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X-Radiography of Archaeological Ceramics

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Abstract and Keywords

This chapter summarizes the history, theory and methodology of ceramic X-radiography. Particular emphasis is placed upon the two most common uses of ceramic X-radiography, namely the identification of forming techniques and the characterization of clay fabrics. Practical considerations are offered for the choice of X-ray set-ups, exposure parameters, digitization, image enhancement, analysis and interpretation of the resulting X-ray. The chapter concludes with three case studies that demonstrate the great value of this technique and its potential to help illuminate many socio-cultural dimensions of ancient pottery production. The authors emphasize that deep understanding of the theoretical and practical dimensions of this technique are an essential foundation for subsequent interpretation.

Keywords: X-radiography, forming technique identification, clay fabric characterization, X-ray set-ups, digitization, image enhancement

History

IN 1895, Wilhelm Röntgen discovered a new type of radiation, which he termed “X-rays,” while experimenting with vacuum tubes. These rays proved to be more penetrative than light and thus could be used to produce images of dense materials. The first X-ray image ever published was that of Röntgen’s wife’s hand with her ring clearly visible on her finger (Röntgen, 1896). The scientific community rapidly recognized the potential of the technique and almost immediately began to use X-rays to illuminate a wide variety of medical problems (Posner, 1970). Röntgen was awarded the Nobel Prize in 1901 in recognition of his important discovery.

The technique's power was by no means limited to medical uses and it quickly became an invaluable tool in art and archaeology, where it has since been applied to a great variety of materials, including human and animal bones, metals, ceramics, paper, paintings, and soils (for a recent summary see Lang and Middleton, 2005). The earliest application of X-radiography to ceramics dates to 1935 when Titterington published a radiograph of seven sherds from North American Indian burials in order to illustrate differential proportions of inclusions. A decade later, Digby employed the technique to investigate a defect in the construction of a Peruvian stirrup-handled pot (1948). However, it was only in 1977, when Rye laid down the fundamental rules of ceramic X-radiography, that the analytical potential of this technique was fully appreciated (1977; 1981). A comprehensive summary of the technique and its application to ceramics was published in the 1990s (Carr, 1990; Carr and Riddick, 1990) and further expanded and updated by Berg (2008).

Radiography and Ceramic Technology

Radiography offers many advantages for the study of ceramics which make it a very effective technique for archaeologists and conservators alike, whether used on its own or in (p. 545) conjunction with other methods such as microscopy or conventional destructive provenance analyses. Although almost all published radiographic studies of ceramics focus on clay vessels, the underlying technological principles make it a suitable investigatory technique for almost any kind of clay object. Its advantages are manifold as it provides access to the internal structure of an object, is non-destructive, can be used on both fragments and complete objects, is comparatively rapid and cheap, and suitable medical or industrial facilities are easily and generally available worldwide.

X-radiography is most commonly applied to cultural materials to answer a number of questions, particularly:

- identification of the object and its condition;
- identification of the material(s) present;
- identification of manufacturing method(s);
- identification of joins, faults, breaks, repairs, and reuse;
- identification of finishing methods and decoration;
- identification of forgeries.

In the case of archaeological ceramics, radiography is used extensively to answer many of these questions, particularly to study condition and repairs to inform conservation treatments and questions of authenticity. However, two of these themes—namely, the identification of materials and of manufacturing methods—have received by far the greatest attention, with work specifically concentrated on the characterization of clay fabrics through inclusions or tempers and the identification of manufacturing details (Carr, 1990). These two subjects are discussed in more detail in the following section.

Characterizing Clay Fabrics

Under the right conditions, that is when the clay body and inclusions are of different radiodensities and vessel walls are not too thick, X-radiographs can be used successfully to characterize ceramic fabrics by determining the size, proportion, type, and general mineralogy of inclusions and/or tempering materials. Scholars have been able to distinguish between classes of minerals, such as felsic, mafic, and opaque, by considering the radiographic density and morphology of the particles, and the presence, number, and angle of their crystal faces. More specific attribution of minerals is often problematic, especially when inclusions/particles/grains have a similar chemical composition and exhibit similar morphology and radiodensities (e.g. chert, quartz, pure sandstone) (Carr and Komorowski, 1991). Grog, for example, is most visible when it is of different clay from the surrounding clay body (Foster, 1985). In contrast, organic inclusions (such as straw, wood, sponge, insects, seeds, shell) and the burnt-out voids left by them are easily recognizable, since the density of the ceramic body is significantly different from that of air.

Once inclusions have been characterized, their volumetric proportion and (size) distribution within the vessel can be measured and used to determine fabric groups (Rye, 1977; Braun, 1982; Maniatis et al., 1984; Foster, 1985; Blakely et al., 1992). Blakely and colleagues tested the potential of radiography to assign vessels to fabric groups, and the technique was able to successfully divide their sherd assemblage of Pompeian red ware into two major fabric groups. Petrology and heavy mineral analysis were subsequently able to confirm the (p. 546) validity of these two groups (Blakely et al., 1989). In a related study, X-radiographs were used to successfully determine whether body sherds found in close proximity to each other during excavation belong to the same vessel or to different ones, providing certainty where macroscopic analysis is ambiguous (Carr, 1990: 21, 1993: 103–105). However, success of X-radiography for establishing fabric groups is variable, as demonstrated by Adan-Bayewitz and Wieder (1992), and depends upon the exact nature of the fabric(s) under investigation. It seems most prudent, therefore, to consider radiography as a complementary tool rather than a replacement for petrography and chemical analyses.

