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Radiography: theory

Andrew Middleton and Janet Lang

Introduction; types of radiation, safety; generation and properties of X-rays; objects and X-rays

INTRODUCTION

The cartoon reproduced as Figure 1.1 was published in the magazine *Life*, within a few months of Röntgen's discovery of X-rays. It is a typical manifestation of the excitement and public interest which his work provoked. However imperfectly, the public grasped that Röntgen had discovered a new way of 'looking' not just at objects but also through them. Of course, everyone knew that light passed through transparent and semi-transparent materials such as glass and paper; even a human hand gave a blood red

The new Roentgen photography
'Look pleasant, please.'

Figure 1.1. *Contemporary cartoon from* Life *magazine, February 1896.*

glow when held up to a strong light, but no details could be seen. Röntgen's first published pictures showed a hand, with the bones, flesh and a ring on one of the fingers, all clearly visible (Röntgen 1896). This was a totally new phenomenon. Within months, a beam of X-rays had been used to show up lead pellets accidentally shot into a New York lawyer's hand. The medical use of X-rays was launched. Archaeological applications also followed swiftly on Röntgen's discovery: a paper published by Culin in 1898 describes work carried out by Dr Charles Leonard to produce radiographs of a Peruvian mummy and other artefacts from the University of Pennsylvania Museum (see Chapter 7).

Nowadays we are quite familiar with the medical uses of X-rays; for instance, to image bones or to produce dental or chest X-rays (or, more correctly, chest radiographs). These illustrate several of the key characteristics of radiography – the images are life-size, denser regions, such as bone, stand out from softer tissues as lighter areas on a conventional film radiograph, and they contain information from the whole depth of the subject, from the ribs through to the spine on a chest radiograph. This means that all the internal features of the patient (or any other object) are superimposed on top of one another. This can sometimes result in radiographic images that are difficult to interpret. However, these difficulties arising from the projection of a three-dimensional subject onto a two-dimensional radiograph can usually be overcome, for instance, by recording radiographs from different angles or by the use of more sophisticated techniques such as stereo-viewing, real-time radiography or computed tomography (CT scanning) (see also Chapters 2 and 7).

Thus, radiography offers the possibility of obtaining a fascinating insight into the internal structure of objects as disparate as the human body and complex pieces of machinery. Given that this can be done without inflicting any damage to an inanimate object (the exposure of living tissues must always be carefully controlled, see Box 1.2), it is easy to appreciate why radiography is being used increasingly in the study of archaeological and cultural objects. It is capable of answering many questions about manufacture, function and state of preservation, sometimes providing information that is unobtainable by any other technique. The purpose of this chapter is to provide some technical background in order to indicate the scientific framework on which radiographic practice rests. It is hoped that this will also help to indicate the general potential and limitations of radiography in the study of cultural material, but these aspects will be discussed more fully in relation to particular materials and classes of artefact in the chapters which follow.

RADIATION USED IN RADIOGRAPHY

In addition to X-rays, several other types of radiation are used in radiography to produce images, including electrons, neutrons and γ-rays. Sources of all four types of radiation are discussed briefly in the following sections, although the main concern of this book is with the use of X-rays and also electrons for certain specialist applications.

Electrons

Electrons useful to the radiographer may be derived in two, rather different ways: from the decay of radioactive substances, and from the impact of high-energy X-rays on a heavy metal such as lead. Electrons produced through radioactive decay are known as β-rays or β-particles. Electrons are strongly absorbed by all materials, including air, and have very limited penetration: even the more energetic, such as those emitted by strontium-90 (2.25 MeV), are absorbed by 2–3 mm of aluminium foil. However, this lack of penetration can be used to good effect to radiograph thin, low-density materials. ^{14}C (carbon-14 or radiocarbon) sources have commonly been used. The radioactive ^{14}C may be incorporated in a sheet of Perspex or aluminium foil, and in this form it is convenient and safe to handle provided rubber gloves are worn. Sources are usually supplied with their own shielded containers, but a ^{14}C source can be stored in a secure lockable metal box (e.g. a suitably sized cashbox) as it does not require lead shielding. β-radiography is ideal for imaging thin, flat materials such as paper, where a good contact can be maintained between the sheet or foil source and the subject (see Chapter 5).

Electrons are emitted when some heavy metals, like lead, gold or cadmium, are irradiated with a high-energy X-ray beam and, when generated in this way, are utilized for two different radiographic methods. The electrons emitted during the irradiation of a thin lead foil can be used to make electron radiographs of paper and similar materials, providing an alternative to the use of β-rays. This technique, electron (transmission) radiography, is described in

Chapter 5; an early account of the method was given by Tasker and Towers in 1945. The second application, electron emission radiography (sometimes referred to as autoradiography), can be used where an artist has employed paints or pigments containing heavy metals: a high-energy X-ray beam causes electron emission from the areas covered with the heavy metal paints or pigment. The image of their distribution can be recorded on an X-ray film (see Chapter 5). This technique has also been used to image other flat subjects such as the designs on corroded medieval glass (Knight 1989) and a painting on copper (Bridgman *et al.* 1965). A third use of electrons occurs when lead screens are employed as intensifiers, increasing the contrast range of radiographs.

Neutrons

The possibility of using a neutron beam in radiography was realized only 3 years after Chadwick discovered the neutron in 1932, by Kalman and Kuhn, using a small accelerator source in Berlin (Matfield 1971). From the viewpoint of the radiographer of cultural material, the key property of thermal neutrons (those most-commonly used for radiography) is that they are more strongly absorbed by organic materials than by many heavier materials. This is the converse of X-rays and γ-rays (see below) and offers the possibility of revealing such details as the organic materials in scabbards or the fittings of iron blades (Masuzawa 1986; Tuğrul 1990; Rant *et al.* 1995). An example illustrating the usefulness of this property of neutrons is presented in Box 1.1 (see also Figure 3.3).

Box 1.1. Examination of a lead-wrapped bottle using neutron radiography

This item had been found in the Canadian west, in an area near Frog Creek. An incident of historical significance had occurred in the 1880s and an officer had recorded the details in two copies. He returned to Montréal with one copy, but placed the other in a bottle, which he wrapped with lead and buried.

Before unwrapping or opening the bottle, it was desired to verify the condition of the bottle inside the wrapping, as well as the seal and contents. X-rays are not, of course, very well suited to such an examination.

Neutron radiography was employed, in order to obtain contrast from the paper even behind the lead wrap. Figure 1 very clearly shows folded paper inside a glass bottle with the cork and wax seal askew. Based upon this evidence, the conservators decided not to open the bottle.

Rankin MacGillivray
Nray Services Inc., Canada

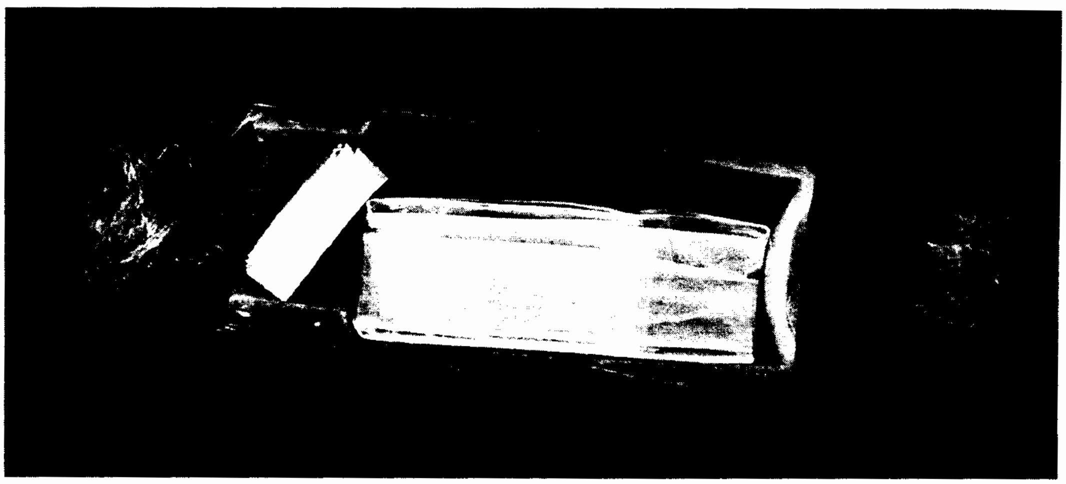

Figure 1. *Neutron radiograph of the lead-wrapped bottle, revealing the folded paper inside.*

However, the practical use of neutrons for radiography is inconvenient and is usually carried out at a specialist facility. A disadvantage is that short-lived radioactivity may be induced in the object which has been irradiated, necessitating safe storage after exposure.

γ-rays

γ-rays are a form of high-energy electromagnetic radiation (Table 1.1) emitted by radioactive materials during decay. Radium, first isolated by Marie and Pierre Curie in 1898, is probably the best-known naturally occurring radioisotope. However, most of the sources commonly used for radiography, such as ^{192}Ir (iridium-192) and ^{60}Co (cobalt-60), are made artificially. The γ-rays are emitted as line spectra of discrete energies and different relative intensities (Figure 1.2), which are characteristic of the particular source. The energies of γ-rays are very high and are usually quoted in million electron volts (MeV), for example the γ-radiation from a cobalt-60 source has energies of 1.17 and 1.33 (MeV). Radiation of this energy has considerable penetrative capabilities: it takes 13 mm of lead to halve the intensity of the γ-radiation produced by a cobalt-60 source. Halmshaw (1995, pp. 29–30) notes that the radiographic qualities of cobalt-60 radiation are equivalent to those of X-rays generated by a potential of 2300 kV: this may be compared with the maximum potential used in a typical industrial X-ray generator of 250 or 320 kV. The volt (V) is the SI unit of electrical potential difference, whereas the electron volt (eV) is a unit of energy. However, it is often convenient to refer to the 'energy' of the X-ray beam in terms of the potential (i.e. the kV) applied to the tube.

Three practical considerations distinguish γ- from X-radiation. Firstly, γ-sources are portable (subject to Health and Safety regulations), they can be operated without the electricity or cooling water required to run an X-ray generator, and are considerably cheaper to buy than an X-ray set. Secondly, γ-radiation is emitted continuously and cannot be switched off, which means that for reasons of safety γ-sources must be kept in special containers shielded with lead, tungsten alloy or depleted uranium in steel. When required for radiography, the source has to be removed from its container by a remote control mechanism. Thirdly, γ-sources gradually lose their activity with time, the rate of loss depending on the half-life of the radioisotope being used: for example, the intensity of a cobalt-60 source decreases to half its original value in 5.3 years, so that the source has a finite useful lifespan. Halmshaw (1995, pp. 52–74) provides a useful discussion on the use of γ-sources. However, the γ-ray sources most-commonly used (^{192}Ir and ^{60}Co) produce high-energy radiation which, unlike the output from an X-ray generator, cannot be controlled and, in general, yields radiographs with rather low contrast.

In view of these disadvantages, it is not surprising that γ-rays have rarely been used for archaeological or art-historical material. However, they have been employed for several high-profile projects where the use of γ-radiography offered particular advantages. In the late 1950s, a ^{24}Na (sodium-24) source was used to survey a fallen lintel stone at Stonehenge, to ensure that it was sound enough to be lifted back

Table 1.1. The electromagnetic spectrum

Type of radiation	*Wavelength, λ (m)*	*Quantum energy*
Gamma rays	10^{-16}	12400 MeV
	10^{-15}	1240 MeV
	10^{-14}	124 MeV
	10^{-13}	12.4 MeV
	10^{-12}	1.24 MeV
	10^{-11}	124 keV
	10^{-10}	12.4 keV
	10^{-9}	1.24 keV
X-rays	10^{-11}	124 keV
	10^{-10}	12.4 keV
	10^{-9}	1.24 keV
Ultraviolet	10^{-8}	124 eV
	10^{-7}	12.4 eV
Visible spectrum	*c.* 5×10^{-7}	
Infra-red	*c.* 7×10^{-5}	

After Tennent (1971).

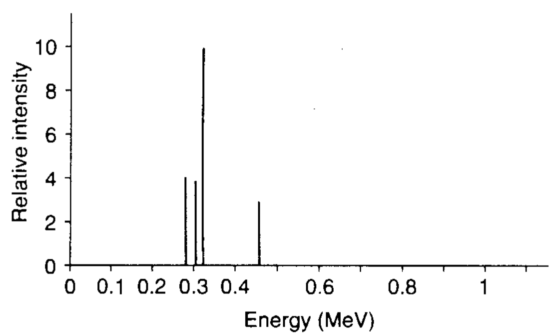

Figure 1.2. *Spectrum of an iridium-192 source.*

on top of two upright stones (Hinsley 1959). More recent examples include a study of a bronze statue of Napoleon in the Brera Gallery in Milan, using an ^{192}Ir (iridium-192) source (Canova 1990), and part of an extensive study of the Chimera of Arrezzo (Massimi *et al.* 1991), using cobalt-60. An iridium-192 source was used also in the study of large Classical bronzes carried out in connection with the Fire of Hephaistos exhibition (Mattusch 1996) when a 300 kV X-ray set did not provide adequate radiographs.

X-rays

X-rays, like γ-rays, are a form of electromagnetic radiation (Table 1.1); they are produced when fast-moving electrons interact with matter. The spectrum of X-rays obtained is, in fact, composed of two superimposed spectra: the characteristic or line spectrum of discrete energies and a general spectrum with a continuous range of energies (Figure 1.3). The characteristic spectrum is unique to the material being bombarded and therefore can be used in elemental analysis, but it does not play a major part in X-radiography. The continuous or 'white' spectrum, also known as Bremsstrahlung ('braking' radiation), arises from the energy released when fast-moving electrons are slowed down rapidly by passing through the electron field around an atomic nucleus. It is the continuous X-ray spectrum which is useful for radiography.

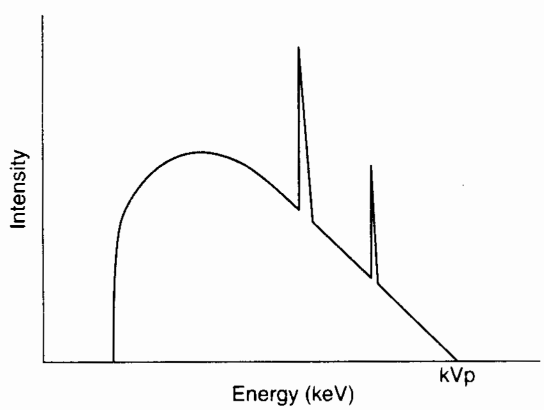

Figure 1.3. *Graph of X-ray intensity and energy showing the characteristic X-ray peaks of the target material superimposed on the general spectrum. kVp is the maximum (peak) kilovoltage. The effective energy of the spectrum will be one-third to one-half of the peak kilovoltage.*

X-rays are commonly characterized by their energy (E) or by their wavelength (λ). These properties are inter-related. In particular, energy and wavelength can be related by the expression:

$$E = hc/\lambda \tag{1.1}$$

where h is the Planck's constant and c is the velocity of light. By substitution of the known values for h and c, the expression becomes:

$$E\ (\text{keV}) = 1.24/\lambda\ (\text{nm}) \tag{1.2}$$

From this equation it can be seen that X-rays of higher energies will have shorter wavelengths. The X-rays with the shortest wavelength (λ_{min}) will be produced by the maximum kilovoltage applied to the X-ray tube (described below). This peak kilovoltage is sometimes referred to as kVp but more generally it is stated simply as kV. There is a sharp cut-off in the X-ray spectrum at λ_{min}: no X-rays of shorter wavelength are produced (see Figure 1.7).

Summary of the Properties of X-rays and γ-rays

X-rays and γ-rays have a number of characteristics:

- they are unaffected by electrical or magnetic fields;
- they travel in straight lines, at the speed of light;
- they penetrate matter and are more or less attenuated in the process, depending upon the material, its density and its thickness;
- they affect photographic films and cause some materials to fluoresce;
- they cannot be detected by human senses;
- they damage living tissues.

Safety

The use of ionizing radiation, as in radiography, is subject to stringent safety regulations (see Box 1.2). Health and Safety issues are also involved in working in workshops with electrical equipment and chemicals, and need to be addressed.

GENERATION OF X-RAYS

The basic equipment and arrangements needed to carry out radiographic examinations of cultural

Box 1.2. Health and safety

X-rays and γ-rays, along with other forms of radiation including β-rays and neutrons, are hazardous to health and each country has its own regulations for the use of ionizing radiation. Readers are strongly advised to familiarize themselves with the current directives and regulations in the country where they are working, always remembering to keep up to date with any changes which may be introduced. The UK regulations are subject to European Union (EU) Directives and therefore similar to those of other EU countries, but it is essential to check in case there are local differences. In the USA, the OSHA (Occupational Safety and Health Administration), part of the Department of Labor, is the relevant organization. Standards for equipment in the USA are set up by the US Food and Drug Administration Centre for Devices and Radiology Health (21 CFR-1020.40). The Internet is a useful source of information.

Radiographic work in the UK is currently governed by the ***Ionizing Radiation Regulations 1999 SI 1999 3232*** which are based on a revision of the EU Basic Safety Statute. The ***Radioactive Substances Act 1993*** may also apply. The Regulations are *Statutory Instruments* and therefore have legal status. The Regulations lay down the rules under which radiography can be carried out and cover the responsibilities of employers and employees. The provisions must be obeyed by all those who are involved in radiography, even as visitors. They are administered by the *Health and Safety Executive* (HSE) which is part of the Department of the Environment, Transport and the Regions (1999). http://www.legislation.hmso.gov.uk/

The Regulations are set out and their implementation is explained in the *Approved Code of Practice*. This document also has legal status and gives practical advice on how to comply with the law.

The *Regulations* and *Code* cover all aspects of the use of ionizing radiation. This includes the initiation, arrangement and monitoring of equipment and facilities, the appointment of Radiation Protection Advisors (RPAs), the provision of Local Rules, dose rates, the monitoring of staff exposure to radiation, the responsibilities and duties of management and operating staff, training and record keeping. It is important to remember that the appointed RPA should be informed and consulted about changes in working practice or equipment or the undertaking of any new work.

The disposal of waste (e.g. radiographic/photographic chemicals and lead, as well as radioactive sources) is also a health and safety matter and must be dealt with according to the current safety regulations, which will also include directives on all matters relating to health and safety, including, for example, working in reduced lighting (i.e. under safelights or in complete darkness).

material are shown schematically in Figure 1.4. Essentially, these comprise a source of X-rays, some means of supporting and perhaps manipulating the object, and a means of observing and recording the radiographic image that results from directing the beam of X-rays through the object.

A modern X-ray set comprises several essential parts which enable it to produce an X-ray beam reliably and on demand. At its heart is the X-ray tube; also required are a control unit and a suitable cooling unit, the nature of which is dictated by the power of the X-ray set.

X-ray Tubes

The X-ray tube shown diagrammatically in Figure 1.5 has a number of necessary features:

1. The source of electrons is usually a wire filament in the cathode, heated to incandescence by a low-voltage electric current (measured in milliamps, mA), causing it to emit a steady stream of electrons.
2. The potential applied between the cathode and the anode accelerates the electrons towards the target; the magnitude of the potential (or accelerating voltage) is usually expressed as kilovolts (kV).
3. The X-rays are produced at the target, which is embedded in the anode. The target is usually made of tungsten because it is an efficient source of high-energy X-rays. It is also a refractory element with a high melting point (3410°C). This is an important consideration because most (typically about 99%) of the energy applied to the tube is converted into heat, mainly at the target. Molybdenum is used as the target in some medical X-ray tubes as it produces a greater X-ray intensity at the lower energy end

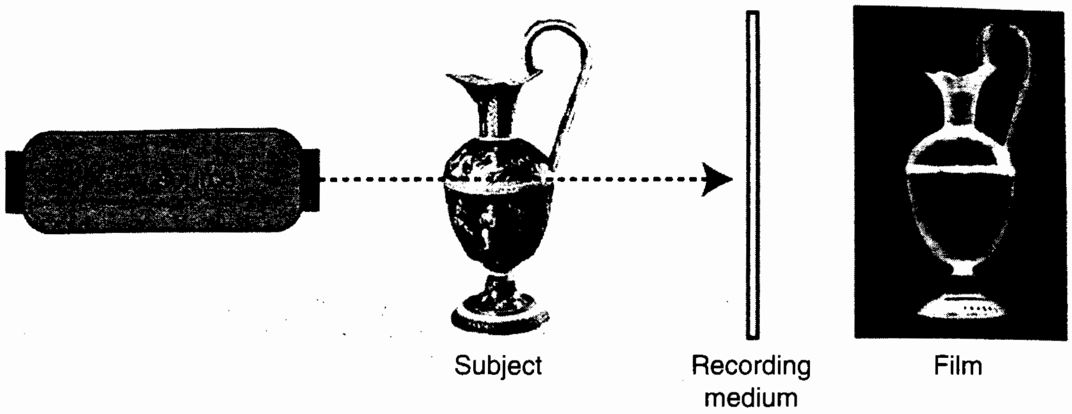

Figure 1.4. *Schematic representation of the radiographic process, with a radiation source, a subject and a means of recording the image (e.g. film).*

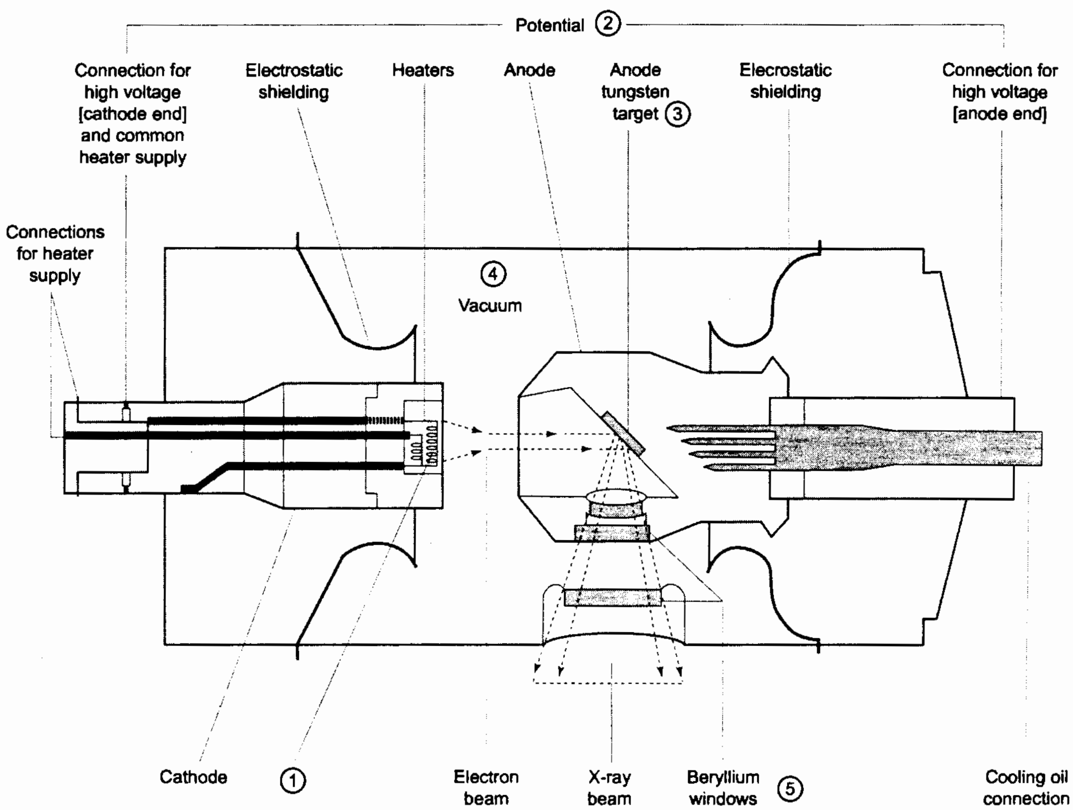

Figure 1.5. *Cut-away diagram of a typical constant potential X-ray tube.*

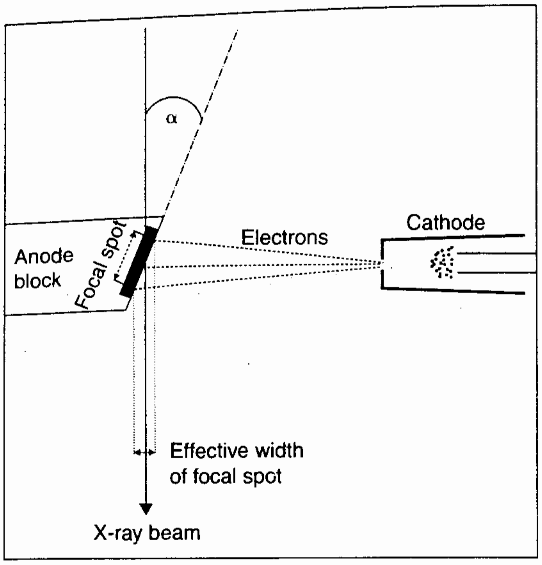

Figure 1.6. *Diagram showing how the effective focal spot size is reduced by 'viewing' the focal spot at an angle α.*

of the spectrum. The target is usually embedded in a good conductor of heat (copper), which is cooled by oil circulating through it.

4. A vacuum surrounds the filament and target, which allows the stream of electrons to be sustained.
5. The exit window for the X-ray beam is often made of beryllium which is a light element; this minimizes absorption of the X-ray beam as it passes through the window, which is particularly important when using low-energy X-rays.

For most applications the line focus type of X-ray tube is most suitable as it has a small effective focal spot (Figure 1.6). The influence of focal spot size on image quality is discussed below under geometrical considerations. Tubes with panoramic rod anodes are used in some medical and industrial applications where an all-round view of a vessel or a tube is required (Halmshaw 1995, p. 40). This type of anode can be put inside the vessel and film is attached around the outside, an arrangement which is very convenient for weld inspection on pipes. The quality of the image is not as good as a line X-ray set although it has the advantage of presenting a single wall thickness of the object on the radiograph, instead of both sides being superimposed.

An X-ray set is designed to operate within set limits of potential (kV) and current (mA). It is not normally possible to use a machine outside those limits, so care must be taken to select a generator with capabilities appropriate to the applications envisaged (see Box 2.2). Typically, an X-ray cabinet may have a range of 10–130 kV, while an industrial set may have a range of 50–150 kV or 50–320 kV; specialized sets may operate at lower potentials or up to 420 kV. More powerful sets (betatrons and linear accelerators or linacs) exist and are used industrially for special applications. X-ray sets in purpose-built shielded cabinets normally have a maximum potential of 150 kV. Medical diagnostic X-ray sets are usually designed to operate with a very short exposure time, high current and low kilovoltage (typically 70 kV, several hundred milliamperes and an exposure time of less than a second for a typical chest radiograph). Minimization of the dose to the patient is of course important, but very short exposure times also serve to reduce the effects of patient movement. These machines usually have a minimum of *c.* 40 kV, although X-ray tubes designed for mammography may operate down to 30 kV. A hospital X-ray set was successfully used to radiograph Byzantine icons painted on wood (Politis *et al.* 1993). As the maximum possible exposure time was very short (between 3 and 4 seconds), multiple exposures of the same icon were made in the same position, giving a total exposure of between 9 and 16 seconds, using a tube voltage between 32 and 40 kV (mammography-type tube). It is important that care is taken not to overload this type of set by running it for longer times than those for which it was designed.

Microfocus X-ray Sets

Although the X-ray beam itself cannot be focused through a lens like light, the electron beam used within the X-ray tube to generate the X-rays can be focused by electrostatic means, so that it is possible to reduce the diameter of the electron beam before it reaches the anode of the X-ray tube. Thus, an X-ray source with a focal spot size of only a few micrometres can be produced. Microfocus tubes with a range of voltages are available, but the current tends to be low (a typical current of e.g. 0.1 mA for a 10 μm focal spot at 200 kV is quoted by Halmshaw 1995, p. 41). Initial problems of the target overheating have been avoided either by deflecting the electron beam electromagnetically to different positions on the target anode or by using a rotating anode. Cabinet X-ray sets with microfocus tubes offering a focal spot size of 70 μm and energy range of 10–110 kVp are available (e.g. Faxitron). The principal advantage of microfocus tubes is that enlarged images can be formed with negligible loss of sharpness; they also offer the possibility of reducing the effect of internally generated scatter (see below) by leaving a small gap (say 20 mm) between the object and film, again without significant loss of sharpness. The use of the microfocus tube is mentioned again in Chapter 2 (in the section on Geometric considerations).

Characteristics of the X-ray Beam

The characteristics of the X-ray beam, such as its intensity and penetrative power, can be controlled by varying the cathode current and the tube voltage (potential). These characteristics, along with the focal spot size and other factors, affect image quality; this is discussed more fully later in the chapter. The current (mA) controls the intensity of the radiation; intensity is defined as the energy per unit area per unit time. The potential (kV) applied to the X-ray tube controls the maximum energy and the energy distribution of the X-rays and therefore determines the penetrative power of the beam.

Changing the Current

The effect of increasing the current (mA) is shown in Figure 1.7. As the current is increased, more electrons are produced, which in turn produce more X-rays. The energy of the X-rays is not increased, so that the wavelength distribution remains the same. The practical effect is to decrease the time required to radiograph an object, but if the object is very dense and difficult to penetrate, increasing the current will not improve matters very much because the penetrating power of the beam is not increased.

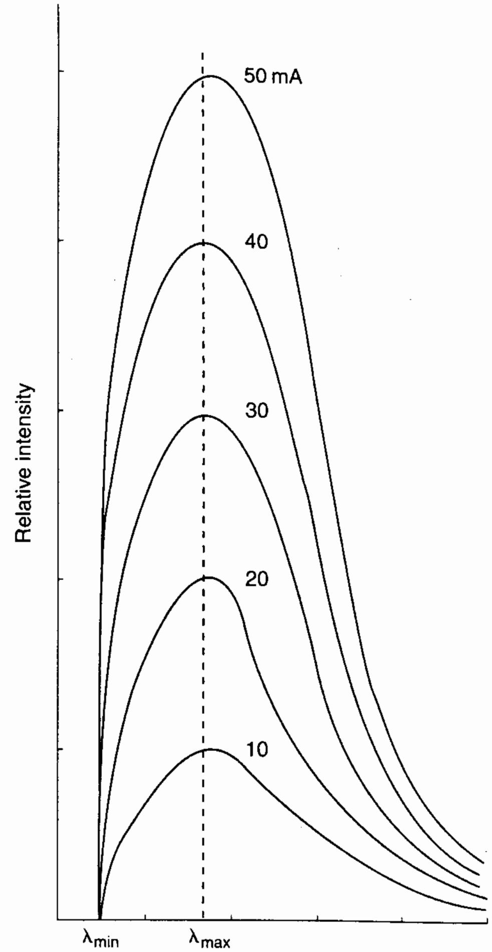

Figure 1.7. *Diagram showing the variation of intensity and wavelength as the current (mA) is varied.* λ_{min} *and* λ_{max} *remain unchanged (after Bertin 1975).*

Changing the Potential (kV)

Figure 1.8 illustrates the effect of increasing the tube voltage (kV). The graph shows that at a higher kilovoltage both the proportion of shorter wavelength (higher-energy) X-rays and the overall intensity increases. At the same time λ_{min} decreases, so that the beam becomes more penetrating. Thus, by controlling the kV the penetrative characteristics of the X-ray beam can be altered: for example, a 100 kV X-ray beam would penetrate 10 mm of steel but by increasing the voltage to 300 kV a steel section up to 40 mm thick could be radiographed. For convenience, X-rays are sometimes classified by their penetrative power: those produced by high-energy sources are more penetrative and are termed hard X-rays, whilst those of lower energy are less penetrating and termed soft X-rays. Particularly soft X-rays with energies less than about 20 kV are sometimes called *Grenz rays* (Graham and Thompson 1980). They can be especially useful for the radiographic examination of low-density materials such as paper, textiles and fish bones (e.g. cartilage), as described in Box 1.3.

Box 1.3. Textiles and organic artefacts

When exploring paint layers on canvas (Chapter 6) or X-raying mummies (Chapter 7), the textiles incorporated in them are often considered as an incidental component or even as a hindrance to gaining a clear image of the intended subject. However, suitably filtered, low-energy X-rays can be used to produce remarkably detailed images of organic objects including textile artefacts (Brooks and O'Connor 2005). The Turin shroud has been recorded and explored using radiography (Mottern *et al.* 1980) and components of upholstery have also been investigated (Gill and Doyal 2001). Nevertheless, textiles have generally not been the primary subjects of radiographic studies. Radiographs can identify hidden aspects such as seaming, fillings, repairs, areas of degradation and structural supports or more subtle details such as internal stitching threads and variations in weave structure. Technological features such as differential metal weightings in woven silk textiles may also been mapped (Brooks *et al.* 1996).

