Chapter 12
A Conservator's Perspective on Ancient Metallurgy

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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

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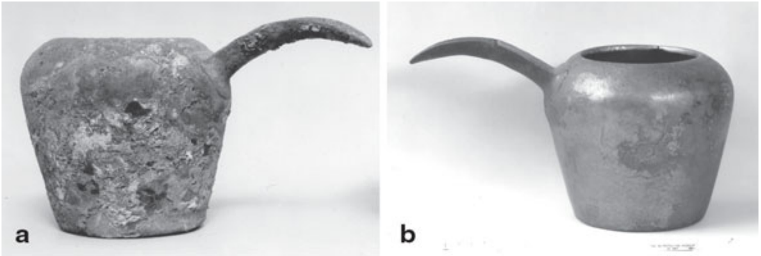

Fig. 12.1 Ewer, Egyptian, Old Kingdom (ca. 2641–2100 B.C.). Hammered arsenical copper sheet with arsenical-enriched surface, H. 11.0 cm. The Metropolitan Museum of Art; Gift of Edward Harkness, 1926 (26.9.13). **a** Condition in 1926 when acquired. **b** Condition in 1932 after electrochemical treatment. (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

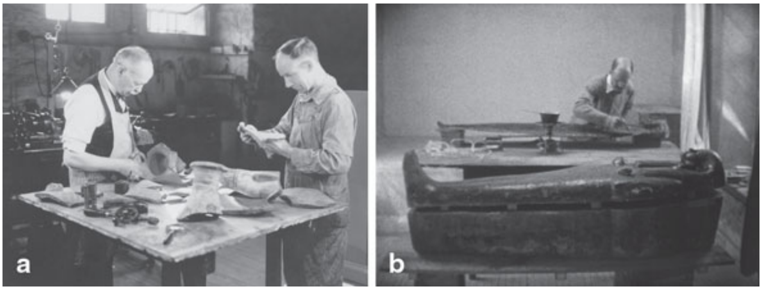

Fig. 12.4 **a** “Repair Shop Wing B Room 135 Basement Floor,” The Metropolitan Museum of Art, 1926. **b** Herbert E. Winlock, Egyptologist and later Director of the Metropolitan Museum, at the Museum’s expedition house in Thebes, consolidating a newly excavated coffin with wax. Still from archival film 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

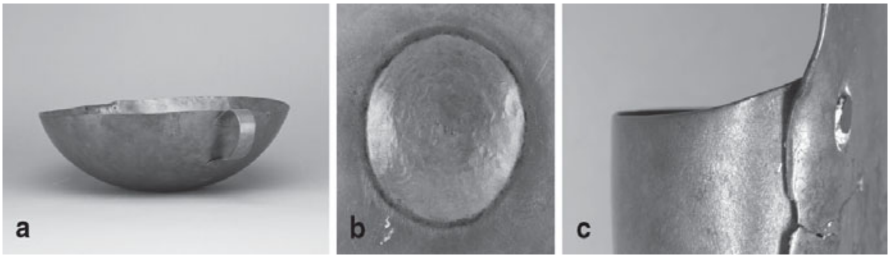

Fig. 12.6 **a** Basin, Egyptian, Thebes, Assasif, New Kingdom, early 18th Dyn. (ca. 1550–1458 B.C.). Hammered bronze sheet, copper rivets. Dia. 44.6 cm. The Metropolitan Museum of Art, Rogers Fund, 1916 (16.10.436). **b** Detail with hammer blows associated with raising process. **c** Detail showing 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.

