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ORIGINAL PAPER

Ceramics investigation: research questions and sampling criteria

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Abstract

Ceramics are a key indicator for the study of cultural heritage:

– A valuable technological indicator because (a) ceramics mark the passage from the simple exploitation to the complex control of fire; (b) they represent the first pyrotechnological product of a certain complexity; and (c) they are able of triggering the development of other technologies such as those involving the processing of metal and glass.
– A valuable socio-economic indicator because (a) ceramics are brought into the houses of both poor and wealthy families; (b) they provide evidence of trade routes and cultural exchange; and (c) they are able to pass on significant information about the evolution of aesthetic taste as well as dietary habits through the centuries.
– A valuable chronological indicator because (a) their comparative study can provide accurate dating; (b) they can provide absolute dates by thermo-luminescence testing; and (c) they enable the dating of other materials found in stratigraphic association.

In this framework, research questions are discussed according to the different steps of a typical research project in progress: from the individuation of the archaeological site or area, to the selection of the ceramic types to be investigated and the samples to be taken for the analyses. It is proposed that research questions should contribute to the reconstruction of a "big picture" covering wide and complex issues such as the circulation of a specific type of goods within large geographic areas and/or the diachronic evolution of production technology. It can be demonstrated that farsighted strategy in research planning can provide material for preliminary articles that satisfy professional obligations to publish periodically while also laying the groundwork for truly important contributions to the field. The distinct fields of provenance, technology, function, use, chronology and conservation are briefly reviewed in order to provide an introductory framework to the following contributions of this Topical Collection. As for research design, the aim here is to reaffirm the importance of typology and contextualization as the basis for all studies undertaken. Finally, it is demonstrated that true multidisciplinary collaboration, rather than working in silos according to different specializations, provides the best approach to obtaining accurate and meaningful results.

Keywords Ancient ceramics · Archaeoceramic and archaeometry · Sampling criteria · Research questions · Design archaeometric research · Archaeometric methodology

Premise

This paper serves as an anchor to the Topical Collection (TC) "*Ceramics: Research questions and answers*" aimed at guiding researchers in the study of archaeological ceramics from excavation to study and preservation in museum collections.

Each contribution has a tutorial approach covering one of the main issues pertaining to the study of ceramics: research questions and sampling criteria (this paper); the chemical (Hein and Kilikoglou 2020) and mineralogical-petrographic

Topical Collection on *Ceramics: Research questions and answers*

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(Montana 2020) investigation of raw materials; the technological character and suitability of raw materials (Gualtieri 2020); the processing (Eramo 2020) and modelling (Thér 2020) of clays; surface finishing (Ionescu and Hoeck 2020) and ceramic firing (Gliozzo 2020); the investigation of different coatings such as black glass-ceramic (Aloupi-Siotis 2020), *terra sigillata* (Sciau et al. 2020) and glazes (Pradell and Molera 2020); the isotopic study of particular types of products such as Chinese high fired ceramics (Henderson et al. 2020); the identification of post-burial transformations (Maritan 2020); the dating of ceramics (Galli et al. 2020); and the restoration and musealisation of ceramics (de Lapérouse 2020). This Topical Collection concludes with a tutorial on statistical data processing (Papageorgiou 2020).

Ceramic as an indicator

Ceramics are ideally suited to identifying and understanding key turning points and continuing traits along the timeline of ancient civilizations. Ceramics have had a widespread distribution reaching every corner of the Ancient World while establishing an unbroken continuity of human existence from the end of the Late Pleistocene epoch (31.000–12.000 calibrated years before present) (Soffer et al. 1993; Nakamura et al. 2001; Boaretto et al. 2009; Farbstein et al. 2012; Wu et al. 2012; Craig et al. 2013) until today. Given their durable nature, ceramics are among the most abundant materials found in the excavations across both geography and time. Therefore, ceramics constitute a valuable historical indicator, providing key archaeological evidence for historical reconstructions given its technological and socio-economic character.

Ceramics as a technological indicator

Steven James wrote: “The manufacture of stone tools and the manipulation of fire are the most important extrasomatic milestones in our early evolutionary trajectory” (James 1989). I would argue that the invention of ceramics represents the next milestone along this trajectory. Ceramic production, in fact, marks a fundamental technological transition from the exploitation of fire for simple uses to its control and management for complex technological processes.

Between the Middle and the Late Pleistocene, i.e. between the discovery of fire likely by *Homo erectus* and the widespread use of ceramics by *Homo sapiens*, there was undoubtedly much experimentation in the productive use of fire. New—likely fortuitous—discoveries (to which the *Nehanderthalensis* also contributed) such as the practice of heating rocks and the production of red earth pigments must have contributed to developing knowledge, in both georesourcing raw materials and the productive manipulation of fire. Aimed at improving the knapping properties of rock, heat treatment marked a significant advance in the field of technological evolution more than 70,000 years ago[1] testifying to a rapid increase in the knowledge of material properties. Indeed, the production of red earth pigment from yellow earth deposits[2]—one of the first achievements in the creation of a truly artificial, inorganic product[3]—is indicative of the awareness that fire could be exploited to transform the physical and mineralogical properties of natural materials.

However, red earth production did not require any special control of the fire other than the exposure of the iron hydroxide to heat for a sufficient period of time. From the ~ 300 °C needed for the transformation (dehydroxylation) of goethite (α-FeOOH) into haematite (α-Fe_2O_3) (Gialanella et al. 2010; Jang et al. 2014), to the 400–550 °C firing temperature required by Mesopotamian pottery of the Uruk period (4th millennium BC; Sanjurjo-Sánchez et al. 2018), further advances were made in the ability to achieve higher temperatures and, especially, in the development of an effective production cycle. This production cycle included sourcing the required raw materials (water, fuel, clay and eventual additives), preparing paste,[4] modelling the pottery, piling dried objects in the open fire/bonfire and firing. This last step required achieving and maintaining a suitable temperature followed by an appropriate cooling procedure to avoid damage. The production of ceramics, therefore, represents the first technologically complex product of human experimentation with pyrotechnology.

From this moment onwards, potters have worked to refine this process and obtain more control over its phases. Experimentation with new types of firing-structures (e.g. bonfire, single chamber kiln, double chamber kiln, etc.) was accompanied by developments in form and decoration such as the application of functional coatings.

At the same time, artisans learned how to use and control fire more efficiently through trial and error: a fundamental expertise that laid the foundation for all subsequent technological advances, including those made in the field of glass and metal production.

[1] The earliest stone artefacts are dated to 3.3 million years ago (Harmand et al. 2015) while the earliest traces of heat treatments identified so far (Delagnes et al. 2019) date to South African Middle Stone Age (MSA) sequences from Pinnacle Point (Brown et al. 2009) and Blombos Cave (Mourre et al. 2010).

[2] It is not possible to propose a date for the beginning of this technology. Studies are still small in number and the distinction between primary and newly formed haematite (i.e. from goethite) is not straightforward. The oldest cave art found so far dates to “a minimum date of 40 ka” (Aubert et al. 2018) and the roasting of goethite would have started shortly after.

[3] In this sense, other processes involving natural organic materials like the production of birch bark tar (Schenck and Groom 2018) are excluded.

[4] The oldest pottery found to date (Wu et al. 2012) bears evident traces of tempering with crushed quartzite or feldspar.

If on that day, the firing technology had not already been developed by potters, it is probable that (artificial) glass would still be attached to the cauldrons[5] at the mouth of the Belus River and we would not enjoy passing on this nice little tale.

There is still much work to be done before arriving at a properly detailed reconstruction, in both diachronic and geographical terms, of the development of ceramic technology and use. However, the potential offered by the evidence that ceramics provide can only be fully exploited when all production-related aspects are taken into consideration. The technological background—so often addressed in the archaeometric literature—should not be reduced merely to a determination of the maximum firing temperatures (see Gliozzo 2020 in this TC). A truly systematic approach requires a detailed evaluation of the boundary conditions (e.g. raw material availability), a close investigation of the entire production cycle (i.e. paste preparation, modelling, firing and, eventually, surface decoration) and a social-cultural contextualization of both the production and the product (e.g. function/use relationship, dietary habits, religious destination, etc.).

Ceramics as a socio-economic indicator

Ceramics have a "representative character" as they mirror the needs, beliefs and tastes of ancient civilizations and are one of the most powerful socio-economic indicators at our disposal. Moreover, ceramics were used widely across the globe and throughout all historical periods, providing the most comprehensive and uninterrupted resource for comparative research.

For example, with ceramics it is possible to identify both daily-use objects, likely of moderate cost, and precious items, that were the prerogative of wealthy families only. Assessing of the social value of both categories of ceramics could be a suitable subject of a research project shedding light on how social dynamics may have shaped both rural and urban economies.

Taking a step forward, if the workshops can be geographically localised, it may also be possible to reconstruct commercial trading networks (e.g. determining issues such as short-range vs. long-range exchange, local consumption or export, etc.) and the type of route (terrestrial, riverine/lacustrine or marine) used for the transportation of goods (for further information on the network analysis and its archaeometric applications see Knappett 2013; Gliozzo et al. 2018, 2020). Furthermore, if the chronology can be securely determined, historical reconstructions can be made continuing along a timeline. To use an analogy from film, one can proceed from a single frame, well anchored to a precise historical moment and/or a geographical area, to a dynamic, bird's-eye view of the multitude of places and periods of human history. This is the ultimate goal which we strive to attain with the studies that each of us perform on individual contexts serving as a frame of this larger story.

Pottery form and decoration can also serve as socio-cultural indicators, offering valuable insight on the evolution of the aesthetic taste (or cultural traits) and the dietary habits. In some cases, it is also possible to retrieve information on the social status of the producers and on the social organization of the production. For instance, the epigraphy of the *instrumentum domesticum* (i.e. the onomastic and prosopographic study of the stamps impressed or engraved on bricks, *dolia*, tableware, etc.) is able to convey personal details and/or social *status* of the producers, as well as the working relationships among *domini*/*dominae* (owners), *officinatores* (managers/workers) and *servi* (workers) within a single ceramic workshop (*opus*/*figlina*).

Using modern terms, ceramics can provide valuable information for the reconstruction of the purchasing power of families, the bargaining power of the producers, the productive capacity of a workshop, commercial demand, fashion trends, consumption practices and the agricultural development. Ceramic containers are also one of the main tools we have for reconstructing the trade of perishable materials such as wine, oil and *garum*.

To be sure, this is an ambitious list that may not always be achievable with the material available at any one site but it is always worthwhile to be resourceful and ambitious when selecting research questions and to keep the "big picture" in mind.

