Radiography of Cultural Material

Edited by

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and

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Ceramics

Andrew Middleton

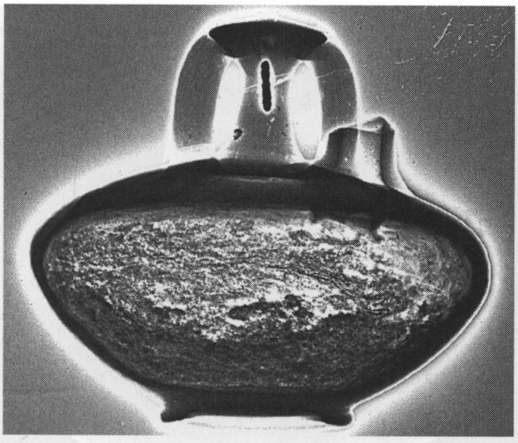
Introduction; characterization of clay fabric, imaging inclusions, identifying inclusions; forming and fabrication techniques, primary-forming techniques, secondary processing, hybrid vessels, composite objects; prospects

INTRODUCTION

Radiography is particularly useful for the non-destructive investigation of complete ceramic vessels, such as the Peruvian whistling pot in the shape of a macaw shown in Plate 4.1. The radiograph reveals clearly the whistle concealed within its head. But radiography can also be useful when applied to broken potsherds. Indeed, the earliest published radiographic examination of archaeological ceramics appears to be that of Titterington (1935), who published a radiograph (*ibid.* figure 7) of some potsherds from Indian burial mounds in Jersey County, Illinois. Inclusions in the clay are clearly visible in the radiograph; it can be seen that the different sherds contain different amounts of these inclusions. Another early study was published in 1948, reporting work carried out at the British Museum some years earlier by Digby and Plenderleith, who were interested in the methods used to make some spout-handled Peruvian pots (Digby 1948) (see below for further discussion).

Both of these early studies were aimed at determining aspects of ceramic technology and this will be the main focus of this chapter. Radiography can assist in the characterization of the clay paste itself and in the elucidation of forming and fabrication techniques. However, radiographic examination can also contribute to other aspects of ceramic study. It may reveal details of old breaks and repairs (Figures 4.1 and 4.2): the use of radiography in this way was noted by Moss (1954) and also mentioned by Heinemann (1976) in a paper describing some of the earliest applications of xeroradiography to archaeological materials. However, the use of radiography in conservation is covered more fully in Chapter 8 and is not considered further here. Another related application of radiography, also considered in more detail elsewhere in this book, concerns the unmasking of heavily restored vessels and outright fakes (see Chapter 9).

Radiographs of ceramics generally exhibit only limited contrast because both the clay and the inclusions in it are typically silicate materials and absorb X-rays to more or less the same degree. This problem can be alleviated to some extent by the use of a softer (lower energy) X-ray beam, which provides a greater contrast between the clay and the various inclusions. In general a setting of less than 100 kV is appropriate for ceramic materials, and for maximum contrast the lowest practicable value should be selected. Different considerations applied when the image was being recorded as a xeroradiograph, rather than on film, and an acceleration voltage of *c.* 150 kV was then appropriate. As has been discussed already in Chapter 2, xeroradiography is now essentially obsolete, with very few sets in active use. However, images with similar characteristics can be created by digital processing of scanned film radiographs (O'Connor *et al.* 2002). This is illustrated by the series of radiographic images of a 19th century water transport jar from Vietnam, shown as Figures 4.3(a)–(c). The use of metal filters, normally used to harden the X-ray beam, is generally unnecessary when radiographing ceramics, whatever the method of recording the image. These technical aspects are discussed more fully in Chapters 1 and 2.



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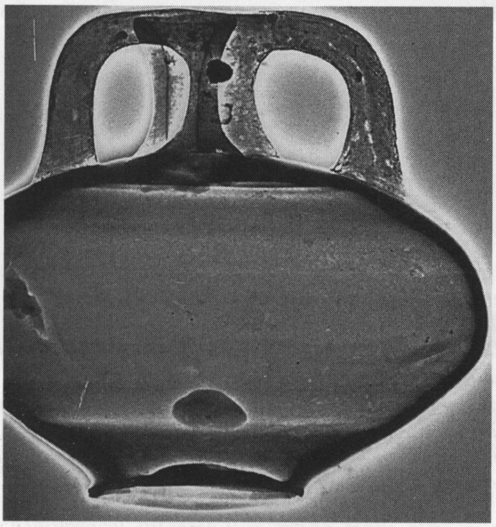

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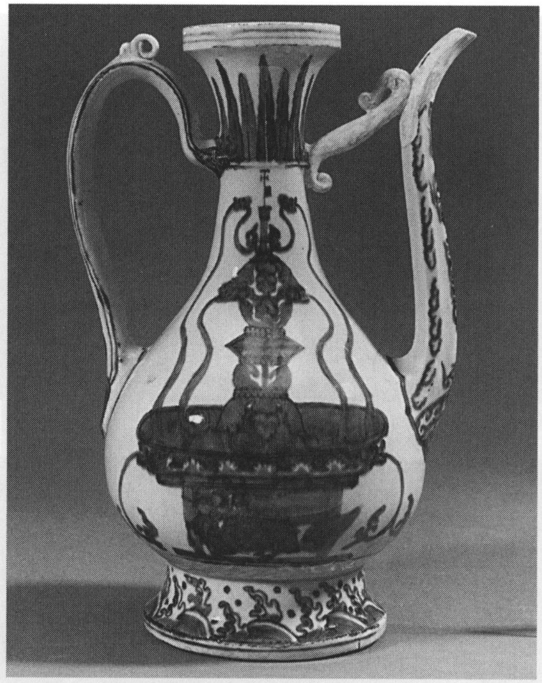
Figure 4.1. *Xeroradiographs of two Late Bronze Age stirrup jars. (a) Jar from the Greek mainland, showing the use of a metal pin to repair the central false neck (GR 1905-6-10.9). (b) Jar from Crete, revealing a plaster replacement of the handle on the right (mottled on the xeroradiograph) (GR 1875-8-25.3).*

It is interesting to note, in passing, the rather different approach to the enhancement of radiographic contrast used by Digby and Plenderleith in their study of Peruvian pottery (Digby 1948). They siphoned X-ray absorbent mercury into the hollow spout of one of the pouring jugs (Figure 4.4), a technique which would not now be appropriate from the viewpoint of either the curator or the archaeological scientist, and which would undoubtedly fall foul of



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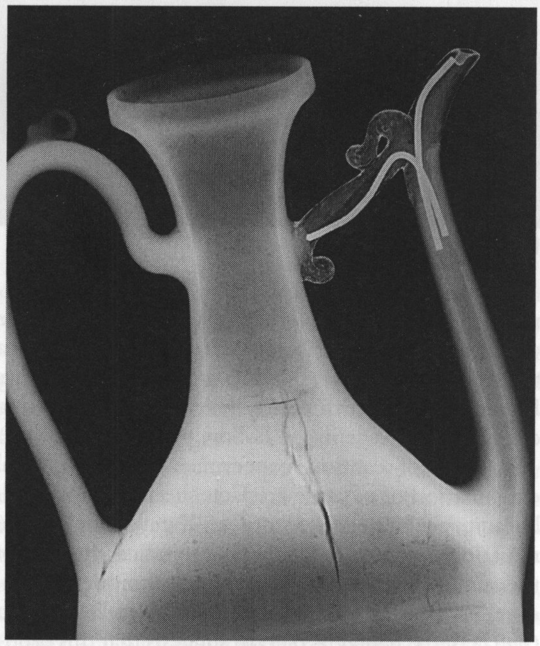