For example, this early 18th century stomacher, the detachable upper front section of a woman's gown, in Figure 1, is constructed from layers of silk, linen canvas and paper stiffened by baleen (whalebone) inserted into closely sewn channels (Figure 2) (Barbieri 2003). It had undergone many modifications and repairs before being concealed in a building (Eastop and Dew 2003). Radiography provided a means of assessing and recording the condition of the internal components of this multi-layered object,

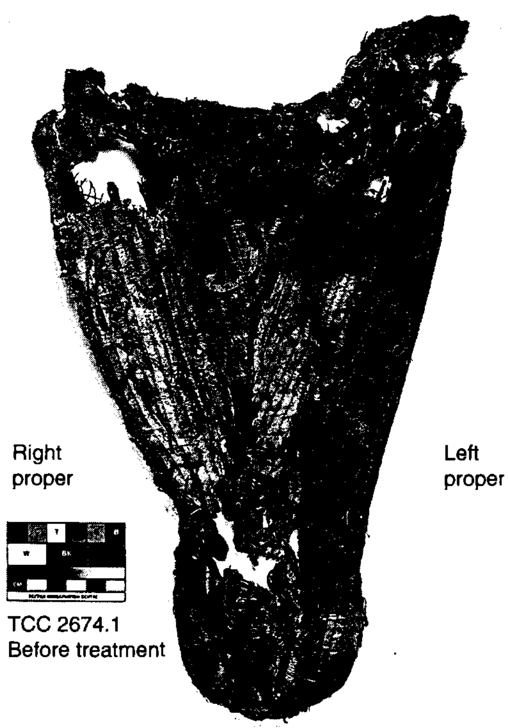

Figure 1. *Early 18th century stomacher in textile, paper and baleen (copyright of the Textile Conservation Centre).*

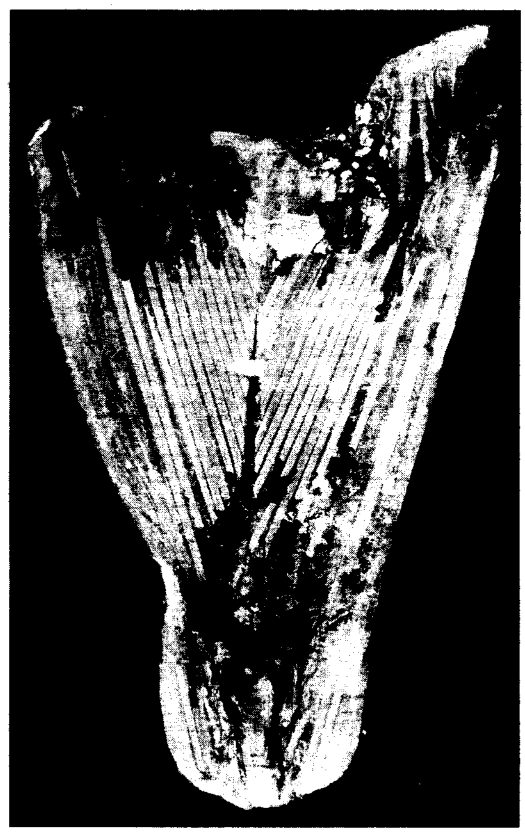

Figure 2. *Radiograph, 15 kV, aluminium foil filter, showing the construction and areas of decay (copyright, Sonia O'Connor).*

revealing details of its construction and contributing insights into its complex 'object biography' (Figure 3) (Kopytoff 1986). This object was radiographed as part of a study funded by the Arts and Humanities Research Board (AHRB) Research Centre for Textile Conservation and Textile Studies. The aim of this interdisciplinary research is to explore the potential of radiography as a tool for the study and conservation decision-making of ancient, historic and contemporary textiles. Specialist equipment and techniques are also being explored, including microfocus radiography, computer tomography and real-time radiography. A book based on this work is planned for this series (O'Connor and Brooks forthcoming).

Sonia O'Connor
University of Bradford
(The stomacher is published by
kind permission of the owner.)

Figure 3. *Detail of radiograph showing the canvas, paper, silk and insect nibbled ends of the baleen strips, stitching and stitch holes (copyright, Sonia O'Connor).*

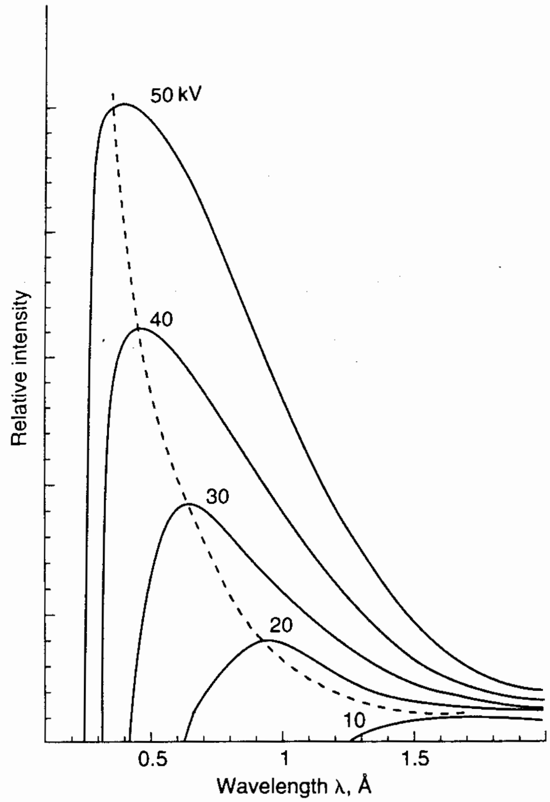

Figure 1.8. *Diagram showing the variation of intensity and wavelength as the potential (kV) applied to the X-ray tube is varied. As the potential is increased, λ_{min} and λ_{max} decrease and the beam becomes more penetrating (after Bertin 1975).*

OBJECTS AND X-RAYS

Attenuation

X-rays (and γ-rays) may be transmitted through matter without suffering any loss of energy or change of direction. However, if all X-rays were transmitted unchanged, there would of course be no useful radiograph but simply a blackened film. It is fundamental to the success of radiography that the X-ray beam is more or less attenuated as it passes through matter. The degree of attenuation depends upon the composition, density and thickness of the object and also upon the energy of the X-rays. The term attenuation encompasses the losses in intensity arising from a number of processes involving absorption (i.e. partial or total loss of energy) and scattering (i.e. the direction of the X-ray beam is changed and it may also suffer a loss of energy). The term absorption is sometimes used interchangeably with attenuation to include all losses, including those from scatter.

The progressive attenuation of the beam as it travels through matter is an exponential process:

$$I_x = I_o e^{-\mu x} \qquad (1.3)$$

where:

I_x = intensity at depth, x;
I_o = intensity of the incident beam;
e = natural logarithm base;
μ = linear attenuation coefficient.

which is to say that a given thickness of a particular material will absorb a fixed proportion of the incident beam. This leads to the concept of half-value thickness; that is, the thickness of a material required to reduce the incident radiation to one-half of its original intensity ($I_x/I_o = 0.5$). The degree of attenuation varies from one material to another: lead absorbs X-rays very strongly because of its high density and atomic number, lighter materials absorb less strongly. The level of attenuation also varies with the energy of the incident X-rays: lower-energy (softer) X-rays are absorbed more strongly and are scattered more readily than higher-energy (harder) X-rays. For these reasons it has been useful to produce tables of comparative data on the absorption of X-rays of different energies by a variety of materials. One such table, after Bertin (1975), is reproduced here as Table 1.2.

Another commonly used aid for estimating suitable exposure conditions for different materials is a table of approximate equivalent thickness factors, shown in Table 1.3 (after Quinn and Sigl 1980). In each column of this table (i.e. at a particular kV) equivalent thickness factors are given for several different metals, relative to a standard metal. Between 50 and 100 kV aluminium is taken as the standard metal, but at higher X-ray energies (150 kV and above) steel is taken as the standard. The exposure required can be calculated by multiplying the exposure needed for the same thickness of the standard metal at the same kilovoltage by the appropriate factor. For example, at 100 kV, 10 mm of copper would require 18 times the exposure of 10 mm of aluminium.

Table 1.2. Approximate half-value thicknesses (mm) for materials of different density (l), at two different X-ray energies

Applied (kV)	*Effective (kV)*★	*Water (l = 1)*	*Aluminium (l = 2.7)*	*Copper (l = 8.9)*	*Lead (l = 11.2)*
300	154	1160	20	3.9	0.4
200	102	530	16	1.7	0.1

After Bertin (1975).
★This takes account of the fact that the X-ray beam includes a spectrum of energies, with only the highest corresponding to the maximum applied kilovoltage (kVp).

Table 1.3. Approximate equivalent thickness factors

Material	*50kV*	*100kV*	*150kV*	*220kV*	*400kV*
Aluminium	1.0	1.0	0.12	0.18	
Steel		12.0	1.0	1.0	1.0
Copper		18	1.6	1.4	1.4
Brass★			1.4	1.3	1.3
Lead			14.0	12	

After Quinn and Sigl (1980).
★Brass containing lead will have a higher equivalence value.

Scatter

Several different processes may give rise to scattered radiation but a discussion of these is beyond the scope of this book (discussion of the various mechanisms is included in texts such as Farr and Allisy-Roberts 1997 and Halmshaw 1995). Some consideration of scatter is important, however, because if scattered radiation reaches the film it does not provide useful information but tends to 'fog' the image with the visual equivalent of noise.

The thicker and more irregular in shape the object is, the more scatter tends to occur. Additional scattered radiation may be generated when the primary and scattered X-rays strike the floor, or any other objects in the immediate vicinity (Figure 1.9). To improve image clarity it is important to reduce scatter to a minimum, and there are a number of steps which may be taken to do this. As discussed, using a sheet of copper (between 0.6 and 2 mm thick) to filter the X-ray beam as it emerges from the exit window of the tube will remove the softer, more easily scattered components: this is useful when radiographing thicker and denser objects (cast statues, for instance). The spread of the beam can be reduced by a heavy metal diaphragm at the X-ray set and a localizer (a metal cone) which acts as a diaphragm between the X-ray tube and the object, preventing the sideways spread of the radiation. Lead sheet laid under the cassette will help to prevent scatter from the floor or table. Scatter can also be reduced by masking around the object with lead sheet, lead shot (in bags) or barium putty (wrapped in plastic). Above about 120 kV, it is usual to put thin card backed lead sheet on either side of the film in the cassette. As well as cutting out scatter this also intensifies the image by the emission of electrons which contribute to the

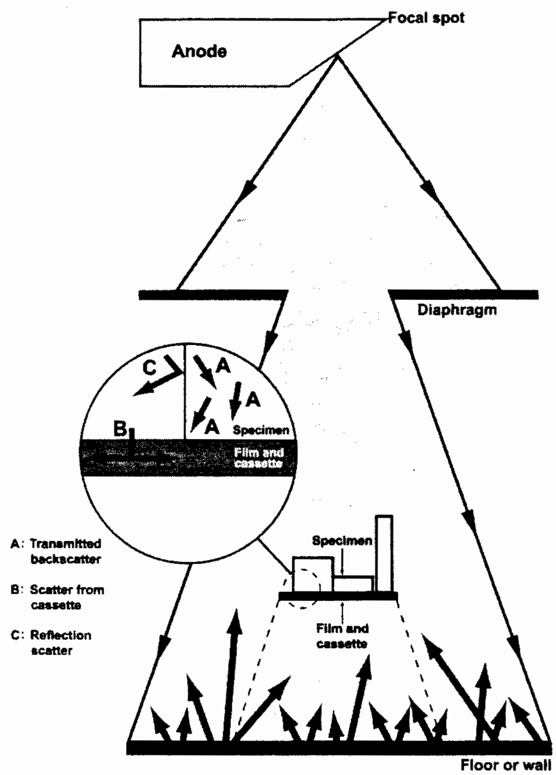

Figure 1.9. *Diagram showing how scattering occurs in radiography.*

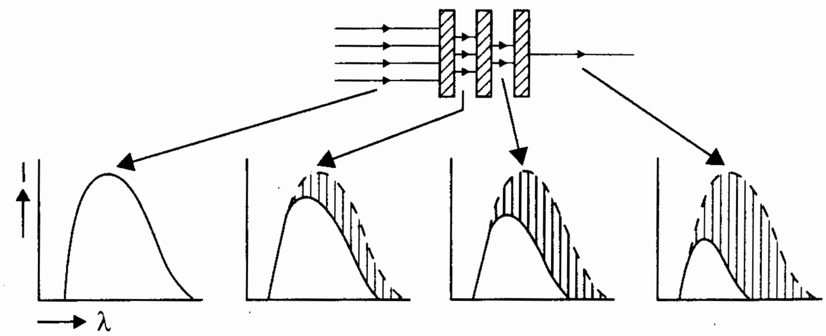

Figure 1.10. *Schematic representation of the effect on the X-ray beam as it passes through successive filters. Intensity and* λ_{max} *are reduced (after Gilardoni 1994).*

development of the image; and the exposure latitude range is increased (see also Chapter 2).

In the medical field, various grids are used; these are made of lead slats arranged and shaped so that the scattered radiation is absorbed by the lead, while the undeviated X-rays from the primary beam pass between the slats when the tube is correctly positioned in relation to the film. To avoid an image of the lead slats appearing on the film, the grid may be motorized (e.g. the Potter-Bucky grid), so that it moves across the film while the exposure is taking place (see Farr and Allisy-Roberts 1997). Such grids are not normally used for cultural material as they are relatively expensive and require longer exposure times.

Filters

The fact that X-ray attenuation varies with the energy of the incident X-rays can be put to good effect. The diagram reproduced as Figure 1.10 shows how the overall intensity of the continuous spectrum X-ray beam is reduced as it passes through several sheets of metal. The less energetic, longer wavelengths are less penetrating and are absorbed more readily, so that the proportion of shorter wavelength X-rays in the emerging beam increases and effectively the beam is harder and more penetrating. However, a longer exposure or higher current is required to compensate for the loss of intensity.

To utilize this effect in practice, metal filters are attached just in front of the window of the X-ray tube. An aluminium filter (about 1 mm thick) will remove the longest wavelength X-rays but, to harden the beam appreciably, copper sheet (usually from 0.6 mm to several millimetres in thickness) or lead (0.25 mm at 150 kV, 0.5 mm at 200–250 kV) are used. The resulting hard and homogeneous radiation is employed in electron radiography (see Chapter 5).

Inverse Square Law

When X-rays leave the target, they travel in divergent straight lines so that a cone-shaped beam is generated by a point source. The intensity of the beam decreases as it moves away from the source, spreading out and covering an increasingly wide area (Figure 1.11). The relationship between the intensity and distance from the source can be expressed by the equation:

$$I_2 = I_1 \cdot D_1^2/D_2^2 \qquad (1.4)$$

if the intensity at a distance D_1 is I_1 and the intensity at D_2 is I_2.

This relationship is known as the *inverse square law*: if the distance of the object from the X-ray source is doubled from say, 50–100 cm, then the intensity at the object will be reduced to a quarter of its original value. If the object is placed too far away from the X-ray tube there will be insufficient intensity to make a radiograph in a reasonable time. Source-to-film distances of between 60 cm and 1 m are commonly used with conventional X-ray sets. Using a shorter distance has the disadvantage that the image quality deteriorates, although the intensity is greater.

Geometric Considerations

Geometric factors influencing the quality of the image, apart from the size and shape of the object

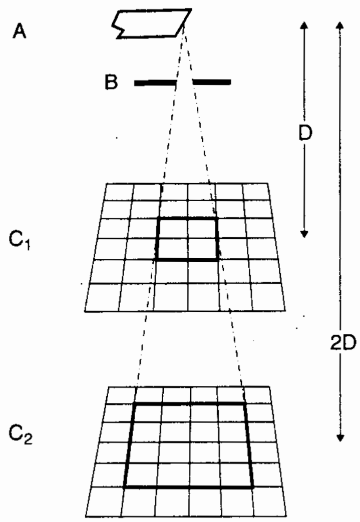

Figure 1.11. *Diagram showing the effect of the inverse square law.*

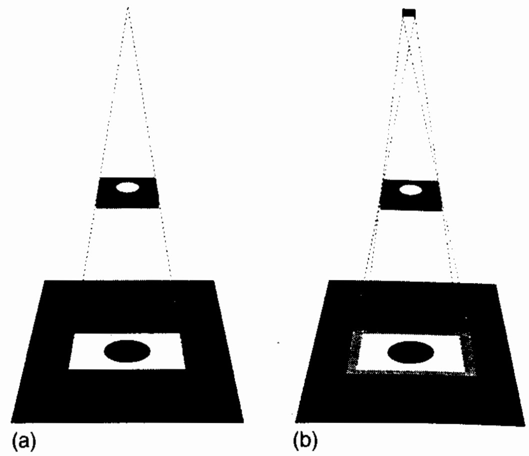

Figure 1.12. *Effect of geometry on the shadow image. (a) Point source with a large distance between the source and the subject: the shadow is sharp edged. (b) Larger source with the same distance between the source and the subject; the shadow has a penumbra or unsharp edge (after Quinn and Sigl 1980).*

itself, include the size of the source (or focal spot), and the spatial relationships between the film, object and source. A good quality image is required to be sharp and the geometric unsharpness, U_g, can be expressed by the formula:

$$U_g = S\, b/a \tag{1.5}$$

where S is the size of the source, a, the object-to-source distance and b, the object-to-film distance. If S is large, or the object-to-film distance, b, is large, U_g increases; in other words, the quality deteriorates. These effects are summarized in Figures 1.12 and 1.13. If the unsharpness increases, the detection of changes in contrast becomes more difficult. If a feature is small (an engraved line, for instance), the difference in contrast between the feature and its background may not be visible (Figure 1.14).

From the figures it can be seen that it should be possible to magnify the image by increasing the object-to-film distance, b. But it is also apparent that because industrial X-ray sets have relatively large focal spots (typically about 1 mm by 1 mm or more), any attempt to deliberately magnify the image on the film by moving the object away from the surface of the cassette will be frustrated: because the unsharpness, U_g, will usually increase to an unacceptable level. Stegemann *et al.* (1992) have expressed the relationship between the magnification (M), the

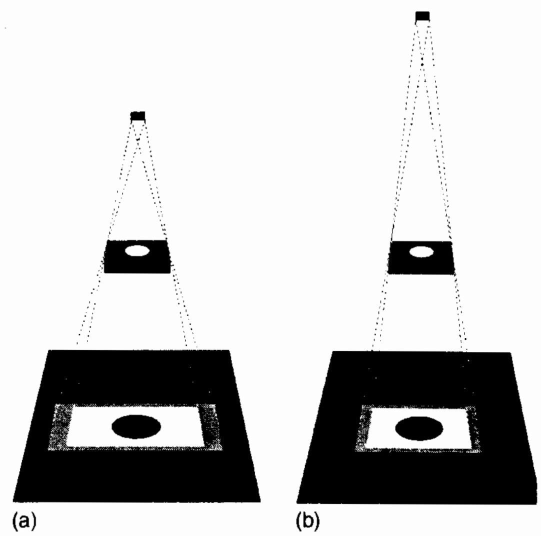

Figure 1.13. *Effect of geometry on the shadow image. As the distance between the source and the subject is increased between (a) and (b), the size of the penumbra in (b) is reduced (after Quinn and Sigl 1980).*

unsharpness (U_g) and the size of the source (S) by the equation:

$$U_g = S(M - 1) \tag{1.6}$$

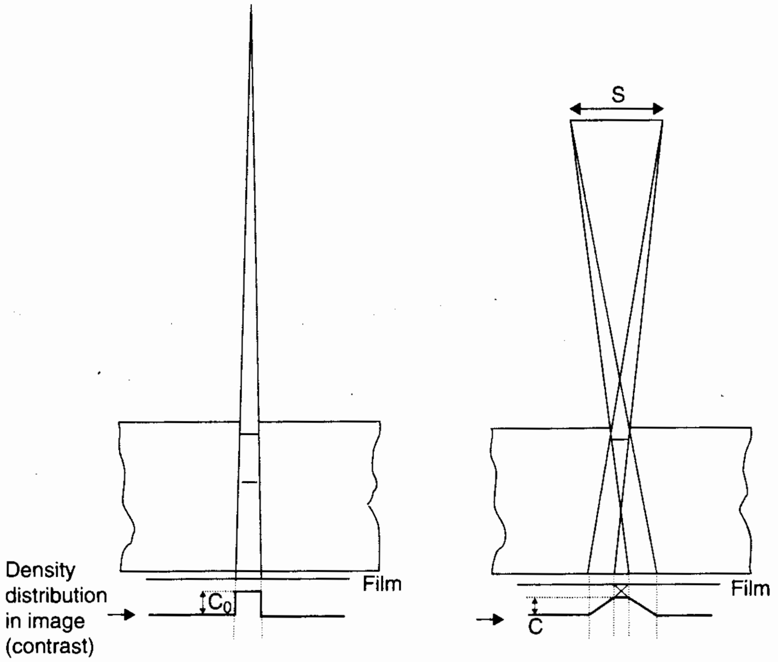

Figure 1.14. *The effect of geometric unsharpness on the image of a small feature, resulting from a large source, S and a reduction in the distance between the source and object: the edges are less defined and the contrast is reduced (from C_0 to C) (after Halmshaw 1995).*

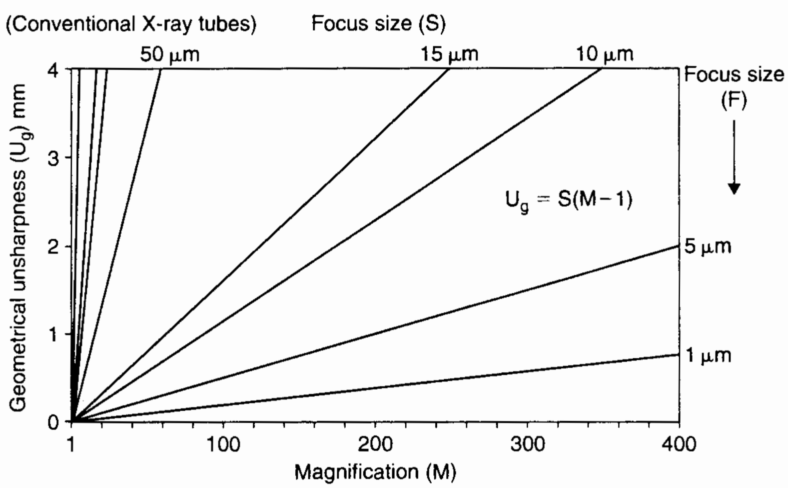

Figure 1.15. *Relationship between focal spot sizes 2 mm to 1 μm, the magnification (M) and the unsharpness, U_g (after Stegemann* et al. *1992).*

If small features or discontinuities, say less than about 1 mm, are being examined, the geometric unsharpness obviously must not exceed 1 mm and, ideally, should be significantly less than this. If the source size is 1 mm, the equation shows that the unsharpness will be unacceptable when the magnification exceeds a factor of 2. With a microfocus tube, however, source size (S) is extremely small (say 0.01 mm), so that high magnifications may be possible without significant loss of quality (Figure 1.15). This is illustrated by the magnified image of part of a Brazilian banknote (Figure 1.16) in which fine details are clearly visible. The potential of microfocus X-ray tubes has not been extensively exploited in the archaeological field as yet, but work on the methods used to join the links of mail from the Anglian helmet from York (Tweddle

Figure 1.16. *Enlarged image of scanned radiograph of part of a Brazilian banknote. The original radiograph was produced using a microfocus X-ray tube. See also Figure 9.6(b).*

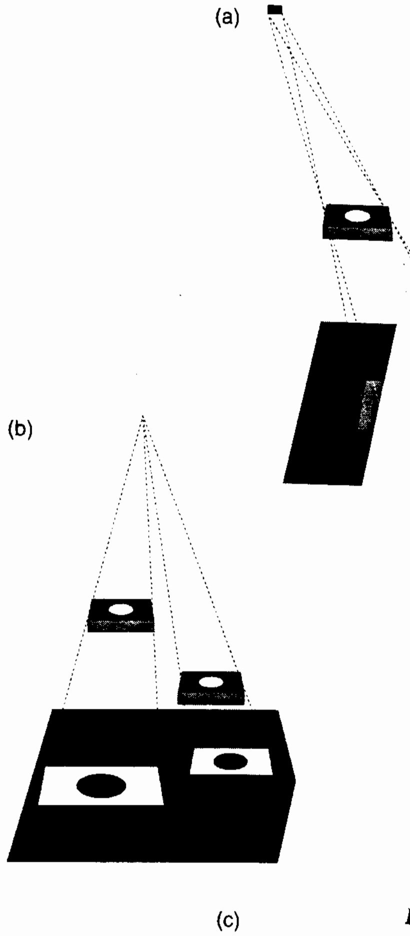

Figure 1.17. *D*
occurs if the subje
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1992), using a microfocus tube, shows that it can be a valuable non-destructive tool for the examination of small areas.

Distortion of the image and other misleading results due to geometric effects are also possible, as illustrated in Figures 1.17 and 1.18. The handles of the 14th century AD inlaid lacquer sutra box (Figure 1.18) are the same size, but the one which was further away from the film has been enlarged. The orientation of any fault or feature of interest relative to the X-ray beam is an important consideration when positioning an object. Ideally, the centre of the X-ray beam should be perpendicular to the film and pass through the middle of the feature. Unfortunately, as shown schematically in Figure 1.19, it is not possible to arrange this in all situations: the

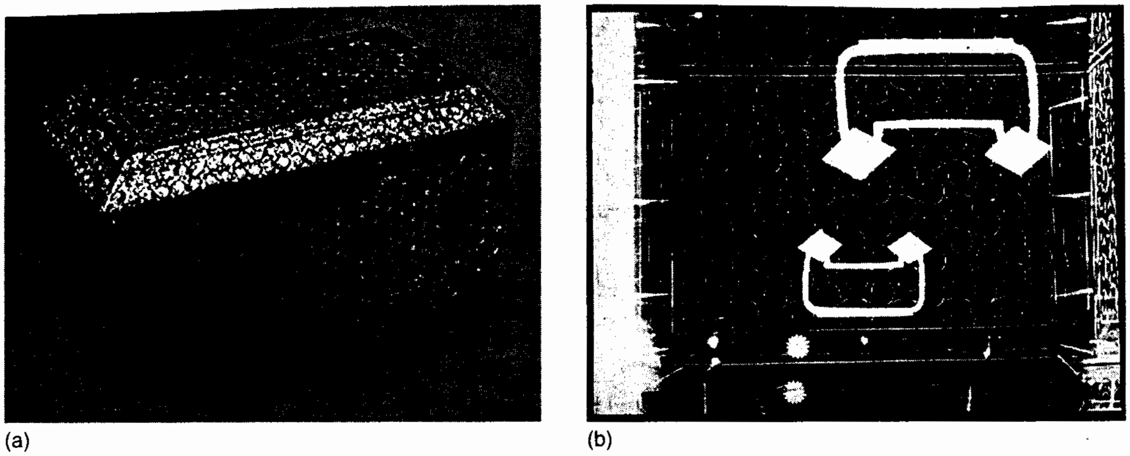

Figure 1.18. *(a) 14th century AD Korean lacquer sutra box with brass handles and inlaid with metal wire and mother of pearl. (b) The handle and wire on the end furthest from the film are enlarged on the radiograph, the nails holding the box together can be seen but the mother-of-pearl inlaid is not dense enough to show.*

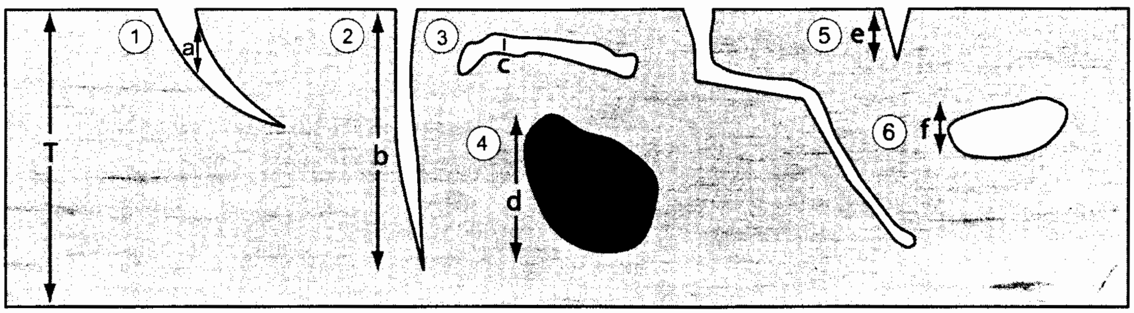

Figure 1.19. *Effects of orientation, geometry and material on the imaging of features. (1) Oblique crack. Distance X-rays travel through the material of the bar (path difference) T − a, but the value of 'a' varies in this case, depending on the orientation and thickness of the crack. (2) Near-vertical crack, depth 'b'. Path difference T − b. (3) Thin horizontal crack, depth 'c'. Path difference T − c. (4) Inclusion of denser material provides a lighter area on the radiograph; the difference depends on the absorption of the material and the thickness, 'd', of the inclusion. (5) Shallow engraved line, depth 'e'. Path difference T − e. (6) Void, depth 'f'. Path difference T − f.*

orientation of the features or their very existence may not even be known, there may be a multiplicity of features with different orientations, or the overall shape of the object may be awkward.

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2

Radiographic images

Janet Lang, Andrew Middleton, Janet Ambers and Tony Higgins

Methods of recording radiographic images, film, X-ray paper, Xeroradiography, fluoroscopy, digital radiography; image quality; image processing; stereoradiography; computed tomography; practical radiography, image quality; problems; setting up and running a radiographic facility

RECORDING RADIOGRAPHIC IMAGES

As X-rays cannot be perceived by eye, the X-ray image must be registered on a suitable material to make it visible. The image may be recorded permanently on photographic film or paper. Images have also been recorded using xeroradiography plates or they can be viewed in real-time on fluorescent or sensitive screens, perhaps linked to a monitor or digital recording system.

Film

Characteristics of Film

Film is probably still the most common method of recording the image, although digital recording is increasingly being used. It is an integrating medium: the nature of the image depends not just on the intensity of the X-ray beam (determined by the tube current, in milliampere, for a given kilovoltage) but also on the duration of the exposure. For this reason, radiographic exposures are often expressed as the product of intensity and time (e.g. mAs or mAmin):

$$E = It \qquad (2.1)$$

This relationship between exposure (E), intensity (I) and time (t) is known as the *reciprocity law*. Film is relatively cheap to buy and to process, does not require any expensive or complex equipment and provides a permanent record. Fortunately, sheet film is available in a variety of sizes, as the radiographic examination of antiquities frequently requires the use of sizes ranging from small dental films to large sheets. Occasionally, exceptionally large sheets have been made specially for radiographing statues. Film is processed using proprietrary photographic chemical solutions which must be handled and disposed of safely (see Box 1.2). Manual Processing in tanks is preferred by some as it is simpler to ensure a long fixing period (e.g. 15 min) and thorough rinsing for film longevity. Use of a film processor is convenient because it avoids mess and saves time, as the film emerges dry and ready for examination (see also Box 2.2). Detailed information concerning the use and processing of film to record radiographs is provided in several standard texts including that by Halmshaw (1995, pp. 76–95) and those produced by Kodak (Quinn and Sigl 1980, pp. 71–107) and Agfa (Halmshaw 1986, pp. 107–24). In this section we will consider briefly only some of the factors which may affect the quality of the radiograph obtained.

Industrial X-ray films usually have an emulsion containing a suspension of silver halide salts (usually of the order of 1–10 μm particle diameter) in gelatin attached by a thin layer of adhesive to both sides of the support film, with a thin coating layer to protect the surface. This double-sided emulsion effectively increases the speed of the film. The level of detail which can be recorded and subsequently developed generally depends on the grain size and thickness of the emulsion layer: a smaller grain size gives better definition and finer detail, but needs a longer exposure. The graininess of the image increases with the energy of the radiation and a γ-radiograph is usually grainier than an X-radiograph, which is one reason why X-radiation is often preferred. Graininess also increases with the length of the development time and the type of developer used.

For some applications, such as the electron radiography of paper, a double emulsion is not desirable and it may be preferable to use a single emulsion film (e.g. medical mammography film) or to take special precautions during processing to avoid development of the emulsion on one side of the film. This is discussed more fully in Chapter 5, where techniques for electron radiography of paper are described.

The photographic emulsion itself contributes to the unsharpness of the image. This inherent unsharpness (U_f) arises because the X-ray beam has sufficient energy not only to interact with the photographic emulsion, making the silver halide crystals developable, but also to produce some secondary electrons. These may have enough energy to move through the emulsion and interact with further nearby silver halide particles. These are also developed, so that the image shows gradual rather than sharp changes of density at edges and discontinuities. The magnitude of this effect increases with X-ray energy but Halmshaw (1971) has shown that the level of interaction is similar for different radiographic films.

Films are available with a wide range of characteristics. The choice of film is usually influenced by the subject and the type of investigation. Industrial direct-exposure films of moderate-to-fine grain size are most frequently used for archaeological radiography and are produced by well-known manufacturers, such as Agfa, Fuji and Kodak. The manufacturers supply details of the characteristics of their films and suitable processing regimes. More general information can be found in the various reference books listed at the end of this chapter. The European Standards Organisation has proposed a system of classification (CEN: prEN-584-1:2005-11); Table 2.1 (after Halmshaw 1995) provides information for some well-known films. For most purposes medium-to-fine grain film (e.g. C5) is used because it is faster, allowing shorter exposure times and providing good detail for most objects, but for the finest detail and highest image contrast a very fine-grained film (C3 or C1) is used, despite the disadvantage of requiring a longer exposure. When in doubt, both films can be used together in the same cassette.

This can also be a good way of capturing the radiographic image of an object which has a range of cross sections or is made from different materials.

Table 2.1. Data on some films suitable for radiography

CEN class	*Film*	*Manufacturer*	*CEN speed*
C.1	D.2	Agfa Gevaert	50–30
	IX25	Fuji	–
C.3	D.4	Agfa Gevaert	100
	MX	Kodak	125–100
C.5	D.7	Agfa Gevaert	400–250
	IX100	Fuji	–
	AX	Kodak	320–250

Data from Halmshaw (1995).

Metallic archaeological objects, for example, are often partially corroded; the corroded areas are much less dense than the sound metal parts, which are likely to be thicker and will also be denser. If only one grade of film is used, several exposures may be needed to show the detail in all areas (but see Digital Processing below).

