalents that reflect particular time periods or regions, as in Sackett's work on isocrestic style; (2) active and passive communication of information, as exemplified by Wobst's and Wiessner's writings; and (3) encoding of cognitive processes, as examined by Hodder and others.

Technological style is essentially the application of all of these aspects of style to the process of production, as opposed to simply the form and material of the end product. Like style of object, technological style also includes culturally specific choices made between functionally equivalent production techniques, which can actively or passively communicate social information, and which can be manifestations of cognitive processes (Miller 2007, pp. 193–194). While achieving renewed popularity in the 1990s, many of the original formulations of the concept of technological style date to the late 1970s, when it was especially applied to metal technology (Lechtman 1977; Steinberg 1977; Lechtman and Steinberg 1979). Technological style includes both technological style of production, focusing on choices about production techniques and materials, as well as investigations of the technological style of organization of production, focusing on the order and number of stages in a particular *chaîne opératoire*, or the organization of workers themselves. (Miller 2007,

p. 194) For example, Killick's discussion (this volume) of changes in the values of different metal types in sub-Saharan Africa, based primarily on color characteristics, illustrates how cultural style can substantially guide the raw material choices made by metal workers, which then affect all other stages of production (see Miller 2007, pp. 191–201 for more discussion and examples).

For the Indus Civilization, we see a number of broad aspects of technological style in the way metal production is both carried out and organized. One characteristic is an apparent focus on *procurement* of metal, including via recycling, rather than *production* of metal from ore via smelting. Another characteristic seems to be a lack of interest in elaborate forming methods, and possibly a greater focus on alloying.

The Indus people seem to have had no trouble in reliably procuring sufficient quantities of copper and alloys in metallic form, both as primary ingots and through recycling, as described above. There is no evidence that they carried out or controlled production of the metal from ores found in the surrounding regions, and so trade for ingots produced by others is the most parsimonious explanation at this time. This situation may reflect the need for further exploration of the mineral source areas in Baluchistan and Afghanistan, but certainly there is no evidence of any significant Indus mining or settlement presence in Oman or the Aravallis. There is, however, plenty of evidence for Indus trade in various materials with at least the first three regions, Baluchistan, Afghanistan, and Oman (Mery and Blackman 2005; Law 2008). It would be of great interest to examine the Indus presence at Nausharo (near Mehrgarh) in the Bolan Pass in southern Baluchistan as possibly a settlement relating to the (metals?) trade with Iran, in the same way that the team from M.S. University-Baroda (Bhan et al. 2004 Chase 2007) has examined the role of the Indus and non-Indus settlement of Gola Dhoro (Bagasra) as possibly a settlement relating to the trade in shell and semi-precious stone ornaments. What was the nature of the Indus period occupation at Nausharo? Work done in many other areas on cultural contact and the varying nature of interactions, from colonization to resistance to conversion, could be usefully applied to the French team's long-term work at this site. Comparative examples include the possible effects (or not) of Egyptian demand for copper metal on the social and political situation in the Levant referenced by Thornton in this volume; Hanks and Doonan's (this volume) discussion of interaction models for the societies of Central Asia; the culture contact models developed by Yao (2008) for indigenous Yunnan interactions with the Han Empire; and Stein and others' work on the nature of the Uruk expansion (Rothman 2001; Stein 2001).

It must be emphasized that trade for ingots is only one method of metal procurement. Recycling of existing metal objects is often referenced in the literature, but seldom seriously incorporated into models of metal production as a significant source of metal. Studies of North American metal use during the European contact period form an important exception (Latta et al. 1998; Ehrhardt 2005). As also discussed by Ehrhardt in this volume, the native people of the Eastern Woodlands of North America were able to procure the metal they needed for fabrication of objects, in the form of traded European metal objects or sheet. They did not develop or adopt techniques of smelting or even melting. This may partially relate to their prior focus on native copper sources, but then such a focus emphasizes again the need to consider other methods of metal procurement besides smelting.

The main effect on an Indus technological style of production of a focus on procurement of metals rather than production of metals from ore is that the emphasis shifts from producing metal ingots with desired qualities at the smelting stage to producing metals with desired qualities at the melting and fabrication stages. If recycling was an important source of Indus raw material, as hypothesized, this implies that Indus metalsmiths developed a repertoire of techniques for working with various (even random) alloys to produce desired attributes. Such techniques would likely include methods for recognizing different types of alloys, flexibility of working methods to deal with different alloy responses within a relatively wide range, and a variety of methods of adjusting desired characteristics such as color or hardness. Smiths would have to be innovative and flexible. Archaeologists studying such smiths will need to focus on different skills and emphases than those relating to smelting, which have tended to dominate Old World metallurgical studies, as is not surprising given the obviously remarkable transformation involved in the smelting of mineral to metal. Hence our strong interest in other stages of production, and especially in consumption, an interest that would have been shared by Indus smiths.

In terms of forming methods, if anything the Indus is remarkable for simplicity of technique—production of cast and fabricated objects is generally very competent but by no means exceptional in technique or intricacy of design. Based on analogies with other Indus technologies, which seem to show an Indus preference for complexity of material over complexity of shape Miller has previously suggested that Indus alloying techniques might have been more complex than their generally simple forming techniques (Miller 1999; Miller 2007; Vidale and Miller 2000). This suggestion has never been tested, due to difficulties with export of materials over the past decade as well as generally very poor preservation of metals at Indus sites, and so remains to be confirmed, overturned, or modified.

Comparable data about methods of manufacture from numerous sites would give us more information on the diffusion and independent invention of metal processing techniques within the Indus Civilization. Such data would also allow investigation of possible regional styles of production within the Indus Civilization, e.g., Indus plains versus Gujarati versus Baluchi techniques. More broadly, Indus production data could also be used to contrast a general "Indus technological style" with other contemporaneous traditions, such as the Chalcolithic cultures of northwestern India, or Iranian, Central Asian, or Mesopotamian traditions (e.g., Thornton in this volume). It will be particularly interesting in this regard to see if the technological traditions from Baluchistan are more similar to the Indus style(s) or the eastern Iranian style(s) of production, or perhaps vary between technological affiliations over time. Similar questions might be posed of the northwestern Indian materials, with additional archaeological work, particularly for the late third millennium and early second millennium. Until such work, it is difficult to say too much about regional production styles from the published photos and tables, although even those might be put to better use for the investigation of the consumption of copper objects, as discussed below.

Consumption: Typologies and the Use of Indus Copper Objects

Previous Typological Studies of Indus Copper Artifacts

The initial excavation reports from Mohenjo-daro (Marshall 1931; Mackay 1938) delineated several broad types for Indus copper tools, weapons, vessels, and personal ornaments. The immediately succeeding excavations (Vats 1940; Mackay 1943) used these types, as did the majority of later excavations at Indus sites (Rao 1979; Joshi 1990; Lal et al. 2003). It is important to note that the typological categories developed, largely by Mackay, were not based on metric data but rather on macroscopic morphological characteristics of forms from Mohenjo-daro. It appears that assumptions were made regarding the use of individual forms and uncritically accepted. Each successive excavation applied this categorization scheme with the addition of new types to the schema as the need arose. As a result, the typology of Indus copper materials has been largely unrevised since the earliest days of archaeological excavation of Indus sites.

The work of Paul Yule (1985a, b) and Miller (2000) has attempted to address this need for a formalized typology of Indus copper artifacts. While both researchers have published updated categorizations, neither has been widely adopted. Both systems have limitations that prevent them from being applied as a fully functional typology for Indus copper and bronze artifacts, although both provided helpful background for the system employed here by Hoffman. The system proposed by Yule provides a detailed and thorough classification scheme for both vessels (Yule 1985b) and ornaments (Yule 1985a); however it does not provide categories for tool forms. The work does represent a solid foundation for future study. Heidi J. Miller's system, for designed to characterize the metal objects from the site of Chanhu-daro exclusively, is much more specific in its definition of typological categories, and is by intention a combination of a morphological and a functional typology. The typology in its published form suffers from three major drawbacks that prevent it from being used as a comparative tool. The first is that it is only able to deal with complete or mostly complete objects. The vast majority of copper artifacts recovered in modern excavations are fragmentary and lacking many of the critical diagnostic elements of Heidi J. Miller's system. This is typically due to either corrosion or breakage from a variety of pre- and post-depositional processes. The second drawback is that, by design, the typology does not incorporate forms absent in the material from Chanhu-daro. While Heidi J. Miller (2000) does provide for the expansion and modification of the system, it is not specifically clear how other investigators would incorporate their definitions into the existing scheme. Finally, the system developed for Chanhu-daro, as a typology partly resting on the functions of objects, relies heavily on inferences relating to function such as the nature of working surfaces and hafting techniques for each tool form. While many of the inferences are likely correct, at this point they cannot be substantiated from the available evidence. This makes it difficult to assign objects confidently to a particular type.

In spite of these difficulties, in reviewing the published images of copper objects from Indus sites Hoffman felt that a typology *broadly* based on function would be best suited for the investigation of the use of copper objects at individual sites, particularly in the light of the need to allow comparison with the extensive work that has been done for Chanhu-daro. In this categorization scheme, function was inferred primarily from the morphological characteristics of the artifact. Definitions based on specific metrical data and any other types of information not readily available from an inspection of published photos and line drawings were avoided. Through the application of this classification system it is possible to make comparisons between the individual sites in order to understand how metal was being used in the Indus Civilization. The classification scheme applied by Hoffman also draws much of its inspiration and format from the system first outlined by Kenoyer in Kenoyer and Miller (1999).

Towards a Working Typology

The following is a provisional typology for understanding the nature of the variation in Indus copper assemblages both within individual sites and between sites. Within each major category, there is a possibility for a number of individual distinct subcategories and the proposed classification system is by no means comprehensive or exhaustive. The primary advantage in the proposed system is its ease of use, flexibility, and ready adaptability to use in both the field and in archival research as well. This system could be modified in order to better understand specific aspects of Indus copper metallurgy, such as manufacturing techniques, alloying patterns, or other specific interpretive questions, without altering the essential overall structure.

Vessels Vessels are a functional category of copper and bronze objects from Indus sites. Roughly one half of the forms have parallels to known ceramic vessel types, but the others appear to be only found as metal forms (Yule 1985a, b). The reason(s) for unique metal shapes are still unclear (see Kenoyer and Miller 1999, pp. 133 for discussion). Typical Indus copper and bronze vessel forms include jars, pots, bowls, dishes, pans, and scale pans. Vessel forms are manufactured from sheet copper using a variety of fabrication techniques. All vessel forms will be considered as a single category here, as it can be argued that their uses as containers were similar. The one exception, the relatively rare subtype of scale pans, will be considered further below. Scale pans come in various sizes and seem to have been used to weigh a variety of substances at Indus sites rather than simply as containers.

Tools Another functional category of Indus copper and bronze forms are those objects that were used as tools. Here a tool is taken to be any object that is used to accomplish a mechanical or manual task. Indus tools take a variety of forms. These forms can be grouped into three broad subcategories; blade tools, rod tools, and axes/adzes. In turn, each of these subcategories of tools may contain specific types. Blade tools are manufactured from sheet copper and distinguishable types include triangular barbed arrowheads, saws, knives, spears, and razors. Blade tool types are morphologically distinctive and further research is needed to determine if additional types and subtypes can be defined. However, all of these tools would have been used as blades; that is, to cut some material. Rod tools are those manufactured by casting and include two distinct types: chisels and pointed tools. Chisels are rectilinear rods with wedge-shaped working ends (Miller 2000, p. 315). Pointed tools are also rods, but can range in cross section from rectilinear to round and have a variety of working ends. At present, this type comprises a variety of morphologically similar objects that may have been used for a range of purposes and tasks. Hooks are another category of rod tools. It is inferred from their shape that these tools would have been used for fishing. A final category of Indus copper and bronze tool forms is that of axes and adzes. All of the objects in the axe/adze category are morphologically similar and would have been used in comparable ways. They are easily differentiated from blade tools even in fragmentary form, since they are not made from sheets and are considerably more massive.

Ornaments Items of personal ornamentation are another major functional category of Indus copper and bronze forms. Four subcategories can be defined based on object morphology. The first is bangles. Bangles are any circlets made of a continually homogenous material (Kenoyer 1992; Miller 2000). There appears to be two major subtypes of Harappan bangles, one that is solid with a round cross section and one hollow with a crescent–shaped cross section (Yule 1985a; Miller 2000). Each of these may also have additional subtypes, continuous and noncontinuous. Rings are similar in appearance to bangles and are always solid. They may consist of a single coil of metal or multiple overlapping coils. A third major subtype is beads, pendants, and discs. All of these objects have been perforated for attachment or hanging. As indicated in Heidi J. Miller's work, there may be five distinct subtypes of beads: round, barrel-shaped, cylindrical, tube, and spacer (Miller 2000, p. 309). Pendants are objects that are perforated at one end (Kenoyer 1992). Discs are objects that are round, with a concavity. They are usually perforated and it is hypothesized that they may have been sewn into clothing or other fabrics as sequin-like decorations. A final subcategory of ornaments is decorative-headed pins. It is unclear specifically how these objects were used, but they appear to be morphologically similar and are typically topped by either a decorative motif or an animal figure.

Other At the present stage of analysis, all remaining metal objects have been grouped into the category of "Other". This is due to the low frequency and/or uncertain status of these objects. Three of the five categories are relatively clear types but are not yet fully studied: mirrors, figurines, and tablet/tokens. Mirrors are round to oval in shape and have a small tang that would have likely been attached to a handle, and represent a clear functional category but are very rare finds. Two morphological types of figurines have been published from excavations so far, human and animal, but it is not yet clear how these objects were used; for example, how many were free-standing objects versus decorative elements of pins. The relatively rare category of tablets/tokens, only found at Harappa and Mohenjo-daro, is also based solely on morphology, with distinctive subtypes apparently present at each site. Tablets from Harappa have Indus script and other symbols molded onto them, while the objects from Mohenjo-daro are inscribed (Fentress 1976). The remaining two categories, miscellaneous objects and manufacturing debris, are currently umbrella groups that require further analysis for more exact characterization.

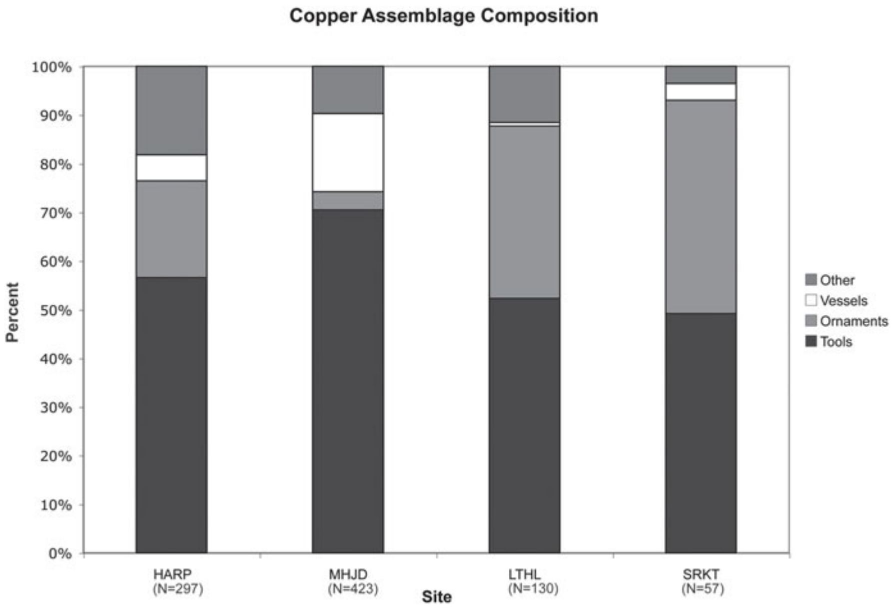


Fig. 24.5 Distribution of copper types at individual sites

Individual Site Breakdowns

Hoffman reviewed the copper objects that were published as either photographs or line drawings from the excavation reports of Mohenjo-daro, Harappa, Lothal, and Surkotada, and categorized them according to the scheme outlined above (references for each site below). In addition, Hoffman reviewed the site report for Kalibangan and the published breakdown for Chanu-daro from Miller's work (2000). Finally, digital photographs of objects recovered by the Harappa Archaeological Research Project (HARP) team at Harappa were also reviewed. The breakdown for the distribution of types for each site is shown in Figs. 24.5, 24.6, 24.7, 24.8, and 24.9, using the categories discussed above.

Mohenjo-daro Mohenjo-daro was first excavated by the Archaeological Survey of India from 1922–1927 and then again from 1927–1931 (Marshall 1931; Mackay 1938). The two reports describing these excavation programs published images, both line drawings and photographs, of approximately 420 copper objects. The published assemblage is comprised largely of tools (see Fig. 24.5). Within the tools category, blade tools are the dominant subcategory (48 %), with rod tools comprising 38 % of the tool assemblage and axes/adzes making up 13 %. Additionally, a large number of copper vessels were recovered from the site. This is likely skewed due to the three large hoards found in DK Area (Mackay 1938). Each of these hoards contained a large number of axes/adzes, blade tools, and vessels. The excavations at Mohenjo-daro published a very small number of personal ornaments made from copper, especially

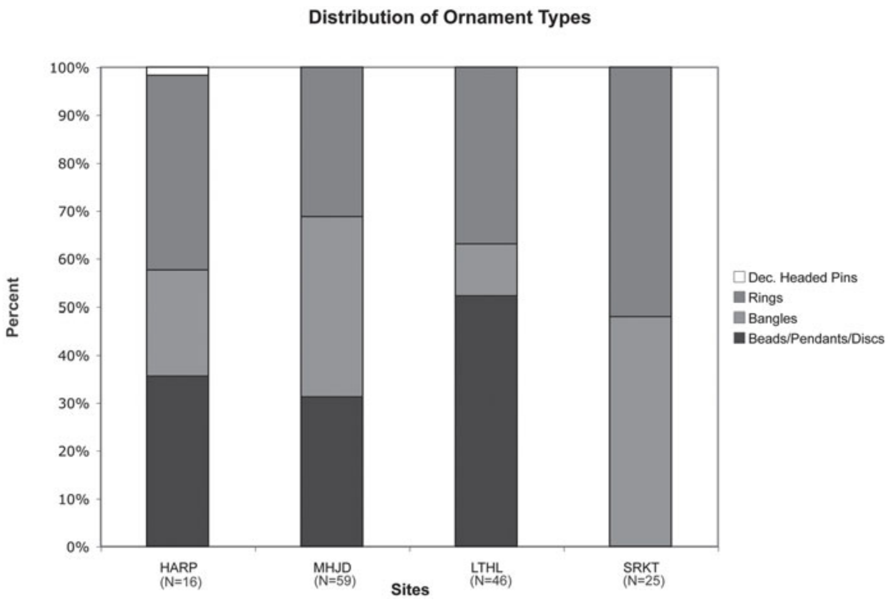


Fig. 24.6 Distribution of ornament types at individual sites

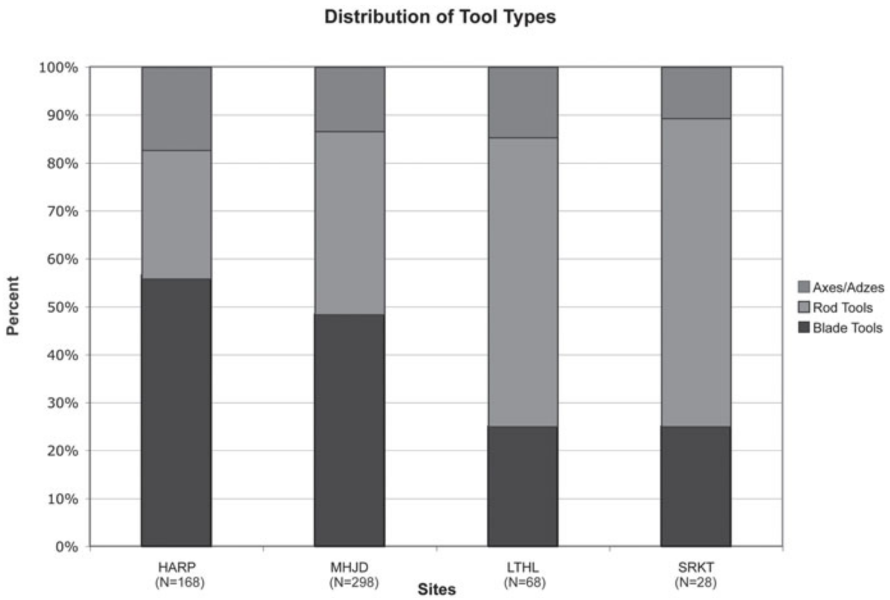


Fig. 24.7 Distribution of tool types at individual sites

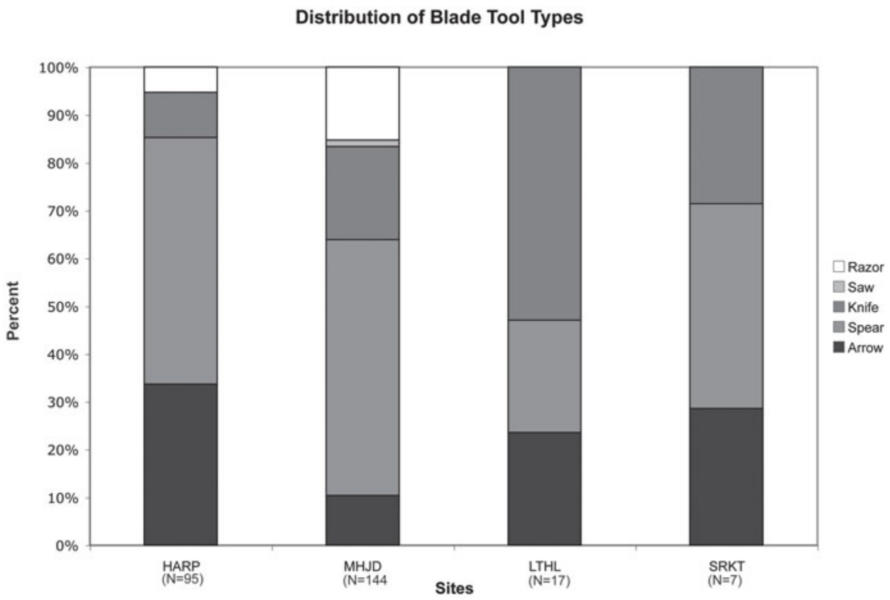


Fig. 24.8 Distribution of blade tool types at individual sites

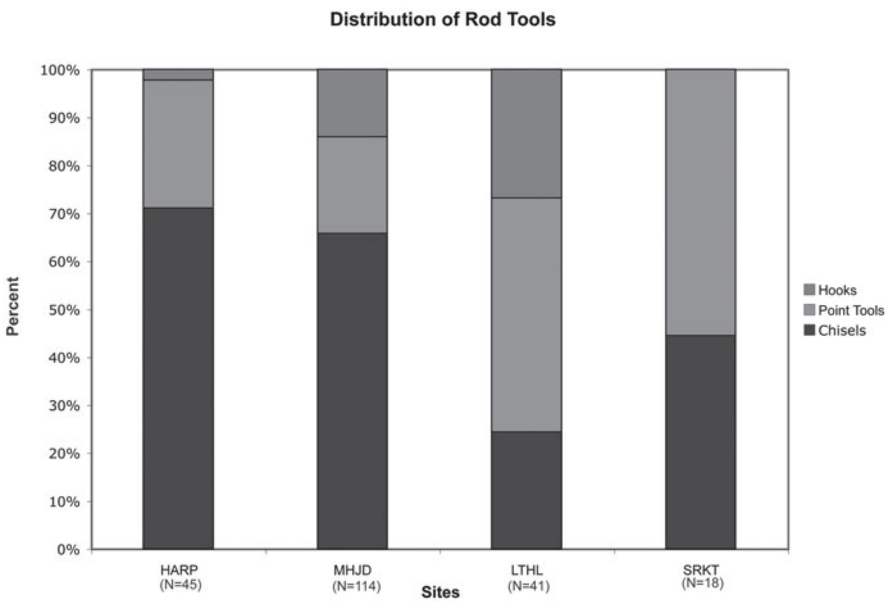


Fig. 24.9 Distribution of rod tool types at individual sites

as most ornaments found in hoards were made from gold, silver, and stone. It is likely that this is a result of a combination of the high amount of post-despositional corrosion of copper at the site and the excavation methods employed in these older excavations, especially the lack of screening.

Harappa The Archaeological Survey of India first excavated the site of Harappa from 1920–1921 through 1933–1934 (Vats 1940). During these excavations a number of copper objects were recovered. Of these, approximately 190 are published in photographs; of these, over 90 came from a single hoard (Vats 1940). Since the assemblage for this portion of excavations at Harappa is dominated by a single hoard find, the distribution of copper types is slightly different from the patterns seen at the rest of the sites. Tools comprise the majority of the assemblage, with only a few dozen items of personal ornamentation being published. Blade tools dominate the tool types, not surprising since the hoard was comprised almost totally of copper vessels, axes, and blades. Rod tools are also well represented, but not in the typically even manner seen at the other sites. The early assemblage from Harappa is also noteworthy for having three tablets and two scale beams. Overall, this group of copper artifacts is overwhelmingly made up of large tools.

In contrast, the excavations by HARP over the past two decades have revealed a slightly different pattern of types and distributions than the previous excavations at the site. An assemblage of 110 complete copper objects so far recorded by the HARP team is comprised mainly of arrow points and ornaments. Tools are less numerous, but are relatively evenly split between the categories rod tools and blade tools. It is important to note that the HARP assemblage includes five examples of scale pans of various sizes and nine copper tablets so far recovered from the site. The types of objects and their proportions recovered during the HARP excavations differ slightly from those of the other sites, likely due to two factors. The first is excavation methods, in this case the screening of fill by HARP in order to recover small objects. The second factor is that the HARP excavations have been primarily focused on tracing the margins of the mounded occupation areas at Harappa and locating the course of the city walls. Investigation of these types of contexts rather than the dense room and house blocks that were the focus of the majority of the earlier excavations should result in the recovery of different types of objects. In addition, Hoffman had access to records of all of the objects found by HARP, rather than only published examples.

Lothal Excavations at Lothal have uncovered 1,500 copper artifacts, of which 130 images are published (Rao 1979). The illustrated assemblage is split relatively evenly between tools and ornaments. In terms of tools, rod tool types dominate the assemblage at Lothal, specifically the category of pointed tools. Typical Indus arrow points have also been found. Stylistically Indus personal ornaments, such as beads, bangles, and rings are also found at Lothal, as well as animal figurines. Unfortunately, no specific find locations are provided for the majority of the objects, so any discussion of context or spatial distribution is not possible. The excavators do report the presence of copper objects of all types throughout the sequence at the site (Rao 1979).

Surkotada The excavators of Surkotada, a small site in Kutch, reported a total of 129 copper objects plus one hoard of beads and bangles (Joshi 1990, p. 266).

They provide illustrations for 57 of these items. The distribution of illustrated types follows a similar pattern to Lothal, as the assemblage is almost evenly split between tools and ornaments. Rod tool types, specifically pointed tools, dominate the tool assemblage. Joshi (1990) indicates that the overall assemblage has similarities with those of Kalibangan, Chanhu-daro, Harappa, Mohenjo-daro, and Lothal. This does appear to be the case. It is also important to note that copper of all types appears from the earliest excavated levels through to the end of the Indus sequence (Joshi 1990). Unfortunately, no specific find locations are provided for the objects, so any discussion of context or spatial distribution is not possible.

Chanhu-daro and Kalibangan Two additional sites with significant metal assemblages from early excavations are not included in these figures, but will be incorporated in future research. Heidi J. Miller (2000) examined 521 tools from and found the assemblage to be dominated by different types of tools (64 %). Of this group, no single type of tool dominated. Overall, the tools were relatively evenly split between blade tools and rod tools (Miller 2000, p. 318). Mackay (1943) reports that four hoards were recovered during excavations at Chanhu-daro, but all were much smaller than the hoards found at Harappa and Mohenjo-daro. The excavations from Kalibangan are only partially published at this point (Lal et al. 2003). While the report concentrates on the Early Harappan (Regionalization Era) component of the site, the volume does include the results of compositional analyses on 19 objects. Two are from the late Early Harappan period and 17 are from the Mature Harappan (Integration Era) period. Unfortunately, no photographs are published. The excavators do list some descriptive information for each object, but these are not specific and do not provide the basis for confident comparison. However, the museum at the site displays a number of copper objects recovered from the excavations. All of these items conform to forms and types seen in the published reports from other Indus sites. Hopefully, with the fuller publication of the excavations, it will be possible to compare the material from this site to the others.

Metal Object Use in the Indus Civilization

The use of copper in Indus cities has traditionally been interpreted through two main lenses. The first is that the forms and artifact types fashioned from copper are largely unchanging over the course of the Indus Civilization (Mackay 1938; Piggott 1950). The second is that copper was widely available and used by all segments of society at sites of all sizes (Shaffer 1992). An extreme form of this line of argument is that copper tools and utensils eventually almost totally replaced lithic implements (Cleland 1977, p. 175); however, more recent evidence makes it unlikely that this is the case. For instance, the HARP excavations at Harappa have unearthed over 12,000 lithic blade tools alone. In addition to more detailed studies on Indus copper production, it is also important to begin to test these traditional interpretations about the consumption of metal in the Indus Civilization.

In examining the six assemblages reviewed above, some trends appear to be emerging from the data. Tool types dominate the assemblages from the two large urban centers, Harappa and Mohenjo-daro; however, it is unclear if this pattern is related specifically to patterns of metal usage and consumption. The techniques of excavation used by the early excavators of Indus sites, combined with the poor preservation conditions of the soil at the sites, would have privileged the recovery of large forms over smaller more fragile metal objects such as beads, bangles, and rings. The massive quantities of material recovered from these very large excavations would also have meant that excavators discarded or ignored fragmentary, unidentifiable, or poorly preserved objects. It is relevant to note that in excavations that have practiced more modern methods of recovery (Lothal, Surkotada, and HARP), the proportional representation of ornament types increases (Fig. 24.5). At Lothal, Chanhu-daro and Surkotada, there is a more even distribution of forms between tools and ornaments.

Furthermore, the existence of large hoards of tool types aides in explaining the shift in distributions. The evidence from excavations indicates that large Indus copper hoards, such as those recovered at Mohenjo-daro and Harappa, were dominated by vessels and caches of axes/adzes and blade type tools (Marshall 1931; Mackay 1938; Vats 1940). The recovery of such hoards has a significant effect on the proportions of tools to ornaments. At Mohenjo-daro and Harappa, the blade tool forms constitute the majority of the tool assemblage (Fig. 24.7). In contrast, at Lothal and Surkotada, where either no hoards only small caches of ornaments were found, rod tools form the majority of the tool assemblage at just over 60 % for both sites (Fig. 24.7). Chanhu-daro exhibits an even split between the two categories of tools (Miller 2000). Note that four small hoards were uncovered at Chanu-daro (Mackay 1943). These results point to very careful collection and storage of large or massive metal objects by the Indus people, with the great majority of metal mass found in hoard situations. This also supports the comments made by Kenoyer and Miller (1999) and Miller (1994, 1999) about the likelihood of recycled scrap as a major source of Indus metal.

The patterns exhibited by the data also appear to validate the idea that Indus sites of all sizes, and from every region, had relatively equal access to copper tools and ornaments. While the presence of hoards at the larger urban centers likely increases the proportional representation of larger or more massive objects such as vessels, axes/adzes, and blade tools, these categories are not significantly absent from any of the other sites. There are two artifact types, however, that do exhibit a degree of difference related strictly to site size: scale pans and copper tablets. Scale pans would have been used to weigh a variety of substances, likely in exchange situations, and may also have had a role in taxation or other aspects of economic control (Kenoyer 1998). Scale pans are present at all sites except Chanhu-daro and Surkotada, two of the smaller sites in the sample. Weights are found in great numbers at Chanhu-daro, though, so the absence of scale pans may simply represent lack of preservation in the areas excavated. Copper tablets, like other tablets and as opposed to seals, have recently been interpreted as having religious meaning, particularly the molded types of tablets (Parpola 1992). Copper tablets are present only at the sites of Harappa and Mohenjo-daro. The presence of these copper tablets may therefore represent the location of pilgrimage centers at these sites, or may represent some economic or social meaning for these objects that was restricted to some type of elite or special interest group. Overall, though, it does seem that Indus sites both large and small were consuming copper metal of all types and in broadly similar proportions.

In sum, the distribution of the various types of copper objects combined with their archaeological contexts does allow for some tentative conclusions about how the metal was used by the residents of Indus sites. The first point is that it does not appear, at present, that copper was a material to which access was restricted. Copper tools and ornaments are typically found from all contexts at Indus sites, but tend to come mainly from inside house and room blocks (Marshall 1931; Mackay 1938; 1943; Vats 1940; Rao 1979; Joshi 1990). There is often little copper in larger more public spaces, from whence it might be scavenged, and all hoards have been recovered from just underneath what are considered to be house floors. It is also noteworthy that there is little copper recovered from Indus burial contexts. Unlike many other third millennium Civilizations, metal was not being interred with the dead in appreciable quantities. This may indicate either that copper objects were not high status or wealth items in the hierarchy of Indus craft products, or that wealth items were not interred with the dead but kept in circulation, as discussed in Rissman (1988, Kenoyer and Miller (1999), and Miller (2007)). (Also compare situation in Iron Age South India, as presented by Gullapalli in this volume.)

The evidence also indicates that one of the primary uses of copper was to help in the production of other components of the Indus material assemblage. It is likely that copper was used in bead production, to carve seals, for carpentry, in food production, and for daily household use as well. While there exists an overall similarity in the copper tool assemblages at Indus sites, some contrasting patterns exist between the larger and smaller sites. At the sites of Lothal and Surkotada, knives are the dominant subtype of blade tool (Fig. 24.8) and point tools are the majority subtype of rod tools (Fig. 24.9). This is in contrast with Harappa and Mohenjo-daro where the larger more robust subtypes of both categories dominate. At both of these large sites, chisels are the overwhelming majority of the rod tool types (Fig. 24.9) and spears are the major subtype of blade tools (Fig. 24.8). While such a contrasting pattern of copper tool type distributions is intriguing, at present it cannot be explained without first resolving possible issues of differential archaeological collection methods or preservation conditions, as discussed above. It is hoped that further research into the use of copper implements and the addition of new information from previously unpublished sites, as well as ongoing research, will provide the necessary data needed to further explore the initial patterning.

One of the major interpretative questions for studies of Indus copper assemblages is how types may or may not have developed and changed over time. At present, the chronological data for excavated copper objects are not sufficient to make any interpretations about this question. The majority opinion remains with Piggott (1950) that Harappan copper forms are remarkably static and consistent over time (Marshall 1931; Mackay 1938; Rao 1979; Joshi 1990; Agrawal 2000). It is hoped that further study of the material recovered from the Harappa Archaeological Research Project will allow for the development of copper production and consumption to be investigated against the precise radiocarbon chronology from the site. But for the moment, the question of the changes in copper metal forms over time in the Indus Civilization remains unresolved.

Future Directions

The present study is an effort to delineate the manner in which copper was used as a resource in the Indus Civilization. The brief review undertaken here is perhaps best viewed as a first step. While some interesting patterns do appear to be present in the data, much more detailed study is required before they can be substantiated. It is critical that the material from excavated Indus Civilization sites that has not been published be brought to press as soon as possible. Information from these sites, particularly those of Dholavira, Rakhighari, and Kalibangan, would provide important comparisons to the presently available evidence. Further, it is necessary to examine the existing copper materials from Indus sites for any changes over time. Unfortunately, for a number of the sites the chronological information is either not available or not published. In order to further refine our understanding of the types of objects that were made from copper and the trajectory of development for Indus copper working, it is necessary to understand how the technology changed and developed over time.

In the absence of secure archaeological contexts and definitive chronological sequences, methods for tracking changes in Indus copper assemblages must be expanded beyond typological examinations. Laboratory-based analytical approaches may provide the most direct approach for understanding the growth and development of this technological tradition. One avenue for investigation would be to expand the existing tradition of compositional research on Indus copper metals. A program of compositional analyses, directed at tracking the composition of artifact types, would assist in answering important questions regarding alloying practices in Indus copper metallurgy. The first of these is whether or not the use of alloys is restricted to certain types or production techniques. Also, it is critical to understand how alloying patterns may have changed. The use of differing alloys over time could result from choices related to changing cultural fashions, or changes in the availability of raw materials, or from technological refinement. Besides data from compositional analyses, an instrumentation-based analytical program can provide data on the types and availability of copper raw material sources over time. Through the application of lead isotope studies to Indus archaeological copper materials, as described in the production section above, a picture of how individual sites were supplied with copper raw materials, and perhaps even finished products, may be developed. Hoffman has begun work along these lines with material from Harappa, as part of his dissertation research on Indus metals.

Acknowledgments Richard Meadow and Mark Kenoyer, co-directors of the Harappa Archaeological Research Project (HARP), and several Director Generals of the Department of Archaeology and Museums, Government of Pakistan, have graciously aided our study of materials from Harappa during the long period of our research. HARP provided funding for much of this research, particularly the analytical work. For access, analysis, and interpretation of the LIA samples, Hoffman thanks Samuel Mukasa and his research group at the University of Michigan, Department of Geological Sciences; James Burton of the Laboratory for Archaeological Chemistry at the University of Wisconsin-Madison, headed by T. Douglas Price; Randall Law and David Meiggs of the University of Wisconsin-Madison; and Kishore Raghubans, formerly of M.S. University Baroda. Randall Law was also of great help with the preparation of the images in this paper. We much appreciate the very helpful editorial comments provided by Chris Thornton, Ben Roberts, and Vince Pigott.

References

Agrawal, D. P. (1971). *The Copper Bronze Age in India*. New Delhi: Munshiram Manoharlal.

Agrawal, D. P. (2000). *Ancient metal technology and archaeology of South Asia*. New Delhi: Ayran Books International.

Agrawal, D. P., & Kharakwal, J. S. (2003). *Bronze and Iron Ages in South Asia: Archaeology of South Asia II*. New Delhi: Aryan Books International.

Bayley, J. (1985). What's what in ancient technology: An introduction to high-temperature processes. In P. Phillips (Ed.), *The archaeologist and the laboratory* (pp. 41–44). London: Council for British Archaeology.

Bhan, K. K., Sonawane, V. H., Ajitprasad, P., & Pratapchandran, S. (2004). Excavations of an important Harappan trading and craft production center at Gola Dhoro (Bagasra), on the Gulf of Kutch, Gujarat, India. *Journal of Interdisciplinary Studies in History and Archaeology*, *1*, 153–158.

Bhan, K. K., Vidale, M., & Kenoyer, J. M. (2002). Some important aspects of the Harappan technological tradition. In S. Settar & R. Korisettar (Eds.), *Indian archaeology in retrospect, Volume 2 (Protohistory: Archaeology of the Harappan Civilization)* (pp. 223–272). New Delhi: Indian Council of Historical Research.

Bisht, R. S. (1997). Dholavira excavations: 1990–1994. In J. P. Joshi (Ed.), *Facets of Indian civilization: Recent perspectives, essays in honour of Prof. B. B. Lal.* (pp. 107–120). New Delhi: Aryan Books International.

Bourgarit, D., Taher, N., Mille, B., & Mohen, J.-P. (2005). Copper metallurgy in the Kutch (India) during the Indus Civilization: First results from Dholavira. In C. Jarrige & V. Lefèvre (Eds.), *South Asian Archaeology 2001* (pp. 27–34). Paris: Éditions Recherche sur les Civilisations.

Calvez, J. Y., & Lescuyer, J. L. (1991). Lead isotope geochemistry of various sulphide deposits from the Oman mountains. In T. Peters, A. Nicolas, & R. J. Coleman (Eds.), *Ophiolite genesis and evolution of the oceanic lithosphere* (pp. 79–85). Sultanate of Oman: Ministry of Petroleum and Minerals.

Chakrabarti, D. K., & Lahiri, N. (1996). *Copper and its alloys in ancient India*. New Delhi: Munshiram Manoharlal Publishers.

Chase, B. A. (2007). *Meat provisioning and the integration of the Indus Civilization: A perspective from Gujarat (India). Department of* Anthropology, University of Wisconsin-Madison. PhD Dissertation. Ann Arbor: Proquest-UMI Microfil

Cleland, J. H. (1977). *Chalcolithic and Bronze Age chipped stone industries of the Indus region*. Department of Anthropology, University of Virginia. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms

Cooke, S. R. B., & Nielsen, B. V. (1978). Slags and other metallurgical products. In G. Rapp & S. E. Aschenbrenner (Eds.), *Excavations at Nichoria in Southwest Greece. Volume I: Site, environs, & techniques* (pp. 182–224). Minneapolis: University of Minnesota Press.

Craddock, P. T. (1989). The scientific investigation of early mining and smelting. In J. Henderson (Ed.), *Scientific analysis in archaeology and its interpretation* (pp. 178–212). Oxford and Los Angeles: Oxford University Committee for Archaeology and UCLA Institute of Archaeology.

Desch, C. H. (1931). Analyses of copper and bronze specimens made for the Sumer Committee of the British Association. In J. Marshall (Ed.), *Mohenjo-daro and the Indus Civilization* (vol. II, pp. 486–488.). London: A. Probsthain.

Dickin, A. P. (1995). Chapter 5—Lead isotopes. In Radiogenic isotope geology (pp. 104–132). Cambridge: Cambridge University Press.

Ehrhardt, K. L. (2005). *European metals in native hands: Rethinking technological change 1640–1683*. Tuscaloosa: University of Alabama Press.

Faure, G. (1986). Chapter 18—The U, Th–Pb methods of dating. In *Principles of isotope geology* (pp. 282–308). New York: Wiley.

Fentress, M. (1976). *Resource access, exchange systems, and regional interaction in the Indus Valley: An investigation of archaeological variability at Harappa and Mohenjo-daro.* Department of Oriental Studies, University of Pennsylvania. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms.

Gale, N. H., & Stos-Gale, Z. A. (2000). Lead isotope analyses applied to provenance studies. In E. Ciliberto & G. Spoto (Eds.), *Modern analytical methods in art and archaeology* (pp. 503–584). New York: Wiley.

Hakemi, A. (2000). Comparison between the plates of Shahdad and other plates that exist in museums. In M. Taddei &G. De Marco (Eds.), *South Asian Archaeology 1997* (pp. 943-959). Rome and Naples: Istituto Italiano per l'Africa e l'Oriente and Istituto Universitario Orientale.

Haquet, J. (1994). *Problématique de la métallurgie dans la plaine de Kachi (Pakistan) du néolithique à la fin de la civilisation de l'Indus au IIIe millénaire avant J.-C.,* Université de Paris. Mémoire de D.E.A.

Hegmon, M. (1992). Archaeological research on style. *Annual Review of Anthropology*, *21*, 517–536.

Hegmon, M. (1998). Technology, style, and social practices: Archaeological approaches. In M. T. Stark (Ed.), *The archaeology of social boundaries* (pp. 264–279). Washington D.C.: Smithsonian Institution Press.

Hoffman, B. C. (2007). *Copper trade and technology at Harappa: Initial results*. BAR.

Joshi, J. P. (1990). *Excavations at Surkotada 1971–72 and exploration in Kutch*. New Delhi: Archaeological Survey of India.

Kenoyer, J. M. (1992). Ornament styles of the Indus tradition: Evidence from recent excavations at Harappa, Pakistan. *Paléorient*, *17*(2–1991), 79–98.

Kenoyer, J. M. (1998). *Ancient cities of the Indus Valley Civilization*. Karachi: Oxford University Press.

Kenoyer, J. M., & Miller, H. M.-L. (1999). Metal technologies of the Indus Valley Tradition in Pakistan and Western India. In V. C. Pigott (Ed.), *The emergence and development of metallurgy* (pp. 107–151). Philadelphia: University Museum.

Lahiri, N. (1993). Some ethnographic aspects of the ancient copper-bronze tradition in India. *Journal of the Royal Asiatic Society*, *3*(2), 219–231.

Lahiri, N. (1995). The alloying traditions of protohistoric and historic India: Some general trends and their ethnographic dimensions. *Puratattva*, *24*, 64–73.

Lal, B. B., Thapar, B. K., Joshi, J. P., & Bala, M. (2003). *Excavations at Kalibangan: The early Harappans (1960–1969)* (Memoirs of the ASI, No. 98). New Delhi: Archaeological Survey of India.

Latta, M. A., Thibaudeau, P., & Anselmi, L. (1998). Expediency and curation: The use and distribution of 'Scrap' trade metal by Huron native peoples in sixteenth-century southern Ontario. *Wisconsin Archaeologist*, *79*(1), 175–184.

Law, R. (2008). *Inter-regional interaction and urbanism in the ancient Indus Valley: A geologic provenance study of Harappa's rock and mineral assemblage*. Department of Anthropology, University of Wisconsin-Madison. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms.

Lechtman, H. (1977). Style in technology—Some early thoughts. In H. Lechtman & R. S. Merrill (Eds.), *Material culture: Styles, organization and dynamics of technology* (pp. 3–20). St. Paul: West Publishing Co.

Lechtman, H., & Steinberg, A. (1979). The history of technology: An anthropological point of view. In G. Bugliarello & D. B. Doner (Eds.), *The history and philosophy of technology* (pp. 135–160). Urbana: University of Illinois Press.

Mackay, E. J. H. (1938). *Further excavations at Mohenjo-daro*. New Delhi: Government of India.

Mackay, E. J. H. (1943). *Chanhu-Daro excavations 1935–36*. New Haven: American Oriental Society.

Marshall, J. (1931). *Mohenjo-daro and the Indus Civilization*. London: A. Probsthain.
Meadow, R. H., & Kenoyer, J. M. (2005). Excavations at Harappa 2000–2001: New insights on chronology and city organization. In C. Jarrige & V. Lefèvre (Eds.), *South Asian Archaeology 2001* (pp. 207–226). Paris: Éditions Recherche sur les Civilisations.
Mery, S., & Blackman, M. J. (2005). Socio-economical patterns of a ceramic container: The Harappan black slipped jar. In C. Jarrige & V. Lefèvre (Eds.), *South Asian Archaeology 2001* (pp. 227–236). Paris: Éditions Recherche sur les Civilisations.
Mille, B., Bourgarit, D., & Besenval, R. (2005). Metallurgical study of the 'Leopards Weight' from Shahi Tump (Pakistan). In C. Jarrige & V. Lefèvre (Eds.), *South Asian archaeology 2001* (pp. 237–244). Paris: Éditions Recherche sur les Civilisations.
Miller, H. J. (2000). A functional typology for metal objects from Chanhu-daro. In M. Taddei & G. De Marco (Eds.), South Asian Archaeology 1997 (pp. 301-320). Rome and Naples: Istituto Italiano per l'Africa e l'Oriente and Istituto Universitario Orientale.
Miller, H. M.-L. (1994). Metal processing at Harappa and Mohenjo-daro: Information from non-metal remains. In A. Parpola & P. Koskikallio (Eds.), *South Asian Archaeology*, *1993* (pp. 497–510). Helsinki: Suomalainen Tiedeakatemia.
Miller, H. M.-L. (1999). *Pyrotechnology and society in the cities of the Indus Valley*. Department of Anthropology, Dissertation. University of Wisconsin-Madison. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms.
Miller, H. M.-L. (2005). Investigating copper production at Harappa: Surveys, excavations and finds. In C. Jarrige & V. Lefèvre (Eds.), *South Asian Archaeology, 2001* (vol I, pp. 245-252). Paris: Éditions Recherche sur les Civilisations.
Miller, H. M.-L. (2007). *Archaeological approaches to technology*. San Diego: Elsevier/Academic Press/Left Coast Press.
Parpola, A. (1992). Copper tablets from Mohenjo-daro and the study of the Indus script. In I. M. Nadiem (Ed.), *Proceedings of the second international conference on Moenjodaro*. Karachi: Department of Archaeology.
Piggott, S. (1950). *Prehistoric India*. Baltimore: Penguin Books.
Possehl, G. L. (2002). *The Indus Civilization: A contemporary perspective*. Walnut Creek: AltaMira Press.
Rao, S. R. (1979). *Lothal: A Harappan port town (1955–62)*. New Delhi: Archaeological Survey of India.
Rissman, P. C. (1988). Public displays and private values: A guide to buried wealth in Harappan archaeology. *World Archaeology*, *20*(2), 209–227.
Rizvi, U. Z. (2007). *Configuring the space in between: Redefining the Ganeshwar Jodhpura cultural complex in northeastern Rajasthan, India*. Department of Anthropology, University of Pennsylvania. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms.
Rothman, M. S. (Ed.). (2001). *Uruk Mesopotamia and its neighbors: Cross-cultural interactions in the era of state formation*. Sante Fe: School of American Research Press.
Sana Ullah, M. (1931). Copper and bronze utensils and other objects. In J. Marshall (Ed.), *Mohenjo-daro and the Indus Civilization* (vol. II, pp. 481-488). London: A. Probsthain.
Sana Ullah, M. (1940). The sources, composition, and technique of copper and its Alloys. In M. S. Vats (Ed.), *Excavations at Harappa* (pp. 378-382). New Delhi: Government of India Pres
Shaffer, J. G. (1982). Harappan culture: A reconsideration. In G. L. Possehl (Ed.), *Harappan Civilization* (pp. 41–50). New Delhi: Oxford and IBH Publishing.
Shaffer, J. G. (1992). The Indus Valley, Baluchistan and Helmand traditions: Neolithic through Bronze Age. In R. Ehrich (Ed.), *Chronologies in Old World archaeology* (3rd ed., pp. 441–464). Chicago: University of Chicago Press.
Sharma, D. P. (2002). *Newly discovered copper hoard weapons of South Asia (c. 2800–1500 B.C.)*. New Delhi: Bharatiya Kala Prakashan.
Srinivasan, S. (2007). Some preliminary insights on copper-base metallurgy at the Harappan site of Dholavira. Paper delivered at the European Association of South Asian Archaeology and Art 14th International Conference on South Asia, July 2-7, 2007. Ravenna, Italy. Not Published.

Stech, T. (1999). Aspects of early metallurgy in Mesopotamia and Anatolia. In V. C. Pigott (Ed.), *The archaeometallurgy of the Asian Old World* (pp. 59–72). Philadelphia: University Museum.

Stein, G. J. (2001). Indigenous social complexity at Hacinebi (Turkey) and the organization of Uruk colonial contact. In M. S. Rothman (Ed.), *Uruk Mesopotamia and its neighbors: Cross-cultural interactions in the era of state formation*(pp. 265-305). Santa Fe: School of American Research Press.

Steinberg, A. (1977). Technology and culture: Technological styles in the bronzes of Shang China, Phrygia and Urnfield Central Europe. In H. L. Lechtman & R. S. Merill (Eds.), *Material culture: Styles, organization and dynamics of technology* (pp. 53–86). St. Paul: West Publishers.

Vats, M. S. (1940). *Excavations at Harappa*. New Delhi: Government of India Press.

Vidale, M. (2000). *The archaeology of Indus crafts: Indus craftspeople and why we study them*. Rome: Istituto Italiano per l'Africa e l'Oriente.

