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The Decoration and Firing of Ancient Greek Pottery: A Review of Recent Investigations

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ABSTRACT

The wealth and diversity of decoration on Greek pottery continues to attract science-based attention. The availability of increasingly powerful analytical techniques has allowed the nature of the decoration to be investigated in ever-finer detail, down to the nano-particle level. Such work has gone hand in hand with replication experiments ranging from sourcing raw materials to experimental firing. As a result, there is a fuller understanding of the many material and other factors controlling the quality of a range of painted or coloured decorations, most notably black gloss, seen to best effect in the Black and Red Figure–style vases of Attic potters-painters in the sixth to fourth centuries BC. Light has also been shed on the manner in which a few of these craftspeople adapted established techniques to give special effects.

Reviewing the progress made on the decoration and firing of several pottery classes as well as other ceramics, such as terracotta figurines, this paper places this information into context in two ways. On the one hand, it covers the corresponding evidence for the decoration and firing of pottery of the Greek Neolithic and Bronze Age to chart diachronically the craft's technological development. On the other hand, it considers recent archaeological evidence for ceramic production.

Contents

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A1. Introduction

Ceramics remain the central artefact type in almost all branches of archaeology in Greece, resulting from excavation, rescue- or research-led, and from field-walking surface survey. Together these activities yield prodigious quantities of pottery every year. This material receives study along traditional lines, describing its context, date, shape, and function. Pottery typologies become increasingly sophisticated and specific to time and place. At the same time, pottery from older excavations or museum collections may need to be revisited and considered in the light of new finds. One aspect of that process of looking at the new while keeping the old in mind is diversification of the nature of the enquiry: new questions demand investigation using new approaches or methods, just as there are traditional questions calling for a fresh look. The application of scientific techniques to ceramics is one branch of artefact study in Greece that has burgeoned during the last few decades because of the wealth of information it can bring on several levels, including technology, origin, and function. The results of the science-based or archaeometric investigations appeared in different formats in a widely dispersed literature directed at different audiences. Welcome though this development was, there was a downside: the significance of some new information was lost to those who could make full use of it, whether archaeologists or archaeological scientists/materials scientists. To mitigate the effects of this issue, I wrote a synthesis of knowledge about Greek pottery drawn from the use of scientific techniques: *Greek and Cypriot Pottery: A Review of Scientific Studies* (hereafter *GCP*), published in 1986.

The reporting of new science-based work on ancient pottery, whether Greek or not, has improved greatly since then. This work has matured and is now presented more confidently. Meetings, conferences, and workshops are platforms for the presentation of new results; they are plentiful in number and are aimed at wide or specific audiences such that in principle, the work gains a well-rounded hearing from the archaeological and science-based disciplines. This is as it should be, yet such is the pace of both new work in the laboratory and new finds in the field that reviews of recent and current work are still desirable.

The present review article therefore aims to consider science-based work on the decoration and firing of Greek pottery carried out or published after the mid-1980s—that is, since the publication of *GCP*. During the intervening time, a number of authoritative accounts of early pottery technology have appeared. They include *The Emergence of Ceramic Technology and Its Evolution as Revealed with the Use of Scientific Techniques* (2009) by Yannis Maniatis and *Ancient Old World Pottery: Materials, Technology, and Decoration* (2016) by the late W. Noll and R. B. Heimann. These provide fundamental background information, but their spatial coverage is too broad for the purposes of this article, whose concern is the Greek world, with a chronological span from the Neolithic to the start of the Roman period. With such chronological limits, decoration involving true glazing is not considered here. The term *pottery* is treated broadly, so that, for instance, terracotta figurines and architectural terracottas are included.

My original intention was to restrict attention to Greek pottery of the first millennium BC, but I appreciated at an early stage that the technology of both decoration and firing had long histories and that to understand how, for example, Attic pottery of the Classical period was made, decorated, and fired required a long chronological context extending back to the earliest Greek ceramics in the Neolithic. It also became apparent that a full review of the decoration and firing of pottery with such a wide chronological scope lay beyond the content of a single article; the relevant literature on prehistoric pottery is substantial. In the event, a compromise has been reached: the Neolithic and Bronze Age periods feature in a more summary than comprehensive fashion here.

The scope of this article essentially concerns the later stages in the pottery production sequence, but in doing so, it naturally draws on, or is influenced by, the initial steps in pottery making, namely the selection of the clay and other raw materials and their manipulation by the potter. Technological investigations into decoration naturally have to take account of the outcome of those first steps—that is, the fabric. Its chemical and petrographic characterization may therefore form a fundamental part of the investigation. But bear in mind that the same characterization more commonly features in Greek pottery studies on issues having to do with defining pottery spatially and assigning origin. This point applies especially to Greek prehistory but has equal validity with the later decorated pottery, which is the prime concern here. Establishing the provenance as well as the technology of production of decorated pottery—defined only stylistically—should go hand in hand. Decorated Archaic pottery from East Greece is a fine example of where the former enquiry has taken the lead: only through chemical analysis of the fabric have well-known East Greek classes been reliably assigned an origin to one or other of the Greek islands and to locations on the Turkish mainland opposite (see, e.g., Schlotzhauer and Villing 2006; Villing and Mommsen 2017:99–101, notes 1 and 2).

A final but important matter: enquiry into the decoration and firing of Greek pottery has become a specialized subfield within a broader technological realm, so its progress can become an end in itself, running the risk of being separated from (or disinterested in!) the bigger picture. Expressed differently but more seriously, that progress may ironically find itself at odds with the principal goal: understanding the (ancient) potter's empirical knowledge and practice of his craft. Here it is instructive to note the wealth and diversity of activity apparent in vase painting studies as perceived by John Oakley (2009). Furthermore, technical studies (his term) is but one of many areas receiving active research attention: attribution and painters, shape, ornament and workshops, chronology and classification systems, inscriptions, trade and economy, iconography, historiography, and reception. An underlying message in his upbeat account is that each of these areas of specialism benefits from being viewed within a broad context. This sentiment is surely correct, and for technical studies it implies an overlap or encompassing of effort with the more archaeological aspects of production. For that reason, I include a short account on the archaeology of the pottery industry with particular reference to Athens and Corinth (Section C9).

For present purposes, the notable feature of the last 20 to 30 years is the way not only kilns *per se* but also elements of the workshop have been discovered in Greece and beyond. Some of these will be mentioned below, but here it suffices to make the general point that, however incomplete the remains, the processes of decorating and especially firing are now able to be viewed in a wider perspective. Tangible evidence of production includes the wheel, tools for working the pot, clay lumps, wasters, and the levigation tank. At another level, the objects and structures found at the workshop can tell us about the range of pottery that was made and roughly over what period of time; for the archaeometrist,[1] it is an opportunity to get to grips with the raw materials used for the body and the paint. At another level again, more archaeological considerations and questions arise: What was the scale of production? Was it seasonal or full-time? How many potters were there and how was workshop space used? For sure, there is overlap of interests on the parts of archaeometrists and archaeologists in the context of the workshop, but as yet, dialogue between the two sides has not "matured," and bigger questions have still to be articulated.

[1] This term is intended here to apply to those working in archaeological, conservation, and heritage science.

I therefore wrote this paper with both archaeometrists and archaeologists in mind, while recognizing that those subject areas are blurred, as this paper addresses a widening diversity of skills and interests. Contributors to the scope of this paper range beyond those two specialisms to vase specialists, professional potters, materials scientists, museum curators, and a company that combines materials research with the creation of technologically authentic Greek pots (Thetis Authentics, Athens).

To set the scene—a synopsis or consensus of what was known about decoration and firing conditions in the mid-1980s—the following is drawn from *GCP* (760f).

We may recognise four main factors that individually or collectively describe a type of ceramic decoration:

a. The nature and morphology of the decorated layer: paint, sinter, gloss, or metal
b. The type of surface to which the material is applied
c. The colouring agent
d. The technique of decoration

a. Nature and morphology of the decorated layer: paint, sinter, gloss, or metal

The term *paint*, used here in the broadest sense, refers to materials that conform to the following descriptive sequence.

The starting material may be either naturally occurring (for example, coloured earths enriched in iron [ochres] or manganese [umbers],[2] white clays, limestone, and carbon) or synthetic (for example, Egyptian Blue). Application of the paint to the ceramic surface *before* firing could be made with: (1) a solid powder, (2) a liquid suspension, (3) a mixture with an organic medium, or (4) a paste. Polishing or burnishing of the painted surface before firing usually created a bright, even lustrous appearance. Application of the paint *after* firing left a less permanent layer, sometimes friable and granular in texture. Evidence for post-firing rests on identification of a component of the decoration whose composition or phase is inconsistent with a temperature necessary for the firing of the pottery.

A sinter is a layer of gloss produced by the sintering of a fine clay, especially the clay mineral illite, originally in the form of a suspension, at a high temperature. It is effectively a silicate paint, applying, for example, to Urfirnis of the Neolithic and Early Bronze Age and to the black gloss/glaze of later times.

A rare type of decoration involved the application of metal foil. Tin was used during the Mycenaean period and gold foil on Attic Red Figure and terracotta figurines.

b. Type of surface

Paint may be applied to one or more of four surface types:

The dried, smoothed clay surface (by brush, smearing, or smudging)

1. A slipped surface. The slip composition is often different than that of the clay body.
2. An incision in the surface before or after firing
3. The fired surface

c. Colouring agents

Colouring agents consist of a wide range of compounds. The more important are the oxides of the transition element metals, iron and manganese, belonging to the spinel group: hercynite $FeAl_2O_4$, magnetite Fe_3O_4, maghemite γ-Fe_2O_3, and jacobsite $MnFe_2O_4$.

[2] It is worth noting the great antiquity of these coloured earths for decorative purposes. The use of red ochre in South Africa has been dated at 73 Ka (Henshilwood et al. 2018) and manganese and iron oxides in Spain have been dated at 65 Ka (Hoffmann et al. 2018). See Siddall (2018).

d. Techniques of painting

This section describes the physico-chemical basis of the main painting techniques, except those involving glaze, and classification is made according to monochrome, bichrome, and polychrome decoration.

Painted decoration giving black or dark colours: Iron reduction technique (IRT)

The paint material is an iron-rich clay, a coloured earth containing iron oxide (an ochre), or a combination of the two. During the reducing phase of the firing, iron oxides of dark colour are formed. The final colour depends on the nature of the paint material's composition, the thickness of the paint layer, and the atmosphere during the final stage of firing and during cooling. The practice of introducing a reducing phase has been recognised as one of the oldest techniques of pottery decoration, originating probably in Mesopotamia (see, e.g., Noll and Heimann 2016:225–27). Moreover, in the Aegean it was one of the few techniques to make progressive technological advance, as we see below.

A1b. Manganese black technique

Decoration with manganese oxides, occurring naturally as dark earth, gives a dark brown or black colour, usually with a matt effect. The potter's practice was probably to mix the raw material, suitably ground up, to a fine clay fraction. The painted layer, consisting of a loose aggregate of rounded pigment particles with diameters of about 0.10 μm, is rather thick (20–50 μm) and not usually sintered. One of the attractions of this technique is its relative simplicity; no strict control over firing conditions is required, one consequence of which is that a bichrome effect can be gained.

A1c. Carbon black technique

The introduction of carbon, whatever its source, into the pores and onto the surface of pottery, a technique known as smoking or smudging, was evidently practised in a number of ways at an early stage of pottery making, giving rise to a surface varying in colour, from jet black to grey, and varying in appearance, from highly burnished to matt. One feature of the firing sequence is a strong reducing phase, sometimes in the presence of organic material. A moderate temperature was adequate: about 700–750°C.

A1d. Painted decoration giving red and related colours

These colours result most commonly from the use of iron-based paints fired in an overall oxidising atmosphere, giving monochrome decoration. A bichrome effect was achieved most commonly as an adaptation of the IRT, depending on the thickness of the iron-rich paint layer; thus a thin layer coloured black during the reduction phase may be subsequently reoxidised either partly (to brown) or wholly (to black). Under the same conditions of firing, a thicker layer remains black because the more effective sintering that takes place during the reduction phase protects it from later reoxidation. Alternatively, a combination of manganese and iron-based paints could be used. On firing under oxidising conditions, these yield dark and red colours, respectively. A variety of techniques, deliberate and accidental, were responsible for the mottling effect on Early Minoan Vasiliki ware; variegated colouration was also the product of differential burnishing. Polychrome decoration extended the bichrome effect by introducing additional colours, such as white, orange, and purple, for example on Middle Minoan Kamares ware. More elaborate polychromy appears on the well-known fifth-century BC white-ground lekythoi; the application of paint was usually post-firing.

A2. Methods of analysis and examination

The techniques referred to in this paper are many and varied, fully reflecting the ongoing major advances in materials science research. New techniques, some of considerable sophistication and available only

Table 1
Techniques of Analysis, Imaging, and Firing Temperature Range Determination

Elemental Analysis	Description/Applications
Atomic absorption spectrometry (AAS)	Fabric composition; D; CA; limited range of elements
Conversion electron Mössbauer spectroscopy (CEMS)	Oxidation and structural state of Fe on surface and in fabric; ND
Electron probe microanalysis (EPMA or EMPA)	Surface composition; good for light elements; ND
Energy-dispersive X-ray analysis (EDS or EDX)	Fabric and surface composition; major and minor elements; usually ND; CA
Inductively coupled plasma-optical emission spectroscopy (ICP-OES), mass spectrometry (ICP-MS), laser ablation ICP mass spectrometry (LA-ICP-MS)	Fabric and surface composition; full range of elements; CA; ICP-ES and ICP-MS: D; LA-ICP-MS: MI
Laser-induced breakdown spectroscopy (LIBS)	Surface composition; capable of giving depth profile; ND-MI; P (Anglos 2019)
Proton-induced X-ray fluorescence (PIXE and μPIXE), proton-induced backscattered protons (Rutherford backscattering or RBS)	Fabric and surface composition; wide range of elements; ND; TNF
X-ray absorption spectroscopy (XAS) and X-ray absorption near-edge structure (XANES)	Surface composition, valence state and electronic structure; D; MI; TNF
X-ray fluorescence spectrometry (XRF) and portable XRF (pXRF)	XRF (D) and pXRF (ND): fabric and surface composition; CA; pXRF cannot usually determine critical light elements, such as Na and Mg.
X-ray photoelectron spectroscopy (XPS or ESCA)	Surface composition; ND but requires high vacuum conditions
Mineral and Compound Analysis	
Fourier transform infrared (FTIR) and near-infrared (FTNIR) spectroscopy	Compound identification; D (MI) but increasingly ND (Aloupi-Siotis and Kalogirou forthcoming)
Raman spectroscopy (Raman)	Chemical composition structure of surface compounds; usually ND
X-ray diffraction (XRD)	(Quantitative) mineral phase composition of surface; MI; CA; ND now possible as fast XRD^2 μ-diffraction (Berthold et al. 2009; see Section C8)
Imaging	
Multispectral imaging: UV-induced visible luminescence (UVL) and visible-induced infrared luminescence (VIL)	ND; P
Optical microscopy (OM)	General examination; ND; CA; P
Optical microscopy with polarising facility for petrographic (thin section) examination (PE)	Petrographic composition; D; CA; P
Reflectance transformation imaging (RTI)	Detailed surface topography and colour; ND
UV/Vis/NIR fibre optics reflectance spectroscopy (FORS)	Spectral information on painted surfaces; ND; P
Scanning electron microscopy (SEM)	High magnification (>1000x) and high-resolution view of surface and its topography; usually ND combined with EDS (see above and text)
Scanning transmission electron microscope (STEM)	Very high magnification (>10000x) and high-resolution view of surface and topography; usually combined with EDS (see above)
Firing Temperature Range Determination	
Differential thermal analysis (DTA)	CA; D
Fourier transform infrared spectroscopy (FTIR)	CA; D
Magnetic susceptibility (MS)	D; see text
Refiring	CA; D
Reflectance spectrometry (colorimetry) RS	D; see text
Thermomechanical analysis (TMA)	D; see text
Organic Analysis	
High-pressure liquid chromatography-mass spectrometry (HPLC-MS)	CA; MI
Time-of-flight secondary ion mass spectrometry (tof-SIMS)	MI
Other	
Experimental (Exp) work directed towards forming, decoration, and/or firing	
Preparation of replication for analysis and imaging (REP)	

Notes: CA = commonly available technique; TNF = technique usually associated with large research centres/national facilities; D = destructive (sample required); MI = minimally invasive; ND = nondestructive; P = portable.

at national research centres, together with ever-improved instrumentation, especially in the area of nondestructive analysis, have benefited archaeometric, conservation, and heritage science research of the kind presented in this paper.

Table 1 sets out the techniques according to the information they provide; within its sections—elemental analysis, mineral and compound analysis, imaging, firing temperature range determination, organic analysis, and experimental/replication work—the techniques are arranged alphabetically. Many of them are well established and need little introduction here, but some other, often newer ones demand brief explanation. Readers are referred to Gilberto Artioli's concise and helpful book *Scientific Methods and Cultural Heritage: An Introduction to the Application of Materials Science to Archaeometry and Conservation Science* (2010), but bear in mind that it was written more than a decade ago. Also relevant are Rice (2015:291f, 376f) and Cuomo di Caprio (2017:540–90). The Getty Conservation Institute's Athenian Pottery Project, which features in this paper, offers a brief overview of the techniques it used: http://www.getty.edu/conservation/our_projects/science/athenian/index.html.

In addressing the issue of whether a sample is required for analysis/examination, Table 1 draws attention to the sliding scale of options by differentiating between invasive (destructive) analysis (D), involving samples of a few hundred milligrams; minimally invasive microanalysis (MI), involving samples of a few milligrams; and nondestructive (ND) analysis. In the case of ND, it is important to distinguish between the technique and the analysis: the former (such as EDS in the SEM) does not destroy the sample; the latter requires that a sample be physically taken from the object, albeit at a minimally invasive level.

There is no doubt that synchrotron-based (or particle accelerator–based) techniques have seen great advances in materials science during the last decades and thus have made a correspondingly substantial impact on some of the work reported here and in heritage science more generally. It is the high intensity and low divergence of the high-energy synchrotron beam (an X-ray, for example) that make it suited to the analysis of very localised spots in the material in order to understand the chemical environment of the element, iron, that features so critically in pottery decoration. In effect, these techniques, together with the transmission electron microscope (TEM), have allowed ceramics to be viewed at the nano scale. Among the relevant techniques are micro-focused beam X-ray fluorescence (μXRF) and X-ray absorption near-edge structure (μXANES) spectroscopy. Within the spectrum obtained from X-ray absorption spectroscopy (XAS) is one narrowly defined region incorporating the pre-edge and near-edge absorptions; the latter, XANES, is sensitive to the coordination geometry or more particularly the average valence state of the element being probed, usually iron, which is shown to good effect in Fig. 41d (and Fig. 42e for copper). Also sensitive to the valence state of iron is Mössbauer spectroscopy, although this technique or its adaptation (CEMS; Vendrell-Saz et al. 1991) seems to have found less application than in the past. But as will become abundantly clear in the review below, the more conventional techniques still have an essential role to play, not least because they are capable of dealing cost-effectively with larger numbers of samples. The fact that several of these techniques have been adapted for portability, so that the instrument goes to the object rather than the object going to the laboratory, coupled with their ability to analyse nondestructively, marks another major methodological step forward of the last 20 years. A final point about nondestructive analysis, notably by portable X-ray fluorescence (pXRF), that is highly relevant to several applications in this review: depending on the thickness and nature of the surface (paint) layer, the analysis may also include a contribution from the underlying layer. This fact, which also applies to other techniques, such as proton-induced X-ray fluorescence (PIXE), emphasises the need to have as much information as possible (from optical microscopy) on the potential presence of such layers in advance of analysis.[3]

The two complementary techniques that allow an estimate of firing temperature range to be made—archaeothermometry—are X-ray diffraction (XRD) and scanning electron microscopy (SEM), which determine, respectively, the mineralogical and microstructural changes occurring as clay is fired. They can be most effective when employed in tandem. The microstructural changes follow the sequence from no vitrification, sintering through to all stages of vitrification as a function of temperature, the clay's texture and composition (especially its Ca content), and, crucially, the firing atmosphere. Because of the lack within this information of a proxy for the duration of firing, only the equivalent firing temperature (EFT) can be estimated. It is "essentially that constant temperature which, in a time similar to the time the specimen had been exposed to sintering temperatures during the original firing, would have brought the specimen to the same stage of sintering" (Roberts 1963:21). The term *EFT* is increasingly used in the interpretation of microstructure/micromorphology observed in the SEM (e.g., Day et al. 2018:354; Schilling 2003:319–20).

Other techniques aiming at the same information have also found application. Among them is thermomechanical analysis (TMA), whose archaeometric potential has long been known (Tite 1969), although it is not usually well suited to highly calcareous ceramics. It monitors the expansion of the ceramic as it is heated; when the original firing temperature is reached, the expansion stops. If heating is continued, the ceramic begins to sinter again, causing it to shrink. A dilation/sintering curve (DS) is the outcome. TMA functions similarly to dilatometry but has the advantage for archaeometric purposes of being able to handle small samples (preferably blocks 1 mm in size). Following its application with dilatometry to Greek pottery by Mavroyannakis (1981), the potential of TMA lay dormant until Schilling (2003) and Mirti et al. (2004b) revived it in studies of test pieces from the Athenian Agora (Fig. 21a) and Black Figure at Locri, respectively. In the case of a relatively low-fired (<800°C) ceramic in which little or no vitrification has occurred, TMA may be superior to SEM because of the dependence in the latter technique on (subjectively) identifying different vitrification levels. Reflectance spectrophotometry to determine colour coordinates can be used to estimate firing temperature, if only in an exploratory manner. This approach, which involves comparison of the colour coordinates in the original sample and in the sample following refiring to known temperatures (Mirti and Davit 2004), is employed in tandem with other techniques.

Fourier transform infrared spectroscopy (FTIR), now becoming more accepted as interpretation of the spectra becomes more standardised (e.g., Maniatis et al. 2002; Mentesana et al. 2017), is very well suited to low-fired ceramics. The near IR holds particular promise as diagnostic absorptions of clay-soil minerals occur there (Aloupi-Siotis and Kalogirou forthcoming). Using petrographically and mineralogically defined samples, Rasmussen et al. (2012) have obtained satisfactory T_{max} firing temperature by measuring the magnetic susceptibility on a stepwise refired sample and determining the first derivative of the magnetic susceptibility change. Kostadinova et al. (2018) have applied this approach to pottery in Bulgaria.

Multispectral imaging techniques—photo-induced luminescence (usually UV-induced visible luminescence [UVL]) and visible-induced infrared luminescence (VIL)—require introduction, as they feature prominently in current studies of terracotta figurines whose polychrome decoration may scarcely be visible today. As Dyer and Sotiropoulou (2017) have explained, they are well suited to the mapping of more intact surfaces and the detection of pigment traces, notably of Egyptian Blue and rose madder lake, which have characteristic near-infrared and visible emissions when excited by red and green light, respectively. The same authors have described the practical advantages of combining UVL and VIL to locate these two pigments. Complementing composition data, they can shed light on the techniques of pigment application and reveal mixtures or layering effects. The well-established, allied technique of UV/Vis/NIR fibre optics reflectance spectroscopy (FORS) helps provide supporting information (Kakoulli et al. 2017). Also from the cultural heritage sphere and finding application beyond ceramics is reflectance transformation imaging (RTI), a photographic method that captures a subject's surface shape and colour, revealing fine-detail information invisible under normal examination. Finally, the increasing recognition of the presence of organic-based colourants on figurines has drawn in chromatographic techniques, principally HPLC, coupled to mass spectrometry.

A3. Firing structures

Thus far in this account, the firing of pottery has featured implicitly, as the step following decoration, and explicitly in Table 1, in outlining the methods of determining firing temperature range. At this point, experimental work on firing and firing structures can be introduced and set beside the archaeological evidence for ceramic production.

Under the heading of "experimental" comes the work of Thér (2014), who monitored duration of firing, T_{max}, soaking time, heating rate, and other variables in the firing profile (Fig. 1) in a wide range of firing structures (Fig. 2a,b) and procedures. His important results are discussed in Section B.

There is a wealth of archaeological information about ancient Greek kilns and more generally firing structures, and rightly so because they form the critical indicator of production in their (immediate) environs. Kilns themselves provide direct if often fragmentary evidence for the *process* of pottery firing, information that can be set beside the material aspects of pottery. On one hand, pottery and pottery waste found in association with kilns provide the ideal material for characterising the material aspects of pottery's fabrics and, where decorated, paint layers. On the other hand, estimation of the pottery's firing temperature range can feed into the enquiry into a kiln's performance and efficiency in terms of fuel consumption and temperature versus time data. This in turn demands or encourages an experimental approach to simulate the ancient or original firing.

[3] The current literature on the application of pXRF to ceramics reflects the recognised need to enhance and standardise the technique's protocol; see Hegenwisch et al. (2021).

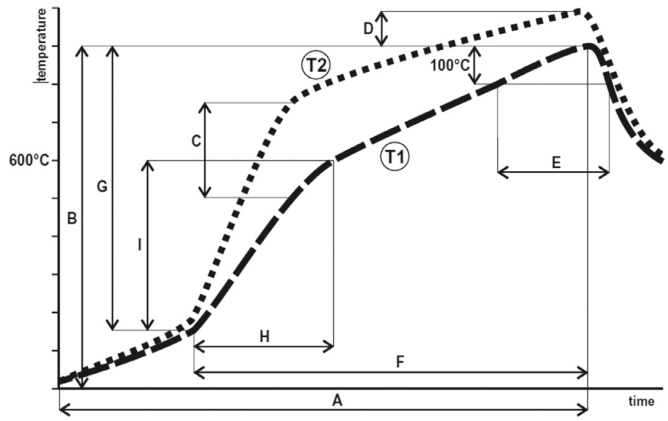

Fig. 1. Variables involved in the thermal profile of a firing, according to Thér. (A) Time taken to reach maximum temperature. (B) Maximum temperature at thermocouple T1. (C) Maximum temperature difference measured at different locations. (D) Maximum temperature recorded by the thermocouples (T1 and T2). (E) Soaking time. (G–F) Heating rate measured at T1. (I–H) Heating rate up to 600°C measured at T1. From Thér 2014:Fig. 1.

The web-based atlas of Greek kilns, https://atlasgreekkilns.arizona.edu/database, covering the prehistoric to post-Byzantine periods (circa 3000 BC – AD 1820), is founded on Hasaki's work (2002, 2006) and in particular her typology (Fig. 3). Shape, dimensions, and the number and form of supports of the perforated floor are foremost in the description of each entry, which often includes an illustration of the kiln. Early Iron Age kilns are treated by Papadopoulos (2003:201–9). Cuomo di Caprio (1978–1979, 1992) presents the principal classification of relevant kilns in Italy. The firing structures of the prehistoric and historical periods are treated in Sections B and C, respectively.

Section C9 considers the archaeological evidence for production in Athens and Corinth to build up an impression of what a workshop looked like and how it may have operated. But because that evidence is sporadic and uneven, it is worth drawing attention to instances within Greece and notably in Magna Grecia where excavation has fortunately led to the recovery of substantial sectors of workshops; these have deliberately been selected to give a chronological spread from Archaic to Hellenistic. In the more common situation, however, little more than the kiln has survived. In this circumstance recourse can be usefully made to the rich ethnographic record to establish a baseline in understanding the factors dictating the location and all aspects of the operation of (twentieth-century) traditional workshops. It suffices here to refer to a few examples of that record: the classic work of Hampe and Winter (1962, 1965); the work of Betty Psaropoulou (1986), who founded the Centre for the Study of Modern Pottery in the Athens Museum (http://potterymuseum.gr/), and Maria Voyatzoglou (2009)—both of whom studied traditional pottery throughout Greece—and the work of Harriet Blitzer (1990) on the storage jars (*koroneïka*) of the Southwest Peloponnese.

A4. Chronology

See Table 2.

Table 2
Chronological Table

Period	Approximate Date Range BC
Early Neolithic	6500–5800
Middle Neolithic	5800–5300
Late Neolithic	5300–4500
Final Neolithic (or Chalcolithic)	4500–3100
Early Bronze Age	3100–2000
Middle Bronze Age	2000–1650
Late Bronze Age	1650–1050
Protogeometric	1050–900
Geometric	900–700
Archaic	700–480
Classical	480–323
Hellenistic	323–146
Roman	Post-146

Note: Section B includes a more detailed chronology for the Bronze Age (Rutter 2021).

B1. The Neolithic

B1a. Surface treatments and firing temperature estimations

The decorated ceramic products of the Neolithic, the formative and experimental period of pottery making in Greece, display a remarkable wealth of shapes, motifs, surface treatments, and raw materials. Macedonia and Thrace, Thessaly, central Greece, the Peloponnese, and Crete (Fig. 4) are the principal regions, each having a distinct Neolithic material culture (Andreou et al. 2001). Investigating the ceramic technology practiced in these regions and beyond over the course of the Neolithic has been and remains a rich area of research, not least for the way that technology is increasingly viewed as the driver or agent of manifesting ideas, perceptions, and symbolisms in creating and reproducing society (Lemonnier 1993). Technology thus belongs to a wider arena of enquiry, extending well beyond production *per se* to issues of consumption, function, distribution, scale of production, specialization, and skill, as well as the social sphere, as Perlès and Vitelli (1999) have conveniently outlined for the Early to Late Neolithic periods. Indeed, as regards decorated pottery, much has rightly been made of the assertion that its function lay not in the domestic food preparation domain but rather in social and symbolic terms (Vitelli 1993:213–19). Whether production of this usually highly visible pottery lay in the hands of specialized potters is still debated (see below), but it is nevertheless the case that pottery was one of the powerful and important elements used by people in northern Greece to build alliance networks among early agricultural communities based at separate villages (Halstead 1989); such networks were based on regular meetings and sharing of food and drink.

Work up until the mid-1980s, led largely by Noll and his coworkers and summarised in *GCP* (766–84, Table 9.6a–b), established that iron reduction, manganese black, and carbon black techniques and graphite painting were already in use at different times throughout the Neolithic and Chalcolithic and in different regions. Since that time, the picture has altered in the direction just outlined, first with an implicit adoption of the *chaîne opératoire* approach that combines the respective choices made by potters in selecting their clay materials to form vessels and subsequently in treating the vessels' surfaces. Fabric analysis by petrographic means has been crucial in determining the nature and firing properties of the local clays that were exploited, including those selected specifically for vessels receiving slip and painted decoration. But in the process of identifying non-local fabrics, this analysis has also shed valuable light on networks of interaction and exchange at (mainly) an intra-regional level, as exemplified by Pentedeka's (2011) study of Middle Neolithic (MN) Scraped ware and especially Late Neolithic (LN) Grey ware at Platia Magoula Zarkou in western Thessaly (Fig. 4). Adopting a similar approach, having isolated the contrasting potting traditions in different zones of Early Neolithic (EN) Thessaly, enabled Dimoula (2017) to conclude that not only were pots circulating but there was probable mobility of potters as well. Most recently, as a result of study of rich LN assemblages at sites in southern Albania, networks of interaction linking those sites with regions as far as Thessaly have been proposed (Elezi in press) (see below).

The section below begins with an overview of investigations of surface treatments.[4] There follows an account of discoveries of firing structures that, although not numerous, have been important in stimulating archaeometric and experimental work.

[4] This overview cannot claim to be comprehensive.

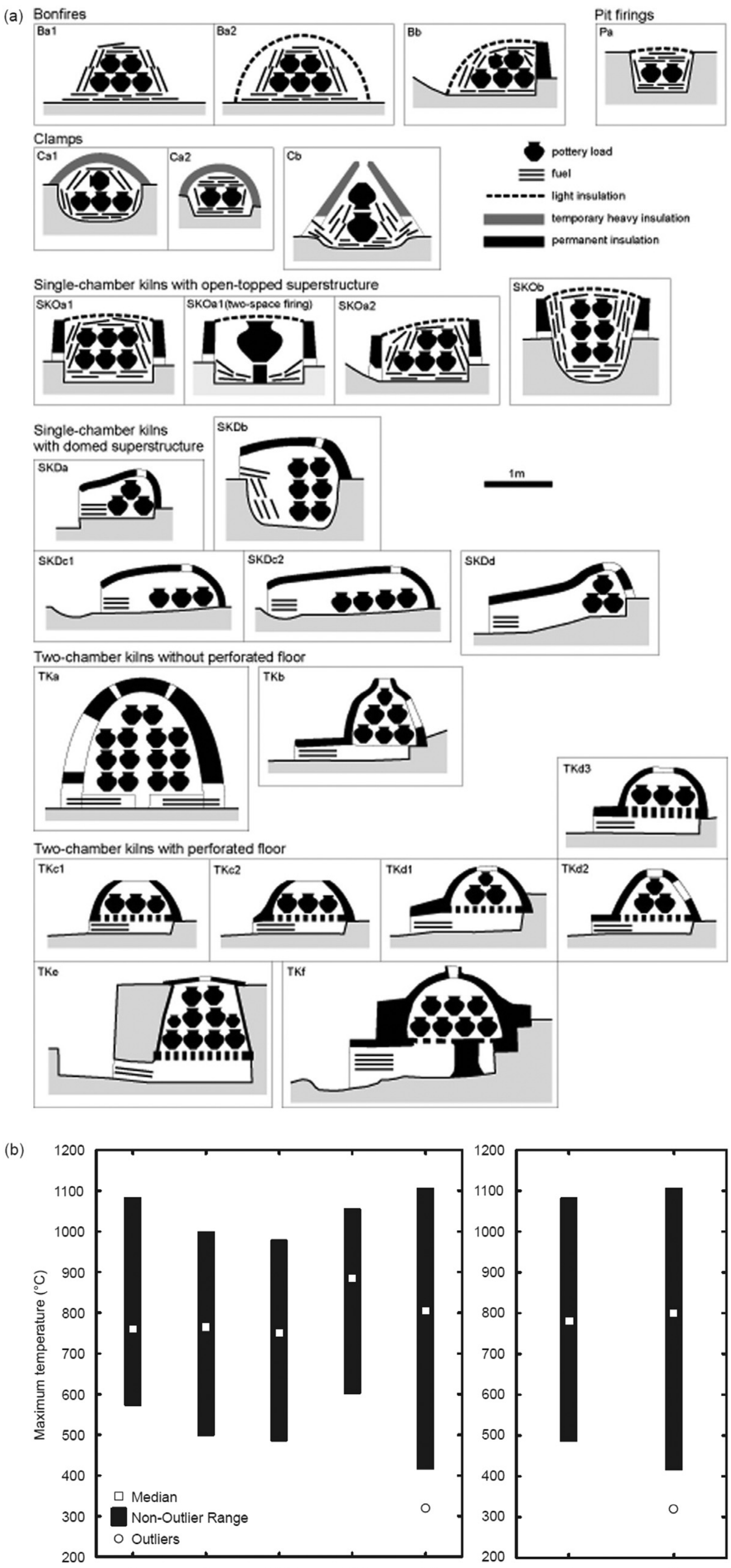

Fig. 2. a Firing structures experimentally tested by Thér. From Thér 2014:Fig. 2.
b. Maximum temperatures achieved according to the firing structure (Fig. 2a) and type of firing: one-space (O) and two-space (T) firings. From Thér 2014:Fig. 3.

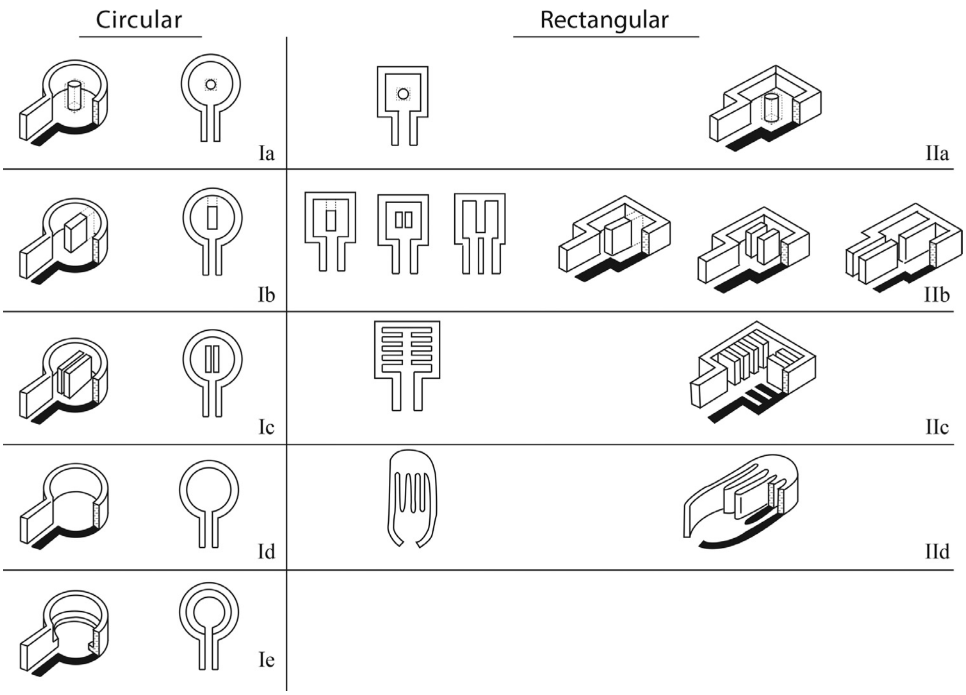

Fig. 3. Typology of ancient Greek kilns. From Hasaki 2002:Plate III.13. Image courtesy of Eleni Hasaki.

Drawing on the numerous studies summarized in Table 3a concerning Neolithic–Chalcolithic pottery, and bearing in mind that many of them need increasingly to be viewed in a Balkan-wide context (see, e.g., Amicone et al. 2019), the following points emerge: burnishing, painted, applied, incised, excised, and impressed decorative effects were achieved in a remarkably varied manner, usually before firing but sometimes after. These effects were achieved by firing clays of varying texture and composition to a range of temperatures in oxidising and/or reducing conditions, employing most commonly iron-based and manganese-enriched slips and pigments to achieve red, brown, and dark colours. Owing to their ready availability and effectiveness, iron-based materials were surely the most commonly used; they ranged from a refined version of the same clay used for the body to an earth/clay naturally enriched with iron oxide(s).

Macedonia, Thrace, Bulgaria, and Albania feature examples of the carbon black technique, white slips and pigments, inorganic coatings, mineral coatings/crusts, organic-based coatings and pigments, and graphite materials (Vajsov 2007:Fig. 3; Yiouni 1995, 1996, 2001). Many of the effects are illustrated in Figs. 5 and 6.

Over the course of the Neolithic (and especially EN and MN), there was increasing ability to control the firing atmosphere, yielding an oxidised light-coloured surface on which iron-based decoration would contrast well (Figs. 5:4, 6:b). Based as well on that contrast are manganese black and polychrome effects. The former enjoyed a popularity related to its ability to give dark colours, irrespective of the prevailing firing conditions, but its use in EN appears to be limited, for example at Podgorie and Kolshi (Ndreçka et al. 2017:23).[5] Also limited in the early phase were polychrome effects, for instance at Promachon-Topolnica with organic pigments (see below) and at Mavropigi-Filotsairi with a ferruginous red slip. This slip was outlined with thin white-painted lines (kaolin or a calcium-rich slip, as at Podgori [Ndreçka et al. 2017:23]), contrasting with the tan-pink background (Bonga 2017:379, 384).