Special high-resolution plates and film (e.g. Kodak high-resolution film DR (double sided) or FR (single sided)) have been used, in conjunction with X-ray sources normally used for X-ray diffraction, to study the microstructure of thin sections of minerals, composite materials and ceramics. The extremely high resolution of the plates means that they can be examined with a transmitted light microscope at useful magnifications of up to ×100 (Clark 1955; Niskanen 1959; Darlington and McGinley 1975). High-resolution film has also been used to examine cast structures (Williams and Smith 1952; Barkalow 1971), the distribution of inclusions or discontinuities by taking film stereopairs (see below and Chapter 3).

The degree of blackening of a film is known as its density; a densitometer can be used to provide a quantitative measurement of film blackening, relating the incident light intensity (I_0) to the intensity of the light transmitted through the film (I_t). The photographic density, D, of a film is defined as:

$$D = \log_{10}(I_0/I_t) \qquad (2.2)$$

Clearly, the density is related to the exposure, E, received by the film and this relationship is conventionally shown by plotting density, D, against the logarithm of exposure ($\log_{10}E$). The resulting graph for a typical film is shown in Figure 2.1; this is known as the characteristic curve for that film. Figure 2.1 shows that control of the exposure can be used to

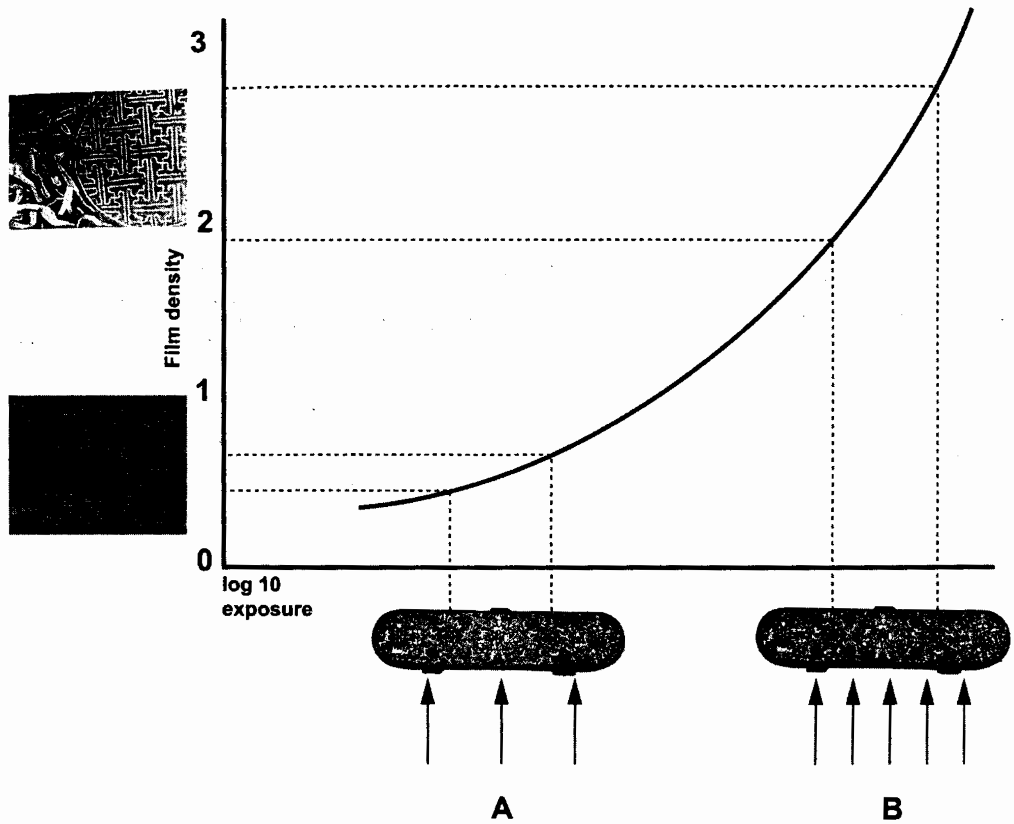


Figure 2.1. *Graph of film density versus log_{10} exposure (characteristic curve for a typical X-ray film) shows that a shorter exposure (A) gives a lower film density and less contrast (see also Figure 3.7(a), (c)) (after Halmshaw 1986).*

produce radiographs with more or less contrast as required. Film density measurements are used mainly in industry, where standardized conditions are important for comparing welds and in quality control. Typically, industrial codes and standards require values of between 1.8 and 4, when only 0.01% of transmitted light reaches the far side of the film. When films are digitized and processed, imaging of the detail is assisted by a slightly higher film density than would be needed for direct viewing. Monitoring film image quality is discussed below. Charts indicating appropriate exposures (mAs) for different thicknesses of various materials at various kilovoltage settings are used industrially, and may sometimes be applicable to archaeological material.

Cassettes and Screens

Film in sheet form is usually exposed in a light-tight cassette which allows it to be handled in the light without risk of exposure. A variety of cassettes is available. A simple black plastic envelope of the type used for film or photographic paper (*Note*: some bags produce distracting textured or striped images on the radiograph.) can be used with a light-tight closure is used when radiographing low-atomic number materials such as card or fabrics at low kilovoltage, or when a soft, flexible cassette is needed to fit a curved surface. At very low kilovoltage, when radiographing paper, for example, it may be necessary to dispense with a cassette altogether. The most commonly used cassette is rigid and designed to open like a book, being hinged at one side. It may be made of metal or plastic and has a front which is radiolucent and must face the X-ray set. The back is made from heavier material to make it radio-opaque. The cassette contains a pressure pad which ensures close contact between the film and intensifying screens when these are used. In very-low-energy applications, such as the radiography of paper, vacuum

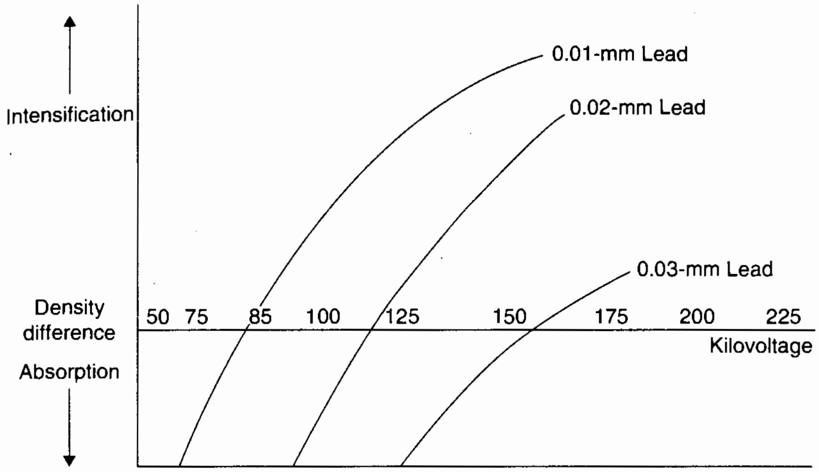


Figure 2.2. *Effects of kilovoltage on intensification properties of lead screens (after Quinn and Sigl 1980).*

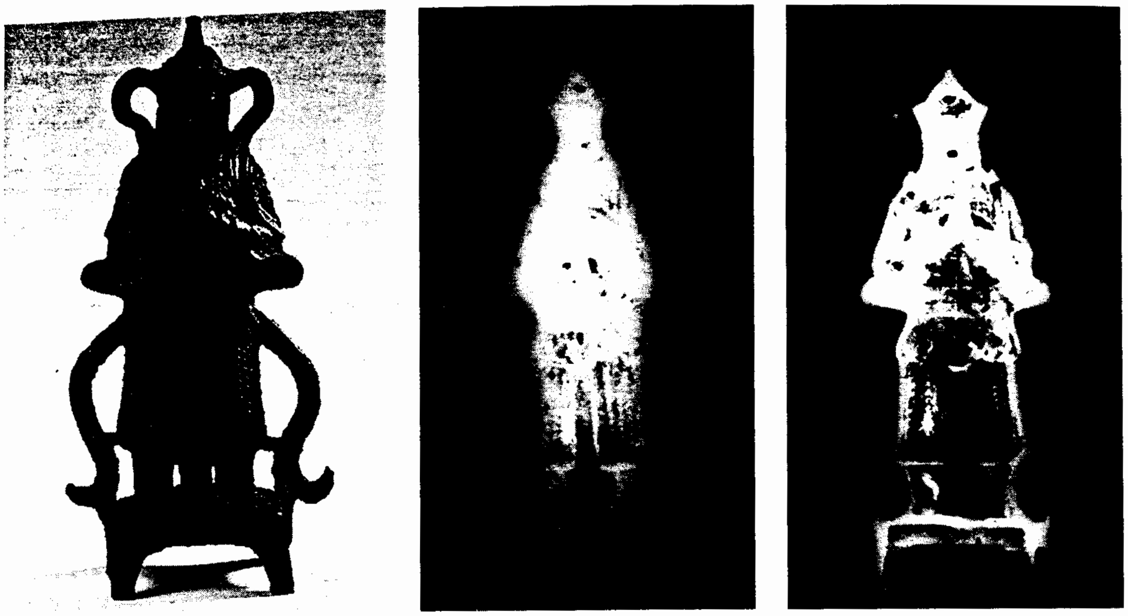
or helium-filled cassettes improve the contact between paper and film (Bridgman *et al.* 1958; Graham and Thomson 1980; Rendle 1993).

In order to reduce the exposure time it is possible to intensify the image by using an intensifying screen, which may be of the salt screen type or a sheet of lead metal. Salt screens produce fluorescent visible or ultraviolet light and have a high intensification factor. They are used in the medical field and also for paper (Chapter 5), but they are rarely used in industrial radiography because there is considerable loss of detail (Halmshaw 1995, p. 94). Lead screens have much lower intensification factors than salt screens but offer two advantages, both of which lead to a reduction in 'noise'. Firstly, they absorb the softer, lower-energy X-rays which have been scattered and would otherwise reduce the clarity of the image. Secondly, the intensification effect is greater for the primary radiation than for the scattered radiation. Intensification occurs because, as higher-energy X-rays (<120 kV) (or γ-rays) pass through the lead screens, electrons are emitted which augment the effect of the X-rays on the photographic emulsion, reducing the exposure time and improving the contrast of the image. The result is a high-quality image with the image contrast of low-kilovoltage images and the penetrating power and exposure latitude of high-kilovoltage images. The screens consist of sheets of polished lead foil, commonly between 0.02 and 0.15 mm thick, backed with stiff paper on one side. To maximize the effect of the electrons it is necessary to have the best possible contact between film and screen, so that the screen is normally used inside the cassette with the lead foil facing the film.

The intensification factor of lead is generally less than five (i.e. the exposure for a desired film density can be reduced by this factor) and it is most effective with harder radiation above c. 120 kV (Figure 2.2). However, lead screens are also used with softer radiation (Figure 2.3) to filter the scattered secondary radiation generated in the specimen. Thin sheets of lead have a greater intensifying effect than thicker ones, although the latter reduce scatter more effectively. For this reason front screens, lying between the film and the object, are between 0.025 and 0.15 mm thick to enhance the intensifying effect of the electrons, whereas back screens are thicker to reduce scatter and should be a minimum of 0.1 mm (for use up to 400 kV).

X-ray Paper

Special X-ray paper, produced by major film companies such as Agfa and Kodak for example, is about 10 times faster than the fastest film and is designed to provide rapid-access, low-cost radiographs. The emulsion is on one side of the paper only and contains developing agents. The paper is loaded into a rigid cassette with a salt intensifying screen in direct contact with the emulsion. A phosphor (calcium tungstate) coating on the screen converts the X-ray image to a pale blue light, which is photographically recorded by the paper's emulsion. The image quality is not as good as that of a fine-grained film. The paper can be



(a) (b) (c)

Figure 2.3. *(a) Cast iron Chinese figure, 16th century* AD *(OA 1990-5-20.1), (b) radiograph made at 7 mA, 3 min, 100 kV, no lead screens, and (c) radiograph at 7 mA, 7 min, 100 kV with lead screen back and front. (b) and (c) both at 1 m, Kodak AX film without filters. Adding lead screens increases the exposure time needed, but reduces scatter.*

processed with the same regime as X-ray film, but for permanence requires a final fixing with conventional black and white paper fixing solution.

Xeroradiography

Xeroradiography was developed as an alternative method of recording medical X-ray images (Boag 1973). The techniques used are similar to those used in the Xerox photocopying process but the recording medium (xeroradiography plate) consists of a layer of amorphous selenium, uniformly deposited on to an aluminium backing plate.

The main features of the xeroradiographic image are as follows:

- *Edge enhancement*, producing sharp delineation of boundaries, including those concealed by overlying structures, good resolution of fine details (e.g. fractures, voids and joins).
- *Wide exposure latitude*, allowing objects of widely varying density to be included in the same radiograph.
- The image is virtually *impervious to scatter* because scattered radiation, whilst reducing the overall charge slightly, has only a minimal effect upon the edge enhancement effect.
- The *image is reversed* with respect to the original and may also be made positive or negative, so that it is important to avoid any confusion in interpretation.

Several studies have been published comparing the results from xeroradiography with those obtained using film to radiograph archaeological materials (e.g. Alexander and Johnston 1982; Watts 1994). In many instances the two techniques have been found to be complementary.

Xeroradiography has been particularly useful for ceramic materials (Chapter 4), for human remains (Chapter 7) and for objects made of organic materials such as wood (Figure 2.4). Xeroradiography of the Winchester Reliquary (Keene 1987) revealed more details of the interior than conventional radiography, and the xeroradiograph of a 19th century Japanese Buddha (Figure 2.4) gives an admirably clear view of its construction. However, xeroradiography is now essentially obsolete because it is no longer used in the medical field and is not supported by the industry. For this reason we have omitted most

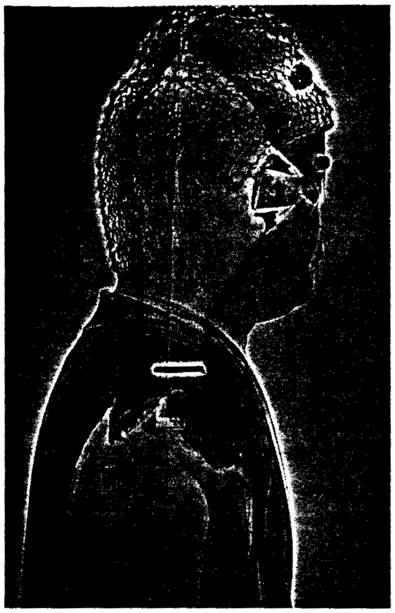


Figure 2.4. *Xeroradiograph of an 18th century AD Japanese wooden Buddha figure, showing the inserted stones in the forehead and hair, and the construction of the eyes, with some glue holding the eye block in position. A metal clip at the shoulder and the wood grain in the dowel at the shoulder can also be seen (OA 1945-10-17.309).*

of the technical details of the method (for these the reader is directed to the first edition of this book). Fortunately most of the features observable by xeroradiography can be achieved digitally by processing images scanned from conventional film radiographs (O'Connor *et al.* 2002) (Figures 2.5 and 2.6) (see below and also Figure 4.3).

The Sensitive Screen (fluoroscopy)

Observing the X-ray image on a sensitive screen is not a recent development. Röntgen himself used a fluorescent barium platinocyanide screen to detect X-rays in his experiments (Röntgen 1896). Fluoroscopy has been used both industrially and medically. In its simplest form, a system consists of a source of X-rays, a fluorescent screen and a means of viewing the screen, either through a lead glass window or by a mirror. If the X-ray tube has a fine focus (0.1–0.5 mm focal spot) the object can be moved away from the screen and an enlarged image obtained. Fluoroscopic systems can be 'stand alone', but the images obtained are often of rather low brightness. The image can be preserved by photographing the screen: this has the advantage that the film contrast can be chosen to enhance the image contrast. The integrating effect of a film exposure can also be advantageous.

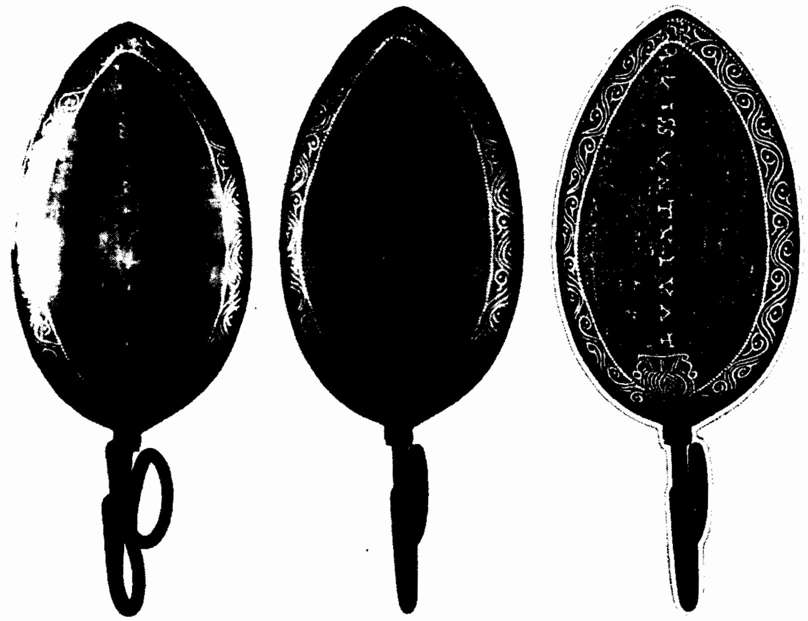
In more sophisticated systems, a remotely controlled manipulator allows the object to be moved while it is in the X-ray beam, allowing a 'real-time' examination. The advantages of such real-time viewing systems are obvious: a large complex of objects (e.g. material from excavation) can be surveyed quickly, allowing rapid assessments to be made for micro-excavation and conservation or for identifying the optimum position for conventional radiography. Moving an object in the X-ray beam produces an almost three-dimensional (3-D) effect; the relative speed with which the components move past each other on the screen allows the observer to form an impression of their relative positions in three dimensions.

Various changes have improved the basic systems; the image intensifier has been developed to give a brighter image, which is usually captured with a CCD camera. The image is transmitted by the camera to a monitor and can be viewed in real-time; the image may be simultaneously recorded on a video recorder, digitized for image processing, or digitally archived.

The criterion of the number of line pairs per millimetre (lp/mm) is commonly used to compare the resolution of different imaging systems: it is the smallest gap between pairs of wires which can be distinguished. For instance, a typical aluminium window/cesium iodide phosphor intensifier is quoted as having a resolution of 4.6, 5.4 and 9 lp/mm for fields of view of 220, 160 and 120 mm, respectively; the resolution of film, similarly expressed is typically 200 p/mm. There is some additional loss of quality as the image is transferred through the camera to the recording medium. Film is therefore better for an accurate representation at high resolution, but the convenience and versatility of image intensification, combined with digital recording and processing has some advantages especially for excavated block complexes. The introduction of microfocus tubes for some applications has improved image quality.

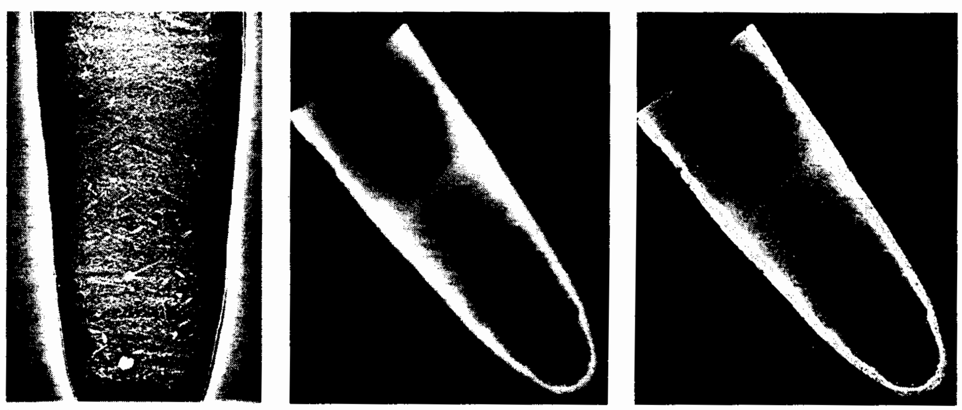
Digital Radiography

Traditionally, radiographic images have been collected on various forms of film or paper, but there



(a) (b) (c)

Figure 2.5. *The Roman* cygnus *spoon no. 103 from Hoxne shows an inscription and decorated border, but the geometry and variable thickness makes it difficult to see the details (see also Figure 3.26, Plate 3.3). It seems to have been deliberately abraded. The radiographs show the decoration and the inscription QVIS SVNT VIVAT, written as a single word. Two different exposures are shown at the same source-to-film distance (1 m): (a) exposure at 7 mA, 90 kV, 20 min, front and back lead screens, Kodak MX film, no filter and (b) exposure at 7 mA, 10 min, 100 kV, front and back lead screens, Kodak AX film, 0.6 mm copper filter. In (a) the contrast is greater because the kilovoltage was lower, and the scrape marks on the bowl show mossre clearly. In (b) the contrast is reduced because a copper screen was used to reduce the low-energy component of the beam. A shorter time was used because the film was faster. Curved objects like these spoons with shallow designs and variable thickness may need several exposures to extract all of the details. In (c) the image (b) has been processed with a high-pass filter and contrast adjustment to make the design more visible and the longitudinal scrapemarks can be seen on the bowl. The appearance is similar to a xeroradiograph.*



(a) (b) (c)

Figure 2.6. *Radiographic images of an Egyptian pottery ibis case. (a) xeroradiograph, (b) unprocessed film radiograph, and (c) digitally scanned and processed 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.*

is an increasing move towards the use of digital images. It seems likely that radiography will follow the pattern shown by photography and move with increasing speed in this direction. As with all forms of computing the equipment and programs available in this field change with bewildering speed, both in terms of what is possible and in cost, so it is not intended to go into great detail here. This section is instead intended as a brief overview of the characteristics of this format and the ways in which such images can be genserated; those with a particular interest in this topic are advised to consult manufacturers and recent literature as to what is available within their budget. At the time of writing, Jones *et al.* 1998; O'Connor & Maher 2001 and O'Connor *et al.* 2002 provide a good starting point for such an investigation.

Expressed in the most simple terms, a digital image is best defined as an image made up of tiny picture elements (pixels), each of which is represented in binary code. A computer is necessary to view this information as an image. In general, the more processing power and faster the computer used the better, particularly in the case of digital radiography, where large file sizes are required to get good images (around 120 mb for a standard 43 × 35 cm plate). Large and good quality monitor screens are also an obvious requirement.

Factors Determining Digital Image Quality

Three factors need to be taken into account when considering digital imaging systems; the resolution, the bit depth and the dynamic (optical density) range. To optimize imaging, all of these factors need to be as large as possible. Unfortunately, any increase in quality tends to be accompanied by an even more dramatic increase in price:

- The *resolution* is defined by the number of pixels per inch present on the image. At the time of writing the best quality digital radiography equipment operates at around 500 pixels per inch. This is the equivalent of approximately a 50 μm grain size in conventional film; a high resolution, but not yet equal to the finest-grained film stock (*c.* 1–10 μm).
- *Bit depth* is a rather more difficult concept to grasp, but controls the number of colours (or in the case of radiographs, shades of grey) which each pixel can represent. The higher the bit depth, the larger the number of shades of grey that the digital image can contain. An 8-bit system can display 256 shades of grey, a 12-bit system 4096 and a 16-bit system 65,536. Given that the human eye can only distinguish between around 50–60 different shades of grey, the advantages of a digital system are immediately obvious. At present, most purpose designed digital radiography systems operate at a bit depth of 12.
- *Optical density* is a term used to define the darkness or lightness of a grey shade held on a radiograph. *Dynamic range* defines how wide a range of optical densities can be recognized in the digital image. Industrial radiographs tend to have a wider dynamic range, with a larger range of near blacks and near whites, than those produced in medical facilities, where the dose rate to the patient is the main consideration. Digital radiographic systems designed for medical purposes therefore tend to have a lower dynamic range than those designed for industrial systems. Again, the wider the dynamic range available the better (but also the greater the expense).

Production of Digital Images

There are currently three methods by which digital radiographic images can be produced: by digitizing the film image with a scanner, by indirect capture, or by direct capture. Each has advantages and disadvantages. These are summarized below in the light of the current state of technical development of the various methods, but, given the speed with which all computer-based facilities develop, these should be treated as a 2004 snapshot. Any potential user should contact manufacturers for current information.

- *Film digitization* is used with film produced by conventional methods. This is scanned to give a digital file. Scanning can be carried out using a wide range of equipment, from a fairly simple, non-specialized, flatbed scanner (providing that it is fitted with a transparency adaptor) through a range of specialized radiographic scanners of either flatbed or roller design. Non-specialist scanners are limited in usefulness because of poor dynamic range and limited physical size, and the use of specialist equipment is strongly recommended. Of the specialized equipment, industrial style scanners tend to be the best suited to work on cultural materials, as they have the greatest dynamic range, but this is achieved at considerably increased cost. Scanning is probably the digital technique most readily available to those involved in work on cultural material; it is the cheapest option, can be used to record pre-existing film stocks, and can be easily outsourced to a number of extant facilities. Used carefully it can produce extremely good images with all the advantages that the digital format supplies (see below). It is, however, an indirect method and offers none of the savings of time or chemical-free properties of purely digital radiography. Digital cameras and video cameras used in conjunction with a light box are sometimes used for details but the image quality is likely to be less satisfactory than small, purpose-built industrial scanners.

- There are currently two methods of *indirect capture* (frequently termed computed radiography or CR) available, involving the use of either flexible phosphor films or flat panels. These are used in place of the films in conventional radiography. Here exposure to an X-ray beam generates a light emission which is then collected electronically to form the image. The exposures required are considerably shorter than those needed to generate images on standard films and the latitude of exposure is higher. The inclusion of a light-dependent stage does mean however that a degree of scatter is generated. No chemicals are needed, with savings in both time and disposal costs. Phosphor films have the advantage of being flexible, so that they can be shaped around objects, but have the disadvantage of requiring a separate plate reader. Flat panels do not require a reader, but are rigid. Both phosphor films and flat panels can be cleared and reused numerous times.
- The final option is *direct capture*, (also known as direct radiography or DR) where the object under examination is placed onto a flat plate and exposed to an X-ray flux. The image is generated directly in the dielectric plate and converted immediately into a digital file. This method produces by far the best image, instaneously, with no light scatter and at high resolution. Again, exposure times are very much shorter than those used with conventional film and there is a wide-exposure latitude, together with no requirement for chemicals. Unfortunately, direct capture is also by far the most expensive of the options available and is unlikely to be generally available within the field of cultural materials for many years. Other disadvantages include a rigid plate which cannot be repositioned to suit the object. The plate is also susceptible to extremely costly damage if treated roughly.

Viewing Digital Images

However the digital image is collected, a suitable computer with a large and high-quality viewing screen will be needed, together with an appropriate image manipulation program. These things will generally be considered with the purchase of any digital radiography equipment and will often be supplied by the same manufacturer, but if it is intended to use only scanned images produced at an outside facility, it is quite possible to use some of the standard, commercially available image manipulation programs such as Adobe PhotoShop (see also Image Processing, below). In any case, for ease of use and storage, programs which are capable of producing images in standard file formats should be selected. Currently TIFF or DICOM (most frequently used in medical environments) are probably the file types of choice. Lossy file formats such as JPG should be avoided during interpretation or for long-term storage and used only for final publication or display purposes (see below).

Digital Radiography; Advantages and Disadvantages

After all the discussion above, and given the costs involved, the obvious question arises as to whether digital radiography is worthwhile. That question is probably best answered by the increasingly rapid movement towards digital format in every part of the radiographic field, as clearly exemplified by the recent announcement that the British National Health Service now intends to move to completely digital format.

File formats

The choice of file format to use with digital radiographs is particularly important. To save storage space, most file types are compressed before being written to a disc. This compression can be *lossy* or *non-lossy* (or lossless), with the description referring to the effect on the data of the compression process. Fairly obviously, in lossy formats, the compression is achieved at the cost of some loss of data (but with the advantage of considerably reducing file sizes). This effect is cumulative, with further losses occurring every time a file is saved in a lossy format. Lossy compressions exist for good reasons, being primarily designed to minimize the disc space and processing time required for an image whilst retaining as much sharpness as necessary for simple viewing, but are obviously not suitable for radiography, where the whole aim of the process is to collect and retain as much information as possible. For this reason lossy formats should be avoided for all purposes except simple display and publications. At the time of writing the most common non-lossy formats available are TIFF, DICOM (which can be compressed in either lossy or non-lossy format) and PNG (normally used for colour images). The most common lossy format, useful for publication, web display or widespread distribution, is JPG.

Image manipulation and enhancement

The greatest advantage of digital format is that it makes accessible evidence which has always been recorded onto film, but which was previously unavailable because of the limitations of human vision. As discussed above, a 12-bit system can distinguish between 4096 different shades of grey, in contrast to the 50 or so which can be differentiated by the human eye. Manipulation of the grey levels shown on the screen, accomplished with extreme ease by a few key strokes or movements of the mouse, can make these additional greys visible to the person reading the radiograph and allow the recognition of previously unseen features. Similarly, magnification is no longer a case of holding a lens close to a film balanced on a light box, but becomes a simple mouse movement, making detailed examination far more straightforward. Even if these were the only advantages of the use of digital radiography, they would make it more than worthwhile.

Image enhancement is also possible. Images can be sharpened, edges and voids clarified and artefacts removed using a wide range of filters. Which filters are appropriate is heavily dependent on the equipment being used and the purposes of the examination, and this is discussed in more detail below. An example of what can be achieved is given in Box 2.1, which describes how the details of the Ur helmet complex (Figure 2.7) were elucidated by digital processing of a scanned radiographic image.

Most proprietary radiography programmes also include a range of other features, such as on screen measurement tools, and some allow for more complex procedures, such as the addition of false colours to

Figure 2.7. *Ur helmet complex (BM ANE 121414).*

bring up certain features (Clogg and Caple 1996). Similarly, software exists to enable the mosaicing of several separate images together to produce a single image of large objects. At the time of writing, an image processing package (VIPS) used by many museums and galleries is available at www.vips.ecs.soton.ac.uk.

Archive and storage

One of the possible advantages of digital format radiography widely hailed at the early stages of development was that it could provide a permanent and space efficient method of archiving. Film, however well processed and stored, does have a finite-lifespan and is bulky, requiring large areas of dedicated storage space. As with most such novel equipment, this initial promise has proved to require some qualification. With increasing usage it is becoming apparent that forms of storage such as CD or DVD are not as permanent as once hoped, and may in fact have a lifespan equivalent to or less than that of film stock. Additionally, the file formats used to store images are constantly evolving and being superseded and even such widespread file types as TIFF and DICOM must be expected to be replaced in time, while the proprietary formats associated with some equipment are far more ephemeral. Unfortunately, archaeology is full of examples of databases constructed in now defunct file types, or stored on media, which are no longer readable. Such problems can be minimized

Box 2.1 Processing the image of the Ur helmet complex

Figure 2.7 shows the skull of a young adult male wearing a copper helmet, excavated by Leonard Woolley from one of the Royal Graves in the ancient city of Ur in modern day Iraq (Irving and Ambers 2002). Despite the early date of these excavations (in the 1920s), Woolley block lifted many of the objects found at Ur, including this (see Chapter 8 for an explanation of this technique). In this case the block was never fully excavated. Instead it was prepared for museum display supported on a board and with only the top surface cleaned, revealing the skull and helmet as found in the ground. Radiography was required to reveal more details of the helmet construction and to visualize the roots of the teeth, which are used to estimate the age at death. This presented a number of problems, most notably because of the wide range of radiographic densities present. The conventional approach here is to take a number of plates at a range of different exposures. An alternative can be to take a more limited number of exposures but to examine them in digital format, taking advantage of the increased range of visible greys. Figures 1 and 2 give an idea of the versatility of this method. Here a single conventional film has been scanned to produce a digital file. This is presented in two ways; in Figure 1 the visible greys have been optimized to show features with similar radiographic density to bone, while in Figure 2 the visible greys are optimized to show the metal helmet. From Figure 2 it is finally possible to make sense of the shape of the helmet; one of the twin earpieces has slipped forward over the front of the skull, giving the impression of a strange nose piece. The parallel lines across the image are due to the corrugated plastic layer on which the entire block sits.

Figure 1. *Visible greys optimised to show bone and material of similar density*

Figure 2. *Visible greys optimised to show metal helmet*

by the storage of images on network drives, where data is subject to frequent backup, and reformatting as required, but a strong argument can be made for the retention of hard copies.

Dissemination and publication

One area where the use of digital equipment has proved to be truly innovative is in the dissemination and publication of images. It is virtually impossible to produce a true copy of a film radiograph, containing precisely equivalent detail. Each one is therefore unique and a precious resource holding in it the time and effort used to produce it. In the situation where an object is conserved, altered or lost, a film radiograph may also be completely irreplaceable as a record. Films also tend to be a very popular resource, in demand by conservators, archaeologists and other specialists, not to mention the owner or curator of the object in question. Films are quite fragile things, easily damaged by handling, scratched (particularly when used to produce measurements) or quite simply lost. Once an image is in a digital format however, endless numbers of identical copies can be produced and disseminated with ease, in hard copy, on CD or by electronic means. Similarly, the publication of radiographic images becomes much simpler. Rather than having to photograph a film on a light box to produce a publishable picture, images can be collected or transferred directly into the form required by the printers and any labelling, arrows, etc. added simply by the radiographer.

IMAGE PROCESSING

What is Image Processing?

Image processing involves the application of a process or series of processes to an image so as to make it more amenable to human or computer interpretation. Simple examples of processing include such operations as changing the brightness and contrast or sharpening an indistinct image; more complex operations might involve pattern recognition or the comparison of two or more images in order to detect subtle differences.

