

Looking through pots: recent advances in ceramics X-radiography

Ina Berg*

Archaeology, School of Arts, Histories and Cultures, University of Manchester, Oxford Road, Manchester M13 9PL, UK

Received 26 April 2007; received in revised form 13 August 2007; accepted 21 August 2007

Abstract

From its first application to ceramics, X-radiography has been used successfully to identify manufacturing details. While many of the key parameters are well understood, several questions require further analysis. These include the radiographic distinction between wheel-thrown and wheel-shaped pots and an assessment of the impact of secondary forming techniques and surface treatments on inclusion orientation laid down during primary forming. To clarify these issues, controlled experiments were conducted. Results indicate that coiled and wheel-shaped vessels can be distinguished radiographically from fully wheel-thrown ones. As regards secondary forming and surface treatments, none of those investigated could be shown to obscure traces of primary forming techniques. Overall, X-radiography is shown to be a valuable tool for understanding forming techniques and sequences of ancient vessels. Assessing X-radiography's contribution in characterising clay fabrics, experiments were conducted with regard to clay body and inclusion visibility. These experiments support Foster's conclusions [Foster, G.V., 1985. Identification of inclusions in ceramic artefacts by xeroradiography. *Journal of Field Archaeology* 12, 373–376].

© 2007 Elsevier Ltd. All rights reserved.

Keywords: X-radiography; Ceramics; Primary forming techniques; Secondary forming techniques; Surface treatments; Wheel-throwing; Wheel-shaping; Experimental archaeology

1. Radiography of ceramics

When in 1895 Wilhelm Röntgen discovered X-rays, this opened up a new way for people to 'look through things' (Röntgen, 1896). Since its invention, the technique has become an invaluable tool for conservators and researchers alike, and has been applied to a great variety of materials, such as 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 back to 1930's when Titterton published a radiograph of seven sherds from North American Indian burials in order to illustrate differential proportions of inclusions (1935). A decade later, Digby employed the technique to investigate a defect in the construction of a Peruvian stirrup-handled pot

(1948; cf. also McEwan, 1997). However, it was only in 1977, with the publication of a seminal paper by Rye, that the potential of X-radiography for ceramics was fully appreciated (see also Rye, 1981). A comprehensive summary of the technique and its application to ceramics was published in this very journal by Carr and his colleague (Carr, 1990; Carr and Riddick, 1990). However, the demise of xeroradiography in the late 1990 led to a noticeable interruption in research activity. It is only now, with a better appreciation of the power of imaging software programmes, that X-radiographic research into ceramics is gaining momentum again. Once digitised, features can be enhanced in visibility, measured, clarified and colour coded, while images can be easily magnified, sharpened and background scatter removed by utilising readily available imaging software programmes (Lang et al., 2005; O'Connor and Maher, 2001; O'Connor et al., 2002).

From its first application to ceramics, the technique was mainly used for two purposes: (1) to characterise clay fabrics through inclusion or tempers and (2) to identify manufacturing details (Carr, 1990).

* Tel.: +44 161 275 7753; fax: +44 161 275 3331.

E-mail address: ina.berg@manchester.ac.uk

1.1. Characterising clay fabrics

Under the right conditions, X-radiographs can be used successfully to characterise clay fabrics by determining 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, morphology of the particles, and presence, number and angle of crystal faces. More specific attribution of minerals is often problematic, especially when compounds have a similar chemical composition and exhibit similar morphology and radiodensities (e.g. chert, quartz, pure sandstone) (Carr and Komorowski, 1991). In contrast, organic inclusions (such as straw, wood, sponge, insects, seeds, shell) and the voids left by them are easily recognisable, while grog is most visible when it is of different clay from the surrounding clay body (Foster, 1985). Once particles have been characterised, their volumetric proportion and (size) distribution within the vessel can be measured and used to determine fabric groups (Blakely et al., 1989, 1992; Braun, 1982; Foster, 1985; Maniatis et al., 1984; Rye, 1977). However, success of this application is variable as Adan-Bayewitz and Wieder (1992) have shown and depends on the fabric(s) under investigation; it therefore seems most prudent to consider radiography as a suitable complementary tool rather than as a replacement of petrography and chemical analyses. Alternatively, X-rays have been employed to identify sherds within a small assemblage that belong to the same vessel (Carr, 1990, 1993).

1.2. Identifying vessel formation procedures

Since its first application by van Beek (1969), X-radiography has established itself as a powerful technique for the identification of primary forming methods, in particular, pinching, drawing, coil-building, slab-building, moulding and wheel-throwing. It was Rye who first recognised that “the application of pressure to plastic clay causes mineral particles, voids and organic fragments to take up a preferred orientation” which will affect the whole clay body. The resulting alignment and distribution of inclusions as well as shape and orientation of voids is characteristic of each forming method and will not normally be obliterated by secondary forming or decoration procedures (Rye, 1977: 206; Rye, 1981) (Fig. 1). Many scholars have employed radiography successfully (e.g. Carmichael, 1990, 1998; Ellingson et al., 1988; Foster, 1983; Henrickson, 1991; Levi, 1999; Nenck and Walker, 1991; Philpotts and Wilson, 1994; van Beek, 1969; Vandiver et al., 1991; Vandiver and Tumosa, 1995), but the two most detailed case studies were undertaken by scholars working in the Near East (Glanzman, 1983; Glanzman and Fleming, 1986; Vandiver, 1987, 1988). Some of the more intriguing case studies have utilised 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 difficult to verify, because

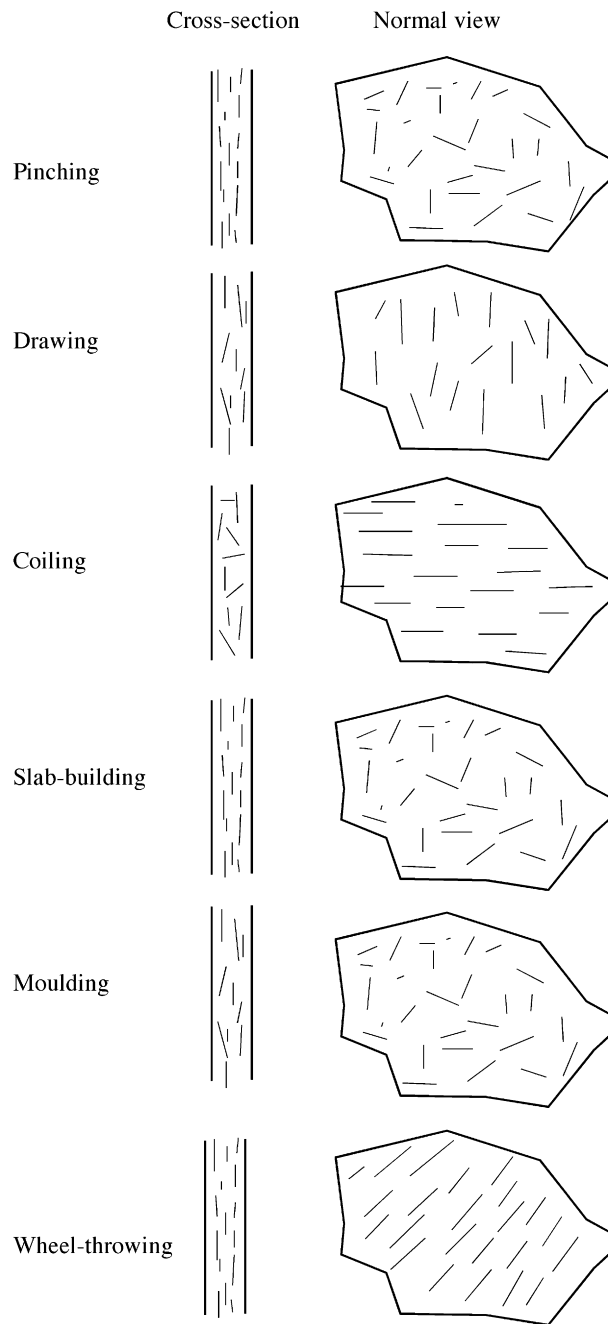


Fig. 1. Characteristic features of the main pottery forming techniques (after Carr, 1990: figure 1; Rye, 1981; Middleton, 1995: figure 4.8).

they do not generally involve severe modification of the clay that would be reflected in an X-radiograph. They are therefore best identified by visual observation. The exception to the rule is the paddle and anvil techniques (Rye, 1981).