Identifying Vessel Formation Procedures

First used by van Beek in 1969, X-radiography has since established itself as a powerful technique for the identification of primary forming methods, in particular differentiating among pinching, drawing, coil-building, slab-building, molding, and wheel throwing. It was Rye who first recognized that “the application of pressure to plastic clay causes mineral particles, voids, and organic fragments to take up a preferred orientation” which affect the entire ceramic body. The resulting alignment and distribution of inclusions, as well as the shape and orientation of voids, is characteristic of each forming method, and these features are not normally obliterated or obscured by secondary forming/shaping or decorative techniques (1977: 206, 1981; Carr, 1990; Berg, 2008). Much innovative X-ray work in this field was carried out in the 1980s and early 1990s. However, waning technical support for xeroradiography (see the section entitled ‘Xeroradiography’) in the late 1990s has led to a noticeable interruption in research activity. It is only now, with a better appreciation for the power of imaging software programs and increasing availability of industrial and medical X-ray equipment, that X-radiographic research into ceramics is once again gaining momentum.

Many scholars have successfully employed radiography to gain a better understanding of manufacturing techniques (see e.g. van Beek, 1969; Foster, 1983; Ellingson et al., 1988; Carmichael, 1990, 1998; Henrickson, 1991; Nenk and Walker, 1991; Vandiver et al., 1991; Philpotts and Wilson, 1994; Vandiver and Tumosa, 1995; Levi, 1999; Giannoulaki et al., 2006; Berg, 2009; Laneri, 2009; Berg and Ambers, 2011a; Corfield, n.d.), but the two most detailed case studies currently available were undertaken by scholars working in the Near East (Glanzman, 1983; Glanzman and Fleming, 1986; Vandiver, 1987, 1988). In their diachronic study of Baq’ah pottery, Glanzman and Fleming were able to show that, contrary to the common assumption of an evolutionary sequence from hand-building techniques to the potter’s wheel, the Baq’ah LB I wheel-throwing tradition was replaced by a coil-building tradition in the LB II and Iron IA periods. Vandiver, on the other hand, employed xeroradiography to reconstruct a specific forming technique, called sequential slab-building, in widespread use in the Zagros region around 3000 BC. Not only was Vandiver able to identify the technique in general, but she was also able to determine the precise shape, size, and sequence with which each slab was applied to form a vessel (1987). Some of the most intriguing case studies have utilized X-radiography to detect hidden vessel parts and added sections, such as the whistling mechanism in Peruvian pots and the fake spout of Aegean stirrup jars (Digby, 1948; Leonard et al., 1993).

Secondary forming techniques, such as scraping, trimming, smoothing, and adding sections, are more difficult to identify radiographically because they do not generally involve (p. 547) severe enough modification of the clay to be reflected in an X-radiograph (Berg, 2008). These secondary modifications and technologies are, therefore, best identified macroscopically. The exception to this rule is the paddle and anvil technique which applies so much pressure to the preshape that it can obliterate all radiographically visible attributes of the primary forming technique (Rye, 1981). Similarly, severe turning of the entire vessel is often identified by the complete lack of evidence/traces of the original forming technique combined with thin vessel walls.

Theoretical Background

The use of radiography in the study of ceramic composition and forming techniques is based on the distribution, alignment, and nature of inclusions and voids within the fabric. In terms of simple compositional studies this is self-explanatory: materials which differ in radiographic density from the clay body can become visible, and hence can be analyzed and interpreted through X-radiographs. The use of radiography to look at ceramic forming techniques is rather more complex. Pressure applied during the formation and shaping of a vessel frequently creates characteristic alignments and orientations of inclusions and voids that become radiographically identifiable within the vessel fabric. Figure 30.1, based on the pioneering work of Rye (1977, 1981), provides a summary of the characteristics which might be expected for different forming techniques. Radiography reveals these alignments non-destructively. It should once again be emphasized that the success of radiography in identifying manufacturing techniques is dependent upon the visibility of these features; that is, they must have different optical densities from the matrix material, as well as the amount of secondary reworking. We advocate, therefore, that small-scale trials or pilot projects always be carried out on unknown or previously unradiographed ceramic types prior to any major commitment of resources.

Pinching—forming shapes by squeezing clay between fingers and thumbs—is probably the simplest of the ceramic forming techniques. It does not result in the type of dramatic orientation of inclusions produced by other forming methods, but can still leave diagnostic traces in the vessel fabric. Figure 30.1a illustrates these features: in cross-section inclusions lie parallel to the surface while in plan view no horizontal or vertical orientation is visible. The surface may also show indentations from the pinching motion.