Image processing can be divided into several non-exclusive groups that include: capture, enhancement, restoration, reconstruction, analysis and compression. *Capture* is the process by which digital images are obtained and also embraces such topics as image resolution and how many colours or shades of grey are to be used to represent the image (see also above p. 28). *Enhancement* is the process of improving the visibility of the image and also making the image 'look' better; it includes the adjustment of brightness or contrast, and edge enhancement. Enhancement is usually an interactive process and the results are often judged subjectively. *Restoration* is used to improve images. In some cases, images may have been degraded so that they are virtually unusable without processing. Degradation may result from geometric distortions in the optical system used to obtain the image. It may also be caused by electronic noise added at source or through transmission or by aberrations arising from the combination by the mosaicing of several separate images (*reconstruction*). *Image analysis* involves the quantification of features within an image but falls beyond the scope of this chapter. *Image compression* deals with the storage and transmission of images and is discussed more fully above.

Processing the Image

When an image is digitized, each pixel is assigned a value to represent the grey level at that point of the image; in a 12-bit image, the values lie between 0 (conventionally black) and 4096 (conventionally white). When the image is displayed on a screen the value of the pixel is converted into an appropriate amount of light. It is a simple matter to change the image so that what was black appears white, in rather the same way that there is a reversal of contrast when a photographic positive print is prepared from a negative. The mechanism for designating the display value of each pixel is called the look-up-table (LUT). Changes to the LUT can be used to modify the appearance of the image, including display in false colour, and on some systems changes can be made so quickly that they appear instantaneously, so that the process can be interactive.

One important method used to describe an image is to present the distribution of grey levels within it, normally in the form of a *histogram*. Figure 2.8 shows the grey level histograms of two areas of the same image. Clearly the distributions are not the same: the histogram of the darker area is concentrated towards the lower (left-hand side) end of the graph, whereas the histogram of the lighter area is concentrated at the higher (right-hand) end. Just as informative is the shape of the distributions. For instance, the histogram for the dark area is quite narrow which shows that the image is made up of pixels which all have rather similar values (i.e. a limited range of grey levels). One technique which can be used is histogram equalization: a new LUT is calculated which 'stretches' the histogram so that most of the available levels of dark to light are used. The result is an image in which more detail is seen (Figure 2.9(a)). The new grey level histogram is shown as Figure 2.9(b). A useful approach with histogram manipulation and included with all image processing software, can be to work only in the areas which are of immediate concern. Treating an image as a series of small sections, and individually optimizing each, will frequently give better results than applying a single approach to the whole image.

Spatial Filtering

Spatial filtering of an image is traditionally performed by applying a *filtering element* to the top

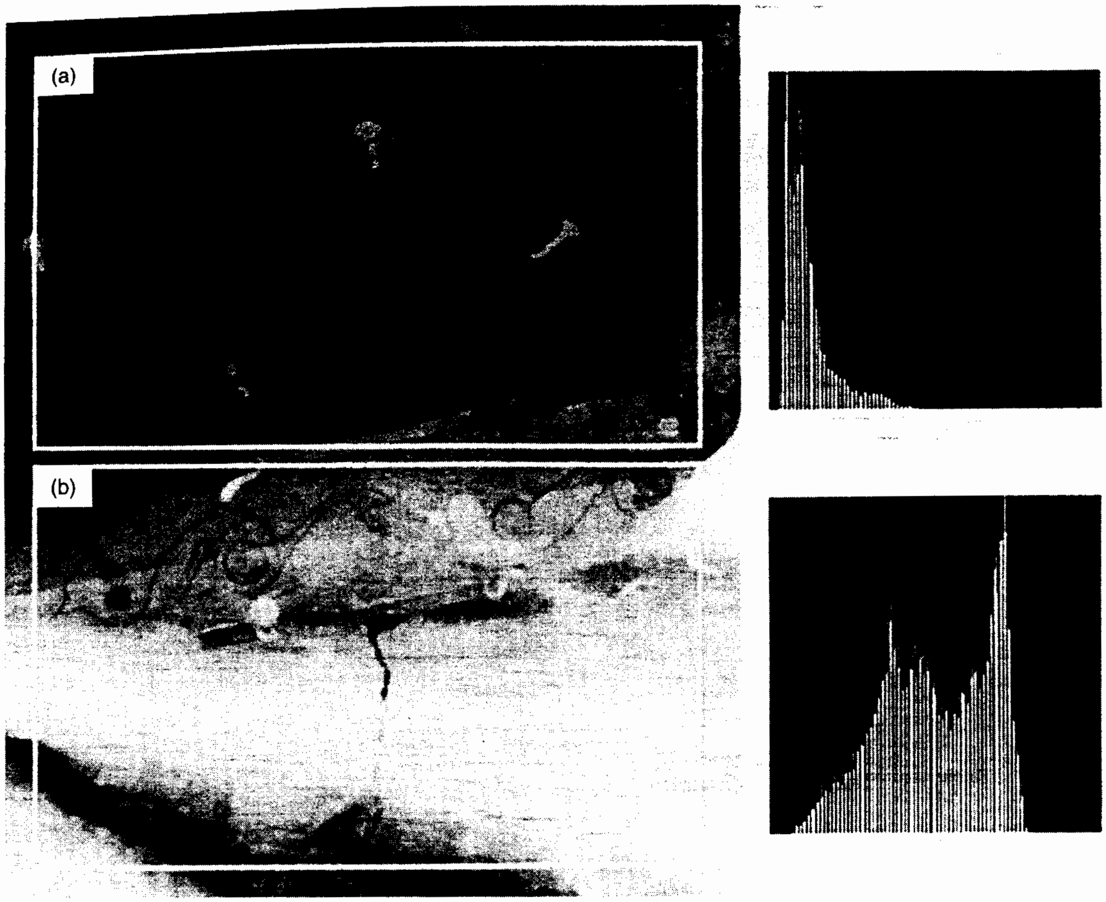


Figure 2.8. *Detail of a digitized radiograph of a shield complex from Essendon, Hertforshire which contains a dark area labelled 'a' and a light area labelled 'b'. An intensity histogram is shown alongside each area.*

left-hand corner of an image and moving it successively one pixel at a time until the bottom right-hand corner is reached. The filtering element is just a simple array of numbers which, in part, defines how the filter works. This type of processing is localized in that the result depends only on the value of neighbouring pixels. For example, a 3×3 filtering element is 3 pixels wide, 3 pixels high, and the result is returned to the middle pixel. The simplest spatial filters blur or sharpen an image, as one might alter the focus of a camera lens. *Blurring* involves the simple averaging of the neighbouring pixels and is suitable for removing noise from an image, although this also tends to remove detail as well. *Sharpening*, the most likely to be of use within the interests of this book, increases the difference between a pixel and its neighbours, the effect depending on the magnitude of the difference. This is a very effective way of enhancing the appearance of details and edges but it also tends to increase the noise within an image. Figure 2.10 shows the effects of sharpening an image. The edges of features within the images have been subtly heightened. Although it may be possible to use sharpening and blurring filters in succession, first to sharpen the image and then to reduce the amount of noise by blurring, there is a risk that vital information may be lost and unwanted artefacts introduced. Caution must therefore be exercised in the successive application of sharpening and blurring filters as there is no guarantee that anything new will be revealed or that the image will be improved.

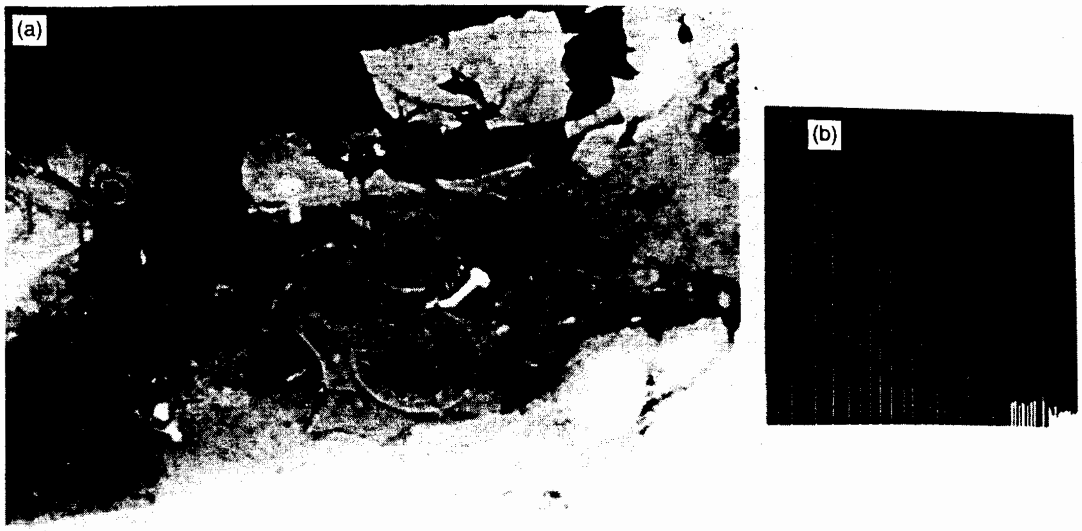


Figure 2.9. *Upper part of Figure 2.8 (a) showing the effects on the image and (b) of equalizing the brightness by manipulating the histogram.*

Figure 2.10. *Upper part of Figure 2.8, showing the effects of enhancing the edges of objects within an image; the decoration is more clearly visible.*

Another useful technique is to arithmetically subtract the processed (blurred) image from the original. In the resulting image the edges of features appear against a black background, somewhat similar to a drawing or etching which has been printed as a negative. There are several filters which have been designed to show different aspects of this type of information. Figure 2.11 shows the image after processing with a set of filters known as gradient filters (Gonzalez and Woods 1992, pp. 414–29). Here, the

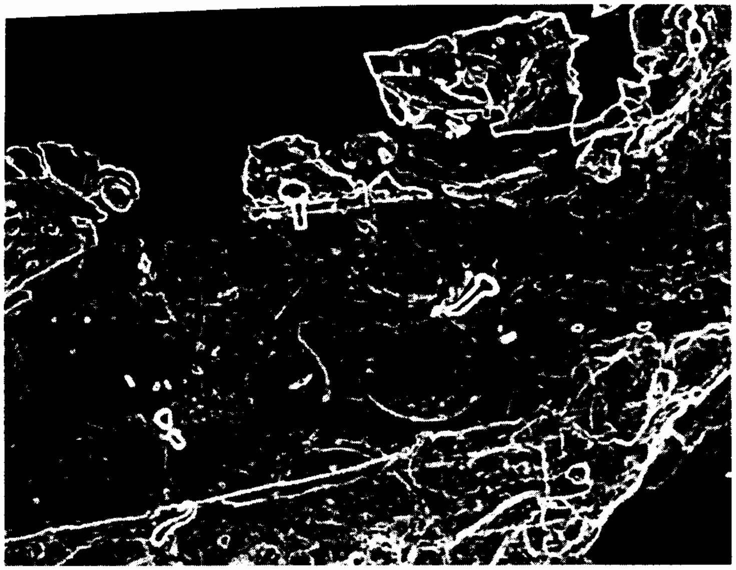


Figure 2.11. *Part of Figure 2.8, showing how the edges have been emphasized by processing the image using gradient filters.*

edges of features stand out, with the thickness of the outline being proportional to the difference between adjacent areas in the image. Complex structure is revealed, but the information given is quite different from that produced by simply sharpening the image or by altering the contrast or brightness.

Morphological Filtering

One way to look at an image is to imagine it as consisting of details superimposed on a background of broad features which cover the entire surface of the image. If the pixel intensity is plotted as a height value, the image can be presented as a topographic map with hills and valleys. A set of image processing filters grouped together under the common title of *mathematical morphology* have been developed to process the shape of objects within an image. Originally these were developed for binary images which contain only black and white pixels (i.e. with no intermediate shades of grey) but their use has been extended to include greyscale images. In the case of greyscale images, the morphological operators do not act upon the shape of a feature as in binary images but on the shape of the *terrain* (the hills and valleys). This type of processing allows the separation of broad features from detail (Serra 1982; Sternberg 1986).

Morphological filtering involves two fundamental operations: erosion and dilation. *Erosion*, as its name suggests, refers to the shrinking of a feature, while *dilation* refers to an increase in the size of a feature. These two operations are usually performed sequentially: an erosion followed by dilation is called an *opening*, and dilation followed by erosion is called *closing*. The enhancement of watermarks will be used to illustrate the power of greyscale morphological filtering.

Watermarks are a rich source of information for the art historian and much can be gleaned from the design of a watermark, from evidence of repairs and also from the spacing of the wire mesh on which the watermark was supported (see Chapter 5; also Higgins and Lang 1995). Figure 2.12(a) shows the scanned image from a β-radiograph of the watermark from a drawing by Rembrandt. In this image it is quite difficult to see the whole of the watermark as there is a dark vertical band at the top, right-hand part of the image. This arises partly from the radiographic technique but mainly from the uneven thickness of the paper. What is required is to mathematically remove the dark band so that the whole watermark can be seen. The filter used to process an image should be one roughly equal in size to the feature that is to be enhanced. In this case, a filter of size 41 × 41 pixels was selected as this was the width of the dark band. Two processed images were produced, one derived from opening the image, the other from closing the image. The resultant image (Figure 2.12(b)) was derived by arithmetically subtracting the opened and closed images from the original.

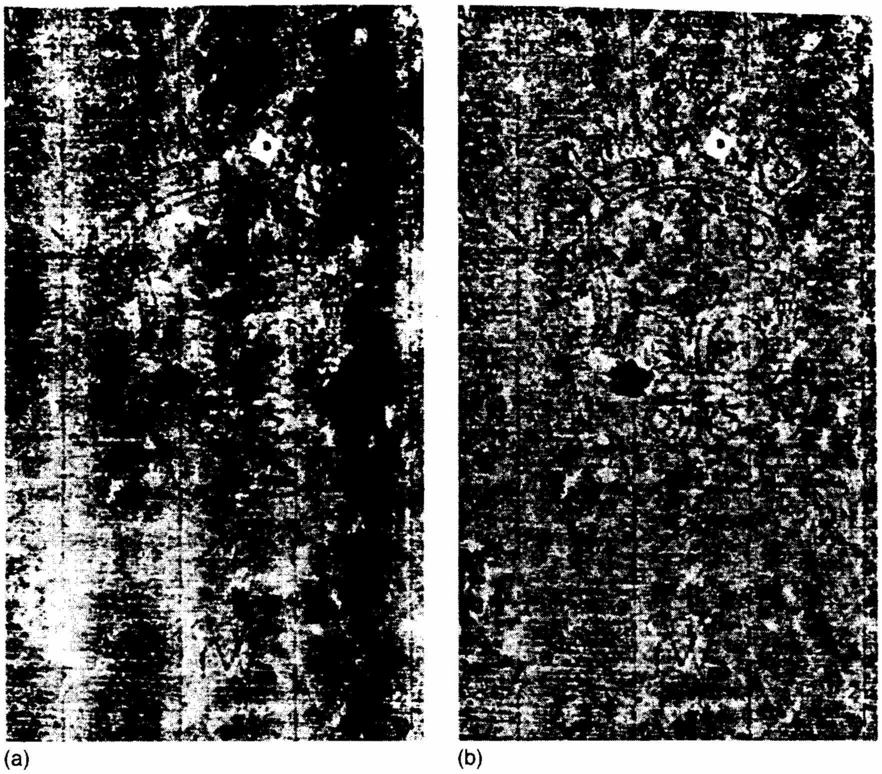


Figure 2.12. *β-radiograph of a watermark from an etching by Rembrandt showing (a) broad dark vertical bands caused by the method of production, which obscure the watermark image; and (b) the same image after processing with morphological filters.*

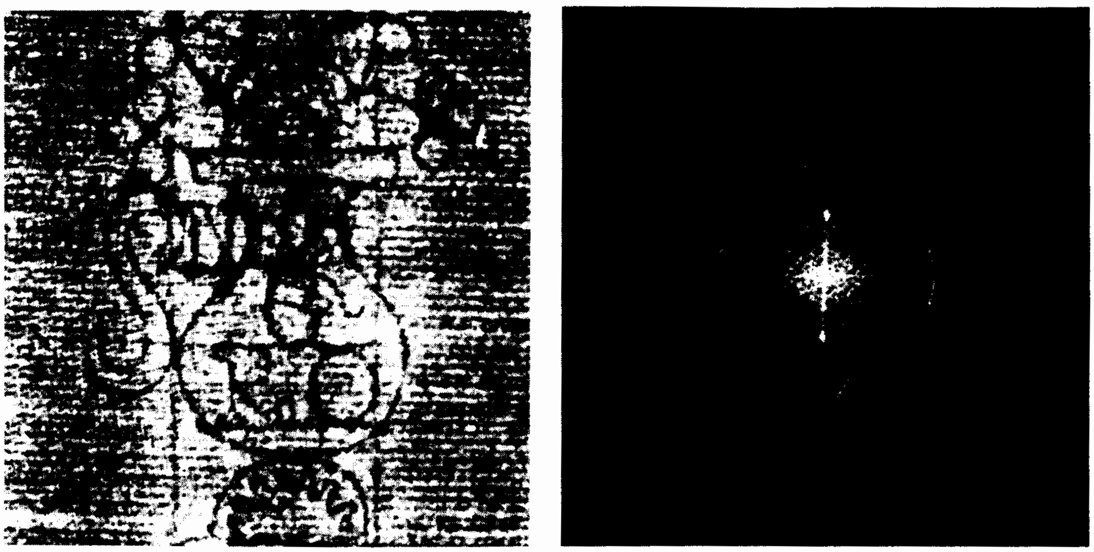
The processing of this image also serves to illustrate an important principle that applies to morphological processing. This principle, known as *deconstruction*, recognizes that the effects of some large filtering elements during erosion and dilation can be replicated by the successive application of smaller filtering elements. This has important implications for the amount of computation required. In the present example of the Rembrandt watermark, the single application of the 41 × 41 pixel filter involved 1681 calculations for each pixel; the same result could have been achieved by 10 successive applications of a 5 × 5 pixel filter, involving only 250 calculations for each pixel in the image.

Fourier Transform

The *Fourier transform* (FT) is a mathematical operation which makes it possible to recognize and examine the periodicity of features within an image (see, e.g., Oppenheim and Schafer 1989, chapter 8; Castleman 1996, chapter 11). Calculating the FT is practical only for very small images because each pixel in the transformed image contains some element or fraction of each and every pixel from the original image. Thus, the number of calculations required rises rapidly as the square of the number of pixels and an image containing a million pixels would require a million calculations for each of the million pixels (i.e. a total of $10^6 \times 10^6$ calculations). Fortunately a variant known as the *Fast FT* (FFT) has been developed which drastically reduces the number of calculations required. One of the limitations to using the FFT is that the original image must be square and the length of each side of the image, in pixels, must be a power of 2 (256, 512, 1024, etc.).

Although the FFT image is very different in appearance from the original image, as can be seen in Figures 2.13(a) and (b), it is important to note that the transformed image contains exactly the same amount of information as the original image. The original image can be restored by applying an inverse procedure. Transforming the image into this new format using the FFT has several advantages as it can be filtered in very subtle ways. However, it is manipulation of the periodic features which is of particular interest here (Jain 1989, Chapter 5; Castleman 1996, Chapter 11).

Figure 2.13(a) shows part of the radiograph of a watermark in which horizontal features created from the imprint of the paper-making mesh can be seen. However, their presence interferes with the viewing of other features in the watermark. The removal of this mesh from the image using non-Fourier filters would be very difficult and might cause some degradation of the image of the watermark itself. The FFT image of the region (Figure 2.13(b)) shows, amongst other things, three bright spots. The central bright spot is related to the overall brightness of the image, but the two spots above and below the centre arise



(a) (b)

(c)

Figure 2.13. *β-radiograph of a watermark showing (a) horizontal 'laid' lines, an imprint left by the mesh used to make the paper; (b) the FFT of the image. The bright spots above and below the centre of the image correspond to the laid lines and wispy artefacts correspond to the lines on the original etching, and (c) the restored radiograph after Fourier processing. Note that the laid lines have been removed.*

from the regular spacing of the mesh. The position and intensity of these spots relate to the periodicity and brightness of the mesh structure in the original radiograph, and it is possible to calculate the spacing of the mesh from the distance of the spots from the central spot (Dessipris and Saunders 1995). Furthermore, by 'editing' the FFT image and then restoring the image by an inverse transform, the appearance of the mesh structure in the radiograph can be modified. In particular, if the upper and lower spots are deliberately removed then the mesh structure will not appear in the restored image thus allowing the watermark itself to be seen more clearly (Figure 2.13(c)).

STEREORADIOGRAPHY

Radiographs contain a 'flattened' two-dimensional (2-D) view of the internal structure of a 3-D object. Although this type of image is valuable there is little information on the relative depths of features within the object. However, by using different views of the same object it is possible to regain depth information. The different methods are discussed by Spicer (1985).

The 3-D component of human vision is derived from the difference between the images received by the left and right eyes. Depth can be reintroduced or simulated using radiographs, provided two radiographs are used and that the images they contain were taken from slightly different positions. This can be done by moving the X-ray tube: the object is first positioned correctly under the X-ray tube and then the tube is moved about 3 cm to the left of the centre and the first exposure made. The tube is then moved an equal distance to the right of centre and a fresh film used to make the second exposure. The two films, viewed side by side, under a stereo viewer, give a 3-D image. Another method is to make both exposures on a single film, moving the tube from one side to the other between exposures. Each exposure time is half of what it would be for a single exposure. It can also be done by moving the object an amount equal to the distance between our eyes (see below, p. 42; also Figure 3.20 and Chapter 7). The perceived depth can be exaggerated by increasing the distance the object is moved or through a combination of rotating and moving the object (Kozlowski 1960), although Spicer (1985) has pointed out the disadvantages of the latter.

The radiographs can be combined optically using an optical instrument termed a stereoscope, although these tend to be expensive and the resulting image is limited in size. Another way to combine the images is to create red-green stereo pairs. Here, the radiographs are scanned and placed into different layers of colour image: one radiograph for the red layer, the other for the green. It is important to align the images where the overlap occurs. When the image is viewed using glasses fitted with one red and one green lens, the red image is seen by the eye which is covered by the red fitter and the green image is seen by the eye covered by the green filter. As long as the viewer has stereoscopic vision, the technique works even if the viewer is red-green colour blind.

An example of a red-green stereo pair is shown in Plate 2.1, which is an image of a part of the Essendon shield (although red-green glasses have not been provided with this book, they can be easily manufactured from the appropriate coloured gelatin sheets). The image shows the structure and placement of objects within the image and aids our understanding of the design on the shield.

COMPUTED TOMOGRAPHY

A further level of sophistication in the development of radiographic methods is provided by computed tomography (CT), also known as CAT (computer-aided/assisted/axial tomography) scanning, which is most familiar in medical applications and was developed mainly for that purpose. In conventional radiography the 3-D structure of the body or object is projected on to a 2-D film, where the optical density at a given point on the radiograph provides a measure of the overall attenuation of the X-ray beam as it traverses through the subject. Consequently, when a radiograph of a patient's anatomy or an object's structure is displayed in 2-D (height and width), information with respect to the third dimension (depth) is lost. This limitation has normally been overcome, where appropriate, by acquiring images from more than one angle. Techniques such as stereoradiography and conventional 'non-CAT' computer assisted tomography may provide some 3-D information. However, these techniques are laborious and the inability of conventional radiography to spatially resolve 3-D structures and to distinguish the soft tissues was a deficiency in the medical field not properly overcome until the advent of CT.

CT was developed in Britain by Sir Godfrey Hounsfield in the early 1970s. Essentially, CT scanners measure the relative transmission of X-rays through an object in different directions and then compute this information to construct a cross-sectional image (Herman 1980). Typically, a scanner consists of a large gantry with a hole in the middle, through which a patient (or Egyptian mummy!) passes, lying on a table (see Figure 7.6(a)). The gantry conceals the complex equipment, including the X-ray source and detectors. First-generation scanners employed a finely collimated pencil beam of X-rays, whilst fan beams have been used in subsequent generations. The beam passes through the patient and then into a detector, collimated to avoid scatter. Separate parallel projections are made at angular intervals around the patient. Having completed this set of projections (or slices) the table is moved slightly (typically a few millimetres), positioning the next axial slice of the patient in the path of the X-ray beam for the next series of projections. The number of slices taken and the linear spatial interval between them is determined by the requirements of the examination. The data from these projections are stored in a computer and this part of the whole process is known as the 'acquisition' (see Chapter 7).

CT scanner images are composed of 3-D information and each element of the image is called a voxel, the 3-D equivalent of the 2-D pixel. Associated with each voxel is a value related to the relative linear attenuation at the X-ray energy being used for the scan. This is known as the CT (or Hounsfield) number, and is calculated by reference to the attenuation of water, measured under the same conditions. Water is used as a reference because its attenuation can be measured conveniently and reproducibly, and because its attenuation is similar to that of human soft tissues. By convention the CT numbers of air and water are defined as -1000 and 0. Thus, the CT number for a tissue pixel is calculated as:

$$\text{CT number} = 1000\,\frac{(\mu_t - \mu_w)}{\mu_w} \qquad (2.3)$$

where:

μ_t = measured linear attenuation coefficient of the tissue;
μ_w = measured attenuation coefficient of water.

A typical CT number for bone is given as $+1000$ by Farr and Allisy-Roberts (1997, p. 102), who provide a more detailed introduction to the use of medical CT scanners.

Once the set-up has been standardized, the transmission data can then be used either as digital information or, by analogue conversion, as a pictorial display on a monitor. Each set of projections, therefore, can provide a CT image which is a representation of an axial slice of the subject at the point where the X-rays were incident. Although the 3-D section is compressed into a 2-D CT image, the slice thickness dimension is very thin (1–10 mm). The resulting image is conventionally shown as a transverse section of the anatomy of the patient. A number of contiguous thin slices can be manipulated in the computer to create images in alternative planes; this is referred to as 'reformatting'. A further refinement of the software has been the introduction of the dimension of distance from the observer which facilitates the production of a 3-D image which can be rotated in any direction on the monitor. Further information on medical imaging can be obtained from Bushberg *et al.* (1994). CT scanners have been used to examine a variety of archaeological and cultural materials, perhaps most extensively in the study of mummies (see, e.g. Hughes 1996; Taylor 2004; also Chapter 7): useful discussions are provided by Bonadies (1994); Illerhaus *et al.* (1995); Ghysels (2003) and Jansen *et al.* have reported studies on ceramics, stone, wood, mummies and scarabs within mummy wrappings (2001, 2002a, b), using high-resolution CT scans (see also Mees *et al.* 2003 for applications to geological materials, including the conservation of stone). The literature is increasing rapidly, much of it is available through the WorldWideWeb. Additional references will also be found in Chapters 3 and 7.

Advances continue to be made, especially in the medical field. CT scanners with multiple arrays of detectors developed in the late 1990s dramatically reduce exposure times. The X-ray source and detectors move round the patient to complete the slice. By 2004, multislice scanners could capture up to 4 slices in 0.5 s and this capability is being increased. An entire body scan takes 1–2 min to show all internal injuries in trauma cases. Virtual postmortems can be carried out, and materials of different density, such as metals or stone, can be distinguished. This enabled the arrowhead which caused the death of the Iceman (see Chapter 7) to be located and identified. At the time of going to press, a CT investigation into the cause of Tutankhamun's death and a programme of examination of other Egyptian mummies has been reported (Booth 2005; see also Chapter 7).

The systems are aimed specifically at medical applications, being designed to produce detailed images at safe dose rates. They are very expensive but suggest future directions in radiography, although speed and dose rate are not as paramount in materials examinations as in the medical field. Developments in the industrial field are often concerned with assembly line inspection and monitoring welds in pipes and constructions. The electronics industry, with increasing miniaturization, has led to the development of microfocus CT and nanofocus X-ray tubes, where the minimum spot size claimed is 900 nm (0.9 μm) with a tube current of 100 kV. This type of equipment is usually mounted in a cabinet and the size of the chamber is quite restricted.

PRACTICAL RADIOGRAPHY

Image Quality

There are a number of factors which determine the quality of the image, some of which have already been mentioned. All the detail required should be as clearly visible as possible, with sharpness or definition maximized and fogging minimized. In the first instance (even before any image processing is carried out), good quality images depend upon optimizing both the conditions of exposure (as discussed in Chapter 1) and the method of recording.

Radiographic contrast arises from variations in the intensity of the X-ray beam emerging from the subject. The overall contrast seen on the radiograph will depend also upon the characteristics of the film (or other recording medium). Films offering the benefit of higher contrast will suffer the disadvantage that they have less exposure latitude than less contrasty films. The level of contrast in the image can also be enhanced by using lower energy, softer radiation, but this will reduce the penetration of the beam. In addition, the range of density or thickness which can be shown on the radiograph is less than with harder, more energetic X-rays (Figure 2.14). Generally, the greater the contrast or density differences within the radiograph, the more clearly the main features stand out. However, if there is too much contrast, details in thicker and thinner parts of the object may be lost and the eye may be distracted by dramatic contrasts in the image, thus missing some of the detail. Image processing, including the use of false colour to represent the different grey shades in the image, can often enhance contrast to make features of interest more visible to the eye (see Image Manipulation, above), but it should be understood that the exposure conditions utilized are often a compromise.

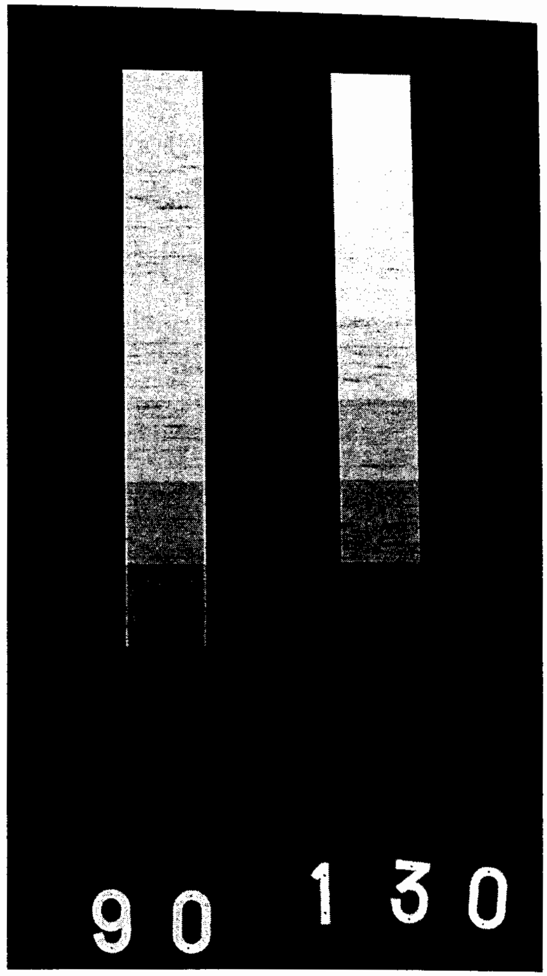


Figure 2.14. *Steel step wedge, radiographed at 90 and 130 kV, the lower energy gives an image with a smaller number of more distinct steps, while the higher-energy image shows a greater number of less distinct steps.*

Definition or sharpness may be described as the clarity with which details can be observed on a radiograph or screen. It is optimized by using a small spot size and a small object-to-film distance, as discussed earlier, in Chapter 1. Fine-grained film and an appropriate film processing regime also help to ensure good definition. The geometry of the object itself may restrict the definition which can be achieved: larger and more variable shapes tend to give less well-defined images. Sharp changes in profile provide abrupt changes in radiographic density, which are easier to discern than gentler changes. Larger objects, especially those which are heavily undercut, such as coin dies or solid statues, produce scatter which fogs the image and reduces definition. Scatter can be reduced by using filters, lead sheet, and packing as described in Chapter 1. The radiographs of the cast iron Chinese figure shown in Figure 2.3 illustrate how an image can be improved by using lead screens.

Sensitivity, in radiographic terms, is a measure of overall quality and in industry is often related to the need to distinguish particular features as a part of quality control. It can be measured by radiographing the object together with a penetrameter or image quality indicator (IQI) made of the same material as the object, and which may consist of plates of known thickness, or a series of elements such as wires or accurately drilled holes. Halmshaw (1995, p. 148) provides a general definition of sensitivity:

$$\text{Sensitivity (\%)} = \frac{\text{thickness of the smallest visible element}}{\text{thickness of the specimen}} \times 100 \qquad (2.4)$$

A step-wedge penetrameter, which consists of a wedge made from strips of suitable material (e.g. steel, if iron or steel is being radiographed), can be used to calculate exposure charts (Figure 2.14). Unfortunately for museum and archaeological radiography, the use of such charts is limited because of the irregular thickness, composition, corrosion and generally unpredictable nature of archaeological material. However, IQIs can be used to provide an objective guide to the sensitivity of the recording medium. Such usage is not restricted to film, and a wire indicator, attached with tape to the aluminium protective screen of an image intensifier, provides an indication of the sensitivity of the image intensifier's screen, cameras and display/recording system (see above, Sensitive screen fluoroscopy).

Problems

It is difficult to generalize about the problems which may arise in relation to archaeological and museum material, but a few examples of the difficulties encountered are discussed below.

Diversity

The sheer diversity of the requests is perhaps the largest single problem. Such requests may include making surveys of large numbers of excavated iron fragments, reporting on the state of a woodworm-ridden medieval statue, determining the construction of an Anglo-Saxon gold and garnet brooch, comparing watermarks in paper, discovering the construction and condition of a whalebone corset (see Box 1.3) or commenting on the construction of similarly styled ceramic vessels of different provenance.