Despite thirty years of ceramic radiography, several questions still remain unanswered. These issues include the visibility of secondary forming techniques/surface treatments and their impact on the primary forming, the distinction between wheel-throwing and wheel-shaping and the question of whether the speed of lifting whilst wheel-throwing a vessel can be correlated with the angle of the diagonally oriented inclusions. Experiments were thus designed to address this gap

Table 1
Experimental variables

Clay types	Tempering materials	Primary forming techniques	Secondary forming techniques	Surface treatments
Buff stoneware 1117M	Marble	Pinching	Scraping	Burnishing
Garden terracotta P3150	Granite	Moulding	Turning	Self-slipped
	Quartz	Coiling	Knife-trimming	Wet-smoothed
	Sand	Slab-building	Paddle and anvil	
	Grog	Coiling and wheel-shaping		
	Shell (-sand)	Wheel-throwing		
	Straw			

in our data. Finally, visual evidence will be presented that supports Rye's hypothesised alignment of inclusions in coils.

2. Method

Two potters specialising in hand-building and wheel-throwing respectively produced a range of open and closed shapes (101 vessels in total) using different primary and secondary forming techniques. The precise manufacturing sequence for each vessel was recorded. As modern processed clays are homogenous and finely levigated, particles of different radiodensity to clay were added as tempering materials. Sieving insured that the particles were between 1 and 2 mm in size and represented 5% to 10% of the clay weight. When leather-hard, most vessels were cut in half. Side A remained untreated, while Side B underwent some kind of secondary forming or surface treatment (Table 1). The vessels were subsequently fired in modern electric kilns at temperatures between 780 and 1100 °C. Sixty-nine of the pots were X-rayed at Bodcote in Burton-on-Trent using an industrial Philips 320 X-ray machine with a 2.47 mm focal spot at 1 m focus-to-film distance and at 5 mA. Agfa Structurix D4 industrial film, placed in a plastic cassette without screens or filters, was used in conjunction with an automatic processor (Agfa G135 Developer and Agfa G335 Fixer for 8 min at 32 °C). The remaining 32 pots were X-rayed at the University of Bradford using a Faxitron double cabinet X-ray machine, model 43855, with a 0.5 mm focal spot¹ and 60 cm focus-to-film distance and at 3 mA. Again the film used was Agfa Structurix D4 which was placed into a plastic cassette. In all cases, the aim was to produce high contrast, high definition images by keeping the beam energy as low as possible without reducing exposure latitude so far that this created areas of over and under exposure as result of thickness variation in the ceramic product (Table 2). The film was processed manually (using an Agfa G128 Developer and Agfa G328 Fixer at 20 °C and washed for 15 min to enhance archival stability). The resulting radiographic film images are negative images where radio-opaque components appear lighter than more radio-lucent components; the background colour is black where the film has been fully exposed to the X-ray beam.

Digitisation of the images took place at the University of Bradford using their Agfa FS50B industrial radiographic film scanner. The images were stored as 12-bit TIFF and lossless JPEG files. Advanced filters (e.g. unsharp mask) and edge detection kernels (e.g. Kirsch) available in imaging software programmes (e.g. Photoshop) were applied enhancing the visibility of even the small details. Once radiographic film images have been digitised, it is an easy matter to transform them to positive images. This can make features more noticeable and easier to interpret as the densest components and thickest areas will appear darkest.

3. Results and discussion

3.1. Primary forming techniques

X-radiography is an important tool in understanding primary forming techniques. This is because X-rays detect the internal structure and orientation of inclusions as laid down during the primary forming. Visual inspection by specialists, on the other hand, will focus on those features visible on the surface and often represent secondary forming and surface treatments which may have obliterated traces of the original shaping procedures. The criteria for identifying pinching, coil- and ring-building, slab-building, drawing, moulding and wheel-throwing were established by Rye (1977, 1981) and are based on the orientation of voids and elongated temper particles (Fig. 1). Subsequent research has not been able to add any more details and the criteria have remained the foundation of X-radiography investigations of vessel forming techniques. However, it should be noted that—despite the best possible X-ray procedure, X-ray machine, and digitiser—the investigator will not always be able to identify the forming technique or sequence of a vessel. Based on my own experiments (also personal communications with J. Ambers), a success rate of between 60% and 80% can normally be expected dependent upon the particulars of the inclusions (material, form, size), the forming technique utilised, and vessels thickness. Under these circumstances, and in particular when slab-building or coiling is suspected, a thick section might provide further clues (Glanzman, 1983; Glanzman and Fleming, 1986; Vandiver, 1987, 1991).

One issue which Rye considered but did not provide evidence for is whether the speed of the lifting action during wheel-throwing can be deduced from the angle of the diagonal inclusions (Rye, 1977: 208). He argued that a smaller angle of 20–30° reflects a slow lifting of the vessel wall, while an angle

¹ Due to unavoidable circumstances, two different X-ray units had to be used in these experiments. The machine in Burton had a rather coarse 2.47 mm focal spot and, wherever possible, a smaller focal spot should be utilised in experiments to obtain the sharpest images.

Table 2

Exposure times and kV for clay objects using a Faxitron Cabinet X-ray machine with a 0.5 mm focal spot and 60 cm focus-to-film distance and at 3 mA

Clay thickness (mm)	55 kV	70 kV
19		150 s
18		150 s
17		150 s
16		120 s/150 s
15		120 s/150 s
14		105 s/120 s
13		105 s/120 s
12		90 s/105 s/120 s
11	120 s	90 s/105 s/120 s
10	105 s/120 s	90 s
9	105 s/120 s	90 s
8	105 s/120 s	90 s
7	90 s/105 s	
6	90 s/105 s	
5	75 s/90 s	
4	75 s/90 s	
3	75 s	

The kV shown here only present a guide; radiographs should always be taken using the lowest possible kV to improve image contrast.

of 45° is representative of a fast lifting action. Experiments were thus conducted that required the potter to throw the same shape quickly and slowly (Fig. 2). Our analysis has demonstrated that such an equation between angle and speed of lifting is too simplistic for the potting process. When comparing some randomly selected angles, it becomes apparent that small and large angles can be found in both slowly and quickly lifted

vessels and might even sit comfortably side-by-side at the same height. Surprisingly, some angles are greater in the slowly lifted pot possibly because of remedial or repeat actions by the potter. Since potters vary their speed during the throwing process and continue to rework vessels on the wheel until the final desired shape has been reached, the orientation of inclusions and voids should not be taken as a direct indicator of speed, but their presence merely as evidence of wheel-throwing. At this point experiments have not actually disproved that the inclusion angle is related to speed of the lifting action; in fact, it might even be a very sensitive indicator and further experiments might reveal further information. However, since potters do not generally throw vessels at one speed, in one movement, without any remedial or repeat action, the meaning that can be attached to any angle patterning remains fuzzy.