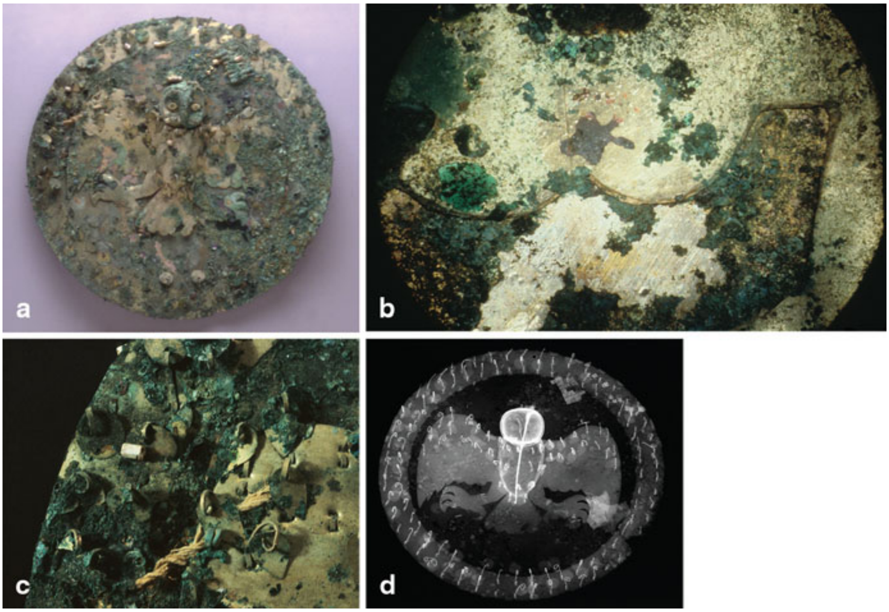

Fig. 12.8 **a** Disk, Moche, from Loma Negra, Peru, 3rd cen. A.D. Hammered copper sheet with precious-metal plating. Dia. 28.2 cm. The Metropolitan Museum of Art, Bequest of Jane Costello Goldberg, from the collection of Arnold I. Goldberg, 1986 (1987.394.56). **b** Detail showing juxtaposed sheets of 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

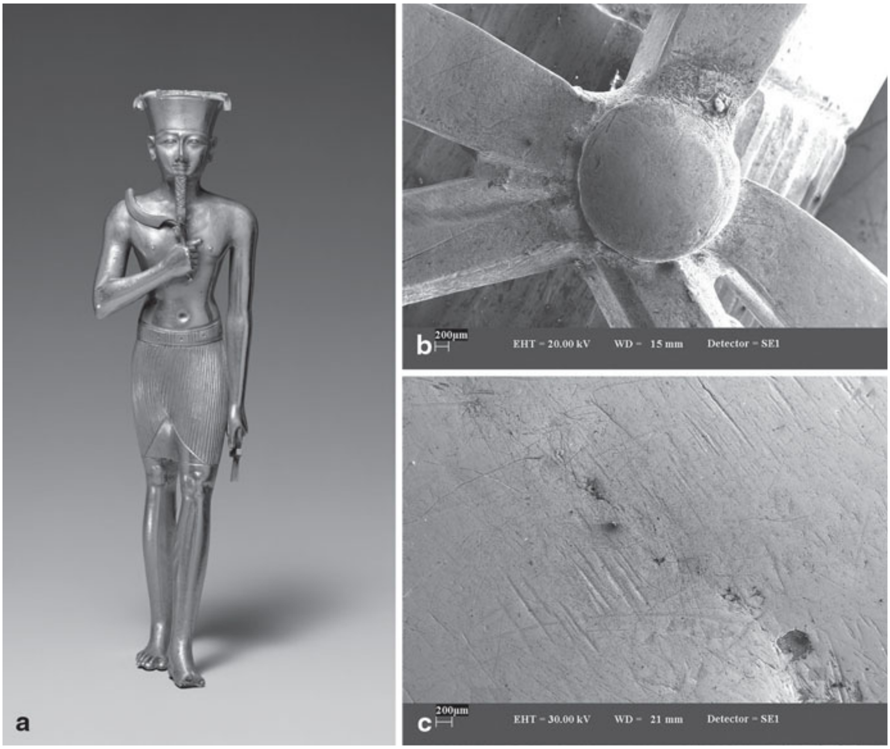

Fig. 12.9 **a** Amun. Egyptian, Third Intermediate Period, early 8th cen. Solid-cast gold, with separately cast components. H. 17.5 cm. The Metropolitan Museum of Art, Gift of Edward S. Harkness, 1926 (26.7.1412). **b** SEM photomicrograph showing solder join (photo by Mark T. Wypyski). **c** SEM photomicrograph 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)