Ceramic as a chronological indicator

The studies carried out on ceramic typology and technology offer a whole range of ceramic "guide fossils" for the identification of historically defined phases and periods. Decades of ceramic studies have provided the chronological grid on which the investigation of entire epochs has been based.

In this way, ceramics often serve as the main chronological indicator for the periodization of the stratigraphic sequence in the archaeological excavation: the most recent ceramic object found in a layer provides the *terminus post quem* for dating the layer. In the same way, dated ceramic types often provide the only means of dating metal and glass objects found in stratigraphic association and there are even cases in which ceramics can date a building with an accuracy of ± 1 year (Fig. 1).

However, the date on which a ceramic object becomes part of a layer does not necessarily coincide with the date on which it actually left the cultural cycle of use. Before it can be used as

[5] Pliny, Nat.Hist. 36, 65: "The story is, that a ship, laden with nitre, being moored upon this spot, the merchants, while preparing their repast upon the sea-shore, finding no stones at hand for supporting their cauldrons, employed for the purpose some lumps of nitre which they had taken from the vessel. Upon its being subjected to the action of the fire, in combination with the sand of the sea-shore, they beheld transparent streams flowing forth of a liquid hitherto unknown: this, it is said, was the origin of glass." (translation from http://www.perseus.tufts.edu/)

a chronological indicator, an assessment of its position (primary or secondary) and nature (residual or infiltrated) must be made.

Moreover, ceramic finds as well as kilns structures can provide samples for absolute dating (see Galli et al. 2020 in this TC).

Establishing research goals

As indicated in broad strokes above, ceramology is a vast and complex field of study, able to frame in a diachronic scenario all information deriving from the study of (a) a particular territory and its georesources, (b) the production technology, (c) the morphological-stylistic evolution of the pottery and (d) the socio-economic dynamics related to the exchange of goods.

Consequently, the questions that can be posed in the course of a ceramic study are manifold (see Fig. 2 for a brief list of the main ones) and conventional distinctions among questions of provenance, technology, chronology and conservation remain useful only for descriptive purposes, provided that further issues regarding the function, use, consumption, trade and several types of "whys" are added to the list.

Indeed, rather than focusing on the classification of questions and related skills, it is crucial to put the object at the centre of our investigations. The more points of view from which an object will be studied, the more information it can provide. It should never be forgotten that the object itself poses a myriad of questions which a single researcher (or research group) will not be able to address fully.

Thanks to the remarkable methodological advances made over the last three decades, we are now able to address both simple and complex questions in an effort to answer larger questions in human cultural history. The questions listed above (and individually discussed below) should be posed at the beginning of a research program so that methodologically accurate and historically contextualised answers are obtained. Provenance, technology, chronology, etc. are necessary steps along the way but the major question should be: Which big-picture idea comes from these details?

The investigation of a small repertoire of ceramics is worthwhile but its contribution to the field will be limited unless it is included within a broader research project. Similarly, the study of a single archaeological context provides a small body of information which often represents a working hypothesis rather than a real conclusion.

Conversely, a broader and farsighted goal, carried out under the umbrella of a multidisciplinary collaboration, will allow a project to overcome a narrow descriptive threshold and provide significant and robust reconstructions which will stand the test of time.

For example, from the study of a single collection of *amphorae* types found in a specific site *y* ➔ to the mapping of the production sites known for the same types ➔ to the reconstruction of trades routes and the exchange of these types within the Mediterranean basin ➔ to the reconstruction of the economy based on goods transported by those types ➔ and so on, our knowledge is progressively enriched by wider, more complex and ultimately more compelling objectives.

To support this effort, it would be preferable to end the practice of (a) sampling unselected contexts which have not been the subject of an appropriate archaeological study, (b) performing non-archaeometric research on archaeological finds and (c) publishing ceramic finds in off-topic journals.

Provenance I: where did the raw materials come from?

The question of provenance involves both the raw materials that were used for the production of ceramics and the ceramic artefacts found at the production and the distribution sites. In all cases, the goal is to proceed from the chemical and mineralogical-petrographic composition of a ceramic to levels of ever-increasing detail:

1) Identify the type of geological environment (i.e. sedimentary, volcanic, metamorphic) which may have represented the supply area.

Fig. 1 Exemplar of the 114 AD consular stamp of VOP • ET • HAST • COS [reading: *Vop*(*isco*) *et Hast*(*a*) *co*(*n*)*s*(*ulibus*)] impressed on a tile from Mezzomiglio (Chianciano Terme, Siena) and preserved at the Archaeological Museum of Chianciano Terme (*CIL* XI, 6689,2; Paolucci 1988, pp. 53–54; Romer 2006)

Fig. 2 A short list of possible questions that may arise when studying ceramics

These are some relevant questions:

- *Which kind of raw materials were used?*
- *Were the raw materials used as found or intentionally modified?*
- *Where raw materials were obtained?*
- *Was the supply area close to the production centre? Did the artisans have to travel far from the production site to find the required raw materials?*
- *Were potters knowledgeable enough to select the best raw materials available in their locality?*
- *Why were specific raw materials used?*
- *What was the relationship between the potters and their surrounding territory? Were the available georesources suitably exploited?*
- *How were the raw materials prepared?*
- *Was temper added? Why?*
- *What materials and proportions should be used when attempting to experimentally reproduce a specific ceramic body type?*
- *Was a wheel used? If yes, was it slow or fast?*
- *Were surfaces polished? Why?*
- *What type of atmosphere was obtained during firing? Was this intentional?*
- *Where the potters capable of reaching and maintaining a suitable temperature during firing?*
- *Were surfaces coated and/or decorated? How? Why?*
- *Was the ceramic body prepared for a surface coating or left rough?*
- *Which raw materials were used for the surface finish? Where they available onsite or imported?*
- *Were the surface coating materials the object of a dedicated trade or were they imported along with other goods?*
- *How was the coating layer applied?*
- *Did the coating technique require a specific firing temperature and/or atmosphere?*
- *How many firing cycles were carried out?*
- *Where did a specific technique develop and how far it spread?*
- *Is it possible to reconstruct the social organization of a ceramic production?*
- *What was the finished object used for?*
- *Is there a correlation between shape, composition and function?*
- *Was the finished object suitable for the function for which it was intended?*
- *Was the object destined for local use or export or both? Why?*
- *Where the ceramics distributed outside of the production locale? Why?*
- *How did ceramics travel?*
- *Is it possible to observe compositional variations within the period that a ceramic type was produced?*
- *Was the pottery type successful commercially?*
- *Which dietary habits or other daily practices can be deduced from the ceramic evidence?*
- *How long was a specific type produced? What were the reasons for its development and abandonment?*
- *Was a ceramic type utilized by poor or wealthy families or both?*
- *Was there any relationship between the degree of production complexity and the status of the consumers?*

2) Determine the geological Formation and Unit bearing the most similar characteristics.

3a) Find the narrowest possible raw material supply basin, when dealing with raw materials (see Hein and Kilikoglou 2020 and Montana 2020, both in this issue), or

3b) The narrowest possible production area, when dealing with the provenance of a workshop (see below).

In general, the smaller the geographic area individuated by the provenance research, the greater will be the effectiveness and usefulness of the obtained results.

Figure 3 illustrates a progression of research goals based on a geographic scale. From the least specific level, reflecting merely the identification of the general geological environment (i.e. sedimentary, volcanic and metamorphic environment), to the most specific level, leading to the identification of the actual quarry, some intermediate levels have been indicated and can be used as a reference:

– The "areal scale" covers a wide cultural/geographic and geological territory (e.g. the extension of a Supergroup) and delimits clearly defined areas on a 1:100.000.000 scale map.
– The "regional scale" may correspond to the extension of a geological Group or of other type of administrative boundary (e.g. a Region) which can be clearly delimited on a 1:10.000.000 scale map.
– The "district scale" should not exceed the extension of a geological formation (i.e. a few kilometres), delimiting thus well-defined areas on a 1:1.000.000 scale map.
– The "local scale" defines the boundaries of a particularly defined site and its extent should be clearly delimited on a 1:100.000 scale map.

While this represents only one of the possible scale progressions—local, area, region, etc. can be associated to very different geographic extensions—it is always correct to refer provenance results to a geographically or social verifiable scale. Methods of identifying and locating the supply basins of raw materials are described in this TC by Hein and

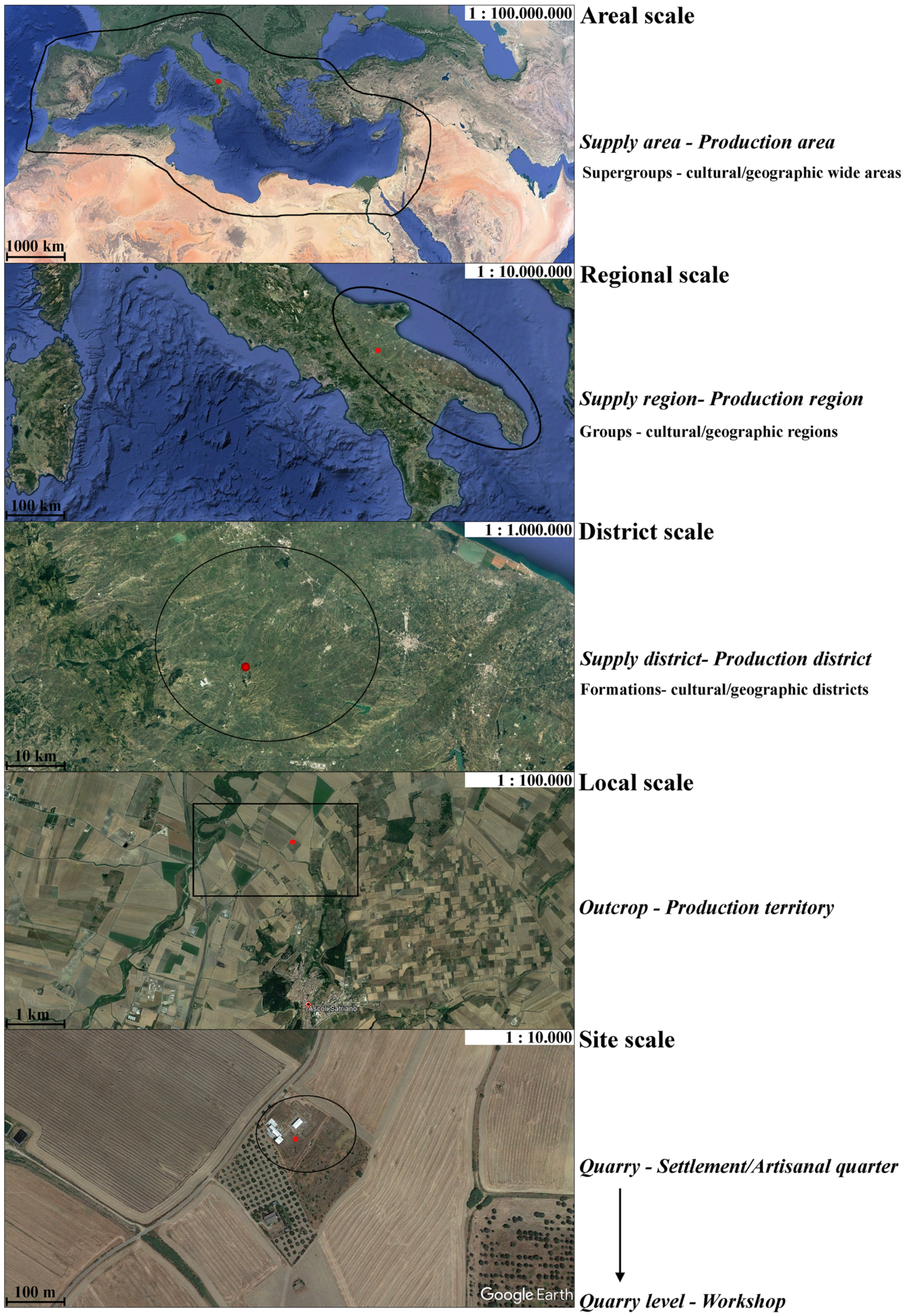

Fig. 3 A geographic scale to describe the level of detail achieved by the research

Kilikoglou (2020) and by Montana (2020) from the chemical and mineralogical-petrographic perspective, respectively.