Figure 30.1b illustrates the distribution patterns expected for coil- or ring-built vessels. It is extremely difficult to attain perfect cohesion for every coil joint, however expert the potter, and despite careful secondary working to smooth out and strengthen these joins, in most cases some evidence will survive somewhere within the vessel fabric. As a result, coil joins are often visible as voids between the coils and are typically roughly concentric on the base and roughly horizontally parallel on the vessel sides. Joining techniques, such as overlapping, smearing, or crushing individual coils, are sometimes applied to strengthen coil joints. In these cases it can be necessary to vary the angle of the X-ray shots to capture the joins and, sometimes, even to resort to the "thick section" method of examination (described below in "Tips and Tricks") to capture proof of coiling. In addition, the coils themselves, having been prepared as long rolls prior to vessel formation, may exhibit a degree of horizontal parallel orientation with inclusions sometimes visible in the X-ray image (Figure 30.2). (p. 548)

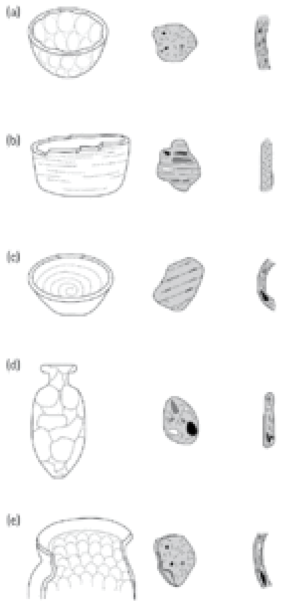

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Figure 30.1 Characteristic X-ray features of the main pottery forming techniques (after Rye, 1981; Carr, 1990: figure 1; Middleton, 1995: figure 4.8), showing, from left to right, vessel, distribution of voids and inclusions in the vessel side, distribution of voids and inclusions in the vessel cross-section. Techniques shown are (a) pinching, (b) coil building, (c) wheel throwing, (d) slab building, (e) secondary working using the paddle and anvil technique.

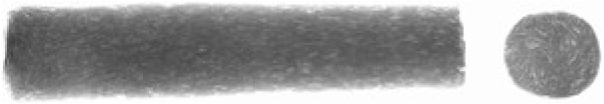

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Figure 30.2 Inclusion alignment in a clay coil. Normal view (left) and cross-section (right). Enhanced positive radiographic image. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 70 kV, 150 s, 3 mA.

(p. 549) Wheel-thrown vessels do not exhibit joins but the combined upward and rotational movement associated with pulling the walls of a vessel results in a spiral orientation of voids and inclusions (Figure 30.1c). In cases where a vessel is complete, X-rays are able to pass through both the near and far walls, and the resultant X-radiography will show superimposed images of both sides of the vessel. Wheel throwing, therefore, can reveal itself in the radiograph as either a series of diagonal lines in the vessel's surface or as two sets of diagonal lines in apparently opposing directions (this effect can be avoided by placing film inside a complete or near complete vessel in order to capture only one side). The initial suggestion by Rye that the angle of these lines reflects the speed of the wheel is not supported experimentally (Berg, 2008), but the same study did show that it is possible, in some circumstances, to differentiate between wheel-made ceramics, where the entire forming process is carried out on a turning wheel, and wheel-shaped or wheel-finished vessels, where items initially made by other techniques are then finished and improved on a fast wheel.

Joins between flattened sheets of clay are the primary radiographic evidence for slab-built vessels (Figure 30.1d). The orientation of inclusion in these sheets is dispersed and unaligned as a consequence of flattening of the clay sheets.

Other manufacturing techniques, notably molding, are more difficult to identify radiographically. For molding, the nature of the method means there is little or no development of preferred particle orientation within the clay, but thickening of the clay along the lines where the separate parts of the molds meet frequently occurs, and it is sometimes possible to successfully identify mold-made ceramics in this way.

A wide range of secondary forming processes are used in ceramic construction in order to increase strength and resistance or simply to improve appearance. They are seldom detectable by radiography and do not normally impact the visibility of primary forming techniques (Berg, 2008), except in cases where a large proportion of the wall thickness is removed. The one notable exception is the paddle and anvil technique, whose use may make the identification of the primary forming method more difficult. The effects on alignment and orientation of particles and voids in the vessel created/modified by the paddle and anvil technique are shown in Figure 30.1e. This technique, designed to thin and shape vessel walls, consists of beating one side of the vessel wall (usually the exterior) with a paddle, while the inside is supported with the smooth hard surface of a tool or implement, often a pebble. This “beating” causes localized distortions of voids and inclusions in the vessel walls, and the resultant variation in thickness and distinctive star-shaped cracks around large mineral particles are clearly visible in X-radiographs and are among the easiest ceramic features to identify radiographically. In contrast, very severe turning of the entire vessel may potentially be identified by the total lack of traces of the original forming technique and thin vessel walls, as demonstrated in an unpublished study of Bronze Age Cypriot vessels investigated by one of the authors (Ambers).

Based on our experience with ancient vessels, together with experimental data from replica vessels, a firm identification of forming techniques should be possible for approximately 70% of vessels within an assemblage. Success rates will be lower when the vessel walls are very thick, when clay body and inclusions have a similar radiodensity, or when the pots have been heavily turned.

(p. 550) Methodology

Historical Development

The earliest X-radiographic investigations of ceramics (van Beek, 1969; Rye, 1981) used conventional film radiography and met with only limited success. In order to characterize archaeological ceramics it is necessary to locate and identify small particles with densities only minimally different than an already radiographically light matrix. With skill and care such subtle changes can be identified on unmodified X-ray films, but the process is not easy and requires considerable expertise. The development of a novel radiographic technique in the 1970s, xeroradiography, made the identification of such small changes in density much more accessible, and was followed by an explosion in the number of ceramic studies dependent on radiography published.