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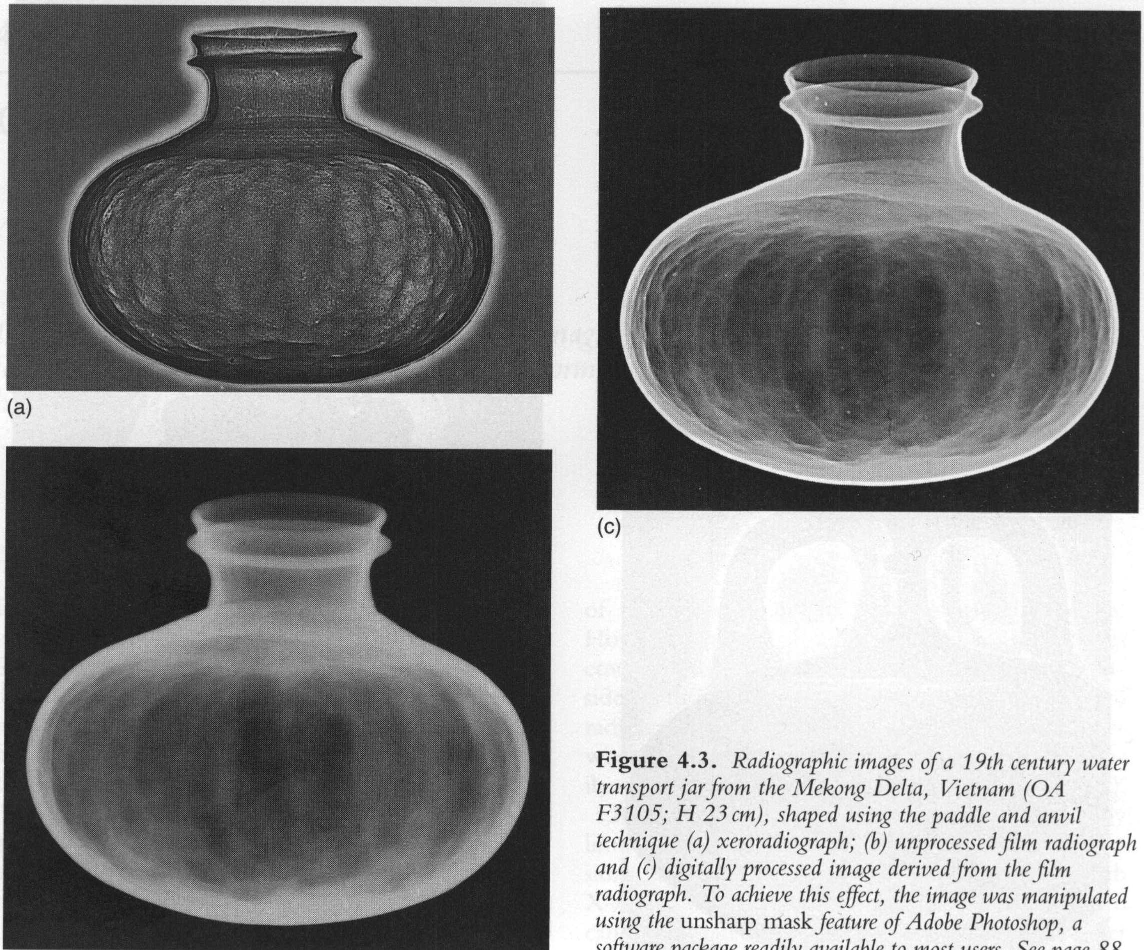
Figure 4.2. *(a) 16th century Islamic ewer, with underglaze blue decoration (OA Franks Collection, No. 150). (b) Radiograph of the upper part of the vessel revealing extensive repair and restoration. 5 mA, 3 min, 100 kV, Kodak MX.*



(a) (b) (c)

Figure 4.3. *Radiographic images of a 19th century water transport jar from the Mekong Delta, Vietnam (OA F3105; H 23 cm), shaped using the paddle and anvil technique (a) xeroradiograph; (b) unprocessed film radiograph and (c) digitally processed image derived from the film radiograph. To achieve this effect, the image was manipulated using the* unsharp mask *feature of Adobe Photoshop, a software package readily available to most users. See page 88 for further discussion of this vessel.*

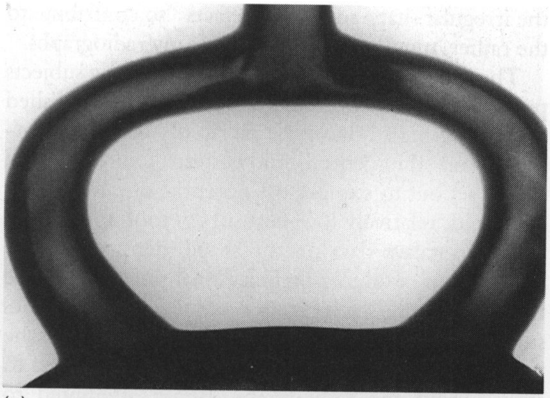
modern Health and Safety legislation! However, the effectiveness of their approach can be seen from their figure (*ibid.* Plate XXXI, 5, reproduced here as Figure 4.4(b)), which clearly reveals a manufacturing defect – a blockage in the hollow pouring handle.

A note of caution concerning the radiological examination of ceramic artefacts should be sounded, because prolonged exposure to X-rays may induce radiation damage, which will prejudice the use of thermoluminescence (TL) dating techniques. However, unpublished experimental work by Debenham (1992) (see Chapter 9, p. 176) suggests that this problem may be less serious than has sometimes been thought; nevertheless, multiple exposures or prolonged exposure, such as might occur during real-time examination, can seriously compromise TL dating. Should dating be contemplated, it is therefore prudent to remove samples prior to radiographic examination.

In this chapter the application of radiography to ceramic artefacts will be considered under two main headings – the characterization of the clay fabric and the investigation of forming and fabrication techniques.

CHARACTERIZATION OF THE CLAY FABRIC

Despite the inherently low contrast of ceramic artefacts, useful radiographs revealing the internal texture of the clay fabric may be obtained. Although many modern ceramics are manufactured from highly refined, smooth clay bodies, much of the pottery of



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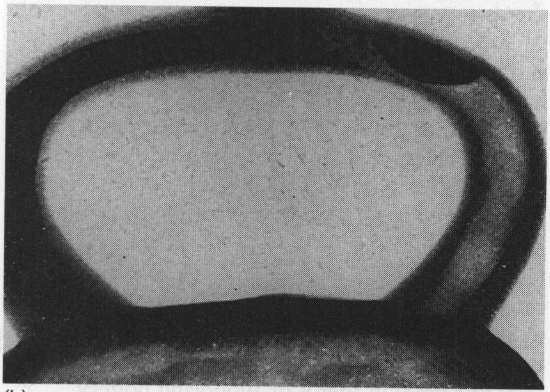

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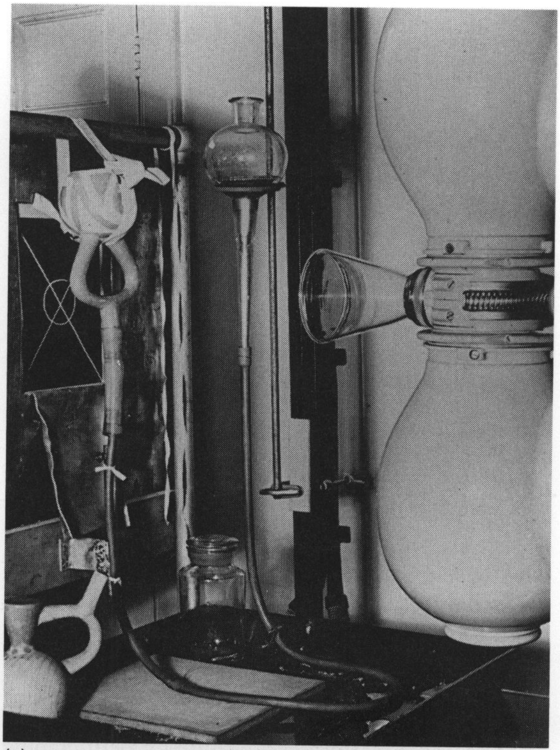

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Figure 4.4. *(a) Radiograph of a Peruvian stirrup-handled pot (ETH 1909-12-18.248). (b) Radiograph of the same vessel after mercury had been siphoned into the hollow handle using the apparatus shown in (c). All photographs were recorded by Plenderleith in the late 1930s.*

archaeological interest was made from clay pastes which contain variable proportions of coarse, aplastic inclusions. This coarse material may have been natural (or *intrinsic*) to the clay or it may have been added deliberately by the potter for a variety of reasons (see, e.g. discussion in Rice 1987); in the latter case it is often termed *temper.* Temper may have been added to modify the working properties of the wet clay; for instance, the addition of aplastic material can reduce the plasticity of clays, which might otherwise be unworkable. The addition of temper can also help to control shrinkage of the clay body as it dries. Fibrous organic material, such as chopped grass or dung (London 1981), contributes to the wet strength of the vessel in rather the same way as modern plastic materials are often reinforced by the addition of glass fibre. But the coarse inclusions also play a vital role during firing, particularly the rather uncontrollable conditions of an open bonfire or pit firing under which much prehistoric pottery was fired. They serve to 'open' the clay fabric, and allow the volatile gases generated during the firing to escape. Refined modern clays subjected to the conditions of a bonfire frequently explode (Woods 1986).

The aplastic inclusions (or the voids left after organic matter, such as chaff, has burned out) can be imaged using radiography, which yields information on their size and shape. However, the examination of thin sections made from slices of pottery, using a petrographic microscope, provides images (Figure 4.5) with much better resolution and will generally permit considerably more reliable mineralogical identification and characterization of these inclusions (for a review of the techniques and application of petrography to archaeological ceramics, see Freestone 1995). The petrographic microscope also allows the

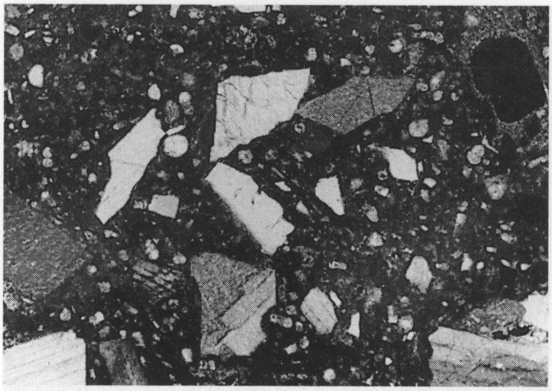

Figure 4.5. *Photomicrograph showing coarse inclusions of calcite in a Late Bronze Age sherd from Um Hammad, Jordan (WA 1989-1-29.20). Width of field, c. 2 mm.*

fabric to be viewed at high magnification if required, whereas radiography is typically restricted to life-size or only relatively low magnification (but see mention of microfocus and computed tomography (CT) imaging below and in Chapter 2. Nevertheless, radiography offers some particular advantages which may make its application appropriate, either as a complement or, more rarely, as a substitute for petrographic examination. It is, of course, non-destructive, whilst petrographic examination requires the removal of a sample for preparation as a thin section. An additional advantage of radiography is that the observations are based upon the examination of a larger and potentially more representative volume of material; that is, over a greater area and through the whole thickness of a sherd, rather than just the 0.03 mm thickness of a petrographic thin section. Furthermore, provided that the variation in thickness is not extreme, the radiographs from a series of sherds can be recorded on a single film or xeroradiograph. Thus radiography may be useful as a relatively rapid and economical survey tool for the general characterization and classification of the fabrics of a large number of pottery sherds, particularly with respect to the nature and proportions of the inclusions in the clay.