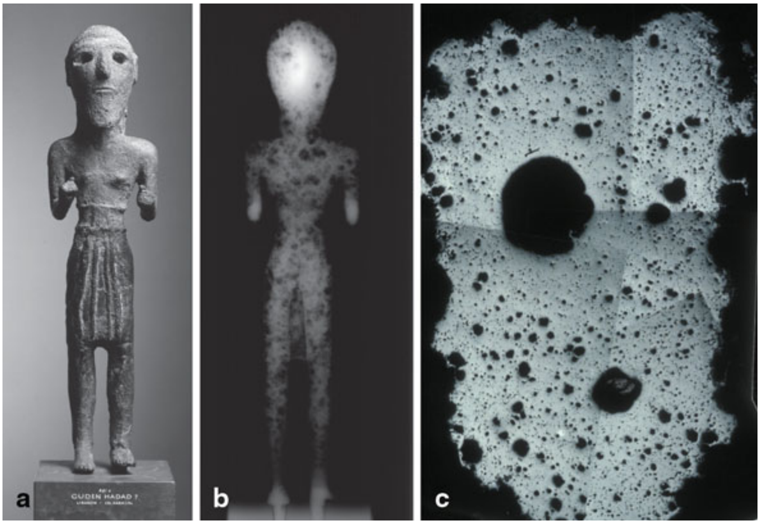

Fig. 12.11 **a** "Lebanese Mountain" figure said to be Syria. beg. 2nd mil. B.C. Solid cast, unalloyed copper. H. 39.5 cm (with tangs). Ny Carlsberg Glyptotek, Copenhagen (2836). **b** X-ray radiograph, showing highly porous internal structure Images: Ny Carlsberg Glyptotek. **c** Composite archival photomicrograph of polished section. (Image © The Metropolitan Museum of Art)

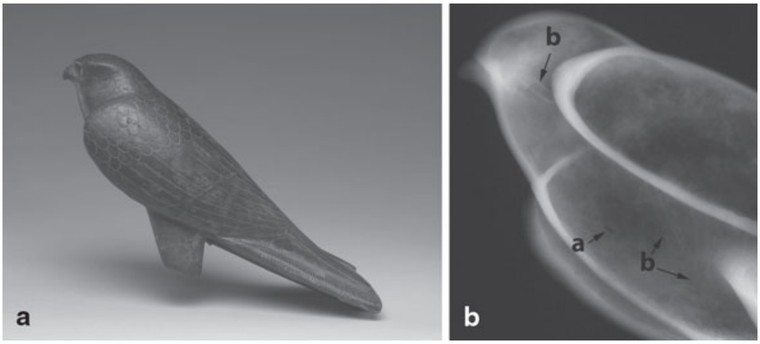

Fig. 12.12 **a** Falcon sarcophagus. Egyptian, Macedonian-Ptolemaic Period (332–30 B.C.). Hollow cast leaded bronze, with falcon remains. H. 18.1 cm. The Metropolitan Museum of Art, Rogers Fund, 1925 (25.2.11). **b** Detail of X-ray radiograph, showing mottled texture associated with segregated lead 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.