Range of Materials

The wide range of materials encountered in archaeological radiography might include environmental remains such as fragile fish bones, wood, or fibres, textiles and paintings which require low-energy X-rays, often less than 60 kV (Gilardoni 1994) (see also Box 1.3). At the other end of the radiographic scale are large bronze statues (Born 1985) and artillery pieces such as cannon (Smith and Brown 1989). To radiograph such heavy objects as these, the radiographer probably has to consider approaching outside agencies, either industrial or academic research facilities, which may have equipment such as betatrons. As the work of Born and others has shown, this can be well worthwhile.

Most archaeological radiographers probably have access to generators capable of operating in the range 10–130 kV or 50–320 kV. Back-scattered electron radiography is effective for paper and paint images if a set capable of reaching 250 kV is available; alternatively, a ^{14}C source can be used for paper. Mention should also be made of a cabinet which can be attached to an X-ray diffraction set, allowing it to be used for radiographing paper, card and other light materials (Rendle *et al.* 1990). However, it is probably only in an industrial or government research facility (such as Bundesanstalt für Materialforschung und Prüfung in Berlin) that a range of equipment would be found capable of coping with the full range of archaeological materials.

Sometimes a wide range of materials is found on one object: the animal head from Mexico (McEwan *et al.* in press) (Figure 2.15) incorporates several different materials but nevertheless the radiograph was successful in distinguishing them and showing their distribution.

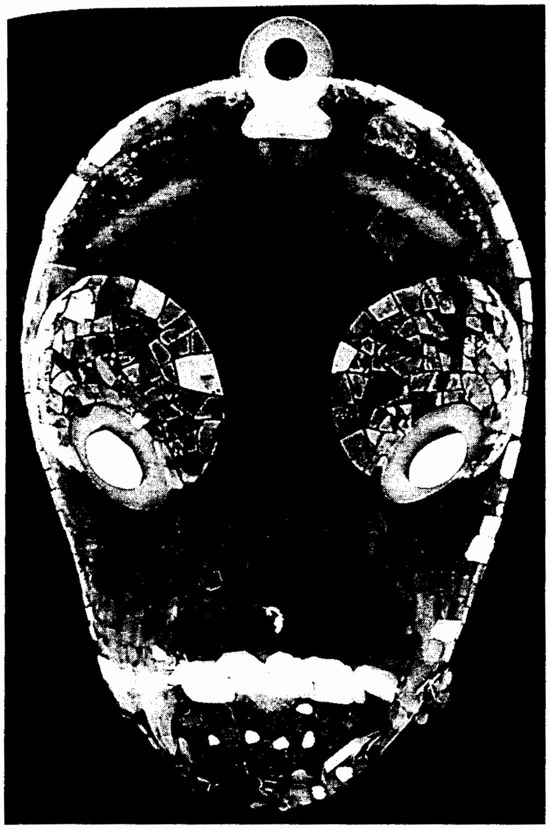


Figure 2.15. *Mosaic-decorated animal head from Mexico, made from wood,* AD *1400–1521 (ETH. St. 400a). The eyes are pyrite with rings of shell around them, the teeth are sharks' teeth, the head and eyebrows are decorated with seed pearls, and in the lower part of the mouth zircons, which are relatively radio-dense, show as the bright white stones. The roof of the mouth is covered with rectangular slabs of garnet, which because they are viewed edge-on also appear white, although they are not especially dense. The tesserae are mainly turquoise but some are malachite, which can easily be identified by its greater density on the radiograph. A small twist of wire in the mouth may have been an original attachment or part of a repair, probably made of gold. 3 mA, 5 min, 60 kV, 1 m distance, Kodak MX film.*

Awkwardly Shaped Objects

Awkwardly shaped objects test the radiographer's ingenuity: real-time radiography is ideally suited to examining large and bulky objects, as long as they can be fitted on to a turntable and moved safely (see also Chapter 8). A grid of lead letters and numbers laid over the surface of a large featureless item, such as an excavated block, is a great help in locating the position of finds (see Figure 8.9): distortion of the image, with some areas enlarged by geometric effects may make it difficult to identify the corresponding positions on the block and the screen. After an area of interest has been located, it can be radiographed using film.

Positioning the film close to the object, using packing and straps (as long as the integrity of the object is in no way compromised), helps to improve the quality when radiographing awkward features, such as the arms and legs of statues, which do not lie flat on a cassette. Using film in lead lined paper cassettes or light-tight plastic bags improves the film-to-subject distance and lead sheet or bags of lead shot as shielding help to prevent scatter in such circumstances. Several exposures at different settings are sometimes required for objects which vary considerably in thickness. The Anglo-Saxon single blade seax from Sittingbourne illustrated in Chapter 3 (Figure 3.24) required one exposure to show the iron blade and a second, longer one, with a lead front screen, to show details of the inlay.

Masking

Problems due to masking may arise when one part of an object is obscured or masked by another part. Masking difficulties were encountered while trying to discover the structure of a complex Anglo-Saxon brooch from Boss Hall (Figure 2.16). The upper surface is decorated with gold wire and cloisonné garnets and has a domed central panel. The pin is secured inside a small garnet-encrusted drum on the back surface. As the components masked each other, it was difficult to determine with certainty the internal construction of the brooch, even using conventional radiography, real-time viewing and image processing. Microfocus CT scanning would have been very helpful, had it been available.

The examination of the paint layer on a sheet of copper has already been mentioned in connection with back-scattered electron radiography (Bridgman *et al.* 1965); in this case, the paint layer would have been masked by the copper substrate in a conventional radiograph. Sometimes the problem appears insoluble: an attempt was made to radiograph the sheet copper interior of a glass table leg in the British Museum. The glass is a heavily leaded millefiore and it was not possible to image the copper interior of the leg; on the radiograph the thick layers of lead glass completely obscured any details of the thin, folded sheet copper within.

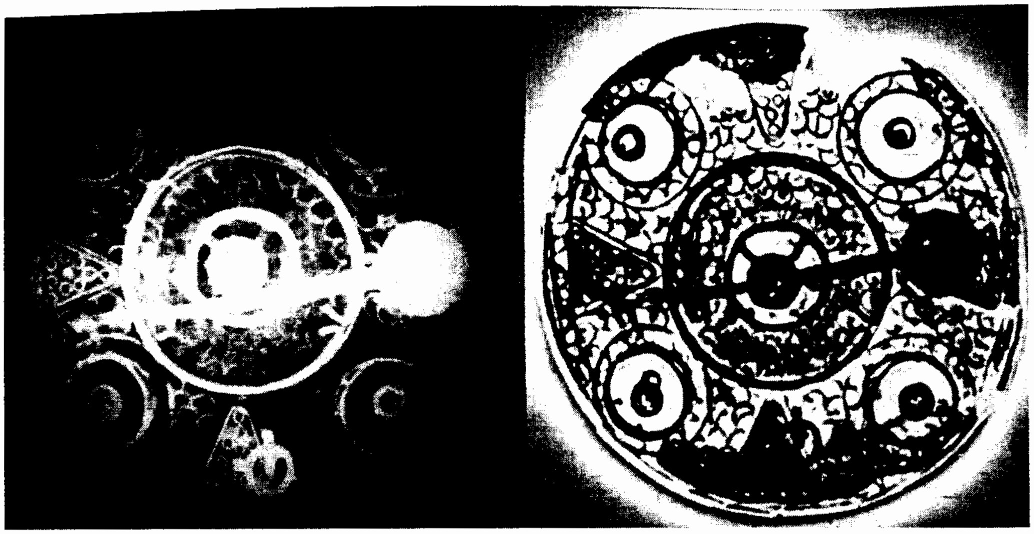


Figure 2.16. *Two views of an Anglo-Saxon gold and garnet brooch from Boss Hall, Ipswich. The brooch was made from several components and even with real-time viewing it was impossible to be certain of the construction.*

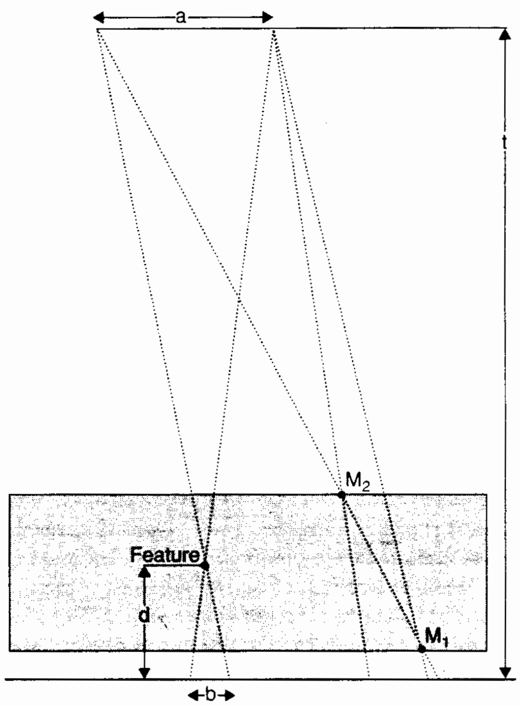


Figure 2.17. *Stereoradiography can be used to locate a feature within an object. The distance 'd' of the feature from the film can be calculated from the formula: $d = bt/a + b$, where 'a' is the tube shift, 'b' is the shift in position of the image of the flaw, and 't' is the source-to-film distance. Lead markers (M1 and M2) on the top and bottom assist in measurements (after Quinn and Sigl 1980).*

Superimposition

As the image of a 3-D object is displayed in 2-D when it is radiographed, designs or inscriptions from both sides of the object are superimposed which makes interpretation difficult. Real-time viewing can help to distinguish the images. Stereoradiography can also be used: this is a simple procedure, described in many textbooks (e.g. Quinn and Sigl 1980, pp. 114–16; Halmshaw 1995, p. 143). It has been of use in a number of applications, including the reconstruction of the metal thread design decorating a cushion found under the head of Archbishop de Grey (1216–55) in York Minster (Ramm 1971). Its use has been mentioned in this chapter (p. 37) and is also discussed in Chapter 7. The technique was used successfully for reading the pattern-welded inscriptions on both sides of an Anglo-Saxon sword (Figure 3.20). The surface of the sword was so corroded that it was difficult to see the inscriptions and reading them was impossible. Using stereoradiography, however, made it possible to separate the two inscriptions completely when viewed with a stereo viewer. Stereoradiography can also be used to calculate the position of features within an object, using lead markers attached to both surfaces to act as reference points (parallax method, Figure 2.17). Using very fine-grained film, microstructures and fine details such as cracks can be examined using stereopairs (Williams and Smith 1952).

Shallow Designs

If a design or inscription is only partly visible, the radiographer may be asked to try to reveal the missing section. This can prove to be difficult and is not always possible. The problems of geometry and unsharpness have already been mentioned: the edges of features such as chased or engraved designs or inscriptions, casting flaws or cracks tend to be small in relation to the source which leads to loss of contrast and blurring of the image. The difference in the absorption of the X-rays passing through the complete cross section (T in Figure 1.19) and the cross section reduced by the depth of a chased letter or an engraved outline (e in Figure 1.19) is very small. Generally the radiographer can try to ensure that the contrast range shows the maximum separation by using as low a tube voltage as possible. Sometimes it is helpful to record several radiographs of the same object under different exposure conditions, in order to optimize the visibility of different features. This is illustrated by the radiographs of the Roman spoon from Hoxne, shown as Figure 2.5 (see also Chapter 3 for further discussion of this and other inscribed spoons from Hoxne). Digital processing of a scanned radiograph may sometimes be useful in improving the visibility of cracks and other features. As in all types of imaging processes, radiographs are often a compromise, in which the radiographer seeks to optimize the conditions in order to show the features of interest clearly (Boxes 2.2 and 2.3).

Box 2.2 New radiographic facilities

Usually the type of objects and the materials to be radiographed in a new radiographic facility will dictate the choice of equipment, although this may be constrained by budgetary considerations and the space available. This section is intended to highlight some of the factors worth considering (see also Fell *et al.* forthcoming).

It is essential that a Radiation Protection Advisor (or outside the UK, a similar advisor) (see Chapter 1) is involved at the design stage of any new or refurbished facility. This will help to ensure that all the safety factors required by the Ionising Radiation Regulations and the Code of Practice (or equivalent legislation), such as shielding, interlocks and controls appropriate for the intended equipment, are included at the design stage. This point is worth emphasizing, because the regulations and their requirements are not always understood by non-specialist architects, which can result in costly problems and budgetary difficulties at a later stage.

The decision to use a self contained radiographic cabinet or free standing equipment is an important one. The main points to be considered are listed in the following table: much depends upon the types of objects being examined and the space and funding available:

	Cabinet	*Free standing set*
Shielding integral to system	Yes	No
Self contained	Yes	No
Power limitation	Yes (usually 150 kVp)	No (up to 450 kVp)
Object size limitation	Yes (size of chamber)	No
Film to source distance	Usually 1 or 2 fixed distances	Continuously variable
Space requirement	Operator can be in same room	Needs separate shielded room
Upgrading	Depends on manufacturer	Easy to add equipment (e.g. image intensifier)
Variable exposure time[a]	May be limited	Flexible
X-ray source position	Fixed	Flexible[b]
Variable milliampere	Fixed	Flexible (some limitations)

[a] It is useful if the exposure time is controlled digitally as this means that accurate repeat exposures can be made.
[b] The X-ray tube may be mounted on a trolley or a gantry and the tube head may be rotatable, but suitable shielding must be provided.

When examining large objects, such as statues or pictures, it is convenient to have the X-ray tube mounted on a gantry, so that it can be moved to different positions to radiograph various parts of an object or the angle at which the beam passes through the object can be changed. Tube manoeuvrability is desirable when radiographing large or fragile objects because it minimizes the disturbance to the objects. It is also useful for stereoradiography (see pp. 36, 42; Ch. 7). The addition of a light (or laser) guide to the system which shows the position of the centre of the beam, is extremely useful and time saving. Pictures or textiles are often radiographed in specialized set-ups where the object rests on a table of variable height with the X-ray tube positioned underneath. If low-energy work is to be carried out, with the recording medium (e.g. film) directly exposed to the radiation, it is necessary to operate under darkroom conditions; this means that both the cabinet itself and the room where it is housed need to be blacked out and a suitable safelight installed. The same would apply to a radiography room and its antechamber.

The selection of the radiographic equipment will include the image recording system as well as the X-ray generator. Increasingly, digital recording is being used and it is likely that this trend will continue. If an all-digital system is selected, archive deterioration and disc reading problems should be borne in mind, as discussed above (pp. 29–31). At present the vast majority of archaeological material is recorded on film, at least in the first instance. Film does have the advantage that it provides a reasonably permanent record and can be examined anywhere with a light box (or even held up to the light!!). However, film requires a dark room for processing, with running water and proper ventilation. Suitable space is also needed for the storage of film, chemicals, various sizes of cassettes and intensifying screens, etc. and for the temporary storage of chemical waste.

When the throughput of film is relatively small, manual tanks of developer, stop bath and fixing solution can be used. Drying cupboards speed drying and the film is protected from atmospheric dust. If the number of films is large, a small film processor can be very useful (the types used by vets or some dental models are suitable). Typically, a finished film, ready for examination and storage, is delivered in about 5 min, but all the processing times can be set to different values if desired. It is very important to make sure that the equipment is clean and well maintained and that film is thoroughly washed to conservation standards in order to prevent deterioration and ensure long-term preservation.

It is also important to provide a bench or table in a secure, clean, dry area, preferably with wipe-clean laminated worktops, where objects can be prepared for radiography. Ideally the preparation area should be situated adjacent to the X-ray facility, to minimize the possibility of displacement of objects and identifiers or damage during transportation. The provision of a light box, fitted with an intense light source in this area enables radiographs to be checked against objects for identification and investigation of features of interest. It should be possible to provide a low ambient light which is best for viewing. Some lightboxes have shutters that can be moved to fit the size of the film to cut out unwanted light which distracts the eye and makes it difficult to see the radiograph properly. The same effect can be achieved with strips of any non-translucent material. It should also be possible to secure the area where the specimens are laid out to prevent damage, disturbance or theft.

Box 2.3 Running a radiographic facility

The basic aims of a radiographic facility (see also Fell *et al.* forthcoming) are to produce images which provide some form of long-term (ideally permanent) record of an object and answer questions for archaeologists, art historians, conservators, curators and archaeo-technologists:

- In a way which is sensitive to the objects themselves and also efficient and cost effective in terms of time, equipment use and materials.
- The unit must also operate so as to follow the appropriate Safety rules in relation to the use of ionizing radiation (see Box 1.2 on p. 6):
  - keep a record of use, operators and of any problems and outcomes;
  - provide assessments of risk and establish safe working practices in relation to local health and safety legislation. Hazards may be exacerbated by the need to carry out some procedures using safelights or completely in the dark;
  - make provision for the proper storage and disposal of any radioactive sources and chemical waste, including spent developer and fix.
- Ensure the integrity of images. A film radiograph provides a record of an object. It can also be scanned and recorded digitally which increases its usefulness. While it would be possible to alter important features in a digital radiographic image, it would not be easy to do this in a conventional radiograph. Industrial systems safeguard the original image and this would seem to be appropriate for cultural material as well.

The organization responsible for the facility will determine to some extent the nature of the work and what is a realistic throughput. Where material from excavations is radiographed there is often a huge number of objects to be recorded and much depends on the grouping – it is easier to produce a satisfactory radiographic exposure with maximum information when the objects are of a similar radiographic density. If film is used, film costs can be reduced if several exposures are made on the same film. This is done by laying out the objects on part of the cassette and 'masking off' the rest of the surface with lead sheet. After the exposure, the objects are removed and the lead is moved to cover the exposed area. The unexposed film is then covered with the new or re-orientated objects, and a second exposure made. This may be at a different kilovoltage or for a different milliamperes value. The use of lead screens also increases exposure latitude, enabling satisfactory exposures to be obtained for a greater variety of objects.

To ensure quality control, a standard step wedge made with different thicknesses of a material with a similar radiographic density to the objects should be included (see pp. 39–40). A lead letter can be attached to the back of the cassette to monitor backscatter and measures should be taken to reduce scatter from all sources (see pp. 13–14). Unless a high-quality radiograph is assured with step wedge or penetrameter to show the dynamic range, there is always the possibility that unexpected information could be missed. Scratches on the lead screens in the cassette can be reproduced on the radiographs, so the lead surfaces should be checked for damage.

Frequently objects are radiographed in plan and profile views. If very specific questions are being asked of an object, especially in regard to construction or decoration, a number of different exposures at several angles may be required which is much more time consuming. Lead-lined paper cassettes, such as Readypack, can be shaped to fit closely around an object to improve contact, or small cut pieces of film, sealed in light-tight bags, with or without lead foil, can be used. Dental film has already been mentioned. It is also useful to have a supply of pieces of lead sheet available to place under and around an object to reduce scattered radiation. Variously shaped pieces of expanded polystyrene or similar material can be used to support the objects and retain them at the correct angles during radiography. Ideally, the person who requested the radiography should be present to explain what they want (and why), and to assess the information before the objects are removed, as it is very irritating (cost ineffective too) to have to reconvene when better communications would have allowed the work to be completed more efficiently. If this is not possible, written explanatory notes should be supplied. It helps to involve the radiographer as part of the investigative team.

It is important to maintain the temperature of film processing at the correct level and ensure that the solutions have not become exhausted in order to maintain radiographic standards. Film processors are designed to run at appropriate temperatures so this is not usually a problem, but needs to be checked periodically. Tanks used for manual processing can be surrounded with running water in large sinks (if a temperature of 20°C can be maintained) or a thermostatically controlled water jacket to keep the temperature even, otherwise the development and fixing times can be adjusted to take account of the ambient room temperature, according to the manufacturer's instructions. The chemicals are kept fresh by excluding air as far as possible when not in use. It is helpful to note the date when they came into use and if there are any doubts, a step wedge can radiographed, and the film processed and compared (using a densitometer) with a standard film of the same wedge, prepared for the purpose under ideal conditions. In industry, processing monitor control (PMC) strips are used to maintain film processing standards. Fully exposed areas which appear grey rather than black or a slightly brownish hue in the radiograph are warning signs. If a processor has not been used for a week or so it is advisable to pass a test strip through the machine make sure it is functioning correctly. Solutions are replenished automatically during use, but a processor should be drained and cleaned if it is to be idle for any length of time. Some radiographers feel that manual tank development is more satisfactory because of the possible buildup of chemicals on the rollers and also that the washing sequence may not fulfill conservation standards, but these pitfalls can be avoided with care. The main disadvantage of a processor is that it is relatively expensive to buy in the first place. Film radiographs should be stored at a low relative humidity, in the dark, held upright in clear inert sleeves to protect them from scratches and finger marks during examination.

Each facility will have its own recording system but it is safer to have a paper record as well as an electronic one. A radiograph needs a unique number and lead numbers or letters can be used for this. They can also be used to identify individual objects when several are included on the same radiograph (see Figure 8.9), and to indicate the orientation or distance (e.g. on the front and back of a large object, such as an excavated block) during exposure. Usually the operator's name, date and exposure conditions are noted (film-to-source distance, kilovoltage, milliampere, time, screens, filter, film) at the time of exposure, together with any comments by the radiographer and the details of the object or objects, including the archaeological date, find site, etc. Where several objects are included on the same radiograph, it is helpful to number each artefact on the radiograph itself, either using lead letters or numbers (see Figure 8.9) or by writing on the film directly with a fine permanent overhead marker pen or a pencil or a suitable ink, so that everything can be identified. However, it should be mentioned that writing with thick white ink is not suitable for use with some scanners as it can adhere to the rollers. Written or electronically recorded reports should contain the recorded information together with any appropriate comments, deductions or recommendations made by the radiographer. That radiographers are successful in much of their endeavour is suggested by the increasing number of investigations which make use of radiography, often as an adjunct to other microscopical and analytical techniques, in the technical and scientific examination of antiquities. In radiography, technological development, fuelled by the demands of the medical and industrial fields, has provided archaeological scientists and conservators alike with a powerful, non-destructive, investigative tool to answer many of their questions.

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3

Metals

Janet Lang

Introduction; identification and function; manufacture, casting, wrought objects; composites, joins, solders, welding; finishing, decoration, inscriptions

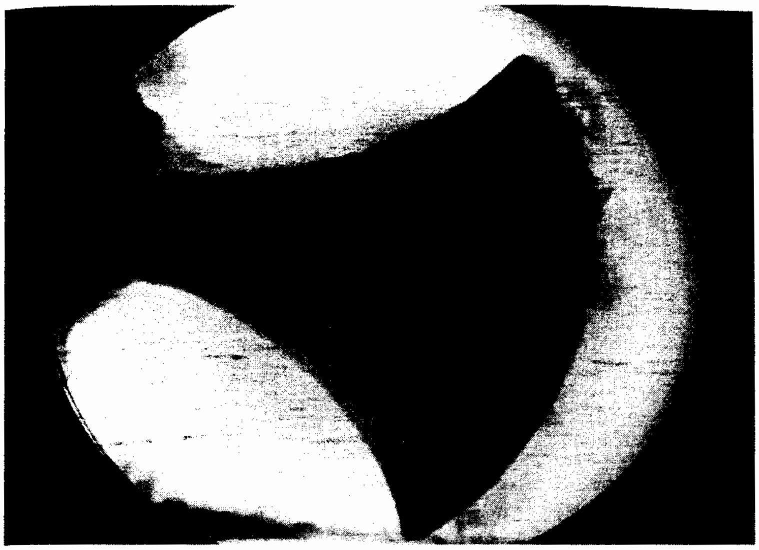
INTRODUCTION

Metals are useful and versatile materials with both strength and ductility, and their exploitation has been a key element in the development of human material culture. As most metals are not immediately available but have to be extracted from their ores, their use implies a certain level of technical expertise, and recognition of technical advance is reflected in the use of the terms 'Bronze Age' and 'Iron Age' to describe the cultural horizons when these metals began to be used extensively. Metals can be formed into a desired shape by casting molten metal in a mould or by working solid metal with tools. Metals can be cut and joined, decorated by chasing or engraving and embellished by the addition of inlays, enamels and stones. The methods used to work the metal and fabricate objects reveal the particular skills of the craftsman and may also reflect the craft-cultural traditions of their society. Radiography has an invaluable role to play in the recognition of these techniques of manufacture and thus contributes to our knowledge of the societies that produced the artefacts, and to our broader understanding of the history of technology.

The details of the construction of an object are not always immediately obvious: surface features and decoration may be concealed under layers of corrosion, joins might be internal and sometimes the signs of casting or working can only be found within the metal itself. Radiography can often be used to reveal these hidden clues to constructional techniques. However, it is frequently necessary to use information from other investigatory techniques as well. Examination at low magnification using an optical microscope may precede radiography, and chemical analysis is often necessary to confirm compositional differences indicated by the radiographic examination. This chapter indicates how the information obtained by radiography can help to identify the nature and function of an object, and describes the features by which some of the fabrication processes can be distinguished and decoration revealed using radiographs.

IDENTIFICATION AND FUNCTION

When an object is excavated, it has to be described and identified in order to be fully recorded and its significance explained. The identification of an object may present a problem if it is encased in soil or covered with corrosion products and its outline or shape is obscured (see also Chapter 8). For example, soil and concreted corrosion products obscured the horse bit, shown in Figure 3.1, when it was excavated in 1991 at the Anglo-Saxon burial mound (known as the Prince's grave) at Sutton Hoo, in Suffolk. It was radiographed before cleaning, fresh from the excavation, and was identified from the radiograph as an Anglo-Saxon horse bit with gold chip-carved panels, confirming the high status of the burial. It was examined by real-time radiography, which sometimes provides much more information than a normal, two-dimensional image, because the object can be moved about in the X-ray beam, giving the image a three-dimensional appearance. The real-time image


(a)

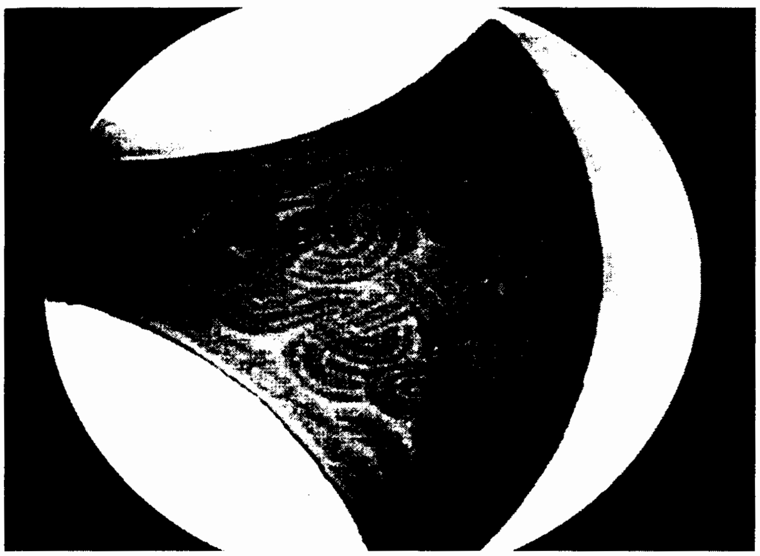

(b)

Figure 3.2. *Real-time radiographic images of a horse bit, shown in Figure 3.1. (a) with no processing and (b) after frame averaging.*

especially when the process employed differs from that used for comparative material. For example, it was thought, at one time, that Sasanian bowls were constructed from two separate layers soldered together (the double skin technique). However, because recent studies by Gunter and Jett (1992) and Meyers (1978) discovered that Achaemenid and Sasanian silver dishes were formed from a single cast silver blank, hammered to shape, the authenticity of a Sasanian dish found to have a double skin would merit close scrutiny (see also Chapter 9).

Cast Objects

Casting can be carried out in a variety of ways, directly into stone, ceramic or sand moulds or by lost wax (ciré perdue) methods (described below). Moulds may consist of a single piece, or two or more pieces, which are made so that they can be separated, in order to remove the casting easily. When multi-piece moulds are used, traces of porosity and fins where the metal has leaked out between the mould pieces can be detected at the join. Large

Figure 3.1. *Anglo-Saxon horse bit from mound 17, Sutton Hoo, Suffolk, as received from the 1991 excavation, with soil and small stones adhering to it.*

was processed which revealed the details of the chip-carved designs (Figure 3.2, see also Chapter 2). Most of this information could have been revealed by conventional film radiography, using small pieces of film positioned on the soil and corrosion accretions covering the decorated panels. There would have been some loss of image sharpness, however, because the shape is so irregular and the film could not have been placed directly on the metal.

Large numbers of heavily corroded iron objects are found on Roman and medieval sites and standard film radiography is therefore used as a survey tool for identification and for the selection of items which need further attention. In combination with Geographical Information Systems (GIS), radiography has even been used to correlate the state of preservation with the find location in a water-logged environment (Nydam, Denmark) and with the method of deposition (Matthiesen *et al.* 2004).

Several objects can be radiographed at once and a permanent record of badly corroded material is provided. The radiographs are probably the most informative image of this type of material which can be achieved, because iron corrosion may bloat the size and distort the shape to such an extent that, for example, a nail appears to be indistinguishable externally from more archaeologically significant artefacts such as keys or tools. This is discussed in more detail in Chapter 8.

Once details of an object have been revealed by radiography, the function is usually fairly easy to determine. However, there are exceptions, such as the so-called 'bean can' from an Iron Age cart burial at Wetwang, Yorkshire. This decorated bronze cylinder, which is closed at both ends, contains material which rattles and, was thought to be organic remains. In an attempt to image this material, the can was subjected to neutron radiography (Figure 3.3; see also Box 1.1 on p. 3). Although the radiograph shows some lumpy material, this was not identifiable and the function of the can remains a mystery (Dent 1985).

MANUFACTURE

Significance of Method of Manufacture

The method of manufacture is important in the characterization of the object itself and in setting it in a craft or technological context. Such information is used for more wide-ranging research into historical metallurgy and is also required for museum catalogues, displays and exhibitions. Where a group of objects purporting to come from the same workshop or craft tradition are under examination, radiography can provide pertinent information. A study of Renaissance bronzes (Bewer 1995) was undertaken to identify the characteristics of the Florentine workshop of the Flemish sculptor Giambologna (1529–1608) and radiography was considered to be the most informative tool for identifying key technological features. Anglo-Saxon knives from York and Southampton were radiographed as an integral part of studies which enabled the knives to be assigned to appropriate typological groups (McDonnell *et al.* 1991; Ottaway 1992).

Radiography helps to distinguish between the two basic methods of making metal objects, by casting or working, usually as part of a stylistic and technical examination (discussed in more detail in the next section): this distinction may be important,

Figure 3.3. *Neutron radiograph of Iron Age sealed bronze canister from Wetwang, Yorkshire (Harwell Neutron Radiography Service).*

statues are usually cast in separate sections and joined together with molten metal, a process termed flow welding (Mattusch 1996) (see below): the joins can usually be seen on radiographs even when they are not visible on the surface.

Radiography may show concentrations of trapped impurities and porosity, indicating the orientation of the mould when the metal entered it. Computed tomography (CT) is a particularly useful technique for making detailed studies of casting techniques (Heilmeyer 1985; Goebbels *et al.* 1985, 1995). Avril and Bonadies (1991) have described how CT revealed the skill of the Shang Dynasty Chinese bronze casters (13th to 11th century BC) who produced thin-walled, symmetrical vessels by positioning the cores and mould parts accurately. Small variations in wall thickness and the distribution of porosity in different parts of the vessels could be seen on the CT slices. It was also possible to explore the interior surfaces of closed hollow structures, such as handles.

Cast objects can be distinguished from wrought metal objects by metallographic cross sections; this requires samples to be removed from the object, mounted and then polished, which is not only time-consuming but also destructive. Radiography is often a better option, especially for fine metalwork in good condition. Castings exhibit features which can be identified on radiographs, including porosity, thickness variations characteristically different from those produced by working and a coarse granular appearance or texture. The presence of casting faults, cores, chaplets (used to hold the core in position) and cast-on sections also indicates that an object has been cast. These features are described in more detail below.

Porosity

Porosity in metal can be recognized on film radiographs as circular black or dark areas which may be pinhole sized or considerably larger, as seen on a 4th century BC bronze ring from Piceum in Italy, shown in Figure 3.4. The pores are caused by gas trapped in the cooling metal. As might be expected, fine porosity can be distinguished more readily in

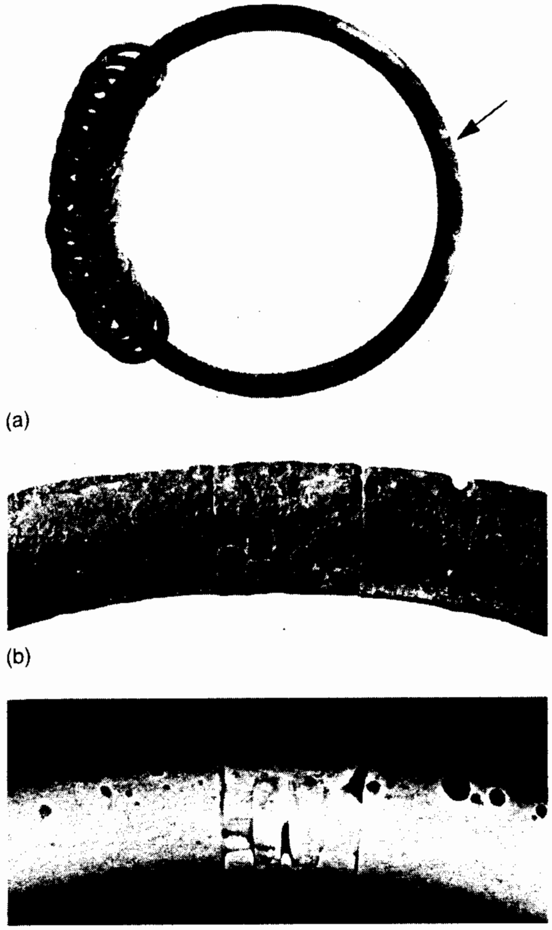


Figure 3.4. *(a) Bronze ring from Piceum, Italy, 8th to 7th century* BC *(GR 1824-4-98.32). The clip join is arrowed, (b) enlargement of the clip which can be partly seen on (a) and (c) enlargement of a positive xeroradiograph of the clip. The dark rounded holes are casting porosity. The radiographic density is relatively uniform and the coarse texture indicates that the ring was cast (Note: Xeroradiographic equipment is no longer available, see Chapter 2.).*

thinner cross sections than in thicker sections; radiography is unlikely to permit identification of the pores if they are minute in comparison with the overall thickness.