Xeroradiography

Xeroradiography is an X-radiographic technique in which the image is collected on an aluminum sheet coated with a uniformly deposited film of amorphous selenium, rather than on a photographic film or a digital imaging plate, within an otherwise conventional radiographic setup. The plate is electrically charged before use, and during exposure this charge dissipates differentially in proportion to the dose of radiation it receives, thereby generating a latent image which can be fixed onto paper by processing with oppositely charge particles (usually in the form of a blue colored powder), as a variation of the Xerox photocopying process (Boag, 1973; Lang and Middleton, 2005). While this method cannot produce high-resolution images, it has other advantages which established its importance for a range of medical applications, most notably mammography. Xeroradiography has a wide exposure latitude, is virtually impervious to scatter, and, because of the way in which the dry toner responds to electrical fringing between high- and low-charged areas, shows a pronounced edge enhancement effect (Figure 30.3). These characteristics make it particularly suitable for the examination of small differences in density, particularly if they have sharp, well-defined edges. Originally developed for medical examination, xeroradiography was rapidly taken up by the archaeometric community for a number of purposes, but most particularly for the study of ceramics (see e.g. Vandiver, 1987). Xeroradiography is now effectively obsolete, as it has long been replaced in medicine by techniques which require lower doses of radiation. Instead radiographers have turned to digital image manipulation to extract similar information from radiographic images, as discussed in detail in the section entitled “Image Enhancement” (O’Connor et al., 2002).

Modern Practice

A wide range of X-ray equipment, which can broadly be divided into medical and commercial/research setups, is now available to archaeologists. Medical units can be found in (p. 551) hospitals, private clinics, and veterinary surgeries (Figure 30.4a), while commercial/research machines can be found in industrial settings, museums, and universities (Figure 30.4b). The key difference between them is that medical setups are designed to minimize the radiation dose to living tissue, and are, therefore, only designed to permit short exposure times. As a consequence, the voltage (kV) has to be proportionately greater to achieve penetration, resulting in images with reduced contrast. However, in industrial and research settings the imperative to minimize patient dosage does not exist. This means that exposure times can be increased and the kV kept low in order to achieve high-contrast images. For this reason, if the opportunity to work with a commercial/research setup is available, this is to be preferred over a medical facility.

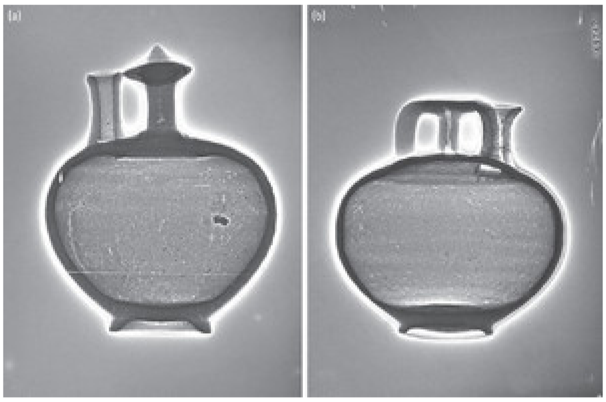

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Figure 30.3 Xeroradiographs of two stirrup jars showing both the blue color and edge enhancement inherent to the technique. The scratch across a) is an unfortunate result of the use of ageing equipment. a) Stirrup jar with solid false central spout from mainland Greece (BM registration number G&R1978,0701.4); b) Cretan stirrup jar with hollow false central spout (BM registration number G&R1857,0825.2).

The advantages of using radiographic equipment at medical facilities, on the other hand, are their relative abundance, comparative ease of access, and potential portability (many large animal veterinary practices and some hospitals have mobile equipment). If medical equipment is to be used, it is best to avoid specialist mammography units, because mammography film is generally only available in very small sizes and also tends to be too responsive to very small thickness changes, making it overly sensitive for ceramic analysis. The truth, however, is that it is possible to work with most commercial, research, and medical X-ray units and achieve a reasonably detailed image.

One further choice exists when selecting X-ray equipment: whether to use digital or conventional wet(-film) processing. At the time of writing there are few qualitative differences (p. 552) between the two; currently available instrumentation digital image quality is as good as that of film and the speed of technical development is such that digital may soon overtake conventional film radiography. Digital equipment has several practical advantages: the image can simply be downloaded without having to be scanned; the latitude of exposure is greater; the lack of processing time means digital work tends to be quicker than film radiography; and, while the initial outlay for equipment is higher, there are no recurrent costs for film and chemicals. There are currently two types of digital systems available, which differ in the image collection method used: CR (computed radiography) and DR (direct radiography). In CR, a reusable phosphor plate is used in place of film in a conventional system, while in DR the image is captured on a fixed plate and transmitted directly onto a computer screen. DR systems are currently considerably more expensive, but, at present, the image quality of the two systems is similar.

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Figure 30.4 Examples of types of radiographic equipment available. (a) Portable medical Sirio 110/100 CR system; (b) Faxitron single-cabinet X-ray unit.

An archaeologist's choice of system will most likely be governed by availability and training, but looking into the future, chemical processing is slowly being phased out in all areas, and digital X-ray machines will soon become the norm. A radiographic imaging technique called computed tomography (CT or CAT) may occasionally be available to researchers. In addition to presenting a frontal view of an object, like regular X-rays, CT can also "slice" through an object, providing the researcher with cross-sectional views.