As the LN approached, the probable hallmark innovation of its time was a more consistent reducing firing, which Urem-Kotsou (2016:37) sees as a potential response to the desire for more elaborate tableware, in keeping with the social function mentioned above. Black-topped vessels (Fig. 6a), achieved by the carbon black technique, specifically carbon smudging during firing (Courtois 2004:23; Yiouni 1995), exemplify the ability to maintain a reducing phase during the firing cycle. Together with black burnished ware, these vessels were produced in LN, if not earlier. But more effective and popular at this time was decoration with manganese-rich materials. Experimentation with the effects of a paint of varying thickness, rich in both manganese and iron oxides (over a usually calcareous clay-based slip) and receiving often incomplete reducing firing, is a feature of LN Brown-on-Cream or Akropotamos ware (Figs. 5:4 and 6b) (Vajsov 2007:85–86; Yiouni 2001:7, Table 2, Plate 3c). This ware is common at sites in the Strymon River valley, where a distinctive, similarly decorated style—LN Black-on-Red ware—was also produced (Malamidou et al. 2006) (Figs. 5:7, 6f). According to neutron activation analysis data, its main production zone in the region was around the Strymon and Angitis rivers (Kilikoglou et al. 2007:Fig. 3) (in the area including Kryoneri and Dimitra in Fig. 4). A low-calcium, fine-textured clay was used to make the ware in this region and also, to judge by the ware's elemental body composition, at (or near) Polyplatanos in western Macedonia (Sakalis et al. 2013:Table 2), thereby providing independent support for inter-regional transfer of knowledge and/or potters. Other wares at Polyplatanos were clearly the products of additional clay recipes, notably another instance employing manganese-based decoration, what Sakalis et al. (2013) term Classical Dimini, which was made of a more calcareous clay (with variable but distinctively high Cr and Ni contents). Capable of yielding better-quality, more consistently higher-fired (>800°C) decorated pottery, calcareous clay was coming to be recognised for its advantages. Manganese features prominently alongside iron-rich materials in Brown-on-Cream and polychrome wares at the LN sites in southern Albania examined by Elezi (2020) and Elezi and Fischer (in prep.). One feature of their XRD results, amplifying what Yiouni (2001) and previous studies have shown (*GCP*, 762–63, 778, Table 9.6a), is the lack of uniformity in the raw material, ranging from mixtures of manganese and iron-rich materials/earths to iron-rich materials on their own through to manganese minerals.

Before proceeding to consider other wares, some firing temperature determinations derived from different techniques can be briefly reviewed. They range widely, from 650°C to 850–950°C (or even higher; see Yiouni 2001:Table 2). By the later MN and during LN, 850–950°C may have been regularly achieved, for example at Dimitra, where

[5] And elsewhere to the north, such as EN Romania (Spataro et al. 2019).

Fig. 4. Map of the Aegean showing sites mentioned in Section B. The inset indicates site locations in central and western Macedonia. M is Magoula.

about 35% of the decorated sherds were fired at >900˚C, with a tendency towards higher temperatures in LN than in the preceding period (Kessisoglou and Mirtsou 1997). The upper part of the 850–950˚C range was the case with Black-on-Red ware. Gardner's (2003:284, 293) estimates at Sitagroi, 750–1100˚C, are high. Determined as they were by the onset of sintering, they should represent the upper limits. The lower limit was established in the same ware at nearby Dimitra (Kessisoglou and Mirtsou 1997:89).

Graphite-painted pottery has continued to attract attention for its unusual aesthetic appeal of high-metallic lustre as much as for its possible chronological and technological relation with the smelting of metal ores. This type of decoration manifested itself in different ways. Figs. 5:6 and 5:8 illustrate two forms at Dikili Tash (see also Treuil 2004:Plates C and D) and Sitagroi. Fig. 6e shows the chronologically later (Chalcolithic) manifestation at Promachon-Topolnica. Amicone et al. (2020) have admirably reviewed previous work on black-faced pottery in the Balkans as a whole in connection with their own study of this pottery from two neighbouring Vinca-period sites: Belovode, where there is the earliest evidence of copper smelting (circa 5000 BC), and Pločnik in Serbia. Before outlining the outcomes of their enquiry, mention should be made of Kreiter et al.'s (2014) experimental work on graphite-painted pottery. Their best results were obtained by applying finely powdered graphite (from the archaeological site of Méfőcsanak-Széles földek in northwestern Hungary) to the leather-hard pottery surface before burnishing (with a pebble). This was followed by firing in an electric kiln under reducing conditions in the range 700–1000˚C, yielding graphite layers of 1–1.5 μm thickness, which were morphologically comparable with those on archaeological specimens (see Table 3a) of 1-5 μm thickness. Although Kreiter et al.'s recipe might appear relatively straightforward, they were at pains to emphasise the importance of maintaining a fully reducing atmosphere throughout the firing, and in so doing they acknowledged both the complex technological knowledge and the high skill level of the potters. However, that view may require revision in light of the results of Amicone et al., who emphasised the importance of considering firing parameters other than temperature, such as redox conditions and length of firing. The fabric of many of their sherds displayed a light-coloured core,

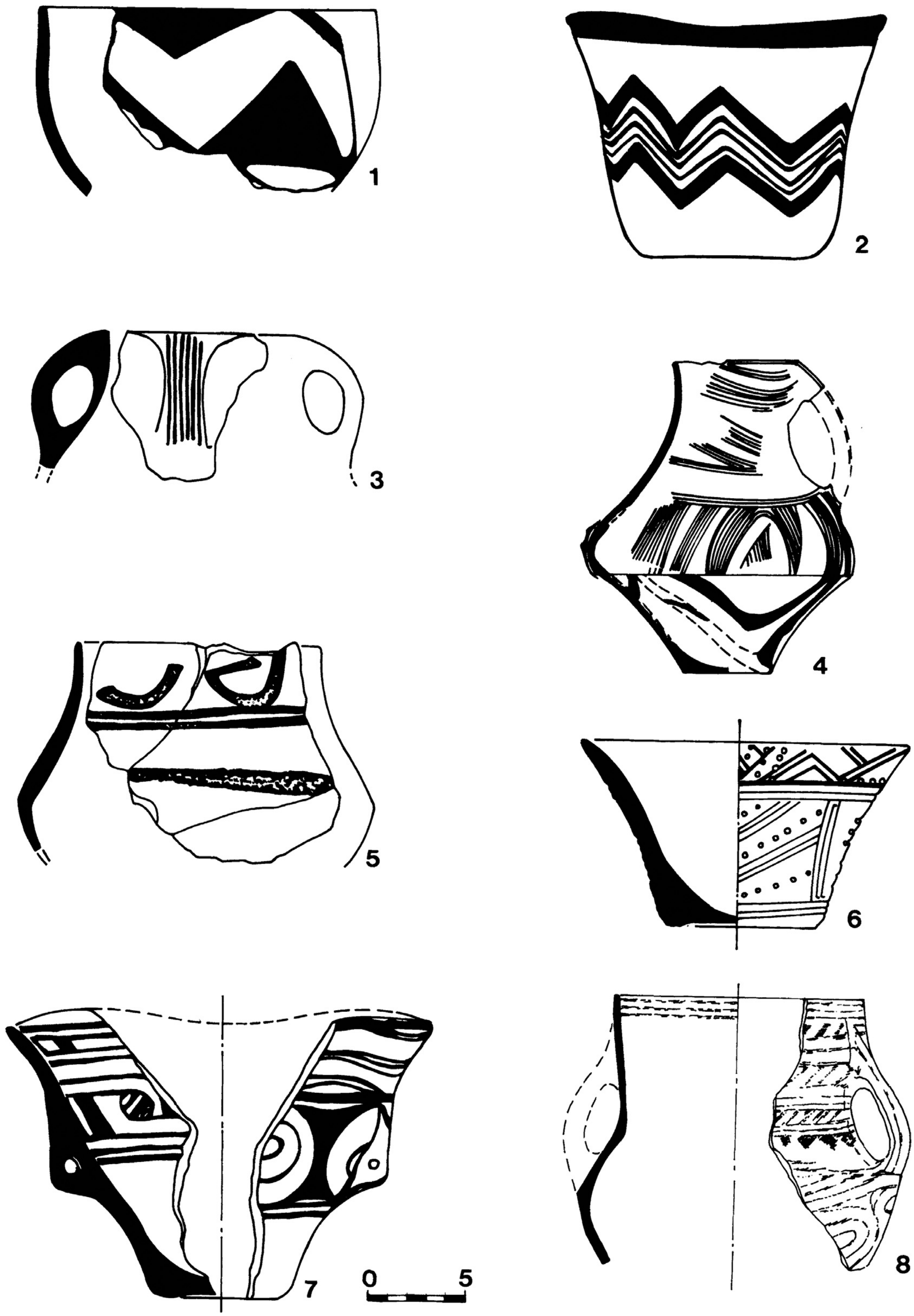

Fig. 5. Neolithic painted vessels in northern Greece. (1) Red-on-White (EN Nea Nikomedia). (2) Grey-on-Grey (LN Servia). (3) Organic coating (LN Dimitra). (4) Brown-on-Cream (LN Dikili Tash). (5) Brown-on-Grey (LN Dimitra). (6) Graphite excision (LN Dikili Tash). (7) Black-on-Red (LN Sitagroi). (8) Graphite painted (LN Sitagroi). From Yiouni 2001:Fig. 2.

as also observed by Gardner (2003:289) at Sitagroi, which indicated that the firing was likely usually in two, no doubt intentional, steps: oxidising conditions when the maximum temperature was reached and sintering had begun, followed by a reducing phase during which the temperature fell. To reinforce the reduction, increase the smoke, and deposit carbon onto the surface, Amicone et al. proposed the possible addition to the fire of “a readily combustible fine-textured organic material.”

Amicone et al.’s XRD data pointed to a maximum firing temperature range of 750–850°C for most sherds, manifesting itself as initial vitrification in the SEM images. Taken together, these data sets were

Fig. 6. Decorated pottery from Promachon-Topolnica. (a) Black-topped carinated bowl (photo © K. Georgiev). (b) Brown-on-Cream ware (imported Akropotamos Type A) of Promachon-Topolnica Phases II and III (photo © I. Vajsov). (c) Organic-painted Topolnica Type C ware (photo © K. Georgiev and I. Vajsov. (d) carinated organic-decorated vessel, Topolnica Phase II (photo © K. Georgiev). (e) Graphite-painted ware, Type D4.1 (thick-lined), Topolnica Phase IIIA (photo © K. Georgiev). Images from Vajsov 2007:Figs. 10B, 9, 1, 5, 8A, and 13, respectively. (f). Black-on-Red two-handled pot (Malamidou 2005:variety 1) from Dikili Tash (Treuil 2004:Plate E.1). Reproduced with permission from Kilikoglou et al. 2007:Fig. 1.

rationalised as being equivalent to 800–850°C in an oxidising atmosphere and 750–800°C in a reducing atmosphere (whether a calcareous or non-calcareous clay). Estimates obtained from Vasilika (Sikalidis et al. 1983), Dimitra (Kessisoglou and Mirtsou 1997:Table 1), and Dikili Tash (Maniatis and Tite 1981) all converge on <750°C. Such temperature ranges, while lower than some previous estimates, are consistent with a growing consensus that, although the temperatures were variable given that this pottery was made at many different locations over a long time period, they were generally at the lower rather than the higher end of the scale (Yiouni 2001:Table 4). Accepting this view, which I believe is correct, implies that there can be no direct connection between the production of black-faced pottery and the smelting of copper ores, because the latter requires a higher temperature (up to 1083°C to melt copper). As Amicone et al. put it, “The two crafts are likely to have been generally linked, making them ‘close cousins’ rather than one being the precursor to the other” (2020:16). Returning to the issue of skilled versus specialised, if, as Radivojević and Rehren (2016) have suggested, during its earliest phases metalworking could have been a nonspecialised *household* activity, the need to invoke specialised craft activity is diminished; it was skill that counted.

As for characterising the painted layer, μRaman proved more definitive than μXRD, the former identifying it as crystalline graphite (Amicone et al. 2020:Fig. 8). A final point to make in this examination is that the natural occurrences of graphite in the Balkans (for Bulgaria, g

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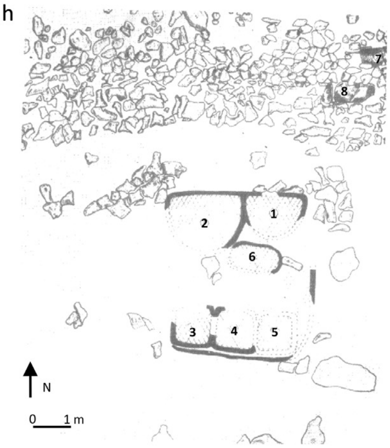


Fig. 6. Continued (g) Left: The pit-like firing structure at Kryoneri. Right: The same structure and in the foreground the adjoining pit (Malamidou 2016:Figs. 4 and 5). Images courtesy of Dimitra Malamidou. (h). Firing structures 1–5 at Kamnik. No. 6 is a "hearth." A stone wall and medieval graves (nos. 7 and 8) lie to the immediate north. Adapted from Prendi and Aliu 1971:Fig. 3.

Table 3a
Investigations of Neolithic Pottery in Greece and Beyond, Arranged According to Region and by Year of Publication

Date, Pottery Type, Site	Samples	Techniques	Publication
Northern Greece, Albania, Balkans			
MN–LN, R, Makri	30	PE, refiring	Yiouni 1995
EN, R, Nea Nikomedia	many	PE, refiring	Yiouni 1996
MN (19), LN (44), mainly decorated, Dimitra	63	XRD, DTA	Kessisoglou and Mirtsou 1997
LN, R, Vasilika		XRD, DTA	Sikalidis et al. 1983
MN–FN, R, C, Kitrini Limni (Megalo Nisi Galanis)	55 13	PE (LN–FN) GC-MS FTNIR, nd-XRF, REP	Aloupi-Siotis and Kalogirou forthcoming; Fotiadis et al. 2019:15–16; Kalogirou 1994
EN–FN, R, Nea Nikomedia, Dikili Tash, Sitagroi, Makri, and nine other sites in Macedonia and Thrace	140	PE, SEM, refiring	Yiouni 2001
EN–EBA, R, esp. G, Sitagroi	many	refiring (sinter determination), XRD	Gardner 2003
LN, carinated pot, Dikili Tash	1	SEM-EDX, FTIR	Maniatis and Tsirtsoni 2002
MN–LN–EBA, R, Dikili Tash	83	PE (XRD, DTA)	Courtois 2004
LN, tableware, Stavroupoli	3	GC-MS	Urem-Kotsou et al. 2004
LN, B-on-R, 13 sites mainly in the Strymon and Angitis Valleys, E. Macedonia	195	clay prospection; NAA	Kilikoglou et al. 2007; Malamidou et al. 2006
LN, B-on-R, C, CD, G, Polyplatanos	44	μXRF, OM	Sakalis et al. 2013
LBA, G, Tiszabura Bónishát, Hungary	65	Exp, SEM	Kreiter et al. 2014
EN, R, Blazi, Kolshi, Vashtëmi, and Podgorie, Albania	96	μXRF, pXRF, XRD	Ndreçka et al. 2017
LN–Chalc, G, and DB, Belovode and Pločnik, Serbia	88	μXRD, μRaman, SEM	Amicone et al. 2020
LN, R, Kamnik, Maliq, Kallamas (Albania)	many	pXRF, XRD, GC-MS	Elezi 2020
Cyclades, Central and Southern Greece			
LN, R, Ftelia, Mykonos	31	SEM, PE, XRF, XRD	Aloupi 2002
MN, Urfirnis, Peloponnese		SEM Exp	Panakleridou et al. 1985; Vitelli 1997
MN–LN, R (mostly surface finds), Sesklo, Dimini, Soufli, Platia Magoula Zarkou, Makrichori 2, and other sites in Thessaly Sesklo	c. 1000	PE, XRF (XRD, SEM) XRF, XRD, SEM	Schneider et al. 1991; Maniatis et al. 1988
MN, decorated, 10 sites in Thessaly, including Tsangli and Zerelia	47	pXRF	Rondiri and Asderaki-Tzoumerkioti 2016
LN, R, Tharrounia	8	SEM-EDX	Kilikoglou and Maniatis 1993
Grey ware		Exp	Vitelli 1994
MN clay structure, Kouphovouno		SMM	Ballut et al. 2017
MN clay structures, Magoula Imvrou Pigadi		SMM, FTIR, XRD, XRF	Roussos and Kyparissi-Apostolaki 2018
LN, CD, P, Dimini	many	pXRF, XRD	Elezi 2020

Notes: Pottery type: R denotes a range of plain and decorated wares; B-on-R = Black-on-Red; C = Crusted, CD = Classical Dimini; DB = Dark Burnished; G = graphite; P = Polychrome wares; SMM Soil micromorphology. "Samples" refers to the total number examined, any or most of which are decorated/painted.

see Leshtakov 2004) are relatively few and their properties are far from uniform, so graphite may have been regarded as a status material and one involved in exchange networks; in this connection, the identification of graphite in a polychrome sherd at Kamnik (Elezi in press) and other sites in Albania is relevant (Hasa et al. in press). Gardner (2003:296) contrasts the sparkling crystalline appearance of the thickly applied and well-bonded graphite layer in pottery south of the Rhodope Mountains with that to the north, which tends to be more ephemeral, thinly applied, and less well bonded.

Organic-based pigments

Black decoration was achieved in an additional manner during the LN, with the application of the tar of birch and related trees, prepared by heating the bark in a probable sealed container. This type of organic decoration, confidently identified by GC-MS, has been found at several LN sites, notably Promachon-Topolnica (Vajsov 2007), Stavroupoli

(Urem-Kotsou et al. 2004), and Varemenoi (Urem-Kotsou et al. 2017:332).[6] The same material also found use in sealing and repairing, for example at Paliambela and, together with pine pitch and resin, at Makriyialos (Mitkidou et al. 2008). At Promachon-Topolnica it even appears as decoration on bark itself (Koukouli-Chryssanthaki et al. 2007:Figs. 16, 19). The distribution of birch tar products appears to be relatively wide, yet although birch is quite common today (for example in the woodlands north of Drama and into the Rhodope range), that was not the case during prehistory, when oak and conifers dominated, to judge from pollen and charcoal data (Gerasimidis and Athanasiadis 1995; Ntinou and Badel 2000). So the birch tar may have been a special product and therefore a potential item of exchange (Urem-Kotsou 2016:126–27).

On the basis of the finds from Promachon-Topolnica, Vajsov (2017:89–90) offers a possible outline of how this striking, post-firing decoration (Fig. 6e) was achieved mostly on the upper part of vessels, typically with carinated profiles and vase-like shapes with high necks. The different decorative shapes were cut out from birch bark, covered with tar, and glued onto the still-warm vessel surface, creating a very thin (0.1–0.2 mm) layer. The decorations were carefully cut out with a sharp, fine tool, without leaving any incision marks.

Elaboration through experimental replication of what must have been a skilled procedure would now be most appropriate, but in the meantime, there is the important issue of nomenclature to resolve. The term *bitumen*, which is used in the description of this pottery at Promachon-Topolnica and sites to the north in Bulgaria, should, pending confirmation by analysis, more correctly be called plant-based tar. This would leave *bitumen* to refer strictly to oil-based tar, a dark material that, most significantly, has recently been documented as undertaking the same functions: decoration, coating, and repair. Particular saturated and aromatic hydrocarbons acted as markers for the identification (by GC-MS) of bitumen on LN pottery from Kamnik (Elezi 2020); a likely (and well-known) source is Selenicë, lying some 110 km northwest of Kamnik. It will be interesting to see the distribution of this decorative material in Albania and into western Macedonia.

What was initially diagnosed as a black, possibly organic crust on the interior of an LN decorated jar found in a house at Dikili Tash was found on analysis to be pure iron oxide, probably hematite, which had partially converted to maghemite and magnetite in the house's fire destruction (Maniatis and Tirtsoni 2002). This mineral pigment could have found several applications in addition to its use as a post-firing decorative medium in Crusted ware. The materials appearing as the crust in this ware are mainly red (red ochre/hematite-rich) and white (calcite) but also include shades of yellow to pink. Moving to Megalo Nisi Galanis, where Kalogirou (1994:119–20) has usefully outlined the criteria required to assess when the crust was applied, there were four instances of pre-firing application; FTNIR identified the presence of mineralogical phases indicative of >600°C firing, eight examples of post-firing, and one intriguing instance of red and brown paint layers overlying a light-coloured coating that had been applied *after* firing (Aloupi-Siotis and Kalogirou forthcoming:Table 2). Unusual but local clay minerals rich in talc-saponite, distinguished chemically by high Cr and Ni contents, featured in the body and often with related serpentine in the white and red crusts; hematite provided the colouring in the latter. An unidentified organic compound was also commonly present, as discussed below.

These results recall those obtained at nearby Polyplatanos in the same region, where the Cr and Ni were variable and high in the body, higher still in the crusts (up to 2000–3000 ppm) (Sakalis et al. 2013:494–96, Table 2); the authors proposed that the crusts were probably post-firing. The CaO content in the white crust and the cream in Cream-on-Red at the same site differed considerably: about 10% and >20%, respectively. Talc, which occurs on Mykonos, appears as a post-firing white crust (and red hematite-rich crust) on LN pottery at Ftelia on that island (Aloupi 2002). This pottery had been rapidly fired, perhaps in an open pit, at temperatures not exceeding 750–800°C.

A final point in this section concerns the white coating/slip on the interior of plain EN bowls at Revenia and Paliambela, which appears to be bone-based (Urem-Kotsou et al. 2017:326, Fig. 3). This unexpected finding recalls the definitive identification (by FTIR and SEM) of bone (powder) forming the beige residue found in the interior of many EN pots at Kovatchevo (Vieugué et al. 2015); the residue had no connection with the white decoration on the exterior of some pottery from this site, which was found usually to be white clay (Vieugué et al. 2015:505). That said, bone paste occurs not infrequently as the white decorant in incrusted pottery in later prehistory, for example in Iberia (Odriozola and Hurtardo Perez 2007), northwestern Italy (Giustetto et al. 2013), and Hungary (Roberts et al. 2008).

I have referred above to programmes of petrographic analysis of clays selected for pottery making in Thessaly that built upon a major study undertaken by Schneider et al. (1991); that study included technological characterisation of the painted wares (Schneider et al. 1991:48–50), supplementing the results of earlier work by Letsch and Noll (1983) and others. The manganese black technique, well represented in LN Thessaly, notably at Dimini (Elezi in press), was skilfully combined with iron-based paints and a calcium-rich white to give the polychrome effect. Another painted ware—Thessalian Grey-on-Grey—has continued to arouse interest for its high firing temperature (900°C and above [Schneider et al. 1991: 25]), low calcium fabric, and uniform composition characteristics, pointing to specialised production in a restricted area of Thessaly.

Non-calcareous clays were commonly used throughout most of the region for the body of MN Red-on-White slip pottery. The most common type of white or pale slip forming the background on which red was painted on MN pottery in Thessaly was calcareous (22 of the 33 samples), followed, unexpectedly, by gypsum/selenite (10) (mainly at Tsangli, Zerelia, and Aidiniotiki) and lead white (1) (at Dasolofos west of Tsangli) (Rondiri and Asderaki-Tzoumerkioti 2016). Less unexpected was the use of iron-rich materials for the red decoration, including one instance of possible iron sulphite (at Kamara). The use of calcareous clays, mentioned above, had appeared, for example at Sesklo, by the end of the MN (Maniatis et al. 1988) and became increasingly the norm thereafter into the Bronze Age (cf. *GCP*, 895)

To these findings can be added the outcome of experiments on Grey ware reported by Vitelli (1994). Besides two of their prominent outcomes—(a) the relative difficulty of firing a small crude kiln to >950°C and maintaining that temperature under reducing conditions and (b) that the pots that achieved a uniform grey colour had been enclosed in a saggar effect by other pots—was a valuable cautionary note: some Grey ware could have been the product of either accidental firing conditions in the potter's kiln or, given that Grey-on-Grey ware occurs at certain cemetery sites, such as Platia Magoula Zarkou, some subsequent fire/firing. A controlled reducing atmosphere accounts for the Grey ware (with 8% Ca content) at Tharrounia (and Varka Psakhnon, north of Chalkis) in Euboea, which together with a manganese black decoration on a similarly calcareous fabric had been fired as high as about 1000–1080°C,[7] unlike the other decorated pottery from that site (Kilikoglou and Maniatis 1993:Table 1).

Comment on the decoration of Urfirnis in southern Greece appears in the next section.

B1b. Firing structures

How vessels with such a wealth of decorative effects were fired remains a major issue. On the issue of terminology, the term *kiln* here means a structure in which the pots are separated from the fire—that

[6] Mitkidou et al. (2019) reported comparable results from sites in Serbia. There was also evidence of admixture with animal fat and pine pitch.

[7] This estimate, based on the microstructure observed in the SEM, could be lower if redox firing conditions are accounted for.

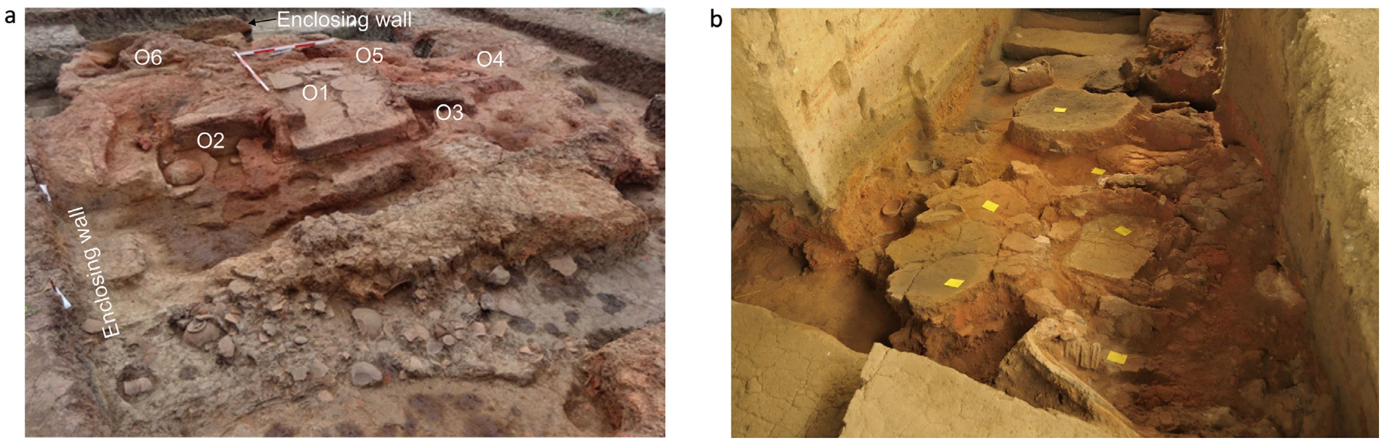


Fig. 7. a. Oven complex at Magoula Rizava (Krahtopoulou et al. 2018:Fig. 2). Photo courtesy of Athanasia Krahtopoulou, with annotation by the author. b. Remains of firing structures situated between two clay walls at Magoula Imvrou Pigadi (Kyparissi-Apostolika 2012:Fig. 9). Photo courtesy of Nina Kiparissi.

Fig. 8. Middle Neolithic Urfirnis vase from Franchthi Cave, Argolid. From Theocharis 1973:Fig. 51; © Hellenic Ministry of Culture.

is, a two-chambered structure (Fig. 2a). I emphasize at the outset here that, as experimental and ethnographic studies have shown, maximum temperature is not a reliable guide to the firing structure. For example, it can be up to 900°C (or higher) in a pit firing (well demonstrated in Thér 2014:Fig. 3), the point being that that temperature would not be maintained or controlled in a way that would be possible in a kiln.

Open firing in a bonfire would account for EN vessels, as evidenced, for instance, by the appearance of firing clouds and variegated surface colour on individual vessels at EN Nea Nikomedia (Yiouni 2001:22). By early LN, a more controlled firing environment was becoming more commonplace, achieved presumably in a kind of pit. LN Grey-on-Grey ware and probably Black-on-Red ware as well are two candidates that demanded a more sophisticated firing structure, possibly in the form of a kiln. But as valuable as the firing temperature estimations are, as outlined above, in demonstrating the ranges that could be achieved during the course of the Neolithic, they can be associated with a particular firing structure in only a very broad sense. Compounding this limitation is the relative paucity of excavated firing structures that can be confidently linked with pottery making. In addition to the example at Olynthos excavated by Mylonas (1929), which has previously been discussed (*GCP*, 776–77, Fig. 9.5a), possible candidates in Macedonia include:

- MN Dikili Tash—the floor of a deformed, burnt oven on which were sherds and stones within a habitation area (Treuil 1992:42–43, 46–47)
- LN Stavroupoli—a circular oven constructed within a large pit and associated with a hearth, a grid-like construction, and many sherds (Grammenos and Kotsos 2002:292–23)
- Limenaria on Thasos—a similar grid-like feature (Papadopoulos and Malamidou 2002:26–27)
- LN Kryoneri—a cylindrical pit built into the hillside with an opening on its side (Fig. 6g). At the opening there was much fuel and ash, as was also the case in an adjoining pit containing sherds, daub, and bone (Malamidou 1997:515, Fig. VII5; Malamidou 2016:Figs. 4 and 5)
- Amyndaion in northwestern Macedonia—an oven with associated pottery relating in shape with those in northwestern Thessaly, described below (Chrysostomou and Giagkoulis 2018:Fig. 8b).

Moving west to Kamnik in Albania, there are the firing structures reported by Prendi and Aliu (1971), constructed against a stone wall and lying just outside the habitation area. Three of them are linked, rectangular in shape, and separated by a hearth from two oval-shaped ones (Fig. 6h). Elezi (2020:98) reports that their upper parts form arches that have holes for controlling the firing temperature and that "several intact semi-fired vessels" were recovered within the structures. The way they form a complex recalls earlier (MN) examples at Magoula Rizava and possibly also at Magoula Imvrou Pigadi in Thessaly (see below).

Reference should also be made here to the materials and tools linked to pottery making—"pieces of raw clay prepared for pottery manufacture, lumps of ochre in various colours, cone-shaped pieces of graphite, stone and bone tools as well as several almost complete and fragmented ceramic vessels"—as well as a firing structure from the interior of Yagodina Cave in the western Rhodope Mountains (Todorova and Avramova 2016:Fig. 5:3). Graphite-painted and Crusted wares are the main types of decorated pottery, dating to the (early) Chalcolithic period. Some intriguing detail is given about the firing structure: the floor (1.90 × 1.75 m) was made from uneven plaster, 3 to 4 cm thick, laid directly on the yellowish virgin soil, and on that floor was a 6 cm–thick layer of fine ash overlain by the remains of the dome, consisting of 4 cm–thick fragments that were strongly fired and plastered on both sides. However, if this was a firing installation instead of a kiln, it remains hard to visualise any firing of pottery in view of its location in a gallery deep within the cave. The term *plaster* needs definition, although it may not be entirely out of place in view of the lime-covered clay associated with the clamp firing at Kouphovouno (see below) (Ballut et al. 2017:Fig. 4.1).

At this point it is helpful to refer to the firing structures that Thér (2014) constructed for experimental firings carried out in Bohemia. Fig. 2a gives a sense of their variety when the vessels are in direct contact with the fuel: Ba, Ca, SKO, and even SKD. Although his results bear

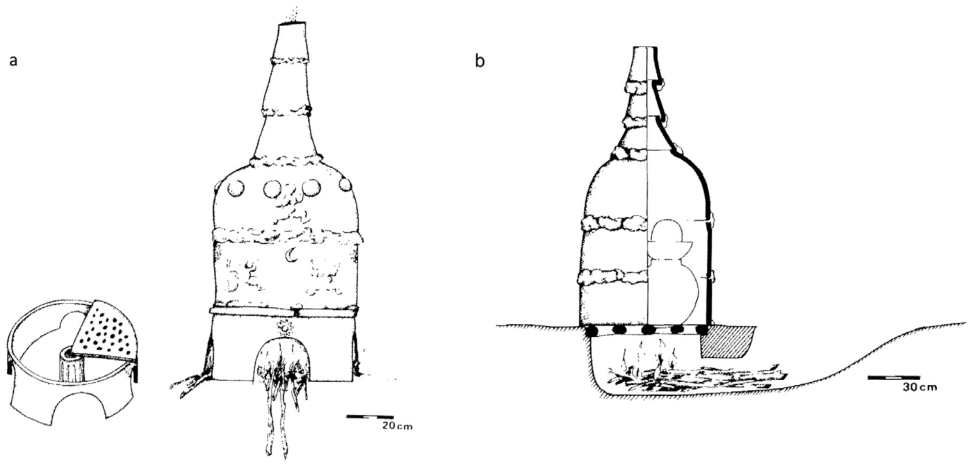


Fig. 9. (a) Experimental kiln supported on a base. (b) Experimental "bottle" kiln. Reproduced with permission from Vitelli 1997:Figs. 7–8.

out those of other researchers, it remains very difficult to discriminate between those individual structures on the basis of thermal characteristics gained in the firing experiments, such as duration, maximum temperature, heating rate, and soaking time, Nevertheless, the example at Kryoneri superficially appears close to Thér's SKDb (Fig. 2a).

Contrasting in function are the ovens, hearths, and fire-pits inside houses and in courtyards that were all most likely associated with the preparation of food (Demoule and Perlès 1993:377; Kalogiropoulou 2014) and that are such a common feature at Neolithic and EBA settlements in northern Greece—for example Dikili Tash (Papadopoulou and Prévost-Dermarkar 2007) and Archontiko (Papaefthymiou et al. 2007). In support, Maniatis et al. (2002), using mainly FTIR, established that these were low-fired structures; at the latter site, the clay walls and floors of the structures had reached temperatures well below those determined in early pottery: 400–650°C.

Moving to Thessaly, besides the well-known likely potter's workshop at MN Sesklo (Andreou et al. 2001:note 14), there is a locus of production of pottery and probably other artefacts at LN Dimini—workshop S8. It consists of a circular structure of stone and clay around a pit associated with sherds of incised ware, ash, and clay lumps (Souvatzi 2008:141–43, Figs. 5.30, 5.31). Two recent exciting discoveries of firing structures in northwestern Thessaly have widened our knowledge of pre-kiln firings: an oven complex at Magoula Rizava (Fig. 7a), where (mostly) MN Scraped ware was fired (Krahtopoulou et al. 2018:Fig. 6), and a different setup of the same date at Magoula Imvrou Pigadi (Kyparissi-Apostolaki 2012; Roussos and Kyparissi-Apostolaki 2018) (Fig. 7b).

At the former were six firing features, here called ovens, enclosed by a mud-brick wall and lying at the western edge of the tell. Recovered from the best preserved of them, O1, were the floor, front opening and walls (which would have led up to the domed superstructure), and a bench outside, all set on a raised platform (Fig. 7a), but no ash. The SKDa structure of Thér (2014) (Fig. 2a) may offer some comparison apart from the step at the rear of the oven. Beyond the enclosing wall was a "corridor" where large quantities of sherds, clay lumps, and non-ceramic debris had been dumped. Beyond that corridor were the remains of a similar set of ovens as well as evidence of much burning. Pending the results of petrographic analysis, the finds hint at a level of ceramic activity suggesting that the site may have been a regional centre capable of producing high-quality well-fired pottery, Scraped ware.

At Magoula Imvrou Pigadi, between two mud-brick walls was an area of intense burning comprising clay structures, together with ashes and monochrome pottery (Fig. 7b). These are ovens rather than kilns, but it is not yet possible to relate them in shape to Thér's scheme. Combined FTIR, XRD, and micromorphological analyses of clay materials rather than pottery within this area (Phase C) indicated temperatures in the range 600–700°C.

In the Peloponnese, interest has focused on MN Urfirnis ware, a very early and effective example of the use of the iron reduction technique; examples of Urfirnis highlighting the technique at its best are impressive for their vivid and contrasting colours (Fig. 8). Based on the plentiful finds from Franchthi Cave, Vitelli (1993:199–211) has fully outlined its technological development, which can now be set beside the results of her experimental firings (Vitelli 1997; cf. Vitelli 1994). These explored several important features: stacking the pots and usually capping with an inverted pot, and placing the stack within a large bottomless pot built up in sections topped by a "chimney." This assembly sat on a grill either over a base that held the fire, thereby creating in effect a portable kiln (Fig. 9a), or over a pit (Fig. 9b). In an oxidising firing of this "bottle kiln," the temperature reached 850°C in two hours in the centre of the stack. The stacking arrangement would have created localised variations

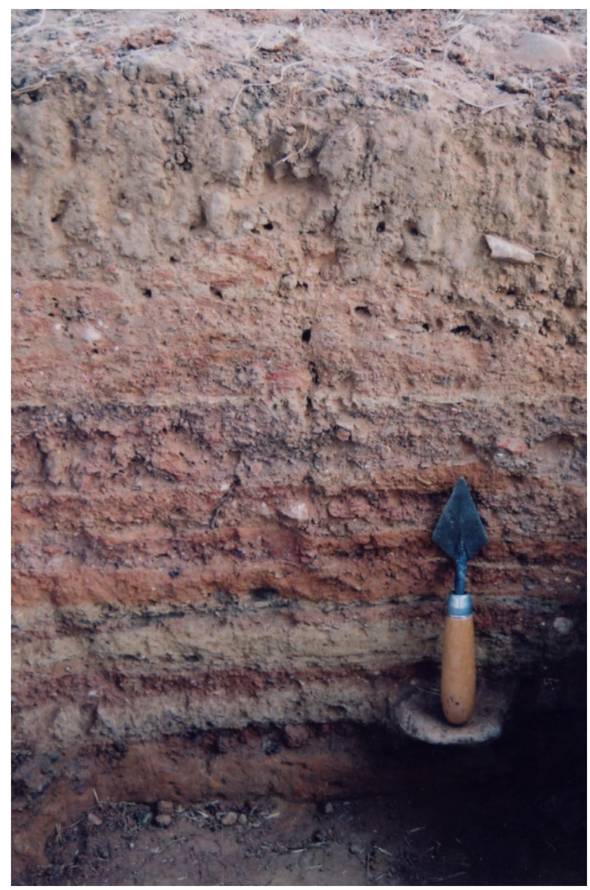


Fig. 10. "Millefeuille" effect in the clamp excavated in Area C at Kouphovouno, Laconia (Ballut et al. 2017:Fig. 4.1). Photo courtesy of Christele Ballut.

in redox conditions such that the pots would have emerged from firing with variegated colours.

Both arrangements are attractive in the way they accord, as we have seen, with the very limited evidence for prehistoric pottery firing structures in the archaeological record; the portability of the former setup would leave little if any evidence after use, while the pit in the latter case is a common feature at early prehistoric settlements. Neither arrangement features in Thér's scheme (Fig. 2a); both are small scale but could be scaled up in size.