Technology: how was it made?

The overall objective of technological investigation is to reconstruct the entire production cycle, from the manipulation of the raw materials to the finishing of the object. In other words, it involves reconstructing everything that happens inside a ceramic workshop where raw materials come in to be worked and products go out to be used. At the same time, this investigation does not refer exclusively to the finished product but extends to tools and infrastructures associated with production.

Technological questions start with the processing of raw clay. In practice, the clayey raw materials may have been used as found (i.e. without being processed), or may have been subjected to granulometric separation by decantation. A suitable temper may have been added and/or clays of different compositions may have been mixed together or with other materials such as sands or organic matter, in order to obtain a desired plasticity, shrinkage characteristics and resistance to thermal stress (see Eramo 2020 in this TC).

The next step to be investigated in this process involves the modelling of the paste. It is important to determine whether the "colombino" or slow wheel was employed or if a fast wheel was used and to identify related surface features (see Thér 2020 and Ionescu and Hoeck 2020, both in this TC).

Next, ceramic firing issues must be addressed. Was the firing effective? Was the atmosphere and the temperature reached inside the firing structure suitable with respect to the final product? How many firing cycles were performed? etc. (see Gliozzo 2020 in this TC).

Additional issues regarding clay types and decoration must also be addressed. For example, the technology of porcelain production differs considerably from that of earthenware (see Henderson et al. 2020, in this TC). Moreover, if the ceramic was covered with a slip or glaze, a whole series of questions regarding composition, material sourcing and related production steps warrant investigation. Adequate understanding of technologies used for the so-called black gloss (Aloupi-Siotis 2020 in this TC), *terra sigillata* (Sciau et al. 2020 in this TC) as well as for different types of glaze (Pradell and Molera 2020 in this TC) requires specific background knowledge and analytical strategies.

Function: how have ceramics been used? Were they fit for purpose intended?

Sometimes considered as a technological sub-issue, the function and functionality of ceramics are in fact so complex and important that it is appropriate to deal with them as self-standing topics.

While studies focusing on the relationship between shape, composition and function are few, they represent a harbinger of important developments. Ceramics have fulfilled very varied functions over time. From the light-ware for the table, the pantry, the lighting equipment (e.g. *lucernae*), the workshop (e.g. loom weights and stamps) and the temple (e.g. cultic implements such as votive offerings), to the heavy-ware for the kitchen (e.g. braziers, *clibani*), the warehouse (e.g. *dolia*), the commercial trades (e.g. *amphorae*), the *cantiere* (e.g. bricks and tiles) and the life after death (e.g. funeral urns), ceramic products have covered a diverse range of uses since prehistoric times and have only recently been partially superseded by plastics and modern technical glass.

Production cycles have been modified from time to time and adapted to fulfil the many social, technical and economic requirements of ancient (and modern) societies. Types, shapes and technical features have changed in step with the evolution of the dietary habits (see, e.g. Arthur 2007b), which in turn may be dependent on socio-economic factors triggered by variables such as climate change (Arthur 2010). For example, amphora shapes and sizes were modified in ancient times to adapt to the changes introduced in the market and network of trade routes (see, e.g. Arthur 2007a; Zanini 2010). In addition, the dimensions of the bricks changed over time, depending on the evolution of building techniques (see, e.g. mensiochronology analyses in Cantini et al. 2019; Mannoni and Milanese 1988; Pittaluga 2009).

It becomes clear, from the examples illustrated above, that this question can be divided into two levels of inquiry. The first level concerns the intended use of the ceramic: "what use has been made of it?" or "what purpose did it serve?". These questions involve reconstructing a posteriori what use was made of a specific object once it was in the hands of the user (function question). For example, an open-shaped vessel may have been used to prepare food or to serve them on the table; or a large basin may have been polyfunctional, ranging from garment washing to the storage of perishable materials. As a further example, when the content of an amphora cannot be deduced (e.g. oil, wine or *garum*), research offers the possibility of identifying contents by analysing extant traces (Dunne et al. 2016, 2019; Oliveira et al. 2019; Robson et al. 2019; Tarifa-Mateo et al. 2019). Evidence of use also aids in the functional assessment of ceramics within a socio-cultural context (see, e.g. Spataro et al. 2019).

The second level of inquiry concerns the suitability of a specific raw material or ceramic for the intended use (functionality). In this case, the questions are closely related to the suitability and preparation of raw materials. For example, has a pot intended for cooking food been adequately tempered with materials increasing its fire resistance? Were clay selection, preparation and firing suitable for minimizing the effects of meteoric alteration on the investigated tile? Was the ceramic suitable for the function it was to perform? Archaeometric research can provide answers to all these questions (see Gualtieri 2020 in this TC).

Provenance II: where does it come from?

The question of provenance concerns both raw materials (discussed above) and finished products. The initial inquiry: "Where does it come from?" can lead to complex and intriguing additional questions and scenarios. Since ceramic artefacts can be found at variable distances from the place where they were produced, provenance may be posed in terms of:

– Consumption modalities (i.e. were they produced to be locally used or to be traded on the market?)

- Taste (e.g. why one type continued for a long period of time while another had limited success both chronologically and geographically?)
- Networks (e.g. were they transported by land, by river or sea?)
- Cultural transfer (e.g. were finished ceramics imported or were foreign workers capable of performing specific techniques brought in?)
- Exchanges (e.g. what was the distribution area of a specific type?)

When the starting and end points of the journey made by an artefact are known, truly interesting multi-scale reconstructions of ancient economies can be made. These reconstructions may concern a single family unit, an entire village or a region or even geographically vast cultural areas such as the whole Mediterranean basin. For this reason, the geographic (or social) scale of the results provided must be indicated, as well as those pertaining to the raw materials (n.b. the scales provided in Fig. 3 can be used for this purpose).

In this respect, an accurate and complete definition of the ceramic type will be crucial. In order to identify a type produced in the kiln *x* at the distribution site *y*, the morphological-stylistic characteristics will not be sufficient as it is also necessary to know, in detail, the chemical and mineralogical-petrographic composition of the specimens found at kiln *x*, as well as that of the specimens found at a site *y*. This aspect deserves an in-depth discussion because it is closely correlated with the issues concerning (a) the creation of the so-called "reference groups", (b) the research "priority" given to different kinds of archaeological contexts and (c) the definition of ceramic types.

The creation of the so-called reference groups

Many scholars have focused their attention on how to group ceramics analyses for provenance issues (see Weigand et al. 1977 for the "provenance postulate"[6]; Fillières et al. 1983; Arnold et al. 1991; Day et al. 1999; Buxedai Garrigós et al. 2001; Fantuzzi and Cau Ontiveros 2019; Mommsen 2011 for compositional group making and use), since it is clear that raw material compositions cannot be placed *tout court* in direct correlation with those of the finished products due to the "human factor" (see, e.g. Fowler et al. 2019). Clay can be used as found, granulometrically separated, or modified by mixing in tempers or clays of different compositions. Water can be added in varying proportions, affecting both drying and firing. Firing itself introduces physical, chemical and mineralogical-petrographic transformations (see Gliozzo 2020 in this TC).

[6] "(…) there exist differences in chemical composition between different natural sources that exceed, in some recognizable way, the differences observed within a given source".

After firing, the ceramic is used and eventually buried. Consequently, the finished product may be *comparable* to the raw material from which it was produced but never compositionally identical.

In these terms, the provenance issue may appear too complex or even unsolvable, but there are two basic conditions which can guarantee either the possibility of creating *exploitable reference groups* or obtaining provenance results with the highest degree of *likelihood*: (1) a systematic definition of the ceramic types to be submitted to investigation and (2) an equally systematic characterisation of the ceramic composition.

The past years have seen a heated debate regarding whether chemical or mineralogical-petrographic analyses are better suited in archaeometric research (see, e.g. Stoltman et al. 2005; Stoltman 2006; Neff 2012). Today it is recognized that a systematic characterisation of a ceramic object mandatorily requires the use of both methods (see also Maritan 2019 for the latest advancements). Hence, it is now possible to make a list of three criteria for creating a solid "reference group":

1. The reference group must be firmly anchored to a specific geographical location.

At best, this space will be represented by a kiln *x* but it can also be extended to the size of a settlement (i.e. "local scale") when other evidence testifies to a local ceramic production. For instance, they may be cases in which archaeologists may have not yet identified/excavated the artisanal quarter of a settlement or where the workshops no longer exist because of subsequent development.

2. The reference group must be firmly anchored to a ceramic typology that has been accurately defined in terms of morphology, style and composition.

To give an example, let us assume that the kiln *x* produced multiple types, using different raw materials and different technological expedients. Characterising the production of polyfunctional kiln *x* will thus result in the creation of multiple production groups, distinguishable on the basis of the two main variables: morphology/style and composition. When all types are characterised, it will be possible to define the entire production of the kiln *x* while the inverse procedure—i.e. from a set of samples randomly taken on the site to the single type—will not be equally possible. Consequently, establishing reasonable and effective criteria for the selection of the samples is crucial.