Image Enhancement

Whatever the initial image collection method, the minimal differences in radiographic density between ceramic bodies and the voids and inclusions within them mean that some form of image enhancement is necessary prior to interpretation of the radiographs. In xeroradiography, edge enhancement was an integral part of the method, but for conventional X-radiography edge enhancement must be artificially produced by digital manipulation of (p. 553) the image. In order to do this, the images must first be in a digital format and of the highest resolution possible. With the increasing availability of digital radiography no interim stage may be necessary, but, given that archaeology tends to be both poorly funded and conducted in areas with limited resources, at the time of writing, most radiography of ceramic materials will have been recorded on film.

Low-cost methods of film digitization exist (films can be scanned on office-style flatbed scanners with transmission capacity or placed on a light box and imaged with a standard digital camera), but by far the best results are obtained using specialist X-ray scanners (O'Connor and Maher, 2001; Lang et al., 2005). These are designed to maximize the information collected from film radiographs and have high dynamic ranges (dynamic range is defined as the range of optical densities that can be recognized in the image), and high resolution (resolution is the number of pixels per unit length in the image; for most specialist equipment the pixel pitch will be 50 microns (*c*.512 pixels per inch) or better) and a bit depth of 12 or more (bit depth controls the number of shades of gray which can be distinguished within the image; in an 8-bit system 256 shades of gray can be defined, in a 12-bit system 4,096, and in a 16-bit system 65,536). Such specialist equipment is very expensive and its purchase is not cost effective for most museum and academic departments. However, demand for the storage of industrial images means that commercial scanning services are readily available at reasonable rates, particularly when judged against the cost in time and effort of producing high-quality radiographic images in the first place.

Regardless of how the digital image is produced, it is important that it is generated and stored in an accessible and widely supported format, partly for ease of publication by the researcher, but also, and crucially, for archiving purposes; much archaeometric data has been lost over the years owing to the use of data formats which have become redundant. Most digital radiography or radiograph scanning equipment produces data in both proprietary and generic formats. For archaeometric images, it is important that a widely available generic and uncompressed format is selected for archiving. At the time of writing (2013), this will be either as TIF or DICOM files. DICOM is a lossless data format originally devised for the distribution of medical images but now adopted into the industrial world in the form of DICONDE. It is possible that both these formats may eventually be superseded, but they are currently so prevalent that it is difficult to foresee a time when conversion programs for these formats are no longer available.

Once an adequate digital image has been generated it must be enhanced to make the edges of the included materials visible for interpretation. One way to achieve this is first to detect and then enhance the edges, a process generally carried out using a kernel-based algorithm. A detailed study of suitable edge detectors (O'Connor et al., 2002) suggested that a Kirsch edge detector was the most suitable for archaeometric work. While most commonly available imaging programs, such as Adobe's Photoshop and Corel's PaintShop Pro, have the capacity to run such specialized filters as add-ons, they are not generally included in the off-the-shelf version. However, experimentation by the authors has found that in the majority of cases the use of the Unsharp Mask filter, originally devised to increase the resolution of photographic images and conventionally included in most digital imaging packages, provides a perfectly adequate and more accessible alternative to these more expensive add-on features. (p. 554)

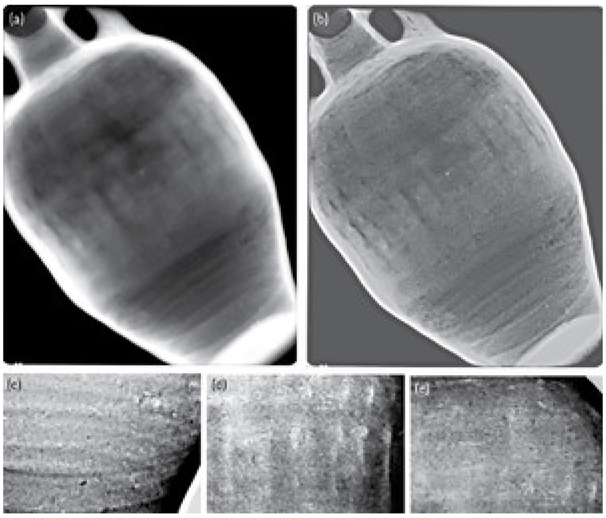

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Figure 30.5 Radiographs of a Middle Minoan amphora (BM registration number G&R1906,1112.90) from the British Museum. All radiographs were recorded on Kodak Industrex MX film in a hard plastic cassette with 0.25 mm lead sheets on either side of the film. (a) Whole side of vessel, unenhanced image. Exposure parameters: Siefert DS1, 0.5 mm focal spot, I m focus-to-film distance, 70 kV, 25mA mins. (b) Image from 4a, enhanced using Adobe Photoshop Unsharp Mask filter. (c) Detail of lower body from 5b showing diagonal voids characteristic of rotative kinetic energy. (d) Detail of central zone from 5b showing parallel joins characteristic of coil forming and evidence of secondary working. (e) Detail of upper body from 5b showing evidence of coil forming.