Vidale, M.,& Miller, H. M.-L. (2000). On the development of Indus technical virtuosity and its relation to social structure. In M. Taddei & G. De Marco (Eds.), *South Asian Archaeology 1997* (pp. 115-132). Rome and Naples: Istituto Italiano per l'Africa e l'Oriente and Istituto Universitario Orientale.

Weeks, L. R. (2003). *Early metallurgy of the Persian Gulf: Technology, trade, and the Bronze Age world*. Boston: Brill.

Yao, A. (2008). Culture contact and social change along China's ancient southwestern frontier, 900 BC-100 AD. Department of Anthropology, University of Michigan. PhD Dissertation. Ann Arbor: Proquest-UMI Microfilms.

Yule, P. (1985a). *Figuren, Schmuckformen und Täfelchen der Harappa-Kultur*. München: Beck'sche Verlagsbuchhandlung.

Yule, P. (1985b). *Harappazeitliche Metallgefabe in Pakistan und Nordwestindien*. München: Beck'sche Verlagsbuchhandlung.

Yule, P. (1985c). *Metalwork of the Bronze Age in India*. München: Beck'sche Verlagsbuchhandlung.

Chapter 25
Early Metal in South India: Copper and Iron in Megalithic Contexts

Praveena Gullapalli

Introduction

There exist heterogeneous archaeological traditions in South Asia, including varying histories of metallurgy (e.g., see Chakrabarti 1992; Chakrabarti and Lahiri 1996; Possehl and Gullapalli 1999 Tripathi 2008). Consequently, multiple models of the development and adoption of copper and iron metallurgy are necessary and appropriate. For example, while northern South Asia has witnessed a Bronze age followed by an Iron age, the situation in the southern peninsula (South India) seems to be significantly different. An early (pre-iron) copper/bronze metallurgical industry in South India is not well attested; rather, it is indicated only by relatively sparse occurrences of copper artifacts in late Neolithic contexts. The archaeological record for the occurrence of metal (both iron and copper/bronze) in the Iron Age Megalithic contexts, by contrast, is much more robust, and it is this corpus of material that forms the early metallurgical tradition of South India (Fig. 25.1).

There are three interrelated issues that shape any discussion of early metallurgy in South India: the megalithic monuments that constitute a significant part of the archaeological landscape of South India during the Iron Age, the dominance of iron, and the relative paucity and limited distribution of early copper. The prominence of iron in the archaeology of South India stems from its significantly greater presence in the archaeological record, and from a theoretical framework that privileges iron over copper. The dominance of the archaeological research by megalithic monuments makes it difficult to tease apart issues of the early metallurgy and megalithic traditions—indeed, attempts to explain the nature of the megalithic monuments have defined much of the research into the Iron Age.

In this chapter, I provide an overview of the early South Indian metallurgical tradition. My goal is to outline the trends and developments in the field and to highlight potentially useful avenues of further research. This cannot be and is not

P. Gullapalli (✉)
Anthropology Department, Rhode Island College, Gaige Hall,
600 Mount Pleasant Avenue, Providence, RI 02908-1991, USA

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_25,

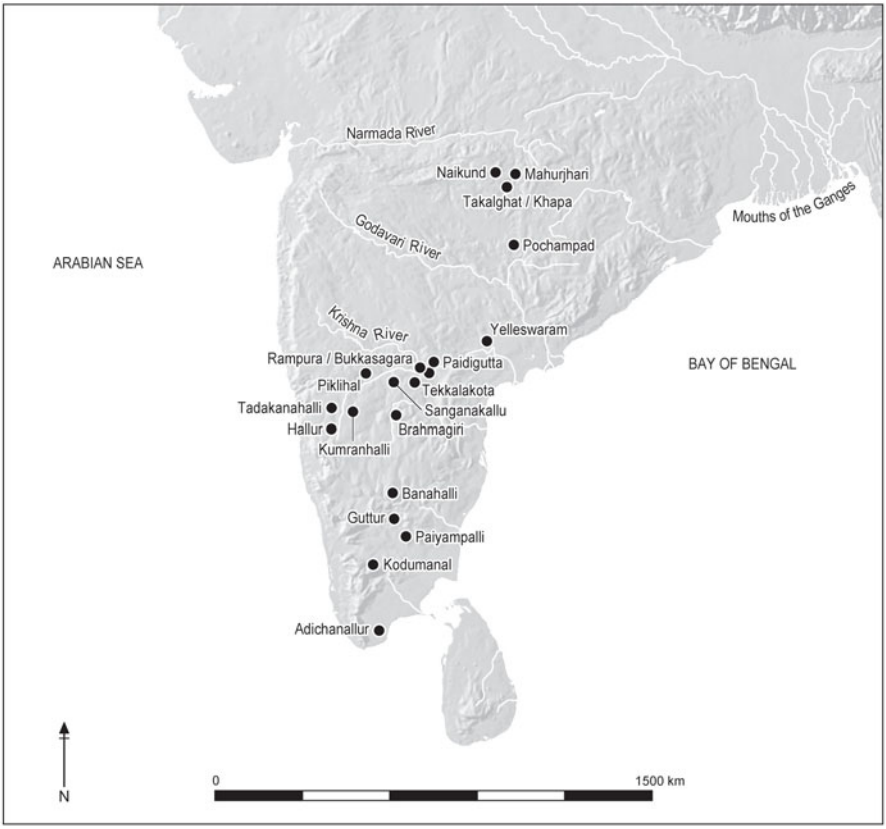


Fig. 25.1 Map showing the location of sites mentioned in the chapter. Note that Naikund, Mahurjhari and Takalghat/Khapa are located in the Vidarbha region of Maharashtra

meant to be an exhaustive catalog of all sites and all evidence. I begin with a discussion of dominant models of early metallurgy—specifically of iron metallurgy—in South India, focusing on the question of diffusion versus indigenous development. I then briefly review the nature of megalithic archaeological record before delving into the evidence for early metallurgy. I end by discussing possible directions for future research.

Modeling Early Metal in South India

Interpretation and modeling of early metallurgy in South India has been shaped by two primary concerns, both focusing on iron metallurgy because of its dominance in the archaeological record. The first is whether the early iron in the peninsula was the result of diffusionary or migratory processes or whether iron was an indigenous development. The second concern has been to understand and demonstrate the skill of the early practitioners of metal technologies. Taken together, these concerns have directed archaeological research towards an emphasis on uncovering the earliest evidence for various ferrous metallurgical practices through excavation and through artifact analyses.

Concern with whether or not the early metallurgical traditions of South India (and indeed, all of South Asia) were indigenous developments arises from the fact that early models privileged migrations of various groups of people into the subcontinent, with each group bearing a specific cultural or archaeological correlate. Early attempts to investigate and explain the presence of the megalithic monuments and their attendant cultural characteristics focused on diffusionary paradigms that connected the South Indian megalithic monuments to others in Southwest Asia and beyond. Their presence in the peninsula of South Asia was explained through a variety of migration theories that also included linguistic and anthropometric data (e.g., Parpola 1973; see Kennedy 1975 for an overview). The most persistent of these groups has been the Aryans, Indo-European speaking peoples, whose entry into the subcontinent has been understood to be the explanation for everything from the decline of the Indus Civilization to the advent of iron technology (see Leach 1990; Parpola 1973; Shaffer 1984; Shaffer and Lichtenstein 1995).

No archaeological evidence exists for the requisite type of large scale migrations, but with or without the Aryans, others (e.g., Wheeler 1959) saw the beginning of iron technology as a result of diffusionary processes. For example, the excavator of Hallur notes in the excavation report that the "people who arrived here with iron, came with the full knowledge of metallurgy and finished tools (Nagararaja Rao 1971, p. 91), " and more recently the excavator of Paidigutta (in Andhra Pradesh) posits that "the newly arrived iron-age folk co-existed with the already existing Neolithic-Chalcolithic people. Though the newcomers had the advanced trends such as iron in their tool-kit and stone for building structures, they preferred to dwell at the same site and in the same rich context (Sastry 2000, p. 29)." This latter statement highlights the emergence of a new technology within apparent cultural continuity and the fact that the question of indigenous development and diffusion needs to be further delineated within South India (see further).

Analysis of skeletal material from the graves points to a phenotypic variability in the Iron Age populations and, importantly, shows no sign of an invasion of people. Kenneth Kennedy asserts that "earlier statements of racial identities based upon a specific set of morphometric criteria [do not] support any theory that iron was diffused to South Asia by foreign populations whose origins lay outside of this part of the world. . . . The skeletal evidence does not support any hypothesis of catastrophic and sudden population replacements in peninsular India during the Iron Age (Kennedy 2002, p. 123; see also Kennedy 1975)."

Obviously, diffusion of technological practices does not necessarily imply movement of people, and the lack of evidence for migration does not mean that diffusion of such practices did not take place. However, beginning with Chakrabarti (1976, 1977, 1992), the model of diffusion into South Asia has been successfully challenged using material from archaeological excavations and survey over the past two decades. Chakrabarti used radiocarbon dates, the tradition of pyrotechnology in the subcontinent, and the varied character of the Iron Age to argue for indigenous development within the subcontinent (see also Possehl and Gullapalli 1999; Tripathi 2008). Not only is there is consistent evidence of continuity between pre-Iron Age and Iron Age deposits, but there is also evidence of pre-Iron Age experimentation with iron and no evidence of possible diffusionary mechanisms. Also, most pertinent here, the earliest Iron Age dates in the subcontinent (c. 1000 BC) have come from South Indian contexts, and therefore render problematic diffusionary models that hypothesized overland introduction of iron into South Asia from the Iranian plateau and which would indicate that the earliest iron be found in the northern subcontinent (but see Tewari 2003 for new dates that may push back the earliest iron in northern India; Tripathi 2008).

Although the early date of iron technology has been established, there has been little explicit discussion of how iron was adopted or adapted into society. That is, while iron metallurgy seems to have been an indigenous development, we still do not know how the knowledge of iron production was organized, maintained (and perhaps even guarded), and transmitted within and between the various groups that inhabited the South Indian Iron Age landscape (see discussion of Johansen (2007) below).

There is geographic variation within South India with regard to when iron metallurgy appears, a variation that needs to be investigated and explained, since even though for the region as a whole there is evidence for indigenous development, there remains the question of how many centers of development existed within South India. If iron metallurgy emerged in a restricted area, how was it spread to other areas of South India so that by the late centuries BC there seems to be such widespread evidence for it?

Bridget and Raymond Allichin argue that "the range of identical tool-types, repeated many times, at site as far apart as Nagpur and Adichanallur—some 1450 km apart—must testify to the diffusion of a fairly tightly knit group of iron workers (Bridget and Allichin 1967–1968, p. 335)." The fact that there seems to be pastoral and agricultural components to the Iron Age economy lends support to the idea of an itinerant group of specialist metalworkers moving across the landscape. If the similarity in morphology is further enhanced by similarity in technological style, it may indicate that we do have a situation in which specialized knowledge is being disseminated to a select group of producers. However, identifying these mechanisms would require significantly more metallurgical analyses on larger sets of artifacts.

Concomitant with the focus on early iron have been attempts to ascertain the level of metalworking skill of these early producers, including identifying the earliest evidence for steeling. The apparently utilitarian nature of the iron artifacts has emphasized a utilitarian approach to explaining adoption—the hypothesized technical superiority of iron over copper and bronze. This emphasis on utility and desirability is evinced in the nature of technical analyses of iron artifacts that focus on evidence for steeling and hardening, for example. There is also an emphasis on determining level of skill as other metallurgical analyses (of iron) have focused on determining the efficacy of iron extraction, the frequency of steeling, and the ability to exploit certain characteristics (as seen in the discussion of technical analyses).

Because of this emphasis on early iron, research into early metallurgy in South India has tended to neglect early copper and gold. Of course, the limited presence of these metals combined with the greater and relatively early presence of iron associated with the striking megalithic monuments and the existence of a Bronze Age in northern South Asia makes this understandable. Explanations of the presence of pre-Iron Age copper tend to imply diffusion from the more established copper and bronze traditions of central and northern South Asia (see Chakrabarti and Lahiri 1996, Bhardwaj 2000) , while others (notably Srinivasan 2006) have postulated a local indigenous tradition of copper and bronze working based on ethnographic fieldwork and their metallurgical analyses.

More systematic investigation of the early copper metallurgy in South India, moreover, would also enhance current understanding of iron development, since both technologies seem to be fully elaborated together rather than in sequence, as is the case in many other contexts. While it is clear that the development of an Iron Age without a preceding Bronze Age has significant implications for contemporary paradigms of early metallurgy, the nature of those implications is not yet clear.

Megalithic Monuments

Although the distribution of megalithic monuments spans much of South Asia, with significant traditions in the north, northwest, and central parts of the subcontinent, the greatest concentration occurs in the south (Deo 1985). Here, the focus will be on the megalithic tradition usually associated with the Iron Age in South India. Many of the monuments are found along the Godavari and Krishna Rivers and their tributaries (such as the Tungabhadra River); there is also a cluster of monuments known as the Vidarbha megaliths that are located in eastern Maharashtra, set apart geographically and chronologically from those monuments further south (see Brubaker 2001 for a good discussion on geographic and chronological distribution and attendant maps). The megaliths are funerary monuments or memorials incorporating a variety of large stone constructions. Most—but definitely not all—of these monuments contain primary and secondary inhumations and associated burial furniture, sometimes in great quantity. There exists variation in their form, nature, and function; however, while variations have been identified, it is not yet clear what, if anything, those variations mean. Furthermore, although it is possible to delineate numerous regional groupings of megaliths within South India, the two broad groups mentioned above (in the Godavari and Krishna systems and the Vidarbha region) will be of concern here.

These megalithic monuments are visible and relatively easily recognizable on the landscape (for example, as alignments of standing stones, stone slab supported by boulders or arrangements of boulders and cairns) and consequently have been the focus of more sustained research than the habitation sites related to the cemeteries.

Once thought to be minimally or even nonexistent, habitation sites have now been much more widely identified.

Most of these monuments do include large stones as structural or identifying elements, but not all sites defined as megalithic contain large lithic elements. Perhaps the best example of this is Adichanallur (also spelled Adittanallur). Adichanallur is one of 38 sites reported by Alexander Rea on the banks of the Tambraparni River, with skeletal remains (skulls and some post-cranial material, and sometimes ash) in large red-ware urns. The urns were buried in pits, some as large as 2.74 m in diameter and 4.5 m deep, and also contained grave goods that included artifacts of iron, copper and gold, stone beads, black and red pottery, traces of cloth and rice and millet (Rea 1915; Kennedy 1987, p. 263). There is no significant lithic accompaniment and, although technically not megalithic in the literal sense, this and other sites like if are included within the megalithic tradition on the basis of chronology and associated material culture, especially the presence of iron and the Black and Red Ware.

The term "megalithic" not only has chronological and cultural connotations but also has been used to identify the South Indian Iron Age. Even though iron is associated with megalithic monuments, the monuments are not chronologically confined to the Iron Age, as their construction continues into the first centuries AD in the South, and is further attested to ethnographically in various parts of the subcontinent. So although megaliths persist, the Megalithic period in the archaeological literature has become synonymous with the Iron Age.

Sir Mortimer Wheeler (1947–1948) established the relative chronology of the Megalithic period at Brahmagiri and Chandravalli in Karnataka (then Mysore), by fitting it between the southern Neolithic and Early Historic periods (although his absolute dates have now been revised earlier). Radiometric dates from various sites indicate that the earliest Iron Age levels at these Megalithic sites date to the beginning of the first millennium BC; the earliest date for contexts with iron in the region (ca. 1100 BC) is from the Neolithic/Megalithic Transition Period at Hallur on the Tungabhadra River in Karnataka (Nagaraja Rao 1971, 1985; Possehl and Gullapalli 1999, pp. 168–169). The earliest dates for the Vidarbha megaliths as a whole fall in the seventh century BC (Deo 1970), so as a group they are slightly later than those further south. The Iron Age spans the period from approximately 1200 BC to 300 BC, with the terminal dates assigned on the basis of the emergence of Early Historic cultural indicators (e.g., urbanism, Indo-Roman long-distance trade, and epigraphy) (Chakrabarti 1992, p. 80; Moorti 1994, p. 5). Evidence from the late Megalithic contexts has pointed to participation in the long-distance exchange networks (Moorti 1994; Srinivasan 2004) that also characterize the subsequent Early Historic period.

Jane McIntosh (1985) has identified four periods of megalith building that can be divided into two phases based on the distribution of sites, funerary rites, and grave morphology. She notes that the earliest period is coterminous with the distribution of the Neolithic cultures of South India (in Andhra Pradesh, Tamil Nadu, and Karnataka), indicating a continuity of cultural tradition rather than intrusion. The next period sees the spread of megalithic monuments into the Vidarbha region of Maharashtra and the appearance of horse skeletons and equipment in the graves. Horses and vehicles are present, along with pottery and metal artifacts including tools and horse trappings. The horse skeletons in some cases exhibit cut marks on the bone indicating possible sacrifice and burial along with the human interment (Thomas 1992, p. 13). The final periods of megalith building are associated with innovations in the style of the graves and the introduction of funerary containers such as urns and sarcophagi (McIntosh 1985).

The number of habitation sites recorded and investigated is small compared to the number of cemeteries and tombs excavated. The research that has focused on the nature of the funerary monuments themselves has been dominated by attempts to create inclusive typologies and have been many descriptions of the varieties of Megalithic burial monuments in South India (e.g., Krishnaswami 1949; Wheeler 1959, pp. 154–158; see also Allchin and Allchin 1967–1968, pp. 331–333), resulting in varied typologies. For example, Wheeler (1959) offers eight types while Moorti (1994, p. 2–3), on the other hand, offers only two major categories. These attempts, however, have for the most part been unsuccessful. The large number of monuments as well as variations in their construction has made typologies cumbersome as analytical tools (see Moorti 1994 for further discussion). Until recently little attempt had been made to move beyond his work, with research focusing on description and categorization of the monuments and the material culture (see Chakrabarti 1992, pp. 80–85; Moorti 1994 for further discussion; also Brubaker 2001; Mohanty and Selvakumar 2002; Mohanty and Walimbe 1993). Not surprisingly this imbalance in research has led to an incomplete understanding of the society and culture that erected these monuments, including but not limited to their metallurgical practices.

Neolithic Copper

The earliest metal artifacts from the South Indian archaeological record are of copper. They appear in small numbers during the Neolithic and continue into the Iron Age. Although their number increases during the Iron Age, they are consistently fewer than those made of iron and they tend to include fewer tools and more decorative and ornamental artifacts. Unstratified contexts of copper artifacts include copper hoards, which have been found in Tamil Nadu, Karnataka, Andhra Pradesh and Kerala (Chakrabarti and Lahiri 1996, p. 75; Gupta 1989, p. 92).

The Southern Neolithic of India has been dated from the mid third millennium BC, though most dates fall in the mid second millennium BC, and lasts until c. 1000 BC, or the beginning of the Iron Age (Korisettar et al. 2002; Nagaraja Rao 1985; Paddayya 1973). Copper artifacts begin to appear in Late Neolithic contexts (Biswas 1996: 158–60), with the earliest ones confined to sites in Karnataka and Andhra Pradesh (Chakrabarti and Lahiri 1996: 75). They consist of axes, fishhooks, needles, chisels, swords, beads and other ornaments, and various fragments (Allchin 1960; Biswas 1996, pp. 158–160; Chakrabarti and Lahiri 1996, p. 75; Sastry 2000).

One site with Late Neolithic copper artifacts is Hallur, a habitation and burial site on the left bank of the Tungabhadra River in western Karnataka. It is a mounded site with two periods of occupation—Neolithic and Early Iron Age—with an overlap between the two that indicates continuity of earlier cultural characteristics with the emergence of Iron Age ceramics and iron artifacts. Megalithic monuments—cairns and dolmenoid cist-circles—are located approximately 2 miles to the west and north of the site, on hilly slopes, which may be contemporary with the site but were not excavated (Nagaraja Rao 1971, pp. 12–13, 30).

The Late Neolithic phase at the site yielded three copper artifacts in conjunction with a Late Neolithic stone blade industry, polished stone axes, beads (including one gold bead, which was identified as an intrusive Early Iron Age artifact based on its type) and ceramics. The copper artifacts were found associated with floors of circular structures, and are described as "a miniature, double-edge axe, made on thin sheet of copper with a broad edge and concave middle, looking like a brooch or bow. . . . [A] flat, miniature axe, with a broad cutting edge, and is like a *Parasu* in shape. Made on a thin sheet of copper. . . . A small fish hook, with the out-curved upper end flattened and the end of the hook pointed. Made on a round copper wire (Nagaraja Rao 1971, pp. 89–91)." a similar double edged axe comes from Paidigutta, Andhra Pradesh: Sastry 2000: 182–83). The small size of the first two artifacts (smaller than 5 cm) leads the excavator to speculate that they were either cult objects or, in the case of the *Parasu* axe, a tool used for detailed work in scraping leather (Nagaraja Rao 1971, pp. 89–91). Analysis of Neolithic copper artifacts from two other sites (Tekkalakota and Brahmagiri) indicates that they are over 90 % copper. However, there is no evidence of smelting associated with the Neolithic sites (Bhardwaj 2000, p. 38; Chakrabarti and Lahiri 1996, p. 75; Rao and Malhotra 1965).

An intriguing feature of the southern Neolithic is the presence of ashmounds. These accumulations of often vitrified ash dot the landscape of the southern Deccan, and have been the focus of some speculation. Local inhabitants regarded them as the graves or remains of *rakshasas* or demons; early explorers thought the ash to be volcanic or slag resulting from industrial activity. However, the first excavation of a mound proved that they were artificial, and Bruce Foote associated them with Neolithic settlements and proposed that the ash was burnt cow dung (Allchin 1963). In the 1950s the ash was chemically identified as cow dung. Allchin and Allchin (1967–1968) proposed cattle pens and domestication centers, with periodic burning of the dung accounting for the creation of the mounds. Paddayya's (1998, 2002) work in Budihal has shown that far from being single purpose cattle pens, these mounds are a combination of animal penning yards and settlement areas, with the yard occupying a central area, surrounded by habitation. The evidence points to a pastoral camp, since the mound is located in poor agricultural soils, but in areas that would have provided good pasture. Included in the material culture are ceramics and stone implements including flakes stone tools. At Budihal an enormous area of debitage characterized as a chert workshop, 'the only known blade industry workshop in the context of the southern Neolithic culture', was excavated (Paddayya 1998, p. 12). Furthermore, at Kupgal bits of quartz and feldspar were found to be mixed in with the ash, indicating a redeposition of the dung (Paddayya 1973).

Thus what emerges clearly is that the nature of the ashmounds is not yet settled, and more recent scholars have emphasized the symbolic, monumental, and phenomenological aspects of these features (see Bauer et al 2007; Boivin 2004;

Johansen 2004). Of interest here is the fact that some of these ashmounds are in proximity to megalithic monuments. While earlier scholars saw the megaliths and the attendant iron technology as intrusive phenomena (e.g., Wheeler 1947–1948, pp. 199–202), excavations at Palavoy in Andhra Pradesh have found Iron Age pottery and two iron artifacts within an ashmound. The fact that ash mounds seem to be in the vicinity of megalithic sites combined with the stratigraphic overlap between the two periods and similarities in the creation of cultural landscapes and in burial patterns have been used to argue for a continuity between the Neolithic and Megalithic periods (Chakrabarti 1999, p. 239; Moorti 1994, p. 111; Rami Reddy 1990; see Johansen 2004, p. 310) and consequently a continuity of technological traditions as well.

Iron Age Metal

It is with the first millennium BC that significant numbers of metal artifacts—specifically, of iron, copper, and gold—appear in the archaeological record, along with evidence for iron production. Although from limited contexts these two lines of evidence argue for the emergence of a metal age (see discussion in "New Directions" below). The paucity of copper in earlier contexts contrasts with the *relatively* greater presence of copper. Although there is more copper than during the previous period, there are still fewer artifacts of copper and bronze than of iron.

A wide variety of iron artifacts are associated with megalithic Iron Age burial and habitation contexts, and the habitation mound at Hallur provides some of the earliest contexts. Eighteen iron artifacts were found, most of them associated with ashy and burnt deposits and pits cut into such deposits. They were not associated with any structural remains, unlike the earlier copper artifacts. One copper rod fragment was found from the Early Iron Age contexts, and one gold bead assigned to the Early Iron Age although found in earlier deposits. The iron artifacts consist of arrowheads (9), spearheads (2), knife blades (4), and points (2) with one artifact not described. Two arrowheads from the same context are described as being heavily encrusted with grains of rice and millet (Nagaraja Rao 1971, pp. 91–92).

Chakrabarti (1992, pp. 81–85; see also Tripathi 2008, pp. 113–118) provides a list of early artifact types that includes axes, hoes, spades, sickles, pickaxes, stone-cutter's wedges, bar wedges, crowbars, chisels and adzes, knives, tripods, swords, daggers and dirks, spear arrowheads, ceremonial scalloped axes, trisula (trident), hook-lamps, pendants, unknown objects. As a whole, taking into account later Iron Age contexts, these artifacts include weapons (e.g., daggers, swords, arrowheads, spearheads), tools (e.g., axes, knives, sickles, chisels, hoes, nails, adzes), utensils (e.g., pans, saucers, ladles), and toiletry articles (bangles, nail parers) as well as horse equipment (bits and ornaments). Horse equipment seems to be concentrated in the Vidarbha region (see Brubaker 2001). Excavations at the associated habitation/burial sites of Takalghat and Khapa (in the Vidarbha region, seventh-sixth century BC) point to a potential differential deposition of iron artifacts between the two contexts.

While artifacts like ladles, bangles, and arrowheads are common to both contexts, the excavator notes that the burials contained more tools and weapons than domestic artifacts (Deo 1970, p. 45; Fig. 25.1).

There have been some instances of bimetallic artifacts. A megalith at Mahurjhari (a site in the Vidarbha region) yielded a dagger with an iron blade and a bronze hilt (Deo 1973, p. 46). Other such artifacts have been reported from Pochampad, from the grave pit of Megalith 1: "On the eastern and western fringes of the pit were placed two iron implements, probably javelins. . . . Few barbed and socketted arrow heads were placed to the left of the skull. . . . Daggers and copper hilted knives were kept on either sides to the skull. In the south eastern corner of the pit, a large copper hilted dagger was also found fixed in between a red ware pot and stone pedestal (Murthy 2000, p. 98)."

Additionally, from the burials at Mahurjhari, copper bowls, lids with decoration, bangles, horse ornaments like bells and face pieces, and pieces of copper wire (compared to iron weapons, carpentry tools, agricultural tools, toiletry articles, and horse equipment) (Deo 1973, pp. 37–43). It is also interesting to note that at Takalghat and Khapa, which offer a direct comparison of habitation and funerary contexts, the majority of the copper artifacts (in categories similar to Mahurjhari) were found in the burials rather than in the habitation (Deo 1970, p. 51; see Brubaker 2001 for a discussion of regional characteristics).

Some sites have yielded significant numbers of bronze artifacts. The excavation of the urn burial field at the site of Adichanallur in southern Tamil Nadu has yielded bronze artifacts including ornamental vase stands, bowl lids, bowls, jars, cups, sieves, strainers, plaques, bangles, necklaces, ear ornaments, and diadems. The excavator, Alexander Rea, lists 122 bronze artifacts (compared with 394 iron artifacts). He also identifies 20 gold artifacts, 19 of which he identifies as diadems, items of various shapes with holes through which strings could pass that attached them to the body (Rea 1915; see also Chakrabarti and Lahiri 1996, pp. 90–92; Sundara 1972).

Gold artifacts are regularly found in Iron Age contexts, although not always and not in great numbers. Mahurjhari (in addition to Adichanallur discussed above) may be an exception. The excavators describe 2 necklaces, several groups of beads and ear ornaments, gold leaf fragments, and a group of circular disks, all from burial contexts (Deo 1973, pp. 54–56; see also Deglurkar and Lad 1992).

Production Evidence

Investigations into metal production practices have, for the most part, focused on the Iron Age and consequently that will be the focus of discussion here. Compared to the number of metal artifacts that have been uncovered from Iron Age contexts, there is limited production evidence, partially due to the fact that few habitation or non-funerary sites have been excavated. Samples of metal artifacts have been analyzed to identify composition and, less frequently, to provide information on techniques of production. However, such analyses have addressed only a very small number of the available artifacts, making it difficult to identify trends within and across sites and to hypothesize effectively about the nature and distribution of production practices. The data on furnaces and associated pyrotechnological installations are even fewer, and, as with the artifact analyses, their small number makes it difficult to assess to what extent their characteristics are typical of Iron Age metal production practices. Investigation of ancient mining locations and practices have come to light mainly through survey, especially the work of geologists.

Mining

Gold, copper, and iron ore are present in South India and there is evidence that all three metals were mined and exploited in antiquity, although there has been little archaeological investigation of mining operations.

Allchin (1962; see also Dube 2001) provides an overview of the evidence for ancient gold mining activity in South India, incorporating material reported by British geologists and officers. There is evidence for old workings in and around the Kolar, Gadag, and Hutti regions of Karnataka, where there is still significant contemporary gold mining. Although the shafts and depressions that indicate ancient mining have been recorded, less has been noted of the associated artifacts, if any, making determining chronology of use and cultural affiliation more difficult. The workings are indicated by shallow depressions, mounds of rubble, stone mauls, and hollows in rocks. Some areas (such as that around Hutti) have a high density of old workings-several hundred in less than 200 km^2. Shafts range from 30 m to 100 m deep, with timbering used in galleries. Firesetting was used as a method of excavation, indicated by presence of ashes, charcoal, and ventilation shafts. The fact that there were attempts to bail out water from the deeper shafts is evinced by water pots at the bottom of some old workings. Rope marks on timbers and stone attest to ore being hauled up to the surface. Mortar holes and depressions in rocks adjacent to the shafts and boulders used to crush ore indicate that ore processing began near the mines (Allchin 1962; Willies 1992).

There are several dates from the Hutti and Kolar gold mines. Two samples of timbers from a depth of 250 ft in the Hutti mines were dated to 1890 +/− 70 BP and 1810 +/−70 BP (Allchin 1962; Agrawal and Margaband 1975–1976, p. 139 note that the dates were probably based on a 5568 half-life and thus when converted to 5730 half-life would be 1945 +/− 70 BP and 1865+/−70 BP). A wood sample from a mine in the same area was dated to 1290+/−60 BP (Nagabhushanam et al. 2008). Two dates from the Kolar mines are 1290+/−90 BP and 1500+/−115 BP, although no information was provided regarding the context or nature of the samples (Agrawal and Margaband 1975–1976, p. 139). There are also two dates from gold mines in Chigargunta in Andhra Pradesh. Charcoal and wood samples were dated to 1270+/−110 BP and 1050+/−110 BP respectively (Agrawal et al. 1991, p. 330).

Taken together, these dates indicate gold mining activities spanning from the late centuries BC to the late first millennium AD, with an overlap in the dates of the Kolar and Hutti mines indicating contemporary exploitation. However, since mines by their very nature tend to be long-lived, with potential reuse of framing timbers and other such features, reliance on only radiocarbon dates tends to mask nuances in changes in use patterns. Addressing this requires investigating mining sites as archaeological sites, with the attendant emphasis on material culture and on integrating the mines into their broader social and economic contexts. Allchin (1962), for example, points to diagnostic artifacts found at Hutti-a stool, pot, grinding stone, and stone disks-to support the dating of the mining there to the last centuries BC and first centuries AD, possibly related to the expansion of the Mauryan polity. He also notes that iron gouges were found at Kolar and Hutti and argues that gold mining could not have predated the South Indian Iron Age (although exploitation of surface gold could have started during the Neolithic). These hypotheses must remain tentative until further investigation.

Ancient copper mines are located in Karnataka and Andhra Pradesh, although information about them is less robust. In Andhra Pradesh, old workings have been identified in northern districts (Bellary, Guntur, Kurnool, and Nellore). At Agnigundala (also spelled Agnikundala) in Guntur, old copper workings are spread over 3 km2 and are indicated by ore dumps, pounding stones, furnaces, and slag. Although no datable artifacts were recovered from these workings, material from Bandlamottu Hill in the same range was dated to 900+/−80 BP, 655+/−90 BP and 535+/−90 BP (Agrawal et al. 1976; Biswas 1996; Shrivastava 1999). Wood from the Ingaldhal copper mines of Karnataka was dated to 2010+/−110 BP (Agrawal et al. 1991, p. 332). Biswas (1996, p. 320) notes an undated copper mine associated with a megalithic settlement in the Hassan district of northern Karnataka. The mine shafts were associated with evidence for crushing, washing, and smelting ore.

Iron ore is prevalent throughout much of South Asia, and South India is no exception (Chakrabarti 1977, 1992). Ironically, despite the number of iron artifacts and the instances of iron smelting furnaces and slag that have been uncovered, there is the almost no information about ancient iron mines in South India. Various types of ores such as magnetite, hematite, and limonite are present in various forms including iron rich sand. Scholars have also argued that iron ore is more easily available on or near the surface (including in the form of ferruginous sand) and therefore may have left less significant traces of mining (see Tripathi 2008, pp. 103–111). Chakrabarti (1977, pp. 168–169) also makes the important point that while much of this iron ore may not be of high enough quality for modern iron smelting industries, it was apparently more than adequate for ancient metalworkers. Therefore, modern assessments of the presence of iron ore are of limited utility since they are concerned with ores appropriate for modern industry.

Unlike gold mining and production, there seems to have been no hiatus in the production of iron in the region. Therefore, while early scholars and chroniclers had to deduce the existence and impact of gold mining based on old workings, they encountered plentiful evidence of robust iron production practices. Such ethnographic information describing pre-industrial iron smelting has played a prominent role in attempts to reconstruct ancient iron production practices.

Smelting and Forging

The primary indications of production activities are deposits or heaps of slag which have been reported from numerous sites and from surface surveys. The frequency and consistency of such reports is such that it indicates that production activities were widespread across the landscape and among sites. Although a series of furnaces have been excavated from various sites, there exists an overall paucity of such evidence. The published material provides relatively limited descriptions of the furnaces, their contexts, and associated material culture, making tenuous any assessment of or elaboration on the data provided. While all the furnaces do indicate production practices, the precise nature of those practices-for example, distinguishing between bloomery and cast iron production, or identifying crucible steel production-is sometimes unclear (see below). Additionally, because of the relatively small number of excavated furnaces, it is difficult to identify patterns in production practices and therefore difficult to determine whether a given instance is indicative of widespread techniques or whether it is an aberration. Furthermore, the excavated furnaces are mostly dated to the latter part of the Iron Age, rather than to the beginning, meaning that they are less relevant to investigations of how iron technology may have initially emerged in South India.

Here I provide an overview of the evidence for metal production taking place in South India. While there is significant evidence of ferrous metallurgical activity, the evidence for the production of other metals such as copper and gold is less.

Of the 399 megalithic sites analyzed by U.S. Moorti (1994, pp. 38–42, 110), 91 have yielded evidence of various production activities, including ore, slag, and furnace fragments relating to iron, copper, and gold metallurgical activities. He lists 68 sites that have evidence of iron smelting, 3 with evidence for copper smelting, 18 with evidence for gold working and 2 with evidence of silver working. He further notes that approximately 40 % of megalithic sites are located in resource-rich zones that include metal ore deposits.

Mudhol (1997, pp. 6–8) identifies a series of ancient iron working sites in northern Karnataka, based on the presence of slag and ash. He argues that there is evidence that many megalithic sites are associated with nearby iron-smelting and iron-working installations. However, there is little or no excavation or further evidence to corroborate most of these identifications, and it is unclear whether the indications of iron slag are from surface or excavation contexts and what the stratigraphic relationship is between the slag and the Megalithic monuments (e.g., Allchin 1960, where the slag is noted on the surface and is dated to the medieval period). If these identifications are accurate, however, then it would seem to indicate that there is a significant occurrence of iron working in proximity to these Megalithic monuments and habitation sites.

A furnace that has been often cited in discussions of early iron production evidence comes from the Iron Age Megalithic site of Naikund in the Vidarbha region (Deo and Jamkhedkar 1982). This is a well described furnace with an associated habitation area dated from the sixth to the fourth centuries BC. Gogte (1982a) found the furnace, located at a distance from the two mounds being excavated, using a three-probe resistivity survey. It was excavated independently in a 4×4 m trench. As outlined in Possehl and Gullapalli (1999), the furnace was circular, built up of interlocking clay bricks, about 30 cm in diameter and 25 cm in height. The bottom of the furnace was paved with bricks. A tap hole for the slag was detected, and two (vitrified) tuyères were recovered, as well as 40 kg of slag. Only one piece of iron was recovered, corroded and approximately 5 cm long by 5 cm thick. A few pieces of iron and manganese ores were also recovered, which, along with debris located about 1 km to the southeast of the site, indicate the possible exploitation of the nearby manganiferrous belt. However, despite the relatively detailed description of the furnace, there does not seem to be any architectural context that can help reconstruct the relationship between production activities and the habitation. Gogte (1982b) also attempted to evaluate the efficiency of iron smelting carried out at the site. He determined that using about 10–12 kg per operation, these Megalithic smelters were able to produce 3.0–4.2 kg of pure iron.

An iron smelting furnace has been reported from Banahalli in Karnataka (dated 400–300 BC). Excavations revealed a bowl shaped cavity in the ground, associated with slag, ash, and charcoal. At the bottom of the furnace were a "cake of metallic iron" (Mudhol 1997, p. 35) and a large amount of slag, while excavations at Paiyampalli (c. 640–380 BC) in Tamil Nadu yielded large amounts of iron slag (Ramachandran 1989, p. 326; Archaeological Survey of India 1964–1965, p. 22, 1967–1968, p. 28). Sasisekaran (2004, pp. 17–21; see also Sasisekaran and Raghunatha Rao 2001) notes that a series of sites in Tamil Nadu have yielded fragments of furnaces, tuyères and slag. Although many of these remains have either been disturbed or are not well described (or both), their consistent presence across the archaeological landscape does indicate that metallurgical practices were not confined to certain regions. The scale of production at these sites as well as the distribution of production practices in relation to sites in their immediate vicinity would begin to provide information regarding the organization of production. A glimpse of such patterning comes from the site of Kodumanal, discussed below.

Evidence from two sites—Kodumanal and Guttur—has been identified by their excavators and by other scholars as being of special importance in the development of iron and steel metallurgy in South India. As will be discussed below, however, these assertions can only be tentative until more information is brought to light about the metallurgical installations in each case and more systematic analyses of metal artifacts are undertaken.

Kodumanal (Rajan 1994) is a megalithic burial and habitation site that covers approximately 100 acres and is located on the banks of a tributary of the Kaveri River in Tamil Nadu. Its occupation has been dated to between the third century BC and the third century AD, based on ceramic and epigraphic evidence. The site has yielded significant evidence of bead and metal (iron) manufacture, as well as of participation in long distance trade, including the Indian Ocean trade. The evidence for metal production comes from two distinct areas of the settlement, in the northern and southern areas, each of which has yielded two different types of metallurgical installations (Rajan 1998b; see also Rajan 1998a; Sasisekaran 2002).

One of the iron smelting furnaces was delineated through excavation and is described as having a circular base surrounded by slag, vitrified brick bats, and tuyère fragments. There was also a granite slab associated with the furnace, which is interpreted as an anvil; if this is so, it seems to indicate both smelting and forging occurring at this site.

To the north of the smelting furnace two additional furnace installations were excavated, one of which is described. It consisted of a large oval furnace which is surrounded by more than twelve smaller, circular furnaces. A crucible was found in one of these furnaces, and the entire installation is interpreted by the excavator as an early furnace for the production of crucible steel (as opposed to the production of wrought iron, which was taking place at the southern furnaces described above) (Rajan 1994, pp. 95–96). Other scholars have characterized this as the production of wootz (Sasisekaran and Raghunatha Rao 1999, p. 266).

This assertion of early crucible steel production needs further investigation, clarification, and elaboration. Crucible production of steel allows for a product with carbon and structural homogeneity, while limiting the presence of slag and other inclusions. Paul Craddock notes that in the South Asian context, "the most familiar products of crucible steel were the so-called Damascus-patterned blades forged from a very special variety of the crucible steel, and the term wootz could be used specifically for this patterned variety" (2003, p. 239). Confusion arises because of a conflation of all crucible steel with wootz; if the two terms are understood to mean the same thing, then any evidence for pre-medieval crucible steel would necessarily be understood to refer to wootz. However, it is possible to be engaged in the production of crucible steel without producing wootz, and Craddock (2003), through an examination of documentary material, argues that there is evidence for early (first centuries AD) crucible steel production in South Asia. He notes that the evidence from Kodumanal (and from sites in Sri Lanka) could be the archaeological confirmation of the documentary evidence. This assessment is dependent on further information about and analyses of the crucible and the iron artifacts manufactured at the site (see next section for discussion of the analysis of iron artifacts from Kodumanal).

The excavator notes that there are discernible differences between the locations of iron smelting as opposed to steel production. Based on the distribution of artifacts and production debris, he argues that craftworkers involved in the stone and steel industries were located in the northern part of the site, with agriculturalists in the center and agriculturalists and iron smelters in the southern areas. The iron and steel production areas of the settlement were separated by approximately 300 m. A resistivity survey suggested that iron smelting furnaces were concentrated in the southern area of the settlement (spread over 100 m^2), and a lack of significant structural remnants or artifacts besides potsherds suggests that this was the edge of the habitation. The steel production area, by contrast, had evidence of post-holes, indicating a superstructure as well as coins and inscribed sherds, which in conjunction with adjacent trenches seems to indicate a more central location. The stratigraphic relationship between the iron and steel installations is unclear, although they are interpreted as being contemporary. The excavator argues, based on the differential nature of structural remains, that the steel producers occupied a higher social/economic position than the iron producers, which indicates the apparently differential valuing of steel over iron (Rajan 1994, pp. 61–66).

Guttur (Archaeological Survey of India 1982–1983, pp. 71–72; see also Raghunatha Rao and Sasisekaran 1997; Sasisekaran 2002), is a site in northwestern Tamil Nadu whose occupation spans from Megalithic to Late Medieval and modern periods (third century BC to ninth century AD, based on ceramics and other artifacts), with no earlier Neolithic component. Excavation in three trenches has revealed structures with several rooms constituted of stone and brick walls and earth floors. In another trench, whose spatial and stratigraphic relationship to those with the structures is unclear, the excavators uncovered what were initially described as "elongated, oval shaped, trough-like terracotta objects recalling Megalithic sarcophagus" (*sic*; Archaeological Survey of India 1982–83, p. 72). Due to the lack of funerary objects or bone, and the presence of terracotta pipe fragments encrusted with iron and a large quantity of iron slag, the excavators hypothesized that these installations might have been iron smelting furnaces; they did not assign a time frame for these installations.

During later surveys, fourteen other sets of similar installations, now identified as "twin furnaces," were located in addition to those already excavated (Raghunatha Rao and Sasisekaran 1997; Sasisekaran 2002). Raghunatha Rao and Sasisekaran (1997, pp. 349–350; see also Sasisekaran 2002, p. 21)) argue that these installations were iron smelting furnaces based on the presence of slag and apparent bellows and tap holes, and also on the fact that they closely resemble working furnaces described by European travelers and chroniclers such as Robert Bruce Foote. While these historical reports indicate that the furnaces were producing wrought iron, those at Guttur have been identified as potentially producing cast iron.

The assertion that the Guttur installations produced cast iron is based on metallographic analysis of one artifact and the presence of possible terracotta "molds." These hollow terracotta rings dating from the late Iron Age (c. third century BC) have been found at other sites in Tamil Nadu. They are approximately 30 cm in diameter and have a spout (Sasisekaran 2002, p. 22). However, it is unclear if there is any explicit evidence connecting these terracotta objects to iron production activities.

Most recently, Peter Johansen's (2007, 2008) work at the Iron Age sites of Bukkasagara and Rampuram reinforces and elaborates on the spatial patterning of production activities apparent in the studies mentioned above. Significant evidence for metal production in the form of smithing and forging slag occurred at Bukkasagara and was concentrated in a circumscribed area. There was less metallurgical evidence at Rampuram; however, it too was spatially delimited within the site and indicates smithing rather than smelting activities. Such evidence means that the smiths would have had to acquire their iron from elsewhere, and perhaps points to a systematic differentiation of iron production activities based on stage of production, an argument that has also been made for other parts of South Asia. Iron production is too broad a term in that it does not capture the potential for differential organization of the various stages of production (see Gullapalli 2005).

At Bukkasagara and Rampuram, Johansen's ceramic and architectural (including mortuary) analyses at these sites reveals patterns of social differentiation in which certain practices such as commensality, mortuary rituals, and iron production were of significance. Although in its initial stages, this research begins to delineate possible relationships between the control of iron production (at least one stage of it) and social and political distinctions within Iron Age society, such as those that are also reflected in Robert Brubaker's (2001) analysis of megalithic cemetery size, form and distribution across South India.

Analysis of Metal Artifacts

A number of metal artifacts have been analyzed, and in most cases it has been to identify the constituent elements of each artifact. Indeed, many excavation reports contain a compositional analysis of some iron and copper/bronze artifacts to determine the nature and extent of alloying. For example, a number of iron artifacts have also been analyzed for their composition, primarily to determine carbon content and therefore the extent (if any) of steeling (see Chakrabarti 1992, pp. 93–95 for a general discussion; examples include analyses of 1 to 2 artifacts from Takalghat and Khapa (Munshi and Sarin 1970, pp. 78–79) and Mahurjhari (Joshi 1973, p. 77)). Here, the focus is on studies that have gone beyond composition and that have addressed other aspects of production.

As Possehl and Gullapalli (1999) note, analyses of early iron artifacts have revealed that specific properties of iron were being exploited by Iron Age smiths and that there existed an apparently long tradition of lamination techniques used in their fabrication (see also Agrawal et al. 1990; Agrawal et al. 1983) analyzed three iron artifacts—two implements and an axe—from Tadakanahalli (northern Karnataka, ca. 1000 BC). Multiple sections were taken from each sample, allowing the reconstruction of the production process. The investigators concluded that each artifact was composed of two definite layers; that the edge was mainly martensite, meaning that the implements had undergone quenching; that layers of ferrite and pearlite are present; and that martensite decreases and pearlite/ferrite increases toward the interior. Similarly, metallurgical analysis of two iron artifacts (fragments of a sword and dagger) from Kodumanal in Tamil Nadu indicated a differential hardness between core and edge of the blade (Sasisekaran and Raghunatha Rao 1999, p. 266–272).

The artifacts from Tadakanahalli discussed previously showed that layers of wrought iron, which had been carburized, were forged with high carbon sheets, indicating that the smiths were able to manipulate high carbon and low carbon sheets to their advantage. A spear from Kumaranhalli (northern Karnataka, c. 1200 -1100 B.C.) and another axe from Tadakanhalli were subjected to metallographic analysis. The results also revealed alternating layers of carburized (characterized as a hypoeutectoid steel) and uncarburized iron,which had been hammered and welded together (Agrawal et al. 1990). Mudhol's metallographic analyses of various iron artifacts indicate the presence of this technique at other sites (Mudhol 1997, pp. 61, 64). Analysis of four artifacts from the Vidarbha megaliths also indicates consistent evidence for lamination (Joshi et al. 2008), as did that of an iron bar from Mallappadi, Tamil Nadu (Sasisekaran 2004, pp. 38–39).

Seven iron artifacts and a piece of slag from Kodumanal were analyzed –two arrowheads, an iron chisel, a sword bit, dagger, nail, and bead (Sasisekaran 2004, pp. 44–54). The two arrowheads were hot forged, which resulted in higher carbon contents at the surface. They had variable microstructures and varying hardnesses at different areas. The chisel was of a high-carbon steel resulting from carburization during the forging process, while the dagger had a body of low carbon steel with a high carbon cutting edge and exhibited evidence of bands having been welded together. The nail and bead were hot forged and exhibited varying microstructures. All of these artifacts had slag inclusions. The exception seems to have been the sword bit which was heavily corroded but whose microstructures revealed spheroidal graphite iron. However, the investigator points out that more artifacts would have to be analyzed to determine whether this was an accident or intentional.

The microstructure of an iron artifact (not described) from Guttur was analyzed and revealed significant variations across a cross section of the artifact and included pearlite, cementite, and ledeburite. The latter is interpreted as evidence for the presence of molten metal (cast iron), with variation in cooling resulting in the variation in microstructures. Compositional analysis of another heavily corroded artifact yielded the presence of iron oxide, phosphorus, and sulfur. The ore for the furnaces may have been the locally available ferruginous sand, and XRD analysis of slag indicates that the ore was of high quality and high in iron oxide (Raghunatha Rao and Sasisekaran 1997, pp. 353–354).

The copper artifacts of the Iron Age have received relatively less analytical attention. Srinivasan (1997, 2006; Srinivasan and Glover 1995, 1997) has analyzed high-tin bronzes from megalithic sites in South India, including Adichanallur. She argues that these artifacts "reflect sophisticated bronze working practices with the use of a specialized alloy known as wrought and quenched high-tin bronze alloy. . . . These not only rank amongst the earliest such alloys known in the world but also suggest that bronze metallurgy at the time was more advanced than previously suspected (Srinivasan 2004, p. 1)." Her analysis of slag from northern Karnataka has also pointed to the existence of local bronze working, refuting arguments that these metal objects (if not the technology as well) were imported from Southeast Asia (Srinivasan 1998; see Rajpitak and Seeley 1979). Other analyses of copper have focused on identifying the composition of the artifacts (e.g., Joshi 1973, p. 77; Munshi and Sarin 1970, pp. 78–79).

Six of the gold artifacts from Mahurjhari were analyzed (Nasnolkar 1973, pp. 78–79): a ring, three earrings, an ear ornament, and some gold leaf. Although all of these artifacts have been identified as gold, compositional analysis revealed that all were composed of gold and silver. Prasad and Ahmad (1998) note that the gold deposits of South India contain silver of varying percentages, such that the color of the gold ranges from yellow to almost white. They also note that native silver deposits are extremely rare in India. In this case, the percentage of gold ranged from 6 % (the gold leaf) to 74 % (the ear ornament), which resulted in varying shades of gold. Nasnolkar suggests that although the ear ornament now looks blackish because of tarnish, if it was heated it would look perfectly white. All except one pair of small earrings were manufactured by hammering. The small earrings are tubular, and were manufactured by pulling the metal through a piece of bone or stone. The tube was then filled with a lacquer or resin and then shaped using a wooden cylinder.

What emerges from this overview of production evidence is that there is a great deal of interesting and significant information waiting to be exploited. The fullest potential of such data can only be realized when more mines and furnaces are located and when series of artifacts are analyzed, rather than small samples. Such analyses will then yield patterns that can speak to the intentions and capacities of the metalworkers of the Iron Age.

New Directions?