3. The reference group must be firmly anchored to a securely dated and narrowly defined chronological period.

To give an example, let us assume that the kiln *x* is located in a craft district, whose activity lasted for a few centuries during which several different ceramic types were developed. In such cases, defining a production group based on a morphological-stylistic type may not be sufficient because the general type itself may have been continuously produced over the centuries while the craftsmen inevitably alternated, each imparting their own skills and preferences. In a less likely but still conceivable scenario, the source of the raw materials may have been exhausted or may have become unavailable. In other words, the possibility that the same type of ceramic produced in the area of kiln *x* shows different compositions over time must be taken into account.

A *production group*, therefore, can serve as the best reference for a provenance investigation if it is geographically, technologically and chronologically well anchored. To expand on this point, consider the case of a ceramic collection *z* taken from a distribution context *y*. If suitable production groups have already been published in the literature, the provenance investigation of collection *z* will undoubtedly be favoured. The collection should first be typologically investigated (including both morphology and composition). Then its composition should then be compared against the composition of known production groups and, finally, it should be "assigned" to specific production/supply areas, regions, districts or, at least, to specific sites. The accuracy of this last step will depend on both the composition of the investigated ceramics and the accuracy with which the raw materials and the production groups have been characterised within the boundaries of a given territory.

When no suitable production groups can be found in the literature for comparison, the provenance investigation will certainly be longer and more complicated. Furthermore, it is very likely that it will not lead to detailed conclusions but may provide geographically wide new information. In the absence of established production groups and/or known (or even merely hypothetical) production sites, collection *z* will not constitute a production group given that the geographical area of reference would be too wide. Instead, it may be regarded as a *distribution/consumption group*. Such groups are only vaguely anchored to a wide area and, consequently, should be viewed as a set of orphan materials whose provenance is not yet known. This does not mean that distribution groups are not potentially interesting as they can convey useful information and provide meaningful answers to specific questions, especially those related to production diversity. However, a distinction must be made between "true" production groups, which are unquestionably anchored to a clearly delimited provenance site, and distribution/consumption groups, which can be typologically or chronologically framed but lack a precise geographical point of origin. In this sense, the terms "distribution" and "consumption" serve to describe this uncertainty rather than to qualify the production itself. Undoubtedly, this distinction is valid not only for ceramics but also for other materials such as glass, whose reference groups have become all too "liquid" in recent years.

Research "priority" should be given to different kind of contexts

Based on the discussion above, it is clear that, from the perspective of archaeometric analysis, the study of a production contexts—preferably including not only the kiln *x* but also its wasters and finished products—is highly valuable and should be a research priority, because its characterisation will support the provenance investigations carried out at distribution sites *y*. However, it is worth clarifying that this "priority" does not derive from a qualitative assessment of the relative importance of each context—assuming that it would be possible to draw up a ranking of this kind—but instead derives from the operational strategy in Archaeometry, whose basic criterion is *compositional comparison*. Both types of context are undeniably worth investigating but the overall quality and level of detail of our reconstructions will mostly depend on having a strong "anchor".

Chronology: how long ago?

As noted above, absolute dating is crucial factor in the detailed periodization of a stratigraphic relative sequence as the dating of a single feature can be functional to the division and vertical allocation of phases and periods within a matrix.

Absolute dating can be obtained for ceramic objects (see, e.g. some case studies as those provided by Gliozzo et al. 2009; Galli et al. 2014; Panzeri et al. 2019; and especially Galli et al. 2020 in this TC), for the last fire in prehistoric hearths (see, e.g. Sun et al. 2018) and for production workshops (see, e.g. a case study such as that provided by Valladas 1977; Liritzis and Thomas 1980; Tema et al. 2015; Aidona et al. 2018).

In the first case, the dating of individual objects is carried out not only to date an archaeological find but also for the identification of forgeries. In this regard, thermoluminescence (TL) dating can provide an accurate date for ceramic objects ($\pm$ 5–10% of the age, or even $\pm$ 4% in special cases) that is beyond the limits imposed by radiocarbon dating (see Galli et al. 2020). In the second case, encouraging preliminary results have been achieved using optically stimulated luminescence (OSL). Finally, the date of the last activity of a kiln, as well as any conflagration that may have occurred at an ancient site can be obtained by archaeomagnetism and TL. These two techniques have been applied in tandem to the chronological investigation of kilns and fires, minimizing the practical limits imposed by the analytical techniques themselves (i.e. the availability of appropriate material, the character and eventual alteration of the samples, chronological boundaries, etc.).

Post-depositional transformations: what happens after abandonment?

A ceramic artefact may represent an indicator or an object of beauty at the same time. Regardless of its aesthetic qualities, it should be considered as a valuable survivor from the past and worthy of being handed down to posterity. In order to achieve this goal, its life should be reconstructed in its entirety, from the day it was produced to the day it entered a collection. In this regard, post-depositional phenomena are of key importance in understanding the physical, chemical and mineralogical transformations that a ceramic object may undergo in different burial conditions (see, e.g. Buxeda i Garrigós 1999; Maritan and Mazzoli 2004; Schwedt et al. 2006; Maritan et al. 2018; Owen et al. 2019). On the one hand, correct evaluation of post-depositional alterations is crucial when planning conservation interventions (especially when alteration corresponds to degradation). At the same time, these alterations may distort data interpretation for technological and provenance investigations as well as dating (Zacharias et al. 2007). Other types of condition-related errors are discussed by Maritan (2020) in this TC.

Conservation: developing preservation strategies

The investigation of alteration and degradation processes seen in ceramic artefacts or building materials such as bricks or tiles may help in the development of preservation products (e.g. binders, consolidants, biocides, etc.) and treatments used by restores and conservators. Archaeometric methods, therefore, can provide a valuable aid to preservation of our shared cultural heritage (de Lapérouse 2020 in this TC). In fact, in order to be successful, preservation must be a multidisciplinary effort joining the expertise of conservators and restorers with the insight provided by archaeologists, physicists, chemists, mineralogists and petrographers.

The "whys" of ceramics research

The simplicity of the schematization proposed here should be seen as a trunk from which a series of correlated questions and consequent investigations branch out. The time is ripe, in fact, to move past the level of simple questions and to allow the discipline to advance towards reconstructions of higher quality, consistency and durability:

– *Quality*, due to analytical advances that have increased the number and types of questions we can address
– *Consistency*, due to more comprehensive multidisciplinary integration
– *Durability*, due to a methodologically correct interpretation of all previous and present data[7]

At this point in archaeometric research, we need to ask ourselves: do we really want to stop at the characterisation of the materials, or we want to proceed further, reconstructing the cultural dimension evidenced by these materials? To answer this important question, I rely on the words of Manacorda (2009):

"The infinite series of artefacts (...) incorporate wo/man's fatigue, but also her/his knowledge, her/his behaviours, the cultural values shared by entire societies or by social groups. Paying attention to the phenomena that are repeated more than to unrepeatable event, to the analogy rather than the anomaly, to the 'background' rather than emergencies, the history of material culture traces back women and men life and their social relationships. *We study things*, *but to understand the material and spiritual aspects of the world that produces them*. It is quite clear that the artistic quality given to the matter through a shape and a style allows to the expression of messages that go far beyond the material dimension."[8]

Why was one type of raw material chosen instead of another? Why was a production centre set on this site instead of elsewhere? Why did producers focus on certain ceramic types instead of others? Why was a more complex production cycle used instead of a simpler one? The next frontier of the archaeometric should be represented by these intriguing questions ("Why...?") because these are the types of questions that will allow us to see the big picture lying within sets of data.

In order to address these questions, however, the framework of a research project should be carefully constructed and the barriers between disciplines should be definitively overcome.

Labelling questions: an operative, non-conceptual distinction

In all of the disciplines relevant to the study of ceramics, it is unlikely that a single researcher will have all of the necessary skills to solve all types of questions. The obvious consequence of this fact has been a division of the academic *curricula* into fields that cover the necessary operative tasks.

Taking up the concept expressed at the beginning of this section, however, if we put the object back at the centre of the investigation, the questions listed in the preceding paragraph would not be divided between categories such as "scientific", "archaeological" or "archaeometric". Instead, the methodologically logical and correct approach would be multidisciplinary. It is not always obvious, however, that good theories translate into equally effective operational strategies, especially when innovative and multidisciplinary approaches are concerned.

[7] In this respect, the value of a comprehensive bibliographic search, able to frame and support the new discoveries must be stressed although it does not seem any more "fashionable".

[8] The original text has been translated from Italian with the approval of the Author.

One must make sure that the operational division of tasks does not turn into a justification for the continuation of anachronistic distinctions (e.g. Archaeometry and Archaeological Sciences); the rise of unsound questions (like some on firing; Gliozzo 2020 in this TC) or the illogical sorting of funds that is sometimes more focused on sectors and politics rather than on research questions and the expertise involved.

It is helpful to start with the practical aspects of an investigation, see how the questions translate into research questions and then plan an operative strategy that leads to answers. Undoubtedly, research questions pertaining to the identification of ceramic classes and types will be viewed as being within the purview of archaeological expertise while those regarding the materials used, evidence of original contents and issues of absolute dating will be assigned to those with scientific competence.

This differentiation is basically valid as no one person can be an expert in all of these fields, but it is instructive to see what happens if those of different skillsets work separately or collaborate.

Case A If the research is conducted only with an "archaeological approach", the archaeologist will lose:

a) An accurate compositional characterisation of the ceramic bodies which is necessary in order to identify examples of the same production at distribution sites.
b) A careful reconstruction of the technological cycle adopted by the ancient ceramists, beginning from the supply of raw materials to the application of slips and glazes as well as information regarding the relationship between wo/men, the environment and georesources.
c) The possibility to determine correctly the use of the investigated ceramics (for example through the analysis of organic residues) and their chronology (especially for productions with a wide period of use).

Case S If the research is conducted only with a "scientific approach", the scientist will lose:

a) The possibility of having a representative set of samples, the first requirement for any meaningful study, which s/he does not have the expertise to select.
b) The possibility of formulating relevant and insightful questions on the context under examination; i.e. those questions that go beyond those of technology, provenance, classification.
c) The possibility of integrating the collected data in support of robust and wide-ranging reconstructive hypotheses.

While these examples may be oversimplified, they represent a path that remains all too frequent today.[9]

The results of such approaches can lead to poor outcomes:

Case A Instead of collaborating with a scientist in the research, the archaeologist thinks that s/he can simply get missing data for a fee. This course of action ignores the fact that the scientific *datum* does not consist of information reflecting absolute truths on its own but of information that must be interpreted and used to identify likely and unlikely hypotheses. This interpretation goes beyond the terms of a mere "lab service". In this regard, the appendices with lists of data at the end of many archaeological publications are almost useless when they do not "communicate" with the preceding text.