A dramatic example of the successful use of a scanned film radiograph, enhanced with Unsharp Mask, is given in Figure 30.5. Here a Middle Minoan III oval-mouthed amphora (BM registration number G&R 1906,1112.90) was radiographed using Kodak Industrex MX film. The film was then digitized using an Agfa RadView scanner with a 50 micron pixel size and 12-bit resolution, and the resultant image enhanced using the Unsharp Mask filter within Adobe Photoshop. Figure 30.5a shows the unenhanced scanned image, while 30.5b shows the same image with an Unsharp Mask filter applied.

Figures 30.5c, d, and e illustrate individual details of the lower, center, and upper body of the vessel, individually processed for the greatest clarity. In Figure 30.5c, clear diagonal voids can be seen representative of evidence of the rotative kinetic energy of wheel throwing. Parallel joins in Figure 30.5d show that this zone was produced by coil forming, and the localized distortion indicates that there was secondary reworking of this area. Figure 30.5e, the (p. 555) shoulder at the top of the amphora, also reveals parallel joins indicative of coil building, but here there was no secondary treatment, thus making the coil joins more easily recognizable.

Radiography of Ceramics—Producing the Best Results

Crucial for the radiographic study of archaeological ceramics is the generation of a high-contrast radiograph. In order to achieve this, the kV should be kept low and the exposure time long. In work carried out by the authors, using either a Faxitron cabinet with a 3mA fixed tube current or a Siefert DS1 320 kV industrial X-ray tube, voltages between 55 and 70 kV were found to produce the best images of ancient and modern ceramics with a range of wall thicknesses, although such parameters will vary between equipment and between film and digital setups. The exposure chart in Table 30.1 provides some basic guidance for Faxitron users using standard industrial-type film. Exposure times will be considerably shorter for digital capture and other X-ray setups will require experimentation to determine the most suitable exposure parameters.

It is important to note that exposure time and kV are directly related to the thickness of the ceramic object—the thicker the vessel, the longer the exposure and/or the greater the kV. None of the many clays and tempering materials tested in experiments by the authors have showed any deviation from this basic rule. To find the correct exposure for each pot, simply measure the thickness at several points along the vertical axis of a pot; vessels typically change thickness most radically from base to rim. Select the exposure time and range that best fits with the thickness range of the majority of the area to be imaged. In circumstances where the pot has drastic thickness changes, one will have to take several images at different exposure parameters to capture the entire vessel accurately. It is important to remember, however, that one must double the wall thickness when X-raying a complete vessel to ensure that the X-ray beam penetrates both sides of the object.

While it is always best to position objects at the center of the focal spot of the X-ray tube, in order to keep geometric distortion to a minimum, several small ceramic objects of similar thickness can be imaged together in the same exposure without loss of quality, helping to keep costs low and conduct a project speedily. Larger objects may each require their own plate. X-ray translucent supports can be used to prop up objects, prevent them from rolling off their spot, and align them as parallel as possible to the horizontal surface of the film, cassette, or imaging plate being used. For most exposures, pieces of bubble-wrap or plastizote are suitable supports. The object should be in as much direct contact with the cassette as possible and cassettes can be either solid or flexible. In most circumstances, a solid cassette will suffice, but flexible cassettes have advantages for the examination of complete vessels because they can be bent to fit inside objects, allowing an image to be collected for a single side of a vessel. Because of the low energies employed in ceramic radiography, the use of filters (lead, aluminum, etc.) to remove low-energy scatter and sharpen the image, essential for the radiography of denser objects, is unnecessary for ceramics. (p. 556)

Table 30.1 Exposure times and kV for clay objects using a Faxitron cabinet X-ray machine with a 0.5 mm focal spot, 60 cm focus-to-film distance, 3 mA, and Agfa Structrex D4 Film. The kV shown here only present a guide—radiographs should always be taken using the lowest possible kV to improve image contrast

Clay thickness (mm)	55 kV	70 kV
19		150 sec
18		150 sec
17		150 sec
16		120 sec/150 sec
15		120 sec/150 sec
14		105 sec/120 sec
13		105 sec/120 sec
12		90 sec/105 sec/120 sec
11	120 sec	90 sec/105 sec/120 sec
10	105 sec/120 sec	90 sec
9	105 sec/120 sec	90 sec
8	105 sec/120 sec	90 sec
7	90 sec/105 sec	
6	90 sec/105 sec	
5	75 sec/90 sec	
4	75 sec/90 sec	

3	75 sec	

Tips and Tricks

Experience has shown that there are a number of tips and tricks that can increase the likelihood of producing good images, the quality of the images, and/or increase visible detail, and, as a result, our ability to analyze and interpret a ceramic object confidently.

(1) The inclusions and clay body are normally sufficiently different in radio-density to allow successful interpretation of features. Despite this, it is highly recommended that a pilot study of the assemblage be conducted to avoid disappointment and/or (p. 557) wasted time and resources, because some ceramics have characteristics which make their analysis difficult. These difficulties include: inclusions and clay body with similar radio-densities, for example grog; large and abundant inclusions that obscure subtle features; the vessel walls are very thick, for example large storage vessels; and/or the vessel was heavily turned, as was the case in the above-mentioned Bronze Age Cypriot pots.