A great deal of progress has been made over the past decades in the investigation and understanding of the megalithic monuments of South India and their associated metal technologies. However, it is also very obvious that a great deal has yet to be done. New approaches to the monuments are emerging that situate them within the construction of political and symbolic landscapes (e.g., Bauer et al. 2007; Brubaker 2001; Johansen 2004). This move from a static and descriptive to a dynamic approach is a promising one that offers alternative means of engaging with the Iron Age landscape of South India. Similar shifts need to occur in the investigation of metal technologies in order to build on what has been done (see also Mohanty and Selvakumar 2002).

A primary concern is the lack of contextual information regarding production practices. A focus on funerary contexts has meant that little evidence of production has been uncovered leading to an inadequate understanding of how metal technologies functioned within Iron Age societies. The research has also been dominated by one mode of consumption—that of funerary contexts—but with little relation to daily activities and other forms of consumption of such trade. In many ways, the symbolic and ritual significance of the funerary deposits can only emerge through comparison with other modes of using and disposing of the metal artifacts. It is interesting that the initial appearance of this new technology—one that is especially amenable to recycling—is associated with significant numbers of artifacts being taken out of circulation as they are interred with the dead. This seems to indicate that symbolic understandings of metal technology were as important as (or more important than?) utilitarian ones.

Certain trends that have only been hinted at so far—the differential deposition of copper in habitation and funerary contexts—need to be further investigated. Such investigations can also help us to understand the role of the multiple metal technologies within Iron Age societies. What was the relationship between iron, copper, gold, and silver? Furthermore, what was the significance of the bimetallic artifacts, if any? Is there any significance to the recurrence of laminating as a technique of production? Finally, what was the dynamic between metal and stone technologies? Allchin and Allchin (1982, p. 329), for example, note that the stone blade and stone axe industries of the Neolithic differentially persist in the Iron Age. Mohanty and

Selvakumar (2002, pp. 333–334) argue that a paradigm shift needs to occur, one in which megalithic sites are not simply understood as discrete entities within a chronological or typological framework but are instead situated within local and regional landscapes arising out of specific cultural processes and patterns.

Such a repositioning requires moving away from general discussions of diffusion and migration that tend to mask the various levels at which such processes can work and that blur the distinction between initial local development and the subsequent dissemination of the new technology across the landscape. The utility of an emphasis on determining antiquity (and therefore "origins") has been exhausted; delineating metallurgical traditions and their roles within and relationships to social forms may prove to be a more fruitful avenue—one that builds on past research rather than replicates it. Although Allchin and Allchin (1982, p. 335) point to a similarity of form, there is also emerging evidence for a differentiation of process. Craddock (2003; see also Bronson 1986) notes two methods for the production of crucible steel in South India; Johansen's (2007) research may lead to identification of forging sites as distinct from smelting sites, while at the same time Rajan's (1994) work at Kodumanal seems to indicate several production related activities at one site, with attendant social implications. Although chronologically separated, these examples indicate potentially dynamic landscapes in which control over production and metallurgical production techniques may be two of many dimensions. Indeed, the variation and similarity embodied within the aspects of the archaeological record of the Iron Age—a combination which has tended to stymie attempts at comprehensive typologies—may best be approached, in part, by investigating how iron production practices were manipulated and adapted within the contexts of dynamic local Iron Age societies.

An emphasis on origins and expertise—on the first appearances of a predetermined technological standard—undervalues its subsequent manipulation, adaptation, and elaboration within specific social and cultural contexts. Such an approach obscures any potential stages of experimentation that may have been a prelude, in this case, to the consistent and purposeful production of iron. In South India such a stage is yet to be defined, so although we know when iron artifacts begin appearing in the archaeological record, we do not know how the metalworkers arrived at that point. Ironically, the delineation of such a stage may put to rest any lingering doubts about the indigeneity of iron in South India for we would be able to situate iron production within a set of local practices. Joyce White and Elizabeth Hamilton (this volume) put forward an effective argument about the origins of Southeast Asian bronze metallurgy by moving beyond formal similarities in artifacts. They argue that the practice of metal production in Southeast Asia has affinities to Eurasian metal traditions and that this is an important component of the problem that must not be overlooked. Their holistic approach to metal technologies can be instructive here, for it highlights the efficacy of systematically incorporating production techniques and the social contexts of use and production into the discussion.

These are by no means all of the questions and possible directions that emerge regarding early metal in South India. However, if we are to be able to address the types of questions put forth by the editors of this volume, we need to significantly change the paradigm that structures our approach to the megalithic monuments and metal technologies of the Iron Age of South India.

Acknowledgments I would like to thank Ben Roberts and Chris Thornton for inviting me to be a part of their Society for American Archaeology (SAA) session and of this volume. I would also like to thank Robert Brubaker and Peter Johansen for sharing with me some of their work. This chapter benefitted greatly from the comments of the reviewers and of Paul Craddock, who kindly pointed me in some very fruitful directions. All errors of commission and omission are of course my own.

References

Agrawal, D. P., & Margaband, C. (1975–1976). Ancient gold workings: Some new ^{14}C dates. *Puratattva, 8,* 138–139.

Agrawal, D. P., Margabandhu, C., & Shekar, N. C. (1976). Ancient copper working: Some new ^{14}C dates. *Indian Journal of History of Science, 11*(2), 133–136.

Agrawal, D. P., Kusumgar, S., & Yadava, M. G. (1991). Physical research laboratory radiocarbon date List VI. *Radiocarbon, 33* (3), 329–344.

Agrawal, O. P., Narain, H., & Bhatia, S. K. (1983). Technical studies of iron implements from the megalithic site Tadakanahalli. *Puratattva*, *12*, 97–100.

Agrawal, O. P., Harinarain, Prakash, J., & Bhatia, S. K. (1990). Lamination technique in iron from artifacts in ancient India. *Journal of the Historical Metallurgy Society 24*(1), 12–26.

Allchin, F. R. (1962). Upon the antiquity and methods of gold mining in ancient India. *Journal of the Economic and Social History of the Orient, 5* (2), 195–211.

Allchin, F. R. (1960). *Piklihal Excavations*. Hyderabad: Andhra Pradesh Government Archaeological Series No. 1, Government of Andhra Pradesh.

Allchin, F. R. (1963). *Neolithic Cattle Keepers of South India: A Study of the Deccan Ashmounds*. Cambridge: Cambridge University Press.

Allchin, B., & Allchin, R. (1982). *The rise of civilization in India and Pakistan*. Cambridge: Cambridge University Press.

Archaeological Survey of India. (1964–1965). Excavation at Paiyampalli, District North Arcot. Indian Archaeology—A Review, 22–23.

Archaeological Survey of India. (1967–1968). Excavation at Paiyampalli, District North Arcot. Indian Archaeology—A Review, 26–30.

Archaeological Survey of India. (1982–1983). Excavation in Gutturmalai, Guttur, District Dharampuri. Indian Archaeology—A Review, 71–72.

Bauer, A. M., Johansen, P. G., & Bauer, R. L. (2007). Toward a Political Ecology in Early South India: Preliminary Considerations of the Sociopolitics of Land and Animal Use in the Southern Deccan, Neolithic through Early Historic Periods. *Asian Perspectives*, *46*(1), 3–35.

Bhardwaj, H. C. (2000). *Metallurgy in Indian Archaeology*. Varanasi: Tara Book Agency.

Biswas, A. K. (1996). *Minerals and Metals in Ancient India: Volume I, Archaeological Evidence*. New Delhi: D.K. Printworld.

Boivin, N. (2004). Landscape and Cosmology in the South Indian Neolithic: New Perspectives on the Deccan Ashmounds. *Cambridge Archaeological Journal*, *14*(2), 235–257.

Bronson, B. (1986). The making and selling of wootz, a crucible steel of India. Archaeomaterials, 1 (1), 13–51.

Brubaker, R. (2001). Aspects of Mortuary Variability in the South Indian Iron Age. *Bulletin of the Deccan College*, *60–61*, 253–302.

Chakrabarti, D. K. (1976). The Beginnings of Iron in India. *Antiquity*, *50*, 114–124.

Chakrabarti, D. K. (1977). Distribution of iron ores and the archaeological evidence of early iron in India. *Journal of the Economic and Social History of the Orient*, *20*(2), 166–184.

Chakrabarti, D. K. (1992). *The Early Use of Iron in India*. Delhi: Munshiram Manoharlal Publishers.

Chakrabarti, D. K. (1999). *India: An Archaeological History*. Oxford: Oxford University Press.

Chakrabarti, D. K., & Lahiri, N. (1996). *Copper and its Alloys in Ancient India*. Delhi: Munshiram Manoharlal.

Craddock, P. T. (2003). Cast Iron, Fined Iron, Crucible Steel: Liquid Iron in the Ancient World. In P. Craddock & J. Lang (Eds.), *Mining and Metal Production Through the Ages* (pp. 231–257). London: The British Museum Press.

Deglurkar, G. B., & Lad, G. P. (1992). *Megalithic Raipur (1985–1990)*. Pune: Deccan College Post Graduate and Research Institute.

Deo, S. B. (1970). *Excavations at Takalghat and Khapa (1968–1969)*. Nagpur: Nagpur University.

Deo, S. B. (1973). *Mahurjhari Excavation 1970–1972*. Nagpur: Nagpur University.

Deo, S. B. (1985). The Megaliths: Their Culture, Ecology, Economy and Technology. In S. B. Deo & K. Paddayya (Eds.), *Recent Advances in Indian Archaeology: Proceedings of the Seminar held in Poona in 1983* (pp. 89–99). Poona: Deccan College Post-Graduate and Research Institute.

Deo, S. B., & Jamkhedkar, A. P. (1982). *Excavations at Naikund 1978–1980*. Bombay: Government of Maharashtra, Department of Archaeology and Museums.

Devaraj, D. V., Patil, C. S., Joshi, N. V., & Gangadhara, T. S. (1996). *Heggadehalli: Report on Megalithic Excavation: 1995*. Mysore: Directorate of Archaeology and Museums.

Dube, R. K. (2001). India's contribution to the mining, extraction and refining of gold: Some observations related to the pre-Christian era. In Ramachandra Rao, P. & Goswami, N. G. (Eds.), *Metallurgy in India: A retrospective* (pp. 163–181). New Delhi: India International Publisher.

Erdosy, G. (1995). Language, material culture and ethnicity: Theoretical perspectives. In G. Erdosy (Ed.), *The Indo-Aryans of Ancient South Asia: Language, Material Culture and Ethnicity* (pp. 1–31). New York: Walter de Gruyter.

Gogte, V. D. (1982a). Megalithic iron smelting at Naikund (Part 1): Discovery by three-probe resistivity survey. In S. B. Deo & A. P. Jamkhedkar (Eds.), *Excavations at Naikund 1978–1980* (pp. 52–55). Bombay: Government of Maharashtra, Department of Archaeology and Museums.

Gogte, V. D. (1982b). Megalithic iron smelting at Naikund (Part 2): Efficiency of iron smelting by chemical analysis. In S. B. Deo & A. P. Jamkhedkar (Eds.), *Excavations at Naikund 1978–1980* (pp. 56–59). Bombay: Government of Maharashtra, Department of Archaeology and Museums.

Gullapalli, P. (2005). *Smelting and Smithing: The organization of iron production in Early Historic southeastern Rajasthan*. PhD Dissertation submitted to the Department of Anthropology, University of Pennsylvania, Philadelphia.

Johansen, P. G. (2004). Landscape, monumental architecture, and ritual: A reconsideration of the South Indian ashmounds. *Journal of Anthropological Archaeology*, *23*, 309–330.

Johansen, P. G. (2007). *The Production of Settlement Landscapes and Social Difference in Iron Age South India: Surface Collection and Documentation at Bukkasagara and Rampuram, Karnataka*. Poster presented at 2007 Annual Meeting of the American Anthropological Association, Washington DC.

Johansen, P. G. (2008). *A Political Economy of Space: Social Organization and the Production of an Iron Age Settlement Landscape in Northern Karnataka*. PhD Dissertation submitted to Department of Anthropology, University of Chicago, Chicago.

Joshi, A. P. (1973). Analysis of Copper and Iron Objects. In S. B. Deo (Ed.), *Mahurjhari Excavation 1970–1972* (p. 77). Nagpur: Nagpur University.

Joshi, S. V., Deshpande, P. P., Mohanty, R. K., Dhokey, N. B., & More, M. A. (2008). Metallographic investigations of iron objects found in the Megalithic burials in Vidarbha region of Maharashtra. *Puratattva, 38,* 244–250.

Kennedy, K. A. R. (1975). *The Physical Anthropology of the Megalith Builders of South India and Sri Lanka*. Canberra: Oriental Monograph Series of the National University of Australia.

Kennedy, K. A. R. (1987). Hauntings at Adittanalur: An Anthropological Ghost Story. In J. Jacobson (Ed.), *Studies in the Archaeology of India and Pakistan* (pp. 257–295). New Delhi: Oxford and IBH.

Kennedy, K. A. R. (2002). Megalithic Pochampad: The Skeletal Biology and Archaeological Context of an Iron Age Site in Andhra Pradesh, India. *Asian Perspectives*, *41*(1), 103–128.

Krishnaswami, V. D. (1949). Megalithic Types of South India. *Ancient India*, *5*, 35–45.

Korisettar, R., Venkatasubbaiah, P. C., & Fuller, D. Q. (2002). Brahmagiri and beyond: The archaeology of the Southern Neolithic. In Settar, S. & Korisettar, R. (Eds.), *Indian Archaeology in Retrospect, Volume I: Prehistory* (pp. 151–225). New Delhi: Manohar.

Leach, E. (1990). Aryan Invasions over Four Millennia. In E. Chnuki-Tierney (Ed.), *Culture Through Time: Anthropological Approaches* (pp. 227–245). Stanford: Stanford University Press.

McIntosh, J. R. (1985). Dating the South Indian megaliths. In J. Schotsmanns & M. Taddei (Eds.), *South Asian Archaeology 1983* (pp. 467–494). Naples: Universitario Orientale, Dipartimento di Studi Asiatici.

Mohanty, R. K., & Selvakumar, V. (2002). The Archaeology of the Megaliths in India: 1947–1997. In S. Settar & R. Korisettar (Eds.), *Indian Archaeology in Retrospect, Volume I: Prehistory* (pp. 313–351). New Delhi: Manohar and Indian Council of Historical Research.

Mohanty, R. K., & Walimbe, S. R. (1993). A Demographic Approach to the Vidarbha megalithic culture. *Man and Environment*, *18*, 93–103.

Moorti, U. S. (1994). *Megalithic Culture of South India: Socioeconomic Perspectives*. Varanasi: Ganga Kaveri Publishing House.

Mudhol, M. S. (1997). *A Technical Study of Megalithic Metal Objects*. Mysore: Directorate of Archaeology and Museums.

Munshi, K. N., & Sarin, R. (1970). Analysis of Copper and Iron Objects from Takalghat and Khapa. In S. B. Deo (Ed.), *Excavations at Takalghat and Khapa (1968–1969)* (pp. 78–79). Nagpur: Nagpur University.

Murthy, P. R. (2000). *Megalithic Culture of the Godavari Basin*. Sharada Publishing House, Delhi.

Nagabhushanam, P., Sangurmath, P., Patil, M. L., & Sukhija, B. S. (2008). Ancient gold mining activity in the Hutti-Maski greenstone belt, Karnataka, India: Radiocarbon perspective. *Current Science, 95*(3), 389–391.

Nagararaja Rao, M. S. (1971). *The Protohistoric Cultures of the Tungabhadra Valley*. Dharwar: M.S. Nagaraja Rao.

Nagararaja Rao, M. S. (1985). The earliest Iron Age graves in Karnataka. In V. N. Misra & P. Bellwood (Eds.), *Recent Advances in Indo-Pacific Prehistory* (pp. 469–470). Leiden: E.J. Brill.

Nagaraja Rao, M. S., & Malhotra, K. C. (1965). *The Stone Age Hill Dwellers of Tekkalakota.* Pune: Deccan College Post-Graduate and Research Institute.

Nasnolkar, M. M. (1973). Analysis of Gold Objects. In S. B. Deo (Ed.), *Mahurjhari Excavation 1970–1972* (pp. 78–79). Nagpur: Nagpur University.

Paddayya, K. (1973). *Investigations into the Neolithic Cultures of the Shorapur Doab, South India*. Leiden: E.J. Brill.

Paddayya, K. (1998). Evidence of Neolithic cattle penning in Budihal, Gulbarga District, Karnataka. *South Asian Studies 14*, 141–153.

Paddayya, K. (2002). The Problems of Ashmounds of Southern Deccan in the Light of Recent Research. In K. Paddayya (Ed.), *Recent Studies in Indian Archaeology* (pp. 81–111). New Delhi: Munshiram Manoharlal Publishers and Indian Council of Historical Research.

Parpola, A. (1973). *Argument for an Aryan Origin of the South Indian Megaliths*. Tamil Nadu: State Department of Archaeology, Government of Tamil Nadu.

Possehl, G. L., & Gullapalli, P. (1999). The Early Iron Age in South Asia. In V. C. Pigott (Ed.), *The Archaeometallurgy of the Asian Old World* (pp. 153–175). Philadelphia: University Museum Press.

Prasad, B., & Ahmad, N. (1998). Probable sources of silver in ancient India: A historico–scientific approach. In Tripathi, V. (Ed.), *Archaeometallurgy in India* (pp. 185–190). New Delhi: Sharada Publishing House.

Raghunatha Rao, B., & Sasisekaran, B. (1997). Guttur—An Iron Age industrial centre in Dharmapuri District. *Indian Journal of History of Science*, 32(4), 347–359

Rajan, K. (1994). *Archaeology of Tamilnadu (Kongu Country)*. Delhi: Book India Publishing Company.

Rajan, K. (1998a). Archaeology of the South Arcot Region with Special Reference to Megalithic Burial Complexes. *Man and Environment*, *23*(1), 95–105.
Rajan, K. (1998b). Further excavations at Kodumanal, Tamil Nadu. *Man and Environment*, *23*(2), 65–76.
Rajpitak, W., & Seeley, N. J. (1979). The bronze bowls from Bon Don Ta Phet, Thailand: An enigma of prehistoric metallurgy. *World Archaeology, 11*(1), 26–31.
Ramachandran, K. S. (1989). Paiyampalli. In Ghosh, A. (Ed). *An Encyclopedia of Indian Archaeology: Gazetteer* (pp. 325–327). New Delhi: Munshiram Manoharlal Publishers.
Rami Reddy, V. (1990). Ashmounds in South India: A Review. In A. Sundara (Ed.), *Archaeology in Karnataka (Papers Presented at the National Seminar on Archaeology, 1985)* (pp. 85–99). Mysore: Directorate of Archaeology and Museums.
Rea, A. (1915). *Catalogue of the Prehistoric Antiquities from Adichanallur and Perumbair*. Madras: Madras Government Museum.
Sasisekaran, B. (2002). Metallurgy and metal industry in ancient Tamil Nadu—An archaeological study. *Indian Journal of History of Science*, 37(1), 17–29.
Sasisekaran, B. (2004). *Iron industry and metallurgy: A study of ancient technology.* Chennai: New Era Publications.
Sasiekaran, B., & Raghunatha Rao, B. (1999). Technology of Iron and Steel in Kodumanal—An Ancient Industrial Centre in Tamil Nadu. *Indian Journal of History of Science*, *34*(4), 263–272.
Sasisekaran, B., & Raghunatha Rao, B. (2001). Iron in Ancient Tamilnadu. In Ramachandra Rao, P. and Goswami, N. G. (eds.), *Metallurgy in India: A Retrospective* (pp. 92–103). New Delhi: India International Publisher.
Sastry, D. L. N. (2000). *Paidigutta Excavations: A Proto Historic Site in Lower Thungabhadra Valley, Mehaboobnagar District, Andhra Pradesh*. Jaipur: Publication Scheme.
Shaffer, J. G. (1984). The Indo-Aryan Invasions: Cultural Myth and Archaeological Reality. In J. R. Lukacs (Ed.), *The People of South Asia: The Biological Anthropology of India, Pakistan and Nepal* (pp. 77–90). New York: Plenum Press.
Shaffer, J. G., & Lichtenstein, D. A. (1995). The concepts of "cultural tradition" and "palaeoethnicity" in South Asian archaeology. In G. Erdosy (Ed.), *The Indo-Aryans of Ancient South Asia: Language, Material Culture and Ethnicity* (pp. 126–154). New York: Walter de Gruyter.
Shrivastava, R. (1999). Mining of copper in ancient India. *Indian Journal of History of Science*, 34(3), 173–180.
Srinivasan, S. (1997). The Composition of Bronze Slags from Kalyadi in South India, and its Implications for the problem of Tin in South Indian Antiquity. In A. Sinclair, E. Slater, & J. Gowlett (Eds.), *Archaeological Sciences 1995* (pp. 136–142). Oxford: Oxbow Books.
Srinivasan, S. (1998). High Tin Bronze Working in India: The Bowl Makers of Kerala. In Tripathi, V. (Ed.), *Archaeometallurgy in India* (pp. 241–250). Delhi: Sharada Publishing House.
Srinivasan, S. (2006). Megalithic High-tin Bronzes: Ethnoarchaeological and Archaeometalurgical Insights on Manufacture and Possible Artistic and Musical Significance. *Man and Environment*, *31*(2), 1–8.
Srinivasan, S., & Glover, I. (1995). Wrought and Quenched and Cast, High Tin Bronzes from Kerala State, Southern India. *Journal of Historical Metallurgy*, *29*(2), 69–75.
Srinivasan, S., & Glover, I. (1997). Archaeometallurgical Implications of New Findings of Traditional Crafts of Making High-tin 'delta' Bronze Mirrors and 'beta' Bronze Vessels in Kerala State of South India. In P. Vandiver, J. Druzik, J. Merkel, & J. Stewart (Eds.), *Materials Issues in Art and Archaeology V* (pp. 81–105). Warrendale: Materials Research Society.
Sundara, A. (1972). Chronological Order of Megalithic Tomb-types in Karnataka. In D. P. Agrawal & Ghosh, A. (Eds.), *Radiocarbon and Indian Archaeology* (pp. 239–251). Bombay: Tata Institute of Fundamental Research.
Tewari, R. (2003). The origins of iron-working in India: New evidence from the Central Ganga Plain and the Eastern Vindhyas. *Antiquity, 77*(298), 536–545.
Thomas, P. K. (1992). Faunal background of the Iron Age culture of Maharashtra. *Man and Environment, 17*(2), 75–80.

Tripathi, V. (2008). *History of iron technology in India (from beginning to pre-modern times).* New Delhi: Rupa & Co.
Wheeler, M. (1947–1948). Brahmagiri and Chandravalli 1947: Megalithic and other cultures in the Chitaldrug District, Mysore State. *Ancient India*, *4*, 180–310.
Wheeler, M. (1959). *Early India and Pakistan: To Ashoka.* New York: Frederick A. Praeger.
Willies, L. (1992). Ancient and post-Medieval mining sites in the Khetri Copper Belt and Kolar Gold Field, India. *Bulletin of the Peak District Mines Historical Society 11*(6), 285–295.

Chapter 26
Metals, Society, and Economy in the Late Prehistoric Eurasian Steppe

Roger Doonan, Bryan Hanks, Dmitry Zdanovich, Elena Kupriyanova, Derek Pitman, Natal'ya Batanina and James Johnson

Eurasian Steppe Prehistory and the Study of Metals

The dynamic relationship between the production and use of metals has been tied persistently to the emergence and development of complex social orders in many regions of the ancient world and has played a crucial role in the rise of the modern industrial world (Knapp et al. 1998; Maddin 1988; Levy 2003; Linduff 2004; Tylecote 1987). Importantly, as Knapp (1998, p. 1) observed, "the study of the mining of metals—the bailiwick of several different disciplines—reveals great diversity of approach." When harnessed together, however, such diversity provides a formidable conceptual and methodological approach capable of yielding more holistic understandings of societies, metals, and the shifting historical and cultural values that surround them. The articles contained within this reader are a solid example of this

R. Doonan (✉) · D. Pitman
Department of Archaeology, University of Sheffield, Sheffield, UK
e-mail: r.doonan@sheffield.ac.uk

D. Pitman
e-mail: d.pitman@sheffield.ac.uk

B. Hanks
Department of Anthropology, University of Pittsburgh, Pittsburgh, PA, USA
e-mail: bkh5@pitt.edu

D. Zdanovich · E. Kupriyanova
Scientific and Educational Centre for Research on the Problems of Nature and Man, Chelyabinsk State University, Russia
e-mail: dzdan@mail.ru

N. Batanina
Reserve "Arkaim", Chelyabinsk, Russia
e-mail: someone2005@pisem.net

J. Johnson
Department of Anthropology, University of Pittsburgh, Pittsburgh, PA, USA
e-mail: jaj41@pitt.edu

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_26,

approach and provide an important up-to-date synthesis on metallurgical studies in many parts of the world.

Eurasian steppe metallurgy is frequently viewed as existing well beyond the initial innovation of exploitative metal technology in northwestern Asia (Roberts et al. 2009). Subsequent to developments in this core region, it has been suggested that metallurgical technologies made their way into the Caucasus and northward into Europe and then eastward across the great northern Eurasian region in an ever-expanding zone of contact and exchange. Unfortunately, much is still unknown about the processes by which such technologies moved within and between larger regions and even less is understood regarding how the formation of new technological practices became intertwined with local social and economic settings. In many cases, we would argue, too much emphasis has been placed on large-scale diffusion and too little on understanding the articulation between local and regional contexts of metal production and use. In contrast, some scholars have focused on this very problem and have contributed research in recent years that now provides an extremely valuable comparative perspective for those of us working on similar issues (e.g., Chernykh et al. 2000; Chernykh 2002a, b, 2004a, b; Kassianidou and Knapp 2005; Knapp et al. 1998; Levy 2003; Peterson 2009; Peterson et al. 2006; Shennan 1998; Roberts et al. 2009). Much of the detailed study of metals and the diffusion of technology in the northern Eurasian region, including the grassland steppes zone, can be attributed to the work of Evgenii Chernykh and colleagues at the Institute of Archaeology, Russian Academy of Sciences, Moscow. The detailed study of more than 120,000 objects and attainment of more than 1,700 radiocarbon dates has provided the empirical foundation for what (Chernykh 2009) has conceptualized as several distinct *metallurgical provinces* for the Eurasian area. According to Chernykh, these provinces reflect specific geographical regions of metallurgical production, trade, and consumption, and similarities in the use of regional base metals and technologies (see Chernykh and Kuz'minykh 1989; Chernykh et al. 2000). While these studies have emphasized the regional nature in production and use of metal objects, they have also brought to light more wide-ranging geographical distributions of specific forms of metal objects. The Seima–Turbino transcultural phenomenon is one such pattern.

The important Seima-Turbino development has been recognized from the excavation of several hundred metal objects and molds, with most found in five major burial grounds located in the forest and forest-steppe zones of northern Eurasia (Chernykh and Kuz'minykh 1989). The widespread diffusion of these materials, coupled with the lack of contemporaneous settlement evidence, has led to debate between scholars over the exact socioeconomic processes responsible for this. Trade from east to west within the forest zone and the migration of either warriors or warrior–metallurgical specialists are the most frequently discussed interpretations by regional specialists (see Koryakova and Epimakhov 2007, p. 39 for recent discussion). Unfortunately, without better local contextual information, the exact nature of the Seima-Turbino material finds and their spatial–temporal relationships are impossible to understand with better clarity. The Seima-Turbino case study is but one of many current challenges within the broader Eurasian region in terms of connecting detailed, analytical studies of metal objects with the complex social and economic phenomena that produced them. This is precisely where a more holistic approach to the study of metals and society is needed, as resting on purely technological analyses will not lead to the comprehensive interpretations of early societies and their economies that we wish to attain.

For example, one of the key debates in the wider field of metallurgical studies in recent years has been the use of lead isotope proveniencing—particularly in the Mediterranean region (Baxter et al. 2000; Macfarlane 1999; Stos-Gale & Gale 2009). While much ink has been spilled over the problems connected with this method, discussion over this problem has been very effective in stressing the need for larger sample sizes, both in terms of material artifacts and local and regional ore sources. Furthermore, it has been shown that researchers must have a greater awareness for the possible mixing of various ores and the influence that recycling of local and nonlocal metals may have on patterns of metal production and trade. Such issues emphasize the necessity of building programs of research that include intensive archaeological and geological reconnaissance surveys both regionally and within local catchments connected to settlements and mines. In turn, this approach provides the necessary contextual data for better understanding base metals exploitation and its relationship to settlement and economic patterning. These important concerns cross the traditional boundaries that have been at the heart of metallurgical studies—wherein archaeological fieldwork is often separated from the detailed laboratory analysis of ores, slags, metal objects, and other metallurgical materials. Of course, research focused on the specific technological aspects of metal production, such as ore processing, roasting and smelting, and metal alloying are vital components in the study of early metallurgy. Yet, when attempting to expand beyond the reconstruction of specific technological patterns, especially in order to evaluate the broader social and economic forces that structure mining and metal production, one must evaluate several other lines of material evidence (Knapp et al. 1998, p. 9). This includes a more general understanding of human–environment relationships, subsistence and socioeconomic orientations, and diachronic trends in social organization. All of these issues are vital elements in regional archaeological research and the comparative study of early societies. A broader rationale for examining these issues in the context of field archaeology in north-central Eurasia was published recently by Hanks and Doonan (2009) and therefore will not be repeated here. We do, however, provide a more specific discussion of these issues in the context of our case study below.

Modeling Early Metal-Producing Societies

The Eurasian Bronze Age has traditionally been viewed as somewhat peripheral to core developments in Mesopotamia, the Near East, and the Aegean. Drawing on various elements of Wallerstein's World Systems model (1974), numerous scholars have emphasized the influence and expansion of urban cores and the role of elites, or of specific polities, in controlling the circulation and use of metals—determining both local settings of cultural value and the formation of regional trade networks (Rowlands et al. 1987; Shennan 1986; Kristiansen 1984). This has led to an emphasis on the connection between metal production, trade and consumption, and the emergence of elites within Bronze Age societies. Some scholars, such as (Shennan

1993, 1998), have argued more recently that this emphasis on elite control has overshadowed more complete understandings of the social, economic, and ideological systems of the communities involved in the actual mining and production of metals. Recent research in the Eurasian steppe zone has indicated a similar set of issues. That is, that copper production, and the technological knowledge connected with it, cannot easily be linked to the emergence of hierarchical systems of control over production and circulation. Rather, various strategies were employed in the obtainment of base metals and the production and circulation of metal goods.

Kohl has argued that what has been termed the "Bronze Age World System" (late third and early second millennia BC) was not comprised of a single core region exploiting peripheral zones. Rather, much of central Asia comprised a "patchwork of overlapping, geographically disparate core regions or foci of cultural development, each of which primarily exploited its own immediate hinterland (1987, p. 16)." As Kohl argues, archaeological evidence substantiates the role of *transferable technologies,* such as the knowledge and expertise required for metal production. Such technologies do not appear to have been easily constrained, or controlled, by any one, single, political entity (1987, p. 17). This view suggests that the appearance of widespread mining and metals production in the late prehistoric Eurasian steppe region must be better understood in terms of localized social, technological, and political formations based on the exploitation of regional resources and the development of networks of trade and interaction. Furthermore, the emergence, development, and decline of specific core regions, if we choose to define them as such, should be understood in terms of local resource availability and issues connected with overexploitation and/or the disruption of trade networks. Field research over the past two decades in the steppe and forest-steppe regions of north-central Eurasia has moved productively in these directions. Two excellent examples of this should be touched on here. The first is the work undertaken by Evgenii Chernykh and colleagues at the mining complex of Kargaly, situated in the southwestern Ural Mountains region of Russia. The second case study is the research undertaken by David Peterson and colleagues in the Samara Valley region in the Middle Volga River basin of Russia.

At the site of Kargaly, a number of detailed publications in Russian have been produced that focus on the evidence recovered for mining and quarrying, ore processing, and metallurgical production (Chernykh et al. 2000; Chernykh 2002a, b, 2004a, b; see Kohl 2007, pp. 170–178 for recent overview in English). These publications also contain crucial information on local surveys and the excavation of synchronous settlement and cemetery features. This highly successful international project has revealed extensive exploitation of copper deposits distributed within an estimated 500 km^2 zone. Research at Kargaly has provided a valuable case study for examining diachronic developments in mining activities. This extends from the Early Bronze Age (Yamnaya culture, fourth millennium BC) through to what appears to be the highest level of prehistoric extraction connected with the Late Bronze Age Srubnaya culture (1700–1400 BC). After 1400 BC, a substantial decline seems supported by the archaeological and paleoenvironmental evidence (Diaz del Rio et al. 2006). Intensive palynological study at Kargaly has revealed a probable connection between overexploitation of local timber resources and what is interpreted as a c. 1400 BC decline in large scale smelting activities (Vicent et al. 2006). Chernykh has argued that an overexploitation of locally available timber led to a greater focus on extraction and trade of copper ores out of the Kargaly region (Kohl 2007, p. 174), rather than the continuation of localized smelting. This model of a “community” of specialist miners is further supported by the recovery of approximately 2.3 million animal bones from an approximately 1,000m^2 excavated area in the Gorny settlement, which is situated within the Kargaly mining complex. Analysis of the bones indicates that 99.8 % of them come from domesticated animals and approximately 80 % from domesticated cattle (Antipina 2004). Such an intensive concentration of faunal remains certainly lends support to Chernykh’s model (1997) that the settlement of Gorny was occupied by a community of specialist miners that traded copper ores for cattle, which then were used both for subsistence and the utilization of bone elements such as long-bone fragments for picks and wedges for shaft mining and the extraction of copper ores. The research at the settlement of Gorny and the larger Kargaly complex has generated many questions about the nature of base metals exploitation, metal production, and trade during the Late Bronze Age (LBA) period, particularly with regard to socioeconomic organization. What is particularly intriguing is that the increasing scale of exploitation at Kargaly cannot be tied to an intensification of social or political organization in the region. Instead, the archaeological evidence indicates the emergence of a more specialized community of miners who were likely connected to a broader regional trade dynamic.

In addition to the Kargaly project, the work of Peterson and colleagues (2006, 2009–Samara Bronze Age Metals Project) has emphasized the importance of technological shifts in metal industries and the transformation of value surrounding the manufacture and trade of metals and metal objects within the Middle Volga region. In particular, the recovery of metalwork, and occasionally metalworking tools, from Bronze Age burials within the steppe region has suggested an important relationship between these objects and social status and identity (Peterson 2009, p. 193). Yet, scholars often exaggerate the actual scale of metalworking and production linked to such evidence. As Peterson has noted, “identifying the metal-making activities that were carried out in a site or region during a particular period is important to understanding the relationships between metal and social complexity in that instance. Without such an understanding, there is a risk of evaluating every case in terms of a standard of large-scale, industrial production (2009, p. 194).” Recent detailed metallurgical studies on objects recovered from the Samara region for the Middle Bronze Age (MBA) II period (2200–1800 BC) have indicated that a variety of sources for base metals was used and that the local recycling of metals brought about a certain level of autonomy in the production of objects (Peterson 2009, p. 207). Such evidence highlights the various strategies that may have been used by communities both in obtaining necessary base metals and in producing required metal objects for local practices.

Both the work at Kargaly and that in the Samara region illustrate important advances in the study of metals, economy, and society in north-central Eurasia near the southern Ural Mountains region. In particular, the identification of communities of specialist miners (i.e., Kargaly) and what appears to have been a significant degree of autonomy in the attainment and the production of metals in the Samara Valley region support Kohl’s more general model of transferable technologies. These projects have added important information, and stimulated new questions, on the relationship between social and economic organization in the context of metal production and consumption practices. A third case study, the Sintashta culture development in the MBA (2100–1700 cal. BC), adds importantly to recent work undertaken on these issues in the southern Ural Mountains. Since initial fieldwork by Soviet scholars in the 1970s, sites connected with the Sintashta culture have generated great interest and debate. One key characteristic is the ubiquitous evidence of furnace features and metal smelting within domestic houses in the settlements. This has raised a number of questions about the social and economic organization of Sintashta communities, scale of metal production, and regional and interregional trade.

Sintashta Metal Production, Economy, and Organization (c. 2100–1700 cal. BC)

In recent years, the relationship of metal production to hierarchical forms of social organization and new forms of settlement patterning in the Eurasian steppe have been frequently linked to the MBA Sintashta culture (Gening et al. 1992; Zdanovich & Zdanovich 2002). Archaeological sites (fortified settlements, kurgan cemeteries, and open pit mines) connected with this development are situated in the southeastern Ural Mountains region (Fig. 26.1) and a recent large-scale-dating project has provided a firmer chronology for the emergence, development, and decline of this archaeological pattern (Epimakhov et al. 2005; Hanks et al. 2007). Artifacts recovered from Sintashta fortified settlements and associated cemeteries have received a great deal of international attention. Certainly, such evidence is intriguing as it appears in the form of 23 nucleated, fortified settlements, richly furnished tombs that often include spoke-wheeled chariots, sacrificed horses and other animals, and metal and stone weaponry. Moreover, evidence in the form of furnaces, slags, and other metallurgical debris are frequently recovered from domestic house structures within the settlements. It has been suggested that Sintashta communities may have produced metals at a significant enough level to stimulate the interregional trade of ores and/or metals with the Bactria Margiana Archaeological Complex in central Asia (Anthony 2009, pp. 64–67). Such a trade relationship would have brought nonlocal prestige goods into the Sintashta region—potentially reinforcing the aggrandizement of status of chiefly elites (ibid). In fact, numerous scholars have characterized Sintashta populations in terms of “chiefly” societies and/or the nucleated, fortified settlements as “proto-urban” towns (Boyle et al. 2002; Jones-Bley and Zdanovich 2002; Chernykh and Kuz’minykh 1989, 1994, 2000, 2002; Lamberg-Karlovsky 2002; Levine et al. 2003; Zdanovich 1988, 1989, 1995, 1997a, b; Zdanovich and Batanina 2002; Zdanovich and Zdanovich 2002). However, it is important to note that not all Russian scholars have supported the model of large-scale metal production and have suggested that metal production may not have played a significant role in Sintashta economies (Grigor’yev, 1999, pp. 128).

It is important to note that even though considerable field research has been focused on Sintashta sites, numerous questions still remain unanswered regarding Sintashta social organization, scale of mining and metal production, and nature

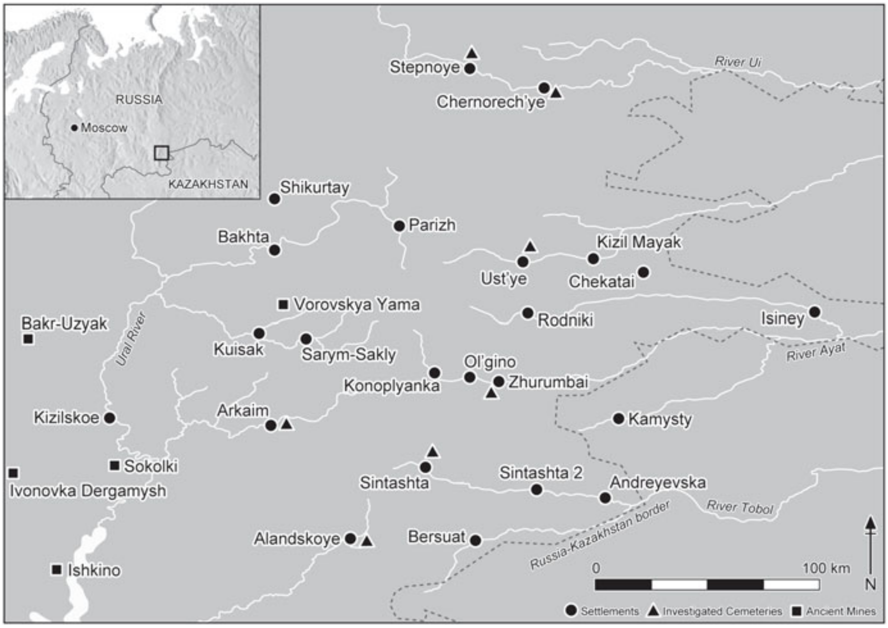


Fig. 26.1 Map of southeastern Ural Mountains region indicating key sites associated with Sintashta culture developments

and scale of inter- and intraregional trade. This is, in part, due to the lack of detailed publications stemming from Sintashta settlement excavations, although cemetery excavations have been, by comparison, well published (Epimakhov 2005; Vinogradov 2003; Zdanovich 2002). Recent publications in English have provided good overviews on Sintashta archaeology and so it is not necessary to provide another detailed treatment here (Anthony 2007; Hanks & Doonan 2009; Jones-Bley and Zdanovich 2002; Kohl 2007; Koryakova & Epimakhov 2007; Zdanovich & Zdanovich 2002). Instead, we will focus on a few specific issues connected with Sintashta mining and metal production (also see Hanks 2009 for further discussion). We suggest that the emergence and decline of the Sintashta archaeological pattern is an especially important case study in terms of reflecting some of the major challenges confronting more detailed understandings of the relationship between prehistoric metal production and societal developments in the broader Eurasian steppe zone.

In the past 15 years, Russian scholars have undertaken the investigation of Sintashta-period metal objects, metallurgical slags, and local ore resources. This has included work by V.V. Zaikov, with his colleagues from the Institute of Mineralogy, Urals Branch of the Russian Academy of Sciences and Chelyabinsk State University (Zaikov et al, 1995, 1999, 2002) and the work of S.A. Grigoryev (for overview of research, see Grigoryev 2000). This research established that some ore deposits might have played a contributing role in producing the raw ores exploited by Sintashta metallurgists (Dergamysh, Elenovka, etc.). Yet, these deposits, with evidence of prehistoric mining, are all situated beyond the local catchments of the

Sintashta fortified settlements. This is a central concern with regard to the ongoing fieldwork of the authors and so a more detailed discussion of recent research and findings will be presented here. These results are part of a larger collaborative project undertaken from 2007 to 2010 with several Russian colleagues, which was funded by the National Science Foundation (NSF) and the Wenner-Gren Foundation. Our main focus here within this chapter will be on local field survey, test pitting, and the preliminary analysis of base metals and archaeological materials.

It is important to note that our field activities and the collection of data have been undertaken with the aim of better understanding the relationship of Sintashta settlements to their local catchment zones and the nature and scale of copper metallurgy and its connection to socioeconomic organization. Conceptually, we have drawn on anthropological theory and models that favor a more "community"-based approach to the study of mining and metal production (Knapp et al.1998; Levy 2003; Linduff 2004; Yener 2000). Such views emphasize community models in order to extend beyond settlement sites as a primary unit of investigation for material evidence relating to mining and metal production activities (Knapp et al. 1998, p. 13). This approach connects with recent trends in anthropological archaeology, which favor the community as a mid-level unit of analysis and extend beyond traditional perceptions of settlement sites as mere aggregations of households and as the primary loci for societal organization and activity (Kolb and Snead 1997). This multiscalar view provides an especially coherent and effective model for investigating the unique spatial, temporal, and social conditions of mining and metallurgical production activities and how they intersect with local landscapes and environmental resources (Kassianidou and Knapp 2005, p. 235).

The specific research questions connected with this conceptual approach and the data we present further below can be noted as follows: (1) Do fortified zones and the household structures contained within them accurately represent the settlement pattern for Sintashta communities or were these only specialized areas for metallurgical production and defense? (2) Was metal smelting within the households a part-time activity (seasonal) or was it a full-time community occupation reflecting a more specialized form of productive economy? (3) Were Sintashta communities exploiting localized ore resources near the settlements (local catchment zones) or did they obtain raw materials from other sources and regions in order to carry out on-site smelting—reflecting greater social and political autonomy on the one hand or more complex systems of trade and networking on the other? (4) If Sintashta settlements were autonomous "polities," what specific environmental resources (ore and timber resources, grazing land, water, etc.) and restrictions may have contributed to the specific location of Sintashta settlements and also to their decline in certain areas?

Recent Collaborative Field Research at Stepnoye

Recent fieldwork campaigns undertaken by the authors have provided opportunities to examine the questions noted directly above. Field activities since 2007 have focused on the settlement and adjacent cemetery at the Stepnoye fortified settlement

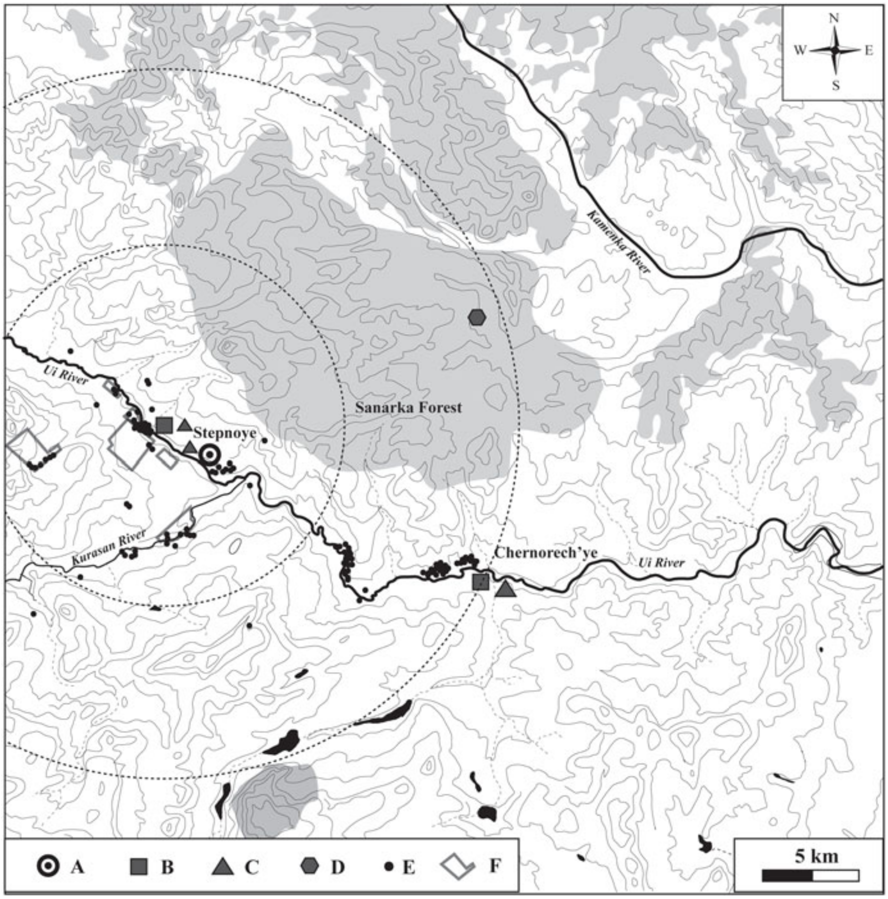


Fig. 26.2 Map of Ui River Valley indicating key sites of interest and survey zones (*shaded areas* are modern forest cover). **a** Modern villages. **b** Sintashta-period fortified settlements. **c** Sintashta cemeteries. **d** Sanarka Dacha A mining area. **e** Location of artifacts from surface collection. **f** *Polygon* denotes area of full-coverage pedestrian survey. (Map prepared by J. Johnson)

along with its surrounding catchment, specifically the Ui River Valley and the area immediately to the north known as the Sanarka Forest (Fig. 26.2). Stepnoye is rather unique with regard to the Sintashta settlement pattern. It is the most northern of the 23 fortified settlements and it is associated with one of the largest Bronze Age cemeteries in the southern Urals region. The cemetery, Stepnoye 1, consists of over 50 multiburial kurgan complexes dating from the MBA to the LBA (approximately 2100–1400 BC). One additional large cemetery dating to the LBA, named Stepnoye 7, is situated 2.5 km to the east. A second Sintashta period fortified settlement (Chernorech'ye) and associated cemetery (Krivoe Ozero) complex are situated 21 km to the southeast of Stepnoye. No large-scale excavation of either settlement was undertaken prior to 2007, although extensive field research has been undertaken at both

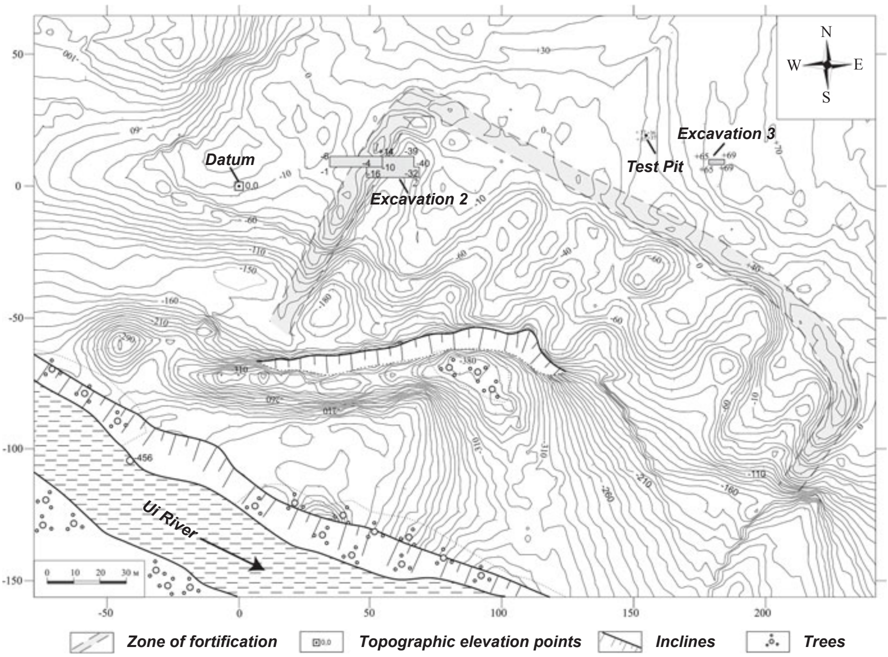


Fig. 26.3 Topographical plan of Stepnoye indicating zones of excavation and test pitting. (Prepared by N. Batanina and S. Batanin)

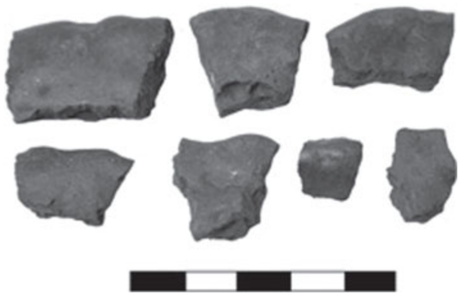


Fig. 26.4 Plate slags recovered from the Stepnoye settlement. (Photo courtesy of R. Doonan)

the Krivoe Ozero (Anthony and Vinogradov 1995; Vinogradov 2003) and Stepnoye 1 and 7 cemeteries (Kupriyanova 2008).

Stepnoye Settlement—Geophysics and Test Pitting

Surface finds of plate slags from across the Stepnoye settlement (Fig. 26.3) attest to the practice of copper metallurgy (Fig. 26.4). The distribution of surface finds is wide ranging although concentrated areas were noted, especially to the northeast of the site where a modern road appears to cut through a concentrated deposit. In an attempt to understand the organization of copper metallurgy at Stepnoye, a multiscale investigation was undertaken employing a range of methods. Investigation was targeted across the settlement site and in its immediate proximity. Our field research in the summers of 2007–2009 employed a suite of multidisciplinary methods in the form of topographical survey, remote sensing (fluxgate gradiometry and electrical resistivity surveys, see Merrony et al. 2009), geochemical survey (phosphate and multielement analysis), small-scale stratigraphic excavation (200 m^2 plan excavation, six small 1 m × 1 m (2 m) trenches and one 2 m × 6 m trench), artifact analysis, and accelerator mass spectrometry (AMS) dating. Accompanying the site-specific investigation at Stepnoye, a desk-based assessment of the local geology and archaeological sites was undertaken in the vicinity. The results from this assessment and information gained through discussion from local geologists and mining historians allowed a reconnaissance survey to be undertaken in the wider catchment (20 km), which sought to identify relevant archaeometallurgical features connected with copper-ore exploitation.