Of considerable interest, not to say surprise, is the contrast between Vitelli's experimental scheme and the archaeological evidence for clamp firing of Urfirnis at Kouphovouno in Laconia, arising from excavation and subsequent micromorphological study of the sediments recovered in a courtyard within the settlement (Ballut et al. 2017). The clamp was built on a flat or slight hollow, fuel was placed at the bottom, and above were the (well-dried) pots, which sat on stones and were stacked up, covered by a mantle made of a composite of sherds, earth, and/or wattle/daub. Openings in the mantle allowed the atmosphere to be controlled as necessary; at the end of firing, the mantle was broken up and discarded. The clamp manifested itself as a "millefeuille" effect of alternating red and white bands (Fig. 10), the former being the burnt deposits of the mantle's construction materials and the latter being lime-rich, perhaps formed during firing from the limestone pebbles on which the pots were stacked. This effect recorded firing sequences that occurred immediately prior to an episode involving raising the level of the courtyard's floor. The Kouphovouno clamp is not paralleled in Thér's (2014) scheme (Fig. 2a).

Study of the Neolithic pottery and the clamp firing at Kouphovouno has reopened discussion about the significance of Urfirnis. It was surely made by skilled potters (Mee 2007:210), but in view of the high level and particularly the household aspect of its production at least at Kouphovouno, these craftspeople were not necessarily specialised. Nor did they necessarily have the status of shamans or ritual healers as advanced by Perlès and Vitelli (1999:102–3). Urfirnis, representing a stylistic uniformity that contrasts with greater diversity in the LN, fulfilled a crucial social role at a time when the presentation and consumption of food and drink was important in emphasising shared values and a sense of identity and in promoting integration (Mee et al. 2014:93). The commonality of the decorative style and technology of Urfirnis at sites in the northeastern Peloponnese such as Asea, Franchthi Cave, and Lerna, and probably extending to Kouphovouno, hints at a level of intersite interaction. Vitelli (1984:126) has explained this situation in terms of the movement of potters rather than their products. On the basis of her analysis of the decorative style and supported by (unpublished) archaeometric analysis, Cullen (1985) took this important hypothesis further, suggesting that woman potters may have "married" outside their communities, taking their skills and knowledge with them: "The hypothesized relocation of women from one community to another provides the necessary opportunity for close interaction and instruction among potters" (Cullen 1985:96).

B1c. Discussion

Clearly emerging from this brief survey of the long early period of pottery making in Greece is the diversity of shape and form of firing structures, and the same is reflected in contemporary neighbouring areas (for Italy see Robb 2007:148f; see Moffa in Jones et al. 2014:386f). It is also clear, but less fortunate, that their remains are incomplete to very incomplete, thereby hindering assessment of their functioning with the aid of 3D reconstructions. However, the basic point remains that the archaeological record has yielded no true kilns dating to the Neolithic. Pending new discoveries, Vitelli's experimental structures and those postulated to fire Grey-on-Grey ware are important, yet speculative, reference points. Viewed in a broader perspective, the incomplete nature of the archaeological record of firing structures is at least partially compensated for by information gained from pottery found in or associated with the structures. In other words, the macroscopic and laboratory-based examinations of this pottery have, as we have seen, yielded as much or more about firing as have interpretations of the functioning of the structures themselves.

The results presented here expose some contrasting aspects of the decorating and firing of pottery, likely including the preparation of raw materials and the forming of the vessels. During the EN, choices throughout the *chaîne opératoire* were generally made at a local level, drawing on long-standing empirical experience and to meet communal needs. But during the later phases of the Neolithic, and as pottery making was usually undertaken on a larger scale, social and economic contacts linking sites on an intra-regional basis encouraged a greater dissemination of pottery making knowledge and experience as potters as well as their products may have moved within a region. Production of LN Black-on-Red ware in the region around the Strymon and Angitis Rivers in Macedonia is one example, and above I have referred to instances within Thessaly and, for MN Urfirnis, parts of the Peloponnese. Now the stage is being set to look beyond that to the *inter*-regional level, stimulated in particular by recent work at Kamnik and neighbouring LN sites. Elezi (in press) has proposed possible networks of interaction between those sites and Thessaly. In any case, we are left to marvel at how apt the term *technological choice* applies to all steps in pottery making sequence throughout the Neolithic; the diversity of materials selected for decoration is but one facet of that term. Archaeometric and related methods have indeed enjoyed a field day in Neolithic ceramics, as of course they have in other spheres of the period's material culture.

The one step that has proved tantalisingly difficult to characterise confidently is firing. Its locations are few in number. I have already mentioned the incomplete nature of structural remains and their usually poor condition of survival, which complicates their interpretation. Besides, they give a sense that rather than being uniform in layout and function, they were a response to local, varied circumstances. Nevertheless, some admittedly indistinct trends may be apparent: (a) a tendency for firing to take place at the edge of the settlement (for example, Kryoneri, Magoula Rizava, and Kamnik) and (b) hints that pottery firing was perhaps joined in a given location by other activities: the presence of pits adjoining the firing area, for example at Dikili Tash, and the presence of bone among other debris in the pit at Kryoneri (Fig. 6g). It is striking that the examples just described in Thessaly and Laconia all belong to the MN period. Looking to the future, this is a topic that could only benefit from collaboration between excavator and relevant specialist, especially at the critical time of excavation. Attention has already been drawn to the ovens, hearths, and fire-pits inside Neolithic houses that have a direct connection with food production. An open mind is called for in considering the relationship between these structures and pottery firing installations as they need not and should not be treated separately; the former led to the latter.[8]

At a methodological level, the contribution of soil micromorphology in two studies reported here is welcome. Several techniques, varying in sophistication, have been applied to firing temperature range estimations. As Amicone et al. (2020) have shown, the combination of XRD and SEM is a powerful one, as it draws on, respectively, mineralogical and microstructural reference data obtained as a function of both temperature and atmospheric conditions. Thér (2014:96) mentions cracked quartz grains and pores as potentially promising indicators of certain firing procedures, resulting, for example, from high heating rates.

B2. The Bronze Age

Rutter (2021) gives a full archaeological background, drawing on reviews by Watrous (2001), Rehak and Younger (2001), Shelmerdine

[8] A Balkan-wide perspective is useful here. See, for example, the LN oven with divided baking plate found at LN in the Hungarian Plain (Raczky and Anders 2016).

Table 3b
Investigations of Bronze Age Ceramics, Arranged by Region and Date

Date, Pottery Type, Site	Samples	Techniques	Publication
Crete			
FN III–EM IB, R, Phaistos	304	SEM, FTIR. and PE	Mentesana et al. 2017
EM I–II, R, Knossos	16	SEM-EDX and PE	Kilikoglou in Wilson and Day 1994
EM III–MM III, white-painted wares, Kommos, Palaikastro, Knossos, Mochlos, Gournia	26	PIXE	Ferrence et al. 2001, 2002; Betancourt et al. 1984
MM, Kamares, Phaistos, Ayia Triadha	8 and 12	PIXE, PIXE-α	Pappalardo et al. 2010, 2015
EM II Dark-on-Light, MM, Kamares, Phaistos, Knossos, Malia, Palaikastro, Myrtos-Pyrgos	many	PE and SEM	Day et al. 2006
MM, Kamares, Knossos	73	SEM-EDX	Faber et al. 2002
LM IA, kiln pottery, Kommos	57	SEM-EDX, PE, NAA	Shaw et al. 2001
LM IIIA larnakes, Armenoi and Maroulas cemeteries	40	pXRF, pRaman	Fovakis et al. 2021
Mainland			
EH, light and black-red slipped wares, Manika	20	SEM-EDX	Aloupi 1993:178
MH–LH and later, decorated, Kynos	45	XRF, SEM-EDX	Tsiachri et al. 2018
EB III–MB, pattern- (matt-) painted and solidly painted wares, Kolonna, Aegina	80	SEM-EDS (15), PE, refiring, ICP	Gauss and Kiriatzi 2011; Kiriatzi and Iliopoulos 2011
MH, matt-painted (12), Minyan, and others, Eleusis	27	SEM-EDX	Cosmopoulos et al. 1999
LH III, Mycenaean, Mycenaean-derived and -related, Assiros, Thessaloniki Toumba, Mycenae; Broglio di Trebisacce (Italy) LH III, Italo-Mycenaean, multiple sites in Italy	136	SEM-EDX (106), NAA, XRD (44), PE SEM-EDX, radiography	Buxeda i Garrigos et al. 2003; Jones et al. 2014, 2021
LH IIIA–B tin-coated vessels, Asine	7	SEM, XRD, and Exp XPS (ESCA), tof-SIMS	Gillis 2001 (and references therein); Gillis and Bohm 1994
LH III, decorated, Berbati and other sites	20	XRD, NAA	Buxeda i Garrigos et al. 2002
Cyclades			
MC, R, Akrotiri, Thera	20	SEM-EDS, PE	Day et al. 2019
MC, R, Akrotiri, Thera	19	SEM-EDX, NAA	Kilikoglou et al. 1990
LC I, decorated wares, Akrotiri, Thera	29	SEM-EDX	Aloupi and Maniatis 1990

Notes: FN = Final Neolithic, EH = Early Helladic, MH = Middle Helladic, LH = Late Helladic, MC = Middle Cycladic, LC = Late Cycladic, R = range of wares.

(2001), and others, and also provides a more detailed chronology of the Bronze Age beyond that in Table 2:

Minoan Crete

Pre-palatial EM I–MM IA (c. 3100/3000–1925/1900 BC)

Protopalatial (or Old Palace) MM IB–MM IIB (c. 1925/1900–1750/1720 BC)

Neopalatial (or New Palace) MM IIIA–LM IB (c. 1750/1720–1490/1470 BC)

Post-palatial LM IIIA–C (c. 1490/1470–1075/1050 BC)

Mycenaean Mainland

LH I–II (c. 1700/1675–1420/1410 BC)

LH IIIA (c. 1420/1410–1330/1315 BC)

LH IIIB (c. 1330/1315–1200/1190 BC)

LH IIIC (c. 1200/1190–1100 BC)

B2a. Surface treatments and firing temperature estimations

Early work on Bronze Age pottery (*GCP*, 779–95, Tables 9.7a–b, 9.8a–b) explored the distinctive decorated pottery of Minoan Crete before the palaces (Vasiliki ware [EM I] and White-on-Dark ware [EM III–MM IA] [Fig. 12a]), followed by the polychrome decoration on Kamares ware (Fig. 12b) so characteristic of the First Palace period; the use of Mn-based pigments on matt-painted ware during the Middle Bronze Age in parts of the mainland; the increasing sophistication of the iron reduction technique in decorated Mycenaean pottery; and the rare appearance of tin-coated Mycenaean pottery in funerary contexts.

Table 3b lists the investigations, arranged by region—Crete, mainland, and Cycladic Islands—and chronologically.

(1) Crete

The rich ceramic repertoire from the Final Neolithic (FN) to the Pre-palatial period and throughout the time of the palaces has received, since the 1990s, considerable attention from the point of view of technological traditions relating to clay selection, surface treatments, and firing procedures, particularly for pottery of the south-centre of the island (Mesara), the Knossos area, and eastern Crete. Petrographic and to a lesser extent chemical characterisation of pottery belonging to all phases of the Minoan period has laid a fundamental foundation stone for technological enquiries.

(2) Crete: Final Neolithic–Middle Minoan

Innovation appearing alongside continuity in the technological aspects of potting traditions, the regional basis of those traditions, and their relative interconnectedness are central themes arising from recent work on Early Minoan pottery (Betancourt 2009:13–23; Papadatos and Nodarou 2018). In the same spirit, Day et al. (2006) have followed the transition from the Pre-palatial period to the emergence of the first palaces through the lens of the material and social parameters of ceramic production in the Mesara.

Moving to some relevant studies, Mentesana et al. (2017) showed that the transition from FN to Early Minoan at Phaistos in the Mesara (Fig. 4) manifested itself by the greater use of calcareous clays (cf. Neolithic Thessaly, above) and more consistent firing in an oxidising atmosphere to high temperatures (up to 950–1050°C) to achieve different surface effects as well as greater functionality. An important feature of the firing of the EM material was its slow rate, which would be consistent with a firing structure allowing good control of atmosphere and temperature. The observed improvement in firing was more likely part of an evolutionary process than the (sudden) arrival of a new technology, an argument similar to that concerning the introduction of the potter's wheel (Jeffra 2013; Roux and Jeffra 2015:169–71). The highly visible and contrasting surface treatments of EM pottery (Fig. 11) were, as Papadatos and Nodarou (2018:297) have argued, motivated by consumers' rather than producers' preferences.

The major role played by potters during EM I–II at workshops in the Mesara emerges strongly from the detailed study by Wilson and Day (1994) of the combined stylistic (and other macroscopic) attributes, together with the petrographic and microstructural characteristics of sev-

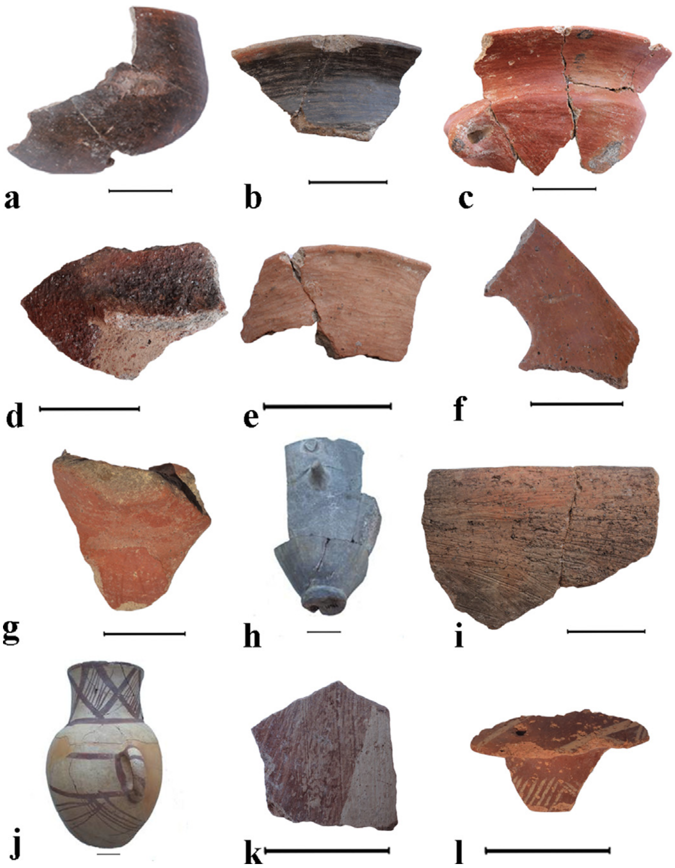


Fig. 11. FN III–EM IB wares at Phaistos. (a) Burnished bowl. (b) Scribble Burnished bowl. (c) Red Slipped and Mottled bowl. (d) Burnished and Granulated jar handle. (e) Orange buff bowl. (f) Brown Slipped and Polished handle. (g) Red Burnished chalice. (h) Dark Grey patterned chalice. (i) Coarse deep bowl. (j) Dark-on-Light jar. (k) Wiped and Washed jar. (l) Light-on-Dark pyxis. From Mentesana et al. (2017). Photo courtesy of Roberta Mentesana.

Fig. 12. (a) EM III White-on-Dark shallow bowl from Pyrgos. (b) Polychrome Kamares small pithos from Phaistos. Heraklion Museum. © Wikimedia Commons.

eral pottery classes of this period found at Knossos. Attention is drawn here to two technologically distinct classes imported from the Mesara: fine Grey ware in a consistent calcareous fabric displaying impressive control of the reducing firing (800–900°C), contrasting with fine painted ware appearing in more varied (calcareous) fabrics, consistent with production probably in different workshops also in the Mesara; it was fired at higher temperatures (850–1050°C), with a hint that the creation of dark and red decoration was intentionally produced (Kilikoglou in Wilson and Day 1994:76–77). That Knossos itself produced its own versions of these classes serves to emphasise the sense of ceramic regionalism occurring in Pre-palatial Crete.

The same region—the Mesara plain—was an important locus of production of high-status Kamares ware (Fig. 12b) belonging to the first palace period, investigated by Day et al. (2006). Treating together the vessels' clays, forming techniques, polychrome decoration, and firing, they reached a convincing picture of Kamares ware as a product of distinctive long-standing local production practices reaching back into the Early Minoan while at the same time adapting to the needs of the palaces to project Kamares ware as a high-status ceramic symbol of the palaces' authority and power. Supplementing their presented results on polychrome decoration applied to the high-quality black slip produced by iron reduction (Fig. 14a) are the findings of Faber et al. (2002) and Pappalardo et al. (2010; 2015), while Ferrence et al. (2001) focused more on White-on-Dark ware (Fig. 12a). A common interest has been the use of the magnesium silicate, talc, not only as a white paint in its own right but in other coloured layers, where it was frequently mixed with iron-rich red to give orange (Fig. 14b) and occasionally purple. Day et al. (2006:56, Fig. 17) noted the morphological difference of the talc grains according to whether the talc was on its own or mixed, perhaps due to preparation methods.

Considering the combined data for the white slip from six sites in central and eastern Crete obtained by Ferrence, Betancourt, Pappalardo, and coworkers using PIXE, Fig. 13 indicates the presence of at least two types, one with high Mg equating with talc, the other with variable high Ca, which has previously been termed calcium silicate. An exploratory multivariate view by principal components analysis of the same data set makes the case for a group in the Mesara, where talc occurs naturally, comprising the samples from Kommos and Phaistos. The presence of Palaikastro 844 in that group makes sense, as its fabric is macroscopically recognisable as central Cretan (Ferrence et al 2001:53). Belonging to the second (and notably uniform) group are the samples (all White-

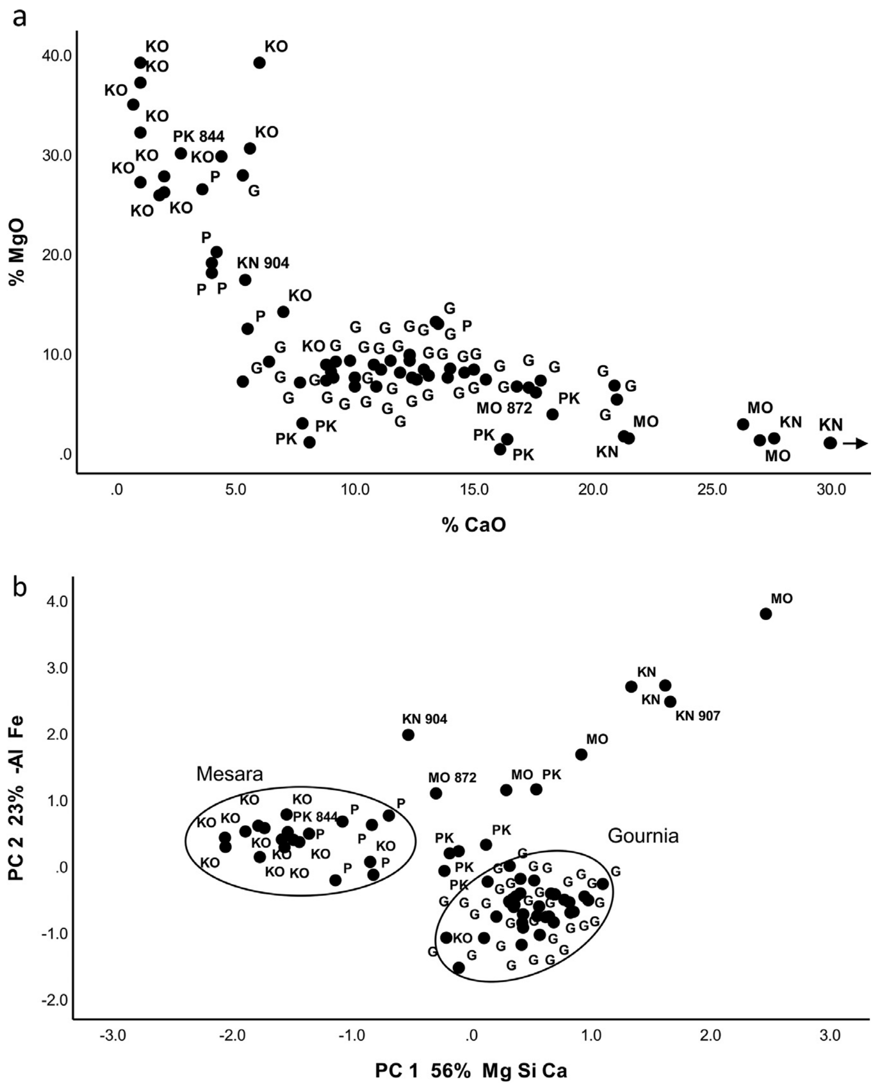


Fig. 13. Plots of (a) MgO-CaO and (b) principal components 1 versus 2 of white slip compositions (Mg, Ca, Al, Si, and Fe oxides) at Kommos (KO), Phaistos (P), Gournia (G), Mochlos (MO), Palaikastro (PK), and Knossos (KN). PIXE data from Delaware (Ferrence, Betancourt, and coworkers) and Catania (Pappalardo and coworkers) laboratories. One KN sample lies off scale in Fig. 13a, owing to a high CaO content.

on-Dark) from Gournia and one from Kommos, which in view of their notably high Al contents can be classed as a white clay. That leaves the samples, all calcareous in composition, from Mochlos and Palaikastro (East Cretan polychrome) and Knossos (Kamares) unassigned, representing perhaps sources in the vicinity of each site. The calcium silicate attribution seems appropriate for the Mochlos and Knossos samples owing to their Al content, thereby demonstrating in the case of the former that its source was not the one exploited by potters at Gournia in the Ierapetra Peninsula. Stylistically assigned to the Mesara is Knossos 904, which is close to the Phaistos samples in Fig. 13a but not in Fig. 13b.

The high Ca feature among the Palaikastro samples was corroborated by Day et al. (2006), who also found high Ca in polychrome specimens at Myrtos-Pyrgos and Malia. The absence of composition distinctions within the Mesara group in Fig. 13a–b suggests that this region relied on a single desired material—talc—derived from one or more related sources that were not uniform in Ca rather than invoking a second, separate material, the calcium silicate. That natural variation in the talc sources would explain Day et al.'s (2006:56) observation of variation in Mg/Si ratio in their examples of white at Phaistos. Critically, their chemical and petrographic compositions were sufficiently similar to suggest that they came from the same workshop. Firing temperature estimates are high: about 950–1080°C.

The results just discussed for Kamares ware found at Knossos can now join with those investigated by Faber et al. (2002). They found a roughly equal distribution of high Mg (that is, talc; see Fig. 14c) and high Ca among examples of white slip (10–40 μm thick) in low- to medium-calcareous coarse Fabric A and fine Fabric B, fired in the range of about 800–1080°C. On the other hand, there was only high Ca in the white slip (5–45 μm thick) in Fabric C, similarly low to medium calcareous but very fine textured and fired in the range of about 850–1080°C (Fig. 14d). In light of Fig. 13a–b, the most economic interpretation of these results is that the high Mg examples in Fabrics A and B may be products of Mesara workshops, while some or most of the high Ca examples in Fabrics A, B, and C are local or from elsewhere in central Crete.

Further work on the white slip could usefully focus on mineralogical analysis, incorporating examples of the white on EM I Lebena ware (Day et al. 2006:56) and exploring further the chronological and spatial dimensions of this type of decoration.

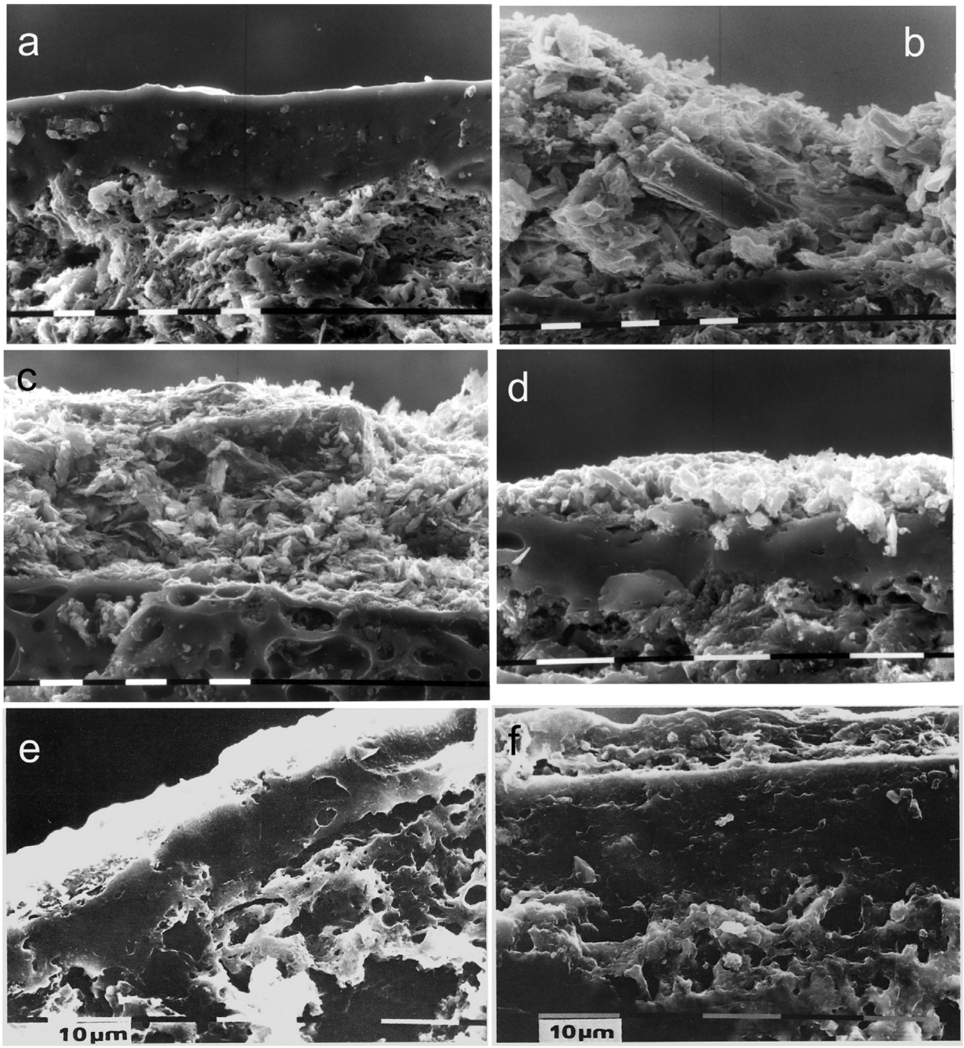


Fig. 14. SEM images of Kamares ware at Knossos (a–d) (Faber et al. 2002:Figs. 7, 10, 12, 14) and imitation Kamares at Akrotiri, Thera (e, f) (Aloupi and Maniatis 1990:4, 7). Knossos: (a) black slip on well-vitrified body on an MM IIIB jug; (b) orange decoration on an MM IA jar consisting of very coarse iron-rich material and talc plates overlying a vitrified black slip with fine bloating ores; (c) talc white decoration on an MM IIA bridge-spouted jar—no sintering, nonvitrified talc platelets over a vitrified black slip with coarse bloating pores; (d) high-fired calcium-rich white decoration above black slip on an MM IB jug/jar (a–d: scale bar 10 μm). Akrotiri: (e) good-quality, vitrified black layer with few small bloating pores; (f) talc white decoration of extensively sintered flakes on top of black vitrified layer.

Fig. 15. LM III larnax from Kavrochori, Archaeological Museum of Heraklion. Photo Zde, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=53065006.

(3) Crete: Late Minoan

The LM polychrome larnakes (Fig. 15) offer an attractive target for analysis. Preliminary results from portable XRF and Raman analysis have indicated the use of colourants usually associated with Minoan wall painting, such as ochres and Egyptian Blue, but there were apparent differences. An example is the possible use of organic colourants detected by pRaman: purpurin, presumably from madder, and saffron yellow (Fovakis et al. 2021). If confirmed by further analysis, this would implicate post-firing decoration. Both calcite and gypsum seem to have been used for the white ground.

(4) Mainland: Early–Middle Helladic

At EH Manika, the white slip was a non-calcareous material, and decoration giving black and oxidised colours was obtained from very fine-grained, iron-rich illitic clays, in both cases on a low-Ca (5–8% CaO) body. Firing, probably in a kiln, was typically at about 800–1000°C and >850°C, respectively (Aloupi 1993:184, Table 6.15).[9]

Matt-painted pottery consists of pattern-painted wares decorated with one or more paints that lack lustre. During the Middle Helladic period, this decoration is usually equated with the use of manganese black, and the pottery itself has long been associated with the island of Aegina. Gauss and Kiriatzi's (2011) large study of Bronze Age pottery from the principal prehistoric site on the island, Kolonna, included a wide-ranging material characterisation of relevant classes, using SEM to supplement the larger data set based on refiring to determine the paint as either iron- or iron and manganese–based. EH III pattern-painted and MH solidly painted, on the one hand, and MH pattern painted on the other, were decorated with materials that were rich in iron oxides and

[9] A cautionary note: An explanation for a firing temperature of >1050°C among heavily reduced sherds at Manika was that they had received an accidental second firing (in a recent forest fire?).

iron-manganese oxides, respectively. Underlying this basic distinction is a recognition of some variability in the decorative materials and fabric (but all were local and calcareous). Firing was also not uniform: about 800–1050°C overall.[10] The decoration on the matt-painted examples at Eleusis were all manganese-rich and similarly fired over a wide range, 800°C to >1080°C (Cosmopoulos et al. 1999:Table 1).

(5) Mainland: Late Helladic

In recent years, studies of the decoration on Mycenaean pottery have been incorporated into broader enquiries linking this pottery's origins with its production technology, contrasting, for example, pottery made and found in the heartland of the Mycenaean world with local imitations or imports in the periphery (Macedonia: Buxeda i Garrigos et al. 2003) and beyond (Italy: Jones et al. 2014). In Mycenaean Macedonia, where no updraft kilns with a firing floor have yet been found, the locally made (non-calcareous) Mycenaean pottery was subject to rapid (non-kiln) firing in the range of 800–900°C, as inferred from the continuously vitrified microstructure with a high concentration of small (<5 μm) bloating pores and macroscopically by the grey core sandwiched between brown-red layers. As expected, decoration was in the Mycenaean tradition, that is, iron-based, but the firing was such that black was rarely achieved; red was the norm. The analogous results in southern Italy showed the locally made so-called Italo-Mycenaean ware to be fired higher (about 850–1050°C) and to be more consistently fired with black and red decoration being produced (Buxeda i Garrigos et al. 2003:Table 5; Jones et al. 2014:377–86, Table 5.2). As for the reference sherds from Mycenae, they effortlessly revealed the basis of their technical superiority under the SEM. Experimental firings of Italo-Mycenaean and Italian Grey ware are mentioned below in connection with the kiln at Kommos.

The nature and purpose of the tin coating of Mycenaean-shaped drinking vessels has continued to attract attention. Appearing most commonly on *kylikes* and almost always in mortuary contexts, these vessels appear in concentrations at sites in the Argolid and Messenia (LH II–IIIA) and in north-central Crete (LM IIIA) (Aulsebrook 2018:Fig. 1). The analyses and replication experiments by Gillis and coworkers, conveniently summarised by Gillis (2001), have revealed that the effect was most likely produced by attaching thin strips of tinfoil to the surface with organic binder, identified by tof-SIMS as probably pine resin rather than mastic or animal glue, instead of by dipping the vessel into molten tin (Holmberg 1983). Such a vessel would have a silver colour, but if that same vessel was heated to about 232°C, a golden colour was created (Gillis and Bohm 1994:colour Fig. 4). In principle, then, the maker had the option of creating a silver or gold surface. In practice, it appears from analysis of the upper sub-micron by ESCA that the latter was more common: the layer's C/O ratio in the tin-coated spots on vases (from a chamber tomb at Asine) frequently resembled the corresponding value for modern gilded tinfoil rather than untreated tinfoil. Recognising that, whatever the colour, the decoration would deteriorate quite rapidly by allotropic transformation (tin pest) to give a grey, flaking material. This gives rise to the colour symbolism of original silver or gold now taking on a further dimension, namely that the decay of the tin could be associated with the body's decomposing flesh in the tomb (Dimaki and Papageorgiou 2015:851). Indeed, the hypothesis that nitrogen from the flesh protein had found its way to the vase's (bare) clay surface rather than the decorated surface was tested by ESCA. In the four samples analysed, the N content on the vase's clay surface was deemed to be sufficiently high to suggest that flaking had started to occur during the tomb's lifetime (Gillis 2001:Table 2), thereby nullifying in effect the vase's value. Recent advances in proteomic analysis could encourage further work of this kind, for instance from sites with several examples, such as Berbati, Prosymna, Ialysos, and Katsambas.

In sum, these vases were more subtle than mere precious metal skeuomorphs. In a full review of the tinning effect, Aulsebrook (2018:98) concluded that "their use was an obvious and potent act of conspicuous and irreversible consumption; it was a permanent offering by the living to the realm of the dead."

(6) Cyclades: Early–Late Cycladic

As in Early Minoan Crete, the corresponding pottery in the Islands is wide-ranging in shape, decorative motifs, and surface treatments, especially in EC II, when painted decoration arrived on the scene. Petrographic analysis has again played a crucial role, including assigning wares to individual island centres (Hilditch 2015; Vaughan 1990).

Investigation of the surface treatments employed at Akrotiri on Thera during the Middle Cycladic Phase A (circa 2100–1850 BC) has shown the use of calcareous light-coloured slips, 50–100 μm thick in the case of Dark-on-Light ware, on which was applied a thin (about 5 μm) iron-rich paint. A white paint, similarly calcareous, on an iron-rich slip appears on Light-on-Dark ware (Day et al. 2019:365–70, Table 3.8). Decoration in Mn black also features in this period on Cycladic White ware. The equivalent firing temperatures in these wares were generally high, 900–1050°C, but, for example, contemporary Dark Burnished and Incised ware was fired significantly lower. There was no significant material difference between surface effects in (iron-rich) Red Slipped and Burnished ware belonging to Phase A and the previous so-called Kastri phase.[11] The petrographically defined fabrics in these wares are for the most part calcareous (range about 3.5–16.5% CaO; median >10% CaO), and this feature continues into Late Cycladic I, a period that sees no apparent diminution in the range of surface treatments (Fig. 16) (Marthari 1990). The combination of Mn black and Fe-based paints producing the bichrome effect continued into this later period, alongside a new tradition inspired from Minoan Crete.

Theran potters produced their own version of Kamares (Fig. 16, Group B), using the (usual) local calcareous clay, coating the vessel body with an iron-rich slip but often not succeeding in reproducing the high-quality black gloss of good Kamares (see discussion of Crete, above), as can be judged from the chemical composition (Aloupi and Maniatis 1990:Table III) and that there was probable deliberate addition of iron-rich material. Since there was also the likely difficulty of maintaining the reducing firing phase at 900°C or more (Fig. 14e), the slip coating was often red or brown rather than the desired black. Talc[12] was used not only in the white decoration of Kamares imitations (Fig. 14f) but also in the much less common white-coated vessels designed to create a good background for detailed painting (Fig. 16, Group C). Here a thin layer of talc possibly in an organic medium was applied to the whole surface; firing was frequently in the 750–900°C range (Aloupi and Maniatis 1990:Table V), which was insufficient to prevent the coating from peeling off. Regarding the more common decorated wares (Marthari 1990:Groups A and B), which were fired in the range of 750–1080°C (Aloupi and Maniatis 1990:Table V), while the kilns at Akrotiri were evidently capable of reaching high temperatures, the potters were unable to consistently control the firing.

B2b. Firing structures

Hansen Streily's (2000) detailed catalogue of 102 pottery firing structures is valuable for its treatment of Bronze Age kilns in the Aegean and beyond. The main criteria in her tenfold typology are the number, arrangement, and design of kiln chambers, the draught and firing system, and kiln proportion.

The number of known prehistoric kilns has increased significantly in the last few decades. Updraft kilns make their appearance in the MBA in Crete and the mainland, but the identification of kilns during the EBA

[10] Karkanas et al. (2019) have described the operating characteristics of the LBA kiln at Kolonna.

[11] Jill Hilditch, Vassilis Kilikoglou, and I have recently completed a corresponding petrographic, chemical, and technological study of EC-LC wares at Phylakopi on Melos.

[12] Talc occurs geologically on Siphnos and Seriphos but not Thera (Vaughan 1990).

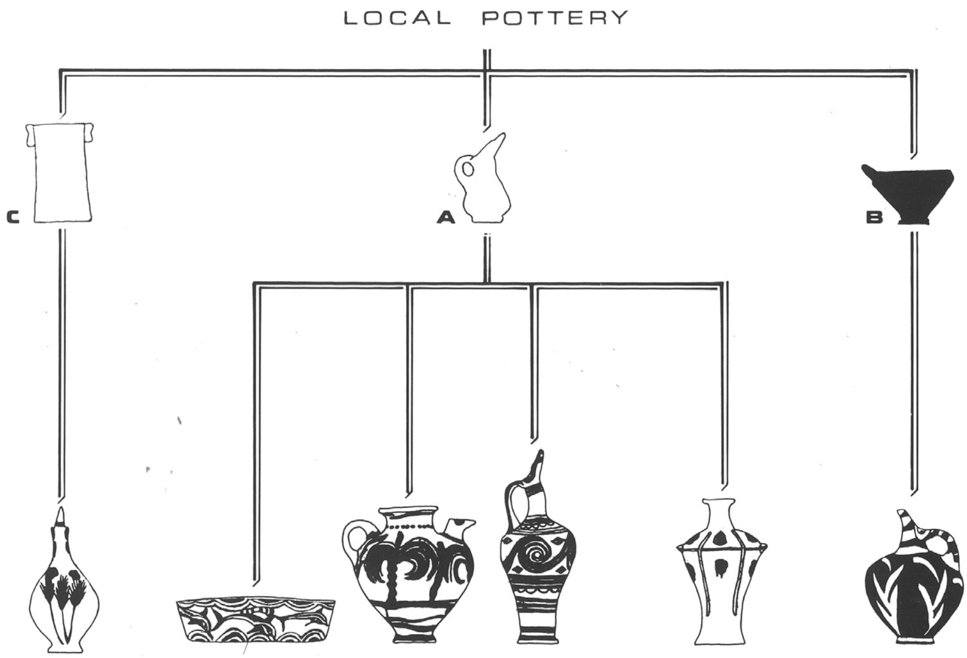


Fig. 16. Local LBA pottery at Akrotiri. Group A: plain and decorated. Group B: dark-coated and decorated. Group C: white-coated and decorated. From Marthari 1990:Fig. 1.