Case S The scientist, after analysing ceramics (or other archaeological materials) for some time, believes s/he can conduct research without the archaeologist. The resulting papers maybe technically unobjectionable but are (a) useless when focusing on a poorly selected collection (e.g. samples randomly taken just because available); (b) lacking a valid research focus; (c) dangerous, when divulgating an approach which is not to emulated; or (d) incomplete like a film without a conclusion, with the results presented without a historically-accurate framework.

It should be recognized that Archaeometry is both a method and a team game. As inherent in its very name, an "archaeometric" question is both scientific and archaeological at the same time: scientific in terms of the methods applied which are constantly being evaluated and improved (by both hard scientists and archaeologists) and archaeological in terms of being able to place the material evidence within an

[9] This is a diehard phenomenon which can be the result of a poor professional advancement (e.g. those who still cling to the anachronistic Italian concept of "subsidiary sciences") and/or is maintained by those who insist on maintaining a hide-bound hierarchy of importance and intellectual superiority between disciplines and those who practice them. Unfortunately, staking out one's territory in a multidisciplinary field represents an inauspicious and methodologically incorrect course of action because it shifts the research focus from relevant questions/objectives—i.e. those that are able to really advance the state of knowledge—to those that merely reflect a single individual's skills. In this regard, the opinions expressed by Volpe (2014) and Manacorda (2014) on professional specialization are particularly relevant: "The main risk consists (...) in confusing specialisation and totality, if a specialisation ends up considering itself not as part of a more complex ensemble, but itself as a whole, attributing itself a license of totality. In this way, what is a necessary condition for the advancement of knowledge turns into an obstacle, condemning the specialist to isolation and self-reference. Such a reductionist attitude is, in fact, unable to reach an understanding of complex objects and phenomena." (Volpe 2014); "The ability to have an organic view of the Heritage, beyond the fences of the specialised partitions, is not a widespread quality in the individuals who (...) are conveniently oriented to plough the fields of the different specialisations (...) The multidisciplinary teams are those who should give form and substance to research and institutions, making vain the discussion on who should see at the top because it is teamwork that allows researchers to grasp all sides of the whole polyhedron, taking advantage of multiple knowledge and mixing different projectualities." (Manacorda 2014) (translations approved by the authors).

historical perspective. Archaeometry should then represent the privileged meeting place to reach those detailed and global reconstructions that I've called here "big picture".

In conclusion, the best operative strategy is that in which all of the different areas of expertise participate in both the formulation and the solution of research questions. This multidisciplinary collaboration should be explicitly recognized at the beginning of a project and not created ad hoc. It is particularly important that students entering the field recognize that this is not only the methodologically correct approach, but also is the most rewarding as it will result in truly meaningful contributions to our understanding and preservation of cultural heritage.

What are the characteristics of an appropriate sampling strategy?

Sampling can refer to the act of selecting a context (e.g. within specific archaeological area) or a group of objects (e.g. a ceramic collection), as well as the act of taking a portion from the object under examination. In the preceding paragraphs, I have already discussed which contexts deserve a particular attention. Now I will focus on how to choose a repertoire of materials to be investigated archaeometrically.

Requirements, characteristics and variables for sampling

An operational sketch illustrating the main steps and requirements of appropriate sampling is provided in Fig. 4. Three conditions must be met before any sampling is undertaken:

1. Completion of the archaeological study of the territory (e.g. in case of archaeological surveys) and/or the archaeological site (e.g. in case of excavation; including the periodization of the stratigraphic matrix) and, especially, the completion of the morphological-stylistic analysis of the ceramic collection
2. Formulation of the archaeometric research questions
3. Determination of the experimental procedure

These three preliminary steps provide the necessary groundwork for effective sampling and help to ensure the appropriateness of the sampling criteria—representative, functional and suitable—and eventually the quality of the entire project.

The first requirement is that the sample collection is *representative* of the entire repertoire, given the fundamental variable of typology and stratigraphy which are both linked to chronology. A single type should be analysed for both its typological definition—in order to pass from M-typology to MM-typology (see below)—and the contribution it can offer to solving the research questions being posed.

Each individual type should be sampled using examples from different stratigraphic phases and periods in order to verify possible compositional differences which may lead to the definition of sub-types and variants. In an excavation, stratigraphic variables should be used to provide a chronological serialization of the samples, whereas in the case of an archaeological survey, chronological variables should be used independently. All variables should be used jointly; however, when context information is missing (e.g. materials purchased by museums in the past or illegally excavated whose place of discovery is unknown), it may be possible to rely on typology. At the same time, a study of the finds by a conservator may help to identify condition issues that may have an impact on sampling as well as eventual preservation and treatment strategies.

The second requirement will ensure the *functionality* of the sampling strategy with respect to the overall research objectives. For example, a research question regarding the characterisation of the production group of "kiln *x*" will require a collection of samples representative of both the production (using the three variables listed above) and the raw materials available nearby; the latter taken in an amount sufficient to allow both their analysis and the preparation of the experimental tests (following the criteria explained in Hein and Kilikoglou 2020 and Montana 2020, both in this TC). Conversely, a research question regarding the technological investigation of a slipped and/or glazed pottery found at distribution site *y* will require a collection representative of slipped and/or glazed types only. In this latter case, the need for further sampling (e.g. of raw materials or comparative pottery) is decided on the basis of the preliminary characterisation and is, therefore, not predictable from the beginning. It is worth adding that sampling should always remain elastic enough to allow for the expansion of research if new questions arise in the process of the analysis. With research questions related to conservation and chronology, sampling may be restricted to examples exhibiting a particular state of preservation or those types that have not yet been securely dated.

Selected research questions will exert a primary influence on the collection of samples but it should keep in mind that (a) information deriving from the investigation carried out on a single sample (e.g. bulk chemistry, optical microscopy, etc.) can be exploited for the resolution of multiple questions; (b) sampling is often a destructive operation and should only be undertaken once, when the objectives of the sampling are clearly understood.

This point leads to the third and last requirement that *suitability* between the types of samples taken and the analytical techniques used is observed. These techniques may be non-destructive, micro-destructive or destructive.

When dealing with particularly precious objects and/or *unica*, analysis is usually restricted to non-destructive techniques. When dealing with ceramic types that have found in abundance, however, destructive techniques are to be

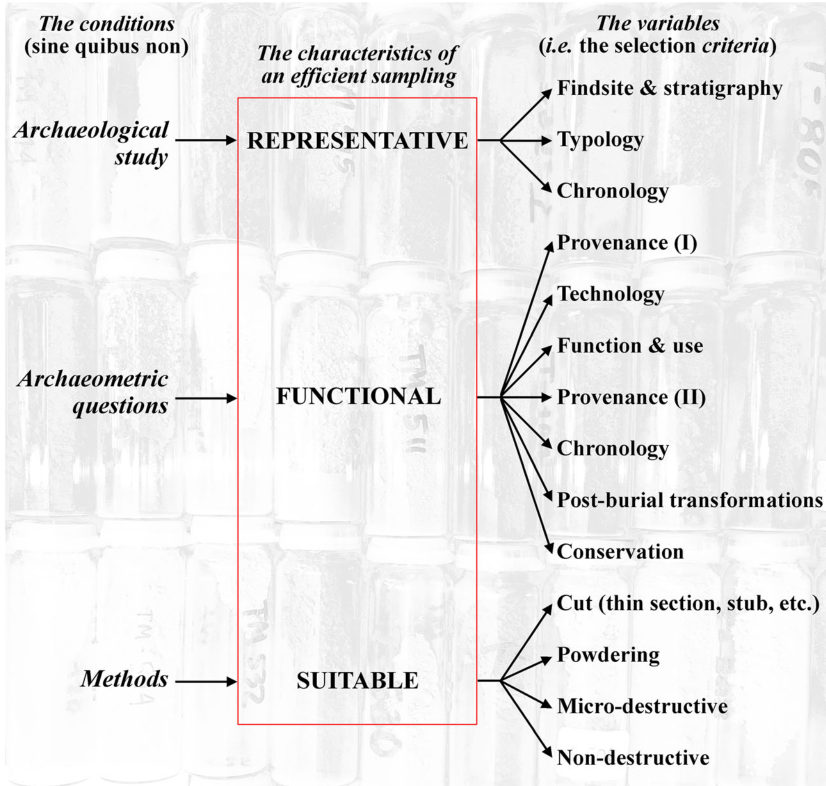

Fig. 4 Research steps and selection criteria for a proficient sampling

preferred as they usually guarantee a higher level of accuracy. In practice, archaeologists (or curators), conservators and scientist should work together to come up with sampling strategies that balance preservation with the value of the results provided by archaeometric investigations.

Some techniques require a representative piece of sample obtained by cutting (e.g. thin sections), while others require pulverized or drilled samples. For some techniques, a few milligrams are enough (e.g. ICP-MS and TL), while for others, a few grams are needed (i.e. XRF). For some techniques, the sample is not destroyed but remains radioactive for a certain period (e.g. INAA). For others, the sample is destroyed and can no longer be reused for other measurements (e.g. XRF pearls). All these parameters must be known when a material sample is taken to ensure that it is of the correct type and quantity.

Lastly, the availability of analytical techniques and related expertise should not guide the research. For example, it is not acceptable for a research team to omit clay analyses because suitable instruments for a bulk chemical analysis are not at hand. Similarly, it is not acceptable to take destructive samples simply because a specific laboratory is not equipped with non-destructive analytical techniques or to omit the application of a relevant technique because the team does not have someone with the right skills to interpret the resulting data. The choice of analytical techniques is fundamental to the resolution of archaeometric questions and not vice versa.

In conclusion, satisfying the three conditions examined above leads to (a) appropriate selection criteria, (b) a selection of samples that are quantitatively and qualitatively both functional and suitable and (c) a good foundation on which the research team can construct a project leading to significant and important results. Conversely, when find-site and/or chronological and/or typological information are not available, such ambitious goals are not possible and work should be limited to diagnostic observations and preservation. These criteria apply not only to ceramics but also to other archaeological materials such as glass and metals in which a series of non-localized, undated and non-typologically defined contexts are all too frequently investigated.

How many samples?

This is a seemingly simple question to which it is all too often impossible to provide an answer until sampling has actually ended. A reasonable estimate, nevertheless, can be obtained given knowledge of the starting context and the research priorities that have been chosen.

For example, if the creation of a production group is the main objective of the research and the production, deemed to be local, is testified by only two types, then overall sampling cannot be limited to taking two samples (one per each type) because the compositional analyses will not reach a statistically acceptable degree of representation. In these cases, typology and stratigraphy will allow for the selection of additional samples of the same type (e.g. subtypes in different stratigraphic units).