Magnetometry and resistivity surveys were employed at Stepnoye to establish the range and distribution of anomalies across the settlement site. It was anticipated that any pyrometallurgical features and/or concentrations of plate slag would provide strong magnetic anomalies that would ideally guide further investigation at the site. It was surprising to discover that the archaeological deposits at Stepnoye are not particularly amenable to magnetic survey in that the results did not indicate areas associated with metallurgical production. In general, the results of the resistivity survey have been much more productive although these data are not suited to providing information on the kinds of features produced by metallurgical practice. The failure of magnetometry to identify concentrations of slag was somewhat at odds with our expectations as many slags are profoundly magnetic, with many examples recorded that are capable of attracting a magnet. As surface survey had recovered a number of slag finds from across the site, it seems that the magnetometry results can be understood in two ways. First, it is possible that any significant slag deposits are located deep in the soil meaning that they are not being detected. While possible, this is an unlikely explanation given the nature of stratified deposits within the Stepnoye settlement. A number of test pits and trial trenches have established that significant cultural deposits occur at levels well within the depth suitable for magnetometry survey. Second, the absence of any discrete anomalies that might indicate a significant slag concentration suggests that slag was not deposited in such a structured manner. While the concentration of slag referred to on the northeast of the site is notable, surface evidence did not suggest that it was a continuous layer of slag, as would be expected with a concentrated slagheap. A campaign of targeted test pitting was carried out across the site to establish if slags comparable to those from surface survey could be recovered from horizons associated with Sintashta occupation. Further, test pits were excavated within and adjacent to concentrations of slag established through a surface survey to establish if significant deposits could be located.

Test pits were located on magnetometry anomalies and on areas noted to have surface concentrations of plate slag. Test pits that targeted geophysical anomalies established that the anomalies were caused by modern ferrous objects; yet, it was common to find occasional pieces of plate slag. Of those test pits which were situated on or adjacent to noted surface concentrations, none revealed significant concentrations of slag that could be described as a slagheap or significant deposit. Furthermore, slag fragments were found as scattered finds and not in association with other metallurgical paraphernalia, such as vitrified ceramics, tuyères, or charcoal.

To date, a total of *292 fragments of plate slag (2,482 g)* have been recovered from our field research at Stepnoye. A frequent characteristic of the plate slag is that it retains on its underside the impression of the solidified plano-convex "ingot" of copper that would have formed in the hearth; indeed, a fragment of such an ingot has been found at Stepnoye. This means that it is possible to calculate, with reasonable accuracy, the quantity of slag produced in association with a projected weight of copper. The ratio approximates 1:1, which is to say for each kilogram of copper produced we can expect about 1 kg of plate slag to be produced. It is also possible to calculate, based on the curvature of the meniscus impressions and slag edges, that the slag plates at Stepnoye were predominantly 10–18 cm in diameter and the ingots produced were predominately 8–16 cm in diameter. It is possible to calculate using these measurements that the ingots would have weighed between 250 and 900 g; however, the fragments were typically at the smaller end of this range. In the context of these calculations, it is important to note here that S.A. Grigor'yev's investigation of slag from other Sintashta settlements indicated that plate slag varied with diameters from 10 to 17 cm and weights from 300 to 900 g (typically 400–600 g). The estimated weights of the metal ingots ranged from 50 to 130 g (Grigor'yev 2000, p. 490). These results can therefore directly inform our current interpretations of Sintashta metallurgy both in terms of technological tradition and of scale. Although slag is a frequent class of find, the total recovered from Stepnoye, to date, represents no more than approximately 3 kg of copper and perhaps about equivalent to the contents of three kurgan burials. Of course, the 3 kg of Stepnoye slag does not represent a total sample but at present it suggests that the scale of production many not be on an order of magnitude that has been suggested in some recent publications for Sintashta communities (Anthony 2007, 2009; Zaikov et al. 1995, 2002). Investigations at Stepnoye are ongoing and it is premature to indulge in scaling calculations based on this preliminary figure. What is currently needed is an effective methodology that would better identify zones of production within the settlement and then to proceed with targeted excavation that seeks to define discrete contexts of practice.

As mentioned above, a notable quality of the slag finds from Stepnoye is the consistent morphology (Fig. 26.4). All slag samples recovered were fractured and ranged in size from 1 to 4 cm (major axis). All conformed to a single type, a gray–black plate slag that was approximately 7–12 mm thick. Although fractured, several pieces of slag preserved an original outer edge that enabled the complete form to be reconstructed. The fragments suggest that they derive from a circular plate slag of less than 20 cm in diameter. The texture on the upper surface indicates that the slag has cooled quickly, possibly having been quenched with water. The lower surface appears to have solidified while floating on a liquid, presumably molten metal. A smooth, continuous indentation on the underside edge of some samples was reminiscent of the meniscus of a molten pool of metal confirming that these slags had solidified

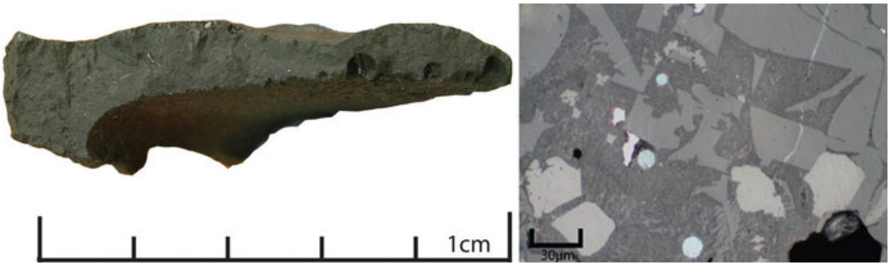


Fig. 26.5 **a** Section of slag sample (117). **b** Photomicrograph of polished section showing iron silicate phases and sulfide inclusions. (Photos courtesy of R. Doonan)

while in contact with molten metal. All the slag fragments examined were uniformly gray–black and had no visible inclusions of mineral, gangue, or charcoal. The overall appearance was of a homogeneous, fine-grained crystalline material. Localized spots of copper corrosion products suggested that these slags were associated with some aspect of copper metallurgy.

Preliminary microstructural analysis of the slags identified the presence of numerous metallic inclusions. The most common metallic inclusions were copper prills often surrounded by a sulfide phase. While multiphase sulfide inclusions were common, copper prills also occur without direct association with sulfides (Fig. 26.5). Other inclusions were absent; initial examination of 14 samples failed to identify a single-ore mineral, gangue, or charcoal inclusion. The absence of any such inclusions may indicate the possibility that these slags were not derived from a primary production step involving the conversion of ore to metal but instead might represent a subsequent *refining* or *secondary processing* step. Most slags were predominantly iron silicate with a fine-grained lath structure, although there were isolated regions of equi-axed iron silicates. Most examples had free iron oxides in the form of magnetite spinels. The presence of trivalent iron minerals indicates that the slags formed in mildly reducing to oxidizing conditions.

Although only a preliminary assessment, the frequent presence of copper sulfides in association with magnetite spinels in the slag points to the possibility that this is a matte conversion slag. Unlike the production of copper from weathered oxide ores, copper is rarely produced in a single step from sulfide ores. From a chemo-technical perspective, there are several pathways by which sulfide minerals can be transformed into copper metal.

The most straightforward method involves roasting the ore until all the sulfur is removed and then smelting the ore in a reducing environment (pathway one):

$$CuFeS_2{+}3O_2 \rightarrow CuO{+}FeO{+}2SO_2$$

$$C + O_2 \rightarrow CO_2; CO_2 + C \rightarrow 2CO$$

(furnace operates with an excess C-reducing environment)

$$CuO + CO \rightarrow Cu_{(metal)} + CO_2$$

The second method involves a partial roast followed by a co-smelt (pathway two):

$$2CuFeS_2 + 3O_2 \rightarrow CuO + FeO_{(slag)} + CuS + FeS + 2SO_2$$

The products of a partial roast may then be co-smelted in a mildly oxidizing smelt:

$$2CuO + CuS \rightarrow 3Cu_{(metal)} + SO_2$$

$$FeS + CuO \rightarrow CuS + FeO_{(slag)}$$

The third method involves an initial step of smelting the sulfide ores to produce an enriched copper matte (a metalloid substance comprising copper, iron, and sulfur) and then the conversion of the matte to copper in an oxidizing environment:

$$2CuFeS_2 + \text{heat} \rightarrow CuFeS + S$$

$$CuFeS + \text{heat} \rightarrow CuS + FeS + FeO_{(slag)}$$

The matte (CuS + FeS) is then either dead roasted and reduction smelted, partially roasted and resmelted, or "converted."

Matte conversion follows the following pathway:

$$CuS{+}3FeS{+}5O_2 \rightarrow CuS{+}Fe_3O_{4(slag)}{+}3SO_2$$

Since copper has a higher affinity for sulfur than iron, the copper will remain sulfidized until all the FeS is oxidized and slagged off. When all Fe is removed, CuS is converted to copper according to the following equation:

$$CuS + O_2 \rightarrow Cu_{(metal)} + SO_2$$

These differing pathways are important to acknowledge since they provide an insight into the practicalities of *technological organization*. Preliminary analysis suggests that the slags from Stepnoye may be derived from the *final step in pathway three*. Unless other classes of slag are forthcoming from the settlement, it seems that the Sintashta metallurgical tradition was a segmented process with only the latter steps of production been undertaken at the settlement site. The immediate implication of this is that future surveys in the vicinity of Sintashta sites must anticipate other types of metallurgical sites which, to date, have not been recognized. Furthermore, if the copper production process is a "segmented" process, then there are issues of control and access that need to be considered. More specifically, one can ask the important question: What is the relationship between the control of mineral deposits and the primary production sites, so far unidentified, and how do these articulate with the settlement sites?

Concurrently with the investigation of the settlement for areas associated with production, reconnaissance has also been undertaken in the immediate proximity (< 1 km) of the settlement to identify the presence of satellite sites, as suggested by slag analysis and the availability of raw materials. Wood for fuel is readily available as is good-quality clay for the manufacture of technical ceramics and furnace structures. To date, no outcrops of copper mineral or evidence of mining activities, either modern or ancient, have been identified and it was on this basis that a wider microregional survey (Fig. 26.2) was undertaken.

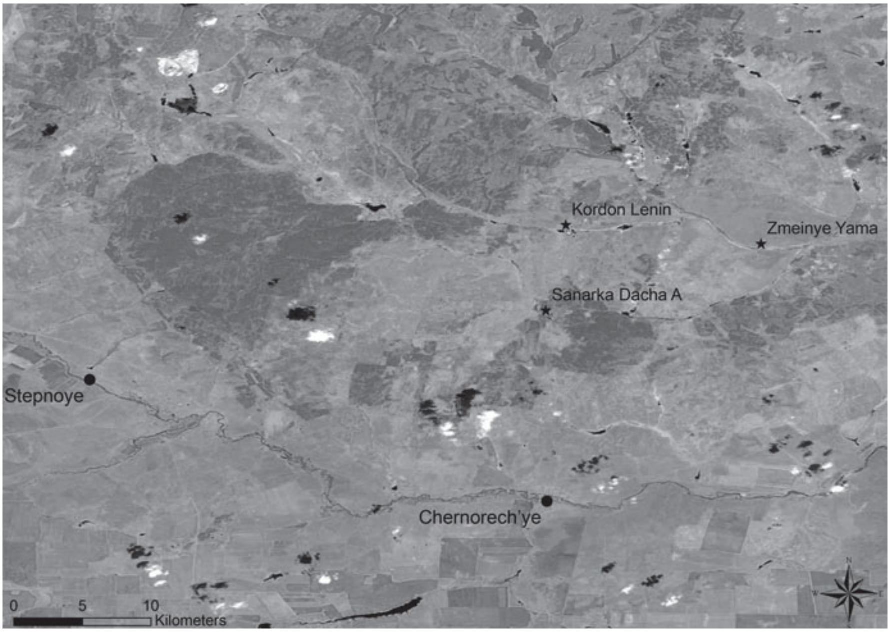


Fig. 26.6 Map showing the location of the mining sites discussed in the text and modern forest cover (*dark gray areas*). (Landsat imagery courtesy of NASA Goddard Space Flight Center and U.S. Geological Survey)

Regional Resources and Mineralization in Sanarka Forest

The Stepnoye settlement and its surrounding region are ideally situated to answer questions relating to the relationships that may exist in metallurgical practice, community organization and social development. This is so because the region is among the most mineral- rich areas of the Urals and western Siberia, with this mineral wealth coinciding with a density and intensity of Sintashta activity implied by the settlement patterning (Fig. 26.1). While reconnaissance around the immediate vicinity of the settlement has suggested that copper mineralization is absent, something both geologists and their charts concur with, preliminary reconnaissance in the wider area around Stepnoye (Fig. 26.6), specifically Sanarka Forest, has identified mineralized zones with evidence resembling early mining sites. The recovery of both secondary weathered minerals (azurite and malachite) and sulfide ores, specifically chalcopyrite, in close proximity to mining features reminiscent of attested Bronze Age mines has provided the impetus to investigate these sites systematically.

It is important to note that the Sanarka Forest region has been the focus of intensive historical mining activities as a result of the rich mineralogical resources located there. For example, the modern city of Plast, located 42 km northeast of the Stepnoye settlement, has been considered one of Russia's main gold-producing sites. The so-called Svetlinskoye gold lode in Plast has been estimated to contain over 100 tons of gold and 80 tons of silver and is a major source of exploitation by the ZAO

Yuzhuralzoloto mining consortium. The mining landscape within the Sanarka Forest and within the Stepnoye settlement catchment is, therefore, a very complex one and reflects over 200 years of exploration and exploitation by various independent and state-sponsored mining communities. The assistance of local historians and geologists from the Plast region was therefore crucial in helping to situate our research focus on areas and features believed to be related to prehistoric exploitation. Three specific areas within the Sanarka Forest were targeted in our survey campaigns: Zmeinye Yamy, Kordon Lenin, and Sanarka Dacha (Fig. 26.6). The investigative methodology for each site was comparable and involved increasingly detailed and focused examination of the site. Each site and its surrounding area (↔200 m) was initially field walked to gain a familiarity with surface features and to identify any surface finds such as mining tools, mineral fragments, slag, etc. During the process of reconnaissance, an area was defined for a more detailed earthwork survey. Upon completion, targeted test pitting sought to establish evidence for the history and sequence of exploitation. The results of these investigations are outlined below.

Zmeinye Yamy (DZK)

This site is the most easterly of the mineralized zones surveyed and is approximately 30 km from the Stepnoye settlement. The site is located just to the north of the Kamenka River where the land slopes gently northwards toward a subtle crest upon which are located a cluster of three kurgans about 1 km north of the site itself. To the northwest of the site is a small hill with some visible rock outcrops. The area is a mix of steppe grass and discreet birch coppice. The main mining complex consists of 11 features centered around a small wooded area adjacent to a modern track (Fig. 26.7). Northwest of the main site there are more than 20 pit depressions, both linear and circular, which are no more than 3 m in size. These are thought to be prospection pits as they are all of similar size and are most likely later than the main workings. There was one accessible adit in DZK 5 (Fig. 26.8), which was believed locally to be prehistoric. This was thoroughly explored and found to run in after about 3 m (Fig. 26.9). Judging from the condition of the worked surfaces, there were no indications of prehistoric mining and it is assumed that the latest phase of exploitation was modern. The spoil heaps in association with the main site show signs of being disturbed. This is particularly evident in the spoil heap associated with DZK 11, where it was clear that a mechanical excavator had been used to move some of the spoil.

Excavations at Zmeinye Yamy

In selecting areas for excavations the major spoil heaps were avoided, as it was clear that these had been subject to mass relocation and redeposition. Instead, excavation focused on up-cast material in tight association with mining pits. The aim of these

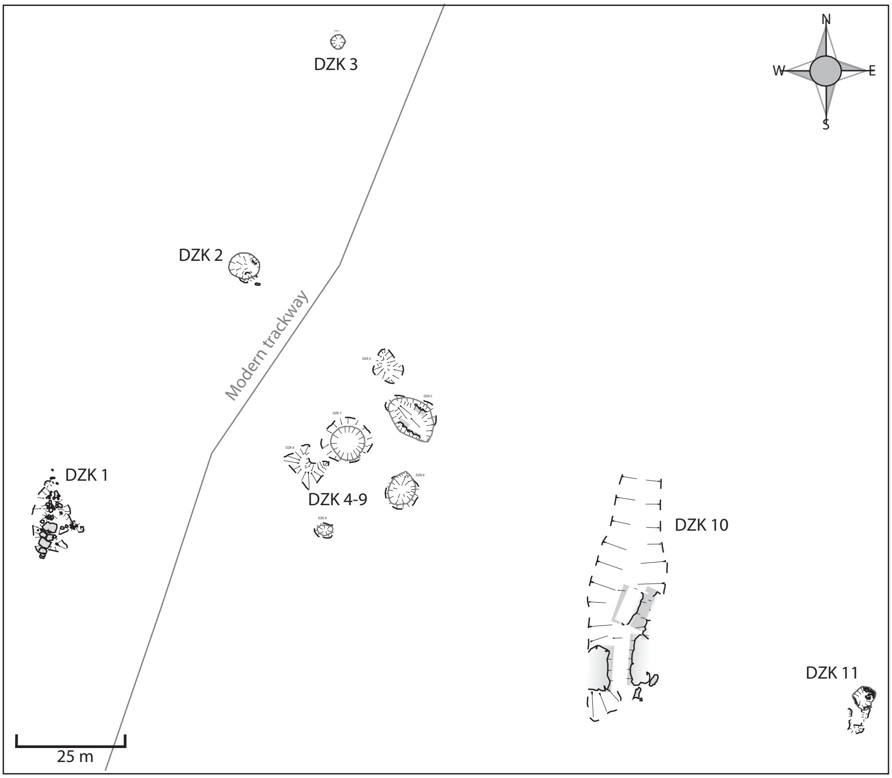


Fig. 26.7 Plan of the main mining features at Zmeike Yama with the main mining complex at the *centre left* of the image and the large excavated trench feature to the *right*. (Plan by D. Pitman)

excavations was to examine the nature of the spoil, locate any material culture associated with a phase of exploitation, determine whether such features relate to a single or multiple event, and secure any evidence for dating. The deposits chosen appeared to underlie the more significant spoil heaps referred to above. It was anticipated that the trench locations (Fig. 26.8) would allow the excavation of some of the earliest phases of exploitation.

Trench 1 yielded no cultural material; however, the excavation did show two distinct phases of excavation separated by a period of abandonment (layer 3). Trench 2 also yielded no cultural material. The stratigraphy in this trench was similar to trench 1, showing two horizons separated by a period of abandonment. The spoil heaps were notably free of copper mineral. The only samples recovered from this site were fragments of schist covered with thinly brecciated copper carbonates. There was no evidence for primary sulfide mineralization.

While it was clear that Zmeinye Yamy had evidence of copper mineralization, the prehistoric exploitation of this site could not be confirmed. An equally wide

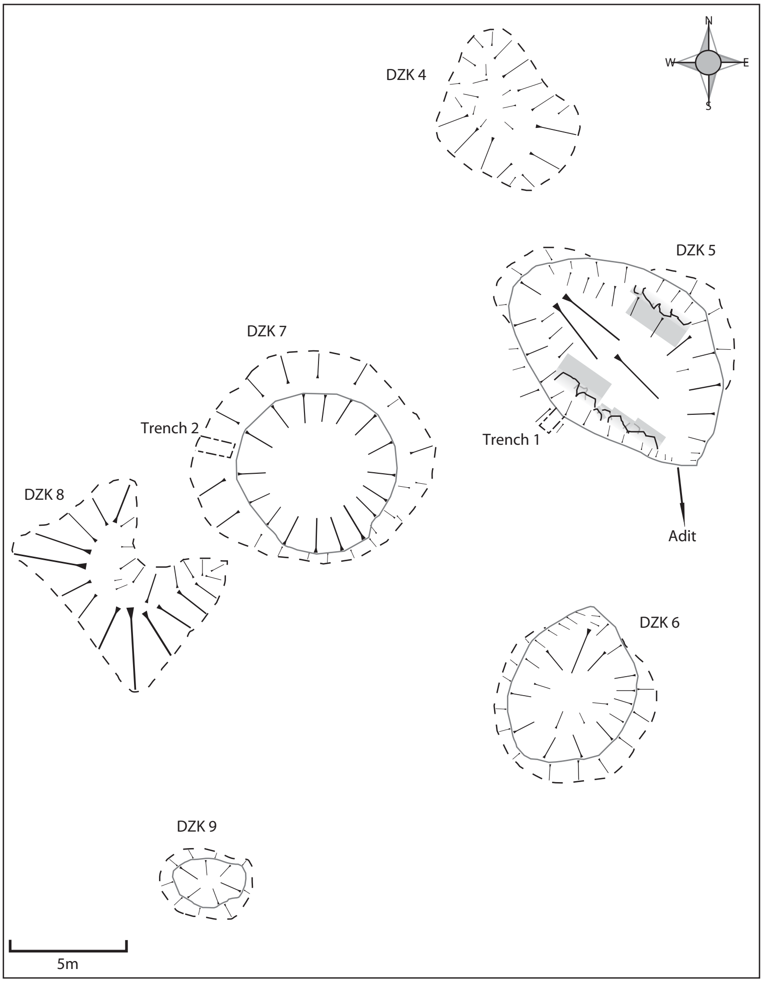


Fig. 26.8 Main complex at Zmeike Yama showing the location of excavation trenches and the entrance to the adit in DZK 5. (Plan by D. Pitman)

pedestrian survey found no evidence of any sites that appeared to relate functionally to the extraction of copper mineral from this site. Excavations of trenches 1 and 2 seem to suggest that there were at least two main phases of exploitation. The relatively fine nature of the first phase of spoil suggests that this was undertaken without the use of explosives or significant mechanical assistance. In light of these results, it was felt that Zmeinye Yamy does not hold significant potential for being connected with the Sintashta MBA exploitation within the region.

Fig. 26.9 Photograph of DZK 5 showing the outcropping of country rock and the horizontal entrance to the adit. (Photo courtesy of D. Pitman)

Kordon Lenin

Kordon Lenin is located just north of a tributary to the Kamenka River on the periphery of an expanse of birch forest. The main complex covers an area of over 100 by 80 m and is located within a wooded area surrounded by grassland (Fig. 26.10).

Fig. 26.10 Plan of the main mining complex at Kordon Lenin showing the extent of the overlying spoil heaps and the large excavation pits. (Plan prepared by D. Pitman)

Surrounding the main complex are a number of prospection pits and other small earthworks. To the north of the main complex are the remains of some large-scale mining works that are almost certainly modern. A datum point, located on the top of a spoil heap in the center of the site, is dated to 1951; yet, local historians are adamant that no exploitation has taken place since the nineteenth century. The presence of secondary copper mineral nodules is frequent in the silty up-casts from several pits. The presence of rich nodules of malachite and azurite seems to be a key reason why this site is considered to be a potential early mining site among local mining historians. However, stratigraphic analysis of the mining spoil suggests that the clayey silts are not derived from deposits of original mining campaigns but are the more recently excavated sediments which have accumulated in mining pits over time. The rich copper carbonate nodules are clearly embedded in this material and therefore must have formed in aqueous conditions (Kirchmayer 1987) that occurred as the original pit flooded and became infilled. They are not then a realizable ancient ore source and as such should not be seen to infer the availability of easily accessible, rich, secondary minerals at this site.

Overall, the site is complex with a number of large pits intercut with smaller prospections and overlain with the reworking of spoil heaps. Two pits had barely accessible adits with timber supports being extensively rotted, again indicating a more recent date for exploitation. There was no surface evidence for ancient exploitation and, indeed, no mineral outcrops were noted as the entire site was covered in deep sediments.

Excavations at Kordon Lenin

The excavation strategy at Kordon Lenin presented a challenge. The complexity of the site meant that it was unlikely that prehistoric remains, if they existed, could not be targeted without removing significant quantities of later spoil and overburden. Being limited to hand tools, this strategy presented a significant task. For these reasons, a series of 1-m test pits were planned (later extended) so as to establish the depth and character of deposits across the site.

The first test pit (TP1) identified two distinct phases of activity. The latest phase is associated with presence of cans of food and broken glass. The type of packaging suggested that this might well relate to the attested presence of the site in 1951. No datable cultural material was recovered from earlier deposits. Test pit 2 identified a significant layer of clinker derived from modern boilers, which again is suggestive of significant post-nineteenth-century activity at the site. Test pit 3 (TP3) was located adjacent to the main complex, in an area that was not obviously part of a spoil heap. Significant deposits of spoil again were encountered in the upper layers associated with clinker. Gray ashy layers and a buried soil horizon, again supporting the idea of distinct phases of occupation, characterized earlier layers. A significant fragment of sulfide ore was recovered from TP3.

In summary, Kordon Lenin proved to be a difficult site to characterize. It was held as the best candidate for prehistoric mining based on the easily visible secondary

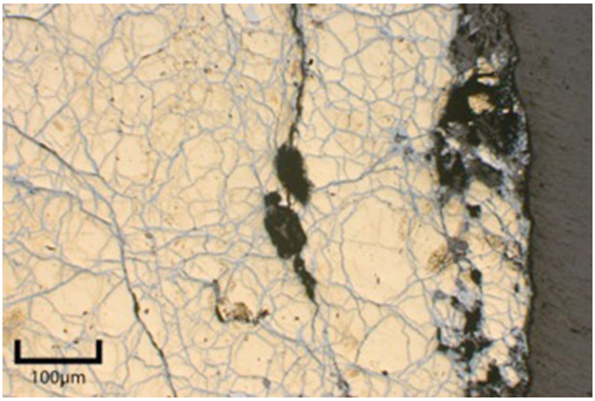


Fig. 26.11 Micrograph of the sulfide nodule from Kordon Lenin, showing chalcopyrite (*light*) and enriched sulfide phase (*dark*). (Photo courtesy of R. Doonan)

ores, but this is a misleading factor. Equally, the contention that the site was not exploited after the nineteenth century seems inaccurate. The latest exploitation is securely dated to the mid-twentieth century (1951?) and the oldest is likely to date to the nineteenth century. It is likely that the activities associated with the 1951 survey involved a limited amount of prospection and reworking of existing spoil heaps. The presence of clinker across the site is related to steam-powered machinery. Although it is not possible to deny evidence of prehistoric activity, investigations cannot be seen to support this contention.

Despite the tentative dating of the material to later periods, a number of samples were taken from Kordon Lenin. The nodule of sulfide ore (Fig. 26.11) was characterized using optical microscopy and its chemical composition determined using **X-ray fluorescence** (XRF). Analysis of the secondary minerals recovered indicates that they are carbonates with an average copper concentration of 30 % (± 8 %). The sulfide mineral fragment was predominantly chalcopyrite accompanied by enriched sulfides such as covellite. While not particularly instructive, the analysis of mineral samples from Kordon Lenin does establish the fact that the only primary mineral identified was sulfidic. The nodule was a massive fragment (5 cm major axis) and particularly rich with the presence of enriched sulfides and with no associate gangue or host rock. Although the potential for it being an ancient source remains, it is unlikely that this will be demonstrated as modern activities and their large-scale impact detract from further study at the site.

Sanarka Dacha A (SDA)

Sanarka Dacha is the most proximal site to the Stepnoye settlement. The complex lies within an area of dense birch forest to the north of the River Dacha and is situated on one of the tributaries to the Sanarka River. The site is located in an interesting geological context, being on the contact of a fine-grained schist and a coarse-grained granite—geological conditions that seem to have been recognized in

Fig. 26.12 SDA 4, one of the exploited mineral veins at SDA, which is cut vertically into the country rock. (Photo courtesy of R. Doonan)

the siting of Sintashta settlements. The site is characterized by numerous depressions and rock outcrops extending over 300 m. Several granite outcrops exhibited features consistent with prehistoric mining, namely surface workings that are best described as trench mines where miners presumably followed the mineral vein (Fig. 26.12). The surfaces were well rounded and were again consistent with a technology that relied on fire-setting and stone mauls. The complex at SDA is shown in Fig. 26.13, in which multiple trench features are evident. Trench features ranged from 1 to almost 3 m deep and varied between 1.5 m and 50 cm wide. Of all the sites examined, SDA offered the greatest potential for the identification of ancient mining remains.

Excavations at SDA

The morphology of the mining activities at SDA were clearly of limited scale and seemed to rely on the removal of rich vein material rather than the opening up of wider areas to facilitate access. Such features are considered typical for ancient mining. In the first instance, a test pit was located in the deposits that had accumulated in trench feature SDA4. Second, a test pit was located in an open area where it was thought likely that tools or other material culture might naturally accumulate and could be recovered without extensive removal of overburden. TP1 exposed four layers of dark, humic, organic-rich soil. Accompanying this were layers of broken country rock, almost certainly spoil from the excavation of the adjacent features. In addition, a calcrete layer was defined beneath these layers. The upper layers of the

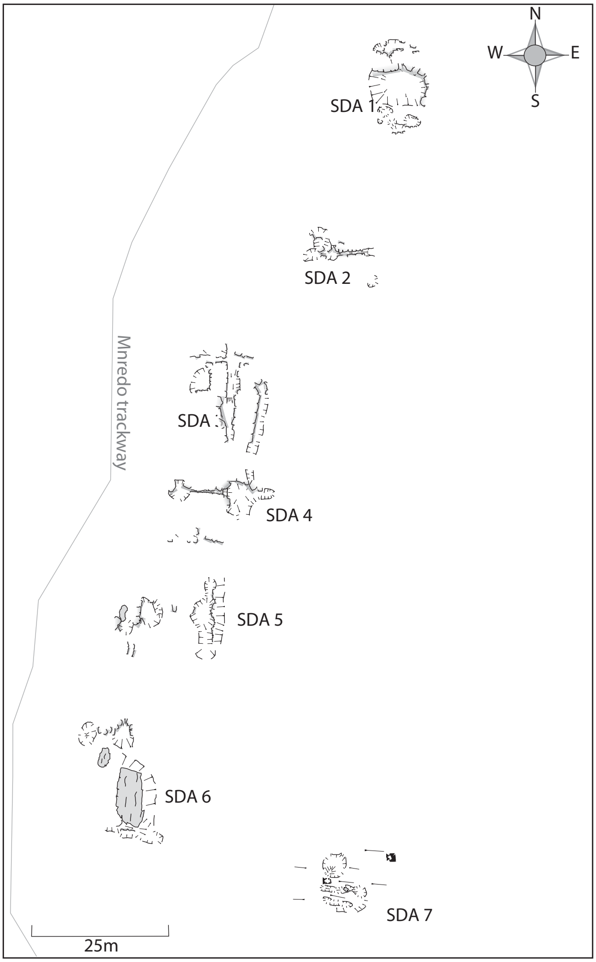


Fig. 26.13 Plan showing the extent of the outcropping trench features at SDA. (Plan prepared by D. Pitman)

fill contained a significant amount of cultural material which was likely to have been deposited in the surrounding area and transported into this depression. The finds consist of a collection of low-fired, coarse ceramic fabric and one piece of Bronze Age ceramic. This test pit was extended the following season and, while no further ceramics finds were recovered, a rich nodule of mineral was identified and the surface morphology of the trench included several scars (Fig. 26.14) that were similar to pick marks associated with early copper mining (cf. Timberlake 2003). The second test pit revealed three alternating groups of activity layers followed by a long phase of abandonment. Unfortunately, the test pit had to be abandoned at layer 10, as there was a large quartz boulder at the base that prevented any further excavation without significantly expanding the pit.

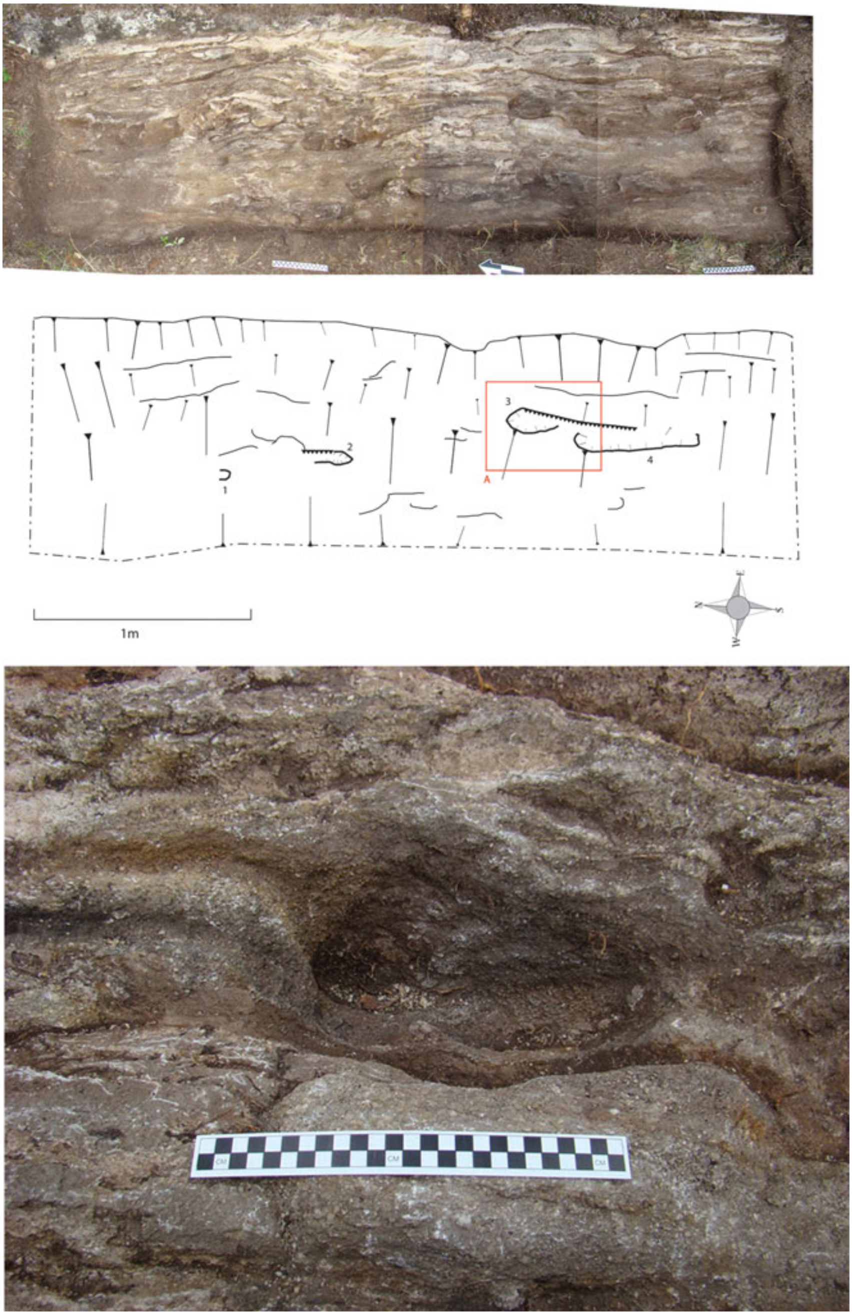


Fig. 26.14 **a** Photo (*upper*) and plan view (*lower*) of trench one showing the three distinct depressions (1–4); **b** Close-up photo of depression 3. (Photos and plan courtesy of D. Pitman)

The samples recovered from this site include four pieces of suspected sulfide ore, one piece of possible roasted ore, ceramic material, and a sample of the calcrete from TP1. Some of the pieces of suspected sulfide ore have clear chalcopyrite mineralization visible on the exterior. The presence of chalcopyrite was confirmed microscopically. Petrographic analysis of the large ceramic samples found on the site proved ambiguous, though it did show the presence of a deliberate temper, it is impossible to say much more without comparative material. XRF analysis revealed very low levels of copper in both the surface and core of the ceramic samples suggesting that these were not ceramics associated with copper metallurgy.

While many of the investigations in the Sanarka Forest area have either refuted the potential for locating prehistoric mining or failed to confirm previous assertions, the Sanarka Dacha site has produced compelling evidence for prehistoric exploitation. The presence of characteristic trench mines in association with Bronze Age ceramic and rich copper minerals highlight the potential of this site to satisfy the criteria of a copper mine within the catchment of the Stepnoye settlement. To this end, the presence of copper mines in the vicinity of Stepnoye draws attention to the relationship of the settlement community and its regional environment. While precise dating is yet to be established, the identification of proximal mineral deposits serves to remind us that metallurgy is a practice that extends across space and as such through time. From mine to final casting, the process of metal artifact fabrication brings together diverse factions of a community in a collective practice where the diversity of skills and technical and local knowledge may serve to reinforce or challenge existing power relations. As such, the scale at which these various activities are articulated across the landscape is critical to any study that seeks to investigate social complexity in the Urals MBA.

At this stage, it seems likely that we have identified one potential beginning of the *Chaîne Opératoire* for metal production. Combined with the materials and data collected from the Stepnoye settlement and cemetery complex, we may well have at least one of the end points of that same production process. What remains to be established in the near future with better clarity is the intermediate stages in this process and critically the relationship between them, both in terms of space and proximity to the settlement community.

Future Directions in Research

Further field research and excavation is now planned for Stepnoye and the Sanarka Forest. Funding has been obtained from the National Science Foundation (USA) and Arts and Humanities Research Council (UK) for these activities and will be conducted during 2011–2013. Continued investigation of the SDA site will include broader pedestrian survey, geophysics, and the excavation of several additional surface and trench mine features. Additional research at the Stepnoye fortified settlement will include further excavation within the enclosed area, particularly in the eastern zone of the settlement where test pitting and geochemical surveys have identified a greater concentration of slag artifacts.

In addition to research activities at the Stepnoye settlement and within the Sanarka Forest, we also employed a survey in the local catchment zone of Stepnoye (20 km radius) during the final 2009 season. This work extended on from previous surveys (roadside survey coupled with detailed air photo analysis) by our Russian colleagues Elena Kupriyanova, Dmitri Zdanovich, and Sergey Batanin in 2000 and 2001. Our 2009 survey focused on the identification, **Global Positioning System** (GPS) recording, and additional pedestrian survey of all the sites/artifact scatters first located in Kupriyanova's surveys. Systematic pedestrian survey of open, arable fields was also employed in areas immediately adjacent to the Stepnoye settlement (within 2–3 km) and a sample polygon along the west bank of the Kurasan tributary (see Fig. 26.2). The pedestrian survey covered a total of 160 ha and was supervised by J. Johnson, a PhD candidate at the University of Pittsburgh. Recovered artifacts from this survey included lithic artifacts ($n = 184$), pottery sherds (MBA = 5; LBA = 54; Final Bronze Age (FBA) = 19; general prehistoric sherds = 90), and copper slags ($n = 49$). In total, 11 new "sites" and three clay sources were identified through the pedestrian survey of arable fields and exposed, adjacent riverbanks. Our combined survey results with Kupriyanova's thus far have identified a total of 59 sites within a 20-km catchment zone (Fig. 26.2). In addition to the two previously known MBA Sintashta settlements (Stepnoye & Chernorech'ye), 14 unfortified LBA settlements were identified through our combined surveys. Other "sites," or what may be better categorized as occupation or activity zones at this preliminary stage, were identified from ceramic and lithic scatters and ranged from the Neolithic/Eneolithic to the early Medieval Ages. Currently, all survey data are being digitized and prepared through ArcGIS. Johnson's NSF-funded PhD dissertation research during the summer of 2011 focused on a 150 km^2 full-coverage pedestrian survey between the Stepnoye and Chernorech'ye settlements, including a section of the Kurasan tributary. The employment of a systematic survey, coupled with **geographic information system** (GIS) technology, provides an important new approach to microregional Sintashta settlement patterning for the region and has already substantiated a clear shift from the MBA to LBA phases for the Ui River Valley. Such an approach extends on our other research activities to provide an effective multiscalar approach to understanding settlement patterning and local site catchment resources in a diachronic perspective.

Conclusion

Various aspects of the Sintashta case study reflect some of the most persistent problems that currently confront the broader study of early metallurgical production, trade, social organization, and human–environment orientations in the Eurasian steppe region. To overcome these challenges, we have suggested that new conceptual models and field strategies must be employed (Hanks & Doonan 2009). As outlined above, we have drawn on more recent anthropological approaches to early mining and metal production. Such research emphasizes a broader community model and draws on comparative case studies of metal-producing societies to better theorize the practice of metallurgical production and the socioeconomic characteristics of such societies. While the data presented in this chapter are preliminary at this stage, we have attempted to provide an overview of the questions driving our research, as well as the multidisciplinary nature of our methods and field strategies. We are encouraged by our results to date and credit the productive international nature of our research team and commitment to common research goals.

Acknowledgments The authors would like to thank Ben Roberts and Chris Thornton for their invitation to contribute to this important volume and for their patience in the preparation of this new version of our original paper (Hanks & Doonan 2009). We also gratefully acknowledge the following individuals and institutions for their generous support of our collaborative field research in the southern Urals, from which many parts of this chapter originate: R. Khayryatdinov, N. Batanina, M. Batanina, S. Batanin, I. Batanina, L. Gayduchenko, C. Merrony, V. Valdaiskykh, E. Efimova, M. Gorbunov, and numerous students of Ural State University, Southern Ural State University, Chelyabinsk State University, and the Plast regional schools. We also gratefully acknowledge financial support from the National Science Foundation (BCS #0726279; BCS #1024674-AHRC-NSF-MOU) and Wenner-Gren Foundation (#7552). All opinions and mistakes within this chapter remain the sole responsibility of the authors.

References

Anthony, D. W. (2007). *The horse, the wheel and language: How Bronze-Age riders from the Eurasian steppes shaped the modern world*. Princeton: Princeton University Press.

Anthony, D. W. (2009). The Sintashta Genesis: The roles of climate change, warfare, and long-distance trade. In B. Hanks & K. Linduff (Eds.), *Social complexity in prehistoric Eurasia: Monuments, metals and mobility* (pp. 47–73). Cambridge: Cambridge University Press.

Anthony, D. W., & Vinogradov, N. B. (1995). Birth of the chariot. *Archaeology*, 48(2), 36–41.

Antipina, E. E. (2004). Arkheozoologicheskie materialy. In E. N. Chernykh (Eds.), *Kargaly* (Vol. III, pp. 182–239). Moscow: Nauka.

Baxter, M., Beardah C., & Westwood, S. (2000). Sample size and related issues in the analysis of Lead Isotope data. *Journal of Archaeological Science*, 27, 973–980.

Boyle, K., Renfrew, A. C., & Levine, M. (Eds.). (2002). Ancient interactions: *East and west in Eurasia. Cambridge*: McDonald Institute Monographs.

Chernykh, E. N. (1997). *Kargaly: Zabytyi mir*. Moscow: NOX.

Chernykh, E. N. (Ed.). (2002a). *Kargaly* (Vol. I). Moscow: Nauka.

Chernykh, E. N. (Ed.). (2002b). *Kargaly* (Vol. II). Moscow: Nauka.

Chernykh, E. N. (Ed.). (2004a). *Kargaly* (Vol. III). Moscow: Nauka.

Chernykh, E. N. (2004b). Kargaly: The largest and most ancient metallurgical complex on the border of Europe and Asia. In K. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* (pp. 223–237). Lewiston: The Edwin Mellen Press.

Chernykh, E. N. (2009). Formation of the Eurasian steppe belt cultures: Viewed through the lens of archaeometallurgy and radiocabon dating. In B. Hanks & K. Linduff (Eds.), *Social complexity in prehistoric Eurasia: Monuments, metals and mobility* (pp. 115–145). Cambridge: Cambridge University Press.

Chernykh, E. N., & Kuz'minykh, S. V. (1989). *Drevnyaya metallurgiya Severnoi Evrazii (seiminsko– turbinskii fenomen)*. Moskva: Nauka.

Chernykh, E. N., Avilova, L. N., & Orlovskaya, L. B. (2000). *Metallurgicheskiye provintsii i radio-uglerodnaya khronologiya*. Moskva: Institut Arkheologii RAN.

Diaz del Rio, P., Lopez Garcia, P., Antonio Lopez Saez, J., Isabel Martinez Navarrete, M., Rodriques Alcalde, A. L., Rovita-Llorens, S., Vicent Garcia, J. M., & de Zavala Morencos I. (2006). Understanding the productive economy during the Bronze Age through archaeometallurgical and palaeo-environmental research at Kargaly (Southern Urals, Orenburg, Russia). In D. Peterson, L. Popova, & A. Smith (Eds.), *Beyond the steppe and the sown: Proceedings of the 2002 University of Chicago conference on Eurasian archaeology*. (pp. 343–357).

Epimakhov, A. V. (2005). *Rannie kompleksnye obshchestva severa Tzentral'noi Evrazii (po materialam mogil'nika Kamennyi Ambar-5), K. 1. Chelyabinsk*: Chelyabinskiy Dom Pechati.

Epimakhov, A. V., Hanks, B. K., & Renfrew, C. (2005). *Radiouglerodnaya khronologiya pamyatnikov bronzovogo veka Zauralya. Rossiiskaya Arkheologiya*, 4, 92–102.

Gening, V. F., Zdanovich, G. B., & Gening V. V. (1992). Sintasthta. *Arkheologicheskie pamyatniki Ariiskikh plemyon Uralo–Kazakhstanskikh stepei. T. 1*. Chelyabinsk: Uzhno-Ural'skoe knizhnoe Izd-vo.

Grigoryev S. A. (1999). *Drevnie indoevropeitsy. Opyt rekonstruktsyi*. Chelyabinsk: Ural'skoe otdelenie RAN.

Grigoryev S. A. (2000). Metallurgicheskoe proizvodstvo na Uzhnom Urale v epokhu sredney bronzy. In N. O. Ivanova (Ed.). *Drevnyaya istoriya Uzhnogo Zauralya. T.1*. Chelyabinsk: Uzhno-Ural'sky Universitet, 443–531.

Hanks, B. K. (2009). Late prehistoric mining, metallurgy and social organization in north central Eurasia. In B. Hanks & K. Linduff (Eds.), *Social complexity in prehistoric Eurasia: Monuments, metals and mobility* (pp. 146–167). Cambridge: Cambridge University Press.

Hanks, B. K., & Doonan, R. (2009). 'From scale to practice: A new agenda for the study of early metallurgy on the Eurasian Steppe'. *Journal of World Prehistory, 22*, 329–356.

Hanks, B. K., & Linduff, K. M. (Eds.). (2009). *Social complexity in prehistoric Eurasia: Monuments, metals and mobility*. Cambridge: Cambridge University Press.

Hanks, B. K., Epimakhov, A., & Renfrew, C. (2007). Towards a refined chronology for the Bronze Age of the southern Urals, Russia. *Antiquity*, 81, 333–367.

Jones-Bley, K., & Zdanovich D. G. (Eds.). (2002). *Complex societies of Central Eurasia from the 3rd to the 1st Millennia BC—Regional specifics in light of global models*. Volumes I and II (Journal of Indo–European Studies Monograph Series 45–46). Washington: Institute for the Study of Man.

Kassianidou, V., & Knapp, A. B. (2005). Archaeometallurgy in the Mediterranean: The social context of mining, technology and trade. In E. Blake & A. Bernard Knapp (Eds.), *The archaeology of Mediterranean prehistory* (pp. 213–251). Oxford: Blackwell.

Kirchmayer, M. (1987). Universal stage grain fabric statistics on dendrites of mine cave pearls. *Carbonates and Evaporites, 2*(1), 59–65

Knapp, A. B. (1998). Social approaches to the archaeology and anthropology of mining. In A. Knapp, V. Pigott, & E. Herbert (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 1–23). London: Routledge.

Knapp, A. B., Pigott, V. C., & Herbert, E. W. (1998). *Social approaches to an industrial past: The archaeology and anthropology of mining*. London: Routledge.

Kohl, P. L. (2007). *The making of Bronze Age Eurasia*. Cambridge: Cambridge University Press.

Kolb, M. J., & Snead, J. E. (1997). It's a small world after all: Comparative analyses of community organization in archaeology. *American Antiquity, 62*(4), 609–628.

Koryakova, L. N., & Epimakhov, A. V. (2007). *The Urals and western Siberia in the Bronze and Iron ages*. Cambridge: Cambridge University Press.

Kristiansen, K. (1984). Ideology and material culture: An archaeological perspective. In M. Spriggs (Ed.), *Marxist perspectives in archaeology* (pp. 72–100). Cambridge: Cambridge University Press.

Kupriyanova, E. (2008). *Ten' Zhenshiny: zhenskii kostum epokhi bronzy kak "tekst" [po materialam nekrpoloei Yuzhnogo Zaural'ya i Kazakhstana]*. Chelyabinsk: Avto Graf.

Kuz'mina, E. E. (1994). *Otkuda prishli indoarii? Material'naya kul'tura plemen andronovskoi obshchnosti i proiskhozhdeniye indoirantsev*. Moskva: Vostochnaya Literatura.