3.2. Wheel-made vs. wheel-shaped

Pottery specialists commonly classify vessels as either wheel-made or handmade vessels based on distinct surface features. However, anthropological case studies have shown that this binary classification is a modern construct and does not reflect past reality (Blandino, 2003; Bresenham, 1985; Courty and Roux, 1995; Foster, 1959; Franken and Kalsbeek, 1975; Gelbert, 1999; Mahias, 1993; Miller, 1985; Nicholson and Patterson, 1985; Roux and Courty, 1998; Saraswati and Behura, 1966; van der Leeuw, 1993). Instead, pottery manufacturing techniques should best be visualised as ranging from completely

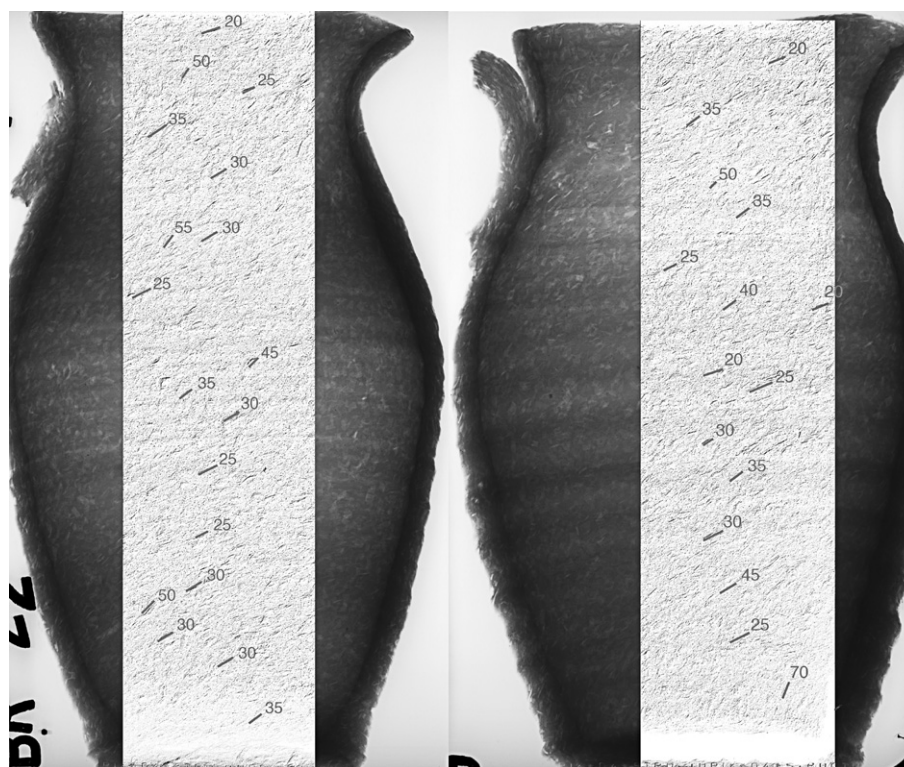


Fig. 2. Comparison of angle of diagonal inclusions between rapidly lifted wheel-thrown vessel on left and slowly lifted wheel-thrown vessel on right. Enhanced positive radiographic image. In-set strips have been modified by digital processing to enhance the edge of diagonal features using the Kirsch detection kernel (-45) in Photoshop. Random voids were selected and their angle measured. Exposure parameters: (a,b) Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 55 kV, 90 s, 3 mA.

handmade through combination techniques to completely wheel-made ones. In particular in relation to combination techniques, X-radiography has played a considerable part in identifying which methods have been combined and the sequence in which they have been applied (Carmichael, 1990; Glanzman, 1983; Glanzman and Fleming, 1986; Henrickson, 1991; Magrill and Middleton, 2004; Middleton, 1995; Nenck and Walker, 1991; Vandiver, 1987; Vandiver and Tumosa, 1995).

However, X-radiography can help in more sophisticated ways than merely distinguishing between the two main categories; it can also contribute considerable information on the distinction between and identification of wheel-made and wheel-shaped vessels. Wheel-made is hereby understood to imply the use of a potter's wheel that runs at speeds sufficiently high to develop rotative kinetic energy (RKE) which is used by the potter to pull up and shape the clay. Scholars consider the existence of grooving on the body, concentric striations on the base, ripples around the neck, S-shaped fractures in the base and vertical herringbone patterns as features distinct to wheel-thrown pots (for a bibliography see Courty and Roux, 1995: 17–18; for a critique of these criteria see Berg, 2005). Wheel-shaping, on the other hand, refers to vessels where speeds are either not high enough to develop RKE and are merely used to join, thin or smooth the walls that have been built using a handmade technique or where speeds are sufficient, but are not taken advantage of. Scholars have had difficulties in identifying wheel-shaping and, due to the existence of rilling, such vessels have often been lumped together with wheel-thrown ones. However, experiments undertaken by Roux and Courty have identified four different methods of wheel-shaping depending on the stage within the production process during which RKE is applied, i.e. coil building, coil joining, wall thinning or pot shaping (Roux and Courty, 1998, also Courty and Roux, 1995). They concluded that all methods can potentially be distinguished by characteristic features detectable through visual inspection and optical microscopy. Arguing that wall thickness is directly related to fashioning technique, Pierret and his colleagues utilised specific filters and calibrations to extracted relevant quantitative data from digitised X-ray films of three sherds (Pierret et al., 1996). Their results indicate that coiling with shaping on the wheel, coiling with thinning and shaping on the wheel and throwing can be distinguished by different thickness patterns vertically across a sherd. The drawback of the two discussed sets of experiments, with their emphasis on macroscopic observation and thickness measurements respectively, is that they are only successful if the pot did not experience subsequent surface-changing treatment. However, not unlike thin sectioning and microfabric examination, the advantage of X-radiography is that it allows us to look into the internal make-up of a vessel rather than visual variables that can be changed.

Henrickson was the first to investigate whether wheel-throwing and wheel-shaping can be distinguished by orientation of inclusions and voids alone (Henrickson, 1991). Unfortunately, in his discussion the author focuses on macroscopic observations and draws on X-radiography only sparingly. However, from

the illustrations published and the resulting interpretations, we can conclude that Henrickson felt that such a distinction is indeed possible because wheel-thrown pots will have the characteristic diagonal alignment of inclusions and wheel-shaped vessels will have a horizontal one indicative of coiling as the primary forming technique.

To provide a firmer identification of wheel-shaping through X-radiography, a new set of experiments was conducted. A potter produced a range of vessels completely wheel-thrown as well as coiled and wheel-shaped. For these experiments, wheel-shaped vessels were made by making a coil which was placed on top of underlying coils (or the base in the first instance). Joins were obliterated by smearing. Each new coil was thinned and the wall evened out while rotating the vessel on a potter's wheel at speeds able to create RKE (equivalent to Roux and Courty's Method 2). The most successful images are recorded with the straw temper which, due to its elongated form, leaves clear traces of forming techniques. Completely wheel-made vessels display the characteristically diagonal orientation of the particles when seen in frontal view and a parallel vertical alignment when focusing on the wall detail. Ignoring obvious evidence of coil seams in the wheel-shaped pots, the sections that were coiled and then wheel-shaped merely show a horizontal alignment of the inclusions in frontal view, while a random to partial preferred vertical orientation of the straw is apparent for the vessel wall (Fig. 3; cf. also Fig. 5). These findings are consistent with those by Henrickson (1991). This experiment thus indicates that those methods of wheel-shaping where RKE is applied in the later stages of the forming process can be detected successfully through X-radiography because they, despite their outward appearance, maintain the horizontal particle alignment representative of coil-making. This is so because the shape of the vessel is already defined by the coils; the rotational force is concentrated horizontally to thin and even out the wall rather than vertically to pull up and shape a vessel. Whether the same applies to Roux and Courty's Methods 3 and 4 requires further experiments.