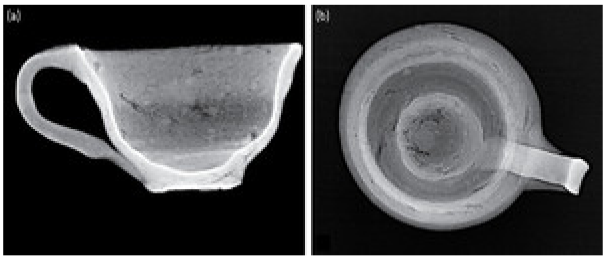
(2) When radiographing a complete or largely complete vessel for the purpose of determining forming technique, it is always advisable to take two views: one from above (a plan view) and a side view. This is because some voids, such as the spiral void arrangement of wheel-thrown pots, are sometimes only or more visible in one view than the other. There does not seem to be a discernible and persistent pattern as to which view will provide the clearest view of these features. Consequently, it is only by taking both views that an accurate identification is possible (Figure 30.6).

(3) Always base interpretations only on clearly visible patterns. When determining a forming technique, there is always the potential danger of assigning meaning to a random or unrepresentative alignment of voids or inclusions. One way to counter this tendency is to turn the radiograph through 90 degrees and look for the alignments again. If you find alignments along this rotated axis, then it is most likely that they are not true alignments and the radiographs do not provide a clear indication of how the vessel was made. If there is any doubt about the interpretation of features in the radiograph, analysts should err on the side of caution. Also, since different people perceive black and light areas on radiographs differently, it is sometimes helpful to reverse the grayscale of a radiograph, making previously light sections darker and dark sections lighter.

(p. 558) **(4)** In cases where it is possible to conduct destructive analysis, thick-sectioning, a variation on the standard X-ray method, can be used to attain a more detailed understanding of vessel formation. Thick-sectioning was pioneered by

Vandiver, who used it to reconstruct the precise size of each clay slab and building sequence of slab-built vessels (1987: plates 5–7; Vandiver et al. 1991: figures 8–11). Thick-sectioning involves cutting a vessel or sherd vertically into thin slices with a radiograph being taken of each slice's cross-section. The resulting images display features diagnostic of the chosen forming technique and often provide clues about the building sequence.

(5) It is absolutely essential that any radiographic interpretation is based on a deep and thorough understanding of formation processes as well as the characteristic radiographic fingerprint of each technique. We therefore strongly recommend that scholars work together with a practicing potter to create a control group of modern replicas against which they can compare radiographs of archaeological ceramics.



Click to view larger

Figure 30.6 Radiographs of a bell-shaped handled cup (Middle Minoan I) from Knossos (BM registration no G&R1950,1106.16) Taken from the side (a) and above (b). The diagonally stretched voids indicate that rotative kinetic energy (RKE) was used in the making of this vessel and hence that the main body is wheel-thrown. The handle was pulled and its bottom attachment only lightly pressed onto the body. The details of the handle can only be seen in a, while the spiral pattern of inclusions in the main body is far clearer in b. Exposure parameters for both exposures: Siefert DS1, 0.5 mm focal spot, I m focus-to-film distance, 60 kV, 20 mA mins, Kodak Industrex MX film. Enhanced using Adobe Photoshop Unsharp Mask.

Case Studies

To demonstrate the power of radiography as a technique for the study of archaeological ceramics and to illustrate its potential contribution to the development of a more detailed understanding of sociocultural patterns and changes, we provide a summary of three case studies of objects in the collections of the British Museum.

Case Study 1: the Cretan Bronze Age

In 2006, the authors collected X-ray images of twelve open and closed Middle Bronze Age vessels with a firm Cretan (Knossian) provenance from the British Museum's collection (Berg and Ambers, 2011a). Analysis of the radiographs indicated that two vessels, a jug and an amphora, were produced by coiling, and a jar, a jug, an amphora, and two cups were manufactured by wheel throwing; no forming technique could be conclusively determined for four vessels, an amphora, a cup, a heavily restored jar, and a jug. The most exciting finding, however, was that one amphora (BM registration number G&R 1906,1112.90) was made using three different techniques in sequence (Figure 30.5): the diagonally stretched voids around the lower body indicate that this section was wheel-thrown using rotative kinetic energy (Figure 30.5c). The middle section or vessel body is characterized by parallel joins indicative/diagnostic of coil-building, although these are partially concealed by secondary shaping visible as the differential thickness of the wall (Figure 30.5d). This secondary working is also apparent as elongated vertical lines on the radiograph. These vertical lines probably represent drawing marks, although there is no evidence of preferential vertical orientation of the inclusions or voids to confirm this, and there is a chance that this feature results from the use of the paddle and anvil technique using a rod-shaped paddle. The vessel's shoulder was also made using coils, but did not receive any secondary treatment, leaving the coil joins more easily recognizable (Figure 30.5e).

(p. 559) At its most basic, this case study demonstrates the great variability in forming techniques employed by Bronze Age potters on Crete. On a more detailed level, it hints at a degree of specialization within the potting tradition of Crete with small, open vessels generally being wheel-thrown, while large, closed vessels are often handmade. This observation was subsequently tested in a larger X-ray-based project and found to apply throughout the Cretan Bronze Age and across all of Crete (Berg 2009, 2015).