Kuz'mina, E. E. (2002). On the origins of Indo–Iranians. *Current Anthropology, 43*(2), 303–304.
Kuz'mina, O. V. (2000). Metallicheskiye izdeliya i voprosi otnositel' noi khronologii abashevskoi kul'turi. *Drevniye obshchestva yuga Vostochnoi Evropi v epokhu paleometalla (rannie kompleksnye ob- shchestva i voprosi kul'turnoi transformatsii). Arkheologicheskie iziskaniya* (pp. 65–134). Vip. 63. SPB: Evropeiskii dom.
Lamberg-Karlovsky, C. C. (2002). Archaeology and language: The Indo–Iranians. *Current Anthropology, 43*(1), 63–88.
Levine, M., Renfrew, A. C., & Boyle, K. (Eds.). (2003). *Prehistoric steppe adaptation and the horse*. Cambridge: McDonald Institute Monographs.
Levy, T. E. (2003). Production, space and social change in protohistoric Palestine. In A. Holl & T. E. Levy (Eds.), *Spatial boundaries and social dynamics: Case studies from food-producing societies* (pp. 63–81). Ann Arbor: International Monographs in Prehistory.
Linduff, K. M. (Ed.). (2004). *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River*. New York: Edwin Mellon Press.
Macfarlane, A. (1999). The lead isotope method for tracing the sources of metal in archaeological artefacts: Strengths, weaknesses and applications in the Westrn Hemisphere. In S. Young, A. Pollard, P. Budd, R. Ixer (Eds.), *Metals in antiquity, BAR International Series 792*. (pp. 310–316). Oxford: Archaeopress.
Maddin, R. (Ed.). (1988). *The beginning of the use of metals and alloys*. Cambridge: MIT Press.
Merrony, C., Hanks, B. K., & Doonan, R. C. P. (2009). Seeking the process: The application of geophysical survey on some early mining and metalworking sites. In T. K. Kienlin & B. W. Roberts (Eds.). *Metals and societies. Studies in honour of Barbara S. Ottaway. Universita ⊂tsforschungen zur pra ⊂historischen Archa ⊂ologie*. Bonn: Habelt.
Peterson, D. L. (2009). Production and social complexity: Bronze Age metalworking in the Middle Volga. In B. Hanks & K. Linduff (Eds.), *Social complexity in prehistoric Eurasia: Monuments, metals and mobility* (pp. 187–214). Cambridge: Cambridge University Press.
Peterson, D. L., Kuznetsov, P., & Mochalov, O. (2006). The Samara Bronze Age metals project: Investigating changing technologies and transformations of value in the Western Eurasian Steppes. In D. Peterson, L. Popova, & A. Smith (Eds.), *Beyond the Steppe and the Sown: Proceedings of the 2002 university of Chicago conference on Eurasian Archaeology* (pp. 322–342). Leiden: Brill.
Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of metallurgy in Eurasia. *Antiquity*, 83.
Rowlands, M. J., Larsen, M., & Kristiansen, K. (Eds.). (1987). *Centre and periphery in the ancient world*. Cambridge: Cambridge University Press.
Shennan, S. J. (1986). Central Europe in the third millennium BC: An evolutionary trajectory for the beginning of the Bronze Age. *Journal of Anthropological Archaeology, 5*, 115–146.
Shennan, S. J. (1998). Producing copper in the eastern Alps during the second millennium BC. In A. B. Knapp, V. C. Pigott, & E. W. Herbert (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 191–204). London: Routledge.
Stos-Gale, Z. A. & Gale N. (2009). Metal proveniencing using isotopes and the Oxford archaeological lead isotope database (OXALID). *Archaeological and Anthropological Sciences*, 1(3), 195–213.
Timberlake, S. (2003). Early mining research in Britain: The developments of the last ten years. In P. T. Graddock & J. Lang (Eds.), *Mining and metal production: Through the ages*. London: The Trustees of the British Museum, 21–42.
Tylecote, R. F. (1987). *The early history of metallurgy in Europe*. London: Longman.
Vicent, J., Ormeno, S., Martinez-Navarrete, M. I., & Delgado, J. (2006). The Kargaly project: Modeling Bronze Age landscapes in the steppe. In S. Campana & M. Forte (Eds.), *From space to place: 2nd International conference on remote sensing in archaeology* (*BAR International Series 1568*) (pp. 279–284). Oxford: BAR.
Vinogradov, N. B. (2003). *Mogil'nik bronzovogo veka Krivoe Ozero v Yuzhnom Zaural'ye*. Chelyabinsk: Yuzhno-Ural'skoe knizhnoe izd-vo.

Wallerstein, I. (1974). *The modern world system*. New York: Academic Press.
Yener, K. A. (2000). *The domestication of metals: The rise of complex metal industries in Anatolia*. Boston: Brill.
Zaikov, V. V., Yuminov, A. M., Bushmakin, A. P., Zaikova, E. V., Tairov, A. D., & Zdanovich G. B. (2002). Ancient Copper mines and products from base and Noble metals in the Southern Urals. In K. Jones-Bley & D. G. Zdanovich (Eds.), *Complex societies of Central Eurasia from the third to the first Millennia BC: Regional specifics in the light of global models* (pp. 417–442). (Chelyabinsk State University, Chelyabinsk, Russian Federation/Journal of Indo–European Studies Monograph Series.) Washington D.C.: Institute for the Study of Man.
Zaikov, V. V., Zdanovich, G. B., & Yuminov, A. M. (1995). Mednyi rudnik Bronzogo veka 'Vorovskaya Yama'. In Rossiya i Vostok: Problemy Vzaimodeistviya, Chast V, Kniga 1: *Kul'tury Eneolita–Bronzy Stepnoi Evrazii*. Chelyabinsk: 3-ya Mezhdunarodnaya Nauchnaya Konferentsiya (pp. 157–162).
Zaikov, V. V., Bushmakin, A. Ph., Yuminov, A. M. et al. (1999). Geoarchaeological research into the historical relics of the South Urals: Problems, results, prospects. In Pollard, A. M. (Ed.). *Geoarchaeology: Exploration, environments, resources. London: Geological Society* (Special publications) (pp. 165–176).
Zdanovich, G. B. (1988). *Bronzovyi vek Uralo–Kazakhstanskikh stepei (osnovy periodizatsii)*. Sverdlovsk: Izd-vo Ural'skogo Universiteta.
Zdanovich, G. B. (1989). Fenomen protogorodskoi tsivilizatsii bronzovogo veka Uralo–kazakhstanskikh stepei. Kulturnaya i sotsialnaya obuslovlennost. In V. M. Masson (Ed.), *Vzaimodeistvie kochevykh kultur i drevnikh tsivilizatsiy* (pp. 179–189). Alma-Ata: Nauka.
Zdanovich, G. B. (1995). Arkaim: Arii na Urale ili nesostoyavshayasya tsivilizatsiya. In G. B. Zdanovich (Ed.), *Arkaim: Issledovaniya. Poiski. Otkrytiya* (pp. 21–42). Chelyabinsk: Kamenny Poyas.
Zdanovich, G. B. (1997a). Arkaim—kul'turnii kompleks epokhi srednei bronzi Yuzhnogo Zaural'ya. *Rossiiskaya Arkheologiya, 2*, 47–62.
Zdanovich, D. G. (1997b). *Sintashtinskoye obshchestvo: sotsialnye osnovy kvazigorodskoi kultury Yu- zhnogo Zauralya epokhi srednei bronzy*. Chelyabinsk: Chelyabinskiy Gosudarstvenny Universitet.
Zdanovich, D. G. (Ed.) (2002). *Arkaim: Nekropol', Kn. 1*. Chelyabinsk: Yuzhno-Ural'skoe knizhnoe izd-vo.
Zdanovich, G. B., & Batanina, I. M. (2002). Planography of the fortified centers of the middle Bronze Age in the Southern Trans-Urals according to Aerial photography data. In K. Jones-Bley & D. G. Zdanovich (Eds.), *Complex societies of central Eurasia from the third to the first Millennia BC: Regional specifics in the light of global models* (pp. 121–147). (Chelyabinsk State University, Chelyabinsk, Russian Federation/Journal of Indo–European Studies Monograph Series.) Washington D.C.: Institute for the Study of Man.
Zdanovich, G. B., & Zdanovich, D. G. (2002). The 'country of towns' of southern Trans-Urals and some aspects of steppe assimilation in the Bronze Age. In K. Boyle, A. C. Renfrew, & M. Levine (Eds.), *Ancient interactions: East and West in Eurasia* (pp. 249–263). Cambridge: McDonald Institute Monographs.

Chapter 27
Metallurgy in Ancient Eastern Asia: Retrospect and Prospects

Katheryn M. Linduff and Jianjun Mei

Introduction

The use of metals and the development of metallurgy are considered fundamental to the emergence of complex societies in many locations in the ancient world, but particularly in western and eastern Asia. Metallurgical technology provided copper, iron, and their alloys, which in turn furnished ritual and working implements, weapons, and materials for construction. How the knowledge of and interest in metals developed in present-day China has been the subject of much speculation, with the place of origin often the central topic of debate. Until fairly recently, however, little evidence could be gathered to argue convincingly that the Chinese Bronze Age was an indigenous affair, or one that was sparked by impetus from beyond the Great Wall. In light of recent excavations in both China and adjacent regions of Eurasia (Hanks and Doonan, this volume) and Southeast Asia (White and Hamilton, this volume), and of analytic approaches developing to explain the emergence of the technology that include a broader focus on societal change, the situation in China can be reassessed and different models for its development can be proposed. Such changes in approach may require the application of new research questions and even perhaps field methods.

Debates and assessments of incipient metallurgy and its consequences in the ancient western world have centered on several crucial factors: the presence of ores and the corollary existence or creation of adequate trade networks; the presence of knowledgeable local and/or itinerant artisans who knew metals and their properties;

K. M. Linduff (✉)
Department of Art History, 104 Frick Fine Arts Building,
University of Pittsburgh, Pittsburgh, PA 15260, USA
e-mail: linduff@pitt.edu

J. Mei
Institute of Historical Metallurgy and Materials,
University of Science and Technology Beijing,
100083 Beijing, People's Republic of China

The Needham Research Institute, 8 Sylvester Road,
Cambridge, CB3 9AF, UK

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_27,

a community able to support such workers, or with a degree of social and/or ritual complexity to create a demand for metal products; the ability to create high temperature furnaces for smelting and refinement of ores and final castings. The most sophisticated metal-producing industries were located in or near the more complex societies in the Near East, where these products were used for many purposes ranging from utilitarian to luxury items, for use in activities ranging from the everyday to solemn rituals. Such questions are not always behind the study of metallurgy in China.

Consideration of the Chinese development of metallurgy and its setting has centered on two issues: first, documentation and scientific examination of the internal development of metal technologies and second, and more recently, on the emergence of metallurgy in eastern Asia and whether any stimulus from outside was responsible for its inauguration.

Background: Archaeology in China

Since the founding of the People's Republic in 1949, we have witnessed a period when archaeology has served many functions in China : scientific, nationalistic, touristic, and economic, to name a few. Since the introduction of scientific archaeology in the 1920s, archaeological activity has followed two paths in China; historiographically oriented Neolithic and Bronze Age archaeology and Paleolithic archaeology aimed at the study of human evolution. Because there is a common approach, some discussion follows on both.

These divisions can be found in two different bureaucratic houses in Beijing, provincial government and university offices and institutions. Both divisions have histories based on inherited Chinese intellectual traditions as well as those appropriated from the West. Chinese Paleolithic archaeology was strongly influenced by the French tradition of the 1920s and 1930s; Neolithic and historic archaeology was modeled on the field methods and philological traditions introduced both from Europe and from the USA. Even so, all archaeological research in China can be said to emerge from a common Chinese intellectual tradition. Whether attempting to reconstruct Pleistocene human prehistory or to explain the emergence of Dynastic China, the most fundamental issue addressed by archeologists has been to reconstruct the origin and development of the Chinese people and their civilization.

The search for the origins and locations of archeological cultures has been tied to theories of cultural diffusion and migration. Traditional historiography as well as the modern Marxist model are particularistic and evolutionary and propose that Chinese civilization emerged in the Yellow River "core" and then spread to "peripheral" areas by way of political expansion and cultural diffusion over many millennia. Most Chinese archaeologists have accepted the main premise of this model. The underlying assumption is that there is a cultural norm so that major early excavations were concentrated in those areas where the archaeologists expected, or at least hoped, to verify the early histories through the construction of chrono-typologies for material cultural, human and faunal remains. Thus, the most prestigious and guarded research is that on the Yellow River Basin. Even in Paleolithic studies, the evolution of human Pleistocene prehistory has been sought within China, and comparative studies are a relatively recent endeavor. Chinese archaeologists have very rarely gone abroad to work, although with the new policy of the Ministry of Education in 2005 that underwrites Chinese graduate students to go abroad as visiting scholars for one year, this could be changing.

Many factors have affected Chinese archaeology, including material science and historical metallurgy. The sheer volume of materials unearthed in scientific excavations in the twentieth and early twenty-first century is probably the most significant factor. Regulations on preservation of cultural remains instituted since 1949 have necessitated examination of sites through construction work; this has produced data from beyond the core area have come to light and have fundamentally affected the analysis of early China (Fong 1980, pp. 20–34; An 1989; Faulkenhausen 1995, pp. 198–217; Chang 1981, pp. 156–168; Linduff 1998, 2000, pp. 1–29; Liu and Li 2007).

In addition, since the early 1980s the central government has loosened its controls on provincial and local efforts, and archaeological investigation has witnessed an increase in regionalism as a result of decentralization. Since then most provinces have developed their own teams led either by University faculty or by Museum scholars and many publish journals dedicated to presenting area finds. The officially sanctioned journals continue (*Kaogu, Wenwu*, *Kaogu Xuebao*, *Kaogu yu Wenwu*, etc.) with the addition of several journals that focus on regions (*Southern Ethnography and Archaeology*), or Provinces (*Archaeology of Inner Mongolia, Sichuan Cultural Relics*), for instance. Some are cleared for export, but many are not available outside of the People's Republic of China (PRC). The publication of monographs and field reports is now and will continue to be expensive and the exception frequently depends on subvention from outside sources.

The primary focus of these publications is now, and presumably will continue to be, the reporting of new sites and the typology and periodization of objects or the decipherment of the iconography of decor. These typologies are the basis of geographic and temporal definition of "cultures" in China today. How to interpret the new material and its implications for Chinese history has met with much more interest and controversy than discussions of method and theory.

With the archaeological fieldwork conducted in the last 25 years, perhaps the single most challenged notion about the formation of early Chinese culture has been whether it emerged in a unilinear fashion, from a single core which developed in the Central Plain and spread from there to other parts of Asia, or otherwise. Most current research suggests that "otherwise" is the more plausible explanation. Many questions follow from the new data. Along with late twentieth-century efforts in the PRC to maintain a unified nation, archaeological investigations have been useful when they studied areas where ancient minorities might be traced. More recently, when the mononuclear theory necessarily weakened as more and more diverse materials were unearthed, a regional paradigm has been proposed (Zhang 1986; Lin 1986; Wu 1995). Using Su Bingqi's regional model, some (Zhang 1986) suggest that among the many goals of Chinese archaeology the search for the origins of the "Hua", or the ethnic Chinese, as well as for the ancient minorities is especially worthy. But what and who contributed to Chinese culture are questions that strike deep into nationalistic, as well as ethnic sentiments. For instance, the most recent attempts to ‘regularize’ the chronology of early dynastic, or Bronze Age, China engaged over 200 Chinese scholars and produced a well-informed, but consistently unilinear, chronology (XSZ 2000). And whatever the nature of one’s interpretation of culture and its formation and change, the point or points where such questions could be tested have not, until very recently, been identified archaeologically.

Because the salvage recovery has been, and presumably will continue to be, the norm for Neolithic and historic archaeology, those regions that are most prosperous or where new road-building, housing, or nationally designated projects (such as the Three Gorges Dam project) are undertaken will be where most new information will be yielded. Surely South and South-central China will see increased archaeological activity as a result of the booming economy there. Even so, we will probably not see a de-emphasis on research on or in the Central Plain, but unless unexpected prosperity reaches the region, few new large-scale projects will be initiated there soon without outside funding.

An exception to activity centered on salvage recovery will be that provided by Sino-foreign projects (Murochick 1997). In the 1990s a few Sino-foreign teams began to conduct problem-oriented research that spans the Bronze Age (Liu 1996; Underhill et al. 1998; Linduff et al. 2002–2004). These regional surveys and test excavations have focused on the reconstruction of human behavior. This is a significant shift in emphasis, but one in which previously developed typologies and chronologies often play a significant role. Both new methods and theory, particularly those developed in North America since the 1960s, including computer technology, are of great interest to mid-career and younger Chinese archaeologists and have allowed real cooperation to develop. Experimentation and use of newly created collaborative methods inside of China are underway (CICARP 2003).

Emphasis on the context of human behavior has allowed some increased interest in systematic collecting and testing of information on environment, climate, ecology, animal and plant evolution, and so forth, although increasingly the data are integrated into studies of overall patterns of behavior in some regions (see, for example, Li et al. 2006). Technical studies on materials, such as those on metals and ceramics, on the other hand, do take place with some regularity and are quite telling in relation to the activities of communities in many regions.

The Study of Early Metallurgy in China

Most studies of incipient metallurgy focused only on fully developed phases dating from the second millennium BC. There is no question that by the early dynastic period in China, or no later than the Shang Dynasty (c. 1550–1050 BC), the ancient Chinese had already considered technological options and made technological choices about metals (Barnard 1961, Gettens 1967; Barnard and Tomatsu 1975). For use in ritual, they preferred tin-bronze for use in ritual to either silver or gold, even though resources for both were close at hand (Bunker 1993, 1994a, b; So and Bunker

1995; Linduff et al. 2000: Map 8, p. 277). They had developed a very sophisticated piece-mould system of casting, understood the properties of metals, and used their knowledge in the alloying process. A prescriptive tin-bronze industry was highly developed at that time and was supported by patrons of the political and social elite.

The tin-bronze items produced were used in rituals that paid reverence to ancestors, including the recently deceased, and were often placed in elaborate burials. As signs of political and/or social position and wealth associated with it, such metal items are unmistakable evidence of social inequality in the already highly stratified society of the late Shang period. Metal farming implements as well as tools are absent from the archaeological record of the Shang period, for instance, further confirming the exclusivity of the technology and highlighting its restricted use. This dedicated role for metal production and its resulting artifacts mark late Shang society in the Central Plain as well as elsewhere (Sichuan for instance), where large production centers have now also been found. This is unusual among ancient world cultures, for in Mesopotamia, for example, metal items served multiple purposes including utilitarian ones.

But this late Shang tin-bronze industry was not a primitive stage in the development of metallurgical technology; it was simply the first one documented in East Asia. Research on ritual tin-bronzes and the implications of their use among the Shang have been refined over the years since the discoveries were first made in the late 1920s, but questions about where and how metals were used and about how and where the technology developed prior to that period have suffered from lack of information from excavated contexts. This situation has changed in the past two decades. More than 70 sites that can be dated either by C and/or by archaeological context earlier than 1500 BC have been published (Linduff et al. 2000: Table II, pp. 355–384). These published sites yielded metal artifacts and/or metal production materials such as crucibles, or slag, and so forth (Linduff et al. 2000: Tables I and II, pp. 322–384). Analysis of the data, including the metallurgical content of many items, casting technology, as well as the types and uses of metal artifacts in the period from about 3000–1500 BC, leads to some surprising observations about the advent of metallurgy in eastern Asia and about its role and development in complex society.

Recent syntheses that investigate early China usually now view the archaeological landscape during the fourth millennium BC as a mosaic of regional groups that interacted with each other (Chang 1986). When dealing with the period of early metal use however, most Chinese archaeologists have accepted a traditional model which regards the Central Plain of northern China as the dynamic center of social, political, and technological change and propose that complex societies emerged in Asia through a process of interaction with the Yellow River Basin (BUIST 1981; An 1993; Linduff et al. 2000: Map 1, 2, 3, 4, 5) (Fig. 27.1). The elevated position of metal artifacts as well as the highly specialized and sophisticated multi-piece mold technology developed to produce them in early Chinese society have fueled the assumption/conclusion that the commencement of metallurgy in East Asia was to be found inside the early Chinese cultural, and/or even the political, sphere (BUIST 1981; An 1993; Barnard 1987, 1993). Now this conclusion is being challenged because there is adequate information to show that metal artifacts, in at least one other area, to the west of the Central Plain, were locally produced in enough volume

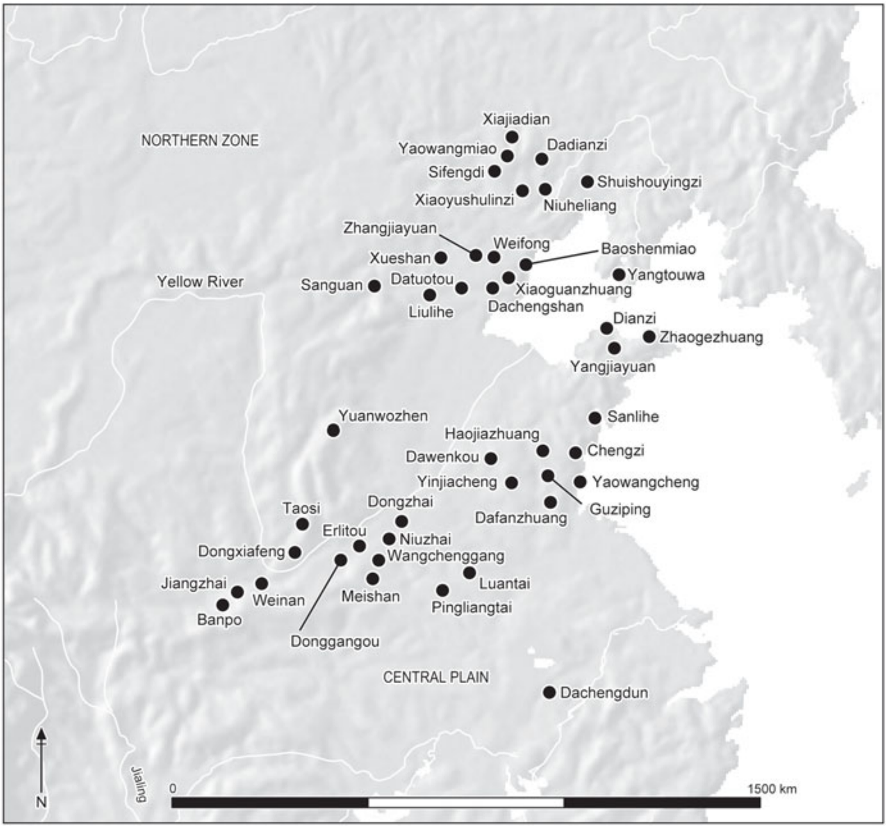


Fig. 27.1 Northern China, Yellow River Basin, showing key early metal sites

to confirm its regular use (An 1993; Mei and Shell 1998; Mei 2000; 2003a; Linduff et al. 2000: Maps 1–4, I.2, pp. 1–29; Liu and Li 2007). In addition, the types of objects found in this region as well as the component percentages of metals in the mix do not correspond to tin-bronze types and alloying formulae found in the Central Plain (Linduff et al. 2000: Table I, II.10; Sun and Han 1997).

From these recently excavated and reported sites where metal artifacts have been reported dating prior to 1500 BC, we can see that one of the most striking, as well as usual, additions to late Neolithic village life in northeastern Asia was the beginning of the use of metals. Cultures where metals (including copper as well as alloyed metals) were first used and manufactured are located across a large area from the west, across the northern frontier, to the eastern seaboard in and to the north of what has been traditionally been called 'China proper.' The growth of the industry did not solely, or even primarily, occur in the Central Plain associated with early dynastic China, but in several regions (Linduff et al. 2000: Map 1). Moreover, preliminary observations on the process by which and the places where the technology developed as well as the role of metals and metal objects in these societies suggest that whereas each locus was quite distinct culturally even during the early dynastic period, they were also probably interconnected.

Scientific examination of metal artifacts dating prior to 1500 BC has been playing a major role in the study of early metallurgy in China. Leadership in this arena has been consistently provided by the Institute of Historical Metallurgy and Materials (IHMM) and University of Science and Technology Beijing (USTB), first under the direction of Ko Tsun, Han Rubin, Sun Shuyun, and Mei Jianjun. Although research interest in the development of ancient metal technologies appeared in China as early as the 1920s, the history of metallurgy as a discipline became established only in the mid-1970s, when Ko Tsun and a small group of scholars (Archaeometallurgy Group) from several different institutions in Beijing initiated a series of research programs on ancient Chinese metallurgy, including the first systematic scientific investigation of early copper and bronze artifacts recovered in the present-day China. The mid-1980s witnessed the introduction of training programs for graduate students in the history of metallurgy, an important step that brought in young generations of scholars who have now become active in the field in China. While the science-oriented research approach has become widely adopted and has been making substantial contributions to a new understanding of early metallurgy in China, the need for an interdisciplinary approach that would combine social, anthropological, and scientific perspectives has become increasingly obvious. A emerging new trend emphasizes the examination of early Chinese metallurgy within its social and cultural context and the exploration of relationship between early metallurgy and social complexity.

The Evidence

The earliest sites that have yielded metal objects date to the late fourth and third millennia BC (Linduff 1997, pp. 306–418; Mei 2000) (Fig. 27.1). Quite early metal-using communities are found in Qijia/Siba sites in Gansu, with comparable sites in Xinjiang in the west, and others in Shandong, Liaoning, and Inner Mongolia in the east and north, and in the Central Plain in the lowest levels at Erlitou (Fig. 27.1). Because several levels of excavations are 14C dated and those dates have been matched up to ceramic types and styles, chronologies are more secure. An approximate chronological correspondence between the sites in the eastern Eurasian steppe and China is now clear, and suggests that the emergence of metallurgy was supraregional (Linduff et al. 2000, pp. 1–28).

Analysis of the data, including metallic composition, casting technology, as well as types and uses in the period from about 3000–1500 BC yielded evidence of the use of metals in late Neolithic in northeastern Asia as far east as the Russian Far East. Sites where metals (including copper as well as alloyed metals) were first used and manufactured are located across this large area, showing that the growth of the industry was not confined to the Central Plain. Moreover, preliminary observations on the process and patterns of use of the technology are both shared and diverse such as at Siba and Erlitou (Sun and Han 1997).

Areas in China where metallurgical knowledge was in use emerged near ore sources of metals, especially copper in several combinations (Barnard 1993, pp. 3–48; Barnard 1987, pp. 3–37; Linduff 1997; Linduff 1998, pp. 619–643). For instance, arsenical copper objects produced in Gansu at Siba sites must have been manufactured by exploiting local arsenical copper resources still available in present-day Gansu. All areas developed a taste for items made from 'pure' copper and copper alloys, and gold items have been found in the Northeast and Northwest China. Trumpet-shaped earrings, for instance, have been found all over eastern Eurasia and northern China and were made from copper, tin-bronze, as well as gold and sliver, according to the local preference and show a clear regional choice, unlike that in the central Yellow River Basin where the earliest Chinese states were located (Liu and Chen 2003, pp. 80–81). The lack of consistency in formulae suggests that knowledge was gained from several sources and not through local invention (Sun and Han 1997; Mei 2003a, b).

Areas where metal objects were recovered stretches across an area from the west, across the northern frontier (of early dynastic China), to the eastern seaboard, and these are dated from the third and early second millennia BC.

These are:

1. Area I: **The Qijia** culture (c. 2500–1900 BC) of Qinghai, Gansu and western Shaanxi has yielded copper and copper-based alloyed utilitarian items and gold, copper, and copper-based alloyed personal ornaments. The earliest dates for metal in this region are found at a Majiayao site at Linjia (see Fig. 27.2), Dongxiang, Gansu. "Copper" (analyses of metal knife and awl showed 99 % copper with impurities of lead, tin, and so on of less than 0.4 %) implements including knives, chisels, awls, and rings, and in one site a mirror (at Gamatai in Guinan, Qinghai see Fig. 27.2) were unearthed in several sites (KGYWW 1980).
2. Area II: **Zhukaigou** (Levels 3, 4, and 5; c. 2000–1500 BC), in South-central Inner Mongolia, has yielded copper, tin-bronze and bone weapons, and tools typical of both the Central Plain and the Steppe cultures (both Andronovo and Karasuk) (KGXB 1988).
3. Area III: the **Lower Xiajiadian** culture (c. 2000–1600 BC) in eastern Inner Mongolia, Liaoning, northern Hebei produced highly specialized pottery and walled villages as well as copper and copper-based alloyed utilitarian tools and personal ornaments which parallel those of the Andronovo culture (KG 1978; Zhang 1986).
4. Area IV: **Erlitou**, Henan, in the Central Plain (Phases 3 and 4; c. 1750–1530 BC) is exemplified by tin-bronze tools, weapons and piece-mould vessels, jade ritual materials, as well as walled villages.
5. Area V: the **Yueshi** culture (c. 2400–1600 BC) in Shandong yielded bronze and brass utilitarian items including nose rings, but larger than those from Huoshaogou in Gansu (Linduff et al. 2000: I.6; Xu 1989).

The archaeological record suggests that at the critical, protodynastic period in the late third and early second millennia B.C., all these cultures were at a similar level

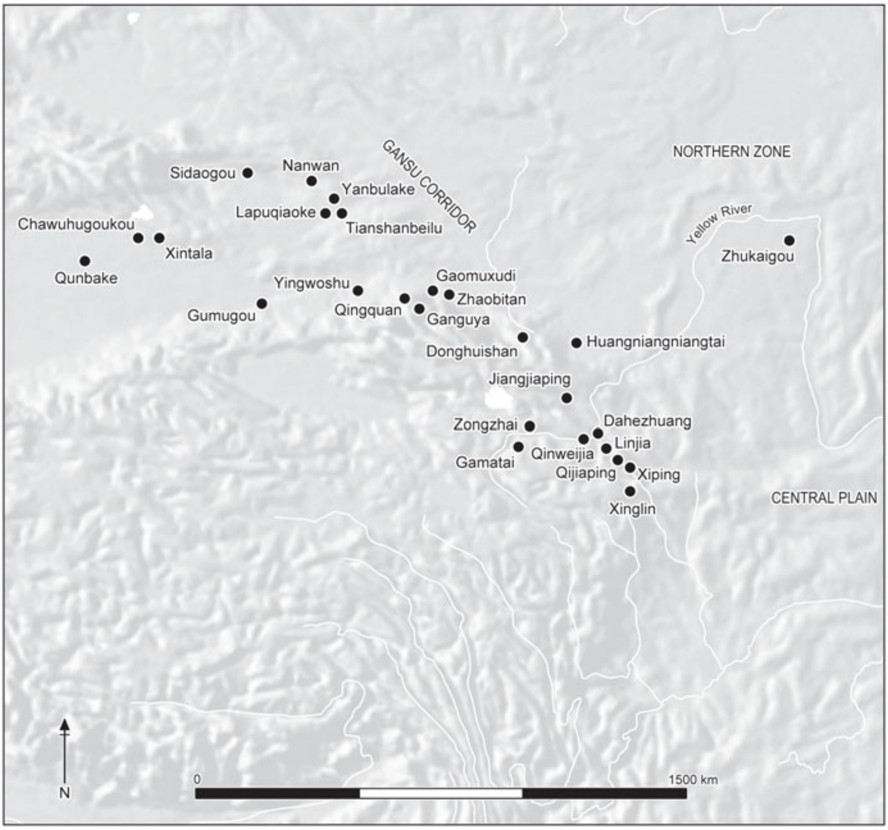


Fig. 27.2 Central China, Gansu Corridor, and upper Yangtze, showing key early metal sites

of societal development. Those outside of the Central Plain were producing both worked and simple cast objects on a small scale (Linduff 1998). These sites locate the use of metal working (Areas I, II, III, and V) and casting (all Areas) as well as regionally specialized ritual materials all at about the same time. With this evidence, the possibility that metal technology was introduced to the Yellow River Basin must be considered, while maintaining the possibility that the elaborate piece-mould casting methods used to cast ritual vessels in the Shang Dynasty may likely have developed independently in the Central Plain.

The appearance, but also the demise of these metal-using communities outside of that in Dynastic China is also a great dilemma. The type of social complexity at Areas II and III worked against their emergence into ranked, hierarchically ordered societies like those developed in the rich agricultural lands of the Central Plains. Their economies likely did not collapse, but rather were recast by increased dependence on pastoralism in Area II (Indrisano 2006) and hunting, trapping, and pig farming in Zone III (Shelach 1994, 1999), thus, dramatically separating their lifeways from that of Chinese agriculturists.

Implications of the Data

Taken together, these sites locate a broad area across northern East Asia where the beginnings of metal use can be located and dated at about the same time. All areas where metallurgy emerged were near ore sources of metals, especially copper in several combinations (Linduff et al. 2000: Maps 5–8). For instance, the distinctive arsenical copper objects must have been manufactured by exploiting local resources that are still available in present-day Gansu. (Linduff et al. 2000: Map I) Although each area developed a taste for items made from copper and copper alloys, gold items have been found only in the northeast and northwest. These gold items (earrings and nose ring) are only occasionally found, and may be imports, valued perhaps for their rarity, or they may have been manufactured locally and used because of their form to signify group affiliation. The earring (including nose rings) types were known in far greater numbers made from copper and tin-bronze, and especially in Qijia and Siba sites in Area I.

The makeup of each culture area, even in this preliminary survey, belongs to a distinctive archaeological culture identified by its pottery and speculated upon by some according to ethnicity (Linduff et al. 2000, I.9, II.10). In all regions, the economy is mixed; excavated villages have yielded evidence of both cultivated crops and domesticated animals, as well as the continued practice of hunting with improved arrowheads made of tin-bronze. Many early copper products show an uncanny resemblance to each other across the Northern Corridor—from Gansu, to Lower Xiajiadian in the northeast, to Yueshi in the Shandong Peninsula. Metal ornaments and simple tools seem not to designate rank in any of the sites outside of the Central Plain as, for example, in burials at Huoshaogou, where metal items are included in most burials. That is to say, the material of their manufacture is not noticeably restricted as it is in sites associated with dynastic China throughout the mid-second and first millennia BC.

The presence of comparable tin-bronze tools and many other shared traits mentioned above suggests, nevertheless, that there was a network of some type, however loosely connected. As part of a network, those outside may have contributed to the development of state-level society in the Central Plain (oracle taking, for instance, or more substantively through interdependent economic systems) (Shelach 1994; Linduff 1998), rather than merely acting as passive receivers of metallurgical technology and other features of complex society from the Central Plain, as has been suggested in the past. They are linked through comparable artifact types and by shared metallurgical technologies not easily transmitted without movement of craftworkers or even larger groups of travelers.

The expansion of the metal tool-kit and the production of it in alloyed metals in the early second millennium BC in Gansu and the surrounding area did not witness an intensification of its use as a political marker, as was the case with tin-bronze items produced and buried in the Central Plain, but perhaps as a cultural identifier. The consistently local character (pottery types and styles) of sites, as well as the appearance of metal items with affinities to cultural debris of Bronze Age southern Siberia, suggests that there was movement into the Gansu Corridor of newcomers who were possibly horse herding (Anthony 2007), but certainly metal-producing peoples of Andronovo background (Peng 1998; Mei and Shell 1998, 1999). Movement of groups along a north–south path must also be considered as such movements are still very much part of life on the eastern Eurasian steppe today (Sandra Olsen personal communication). Among those eastern Inner Eurasian peoples, animal sacrifice also signified status and/or leadership in burial and metal items included tools, weapons, and personal ornaments associated with individuating societies, not with one whose symbol system was used to identify all members of the same political unit, as exemplified by the use of the tin-bronzes at Erlitou.

Still, the best-known cultural trajectory is the one at Erlitou and its surrounds. The sophisticated tin-bronze industry was apparently the exclusive commodity of the elite and developed along with the emergence of social complexity and ritualized social hierarchy (Chang 1980). This development is already apparent in the second millennium BC, where status-based and role-related social decorum operated in the religious, social, and political spheres (Keightley 1990, p. 42) and demanded the production and use of the ritual items such as vessels and weapons cast out of tin-bronze as at Erlitou. They experimented with metals in the region in the late third and early second millennium BC, but by about 1750 BC, they were on a different track from the cultures to their northeast and northwest. The emergence of state-level society no later than the Shang was synonymous with tin-bronze production. Where the advanced methods of piece-mould casting were invented is yet to be determined, but their restricted use of alloyed tin-bronze was apparent from at least as early as the sites at Erlitou, Henan.

Outside of the Central Plain, the story is different, and the archaeological record is beginning to clarify those differences. Each area experimented with metal use at the household level well before 1750 BC. Each area made artifacts from copper or alloyed metal items of comparable shape and style for utilitarian or decorative use; and each followed its own local historical path. The Shandong peninsula contributed to and finally was absorbed into the Chinese dynastic society in the second millennium BC. The cultures in the northeast region continued a sedentary lifestyle and increased independent tin-bronze production substantially after about 1000 BC. In the northwestern region, the local cultures called the Qijia and Siba were seemingly more connected with cultures to their own west, never established centrally managed state-level societies, and remained outside of the Chinese cultural and political dynastic arena until the Qin conquered these lands in about the fifth century BC. This area seems not to have been inspired by the Central Plain about tin-bronze metallurgy or much of anything else detectable in the archaeological record. Their knowledge of horses and of certain metal tools were eventually probably imported into the Central Plain.

The communities in these four areas are all late Neolithic agricultural communities, but their economic strategies, social organization, probably their political systems, and surely their ideologies differed. Some, especially those west of the Wei River, gained much greater benefit from their western neighbors, who inhabited the plains of eastern Inner Eurasia, than from the Chinese dynasts to their east and remained outside of Chinese political control and cultural sway for centuries following.

China and Eurasia

Because little was documented to suggest an earlier phase of metallurgy and because of the prevalence of a diffusionist model of explanation among western scholars, knowledge of metals in regions east of the Caucasus has most often been explained by proposing a route of transmission from the Near East across Russia to the Far East. Two possible routes have been suggested: the Northern and/or a Central Asiatic. Both routes were thought to have begun in the Anatolian–Iranian area and traversed the Caucasus across the Eurasian Steppe or from Iran up to the Amu Darya and over the Tianshan Mountains to Kashgar (Tylecote 1976, pp. 14). Such diffusionist theories rested on the chronology of the Near Eastern sites. The lack of reports on early use and manufacture and the limited availability of reports written only in Russian and Chinese have hindered reliable testing of the diffusionist model.

Among Chinese and Russian scholars, study of the industry and proposals about who initiated the movement of ideas have been affected by mutual lack of information because of language barriers, but especially because of political borders and nationalistic sentiments. The now-dated debate between Profs. B. Karlgren and M. Loehr presented judgments on the direction of transmission for the technology, for example, based on analysis of style of artifacts and the manner of its transformation across time and space (Karlgren 1945; Loehr 1949a, b). Their arguments, Karlgren as the champion of China and Loehr of Siberian cultures as the primary source for certain artifact types and ultimately for the technology itself, were mounted at a time when excavated, tested, and dated materials earlier than about 1250 BC were lacking from both sides. And although archaeologists and metallurgists have questioned the diffusionist model, this view and others are now being reassessed in light of new archaeological information (Mei 2003a; Liu and Li 2007).

The translation of Evgeny Chernykh's text on the early metallurgy in the USSR has allowed access to readers of English to excavated materials from the territories between the Near East and central Siberia (1992). In addition, better and more complete reports on copper- and metal-using as well as mining sites in Russia, especially those east of the Ural Mountains such as Arkaim and Sintashta-Petrovka (Gening et al 1992; Chernykh and Kuz'minykh 1989) and Kargaly (Chernykh 2003) and from northern East Asia dated to the third millennia BC are also available, still largely in the local languages (Linduff 1997; Chase and Douglas 1997). Not only do such reports suggest that there was contact between cultures of the eastern Eurasian steppe and China, but also that the beginnings of metallurgy in this part of the world was regional and took direction according to the host culture and local demands. Wide-ranging studies on the process of this development are still rare (Barnard 1983, 1987; Linduff 1997, 1998; Linduff et al. 2000, pp. 1–28). These studies do not allow independent evaluation of the sources, however, by those trained either outside of Chinese area studies or in metallurgy.

The Chinese preoccupation with the notion of the primary role of the Central Plain to the emergence of Chinese civilization (An 1989; Chang 1977; Chen 1988; Olsen 1987; Falkenhausen 1993) is apparent still, even though it is also clear that there are many early, precocious metal-producing sites outside the area considered as the homeland of the dynastic Chinese. This struggle has an extensive and very well-argued history in Chinese scholarship, making long-held mononuclear notions about the rise of Chinese civilization not only hard to change, but also striking when the view is challenged. For example, An Zhimin's 1993 article suggesting that there may have been multiple centers where the experimentation with metals took place was a landmark in Chinese scholarship. This well-established leader of the archaeological community in China joined other, earlier speculations on the matter, but it was his voice that was widely heard. The introduction of sophisticated methods of scientific examination of the composition, structure, and sources of metals has added yet another, very powerful analytic tool to the study of early Chinese technology.

Another problem has vexed Chinese archaeologists as they excavated and published early materials—the question of dating. Of central concern to archaeologists in China as elsewhere, the use of carbon dating and the calibration of these dates have revolutionized methods of dating, formerly based entirely on stratigraphy and the development of ceramic, or other, diagnostic typologies. The combination of these two methods is now in use in many locations in China and yields evidence of periodization that can be more confidently accepted and compared to other areas of the world. In some cases, these newly calculated Chinese dates have necessitated a reevaluation of those metal-producing sites across its borders in Russia (Mei 2000, 2003b). A collection of essays, bibliography, lists of calibrated C14 dates, and maps have made available some important papers and data, but much was not covered in that text (Linduff et al. 2000). Work on mining, for instance, brings data to the discussion that was all but missing before the mid-1980s (Hua 1986, 1987, 1991; Li, et al. 2007).

This region of eastern Eurasia is linked through comparable artifact types, by closeness to ores, and by shared metallurgical technologies not easily transmitted without movement of craft workers or even groups of travelers. The consistently local character of pottery types and styles in sub-areas, as well as the appearance of metal items with affinities to cultural debris from Bronze Age southern Siberia, suggests that there was movement into the area of western China, likely metal-producing peoples from eastern Kazakhstan and/or Transbaikalia (Shui 1993; Chen and Hiebert 1995; Mei and Shell 1999). As mentioned above, animal sacrifice signified status and/or leadership in burial and metal items included tools, weapons, and personal ornaments associated with individuating societies in the region of Gansu, metal items ultimately were used to identify only elite members of a centralized political unit at Erlitou in the center of early dynastic China. As Kuz'mina suggests (2003) the appearance of wheeled transport, metallurgy and use, and/or breeding of horses signal not only movement of ideas, technology, and perhaps peoples, but also significant societal change, and often lead to a more complex social order. This process may or may not characterize the village settings in western and northern China (Linduff et al. 2000, pp. 1–29), but changes in social complexity are clearly identifiable in and around Erlitou in the Central Plain.

Further, we may note that this change evidenced for the earlier to middle second millennium BC was not a one-time affair. That was not the only period of interchange between the peoples of western China and points west. Continued stimulation, moving in both directions, can be witnessed in the later second and early first millennia BC. Nor are the border regions of present-day western China the limit of that exchange system. Both local pottery and early metal artifacts suggest that knowledge of metallurgical traditions and artifact types extended into northeastern China and into what is now the Russian Far East.

Nevertheless, when considering the advent of metallurgy in the late fourth and third millennia BC, all the criteria of the Eurasian Metallurgical Province (EMP) defined by Chernykh are found in the "Chinese" contexts. If separated from modern nationalistic and centric views of ancient culture and considered as part of a larger metallurgical context, even the multi-piece-mould casting method developed in the early second millennium BC at Erlitou, thought of as a hallmark invention of early dynastic China, may be seen as a local technological variation within the easternmost Eurasian territory made for specialized ritual use (Linduff 2004).

The Future

It is clear that more work needs to be done before analysis of metallurgy and societal change can be productively carried out. A few suggestions follow:

Further regional and local analysis needs to be done, including multidimensional study of communities including excavation of habitation sites, hopefully production sites, as well as mines, etcetera. From these contexts, clearer chronologies could be created. Study of the region would benefit from expansion to a more concentrated analysis that includes southwestern and south central China, which is not studied well and could be important to further analyses. Connections with Southeast Asia are just beginning to be investigated systematically (Higham and Higham 2009; Pigott and Ciarla 2007; White and Hamilton, this volume).

More intensive technological analysis would add immeasurably to the discussion. Both metallographic and compositional analysis could lead to discussion about where and how alloys were produced. Especially problematic is the fact that technical data on excavated materials produced in the Central Plain are largely absent. These data are essential to any study in East Asia. Although scientific examination of dozens of metal objects excavated at the Erlitou site, for instance, has been completed, the results have not yet been published. The major alloy types of the Erlitou metals include Cu–Sn and Cu–Sn–Pb, though there are a small number of artifacts made of Cu–As, probably an indication of connections to other regions. Generally speaking, the Erlitou tin-bronze industry is slightly later than what we have seen in Northwest China. Therefore, evidence for the existence of some borrowing from Northwest and North China in the Central Plain during the Erlitou period is becoming strong, but this is not yet decisive or adequately documented. Regional interaction needs to be documented as well, especially from several distinctive regions including the Central Plain, Gansu-Qinghai, Xinjiang, and the Northern Zone.

In addition, perhaps one of the most intriguing questions yet to be addressed systematically is about the invention of piece-mould casting methodology. We need to examine this issue from both technological and socio-cultural angles.

More study of mining and ores would allow a more firm understanding of sources and the relationship between trade and interaction with the emergence of societal complexity. Although we suspect that in all the metal production regions local mineral resources existed, we cannot deny the importance of interregional trade networks. Some hard evidence for mining has been located in recent years. In 2007, for instance, an early mining site (Lower Xiajiadian period?) was discovered in Inner Mongolia, and analytical work is now being carried out on the data from that site. Similarly, also in 2007, two early smelting sites (second millennium BC) were discovered at unexpected locations in the Hexi corridor in Gansu. The discovery has raised questions concerning the organization of early mining and smelting activities, as one site is located in the desert, almost 100 km away from the Qilian Mountain where the most likely source for the metal ores is located. This suggests that it may become increasingly important to look at the societal context of early metallurgy, since it is likely that early communities in the Hexi Corridor were village level societies and could presumably only support metallurgical activity on a relatively small scale.

If as more and more sites are excavated, greater information on soil, on animal life, on diet, on regional patterns including economic, political, and social organization were gathered, analysis of the data could lead to more firm explanations for cultural interaction, trade, as well as for the function of metal products and their production in society.

In contexts where manufactured metal artifacts have been found in China, excavated villages have yielded evidence of both cultivated crops and domesticated animals, as well as the continued practice of hunting with improved arrowheads made of metal, especially in the northeast. Chernykh's fanciful speculation that the Seima-Turbino was formed through a fusion of metallurgists and warrior horse riders of the forest zones of the Altai and eastern Siberian taiga mobile hunters (1992), he claims, is supported in the recent excavations of the village at Gorny (Chernykh et al. 1998), Kargaly (Chernykh 1997; 2002–2007), and many others including Arkaim and related sites (Zdanovich 1997). Located close to vast resources of ores in the Urals, these excavations reveal that isolated groups of miners and metallurgists worked in specialized communities for many generations supplying patrons across western, and possibly eastern, Eurasia. In China's Central Plain, with an emerging ruling class, state-level society and the ritual significance given to alloyed metals, the network included not only the regional importation of metal ores, but also of salt (Liu and Chen 2003, pp. 80–81), and supported a very specialized metal industry that developed quite differently and perhaps independently from those communities/polities in areas to the north, northeast, and west of ancient China (Linduff et al. 2000). Those outside of the Central Plain emerged perhaps in concert with, however, interactions with eastern Eurasia.

Therefore, in considering the directions for future research, four points may be emphasized: first, technological analysis is basic and should be carried on, with a greater emphasis on the samples collected from production sites, including slag, ores, and furnace materials. Comparative studies based on analytical data should be done in order to characterize the regional technological features, which could be used as evidence understanding the pattern of contacts or interactions between various regions. Second, regional analysis may include an examination of sociocultural context for metallurgical production, such as ceramic production, ritual preference, burial custom, religious tradition, artistic choice, and so on. More attention should be paid to exploring how early metallurgical activities were organized and what they contributed to the increase of social complexity. A combination of technological and archaeological approaches will be necessary. Third, local innovations and long-distance contacts are two vital issues that are worthy of in-depth exploration by employing an interdisciplinary approach. Several important early metallurgical innovations have been noted, such as piece-mould casting, arsenical copper, leaded bronze, decorated mirrors, but how they emerged and developed still remain unclear and required further research. Fourth, more comprehensive scientific dating must guide all considerations above, and could be provided in new as well as previously excavated and surveyed locations. Then, if these issues were examined within a wider Eurasian context, the contributions from both local innovations and outside impetus could be properly highlighted. It is important to understand the scale, patterns, and mechanisms of early interaction, including trade and exchange, movement of people, as well as community conflict.

Furthermore, as western research approaches as well as theoretical thinking continue to be introduced into China, academic discussion and debate among scholars will be stimulated. Much more is still to be learned and close collaboration and academic exchange between Chinese and other scholars should and is being encouraged.

Bibliography

An, Z. (1989). Chinese archaeology: Past and present. *Archaeological Review from Cambridge*, *8*(1), 12–18.

An, Z. (1993). On Early Copper and Bronze Objects in Ancient China. *Kaogu*, *12*, 1110–1119.

Anthony, D. W. (2007). *The horse, the wheel and language*. Princeton: Princeton University Press.

Barnard, N. (1961). *Bronze Casting and Bronze Alloys in Ancient China*. Australia & Lagya: Canberra.

Barnard, N. (1983). Further evidence to support the hypothesis of indigenous origins of metallurgy in ancient China. In D. N. Keightley (Ed.), *The origin of Chinese civilization* (pp. 237–277). Berkeley: University of California Press.

Barnard, N. (1987). Bronze casting technology in the peripheral ‘Barbarian’ Regions. *Bulletin of the Metals Museum*, *12*, 3–37.

Barnard, N. (1993). Thoughts on the Emergence of Metallurgy in Pre-Shang and Early Shang China, and a Technical Appraisal of Relevant Bronze Artifacts of the Time. *Bulletin of the Metals Museum*, *19*, 3–48.

Barnard, N., & Tomatsu, S. (1975). *Metallurgical Remains of Ancient China*. Tokyo: Nichiosha.

BUIST (Beijing University of Iron and Steel Technology, Archaeometallurgy Group). (1981). A Preliminary Study of Early Chinese Copper and Bronze Artifacts. *Kaogu xuebao*, *3*, 287–302.

Bunker, E. C. (1993). Gold in the Ancient Chinese World: A Cultural Puzzle. *Artibus Asiae*, *LIII*(1/2), 27–50.

Bunker, E. C. (1994a). The Metallurgy of Personal Adornment, *Adornment for Eternity: Status and Rank in Chinese Ornament* (pp. 31–39). Denver: Denver Art Museum and The Woods Publishing Co.

Bunker, E. C. (1994b). The enigmatic role of silver in China. *Orientations*, *25*(November), 73–78.

Bunker, E. C., Kawami T., Linduff K. M., & Wu E (1997). *Ancient Bronzes of the Eastern Eurasian Steppes from the Arthur M. Sackler Collections*. New York: the Arthur M. Sackler Foundation.

Chang, K. C. (1977). Chinese Archaeology since 1949. *Journal of Asian Studies*, *XXXVI*(4), 623–644.

Chang, K. C. (1980). *Art, Myth and Ritual: The Path to Political Authority in Ancient China*. Cambridge: Harvard University Press.

Chang, K. C. (1981). Archaeology and Chinese Historiography. *World Archaeology*, *13*(2), 156–168.

Chang, K. C. (1986). *The Archaeology of Ancient China* (4th Ed). New Haven: Yale University Press.

Chang, K. C. (1989). Ancient China and its Anthropological Significance, in *Archaeological Though in America*, edited by C.C. Lamberg-Karlovsky, pp. 155–166. Cambridge: Cambridge University Press.

Chase, W. T., & Douglas, J. G. (1997). Appendix 2: Technical Studies and Metal Compositional Analysis of Bronzes from the Eastern Eurasian Steppes. In E. C. Bunker, et al. (Ed.), *Ancient Bronzes of the Eastern Eurasian Steppes from the Arthur M. Sackler Collections* (pp. 306–418). New York: The Arthur M. Sackler Foundation.

Chen, C. (1988). Chinese Archaeology and the West. *Archaeological Review from Cambridge*, *8*(1), 26–35.