Thickness of Castings

Radiographs of cast objects exhibit a fairly even density if the mould into which the molten metal was poured had a uniform thickness and the metal

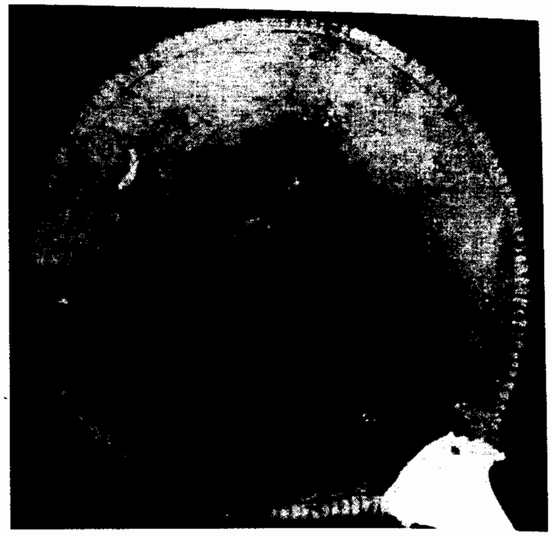


Figure 3.5. *Late Etruscan mirror, Danish National Museum No. 12889. The light (radiographically denser) areas are lead. The dark areas show where the metal is thinner. Traces of the design and cracks in the rim are also visible.*

has been properly cast. The thickness of the Picean ring (Figure 3.4) only varies at the edges, where it tapers slightly. Apart from the large pores, this uniformity is reflected in the even overall radiographic density, although in this case the texture of the ring is rather coarse and granular. Unevenness in the thickness of cast metal is indicated on a radiograph by irregular light and dark areas, like those appearing in Figure 3.5, which is an Etruscan mirror discussed by Craddock (1985). However, castings, such as bowls, were sometimes turned on a lathe to remove uneven surfaces and even-up the wall thickness. Figure 3.6 shows a cast, faceted silver bowl from Carthage, the interior of which was turned, probably to remove casting asperities: the base has also been hammered, and the irregular marks can easily be seen on the xeroradiograph. The wall thickness of hollow-cast statues tends to be variable and is particularly amenable to examination by CT (Heilmeyer 1985; Goebbels *et al.* 1985, 1995).

Cast objects are usually thicker in cross-section than those which have been wrought; this is especially noticeable at the areas of greatest curvature. However, metal thickness cannot always be used as a reliable indicator of how an object was manufactured as it is possible to make extremely thin castings. In the case of the radiograph of an Islamic inlaid brass pen box,

Figure 3.6. *Roman silver bowl from Carthage c. 400* AD *(EC 361). Negative xeroradiograph of the bowl, which was cast: the upper part was finished by turning, while the base was hammered and then scraped.*

dated AD 1281 (Figure 3.7), there is clear evidence that it was cast, although the wall is only 1.5 mm thick. A similar pen box dating to AD 1210, from Iran or Afghanistan, has been published by Atil *et al.* (1985). It also was cast and is interesting because the radiographs show that chills were used. These are small pieces of solid metal placed in the mould to initiate solidification and to promote a small grain size. They can be recognized on radiographs as small dark rectangles, placed in regular positions.

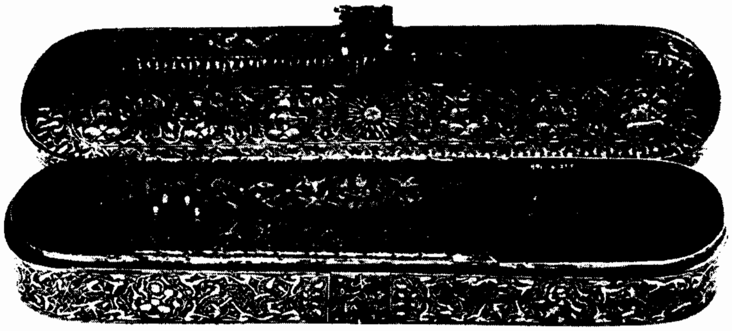
Generally, long exposures, beam hardening filters and high kilovoltages are necessary to ensure an adequate exposure when radiographing thicker cast objects. Copper filters are used to decrease the proportion of low energy components in the beam, which reduces scatter and at the same time increases the proportion of high-energy X-rays, thus effectively improving penetration. Lead sheets in the cassette help further to reduce the scatter and also intensify the image. Thicker lead sheets underneath the cassette itself also help to cut down scatter. A diaphragm can be used to restrict the spread of the X-ray beam, reducing scatter from the area around the object.

Texture

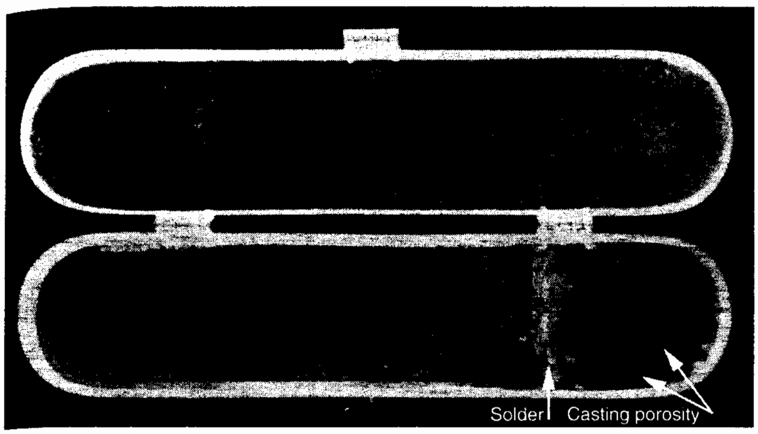
Not all cast objects appear to have an even texture on a radiograph. Some castings, especially large bronze statues, cool slowly which encourages grain growth, resulting in coarse grains which are large enough to show as a texture on a radiograph as in Figure 3.8. High-resolution film and been used to make stereopairs of study cast structures (Williams and Smith 1952; Barkalow 1971). Branched tree-like (dendritic) forms of growth, typical of cast structures, are normally identified under a microscope, but occasionally, if the metal has cooled very slowly, the dendrites are sufficiently large to appear on radiographs (Figure 3.9). Lead is barely soluble in copper (or bronze) and can be seen as discrete globules on radiographs of leaded bronze, such as the Etruscan mirror in Figure 3.5, where the denser lead is visible as small white globules. An uneven density distribution may occur if a casting has been made from different batches of metal of varying composition. Gettens (1969, pp. 129, 152–3) has published radiographs of the base of a fragmentary Chou dynasty vessel: one part of the fragment is much denser than the rest and the interface is zoned. Subsequent analysis showed that the dense metal contained 18.3% of lead, while the lead content of the less dense material was 9.9%. It is clear that this vessel had been cast from two different batches of metal. Figure 3.10 shows a decorated silver dish from Carthage, which has a very uneven density. In this instance, however, the patchy appearance is due to a different cause: parts of the object have suffered severe, localized corrosion attack in the burial environment.

Casting Faults

Casting faults on the surface of an object may be covered by a layer of corrosion or soil and are only visible on radiographs or after cleaning. Splashes occur when the molten metal is poured into the mould: if the mould surface is cool, the splashing metal solidifies and is not remelted as the mould fills up. Cavities or discontinuities such as cold shuts or interfaces (i.e. welds) are difficult to detect, for the reasons explained in Chapter 1: the difference in absorption between the defect and the surrounding sound metal must be sufficient to be detectable. Real-time viewing, if available, makes it easier to locate the best orientation to assess and radiograph a defect. Radiographic studies have shown that contemporary repairs were sometimes made by casting on (see below), making patches (Mattusch 1996), soldering extra material into cavities or even inserting metal spikes into areas of porosity, as in some South American cast gold pendants (Howe 1985).



(a)



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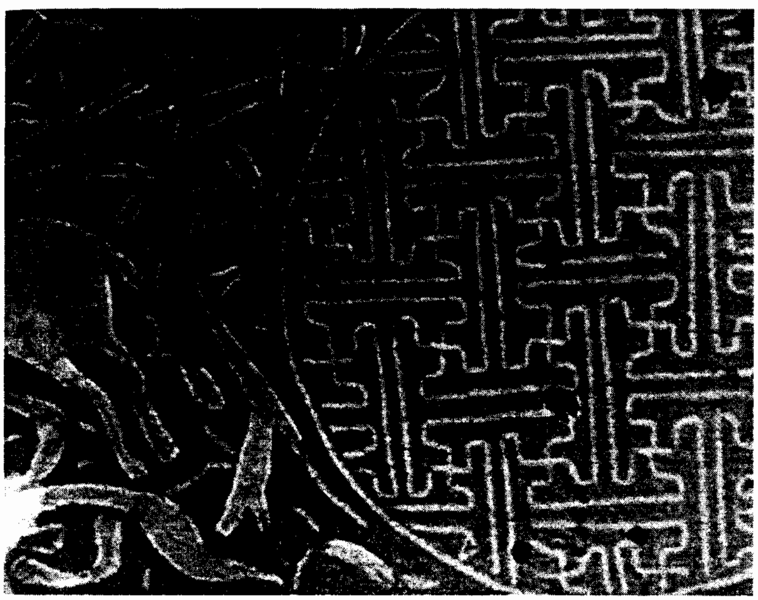


(c)

Figure 3.7. *(a) Cast Mamluk pen box (OA 1891-6-23.5) inlaid with gold and silver, (b) the radiograph shows dense areas, such as the gold inlay of the sun in the middle of the lid, and the tin-lead solder smeared across the base on the left appear light (arrowed) and (c) an enlargement of the right hand end of the base shows traces of a cast texture and porosity appears as black spots which are also indicative of casting.*

Cores and Chaplets

Cast objects may be either solid or hollow. To make a hollow casting, it is necessary to have a core, often made of clay, to prevent the metal filling the whole cavity. Hollow casting is used to reduce the weight of the vessel or to economise on the quantity of metal required to make the casting. The process of casting with a core is illustrated by Goldman (1985) and Mattusch (1996). The core is held in place within the outer mould by small bars or pegs known as chaplets, which protrude out from the core, through the cavity to be filled with metal, into the mould wall. Their remains can sometimes be seen on the surface of the casting. The number and location of the chaplets provides useful information about the mould design. If they are covered in corrosion or are otherwise invisible, radiography helps to show their location. When both sides of the object are superimposed on the radiograph, it may be necessary to take radiographs at different angles to determine in which wall the chaplets are located. An early example of hollow casting is an arsenical copper Sumerian ibex, *c.* 2500 BC, radiographed by Meyers (1978), which has a ceramic core supported by two copper rods. In a study of Classical statues Mattusch (1996) found that all the chaplets were rectangular in shape; those remaining *in situ* are made of iron and are therefore easy to pick out on radiographs as iron is less dense than bronze. A variation in the material used to hold the core in place is found in gold castings from South and Central America, where thorns, wooden pegs and extensions of the core itself were employed. The organic material burned out, leaving holes which were sometimes plugged, either by further casting or with shaped plugs. Small local variations in these technical processes were recognized by Howe (1985), using radiography.

Figure 3.8. *Detail of radiograph of an Egyptian statue (EA 60719), showing a coarse cast structure. Damage allows a single thickness of metal to be radiographed: porosity (black areas), lead (white areas), a chaplet (arrowed) and metal seepage into the core. 7 mA, 5 min, 170 kV.*

The lost wax process is used for more complex subjects and remarkably thin and complex castings

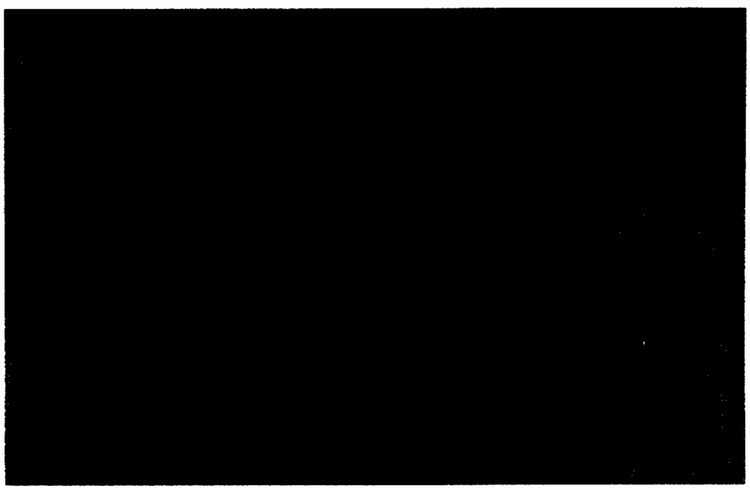


Figure 3.9. *Enlargement of a radiograph of a cast silver object showing a dendritic structure of grains, with different orientations. Some interdendritic porosity can be seen.*

can be achieved. In its simplest form, direct wax casting, which is used mainly for small castings, the subject is modelled in wax before being encased in clay moulding material. The wax is melted out by heating and the molten metal is then poured into the empty mould cavity. A radiograph of such a casting shows featureless solid metal, perhaps with a little porosity. The wax was sometimes modelled over a clay core (described by Mattusch 1996, p. 167), which can be recognized as an area of lower density on a radiograph. A more complex process, indirect wax casting, can be used to make large items, including statues in sections. A wax mould is made by filling a clay mould of the subject with wax, and then, before the wax sets, pouring most of it out, leaving a coating of wax on the mould surfaces. The hollow wax is filled with core material; finally, the wax is melted out and molten metal poured in to fill the cavities left after all the wax has been removed. It is characteristic of this process that wax is often retained in the extremities (e.g. fingers) so that the core material is prevented from entering these parts. Radiographs often show that the main part of the casting is hollow, except at the extremities, which have been filled with solid metal. Casting technology, explored mainly by radiography with some compositional analysis, featured in a study of Khmer cast bronzes (7th to 13th centuries) carried out by (Bourgarit *et al.* 2003). The figures varied in height between 7 cm and 86 cm. It was possible to determine if the figures were solid or hollow cast, with or without armatures and if direct or indirect wax casting had been used. The thickness and evenness of the walls were noted. Separately cast limbs and soldered or mechanical joins could also be distinguished.

Casting On

Casting on is another technique which may be identified by radiography. It is used as a method of construction, as well as for making good a poor casting or repairing a badly damaged object. A mould of the missing area is modelled on to the object and filled with molten metal after heating both mould and object; if they are not preheated, the join will not be sound. The cast-on segment may show a difference in thickness, density or porosity, or the join may appear as a discontinuity on a radiograph, especially if the surface has not been adequately cleaned with flux beforehand. Chinese bronze casters seem to have used the technique both to repair damaged or inadequate castings (Gettens 1969, pp. 12, 113) and also as a constructional technique (*ibid.* pp. 78–9).

Wrought Objects

From the earliest times metal was worked to shape by hand hammering. To shape the metal by hammering, working is carried out on the outside (raising) or from the inside (sinking): these processes are

Figure 3.10. *Xeroradiograph of a Roman silver bowl (AF 3279) and two ladles (AF 3283, 3285) from Carthage c. 400 AD. The frog dish has been damaged and is quite heavily corroded in one area. It has been repaired since excavation with soft solder (white areas) and the cracked area is supported by fibreglass and resin which is invisible on the radiograph. The corrosion obscures the worked texture which shows on the rest of the bowl. The two ladles were also worked but were heavily turned, as shown by the many concentric lines.*

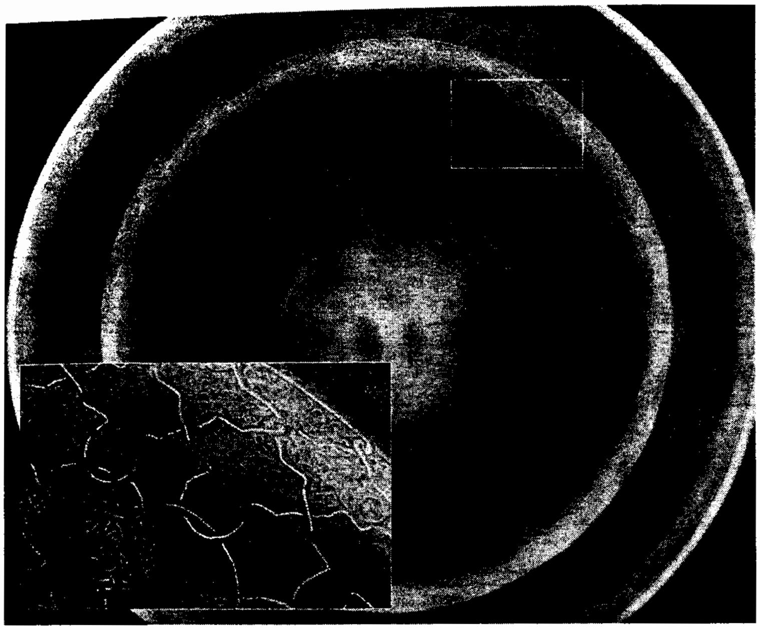


Figure 3.11. *Veneto-Saracenic Islamic brass tray (OA 1957-2-2.3) c. 1500 AD. The radiograph shows the regular impressions of the hammer marks and traces of a silver inlay, which only remains in the keying, are visible on the original radiograph (see also Plate 3.1).*

illustrated very clearly by Tylecote (1986, p. 113). An uneven thickness, clearly visible on radiographs, is produced where the metal has been thinned by the hammer blows, often in a regular pattern (Figures 3.6, 3.10, 3.11). The radiograph of the wrought brass tray (Figure 3.11; see also Plate 3.1) shows the hammering marks spiralling outwards from the centre, which can be compared with the irregular radiographic density of the cast Etruscan mirror shown in Figure 3.5.

Fibring is most obvious on radiographs of swords, especially pattern-welded swords which were constructed from rods or strips of ferrous metal, heavily worked and forge-welded together, side-by-side, to form the blade. During prolonged unidirectional working, the microstructure becomes elongated and fibrous which shows on the radiographs as slightly irregular light and dark lines or bands, parallel to the main axis. Enlarged microfocus radiographs of mail from York show the fibrous structure of some of the rings (Tweddle 1992, figure 468).

Porosity is unlikely to be found on well-worked objects, because the small cavities are welded up during working and larger pores would be likely to cause fracture: the casting porosity seen in Figure 3.4 is not found on wrought objects.

Some indications of the process used to shape a vessel may be obtained by comparing the thickness of its centre, sides and rim, which is usually easy to see on a radiograph. When an object is raised, the thickness of the sides and the rim are reduced in comparison with the centre of the base. Sinking, on the other hand, tends to thin the material at the centre, while the walls and the rim remain relatively thicker. However, a thicker rim cannot be regarded as a sure indication that a vessel was made by sinking, because the rims of many raised bowls are 'knocked down' by edge-hammering, to strengthen them and improve their appearance. It should also be noted that both raising and sinking may be used on the same object, so that a distinction cannot always be made between the two techniques. Radiographs may be of assistance in showing how the thickness varies and hence the likely contributions of the two techniques. The dimensions of an object can also be decreased by working: radiographs of narrow tapering vessels, such as flagons, may show vertical lines, not visible on the outer surface, where the metal has been compressed by working to reduce the diameter towards the base (Megaw and Megaw 1990). The wall thickness of a vessel may also be altered by the finishing processes (e.g. turning on a lathe, see below).

Metal can also be pressed into a mould or die to make the basic shape or to imprint a design into the surface. Usually pressing or stamping can be identified by visual inspection, but sometimes the evidence is accessible only on a radiograph. Schorsch (1995), for example, discusses an Egyptian 12th Dynasty necklace made from hollow gold beads, which showed puckers on their inner surfaces, suggesting that they had been shaped by being pressed into a mould.

COMPOSITE OBJECTS

Large numbers of objects were made from several separate components which may or may not have been fabricated by the same processes: radiography can indicate how they were made. Schorsch (1995) describes how hollow spherical 12th Dynasty silver beads, made from two flanged hemispheres, were joined by a form of soldering. Radiographs show the joins and also how the hemispheres were punctured, allowing the insertion of two small cylinders made of rolled-up silver sheet through which a thread was passed to string the beads. It is unusual to find an object with as many components as the 18th century Tibetan Dakini statue radiographed by Delbourgo (1980), who found that it was made from 34 pieces; hammered copper was used for the limbs and cast brass for the hands, ears and bracelets. The joining methods used to assemble composite objects are varied and many of them can be identified by radiography, as discussed below.

Mechanical Joins

Mechanical joins take many different forms. A dowel might be used to secure one component to another or to a base and their use has been identified radiographically in objects as diverse as a Sumerian ibex (Meyers 1978) and the Irish Derrynaflan chalice (Ryan 1983).

Another type of mechanical join is effected by using rivets or pins. Minute rivets could be seen in the radiographs of a late Bronze Age Cretan gold ring (Müller 1994). Rivets located in an archaeological complex by radiography can help to identify the nature of fragmentary metal within the complex, or even yield archaeological information about the original location and orientation of a missing substrate to which the pins were originally attached (e.g. the Essendon Iron Age shield complex discussed in Chapter 2).

Sometimes mechanical joins are made in order that the object can be undone or disassembled. Radiography contributed to the understanding of the complex fastening on the Picean ring (Figure 3.4), which consists of a bronze clip holding the knobbed terminals of the ring together. Holes in the clip locate on the knobs and secure it in position (Middleton *et al.* 1992). The ends of some Iron Age bronze torcs are permanently fixed together with a bead of metal while others are joined by simple hooks or removable clips. Radiography helps to distinguish which type of join was used: in an example of the fixed join published by Borel (1995), the free ends of the torc can be seen clearly within the bead.

Without radiography it would have been difficult to determine how the Iron Age Basse Yutz bronze flagons from Lorraine were made, as these well-known, outstanding examples of early Celtic metallurgy are complex in their construction. The flagons are not easy to radiograph because they are tall and narrow with awkwardly shaped tops and spouts. However, by using small pieces of film it was possible to see that the base was not joined to the sides but entirely separate, and that the spout and cover were pinned together (Figure 3.12), unlike the spout assemblage of the stylistically similar Dürrnberg flagon (Hundt 1974) which was cast. It was clear that although there are some modern soldered repairs at the neck, none of the original joins was soldered. According to Craddock (1990) '... the whole assemblage was packed with resin ... this served both to hold it together and render it watertight, leaving just a central pouring channel free ...'. The ewer (Figure 3.13), elaborately enamelled in the Renaissance style and attributed to the Limoges workshops, is constructed from several components. Radiographs show that the upper and lower parts of the vessel were tied together with small twists of wire before the join was secured by brazing with a high melting point alloy (probably copper/silver). The handle, base and top spout section were also brazed on. This must have taken place before enamelling. Subsequent repairs can also be seen on the radiograph (Figure 3.14).

Complex objects, such as a portable sundial (Johansson 1986), or mechanical devices such as locks (Tuğrul and Soyhan 1996) and watches, can also be radiographed to provide information on details which are otherwise inaccessible without taking them to bits. A watch made by John Cooke, dated 1670, which had been recovered from the foreshore of the River Thames was radiographed at the British Museum to determine if the pins which

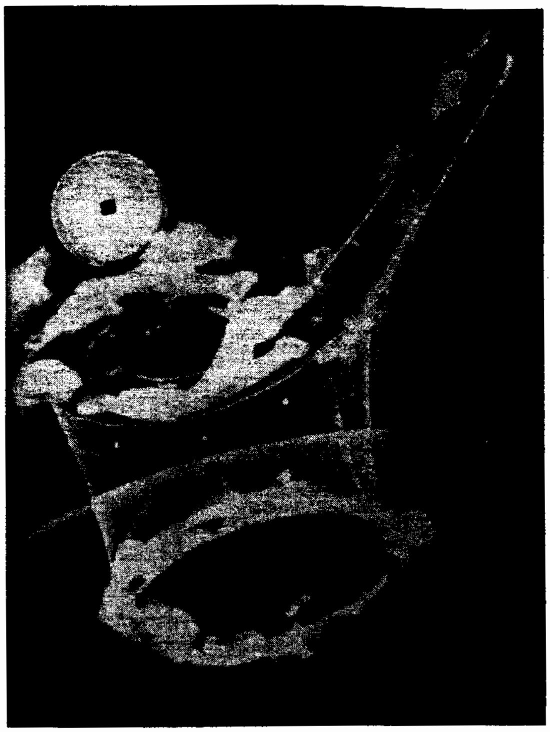


Figure 3.12. *Radiograph of the top of the 4th to 5th century* AD *Iron Age bronze flagon from Basse-Yutz, Lorraine (PRB 1929-2-11.2), decorated with cast animals, showing that the spout was assembled with pins. The solder at the neck is a recent repair. 10 mA, 10 min, 120 kV.*

Figure 3.13. *Ewer (Waddesdon Collection 57.1997) enamelled in the Renaissance style, attributed to the Limoges workshops (courtesy of Waddesdon Collection).*

hold the face plates in position were corroded or not. To show the condition of the pins, the watch was viewed in real time, which made it possible to determine the optimum angle for showing the pins unobscured by other components. In this position, the pins were successfully radiographed using film, allowing a detailed examination; this suggested that it would be possible to take the plates apart (Meehan *et al.* 1996). The details of an unprovenanced 1st century AD Graeco-Roman pen were revealed by the radiographs which showed that it was a cleverly devised multipurpose writing implement (Figure 3.15). It has a stylus for scribing on wax at one end with an eraser/burnisher to remove mistakes at the other. Inside is a split-nibbed pen for writing on bark or parchment with ink.

Crimped and folded joins are not commonly found, but can be identified by radiography. The top and bottom plates of the so-called 'bean can' from Wetwang (see p. 52, Figure 3.3) were crimped on to the cylindrical sides. Radiographic examination revealed, surprisingly, that the Sea City dish from Kaiser Augst (Cahn and Kaufmann-Heinemann 1984) had a footring which was made from a folded join between the outer and inner sections of the dish. Another type of mechanical join on the sides of South American jaguar figures, made by inserting a series of tabs cut out of one edge into slots cut close to the other edge, was also recognized by radiography (Tushingham *et al.* 1979).

Finally, in this section, mention might be made of screw joins found in a few late Roman brooches where the screw threads can be seen very clearly by radiography. Published examples include a Roman fibula from Kaiser Augst and another from Pistoja, Florence (Deppert-Lippitz *et al.* 1995). In the

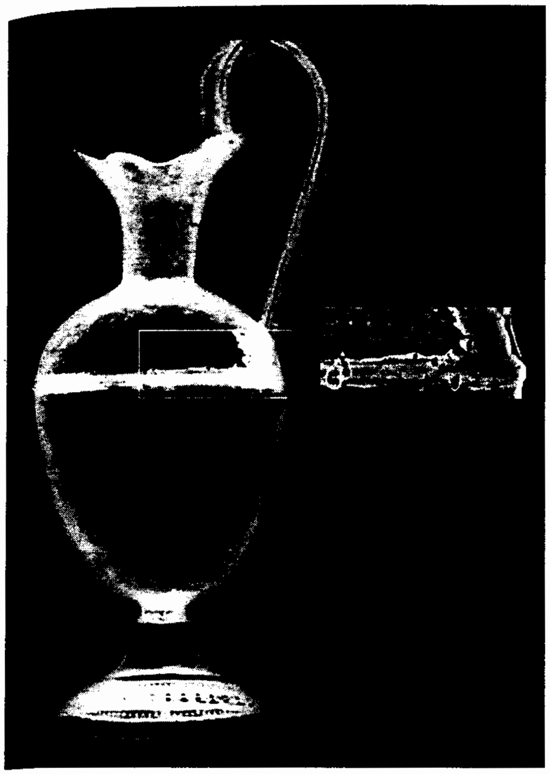


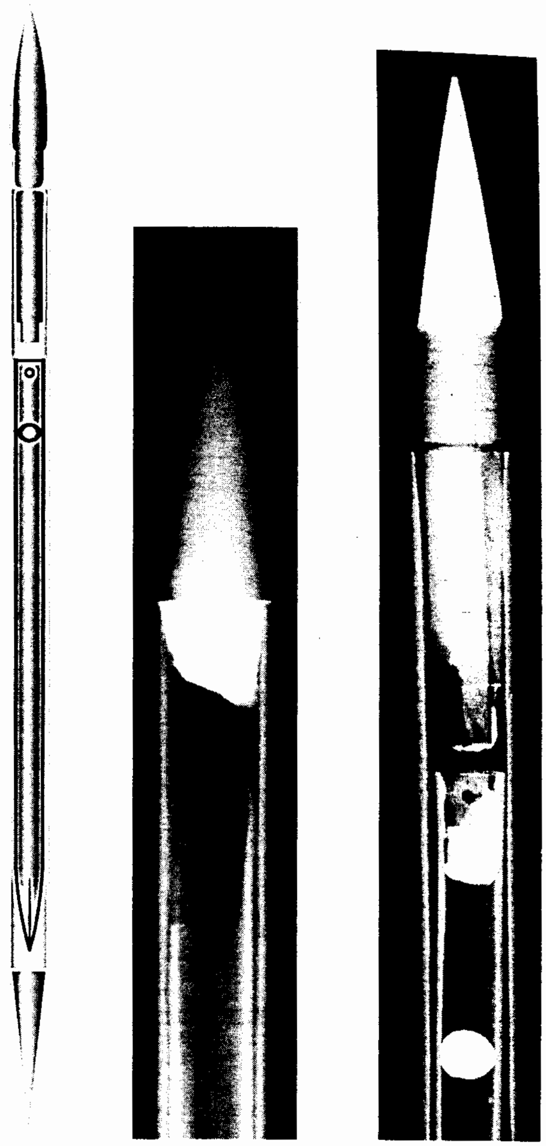
Figure 3.14. *Radiograph of the enamelled ewer no. 57.1997 showing the wires securing the top and bottom sections, the brazed joins, soft soldered repairs, the construction of the handle from rolled sheet. Variations in the enamel thickness on the side of the vessel are visible where the handle is attached. The enlarged detail has been processed to show the wire loops and variations in the enamel layer at the join.*

recent past, screws were often used in restoration work because the screw threads provide a key for other materials (Chapter 8).

Soldered Joins

Soft Soldered Joins

Soft solder is an alloy of tin and lead and has a low melting point (below 300°C). A soft soldered join shows very clearly on radiographs of bronze or silver vessels because tin and lead are radiographically denser than either bronze or silver. On the surface, soft solder can be identified visually and confirmed by X-ray fluorescence (XRF) analysis, but even if



(a) (b) (c)

Figure 3.15. *Unprovenanced 1st century AD Graeco-Roman pen, 13 cm in length; 4.6 mm maximum diameter, brass casing. (a) Drawing of the pen and its components. (b) Enlargement of the radiograph showing the stylus point, with the split nib inside. (c) Wedge shaped scraper or eraser, originally held in place with soft solder and a rivet.*

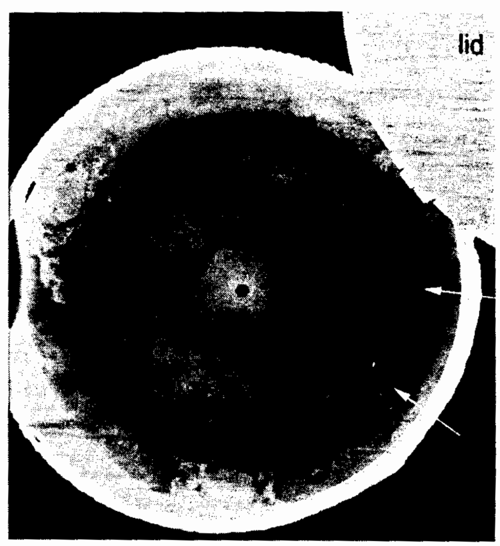
the join is internal, inaccessible or buried under corrosion or soil, it is visible on a radiograph as a denser area, sometimes exhibiting an uneven bubbly texture. A radiograph of a copper Islamic ewer, which is constructed from a number of plates and has also been repaired with soft solder, is shown in Figure 9.3. In a development of the soft soldered join, known as a coppersmith's join, the edges of the sheets have interlocking teeth which are soldered together, making it stronger than a simple butt joint. Early examples of coppersmith's joins were identified by radiography on vessels dating to about AD 800, from the Ummayyid *qasr* of Umm el Walid in Jordan (Schweizer 1994).

Handles were soldered onto Roman silver plate using soft solder because of its low melting point. If an object is assembled and decorated in a sequence of operations using heat, one of the last tasks might be to attach the handles, so a low melting point solder is essential in order to avoid earlier joins melting and the object falling apart. In the case of the silver canister from the Walbrook Mithraeum in London, radiographs revealed not only the presence of the soft solder by which the feet were originally attached, but also repairs in the base which have been made with high melting point solders. Subsequent analysis showed that these are of a composition consistent with being original repairs (Figure 3.16). Soft solder was also used in 19th or early 20th century restoration or conservation, but because some modern solders have compositions which differ from those used in antiquity, compositional analysis can sometimes determine if a join or repair was carried out in antiquity. The radiograph of the silver dish which bears the designs of the Risley Park Lanx is illustrated in Figure 9.5.