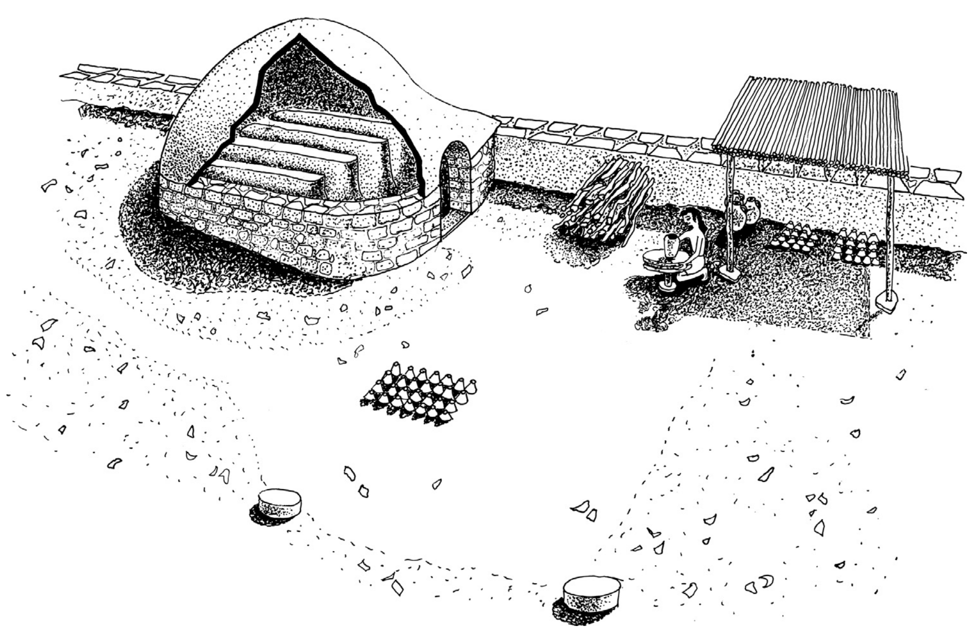


Fig. 17. Reconstruction of the LM IA potter's work area and kiln at Kommos. From Shaw et al. 2001:Fig. 24. Image courtesy of the Trustees of the American School of Classical Studies at Athens.

remains problematic. In northern Greece, for example, the firing structures at Ayios Mamas and Polychrono (Pappa 1990) lack a supported firing floor; I have argued that the former is an oven (*GCP*, 783, Fig. 9.5b). In the Cyclades there is a striking lack of kilns or other firing structures. One apparent exception is an EBA kiln at Ayia Irini on Kea of surprisingly advanced design (Caskey 1971:372, Plate 69d). Roughly circular (about 1.5 m in diameter), it had three cylindrical pillars but no remaining raised floor; large jar fragments were found inside. Kilns will surely be found at Late Cycladic I Akrotiri when excavations extend beyond the residential areas that have largely been the focus of attention thus far, but it remains a surprise that no evidence for firing has yet been found at or in the vicinity of Phylakopi on Melos.

Regarding the Middle and Late Bronze Age, reference should be made to three workshops. The first is from Miletus, where up to nine kilns of LBA date (Hansen Streily 2000:M1–M9, 147–79; Niemeier 1997) have been recovered. They belong to at least three types, mainly the channel type common in Minoan Crete and the circular type that is the norm on the Mycenaean mainland but is also found on Crete.[13] The second is an LM IA kiln in good condition at Kommos, with pottery in it, as well as a large adjacent pottery dump containing at least 300 wasters. This presented an ideal opportunity to undertake an integrated study, and this aim was realised in Shaw et al.'s (2001) publication. From the kiln's west-facing opening were three steps down to the firing (stoking) pit, leading directly (with no intervening wall) to four parallel channels extending to the back of the kiln (Fig. 17) (Hasaki 2002:Type IIe). In

[13] See the rectangular-shaped early MBA kiln and LBA kilns at Liman Tepe to the north of Miletus (Aykurt and Erkanal 2016).

the apparent absence of a perforated floor,[14] the pots were most likely placed on a temporary floor over channels created by large-diameter pots, slabs, or large sherds. The pots (an estimated 1,158 pots in the kiln and dump) were for household consumption (conical cups and jars). There were perhaps also amphorae for trade but no cooking pots or vessels of the highest quality. Production output was therefore at a rather specialised level involving standardisation of shapes and fabrics. Most of the pots were wheel thrown, and decoration, where present, was commonly light-on-dark. There were several indications that speed and efficiency in manufacture were important. The kiln had advantages over the simpler updraft kiln (which was the norm in LM III Crete, as on the mainland): the cross-draught of the Kommos kiln was better suited to the creation of the reducing phase, which was critical for achieving the sintered black slip. Moreover it was more heat-efficient and so better able to reach high temperatures (Day and Kilikoglou in Shaw et al. 2001:132). The estimated firing temperature range in the typical medium-calcareous fabric was wide: <750°C to >1080°C, with the decorated pots and some large vessels represented in the upper part of that range. This ability to control the firing temperature may be partly linked to the different depths of the channels, which could have provided a variety of temperatures during firing.

Vanzetti et al. (2014:Figs. 5.25a–b, 27) used the Kommos kiln as the model for an experimental firing of decorated and other Mycenaean-influenced pottery made in Italy, replicated on the basis of examples found and made at Broglio di Trebisacce in southern Italy. The replicas fired well, but despite the use of local clay, the bodies appeared too white and the decoration lacked glossiness, probably because the goethite colourant (mixed with slip) was insufficiently levigated. The corresponding results from a pit firing were also reported. The potters, who emigrated from the Mycenaean world to several locations in Italy following upheavals in the Aegean around 1200 BC, brought with them a new technological package: the use of the wheel; decoration in lustrous red, brown, and black colours; and kiln firing. The transfer of this technology to local potters over the course of the next century or more manifested itself in different ways, and these have been explored by archaeometric means and according to archaeological criteria (Jones et al. 2021).

The third example is a potter's workshop at Berbati near Mycenae in the Argolid. It included a circular kiln with a central wall flanked by two short, free-standing supports (Fig. 18a) (Hasaki 2002:Type II).[15] It was built in LH II and continued into LH IIIA (Schallin 1997), when Pictorial-style pottery (Fig. 18b), a fine example of the iron reduction technique, was produced and exported mainly to the east. Buxeda i Garrigos et al.'s (2002) study of Mycenaean decorated sherds found at Berbati and other sites and attributed on the basis of chemical composition to the Mycenae-Berbati area included firing temperature estimation by XRD. The results were comparable with those at Kommos: the decorated pottery fell at the upper end of the range <800°C to >1050°C.

Both kilns raise questions about their design and performance. The larger the kiln, the smaller the energy lost through the exterior surface. Shape is also important, with round kilns being better in this respect. Prillwitz and Hein (2015) highlight the requirement of suitably low-conducting kiln-building materials—clay (fired brick) and stone—and the use of an efficient clay lining, such as a calcareous clay, on the exterior of the kiln to minimise heat losses. A compromise has to be reached between thick walls minimising heat loss and an increase in heat input to bring the kiln interior to its maximum temperature, since maintaining the temperature would thereafter require less fuel. Inside the kiln, the venting holes in the kiln floor, the size of the stoking chamber, and the space therein for fuel, among other parameters, affect the flow of gases and the temperature distribution. On top of that is the potter's constant monitoring of the firing sequence, being ready at a given moment to replenish or alter the fuel and to alter the airflow. The complexity of these variables and their interrelationship call for computer-based modelling, which Hein et al. (2017) have begun to explore using as a model a kiln at Ialysos on Rhodes (Fig. 18c) (Hasaki 2002:Type Ib; Marketou 2004), which is contemporary with that at Berbati. Computational fluid dynamics allow visual imaging of, for example, temperature (Fig. 18d) and air/gas velocity distributions inside the kiln under set conditions (Hein et al. 2017:Figs. 4 and 5).

The future direction of technological research on the Bronze Age mainland, as with other places in Greece, will benefit from close coordination of effort on the recovery of newly discovered firing structures, on replication experiments, and on in situ and laboratory analyses. Many other issues remain to be resolved. One of them concerns the better-quality Minyan (Grey and Yellow). Was it fired in specialised kilns? (Bear in mind that the charge of most kilns would have been a *range* of wares and fabrics.) The adoption on the mainland, probably via Kythera, of the Minoan ceramic tradition of lustrous iron-rich decoration towards the end of the Middle Bronze Age and into the Shaft Grave Mycenaean period could be usefully investigated at a technological level. Why did Mn black decoration lose its popularity apparently so decisively in most of the Mycenaean heartland (but see northern Greece: Buxeda I Garrigos et al. 2003:274), in contrast, say, to the situation in Cyprus (Aloupi et al. 2011)? White slips and paints have attracted much attention on Crete but much less on the mainland; there is scope for further work here. A few final remarks appear in C12.

Section C

This section deals with decorated pottery from the Protogeometric to the early Roman periods (Table 2) but focuses particularly on the Archaic to Hellenistic periods. While science-based investigations are the primary concern here, allied directions of enquiry must also feature, as they do in the previous section. The latter concern experimental work, ethnographic observations (highlighted in Section A), iconographic depictions of potters at work, and the contribution of the archaeological record in the form of the remains of potters' workshops, including kilns. The pride of place that decorated Attic pottery occupies in this section justifies the inclusion of brief accounts of the pottery industry in Athens and Corinth.

Table 4 lists the entries in this section, which are made according to pottery chronology and type. As explained in Section A, I place attention on studies carried out in the last 30 or so years, although reference to earlier, often fundamental work is made where relevant. Within each subsection entries are arranged by publication. Fig. 19 marks the locations of sites discussed in this section.

Analytical, imaging, and other techniques are abbreviated, as in Table 1, and the main chronological divisions in the historical period appear in Table 2.

C1. Protogeometric and Geometric pottery

However fundamental the societal changes that took place at the end of the Bronze Age, the potter's craft continued into the first millennium BC little changed.

A striking of feature of some Greek Protogeometric pottery is the use of semi- and full-circle decoration (Fig. 20a), traditionally thought to have been achieved with a multiple-brush compass. In reinvestigating how this decorative effect was produced experimentally, Papadopoulos et al. (1998) obtained best results from a different device, a pivoted triple brush: "A row of brushes made of equal lengths of animal or human hair are fixed to a small beam of wood—in this case olive—that is rigidly attached close to the point of, and perpendicular to, a pivot shaft. . . . The point of the pivot shaft extends about the same distance below

[14] Tomasello (2011) has proposed that there could have been a mud-brick floor in the analogous Type-IIe kiln at nearby Ayia Triadha; see also Pappas (2019:50).

[15] The reconstruction in Fig. 18a may be incorrect, as its height looks too large for the preferred 1:1 height:width ratio for optimal kiln functioning (Whitbread and Dawson 2015:33).

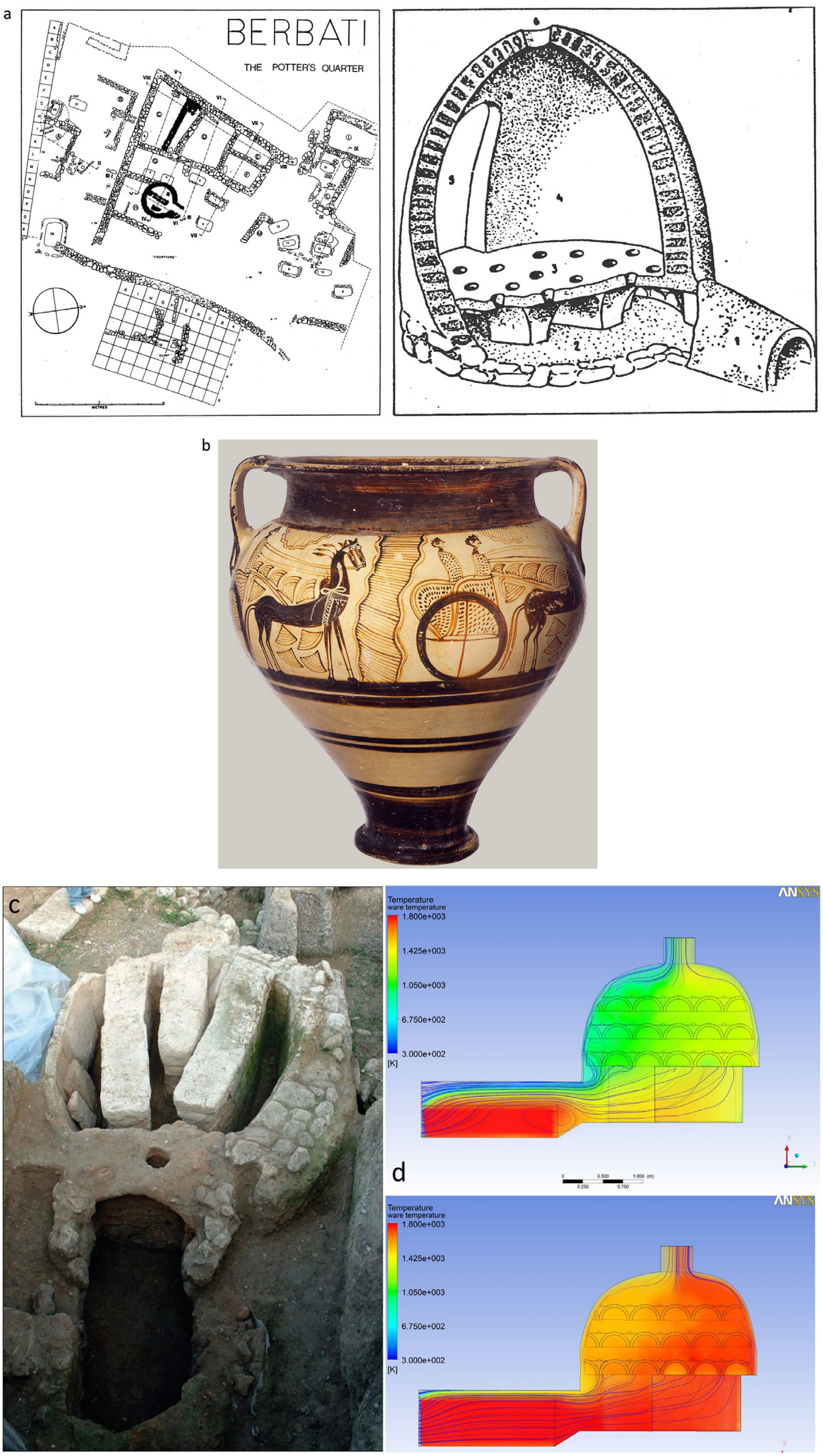


Fig. 18. a. Plan of the potter's workshop at Berbati (left) and reconstruction of the kiln (right). Reproduced with permission from A-L. Schallin (1997:Figs. 4 and 8). b. Mycenaean pictorial-style krater showing a chariot scene. Photo courtesy of the Metropolitan Museum, https://www.metmuseum.org/toah/images/hb/hb_74.51.964_av1.jpg. c–d. View of the Mycenaean-period kiln on Rhodes (c) and effect of fuel bed height (40 cm top, 60 cm bottom) on temperature distribution inside the kiln, assuming a flame temperature of the burning fuel of 1800°K (d). The fuel beds cover about 57% and 86% of the internal height of the stoking chamber. respectively. The blue curves indicate the flow of air and flue gas inside the kiln. From Hein et al. 2017:Figs. 1 and 4. Photos courtesy of Anno Hein.

Table 4
Investigations of Protogeometric to Hellenistic Pottery

Description, Date (BC) (Findspots)	Samples	Techniques	Publication
Protogeometric			
(Mainly) PG fine wares (Asine)	33	TCT	Hulthén and Olsson 1983
Attic PG (and later) test pieces	68	TMA	Schilling 2003
Geometric and Archaic			
LG slipped ware (Eretria, East Attica, Naxos, Thera)	100	SEM, pXRF	Aloupi 1993:152–68; Aloupi and Kourou 2007
Archaic Corinthian and Boeotian (Thebes)	47	OM, SEM-EDS, XRF, XRD	Mastrotheodoros et al. 2013
Corinthian polychrome slipped and painted sherds, mainly seventh century but one earlier (eighth century) and nine of the sixth century (Carnegie Institute Geophysical Laboratory, Washington, DC)	27 for FTIR only	EPMA, SEM-EDS, FTIR, μRaman	Klesner et al. 2017; Stephens et al. 2014
Corinthian slipped and painted sherds, mainly EPC, MPC, and LPC-EC trans. but including Mycenaean, EC–LC Clays and other raw materials	98 19	pXRF Shrinkage and porosity tests, pXRF	Rodriguez-Alvarez 2019
Attic Black Gloss on BF and RF			
Attic BG (fifth–fourth century)	5	EMPA, replication experiments	Kingery 1991
Attic BF and RF (mainly from Paros)	8	SEM-EDS, EPM, TEM, laser reflectance	Aloupi 1993:169–77; Maniatis et al. 1993
Attic BF and RF, sixth–fourth century (Tharros, Sardinia)		SEM-EDS, XPS	Ingo et al. 2000
Attic BF, sixth–late fifth century (Athenian Agora)	3	HRPD, SEM	Tang et al. 2001
RF, late fifth–early fourth century (Cabezo Lucero necropolis, Guardamar del Segura, southeastern Spain)	5	μRaman	Pérez and Esteve-Tébar 2004
BF Priam Painter amphora (sixth century)	1	ICP-OES, SEM-EDS, XRD, RS	Mirti et al. 2006
BG Attic? (Motya, Sicily)	20	μRaman, SEM-EDS, XRD	Medeghini et al. 2014
RF stamnos attributed to the Tyszkiewicz Painter, early fifth century (Worcester Art Museum)	1	RTI, scanning laser confocal microscopy	Artal-Isbrand et al. 2011, 2013
Attic RF (Gioiosa Guardia, Sicily)	2	XANES	Bardelli et al. 2012
RF Kleophrades Painter, early fifth century (Getty Museum)	1	STEM, LA-ICP MS, XANES	Walton et al. 2013
BF (Archaic) and RF (Classical and HL) (Acropolis, Kerameikos)	3	XANES, REP	Lühl et al. 2014
RF hydria by Berlin Painter, early fifth century (J. P. Getty Museum)	2	Raman, REP	Cianchetta et al. 2015a
RF hydria by Berlin Painter, early fifth century (J. P. Getty Museum)	2	XANES, REP	Cianchetta et al. 2015b
Decorated pottery, including BF and RF, eighth–fourth century, mainly from Athens; also Kavirion (9) and Corinth (11) (see entry above)	102	pXRF, SEM-EDX, XRD, REP (PIXE)	Aloupi-Siotis 2020; Chaviara and Aloupi-Siotis 2015
Attic BF (3), RF (14), sixth–fifth century; Corinthian BF (1) (see entry above); Etrurian RF (1)	19	ICP-MS, XANES	Walton et al. 2015
Attic replicas	many	(S)TEM-EDX, RS	Cianchetta et al. 2016
Attic RF, fifth century (Lattes, France)	10	SEM-EDX, EMP	Sciau 2016
6 Attic RF, fifth century, 20 Attic BG, mainly fifth century (Lattes, France)	26	SEM-EDS, Raman, EPMA, μXRF, FF-XANES	Tian 2016
2 Attic RF, fifth century, 16 Sicilian RF	16	PIXE	Pappalardo et al. 2016
(Attic) BF, RF		experimental	Balachandran 2018
Attic BF (Izmir Archaeological Museum)	10	pXRF	Muşkara and Kalayci 2021
Red and Other Colours/Effects			
Coral Red, gilding, and applied pigments and their grounds	several	SEM-EDS	Maish et al. 2006
Coral Red		OM	Maish 2006
Coral Red, sixth–early fifth century	13	STEM-EDX	Walton et al. 2008, 2009
Coral Red	several	SEM, REP	Aloupi-Siotis 2008
White-Ground Lekythoi			
WG lekythoi (Merenda [Athens and Vergina])		pXRF, FTIR	Aloupi et al. 2009
WG lekythoi	2	SEM, EPMA, μXANES	Walton et al. 2010
WG lekythoi, 460 and 430 BC	2	μ-XRD, μ-XRF), X-ray colour camera, 3D laser scanning microscopy	Berthold et al. 2017
Classical to Early Roman in Southern Italy, Etruria, Greece, and Turkey			
Proto-Campanian and Campanian A (Rhode, Girona, Spain)	12, 6	CEMS, XRD, SEM-EDS	Vendrell-Saz et al. 1991
Campanian A, B, C (six sites in Calabria)	18	SEM-EDS, XRD, TMA	Mirti and Davit 2001
BG fourth–first century (Populonia, Marcianella, and Voltera in Tuscany)	4	SEM-EDS, TEM, XRD	Giorgetti et al. 2004
BG late fourth–second century (Voltera, Populonia, and Chiusi-Marcianella in Tuscany)	18	SEM-EDS, EMP, μXRD, XAS	Gliozzo et al. 2004
Apulian, fourth century, RF (Altamira, M. Sannace, Canosa) and Gnathian fourth–third century (Egnatia, M. Sannace) Apulian RF and other wares (Arpi)	38, 11 22,18	OM, SEM-EDS, XRD, FTIR, NMR OM, ICP-MS, SEM-EDS, XRD	Mangone et al. 2008, 2009, 2011 Giannossa et al. 2019, 2020
Mid-second to late first century, local red-slipped, eastern and western *terra sigillata* (Kassope)	38	XRD, XRF, SEM	Papachristodoulou et al. 2010
Campanian A and Sicilian imitations	39	SEM-EDS	Montana et al. 2013
Attic and Atticising, fourth-century BG (Iasos, Turkey) and two late fifth-century Attic	15	pXRF, PE, SEM-EDS	Amicone 2015
Campanian A and B	8, 11	SEM-EDS, EMPA	Sciau 2016
Campanian A and Cales (Ilduro and Illuro, Spain)	63	XRF, XRD, SEM-EDS	Madrid i Fernández and Sinner 2019

Notes: BF = Black Figure; BG = black gloss; RF = Red Figure; WG = white ground; PG = Protogeometric; EPC, MPC, and LPC = Early, Middle, and Late Protocorinthian (720–630 BC); EC-LC = Early to Late Corinthian 620–500 BC); HL = Hellenistic; ORO = oxidising-reducing-(re)oxidizing.

Fig. 19. Locations of sites mentioned in Section C.

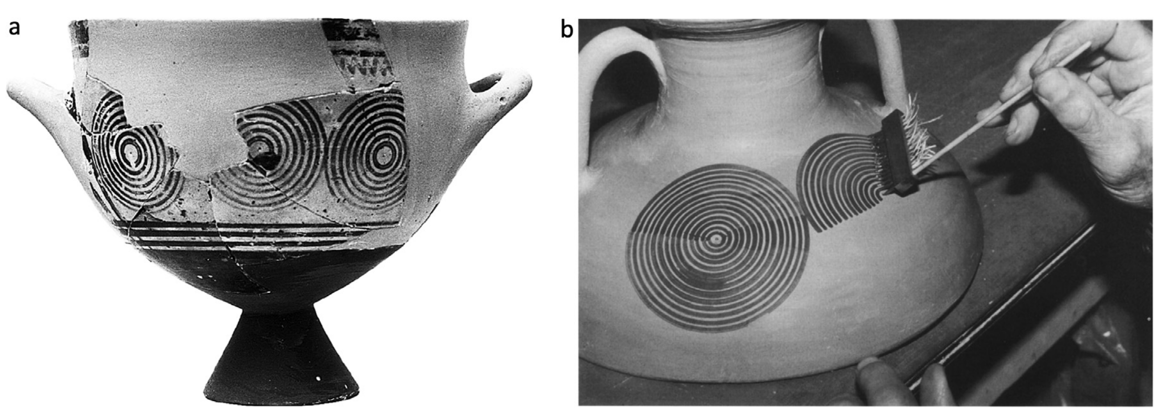


Fig. 20. (a) Athenian Protogeometric skyphos from the Athenian Agora, P 6846. From Papadopoulos and Smithson 2017:Fig. 2.234. Photo by C. Mauzy; image courtesy of the Trustees of the American School of Classical Studies at Athens. (b) Painting concentric circles on the shoulder of an amphora. Papadopoulos et al. 1998:Fig. 22. Photo by R. Schreiber; image courtesy of the Archaeological Institute of America and the *American Journal of Archaeology*.

the beam as do the brushes" (Fig. 20b) (Papadopoulos et al. 1998:Fig. 18).

The firing temperature range in PG pottery, including fine wares at Asine (Hulthén and Olsson 1983), was determined to be 600–800°C. These values are slightly lower than for the test pieces (mainly PG but extending to Geometric and a few examples of Attic BF and RF) (Fig. 21) from the potters' quarter in Athens in what was later to become the Agora (see Section C9). The impressive number of pieces examined by TMA (outlined in Section A) yielded a range of 700–850°C, irrespective of date, context, or colour (Schilling 2003) (Fig. 21b). The apparent continuity of firing temperature in Athens over several centuries is notable. Significantly, the role of a majority—43%—of the 88 test pieces that Papadopoulos examined macroscopically (Schilling 2003:Table 3.1) was to monitor the transition to (and including) the final reoxidation phase; 37% showed differing extents of reduction; only 19% were more or less fully oxidised from the initial phase.

C2. Late Geometric slipped wares

The pottery painted on a pale slip belonging to the Late Geometric (LG) period is well-known stylistically, not least because it includes the work of the so-called Cesnola Painter, a major figure of the time, and it is represented in (East) Attica, Euboea, and the Cyclades. Aloupi and Kourou (2007) examined examples of this pottery from Eretria on Euboea; sites in East Attica, Grotta, and Aplomata on Naxos (Fig. 22); and Thera. Using two element ratios, K/Si expressing the illitic and micaceous component of the clay slip and Ca/Fe, which would be sensitive to colour assuming broadly similar firing conditions, it was possible to discriminate between the slips of the three production regions. The colours ranged from cream to yellow to pink. But whereas the Euboean products in various styles were technologically uniform, the Naxian workshops were also working in different styles while employing different local materials, as observed in SEM imagery (Aloupi and Kourou 2007:Figs. 1, 2, 4). On the basis of the slip, many Cesnola-style vases, including the Cesnola krater in New York, were macroscopically similar to Euboean, but that same style and Euboean-type slip were also represented on Naxian products, suggesting that Cesnola slip technology was exported along with the style from Euboea to Naxos. The chemical differentiation of the clay body of Geometric pottery from Eretria and central Naxos has been reported elsewhere (Charalambidou et al. 2017, 2018).

C3. Archaic–Hellenistic black gloss

This long section considers the large body of data concerning black decoration on pottery of the Archaic to Hellenistic periods, roughly 700 BC to the mid-second century BC. Treatment of this decoration at Corinth and Athens requires a separate introduction. On the matter of terminology, I (*GCP*, 805) have a strong preference for the term *black gloss* (BG) over the term *black glaze*. The principal objection to the latter, which still has common currency among classical archaeologists, is that glaze is glass-based and did not evolve in pottery decoration until Roman times. The plea in favour of *black gloss* has met with implicit approval in the archaeometric sphere, although Chaviara and Aloupi-Siotis (2015:2) have objected, arguing that the term more correctly refers to only the external, macroscopically observed appearance. For sure, this issue is not yet settled, as there is a new term to consider—*Black Glass-ceramic*—proposed by Aloupi-Siotis (2020) and discussed in Section C3d, below. But for the purposes of the present account, the word *gloss* is retained.

C3a. Corinth

As a counterbalance to the prolific attention paid to the decoration on Attic pottery (Section C3b, below), technical studies of decorated Corinthian pottery (Fig. 23), which began with Marie Farnsworth's pioneering work (Farnsworth 1970) and have received renewed impetus in recent years, are most welcome, for Corinth led the Greek world in producing and exporting pottery during much of the seventh and sixth centuries. This section concerns the development of new methods and materials in the Middle Protocorinthian period (690–650 BC) that accompanied the Black Figure style as well as polychromy. While Mastrotheodoros et al.'s (2013) study was concerned with differentiating technologically between Corinthian and Boeotian (and Euboean) BG from the seventh and sixth centuries, using plentiful material from a Heracles sanctuary in Thebes, Stephens et al. (2014), followed by Klesner et al. (2017), examined individual examples of Corinthian polychrome from the eighth to sixth centuries. Section C9 treats production of this pottery in a broader archaeological perspective.

A starting issue has for long been the nature and locations of clays suitable for pottery making in the area of ancient Corinth, a subject that has been critically reviewed by Whitbread (2003) and extended by Sapirstein (2008) as part of his experimental work on roof tile production at Corinth (C10). Of the three types of clay identified by Farnsworth (1970), the one of relevance here is her fine-textured white clay of the Corinthian plain (Fig. 24), creamy to pale yellow in colour with green overtones and a mineral composition (determined by XRD) of smectite interlayered with illite, large calcium carbonate, some chlorite, and feldspar. The problem is that chemically, as shown by many, including myself (*GCP*,178, Table 3.8) and more recently Rodriguez-Alvarez (2019), examples of such marl clays have been too calcareous (usually >20% CaO) for making pottery. As a point of comparison, CaO in fine wares ranges from 6.5% to 7.5% (Late Geometric and Protocorinthian) (Grimanis et al. 1980) to 14% (seventh–sixth centuries) (Farnsworth et al. 1977) to 15% (fourth century) (*GCP*, Appendix II, Corinth 5). Not only would these clays be ill-suited to working on the wheel because their tendency to dry out rapidly would require potters to apply water continually to the surface but more seriously they fire badly. Some of the calcium oxide formed on firing at >800°C from decomposition of the clay's calcite rehydrates, with consequent volume change causing cracks and peeling within days (Rodriguez-Alvarez 2019:161, Fig. 12). Removal of the calcite by a levigation process to improve the marl's working properties is untenable because the particle sizes are too small (see below). In addition, although levigation tanks/pits at pottery workshops in the Greek world are by no means common, their apparent total absence in the archaeological record at Corinth is perhaps telling (Hasaki 2021:228, note 2; Rodriguez-Alvarez 2019:183). The pale marl clays at Corinth could be rendered more suitable for pottery making by mixing with another clay, supressing spalling, adding salt/seawater, or other mechanisms, but none of these possibilities has yet been fully tested experimentally.

Leaving those problems aside, there is a growing consensus from the programmes of prospection that the clay deposits to the west and southwest of ancient Corinth are good candidates, if not decisively so, for fine ware production from the point of view of colour, texture, and chemical composition. Such an area makes archaeological sense because it encompasses not only the main centre of ceramic production at Corinth, the potters' quarter, lying at the western extremity of ancient Corinth (Figs. 24 and 45) and operating from the seventh to the fourth centuries BC, but also the findspot of the renowned Penteskouphia plaques (see Section C9). The (NAA) composition of a clay from a well boring below the potters' quarter resembled superficially that of a group of Corinthian seventh-century fine wares (Farnsworth et al. 1977), and Penteskouphia lies close to the lignite-related clays found at Nikoreto (Fig. 24), exploited today for brick making and found to have a variable Ca content (Whitbread 2003:10, note 54).[16] The clays at Ayios Antonios, to the

[16] A programme of clay prospection in the area of ancient Corinth and Sikyon currently being carried out by the Fitch Laboratory (British School at Athens) in collaboration with the Danish Institute's 'Finding Old Sikyon' project (https://www.diathens.gr/en/aktiviteter/enaktivitetersikyon) will provide new information.

a

b

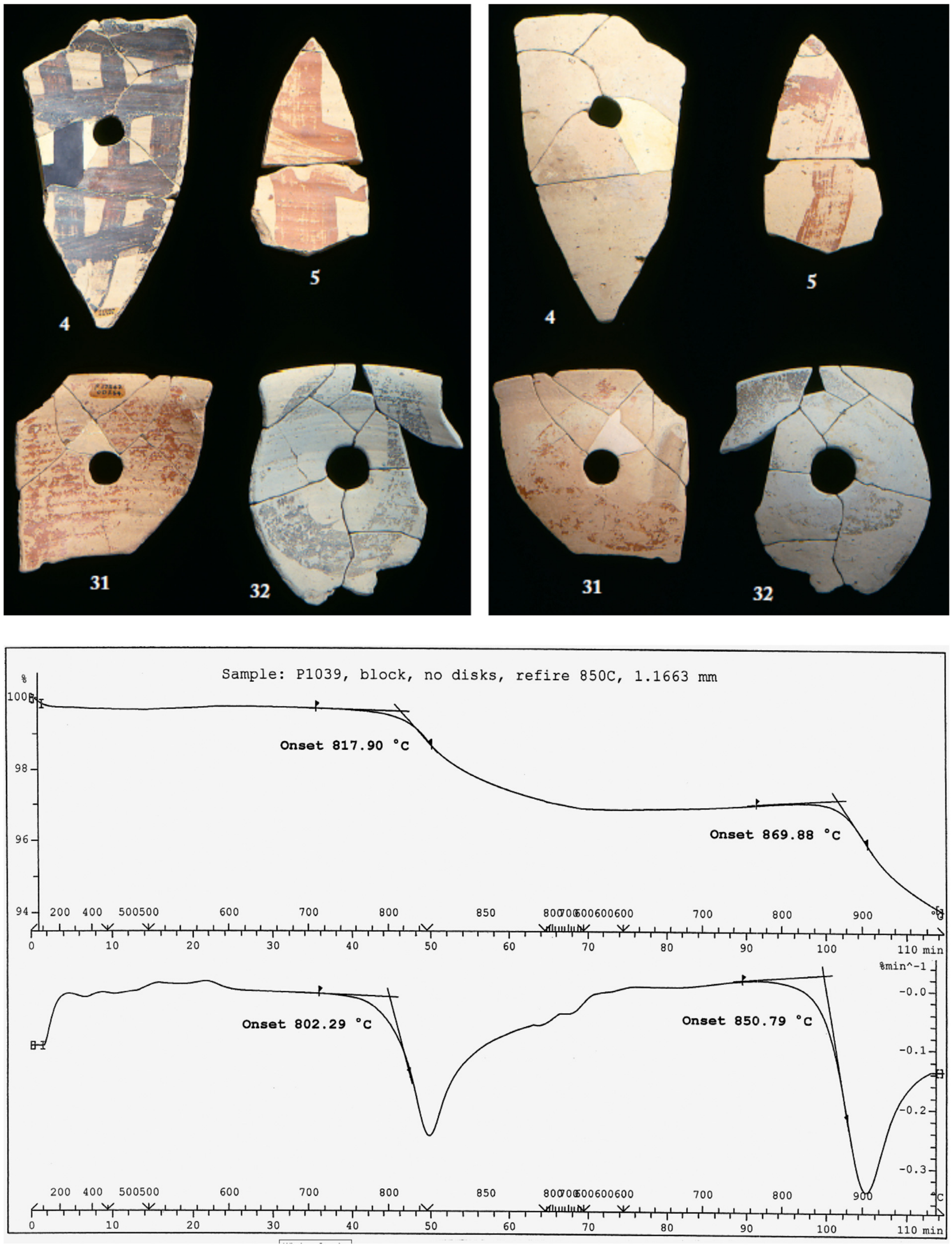


Fig. 21. a. Test pieces from pit or well L11:1 in the Athenian Agora: interior (left) and exterior (right) views. From Papadopoulos 2003:colour Plate 1. Image courtesy of the Trustees of the American School of Classical Studies at Athens. b. Dilation/sintering curve DS and its first derivative dDS of a test piece from the Athenian Agora. From Schilling 2003:Fig. A9. Image courtesy of the Trustees of the American School of Classical Studies at Athens.

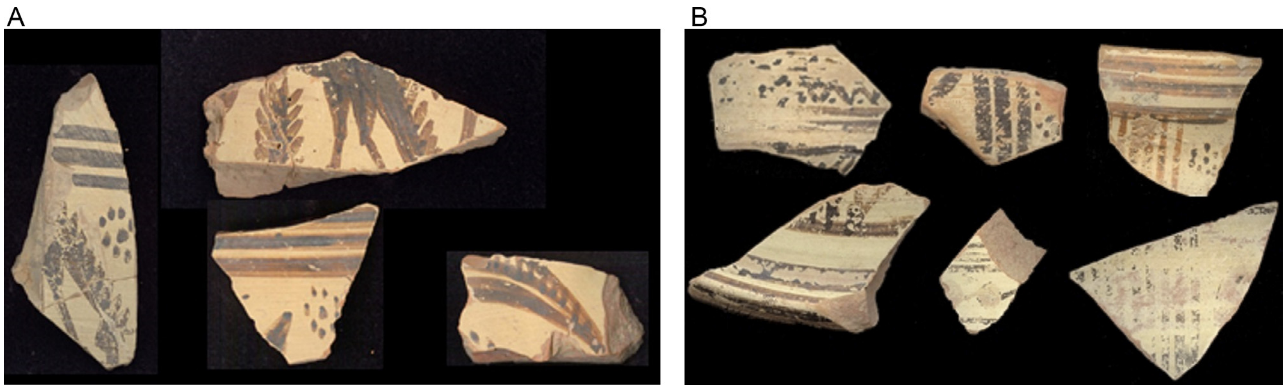


Fig. 22. Euboean LG slipped pottery from Eretria, Euboea (left), and from Naxos (right). From Aloupi and Kourou 2007:Figs. 5 and 12. Photos courtesy of the authors.

Fig. 23. Protocorinthian pottery. Left: Small aryballos of a hunting/shooting scene by the Evelyn Painter, circa 700–790 BC, found at Kamiros (BM 1969.1215.1). Right: Aryballos by the Head in Air Painter depicting hounds, lions, and boars, circa 650–620 BC, found at Kamiros (BM 1860.4-41b). Reproduced with permission; © Trustees of the British Museum.

immediate north of Penteskouphia village, and at Aetopetra, north of the Nikoleto quarry, together with the source at Acrocorinth, proved suitable for experimental roof tile production (Sapirstein 2008:122, Fig. 6.1).

Turning now to the decoration, the black, like its counterpart in Athens, is the product of a clay with low Ca and high Fe, whose sources at Corinth are as yet unknown. Raman estimated about 11% magnetite in the vitrified submicron particles forming the gloss. The best-quality examples of black (Fig. 25a) have high alumina/silica ratios (0.55–0.69), close to those for Attic black (0.64–0.71) (Mastrotheodoros et al. 2013:Fig. 3).[17] The firing temperature range of 15 sherds dated to a 150-year span was estimated (by FTIR and using an illitic clay from Solomos for reference) at 975 +/- 50°C. There was a hint, no more, that the Protocorinthian examples were fired at the lower end of this range. The very small calcite inclusions in the body clay (12–19% CaO) apparently formed two particle size distributions, as observed in the element distribution images, 20 μm and 1 μm (Klesner et al. 2017).

A valuable aspect of Rodriguez-Alvarez's (2019) study is the capture of the diachronic view of the gloss composition, which together with the fabric composition was determined by pXRF of the surface.[18] Although sample numbers are few and there was no direct evaluation of the gloss thickness, there is a trend: an increase in relative K% from Mycenaean to Early Protocorinthian (EPC) to Middle Protocorinthian (MPC) (690–650 BC) (Fig. 25b), which accords well with the macroscopically observed change from a dull brown-black gloss in the earlier periods to a higher-quality, richer black in the Black Figure style appearing in MPC 1. Also satisfying is the steady decrease in K from Early to Late Corinthian, again reflecting the decline in the quality of decoration over the course of those phases (circa 620–500 BC).