Imaging the Inclusions

Many radiographs of ceramic objects, present a rather 'flat' appearance. This arises in large part from the inherently low radiographic contrast of the ceramic subject, rather than from any particular shortcomings in the choice of film or exposure conditions. However, scattering of the relatively soft X-rays and the irregular shape of many artefacts also contribute to the rather 'muddy' appearance of many radiographs.

The inherently limited contrast of ceramic subjects presented a problem to Braun (1982), who published a radiographic study of the fabric of Woodland pottery from the central midwestern United States. Braun set out to explore the potential of radiography as a rapid, relatively low-cost survey tool 'for obtaining quantitative data on the shape, density and size distribution of temper particles'. His aim was to relate these data to an interpretation of technical properties such as the thermal shrinkage behaviour of the unfired clay and the response of the fired fabric to stress. From the radiographs, Braun attempted to estimate the density (i.e. proportion) of temper in the sherds using a point counting technique on a light table. Considerable variation was found both within and between samples, and some difficulty was found in detecting fine particles, in part because he was obliged to use relatively coarse-grained medical film. These problems led Braun to conclude that whilst the technique had potential, improvements were needed in order to increase detail and reduce measurement error. Rather similar problems were reported by Carr (1990). However, by using fine-grained film and carefully controlling exposure conditions he was able to observe the shape and measure the size of rock temper (>0.0625 mm, i.e. grains down to the size of very fine sand) in sherds of Woodland pottery.

The size, shape and proportions of the particles of temper may be characteristic of clay pastes derived from particular sources or prepared in particular ways, so that these data can be used to assist in the classification of sherds from excavation (Blakely *et al.* 1989, 1992). On the other hand, pots made from the same batch of clay, and particularly sherds derived from the same vessel, will be expected to show less variation in fabric. Thus radiographic examination can be used to identify sherds likely to have belonged originally to the same vessel (Carr 1993).

Xeroradiography was used in a study of some La Tène pottery from the Champagne region of France (Middleton 1995). The pottery from the graves includes a group of distinctive bichrome (red and black) decorated vessels, including the so-called Prunay Vase (Figure 4.6(a)), one of the finest examples of Celtic ceramic art. Previous work (Rigby *et al.* 1989) had shown that these vessels were probably the products of a 'Prunay pottery workshop', characterized by novel techniques of manufacture (see below for discussion of the application of radiography to the investigation of forming techniques)

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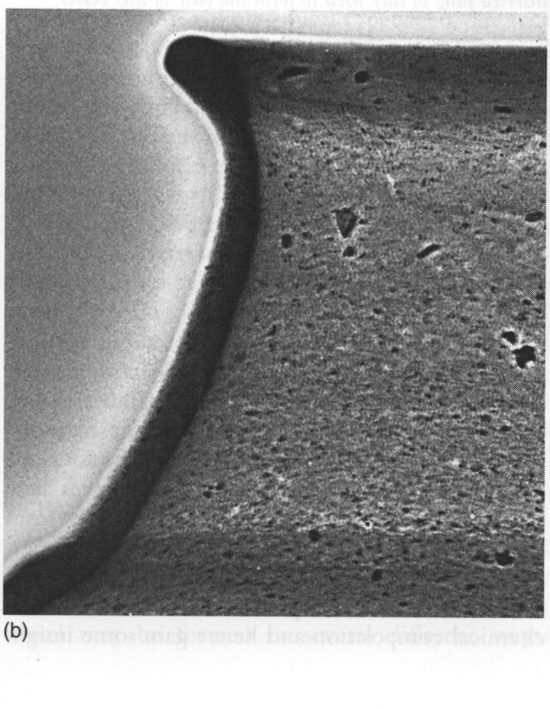

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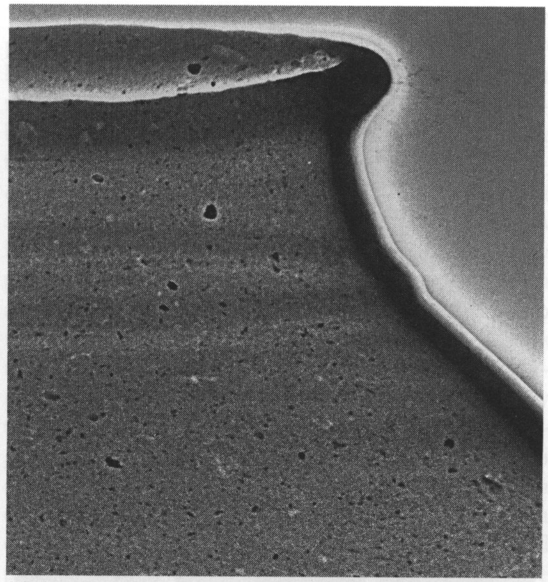

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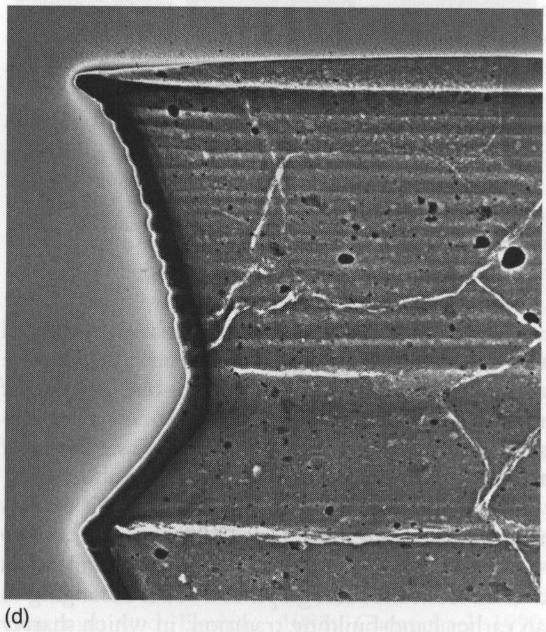

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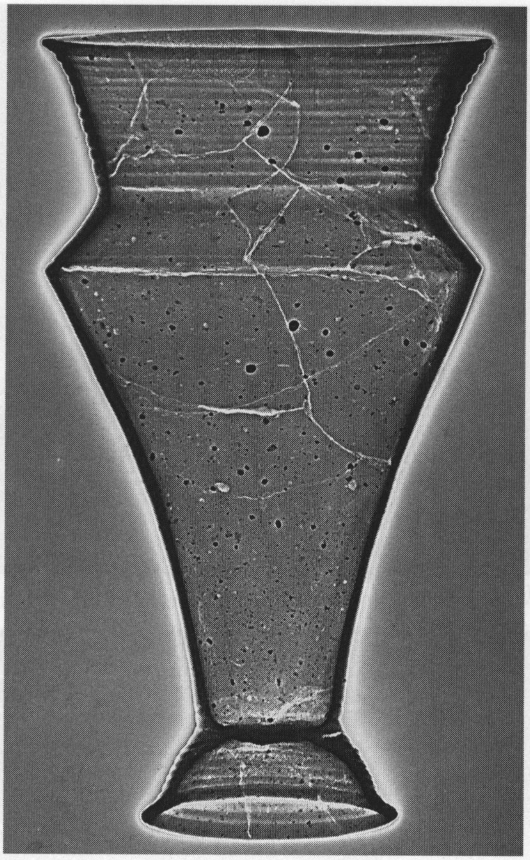
Figure 4.6. *(a) The Prunay Vase, a La Tène funerary vessel from Prunay, Champagne (PRB ML 2734). (b–d) Details from xeroradiographs of some contemporary vessels: (b) PRB ML 2961, from Suippes and (c) PRB ML 2967, no provenance, are both thought to be products of the same workshop as the Prunay Vase; (d) PRB ML 2626, Mesnil, belongs to a different tradition of handmade vessels. Note the similarity in fabric between (b) and (c), and their difference to (d); see text for discussion.*



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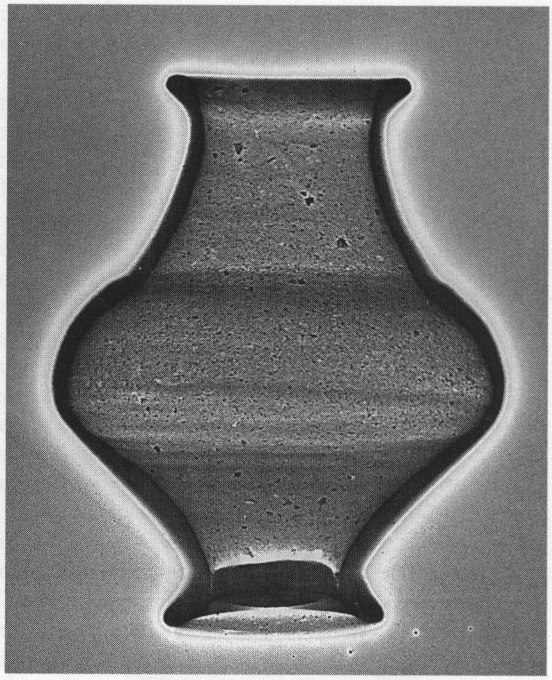

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Figure 4.7. *Xeroradiographs of two of the La Tène vessels from Champagne, illustrating the characteristics of (a) a jar from Mesnil (PRB ML 2626) made in an earlier hand-building tradition and (b) a flask from Suippes (PRB ML 2961) made in the wheel-thrown tradition. Note the inserted plug of clay used to form the base of this vessel.*

and decoration. Macroscopic examination suggested that the vessels were wheel-thrown and that all were made in rather similar sandy fabrics but, because of restrictions on sampling these almost complete vessels, it had been possible to confirm this similarity of fabric for only a few of the decorated vessels.