Most intriguing, however, was the recognition that the potters sometimes combined several methods to manufacture a single vessel. Additional examples of vessel formation using a combination of techniques were identified during the large-scale X-ray study, as well as in the literature. Two important points about ceramic manufacture emerge from analysis of these vessels: first, when the wheel is employed on these large vessels, it is utilized for the basal and lower body sections which are comparatively easy to make. Second, the height of the wheel-thrown sections is approximately 16 cm, the maximum average height achieved using this technique by potters across Crete. It is possible that this height restriction was a consequence of limitations in the design of the potter's wheel, making it unable to store momentum for sufficiently long periods of time to throw large vessels in one sequence (Berg, 2015). Rather than modify or develop a better potter's wheel, Cretan potters employed an alternative technique, wheel-shaping (termed "wheel-coiling" in recent literature), that allowed them to construct vessels in stages, using a preshape made by coiling, and subsequently modify the shape and appearance of the pot with rotative kinetic energy (for the wheel-coiling technique, see Courty and Roux, 1995; Roux and Courty, 1998).

Case Study 2: Aegean Stirrup Jars

The stirrup jar is a distinctive vessel shape from Bronze Age Greece which first appeared in the Middle Bronze Age and reached its greatest popularity in the Late Bronze/ Mycenaean period. These vessels are characterized by a central, false spout closed off with a disk. Two handles reach from this spout to the shoulder where a second, and functional, pouring spout is positioned. Large undecorated stirrup jars functioned as transport containers for olive oil, while smaller, decorated versions were used to store perfumed oils. Owing to the desirability of their contents, stirrup jars were produced in many workshops both inside and outside Greece and traded widely throughout the Mediterranean. Analysis of thirty-nine jars in the British Museum by Leonard and his colleagues in 1993 used NAA to investigate vessel provenance, XRF and XRD to determine the composition of the paint, and xeroradiography to establish whether individual manufacturers and/or workshops could be identified by their differential use of forming techniques (Leonard et al., 1993).

The radiography results were illuminating and two different methods of manufacturing stirrup jars could be documented. In one tradition, the vessel and fake spout were built in one sequence, resulting in a hollow fake spout. The other tradition attached a solid fake spout, thrown as a separate piece, to the completed vessel during the leather-hard stage (Figure 30.3). These distinct manufacturing methods were shown to be indicative of different regional potting traditions, with Attic and Rhodian pots favoring the solid fake spout method and Cretan potters manufacturing vessels in a single process.

An important result of this study is the reminder that similar vessel shapes can be created using very different formation techniques and manufacturing processes, and that the (p. 560) transfer of practical knowledge can create local or regional forming traditions. Therefore, it is valuable/essential to identify these traditions and technologies using X-radiography.

Case Study 3: Mycenaean Pottery

Our knowledge of production equipment, forming techniques, and organization of pottery production in Late Bronze Age mainland Greece, during the Mycenaean period, is surprisingly limited. This is partly owing to the dearth of archaeological evidence from this period that relates to ceramic manufacture; for example, only two wheel heads survive from the Middle Bronze Age. The lacuna is partly also a consequence of research traditions and priorities uninterested or engaged with questions related to ceramic manufacture in general and forming techniques in particular. For example, most archaeologists never explicitly state or appear to investigate manufacture technologies and formation techniques utilized to create Mycenaean ceramic assemblages; and yet there is a tacit assumption that almost all vessel shapes and wares were mass-produced by wheel throwing (Berg, 2013: table 1). It is only (p. 561) with reference to the earlier Middle Bronze Age, during which it is generally accepted that a wide variety of potting technologies and methods were in use, that scholars list forming techniques in their catalogue entries.

Click to view larger

Figure 30.7 Radiographs of a Mycenaean krater (BM registration number G&R1898,1201.112) taken from the side (a) and above (b). The vessel has undergone extensive modern restoration with the long straight lines representing adhesive joins and the speckled area near the center of the rim being modern infill. Nonetheless, clear evidence survives of the use of coil building in the form of numerous elongated voids along the coil joins with rotative kinetic energy applied subsequently creating irregular rilling. The coil joins are particularly clear in the image taken from above. Exposure parameters for both exposures: Siefert DS1 tube, 0.5 mm focal spot, I m focus-to-film distance, 60 kV, 20 mA mins, Agfa Structrex D7 film. Enhanced using Adobe Photoshop Unsharp Mask.

In order to throw some light upon this under-researched aspect of Mycenaean potting traditions and to investigate the existence of other forming techniques, the authors conducted a pilot study of Mycenaean vessels in the British Museum’s collections (Berg and Ambers, 2011b). The results are as follows: three vessels are wheel-thrown (two bowls and a small jar), one vessel is handmade (a miniature jug), and three vessels are wheel-shaped (two kraters and a bowl) (Figure 30.7). Two alabastra and a rhyton are manufactured using a combination of handmade and wheel-made techniques. These vessels demonstrate the great variability in forming techniques and/or potting traditions employed by Mycenaean potters. Like potters in the preceding Middle Bronze Age, it is now confirmed that Mycenean potters also utilized a wide range of techniques and methods for ceramic manufacture and frequently combined several methods to produce a single vessel. Thus, the tacit assumption that all Mycenaean pottery was wheel-thrown has been demonstrated to be inaccurate by this radiographic analysis. The consequences of this research are far-reaching and potentially paradigm-shifting because it imposes a reassessment of our understanding of pottery production in this period, alerts scholars to the need for detailed ceramic analysis, and reminds us always to test our assumptions against the archaeological record.

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