3.3. Secondary forming technique

Secondary forming techniques are those operations that define and complete the shape created during primary forming by modifying its surface appearance; being second in the manufacturing process, they can normally be recognised visually. Techniques include scraping, turning, and beating (Rice, 1987; Rye, 1981). Secondary forming always modifies the visual appearance of the pot's surface—sometimes to such an extent that it obscures macroscopically visible traces of the primary forming. Except for the paddle and anvil technique—which may be recognised by the laminar appearance of inclusions oriented parallel to the surface and distinctive star-shaped cracks around larger mineral particles—secondary techniques are not considered to alter radiographic features as they take place when the clay is leather-hard (Rye, 1977, 1981; but see Middleton, 2005: 88 who postulates radiographic changes in addition to visual ones also for other secondary

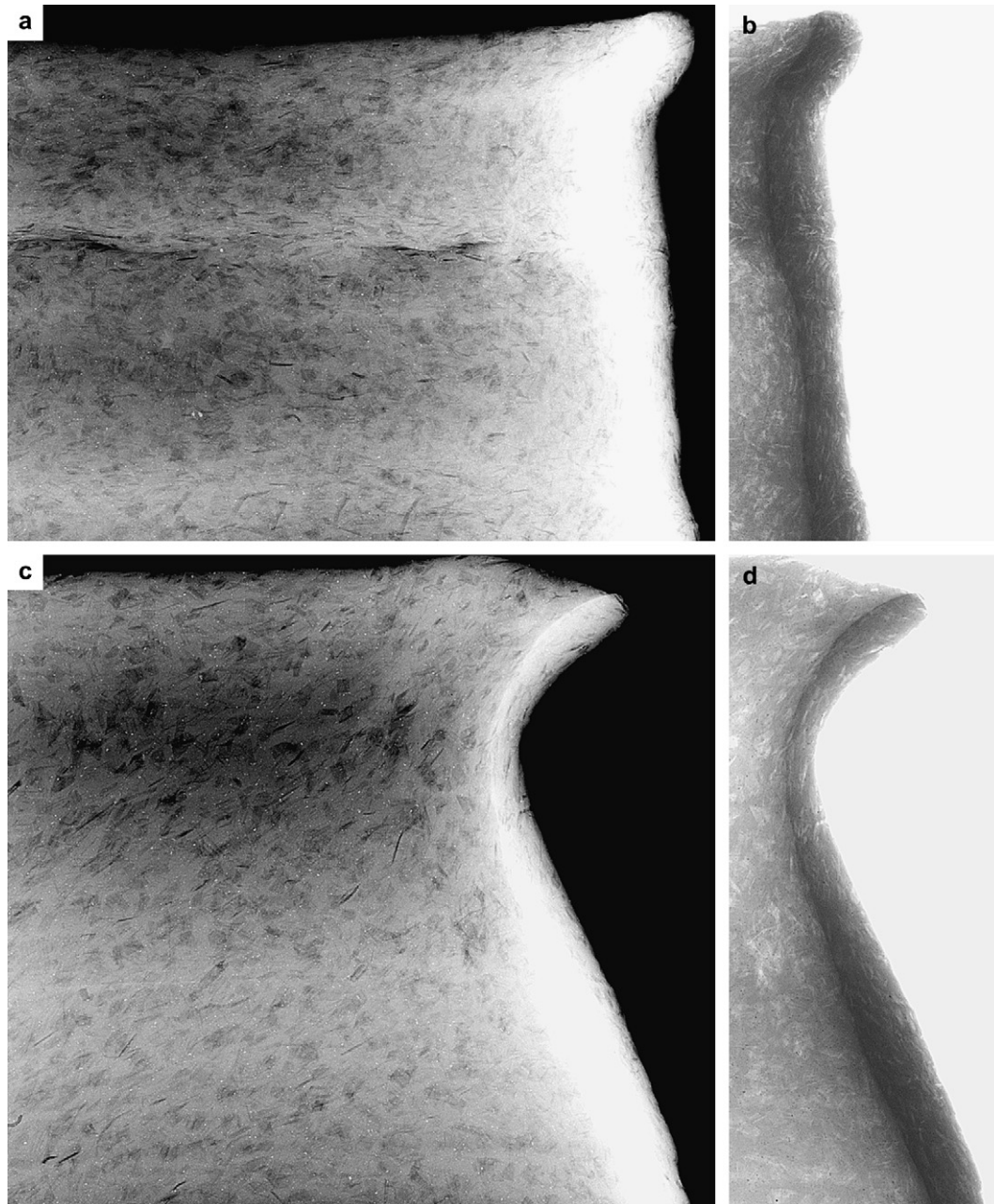


Fig. 3. Radiographic features of wheel-thrown and wheel-shaped pots: (a) normal view of coiled and wheel-shaped pot; (b) detail of (a) (image colours inverted for clarity); (c) normal view of wheel-thrown pot; (d) detail of (a) (image colours inverted for clarity). (a) and (c) are enhanced negative radiographic images; (b) and (d) are enhanced positive radiographic images. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 55 kV, 90 s, 3 mA.

techniques, but does not elaborate). However, no experimental study so far has dealt with this issue in detail.

In order to establish whether secondary forming had an impact on the internal clay structure, controlled experiments were conducted. Each vessel was cut into half when leather hard. Side A was left untreated, while secondary forming treatments were applied to Side B. These were scraping, turning, and knife trimming.

3.3.1. Scraping

Clay is removed with a wooden tool just prior to the leather-hard stage. This procedure evens out the walls both by removing

excessive clay and by re-depositing some of it in hollows. Depending on the size and quantity of inclusions, light or deep drag-marks are present. The tool will leave shallow indentations behind, which may be obliterated by subsequent surface treatment. Scraping may in some instances be indirectly recognised radiographically when larger mineral inclusions are dragged a short distance, creating small air pockets counter to the direction of the scraping motion. Comparison of X-ray images shows that moderately vigorous scraping has no effect on the primary forming technique. Inclusions have the same appearance as regards to surface/edge features, dimensions, size, radiodensity, etc. as the untreated sample (Fig. 4a,b).