Xeroradiography was used to confirm the similarity of fabric for a fuller range of vessels (e.g. Figure 4.6(b) and (c). By way of contrast, Figure 4.6(d) shows a detail from the radiograph of a vessel belonging to an earlier hand-building tradition, in which sharply carinated vessels were produced. These macroscopical characteristics are apparent on the radiograph of the complete vessel (Figure 4.7(a)) and contrast with the smooth, S-shaped profiles of the wheel-thrown vessels thought to have been made by the potters of 'Prunay workshop' (Figure 4.7(b)). The clear differences in the textures of the clay pastes used reinforce the concept of an evolution in ceramic techniques, with different pastes being used for hand-building and wheel-throwing. As noted already, rather similar results could now be obtained by digitally processing scanned film radiographs, and excellent images of ceramic fabrics obtained using CT imaging techniques have been obtained by Ghysels (personal communication; see also Mees *et al.* 2003).

Identifying the Inclusions

In the studies described in the previous section, no attempt was made by the researchers to identify the inclusions in the clay pastes. However, it can be seen from many radiographs of ceramic materials (see, e.g. Figure 4.6) that the various inclusions differ in radiographic density. These differences arise in part from differences in size but primarily from differences in composition. Thus, in theory at least, it should be possible to interpret the radiographic densities of different particles in terms of their chemical composition and hence gain some insight into their mineralogical identity. Various attempts to do this have been described, including some early work by Milanesi (1964). Maniatis *et al.* (1984) compared their radiographic observations on sherds from Punic amphorae found at Corinth with results and classifications based upon chemical analysis and petrography. In particular, they noted that radiography highlighted a high concentration of dense inclusions in the group which contained a high proportion of metamorphic rocks and minerals amongst the temper particles. Foster (1985) attempted to provide more precise identifications of particles and used xeroradiography to produce images of a series of prepared clay bodies containing a variety of aplastic inclusions. He showed that most of the coarser particles (detection down to *c.* 0.01 mm was claimed, and even grog (crushed ceramic) could be detected. Often though, detection was based mainly upon the success of xeroradiography in imaging the interface between the inclusions and the clay matrix (i.e. the edge enhancement effect – see Chapter 1 of the first edition of this book for more details), rather than upon the radiographic contrast between inclusion and clay. Thus, whilst Foster (1986) found that the inclusions could be imaged using xeroradiography and their size, shape and frequency assessed, identification was less successful because of the inherent low contrast of the xeroradiographic plate.

The greater contrast available from film offers some advantages for identification, and some progress in distinguishing radiographically between different types of temper was reported by Carr (1990) and subsequently by Carr and Komorowski (1991). The advent of high-resolution scanning and digital processing of images and also the use of CT imaging techniques (Ghysels 2003) offer new opportunities for this type of study, particularly for the three-dimensional (3-D) imaging of textural features (Mees *et al.* 2003). However, it seems likely that the radiographic identification of aplastic inclusions will be restricted mainly to the recognition of broad mineral groups, rather than providing the more precise identification that can be achieved by techniques such as X-ray diffraction or the examination of thin sections using a petrographic microscope (Figure 4.5).

FORMING AND FABRICATION TECHNIQUES

Wet clay is a versatile raw material and a ceramic vessel may be formed in several different ways. These include various techniques in which separate planar elements of clay are 'stuck together' (slab-building); the use of elongate rolls of clay to construct the walls of the vessel (coil-building or ring-building); moulding of slabs of clay, and throwing from a lump of clay on a rotating wheel (for a discussion of the techniques of potting, in the context of archaeological pottery studies, see e.g. Rice 1987). A knowledge of the techniques of construction may provide an indication of the degree of sophistication and organization of the potters, thus contributing to more general studies of craft specialization, as well as to a wider understanding of the history and development of ceramic technology. The use of radiography to investigate pottery-forming techniques was suggested by Shepard (1956, pp. 183–4), and Milanesi (1963) discussed the usefulness of X-radiography, in conjunction with other methods, in the investigation of the technique of manufacture of some excavated pottery. Radiographic and fluoroscopic studies were used by van Beek (1969, pp. 86–9) to confirm the presence of joins between sections of clay in some sherds thought (on the basis of macroscopical examination) to have been made by coiling. Despite some negative results, van Beek concluded that X-ray methods had considerable potential for the non-destructive study of the forming techniques of ancient pottery. However, it was not until the work of Rye (1977, 1981) that this potential was fully realized. Rye drew extensively upon his anthropological observations and pottery collections to establish criteria by which various forming techniques might be characterized. These observations are summarized in Figure 4.8.

Many of Rye's criteria depend upon the recognition of features such as the orientation and disposition of voids and elongate particles of temper, and xeroradiography was particularly well suited to the imaging of these diagnostic features. Thus during the 1980s and 1990s several papers were published describing the use of xeroradiography to determine the forming techniques used to produce archaeological pottery (e.g. Betancourt 1981; Foster 1983; Glanzman 1983; Glanzman and Fleming 1985; Carmichael 1990, 1998; Vandiver and Tumosa 1995). With the demise of xeroradiography, reliance must now be placed upon other techniques. Sometimes these features can be seen directly on film radiographs but often it will be necessary to resort to scanning and digital processing (see Chapter 2).

Pottery-forming techniques are often conveniently divided into so-called primary techniques, meaning those used to transform the formless clay

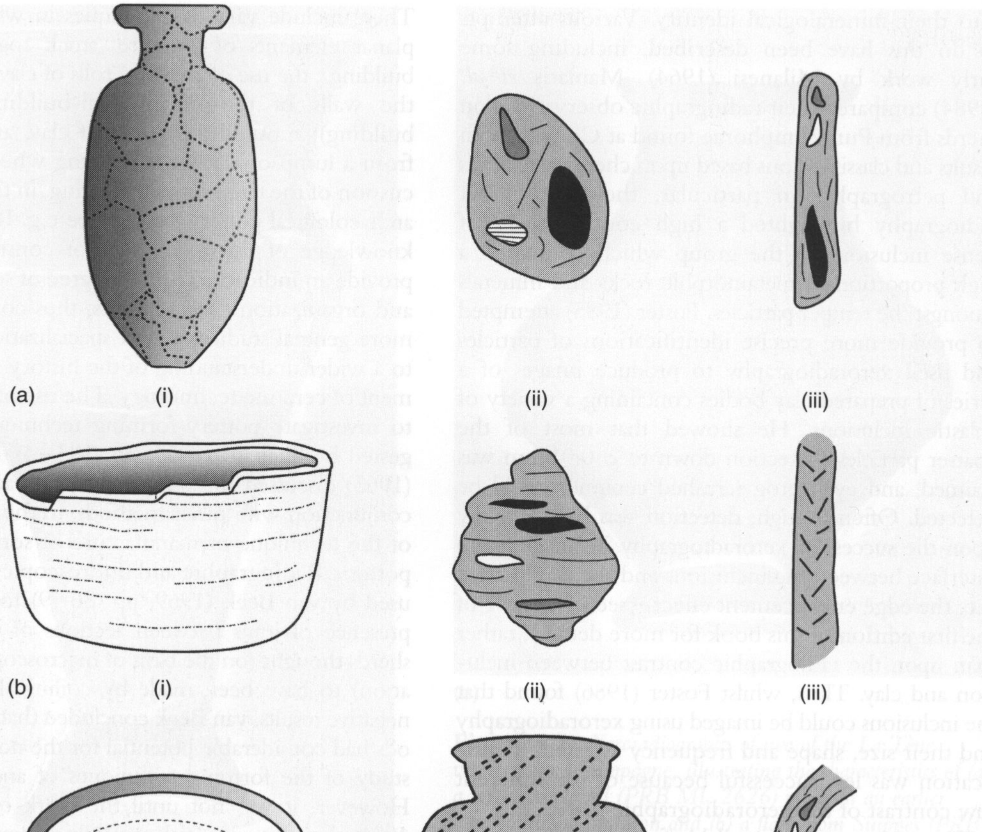


Figure 4.8. *Diagrams illustrating characteristic features of some pottery-forming techniques (redrawn after Rye 1981, Figures 54, 49 and 62). (a) Slab-building: (i) vessel built up from a series of slabs of clay; (ii) random orientation of particles in normal view; (iii) preferred orientation of particles parallel to vessel walls. (b) Coil-building: (i) vessel built up from coils of clay; (ii) preferred orientation of features and coil joins may be seen in normal view; (iii) random orientation of particles in cross section and (c) Wheel-throwing: (i) spiral pattern of grooves and ridges on surface; (ii) oblique arrangement of elongate voids and particles in normal view; (iii) preferred orientation of voids and particles parallel to vessel wall.*

into the basic shape of the vessel, and secondary techniques, meaning those used to modify the basic vessel formed by one of the primary methods (e.g. by thinning or smoothing the walls). A third group of techniques, those used to finish and decorate the vessel, may also be recognized, but these are generally not amenable to radiographic study.