If research is aimed at assessing the extent and quality of site *y* imports, then sampling should include all of the likely imported types that have been identified, along the examples from the chronological phases of their site-life. In such cases, research organised according to type by type progressive steps may lead to a more concrete results than opting for sampling heterogeneity ab initio. The latter option, in fact, may only provide a vague reconstruction which can be difficult to exploit.

The same considerations can be applied to all types of research questions. In general, selection criteria will provide guidance on the numbers of the samples that need to be taken while determining a priori an arbitrary number of samples is an incorrect procedure. Statistical considerations can then verify if sampling was effective in terms of compositional analyses (Papageorgiou 2020, in this TC).

Ceramic classes need a separate consideration. Heavy ceramics or coarseware can, in fact, show a compositional heterogeneity that is higher than that of fine tableware and more dependent on the area where it has been sampled. Consequently, the degree of representativeness of a single sample may be low for the former class of ceramic while acceptable for the latter.

Typology on the move: towards a revived concept of ceramic classification

The concept of an archaeological typology that integrates archaeological data with archaeometrical data is not at all innovative, even if it still remains an elusive goal. The first time I heard a description of this method was in 1996 when Ninina Cuomo di Caprio proposed the use of a series of descriptive parameters, both macroscopic and microscopic, for the study of "black-glazed" ceramics (Cuomo di Caprio 1998). Today, almost 25 years later, we find that we must still advocate that two sets of complementary information are better than one. Hence, this section has the same objectives as those of Cuomo di Caprio, reiterating what constitutes the indispensable and desirable characteristics of a secure ceramic typology.

Let us start with observing what is meant by archaeological typology. First of all, a typology is a classification aimed at identifying homogeneous groupings based on pre-established criteria. These groupings will include a variable number of specimens, all with attributes that are characteristic of a prototype. Operating methods and criteria can vary, so much so that there is no universally accepted model.

Nevertheless, the definition of a type can be based on three criteria:

1. The shape and function of the object (e.g. plate, cup, jug, amphora etc.)
2. Characteristic measurements such as the relationship between maximum height and width, capacity, length, height, depth, etc. or mathematical systems such as the *curve-fitting* (e.g. two curve method; Hagstrum and Hildebrand 1990), the *envelope method* (Orton 1987), the *slice method* and the *mosaic method* (Wilcock and Shennan 1975)
3. The stage of the production process (Schuring 1984)

The first criterion is undoubtedly the most commonly invoked even though the descriptive parameters proper to each of the three proposed criteria are present in all identified typologies. In other words, whatever the starting criterion, information regarding the form, the function, the production process phase as well as the dimensional characterisation should always be present when creating a typological grouping. In this regard, the utility of the computational approach is unquestionable while the adoption of predetermined categories is still matter of debate, especially when compared to quantification methods.

While the macroscopic characterisation of the ceramic bodies has always been considered to be important ("something to do" but not necessarily), the criteria to be followed have not been rigidly set by a universal protocol and have instead varied "from school to school". Ninina Cuomo di Caprio proposed her own scheme in 1996. The FACEM (Fabrics of the Central Mediterranean) project and the PCRG (Prehistoric Ceramics Research Group) further contributed to fabrics characterisation[10] as well as other scholars such as Moody et al. (2003) and Whitbread (2016). In the papers cited above, the features that can be described are quite numerous. Some do not require special knowledge to be described while others involve specific skills and can take a long time to acquire and put into practice.

Personally, I believe that two levels of description—the macro morphological-stylistic and the micro-textural and compositional—should be performed in progression but remain distinct; otherwise, we run the risk of circulating typologies which may appear to be very detailed but, are not particularly accurate. We have to deal here with what I call the Munsell paradox, obtaining what may appear to be specific and accurate data with an inaccurate method.[11] The advantage of the Munsell colour system is that it is easy to use and inexpensive but these are poor excuses for a colour-matching method that introduces an unquantifiable error.[12]

[10] http://facem.at/project/about.php; https://www.prehistoricpottery.org/

[11] The Munsell system provides a code corresponding to three colour properties (hue, lightness and chroma) and each code can be converted into a specific CIELAB coordinate. The Munsell code therefore has a claim to accuracy but the way in which it is obtained is not rigorous. We do not always have constant light conditions, the perception of colour varies from person to person, the chips may have variations with respect to the original colour during printing and, as if these variables were not enough, it has been demonstrated that the chips do not cover the full range of colours available in nature.

[12] I take this opportunity to underline that the same paradox is also recurrent in the use of portable instruments used improperly or on materials that have thick patinas and/or for purposes for which they are not designed and for each other techniques would provide more accurate results.

For this reason, typological serialization based on morphology-style should be further enriched by a very simple and rapid description of its main macroscopic features, i.e. those of a general nature that do not require extensive training to identify (e.g. colour and fracture) and that can be applied to the entire context found in an archaeological excavation. This first step can provide the "M(acro)-typology" which will include all information regarding the find-site and the morphology-style of the prototype but, for example, refrains from identifying mineralogical phases based on their visual appearance.

The second step would be to provide a chemical, mineralogical and petrographic characterisation of the prototypes, passing in this way from "M-typology" to "M(acro and)M(icro)-typology". In this second step, the prototypes should be fully characterised in order to serve research questions related to production, use and distribution. These morpho-stylistic prototypes represent the first nucleus of the materials to be considered for archaeometric analyses. Thus the basic requirements for an archaeological typology are accurate chemical and mineralogical-petrographic investigations. The widespread classification according to "fabric" involves a terminological ambiguity and is insufficient for the description of (proto)types because it includes only the textural and mineralogical descriptions. Moreover, the distinction between paste (not fired) and fabric (fired paste) has nothing to do with the geological definition of the term "fabric" and can create confusion.[13] Perhaps a more immediate terminological distinction may be made between clayey paste and ceramic body.

In conclusion, it should be noted that while it is unthinkable to reach a systematic and complete description of each fragment found during an archaeological excavation, it is certainly possible to foresee two levels of knowledge (M- and MM-typology) corresponding to two successive operative phases. This revived concept of ceramic typology includes the analytical phase (thin section and bulk chemistry) from the start underscoring the fact that the archaeometry should not follow the study of materials conducted by an archaeologist working alone but should be an integral part of the classification process adopted by a multidisciplinary team.

Concluding summary of key concepts

In this paper and in those that follow, we have tried to take stock of the current state of ceramic research and what can be done to ensure its advancement. A given assumption is the undeniable importance of ceramics as a technological, socio-economic and chronological indicator that has played a central and long-standing role in the evolution of human culture. We also must not forget that ceramics can be breathtakingly beautiful.

The key concepts on which attention has been drawn here have concerned the appropriate selection of contexts, research questions and samples. Hopefully, it is now clear that these three steps require multidisciplinary collaboration going beyond mere cooperation beginning in the field, continuing in laboratory and reaching its true fruition in publications and museum displays.

The big picture we want to reconstruct should be clear from the beginning in order to guide procedures at all stages of research (context ➔ collection➔ sample). The selection of the context should represent the first issue while the still widespread idea of studying a context/collection only because it is "available" should definitively be abandoned.

To begin with, the selection of research questions should above all be object-oriented with the focus only on the object and the questions it raises. This will ensure a multidisciplinary approach as only a diversified expertise will be able to address the complex questions that arise. Secondly, the selection of research questions should be ambitious rather than narrow as this will lead to the most interesting, rewarding and worthwhile results.

Unfortunately, in ceramic studies today (as well as those of glass and metal), the fields of expertise seem to become ever more reduced, to the detriment of a global and well-articulated perspectives. Similarly, the lengths of papers are restricted. As a result, it is often necessary to wait through at least two or three publications (e.g. one on the chemical analyses, another on the mineralogical-petrographic analyses, etc.) before being fully informed about a single collection. This procedure is understandable given the "publish or perish" dictates of *academia* but it is methodologically incorrect and stultifies

[13] The terms "structure", "texture" and "fabric" describe non compositional properties and may give rise to ambiguity when applied to ceramic studies, therefore, the definitions are provided below:

Fabric: "Non compositional properties or a rock; includes texture and generally larger scale structures" (Best 2002); "The physical arrangement of particles and minerals in a roc, including its texture and structure, both microscopic and macroscopic" and "Fabric analysis—Analysis of the elements that make up the fabric of a rock to determine the response of that rock to stress. In a rock, the three dimensional pattern comprising the distribution, shape, size, and size distribution of crystals or grains constitutes the fabric" (Allaby 2008); "The relative orientation of parts of a rock mass. This is commonly used to refer to the crystallographic and/or shape orientation of mineral grains or groups of grains, but can also be used on a larger scale. Preferred linear orientation of the parts is termed linear fabric, preferred planar orientations planar fabric, and the lack of a preferred orientation is referred to as random fabric." (Brodie et al. 2007).

Structure: "Features defined by aggregates of mineral grains seen at a scale of hand sample or larger, such as bedding or a folded layer; together with texture constitutes fabric" (Best 2002); "The arrangement of the parts of a rock mass irrespective of scale, including spatial relationships between the parts, their relative size and shape and the internal features of the parts." (Brodie et al. 2007).

Texture: "or microstructure—Size, shape and mutual relations of mineral grains and proportions of glass in a rock; together with structure constitutes fabric." (Best 2002); "In petrology, the sizes and shapes of particles in rock and their mutual interrelationships" (Allaby 2008); as synonymous of microstructure "The relative size, shape and spatial interrelationship between grains and internal features of grains in a rock" or as synonymous of microfabric "The presence of a preferred orientation on the microscope scale" (Brodie et al. 2007).

creative thinking and collaboration to the detriment of the field. Careful preliminary and far-sighted planning should be able to break down research programs into a series of intermediate objectives that can be published as worthwhile milestones leading up to a destination of wide-ranging final reconstructions. In this way, a reasonable compromise can be found between the dictates of *academia* and the quality of publications.

As far as typology is concerned, the two step procedure outlined above (M- and MM-) may represent a useful compromise when faced with the hundreds of ceramics fragments usually found on an excavation of which only a limited number can received detailed micro-analysis. In any case, limiting ceramic typology to morphological-stylistic features is unreliable and scholars able to take a macroscopic sample in their hands and determine its provenance are very few.

In conclusion, there is a great deal of exciting work left to be done in the study of archaeological ceramics. Although these are hard times for high-quality wide-range research, archaeometry should move from the disordered "antiquarian"[14] stage in the manner of Indiana Jones to the equilibrium of a modern archaeometry which, overcoming the complex geometries of the multidisciplinarity, uses the archaeological evidence to propose wide-ranging reconstructions of the lives and creativity of past peoples around the globe.