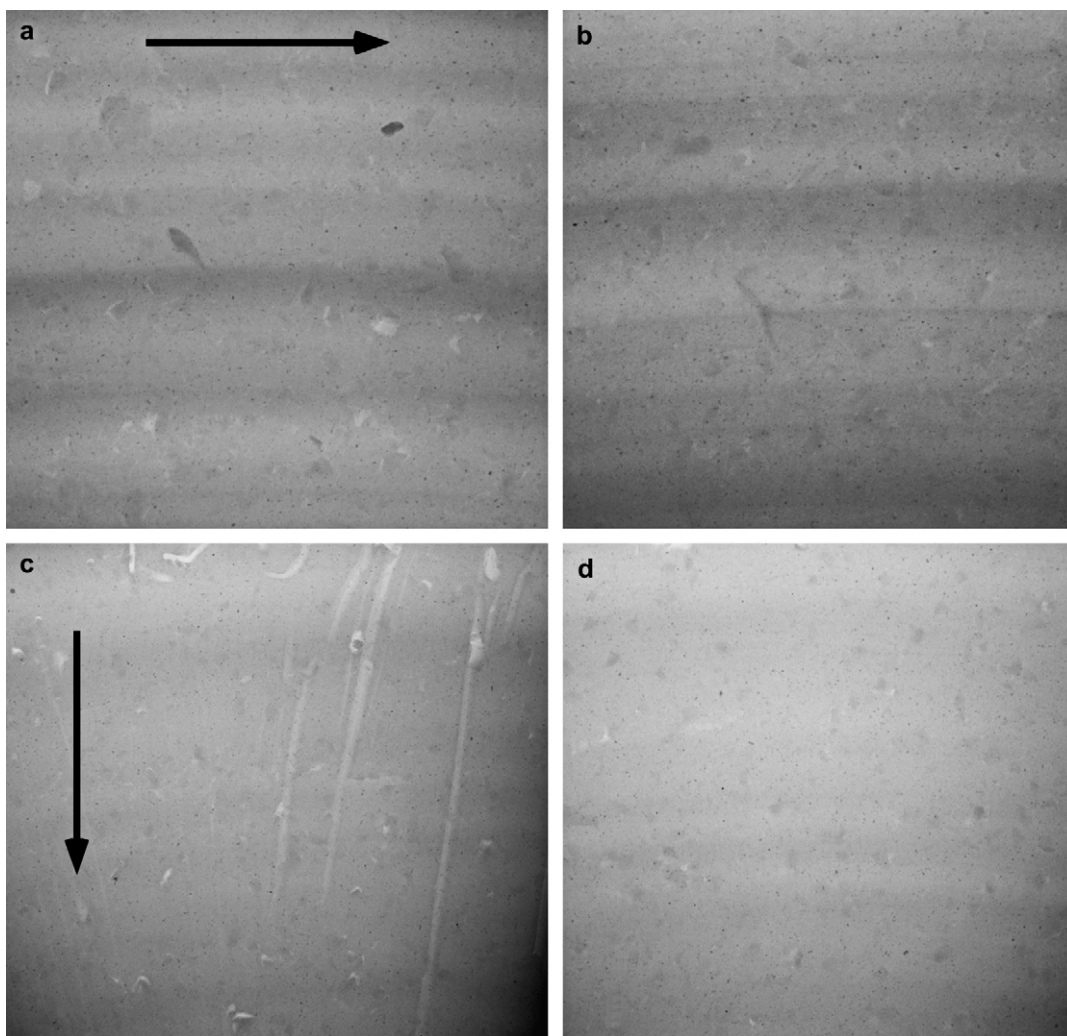


Fig. 4. Radiographic features of secondary forming techniques and their impact on primary forming: (a) horizontal scraping with a wooden tool can create air pockets. (b) no air spaces are visible on the untreated pot; (c) vertical knife trimming can leave obvious indentations and air pockets. (d) the untreated vessel half. The arrows indicate the direction of the scraping/knife-trimming motion. Enhanced positive radiographic images. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 55 kV, 90 s, 3 mA.

3.3.2. Turning

Considerable amounts of clay are being removed with a metal tool held stationary at an angle against the vessels surface while the vessel is revolving rapidly. Because turning was impossible once vessels had been cut in half, horizontal scraping with a metal tool during the leather-hard stage was used to simulate the procedure as best as possible. The scraper can leave considerable indentations. Depending on the size and quantity of inclusions, shallow or deep drag-marks are present;

shallow ones will create a smooth surface, while deep ones will form a rough textured surface. These features may be evident even after subsequent surface treatment. Turning can be indirectly recognised radiographically when drag marks leave obvious tracks behind or large mineral inclusions are dislodged and create air spaces counter to the direction of the turning motion. Comparison of X-ray images shows that moderately vigorous turning has no effect on the primary forming technique. Inclusions have the same appearance as regards to

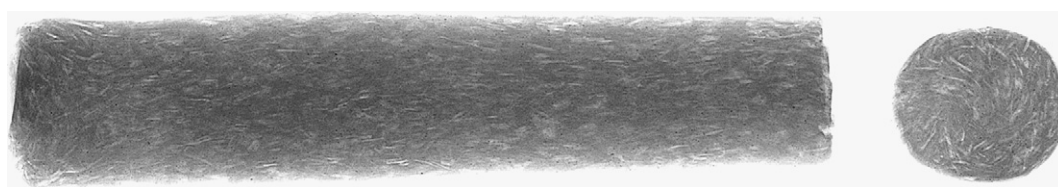


Fig. 5. Inclusion alignment of a coil. Normal view (left) and cross section (right). Enhanced positive radiographic image. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 70 kV, 150 s, 3 mA.

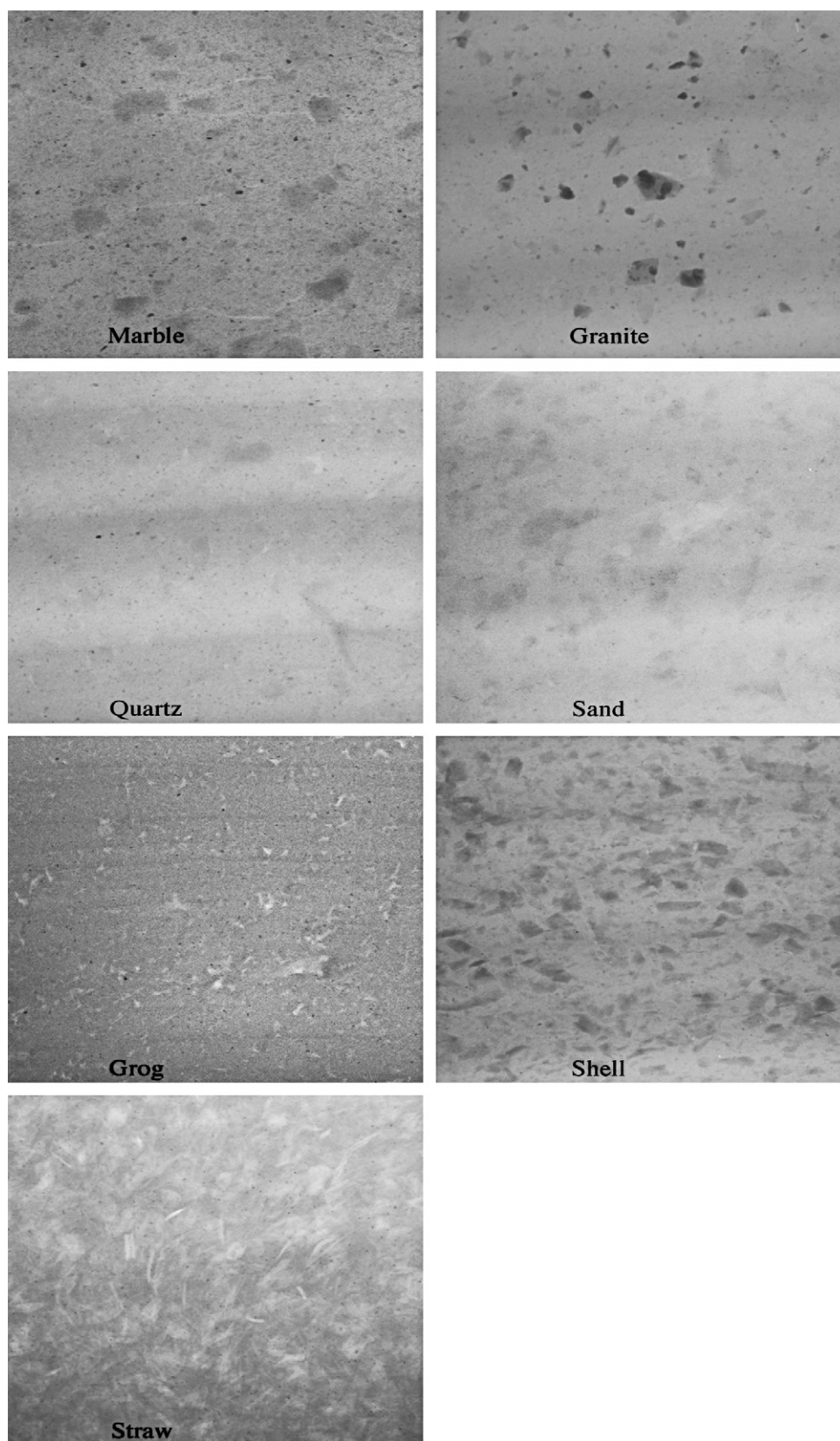


Fig. 6. Visibility of different tempering materials. Enhanced positive radiographic images. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 55 kV, 90 s, 3 mA.

surface/edge features, dimensions, size, radiodensity, etc. as the untreated sample. However, there are suggestions that, as in the case of Cypriot Bronze Age vessels, very vigorous turning can thin walls to such an extent that it obliterates all traces of primary forming (J. Ambers, personal communication).