Recognition of Primary-Forming Techniques

Coil-building and Ring-building

The technique of building up a pot from a series of rolls of clay has been widely practised since prehistoric times. The term coil-building or coiling is

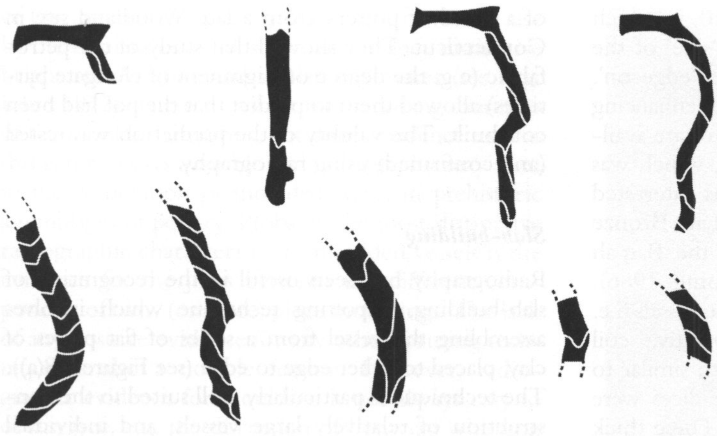


Figure 4.9. *Diagrams showing some methods for joining successive coils or strips of clay (after Scott 1954, figure 227 and Gibson and Woods 1990: figure 11).*

generally applied more particularly when the length of the roll is greater than the circumference of the pot, so that the coil spirals around the vessel wall. Ring-building refers specifically to the use of shorter lengths of clay which pass only once around the circumference. In practice however, it is often impossible to distinguish one technique from the other and they are considered together here. The action of rolling out the clay sometimes imparts a limited degree of preferred orientation to elongate inclusions and voids within the clay (Rye 1977), but only rarely can this texture be recognized in a radiograph.

Usually it is the joins between successive coils, rather than the detailed texture within the coils, that can be observed. Sometimes these joins are visible macroscopically on broken edges of sherds (Figure 4.9; see also, e.g. discussion in Scott 1954; Gibson and Woods 1990). Building upon these observations, Woods (1985) advocated the examination of appropriately orientated petrographic thin sections to permit the recognition of coil joins where they were not visible macroscopically. However, such joins cannot always be observed, even in thin section, and in any case the destructive removal of a slice for preparation as a thin section may be unacceptable. In these circumstances, non-destructive radiographic examination may provide the means by which the diagnostic details can be revealed. For instance, radiographic examination of a Late Bronze Age funerary vessel from Burton Fleming, Yorkshire, revealed that this vessel was coil/ring-built (Figure 4.10). Some joins between the coils are barely visible as roughly horizontal features in regions of the radiograph where the wall of the vessel was approximately parallel to the plane of the radiograph (i.e. perpendicular to the X-ray beam). Such features are,

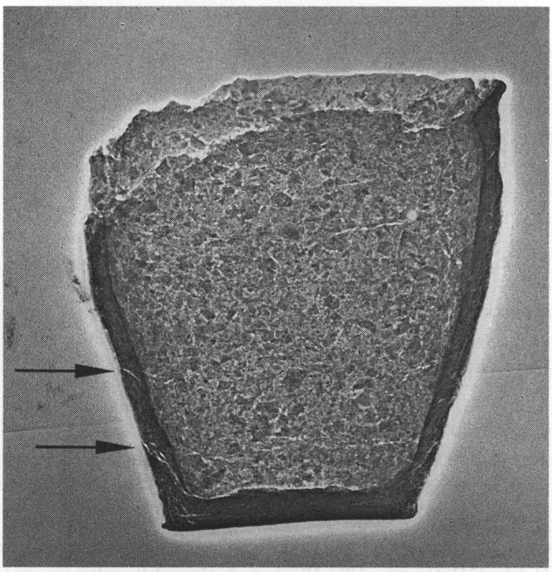


Figure 4.10. *Xeroradiograph of a Late Bronze Age funerary vessel from Burton Fleming, Yorkshire. Some joins between successive coils of clay are visible (arrowed; see text for discussion).*

however, rather diffuse on the radiograph because the coil joins are not strictly planar, are rarely perpendicular to the vessel wall and will vary in their precise orientation around the vessel. Thus, the optimum conditions for imaging the join will not always be fulfilled (see Chapter 1 for further discussion of the imaging of cracks and flaws). The optimum geometry for imaging the coil joins is more likely to be achieved when the wall of the vessel is 'edge-on' in the radiograph (i.e. when the vessel wall is approximately perpendicular to the plane of the radiograph). This can be seen to some extent in Figure 4.10, in which the joins are most easily visible up one 'side' of the vessel (arrowed), where the walls are seen 'edge-on'.

This observation offers the possibility of enhancing the detection of joins where suitable sherds are available, using the 'thick section' approach, which was suggested by Glanzman (1983). He was interested in the techniques used to manufacture Late Bronze Age pottery excavated from tombs in the Baq'ah Valley of Jordan (Glanzman and Fleming 1986). Slices were cut along the vertical axis of the vessels (i.e. approximately perpendicular to any putative coil joins); the slices removed were of a width similar to the thickness of the vessel wall (i.e. the slices were approximately square in cross section). These thick sections were then laid flat with a cut surface parallel to the radiographic plate for exposure. In this orientation the joining surfaces between the coils will be roughly parallel to the direction of the X-ray beam, yielding optimum visibility of the joins in the radiograph (see Figure 1.19). Thus Glanzman was able to produce images in which the joins are more clearly visible than on radiographs taken with the X-ray beam perpendicular to the sherd. However, as for the petrographic approach suggested by Woods (1985), such a destructive approach may not always be acceptable; recording radiographs in several orientations relative to the X-ray beam may sometimes be the only practicable option.

There will be some instances when the present-day observer will be frustrated by the skills of the ancient potter; visible evidence for the coil joins may have been deliberately obliterated by secondary processing (see below), which may also have modified or even removed any radiographic evidence. Van Beek (1969, pp. 88–9) noted this difficulty in his study of South Arabian pre-Islamic pottery and Chapman *et al.* (1988) in their review of xeroradiography and conventional film radiography also commented that coil joins are not always visible in radiographs. In these situations it may be appropriate to carry out detailed micromorphological examination of the clay fabric, using optical microscopical techniques. This approach (together with observation of surface features) was advocated by Courty and Roux (1995) in a study aimed at establishing criteria which could be used to distinguish wheel-thrown vessels from those formed by coiling and subsequently shaped on a wheel (see also Whitbread 1996). Optical microscopy was also used, though in a rather different way, by Philpotts and Wilson (1994) as a part of their comprehensive examination of a sherd of pottery from a late Woodland site in Connecticut. They showed that study of the petrofabric (e.g. the degree of alignment of elongate particles) allowed them to predict that the pot had been coil-built. The validity of the prediction was tested (and confirmed) using radiography.

Slab-building

Radiography has been useful in the recognition of slab-building, a potting technique which involves assembling the vessel from a series of flat pieces of clay, placed together edge to edge (see Figure 4.8(a)). The technique is particularly well suited to the construction of relatively large vessels, and individual slabs may vary in size from a few centimetres to more than 10 cm across. As with coil-building, recognition of the technique depends primarily upon the ability to identify the disposition of the joins between adjacent slabs, thus enabling the observer to 'deconstruct' the vessel into its constituent parts. Betancourt (1981), using xeroradiography, was able to show that Cretan white-on-dark ware vessels were 'built up from slabs of clay up to 10 cm or more wide'. Xeroradiography was also used by Vandiver (1987) in her study of ceramic production technology in West Asia during the 7th to 5th millennia. The xeroradiographs of thick sections, along with radiographs recorded with the X-ray beam perpendicular to the vessel wall, allowed details of the sequential slab technique to be reconstructed. Vandiver's observations on a large number of sherds led her to suggest that this technique of construction had been the dominant forming technique over a large part of West Asia for a period of 3500 years.

Moulding

Open ceramic vessels, such as bowls, can be formed and shaped by pressing clay into or over a mould. The mould may be concave, with the clay being pressed into the interior, or convex, in which case the vessel is formed on the exterior of the mould. Moulds are frequently made from fired ceramic but materials such as plaster, woven baskets and even segments of broken pots may be used. Pottery forms made by moulding may be relatively crude but sophisticated vessels can also be produced. The use of moulds offers the advantage that once the original mould has been made by the master potter, high-quality pots can be produced quickly and efficiently by relatively unskilled artisans. A well-known example of this approach to pottery manufacture was the use by the Romans of moulds to mass-produce distinctive bright red Arretine and samian tablewares (see, e.g. Johns 1977). There are sometimes surviving examples of the moulds themselves, but direct evidence such as this is not always available and radiography may assist in the recognition of moulded wares in prehistoric assemblages of pottery. Probably the most distinctive radiographic characteristic of moulded vessels is the evidence for the joins between the different components of two- (or more) piece mouldings. The lack of any positive evidence for any other forming technique is also a notable feature. However, radiographic evidence for moulding is not always easy to obtain (see, e.g. the discussion of Peruvian whistling pots below) and straightforward visual assessment may be more appropriate.