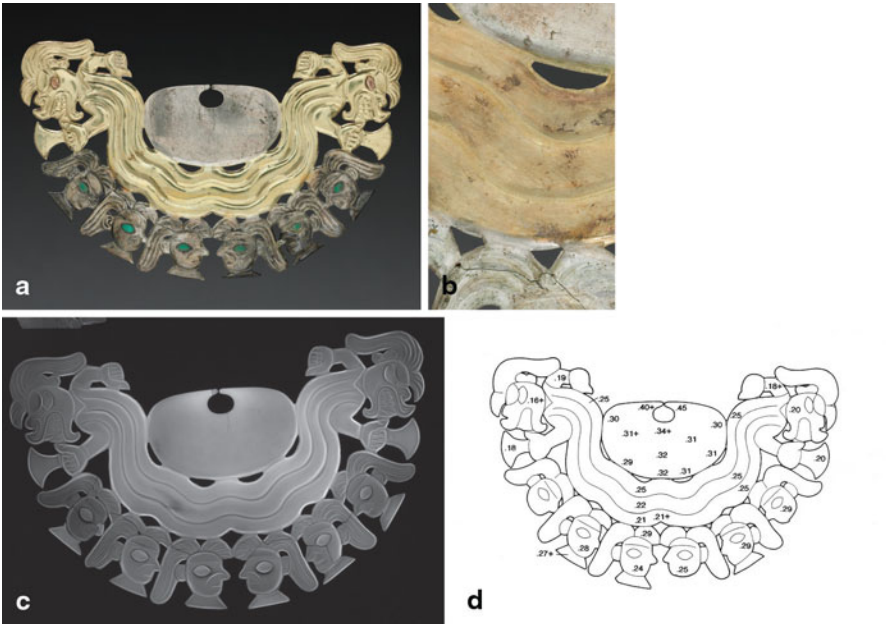

Fig. 12.13 **a** Nose ornament with Decapitators and Human Heads, Peru, Moche, ca. A.D. 100–300. Hammer-welded gold and silver sheet, H. 8.8 cm, L. 14.0 cm. The Cleveland Museum of Art. Severance and Greta Millikin Purchase Fund 2005.176 Photo: The Cleveland Museum of Art. **b** detail of cut-outs; note 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).

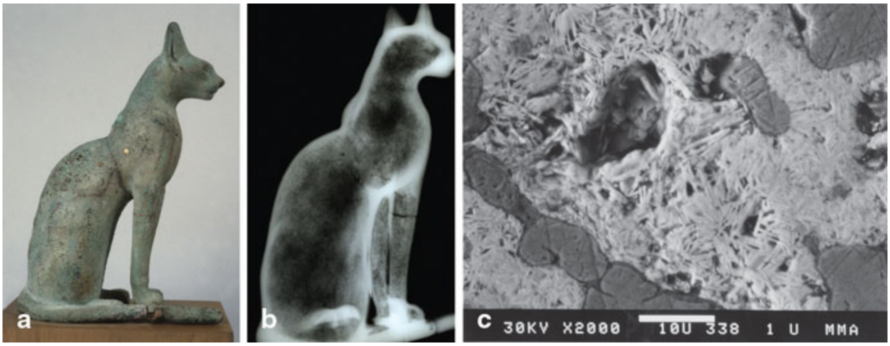

Fig. 12.14 **a** "Cat sarcophagus." 19th–20th cen. Hollow cast copper. H. 38.1 cm. The Metropolitan Museum of Art, Funds from various donors, 1958 (58.38). The figure, believed to be a forgery, seen after the removal of paint intended to disguise an unattractive, blistered surface and screw heads relating 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

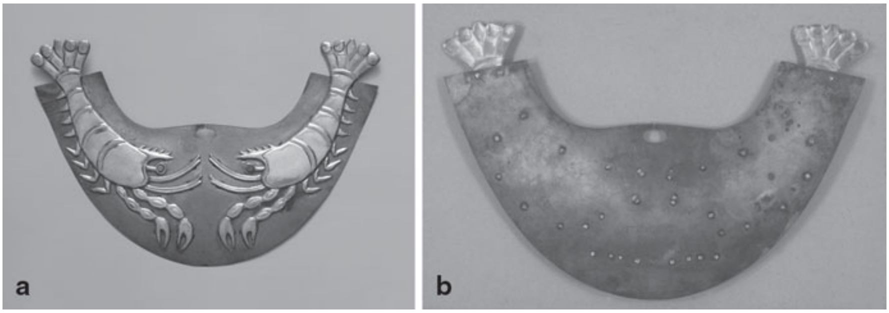

Fig. 12.15 **a** Nose ornament, Moche, from Loma Negra, Peru, 2nd–3rd cen. A.D. Silver and gold sheet, W. 18.7 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1236). A gold lobster was applied to the silver substrate 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

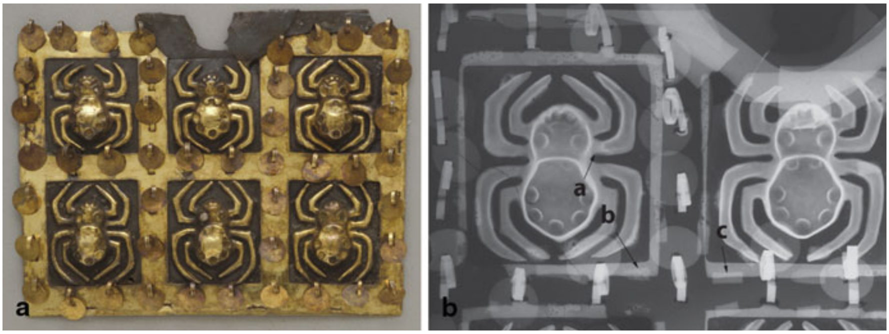

Fig. 12.16 **a** Nose ornament, Moche, from Loma Negra, Peru, 2nd–3rd cen. A.D. Silver and gold sheet, W. 8.6 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1230). Gold spiders were applied to silver back plates set 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)