By comparison with Corinthian (and Attic), Boeotian BG was prepared from less uniform materials (a low alumina/silica ratio, a relatively high CaO content, and usually a low Fe_2O_3 content). Although the firing was somewhat variable, manifesting itself as variable black colour and occasional bloating pores, fine sintered BG layers were achieved (e.g. Mastrotheodoros et al. 2013:Fig. 10 right, over white).

Mention is made in Section C3b6 of investigations into the method of manufacture of Corinthian aryballoi. Returning to polychromy, this short-lived style practised beyond Corinth or Attica from the mid-seventh century, for example in the islands and the Argolid, could be usefully investigated from a materials standpoint.

C3b. Athens

Accounts of the history of research into the identity of the BG on decorated Attic pottery (Fig. 26) are numerous. It is an intriguing story, extending back to the eighteenth century, when Comte de Caylus (1752) described the black glaze as "basically ferruginous earth with a presence of manganese; this earth fired red, the black colour being produced by the admixture of some pigment of various earths or clays." It suffices here to distinguish between the respective contributions to the understanding of Attic black from those who had firsthand knowledge of this pottery, such as the classical archaeologist Gisela Richter (1923) and the classicist Charles Naudé (1959); those combining that knowledge with experimental work (Noble 1988); and chemists. Chief among the last group was the ceramic chemist Thomas Schumann (1942), who receives most of the credit for understanding the nature of black gloss and replicating it, but he was well aware of earlier work, notably by

[17] Cf. values from a much smaller data set: alumina/silica ratio: Corinth 0.74, Athens 0.67 (Klesner et al. 2017:Table 4).

[18] I have not seen the recent publication on this subject by Rodriguez-Alvarez (2021).

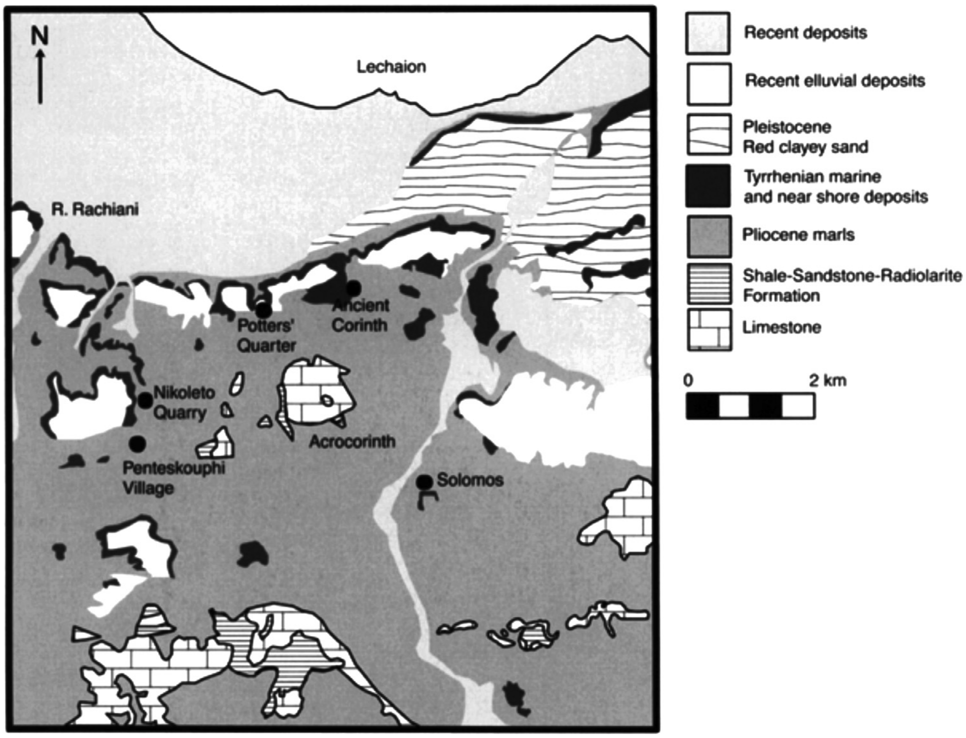


Fig. 24. The regional geology of ancient Corinth. From Whitbread 2003:Figure 1.1. Image courtesy of the Trustees of the American School of Classical Studies at Athens.

Tonks (1908). Noble's *The Techniques of Painted Attic Pottery* remains a fundamental work for giving a rounded picture of the whole process from forming to firing, aided by his successful replication experiments, although it is now known, as explained below, that the use of sodium hexametaphosphate (Calgon) as a deflocculating agent is not relevant to Attic BG.

Fig. 26 illustrates examples of the two main classes considered in this section: Attic Black Figure, which began in the late seventh and continued until the later fifth century BC, and Attic Red Figure (circa 520 to late third century).

At the time of my review in 1986 (*GCP*, 798–809, Table 9.10a), the consensus, expressed at its most basic level, was that the preparation of BG required the fine fraction of an illitic clay. During the reducing phase of the three-stage firing—oxidising, reducing, oxidising (ORO)—the gloss layer turned black and its surface sintered such that during the final oxidising stage it remained black and the unpainted body returned to red (Fig. 27). SEM of the microstructure estimated a temperature range of 850–1000°C (or higher, as estimated by TE) and the thickness of the black gloss in the range 10–40 µm. There was less agreement on the sources of suitable clays in Attica and, as just mentioned, the nature of the deflocculating agent.

We can now consider the many more recent enquiries. In essence they have been stimulated first by the availability of ever more powerful techniques of analysis and imaging, taking the enquiry from the microscopic micron level to the nano scale (see Table 1). The Getty Conservation Institute's Athenian Pottery Project (http://www.getty.edu/conservation/our_projects/science/athenian/) was prominent in pursuing those investigations using vases in the Getty Museum's rich collection (Lapatin 2008), stimulated in part by the museum's major exhibition *The Colors of Clay: Special Techniques in Athenian Vases* (Cohen 2006a). Elsewhere, consistent progress in investigating black gloss in the laboratory and experimentally has lain in the hands of Eleni Aloupi-Siotis, whose first results appeared in Aloupi (1993:chapter 4), and has come through the wide range of activities of her company Thetis Authentics in Athens. Second, the ways in which BG technology was adopted and developed in the wider Greek world—notably in Magna Grecia—have appealed to researchers in Greece and many other countries, as has the transition from BG to its later, red gloss manifestations in the Roman west in the form of *terra sigillata*.

But before coming to the individual studies, I should set the scene by acknowledging that just as there has been an upsurge of interest during the last 20 years in how Greek prehistoric pottery was made, as explained in Section B, the corresponding documentation of the later Greek potter's craft is essential. To this end, Schreiber (1999) provides an authoritative and richly presented account of the construction methods used by Attic potters in making decorated vases. A potter herself, Schreiber outlines, with reference to illustrations of particular vases in the J. P. Getty Museum and in other collections, how each shape was formed, how the attachments were made, surface treatments, the idiosyncrasies of certain potters, and important information derived from common flaws and defects.

The results and issues arising from individual studies, listed in Table 4, are presented here in roughly chronological order of publication. Some of these studies are exploratory in nature. Others vary greatly in scope in terms of the techniques employed and sample sources and numbers. As a result, their treatment here carries an important implication: they lack a coherent narrative. Some are very detailed, but they all have individually contributed to the subject and have each yielded results of relevance, which divide into the following subsections: (1) broad chemical characteristics, (2) morphology of BG and firing temperature, (3) iron minerals and iron oxidation states (usually incorporating the use of replicas), (4) sources of BG clay, (5) experimental firings, and (6) contour and relief lines. The summary in Section C3d aims to provide a consensus picture.

(1) Chemical characteristics of BG

Many studies have reported the contrasting compositions of BG and the body, usually determined by SEM-EDS, which consistently shows the higher Al, Fe, and K and lower Ca contents in the gloss. The relevant data, sometimes expressed as Al_2O_3/SiO_2 and Al_2O_3/FeO ratios,

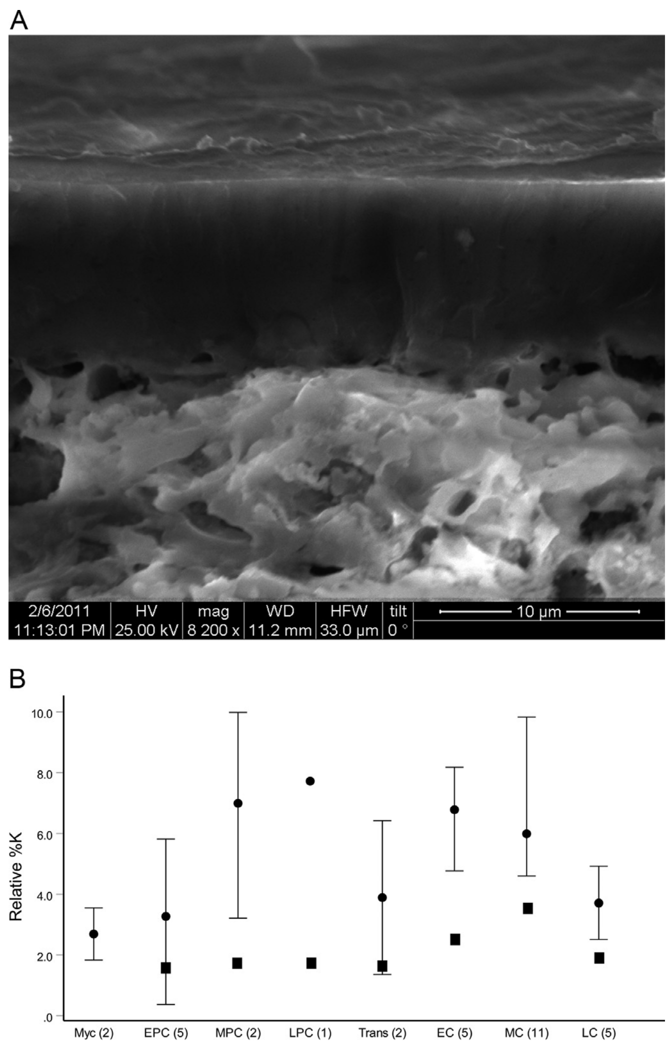


Fig. 25. a. A well-vitrified, homogeneous black layer (secondary electron image) on Corinthian pottery from the Herakles Sanctuary at Thebes. From Mastrotheodoros et al. 2013:Fig. 4. Image courtesy of Giorgos Mastrotheodoros. b. Percent relative K content in gloss (of different colours) and fabric of Corinthian pottery according to date, Mycenaean to Late Corinthian. Gloss (black circle: mean; bars: maximum and minimum). Fabric (black square: mean). Analyses by pXRF. Adapted from Rodriguez-Alvarez 2019:Fig. 6.36.

which are higher in the BG, has been assembled in many reports. Aloupi-Siotis (2020:Table 1) gives a mean (of 26 values) Al_2O_3/SiO_2 of 0.65 BG and 0.42 body (cf. 0.75 BG and 0.34 body at Corinth [Klesner et al. 2017:Tables 4 and 5]). The K_2O/Al_2O_3 ratio is also instructive. Kingery (1991) confirmed that it remained almost constant among the different fractions prepared from clay from Amarousi (Fig. 29), as would be expected, but this ratio was not entirely constant among the examples of Attic BG. A low value was indicative of simple sedimentation whereas higher values were suggestive of the addition of either a potassium-rich ingredient (such as wood ash) or a particular "glaze clay." However, in the light of more recent data, the addition of the wood ash seems not to be applicable to most Attic BG, although there are exceptions.[19]

(2) Morphology of BG and firing temperature

Some of the earliest images of Attic BG observed in the TEM were obtained by Maniatis et al. (1993), who found polycrystalline magnetite particles embedded in the amorphous vitrified matrix of the roughly 20 µm–thick gloss layer. Larger in size (>0.5 µm) but less frequent were titanomagnetite (Fe_2TiO_4) grains. The gloss layer was not necessarily uniform in microstructure. For instance, on its outer top layer lay a very thin (about 1–2 µm) glassy film that was responsible for the surface sheen. This film, which was rich in Al and Fe but depleted in Si, owing probably to weathering, has also been noted on other vases (Mirti et al. 2004b:715) and, significantly, on some modern replicas. The shallow layer (visible in the top half of Fig. 28a) on a BG replica prepared by Aloupi and Chaviara probably corresponds to this film. It could be attributed to a layering effect occurring in the application of the slip before firing, which would cause the ultra-fine clay particles and iron oxide grains to vitrify completely, forming the outermost layer. So its presence is likely to be restricted to only the best-quality BG. With SEM, Tang et al. (2001) estimated the thickness to be about 20 µm, extending down to 5 µm, in keeping with the variability of the gloss layer observed macroscopically and mineralogically (ranging from hematite—grain size 0.027 µm—magnetite/maghemite, and hercynite to solid solutions of probable hercynite-ferrian spinel). A highly vitrified layer, 20–25 µm thick, on the BF Priam amphora was consistent with firing that reached 900–950°C, as determined by XRD and reflectance spectroscopy, but it was the latter technique that helped establish that the final reoxidation phase occurred at around 800°C (Mirti et al. 2006).

The resilience of good-quality BG is well-known, but burial in harsh terrestrial and especially marine environments gives rise to surface pits, cracks, and discolouration. These effects have chemical correlates: a decrease in Si and K and an increase in Mg (Aloupi-Siotis 2020:Fig. 9). The appearance of starlike cracks is mentioned in Section C3b4.

(3) Iron minerals and iron oxidation states

Hematite Fe_2O_3 (Fe3+), magnetite $Fe^{2+}Fe^{3+}O_4$, hercynite $FeAl_2O_4$ (also a mixed Fe^{2+} and Fe^{3+} oxide), maghemite γ-$Fe^{3+}{}_2O_3$, FeO wustite (Fe^{2+}), and FeO metallic iron are relevant here. Using µRaman, magnetite was identified by Pérez and Esteve-Tébar (2004) and Medeghini et al. (2014) as the main component of the BG on RF vases and BG from Motya. Carbon (1350 cm^{-1} and 1584 cm^{-1} peaks) from the fuel was also detected in both cases. XPS data was consistent with iron grains consisting of discrete layers of single phases with Fe^{3+}, Fe^{2+}, and Fe^0, in effect a composition gradient, all dispersed in the aluminosilicate and containing C-C carbon (Ingo et al. 2000).

Turning now to studies based on what has perhaps become the technique of choice—XANES—Lühl et al. (2014) used its confocal mode to achieve fine-depth resolution without interference from the underlying body. With tight controls consisting of, first, reference materials of previously studied minerals and glass containing iron, and, second, replicas, the treatment of their XANES spectra allowed estimates to be made of the Fe valency state contents present in BG's mineral and glassy components. They established that Fe^{3+} decreased as firing temperature increased to 890°C and as grain size decreased, only to increase at the highest temperature, 930°C. Accordingly, their archaeological specimen with the highest-quality bluish-black gloss had the most reduced iron (Fe^{3+} 20%), corresponding to magnetite grains (<200 nm in size) with an $Fe^{3+}/Fe^{2+}+Fe^{3+}$ ratio of about 50% and leaving a significant Fe^{2+} content in the glassy phase. This matched their modern replica gloss from the finest clay paint (<0.3µm) when fired at 890°C in ORO conditions, in turn agreeing well with observations made in the course of replicas prepared at Thetis Authentics in Athens. The amount of Fe^{3+}, although low, can manifest itself visually as a brown-red band or zone within the BG layer, such as when the outer glassy layer has weathered. It was also present in a replica made from clay from Panakton (Chaviara and Aloupi-Siotis 2015:Fig. 5; see next section).

From those same replicas and other experiments in a kiln of volumes 1 l, 1/8 m^3, and $\frac{1}{2}$ m^3 and drawing on earlier work (Aloupi 1993:84–94), Aloupi-Siotis (2008:120–21) summarised her findings succinctly: reduction starts at 925 +/- 25°C and "must occur while the temperature

[19] Such as an example of earlier Attic (Protogeometric) with high K in the black layer (Aloupi-Siotis 2020:Fig. 10).

Fig. 26. Left: Black gloss decoration on Black Figure (BF) neck amphora vase attributed to the Group of Würzburg 199 (last quarter of sixth century), depicting Herakles bringing the Erymanthian boar to Eurysthenes, warrior and archer. Metropolitan Museum 41.162.190. Right: Red Figure (RF) amphora attributed to the Syracuse Painter, 470–460 BC, depicting Poseidon and Nike. © Metropolitan Museum 06.1021.151. Open access images.

Fig 27. The three-stage firing (ORO) leading to the creation of a sintered black paint layer on the vase surface. Left to right: Decorated leather-hard vessel and, after the oxidising, the reducing and final oxidising phases of firing. The leather-hard vessel's clay body would be more grey than is represented here. Photo courtesy of Josh Brouwers (https://www.ancientworldmagazine com/articles/making-ancient-greek-vases-look-red-figure-black-figure-pottery/).

is falling to about 825°C, below which reoxidation can start. The reducing phase must be intense and last no more than 20–30 minutes."[20] It is this firing protocol that prevents dissociation of the magnetite and, to repeat, enhances the quality of the gloss. The lower temperature of the reoxidising phase is necessary to prevent reoxidation of the BG. Broadly similar in aim and outcome were Cianchetta et al.'s (2016) detailed experiments using replicas.

(4) BG clay—sources and chemical and physical characterisation

Efforts to locate sources of the raw material yielding Attic BG have traditionally focused on what was close to hand in or near Athens itself, but the spatial coverage has now expanded. Chaviara and Aloupi-Siotis (2015) compared the physical and chemical characteristics of experimentally produced and archaeological BG.[21] Of the 36 clays they collected in different areas of Attica (Fig. 29), most were capable of producing, without the addition of a dispersing agent, a slip in the form of a colloidal suspension, which on firing became a dark gloss. These clays were iron-rich, low in calcium (about 1% CaO), and illitic, but with some presence of kaolinite (Chaviara and Aloupi-Siotis 2015:4). As fired replicas, their colour and surface appearance varied. One group included orange-red clay from a large bed at Krora near Panakton on the Attica–Boeotia border exhibiting spontaneous colloidal dispersion in rainwater (shown to good effect in Aloupi-Siotis 2008:Fig 3a; 2020:Fig. 3)[22] as well as others from the area and from Mount Parnes; these had a black-brown colour combined with starlike cracks (Fig. 28b), a feature that seemed to be independent of slip thickness or the firing sequence. The cracks were due to differential shrinkage of body and gloss occurring before or during the heat soaking/annealing phase—that is, below

[20] And similarly re-expressed by Aloupi-Siotis 2020.

[21] Chaviara (2018) provides much additional information on the subject, including estimates of how much raw clay was needed to produce sufficient volume of slip to decorate vases of different sizes, as well as full pXRF composition data.

[22] See also Aloupi (1993:106, Fig. 4.24). Winter (1959, 1978) was probably the first to recognise the potential of the clay at Krora, but his experimental results were modest.

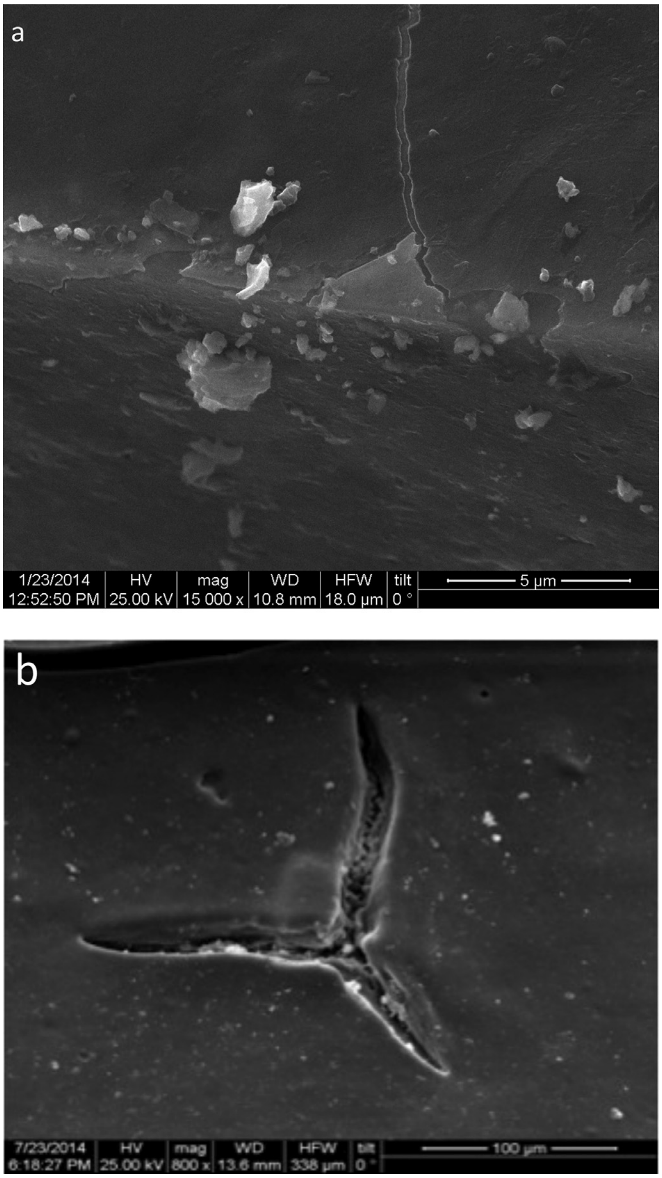


Fig. 28. (a) SEM micrograph of a modern BG replica using a colloidal suspension of a ferruginous clay from Mount Hymettus (sample HMT-30, Chaviara 2018 archive) and fired according to the three-stage scheme proposed by Aloupi (1993) and Aloupi-Siotis (2008). Secondary electron image, fresh fracture surface. (b) SEM micrograph of a starlike crack on a laboratory specimen surface. From Chaviara and Aloupi-Siotis 2015:Fig. 6b. Both images courtesy of Eleni Aloupi-Siotis.

820–800°C. Significantly, half of the Archaic BF vases examined shared this same feature, as may have Exekias' Dionysus cup (Fig. 38).

Chemical analysis (pXRF supported by µPIXE) of the gloss on the experimental replicas and the large, chronologically wide set of archaeological specimens revealed some unexpectedly high Zn contents (400–800 ppm) (or Zn/Ti ratios, as in Fig. 30), certainly higher than in the body, in a few clays, including those from the Lavrion. This characteristic also appeared in much of the Archaic BG from the Acropolis (600–500 BC), as it also did in the Attic BF and RF vases (sixth–fourth centuries) studied by Walton et al. (2015), who found 271–1959 ppm Zn in the gloss compared with <361 ppm in the body. XANES analysis showed that the Zn was hosted in a spinel environment, which in turn was indicative of this element being naturally present in the clay rather than as a post-depositional contaminant. An important observation was the lack of correlation between Zn and any other measured element. Rare earth element analysis identified another chemical marker in the gloss in the form of a Cerium (Ce) depletion anomaly.

Fig. 29. Locations (black circles) of ferruginous, illitic clay soils in Attica collected by Chaviara and Aloupi-Siotis (2015).

That the Zn and Ce markers were detected in the gloss of not only the Attic but also the *single* samples from Corinth (sixth century BF) and Etruria (fourth century RF) appeared to weaken any argument that the clay for the gloss was linked to a single Zn-rich environment like that at the Lavrion. Walton et al. proposed instead that the gloss clay was soaked in vitriol, prepared as a product of the working of silver-rich lead ores such as those at the Lavrion, which naturally contained zinc sulphide. The sulphuric acid–rich acid mine drainage (AMD) formed in this way would be rich in zinc rather than lead compounds owing to the greater solubility of the former. The desired end product then was crystalline zinc sulphate. Among the varied functions of vitriol already known in antiquity (e.g., Pliny *Natural History* 35:section 32) may have been its use as a dispersing agent. According to Walton et al., the clay having received a first levigation would then be treated with vitriol to allow the fine-grained clay to be removed from suspension and to dissolve any calcite particles present. They speculated that the zinc-rich vitriol might have been available in widely dispersed locations, thereby explaining the occurrence of vases with high Zn gloss outside Athens.

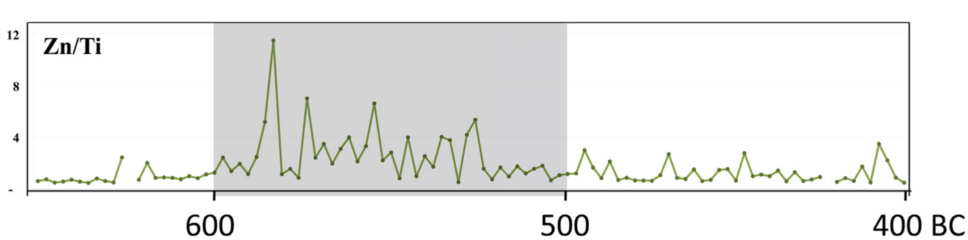


Fig. 30. Ratio of zinc to titanium as a function of date in all the archaeological BG samples. Highlighted is the sixth century, when the Zn/Ti ratio in Attic Black Figure is highest. Adapted from Chaviara and Aloupi-Siotis 2015:Fig. 11; image courtesy of the authors.

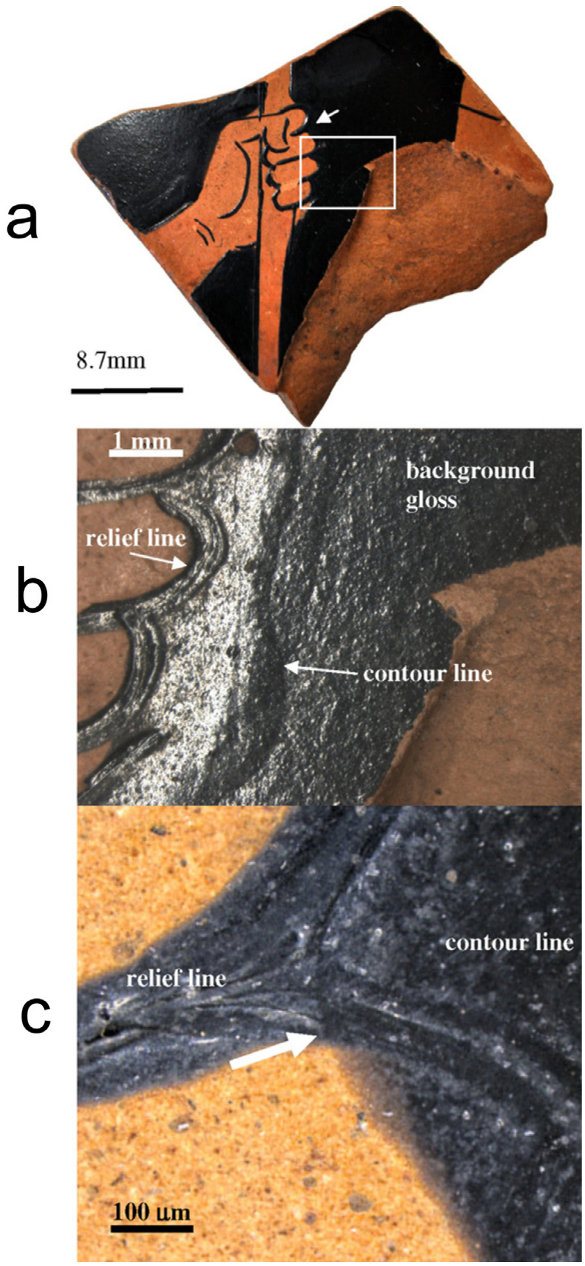


Fig. 31. Optical images of a vessel fragment attributed to the Kleophrades Painter. (a) Image of whole fragment depicting a hand grasping a staff. The box and arrow show the location of Fig. 31c. (b) Raking light image of hand showing the three main components of the applied decoration, labelled as relief line, contour line, and background gloss. (c) The arrow marks where a dilute wash of contour line overlaps the relief line in a region near the knuckles of the hand. From Walton et al. 2013:Fig. 1.

On the other hand, Chaviara and Aloupi-Siotis objected that the application to the vase surface of such an acid-rich gloss would have had deleterious effects on the quality of the painting, preferring instead the use of another zinc compound, calamine ($ZnO/ZnCO_3$), which would have been more pH neutral. Meanwhile, Muşkara and Kalayci (2021) have followed up the feature of the Zn marker with respect to 10 BF vases attributed to known sixth-century painters. Their carefully controlled pXRF analyses confirmed high Zn (373–544 ppm) in the BG compared to the body (141–229 ppm) of six of them. The appearance of the same feature among some of the red gloss and white decoration should probably be attributed to the presence of the underlying BG. Two painters were represented by more than one vase, with Sophilos and Lydos appearing consistently in the high and low Zn groups, respectively. Several points from this section are taken up in the summary (Section C3d).

The finding of a depletion of the rare earth element cerium is potentially important because of its association with anoxic weathering environments; their iron-rich red soils/clays are common enough in the Mediterranean (Walton et al. 2015:434). But although this in itself might help explain the Ce anomaly in the samples outside Attica, there are surely other factors contributing to this anomaly and the observed rare earth patterns.

One final point in connection with Chaviara and Aloupi-Siotis's clay prospection and experiments: the quality and yield of paint would be dependent on pH and temperature. Aloupi-Siotis (2008:119) found that from freshly collected clay, the paint can be obtained at pH >8.7 and T >15°C, whereas if the same clay were soaked in water for six months, the same results would be reached at pH 7 and T >15°C.

(5) Experimental firings

Having followed Noble's methods in making and decorating Attic vases, Kahn and Wissinger (2008) proceeded to fire their products using a small oak-burning kiln holding six medium-size pots (cf. some 10 vases in one of the Penteskouphia plaques [Fig. 44]). The first phase of firing took the temperature to 850°C, at which point the flue and firebox were closed off. This action, however, caused significant back pressure, preventing the temperature from rising. As a result, the temperature was raised to its maximum—940°C—before reduction began; after 30 minutes the kiln cooled to 750°C. In the final oxidising stage, the temperature was raised to 815°C, followed by cooling for 15 to 20 hours (Kahn and Wissinger 2008:Table 1). Results were encouraging (Kahn and Wissinger 2008:Fig. 5). The frequent problem of flame marks and ash on the surface of the pot was largely overcome by using a saggar box, and increasing the flue brought improvements. In each firing, 45 kg of wood was consumed.

Using a kiln based on that of Kahn and Wissinger, Balachandran (2018) reported experimental firings at the J. Hopkins Archaeological Museum using a local illitic, low-Ca clay. It took five hours to reach almost 1000°C, followed by a 40-minute reduction to 800°C and then reoxidation. Undertaking the firings provided an ample, vivid reminder of the level of skill demanded of the Athenian potters in this critical last stage of the pottery making *chaîne opératoire,*[23] so much so that Balachandran (2018) invoked a strongly sensory aspect to the operation; these potters were surely highly attuned to the senses. In his thought-provoking account, in the first phase of firing, the pots' growing red colour was accompanied by the changing sound of the fire and, for example, steam emanating from the kiln walls, leading finally to a loud whooshing sound, the expulsion of bright orange embers, and a bright orange flame at the chimney. Reduction brought out distinctive smells, sights, and sounds, including billowing, sharp-smelling smoke, flames appearing from the chimney and firebox, and the darkening colour of the pots. Finally there was acute sensory awareness in controlling the end of that phase, changing the atmosphere, and lowering the temperature.

(6) Contour and relief lines

On a single sherd (Fig. 31a) from a vase by the Kleophrades Painter, Walton et al. (2013) identified the three essential decorative features used to design RF vases: relief line, contour line, and background gloss (Fig. 31b–c). They were all similar in their major and trace element composition, as if to suggest that they were prepared from different batches of the (single) clay used for preparing the black gloss. However, the relief line, lying below the contour line, was painted first. It consisted of well-

[23] It is appropriate to note here the words in *Geoponica* 6.3(5): "The firing is no small part of the potter's craft. Not too small or too much fire should be built under the pots, but just enough." See Papadopoulos 2003:191–97 and the demons who feature in the poem "Kiln" or "Potters" by pseudo-Herodotus, epitomising the potential pitfalls that can accompany the operation of the kiln (Noble 1988:148–50, Appendix III).

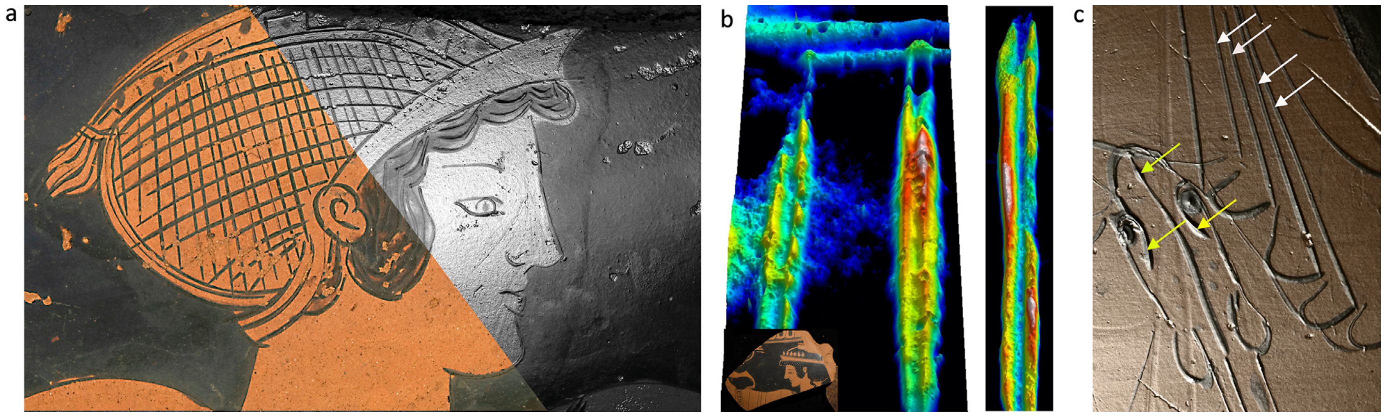


Fig. 32 a. Split-image detail of Thetis' head depicted on the stamnos. The image shows RTI still-captures of the detail, one with specular enhancement (upper left) and the other under normal illumination (lower right). From Artal-Isbrand and Klausmeyer 2013. Photo courtesy of Paula Artal-Isbrand. b. 3D confocal images as elevation maps of three ancient pulled lines from the stamnos (with photo inset for location) (left) and a modern pulled line (right). Line lengths are 2.7 and 3.1 mm, respectively. Clearly similar are the furrowed profiles of the ancient and modern lines. From Artal-Isbrand and Klausmeyer 2013:Fig. 13. Photo courtesy of Paula Artal-Isbrand. c. RTI still-capture of a detail of the stamnos. Examples of ridged lines are indicated with yellow arrows and furrowed lines with white arrows. From Artal-Isbrand and Klausmeyer 2013:Fig. 5. Photo courtesy of Paula Artal-Isbrand.

faceted Fe-spinel crystals embedded in a glassy matrix. By contrast, the contour line was composed of lamellae of the sintered remnants of phyllosilicate clay grains, stacked and oriented parallel to the gloss surface. This microstructure was similar to that of the background gloss, which was painted last and, critically, was indicative of a different (lower) temperature of formation than that of the relief line. The authors' concluding suggestion "that the decorative elements were painted in stages, with at least two stages separated by a reduction firing of the vessel" is important because it demonstrates that the option of a multiple firing was open to some Attic potters. This point is taken up in the summary, Section C3d.

Using reflectance transformation imaging (RTI) and a 3D measuring laser microscope with a dual confocal system, Artal-Isbrand and Klausmeyer (2013) investigated how a sophisticated Attic RF stamnos, attributed to the Tyszkiewicz Painter, was decorated, focusing on the glossy black relief lines, contour lines, and dots. Representative images from these two techniques appear in Figs. 32a and 32b, respectively. The relief lines could be short, long, thin, or quite thick, some of them having a single ridge down the centre, while others had a distinctly furrowed profile (Fig. 32b). The two types were termed ridged and pulled lines, respectively (Fig. 32c). The results of their experiments with a range of tools of different sizes and thicknesses—a feather tip, brushes made of hair (horse, human, pig), and a syringe[24]—on ceramic surfaces pointed to the efficacy of Seiterle's (1976) *linierhaar*, a brush made with only one or very few hairs. This was dipped into the gloss, "laid down onto the surface of the vessel, and then lifted straight up to create a relief line" (Artal-Isbrand and Klausmeyer 2013:Fig. 8). Seiterle's methods of creating loop-shaped laid and long relief lines also worked well in the experiments. The long relief lines later required the tip of the brush to rest on the surface and then be pulled along the surface to create a line of the desired length. These actions recall the scene of the painter on the well-known Antiphon Painter RF vase (in the Boston Museum of Fine Arts: MFA 01.8073), proposing, plausibly enough, that the implement in the painter's left hand is a reservoir for the gloss mixture. The authors also replicated the relief dots using a conventional brush. Images of both ancient and modern dots were sufficiently similar to suggest that they were probably produced in the same manner. None of the authors' experimental mock-ups were fired, as it was assumed that no significant alteration to them would have taken place (Artal-Isbrand and Klausmeyer 2013:341).

The findings on the stamnos were encouragingly supported by their macroscopic observations on other RF vases (Artal-Isbrand and Klausmeyer 2013:Tables 2 and 4). It was apparent that all Attic RF vases featured the pulled line technique, whereas laid lines seem to become more common at a later stage of the Classical period. Southern Italian vase painters (circa 390–320 BC) used both line types in RF production.

The Getty's Athenian Pottery Project has employed a similar approach to visualise painted outlines, fine detail lines, and incised lines. See http://www.getty.edu/conservation/our_projects/science/athenian/visual.html.

Relief lines and dots also formed part of an investigation by Chia-Lin Hsu (2010). Subsequent examination of RF vases in tandem with the results of experimental work persuaded her that the applications of relief lines and dots were made on a range of surfaces from unfired to highly fired (Hsu, personal communication). This, together with the coexistence on a few vases of both high-relief dots and two-ridged relief lines, seemed to be indicative of multiple firings. The consistency or porosity of the slip was an important parameter.

In a different direction, following the experimental application of computed tomography on Greek pottery by Koens and Jansen (1999), Karl et al. (2014) exploited the potential of nondestructive X-ray computed tomography (CT) for examining the method of manufacture of Corinthian aryballoi. For repair to the damaged surface of a Corinthian alabastron as illuminated by CT together with SEM-EDS and XRD, see Karl et al. (2018).

C3c. Classical (BG on Black and Red Figure pottery) to early Roman (Campanian, terra sigillata*) in southern Italy, Etruria, Greece, and Turkey*

Here I consider studies of BG on Black and Red Figure pottery of the Classical and Hellenistic periods in Greece and their various manifestations in Magna Grecia (Fig. 34) and elsewhere. The latter include BG Campanian pottery of the fourth to first century BC produced in Italy and beyond, which has received much science-based attention since the early work of Maggetti et al. (1981) and others. This section includes red gloss, the counterpart in all respects of BG but produced without a reducing phase. It is from Campanian pottery that the red gloss Samian ware emerges in the first century BC in central Italy.

At least two studies have drawn on chemical analysis of the body to confirm the status of the pottery as either Attic or imitation Attic/Atticising. This was accomplished confidently at Locri (Lokroi

[24] A syringe-like instrument could have been used for relief dots (J. K. Papadopoulos, personal communication).