Wheel-throwing

The use of a potter's wheel allows clay vessels to be formed very rapidly and efficiently. For successful throwing the wheel must rotate continuously at a relatively high speed: various minimum rates of rotation have been indicated but Rye (1981) refers to the need for speeds of the order of 50 to 150 rpm. Due to this requirement for continuous high-speed rotation, the potter's wheel is sometimes termed the fast wheel. This serves to distinguish it from turntable devices, often referred to as tournettes, which are rotated discontinuously, although not necessarily at low speed. As the rotation of the tournette is discontinuous and the device lacks the momentum of a true potter's wheel it does not provide the sustained energy necessary to enable the clay to be thrown. Thus tournettes and turntables are generally used as an aid to other primary-forming techniques such as coiling, and to facilitate the finishing and decorating of pottery vessels (see, e.g. Rice 1987, pp. 132–5).

The action of raising the walls of the vessels during the throwing process imparts a characteristic oblique orientation to elongate inclusions and voids in the clay paste (see Figure 4.8(c)). The inclusions are drawn out in a spiral pattern, which rises up and around the walls of the vessel; the handedness of the spiral even reveals the direction of rotation of the wheel, although any reversal of the image due to the recording or photographic printing process must be taken into account. Rye (1977, p. 208) noted this and also suggested that as the speed of rotation of the wheel and the speed of raising the vessel increased, so did the steepness of the spiral; in radiographs, this is reflected

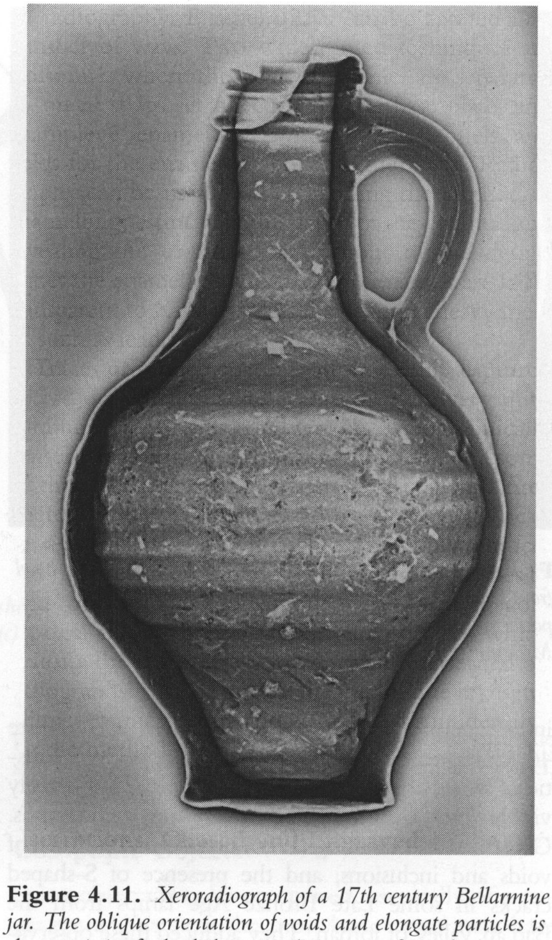


Figure 4.11. *Xeroradiograph of a 17th century Bellarmine jar. The oblique orientation of voids and elongate particles is characteristic of wheel-throwing (Museum of London).*

in the angle to the horizontal of the elongate features. The oblique orientation of elongate features can be seen very clearly in the radiograph of a 17th century Bellarmine jar (Figure 4.11). Since this radiograph shows the superimposed textures from both the front and the back of the jar the oblique features arising from opposite sides give rise to a cross-hatched pattern (particularly noticeable on the neck region).

Radiographic evidence for wheel-throwing may also be seen in radiographs taken with the X-ray beam directed vertically down through shallow open vessels. Vandiver (1986) published several xeroradiographs showing spiral patterns of voids in some Egyptian vessels thought to have been thrown on a wheel. Figure 4.12 shows the xeroradiograph of a Late Bronze Age bowl from Lachish, in which a very clear spiral pattern of voids can be seen (Magrill and Middleton, 2004). Further evidence for wheel-throwing may also be seen

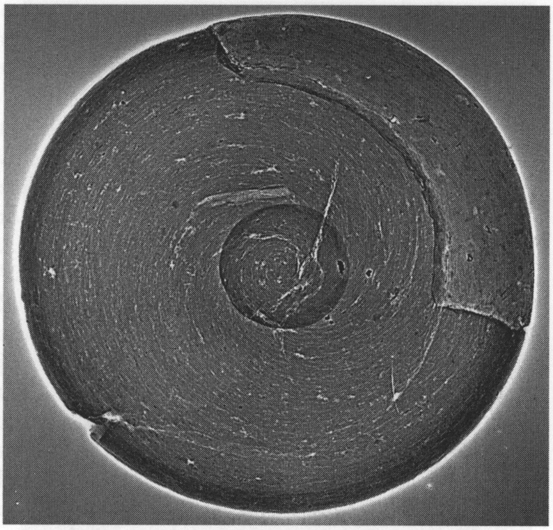


Figure 4.12. *Xeroradiograph of a Late Bronze Age bowl from Lachish, Israel (viewed from above) showing spiral patterning, characteristic of wheel-throwing (Oriental Museum, University of Durham, GM 1964–262.).*

in radiographs of the bases of vessels. Rye (1981, figure 46) illustrated examples of S-shaped cracks characteristic of wheel-thrown vessels; these are not always easily visible but may often be seen on radiographs. Glanzman and Fleming (1986) noted spiral patterns of voids and inclusions, and the presence of S-shaped cracks in some Late Bronze Age lamps from the Baq'ah Valley of Jordan. They adduced these observations as evidence that the bowls were thrown on a potter's wheel.

Recognition of Secondary Processing

The unfired vessel is often subject to secondary processing, in order to modify such properties as surface appearance, wall thickness and porosity. These secondary processes, which include operations such as beating, scraping, trimming and turning, are discussed fully by Rye (1981) and also by Rice (1987). In many instances these processes obscure or modify both the visual and the radiographic features which are characteristic of the primary-forming technique; they may also generate a new set of distinctive features (see Rye 1981). Many of the effects of these secondary processes are best identified by visual observation but a commonly used secondary-forming technique which can be recognized radiographically is the so-called 'paddle and anvil' technique. This process is used to thin and shape the vessel walls: it involves beating one surface (usually the exterior of the vessel) with the paddle, whilst the wall of the vessel is supported from the inside using a smooth tool such as a pebble. This causes local distortion of the clay wall between the paddle and the anvil (see Figure 4.13), which is reflected in a characteristic patterning on the radiograph (see Figure 4.3; see also Vandiver 1988, figure 12). Paddling is typically employed on vessels made by coiling as a means of smoothing the surface and strengthening the bonds between adjacent coils of clay. However, the technique can be applied to any vessel, even those thrown on a wheel (see Rye and Evans 1976, plate 26) and it is important to establish what came before the paddle and anvil treatment, if the production process is to be understood fully (Cort *et al.* 1997). The Vietnamese water transport jar, shown in Figure 4.3, is thought to have been formed from a cylinder of clay made by joining the two narrow ends of a rectangular slab of clay; the final shape of the bulbous body of the jar would have been achieved using paddle and anvil (Cort personal communication).

'Hybrid' Vessels

The various primary-forming methods each present to the potter their own set of advantages and limitations. Hand-building techniques are generally rather slow and laborious but very well suited to the transformation of slabs or coils of coarsely tempered clays into relatively large vessels with round bases (i.e. including vessels which will meet the technical requirements to be used over open fires as cooking pots). Wheel-throwing, on the other hand, provides a very fast and efficient method for dealing with more finely tempered clays. It is not possible, however, to throw a vessel with a rounded base; it is necessary instead to use a two-stage process, perhaps involving the modification of the original vessel by one of the secondary processes mentioned above. Alternatively, the potter may choose to combine two (or more) of the primary-forming techniques. A modern example of this approach from the Northwest Frontier of Pakistan is illustrated by Rye (1981, figure 66). The rounded base of the vessel illustrated was made by moulding but the walls and rim were wheel-thrown. A similar approach appears to have been used in the manufacture of the medieval cooking pot, a xeroradiograph of which is shown as