Chen, K. T., & Hiebert, F. (1995). The Late Prehistory of Xinjiang in relation to its neighbors. *Journal of World Prehistory*, *9*(2), 243–300.

Chernykh, E. N. (1992). *Ancient Metallurgy in the USSR: The Early Metal Age*. Cambridge: Cambridge University Press.

Chernykh, E. N. (1997). *Kargaly, Zabytyi mir* (Kargaly: The Forgotten World). Moscow: Izdatel'stvo 'NOX'.

Chernykh, E. N. (2002–2007). *Kargaly Vols. 1–5*. Moscow: Nauka.

Chernykh, E. N., & Kuz'minykh S. V. (1989). *Ancient Metallurgy in the Northern Eurasia: Seyma-Turbino Phenomenon*. Moscow: Nauka.

Chernykh, E. N., Antipina, E. E., & Lebewedeva E. Y. (1998). *Produktionsformen der Urgesellschaft in der Steppen Osteuropas (Ackerbau, Viezucht, Erzgewinnung und Verhuttung)*, *Das Karpatenbeckens und die osteuropaische Steppe: Nomadenbewegungen und Kulturaustausch in der vorchristlichen Metallzeit (4000–500 v. Chr.)*. Sudosteuropa-Geselschaft, München. B. Hensel und Rahhen/Westf: Leidorf, pp. 233–252.

CICARP The Chifeng International Collaborative Archaeological Research Project 赤峰中美联合考古研究项目（编著）(2003). *Regional Archaeology in Eastern Inner Mongolia: A Methodological Exploration*. 内蒙古东部（赤峰）区域考古调查阶段性报告, Beijing 北京: Science Press 科学出版社. (In Chinese and English)

Falkenhausen, L. von. (1993). On the historiographical orientation of Chinese Archaeology. *Antiquity*, *67*, 839–492.

Falkenhausen, L. von. (1995). The regionalist paradigm in Chinese archaeology. In P. Kohl & C. Fawcett (Eds.), *Nationalism, Politics, and the Practice of Archaeology* (pp. 198–217). Cambridge: Cambridge University Press.

Fong, W. (1980). *The Great Bronze Age of China*. New York: The Metropolitan Museum of Art.

Gening, V. F., Zdanovich G. B., & Gening, V. V. (1992). *Archaeological Sites of Aryan Tribes of the Ural-Kazakh Steppes*, Chelyabinsk.

Gettens, J. R. (1967). The *Freer Chinese Bronzes*. Washington, DC: Smithsonian Institution (Oriental studies, no. 7).

Higham, C., & Higham, T. (2009). A new chronological framework for prehistoric Southeast Asia, based on a Bayesian model from Ban Nok Wat. *Antiquity*, 83, 125–144.
Hua, J. (1986). *On the History of Metallurgy and Casting in China*. Beijing: Wenwu Chubanshe.
Hua, J. (1987). Technological characteristics of metal technology in ancient China. *Ziran Kexueshi Yanjiu 1*.
Hua, J. (1991). A discussion of the origin of chinese metallurgy. *Ziran Kexue Shi Yanjiu*, *4*, 364–369.
Indrisano, G. (2006). *Subsistence, Environmental Fluctuation and Social Change: A case Study in South Central Inner Mongolia*. PhD Dissertation, University of Pittsburgh.
Karlgren, B. (1945). Some Weapons and Tools of the Yin Dynasty. *Bulletin of the Museum of Far Eastern Antiquities*, *XCII*, 101–144.
Keightley, D. N. (1990). Early Civilization in China: Reflections on How It Became China. In S. R. Paul (Ed.), *Heritage of China: Contemporary Perspectives on Chinese Civilization*. Oxford: University of Oxford Press, Ltd.
KG Kaogu. (1978). *1*, 23–34.
KGXB (1988). *Kaogu Xuebao*, *3*, 322–331.
KGYWW (1980). *Kaogu yu Wenwu*, *3*, 22–24.
Li, Y., Willis, K. J., Zhou, L., Cui, H. (2006). The Impact of Ancient Civilization on the Northeastern Chinese Landscape: Palaeoecological Evidence from the Western Liaohe River, Inner Mongolia. *The Holocene*, *16*(8), 1109–1121.
Li, Y., Zhu, Y., & Chen, J. (2007). *Bronze Metallurgy of the Upper Xiajiadian Culture*. BUMA-V Meeting, Beijing, unpublished paper.
Lin, Y. (1986). A Reexamination of the Relationship between Bronzes of the Shang Culture and of the Northern Zone'. In K. C. Chang (Ed.), *Studies in Shang Archaeology* (pp. 237–273). New Haven and London.
Linduff, K. M. (1997). An Archaeological Overview: Section 1. Reconstructing Frontier Cultures from Archaeological Evidence. In E. C. Bunker, et al. (Ed.), *Ancient Bronzes of the Eastern Eurasian Steppes from the Arthur M. Sackler Collections* (pp. 18–33). New York: The Arthur M. Sackler Foundation.
Linduff, K. M. (1998). The Emergence and Demise of Bronze-using Cultures Outside the Central Plain in Ancient China. In, by Victor Mair (Ed.), *The Bronze Age and Early Iron Age Peoples of Eastern Central Asia* (pp. 619–643). Washington, DC: The Journal of Indo-European Studies/The University of Pennsylvania Museum of Archaeology and Anthropology, Monograph Series.
Linduff, K. M., Han, R., & Sun, S. (2000). *The Beginnings of Metallurgy in China*. Lampeter: Edwin Mellen Press.
Linduff, K. M., Drennan, R. D., & Shelach, G. (2002–2004). Early complex societies in Northeast China: The Chifeng International Collaborative Archaeological Research Project. *Journal of Field Archaeology*, *29*, 45–73.
Linduff, K. M. (2004). The beginnings of metallurgy from the Urals to the Yellow River. In K. M. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* Lewiston: MellenPress.
Liu, L. (1996). Settlement patterns, chiefdom variability, and the development of early states in North China. *Journal of Anthropological Archaeology*, *15*, 237–288.
Liu, L., & Chen X. (2003). *State Formation of Early China*. London: Duckworth.
Liu, X., & Li, W. (2007). Zhongguo zaoqi qingtong wenhua de quyuan ji qi siangguan wenti xintan (A New Study on the Origin of Early Chinese Bronze Culture and Relevant Issues). *Zangxue xuekan (Journal of Tibetology)*, *3*, 1063.
Loehr, M. (1949a). Weapons and tools from Anyang and Siberian analogies. *American Journal of Archaeology*, *LIII*, 126–144.
Loehr, M. (1949b). Ordos daggers and knives: New material classification and chronology. *Artibus Asiae, XII*, 23–83.
Mei, J. (2000). *Copper and Bronze metallurgy in late prehistoric Xinjiang: Its cultural context and relationship with neighboring regions*. BAR International Series 865. Oxford: Archaeopress.
Mei, J. (2003a). Cultural Interaction between China and Central Asia during the Bronze Age. *Proceedings of the British Academy*, *121*, 1–39.

Mei, J. (2003b). Qijia and Seima-Turbino: The Question of Early Contacts between Northwest China and the Eurasian Steppe. *Bulletin of the Museum of Far Eastern Antiquities*, *75*, 31–54.
Mei, J., & Shell, C. (1998). Copper and Bronze Metallurgy in Late Prehistoric Xinjiang. V. Mair (Ed.), *The Bronze Age of Early Iron Age Peoples of Eastern Central Asia* (pp. 581–597, Vol. 2). Washington, DC: Institute for the Study of Man.
Mei, J., & Shell, C. (1999). The existence of Andronovo cultural influence in Xinjiang during the second millennium BC. *Antiquity*, *73*(281), 570–578.
Murowchick, R. E. (1997). The State of Sino-foreign Collaborative Archaeology in China. *Orientations*, *28*(6), 26–33.
Olsen, J. W. (1987). The practice of archaeology in China today. *Antiquity*, *61*, 282–290.
Peng, K. (1998). The Andronovo Bronze Artifacts Discovered in Toquztara county in Yili, Xinjiang. In V. Mair (Ed.), *The Bronze Age and Early Iron Age Peoples on Eastern Central Asia* (pp. 573–580). Washington, DC: The Institute for the Study of Man, and Philadelphia: The University of Pennsylvania Museum Publications.
Pigott, V. C., & Ciarla, R. (2007). On the origins of metallurgy in prehistoric Southeast Asia: the view from Thailand. *Metals and Mines: Studies in Archaeometallurgy* (pp. 76–88). London: British Museum, Archetype Publications.
Shelach, G. (1994). Social complexity in North China during the early bronze age: A comparative study of the Erlitou and Lower Xiajiadian Cultures. *Asian Perspectives*, *33*, 261–292.
Shelach, G. (1998). Settlement pattern study in Northeast China: Results and insights on potential contributions of western theory to Chinese archaeology. *Antiquity*, *72*, 114–127.
Shelach, G. (1999). *Leadership Strategies, Economic Activity, and Interrogational Interaction: Social Complexity in Northeast China*. New York: Kluwer Academic, Plenum Publishers.
Shui, T. (1993). Xinjiang qingtong shidai zhu wenhua de bijiao yanjiu (A Comparative Study of the Bronze Age Cultures in Xinjiang) *Guoxue yanjiu (Studies in Sinology)*, *1*, 447–490.
So, J., & Bunker, E. C. (1995). *Traiders and Raiders on China's Northern Frontier*, Arthur M. Sackler Gallery, Smithsonian Institution, Seattle: University of Washington Press.
Sun, S., & Han, R. (1997). Study of Casting and Manufacturing Techniques of Early Copper and Bronze Artifacts found in Gansu. *Wenwu*, *7*, 54–84.
Tylecote, R. F. 1992 (1976). *A History of Metallurgy*. London: Institute of Materials.
Underhill, A. P., Feinman, G. M., Nicholas, L., Bennett, G., Cai, F., Yu, H., Luan, F., & Fang, H. (1998). Systematic, regional survey in SE Shandong Province, China. *Journal of Field Archaeology*, *25*, 453–474.
Wu, E. (1995). Bronze Artifacts from Yin to Zhou Periods in Northern China. *KGXB*, *2*, 135–55.
Xu, Y. (1989). The Siba Culture at Houshaogou, Donghuishan, Minle County. *The Almanac of Chinese Archaeology* (pp. 246–247). Beijing: Wenwu Press.
XSZ. (2000). Xia-Shang-Zhou Chronology Project Zhuanjiazu. *Xia-Shang-Zhou duandai gongcheng 1996–2000 nian jieduan chengguo baogao, Jianben*. Beijing: Shijie Publishing Co.
Zdanovich, G. B. (1997). Arkaim – kul'turnyi kompleks epokhi srednei bronzy luzhnogo Zaural'ia. (Arkaim: A Cultural Complex of the Middle Bronze Age in the South Ural Region). *Rossiikaia arkheologiia*, (Russian Archaeology) *2*, 47–68.
Zhang, Z. (1986). *Zhongguo Beifang Kaogu Wenjiu* (Collection of Articles on the Archaeology of North China). Beijing: Wenwu Press.

Chapter 28
The Transmission of Early Bronze Technology to Thailand: New Perspectives

Joyce C. White and Elizabeth G. Hamilton

Introduction

Archaeological research in Southeast Asia is a relatively new field and there are huge gaps in our fundamental data and understanding. Large areas such as Myanmar and Laos remain little explored. Even in subregions such as Northeast Thailand, where there have been several decades of research, the data are quite thin. For example, there are no fully articulated, dated and published, and stratigraphically based regional ceramic sequences widely used by prehistorians in mainland Southeast Asia. Southeast Asian archaeologists debate many of the most basic aspects of regional culture history—how old a pottery type is; when glass, iron, or any other technology first appears; when and where social forms such as chiefdoms or states first appear; and so forth. The paucity of much basic archaeological evidence does not, however, dampen the interest in broader disciplinary questions such as why and how technological, social, economic, and other changes have occurred, even if the data allow only preliminary and speculative statements rather than enduring and quantitatively based assessments.

When, where, and by what mechanisms bronze metallurgy first appeared in Southeast Asia have been topics of scholarly debate for more than 40 years. Because the evidence for the earliest bronze metallurgy in the region indicates that it appeared fully developed, and no signs of an experimental period have been found, the scholarly consensus, despite occasional flashes of discussion (e.g., Higham 1996, 2002, p. 166, 353, 2006, p. 19; vide Sherratt 2006, pp. 43–44), is that metallurgy—the

J. C. White (✉)
Asian Section, University of Pennsylvania Museum,
3260 South Street, Philadelphia, PA 19104, USA
e-mail: banchang@sas.upenn.edu

E. G. Hamilton
University of Pennsylvania Museum, 3260 South Street,
Philadelphia, PA 19104, USA

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3_28,

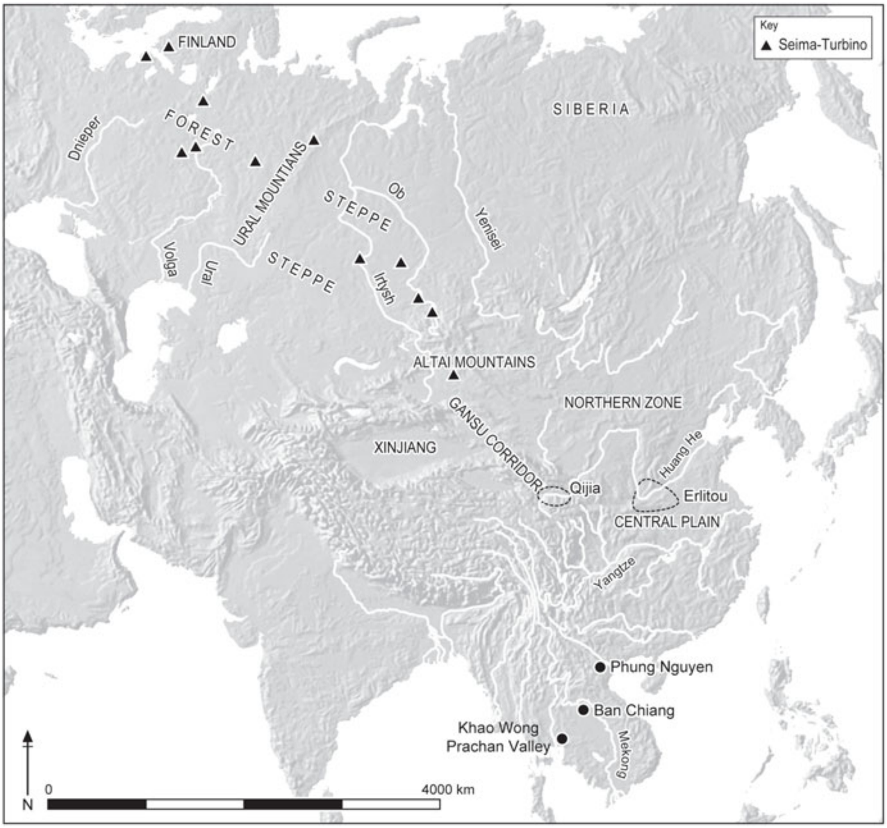


Fig. 28.1 Map of Asia and eastern Europe showing important sites and geographic features mentioned in the text. (Adapted from the Encyclopedic World Atlas 2002, p. 10. Seima–Turbino sites (*triangles*) in Eurasia are taken from Chernykh 1992, p. 192. Ardeth Abrams, illustrator)

system of manufacturing, distributing, and using metals and metal objects—was derived from elsewhere (Roberts et al. 2009, p. 1016). The dating and source of the earliest metals in the region remains a major topic of dispute even today (Higham and Higham 2009; Pigott and Ciarla 2007; White 2008). Scholars interested in the issues include many who are not regional prehistorians (Linduff 1998, p. 633; Mair 1998a; Muhly 1988; Sherratt 2006), because metal technology may be one of the best media through which to explore the details of sociocultural interactions and relations across Eurasia from the fourth through to the first millennium BC (Kohl 2008). In short, understanding the adoption of metallurgy in mainland Southeast Asia could provide important insights into the nature and events of late Holocene Eurasian technology and culture at a continental scale (Sherratt 2006, pp. 43–44).

Most current attempts to explain the appearance of bronze in Southeast Asia look north to early states of the Huang He (Yellow River) Central Plain and their sophisticated bronze tradition for the initial stimulus for bronze metallurgy reaching Southeast Asia (Fig. 28.1; Higham 1996, 2002; Pigott and Ciarla 2007). In this chapter, mainland Southeast Asia refers to the territory encompassed by modern Myanmar (Burma), Thailand, Laos, Vietnam, Cambodia, and the peninsular portion of Malaysia. (To avoid any implied conflation of the modern nation-state of China with past cultures that existed within its territory, we use People's Republic of China or PRC to refer to the modern nation-state, and geographic terms such as river basins or specific provinces when referring to a geographic zone or subunits within PRC boundaries inhabited by past societies).

Proposals for the source of Southeast Asian bronze technology that look to the Huang He Central Plain are framed in a diffusionist idiom (cf. Kroeber 1963 [1923]), e.g., tracing the geography of cultural traits in terms such as the "spread of the idea" of smelting from the more sophisticated Erlitou–Erligang–Shang Chinese cultures to the less-complex societies of Southeast Asia via networks of contact and exchange. We argue that these Sinocentric models are flawed for chronological, technological, and conceptual reasons.

One conceptual problem in Sinocentric models is the primacy given to state-level societies in traditional understandings of the Bronze Age.

> In all other corners of the Bronze Age world—China, Mesopotamia, Anatolia, the Aegean, and central Europe—we find the introduction of bronze metallurgy associated with a complex of social, political, and economic developments that mark the "rise of the state." Only in Southeast Asia, especially in Thailand and Vietnam, do these developments seem to be missing, and explaining (or eliminating) this anomalous situation is one of the major challenges of archaeological and archaeometallurgical research during the next decade. (Muhly 1988, p. 16)

This oft-cited quotation has stimulated considerable research and discussion by Southeast Asian archaeologists in the years since its publication. Some (e.g., Higham 1996, 2006, p. 19, 2009; Higham and Higham 2009) have sought to eliminate the "anomaly" by advocating short chronologies and seeking evidence for a clear relationship between bronze metallurgy in Southeast Asia and intra- and extraregional development of economic and political élites, marked social hierarchies, and state formation activities. Others (O'Reilly 2001; White 1995; White and Pigott 1996) have examined the socioeconomic context for early metal-using cultures in Southeast Asia to understand how nonurban, nonstate societies organized production and use of metals in less-stratified configurations.

Since the discovery of early bronze in Thailand, the opening of formerly inaccessible parts of the Eurasian continent to modern archaeological research, and translations of Russian and Chinese archaeology have provided new data and new conceptual models pertinent to the history of metals in Asia (Linduff and Mei 2009). New evidence ranges from discovery and definition of formerly unknown bronze-producing cultures, such as Tianshanbeilu in eastern Xinjiang (Mei 2003, 2004), to recognition of the great cultural dynamism of metal-using societies in central parts of Asia, beginning in the fourth millennium BC (Anthony 2007; Chernykh 1992; Kohl 2007, 2008; Koryakova and Epimakhov 2007; Kuz'mina 2008; Linduff 2004a; Mair 1998b), to new accelerator mass spectrometry (AMS) dates that have provided an absolute chronology for, and sometimes reordered, cultural sequences that had previously been organized using relative culture-historical frameworks with poor or no chronometric evidence (e.g., Hanks et al. 2007).

As more nonstate bronze-producing societies have been discovered or made better known by the availability of translations of Russian archaeological scholarship, the idea that the Bronze Age was necessarily associated with early state formation (e.g., Muhly 1988, p. 16) has required revision (Linduff and Mei 2009). Examinations of the spread of metallurgy in nonurbanized Eurasia by Chernykh (1992, p. 191) and Kohl (2007, pp. 178–179) led to the observation that “the Late Bronze archaeological record for the western Eurasian steppes documents relations that are more egalitarian and less stratified than what is known of the Early and Middle Bronze periods” (Kohl 2007, pp. 178–179). Kohl’s (2007) concluding Chap. 6 portrays a vastly different, richer, and more diverse Bronze Age than the one envisioned in the influential but now dated Muhly quotation. In the context of these nonurban, less-stratified Eurasian Bronze Age societies, the weakly ranked metal-producing prehistoric societies of Thailand appear less aberrant than when they were first discovered.

Recent scholarship on the anthropology of technology transmission (e.g., O’Brien 2008; Schiffer 2001a, b, 2005, 2008) also provides new conceptual tools with which to address the complexities of why and how technologies move from one society to another. In this regard, it is important to differentiate a “technology” (the application of knowledge of the material properties of physical things to achieve practical purposes) from a “technological system” (the way technological knowledge is implemented in a specific context). So for example, during the second millennium BC, the Huang He Central Plain states and Southeast Asia each had knowledge of bronze technology, but the technological systems for producing and using bronze artifacts in the two regions were markedly different.

The production of metal and metal artifacts is a “complex technological system,” here defined as a system involving suites of interacting technologies comprising more than one material and requiring multiple production steps (modified from Schiffer 2005; see also Costin 2005, p. 1054). Technological knowledge is applied to the manipulation of two or more materials in order to attain a finished product, and a division of labor is also required to conduct the full sequence of steps to implement the technology. The smelting of copper and the production of bronze artifacts are parts of a complex technological system involving the acquisition and manipulation of ores and fuels, the creation of refractory ceramics, the refining of molten metal, alloying, casting, fabrication, and manipulation of molds, and the management of post-casting treatments such as working. When one appreciates the amount of knowledge, and the number of skills and steps involved in even the simplest metal production system, it is difficult to imagine how the transfer of this technology to a society with no prior experience of working with metals could occur without direct instruction.

As ancient metal production systems around the world are studied, it is clear that different solutions to the innumerable technological challenges entailed in creating metal artifacts have been developed by different societies. These variant solutions have been considered “ technological choices,” in that other possible roads to addressing that technical problem exist and were in fact likely known. For example, one society chooses blowpipes, another double piston bellows to apply air to raise temperatures during a smelt, and frequently choices are made for reasons unconnected with Western notions of labor efficiency or scale (Epstein 1993; Hosler 1995; Killick

Table 28.1 Lower Early Period metal artifacts and crucibles found at Ban Chiang

BC			BCES		
Levels	Burial metals	Nonburial metals	Levels	Burial metals	Nonburial metals
7		3 amorphous	2d	5 bangles	–
		2 flat	2c	–	1 crucible fragment 1 amorphous
		2 crucible fragments	2b	–	1 wire/rod
6		2 amorphous 1 slag 1 crucible fragment	2a	1 spear point	1 flat
5		1 flat 2 amorphous 1 wire/rod	1a		
4		1 amorphous			
Total		16		10	

BC the 1974 excavation, *BCES* the 1975 excavation, 100 meters from BC

2004; Schiffer 2004). Defining the particular technological system of an area and its range of technological choices requires investigating not only finished products, but also the manufacturing equipment and debris, evidence of the production steps, the materials technology for both finished products and manufacturing equipment, and the systemic interrelationships among all these components. To determine the source of the knowledge of metalworking in Southeast Asia requires looking at not merely who produced the geographically nearest metal artifacts at a suitable period of time, but who produced the nearest artifacts using a similar technological system.

Transmission of complex metal technologies to an area with no prior experience in metalworking is not likely to have occurred by mere exposure to the idea of smelting or by emulation of goods made of metal (vide Schiffer 2008, p. 107; Van Pool 2008), particularly in areas lacking evidence of a period of experimentation. We now review the technological system evident in the earliest bronze evidence of Southeast Asia in order to better assess its possible source(s).

The Early Southeast Asian Metallurgical System

The Earliest Metal Evidence

The clearest evidence for the appearance of metallurgy in Southeast Asia comes from Ban Chiang in Northeast Thailand (Table 28.1), from the excavations conducted by the University of Pennsylvania Museum and the Fine Arts Department of Thailand in 1974 and 1975 (hereafter Penn/FAD excavations). Ban Chiang is a mixed mortuary/occupation site with prehistoric deposits extending at least from the late third millennium BC to the first millennium AD. (All chronometric dates presented here are calibrated, based on the IntCal04 calibration curve by OxCal v. 4.0.1.) The earliest metal evidence comes from the Ban Chiang lower Early Period. AMS dates on rice inclusions in burial pottery provide a range of c. 2100–1700 BC for the lower Early Period of the site (White 2008). Bronze is missing from the very lowest cultural contexts in the lower Early Period, but fragments are found in occupation contexts in levels producing AMS dates around 2000 BC. The earliest metal grave good recovered from the Penn/FAD excavations, a bent-tip socketed spear point (Fig. 28.2a), comes from a lower Early Period level which dates around 1800 BC (a full discussion of AMS dating of early Ban Chiang metals is in White 1997 and 2008).

Of the 26 metal or metal-related artifacts excavated from lower Early Period burial and nonburial contexts at Ban Chiang by Penn/FAD (Table 28.1), five copper-base bangles (Fig. 28.2b) and one copper-base socketed spear point (Fig. 28.2a) were grave goods. One wire, one rod, four flat pieces (possibly fragments from implements), and nine amorphous copper-base pieces (probably casting spillage) came from nonburial occupation contexts such as general soil matrix, features, or fill around graves. The presence of one piece of slag and four crucible fragments from Ban Chiang lower Early Period contexts suggests that on-site casting (but not necessarily smelting) was practiced from the initial appearance of metal at the site. This early second millennium BC evidence supports the conclusion that bronze appeared at Ban Chiang as a fully developed technology.

Evidence from other Southeast Asian sites of copper-base metallurgy older than 1500 BC is rare and less thoroughly documented than at Ban Chiang. The dating of the earliest copper-base metals from the mortuary/occupation site of Non Nok Tha has long been debated (Bayard 1972, 1979, 1981, 1996–1997; Higham 1996–1997, 2002, p. 129, 2004; Solheim 1968); but there is evidence that the oldest metal there, including a remarkable, thin-walled, deep-socketed tin-bronze implement (known by the nickname WOST, for World's Oldest Socketed Tool; Fig. 28.2c), could date to the late third millennium BC (Bacus 2006; Bayard 1996–1997; Higham 1989, p. 98, 102; Spriggs 1996–1997, p. 943). In central Thailand, a bronze bar recovered from a lower Bronze Phase burial 6ii at Ban Mai Chaimongkol (Fig. 28.2d) has been cross-dated to some time during the early second millennium BC, based on its position in the Ban Mai Chaimongkol ceramic sequence relative to dated ceramic sequences from other sites in central Thailand (Onsuwan 2000, p. 114; Eyre 2006, pp. 100–101, 161, 327). In northern Vietnam, the earliest appearance of copper-base artifacts appears to date from the early second millennium BC in deposits from Phung Nguyen and other contemporaneous cultures. The earliest metal remains are described as "bronze waste material" from six Phung Nguyen sites, "traces of bronze" from Doan Thuong, a site related to Ma Dong, and "two baked clay casting moulds" from the late Phung Nguyen site of Dong Vong (Huyen 2004, p. 190).

In summary, the earliest evidence for copper-base technology in Southeast Asia consists of: (1) jewelry, particularly bangles; (2) socketed implements, cast in bivalve molds with suspended cores (the Ban Chiang bent-tip spear point and the Non

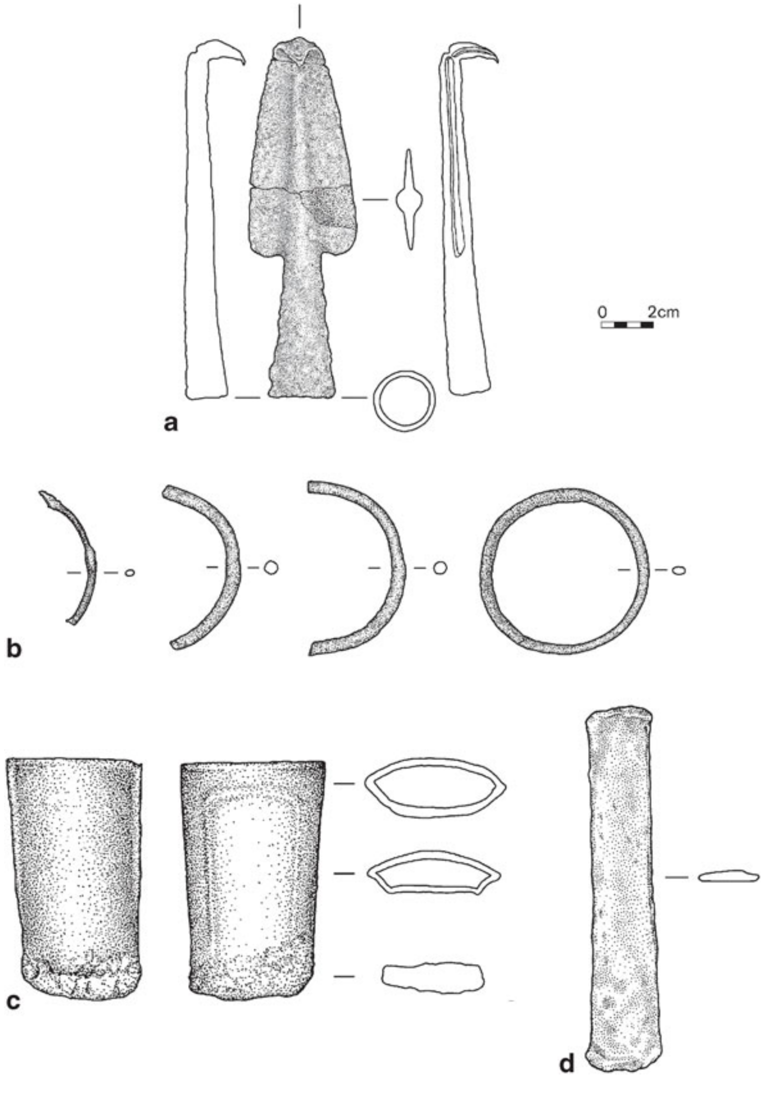


Fig. 28.2 Bronze grave goods from prehistoric Thailand, from the early second millennium BC. **a** Socketed bent-tip spear point BCES 762/2834, from Ban Chiang BCES Burial 76, the flexed grave of a 25–30-year-old man. **b** Anklets BCES 526/1592, BCES 594/1984, BCES 595/1984, and BCES 596A/1984, from Ban Chiang BCES Burial 38, a supine burial of a child about 4 years old. **c** Deep-socketed implement NNT-152, from Non Nok Tha. **d** Bar from Ban Mai Chaimongkol Burial 6ii

Nok Tha deep-socketed implement); (3) flat cast artifacts, including the Ban Mai Chaimongkol bar and occasional fishhooks and arrowheads; (4) flat and rod-like pieces that could have been fragments of implements; (5) small amorphous pieces, most of which are probably casting spillage; (6) crucibles and crucible fragments; and (7) ceramic casting molds.

Technological System Overview: Evidence for Style and Choices

Raw Material Acquisition

Elemental analyses of prehistoric copper-base artifacts from Thailand indicate that tin bronze was the preferred metal from the initial appearance of copper-base metallurgy, so the earliest metalworkers needed to obtain both tin and copper. Systematic archaeological research into how copper was obtained in prehistory has only just begun. The Thailand Archaeometallurgy Project (Pigott 1998; Pigott and Natapintu 1988; Pigott and Weisgerber 1998; Pigott et al. 1997) has documented two major locations with evidence of prehistoric copper production. Phu Lon in Northeast Thailand is a copper mining complex located along the Mekong River about 160 kilometers west of Ban Chiang. The Khao Wong Prachan valley in central Thailand has at least three substantial outcrops of copper ore and several ore-processing/smelting sites in their vicinity. No evidence for mining or smelting that dates to the early second millennium BC has been excavated in Southeast Asia, but evidence from these two localities exploited some centuries later can be used to gain some understanding of probable early procedures.

Phu Lon, where the principal ore mined was malachite, has at least two well-defined locales for ore processing located in the immediate vicinity of the mining areas. The early mining efforts consisted of grubbing surface exposures with heavy oblong river cobbles, resulting in small, rounded pits (Pigott and Natapintu 1996–1997, pp. 789–790). These hammerstones may have been handheld, as there is no hafting groove or other indication of hafting (Pigott and Weisgerber 1998). During later periods of use, mine shafts following mineral veins were created. Eventually, it appears, the profusion of mine shafts and galleries in the hill led to the mine collapsing in on itself (Pigott and Weisgerber 1998). Hundreds of stone-mining mauls and ore-crushing tools were found around the site, with the latter especially in ore-crushing locations. Some 96 fragments of crucibles were recovered, often with some adhering slag, of the same morphology but perhaps somewhat smaller than the crucibles found at Ban Chiang and related sites (Vernon 1996–1997). In the absence of fixed installations such as bowl furnaces, it has been suggested that these crucibles were used in smelting processes (Pigott and Natapintu 1996–1997, p. 793). In the slag adhering to crucibles were found prills of copper, tin, and tin bronze, showing that these metals were processed in the crucibles at Phu Lon as well (Pigott 1998; Pigott and Natapintu 1988; Pigott and Weisgerber 1998; Vernon 1996–1997). Tin ore such as cassiterite is not known to exist in the immediate vicinity of Phu Lon; thus, it is possible that tin smelted from elsewhere, or cassiterite itself, was brought to Phu Lon for processing. Sources of alluvial tin are known in northern Laos across the Mekong. Most of the Phu Lon mining and ore-processing remains date from the first millennium BC. There is one mid-second millennium BC date which could suggest earlier activity at the mine. Mining at Phu Lon appears to have been small scale, episodic, and probably seasonal, though exploitation did continue for centuries.

In contrast to the relatively small-scale metal exploitation at Phu Lon, the Khao Wong Prachan valley in central Thailand has evidence for more ore resource locales and more intensive use (Natapintu 1988). Two copper-production sites in the Khao Wong Prachan valley, Non Pa Wai and Nil Kham Haeng, are among the largest prehistoric copper production sites currently known in Asia. The slag remains at Non Pa Wai alone are estimated to weigh hundreds of thousands of tons (Pigott 1999). Unlike at Phu Lon, where the ore-processing locations were adjacent to the mine, the Khao Wong Prachan ore-processing/smelting localities are a couple of kilometers from the probable locations of the actual copper mines. The metal-processing sites suggest sustained prehistoric use, which the excavators argue began sometime after 1500 BC and continued through the first millennium BC (Pigott 1999). Non Pa Wai has evidence of use as a smelting location with its meters-thick deposit of slag, ore, crucible fragments, and cup/conical molds probably used for ingot production. At the base of the deposit are human burials, some of which are thought to date from the late third or early second millennium BC. The earliest burials are not considered related to metallurgical activity, but later burials probably dating to the later second millennium BC contained ceramic bivalve mold pairs for the casting of deep-socketed adze–axes. Massive ore crushing and copper smelting took place at Nil Kham Haeng during the first millennium BC and, as a site, its matrix is composed primarily of slag and crushed ore/host rock. The site yielded mortuary remains from throughout its sequence. Unlike Phu Lon, no evidence of alloying or tin processing has yet been found at Khao Wong Prachan sites.

The ore deposits in the Khao Wong Prachan valley are rich in both iron and copper; the copper deposits include malachite, chrysocolla, and chalcopyrite (Natapintu 1988). Analysis of the ore fragments found in the cultural deposits shows that both oxidic and sulfidic copper ores were smelted (Pryce and Pigott 2008). Rostoker et al. (1989) suggested that the copper metal was produced by co-smelting, involving the inadvertent and simultaneous reduction of oxidic and sulfidic ores. Co-smelting produces metal in a direct one-step process, which may yield large quantities of slag (Pigott 1999; Rostoker et al. 1989). In co-smelting, along with smelted copper, some residual matte is often produced which could then be resmelted to copper. Successful co-smelting requires only a high temperature ($\sim 1250\,^{\circ}C$) and a sulfur-rich atmosphere (Rostoker et al. 1989), but no fixed installations, and can be driven by dry wood fuel. Slag cakes, often fragmentary, were recovered from Non Pa Wai, probably resulting from the pouring out of the smelt product from crucibles on to the ground. At Nil Kham Haeng somewhat different procedures were used and the slag, on current evidence, is presumed to have formed in shallow bowl furnaces lined with chaff-tempered clay. Following smelting the slag was systematically crushed and could have been used for fluxing and resmelting. At Nil Kham Haeng, it is possible that lower-grade ores with higher sulfide contents were increasingly employed as higher-grade oxidic deposits were depleted by intensive production in the region (Pigott 1998; Pryce 2009; Pryce and Pigott 2008).

More investigation of these and other mining and ore-processing sites in Southeast Asia is needed, but one can make some observations regarding technological choices in the early evidence for ore acquisition at these sites. Although the Khao

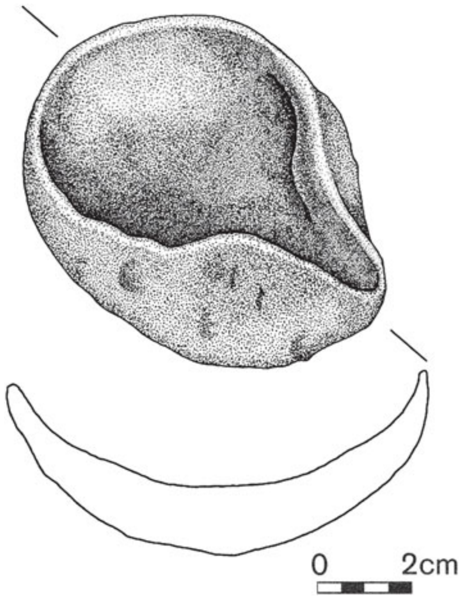


Fig. 28.3 An intact crucible from Ban Chiang illustrating the common Southeast Asian internally heated crucible type

Wong Prachan valley sites, based on the enormous volumes of production debris, strongly suggest greater intensity of exploitation than Phu Lon, with more output and greater permanency of residence, the two areas have elements in common. In both areas, evaluation of the evidence for production organization, in light of Costin's (1991) criteria, strongly suggests that small, essentially autonomous work units of labor, such as households, undertook metal processing using flexible low-technology approaches (White and Pigott 1996).

Refractories

The refractory technological systems in prehistoric Thailand suggest a preference for flexible, portable, multiuse equipment over specialized, task-specific, or large-volume equipment. The evidence indicates that both smelting and melting of metal were done in portable, internally heated crucibles, at least initially, with the later addition of the bowl furnaces at Nil Kham Haeng that date to the first millennium BC.

Common Southeast Asian Crucible Production

The earliest, simplest, and apparently most widespread crucibles are small, usually spouted bowls (Fig. 28.3). Such crucibles (which, because of their wide distribution, we will call "common Southeast Asian crucibles") are found at many mortuary/occupation sites in Northeast Thailand, including Ban Chiang, Ban Tong, Ban Phak Top, and Don Klang (Vernon 1996–1997, 1997), Ban Na Di (Higham and Kijngam 1984, p. 130), Non Nok Tha (Bayard and Solheim 1991), and Ban Non Wat (Higham 2008), as well as at the mining site of Phu Lon (Vernon 1996–1997). Natapintu (1988, p. 122) illustrates an example from Noen Klong Bamrung in central Thailand. Higham (1984, p. 236) implies that similar crucibles are also found in North to South Vietnam and central Cambodia. Spouted crucibles have been noted in Cambodia at Samrong Sen (date unknown), and a larger one (16 cm high) in Dongson contexts at Lang Ca (Murowchick 1988, p. 190, Fig. 17.18). The evidence from Northeast Thailand suggests that these small crucibles were used for all processes requiring containment of molten metal, including smelting, refining, alloying, and melting.

Four fragments of this kind of common crucible, including one fragment with a spout, were found in lower Early Period deposits in Ban Chiang, indicating that this piece of production equipment was adopted at the first appearance of copper-base metallurgy in Thailand. Crucibles of this kind were probably embedded in depressions in the ground or in small hearth-like installations, such as those uncovered at Ban Na Di (Higham 1988, p. 133, Fig. 13.5). The heat source was piled above the crucible and its charge, a point supported by vitrification on the interior of the crucibles (Vernon 1996–1997, p. 816; see also Barnard 1980, pp. 225–227 and Rehren 2003 for descriptions of procedures for using small internally heated crucibles).

Observations made on the Ban Chiang crucibles indicate that their size was suitable for casting the range of copper-base artifacts recovered from the site. This evidence suggests that the goal was to prepare small batches of molten metal suitable for creating one or two artifacts at a time. The crucible fabric is often tempered with rice chaff, which can help the internally heated crucible remain intact during the relatively short processing period necessary for small batches of metal. In the Ban Chiang region, the same crucible type was used for more than two millennia, implying that this refractory style was very successful in meeting the needs of the region's prehistoric societies.

A notable performance-enhancing characteristic of many of the small spouted crucibles is the presence of lagging—a quartz-rich clay slurry lining that probably insulated the earthenware crucibles from the high interior temperatures, helping to prevent cracking of the clay bodies while they held molten metal (Vernon 1997). Lagging may also have facilitated successful pouring of the molten metal during the casting process by preventing the metal from seeping into the crucible body. Lagging contributed to the success of internally heated crucibles made of local earthenware clays that are less refractory than, for example, kaolinite clays.

Technical analysis of the four crucible fragments from lower Early Period Ban Chiang showed that all four had rice husk temper and adhering dross or slag, two had interior vitrification, and a metal prill was extracted from one crucible piece. One with a spout had lagging.

First identified at the mining site of Phu Lon by William Vernon (1996–1997), lagging has since been found in crucibles from most sites in Northeast Thailand where this feature was looked for by analysts (Vernon 1988, 1996–1997; White et al. 1991; Hayden Cawte, personal communication). At least one layer of lagging was present on 62 of the 87 crucibles or crucible fragments found at Ban Chiang, and 31 of the 96 crucible pieces from Phu Lon (Vernon 1996–1997, p. 210). White and Pigott (1996) argued that the finds of the same basic crucible technology near mines, and also in villages some distance from mines, suggest that while primary metal production took place near ore sources, refining and casting took place in the villages. The recovery of these crucibles in the lower Early Period at Ban Chiang, far from ore sources and with almost no evidence for on-site smelting, suggests that a segmented production system (different production steps occurring at different locations) was in place from the initial appearance of metallurgy in Northeast Thailand. More published data on crucibles from other sites in Asia are needed to further define the geographic and temporal extent of common Southeast Asian crucible production.

Khao Wong Prachan Valley Crucible Production

A later crucible variant is found only in central Thailand in the Khao Wong Prachan valley and at a related locus, Khao Sai On about 20 km to the south (Ciarla 1992, p. 126). These distinctive crucibles are unspouted, unlagged (Vincent Pigott, personal communication), and, though the size and shape can be variable, are on average larger (∼ 8–10 cm internal diameter and ∼ 12 cm high: Bennett 1988) than the spouted crucibles found in the Northeast, though still portable and internally heated. They were associated with the use of another distinctive piece of refractory equipment—portable reusable furnace chimneys pierced with holes. It is assumed that the holes were for wind or bellows although no traces of tuyères have been found. Pigott suggested that the strong and consistent winds found during the dry season were enough to power small smelts, and this suggestion is being tested experimentally (Pryce 2009; cf. Bunk et al. 2004; Pryce et al. 2007). While distribution of chimneys in the Khao Wong Prachan valley is currently under review, they are particularly common during the first millennium BC at Nil Kham Haeng where they are even found in burials.

Judging from the hundreds of thousands of tons of slag and hundreds of thousands of crucible fragments, industrial-scale production was undertaken at Non Pa Wai and Nil Kham Haeng and probably other nearby localities. Khao Wong Prachan valley crucible production appears to be associated with casting of ingots in cup/conical molds. Small copper artifacts as well as numerous small bivalve molds for casting these small artifacts have also been recovered. Nil Kham Haeng had abundant thin-socketed cordiform-shaped implements (Pigott 1999, p. 18, Fig. 14) of unknown function, along with bivalve molds for casting such objects. The overall evidence is consistent with a step toward mass production, with the larger (but still portable and internally heated) crucibles having a sufficient quantity of molten metal to pour into multiple molds (Pigott 1999; Pigott et al. 1997). During the first millennium BC, small bowl furnaces came into use at Nil Kham Haeng (Pigott et al. 1997).

The relationship (if any) of the Khao Wong Prachan valley crucible production to the common Southeast Asian crucible production is unclear. Although the Khao Wong Prachan valley was occupied prior to 1500 BC (Pigott and Natapintu 1996–1997), no evidence demonstrates that metal was used or produced during the earlier occupation. Nor has the common Southeast Asian crucible type been identified in the valley, although complete bivalve mold pairs for larger socketed adze–axes comparable to those found elsewhere in Southeast Asia have been recovered from later second millennium metalworkers' burials in basal Non Pa Wai (Pigott and Natapintu 1996–1997, p. 798). Nevertheless, despite their differences, both the common and Khao Wong Prachan valley crucible production styles are based on portable, internally heated crucible technology. The Khao Wong Prachan valley was apparently oriented toward higher volume output, larger batch sizes, and more nucleated production, with multiple production steps occurring in close proximity, but still with a mostly portable technology. The enormous number of ingot molds demonstrates that the area was engaged in providing raw material for casting on-site, and probably at other locations.

Alloying

The elemental analyses done thus far indicate that binary tin bronze was the alloy of choice, beginning with the earliest appearance of Southeast Asian prehistoric copper-base artifacts. So far no evidence of working native copper has been found in prehistoric contexts in Thailand (further supporting the lack of an experimental stage in metalworking in the region). Elemental analyses of three lower Early Period artifacts from Ban Chiang graves show that all were 10 % tin bronze, with no other major elements or impurities. The early thin-walled, socketed Non Nok Tha adze is also a binary tin bronze (Selimkhanov 1979). Scanning electron microscopy/Energy dispersive spectrometry (SEM/EDS) analysis of the flat cast bar from Ban Mai Chaimongkol showed that the tin content ranged from 7 to 13 %, with low levels of lead (Nash n. d.). Deliberately shaped, unalloyed copper artifacts are occasionally found at Ban Chiang. Elevated levels of lead, arsenic, and antimony also are sometimes found, but only the lead is thought to have been deliberately added, suggesting that some flexibility in alloying was present in the second millennium BC. The products of the Khao Wong Prachan valley sites were apparently almost entirely unalloyed copper, which suggests that alloying may have varied by production centers. In this regard, it is noteworthy that there are no tin sources close to the Khao Wong Prachan valley. Based on the study of prills in crucibles from Phu Lon (Vernon 1996–1997), we know that some alloying occurred at this primary production site, but based on studies of prills in Ban Chiang crucibles (Vernon, personal communication), alloying was probably also done far from ore sources, at villages which were doing their own artifact casting.

Object Fabrication

Another fundamental component of any metal technological system is how the smelted and alloyed metal was shaped into the desired form of the final product. The discussion below reviews what are believed to be the two most common object fabrication techniques found in prehistoric Thailand (the source of most of the available analytical data): lost wax casting and bivalve mold casting. In prehistoric Thailand, it appears that both formation techniques aimed to cast the object as close as possible to its final shape, with minimal post-casting modifications. Forging (shaping metal by cycles of heating and hammering) and cold working, while occasionally practiced, were overall less important than in western Old World traditions (Sherratt 2006, p. 44). Metallographic analyses of seven Ban Chiang lower Early Period artifacts demonstrated that all but one were left as cast. The bent-tip spear point had been annealed after casting, perhaps to bend the tip, with some possible work before and after annealing (Ban Chiang Project n.d.; Stech and Maddin 1988). A socketed adze–axe from Non Nok Tha was splayed by hammering and annealing (Smith 1973). The flat bar from Ban Mai Chaimongkol was left as cast (Nash n.d.).

Lost Wax Casting

It has long been thought that the main technique used to create bangles, the most common deliberately shaped copper-base artifacts recovered from prehistoric contexts in Thailand, was the lost wax technique (Higham and Kijngam 1984, p. 81, 125; Smith 1973, p. 29; Stech Wheeler and Maddin 1976, p. 43). The earliest bangles are generally simple closed rings whose shafts have a circular cross section; metallography shows bangles are almost always left "as cast." Fragments identified by the excavators as being from clay lost wax molds for bangles have occasionally been recovered (Higham and Kijngam 1984, p. 128). No univalve or bivalve molds that could create the common simple ring bangles or the more elaborately shaped bangles of later periods have been recovered from Ban Chiang area sites. However, to the south, Higham and Higham (2009, p. 136) report that ceramic bivalve molds for bangles dating to the first millennium BC have been recovered in the upper Mun valley. Over the course of the metal age, 2000 BC – AD 500, more elaborate bangles were made, with complex cross sections, closures, and ornamentation, suggesting that the lost wax technique was gradually exploited for its potential to create complex shapes.

Bivalve Molds with Suspended Cores

A special variant of bivalve mold casting to fabricate socketed implements involves the use of a core or mold plug suspended in the middle of the mold to form a blind (open only at one end) socket in one step with the casting of the working implement. This suspended-core casting of socketed implements was practiced by the early second millennium BC, as evidenced by the bent-tip spear point (Fig. 28.2a), excavated from a Ban Chiang lower Early Period burial. This inference is based on the morphology and metallographic study of the object, as well as the fact that, although no mold pair was found in the lower Early Period at Ban Chiang, stone and ceramic mold halves and full mold pairs for socketed implements, including spear points, have been recovered from other prehistoric metal age sites in Thailand (Non

Nok Tha: Bayard 1980; Non Pa Wai: Pigott 1999; Ban Non Wat: Higham 2008; Cambodia and Vietnam: Murowchick 1988).

The technique of single-process casting of deep blind sockets using bivalve molds with suspended cores is a signature characteristic of the prehistoric Southeast Asian metallurgical tradition. The sockets usually extend deep into the implement, resulting in thin-walled, hollow-core tools, such as the early WOST adze–axe from Non Nok Tha (Fig. 28.2c). Unfortunately, the Ban Chiang spear point (Fig. 28.2a) and Non Nok Tha socketed implement (Fig. 28.2c) were returned to Thailand before their drawings were completed; the depths of the sockets are not indicated. However, see Murowchick (1988, p. 191, Figs. 17.19 and 17.20) for illustrations of similar implements showing the deep sockets of these types of tools.

The formation of the cast blind sockets in bronze implements has been noted as a point of considerable technological significance (Childe 1954; Koryakova and Epimakhov 2007, p. 39; Sherratt 2006, p. 48). More than half a century ago, V. Gordon Childe (1954, p. 11) observed that the technique, which is known by a variety of names including hollow-core casting and core casting, allowed the creation of thin-walled, lightweight tools, reducing the amount of metal needed to create an effective socketed implement. Casting this type of socket is considered more sophisticated than forging the socket around a form as was done in many early metalworking cultures in western Eurasia (for example, at Sintashta: Anthony 2007, p. 444; Sherratt 2006; vide Childe 1954), or casting open-socket forms such as shaft-hole axes, or implements with oblique open sockets such as those identified in the Andronovo technological system (Mei 2000, p. 27, 95, 96).

Casting Small Implements and Other Processes

How other prehistoric copper-base implements, such as the Ban Mai Chaimongkol bar (Fig. 28.2d) and various points, fishhooks, and blades, were formed has not received much attention. Metallographic studies again show that most were cast to shape. A few univalve molds recovered from prehistoric contexts appear to have been used to cast small tanged arrowheads and rings. Bivalve molds can be used to cast tanged implements, although matched mold pairs with tanged point impressions have not as yet been reported in the vicinity of Ban Chiang.