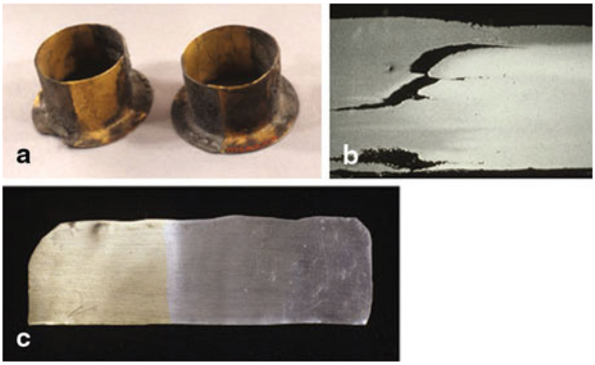

Fig. 12.17 **a** Ear flares, North Coast, Peru, 1st cen. B.C.–7th cen. A.D. Silver and gold sheet, Dia. of plugs (*left* and *center*), 5.2 & 5.3 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1175–1177). **b** Back-scatter 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

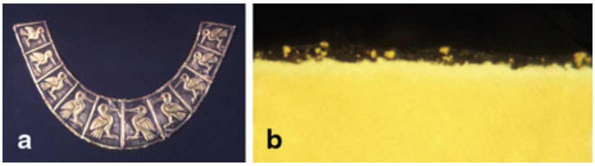

Fig. 12.18 **a** Nose ornament frontal, Peru, Moche, from Loma Negra, 1st-3rd cen. A.D. Partially silvered gold, W. 21.0 cm. The Metropolitan Museum of Art, The Michael C. Rockefeller Memorial Collection, Bequest of Nelson A. Rockefeller, 1979 (1979.206.1226). An extremely thin layer of silver overlies 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

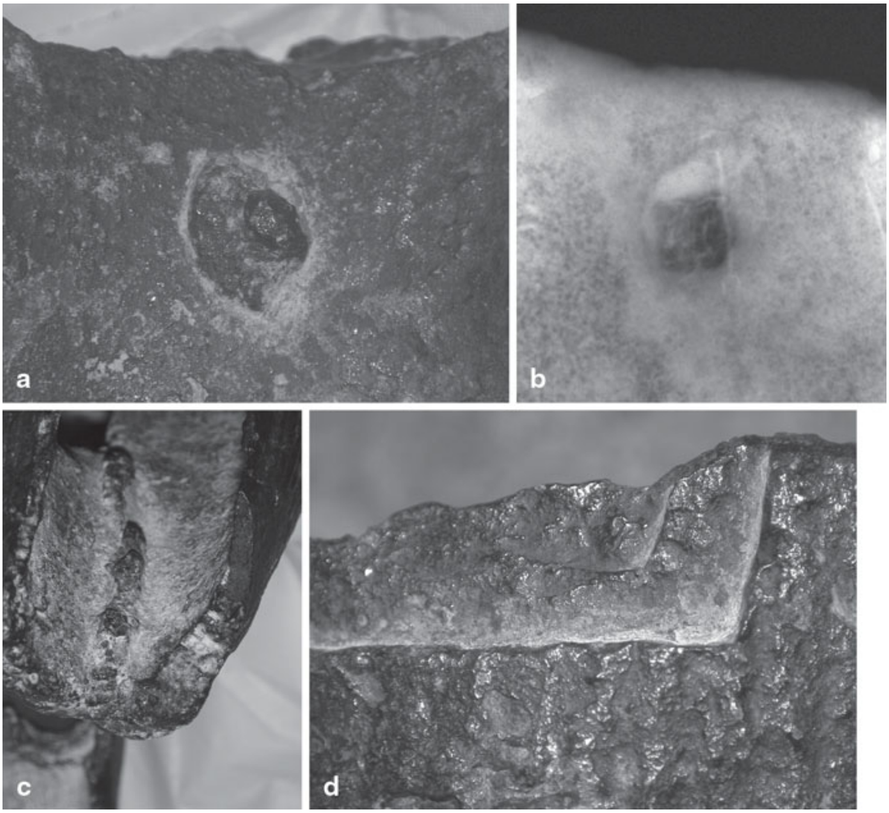

Fig. 12.22 **a** Torso of King Pedubaste. Egypt, Third Intermediate Period, 23rd Dyn., reign of Pedubaste (ca. 818–793 B.C.). Museu Calouste Gulbenkian, Lisbon (52). **b** Detail of an iron core support, seen on interior of abdomen wall and corresponding radiograph. **c** X-ray radiograph showing core 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,