3.3.3. Knife trimming

Clay is cut away with a knife blade during the leather-hard stage. This procedure leaves sharp-edged marks unless they are obliterated by subsequent surface treatment. Depending on the size and quantity of inclusions, drag-marks may be present. Because of the pressure applied, clay in cut areas may appear compressed with a slight sheen. Subsequent surface treatment does rarely completely obliterate these traces. Knife trimming can be directly recognised radiographically when the cut indentations result in differential thickness or indirectly when the drag marks leave obvious tracks behind or mineral inclusions are dislodged and create air spaces counter to the direction of the cutting motion. Comparison of X-ray images shows that moderately vigorous knife trimming has no effect on the primary forming technique. Inclusions have the same appearance as regards to surface/edge features, dimensions, size, radiodensity, etc. as the untreated sample (Fig. 4c,d). Whether excessive knife trimming, similar to extreme turning, could lead to the obliteration of features remains to be investigated.

3.4. Surface treatments

Surface treatments are those techniques that alter the decorative character of a vessel. Rye (1981) divides them into surface finishing (e.g. smoothing, burnishing, polishing), cutting (e.g. incising, perforating), displacing (e.g. impressing, rouletting) and joining techniques (appliqué, modelling). Because they are applied during the leather hard stage and are rarely intrusive, they are unlikely to cause any alterations to the internal patterning of the clay, but are best understood through visual observation. However, two treatments—burnishing and wet smoothing—are more intrusive than others because they compress and add additional layers to the surface respectively. To investigate whether they impact on inclusion orientation established during primary forming, burnished and slipped B sides of pots were compared with untreated A sides.

Burnishing refers to the use of a hard, smooth object (e.g. stone, wood, bone) to rub the vessel surface at the leather hard stage often resulting in narrow parallel facets. By compressing the clay, burnishing creates a characteristic luminous shine. On X-rays, burnishing does not impact on the internal clay structure as laid down during primary forming and both the untreated and treated side of vessels have the same appearance. Burnishing does not leave any traces behind that could lead to its identification on X-ray images.

The application of slip is undertaken at the leather hard stage during which clay slurry is being spread over the vessel's surface by hand or with a tool and, if necessary, smoothed. This procedure is used to give the vessel's exterior and interior a different clay colour from the main clay body and to fill in irregularities in the surface. On X-rays, self-slipping does

not obscure the traces of the original forming technique, nor is this surface treatment visible radiographically.

3.5. Orientation of voids and inclusions in coiled vessels

In his seminal paper Rye (1977) proposed that, due to the rolling motion required to create a coil on a flat surface, inclusions in coil-made vessels would align horizontally when viewed from the front and circular when seen in cross section. Confirmation of this theoretically derived assumption was achieved through X-radiography of single coils. In frontal view, inclusions aligned parallel to each other along a horizontal axis. In cross-section, one can observe the characteristic in-turned spiral pattern or fold. The tightness and completeness of the spiral or fold is presumably determined by the thoroughness of the coil-rolling process (Fig. 5).

4. Variables that influence the success of X-radiography

4.1. Clay matrix visibility

Our ability to identify forming techniques is dependent on the image contrast between the clay matrix and any particles within it (be they naturally occurring inclusions or deliberately added temper). Image contrast can be understood as a function of raw material, shape, size, and quantity of inclusions *vis à vis* the clay matrix (Foster, 1985). The modern processed clays used for these experiments are characterised by the purity and homogeneity of the clay body; as a result, a substantial quantity of temper needed to be added in order to make them suitable for X-radiography analysis. However, whether a result of the plasticity of the clay body or the potters' motor habits, processed clays had the habit of showing stress voids very well which can stand proxy for inclusion alignment. Natural clays (including those used by (pre)historic people) are often not homogeneous or well levigated and contain naturally occurring inclusions that, even without the addition of tempering materials, can aid interpretation. In practical terms this means that ancient vessels often provide great scope for a reliable assessment of forming techniques and the characterisation of fabrics, while the suitability of modern replicas is heavily dependent on the addition of visible tempering materials.

4.2. Inclusion/temper visibility

As the two main applications of ceramic X-radiography (i.e. fabric characterisation and identification of forming techniques) both require the imaging of inclusions, it is important to be aware of the factors involved in determining their greatest clarity on X-rays. Many scholars have grappled with this issue indirectly when utilising radiography to identify different fabric groups (Adan-Bayewitz and Wieder, 1992; Bennett et al., 1989; Blakely et al., 1989; Braun, 1982; Carr, 1990, 1993; Middleton, 1995), but only few have approached this issue systematically through experiments (Carr and Komorowski, 1991; Foster, 1985). Foster (1985) tested the visibility of crushed grog, seeds, straw, wood, coral, sponge, insects, snail, clam,

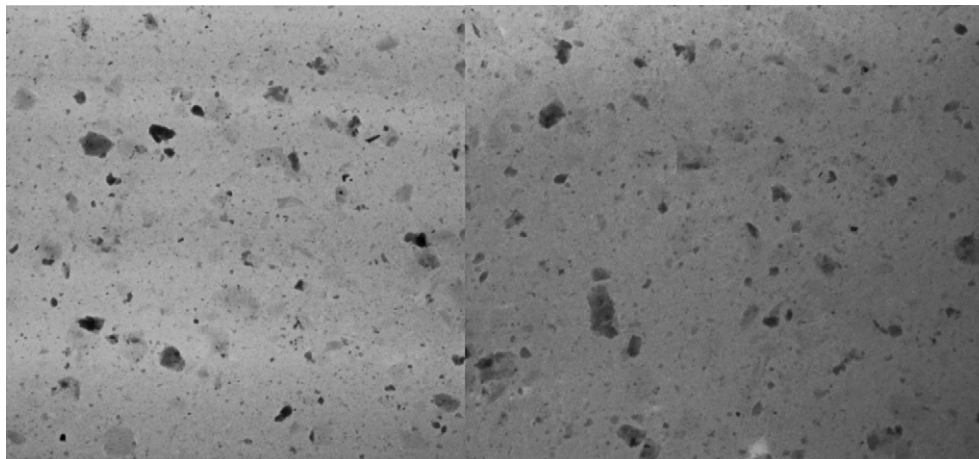


Fig. 7. The impact of sherd thickness on particle visibility. Sherd of 4 mm thickness (left) and sherd of 9 mm thickness (right). Enhanced positive radiographic images. Exposure parameters: Faxitron, 0.5 mm focal spot, 60 cm focus-to-film distance, 55 kV, 75 s, 3 mA (left) and 55 kV, 120 s, 3 mA (right).

sea urchin, mussel, scallop, murex, several gastropods, limestone, granite, alluvial magnetite and quartz in two synthetic and one natural clay. Particles were sieved to fall into several size categories, ranging from less than 0.01 mm to greater than 2.0 mm. Clays contained 1%, 3%, 5% or 10% of inclusions in weight. Clays were rolled into slabs, cut into tiles of varying thickness and fired at 800–900 °C. Based on his experiments, the author concluded that particle visibility is determined by four factors. (1) Differential radiodensity between clay body and inclusions—the greater the difference, the more visible the inclusions. (2) Tile thickness—thick tiles obscure the definition of particles as they overlap. Thin tiles offer better visibility, but do not capture sufficient detail of the fine clay body. (3) Size of particles—particles of at least 0.5 mm appear more visible than smaller particles because they are more radiodense; in contrast, small particles appear as part of the less visible clay matrix. (4) Quantity of particles—fewer particles increased the contrast between inclusions and clay body.