The Organization of Production

White and Pigott (1996) reviewed the archaeological evidence for the organization of production for copper-base metallurgy in prehistoric Thailand in light of Costin's (1991) criteria for different modes of specialized production. The evidence is consistent with production organized into small decentralized production units, possibly kin-based (that is, household production), often in communities, undertaking metal and artifact production in small batches during the dry season. The wide distribution of crucibles in village sites in Northeast Thailand suggests that knowledge, at least of casting, was not restricted in space or by social group, although it is possible that itinerant metalworkers who made crucibles from local clays could also have created such a distribution of crucibles. The regional distribution of crucibles and molds shows that production was segmented geographically, with primary production (mining and smelting) taking place near ore sources and secondary production (such as casting) near consumers. For at least the first thousand years after their first appearance in prehistoric Thailand, metal artifacts have a patchy distribution; a few sites, such as Non Nok Tha, are relatively rich in bronze artifacts, but other contemporaneous sites, such as Ban Lum Khao (Chang 2004, p. 230) and Khok Phanom Di (Higham 1996–1997), have few or none. The early metal and metal artifact production was undertaken at small, apparently autonomous, villages (re Higham 1996, p. 242, 315), with no evidence of centralized control (Pigott 1998), and the products possibly exchanged in the vicinity of each village. The absence of evidence for metalworking in contemporaneous sites in some parts of Thailand (for example, Khok Phanom Di and Khok Charoen) suggests some villages were part of a circuit of production and some were not. There was probably exchange of copper over distances of a few hundred kilometers, as sites like Ban Chiang, where casting was done, are far from ore sources (Pigott 1998). Even the large-scale Khao Wong Prachan valley production appears likely (given the challenges of mining and casting in the wet season) to be a seasonal community specialization, where numerous households undertook production of similar products without coercion or administration by a centralized political authority or economic élite (Pigott 1999). Some villages may have specialized in particular products if they were near a certain raw material; for example, the site of Non Nok Tha, where many adze molds have been discovered, is located near a good source of sandstone for the molds (White and Pigott 1996).

The finished metal artifacts produced during the first two millennia of knowledge of copper-base metallurgy in prehistoric Southeast Asia show a remarkable consistency in artifact repertoire, typological range, and technological style. This enduring coherency led White to propose the existence of a Southeast Asian metallurgical province (White 1982, p. 48; 1988; see also Pigott 1999).

Bronze Consumption

Who were the users of the early bronzes in Southeast Asia, and what roles did metal play in their lives? There is no evidence that this material was of central significance to the everyday utilitarian needs of prehistoric societies in Southeast Asia for the first several centuries of its presence. It was very rare in the first few hundred years, although it did appear in both mortuary and occupation contexts. Nevertheless, there was sufficient demand that quality bronze artifacts were produced, even if not at high volume, for some centuries before the material became more abundant.

Most of the artifacts are small personal ornaments. Based on their occasional occurrence in graves, the bronzes likely had some value as part of mortuary ritual; certainly, the most intact examples were bronzes included in burials as grave goods. Some of the graves richest in ornaments are those of young children. But the rarity in graves does not imply the material itself was extremely precious. For example, 90 % of metal finds at Ban Chiang were not grave goods. Probable casting spillage was a common find, suggesting that spilled metal was not meticulously retrieved for reuse in additional castings. Many of the nonburial metal finds were fragmentary artifacts, suggestive of use in daily life. The implements—points, knives, and fishhooks—were undoubtedly useful, but are not found in quantities or forms that imply that they were essential. There is nothing that is unambiguously a weapon or produced in quantities suggestive of a need for military armaments. Even the spear points, which are rare, could have been used for hunting or even ritual activities like sacrifices. There are no signs of armor, swords, fortifications, or even, among the Ban Chiang and other Bronze Age skeletal populations, traumatic injuries characteristic of endemic warfare (Pietrusewsky and Douglas 2002, p. 117). The most convincing evidence so far recovered by archaeologists in prehistoric Thailand that metal was being turned toward creation of weaponry appears in the late Iron Age, when the quantity of points jumped during the final mortuary phase c. AD 400 at Noen U-Loke (Higham 2007, p. 606). In prehistoric Vietnam, bronze was used more for implements than in prehistoric Thailand, but it was not until the Dongson period of the second half of the first millennium BC that weapons formed a significant percentage of metal artifacts (Murowchick 1988, p. 184).

Most of the sites with metal artifacts also have evidence for metal artifact production in the form of crucible fragments, casting spillage, and/or molds. There is no evidence, however, that the sites that are relatively rich in metal were economically or politically dominant in a region, or exerted any power over other villages. Certain families or small groups within particular villages obtained the metal and made ornaments and small tools, probably for distribution both to other families within the village and to other villages. Yet, extrapolating from mortuary evidence, possession of metal objects does not necessarily indicate great wealth or high hierarchical status; some graves with metal are very poor in other artifact classes and some graves rich in other goods have no metal. More children than adults are found with bronze bangles at Ban Chiang. Nor are there any large, elaborate artifacts designed to display the wealth or status of an entire group, or to be used in group rituals, such as the complex, piece-mold cast Shang ritual vessels or the Dongson bronze drums of the later first millennium BC in Vietnam. The techniques employed are all simple enough to have required no complex hierarchical labor organization or fixed and expensive structures (White and Pigott 1996).

A possible exception to this lack of association between hierarchical status and bronze metal occurs at Ban Non Wat near Phimai in Northeast Thailand, where during its second phase of Bronze Age interments, dated 1000–900 BC, bronzes were found in richly endowed graves (Higham 2009; Higham and Higham 2009, p. 131; Higham and Thosarat 2006). This recent evidence, however, supports the larger regional theme that expressions of social differentiation and the social use and consumption of bronze varied site by site, shifting over time and space (White 1995). Was early bronze—neither used for warfare nor used for a highly regulated prestige good—simply one of a variety of "valuables" that circulated among societies for the conduct and marking of reciprocal social, symbolic, and political transactions, one of many commodities in a regional gift-exchange economy that helped to maintain regional networks of social relationships and alliances (cf. Dalton 1977; Higham 1984)?

Further analysis of the sociopolitical role of metallurgy during its early use on mainland Southeast Asia is beyond the scope of this chapter. Whatever role it played was important enough for groups to go through the trouble of obtaining raw metal, perhaps by traveling to mining sites like Phu Lon to extract and smelt ore, make specialized crucibles using a distinctive technology, and melt, refine, and cast artifacts for daily as well as mortuary use.

In summary, the small, internally heated crucibles made with local clay are a low technology, small scale, and of spatially flexible refractory design that did not require fixed furnace installations or large teams of workers. This spatially flexible technological style facilitated decentralized and segmented production of a limited repertoire of small artifacts, including implements and personal jewelry. Different production steps could be undertaken at primary and secondary metal-processing sites, including average villages far from ore sources, using very similar equipment, without the need for permanent installations. Some processing, such as smelting (primary production), likely took place close to ore sources, and casting (secondary processing) took place at villages at some distance from the primary production sites, but the segmented system was probably flexible and not prescribed. The portable, multipurpose design was also suitable for small production teams and small batch processing requiring short processing times, which implies that efficiency of time and flexibility of location were prized over volume of product. Bronze was used for personal ornaments and implements, and, while not common, bronze artifacts were not the exclusive domain of an élite, but had roles in both daily and mortuary contexts.

Alternative Views of Adoption Processes for Earliest Metallurgy in Southeast Asia

Sinocentric Views of Southeast Asian Bronze Adoption

Since the 1990s, the dominant model has pointed to dynastic China as the source for the bronze technology of Southeast Asia, with knowledge of the technology being transmitted through the mechanism of trade and exchange. The fullest exposition of a Sinocentric view is Charles Higham's *The Bronze Age of Southeast Asia*, published in 1996. Higham's book outlines evidence for a chain of exchange relationships initiated by states in the Huang He Central Plain that led to interactions with Yangtze watershed cultures, who then interacted with societies in the Xijiang watershed of southern China (Lingnan), who ultimately brought metallurgy to mainland Southeast Asia, beginning with northern Vietnam and followed by the Mekong and Chao Phraya drainage basins. Other statements of Sinocentric views also posit the transmission of metals technology from Huang He states to prehistoric Thailand through a similar series of regional steps, cultural filters, and local adaptations (Ciarla 2007; Higham 2006, p. 19; Higham and Thosarat 1998, p. 127; Pigott and Ciarla 2007).

Since Higham's 1996 book, statements on the source for Southeast Asian bronze technology have noted that Huang He Central Plain metallurgy may have had a prior source in the Eurasian steppes, perhaps via Xinjiang, where western and eastern cultures and peoples are now known to have interacted since at least the late third millennium. The technology possibly passed through the Gansu corridor via the Qijia and Siba cultures to the Huang He Central Plain (see Fig. 28.1; An 1993, 1998, 2000; Mei 2000, 2003, 2004; Ciarla 2007, p. 2; Linduff 2000; e.g., Higham 2002, pp. 113–115; Pigott and Ciarla 2007). Nonetheless, Sinocentric models still trace early Southeast Asian metallurgy, via Lingnan and the Yangtze valley, to the spectacular and sophisticated metalworking of Erlitou–Erligang cultures of the Huang He Central Plain. These recent statements argue that the élite desire for goods and raw materials in the early Huang He Central Plain states fueled an ever-expanding regional interaction network that eventually brought the knowledge of bronze working to Southeast Asia.

> Looking at the general picture of the artefact inventories which typify the three main cultural periods of the Central Plain Bronze Age, that is Erlitou (1900–1600 BC), Shang–Erligang (1600–1300 BC) and Shang–Yin (1300–1045 BC)... we can clearly discern exchange networks which brought highly desired raw materials and goods to the Shang élite centres: jade, turquoise and other semi-precious stones, cowries, turtle carapaces, copper and tin, "slaves", and gold... The search for and exchange of these goods and raw materials, implying direct and indirect contacts with quite distant sources, activated an ever increasing and complex chain of interlocked regional interaction spheres... through which copper/bronze casting technology eventually reached Southeast Asia. (Pigott and Ciarla 2007, pp. 77–78, emphasis added)

How then are the marked differences in technological system and artifact repertoire of Huang He Central Plain and prehistoric Southeast Asia, noted by White (1988), addressed by the Sinocentric models? Huang He Central Plain metallurgy was characterized by complex, sophisticated piecemold-cast ritual containers and large-scale refractory systems, based on reverberatory furnaces (Barnard 1980; Tylecote 1996–1997). Higham's explanation for the marked differences between the Huang He metallurgy and the Southeast Asian metallurgy is based on a stimulus diffusion perspective.

> ...it is argued that exposure to actual bronze imports [from Central Plain and Yangtze states], together with the spread of the idea that exposing certain coloured rocks to heat, it was possible to obtain this material for alloying and casting, were stimuli to the beginning of a local industry.... (Higham 1996, p. 312)

It was the newly developed Lingnan local or southern metallurgical tradition, more suitable for less-complex societies, which then spread to the Red and then the Mekong and Chao Phraya River valleys along preexisting networks of exchange, according to this theory.

A recent variant Sinocentric model for Southeast Asian bronze metallurgy presented by Ciarla and Pigott (Ciarla 2007; Pigott and Ciarla 2007) indirectly discusses one of the conundrums not addressed by Higham (1996) regarding the Southeast Asian metallurgical tradition. It has become evident, as the prehistoric bronze metallurgy in Russia has become better known (Chernykh 1992), that the products of Southeast Asian early metallurgy look very similar to Eurasian metallurgy to the north and west of the early dynastic states in the Huang He Central Plain (White 2000). Pigott and Ciarla acknowledge that "the 'southern metallurgical tradition' with its socketed implements, bivalve moulds, bangles, and founders' burials has more in common with the Eurasian steppes than Erlitou–Erligang China" (2007, p. 85). In addition to typological and technological parallels (e.g., use of bivalve molds), there are behavioral parallels of interring metalworkers with the tools of their craft—the "founders' burials"—found in metal age sites in Thailand (Higham 2008; Pigott 1999, p. 13) and in Eurasia (Chernykh 1992, p. 218). Whereas Higham has never addressed the Southeast Asian/Eurasian metallurgical parallels, Pigott and Ciarla's work contains a scenario to account for the Eurasian/Southeast Asian metallurgical similarities within a Sinocentric framework, drawing on data from the PRC that have become accessible in recent years.

In effect, while noting that much work is needed to demonstrate their proposal, Pigott and Ciarla's (2007) implied solution to account for the similarity between the Southeast Asian and Eurasian metallurgical traditions is that there was a "... 'Steppe techno-cultural package' transmitted from the eastern steppe metallurgical tradition to the Shang tradition and then southwards to the Southern tradition" (Ciarla 2007, p. 323, footnote 14). "Socketed tools (for example, ploughshares, several types of spade blades, adzes, chisels, and weapons) begin to appear regularly in the Shang inventory from the Erligang period (1600–1300) onwards" (Pigott and Ciarla 2007, p. 84). Bivalve molds appear in late Shang contexts at Anyang. They suggest that the steppe metallurgical techniques (bivalve molds) were being used to produce utilitarian tools and weapons (Pigott and Ciarla 2007, p. 84), while the piece-mold technology was used to cast the ritual vessels.

Pigott and Ciarla imply that the steppe and Shang metallurgical traditions must both have been transmitted via several steps to the middle Yangtze area and then the Ganjiang tributary, where the Wannian and Wucheng/Xin'gan cultures are "characterized by the hybridization of local elements with Shang-derived bronze technology and artifact types" (Pigott and Ciarla 2007, p. 80). The tributary provides trade connections to Lingnan in the southern PRC. The Zhou period site of Yuanlongpo is pointed to as a site in Lingnan that had both imported ritual vessels in the Shang-Zhou tradition and locally cast weapons and tools, as well as bivalve molds, and vessels that they suggest were crucibles based on their similarity in form to Khao Wong Prachan valley crucibles. The authors imply that only the utilitarian steppe-derived tradition was brought to the rest of Southeast Asia, which would explain why "links (of Southeast Asian metallurgy) to Steppe traditions appear to be more consistent" (Pigott and Ciarla 2007, p. 82):

> the piece-mould technology of the Shang–Zhou dynastic élites did not lend itself well to small-scale, community-based production among less socially complex cultural groups who over time were apparently mobile enough to expand out of southeastern China into new territories to the South. (Pigott and Ciarla 2007, p. 85)

In summary, whereas Higham portrays Lingnan as the creator of the Southeast Asian metallurgical tradition, Pigott and Ciarla imply that Lingnan was the final filter removing the "Chinese" technological traits from a steppe metallurgical tradition, enabling it to move to less-complex societies further south.

Critical Appraisal of Sinocentric Views of Earliest Southeast Asian Metallurgy

Sinocentric models for the initial source of Southeast Asian metallurgy can be critiqued on several grounds.

Selective Use of Chronological Data

In order for the proposed sequences and timing of transfers of metal technology to work, Sinocentric models minimally need the earliest Southeast Asian metallurgy to be younger than the appearance of the Chinese dynastic states that activated the exchange networks. Their discussions, in fact, rely on selective use of data, so that the early metallurgy in Southeast Asia appears to be younger than 1500 BC. Pigott and Ciarla (2007) need the early metallurgy in Thailand to be younger than the beginning of the Erligang (early Shang 1600–1300 BC), when steppe artifact types start appearing in Central Plain sites with some regularity (Pigott and Ciarla 2007, p. 84). For either proposed transmission sequence to truly work, the earliest metals in Thailand must be younger than those of Lingnan, where Higham (1996, p. 94) has argued that bronze metallurgy appeared during late Shang times (after 1300 BC). Therefore, proponents of Sinocentric models must either dispute (Higham 1996, pp. 9–13, 187, 1996–1997, 2002, pp. 133–134, 2009; Higham and Higham 2009; Higham and Thosarat 1998, p. 84) or ignore (Pigott and Ciarla 2007) evidence for early second millennium BC bronze in Southeast Asia.

Higham's most recent chronology advocates extreme selectivity, namely the "rejection of all previous attempts to date Southeast Asian prehistory radiometrically" (Higham and Higham 2009, p. 139). Arguing primarily from a new experimental program of shell dating from a single site, Ban Non Wat, he concludes that the Bronze Age began 1000 BC (Higham 2009; Higham and Higham 2009, p. 138). However, he does not undertake the vital and basic step of systematically cross-dating Ban Non Wat's relative ceramic sequence with any of the sites or regions noted above that have the earliest evidence for metallurgy. His dating, impressive methodologically though it may be, is applicable only to the florescence of bronze use in the immediate area of the upper Mun River valley (perhaps analogous to Henrich's (2001) "takeoff point" in cultural transmission), but not to the initial appearance of the technology in other parts of Thailand or Southeast Asia (cf. Henrich's (2001) "long tail" period of initial transmission).

The evidence for pre-1500 BC bronze in Thailand has been vigorously debated since the late 1960s (for example, Bayard 1996–1997; Bayard and Charoenwongsa 1983; Higham 1996, 1996–1997; Loofs-Wissowa 1983a, b; Solheim 1983; White 2008). White has consistently advocated early second millennium BC dating for the earliest bronze at Ban Chiang. Initially White's argument (White 1982, 1986) was based on conventional ^{14}C dates on charcoal from the site. But in response to the debate, White (1997) presented independent evidence from AMS dates on rice temper in burial pots to support early second millennium BC dating for bronze at Ban Chiang. White's (2008) review of pertinent AMS dates reaffirms the evidence for the early second millennium (c. 2000 BC) for the appearance of bronze at Ban Chiang. Bronze in prehistoric sites in Thailand around 2000 BC invalidates arguments that the early Chinese dynasties were the originating stimulus for the first appearance of bronze in Thailand, and this by itself disproves the Sinocentric models for the source of the earliest bronze in Thailand. That the Huang He Central Plain may have affected later periods of Southeast Asian metallurgy is, of course, a scenario worthy of further investigation (Ciarla 2007).

Selective Use of Technological Evidence

Sinocentric views are selective also in their use of available technological data. Proponents of Sinocentric models explicitly or implicitly reduce technology transfer to "... knowledge of the properties of copper and tin ore" (Higham 2004, p. 52). Sinocentric assessments of the sources for early metallurgy in Thailand do not fully examine characteristic components of Southeast Asian early bronze metallurgy, most notably the probable use of lost wax casting for making jewelry, the full significance of the hollow-core casting of sockets of adze–axes and spear points, and the distinctive common Southeast Asian refractory system. How to account for the presence of lost wax casting in Southeast Asia probably a millennium or more before its use in the Huang He Central Plain repertoire, where it did not appear until sometime in the mid-first millennium BC (Barnard 1996–1997), is not mentioned. (See also Weirong Zhou et al. (2009) for an even later chronology for the appearance of lost wax technique in China; but cf Davey 2009). Pigott and Ciarla do discuss the occurrence of bivalve molds in the Central Plain, southern PRC, and Thailand from contexts dating from the mid-second to mid-first millennia BC. But why the wide range of Shang innovations (nonsteppe implements such as unsocketed halberds, socketed plowshares, spades, or an unusual disk-shaped item from Yuanlongpo) made with bivalve molds in Shang and southern PRC contexts did not transfer to early metal-using contexts in Thailand along with the steppe-derived metallurgical complex is not addressed.

The Sinocentric views do not address how the early common Southeast Asian production system, based on internally heated small crucibles, could have emerged from the Shang system of metal processing that employed large immobile crucibles heated externally in reverberatory furnaces (Barnard 1980; Tylecote 1996–1997).

Pigott and Ciarla (2007, pp. 80–81) do allude, albeit indirectly, to the technological transfer of aspects of the refractory system of the later Khao Wong Prachan valley from the north. There are two components of their argument. First is their general view that a steppe-derived technological tradition co-occurred with the Shang-style tradition. This steppe-derived system employed bivalve molds and presumably a refractory system more suitable for processing the smaller amounts of metal for fabricating utilitarian artifacts, although no evidence is provided for the presence of a steppe-derived refractory system in the Central Plain (see also Linduff and Mei 2009, pointing out the lack of a utilitarian metallurgy in the Central Plain during Shang times).

The second part of their argument points to two examples of artifacts from peripheral parts of the PRC that are similar in shape to two Khao Wong Prachan valley refractory artifact types dating to the late second and early first millennia BC. At Yuanlongpo, a Zhou period (1100–800 BC) site in Lingnan that interacted with Yangtze cultures, one vessel type is proposed as evidence for a source of Khao Wong Prachan Valley crucible technology in southern PRC. However, no evidence is presented that these objects are anything other than bowls, no evidence is presented that they had dross or slag, or interior vitrification, or any other evidence for exposure to molten metal, a point acknowledged by Ciarla (2007). Ciarla and Pigott (2007) and Ciarla (2007) also suggest a possible northern but non-Shang source for the Khao Wong Prachan furnace chimneys at the site of Niuheliang in Lianging Province, in northeast PRC near the Korean border. This possible furnace chimney appears to be Erlitou or older (2300–1600 BC) in age, but outside and to the northeast of the Huang He Central Plain. They note that there is no evidence that furnace chimneys are typical of Eurasian steppe metal production systems and offer no evidence for cultural contact between this far northeast area and Southeast Asia.

The parallels suggested by Pigott and Ciarla in technological systems in Thailand and China, when examined in detail, are thus too tenuous in their metallurgical function and too dispersed in time and space to offer a convincing source for the Khao Wong Prachan valley metallurgical system. In addition, the source of the earlier common Southeast Asian crucible system is the one in need of explanation for those interested in the initial introduction of bronze metallurgy into the region.

Core/periphery Bias

Neither version of the Sinocentric approach references a theoretical framework. Yet it is clear from the lines of reasoning, the language employed, and the selection/rejection of evidence brought into their discussions that they are rooted in theoretical paradigms that perceive explanations of the past in terms of core/periphery dynamics at the scale of world-systems approaches (see the review in Hall and Chase-Dunn 1993).

> The world-systems model emphasizes the role of long-distance trade dominated by the core area as the main factor explaining both the political economy of the periphery and its trajectory of developmental change. (Stein 1999, p. 3)

This viewpoint is reflected in Higham's (2006, p. 19) recent summary statement, "The knowledge of bronze metallurgy may have reached Southeast Asia from the established states in China through the medium of exchange". But, setting aside the misfit of the chronologies, we ask whether a core-to-periphery model is an apt explanation for the initial transmission of bronze technology to prehistoric Thailand, viewing Thailand as the far periphery of state societies in the Huang He Central Plain.

World-systems approaches that emphasize core-to-periphery approaches to understanding the vast Bronze Age networks of peoples interacting in central and northern Eurasia have recently been criticized (Hanks and Doonan 2009; Kohl 2007, pp. 246–247, 2008). The mobile herding economies of this huge region, which developed based on a combination of subsistence choices and strategies, transportation innovations (horseback riding and wheeled vehicles), and metal technology, appear to have had their own dynamic, noncentric development for which world-systems approaches are proving inadequate interpretive frameworks. In particular, transferable technologies such as metallurgy provided different bases for intersocietal interactions, less controllable by political and economic cores or elites, than the exchange of goods and materials.

Chernykh (1992, pp. 300–301) argues, moreover, that in the case of metals, technology transfer often occurred in the reverse direction: the "uncivilized" periphery has, at times, provided technologically superior implements and technologies to the civilized core, such as when the technology for European and North Caucasian shaft-hole axes spread into Asia Minor. Similarly, he notes that in a later time frame of the first millennium BC:

> Chinese written sources speak directly of being repeatedly compelled to borrow technology and weapon forms from the "wild peoples" of the steppes and foothills of Central Asia. . . Chinese sources contain a painful acknowledgement of the superiority of the weapons of the nomadic hordes and the need to acquire them. (Chernykh 1992, p. 301)

Oversimplified Technological Transmission Models

By attributing the transmission of bronze technology to Southeast Asia to exposure to trade goods of more sophisticated societies and the idea of smelting, Sinocentric views underestimate the complexity of transferring metals technology from one society to a second society that has no prior experience with metal processing. Proponents of the Sinocentric models may argue that the kinds of details one would need to reconstruct sociotechnical systems, such as good metal production evidence from along the transmission routes proposed, are not available. But we argue that they bypass technological data that are available and do not take advantage of recent thinking on cultural and technological transmission (e.g., Boyd and Richerson 1985; see recent reviews in O'Brien 2008).

On closer inspection of the data, the Sinocentric diffusionary transmission scenarios—both the "stimulus diffusion" variant of Higham (1996, p. 312) and the "steppe metallurgy surviving cultural filters" variant of Pigott and Ciarla (2007)—do not satisfy. In particular, neither adequately accounts for the loss of Chinese technological characteristics during the transmission process. Higham's scenario does not explain how the distinctive technological choices and styles evident in the Southeast Asian metallurgical tradition could have arisen from the context of the Shang metallurgical tradition but leave no evidence of the technological choices and styles from the Chinese source. The loss of other characteristics of the Shang metallurgical tradition, such as highly decorated surfaces, tanged and other useful implements, and the refractory technology based on large externally heated crucibles in reverberatory kilns, is not dealt with. Pigott and Ciarla do point to the occurrence of steppe-derived bivalve molds for deep-socketed axes in Shang contexts; they also mention that bivalve molds were used for many new shapes, including casting unsocketed items and many new utilitarian items such as plows. Why were these Shang innovations on so-called steppe technology also completely lost by the time bronze reached Thailand, such that the early artifact repertoire in the Southeast Asian tradition ends up with only typical upper Eurasian artifact types and fabrication techniques? The source for several attributes that *are* characteristic of early Southeast Asian metallurgy, such as the common internally heated crucible, the limited though distinctive repertoire of artifacts (including metal jewelry, not found at all in Shang contexts), preference for certain deep-socketed tool forms over others, preference for binary tin bronze rather than a ternary copper–tin–lead alloy that was common in the Huang He Central Plain, lost wax casting, and the decentralized organization of production are not addressed.

A body of literature on the spread of culture and technology has grown during the past two decades and is providing many tools with which to examine "diffusion" and its current broader moniker "cultural transmission" (see reviews and articles in O'Brien 2008). Thinking has shifted away from assumptions that "exposure leads to spread" to fine-grained examination of social contexts for learning, evidence for practitioner networks, the roles of individual agents, impact of various kinds of biases on the shape and rate of transmission, as well as fuller appreciation that different kinds of cultural traits, such as a technology versus a belief versus a style, can transfer from one society to another by different processes (e.g., Killick 2004; Kim 2001; Kuhn 2004; Lemonnier 1986, 1992; Pétrequin 1993; Schiffer 2001a, b, 2008). Understanding transfer of complex technologies requires careful consideration of the context for social learning and the social relations in the community of practitioners (Van Pool 2008, p. 195). Careful attention paid to the technological choices in the various cultures along a proposed route of transmission will help avoid incongruous scenarios for technological transfer.

Recent studies of the cultural transmission of technological knowledge have focused on how recipient practitioners acquire and maintain new technological knowledge from donor practitioners. In one example, Bettinger and Eerkens (1999) examine the transmission of bow and arrow technology in Nevada and California, in light of Boyd and Richerson's (1985) concepts of "guided variation" and "indirect bias." In social contexts with limited or incomplete transmission between the donor and recipient practitioners, such as when recipients "copy" products but do not necessarily receive direct instruction, the products of the recipients have traits indicating experimentation with the new technology. The term used to describe the variability that arises with experimentation, “guided variation,” refers to the trial and error processes as individual practitioners work out their own interpretations of the process, guiding their practices by the successes and benefits to themselves. The end result is that a wide variety of technological choices and processes can be seen in the archaeological record of the recipient society in the early stages of technology adoption. When technology transmission is more complete or direct, such as might occur if practitioners from the source society moved into the receiving society and thoroughly trained members of the receiving society in the technological system, a much closer approximation of the donor technology will develop in the recipient culture. The phrase “indirect bias” has been used in these cases where the technological package is transmitted more completely, with little evidence for experimentation. The complete transmission results in a more homogeneous technological practice and more uniformity in the product line, relative to the guided variation context.

The general concept of cultural transmission and potential biases has been developed further in a variety of ways (Heinrich 2001; Mesoudi and O’Brien 2008a, b; O’Brien 2008), but for the purposes of this chapter we focus on the simple contrast: does the evidence of early metallurgy in Thailand suggest relatively complete and direct transmission with indirect bias, or incomplete and indirect transmission of bronze technology (e.g., emulating trade goods) with guided variation during the earliest stages?

An Alternative to the Sinocentric Model: The Rapid Eurasian Technological Expansion Model

In this section, we strive to investigate the sources for the earliest Southeast Asian metallurgy by prioritizing the study of its technological system. We assume that transmission of metal and metal artifact-production technology likely involved transmission of specific ways of accomplishing the many steps involved—technological choices and technological styles—from prospecting for ore to the creation of the finished artifacts. Thus, we build our study on a close evaluation of not only the chronology of the Southeast Asian metallurgical system within the greater Asian context, but also of the technology of the metallurgical system (described above) for which we seek precursors. We begin with a brief summary of East Asian metallurgy prior to its appearance in Southeast Asia.

Metallurgy in Eastern Eurasia Before 2000 BC

In the past two decades, an explosion of information on the prehistoric nomad groups in the former Union of Soviet Socialist Republics (USSR)(Anthony 2007; Chernykh 1992; Chernykh et al. 2004; Kohl 2007; Koryakova and Epimakhov 2007; Kuz’mina 2008; Linduff 2004a, b; also see Hanks and Doonan 2009 and Linduff and Mei 2009) has shown that copper-base technology has a rich history east of the Urals prior to the second millennium BC. Various instances of copper-base metallurgy dating within the third and even the fourth millennium BC in Asia east of the Urals (Linduff 2004b) demonstrate that knowledge of copper smelting was spread, albeit spottily, over a wide area of northern Asia from the Urals to the Pacific seaboard (Linduff and Mei 2009). Third and fourth millennium metalworking cultures have been found near ore sources, especially copper, but analyses show bronze alloys and gold also appeared in addition to copper working, when the minerals were available. Shared similarities between the artifact and technological repertoire across this swath suggest to Linduff and Mei (2009) that craft workers themselves must have moved in the vast cultural network.

Kohl (2007) has suggested that mobility across Bronze Age northern Eurasia was fostered not only by the search for pasture, cattle, horses, and other animals, but also by the search for metal resources. The socioeconomic context for metalworking in these mobile societies was quite different from classical state-based Bronze Age contexts. As Kohl notes, "... the herders of the steppes were self-sufficient, organized into partially autonomous/independent kin-structured groups that were capable of forming and dissolving alliances with related groups, and increasingly worked metals for eminently practical purposes" (Kohl 2007, p. 248). Even some groups of foragers and hunter-fishers adopted metalworking skills (Anthony 2007, p. 389; Chernykh 1992, p. 187).

One metal-rich area with an early and important history of metal-using cultures is the Minusinsk basin in southern Siberia, along with the Altai Mountains just south. This area had a sequence of metal-producing cultures beginning with the Afanasievo in the fourth millennium. About 100 metal objects, mostly of copper, have been recovered from Afanasievo contexts, one-fourth of which are tools such as flat axes and knives, ornaments (rings), with the remainder unfinished or unshaped fragments. During the late third millennium, the Okunevo and Seima-Turbino groups occupied these areas and employed a more developed metallurgy, including tin bronze. Subsequently in the second millennium, bronze-producing Andronovo groups appeared in this area (Anthony 2007; Gorsdorf et al. 2004; Hanks et al. 2007).

Other areas of East Asia have evidence for occasional copper exploitation in the third and possibly late fourth millennium BC, including Gansu (Majiayao culture, copper and tin bronze) and Huang He Central Plain (Longshan Period, unalloyed copper and bronze), although the details can vary by author (Linduff 2004b; see articles in Linduff et al. 2000; also see Linduff and Mei 2009), for a review of early metallurgy in the northwest PRC.

In summary, current evidence suggests that the knowledge of smelting copper was widespread, though rare and sporadic, across Eurasia during the third millennium BC in a range of sociocultural contexts. Some of the societies familiar with metal processing, such as Longshan, were settled and had evidence of incipient complexity. Nomadic pastoralists like the Afanasievo exploited the copper ores in southern Siberia at a low intensity. Other societies, such as those in Karelia, in the forest and forest-steppe zones of northern Eurasia, and the Surtandy culture of the eastern Urals, demonstrate that relatively noncomplex societies, including settled hunter-fishers, or smaller mobile groups, could mine and smelt copper and produce simple tools and ornaments when close to ore sources (Chernykh 1992, p. 187).

Metallurgy c. 2000 BC in Eastern Eurasia

Eurasian metallurgy showed rapid developments, shifts, and expansions in the period at the end of the third millennium BC (Chernykh et al. 2004, p. 24). Chernykh (1992) views these changes as the end of the Middle Bronze Age and the beginning of the Late Bronze Age when a new Eurasian Metallurgical Province emerged as the preceding Circumpontic Metallurgical Province collapsed. "What is clear is that during the Late Bronze Age peoples from more areas are extracting more ores and producing more metal tools and weapons of related types on a greatly expanded, nearly industrial scale across most of Eurasia" (Kohl 2007, p. 169).

In southern Siberia, the Okunevo culture probably learned about copper-base metallurgy from the Afanasievo (Chernykh et al. 2004, p. 28). However, while the rare Afanasievo metal artifacts are of unalloyed copper, gold, and silver, the Okunevo used both copper and tin bronze for knives, awls, and bracelets. Okunevo finds include one bronze-cast socketed spearhead, the earliest such spearhead this far east.

Seima–Turbino Metallurgy

Among the various cultural entities with metallurgical capabilities east of the Urals around the turn of the third to second millennium BC, one is particularly intriguing for the purposes of this chapter—the one Chernykh calls (1992, pp. 215–234) the "Seima–Turbino transcultural phenomenon."

> The Seima–Turbino phenomenon... stands out from other communities in its metalwork. Three main categories of object lend these assemblages a distinctive appearance: socketed spearheads, socketed axes and knife-daggers... they are all extremely rare in sites of other cultures: the majority of these artefact types are characteristic only of Seima–Turbino burial grounds. (Chernykh 1992, p. 218)

David Anthony (2007, pp. 434–444) has commented, "the tin-bronze spears, daggers, and axes of the Seima–Turbino horizon were among the most technically and aesthetically refined weapons in the ancient world, but they were made by forest and forest-steppe societies that in some places... still depended on hunting and fishing."

This Seima–Turbino phenomenon, recently dated to the late third millennium (Chernykh 2009, p. 4; Hanks et al. 2007), is noteworthy for this chapter for several reasons: (1) it is recognized by characteristic assemblages of copper-base artifacts, which bear a close resemblance to the suite of earliest bronze artifacts in Thailand (Sherratt 2006, p. 43); (2) one of its signature tin-bronze artifacts is the thin-walled celt-axe (Fig. 28.4a), a key innovation of the late Bronze Age that is strikingly similar to the socketed implement from Non Nok Tha (Fig. 28.2c); (3) it is considered to have originated in the Altai Mountain area and almost instantly (in archaeological time)

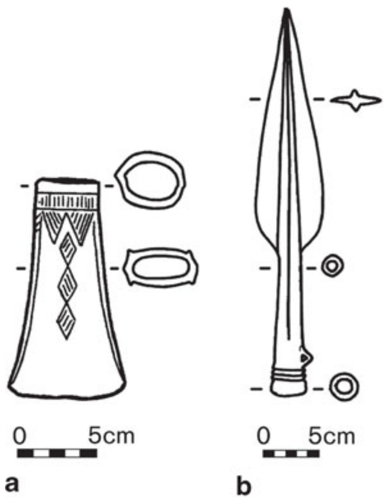


Fig. 28.4 Typical Seima–Turbino hollow-core cast implements. **a** Deep-socketed adze–axe from Rostovka cemetery (Adapted from Chernykh 1992, p. 221). **b** Socketed spear point with single-process cast socket from Seima cemetery (Adapted from Chernykh 1992, p. 219)

moved west as far as Finland, a distance of several thousand kilometers (Fig. 28.1); (4) outside of the Altai, the Seima–Turbino metal assemblage is found in deposits of other traditions, with evidence that the metal technological system was adopted by other cultures, but without a complete migration of the source culture and population; and (5) scholars have argued that it was the Seima–Turbino metals technological system that was an important source for the late third millennium bronze in the Qijia culture of Gansu (Fitzgerald-Huber 1995; Mei 2003).

The technological system of Seima–Turbino metallurgy has additional noteworthy characteristics. Seima–Turbino metals assemblages east of the Urals are predominantly binary-tin bronzes, consistent with their access to the rich tin and copper sources in the Altai region. To the west of the Urals, the same artifact types are more likely arsenical copper, showing that the casting repertoire was undertaken with local resources. Their technological system also employs lost wax casting (to make the figurative flourishes on the hilts of knives), and bivalve molds found in Seima-Turbino sites demonstrate that casting occurred at sites far from ores.

The Seima–Turbino technique of casting blind sockets (Chernykh 1992, p. 191) in spearheads and particularly adze–axes (Fig. 28.4a, b) by suspending a core in the casting between the two mold halves is considered a remarkable innovation in the history of metallurgy (Childe 1954; Koryakova and Epimakhov 2007, p. 39; Sherratt 2006, p. 43). To the west, at contemporaneous sites like those of the Sintashta culture in the southern Urals, as well as in the Middle East and Mediterranean, sockets on spear points were made by forging a metal sheet around a socket form (Anthony 2007, p. 444; Sherratt 2006, p. 44). Hollow-core cast, socketed spear points, and axes appeared in western Europe only several centuries later in the Late Bronze Age. V. Gordon Childe (1954) recognized the technological importance of hollow-core casting of Eurasian "socketed celts," especially for woodworking. He commented that they were superior to flat axes because they could be more securely hafted, and superior to shaft-hole axes for their longer working edge and more economical use of bronze. The latter point could be one key to the desirability and transferability of the hollow-core adze–axe technology to the woodlands of upper Eurasia, far from ore sources. Childe also stated (1954, p. 19) "[a] supply of tin bronze is probably a prerequisite for the postulated advance in core-casting." Once casting the socket is mastered, production of socketed implements will be considerably easier and faster than when forging one, which would require a lengthy and strenuous process of several rounds of annealing and hammering it to shape. Childe further commented on the challenge of positioning the suspended core that formed the socket, requiring an innovation such as inserting metal-spacing pins that would be incorporated into the cast tool, or wax plugs to hold the core in place.

Seima-Turbino Expansion

Although much has been made of the expansion west to east of metalworking pastoralists, such as the Andronovo, across the Eurasian steppe zone during the late Bronze Age, the apparently pre-Andronovo east (originating in the Altai) to west expansion of the Seima–Turbino phenomenon occurred in the forest and forest-steppe zones. This technological system was thus not of steppe pastoralists but rather of forest-oriented groups who may have been mobile hunter-fishers and/or warriors in addition to metalworkers. Such an orientation toward the forest is compatible with the signature Seima–Turbino socketed adze–axe, recognized as most suitable as a woodworking tool (Childe 1954). The distribution of Seima–Turbino cemeteries closely follows rivers (Koryakova and Epimakhov 2007, p. 108; Kuz'mina 2004, p. 51). The metallurgical (including production) evidence from Seima–Turbino sites along waterways across the forest zone of northern Eurasia suggests that an exchange system not only of metal (possibly especially tin), finished artifacts, but also of metalworkers who developed local resources (Kuz'mina 2004, pp. 51–52) emerged along this route.

The consistent morphology and casting technology of Seima-Turbino assemblages, even considering local adaptations such as use of local ores and the loss of some decorative elements, correspond well with a fairly direct and complete transmission of the technological system. The social and technological characteristics that facilitated rapid transmission of the Seima–Turbino metallurgical system across thousands of kilometers are not as yet well understood (cf. Anthony 2007, p. 447; Kohl 2007, p. 169). Various writers seem to have different explanations of how and why such a distribution came about, variably bringing militarism, trade, traveling metalworkers, élite emulation, transportation by horse, and other factors into proposed scenarios (Anthony 2007, p. 443, 446, 447; Chernykh 1992, pp. 227–228; Chernykh et al. 2004; Kohl 2007, p. 169; Koryakova and Epimakhov 2007, p. 108; Kuz'mina 2004, pp. 51–52).

What seems clear is that the geographical spread of Seima–Turbino hollow-core casting involved the movement of highly competent metalworkers to regions outside their home territory; trade is not a sufficient explanation for the extant evidence (but cf. Koryakova and Epimakhov 2007, p. 110). Further elucidation of the transmission process will benefit from explication of the refractory technology throughout the Seima–Turbino distribution. A portable low capital, segmented production system, such as we describe for early Southeast Asian bronze production, may help account for the rapidity with which the Seima–Turbino technological system could be adopted over such a vast region in a short period of time.

Thailand and the Seima–Turbino Transcultural Phenomenon

The typology, alloys, and object formation techniques (in particular, hollow-core casting of socketed adze–axes and spear points, and lost wax casting) of the early bronzes from the Seima–Turbino repertoire appear markedly similar to the artifacts, alloys, and formation techniques found in the earliest metals of prehistoric Thailand. As Sherratt (2006, p. 48) notes, the Seima–Turbino method of manufacturing socketed artifacts "provides a plausible starting point for the tradition of early Chinese and Southeast Asian hollow-cast metallurgy, beginning in the early second millennium." The earliest copper-base materials from Southeast Asia (e.g., Table 28.1; Fig. 28.2) also resemble Eurasian copper-base assemblages generally (bangles, arrowheads, fishhooks). Although investigation of the Seima–Turbino transcultural phenomenon has focused on its spread westward in upper Eurasia, there is no reason to assume that the "impulse to expand" occurred only in one direction. The dating of the early prehistoric metals in Thailand to the early second millennium BC meshes well with the possibility of another extremely rapid expansion of the Seima–Turbino technological system to the south.

The above discussion of the nature of the expansion of Seima–Turbino metallurgy in northern Eurasia lays the groundwork for understanding possible expansions in other directions. To help envision the expansionary ethos of the Late Bronze Age, Kohl (2007, pp. 169–179) postulates a "gold rush model," with many groups like Seima–Turbino seasonally and opportunistically prospecting for ores, extracting them with low-technology procedures, and hauling them away. Exchange networks expanded, and metal processing became common even in ordinary households at sites far from ore sources.

If Kohl is right, then a Seima–Turbino extension south and east from the Altai simultaneous with its extension west is a logical possibility, which we may seek in the archaeological evidence. In the next section, we review such evidence. But first we review what we propose are some basic attributes of the donor sociotechnical system that could also contribute to the rapid dispersal of metal technology: (1) highly mobile economies; (2) widely dispersed technological knowledge; (3) nonexclusive access to the technology, possibly fostered by metalworkers having neither extremely high nor extremely low status, or being controlled by a dominant élite jealous of access to metallurgical knowledge; (4) modest social differentiation and a relatively unstratified society; (5) aggressive search for natural resources supports exploration of new lands for ore; (6) small-scale, flexible, and portable technological system, with small, probably internally heated crucibles and small impermanent refractory installations using local resources for refraction and processing; (7) despite a preference for tin bronze, familiarity with various alloys allowing use of local ore sources; (8) experience in a segmented metal artifact-production system; (9) warfare not so rampant that people and technologists do not interact; and (10) small related groups, each with technological expertise, moving independently.

The homogeneity of the early metallurgy practiced in prehistoric Thailand and its noteworthy similarity to the Seima–Turbino repertoire argue that knowledge of metal production and working was transmitted in a relatively direct and complete manner by experienced practitioners who were trained in the Seima–Turbino technological system. If the transmission was incomplete and indirect, one would expect extensive individual experimentation (guided variation) in the early Southeast Asian copper-base repertoire, of which there are few signs. Might prospecting metalworkers have made their way down the valleys and rivers along the eastern rim of the Himalayan Plateau, seeking copper and tin and ultimately reaching Thailand? We turn now to the evidence, and the gaps in the evidence, for such an occurrence.

Hypothesis for the Routes of the Transmission of Bronze Technology from Southern Siberia to Prehistoric Thailand

This section begins with five points. First, the early metals in Thailand bear a remarkable resemblance technologically and typologically to Seima–Turbino forest bronze assemblages in particular, and to southern Siberian (including Okunevo) bronze metallurgy at the end of the third millennium BC generally. Second, the resemblance suggests a relatively direct and complete transmission of the technology in alignment with the "indirect bias" concept. Third, if this is correct, the transmission must have been very rapid, since the dating of the earliest metals of Southeast Asia is close in age to Seima–Turbino, based on current evidence (cf. Hanks et al. 2007 and White 2008). Fourth, a southern extension of the Seima–Turbino metallurgical system has, in fact, already been identified in Gansu (Fitzgerald-Huber 1995; Mei 2003). Fifth, the archaeological data in the terrain between the Gansu and Thailand are not sufficient to allow us to conclusively evaluate the proposal that the early bronze metallurgy in Southeast Asia was directly derivative of the Altai tradition. Nevertheless, a transmission route can be posited at the very least to stimulate directed archaeological research to test the proposal.

Northwest PRC

South of the Altai Mountains, Xinjiang and the Gansu corridor have been proposed as key links in the transfer of bronze technology from western parts of Eurasia to the Huang He Central Plains (An Zhimin 1993, 1998, 2000; Ciarla 2007, p. 306; Fitzgerald-Huber 1995; Higham 2002, p. 115; Linduff 2000; Mei 2003; Pigott and Ciarla 2007, p. 76, 80; Shuyun and Rubin 2000a, b).

The general area, particularly eastern Qinhai and Gansu, is rich in nonferrous mineral resources. There is as yet no compelling evidence for a late third millennium Seima–Turbino metal tradition in Xinjiang.

Qijia in Gansu

However, in neighboring Gansu and Qinghai provinces there is the remarkable Qijia culture where metallurgy reportedly of Seima–Turbino derivation has been found (Chernykh 2009, p. 7; Fitzgerald-Huber 1995; Mei 2003). Beginning in the late third millennium BC and extending into the early second millennium (Thorp 2006, p. 54; Mei (2003, p. 34) gives 2300–1700 BC), the Qijia culture is notable for its relatively numerous metal finds of more than one hundred copper, arsenical copper, and bronze artifacts. Finds include knives, awls, rings, mirrors, plaques, a flat axe, and several artifacts reflecting Seima–Turbino types and casting techniques, in particular two deep-socketed axes, and a socketed spear point. Fitzgerald-Huber (1995) first put forward the argument that the Qijia metals, particularly the deep-socketed axes and certain knives, indicated close contact with the Seima–Turbino metalworkers. Mei (2003) discusses more recent finds, particularly a socketed spear point with "diagnostic" attributes identical to classic Seima–Turbino spear points. Mei's (2003, 2009) overview of the evidence further indicates that numerous interactions, including a range of metallurgical borrowings, probably occurred among societies in Gansu, Xinjiang, and southern Siberia in the late third to early second millennium BC.

As reviewed in detail in Fitzgerald-Huber's (1995) article, Qijia sites reveal a noteworthy combination of (a) material remains (metals), faunal remains (cattle, horse, and donkey), and mortuary practices derivative of southern Siberian nomadic cultures, most abundantly and clearly but not exclusively the Seima–Turbino, with (b) indigenous practices (regional ceramic styles, sedentary agriculture), and (c) some eastern attributes (scapulimancy and millet cultivation). To account for the archaeological evidence, she argues for a:

> . . . persistent form of contact between the two groups and the more or less sustained presence in the vicinity of the Qijia settlements of northerners linked. . . to the Seima–Turbino. . . We can imagine that in time the Qijia accustomed themselves to their visitors from the north and to matters of metal technology, adapting this technology to their own purposes. . . . (Fitzgerald-Huber 1995, pp. 51–52)

The route by which Seima–Turbino groups connected with Qijia may eventually be found in Xinjiang, but Fitzgerald-Huber (1995, p. 51) says "a somewhat more probable route may have led south along the Mongolian Altai and eventually have followed the Edsingol to the Gansu Corridor."

Another remarkable point about the Qijia is that not only did they maintain wide-ranging contacts with neighboring cultures (Fitzgerald-Huber 2003; Mei 2003), but also a Qijia "colony" settlement has been identified at Damiaopo, over 1000 km to the northeast of the main area of Qijia settlement in Gansu:

> The main reason the Qijia journeyed the long distance to the northeast, and in some cases settled there. . . almost certainly resides in. . . the circumstance that the Qijia were the source

> of metal objects. . . Moreover, the abundance of easily accessible copper ore in the immediate vicinity of several Qijia settlements would suggest the likelihood that the raw material of copper. . . became itself a commodity of trade with the Northern Zone, destined for the production of metal objects by sedentary communities in that area. (Fitzgerald-Huber 1995, p. 36)

This long-distance colony provides additional evidence that Bronze Age groups were willing to move to distant regions and "set up shop" while maintaining contact with the home base over long distances with few or no intermediary settlements.

The Qijia evidence provides numerous insights into the Seima–Turbino phenomenon. It supports the argument that competent metalworkers moved into a territory occupied by other cultures and were apparently assimilated by the indigenous groups. They provided expertise and probably training of locals in metalworking, including casting implements characteristic of the metalworkers' source culture (deep-socketed implements and certain knives). They probably provided expertise in the mining and smelting of local ores. They and/or other northern pastoralists also brought a suite of domesticated animals, including the horse, which the hosts assimilated. Although the Qijia hosts were sedentary agriculturalists, they conducted extensive trade and sent out colonizing groups to great distances from the home territory, probably in relation to metal exchange. In those distant colonies, they may have provided raw material for sedentary village societies in areas without local mineral resources and perhaps also conducted secondary processing (melting and casting). The assimilation was prosperous and enduring, without marked evidence for warfare.

Huang He Central Plain

The turn of the third to second millennium BC finds only traces of copper-base artifacts in the Huang He Central Plain. The cultural period is terminal Longshan horizon, with Erlitou beginning c. 1900 BC. Longshan sites in the Central Plain have a few copper and bronze remains. Casting, forging, and some alloying were practiced, but most casting (including awls and other miscellaneous small pieces) was done in univalve molds. One flat axe with a hole was cast in a bivalve mold (Yan 2000, p. 106). There are no metal weapons, agricultural tools, or bangles. One small copper bell was found in a late Longshan burial at Taosi.

With Erlitou, the picture emerging is that, aside from the ubiquitous small artifact set (awls, fishhooks, arrowheads, and small blades), large copper-base artifacts generally do not reflect direct Seima–Turbino or any other Eurasian steppe prototypes (Chernykh 2009; Mei 2009). Rather, the earliest larger distinctive Erlitou castings (larger bells similar to the Taosi example, plaques with inlaid turquoise, eventually vessels) appear to be of locally derived shapes. Socketed items are absent, and bivalve molds are used, but for flat castings (Yan 2000, p. 109). If Erlitou bronze casting was influenced by upper Eurasian metallurgies, perhaps only a few components were adopted (e.g., smelting ores and casting), but experimentation ("guided variation") with indigenous shapes and purposes was important in the transmission process (Chernykh 2009; Mei 2009). Most discussions imply that metal artifact production was a restricted activity controlled by and for the élite in the emergent state (for example, Linduff 2000, pp. 20–21; Linduff and Mei 2009; Mei 2009). Although from a later context, Thorp (2006, pp. 168–169) notes for Shang that bronze utilitarian tools are found in workshop debris, as are bone and shell tools. He also notes that Shang foundries produced utilitarian bronze artifacts, but that was clearly not their main function.