Both ceramics and archaeometry possess a dual nature: the former encompasses both cultural and technological evidence while the latter combines history and science. Where these dualities intersect is a stimulating place indeed.

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[14] Born in the fifteenth century, the Antiquary is the discipline that laid the foundations for the development of archaeology, so much so that it was an antique dealer (J. Spon) who coined the term "archaeology" in the second half of the seventeenth century. Generally speaking, the Antiquaries proceeded without a historical purpose, merely as collectors of decontextualised facts and objects. More fascinated by the ruins than animated by the thirst for scientific knowledge, they dug the sites obsessed with the idea of freeing the artefacts from the land that hid them. For archaeologists, instead, the archaeological excavation is a historical research practice in which the object (including the earth) is a document that produces knowledge (not collections). The context is the fundamental reference system and the stratigraphic method (no longer a brutal earth removal) is the tool to investigate it.

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References

Aidona E, Polymeris GS, Camps P, Kondopoulou D, Ioannidis N, Raptis K (2018) Archaeomagnetic versus luminescence methods: the case of an early byzantine ceramic workshop in Thessaloniki, Greece. Archaeol Anthropol Sci 10(4):725–741. https://doi.org/10.1007/s12520-017-0494-5

Allaby M (2008) Oxford dictionary of earth sciences. Oxford University Press

Aloupi-Siotis E (2020) Ceramic technology. How to characterise black Fe-based glass-ceramic coatings. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01134-x

Arnold DE, Neff H, Bishop RL (1991) Compositional analysis and "sources" of pottery: an ethnoarchaeological approach. Am Anthropol 93(1):70–90. https://doi.org/10.1525/aa.1991.93.1.02a00040

Arthur P (2007a) Form, function and technology in pottery production from late antiquity to the early Middle Ages. In: Lavan L, Zanini E, Sarantis A (eds) Technology in transition a.D. 300–650. Brill, Leiden-Boston, pp 159–186

Arthur P (2007b) Pots and boundaries. On cultural and economic areas between late antiquity and the early Middle Ages. In: Tréglia Bonifay J-CM (ed) LRCW 2. Late Roman coarse wares, cooking wares and amphorae in the Mediterranean: archaeology and Archaeometry, vol I. Archeopress, Oxford, pp 15–28

Arthur P (2010) Riflessioni intorno alla produzione e circolazione della ceramica nel basso Adriatico. In: Menchelli S, Santoro S, Pasquinucci M, Guiducci G (eds) LRCW3. Late Roman coarse wares, cooking wares and amphorae in the Mediterranean. Archaeology and Archaeometry. Comparison between western and eastern Mediterranean. Volume I. Archaeopress, Oxford, pp 79–88

Aubert M, Setiawan P, Oktaviana AA, Brumm A, Sulistyarto PH, Saptomo EW, Istiawan B, Ma'Rifat TA, Wahyuono VN, Atmoko FT, Zhao JX, Huntley J, Taçon PSC, Howard DL, Brand HEA (2018) Palaeolithic cave art in Borneo. Nature 564:254–257. https://doi.org/10.1038/s41586-018-0679-9

Best MG (2002) Igneous and metamorphic petrology. Wiley-Blackwell

Boaretto E, Wu X, Yuan J, Bar-Yosef O, Chu V, Pan Y, Liu K, Cohen D, Jiao T, Li S, Gu H, Goldberg P, Weiner S (2009) Radiocarbon dating of charcoal and bone collagen associated with early pottery at Yuchanyan Cave, Hunan Provice, China. Proc Natl Acad Sci U S A 106(24):9595–9600. https://doi.org/10.1073/pnas.0900539106

Brodie K, Fettes D, Harte B, Schmid R (2007) A systematic nomenclature for metamorphic rocks: 3. Structural terms including fault rock terms. *Recommendations* by the IUGS Subcommission on the Systematics of Metamorphic Rocks. Recommendations. https://www.bgs.ac.uk/downloads/start.cfm?id=3187

Brown KS, Marean CW, Herries AIR, Jacobs Z, Tribolo C, Braun D, Roberts DL, Meyer MC, Bernatchez J (2009) Fire as an engineering tool of early modern humans. Science 325(5942):859–862. https://doi.org/10.1126/science.1175028

Buxeda i Garrigós J (1999) Alteration and contamination of archaeological ceramics: the perturbation problem. J Archaeol Sci 26(3):295–313. https://doi.org/10.1006/jasc.1998.0390

Buxeda i Garrigós J, Kilikoglou V, Day PM (2001) Chemical and mineralogical alteration of ceramics from a late bronze age kiln at Kommos, Crete: the effect on the formation of a reference group. Archaeometry 43(3):349–371

Cantini L, Previtali M, Moioli R, Della Torre S (2019) The mensiochronology analysis supported by new advanced survey techniques: field tests in Milanese area. In: GEORES 20192nd international conference of Geomatics and restoration (volume XLII-2/W11) - 8–10 may 2019, vol XLII-2/W11. Italy, Milan, pp 359–365

Craig OE, Saul H, Lucquin A, Nishida Y, Taché K, Clarke L, Thompson A, Altoft DT, Uchiyama J, Ajimoto M, Gibbs K, Isaksson S, Heron CP, Jordan P (2013) Earliest evidence for the use of pottery. Nature 496:351–354. https://doi.org/10.1038/nature12109

Cuomo di Caprio N (1998) Indagine tecnica e analisi mineralogiche di ceramica a vernice nera da Tarquinia Civita. Atti del Seminario Internazionale di Studio Indagini archeometriche relative alla ceramica a vernice nera: nuovi dati sulla provenienza e la diffusione, Milano, 22–23 November 1996

Day PM, Kiriatzi E, Tsolakidou A, Kilikoglou V (1999) Group therapy: a comparison between analyses byNAA and thin section petrography of Early Bronze Age pottery from central and East Crete. J Archaeol Sci 26:1025–1036

de Lapérouse J-F (2020) Ceramic musealisation: how ceramics are conserved and the implications for research. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01139-6

Delagnes A, Schmidt P, Douze K, Wurz S, Bellot-Gurlet L, Conard NJ, Nickel KG, van Niekerk KL, Henshilwood CS (2019) Early evidence for the extensive heat treatment of silcrete in the Howiesons Poort at Klipdrift shelter (layer PBD, 65 ka), South Africa. PLoS One 11(10):e0163874. https://doi.org/10.1371/journal.pone.0163874

Dunne J, Mercuri AM, Evershed RP, Bruni S, Di Lernia S (2016) Earliest direct evidence of plant processing in prehistoric Saharan pottery. Nature Plants 3:16194. https://doi.org/10.1038/nplants.2016.194

Dunne J, Rebay-Salisbury K, Salisbury RB, Frisch A, Walton-Doyle C, Evershed RP (2019) Milk of ruminants in ceramic baby bottles from prehistoric child graves. Nature 574(7777):246–248

Eramo G (2020) Ceramic technology. How to recognize clay processing. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01132-z

Fantuzzi L, Cau Ontiveros MÁ (2019) Amphora production in the Guadalquivir valley (Spain) during the late Roman period: petrographic, mineralogical, and chemical characterization of reference groups. Archaeol Anthropol Sci 11(12):6785–6802. https://doi.org/10.1007/s12520-019-00937-x

Farbstein R, Radić D, Brajković D, Miracle PT (2012) First Epigravettian ceramic figurines from Europe (Vela Spila, Croatia). PLoS One 7(7):e41437. https://doi.org/10.1371/journal.pone.0041437

Fillières D, Harbottle G, Sayre EV (1983) Neutron-activation study of figurines, pottery, and workshop materials from the Athenian Agora, Greece. J Field Archaeol 10(1):55–69. https://doi.org/10.1179/009346983791504372

Fowler KD, Middleton E, Fayek M (2019) The human element: discerning the effects of potter's behavior on the chemical composition of ceramics. Archaeol Anthropol Sci 11(1):171–198. https://doi.org/10.1007/s12520-017-0535-0

Galli A, Martini M, Maspero F, Panzeri L, Sibilia E (2014) Surface dating of bricks, an application of luminescence techniques. Eur Phys J Plus 129(5). https://doi.org/10.1140/epjp/i2014-14101-8

Galli A, Sibilia E, Martini M (2020) Ceramic chronology by luminescence dating. How and when it is possible to date ceramic artefacts. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01140-z

Gialanella S, Girardi F, Ischia G, Lonardelli I, Mattarelli M, Montagna M (2010) On the goethite to hematite phase transformation. J Therm Anal Calorim 102(3):867–873. https://doi.org/10.1007/s10973-010-0756-2

Gliozzo E (2020) Ceramic technology. How to reconstruct the firing process. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01133-y

Gliozzo E, D'Aco D, Memmi Turbanti I, Galli A, Martini M, Sibilia E (2009) Common ware production at Thamusida: dating and characterisation of Roman and Islamic pottery. Archaeol Anthropol Sci 1(2):77–85. https://doi.org/10.1007/s12520-009-0006-3

Gliozzo E, Turchiano M, Fantozzi PL, Romano V (2018) Geosources for ceramic production and communication pathways: the exchange network and the scale of chemical representative differences. Appl Clay Sci 161:242–255. https://doi.org/10.1016/j.clay.2018.04.026

Gliozzo E, Fantozzi PL, Ionescu C (2020) Old recipes, new strategies: paleoenvironment, georesources, building materials and trade networks in Roman Tuscany (Italy). Geoarchaeology. https://doi.org/10.1002/gea.21792

Gualtieri S (2020) Ceramic raw materials. How to establish the technological suitability of a raw material. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01135-w

Harmand S, Lewis JE, Feibel CS, Lepre CJ, Prat S, Lenoble A, Boes X, Quinn RL, Brenet M, Arroyo A, Taylor N, Clement S, Daver G, Brugal JP, Leakey L, Mortlock RA, Wright JD, Lokorodi S, Kirwa C, Kent DV, Roche H (2015) 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya. Nature 521(7552):310–315. https://doi.org/10.1038/nature14464

Hagstrum MB, Hildebrand JA (1990) The two-curve method for reconstructing ceramic morphology. Am Antiq 55(2):388–403

Hein A, Kilikoglou V (2020) Ceramic raw materials. How to recognize them and locate the supply basins Chemistry. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01129-8

Henderson J, Ma H, Cui J, Ma R, Xiao H (2020) Isotopic investigations of Chinese ceramics. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01138-7

Ionescu C, Hoeck V (2020) Ceramic technology, How to investigate surface finishing. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01144-9

James SR (1989) Hominid use of fire in the lower and middle Pleistocene: a review of the evidence. Curr Anthropol 30(1):1–26