Fig. 33. a: Apulian RF column krater depicting artists at work, 36–350 BC, by the Group of Boston, 00.348. Metropolitan Museum 50.11.4. b: Gnathian skyphos, 350–325 BC. Metropolitan Museum 26.60.93. © Metropolitan Museum.

Fig. 34. Map of Italy showing sites mentioned in the text.

Epizephyrioi) in southern Italy (Figs. 34, 43b) by Mirti et al. (2004a) using ICP-ES together with colour hue and saturation values from reflectance spectroscopy, which showed the Attic products behaving differently from local products at the high temperature range (Mirti et al. 2004b:Fig. 7). The local potters fired RF and BG slightly higher (up to 1000°C) than the Attic examples (Section C3b2), producing a gloss layer similar to Attic in quality and chemical composition (Mirti et al. 2004b:Figs. 1 and 2). A similar finding emerged at Iasos in southwestern Turkey, where Amicone (2015) applied pXRF to differentiate the body of Attic BG (and red gloss) from that of Atticising pottery produced in Ionia, perhaps at Old Smyrna. The black and red gloss had similar compositions with suitably low Ca (about 1% CaO) and high Al, K, and Fe contents compared to the body. A more powerful nondestructive approach was taken by Pappalardo et al. (2016) using PIXE to differentiate the BG on Sicilian RF from Attic. The former was less uniform in composition, having a lower K/Ca ratio than Attic and a wide Ca range (1.1–5.6% CaO).

The stylistically distinctive RF pottery (Fig. 33a) and related classes in Apulia in southern Italy has merited much investigation by Mangone and coworkers to define their centres of production (using ICP-MS)[25] and the nature of their decoration. Focusing on the latter, their main finding was the existence of two roughly contemporary traditions, one following the "classic Attic" technology and the other, introduced in the later fourth century, using a red engobe to simulate Attic red. For instance, at Monte Sannace (25 km north of Taranto) Mangone et al. (2008) found the former tradition in the form of a fine local *terra rossa* clay for the body, from which a finer fraction was prepared for the BG (Fig. 35a). It had the following familiar characteristics: hercynite, magnetite, haematite, quartz, and feldspar; low Ca, high Al and Fe; a very compact, consistent 20 μm–thick layer. By contrast, the other tradition employed a coarser, more calcareous local clay adopted usually for larger vessels. Between the BG layer and body was an intermediate layer, the *ingobbio rosso*, whose function may have been to prevent the calcareous body clay giving rise to a red surface that was lighter than desired; the thick engobe would ensure a darker and more consistent red resulting from the firing. Firing temperatures were generally high, as estimated by XRD, with equivalent firing temperatures of about 950°C at Monte Sannace (Mangone et al. 2008) and 1000–1100°C at Arpi (Giannossa et al. 2020:244). The black on some unfired RF at Arpi was found to be Mn- and Fe-rich (Giannossa et al. 2020:Table 6).

The same two traditions appear in the production of Gnathian pottery (Fig. 33b) from Egnatia (Fig. 35b) and Monte Sannace (Mangone et al. 2011): *terra rossa* for the better-quality Apulian RF, with the coarser *argille subappennine* deposit characterised by abundant clay minerals (illite, smectite, chlorite, and kaolinite), carbonates, and lesser quantities of quartz, feldspars, and micas. Again there is an engobe between the body and the BG (Fig. 36). The BG's dull aspect could be due to this layer's thinness as compared to RF: 10–15 μm versus 30–40 μm, respectively. A firing temperature range of 900–1050°C was determined by XRD, with support from a novel application of NMR (see Table 1) that compared the temperature-dependent NMR spectra of the white pigment with those of ^{29}Si and ^{27}Al in a kaolinite standard (Mangone et al. 2009:101, Fig. 4).

[25] Note the study with similar aims reported by Robinson (2014) using PIXE-PIGME.

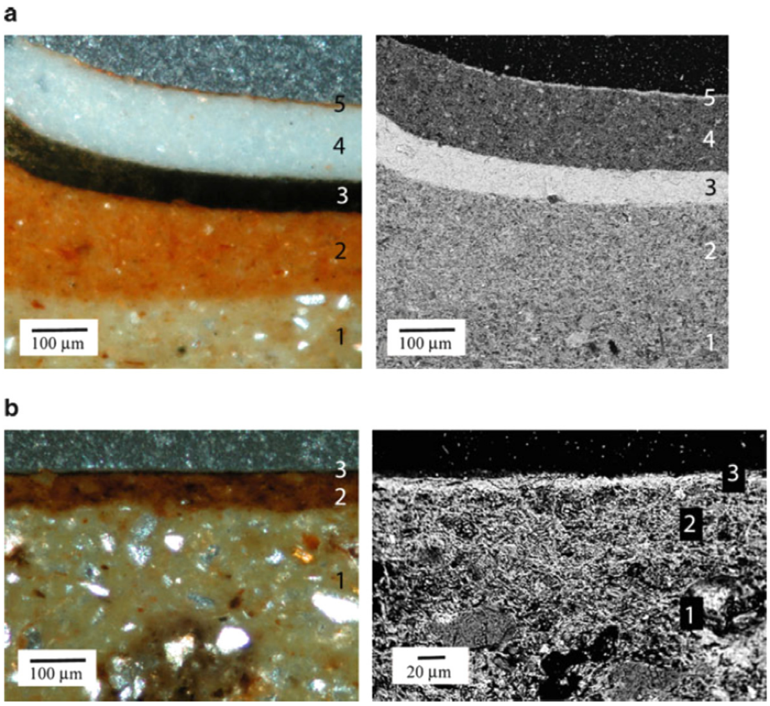


Fig. 35. (a) Gnathian pottery from Egnatia. Left: OM of sherd section showing fine-textured clay body (1), engobe layer (2), black gloss (3), and white (4) and yellow (5) decorations. Right: SEM–BSE image with highlighted characteristic differences of the overlapping layers. (b) Gnathian pottery from Monte Sannace. Left: crossed polars OM showing coarse-textured clay body (1), engobe layer (2), and black gloss (3). Right: SEM–BSE image. From Mangone et al. 2011:Fig. 2.

The decoration in red, white, and other colours is mentioned in Section C6. Of the RF sherds examined from Egnatia, 10% had a tin-foil coating (Mangone et al. 2013:Figs. 6, 8).

Working on BG Campanian pottery from Arezzo, Volterra, Chiusi, and Populonia in Etruria, Gliozzo and Memmi Turbanti (2004) began by chemically characterising the body of this pottery and establishing a complete reference group regarding production at the Chiusi-Marcianella kiln complex. (For the kiln complex see Pena 2017:Fig. 8.3; Pucci and Mascione 2003.) Clays found near the kiln complex matched the pottery well. The detailed technological study that followed (Giorgetti et al. 2004; Gliozzo et al. 2004) focused on examples of contrasting BG quality (Fig. 36a). The thickness of the gloss layer averaged around 20 µ, with a range 5–50 µ. Porosity (frequency, area covered, and maximum dimension of pores) varied considerably, but these parameters were not correlated. Chemically, the matt (from the second-century BC Marcianella pottery kilns in Chiusi), together with vitreous and silver types, had higher silica but lower FeO contents compared to the shining, bluish, metallic, and misfired types. All the glosses were easily distinguished from the corresponding bodies, having a higher Al_2O_3/SiO_2 ratio, much lower CaO, and higher FeO and K_2O contents. As expected, the gloss types contained different iron oxides (Table 5), and the ratios of those oxides as observed in the XANES spectra implied that there was usually a concentration gradient through the gloss layer. Among the contrasting morphologies of the glosses apparent in the TEM images (Fig. 36b), the shining metallic black contains magnetite crystals, as was found in Attic BG (Maniatis et al. 1993:Fig. 5).

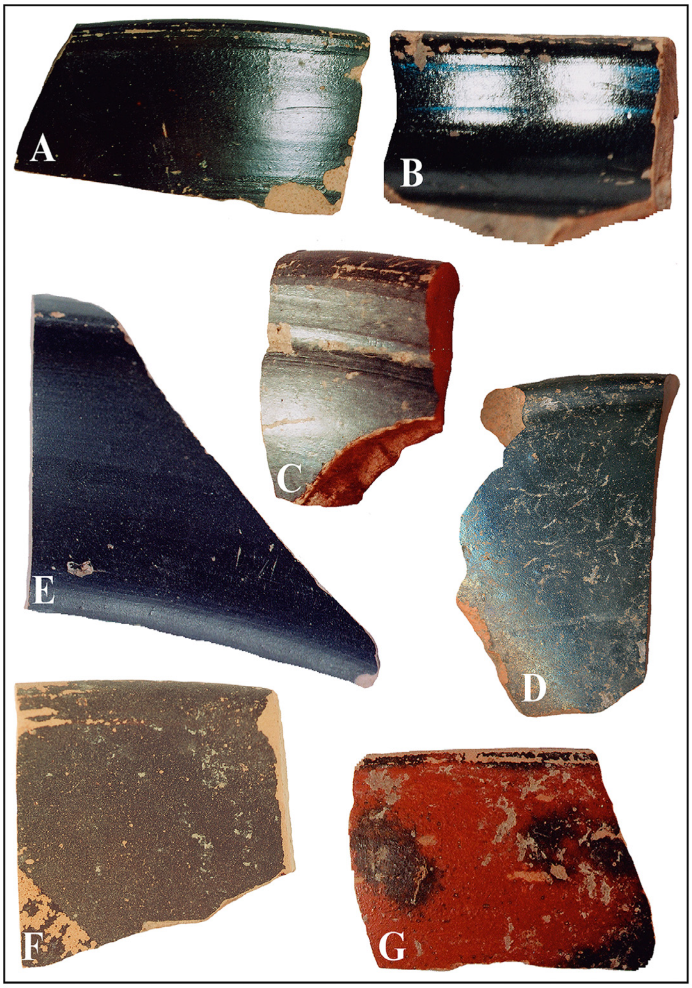
The scale of effort in science-based studies of BG Campanian A, B, and C pottery produced in the last centuries BC in Italy can be gauged from the map in Madrid i Fernández and Sinner (2019:Fig. 2). Of the many studies that have explicitly investigated the gloss layer and firing conditions, only a few are listed in Table 4. Drawing on results obtained by Mirti and Davit (2001), Montana et al. (2013), and Madrid i Fernández and Sinner (2019), the standard formula of low Ca and high Fe, Na, and K contents in the gloss applies generally to all Campanian productions, but in Campanian A it seems that the alkali content is somewhat higher in the body. Other features of Campanian A (produced in the Naples area) include a uniform thickness of 10–15 µm and some variability in the macroscopic appearance of the gloss, paralleling that observed in Etruria, above, reflected in estimated firing temperatures in the range of about 800 to >950–1000°C. This range is similar to that of Cales BG, which was also produced in Campania but of a more calcareous clay (Madrid i Fernández and Sinner 2019). Campanian B (Etruria and to the north) seems to be more consistently fired: 900–1000°C maximum. Greater variability of thickness and firing temperature range are apparent in Campanian C (Sicily); the Na+K contents are lower than in Campanian A gloss.

C3d. Summary

An impressively wide range of techniques has been brought to bear on the nature of BG—from macroscopic observation of the decorated surfaces by vase specialists to highly sophisticated techniques delivering images (from TEM) and analysis (from high-energy synchrotron beams) at the nano level. Notwithstanding the limitations inherent in the experimental approach from the preparation of the raw materials all the way to firing, that practical approach provides an essential complement to the science-based work. It is the accumulated long-term experience in replicating BG and its basis in the use of archaeologically relevant materials, best explored by Aloupi-Siotis (2020), that has mitigated some of those limitations and enhanced confidence in and the relevance of the findings.

As a result, the wealth of data generated about BG is leading to a consensus on its nature. In brief, BG material derives from an illitic iron-rich, low-calcium clay that is dispersed in water, with or without the aid of a dispersing agent, to give a very fine colloidal fraction. When in a suitable paint-like form, it is applied to the surface and the vase is subjected to a three-phase firing (Fig. 27). Drawing on the experience of Aloupi-Siotis (2008) and Kahn and Wissinger (2008), during the first phase, in oxidising conditions, the temperature may reach 900°C. The temperature is raised perhaps as high as 925°C when the flue and firebox are closed and damp fuel is added to create reducing conditions. This short—maybe no more than 30-minute—phase occurs as the temperature falls to around 750–800°C. Thereafter, the temperature rises to more than 800°C during the reoxidation phase, and then the kiln cools for at least 12 hours.

What happens during the reduction phase is critical for the quality of the resultant black gloss, the chief parameters being temperature range, rate of temperature change, duration, and the gas composition within a.



b.

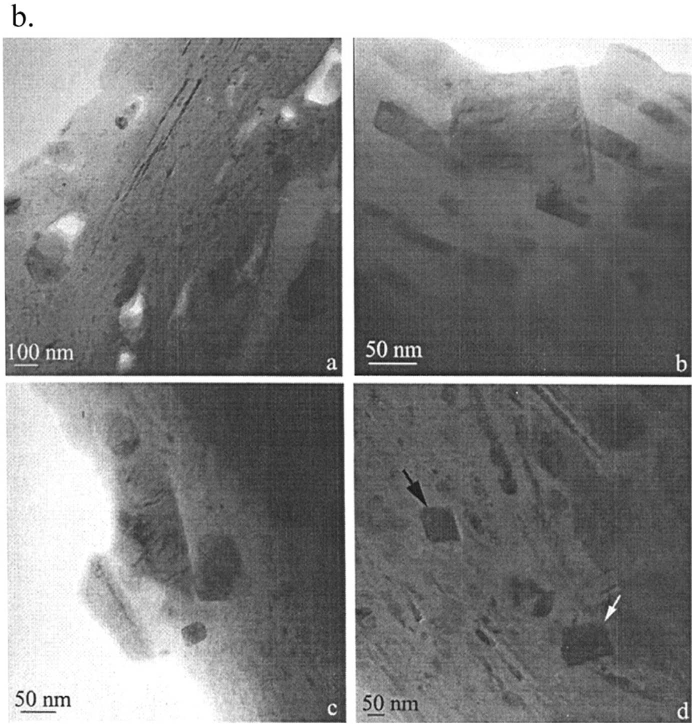


Fig. 36. a. Examples of BG from Etruria: shining, vitreous, silver-black, blue-black, matt, and misfired (red-black). From Gliozzo et al. 2004:Fig. 1. Photo courtesy of Giovanna Giorgetti. b. Representative TEM images showing textures of the glosses. (a) Subrounded and elongated hematite crystals in misfired, opaque black gloss. (b) Large quadrangular and smaller rectangular crystals of hercynite in opaque black gloss. (c) Large subhedral magnetite crystals in shining metallic black gloss. (d) Quadrangular and elongated hercynite crystals (black and white arrows) in bluish-black gloss. From Giorgetti et al. 2004:Fig. 5.

Table 5
Characteristics of the glosses from Etruria

Gloss	Site	Mineralogy (from synchrotron XRD)
Misfired black and red	Populonia	Hematite
Opaque black	Marcianella	Hercynite (tr magnetite)
Shining metallic black	Populonia	Magnetite
Bluish black	Volterra	Hercynite

Source: Giorgetti et al. 2004:Table 1.

the kiln. The blue-black colour that may be seen in the best-quality Attic BG can be linked to a higher concentration of Fe^{2+} than Fe^{3+} ions and thus associated with the presence of hercynite and magnetite. Crystals of these iron oxides are dispersed in a vitrified aluminosilicate matrix. As the relative proportion of Fe^{3+} increases, the colour effect of the BG alters. It is the subtle interplay of (a) the nature of the composition of the BG material, in particular the state of the iron; (b) the BG material's grain size; and (c) the parameters regarding the reduction phase just mentioned that singly or collectively governs the final quality of the BG. That relative complexity explains the variation observed among the results presented in this section, on Attic BG and BG from Etruria and elsewhere, on the one hand in the visual appearance of the BG and on the other hand its composition.

More than 30 years ago, John Boardman (1989:233) wrote,

> The principal characteristic of Athenian vase painting in the sixth and fifth century is the clear evidence for the potter's readiness to take infinite pains over preparation of clay, slips and pigments and his attention to careful firing. It has taken modern science long to discover the essential simplicity of these techniques, meticulously applied, rather than of any obscure formulae, mystery compounds or multiple processes. It is remarkable that these techniques were applied to what became a minor craft, but we must recall that they were first developed for the work of artists whose draughtsmanship on pottery must have rivalled that on any other medium of the day for its finesse.

This essential simplicity belies a relatively sophisticated empirical technology (Kingery 1991:52). Modern science has indeed taken a long time to fully understand this technology because of the necessity to investigate it at increasingly detailed levels. This process has exposed, in light of the presentation above, what has long been evident at the macroscopic level—that BG at a general level represents a single technology but one practised over a long period of time in many different ways. We can now understand better the variations in quality and the effect of BG observed by eye as the consequences of the innumerable parameters involved in the forming, decorating, and firing of the pottery. These are reflected at one level in the observed ranges of the physical and chemical compositions of the raw materials, in their firing properties, and in the nature of the kiln and circumstances of firing, all of which are of prime concern here. But of course at another level there are the myriad of other factors that impact the final product—such human factors as craftsmanship experience, adherence to tradition, and market forces on the one hand and the effects of time, place, and environment on the other.

From the investigations reported here have also emerged results that have exposed more specific issues. The first is of interest as it responds to speculations made over the years about aspects of the firing: evidence for *multiple* firings adduced by Walton et al. (2013) (Section C3b6, above) and Cianchetta et al. (2015a, 2015b) (Section C7, below) in the cases of a fragment attributed to the Kleophrades Painter and a Berlin Painter RF hydria, respectively, as well as on examples of Coral Red (Walton et al. 2009; see below). Collectively, this evidence, based on very careful examination and analysis, appears strong and thus could point to the presence of a number of Attic painters who, with their potter counterparts, were both highly skilled and had an innovative mind-set. As Cianchetta et al. (2015b:675) concluded, "The firing practices of the Kerameikos artists were more complex and less standardized than previously thought, involving multiple firings and the sequential application of slips." Coming from a position of much accumulated experience in replicating BG and CR (see Section C5), Aloupi-Siotis (2008:121–24, Fig. 5a–b) has successfully demonstrated the practical feasibility of creating CR with double or multiple firings, arguing that it may have been a pragmatic response to firing accidents and failures following a single ORO firing. Nevertheless, to return to the Kleophrades Painter fragment, a critical point is the BG of the relief line that Walton et al. (2013) claim required, on the basis of the vitrification state, a higher firing temperature during the reduction phase (>750°C) than that of the contour line and background BG. The difficulty with that scenario is that the BG from the first firing could not withstand such a temperature without melting.

There are, then, issues of interpretation of some of the findings, leading to the conclusion that the evidence for multiple firings is not conclusive, resting as it does on a very few individual cases. For whatever reasons, these perhaps demanded special attention because they were causing unacceptable levels of failure, as Aloupi-Siotis (2008:123) and Walton et al. (2013:2034) have hinted, thereby encouraging the potter-painter to make corrections (for example in colour) and to take the vase through the firing sequence a second time. But there is also the issue of scale. It is likely that craftspeople undertaking such practices were very few in number, and the temptation to see these effects more widely practised should be resisted for very practical logistical reasons—multiple firings would carry major implications in terms of time, labour, and fuel—as much as for the necessary required skill. Out of interest and for contrast, attention is drawn to the evidence for a double firing in a very different context: Etruscan painted terracotta panels (Section C11, below).

The argument that a pre-firing step was sometimes necessary is plausible, unlikely though it may have been on a regular basis. The issue arises from the observation that during decoration and before firing, certain parts of the vessel, such as handle joints, are points of weakness and may actually break off. But this could be mitigated by a mild pre-firing at 450–500°C to eliminate cracks. In support of this claim, Aloupi-Siotis (2008:123) drew attention to the well-known vase (in the Ashmolean Museum) by the Komaris Painter depicting potters at work. One of them carries a krater whose weight is estimated at about 15 kg. Although that would reduce on drying, the krater might be too heavy for the two handles to bear unless the vase were pre-fired.[26] But if a first (bisque) firing was in any way routine, why have not more examples of RF vases with no or partial decoration survived?[27]

Turning now to the investigations by Chaviara and Aloupi-Siotis (2015) and Walton et al. (2015), the former demonstrated the availability of red clays in Attica (Fig. 29), of varying distance from Athens, suitable for the preparation of BG material. While some of them could also have been exploited by potters to make the vases themselves, the likelihood is that we are dealing with two different classes of clay: on the one hand, a very specialised clay for the gloss paint obtained at particular locations in modest amounts and thus capable of being transported easily, and on the other hand, clay dug in bulk by the potter close to his workshop. One scenario envisaged in such a scheme would be a specialist, perhaps itinerant craftspeople who provided those pottery workshops that needed paint material. This suggestion implies that the potter-painter did not prepare, or need not have prepared, his own paint material.

Both investigations, joined now by the work of Muşkara and Kalayci (2021), coincided in finding a potential chemical marker in the compo-

[26] Hasaki (2019:Fig. 15,Table 5) quotes the weight of an Apulian RF crater as 15.8 kg, which would equate to a pre-firing weight of 21 kg using Noble's estimate (1988:156–57, Graphs I, II) of a 33% weight loss on firing (and 21% on drying). On another vessel depicting potters at work, the Caputi hydria, Green (1961) made the case that the craftspeople were more likely to be metalworkers, although that view has not found favour.

[27] I owe this question to discussion with J. K. Papadopoulos.

sition of Attic BG: enrichment in Zn (Fig. 30) and Ce depletion (Walton et al. 2015). Using different arguments, they concluded that this phenomenon could have arisen from the treatment of a clay with a dispersing agent obtained from the metalliferous region of the Lavrion in the form of a crystalline zinc compound: the carbonate (calamine) and sulphate of zinc, respectively. Furthermore, this phenomenon could not be explained as a result of some absorption process from the soil, since other elements that would be expected, notably lead, are not enriched.[28] But whereas Chaviara and Aloupi-Siotis (2015) registered the zinc enrichment to be most prominent in sixth-century pottery, but certainly not consistently so, Walton et al. (2015) noted the effect beyond the sixth into the fourth century. That similar results were obtained in pottery from Corinth and Etruria should be treated with caution, as they were based on single sherds, although, as noted above, the rare earth element data is consistent with a clay/soil environment occurring widely in the Mediterranean.

There are some difficulties with arguments about the Lavrion. First, there is no archaeological evidence of the deliberate working or treating of zinc-rich ores at the Lavrion in the sixth century BC, let alone later in antiquity, these ores having come into their own only in the nineteenth century.[29] Second, the proposed procedures involving a zinc compound appear overly sophisticated and were unlikely to be essential; top-grade BG was surely produced without the intervention of these procedures. Overall, therefore, this remains an intriguing question whose resolution demands further investigation and more analytical data on sherds of a wide chronological span. But for the time being, it is perhaps telling that pXRF analyses of slips of seventh- to sixth-century Corinthian pottery did not reveal anomalous Zn contents in the admittedly uncalibrated data (Rodriguez-Alvarez 2019:Appendix F). I have encountered high Zn contents in BG on a few Classical–Hellenistic vases, some of them possibly Attic, from a cemetery on Lipari, now part of the Stevenson Collection in the Glasgow Museums.[30] Although there is as yet no data that corroborates Walton et al.'s findings for BG pottery from Etruria,[31] this region hosts metalliferous ores, including zinc.

Whatever the mechanism of the zinc enrichment, the effect was not consistent, as it featured in only around half of the sherds analysed by Chaviara and Aloupi-Siotis (2015). The crucial point is that several red clays in Attica, including those in the Lavrion area, were potentially exploited for the preparation of BG. One resulting implication is that the compound, being light and easy to transport, could have become an item of trade. Extending the scenario of the itinerant craftspeople mentioned above, this trade was perhaps mediated by a specialist supplying the high end of the pottery industry with both the appropriate clay and the treatment agent for BG.

Attention should be drawn to the effectiveness of RTI and associated microscopy in revealing detail of painters' techniques in creating effects, in particular relief lines and contours. Artal-Isbrand and Klausmeyer's elegant approach (2013) could surely find further application, perhaps accompanied by firing of the experimental replicas.

It is appropriate to return finally to the issue of terminology. Chaviara and Aloupi-Siotis's (2015) objection to the term *gloss*, mentioned above, is reasonable. What can replace it? In light of the multitude of studies of BG mentioned above, there is no mistaking the presence of a vitreous element in BG, in which case Aloupi-Siotis's (2020) call for the adoption of a new term—*Black Glass-ceramic* (BGc or Fe-BGc)—is logically more correct and thus to be welcomed. Whether the term gains wide currency is another matter, but perhaps more important is an awareness of this new designation among those working on BG.

C4. Archaic–Hellenistic red

Red pigments were iron oxide–based red colourants, typically red ochre. It is recognised that hues of red are assignable to the presence of not only hematite but also the naturally more common iron mineral goethite—FeO(OH). While goethite is usually equated with yellow ochre, on heat treatment above 250°C it transforms to hematite (Siddall 2018:4), as first described by Theophrastus in the fourth century BC (Pliny *Natural History* 35:128, 130). Furthermore, as Mastrotheodoros et al. (2010:Fig. 2) have shown, the hue achieved on heating is a function of temperature, grain size, and starting iron mineral(s). One striking example of an installation where the heat treatment of ochre to deliver a red colourant likely took place is the small kiln-like structure of late Hellenistic date in Athens found in advance of building the Acropolis metro station (Parlama and Stampolidis 2000:14, Fig. 4) (indicated by a white polygon in Fig. 46a).

The best-quality red ochre of Greek antiquity is generally equated with *miltos*, the very fine-textured iron oxide occurring on the island of Kea off the coast of Attica (Fig. 19) (Photos-Jones et al. 2018:Fig. 2). Its function was to enhance contrast between the black-painted surface and the clay body of vases. Deposits of hematite-rich red ochre, some of them of high quality, surely occur at many locations in Attica, not least in the Lavrion area. The issue is whether *miltos* from Kea found its way to potters' workshops. It could in principle have been used as a pigment for artists decorating walls or for potters/coroplasts decorating ceramics post-firing, but in the more common case of application *before* firing, the situation is less certain. As recent work has shown, *miltos* had functions in addition to its role as a pigment: as a cosmetic and in ship maintenance (as an antifouling agent), agriculture, and, crucially, medicine (Photos-Jones et al. 2018:180). The Athenian decree issued in 360 BC to the three city-states of Kea, requiring them to export *miltos* from their respective mines exclusively to Athens, is well-known, and from that epigraphic evidence Lytle (2013) has argued that *miltos* was used primarily in boat maintenance (mixed with tar [*miltopissa*]) and less as a decorative paint. In this light, whether there is an association between *miltos* from Kea and its use as a potter's red colourant is decidedly open to question.

At Corinth the hematite-rich red was similar to but not as well prepared as BG (Klesner et al. 2017). A notable feature of one red-banded decoration is the contrasting gloss and matt effects, achieved by using different recipes; the gloss had a significantly higher flux and Fe and S contents than the matt (Klesner et al. 2017:Fig. 4, Table 2). The red on the contemporary Boeotian pottery was less uniform in composition and surface appearance than that on the pottery at Corinth, reflecting the use of differing materials (Mastrotheodoros et al, 2013:814).

Moving to southern Italian Gnathian, the *ingobbio rosso* seems to have been prepared from coarser, more calcareous local clay (see Fig. 35b), which was applied to the body before application of the black slip over the whole exterior surface. Dark red was a mix of iron oxides, hydroxides, and clay minerals, probably the same as that for the *ingobbio rosso*. Iron oxides provided the red overpainting on RF.

In the late HL–early R red-slipped/coated wares from ancient Kassope in western Greece, Papachristodoulou et al. (2010) determined three groups on the basis of the composition of body and slip. The technologically most accomplished was western *terra sigillata* of the first century BC, probably imported from Arezzo, fired at 850–1000°C with high alkalis and Al, and low Ca and Mg. The second group was imported eastern *terra sigillata* of the late second to first century BC, distinguished by a self-slip rather than a slip *per se* and fired usually to higher tempera-

[28] The Zn-rich environment of the Lavrion would explain raised Zn levels in pottery from Thorikos as recorded by de Paepe (1979) and in soils, for example from the lead ore washery at Agrileza: Zn 1376 ppm mean, 416–2464 ppm range (Photos-Jones and Ellis Jones 1994:Table 10).

[29] It is worth noting the presence in the Lavrion of zinc aluminium sulphate minerals, such as glaucocerinite, zincaluminite, and zincowoodwardite (Voudouris et al. 2021:Table 1).

[30] pXRF results: gloss mean 312 ppm Zn (range 101–939 ppm); body mean 182 ppm Zn (range 58–741 ppm).

[31] Gliozzo et al. 2004 did not analyse for Zn in the gloss from sites in Etruria. The Zn contents in the body of that pottery was low (about 100 ppm) (Gliozzo and Memmi Turbanti 2004:Appendix).

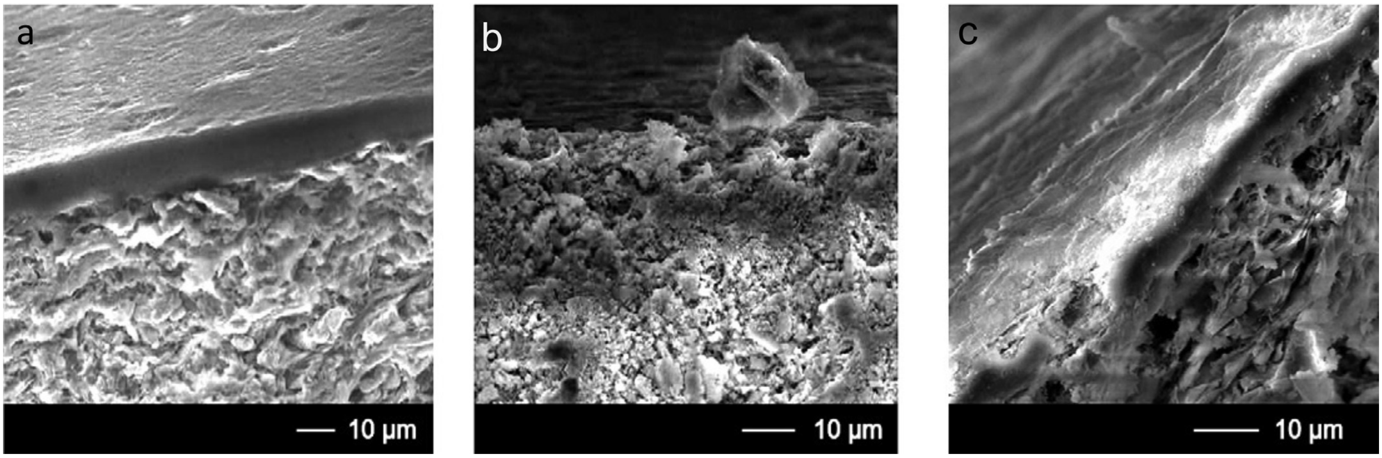


Fig. 37. SEM images showing the body-to-slip interface (bottom) and the main body (top) of sherds at Kassope. (a) Western *terra sigillata.* (b) Eastern *terra sigillata.* (c) Local red slip. From Papachristodoulou et al. 2010:Fig. 5.

Fig. 38. Dionysus cup by Exekias, 540 BC, found at Vulci. Staatliche Antikensammlungen, Munich. © Image by Marcus Cyron; Wikimedia Commons.

ture, up to 1050˚C. Inferior to the imported material was the local red slip (Fig. 37).

C5. Coral Red

Coral Red (CR) is the name given to the lustrous orange-red Attic gloss, quite different from red gloss (Section C3c) and the red of the previous section. A rare technique developed at a time of experimentation among the more innovative potters and painters, it was “generally used in Late Archaic and Classical Athenian pottery workshops as a spectacular alternative to black gloss for covering broad areas of a vase’s surface” (Cohen 2006b:44). Exekias, the likely inventor of this technique in the 530s BC, potted and painted in Athens the famous BF eye cup (Fig. 38), which was later exported and recovered in a tomb at Vulci in Etruria. How the effect was created received attention in the last century (see Cohen 2006b:45; *GCP*, 805–8; Walton et al. 2009:84–86), but here we look at more recent studies. In the first of them, in experiments to reproduce CR, Aloupi-Siotis (2008) found that rather than a single firing, which led to a dull grey-brown gloss, it was necessary to operate the following procedure to achieve the appearance and microstructure of ancient CR: a first firing to produce the black gloss, application of the same gloss material to decorate the reserved areas, and then refiring at 850–860˚C under oxidising conditions (Aloupi-Siotis 2008:Fig. 4a–d). Flaking was found to be a common problem. The double firing, it was argued, was therefore a direct response to firing accidents or failures that occurred in a single ORO cycle.

Walton et al.’s (2009) study of 13 examples (all but two from the J. P. Getty Museum) identified two CR composition types. One type has low Ca and Mg (LCM; five examples) and is very similar to BG in composition but with a much more porous microstructure and less sintering than the black, as observed in the STEM images. The other type has high Ca and Mg (HCM; four examples) and is more refractory and therefore could be fired with BG in a single three-stage firing of the kind outlined above by Aloupi-Siotis. There was no K enrichment in the BG in relation to the body to explain its greater sintering (Walton et al. 2009:Fig. 8). But the lack of material difference between the LCM CR and BG was problematic in that production of red and black gloss *together* on a vessel could not be achieved by a single three-stage firing. Walton et al. (2009) proposed two separate firings instead. The first was reducing. After cooling, the slip of BG composition that was intended to become red was applied. Finally there was a second firing, but oxidising. The main objection to the apparent twofold classification of the composition types is that in ceramic terms, it may be specious. Workshops would each have had a preferred recipe for preparation of the slip. Collectively those slips would display a continuous (but no doubt narrow) range of compositions. That there was one recipe that deliberately required more than one firing to achieve CR seems inherently unlikely.

C6. Archaic–Hellenistic Purple, White, and Yellow

The production of purple at Corinth is ingenuous. Klesner et al. (2017) speculated that the starting material was iron refuse or iron scale, which following acid treatment precipitated the dendrites, which were then ground up. The paint layer has a rough and uneven surface (5–25 μm thick) with particle size in the range of 0.3–1.2 μm, Fe_2O_3 >30%, and a firing temperature of >900˚C without necessarily having a reducing firing phase (Fig. 39) (Mastrotheodoros et al. 2013:816). Klesner et al. (2017) found a higher hematite content (60%) in their purple example. It had occasional 2–3 μm dendritic growth among rounded submicron hematite particles, contrasting with the particles’ more platy shape in a modern replica. Furthermore, the purple was more matt, less sintered than the BG layer.

Dark red, even purple hues, sometimes unintended, observed on Attic pottery are probably the result of only partial reoxidation of Fe^{2+} oxides during the last phase of firing. Mirti et al. (2006:41–42) used this

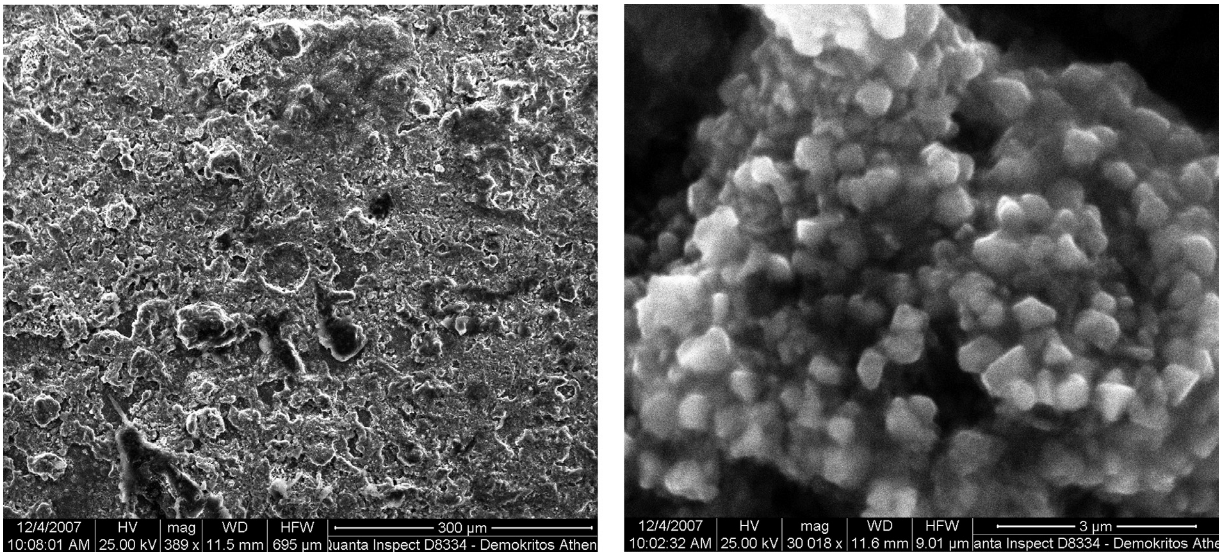


Fig. 39. SEM images of (left) the rough surface of purple paint and (right) its grainy texture on a Protocorinthian sherd. From Mastrotheodoros et al. 2013:Fig. 8. Images courtesy of Giorgos Mastrotheodoros.

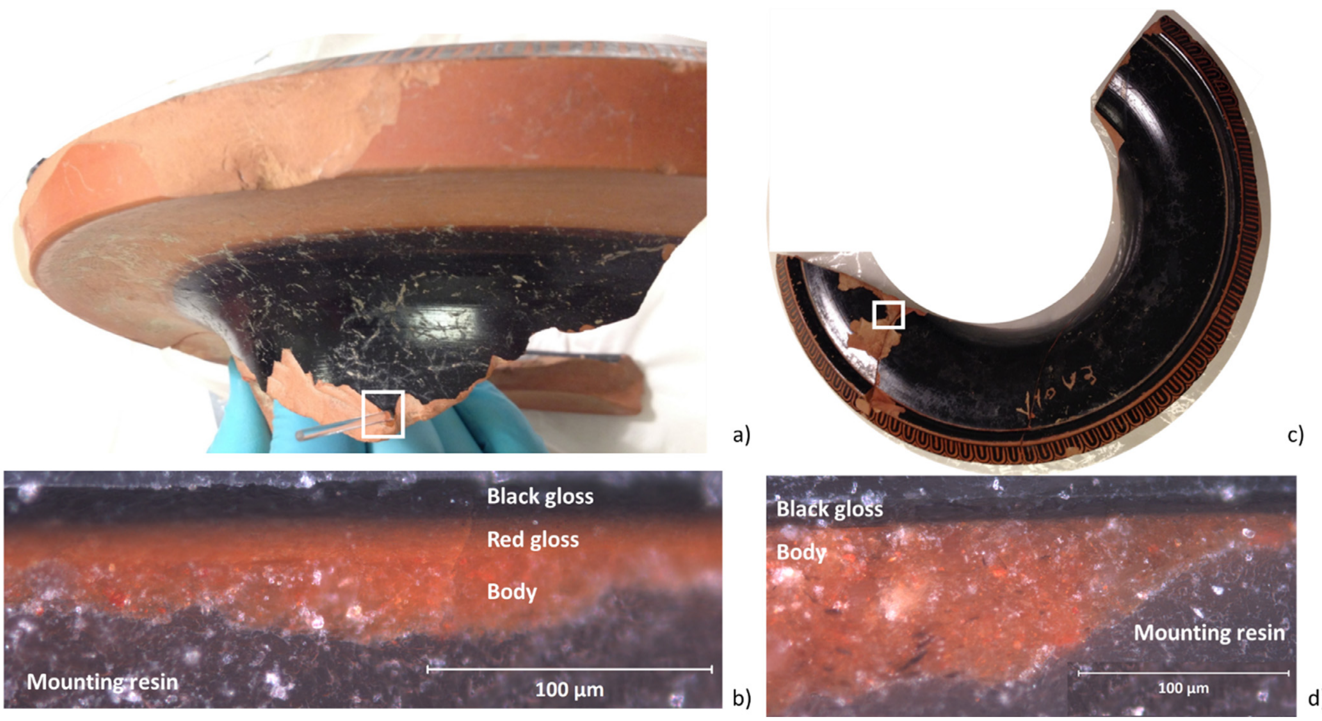


Fig. 40. (a) Sampling of exterior of RF hydria attributed to the Berlin Painter. (b) Cross-section view from top: black gloss, red gloss, body. (c) Sampling of interior. (d) Cross-section view from top: black gloss, body. From Cianchetta et al. 2015b:Fig. 1. Images courtesy of Getty Conservation Institute.

explanation in the case of the Priam BF vase, whose dark red was found to be highly enriched in Fe but lower in alkalis than either the BG or the body. Alternatively or additionally, under this circumstance of high Fe content and a temperature of 900°C or higher, the colour may be a function of the iron particle dimension: darker hues may obtain when particles exceed 0.4 μm in diameter (Mastrotheodoros et al. 2013:815).