Of the tempering materials tested by Foster, all organic particles are clearly visible as they are radiolucent relative to the clay body and have sharp edges. The visibility of grog was heavily dependent on it having been made of different clay than the surrounding clay body. When this was the case, its angular edges made detection relatively easy. Poor wedging of the clay further enhanced visibility as air spaces surround the particles. Mineral inclusions were not discussed in detail by Foster, but his X-ray images show that limestone and, to a lesser extent, alluvial magnetite were clearly visible. Granite and quartz sand, due to their less well-defined edges, were less sharply defined. This conclusion is confirmed by Carr and Komorowski (1991) who demonstrated that the low visibility of quartz is due to its low radiographic contrast with clay and its less clearly defined edges. The authors also reiterated Foster's observation that greatest contrast is obtained when sherds are thin and have a low proportion of particle within the clay body. Also, visibility is enhanced when particles are large; very small particles actually hinder visibility as they create a fog-like appearance on the radiograph.

In our own experiments, a wide range of tempering materials (i.e. marble, granite, quartz, quarry sand, grog, shell (-sand), and straw) was combined with two types of processed clays (buff stoneware 1117M and garden terracotta P3150). Marble inclusions are clearly visible due to their size, sharply defined edges and high radiodensity compared with the surrounding clay body. Thick granite inclusions, despite angular edges, are visible due to greater radiodensity. However, thin ones barely stand out from the clay. In line with observations by Foster (1985) and Carr and Komorowski (1991), quartz is virtually indistinguishable from clay due to similar radiodensity and angular edges. Sand, due to its size, round shape and similar radiodensity, is barely visible within the clay matrix. Grog is virtually invisible due to similar radiodensity and less well-defined edges. As already observed by Foster (1985), being of greater radiodensity and with sharp edges, shell fragments are easily visible. The voids left by burnt out straw are visible due to lower radiodensity; however, large amounts of straw create a speckled clay body which makes identification of individual particles difficult (Fig. 6).

That sherd thickness is an important variable for inclusion visibility is also confirmed by our own experiments. When comparing granite-tempered fragments of 4 and 9 mm thickness it becomes apparent that the thicker sherd the more particles will overlay each other, resulting in obscured images of many of the particles. Shape, dimensions, edges and orientation of particles are most clearly visible in thinner sherds (Fig. 7).

In sum, through experiments it has been demonstrated that inclusions are most clearly visible when the following conditions are met: inclusions and clay body have differential radiodensity; the sherds that are being X-rayed are relatively thin—thicker sherds contain more inclusions that can overlap and cause blurring; inclusions are above 0.5 mm in size—smaller ones blend in with the clay body and do not stand out; inclusions make up a small percentage of the clay volume (probably <5%); this allows for each to be clearly visible without overlapping with others. However, it must be emphasised that, even when these criteria are not being met, vessels should not simply be excluded from radiography. Analysis of prehistoric Cretan vessels

demonstrates that even under less than ideal conditions X-radiography can still add much needed information about a vessel and augment visual and scientific investigations (Berg, *in press*).

5. Conclusion/outlook

It is clear that radiography has a great role to play in the identification of forming techniques and sequences of clay vessels (and indeed other ceramics objects). Because most secondary forming techniques and surface treatments are applied during the leather-hard stage, they do not cause changes to the internal structure as laid down during primary forming. Thus, radiography, combined with visual inspection, has the potential to considerably advance our knowledge of vessel manufacture. In particular the vexing question of wheel-thrown or wheel-shaped can now be addressed with some confidence through radiography and might help reassess the impact of the first potter's wheels. Given the comparative ease and speed with which X-rays can be taken, the non-destructiveness of the technology and the relatively low costs involved make radiography an ideal companion both for visual assessments and established scientific techniques, such as thin section analysis.

Acknowledgements

This research project would not have been possible without the facilities, training and continuous support provided by Sonia O'Connor at the University of Bradford. The pots were made by Veronica Newman and Sandy Budden for whose expertise I am extremely grateful. Thanks also goes to the staff at Bodycote, Burton-on-Trent, who X-rayed part of the pottery collection. This project was undertaken during my sabbatical leave in 2006–7 and I gratefully acknowledge the financial support by the AHRC (Research Leave Scheme), British Academy (Small Grant) and University of Manchester (Research Support Fund).

References

- Adan-Bayewitz, D., Wieder, M., 1992. Ceramics from Roman Galilee: a comparison of several techniques for fabric characterization. *Journal of Field Archaeology* 19, 189–205.
- Bennett Jr., W.J., Blakely, J.A., Brinkmann, R., Vitaliano, C.J., 1989. The Provenience Postulate: thoughts on the use of physical and chemical data in the study of ceramic materials. In: Blakely, J.A., Bennett Jr., W.J. (Eds.), *Analysis and Publication of Ceramics*. BAR Int. Series 551. BAR, Oxford, pp. 31–44.
- Berg, I., 2005. A comparative look at the use of the potter's wheel in Bronze Age Greece. Paper presented at the 2nd International Conference on Ancient Greek Technology, Athens, 17–21 October 2005.
- Berg, I. X-radiography of Knossian Bronze Age vessels: the potential of a new technique for identifying primary forming methods, *Annual of the British School at Athens*, in press.
- Blakely, J.A., Brinkmann, R., Vitaliano, C.J., 1989. Pompeian Red Ware: Processing Archaeological Ceramic Data. *Geoarchaeology* 4, 201–228.
- Blakely, J.A., Brinkmann, R., Vitaliano, C.J., 1992. Roman mortaria and basins from a sequence at Caesarea: fabric and sources. In: Vann, R.L. (Ed.), *Straton's Tower, Herod's Harbour, and Roman and Byzantine Caesarea*. *Journal of Roman Archaeology*, Ser. 5. Ann Arbor, pp. 194–213 (Suppl.).
- Blandino, B., 2003. *Coiled Pottery*. A&C Black, London.
- Braun, D.P., 1982. Radiographic analysis of temper in ceramic vessels: goals and initial methods. *Journal of Field Archaeology* 9, 183–192.
- Bresenham, M.F., 1985. Descriptive and experimental study of contemporary and ancient pottery techniques at Busra. *Berytus* 33, 89–101.
- Carmichael, P.H., 1990. Nasca pottery construction. *Nawpa Pacha* 24, 31–48.
- Carmichael, P.H., 1998. Nasca ceramics: production and social context. In: Shimada, I. (Ed.), *Andean Ceramics: Technology, Organization, and Approaches*. MASCA Research Papers in Science and Archaeology, 15. Museum Applied Science Center for Archaeology/University of Pennsylvania Museum of Archaeology and Anthropology, Philadelphia, pp. 213–231 (Suppl.).
- Carr, C., 1990. Advances in ceramic radiography and analysis: applications and potentials. *Journal of Archaeological Science* 17, 13–34.
- Carr, C., 1993. Identifying individual vessels with X-radiography. *American Antiquity* 58, 96–117.
- Carr, C., Komorowski, J.-C., 1991. Nondestructive evaluation of the mineralogy of rock temper in ceramics using X-radiography. In: Vandiver, P.B., Druzik, J., Wheeler, J.S. (Eds.), *Materials Issues in Art and Archaeology II*. Materials Research Society Symposium Proceedings, 185. Materials Research Society, Pittsburgh, PA, pp. 435–440.
- Carr, C., Riddick Jr., E.B., 1990. Advances in ceramic radiography and analysis: laboratory methods. *Journal of Archaeological Science* 17, 35–66.
- Courty, M.A., Roux, V., 1995. Identification of wheel throwing on the basis of ceramic surface features and microfibrils. *Journal of Archaeological Science* 22, 17–50.
- Digby, A., 1948. Radiographic examination of Peruvian pottery techniques. In: *Actes du xxviii Congrès International des Américanistes*, Paris. Musée de l'Homme, Paris, pp. 605–608.
- Ellingson, W.A., Vandiver, P.B., Robinson, T.K., Lobick, J.J., 1988. Radiographic imaging technologies for archaeological ceramics. In: Sayre, E.V., Vandiver, P., Cruzik, J., Stevenson, C. (Eds.), *Materials Issues in Art and Archaeology*. Materials Research Society Symposium Proceedings, 123. Materials Research Society, Pittsburgh, PA, pp. 25–32.
- Foster, G.M., 1959. The Potter's wheel: an analysis of idea and artifact in invention. *Southwestern Journal of Anthropology* 15, 99–119.
- Foster, G.V., 1983. Kourion votive figures: a study using xeroradiography. *MASCA* 2, 179–181.
- Foster, G.V., 1985. Identification of inclusions in ceramic artifacts by xeroradiography. *Journal of Field Archaeology* 12, 373–376.
- Franken, H.J., Kalsbeek, J., 1975. *Potters of a Medieval Village in the Jordan Valley*. North-Holland Publishing Co, Amsterdam/Oxford.
- Gelbert, A., 1999. Technological and stylistic borrowings between ceramic traditions: a case study from northeastern Senegal. In: Owen, L.R., Porr, M. (Eds.), *Ethno-Analogy and the Reconstruction of Prehistoric Artefact Use and Production*. Mo Vince Verlag, Tübingen, pp. 207–224.
- Glanzman, W., 1983. Xeroradiographic examination of pottery manufacturing techniques: a test case from the Baq'ah Valley, Jordan. *MASCA* 2, 163–169.
- Glanzman, W.D., Fleming, S.J., 1986. Technology. Fabrication methods. In: McGovern, P.E. (Ed.), *The Late Bronze and Early Iron Ages of Central Transjordan: The Baq'ah Valley Project, 1977–1981*. The University Museum, University of Pennsylvania, Philadelphia, pp. 164–177.
- Henrickson, R.C., 1991. Wheelmade or wheel-finished? Interpretation of 'wheelmarks' on pottery. In: Vandiver, P.B., Druzik, G.S., Wheeler, G.S. (Eds.), *Materials Issues in Art and Archaeology II*. Materials Research Society, Pittsburgh, PA, pp. 523–541.
- Lang, J., Middleton, A. (Eds.), 2005. *Radiography of Cultural Material*. Elsevier, London.
- Lang, J., Middleton, A., Ambers, J., Higgins, T., 2005. Radiographic Images. In: Lang, J., Middleton, A. (Eds.), *Radiography of Cultural Material*. Elsevier, London, pp. 20–48.
- Leonard, A., Hughes, M.J., Middleton, A.P., Schofield, L., 1993. The making of Aegean stirrup jars: technique, tradition and trade. *Annual of the British School* 88, 105–123.
- Levi, S.T., 1999. *Produzione e Circolazione della Ceramica nella Sibaritide Protostorica. I. Impasto e Dolii*. All'Insegna del Giglio, Firenze.
- Magrill, P., Middleton, A., 2004. Late Bronze Age pottery technology: Cave 4034 revisited. In: Ussishkin, D. (Ed.), *The Renewed and Archaeological*