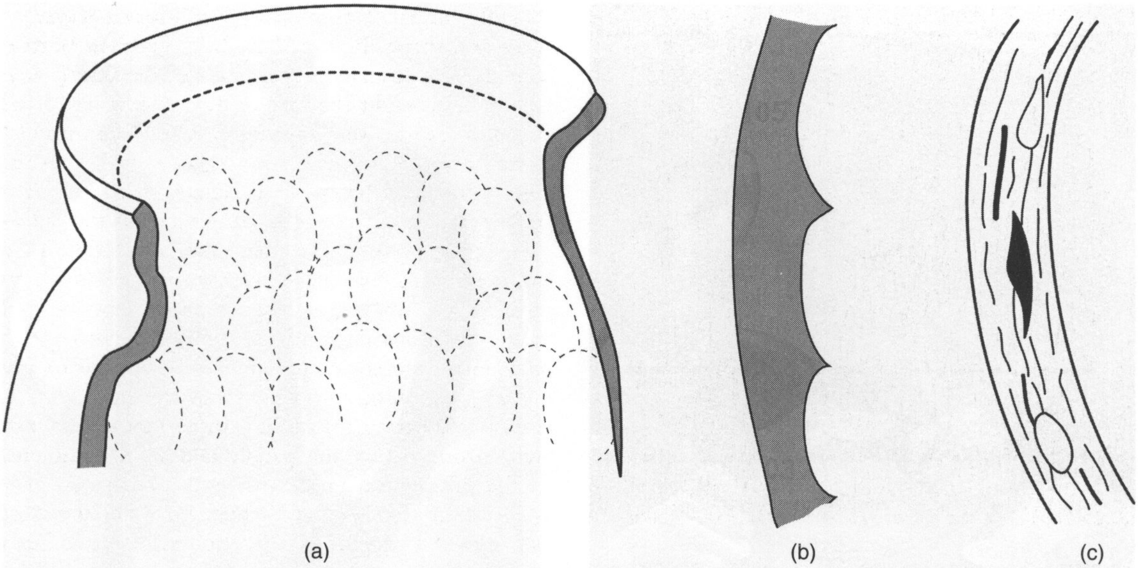


Figure 4.13. *Diagram illustrating some features arising from the use of the 'paddle and anvil' technique: (a) depressions on the interior of the vessel; (b) variations in wall thickness and (c) preferred orientation of particles parallel to vessel walls (after Rye 1981, Figure 70).*

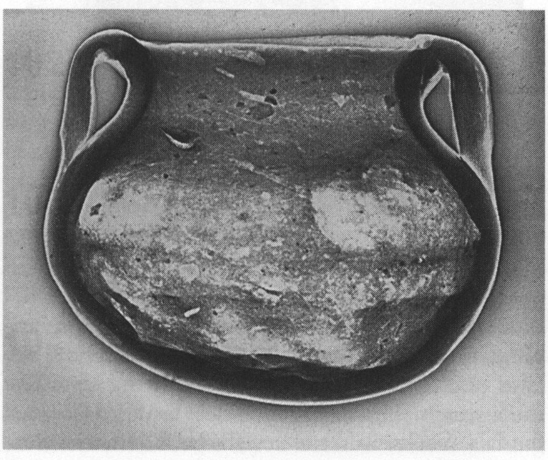


Figure 4.14. *Xeroradiograph of a medieval cooking pot. The lower part of the vessel appears to have been hand-made, perhaps with the aid of a mould, whilst the upper wall and rim were wheel-thrown (note the oblique orientation of the voids) (Museum of London).*

Figure 4.14. The base and lower part were made by hand-shaping a slab of clay (possibly with the aid of a simple mould), but the presence of characteristically orientated voids in the upper part of the vessel suggests that the walls and rim were wheel-thrown, presumably to take advantage of the greater ease and speed of producing a well-finished rim on the wheel.

Composite Objects

Some objects may be comprised essentially of a single entity but even the most basic vessel may have additional added elements such as a spout or handles. Such features may be affixed simply by sticking them to the pre-formed clay body, using a slurry of clay and water as the 'glue'. This process, often termed luting, is typically carried out at the so-called leather-hard stage, once the clay body has partially dried and acquired some inherent strength. The radiograph in Figure 4.11 clearly shows that the handles of the Bellarmine jar were simply luted onto the body of the jar, in exactly the manner used by the modern potter shown in Figure 4.15. In order to achieve a stronger bond, the handle or spout is sometimes inserted through the wall of the vessel; use of this technique to secure the lower end of the handle of a medieval drinking vessel is apparent in the radiograph shown as Figure 4.16. The upper end of the handle was probably also inserted through the wall but, because this joint was more easily accessible to the potter, it was possible to effectively smooth over the join. The characteristic cross hatching arising from

Figure 4.15. *Luting the strap handles onto a modern replica of a Bronze Age stirrup jar (courtesy of Veronica Newman).*

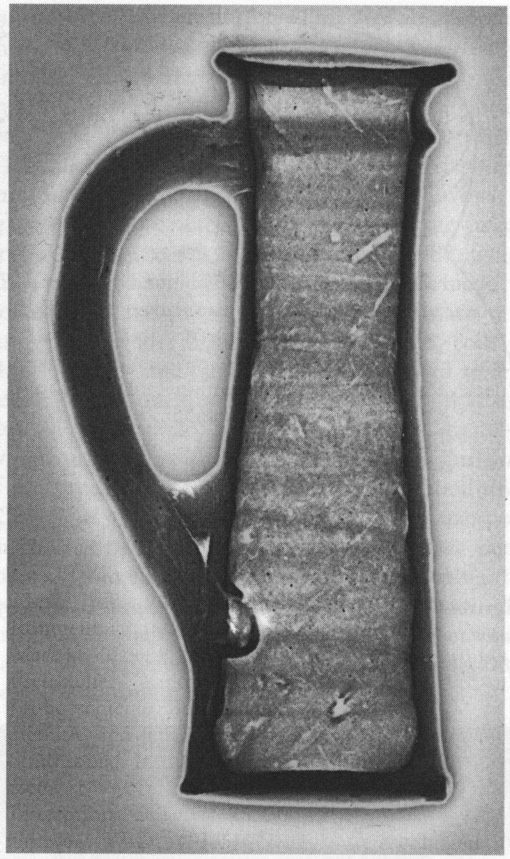


Figure 4.16. *Xeroradiograph of a late 13th to early 14th century AD drinking vessel, revealing evidence for wheel-throwing and method of affixing the handle (see text for discussion) (Museum of London).*

wheel-throwing is also apparent in this radiograph. Bases also may be modified or strengthened by the application of additional patches of clay (see, e.g. Glanzman and Fleming 1986) or even added separately: the xeroradiograph of the flask from Suippes (Figure 4.7(b)) shows that the base of this vessel is formed by a separate plug of clay, inserted into one end of a hollow sinuous cylinder.

Radiography can also contribute to the understanding of more complex vessels. An example is provided by a study of the manufacture of Late Bronze Age stirrup jars. These vessels are one of the most distinctive forms used by the Bronze Age cultures of the Aegean world. They are characterized by a central or false (i.e. non-functional) neck which is capped by a disc from which spring the two strap handles; the true, pouring spout is offset on the shoulder of the globular body (Figure 4.17). In a study designed to investigate the cultural identity of the potters who made stirrup jars found at Tell es-Sa'idiyeh in Jordan (Leonard *et al.* 1993), xeroradiography was used to investigate the techniques for making and assembling the various components (i.e. the body, the false neck, the handles and the pouring spout) of these vessels. The main differences found concerned the false necks: in some vessels the false necks were found to be hollow, in others the central false neck is seen on the radiographs to be solid (Figure 4.18). The hollow false necks appear to be integral with the globular bodies of the jars, and it seems that these stirrup jars were derived from a traditional globular jar, which had a central pouring spout: a disc and strap handles were added (effectively blocking the original pouring spout), and a new functional spout was added on the shoulder of the vessel. The solid false necks appear to have been made separately and to have been luted onto the globular body, suggesting a bespoke design not derived from any pre-existing form.

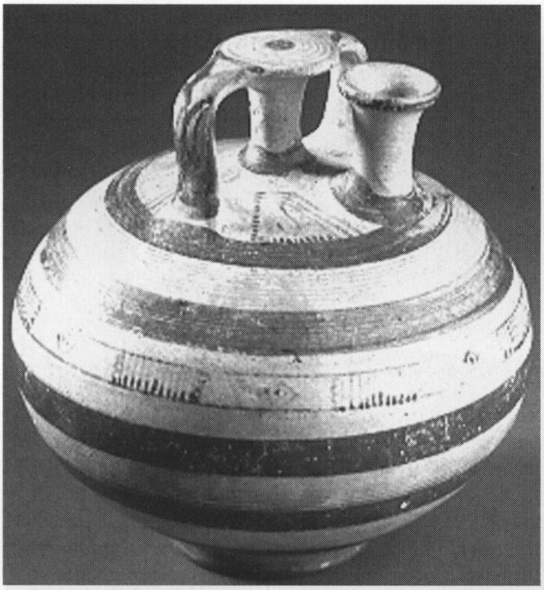
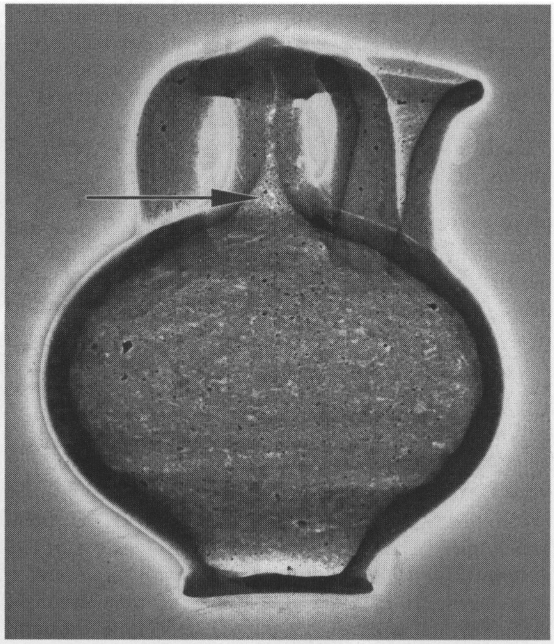
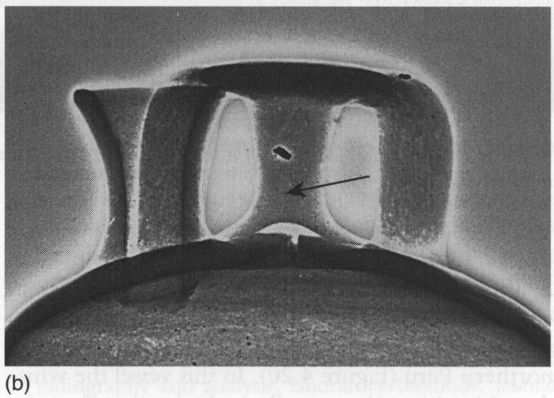