(a)

Figure 3.16. *(a) 2nd century AD Roman silver canister from the Walbrook Mithraeum, London, (b) base of canister showing patches of soft solder where feet were probably attached, and an attempt to repair one of the gaps. (c) The radiograph shows the soft soldered patches for the feet and two patches of hard solder used in an attempt to fill the gap (arrowed).*

(b)



(c)

This shows that the dish is made of fragments soldered together, using two types of solder, that is, soft solder (light in the xeroradiograph) and hard solder (dark). The authenticity of the dish is discussed in Chapter 9.

The presence of solder joins at the rims of double skin or shell vessels can be detected by radiography, which helps distinguish them from cast vessels. The Romans used this double skin technique of manufacture, especially for cups. The thin external, decorated surface is raised with a repoussée design, while the internal section is usually plain and thicker. The two are joined at the rim either by soldering them together or folding over the edges. Normally, in a cast or wrought vessel, areas of a design which are in high relief appear on a film radiograph as lighter in shade, whereas on a double skin vessel these areas appear dark, indicating that they are at least partly hollow although the intervening space is sometimes partly filled with solder (Meyers 1978).

Hard Soldered Joins

The higher melting point, hard solders or brazing alloys usually contain silver and copper and are used to join silver or copper alloys. As there is little difference between the composition of the hard solders and the metal to which they are applied, it is not easy to distinguish the soldered areas. Sometimes porosity indicates the presence of hard solder, but not always. If the join between components is not completely filled with solder a gap may be visible on the radiograph (e.g. Figure 9.5). With smaller objects, such as jewellery, hard soldered joins are sometimes more easily located using the imaging and analytical facilities and elemental mapping programmes of the scanning electron microscope (SEM), although microfocus X-radiography is also very suitable for examining small objects. Reiter *et al.* (1994) examined ferrous metal dress pins with oval heads from the Hallstatt necropolis at Rubenheim in Saarland. They found that the heads of the pins were made in two halves, soldered together with a bronze solder (brazing alloy). The microradiographs show the filets of solder inside the pinhead and small globules of unfused solder; the composition of the solder was determined subsequently by metallography and XRF analysis.

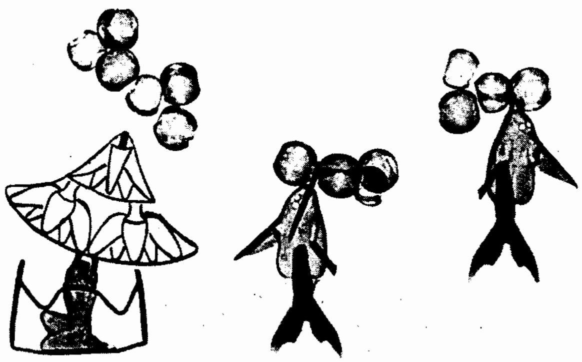
Many bowls have footrings to allow them to stand firmly on a flat surface. Most commonly, the footring consists of a ring of metal soldered on to the base of the bowl, usually with hard solder. The soldered joins at the footrings on Sasanian bowls are very obvious to the eye, but joins made in the Roman period are much more difficult to detect, either visually or radiographically. This is probably because a hard solder was used with a composition close to that of the body metal. Another problem which footrings present to the radiographer is their location: it is usually extremely difficult, if not impossible, to position the film immediately next to the join.

The most delicate joining techniques (reduction or colloidal soldering) involve the use of very finely divided metal or mineral, such as malachite (Littledale 1934), probably mixed with glue which holds the pieces in position. On heating, the glue chars, reducing any mineral to metal, and the minute particles of metal melt and fuse the parts to be joined together. The use of this type of joining technique on jewellery is illustrated in Figure 3.17, which shows two Egyptian necklaces containing beads with reduction-soldered joins. The construction of the bottle-shaped beads in Figure 3.17(b) shows clearly on the radiograph: the closed part of the bottle was made in two parts, with a reduction-solder join, the neck was pushed through a hole in the bottle, and then a flared top was added to the neck.

The stems on wrought cups are usually attached by solder but it is difficult to radiograph the joins satisfactorily because of their geometry. Side and vertical views are usually taken. If a cup, perhaps made of bronze or silver, is in sound condition, it is possible to hold the film (in a flexible cassette) in position close to the surface by strapping it with masking tape over a strong paper or card strip. Soft pads of paper, polyurethane foam or pieces of polystyrene can be used to hold the film in contact with the walls of the vessel. Shaped lead sheet shields and bags of lead shot placed around the outside of the object help to reduce scatter. Real-time radiography is excellent for this type of subject, because of the facility to move the object in the X-ray beam whilst observing the real-time image.

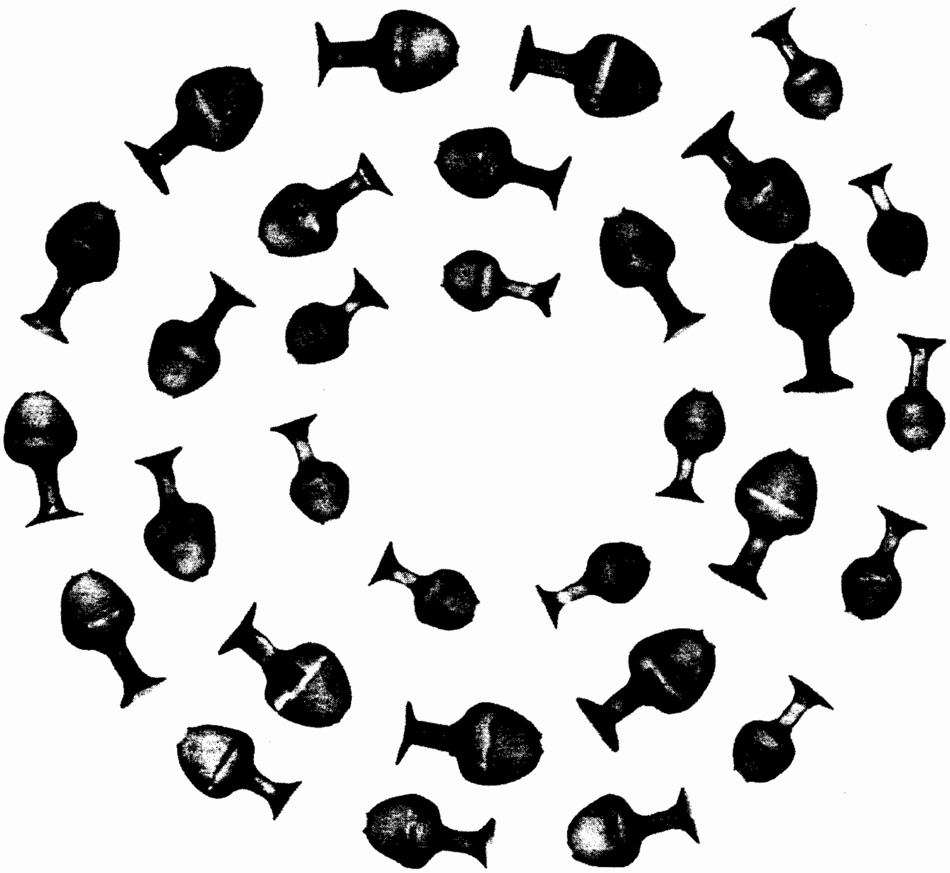
Welding

Welding, for the purpose of this book, is considered to be the joining of two pieces of metal (normally ferrous), using an elevated temperature and/or pressure; both are required for the majority of welds on ferrous items such as tools and weapons. In modern fusion welding a filler metal is used and a very high temperature (>1500°C) is required to melt it; this



(a)

Figure 3.17. *(a) Beads from an amuletic string with pendants, Middle Kingdom (EA 3077). The beads have soldered joins (dark). The fish pendants were made with separate tails, fins and suspending loops added to the body. Enlarged print from radiograph. (b) Amuletic string, Middle Kingdom (EA 14695). The bottle-shaped beads have soldered joins at their maximum diameter: a hole made at one end allows the neck to be made by pushing through a tube of rolled sheet. Open flared ends were added to the free end of the neck. Enlarged print from radiograph.*



(b)

was not achievable in the past so welding in the modern sense was not used. Some non-ferrous items have welded joins achieved by using pressure (Tylecote 1962, pp. 152, 154) rather than elevated temperatures.

Medieval coin dies can be considered as a good example of the use of welding and have been studied by McDonnell (1992) and Lang (Archibald *et al.* 1995). The dies are usually thick rods of iron or steel, 10–25 mm in diameter and may have a separate

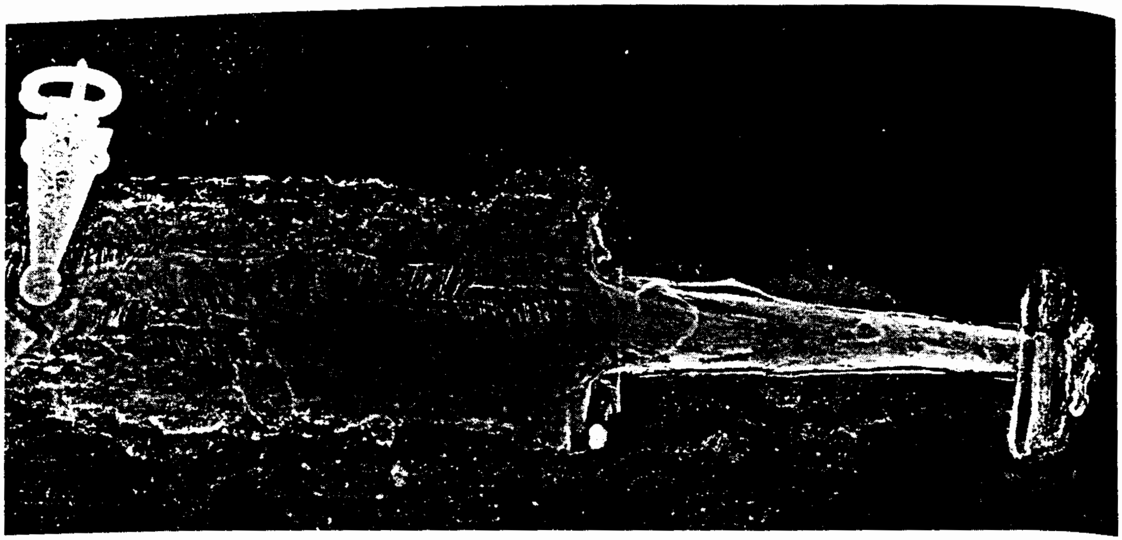


Figure 3.18. *Sword from Sutton Hoo, Suffolk, mound 17, excavated in 1991, straight from the site, before cleaning. The pattern of the sword, the gold and garnet belt fittings, traces of the organic grip, a silver ring for suspension and a break in the tang, presumably sustained during manufacture, all show on the negative xeroradiograph. The post-excavation packaging also showed, indicating that had organics such as wood or cloth been present they would have been visible.*

Figure 3.19. *Xeroradiograph of a late 9th century AD pattern welded Anglo-Saxon sword from Hurbuck, Durham (ML1912-7-23.1). The pattern was made by welding together three twisted rods, side-by-side. The blade has been constructed from two pattern layers (the arrow shows where the two patterns can be seen, superimposed) welded together with a thin cutting edge around the outside.*

strip sandwiched between two patterned strips and completed by a plain cutting edge welded around the outside. Using conventional radiographic techniques (including stereo pairs) it is virtually impossible to show the existence of the plain metal strip between the two pattern-welded strips. However, by taking a succession of cross sectional 'slices', CT shows the surface layers, the edges and the core very clearly, without having to resort to cutting a small slice from the blade for a metallographic cross section (Wessel *et al.* 1994).

The use of Stereoradiography (see Chapter 2) allows the patterned layers to be separated visually. This technique is particularly valuable when trying to distinguish pattern-welded inscriptions which were made by inlaying small letters shaped from pattern-welded strips. These blades were popular in the 10th century AD, when the pattern-welded sword became less common, possibly for economic reasons. The inscriptions are frequently invisible under the corrosion layers, but they can be revealed by radiography and stereo pairs enable inscriptions which are superimposed to be separated (Figure 3.20) (Lang and Ager 1989).

FINISHING

Finishing processes include filing and grinding, polishing, turning on a lathe and fitting the object for its function. Generally the traces of these activities are to be found only on the surface layers and they may not show up on radiographs. Many items of late Roman silver plate were finished by turning on a lathe, removing surface roughness but leaving a crude, almost faceted surface. The radiograph of the ladles from the Carthage Treasure (see Figure 3.10) die face welded on. Radiography can be used to locate the weld, which is usually parallel to the die face. If the weld is at an angle to the face or is not accurately positioned relative to the beam, it is difficult to pick up on the radiograph because the X-ray absorption at the weld is so little different to that on either side of the weld (Chapter 1). It appears that sometimes the asperities on the surface of the shaft in the area of the join were forged over the join, possibly to make for easier handling; this obscures the weld for visual examination and even on a radiograph (Archibald *et al.* 1995). Evidence that the shafts were sometimes made by folding over a bar or strip to give the necessary bulk can also be seen on the radiographs.

To radiograph the dies, a relatively high kilovoltage (*c.* 220 kV) and a long exposure is necessary, together with lead screens, some filtration and masking because the circular cross section increases the propensity to scatter radiation. McDonnell (1992) cut profiles in lead sheet to outline the dies, while Lang (Archibald *et al.* 1995) used lead sheet and bags of lead shot. Barium putty can also be used, but it needs to be wrapped in plastic as it is an unpleasant and sticky material to handle and might adhere to the objects.

Other examples of welding are to be found in larger tools, such as a Romano-British adze from Waltham Abbey, where the heel and the cutting edge had been welded into the blade. Radiography at the British Museum enabled the welds to be located so that the component sections could be studied metallographically. The excavated material from York provided two examples of welding revealed by radiography. The first was a repair to the tip of the sword beater, which had broken off and been welded back into place (Tweddle 1992, p. 882–8). Microradiographs of the mail showed both riveted and welded rings and careful examination indicated that the welded rings were made from a different stock of better, cleaner, more homogeneous metal than the riveted rings, presumably to assist welding (Tweddle 1992, p. 1006).

South American metallurgy provides some examples of non-ferrous joins which appear to have been welded. Lechtman *et al.* (1975, p. 46) used radio-graphy to show the joins on seven hollow jaguars from Peru, which she described as being 'sweat-welded' because a thin strip of metal was interposed between the two edges to be joined. Heating (sweating) causes the strip to fuse with the two edges, albeit somewhat irregularly. Tushingham *et al.* (1979) examined a number of Peruvian nose ornaments by radiography and showed that the joins between silver and gold were made by welding.

Flow Welding

Flow welding was used in constructing Classical statuary from sections which had been cast separately. Molten bronze (lead was used occasionally) was poured into the juncture between the components (Mattusch 1996). The joins can be identified on radiographs, usually as bands of increased radiographic density and thickness.

Pattern Welding

Amongst antiquities, probably the best known use of welding is in pattern welding. This was a method of blade-making practised mainly by the Anglo-Saxons, although it first appeared in the Iron Age. Iron strips or rods were twisted, laid side-by-side and then welded together, by forging. Whatever the purpose of this operation, the finished blade would have shown a patterned surface. After burial for a millennium, an iron sword usually appears to be a rusty strip of metal, recognizable only by its length and thickness. The tang, if it remains, often shows clearly on radiographs (Figures 3.18, 3.19). Striations can be observed on the radiographs of non-pattern welded swords, weapons and tools: these appear to arise at least partly from elongated slag stringers, which are of different radiographic density to the metal. In pattern welding, forging the strips or rods also results in an uneven, striated structure (fibring) which responds unevenly to corrosive attack. At the same time inclusions, such as oxides and other impurities, also tend to be concentrated in the welds between the strips, encouraging preferential corrosion to take place at the joins during burial; this makes the pattern visible on a radiograph. The sword from the Anglo-Saxon ship burial at Sutton Hoo found in 1939 was completely corroded, but radiography provided sufficient information about the pattern for a replica to be made (Bowman 1991, figure 5.13). As the swords are usually corroded, a low kilovoltage is used (e.g. <90 kV), and in order to allow the maximum contrast, lead screens are not used between the object and the film.

Metallographic examination (Tylecote and Gilmour 1982) of this type of sword has revealed that the blades are formed by a long, pattern welded central section, often consisting of a plain ferrous

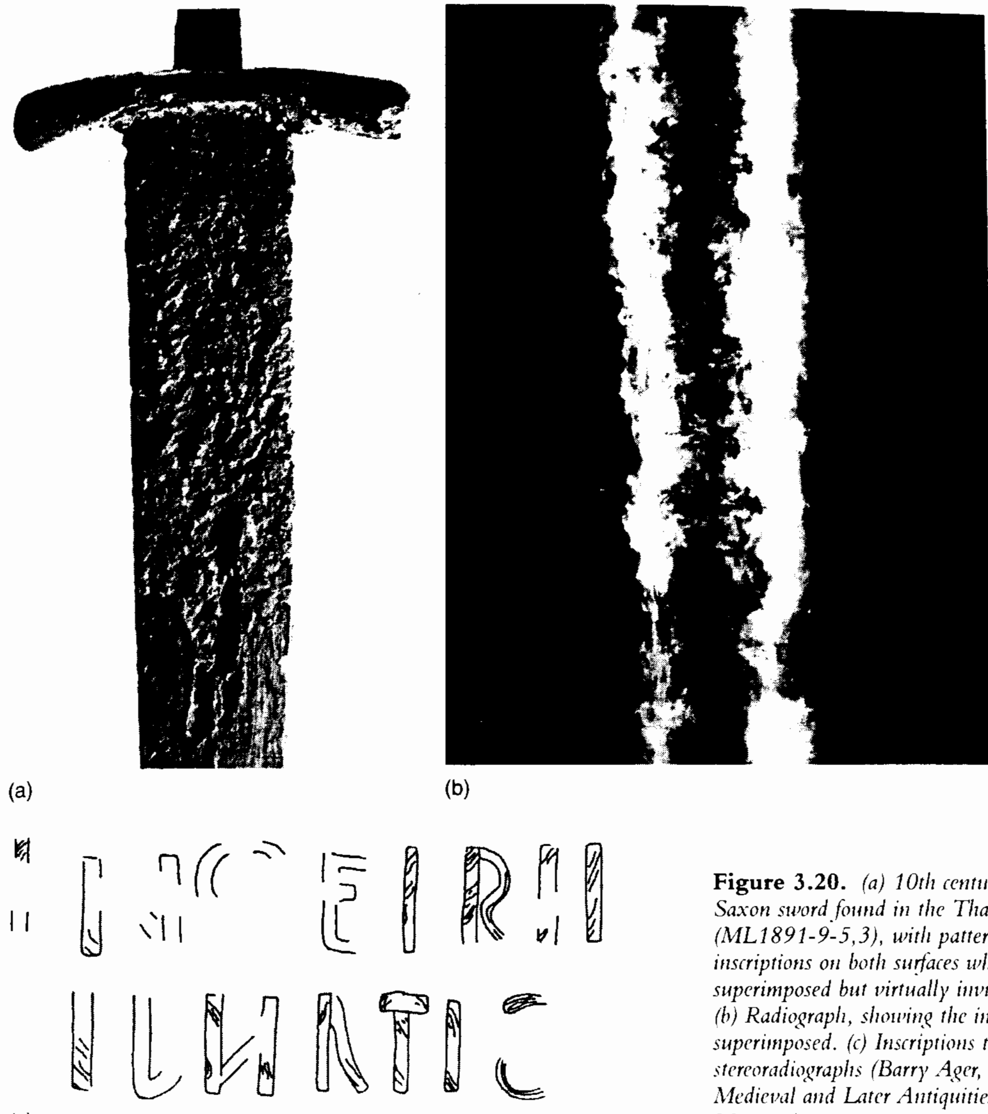


Figure 3.20. *(a) 10th century* AD *Anglo-Saxon sword found in the Thames at Kew (ML1891-9-5,3), with pattern-welded inscriptions on both surfaces which are superimposed but virtually invisible to the eye. (b) Radiograph, showing the inscriptions superimposed. (c) Inscriptions transcribed from stereoradiographs (Barry Ager, Department of Medieval and Later Antiquities, British Museum).*

shows an uneven density due to raising and, superimposed on top, the regular concentric variations due to finishing on a lathe. By the Roman period, lathes were used extensively to finish silverware by holding a bladed tool against the surface to cut or scrape away the irregularities as the object rotated (Craddock and Lang 1983). Concentric variations in thickness are introduced as the tool moves outwards towards the rim. This type of banding can be seen on the radiographs of vessels where the evidence of turning is visible on the surface (e.g. the ladles from Carthage, Figure 3.10).

Sometimes the finishing has a functional purpose. Files, for example, have been studied by Fell (1985). One of the final processes in finishing these ferrous tools is to cut the teeth, before the final hardening heat treatment. As they are made from ferrous alloys, files are frequently heavily corroded. Radiography is extremely useful in their identification, as it is not always possible to clean such objects, either because

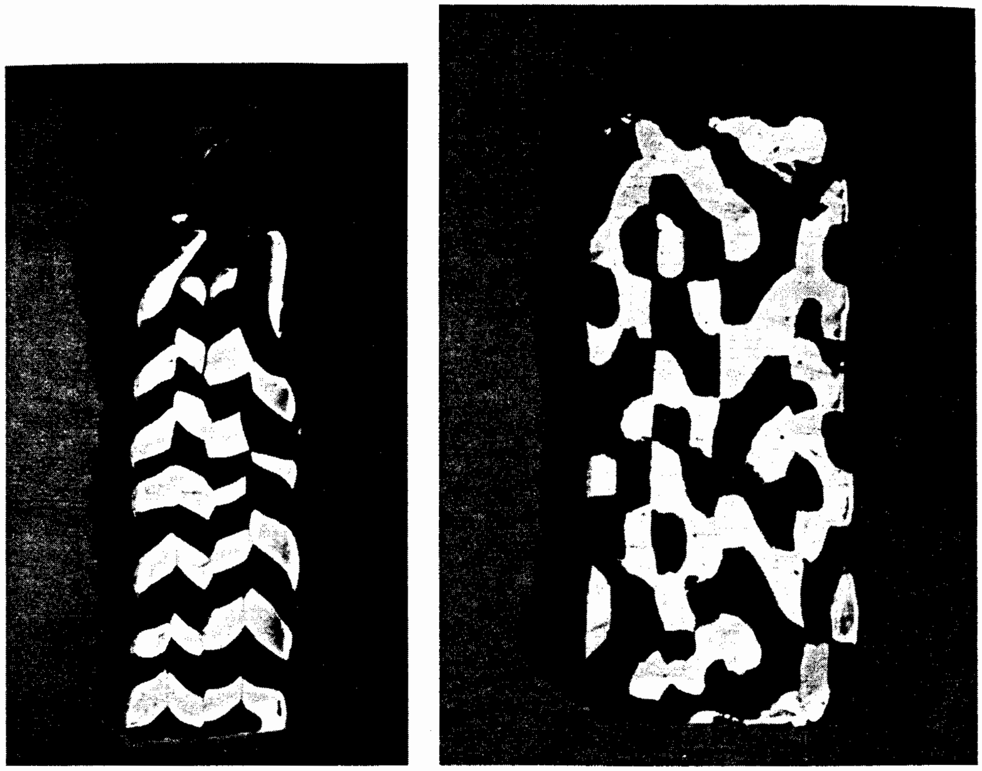


Figure 3.21. *Schematic models of pattern welding made in plasticene after Ypey (1973). (a) Replica of hammered surface and (b) after surface removal (by cutting), curving patterns are revealed.*

they are in a fragile condition or because it is not economic. It should be possible to detect traces of precious metal (gold) if they remain in the fine teeth of jewellery files.

Finishing may have a decorative purpose. Anglo-Saxon swords sometimes have depressions or fullers running down the blade, (sometimes known as 'blood channels'). These channels can be made either by forging with a drift punch or by grinding with abrasives. The method used to produce the channels can be determined by radiography because forging compresses part of the blade without much change to the design, but if part of the blade is ground away the surface (and radiographic) pattern changes characteristically. Ypey (1973) produced a series of drawings demonstrating the changes which occurred in a simple twist design as the blade surface was ground away, based on experiments and radiographs of pattern-welded blades (Figure 3.21). Radiography showed that grinding the channels rather than forging them was more common in continental Europe while the opposite was true in England (Lang and Ager 1989).

Relief Decoration, Plating and Inlays

Decoration includes introducing a design on the surface of an object by punching and chasing from the front, repoussée (working from the back), carving (removal of metal from the front) and engraving (cutting a design by removing metal with a sharp tool). It also includes adding materials to the surface, such as metallic or non-metallic inlays, enamels or stones and also plating layers of a different metal, such as gold, silver or tin, onto the surface.

Not surprisingly, locating decoration is one of the tasks which archaeological radiographers frequently find themselves undertaking; the ease with which decoration can be found depends upon the difference in absorption between the design or inlay and the substrate. The difficulties presented by chased, punched and engraved designs are discussed in the next section, as they are the same as those experienced in trying to record inscriptions. Repoussée work can be identified easily because the metal is thin and details can be seen very clearly on radiographs, especially the cracks and holes which occur when the metal is over-stretched and splits. If the concavities are filled with lead, however, most of the detail is lost because of the high radiographic density of lead. Backings made of wood, plaster or bitumen do not obscure the image of a metal repoussée covering.

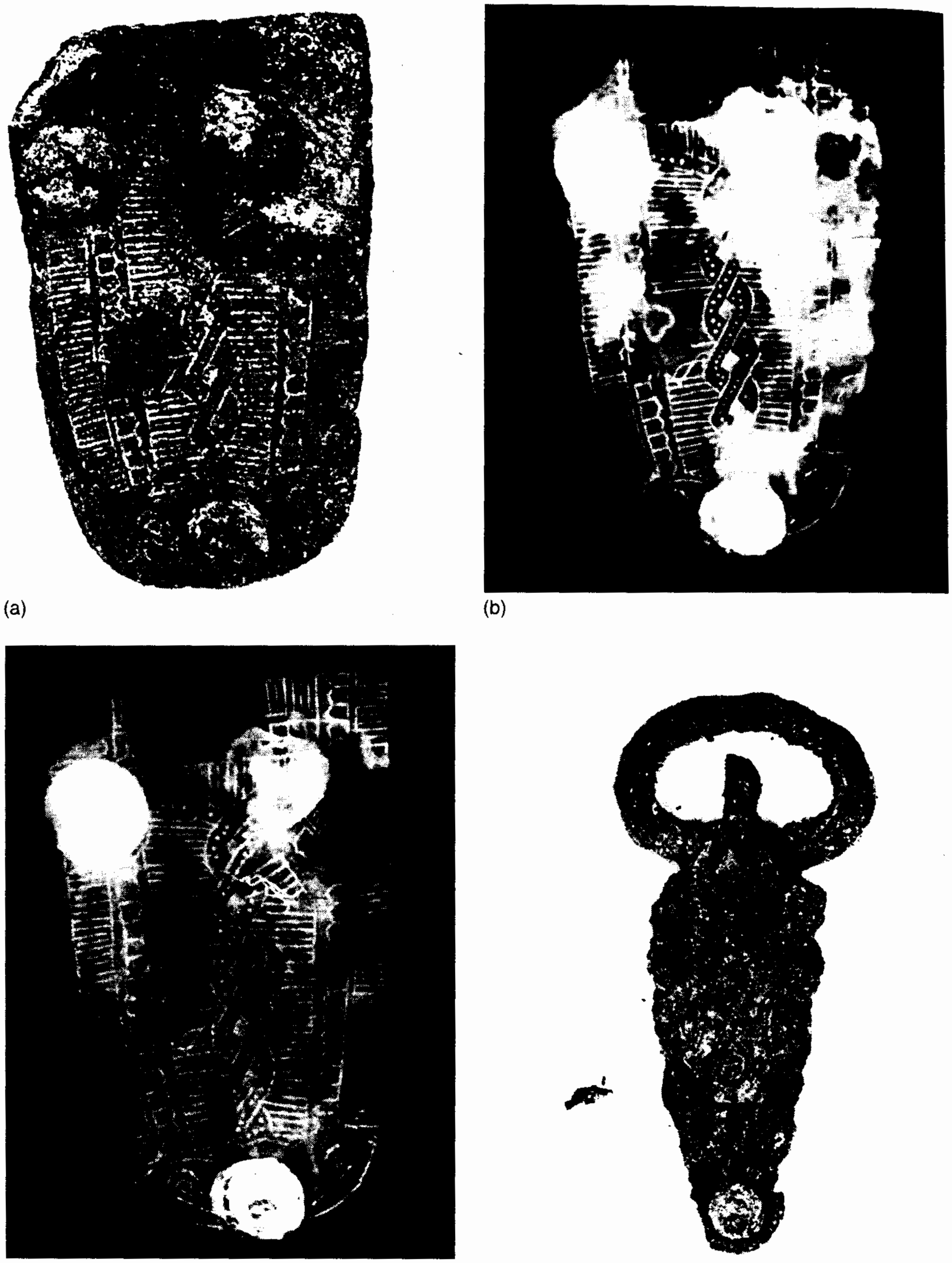
Some Sasanian bowls have small panels of 'let in' silver on the front, to increase the relief of features such as heads (Gibbons *et al.* 1979; Gunter and Jett 1992). The technique was to cut a small channel at an angle around the edge of the feature in the surface of the bowl, and then spring a small, convexly curved, decorated plate representing the head into the groove. The silver from the dish was smoothed over the join with a burnishing type of tool. Radiography shows these added areas very clearly and also the deep depression at the groove (Figure 3.22). Carving was also used by the Sasanian silversmiths to emphasize low relief features (Gibbons *et al.* 1979; Meyers 1981) and is recognized by abrupt changes in thickness at the edge of the feature. A similar effect can be produced by the lateral raising method described by Maryon (1948). In this technique, features are raised from the front by punching with the tool held at a very low angle: this tends to produce hollowing on the back surface, which distinguishes lateral raising from carving. Scott (1991) used both microscopy and radiography to determine that carving rather than lateral raising was used on the *Philosopher and Fisherman* plates in the J. Paul Getty Museum, which he concluded may be Byzantine.

Inlays of different metals often show up well on radiographs. Silver and, to a lesser extent, copper and gold, were used in the form of inlays by the Merovingians to decorate iron buckles, straps and other items (Figure 3.23). As excavated, these objects were covered with a layer of iron corrosion so that the silver was completely obscured; radiography readily revealed the inlay. Radiographs of the Anglo-Saxon single-edged seax blade from Sittingbourne illustrated in Plate 3.2 show plaited wires, lettering and small silver and brass decorative plates (Figure

Figure 3.22. *4th century* AD *Sasanian silver dish (WA 124093) with 'let in' panels increasing the relief of the figures. A groove was cut into the surface at angle and a curved pre-shaped piece of silver was pushed into it. The groove can be seen where the relief panel is missing, and also traces of gilding.*

3.24). A comparison of the radiograph and photographs of the golden-yellow metal inlaid plates on the seax shows that they are less dense than the silver ones, suggesting that they are unlikely to be gold: this was confirmed by XRF analysis. The radiographs of the Veneto-Saracenic brass tray illustrated in Figure 3.11 reveal traces of the silver inlay which remains only in the dotted keying. These brass vessels were often decorated with gold, traces of which still remain but are difficult to detect against the yellow-coloured brass: they show up distinctly on radiographs.

A wide variety of materials other than metals is used as inlays to decorate metal objects. The radiographic density of stones and enamels depends upon their composition and is further discussed in Chapter 9. Like metal inlays, they will often show up on a radiograph depending on the differences in density, even when they are invisible beneath surface corrosion. The knot design in enamel on the Dark Age brooch shown in Figure 3.25 can only be seen on the radiograph. Inlays like enamel or niello, a



(a) (b) (c) (d)

Figure 3.23. *(a) Merovingian buckle counter plate from Northern France, early- to mid-7th century* AD *(ML 1893-12-29.291), (b) photograph of the radiograph of (a). Not all the information which can be seen on the radiograph can be reproduced in a single print, (c) image scanned from the radiograph (b). Localized contrast adjustments enable all the information in the radiograph to be seen, (d) Merovingian buckle from France, mid- to late-7th century* AD *(ML 1905-5-29.291).*

black mixture of metal sulphides applied to silver in the form of a hot paste, required the metal to be keyed or roughened to hold them in place. While the inlay is still *in situ*, the keying can be seen only by radiography. Enamel inlays can be applied in a number of ways. Two widely used techniques are cloisonné, where the fields of enamel are separated by metal strips set on edge on the base plate, and champlevé enamelling, where the channels and fields for the enamel are cut into the metal. Radiography can be useful in determining the method of enamelling, estimating the depth of the enamel, and revealing the original marking-out of the design under the enamel (Stratford 1993). Enamels are fairly transparent to X-rays, unless they contain heavy metals such as lead.

(e)

Figure 3.23. *(e) scanned image of part of the radiograph of (d), with localized contrast adjustment used to reveal details in contrasty areas of the radiograph.*

Traces of surface coatings are not easily captured on radiographs, usually because they are very thin. Gilding can be seen as lighter (i.e. radiographically denser) areas on conventional radiographs, and some of the identifying characteristics of foil and fire- (mercury) gilding enumerated by Oddy (1984) can be recognized. Features such as a bubbly surface, gilding spreading beyond its allotted area, splashes of gold outwith the gilded areas and thicker gold deposits in engraved lines on the surface, which indicate the use of fire-gilding, can be discerned on radiographs which makes the technique a useful adjunct to microscopy and XRF analysis in identifying the method of gilding.