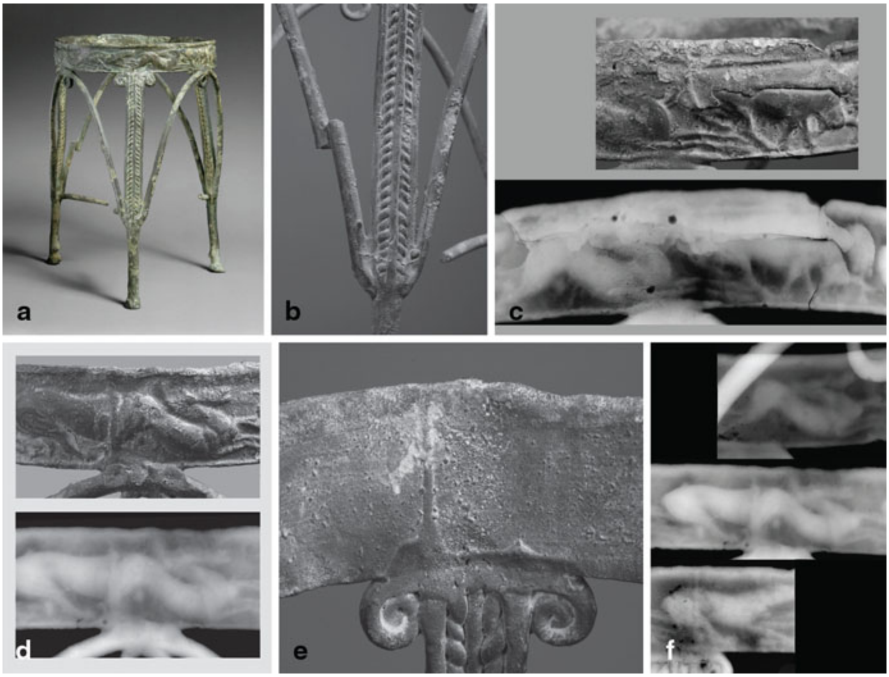

Fig. 12.24 **a** Tripod, Cyprus, Late Bronze Age, ca. 13th-12th cen. B.C. Cast bronze, H. 37.5 cm. The Metropolitan Museum of Art, The Cesnola Collection, Purchased by subscription, 1874–76 (74.51.5684). **b** Cold shut, and fins on surface reflecting lack of surface finishing after casting. **c** Cast-on 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.

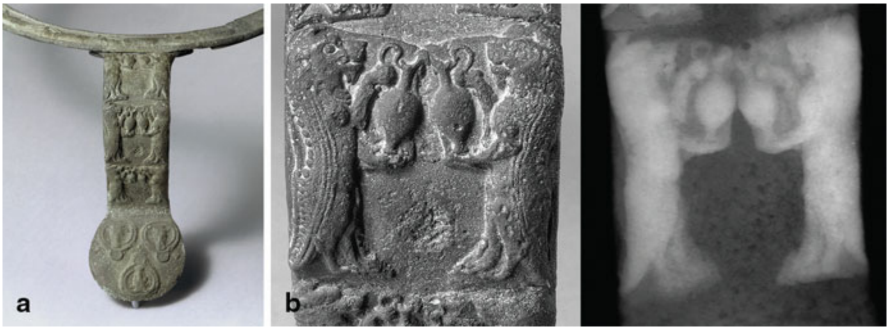

Fig. 12.25 **a** Amphora handle, Late Bronze Age, ca. 13th–12th cen. B.C. Cast bronze, H. 37.5 cm. The Metropolitan Museum of Art, The Cesnola Collection, Purchased by subscription, 1874–76 (74.51.5685). **b** Detail showing untrimmed edges of appliqués that were produced in wax in molds and applied 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.

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