- Excavations at Lachish (1973–1994), Volume V. Institute of Archaeology, Tel Aviv, pp. 2514–2549.
- Mahias, M.-C., 1993. Pottery techniques in India. Technical variants and social choice. In: Lemonnier, P. (Ed.), *Technological Choices. Transformation in Material Cultures since the Neolithic*. Routledge, London, pp. 157–180.
- Maniatis, Y., Jones, R.E., Whitbread, I.K., Kostikas, A., Simopoulos, A., Karakalos, Ch, Williams II, C.K., 1984. Punic amphoras found at Corinth, Greece: an investigation of their origin and technology. *Journal of Field Archaeology* 11, 205–222.
- McEwan, C., 1997. Whistling vessels from pre-Hispanic Peru. In: Freestone, I., Gaimster, D. (Eds.), *Pottery in the Making: World Ceramic Traditions*. British Museum Press, London, pp. 176–181.
- Middleton, A., 1995. Integrated approaches to the understanding of early ceramics: the role of radiography. In: Fabbri, B. (Ed.), *The Cultural Ceramic Heritage, Fourth Euro Ceramics*, 14, pp. 63–74.
- Middleton, A., 2005. Ceramics. In: Lang, J., Middleton, A. (Eds.), *Radiography of Cultural Material*. Elsevier, London, pp. 76–95.
- Miller, D., 1985. *Artefacts as Categories. A Study of Ceramic Variability in Central India*. Cambridge University Press, Cambridge.
- Nenk, B., Walker, H., 1991. An aquamanile and a spouted jug in Lyveden-Stanton ware. *Medieval Ceramics* 15, 25–28.
- Nicholson, P., Patterson, H., 1985. Pottery making in Upper Egypt: an ethno-archaeological study. *WorldArch* 17, 222–239.
- O'Connor, S., Maher, J., 2001. The digitisation of X-radiographs for dissemination, archiving and improved image interpretation. *The Conservator* 25, 3–15.
- O'Connor, S., Maher, J., Janaway, R., 2002. Towards a replacement for xero-radiography. *The Conservator* 26, 100–114.
- Philpotts, A.R., Wilson, N., 1994. Application of petrofabric and phase equilibria analysis to the study of potsherd. *Journal of Archaeological Science* 21, 607–618.
- Pierret, A., Moran, C.J., Bresson, L.-M., 1996. Calibration and visualization of wall-thickness and porosity distributions of ceramics using X-radiography and image processing. *Journal of Archaeological Science* 23, 419–248.
- Rice, P.M., 1987. *Pottery Analysis: A Sourcebook*. University of Chicago Press, Chicago.
- Röntgen, W.C., 1896. On a new kind of rays. *Nature* 53, 274–276.
- Roux, V., Courty, M.A., 1998. Identification of wheel-fashioning methods: technological analysis of 4th–3rd Millennium BC oriental ceramics. *Journal of Archaeological Science* 25, 747–763.
- Rye, O.S., 1977. Pottery manufacturing techniques: X-ray studies. *Archaeometry* 19, 205–211.
- Rye, O.S., 1981. *Pottery Technology. Principles and Reconstruction. Manuals on Archeology*. Taraxacum, Washington.
- Saraswati, B.N., Behura, N.K., 1966. *Pottery Techniques in Peasant India*. Anthropological Survey of India, Calcutta.
- Titterton, P.F., 1935. Certain bluff mounds of Western Jersey County, Illinois. *American Antiquity* 1, 6–46.
- van Beek, G., 1969. *Hajar Bin Humeid. Investigations at a Pre-Islamic Site in South Arabia*. Johns Hopkins Press, Baltimore.
- van der Leeuw, S.E., 1993. Giving the potter a choice. In: Lemonnier, P. (Ed.), *Technological Choices. Transformation in Material Cultures since the Neolithic*. Routledge, London, pp. 238–288.
- Vandiver, P.B., 1987. Sequential slab construction; a conservative Southwest Asiatic ceramic tradition, ca. 7000–3000 BC. *Paléorient* 13, 9–35.
- Vandiver, P.B., 1988. Reconstructing and interpreting the technologies of ancient ceramics. In: Sayre, E.V., Vandiver, P., Cruzik, J., Stevenson, C. (Eds.), *Materials Issues in Art and Archaeology. Materials Research Society Symposium Proceedings*, 123. Materials Research Society, Pittsburgh, PA, pp. 89–102.
- Vandiver, P.B., Tumosa, C.S., 1995. Xeroradiographic imaging. *American Journal of Archaeology* 99, 121–124.
- Vandiver, P., Ellingson, W.A., Robinson, T.K., Lobick, J.J., Séguin, F.H., 1991. New applications of X-radiographic imaging technologies for archaeological ceramics. *Archeomaterials* 5, 185–207.