Jang K-O, Nunna VRM, Hapugoda S, Nguyen AV, Bruckard WJ (2014) Chemical and mineral transformation of a low grade goethite ore by dehydroxylation, reduction roasting and magnetic separation. Miner Eng 60:14–22. https://doi.org/10.1016/j.mineng.2014.01.021

Knappett C (ed) (2013) Network analysis inArchaeology: new approaches to regional interaction. Oxford University Press, Oxford, 350 pp

Liritzis Y, Thomas R (1980) Paleointensity and thermoluminescence measurements on Cretan kilns from 2000 to 1300 B.C. Nature 283:54–55. https://doi.org/10.1038/283054a0

Manacorda D (2009) Prima lezione di archeologia. Universale Laterza, Prime Lezioni

Manacorda D (2014) L'Italia agli Italiani. Istruzioni e ostruzioni per il patrimonio culturale. Bari: Edipuglia, pp. 152. Mannoni, T., and M. Milanese. 1988. Mensiocronologia. In: Archeologia e restauro dei monumenti. All'Insegna del Giglio, Firenze, pp 383–402

Mannoni T, Milanese M (1988) Mensiocronologia, in Archeologia e restauro dei monumenti. Quaderni del Dipartimento di Archeologia e Storia delle Arti. Sezione Archeologica. Università di Siena 12-13:383–402

Maritan L (2019) Archaeo-ceramic 2.0: investigating ancient ceramics using modern technological approaches. Archaeol Anthropol Sci 11:5085–5093. https://doi.org/10.1007/s12520-019-00927-z

Maritan L (2020) Ceramic abandonment. How to recognise post-depositional transformations. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01141-y

Maritan L, Mazzoli C (2004) Phosphates in archaeological finds: implications for environmental conditions of burial. Archaeometry 46(4): 673–683. https://doi.org/10.1111/j.1475-4754.2004.00182.x

Maritan L, Casas L, Crespi A, Gravagna E, Rius J, Vallcorba O, Usai D (2018) Synchrotron tts-μXRD identification of secondary phases in ancient ceramics. Herit Sci 6(1). https://doi.org/10.1186/s40494-018-0240-z

Mommsen H (2011) Provenancing of pottery. In: In *Nuclear Techniques for Cultural Heritage Research*. International Atomic Energy Agency (IAEA), Vienna, pp 41–70

Montana G (2020) Ceramic raw materials. How to recognize them and locate the supply basins. Mineralogy, petrography. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01130-1

Moody J, Robinson HL, Francis J, Nixon L, Wilson L (2003) Ceramic fabric analysis and survey archaeology: Sphakia survey. Annu Br Sch at Athens 98:37–105

Mourre V, Villa P, Henshilwood CS (2010) Early use of pressure flaking on lithic artifacts at Blombos cave, South Africa. Science 330(6004):659–662. https://doi.org/10.1126/science.1195550

Nakamura T, Taniguchi Y, Tsuji S, Oda H (2001) Radiocarbon dating of charred residues on the earliest pottery in Japan. Radiocarbon 43(2b):1129–1138. https://doi.org/10.1017/S0033822200041783

Neff H (2012) Comment: chemical and mineralogical approaches to ceramic provenance determination. Archaeometry 54(2):244–249. https://doi.org/10.1111/j.1475-4754.2011.00621.x

Oliveira C, Araújo A, Ribeiro A, Delerue-Matos C (2019) Chromatographic analysis of honey ceramic artefacts. Archaeol Anthropol Sci 11(3):959–971. https://doi.org/10.1007/s12520-017-0585-3

Orton CR (1987) The 'Envelope': un nouvell outil pour l'étude morphologique des céramiques. In: Chapelot, J., Galinié, H., Pilet-Lemière, J. (Eds.) La Ceramique (Ve-XIXe S.), Fabrication, Commercialisation, Utilisation. Caen, pp. 33-41

Owen JV, Hanley JJ, Petrus JA (2019) Phosphatic alteration of lead-rich glazes during two centuries of burial: Bartlam, Bonnin & Morris, and Chelsea porcelain. Archaeol Anthropol Sci 11:6551–6567. https://doi.org/10.1007/s12520-019-00922-4

Panzeri L, Caroselli M, Galli A, Lugli S, Martini M, Sibilia E (2019) Mortar OSL and brick TL dating: the case study of the UNESCO world heritage site of Modena. Quat Geochronol 49:236–241. https://doi.org/10.1016/j.quageo.2018.03.005

Paolucci G (1988) Il territorio di Chianciano Terme dalla Preistoria al Medioevo. Bonsignori Editore, Roma

Papageorgiou I (2020) Ceramic investigation. How to perform statistical analyses. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01142-x

Pittaluga D (2009) La mensiocronologia dei mattoni. Per datare, per conoscere e per comprendere le strutture storiche. ECIG, Genova

Pradell T, Molera J (2020) Ceramic technology. How to characterise ceramic glazes. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01136-9

Robson HK, Skipitytė R, Piličiauskienė G, Lucquin A, Heron C, Craig OE, Piličiauskas G (2019) Diet, cuisine and consumption practices of the first farmers in the southeastern Baltic. Archaeol Anthropol Sci 11(8):4011–4024. https://doi.org/10.1007/s12520-019-00804-9

Romer F (2006) Vopisco et hasta Consulibus: the Chianciano brickstamp. In: Soren D (ed) *An ancient Spa at Mezzomiglio, Chianciano Terme, Tuscany*, vol 60, Oxford

Sanjurjo-Sánchez J, Montero Fenollós JL, Polymeris GS (2018) Technological aspects of Mesopotamian Uruk pottery: estimating firing temperatures using mineralogical methods, thermal analysis and luminescence techniques. Archaeol Anthropol Sci 10(4):849–864. https://doi.org/10.1007/s12520-016-0409-x

Schenck T, Groom P (2018) The aceramic production of Betula pubescens (downy birch) bark tar using simple raised structures. A viable Neanderthal technique? Archaeol Anthropol Sci 10(1):19–29. https://doi.org/10.1007/s12520-016-0327-y

Schuring JM (1984) Studies On Roman Amphorae I-II. Bulletin Antike Beschaving 59:137–195

Schwedt A, Mommsen H, Zacharias N, Buxeda i Garrigós J (2006) Analcime crystallization and compositional profiles—comparing approaches to detect post-depositional alterations in archaeological pottery. Archaeometry 48:237–251. https://doi.org/10.1111/j.1475-4754.2006.00254.x

Sciau P, Sanchez C, Gliozzo E (2020) Ceramic technology, How to characterise *terra sigillata* ware. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01137-8

Soffer O, Vandiver P, Klíma B, Svoboda J (1993) The pyrotechnology of performance art: Moravian venuses and wolverines. In: Knecht H, Pike-Tay A, White R (eds) Before Lascaux: the complex record of the early upper Paleolithic. CRC Press, Boca Raton, pp 259–275

Spataro M, Cubas M, Craig OE, Chapman JC, Boroneanț A, Bonsall C (2019) Production and function of Neolithic black-painted pottery from Schela Cladovei (Iron gates, Romania). Archaeol Anthropol Sci 11(11):6287–6304. https://doi.org/10.1007/s12520-019-00918-0

Stoltman JB (2006) Ceramics in archaeology: readings from American antiquity, 1936–2002. Geoarchaeology 21:643–645. https://doi.org/10.1002/gea.20129

Stoltman JBJ, Marcus JJ, Flannery KVK, Burton JHJ, Moyle RGR (2005) Petrographic evidence shows that pottery exchange between the Olmec and their neighbors was two-way. Proc Natl Acad Sci U S A 102:11213–11218. https://doi.org/10.1073/pnas.0505117102

Sun T, Chongyi E, Lai Z, Hou G (2018) Luminescence dating of prehistoric hearths in Northeast Qinghai Lake and its paleoclimatic implication. Archaeol Anthropol Sci 10(6):1525–1534. https://doi.org/10.1007/s12520-017-0472-y

Tarifa-Mateo N, Clop-García X, Rosell-Melé A, Camalich-Massieu MD, Comes-Bordas P, Martín-Socas D, Nonza-Micaelli A, Rodríguez-Santos FJ (2019) New insights from Neolithic pottery analyses reveal subsistence practices and pottery use in early farmers from Cueva de El Toro (Málaga, Spain). Archaeol Anthropol Sci 11(10):5199–5211. https://doi.org/10.1007/s12520-019-00874-9

Tema E, Polymeris G, Morales J, Goguitchaichvilid A, Tsaknaki V (2015) Dating of ancient kilns: a combined archaeomagnetic and thermoluminescence analysis applied to a brick workshop at Kato Achaia, Greece. J Cult Herit 16:496–507. https://doi.org/10.1016/j.culher.2014.09.013

Thér R (2020) Ceramic technology. How to reconstruct and describe pottery-forming practices. Archaeol Anthropol Sci [this topical collection]. https://doi.org/10.1007/s12520-020-01131-0

Valladas H (1977) On the magnetic separation of quartz for the thermoluminescence dating of an ancient kiln. Archaeometry 19(1):88–95. https://doi.org/10.1111/j.1475-4754.1977.tb00931.x

Weigand PC, Harbottle G, Sayre EV (1977) Turquoise sources and source analysis: Mesoamerica and the southwestern USA. In: Earle TK, Ericson JE (eds) Exchange systems in prehistory. Academic Press, New York, pp 15–34

Whitbread I (2016) Fabric description of archaeological ceramics. In: Hunt A (ed) The Oxford handbook of archaeological ceramic analysis. Oxford University Press, Oxford, pp 200–2016

Wilcock JD, Shennan SJ (1975) Shape and style variation in central German bell beakers: a computer-assisted study. Science and Archaeology 15:17–31

Wu, Xiaohong, Chi Zhang, Paul Goldberg, David Cohen, Yan Pan, Trina Arpin, and Ofer Bar-Yosef (2012) Early pottery at 20,000 years ago in Xianrendong cave, China. https://doi.org/10.1126/science.1218643

Zacharias N, Schwedt A, I Garrigós JB, Michael CT, Mommsen H, Kilikoglou V (2007) A contribution to the study of post-depositional alterations of pottery using TL dating analysis. J Archaeol Sci 34(11):1804–1809. https://doi.org/10.1016/j.jas.2006.12.017

Zanini E (2010) Forma delle anfore e forme del commercio tardoantico: spunti per una riflessione. In: Menchelli S, Santoro S, Pasquinucci M, Guiducci G (eds) LRCW3 late Roman coarse wares, cooking wares and amphorae in the Mediterranean: archaeology and archaeometry. Comparison between western and eastern Mediterranean. Volume I. Archaeopress, Oxford, pp 139–148