White clays were used for this decoration in Corinth and Boeotia. At the former it had a considerably lower Ca but a higher Mg content than the body but was distinguished from the Boeotian by having a higher Ca/Mg ratio (Klesner et al. 2017; Mastrotheodoros et al. 2013). Attic white is treated in Section C8.

Decoration in white on Apulian RF and Gnathian was kaolinite, homogenised with low-melting albite and K-feldspar. Yellow was usually a mix of BG and white (Fig. 36a, example from Egnatia) (Mangone et al. 2011:103). Attention should be drawn to the flamboyant RF vases at Arpi displaying a rich palette of colours, where yellow was also achieved by mixing iron oxide with kaolin (Giannossa et al. 2020:Fig. 1, 244).

Apparently lacking in documentation are the chemical and mineralogical characterisations of decoration in BG as well as other colours on Laconian-style vases and on the many classes of Archaic and later East Greek pottery, including the white-slipped pottery of Chios.

C7. BG–RG combined

An example of this effect has received detailed attention from Cianchetta et al. (2015a, 2015b). Examination of two samples taken from the neck of an RF hydria attributed to the Berlin Painter (Padgett

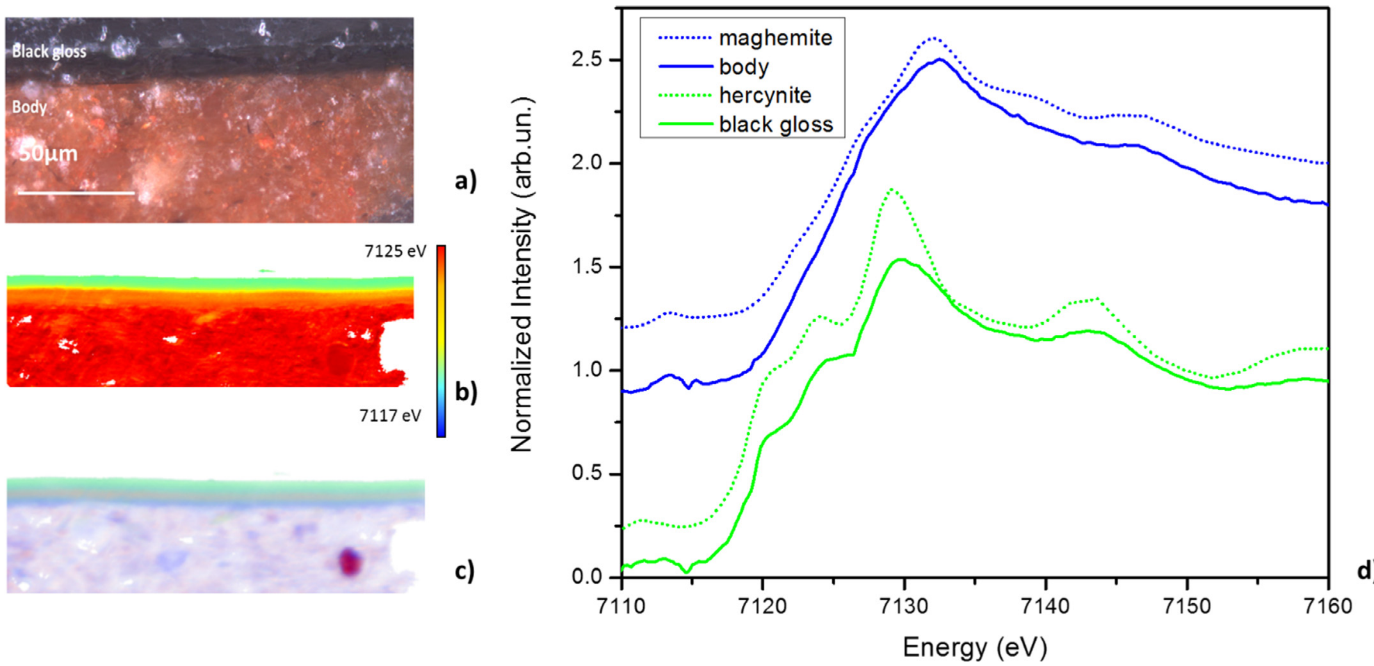


Fig. 41. (a) Optical photomicrograph of interior sample from the Berlin Painter RF hydria. (b) Fe-edge position map with colour-energy scale. (c) RGB phase map showing that the black gloss is composed of hercynite (green) and the body of a mixture of maghemite and hematite. (d) Averaged XANES spectra of black gloss (solid green line), body (solid blue line), and standard spectra of hercynite (dotted green line) and maghemite (dotted blue line). From Cianchetta et al. 2015b:Fig. 3. Images courtesy of Getty Conservation Institute.

2017) revealed the exterior and interior displaying, respectively, sequences of BG over red gloss over the body, and BG over the body (Fig. 40a–c). These were compared with replicates prepared from an illitic clay giving a slip/gloss fraction prepared by the addition of sodium silicate and carbonate. They were fired under ORO conditions more akin to those likely operating in ancient Attic kilns, essentially a longer first-phase oxidising firing (10 hours) at lower temperature (<900°C).

There were two firing sequences: T_1 and T_3 800, 900, and 1000°C (both oxidising) at 12°C/minute and T_2 850°C (reducing) at 12°C/minute. The maximum temperature reached at each stage of T_1–T_3 was maintained for 30 minutes. The first result demonstrated the sensitivity of the intensity, position, and width of the Raman Eg band of hematite at 300 cm^{-1} to firing temperature (Cianchetta et al. 2015a:Fig. 2). The Berlin sample best matched the firing regime T_1 1000°C, T_2 850°C, and T_3 800°C. This progressively decreasing firing temperature was critical in explaining the observed existence of the red gloss under the BG. In those areas intended to be red, the firing was oxidising alone, producing hematite nanocrystals in a red gloss. After cooling, the painter began a second round of decoration, applying the same slip but this time to where black was required. The second firing required extremely careful control of the traditional three phases. In the first oxidising phase, a balance had to be struck between allowing vitrification of the slip but preventing remelting of the underlying red gloss. The reducing conditions in the second phase were maintained at a lower temperature in order to preserve the vitrification of the now black gloss without it remelting. Finally, the last oxidising phase allowed reoxidation of the body while maintaining the integrity of the black gloss. The sequence, therefore, was $T_{red\ gloss}>T_1>T_2>T_3$.

Since Raman spectroscopy did not detect some of the relevant iron species, notably hercynite, greater reliance was placed on XANES (Fig. 41d). Analysis of the replicates indicated that the formation of hematite and a vitrified aluminosilicate matrix resulting from prolonged firing at 900°C was one route to the creation of a red gloss, similar to Walton et al.'s (2009) Coral Red Type 2 (Section C5, above) in which the red and black glosses share the same chemical composition. By contrast, when the glosses differ chemically, the former being more calcareous, a more porous matrix in the final reoxidation phase will have transformed the hercynite and magnetite to maghemite in the red gloss; this occurs in Walton et al.'s Coral Red Type 1. The red gloss on the Berlin Painter sherd belonged to the former pathway. Since its somewhat higher density than that of the black gloss was achieved by a higher firing temperature, that temperature would have ensured that both glosses had vitrified.

The authors claim that the only way to explain the separate black and red gloss layers (black over red on the exterior sample and black over a very thin red layer on the inner sample) was to propose two separate stages: first, high-temperature single-phase firing on the vase treated with slip forming hematite in the resultant red gloss; second, ORO firing at lower temperature to yield black gloss containing hercynite and magnetite.

While Cianchetta et al.'s impressive results cannot be doubted, their interpretation can be questioned. Of the two very small sampling locations on the vase, only the one on the exterior showed what appeared to be red gloss underlying black gloss (Fig. 40a). Indeed, that image recalls the feature of a red-brown zone within the BG layer observed on some Attic vases and in replicas (see Section C3b3), representing the remaining Fe^{3+} content in that layer and occurring naturally in the course of a single firing. Although in terms of composition and morphology the red in Fig. 40a had the hallmarks of a gloss, the fact that a red layer was not observed close by on the interior suggests that the difference was due to the firing conditions affecting differentially an exposed, sensitive area of the vase. In effect, therefore, the red layer is an artefact of firing. Until other areas of that same or a similar vase can be shown consistently to reveal an underlying red gloss layer, there is no need to invoke a second firing. As the authors admit, that second firing would in any case have required exceptional control of the firing phases. In that sense, this study has demonstrated a mismatch between a logical and sophisticated materials science explanation of laboratory-derived data and what might actually have happened in an Attic workshop.

Achieving a deliberate black-and-red bichrome effect using the same paint material—the finer fraction for the BG, the coarser one for red—does not seem to be possible to judge from repeated replication experiments (Aloupi 2008; E. Aloupi-Siotis, personal communication).

C8. White-ground (WG) lekythoi

These vases, intended as grave offerings, were slipped with a white ground (Fig. 42a), and decoration usually took place after firing (the so-called cold and matt painting after firing). To the general picture given by Noll and his coworkers (*GCP*, 809–11; Noll and Heimann 2016:143f) are some important new results.

It is now clear that the white ground was not of uniform composition. Kaolinite, which was applied before firing, featured prominently among examples from Merenda in Attica, the Iera Odos and Plateia Chotzia in Athens (Aloupi et al. 2009), and Berthold et al.'s (2017) Type II example (cold and matt painting after firing, probably by the Bird Painter, 430 BC). But from these same findspots and from Vergina, kaolinite was also found in combination with (a) alunite, present on a complete lekythos from Merenda, which indicates an identification as Melian Earth (see Section C10), and (b) montmorillonite. There were even instances of a talc base (Aloupi et al. 2009). The appearance of gypsum rather than anhydrite as the main component in the white ground of a Type I (mineral painting before firing) lekythos (attributed to the Timokrates Painter, circa 460 BC) is significant in indicating that it must have been applied *after* firing; this material may have been regarded as simpler and cheaper to use than kaolinite (Berthold et al. 2017). Evidently the potter-painter who made the large lekythos at Merenda was familiar with gypsum, as it was used to cover a crack on the vase's shoulder that had occurred and was repaired at the time of manufacture. Concerning the ability to alter the tone of the white ground, Maish et al. (2006) have reported that the creamy ground on lekythoi and the "whiter" whites appearing on vases (in the J. P. Getty Museum) were primarily fine illitic clays with possible mineral additions, such as bone white.

The black gloss on both (Types I and II) lekythoi contained hercynite, magnetite, and/or maghemite, as expected for decoration applied before firing. But there was an exception in the Type I example, specifically where the black gloss of the woman's hair was convincingly shown to *overlie* the white ground (Berthold et al. 2017:Figs. 7, 9). This unexpected observation could only be explained in terms of a process of applying, by some means, the black after firing. A final observation on this same lekythos came from X-ray colour camera imaging showing that a preparatory sketch of the woman's head had been made using a lead-containing material. As regards the colourants, cinnabar, carbon, and red ochre were detected at Merenda, and cuproivaite (Egyptian Blue) was detected on the Type II lekythos.

Following up the observation on several lekythoi of purplish-red discolouration especially or frequently near areas of painting in Egyptian Blue (Fig. 42b), Walton et al. (2010) investigated the fate of the WG lekythos in the funerary process. SEM determined that this discolouration was associated with copper-rich nano-particles (Fig. 42d). These particles, according to XANES, had formed through reduction of the Cu^{1+} dissolved in the glass layer (Fig. 42e). EMPA determined that because Ca and Cu had diffused from the Egyptian Blue into the underlying glass, the lekythos had received a second firing quite unconnected with its original firing. The deliberate application, post–original firing, of a red pigment formed by the reduction of copper but failing to adhere well to the surface was inconsistent with Walton et al.'s data. The observed discolouration had all the characteristics of having arisen from uncontrolled firing in a smoky atmosphere reaching a temperature up to 1000°C. Such a situation accords well with the scenario of the lekythos having been deliberately broken (with differential discolouration occurring on fragments belonging to the same lekythos) and thrown into the cremation pyre during the funerary ritual.[32]

A final point in this section is the post-firing application of gold foil to the surface. On six vases in the Getty collection, the gold was found to be very pure and <0.5 μm thick. How it was attached to the surface remains uncertain; Scott's finding of glucose and fructose under the gilding could be explained as possibly deriving from honey or starch-based glue (Maish et al. 2006:12).

C9. Ceramic production in Corinth and Athens

Before discussing some relevant aspects of ceramic production in Corinth and Athens, a summary taking in the Greek world at large is necessary. The corpus of Archaic and Classical workshops is large, roughly 250 according to Stissi (2020:99), allowing a fair impression to be gained about the layout, scale, and organisation of the Kerameikos. Drawing on the archaeological record at those workshops, Stissi (2012, 2016) established some common characteristics: they were typically concentrated at or just beyond the edge of towns, away from the main habitation areas; this visible location, probably on or close to a line of communication, optimised access to raw materials and probably clients. The workshops were not operating at the household level but rather as technical installations, strongly and efficiently focused on production, so the potters and their assistants did not live on-site but probably nearby. On the other hand, there is no doubt that the archaeological record is uneven. At one end of the scale are the late seventh- to early sixth-century BC workshop at Mandra di Gipari near Prinias in Crete, a remarkably compact unit with most expected components present except for, for instance, (levigation) basins,[33] and the mainly late fourth- to third-century workshops at Locri in southern Italy, a site that features in Section C3c, above (Fig. 43). These two cases contrast strongly with situations in which kilns are frequently the only surviving components. Where associated structures do occur they are often in poor condition or have been incompletely excavated. Some structures may have been impermanent or temporary. Storage areas are often lacking.

In this situation, the rich ethnographic record of pottery making, referred to in Section A, continues to be a valuable baseline of comparison with ancient workshops (Hasaki 2011:Tables 1–3). In the interrogation of that record, interest has widened to include how space is used within workshops, again drawing on the control provided by still-functioning workshops, for instance on Thasos (Papadopoulos 1995) and, more fully, elsewhere (Hasaki 2011). Taken from the viewpoint of the firing process, that same ethnographic record aided Whitbread and Dawson (2015) to argue convincingly that the design and functioning of ancient Greek kilns were the product of knowledge arising through the medium of social networks rather than technological requirements. At the practical level, our knowledge of ancient firing practices often derives less from the kiln remains *per se* than from the pottery fired successfully (and especially unsuccessfully) in the kiln. These remarks may apply as much to pre-kiln firing, as mentioned in Section B.

As regards the physical evidence of kilns themselves and with reference to Hasaki's kiln typology in Fig. 3, of the roughly 86 kilns of Archaic to Hellenistic date throughout Greece, about 57% are of Type Ia (round to oval, with the perforated floor having a single support). Type Ia, whose shape prevails elsewhere in the Mediterranean, "combines simplicity in design with maximum efficiency in firing, since its single support leaves 'cold' only a very small place in the combustion chamber" (Hasaki 2006:224). The diameter of this kiln type varies in size, mostly 1.20–1.50 m, and the ratio of height of combustion chamber to firing (ware) chamber is 1:1.5. On the basis of an optimal draft obtainable when the height and diameter of the firing chamber are roughly the same, the kiln capacity may be about 3 m^3 (Whitbread and Dawson 2015:336). Kiln capacity, time and motion involved in loading and unloading the kiln, cost-benefit analysis of having an additional kiln,

[32] Note that purple could be deliberately produced as cuprite (Cu_2O) by applying before firing either malachite, azurite, or copper oxide (E. Aloupi-Siotis, personal communication).

[33] Thér (2014:88) used the kilns at Mandra di Gipari as examples of his Type TKf (see Fig. 2a).

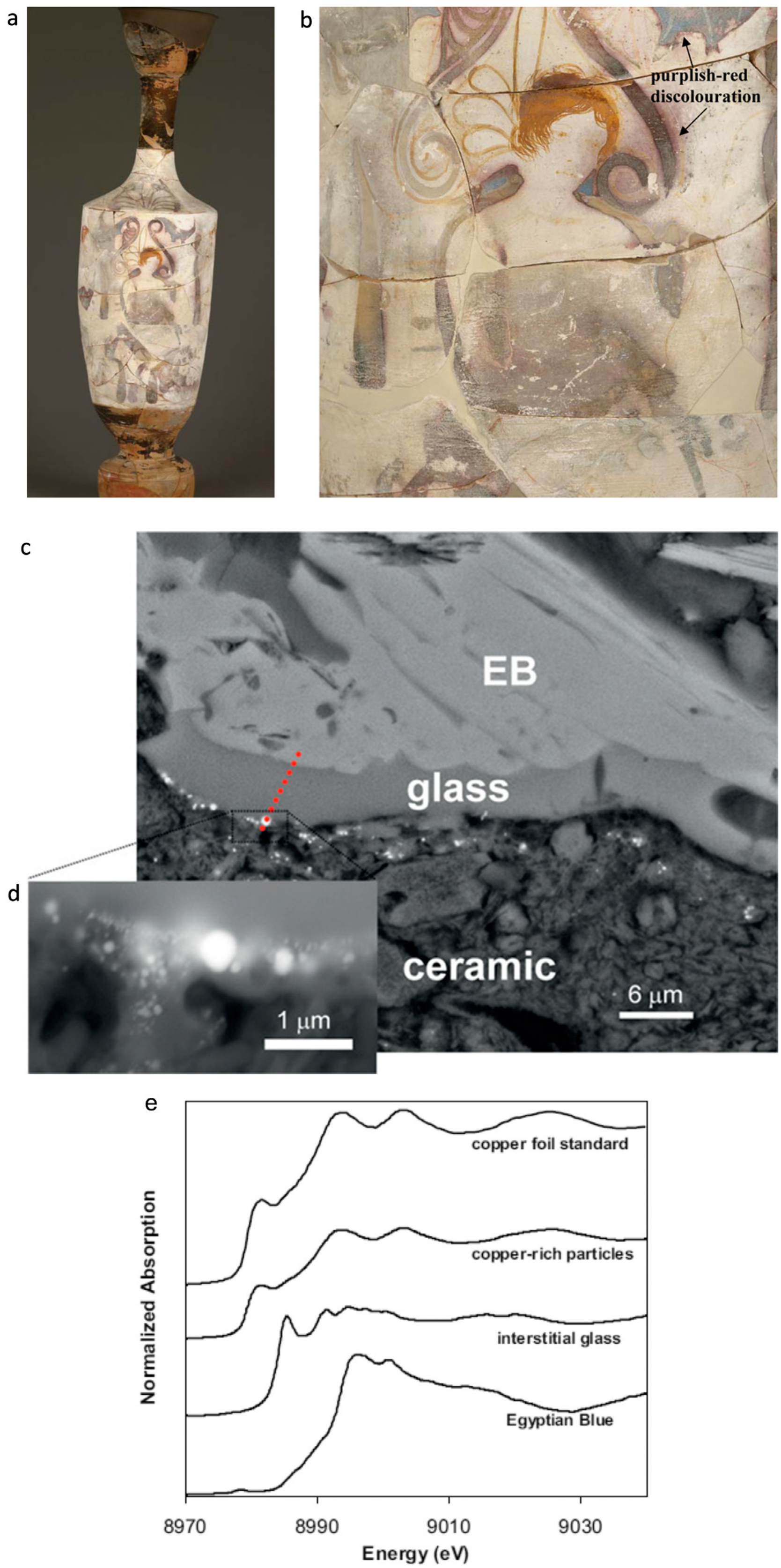


Fig. 42. (a) Attic white-ground lekythos by the Achilles Painter, depicting mourner and deceased at tomb, 440 BC. Metropolitan Museum 1989.281.72. © Metropolitan Museum. (b) White-ground lekythos showing discolouration. Antikensammlung. Antikensammlung Staatliche Museen, Berlin (F 2683). Adapted from Walton et al. 2010:Fig 1. (c). SEM backscatter electron image of cross-section of Egyptian Blue (EB) and underlying copper particles at the interface between the glass phase and ceramic. Inset (d) shows high magnification image of copper particles. From Walton et al. 2010:Fig 2. (e) Cu K-edge XANES spectra of the Cu foil standard, Cu-rich particles, glass layer, and Egyptian Blue from the cross-section shown in Fig. 42c. From Walton et al. 2010:Fig. 3.

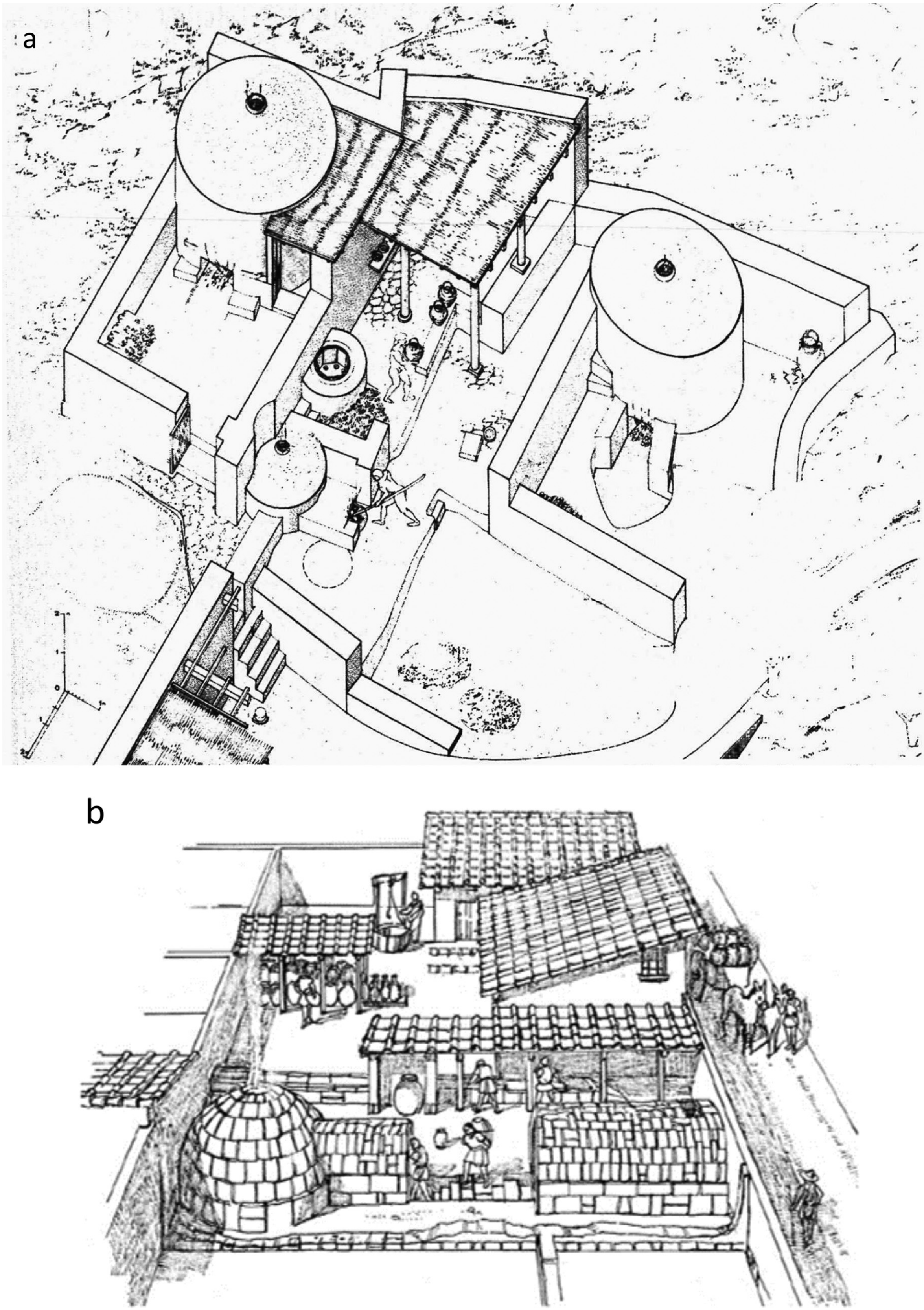


Fig. 43. Reconstructions of (a) the workshop at Mandra di Gipari, Prinias (reproduced with permission from Rizza et al. 1992:155, Fig. 35), and (b) the workshops at Locri (Lokroi Epizephirioi), city block I2, Nucleo 2 (from Barra Bagnasco 1996:29).

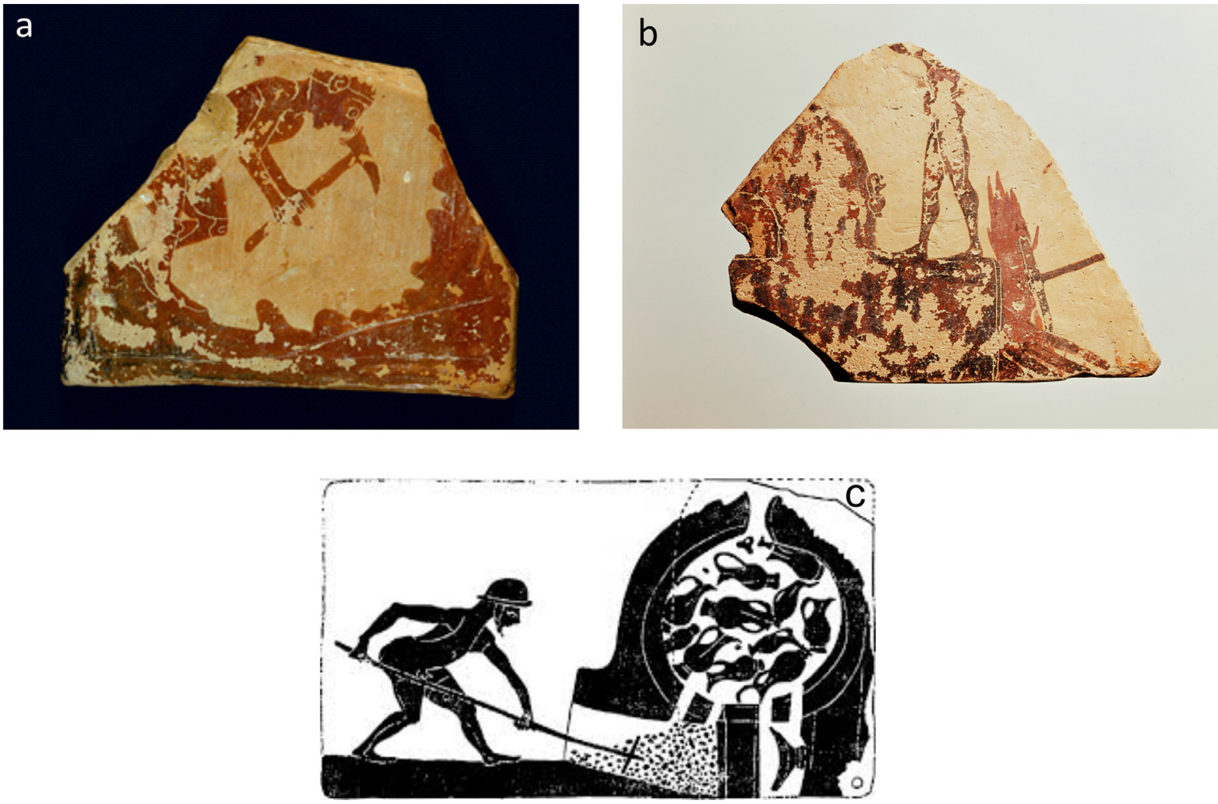


Fig. 44. Plaques from Penteskouphia. (a) Plaque depicting a man with a pickaxe collecting clay. Berlin Antikenmuseum F639, bpk/Antikensammlung, SMB. Photo by Johannes Laurentius. (b) Plaque depicting a potter standing on the *praefurnium*. The flames and firewood at the firebox mouth perhaps indicate a late stage in the sequence requiring the assistance of another worker, whose rod is evident to the lower right. Note the pot hanging on the kiln wall. Berlin Antikenmuseum F827, bpk/Antikensammlung, SMB. Photo by Ingrid Geske. (c) Reconstruction by Hoffmann and Boehm (1965:Fig. 147) showing a potter working a kiln and a cross-section of the kiln, based on Plaque F893.

and above all the skill of the potter in controlling the risks inherent in this crucial final stage of the whole pottery making sequence are among the several issues concerning firing that are now rightly receiving more attention (Acton 2014; Hasaki 2011, 2021).

C9a. Corinth

Section C3a outlines the recent archaeometric work on decorated seventh- and sixth-century BC Corinthian pottery. To this can now be placed on the one hand archaeological evidence for production and on the other hand the series of mid-seventh- to late sixth-century plaques from Penteskouphia (Fig. 44). They number more than 1,000, with some 8% of them depicting pottery firing, in certain cases at its critical stages (e.g., Fig. 44b) and to a lesser extent earlier steps in the pottery making process. Thus these plaques are a unique source of information on the potter's craft at this time. Added to the treatment they have received by many (especially Cuomo di Caprio 1984 but also Papadopoulos 2003:9–10, note 34; Stissi 2002:76f, Plate 39–48; Whitbread and Dawson 2015:339f) is the comprehensive, wide-ranging account by Hasaki (2021). Especially well-known are the views of the potter controlling the firing, carrying an iron rod with a hooked end that would have held a test piece of decorated pottery (Hasaki (2021:front cover). The hook was inserted into the kiln at the small spy hole to check the appearance of the test piece, acting as an indicator of the prevailing temperature and atmosphere.

At the Potters' Quarter (Fig. 45), in operation from the seventh to fourth century BC, production took place mainly in two long buildings (the north built in the late seventh century, the south the following century). Although Stillwell (1948) originally interpreted them as "factory" units subdivided into a series of workshops, Arafat and Morgan (1989:324) suggest that they were more likely small rows of houses than coherently planned installations (but see Stissi 2012:210). The Potters' Quarter was a residential area with cemeteries, surrounded by possible clay working locations and probably also stalls for marketing local products. Terracotta figurines and tiles were produced later on. Kilns have not been found at this location, but evidence for them occurs elsewhere at ancient Corinth (Hasaki 2021:chapter 6).

C9b. Athens

The location of the principal potters' quarter of ancient Athens has long been equated with the Kerameikos, in and around the Dipylon Gate (Fig. 46a) and close to the city's cemetery and the start of the *Iera Odos*, the holy way leading to Eleusis. This view is correct for the time period of most concern in this article—later Archaic and Classical—but it is now clear that burial grounds and potters' activity of earlier date—from Protogeometric to well into the Archaic period—occupied the ground that was to become the Agora. This revision arose out of Papadopoulos' (2003) examination of potters' debris, including many test pieces (Section C1, above, and Fig. 21a) and wasters deposited in pits or wells in the Original Kerameikos (Fig. 46a), together with the presence of a seventh-century BC kiln nearby.

Excavations in areas northwest of the city walls, some of them arising from the building of the new metro railway (Parlama and Stampolidis 2000:171–72, 212–13), have revealed several pottery workshops, studied by, among others, Baziotopoulou-Valavani (1994) and Monaco (2000). Some of those of fifth-century date tend to cluster along the route towards the ancient Academy (Fig. 46a). Those equipped with three kilns at Odos Lenorman-Konstantinopoleos (Fig. 46b) produced

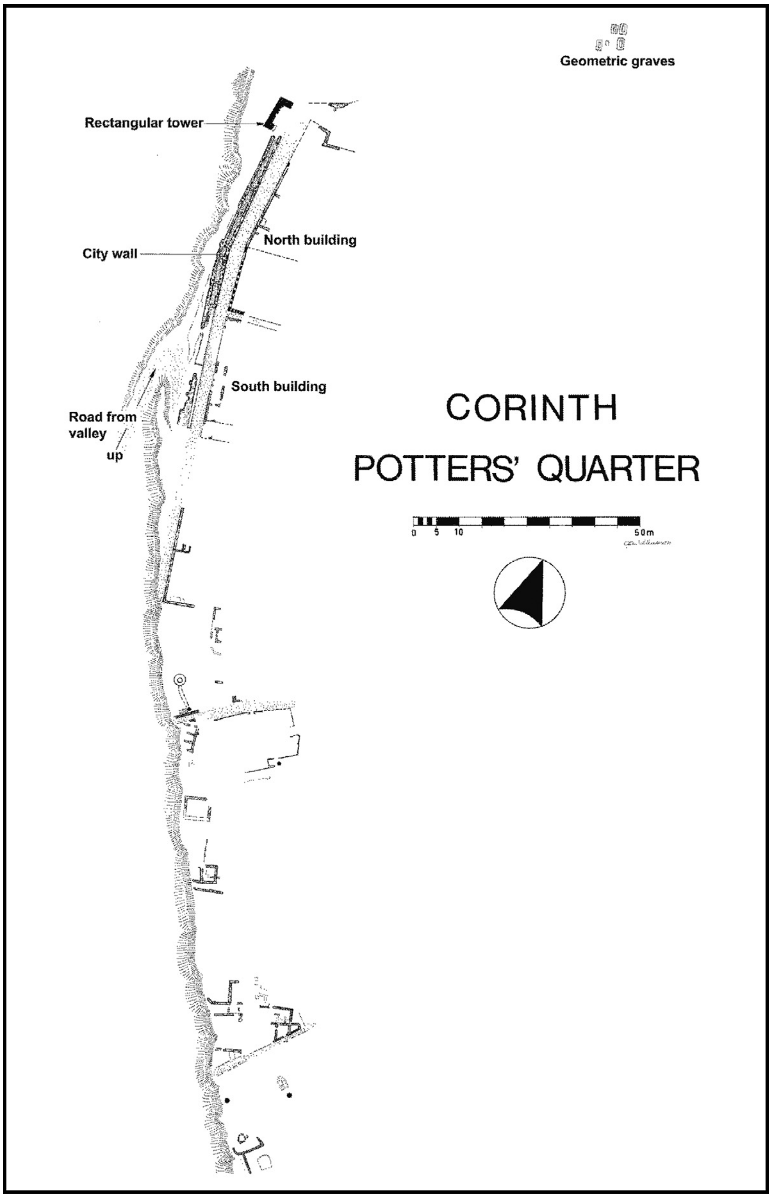


Fig. 45. Plan of the Potters' Quarter, Corinth. From Sanders et al. 2018:Fig. 130. Image courtesy of the Trustees of the American School of Classical Studies at Athens.

BG (Baziotopoulou-Valavani 1994).[34] As regards production in the Hellenistic period, there was activity east of the city: just south of Syntagma Square (Oakley 2002:197, note 7) and farther east at Evangelismos Station (Parlama and Stampolidis 2000:210–13, Fig. 4).

Opinions on the staffing and organisation of workshops abound, but it would be reasonable to say that they were nucleated (Arafat and Morgan 1989:323) and were usually a family- or extended family–run businesses of around six people, while bearing in mind that painters were often mobile, moving from workshop to workshop.[35] Women were, no doubt, involved in the business, but they do not feature as named potters or painters.[36] The Lenorman-Konstantinopoleos workshops just mentioned were well situated by a main road, being visible to passers-by and known in the neighbourhood. They had a simple market structure, supplying local demands, supplemented where necessary by the finest vases from the more central workshops (Arafat and Morgan 1989:322). The countryside was not far away. Indeed, some members of the workshop may have worked part-time on the land, as demands on time in the workshop fluctuated, a view not shared by Stissi (2002:47–48), however. In any case, the members of the workshop formed a unit comprising craftspeople and their assistants, a situation that applies to Franklin's (1990:19–20) term *holistic technology*. Here each member is in control of a particular task and contributes to the making of a product, in contrast to the operation of a *terra sigillata* workshop, in which specialisation is by process (Franklin's prescriptive technology).

According to Sapirstein (2013:504–5), before 515 BC, most painters were potter-painters, but the situation had changed by 500 BC, when the term *specialists* better accounts for most painters. This major change came about with the introduction of the RF technique, which required skills that BF potters did not fully have. Entering into the controversial matter of the size of the Attic industry, Sapirstein (2013:508) suggests

[34] The workshop of the RF Jena Painter has been placed in Hermes (Ermou) Street, which runs within the city walls north of the Agora (Oakley 2002: Fig. 1:3), but this location is now regarded instead as the workshop's waste deposit (Kathariou 2016:158).

[35] Stissi (2012:215f; 2020:105) gives a more nuanced view of this issue.

[36] The report by Agelarakis (2020) of osteological evidence of a woman who may have worked a kick wheel at Archaic Eleftherna in Crete is worth noting.