Details of the refractory aspects of the technology would assist in ascertaining whether Erlitou metalworkers maintained two levels of metallurgy, one for élites and another for the common folk or utilitarian items, producing more Eurasian-looking artifacts (perhaps differentiated in crucible scale and workshop location). In any case, at present we cannot point to close parallels in Erlitou contexts for the earliest evidence of bronze metallurgy in Southeast Asia, the hollow-core cast spear head and adze, lost wax cast bangles, and small spouted crucibles.

Continued investigation of possible sources for Erlitou copper-base metallurgy in Gansu and in pastoral societies in areas north and west of the Huang He Central Plain is an important endeavor. For the purposes of this discussion, however, the Erlitou metallurgy lacks signature Seima–Turbino copper-base socketed forms, especially the suspended-core socket types, found in the Qijia and southern Siberian traditions. This absence further undermines arguments that the Huang He Central Plain is a likely source for the earliest Southeast Asian metallurgy in the early second millennium BC.

Routes South—A Brief Proposal

Let us accept for the purposes of discussion the existence of at least an offshoot of the Seima–Turbino metals technological tradition in the Gansu corridor at the end of the third millennium BC in the Qijia culture. The presence of horses in Qijia suggests a means of long-distance transportation that could assist in the rapid transport of the bearers of metals technology. Did Seima–Turbino metallurgy stop its southward movement there? Archaeological data in the lands between Gansu and Thailand (western Sichuan and Yunnan) are sparse, especially to the scholar who does not read Chinese. Nevertheless, one can glean some possibilities from the literature.

First, is there any evidence that cultures in Gansu interacted with Sichuan to the south in prehistoric times without going through the Huang He Central Plain? Yang Meili (2002 as translated by Lothar von Falkenhausen 2006, p. 213) says:

> . . . communication from southern Gansu to northern Sichuan proceeded first downstream along the Bailong River and then joined the main road along the Jialing River. Archaeological surveys along the Bailong River have revealed numerous prehistoric sites of the Dadiwan, Majiayao, Qijia, and Siwa [Siba] cultures; Qijia and Siwa sites, in particular, are distributed very close to northern Sichuan. . . .

In short, apparently the Gansu–Sichuan connection was present even prior to Qijia times, in pre-metal periods. Prehistoric avenues of communication and contact could have run along river courses (Fig. 28.5), especially in rugged areas like the eastern

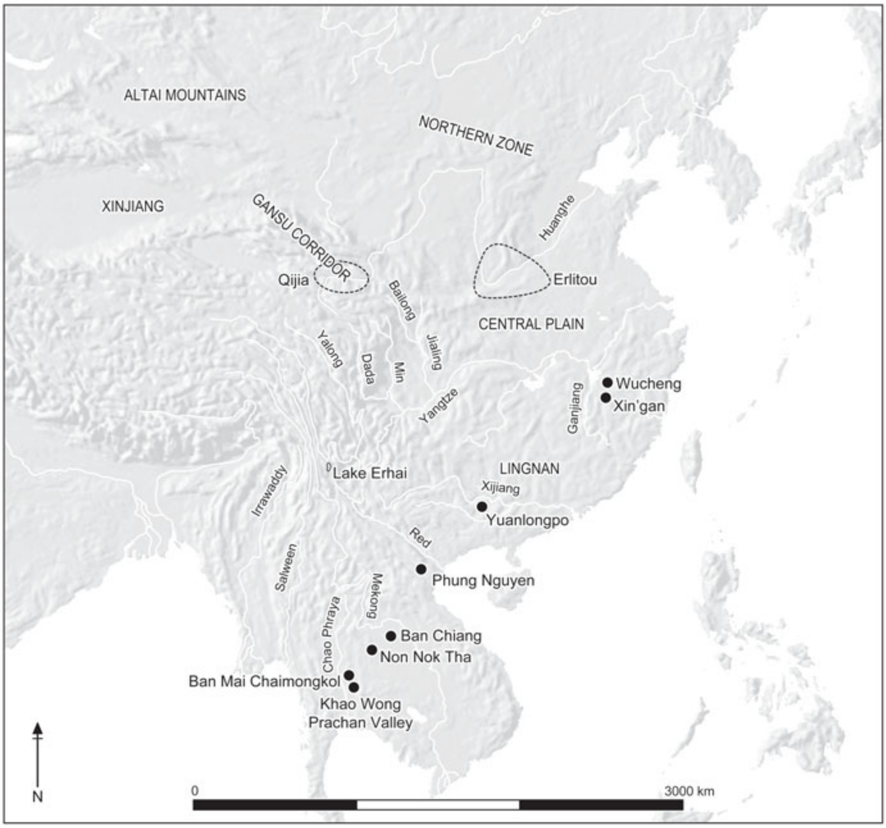


Fig. 28.5 Map of eastern Asia showing major sites, cultures, geographic regions, and rivers mentioned in the text

rim of the Himalayan Plateau. Moreover, as Seima–Turbino-trained metalworkers apparently followed river courses in forested areas of upper Eurasia, it is reasonable to propose that they would look along river courses as possible routes south. The Jialing River provides access to the relatively flat Sichuan Basin and Chendu Plain, entering the Yangtze at Chonqing.

There is less evidence for a c. 2000 BC Sichuan–Yunnan connection, but hypotheses can be formulated on the basis of evidence in later periods. Yunnan is separated from Sichuan by quite a rugged terrain. Nevertheless, during the first millennium BC, the connection of northwest Yunnan to Sichuan, Gansu, and the central Asian steppes is fairly clear-cut. Murowchick notes:

> ...the Bronze Age cultures of northwest Yunnan shared close affinities with the semi-sedentary and nomadic cultures of western Sichuan, and possibly with contemporaneous cultures of the Gansu–Qinghai plain and the central Asian steppes... Besides the distribution throughout this area of stone slab (cist) graves similar to some of those just described in Yunnan, a number of specific bronze artifact types suggest either close cultural contact across this wide area, or the transmission of material goods through intermediaries.... (Murowchick 1989, pp. 117–118)

A more extended discussion of western Yunnan's early connections to the north through Sichuan to the Eurasian steppes is provided by Chiou-Peng (1998, 2009). She stated (1998, p. 299) that the entire area formed a distinct cultural continuum, sharing technology and art as well as a mortuary tradition. It is clear from Chiou-Peng's work (1998, 2009) that the western axis of culture and communication was present from Lake Erhai to the Northern Zone during the second and first millennia BC. Some affinities noted with Qijia and even Majiayao ceramics argue for connections at least by the early second millennium BC (Chiou-Peng 1998, p. 295; Chiou-Peng 2009, p. 83). The Lanchang-Nu Corridor (upper Mekong and Salween rivers) has produced stone and copper-base adzes as well as stone molds and slag thought to be from the second millennium BC. The earliest date for the establishment of such north–south communication routes through Yunnan remains to be determined. Once in the Lake Erhai area, there is easy access to both the Mekong and the Red River drainages, and hence, in theory, to Northeast Thailand and the Bac Bo region of northern Vietnam, two areas where the earliest Southeast Asian copper-base artifacts are found.

For the purposes of developing a transmission model consistent with the technological and chronological evidence, we therefore hypothesize that metalworkers trained in the Seima–Turbino metallurgical system traveled along this western route c. 2000 BC, bypassing the Huang He Central Plain. This model sees extremely rapid dispersal of metalworkers with Seima–Turbino training, not only to the west from the Altai to Finland, as has long been recognized, but to the south as well. These metalworkers presumably actively sought metal resources, so metal-rich Southeast Asia would be attractive. As their social ethos apparently facilitated long-distance travel and their assimilation with other societies, they presumably trained locals in the fundamentals of their technology, and those locals may have carried it forward and possibly further afield.

The proposed route of communication from upper Eurasia to Yunnan along the eastern edge of the Himalayas, of great time depth, and bypassing the Huang He Central Plain, is not a new idea. Watson (1971, 1985, 1992) made similar observations more than 40 years ago. He also pointed out the similarities of the Hiamenko and Huang He socketed axes to inner Asian and Siberian prototypes (Watson 1971, p. 103), and was impressed with the earlier presence of lost wax casting outside of the Huang He Central Plain.

Although the rapidity and directness of the technological transmission from southern Siberia to the middle Mekong Basin may at first glance seem astonishing, the remarkable similarity of the early Southeast Asian metals to the Seima–Turbino technology and artifact repertoire argues that transmission was indeed both rapid and direct. The core Seima–Turbino and southern Siberian technological, and many typological, elements are all present—hollow-core casting of socketed implements in a single process, the artifact repertoire of deep-socketed adze–axes, socketed spear points with midrib, bangles, fishhooks and arrowheads, preference for tin bronze with minimal post-casting treatment, bivalve molds with suspended cores, and lost wax casting. Not found are Seima–Turbino decorative elements and certain kinds of knives, but these aspects may have been filtered out (selected against) in Gansu, where many are also missing.

In contrast, the metallurgy of Huang He Central Plain continued to receive input into its metallurgical system through interactions with and borrowing from the nomadic groups in the Northern Zone (Pigott and Ciarla 2007), resulting in the Shang-period appearance of suspended-core castings of deep-socketed axes. The evidence from Thailand, on the other hand, suggests an initial transmission occurred during a brief and limited period. Thereafter, the prehistoric Southeast Asian metalworkers maintained and eventually elaborated the same technological regime and style they had adopted initially. After 1500 BC, the Khao Wong Prachan valley technological system emerged, although whether it is a local innovation or a transmitted one, perhaps from areas north (Ciarla 2007; Pigott and Ciarla 2007), is not yet clear. Either way, its finished product repertoire bears some evidence of continuity of technological style with the earlier tradition in the continued use of cast blind sockets on adze–axe-like items, even if they are diminutive and possibly nonutilitarian implements. Finally, the similarity of the early Southeast Asian copper-base artifacts to the Seima–Turbino/Qijia technological system, together with lack of evidence for input from the slightly later Andronovo or Siba technological systems (that had a wider range of forms and greater use of forging, for example, of bangles: Chernykh 1992, p. 213), supports timing of transmission of bronze metallurgy to Thailand to a pre-Andronovo period of technological expansion, which would be also compatible with a date around 2000 BC.

Conclusions and Future Research Priorities

This chapter proposes a new interpretation for the source of the earliest bronze metallurgy in Southeast Asia. Drawing on cultural transmission approaches, a technological transmission argument is developed that incorporates current evidence on metal technological systems in Eurasia, social contexts for transmission, and current chronological evidence from Southeast Asia and Eurasia for the earliest appearance of metalworking. This evidence points to southern Siberia as the main source of the Southeast Asian metallurgical system in the early second millennium BC. In particular, characteristic traits of the Seima–Turbino metallurgical tradition of tin-bronze alloys, single-process hollow-core cast deep-socketed adzes and spear points, and lost wax casting of ornaments appear in Southeast Asia, particularly prehistoric Thailand, around 2000 BC. The limited repertoire of the early Southeast Asian metal artifacts is therefore seen as a product of relatively direct and complete transmission of the southern Siberian technological system, not as a product of gradual down-the-line filtering out of Sinitic forms and technologies at the periphery of Huang He states as some (Pigott and Ciarla 2007) have argued. Such rapid transmission of the southern Siberian metallurgical system may appear at first glance remarkable. But considering that other rapid long-distance transmissions were associated with other areas receiving a Seima–Turbino technological package at about the same time, the possibilities proposed seem worthy of further study. The Southeast Asian example may help prehistorians reassess gradualist assumptions for technology transfer in prehistoric times. How metallurgy got to Thailand is, we propose, a story that defies traditional archaeological gradualist expectations and provides new insights into prehistoric events, societies, and processes.

However, there are vast gaps in archaeological data between the Eurasian steppes and Southeast Asia that need to be filled before the argument presented here can be considered demonstrated. We hope that filling those gaps can be a priority in the future. The most exciting archaeology of the next decade in eastern Asia may be along the river systems extending out of the southeastern foothills of the Himalayas. In addition to simply more archaeology, particularly along the major drainage systems of southern and western PRC, two immediate efforts would contribute greatly to the investigation of the sources of metallurgy throughout Eurasia: (1) more detailed reporting, technological analysis, and publication of refractory components of metals technology; and (2) historical linguistic research on vocabulary related to metals and metal artifact production in eastern Asian languages.

From our point of view, the critical question concerning the source of bronze technology in Southeast Asia revolves around the source for the Southeast Asian metal refractory technology. Publication of crucible evidence has been neglected by archaeologists working in East Asia. At best, site publications mention the presence of crucibles, but provide few illustrations and no technical analyses of fabric, residues, vitrification, or other evidence of use without which the role of the crucibles cannot be meaningfully judged. Nonetheless, it is suggested here that when metals technology is transmitted, successful transmission of refractory technological style is probably a crucial component. Thus, refractory technology is the key to determining the source of Southeast Asian metallurgy, including both the Sinocentric and the rapid Eurasian technological expansion models. In particular the Seima–Turbino refractory technological system needs to be reconstructed across its range to see if the type of mobile, "one crucible serves all molten metal needs" model we find in Northeast Thailand was a part of the Seima–Turbino technological package, facilitating its rapid spread. The refractories used to produce utilitarian and local items in Huang He and Yangtze basins, as well as Lingnan and Bac Bo need to be identified, scientifically studied, and published. In addition, historical linguistics, physical anthropology, and faunal studies, in particular of the distribution of domesticated horses, are needed in order to holistically understand the nature of the prehistoric links between southern Siberia, western PRC, and Southeast Asia.

In the end, we will consider this chapter successful if it stimulates not only debates but also research. Not only should researchers look for data that can clarify the north (Gansu) to south (Sichuan–Yunnan–middle Mekong Basin) cultural interactions in prehistoric times, but also excavate, analyze, and publish (with illustrations!) well-dated in situ metallurgical evidence, including crucibles, smithies, furnaces, metal processing by-products, and analytical data. Only with the publication of these kinds of data, along with the application of up-to-date technological transmission concepts, will we begin to understand how Southeast Asia acquired its distinctive metallurgical tradition.

Addendum

Since the text for this chapter was published in White and Hamilton (2009), pertinent new chronometric data have been published (Higham et al. 2011). Although some chronological details for the authors' views may change with future reassessments, they stand by the technological and theoretical arguments presented here. They also emphasize the need to test their model and hypotheses with new archaeological data from southwest People's Republic of China.

Acknowledgments We thank Victor Mair for his enthusiastic mad-dash investigation sparked by a simple email request for references on archaeology in Yunnan and Sichuan to help sort out a possible link from Yunnan to Gansu c. 2000 BC. Thanks to all who answered Victor's emails to them on this topic. Constructive comments from Elisabeth Bacus, Roberto Ciarla, Robert Ehrenreich, Chureekamol Eyre, Victor Mair, Ben Marwick, Vincent Pigott, Oliver Pryce, Ben Roberts, Tim Taylor, Christopher Thornton, and Sarah Wright on previous drafts greatly improved the quality and content of this chapter. We gratefully acknowledge Ardeth Abrams, who prepared the illustrations. Anonymous reviewers have assisted us in strengthening both the arguments and the presentation. Thanks to Robert Murowchick for sending Joyce White his dissertation almost 20 years ago. And we are grateful to Surapol Natapintu for permission to use an illustration of the Ban Mai Chaimongkol bronze bar and to Bill Solheim for permission to use a drawing of WOST. Of course, any errors in scholarship are solely the authors'.

References

An Zhimin. (1993). Shi lun Zhongguo de zaoqi (On early copper and bronze objects in ancient China (in Chinese). *Kaogu (Archaeology)*, *12*, 1110–1119.

An Zhimin. (1998). Cultural complexes of the Bronze Age in the Tarim Basin and surrounding areas. In V. H. Mair (Ed.), *The Bronze Age and Early Iron Age peoples of Eastern Central Asia* (Vol. 1, pp. 45–62). Philadelphia: Institute for the Study of Man.

An Zhimin. (2000). On early copper and bronze objects in ancient China. In K. M. Linduff, H. Rubin, & S. Shuyun (Eds.), *The beginnings of metallurgy in China* (Vol. 11, pp. 29–49). Lewiston: Edwin Mellen. (Chinese Studies).

Anthony, D. W. (2007). *The horse, the wheel, and language: How Bronze Age riders from the Eurasian steppes shaped the modern world*. Princeton: Princeton University Press.

Bacus, E. A. (2006). Social identities in Bronze Age northeast Thailand: Intersections of gender, status and ranking at Non Nok Tha. In E. A. Bacus, I. C. Glover, & V. C. Pigott (Eds.), *Uncovering Southeast Asia's past: Selected papers from the 10th International Conference of the European Association of Southeast Asian Archaeologists* (pp. 105–115). Singapore: National University of Singapore Press.

Ban Chiang Project. (n.d.). The Ban Chiang Project Metals Database: Homepage. University of Pennsylvania Museum of Archaeology and Anthropology. http://seasia.museum.upenn.edu/metals/Web/index.html. Accessed 31 July 2009.

Barnard, N. (1980). The origins and development of metallurgy in China, with special reference to the crucible. In H. H. E. Loofs-Wissowa (Ed.), *The diffusion of material culture: 28th International Congress of Orientalists, Proceedings of Seminar E, Canberra, January 1971* (pp. 215–263). Asian and Pacific Archaeology Series No. 9. Honolulu: Social Science Research Institute, University of Hawaii at Manoa.

Barnard, N. (1996–1997). The entry of *cire-perdue* investment casting, and certain other techniques (mainly metalworking) into south China and their progress northwards. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (Vol. I, pp. 1–94). Taipei: SMC Publishing.

Bayard, D. T. (1972). Early Thai bronze: Analysis and new dates. *Science*, *176*, 1411–1412.

Bayard, D. T. (1979). The chronology of prehistoric metallurgy in north-east Thailand: *Silabhumi* or *Samrddhabhumi*? In R. B. Smith & W. Watson (Eds.), *Early South East Asia: Essays in archaeology, history and historical geography* (pp. 15–32). New York: Oxford University Press.

Bayard, D. T. (1980). An early indigenous bronze technology in northeast Thailand: Its implications for the prehistory of East Asia. In H. H. E. Loofs-Wissowa (Ed.), *The diffusion of material culture: 28th International Congress of Orientalists, Proceedings of Seminar E, Canberra, January 1971* (pp. 191–214). Asian and Pacific Archaeology Series No. 9. Honolulu: Social Science Research Institute, University of Hawaii at Manoa.

Bayard, D. T. (1981). Temporal distribution and alloy variation in early bronzes from Non Nok Tha. *Current Anthropology*, *22*, 697–699.

Bayard, D. T. (1996–1997). Bones of contention: The Non Nok Tha burials and the chronology and context of early Southeast Asian bronze. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (Vol. II, pp. 889–940). Taipei: SMC Publishing.

Bayard, D. T., & Charoenwongsa, P. (1983). The development of metallurgy in Southeast Asia: Reply to Loofs-Wissowa. *Journal of Southeast Asian Studies*, *14*(1), 12–17.

Bayard, D. T., & Solheim, W. G. II. (1991). *Archaeological Excavations at Non Nok Tha, Northeast Thailand, 1966–1968*. Unpublished manuscript, Department of Anthropology, University of Otago, Dunedin, New Zealand.

Bennett, A. (1988). Prehistoric copper smelting in central Thailand. In P. Charoenwongsa & B. Bronson (Eds.), *Prehistoric studies: The stone and metal ages in Thailand* (pp. 125–135). Papers in Thai Antiquity 1. Bangkok: Thai Antiquity Working Group.

Bettinger, R. L., & Eerkens, J. (1999). Point typologies, cultural transmission, and the spread of bow-and-arrow technology in the prehistoric Great Basin. *American Antiquity*, *64*(2), 231–242.

Boyd, R., & Richerson, P. J. (1985). *Culture and the evolutionary process*. Chicago: University of Chicago Press.

Bunk, W. G. J., Hauptmann, A., Kölschbach, S., & Woelk, G. (2004). Wind-powered copper smelting technology from the 3rd millennium BC at Feinan/Jordan. In G.-H. Kim, K.-W. Yi, & H.-T. Kang (Eds.), *Messages from the history of metals to the future Metal Age: Proceedings of the 5th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA V), 21–24 April 2002* (pp. 331–338). Korea: Gyeongju.

Chang, N. J. (2004). The personal ornaments. In C. Higham & R. Thosarat (Eds.), *The excavation of Ban Lum Khao* (Vol. 1, pp. 217–230). Bangkok: The Thai Fine Arts Department.

Chernykh, E. N. (1992). *Ancient metallurgy in the USSR: The early Metal Age*. New Studies in Archaeology. Cambridge: Cambridge University Press.

Chernykh, E. N. (2009). Ancient metalurgy in the Eurasian steppes and China: problems of interaction. In J. Mei & Th. Rehren (Eds.), *Metallurgy and civilisation: Eurasia and beyond. Proceedings of the 6th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VI)* (pp. 3–8). London: Archetype Publications.

Chernykh, E. N., Kuz'minykh, S. V., & Orlovskaya, L. B. (2004). Ancient metallurgy in northeast Asia: From the Urals to the Saiano–Altai. In K. M. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* (Vol. 31, pp. 15–36). Lewiston: Edwin Mellen Press. (Chinese Studies).

Childe, V. G. (1954). The socketed celt in upper Eurasia. *Annual Report of the Institute of Archaeology of the University of London*, *10*, 11–25.

Chiou-Peng, T. (1998). Western Yunnan and its steppe affinities. In V. H. Mair (Ed.), *The Bronze Age and Early Iron Age peoples of eastern central Asia. Volume 1: Archaeology, migration and nomadism, linguistics* (pp. 280–304). Journal of Indo-European Studies Monograph No. 26. Washington: Institute for the Study of Man in collaboration with University of Pennsylvania Museum Publications.

Chiou-Peng, T. (2009). Incipient metallurgy in Yunnan: New data for old debates. In J. Mei & Th. Rehren (Eds.), *Metallurgy and civilisation: Eurasia and beyond. Proceedings of the 6th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VI)* (pp. 79–84). London: Archetype Publications.

Ciarla, R. (1992). The Thai-Italian Lopburi Regional Archaeological Project: Preliminary results. In I. C. Glover (Ed.), *Southeast Asian Archaeology 1990. Proceedings of the Third Conference of the European Association of Southeast Asian Archaeologists* (pp. 111–128). Hull: Centre for South-East Asian Studies, University of Hull.

Ciarla, R. (2007). Rethinking Yuanlongpo: The case for technological links between the Lingnan (PRC) and central Thailand in the Bronze Age. *East and West*, *57*(1–4), 305–328.

Costin, C. L. (1991). Craft specialization: Issues in defining, documenting, and explaining the organization of production. In M. B. Schiffer (Ed.), *Archaeological method and theory, Volume 3* (pp. 1–56). Tucson: University of Arizona Press.

Costin, C. L. (2005) Craft production. In H. D. G. Maschner & C. Chippindale (Eds.), *Handbook of archaeological methods, Volume II* (pp. 1034–1107). New York: Altimira.

Dalton, G. (1977). Aboriginal economics in stateless societies. In T. K. Earle & J. E. Ericson (Eds.), *Exchange systems in prehistory* (pp. 191–211). London: Academic Press.

Davey, C. (2009). The early history of lost-wax casting. In J. Mei & Th. Rehren (Eds.), *Metallurgy and civilisation: Eurasia and beyond. Proceedings of the 6th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VI)* (pp. 147–154). London: Archetype Publications.

Epstein, S. M. (1993). *Cultural choice and technological consequences: Constraint of innovation in the late prehistoric copper smelting industry of Cerro Huaringa, Peru*. Unpublished PhD. Dissertation, Department of Anthropology, University of Pennsylvania, Philadelphia.

Eyre, C. O. (2006). *Prehistoric and proto-historic communities in the eastern upper Chao Phraya River Valley, Thailand: Analysis of site chronology, settlement patterns, and land use*. Unpublished PhD. Dissertation, Department of Anthropology, University of Pennsylvania, Philadelphia.

Fitzgerald-Huber, L. G. (1995). Qijia and Erlitou: The question of contacts with distant cultures. *Early China*, *20*, 17–67.

Fitzgerald-Huber, L. G. (2003). The Qijia culture: Paths east and west. *Bulletin of the Museum of Far Eastern Antiquities*, *75*, 55–78.

Gorsdorf, J., Parzinger, H., & Nagler, A. (2004). ^{14}C dating of the Siberian steppe zone from Bronze Age to Scythian Time. In E. M. Scott, A. Y. Alekseev, & G. Zaitseva (Eds.), *Impact of the environment on human migration in Eurasia* (pp. 83–89). NATO Science Series IV: Earth and Environmental Sciences. Boston: Kluwer Academic Publishers.

Hall, T. D., & Chase-Dunn, C. (1993). The world-systems perspective and archaeology: Forward into the past. *Journal of Archaeological Research*, *1*(2), 121–143.

Hanks, B. K., & Doonan, R. C. P. (2009). From scale to practice: A new agenda for the study of early metallurgy on the Eurasian Steppe. *Journal of World Prehistory*, *22*(4), 329–356.

Hanks, B. K., Epimakhov, A. V., & Renfrew, A. C. (2007). Towards a refined chronology for the Bronze Age of the southern Urals, Russia. *Antiquity*, *81*, 353–367.

Henrich, J. (2001). Cultural transmission and the diffusion of innovations: Adoption dynamics indicate that biased cultural transmission is the predominate force in behavioral change. *American Anthropologist*, *103*(4), 992–1013.

Higham, C. F. W. (1984). The Ban Chiang culture in wider perspective. *Proceedings of the British Academy*, *69*, 229–261.

Higham, C. F. W. (1988). Prehistoric metallurgy in Southeast Asia: Some new information from the excavations of Ban Na Di. In R. Maddin (Ed.), *The beginning of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 130–155). Cambridge: MIT Press.

Higham, C. F. W. (1989). *The archaeology of mainland Southeast Asia: From 10,000 BC to the fall of Angkor*. Cambridge: Cambridge University Press.

Higham, C. F. W. (1996). *The Bronze Age of Southeast Asia*. Cambridge: Cambridge University.

Higham, C. F. W. (1996–1997). The social and chronological contexts of early bronze working in Southeast Asia. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures, Volume II. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (pp. 821–888). Taipei: SMC Publishing.

Higham, C. F. W. (2002). *Early cultures of mainland Southeast Asia*. Bangkok: River Books.

Higham, C. F. W. (2004). Mainland Southeast Asia from the Neolithic to the Iron Age. In I. Glover & P. Bellwood (Eds.), *Southeast Asia: From prehistory to history* (pp. 41–67). London: RoutledgeCurzon.

Higham, C. F. W. (2006). Crossing national boundaries: Southern China and Southeast Asia in prehistory. In E. A. Bacus, I. C. Glover, & V. C. Pigott (Eds.), *Uncovering Southeast Asia's past: Selected Papers from the 10th International Conference of the European Association of Southeast Asian Archaeologists* (pp. 13–21). Singapore: National University of Singapore Press.

Higham, C. F. W. (2007). Summary and conclusions. In C. F. W. Higham, A. Kijngam , & S. Talbot (Eds.), *The origins of the civilization of Angkor, Volume 2. The Excavation of Noen U-Loke and Non Muang Kao* (pp. 595–609). Bangkok: Thai Fine Arts Department.

Higham, C. F. W. (2008). Recasting Thailand: New discoveries at Ban Non Wat. *Current World Archaeology*, *31*, 38–41.

Higham, C. F. W. (2009). Dating the Bronze Age of Southeast Asia: The Cultural Implications. *Journal of Southern Ethnology and Archaeology*. (in press).

Higham, C. F. W., & Higham, T. (2009). A new chronological framework for prehistoric Southeast Asia, based on a Bayesian model from Ban Non Wat. *Antiquity*, *83*, 125–144.

Higham, C. F. W., & Kijngam, A. (1984). *Prehistoric investigations in northeastern Thailand*. BAR International Series 231. Oxford: British Archaeological Reports.

Higham, C. F. W., & Thosarat, R. (1998). *Prehistoric Thailand: From early settlement to Sukhothai*. Bangkok: River Books.

Higham, C. F. W., & Thosarat, R. (2006). Ban Non Wat: The first three seasons. In E. A. Bacus, I. C. Glover, & V. C. Pigott (Eds.), *Uncovering Southeast Asia's Past: Selected Papers from the 10th International Conference of the European Association of Southeast Asian Archaeologists* (pp. 98–104). Singapore: National University of Singapore Press.

Higham, C. F.W., Higham, T., Ciarla, R., Douka, K., Kijngam, A. & Rispoli, F. (2011). The Origins of the Bronze Age of Southeast Asia. *Journal of World Prehistory, 24*(4), 227–274.

Hosler, D. (1995). *The sounds and colors of power: The sacred metallurgical technology of ancient west Mexico*. Cambridge: MIT Press.

Huyen, P. M. (2004). Northern Vietnam from the Neolithic to the Han Period: Part II: The Metal Age in the north of Vietnam. In I. Glover & P. Bellwood (Eds.), *Southeast Asia: From prehistory to history* (pp. 189–201). New York: RoutledgeCurzon.

Killick, D. (2004). Social constructionist approaches to the study of technology. *World Archaeology*, *36*(4), 571–578.

Kim, J. (2001). Élite strategies and the spread of technological innovation: The spread of iron in the Bronze Age Societies of Denmark and Southern Korea. *Journal of Anthropological Archaeology*, *20*(4), 442–478.

Kohl, P. L. (2007). *The making of Bronze Age Eurasia*. New York: Cambridge World Archaeology, Cambridge University Press.

Kohl, P. L. (2008). Shared social fields: Evolutionary convergence in prehistory and contemporary practice. *American Anthropologist*, *110*(4), 495–506.

Koryakova, L. N., & Epimakhov, A. V. (2007). *The Urals and Western Siberia in the Bronze and Iron Ages* (Cambridge World Archaeology). Cambridge: Cambridge University Press.

Kroeber, A. L. (1963). *Anthropology: Culture patterns and processes*. New York: Harbinger books (selections from Kroeber's *Anthropology* published in 1923, 1948).

Kuhn, S. (2004). Evolutionary perspectives on technology and technological change. *World Archaeology*, *36*(4), 561–570.

Kuz'mina, E. E. (2004). Historical perspectives on the Andronovo and metal use in eastern Asia. In K. M. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* (Vol. 31, pp. 37–84). Lewiston: Edwin Mellen Press (Chinese Studies).

Kuz'mina, E. E. (2008). *The prehistory of the Silk Road (Encounters with Asia)*. Philadelphia: University of Pennsylvania Press.

Lemonnier, P. (1986). The study of material culture today: Toward an anthropology of technical systems. *Journal of Anthropological Archaeology*, *5*, 147–186.

Lemonnier, P. (1992). *Elements for an anthropology of technology*. Anthropological Paper 88. Ann Arbor: Museum of Anthropology, University of Michigan.

Linduff, K. M. (1998). The emergence and demise of bronze-producing cultures outside the central plain of China. In V. H. Mair (Ed.), *The Bronze Age and early Iron Age peoples of eastern central Asia, Vol. 2: Genetics and physical anthropology, metallurgy, textiles, geography and climatology, history, and mythology and ethnology* (pp. 619–644). Journal of Indo-European Studies, Monograph No. 26. Washington: Institute for the Study of Man in collaboration with the University of Pennsylvania Museum Publications.

Linduff, K. M. (2000). Introduction. In K. M. Linduff, H. Rubin, & S. Shuyun (Eds.), *The beginnings of metallurgy in China* (Vol. 11, pp. 1–28). Lewiston: Edwin Mellen Press. (Chinese Studies).

Linduff, K. M. (Ed.). (2004a). *Metallurgy in ancient Eastern Eurasia from the Urals to the Yellow River* (Vol. 31). Lewiston: Edwin Mellen Press (Chinese Studies).

Linduff, K. M. (2004b). Introduction: How far does the Eurasian metallurgical tradition extend? In K. M. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* (Vol. 31, pp. 1–14). Lewiston: Edwin Mellen Press. (Chinese Studies).

Linduff, K. M., Rubin, H., & Shuyun, S. (Eds.). (2000). *The beginnings of metallurgy in China* (Vol. 11). Lewiston: Edwin Mellen Press. (Chinese Studies).

Linduff, K. M., & Mei, J. (2009). Metallurgy in Ancient Eastern Asia: Retrospect and prospects. *Journal of World Prehistory*, *22*(3), 265–281.

Loofs-Wissowa, H. H. E. (1983a). The development of metallurgy in Southeast Asia: Reply to Bayard, Pisit, and Solheim. *Journal of Southeast Asian Studies*, *14*(1), 26–31.

Loofs-Wissowa, H. H. E. (1983b) The development and spread of metallurgy in Southeast Asia: A review of present evidence. *Journal of Southeast Asian Studies*, *14*(1), 1–11.

Lyman, R. L. (2008). Cultural transmission in North American anthropology and archaeology, ca. 1895–1965. In M. J. O'Brien (Ed.), *Cultural transmission and archaeology: Issues and case studies* (pp. 10–20). Washington: Society for American Archaeology Press.

Mair, V. H. (1998a). Priorities. In V. H. Mair (Ed.), *The Bronze Age and early Iron Age peoples of eastern central Asia. Volume 1: Archaeology, migration and nomadism, linguistics* (pp. 4–41). Journal of Indo-European Studies Monograph No. 26. Washington: Institute for the Study of Man in collaboration with University of Pennsylvania Museum Publications.

Mair, V. H. (Ed.). (1998b). *The Bronze Age and Early Iron Age Peoples of eastern central Asia, Volumes. 1–2*. Journal of Indo-European Studies Monograph 26. Washington: Institute for the Study of Man, in collaboration with the University of Pennsylvania Museum Publications.

Mei, J. (2000). *Copper and bronze metallurgy in late prehistoric Xinjiang: Its cultural context and relationship with neighboring regions*. BAR International Series 865. Oxford: Archaeopress.

Mei, J. (2003). Cultural interaction between China and central Asia during the Bronze Age. *Proceedings of the British Academy*, *121*, 1–39.

Mei, J. (2004). Metallurgy in Bronze Age Xinjiang and its cultural context. In K. M. Linduff (Ed.), *Metallurgy in ancient eastern Eurasia from the Urals to the Yellow River* (Vol. 31, pp. 173–188). Lewiston: Edwin Mellen Press. (Chinese Studies).

Mei, J. (2009). Early metallurgy in China: Some challenging issues in current studies. In J. Mei & Th. Rehren (Eds.), *Metallurgy and civilisation: Eurasia and beyond. Proceedings of the 6th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VI)* (pp. 9–16). London: Archetype Publications.

Mesoudi, A., & O'Brien, M. J. (2008a). The cultural transmission of Great Basin projectile-point technology I: An experimental simulation. *American Antiquity*, *73*(1), 3–28.

Mesoudi, A., & O'Brien, M. J. (2008b). The cultural transmission of Great Basin projectile-point technology II: An agent-based computer simulation. *American Antiquity*, *73*(4), 627–644.

Muhly, J. D. (1988). The beginnings of metallurgy in the Old World. In R. Maddin (Ed.), *The beginning of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 2–20). Cambridge: MIT Press.

Murowchick, R. E. (1988). The development of early bronze metallurgy in Vietnam and Kampuchea: A reexamination of recent work. In R. Maddin (Ed.), *The beginning of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 182–199). Cambridge: MIT Press.

Murowchick, R. E. (1989). *The ancient bronze metallurgy of Yunnan and its environs: Development and implications*. Unpublished PhD. Dissertation, Department of Anthropology, Harvard University, Cambridge.

Nash, S. (n.d.). *Report on the microstructure and chemistry of two metallic artifacts from Ban Mai Chai Monkol and Ban Pong Manao*. Unpublished manuscript, MASCA, University of Pennsylvania, Philadelphia.

Natapintu, S. (1988). Current research on ancient copper-base metallurgy in Thailand. In P. Charoenwongsa & B. Bronson (Eds), *Prehistoric studies: The Stone and Metal Ages in Thailand* (pp. 107–124). Papers in Thai Antiquity 1. Bangkok, Thai Antiquity Working Group.

O'Brien, M. J. (Ed.). (2008). *Cultural transmission and archaeology: Issues and case studies*. Washington: Society for American Archaeology Press.

Onsuwan, C. (2000). *Excavation of Ban Mai Chaimongkol, Nakhon Sawan Province, central Thailand: A study of site stratigraphy, chronology and its implications for the prehistory of central Thailand*. Unpublished M.A. thesis, Department of Anthropology, University of Pennsylvania, Philadelphia.

O'Reilly, D. J. W. (2001). From the Bronze Age to the Iron Age in Thailand: Applying the heterarchical approach. *Asian Perspectives*, *39*(1–2), 1–19.

Pétrequin, P. (1993). North wind, south wind: Neolithic technical choices in the Jura Mountains, 3700–2400 BC. In P. Lemonnier (Ed.), *Technical choices: Transformations in material cultures since the Neolithic* (pp. 36–76). New York: Routledge.

Pietrusewsky, M., & Douglas, M. T. (2002). *Ban Chiang, a prehistoric village site in northeast Thailand I: The human skeletal remains*. Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology. (Thai Archaeology Monograph Series).

Pigott, V. C. (1998). Prehistoric copper mining in the context of emerging community craft specialisation in northeast Thailand. In A. B. Knapp, V. C. Pigott, & E. W. Herbert (Eds.), *Social approaches to an industrial past: The archaeology and anthropology of mining* (pp. 205–225). New York: Routledge.

Pigott, V. C. (1999). Reconstructing the copper production process as practised among prehistoric mining/metallurgical communities in the Khao Wong Prachan Valley of central Thailand. In S. M. M. Young, A. M. Pollard, P. Budd, & R. A. Ixer (Eds.), *Metals in antiquity* (pp. 10–21). Oxford: Archaeopress. (BAR International Series No. 792).

Pigott, V. C., & Ciarla, R. (2007). On the origins of metallurgy in prehistoric Southeast Asia: The view from Thailand. In S. La Niece, D. Hook, & P. Craddock (Eds.), *Metals and mines: Studies in archaeometallurgy* (pp. 76–88). London: Archetype Press in association with the British Museum.

Pigott, V. C., & Natapintu, S. (1988). Archaeological investigations into prehistoric copper production: The Thailand Archaeometallurgy Project 1984–1986. In Maddin, R. (Ed.), *The beginning* *of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 156–162). Cambridge: MIT Press.

Pigott, V. C., & Natapintu, S. (1996–1997). Investigating the origins of metal use in prehistoric Thailand. In F. D. Bulbeck and N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures, Volume II. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February, 1988* (pp. 787–808). Taipei: SMC Publishing.

Pigott, V. C., & Weisgerber, G. (1998). Mining archaeology in geological context: The prehistoric copper mining complex at Phu Lon, Nong Khai Province, northeast Thailand. *Der Anschnitt. Beiheft*, *8*, 135–162.

Pigott, V. C., Weiss, A. D., & Natapintu, S. (1997). The archaeology of copper production: Excavations in the Khao Wong Prachan Valley, central Thailand. In R. Ciarla & F., Rispoli, (Eds.), *South-East Asian Archaeology 1992. Proceedings of the Fourth International Conference of the European Association of South-East Asian Archaeologists. Rome, 28th September—4th October 1992* (Vol. 77, pp. 119–157). Rome: Istituto Italiano per L'Africa e L'Oriente. (Serie Orientale Roma).

Pryce, T. O. (2009). *Prehistoric copper production and technological production in the Khao Wong Prachan Valley of central Thailand*. Unpublished dissertation, UCL Institute of Archaeology, University College London, London. Available at http://sites.google.com/site/thomasoliverpryce/.

Pryce, T. O., & Pigott, V. C. (2008). Towards a definition of technological styles in prehistoric copper smelting in the Khao Wong Prachan Valley of central Thailand. In J.-P. Pautreau, A. Coupey, V. Zeitoun, & E. Rambault (Eds.), *Archaeology in Southeast Asia: From* Homo Erectus *to the living traditions, choice of papers from the 11th Euraseaa Conference, Bougon 2006* (pp. 139–150). Chiang-Mai: European Association of Southeast Asian Archaeologists.

Pryce, T. O., Bassiakos Y., Catapotis, M., & Doonan, R. C. P. (2007). 'De Caerimoniae' Technological choices in copper-smelting furnace design at Early Bronze Age Chrysokamino, Crete. *Archaeometry*, *49*(3), 543–557.

Rehren, Th. (2003). Crucibles as reaction vessels in ancient metallurgy. In P. Craddock and J. Lang (Eds.), *Mining and metal production through the ages* (pp. 207–215). London: The British Museum Press.

Roberts, B. W., Thornton, C. P., & Pigott, V. C. (2009). Development of Metallurgy in Eurasia. *Antiquity, 83*(322), 1012–1022.

Rostoker, W., Pigott, V. C., & Dvorak, J. (1989). Direct reduction to copper metal by oxide-sulfide mineral interaction. *Archeomaterials*, *3*, 69–87.

Schiffer, M. B. (Ed.). (2001a). *Anthropological perspectives on technology*. Albuquerque: University of New Mexico Press. (Amerind Foundation New World Series, No. 5).

Schiffer, M. B. (2001b). Toward an anthropology of technology. In M. B. Schiffer (Ed.), *Anthropological perspectives on technology*. (pp. 1–15). Albuquerque: University of New Mexico Press. (Amerind Foundation New World Studies Series No. 5).

Schiffer, M. B. (2004). Studying technological change: A behavioral perspective. *World Archaeology*, *36*(4), 589–585.

Schiffer, M. B. (2005). The devil is in the details: The cascade model of invention processes. *American Antiquity*, *70*(3), 485–502.

Schiffer, M. B. (2008). Transmission processes: A behavioral perspective. In M. J. O'Brien (Ed.), *Cultural transmission and archaeology: Issues and case studies* (pp. 102–111). Washington: Society for American Archaeology.

Selimkhanov, I. R. (1979) The chemical characteristics of some metal finds from Non Nok Tha. In R. B. Smith & W. Watson (Eds.), *Early South East Asia: Essays in archaeology, history and historical geography* (pp. 33–38). New York: Oxford University Press.

Sherratt, A. (2006). The Trans–Eurasian exchange: The prehistory of Chinese relations with the West. In V. H. Mair (Ed.), *Contact and exchange in the ancient world* (pp. 30–61). Honolulu: University of Hawaii Press. (Perspectives on the Global Past).

Shuyun, S., & Rubin, H. (2000a). A study of casting and manufacturing techniques of early copper and bronze artifacts found in Gansu. In K. M. Linduff, H. Rubin, & S. Shuyun (Eds.), *The beginnings of metallurgy in China* (Vol. 11, pp. 175–193). Lewiston: Edwin Mellen Press. (Chinese Studies).

Shuyun, S., & Rubin, H. (2000b). A preliminary study of early Chinese copper and bronze artifacts. In K. M. Linduff, H. Rubin, & S. Shuyun (Eds.), *The beginnings of metallurgy in China* (Vol. 11, pp. 129–151). Lewiston: Edwin Mellen Press. (Chinese Studies).

Smith, C. S. (1973). Bronze technology in the East: A metallurgical study of early Thai bronzes with some speculations on the cultural transmissions of technology. In M. Teich & R. Young (Eds.), *Changing perspectives in the history of science: Essays in honor of Joseph Needham* (pp. 21–32). London: Heinemann.

Solheim, W. G., II. (1968). Early bronze in northeastern Thailand. *Current Anthropology*, *9*, 59–62.

Solheim, W. G., II. (1983). The development of metallurgy in Southeast Asia: Another reply to Loofs-Wissowa. *Journal of Southeast Asian Studies*, *14*(1), 18–25.

Spriggs, M. J. T. (1996–1997). The dating of Non Nok Tha and the 'Gakushuin Factor'. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures, Volume II. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (pp. 941–948). Taipei: SMC Publishing.

Stech Wheeler, T., & Maddin, R. (1976). The techniques of the early Thai metalsmith. *Expedition*, *18*(4), 38–47.

Stech, T., & Maddin, R. (1988). Reflections on early metallurgy in Southeast Asia. In R. Maddin, (Ed.), *The beginning of the use of metals and alloys. Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 163–174). Cambridge: MIT Press.

Stein, G. J. (1999). *Rethinking world-systems: Diasporas, colonies, and interaction in Uruk Mesopotamia*. Tucson, AZ: University of Arizona Press.

Thorp, R. L. (2006). *China in the early Bronze Age: Shang Civilization Encounters with Asia*. Philadelphia: University of Pennsylvania Press.

Tylecote, R. F. (1996–1997). Recent observations on early metallurgy in China—a note. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures, Volume II. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (pp. 723–730). Taipei: SMC Publishing.

Van Pool, C. S. (2008). Agents and cultural transmission. In M. J. O'Brien (Ed.), *Cultural transmission and archaeology: Issues and case studies* (pp. 190–200). Washington, D. C.: Society for American Archaeology.

Vernon, W. W. (1988). The crucible in copper-bronze production at prehistoric Phu Lon, northeast Thailand: Analyses and interpretation. *Paper read at the Conference on Ancient Chinese and Southeast Asian Bronze Age cultures, Kioloa, NSW, Australia*.

Vernon, W. W. (1996–1997). The crucible in copper-bronze production at prehistoric Phu Lon, northeast Thailand: Analyses and interpretation. In F. D. Bulbeck & N. Barnard (Eds.), *Ancient Chinese and Southeast Asian Bronze Age cultures, Volume II. The Proceedings of a Conference Held at the Edith and Joy London Foundation Property, Kioloa, NSW, Australia, 8–12 February*, *1988* (pp. 809–820). Taipei: SMC Publishing.

Vernon, W. W. (1997). Chronological variation in crucible technology at Ban Chiang: A preliminary assessment. *Bulletin of the Indo-Pacific Prehistory Association*, *16*, 107–110.

von Falkenhausen, L. (2006). The external connections of Sanxingdui. *Journal of East Asian Archaeology*, *5*(1–4), 191–245.

Watson, W. (1971). *Cultural frontiers in ancient East Asia*. Edinburgh: Edinburgh University Press.

Watson, W. (1985). An interpretation of opposites? Pre-Han bronze metallurgy in west China. *Proceedings of the British Academy*, *70*, 327–358.

Watson, W. (1992). Pre-Han communication from west China to Thailand. In I. C. Glover, P. Suchitta, & J. Villiers (Eds.), *Early metallurgy, trade and urban centres in Thailand and Southeast Asia* (pp. 175–180). Bangkok: White Lotus.

White, J. C. (1982). *Ban Chiang: Discovery of a lost Bronze Age*. Philadelphia: The University Museum, University of Pennsylvania and the Smithsonian Institution Traveling Exhibition Service.

White, J. C. (1986). *A revision of the chronology of Ban Chiang and its implications for the prehistory of northeast Thailand*. Unpublished PhD. Dissertation, Department of Anthropology, University of Pennsylvania, Philadelphia.

White, J. C. (1988). Early East Asian metallurgy: The southern tradition. In R. Maddin (Ed.), *The beginning of the use of metals and alloys: Papers from the Second International Conference on the Beginning of the Use of Metals and Alloys, Zhengzhou, China, 21–26 October 1986* (pp. 175–181). Cambridge, MA: MIT Press.

White, J. C. (1995). Incorporating heterarchy into theory on socio-political development: The case from Southeast Asia. In R. M. Ehrenreich, C. L. Crumley, & J. E. Levy (Eds.), *Heterarchy and the analysis of complex societies* (pp. 101–123). Archeological Papers of the American Anthropological Association No. 6. Arlington: American Anthropological Association.

White, J. C. (1997). A brief note on new dates for the Ban Chiang cultural tradition. *Bulletin of the Indo-Pacific Prehistory Association*, *16*, 103–106.

White, J. C. (2000). Review of 'Prehistoric Thailand: From early settlement to Sukhothai' by Charles Higham and Rachanie Thorsarat. *Journal of Asian Studies*, *59*(4), 1093–1094.

White, J. C. (2008). Dating early bronze at Ban Chiang, Thailand. In J.-P. Pautreau, A.-S. Coupey, V. Zeitoun, & E. Rambault (Eds.), *Archaeology in Southeast Asia: From* Homo Erectus *to the living traditions, choice of Papers from the 11th EurASEAA Conference, Bougon 2006* (pp. 91–104). Chiang-Mai: European Association of Southeast Asian Archaeologists.

White, J. C., & Pigott, V. C. (1996). From community craft to regional specialization: Intensification of copper production in prestate Thailand. In B. Wailes (Ed.), *Craft specialization and social evolution: In memory of V. Gordon Childe* (pp. 151–175). University Museum Monograph 93. Philadelphia: The University Museum of Archaeology and Anthropology, University of Pennsylvania.

White, J, C., & Hamilton, E. G. (2009). The Transmission of Early Bronze Technology to Thailand: New Perspectives. *Journal of World Prehistory*, *22*(4), 357–397.

White, J. C., Vernon, W. W., Fleming, S. J., Glanzman, W. D., Hancock, R. G. V., & Pelcin, A. (1991). Preliminary cultural implications from initial studies of the ceramic technology at Ban Chiang. *Bulletin of the Indo-Pacific Prehistory Association*, *11*, 188–203.

Yan, W. (2000). A discussion of the Chalcolithic Age in China. In K. M. Linduff, H. Rubin, & S. Shuyun (Eds.), *The beginnings of metallurgy in China* (Vol. 11, pp. 100–115). Lewiston: Edwin Mellen Press. (Chinese Studies).

Yang, M. (2002). Erlitou bronze plaques inlaid with turquoise (in Chinese). *Miho Museum Kenky*ū *kiy*, *3*, 27–77.

Zhou, W., Dong, Y., Wan, Q., & Wang, C. (2009). New research on lost-wax casting in ancient China. In J. Mei & Th. Rehren (Eds.) *Metallurgy and civilisation: Eurasia and beyond. Proceedings of the 6th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA VI)* (pp. 73–78). London: Archetype Publications.

ERRATUM
A Conservator's Perspective on Ancient Metallurgy

Deborah Schorsch

B. W. Roberts, C. P. Thornton (eds.), Archaeometallurgy in Global Perspective, DOI 10.1007/978-1-4614-9017-3, pp. 269–301, © Springer Science+Business Media New York 2014

DOI 10.1007/978-1-4614-9017-3_29

The publisher regrets that in the print and online versions of this title, Figure 12.22a is incorrect in the final version of chapter 12 page 295. The correct figure12.22a is given below. In the print and online versions, the remaining four figures should be 12.22b, 12.22c, 12.22d and 12.22e which all agree with their captions.

The online version of the original chapter can be found at
http://dx.doi.org/10.1007/978-1-4614-9017-3_12

Index

B. W. Roberts, C. P. Thornton (eds.), *Archaeometallurgy in Global Perspective,*
DOI 10.1007/978-1-4614-9017-3,

D