Figure 4.17. *Late Bronze Age stirrup jar from Ialysos, Rhodes (GR 1870-10-8.89).*



(a)



(b)

Figure 4.18. *Xeroradiographs of Late Bronze Age stirrup jars. (a) Excavated at Tell es-Sa'idiyeh in the Jordan Valley (WA 1986-6-23.71): note the hollow false neck and (b) Found at Gurob, Egypt (GR 1890–11-7.1): note the solid false neck.*

Figure 4.19 shows a xeroradiograph of a 13th to 14th century aquamanile (Nenk and Walker 1991). Careful examination of the object itself and the xeroradiograph suggested that the cylindrical body of the vessel was made by coiling, the chief technique of the Lyveden-Stanion workshops in Northamptonshire, where the vessel is thought to have been made. Details of the attachment of the filling spout, the handle and legs are also visible on the radiograph. However, this object presented a particular problem, the effects of which are apparent on the radiograph – the presence over most of the outside surface of a lead-rich decorative glaze. This has a relatively high X-ray absorption, which leads to some obscuration of internal structure by a surface texture arising from variations in the thickness of the glaze.

The Moche style whistling pot from northern Peru (Plate 4.1) also deserves mention in this discussion of composite vessels. Moche style pottery was made between about BC 100 and AD 700 (Donnan 1992; see also McEwan 1997) and the Moche potters developed the art of moulding to a high degree, manufacturing a range of vessels including the spouted bottles examined by Digby and Plenderleith (mentioned earlier in this chapter), and whistling pots such as this example. The xeroradiograph reproduced as Plate 4.1(b) clearly shows the complexity of this vessel, which must have been made in several pieces, each separately moulded. Radiographic evidence for joins is rather limited but the joins between the blowing tube and the main body of the macaw can be seen in the radiograph; additional clay appears to have been added to smooth and strengthen the exterior of each join. The whistle

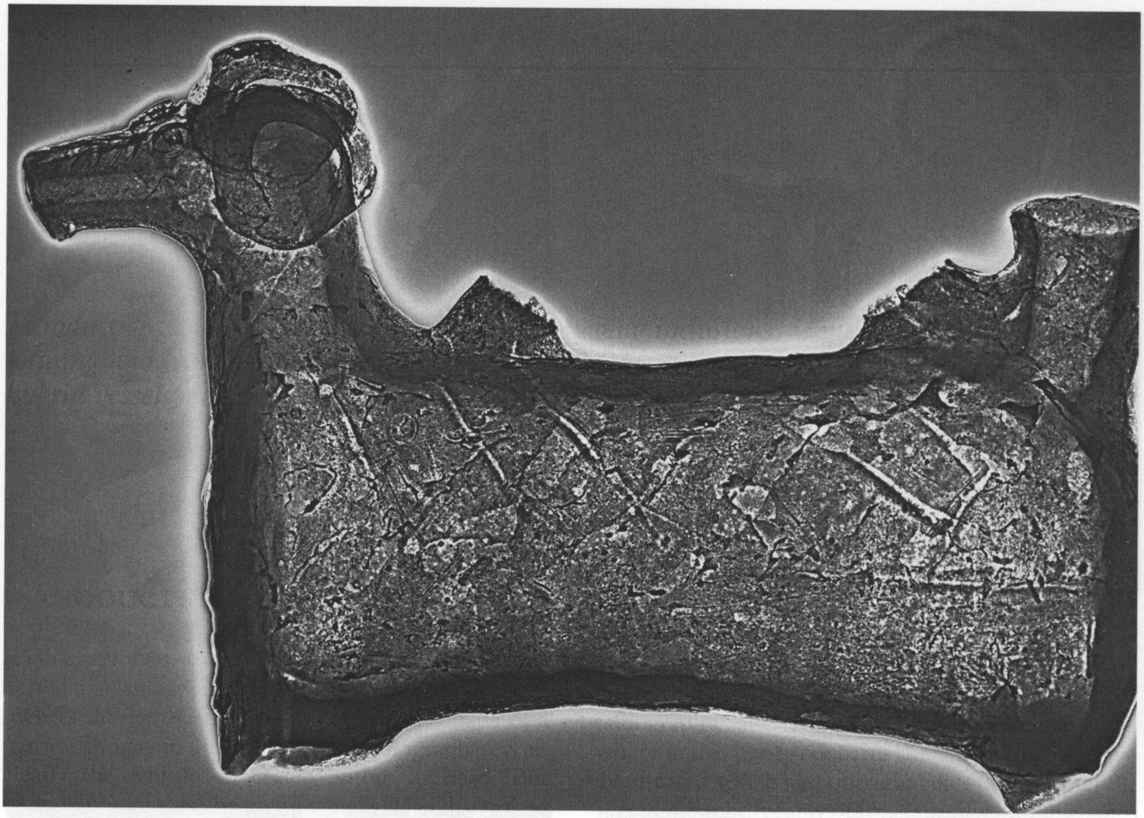


Figure 4.19. *Xeroradiograph of a medieval aquamanile, thought to have been made by coiling. Note the obscuring effect of the lead glaze (ML 1984-6-3.1).*

can be seen within the hollow head of the macaw. A very different technique for joining the various components can be seen in the radiograph of a Chimu style double-chambered whistling pot, also from northern Peru (Figure 4.20). In this vessel the whistle was positioned externally to the head, and can be seen embedded in the strap handle.

PROSPECTS

Microfocus X-ray tubes offering much sharper, high-resolution images and the possibility of the useful magnification of X-ray images, have been applied to modern ceramic materials (see, e.g. Camanzi *et al.* 1992 and De Meester *et al.* 1992). Used in this way, radiography can be applied as a low power X-ray microscope to examine non-destructively the internal microstructure of ceramic materials. High-resolution films and plates, tomography (especially computed tomography), direct digital radiography and the use of photo-sensitive phosphors have all been applied to ceramics. Real-time viewing techniques using image intensifiers to produce an image which is then captured by a television camera for display on a remote monitor have also been used. Some of these techniques are considered more fully in Chapter 2, along with the possibilities for post-capture enhancement and processing of images. The application of digital techniques and their particular advantages and disadvantages for the examination of archaeological ceramics were considered by Carr and Riddick (1990) and by Vandiver and her colleagues in 1991. At that time it was apparent that the use of digital methods suffered from a rather severe loss of resolution relative to analogue techniques such as film and xeroradiography. However, as has been indicated earlier in this chapter and discussed more fully in Chapter 2, digital techniques are now more developed and offer considerable potential (O'Connor and

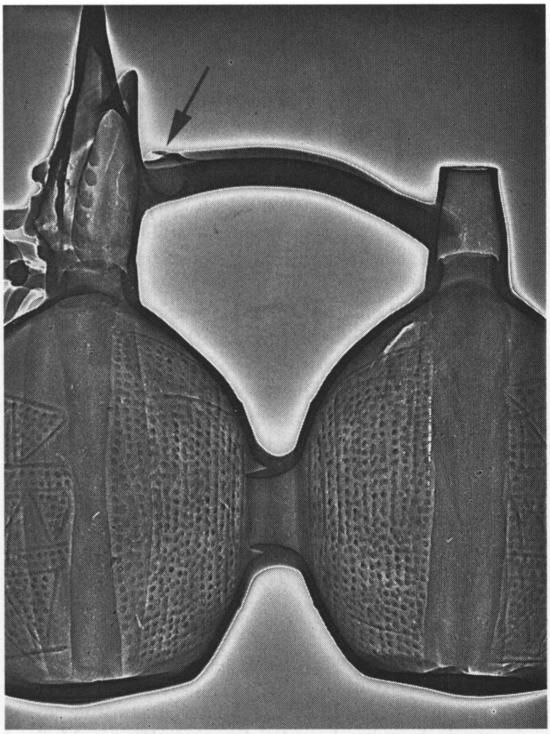


Figure 4.20. *Xeroradiograph of a Peruvian Chimu style double-chambered whistling pot. The radiograph reveals how the various elements were joined together and also the location of the 'whistle', embedded within the handle, close to the head of the figure (arrowed) (ETH 1921-10-27.119).*

Maher 2001; O'Connor *et al.* 2002). Applications to ceramic materials include that published by Pierret *et al.* (1996), who suggest that such an approach offers the possibility of providing quantitative information on sherd wall thickness and porosity. These data can then be used to distinguish not just the various primary-forming techniques, but also more subtle differences in technique, such as coiling combined with shaping on a wheel, coiling with subsequent shaping and thinning on a wheel, and wheel-throwing. As the authors point out, this approach offers a relatively rapid, straightforward and lower cost analysis when compared with the application of CT methods. Although the quality of CT imaging may sometimes justify its cost for particular purposes (Ghysels 2003), it seems likely that conventional film-based techniques, complemented increasingly by scanning and digital processing, will continue to be used widely for the routine examination of archaeological ceramics.

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