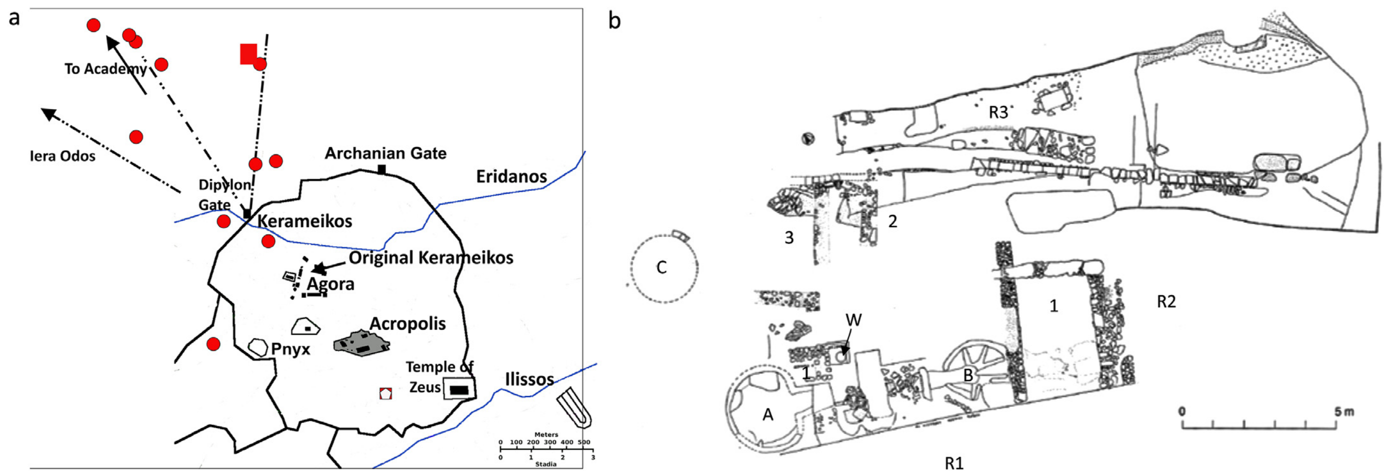


Fig. 46. a The Original Kerameikos, later Kerameikos, and approximate locations of the pottery workshops (red circles) in Athens, fifth–fourth century except for the one between the Kerameikos and the Original Kerameikos (seventh century). The Odos Lenorman- Konstantinopoleos workshop in Fig. 46b is shown with a red square, and the Late HL kiln-like structure mentioned in Section C4 is shown with a white polygon. The rivers Eridanos and Ilissos are marked in blue. Adapted from Wikimedia Commons: map of ancient Athens.png. b. The workshops (*ergastiria*) (550 to early fourth century BC) at Odos Lenorman-Konstantinopoleos in Athens (red square in Fig. 45a), which produced BF, RF, statuettes, and other ceramics. Kilns: A, B, and C. Roads: R1, R2, and R3. Rooms: 1, 2, and 3. Well: W. Adapted from Baziotopoulou-Valavani 1994:Fig. 2. See also Monaco 2000:DIII, Plate 41.

that "the whole population of potters, painters, and assistants engaged in the production of Attic pottery was below 100 for much of the sixth century BC and is unlikely to have risen much above 200 at its maximum." On the basis of the number of extant signed vases, he estimated an annual output of eight vases per specialist and that the figure would rise to between 800 and 1,700 given that only about 0.5–1% of a specialist's output has survived to this day. That in turn gives an estimated total of 50,000 figured vases per year during the early Classical period. By the time of, and as a result of, the Peloponnesian War, towards the end of the fifth century, the Attic industry declined drastically. More realistic in my view is the argument strongly advanced by Stissi (2012, 2020:104) that the number of skilled potters and painters may have been much higher than the number of known "masters"; alongside them were many "minor" hands operating in the background, some of them as apprentices, others more experienced.[37] And that does not account for those in other spheres of the ceramics industry in Athens, such as coroplasts and tile makers.[38]

Turning now to the iconographic representation of the pottery making process, examples on (Attic) vases, although not numerous, are informative (Papadopoulos 2003:191–96; Stissi 2002:75–96, Plate 28–37; Williams 2009). They generally show the forming and decorating stages, unlike their counterparts at Penteskouphia at Corinth, which, as already mentioned, frequently depict the collection of clay materials and firing (Fig. 44) (Hasaki 2013:179).

The archaeometric data on the clays used at these workshops is limited by the relative inability to undertake clay prospection in the greater Athens area (*GCP*, 150–51), and there has been insufficient opportunity to sample clay dumps associated with workshops at the time they were excavated. That said, the clays associated with the rivers Eridanos (which passed through the Kerameikos; Fig. 46a), Ilissos, and Kifissos and clays along the *Iera Odos* and farther afield at Cape Kolias (see Fillières et al. 1983) (Fig. 29) all look relevant. There were others as well (Stissi 2002:44–46). Amarousi, still a focus for pottery making during the twentieth century, is frequently mentioned as a source of red clay during the Classical period, despite the relative lack of archaeometric support for it (e.g., Gautier 1975:55). The clays selected as paint material are discussed above in Section C3b4. Comment on the manufacture of figurines appears in the next section.

C10. Terracotta figurines

I reviewed information on the decoration of terracotta figurines and Canosa ware until the mid-1980s (*GCP*, 813–16, Table 9.11). Since then, Muller (2018) has provided a survey of coroplastic studies, placing laboratory-based work within the broader context of production and diffusion, shaping tools, workshops and craftspeople, distribution, consumption, and function. More recently, and equally admirably, Bourgeois and Jeammet (2020) have reviewed the current state of knowledge of the coroplast's technical skills, drawing particularly on their team's work on figurines in the Musée de Louvre. The Archaeological Museum of Thessaloniki's recent exhibition *Figurines: A Microcosmos of Clay* is a rich source of information and illustration (Adam-Veleni et al. 2017).

For present purposes, attention is restricted first to current imaging and analysis techniques and second to a summary of selected recent work on Hellenistic (and early Roman) figurines and Canosa vases. Multispectral imaging such as luminescence techniques, outlined in Section A, have had a major impact on the ability to detect certain pigments, notably Egyptian Blue and madder, on figurines usually now bearing little visual trace of decoration (Fig. 47a). At the same time, recognition of the chromatic range of the coroplast's palette has demanded a multi-technique approach, which in turn has highlighted the need to incorporate organic analysis using chromatographic methods, principally HPLC-MS. In instances where the figurine assemblage is large, as was the case at sites near Volos (see below), (rapid) pXRF analysis is worthwhile, so long as it is supported by other techniques to detect the carbon-based/organic pigments. At Chania, FTIR analysis was effective, using second derivative spectra to separate overlapping spectral absorbances.

In introducing the results of recent work, it is understood at the outset that the nature of decoration of terracotta figurines as well as white-ground lekythoi (Section C8)—the polychromy and its application, usually after firing—takes us into the realm of Greek painting in such media as plaster, stone, and wood, an enormous subject in its own right. Not only does the polychromatic palette extend beyond the canonical *tetra-*

[37] See commentary on this issue by Acton (2020:137–40).
[38] For an overview of Athens' ceramic industry, see Rotroff 2021.

Table 6
Technical Studies of Terracotta Figurines, Canosa Ware, Bricks, and Architectural Terracottas

Date (findspot)	Samples	Summary Results	Techniques	Publication
Terracotta Figurines				
Archaic–HL Boeotian, Attic, Corinthian, E. Greek, Cyrene, and others	53 (WG), 10 (pigments)	see text	XRD	Bimson 2001; Middleton 2001
HL (Chania)	22	BR, EB, CB, HU, RO	OM, pXRF, XRD, FTIR	Maravelaki-Kalaitzaki and Kallithrakas-Kontos 2003
HL (in and around ancient Pherai)	84	CB, occ CN, EB, M?, MB, RO, RO? + CW (pink)	pXRF and UV	Asderaki-Tzoumerkioti and Doulgeri-Intzesiloglou 2010
HL and R Attic, Boeotian, S. Italian, and E. Greek (Myrina, Smyrna [Louvre])	20	gilding: see text	DM, XRF, RBS (see Table 1), μXRD, μRaman	Bourgeois et al. 2012
Same as above (plus Cyrene)	22	gilding: see text	μPIXE-RBS (see Table 1)	Fourdrin et al. 2016
HL (third–second century BC) and R (first–second century AD) (Thessaloniki)	23	CB, CN, CO, CW, EB, M, RO, YO	OM (PLM), pXRF, μRaman, and HPLC	Fostiridou et al. 2016; Mantzouris and Karapanagiotis 2015
HL (ancient Demetrias, Volos)	160	CN, M, MB, RO, RO + CW (pink)	OM, pXRF, and UV	Tsatsouli and Nikolaou 2017
HL (Canosa (figurine plus head vase, Myrina [British Museum])	3	see text	luminescence imaging, FTIR, Raman, HPLC	Dyer and Sotiropoulou 2017
Canosa Ware				
Examples from J. P. Getty Museum	few	M, YO (goethite), EB, CB mixed with Fe oxide	PM, XRF, FTIR, XRD, SEM-EDS, OES	Scott and Schilling 1991
Head vases (J. P. Getty Museum)	2	see text and Fig. 47	luminescence imaging, XRF, FORS	Kakoulli et al. 2017
Head vase (British Museum)	1	see text	digital microscopy, HPLC-MS	Dyer et al. 2018
Other Ceramics				
Tenth-century bricks (Lefkandi)	8	see text	AAS, XRD	Wilson 1997
Sixth-century Etruscan painted panels (Cerveteri)	2	see text	μRaman	Bordignon et al. 2007b
Sixth-century Etruscan Ceri panel (Cerveteri)	1	see text	μRaman, XRD,	Bordignon et al. 2007a
Sixth-century Etruscan panels; seventh-century white-on-red sherds (Cerveteri)	few	see text	μRaman	Bordignon et al. 2008
Sixth-century Clazomenian-type sarcophagi (Ainos, Turkish Thrace)	2	see text	XRF	Akyuz et al. 2011
Sixth- to fifth-century architectural terracottas (Syracuse, Naxos, and other sites in Sicily)	several	see text	pXRF	Orlando et al. 2015
Etruscan antefixes (470–460, late fourth century, and 400 BC) (Cerveteri and Orvieto; now Ny Carlsberg Glyptotek)	6	see text	OM, luminescence imaging, pXRF, SEM-EDS, EMPA-EDS, GC-MS	Brøns et al. 2016
Sixth- to fifth-century architectural (sima, geison) terracottas (Gela, Sicily)	20	see text	OM, XRD, XRF, SEM-EDS, μRaman	Barone et al. 2017
Sixth- to fifth-century architectural (sima, geison) terracottas (Lentini, Syracuse, Sicily)	10	see text	OM, XRD, XRF, SEM-EDS, μRaman	Barone et al. 2018

Notes: HL = Hellenistic, R = Roman, DM = digital (video) microscopy, BR = bromoindigo, CB = carbon black, CN = cinnabar, CO = cochineal, CuB = copper-based blue, CW = calcite white, EB = Egyptian Blue, HU = huntite, M = madder lake, MB = manganese black, RO = red ochre (hematite), WG = white ground, YO = yellow ochre, Occ = occasional. Entries are arranged by date of publication.

chromia (white, black, red, and yellow) of Greek painting as conceptualised by Pliny the Elder (in his *Natural History* 35), but the approach to decoration has to move away from treating the ceramic surface as a "canvas." In any case, there is a wealth of technical information on decoration in other media resulting from discoveries of wall paintings and decorated stone and wood, especially in northern Greece (Brecoulaki 2014; Kakoulli 2009) and elsewhere in Greece (Jockey 2018), and of artists' raw materials and pigment lumps (Karydas et al. 2009). This point is returned to in Section C11.

Starting with the white ground, kaolinite was most commonly used, sometimes together with alunite ($KAl_3(SO_4)_2(OH)_6$), or occasionally alunite on its own (Middleton 2001). The former occurs on Melos but not uniquely so, whereas the combination of alunite, kaolinite, and silica can be more confidently associated with the white earth, Melian Earth, occurring especially in the southeast of the island at Loulos (Photos-Jones and Hall 2014:188–93). White lead minerals also feature. For example, at ancient Demetrias, the figurines had a probable calcite base onto which was applied lead white (basic lead carbonate), either as a separate layer or as a mixture with calcite, to create a suitable surface and to enhance the facial area with its subtle yellow-red undertone. There was occasional use of gypsum as background. The situation at ancient Pherai was not greatly different: more than half the figurines were with white substrate, usually calcite, rarely gypsum, with lead white on elaborate figurines. Lead carbonate and its alteration product, laurionite, feature in two of the three figurines of Corinthian type examined by Middleton (2001). Recent work has shown that white lead–based minerals, whose source no doubt lay in the Lavrion, had additional applications, namely as the fourth-century female cosmetic *psimythion* (Photos-Jones et al. 2020).

Table 6 summarises some identifications of colourants. Many of them are inorganic (Bourgeois and Jeammet 2020:10–13), and although they are generally well-known, it is the way they could be used individually to highlight, for example, facial features or as a mixture to give subtle variation of tone, such as of flesh, that is striking. The presence of white huntite (Ca/Mg carbonate) at Chania lends weight to the figurines' Egyptian connection (Heywood 2001a, 2001b), as its occurrence in Greece is limited, as an industrial mineral, to the Kozani district in northern Greece (V. Perdikatsis, personal communication). The presence of a bituminous black on an earlier (Archaic) Rhodian figurine appears to be most unusual (Bimson 2001).

Turning to organic colourants, the relative popularity of the dye derived from the roots of madder (*Rubia* spp.) is ascribed to the striking range of colours from pink to purple, in such a way that it becomes almost a trademark of the Hellenistic coroplastic craft (Bourgeois and Jeammet 2020:12). The detection of madder and other colourants by multispectral imaging is illustrated in Figs. 47–48.

In four examples of light red from HL tombs in Thessaloniki, Fostiridou et al. (2016) identified not only purpurin, a marker for madder, but also carminic acid, which is produced by the cochineal insect. The use of the crimson cochineal dye at such an early date is remarkable, not least because it may not reappear in Greece until the fourteenth century (on textiles on Mount Athos) (Mantzouris et al. 2016). Mantzouris and Karapanagiotis (2015) provided evidence that the insect species was probably Armenian cochineal (*Porphyrophora hamelii* Brandt). Yet more intriguing are the results of analysis of a Canosa head vase whose purple colour (in five small areas) consisted of a mixture of Egyptian Blue and a pink lake (Dyer et al. 2018). Detailed analysis by HPLC-MS (more specifically high-pressure liquid chromatography-electron spray ionisation-quadrupole-time of flight [HPLC-ESI-Q-ToF]) of the samples' mild and strong acid extracts revealed compounds associated with three main classes: madder, most likely from a *Rubia* spp.; molecular markers for tannins that could be linked to the dyeing of textiles: ellagic acid, gallic acid, and salicylic acid (2-hydroxybenzoic acid); and carminic and other acids (Fig. 49) from two coccid species, such as cochineal (*Porphyrophora* spp.) and lac (*Kerria Lacca* Kerr). Of great interest is the possible connection between the tannins and an alkaline extraction of a lac-dyed textile, perhaps an ancient form of *lacca di cimatura.* Dyer et al. (2018:130) drew attention to a link with Achaia, in the West Peloponnese, quoting Pseudo-Demokritos' statement about "the dye of Achaia which is named laccha" and noting the excavation of a Hellenistic dye-works at Helike in that region (Katsonopoulou 2011).

The gold leaf gilding on Hellenistic and Roman terracotta figurines from several coroplastic centres may be well-known, but it is its sophistication, quality, and technical uniformity that are remarkable. Indeed, the process could have been in the hands of specialised gilders; "par le seul traitement de surface, la statuette façonnée en argile apparaissait aussi belle que la statuette coulée en bronze, et l'argile dorée se plaisait à tromper la splendeur étoilée du métal" (Bourgeois et al. 2012:509). Fourdrin et al. (2016) established that the gold leaf was in the range 160–710 µm in thickness and was composed of at least 95% gold. Tinfoil also appears, presumably in imitation of silver, with 14 examples at ancient Pherai, three from Myrina, and two from Italy. Meeks (2001) addressed similar questions on gilding on figurines in British Museum collections. That attempts to identify the organic binders that fixed the gold leaf and the paint layers to the surface, as well as potential varnishes (such as resins) laid over the decorated surfaces, have been essentially unsuccessful harmonises with their absence on architectural terracottas and panels (see next section).

A final point is one made by Bourgeois and Jeammet (2020:6) about the many transformations, natural and anthropogenic, that may apply to a figurine in both antiquity and recent times. An instance of the latter is the discovery of Prussian blue and cobalt and cerulean blues among some Tanagra figurines in the Harvard University Art Museum (Mau and Farrell 1993), which emphasises the need for awareness of later interventions in figurines held in museum collections.

The manufacture of figurines and pottery may have operated differently from each other. Recognising that the several stages of the former usually took place in different locations and that some figurines must have been fired in kilns at pottery workshops, Sanidas (2016) has contrasted two urban spaces where some involvement in figurine manufacturing was taking place: (a) commercial space, for example in Hellenistic Athens, where figurine moulds are found, as in two commercial buildings by the side of the Agora, but not clay preparation items or kilns (*atelier-boutique*); (b) domestic space (*atelier-maison*), notably at Olynthus; here a cache of 13 figurine moulds was found in House Bi5 (Cahill 2002:Fig. 56), where other craft activities were also taking place.

C11. Other ceramics

C11a. Coloured bricks

A feature of the remarkable tenth-century BC funerary building at Lefkandi Toumba (Fig. 50a) was the use of much mud brick in its construction, especially in the ramps built up on either side of the building upon its dismantling (Coulton 1993). On the death of this long house's occupants, the building was in effect converted to a funerary monument housing the shaft graves of the two main occupants.

The mud bricks (about $0.30 \times 0.30 \times 0.10$ m) displayed considerable and presumably deliberate variation in colour (Fig. 50b) and texture. Wilson's (1997) study of eight of them, whose colour ranged from pink to many shades of brown, showed they were all naturally occurring sediments with, as expected, wide-ranging calcium (4–29% CaO) and iron (2–7% Fe_2O_3) contents (Wilson 1997). There was a mineralogical similarity with clays and soils collected from the site's vicinity in the Lelantine plain and the nearby River Lelas (*GCP*, 144–45). Elsewhere, a decorative scheme in black-and-yellow mud brick in some walls belonging to the seventh-century South Temple at Kalapodi in Phocis has been noted (Felsch 1987:15, Fig. 22).

C11b. Architectural terracottas

Roof tiles of temples, their terracotta embellishments[39]—sima, geison, akrotiria—and terracotta sculpture are treated briefly in this section (Table 6). Winter (1993:304–8) sets the scene regarding production of roof tiles on seventh-century Greek temples, and Sapirstein (2008:chapter 6) outlines in detail the materials used to replicate and decorate roof tiles at ancient Corinth. Whether the craftspeople who made and decorated roof tiles and other architectural terracottas were always potters,[40] they nevertheless had a very good knowledge of clay materials, as well as of the firing and decorating of ceramics. The firing of tiles of this dimension and thickness required careful attention to a suitable temper to reduce shrinkage, prevent cracking during drying and firing, and promote suitable mechanical properties. Examples are mudstone (from Acrocorinth; Fig. 24) at Corinth (Sapirstein 2008:101; Whitbread 1995:294),[41] Acrocorinth shale at nearby Isthmia (Rostoker and Gebhard 1981:212–14), ferruginous grog at Delphi (Le Roy 1967:199), and volcanic ash at temple sites in southeastern Sicily (Barone et al. 2017, 2018). Tiles usually received a slip, often creamy yellow in colour. Firing temperature estimates, obtained using different techniques, vary. They are lower at Corinth than elsewhere: experimental tile firings at Isthmia and Corinth reached maximum temperatures of about 700°C and 794°C, respectively (Rostoker and Gebhard 1981:223; Sapirstein 2008:152), compared with estimates for Protocorinthian tiles, based on refiring tests, of 700–900°C (Sapirstein 2008:148; Whitbread 1995:294); for tiles at Delphi of about 1000°C, estimated by dilatometry (Le Roy 1967:199); and for architectural terracottas at Lentini and Syracuse of 850–900°C and at Gela of about 950°C (determined from XRD and µRaman with reference to replicas; Barone et al. 2018 and Barone et al. 2017:99, respectively).

Although reports of analyses of the ceramic decoration on Greek temples appear to be few, there is little doubt that the palette closely followed that found on pottery, namely iron-based black and red colourants, and to a lesser extent white colour, applied to the slip before firing. But while this may be the general picture, there was scope for not only applying additional colourants that were otherwise employed by coroplasts (see previous section) but also techniques such as the use

[39] Visualisation of the different seventh-century types appears to good effect in Sapirstein 2016; those at Mon Repos, Corfu, are in Sapirstein 2012.

[40] Several authors say that craftspeople working in the Laconian style were surely potters (e.g. Winter 2002:48).

[41] Mudstone was also used as a parting agent on the underside surface of Protocorinthian tiles (Sapirstein 2008:101).

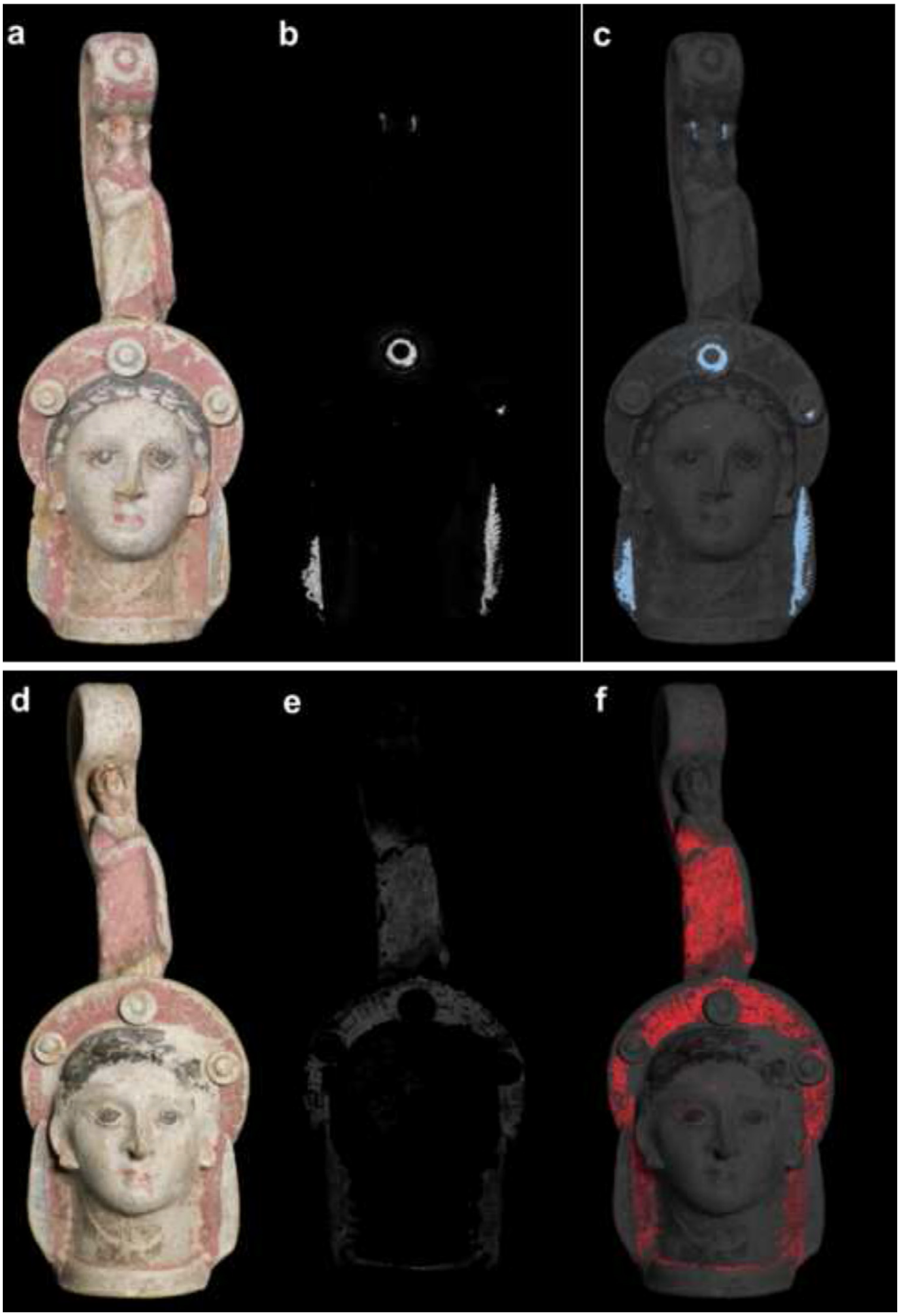


Fig. 47. Digital photographs of Canosa vases 81.AE.156 (top) and 81.AE.157 (bottom). (a, d) Diffuse reflectance. (b) Visible-induced NIR luminescence in greyscale. (c) Spatial distribution of Egyptian Blue and pink madder, respectively, in false-colour composite images. From Kakoulli et al. 2017:Figs. 4 and 7.

of a compass for curvilinear designs. At the sanctuary of Demeter and Kore at Corinth, decoration of the terracotta sculptures occurred initially directly onto the clay surface, without a slip, before a three-phase firing; the resulting red and black were lustrous. But in the early fifth century, a white slip came into quite common usage. If necessary, paints could be applied to it after firing (Bookidis 2010:63–65). Another development was the adoption of manganese black-brown in the sixth century (and continuing into at least the fifth century) at Corinth (on sphinxes on the Temple of Apollo [Bookidis 2000:392, note 54] and at the Demeter sanctuary [pXRF analysis]), and earlier (630–620 BC), in conjunction with ochres and gypsum, on terracotta metopes at Temple C at Thermon (Papapostolou 2002:59–60). Using the manganese black technique had the advantage of creating in a single oxidising firing a bichrome effect with iron red, notwithstanding the possible drawbacks of a matt finish that was often more prone to deterioration than the iron black. Nevertheless, firings in which the manganese black may take on a browner hue, including a reducing phase, are also documented. Shades of yellow, red, purple, and probable madder pink occur at Corinth (Bookidis 2010:64) and elsewhere. Depiction of motifs on architectural terracottas in the later sixth century occurs in a dark colour to give a dark-on-light effect, giving way in the early fifth century to a rendering of motifs in reserve giving the light-on-dark effect (Fig. 51). The latter is in keeping with the contemporary RF technique in vase painting (Winter 2002:49–51).

Fig. 48. Victoire "phainoméride" from Myrina, 150–100 BC. Height: 33.8 cm. Left: As is. Right: UV mapping showing the coloured fluorescences of different materials: yellow for the varnish applied on skin tones, red-orange for the pink of madder, and white for bands of the tunic painted with a lead-based white. Louvre, inv. Myr 163. From Bourgeois and Jeammet 2020:Figs. 27–28. Images courtesy of Brigitte Bourgeois.

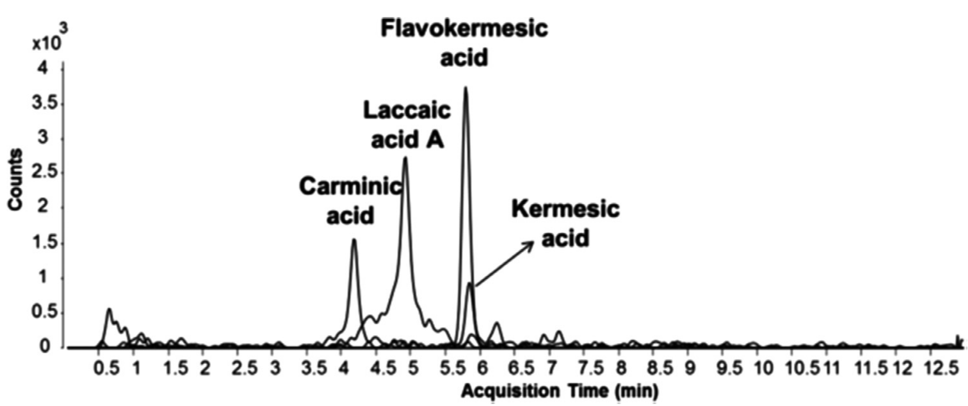


Fig. 49. Chromatogram obtained by HPLC-ESI-Q-ToF analysis of sample S3 of the Canosa head vase, showing the coccid dye-related compounds identified. From Dyer et al. 2018: Fig. 5.

Moving to the temples at Lentini, Syracuse, and Gela in southeastern Sicily (Fig. 34) investigated by Barone et al. (2017, 2018), the architectural terracottas were prepared from local calcareous clays, tempered with volcanic ash. The pyroxene content of that ash, whose major and minor element composition was determined by WD-XRF, was similar among the samples across the three sites. Furthermore, the nature of that ash sand linked its source to the nearby Etna vulcanites and/or Hyblaean basaltic lava (Barone et al. 2018:Fig. 1). Also uniform was the decoration (without an underlying slip): manganese black (such as pyrolusite), iron-rich red, and meta-kaolin white (perhaps obtained from Lipari). Firing was single-phase oxidising at the temperatures given above. The interesting feature of this scenario is the sense of shared materials and techniques within this region and a concomitant movement of materials: pyrolusite and kaolin (perhaps from sources in central Sicily and Lipari, respectively) and ash.[42] Intriguingly, while the Apollonion temple terracottas at Syracuse conformed to this picture, those from the

[42] The black on one of the four sixth- to early fifth-century local antefixes from Morgantina, inland from the three temple sites, had a much higher Mn/Fe ratio than the other three (XRF analysis; Raffiotta 2014).

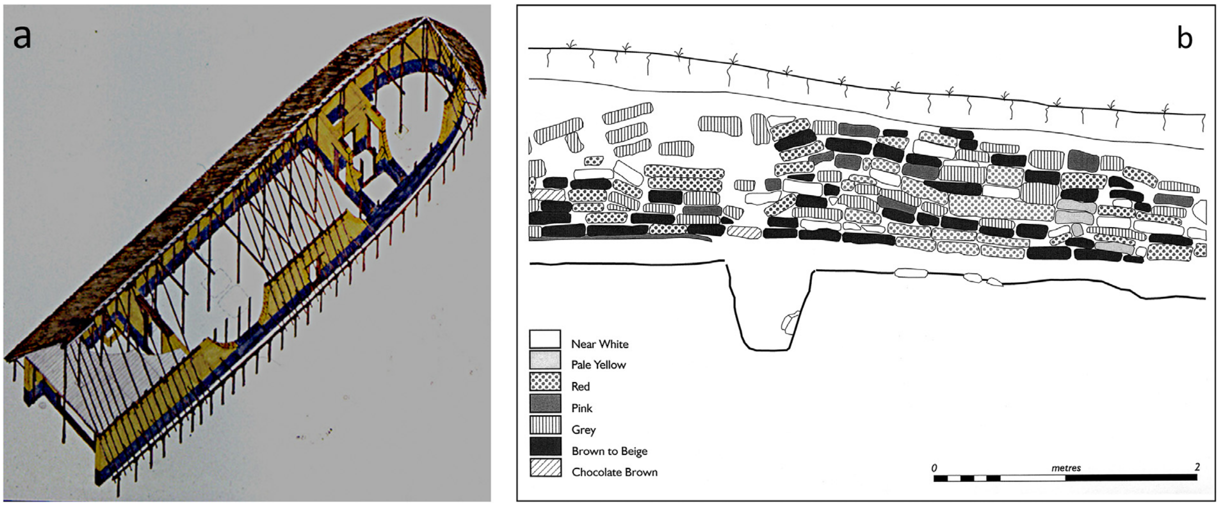


Fig. 50. (a) The funerary building at Lefkandi Toumba. Reconstruction of the whole building (Coulton 1993:Plate 28). Image courtesy of Irene Lemos. At the midpoint along the building (which is about 50 m long) were the set ramps. (b) East section of the ramp showing multicoloured mud bricks (adapted from Coulton 1993:Plate 37).

Fig. 51. Simas with contrasting decoration at Delphi. Top: Dark-on-light, Corinthian profile, 540–530 BC. Length: 27 cm. S.189, T.41(1). Le Roy 1967:96, Plate 1. Bottom: Light-on-dark, Treasury of Knidos, 470–460 BC. Length: 50 cm. S.40+S.175 T.56(2). Le Roy 1967:129, Plate 1. Images © Ecole française d'Athènes.

Athenaion, also at Syracuse, did not: their Fe/Mn ratio in the black differed, and the metamorphic inclusions in their clay fabric suggested a link with the Messina area to the north, pointing to the possibility that the Athenaion terracottas may have been imported from that area as finished products.

The Etruscans of Etruria and central Italy enthusiastically adopted Greek models in the roofing of buildings and even more so their decorative elements. Winter's (2009:chapter 8) treatment of the manufacturing techniques and the evidence for workshops includes information on clays, temper (such as grog and [iron] ore), slip, and paints. Here attention is focused only on Brøns et al.'s (2016) study of antefixes (mainly from Cerveteri) and the work of Bordignon et al. (2007a, 2007b, 2008) on painted terracotta panels. On the former was a wide colour palette; the pigments, all applied to a calcite ground in all likelihood without an organic binder, included carbon black, brown umber, and Egyptian Blue. Notable were first the superposing of layers, commonly Egyptian Blue over red ochre, to achieve a purple hue (Brøns et al. 2016:Fig. 19) and second the mixing of colours to create the appropriate hues of skin and hair. The terracotta panels also displayed subtle hue differentiation by paint mixing, and the polychrome palette extended to occasional madder, malachite, azurite, and cinnabar. Using µRaman and FTIR, Bordignon et al. (2008) showed the white on later sixth-century painted terracotta panels, including the so-called Ceri Warrior panel (Bordignon et al. 2007a), and on seventh-century white-on-red sherds from the Cerveteri area to be a high-quality kaolin, containing two impurity markers that allowed it to be linked confidently to a source on Mount Sughereto nearby: anatase (detected by µRaman) and the kaolin polytype dickite (FTIR). Furthermore, combined XRD and µRaman of the dark yellow colour on the Ceri panel indicated the presence of lepidocrocite (γ-FeO(OH)) and hematite. Bordignon et al. (2008a) interpreted this finding as the painter's use of a yellow ochre (mixed with a little kaolin), which was heat-treated to 250–300°C, resulting in partial conversion to hematite; any higher temperature would have caused full conversion to red hematite. The terracotta panel, made of a low-Ca clay fired to 800°C, was decorated in polychrome and then received the second firing at 250–300°C to fix the pigments.[43] In the case of antefixes, Brøns et al. (2016:52) proposed the same procedure of two separate firings, all the more necessary for the polychrome to withstand (external) weather conditions.

A few issues arise from this section. First, to reinforce what was mentioned in Section C10, it is recognised that the materials used to decorate ceramics, wood, stone, and other media during the Archaic to Hellenistic periods (and of course later) overlap to a greater or lesser extent. Within the ceramics sphere there seems to have been a wide, common knowledge of materials and techniques among coroplasts, at whatever level and wherever those craftspeople were operating, decorating figurines, antefixes, or panels.[44] Second, application of the manganese black technique in Greece and Italy during this time span has been documented, but there is scope for its better definition spatially and chronologically within Greece and for greater clarity on the interplay of firing temperature, atmosphere, and Mn/Fe ratio on the final colour and matt effect. Since the emphasis would be on a wide coverage of ceramics, a programme of pXRF (accompanied by portable Raman or XRD) analysis would be most appropriate. Third, the finding of common materials and techniques adopted at centres in southeastern Sicily producing architectural terracottas is important for the support it lends to what was

[43] The presence of azurite (over red ochre) on the same panel further supports the second low-temperature firing, since it is unstable above 300°C.

[44] Compare, for example, the pigments applied to the sixth-century wooden panels from Pitsa in the Corinthia (Brecoulaki et al. 2017).

outlined above (Section C3b4) regarding specialists who prepared the paint material for black gloss and supplied it to Attic pottery workshops. Furthermore, Barone et al.'s (2018) proposal that the terracottas at the Athenaion at Syracuse, in not following that scheme, may have been brought in as finished products from outside resonates with the results of chemical analysis of simas of Archaic date found at a temple at Cavallino (Lecce) that were probably imported from Corfu (Jones and Caldarola forthcoming). Finally, the evidence favouring a low-temperature second firing on some antefixes and panels now appears strong. It is the control that would have been required of that second firing that is most striking.

C11c. Clazomenian sarcophagi

These fine sarcophagi from the type-site of Clazomenae near Izmir were decorated before firing (Ersoy 2003). Examples of later sixth-century Clazomenian-type sarcophagi at Ainos in Turkish Thrace were found to have high Ca, Mg, and S contents in the white, pointing to the use of calcite, dolomite, and/or gypsum, or rather their products, following firing at >750°C (Akyuz et al. 2011). Black and red were manganese- and iron-rich, respectively.

C12. Final remarks

This review has made an ambitious survey of the technical aspects of the decoration and firing of ceramics spanning nearly six millennia. The short assessment (in Section B) of pottery technology during Greek prehistory demonstrates a number of key points, none of them new but now firmly established: (a) the longevity of some of the methods of painting, such as the iron reduction and manganese black techniques; (b) during the Neolithic, widespread experimentation with raw materials for making, treating, and decorating pots and similar experimentation in the way the pots were fired; (c) the appearance during the Middle Bronze Age on Crete of high-status, high-quality pottery in the form of Kamares ware; and (d) by the end of the Bronze Age, the ability of Mycenaean and Minoan potters to produce standardised yet high-quality decorated pottery.

The potter's craft embarked, then, at the start of the first millennium, with a wealth of accumulated knowledge and experience. Empirical understanding of the underlying technology was already in place. What characterises the craft during the historical period is the way, first, that techniques, in particular the procedures for preparing paint material, became more refined and sophisticated. These reached a peak in the sixth and fifth centuries BC with the production in Athens of black gloss, which was the essential decorative feature accompanying the depiction on the vases of scenes of myth and everyday life. Accounting for a large part of this section are the many enquiries into the nature of black gloss; these have been summarised and discussed in C3d. That wealth of experience extended also to kiln design; by the Early Iron Age there was convergence of thought, whether conscious or uncritical, on kiln design—the rounded shape and internal design worked satisfactorily, and although this kiln type adapted to conditions and individual preferences, it did not undergo major change until the Roman period. That continuity of kiln construction tradition would help explain the continuity in firing temperature achieved in the kilns of the Original Kerameikos of Athens—the firing temperature estimate of 700–850°C applied to the test pieces from these kilns, which ranged in date over at least 300 years, from Protogeometric to Geometric and later. In light of the results on Attic Black presented in C3b2, it was the demands of producing the higher-quality black gloss characterising the later Archaic period and beyond that forced the kiln operator to achieve a temperature greater than 850°C, if only during one phase of the firing.

The second characteristic is the scale of production, which by this time had expanded greatly and diversified in response to new markets and new demands. Third, just as by the fifth century potters and painters were often different people, so specialisation was also occurring at other levels of production. A case is advanced above (Section C3d) that there may have been specialists who prepared, for the Attic pottery workshops, the paint material for black gloss from clays that were not the habitual potters' clays, and possibly the dispersing agent as well. Recognising the skill required to optimise the firing sequence to deliver the best-quality black gloss decoration may lead to he identification of another specialist in Attic workshops, the person who was solely responsible for the firing. Fourth, the working environment of the Attic pottery industry, at its peak in the late sixth and early fifth centuries BC, was sufficiently stimulating that it encouraged a few master potters and painters to take their craft beyond the routine and to experiment. The products of these "special effects," reviewed above, now have a materials basis to them.

Looking to the future, there is in principle much scope for further analytical investigation of ceramic decoration, yielding results that can expand upon what is already known. Only two final thoughts remain. One is the issue of matching the questions posed of analysis to appropriate instrumentation that can provide results with minimal damage to the ceramic (fragment). This is not always straightforward, but such is the pace of current instrument development—becoming more compact and portable while retaining its resolving power—that this obstacle should eventually be largely overcome. The other is to keep in mind what was mentioned in Section A—that the goal of archaeometric effort should be to consolidate its ability to understand the practical realities of the (ancient) potter's craft. Let the science-based work on ceramics become increasingly integrated into the broader archaeological effort.

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