Inscriptions, Chased and Engraved Decoration

The elucidation of inscriptions on metal objects is a frequent source of enquiry and some of the difficulties

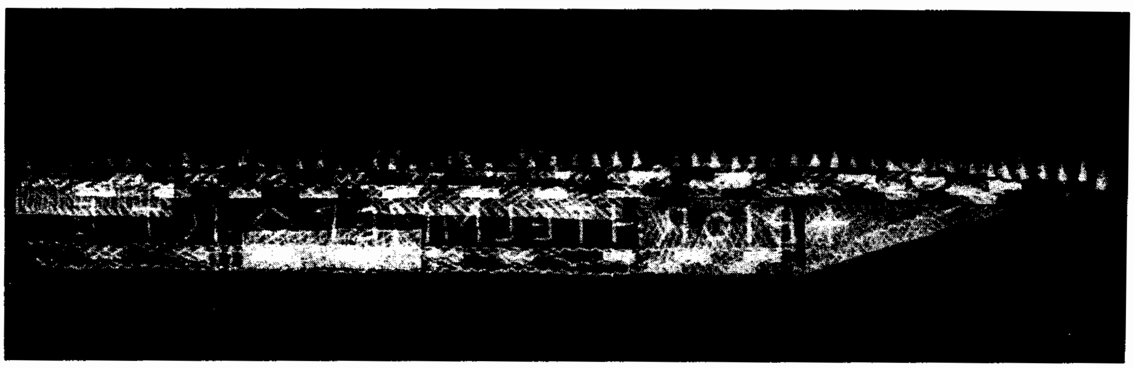
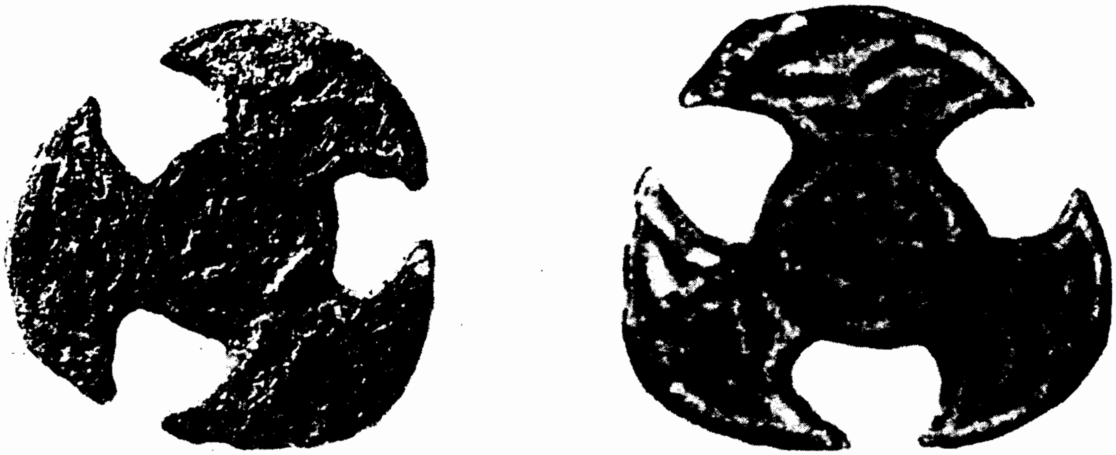


Figure 3.24. *9th to 10th century* AD *Anglo-Saxon seax (ML 1881-6-23.1) from Sittingbourne, Kent. The scanned radiograph shows the two designs superimposed. The engraved pattern (Plate 3.2(left)) is so shallow that it is not visible on the silver panels, but the cross-hatched keying underneath is revealed. The yellow panels are not as dense as the silver and are brass not gold.*



(a) (b)

Figure 3.25. *Unprovenanced Dark Age enamelled disc, 6th to 7th century* AD *(ML 1907-6-12.1). (a) Photograph shows little of the design but the radiograph (b), obtained using an image intensifier and enhanced with sharpening filters, shows the design clearly.*

have been outlined in Chapter 2. Inscriptions are frequently difficult to radiograph because the depth of the inscription is insignificant in comparison with the total thickness. This means that the conditions must be arranged so that maximum contrast is achieved by using low kVs with higher currents and longer exposures if necessary. Image processing may help to increase the contrast.

The radiographic work carried out on the Balawat Gates from Mesopotamia, now on display in the British Museum, revealed a number of the inscriptions which were otherwise obscure, and helped to provide evidence which enabled broken parts to be pieced together (Barnett and Werner 1967). Inscriptions are sometimes of crucial importance in assessing the significance of an object. An inscription on a bronze Elamite bowl was partly obscured by corrosion and wear. With the help of radiography it was possible to decipher that the bowl was owned by Tempti-Agun I, King of the Elamites in 1575 BC, and had been given to him by his son.

The five swan necked spoons from the Romano-British site at Hoxne, Suffolk (Figure 3.26(a); see also Plate 3.3), have inscriptions on the bowls which could only be fully deciphered with the assistance of radiographs (Hassell and Tomlin 1993). These show (Figure 3.26(b)) that alterations had been made to the text: in one (0046), the craftsman had started to engrave the name PEREGRINVS, starting at the handle end and then, presumably realizing a mistake, started again from the other end simply engraving over the first six letters. On another spoon (0008), the inscription (visible on the radiograph) appears to have been deliberately abraded and polished and, as it stands, makes no sense, reading QVISSVNTVIVAT: Hassell and Tomlin suggest that it should be QUINTVSVIVAT.

Sometimes the design remains within the corroded metal only as a discontinuity, which can be recorded clearly on a radiograph although the metal has corroded completely. The decoration on a Phoenician bronze bowl from Nimrud (WA 91420) was revealed in this way, despite the bowl being completely mineralized and any attempt to reveal it by any other method would probably have been unsuccessful (Barnett and Werner 1967).

In a museum or archaeological context, metal objects are probably radiographed more frequently than objects made from other materials: it is hoped that this chapter has indicated why this non-destructive technique is so widely used and how versatile and illuminating it can be in the study of metal objects.

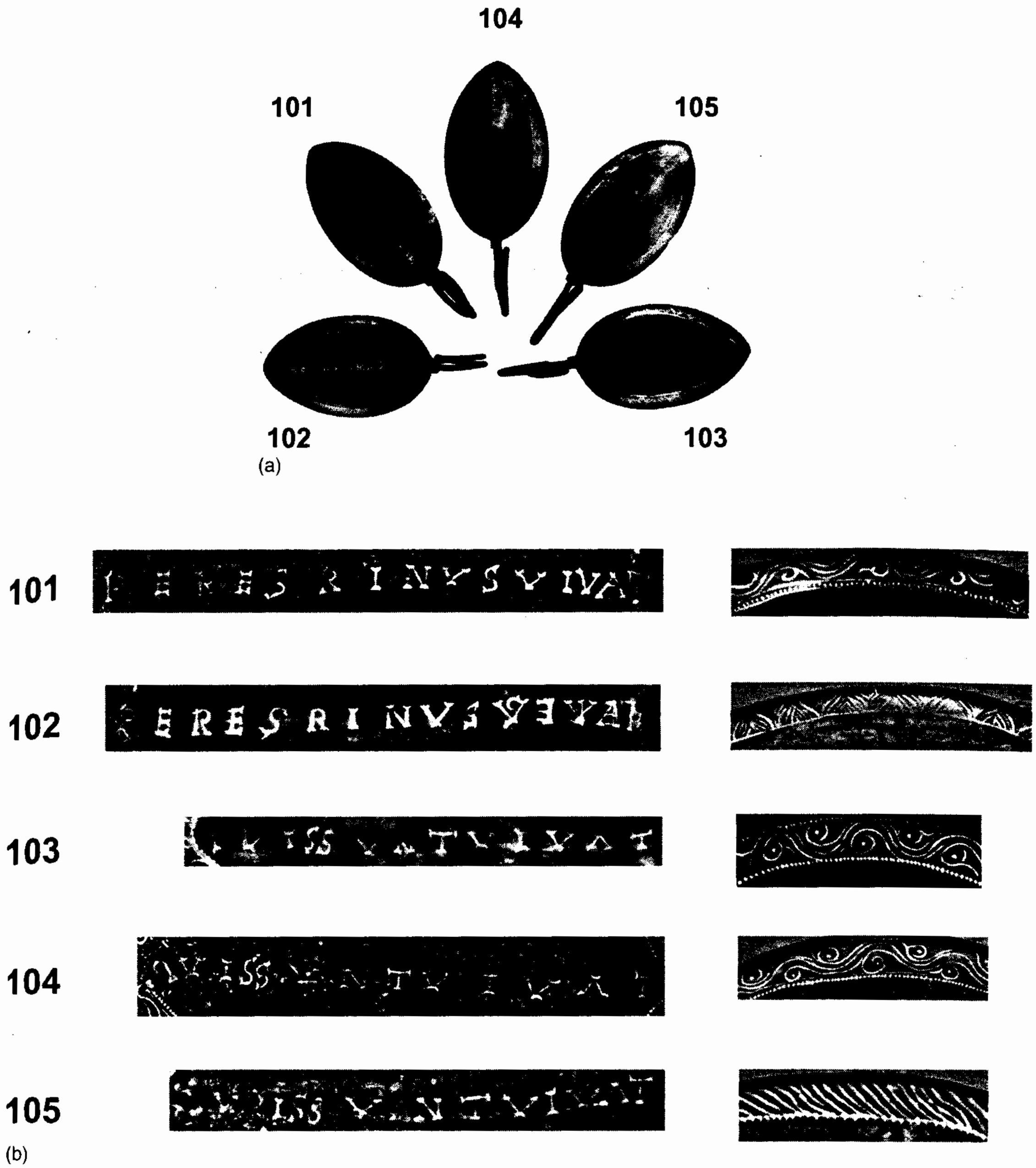


Figure 3.26. *(a) Five late Roman swan necked spoons from the Romano-British site at Hoxne, Hertfordshire, have inscriptions punched in the bowls (see also Plate 3.3). The alterations to the inscriptions are only revealed on the radiographs. 7 mA, 10 min, 100 kV, lead screens, 0.6 mm copper filter, AX Kodak film. (b) The images of the inscriptions and the designs around the rims have been processed digitally to show the details more clearly.*

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4

Ceramics

Andrew Middleton

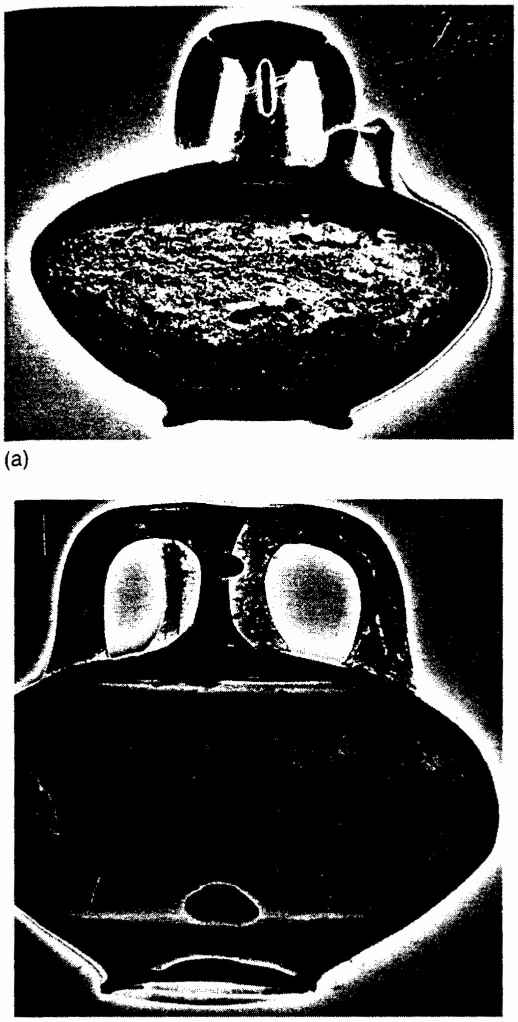
Introduction; characterization of clay fabric, imaging inclusions, identifying inclusions; forming and fabrication techniques, primary-forming techniques, secondary processing, hybrid vessels, composite objects; prospects

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.

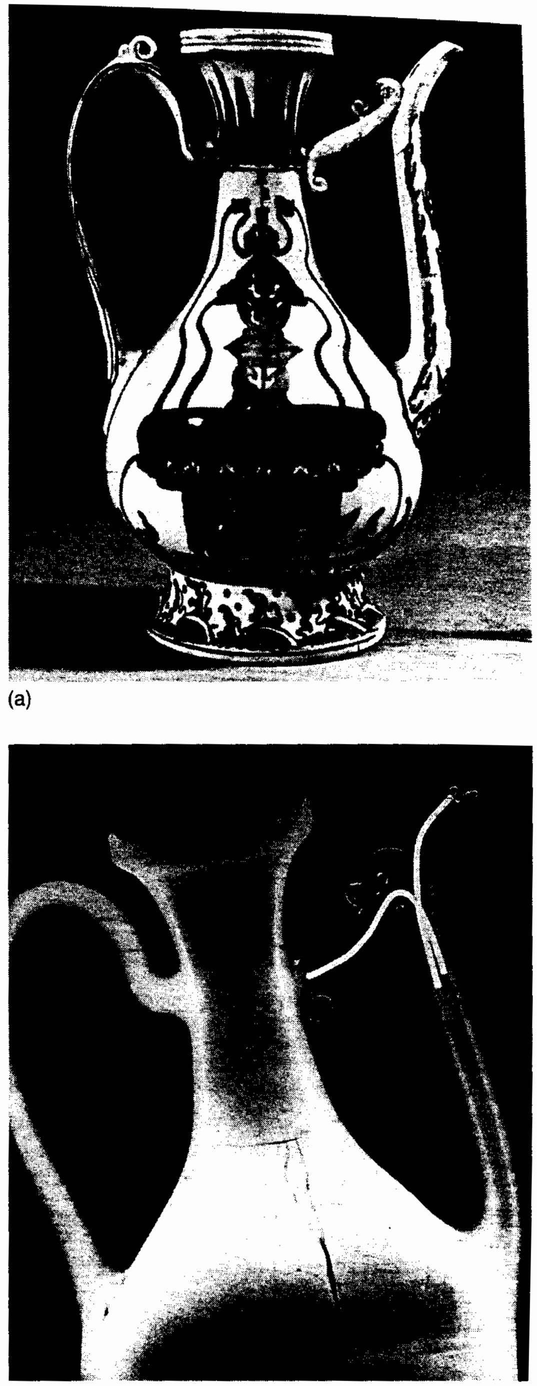


(a)

(b)

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

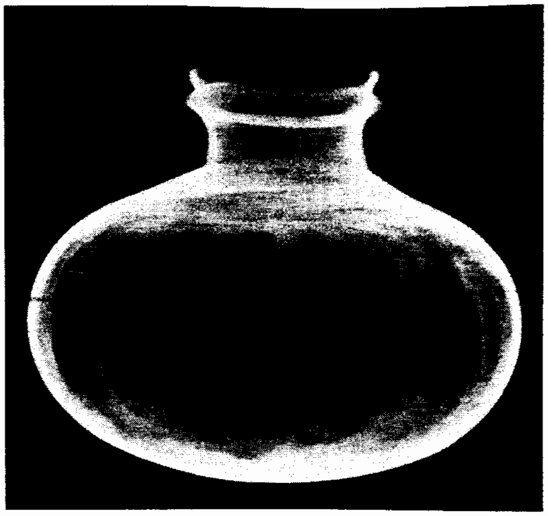


(a)

(b)

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)



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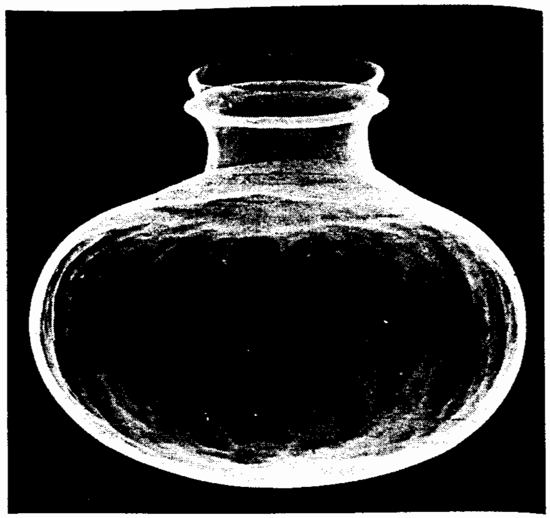


(c)

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

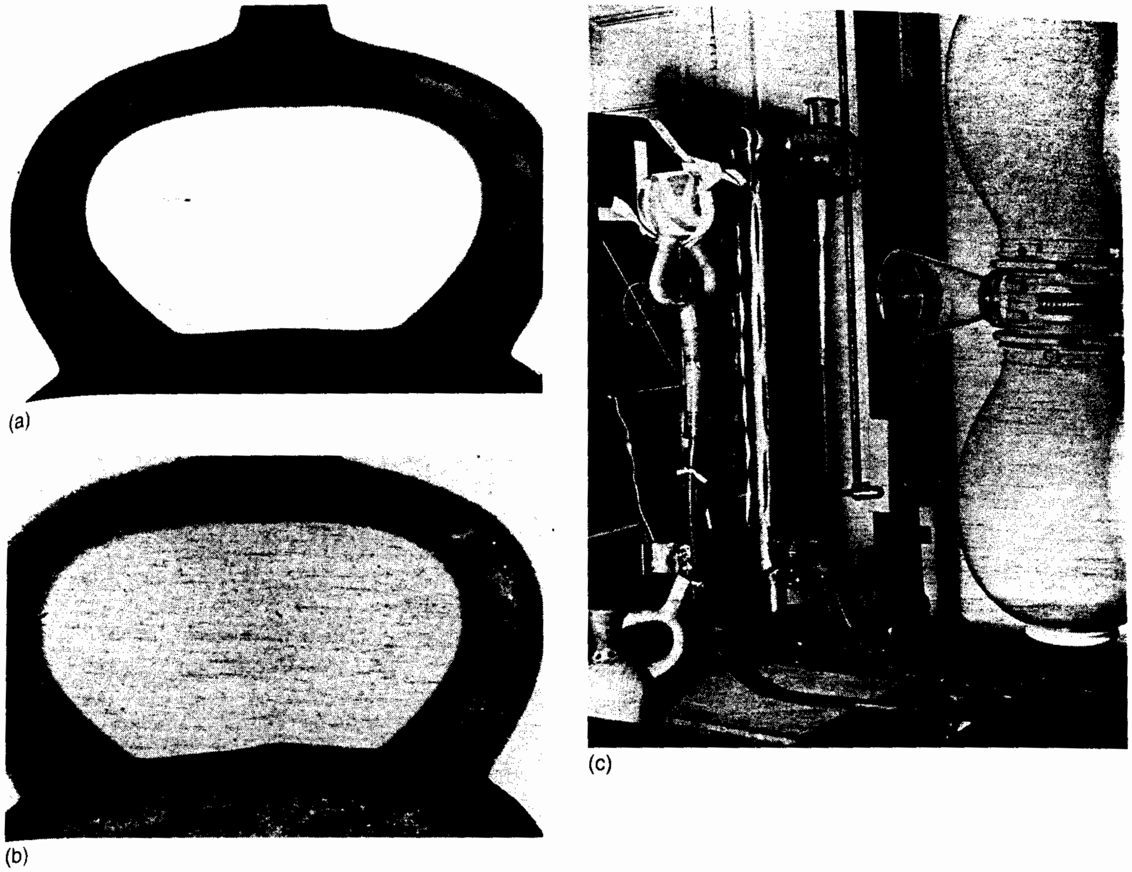


Figure 4.4. *(a) Radiograph of a Peruvian stirrup-handled pot (ETH 1909-12-18.248). (b) Radiograph of the same vessel after mercury had been siphoned into the hollow handle using the apparatus shown in (c). All photographs were recorded by Plenderleith in the late 1930s.*

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

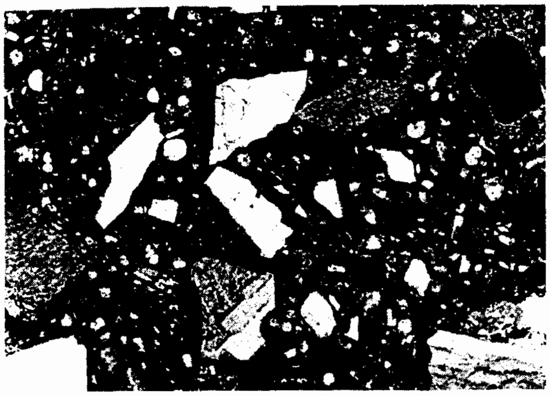


Figure 4.5. *Photomicrograph showing coarse inclusions of calcite in a Late Bronze Age sherd from Um Hammad, Jordan (WA 1989-1-29.20). Width of field, c. 2 mm.*

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

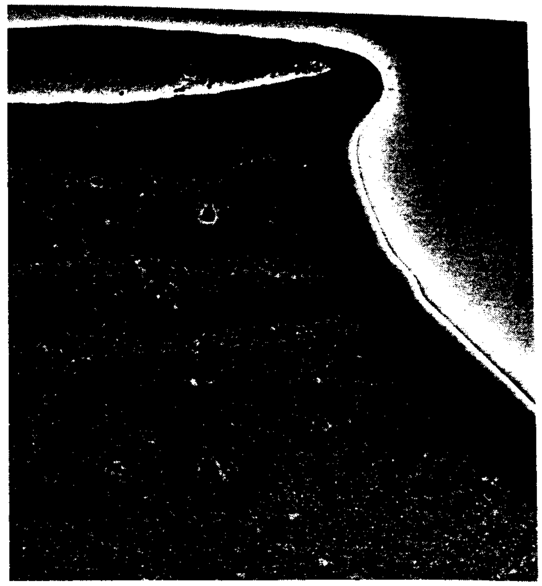
Many radiographs of ceramic objects, present a rather 'flat' appearance. This arises in large part from the inherently low radiographic contrast of the ceramic subject, rather than from any particular shortcomings in the choice of film or exposure conditions. However, scattering of the relatively soft 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)

(a)



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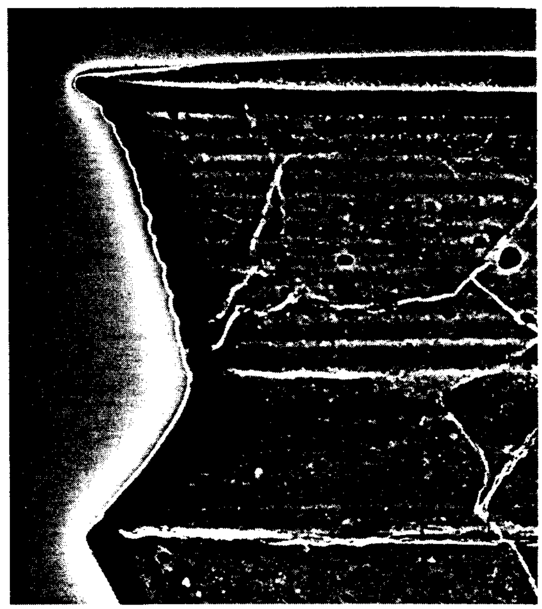

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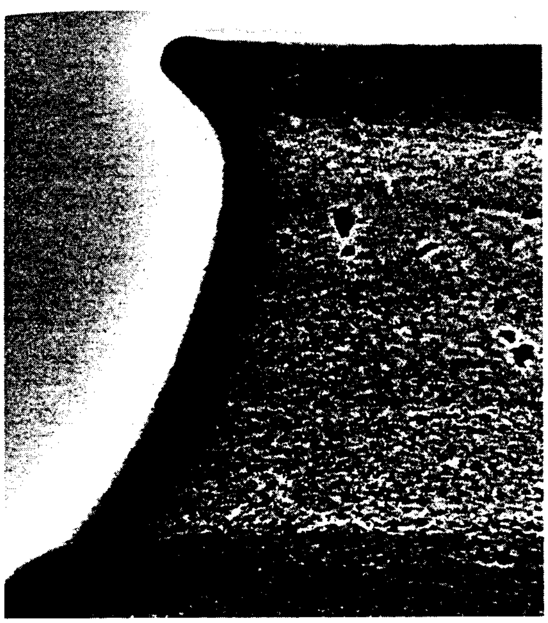
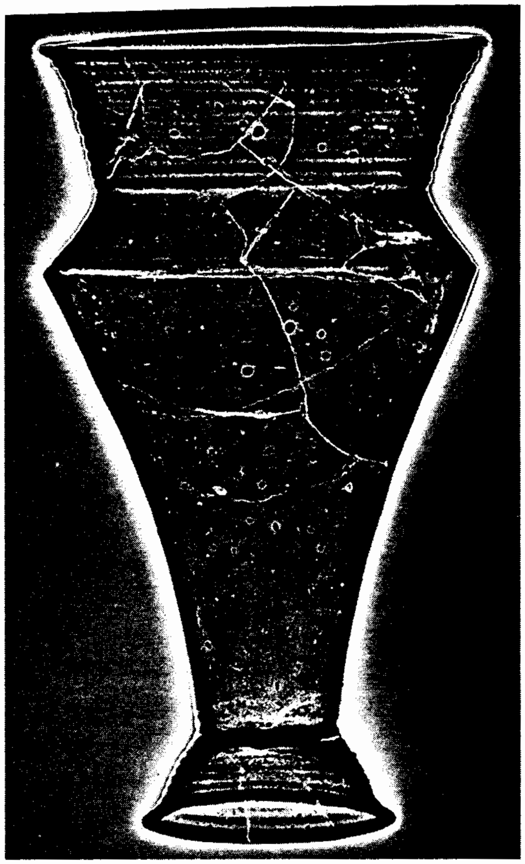
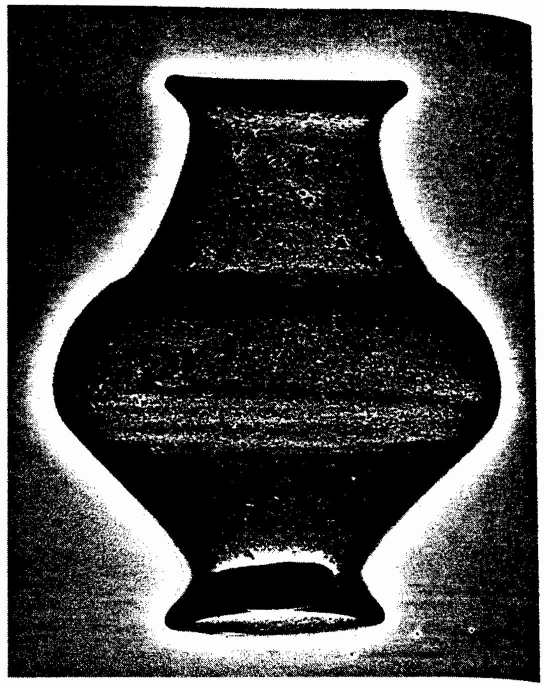


(b)

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.*



(a)



(b)

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

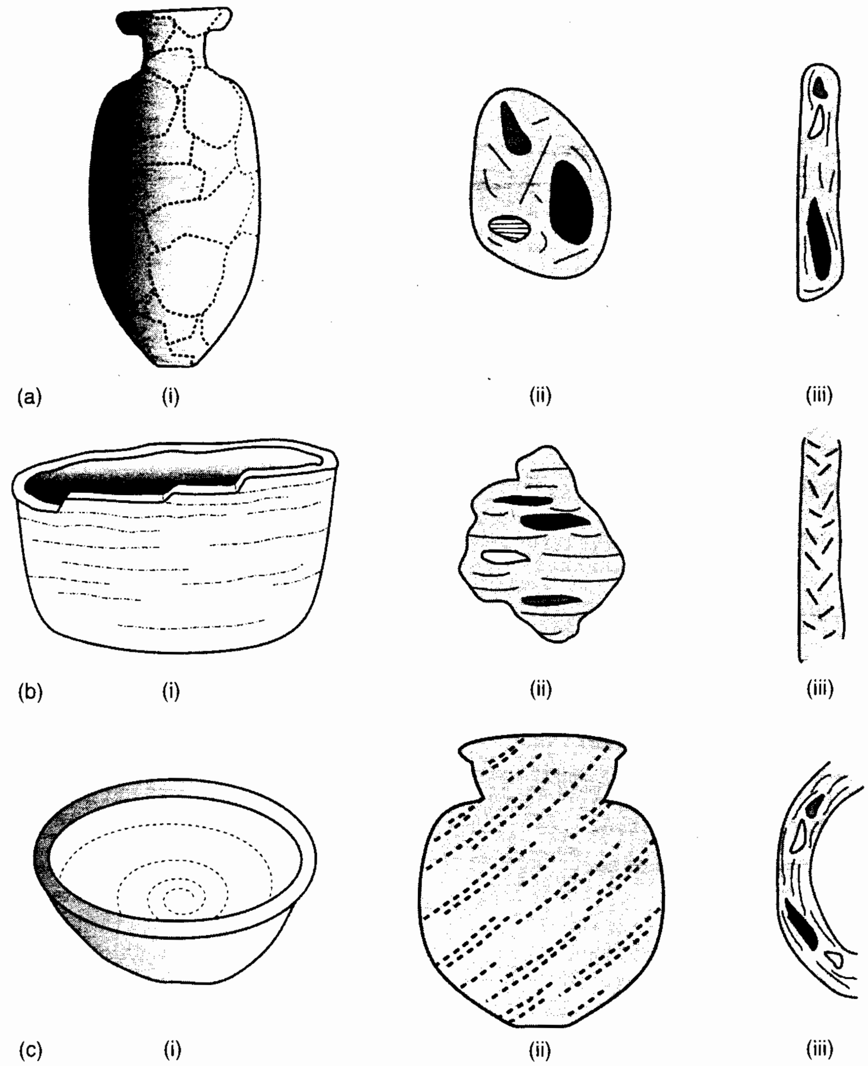


Figure 4.8. *Diagrams illustrating characteristic features of some pottery-forming techniques (redrawn after Rye 1981, Figures 54, 49 and 62). (a) Slab-building: (i) vessel built up from a series of slabs of clay; (ii) random orientation of particles in normal view; (iii) preferred orientation of particles 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, 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

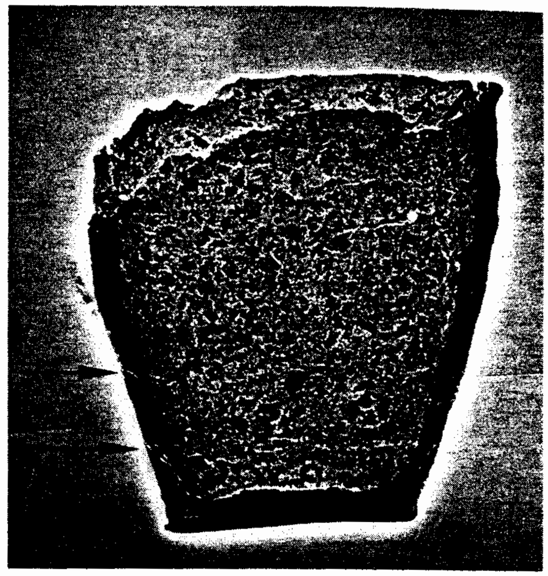


Figure 4.10. *Xeroradiograph of a Late Bronze Age funerary vessel from Burton Fleming, Yorkshire. Some joins between successive coils of clay are visible (arrowed; see text for discussion).*

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

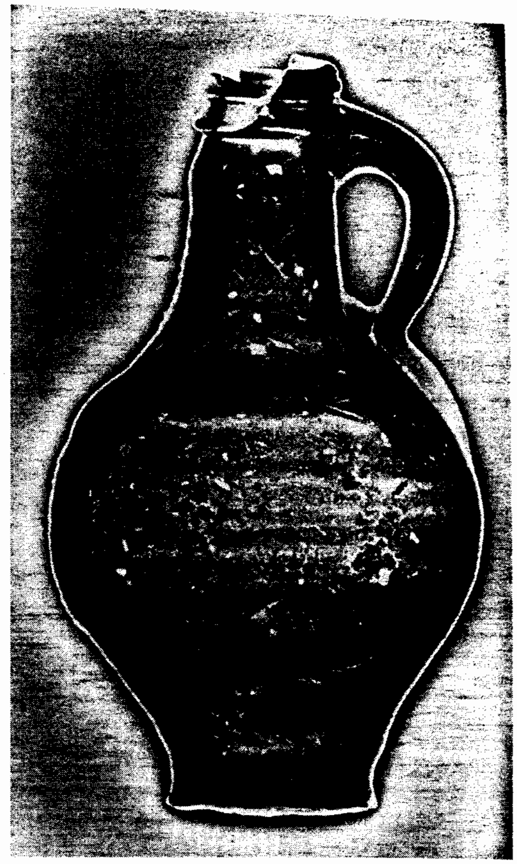


Figure 4.11. *Xeroradiograph of a 17th century Bellarmine jar. The oblique orientation of voids and elongate particles is characteristic of wheel-throwing (Museum of London).*

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

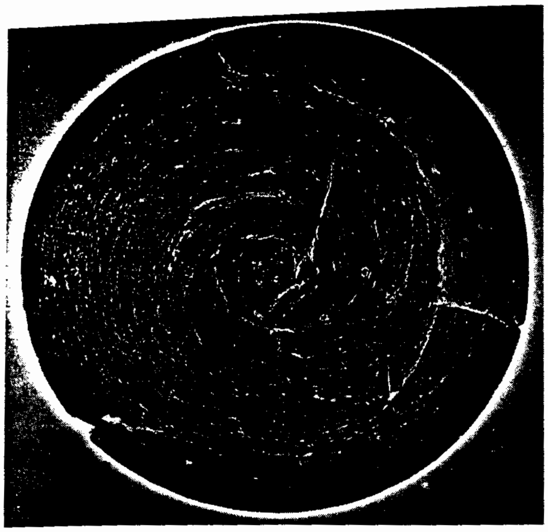


Figure 4.12. *Xeroradiograph of a Late Bronze Age bowl from Lachish, Israel (viewed from above) showing spiral patterning, characteristic of wheel-throwing (Oriental Museum, University of Durham, GM 1964–262.).*

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

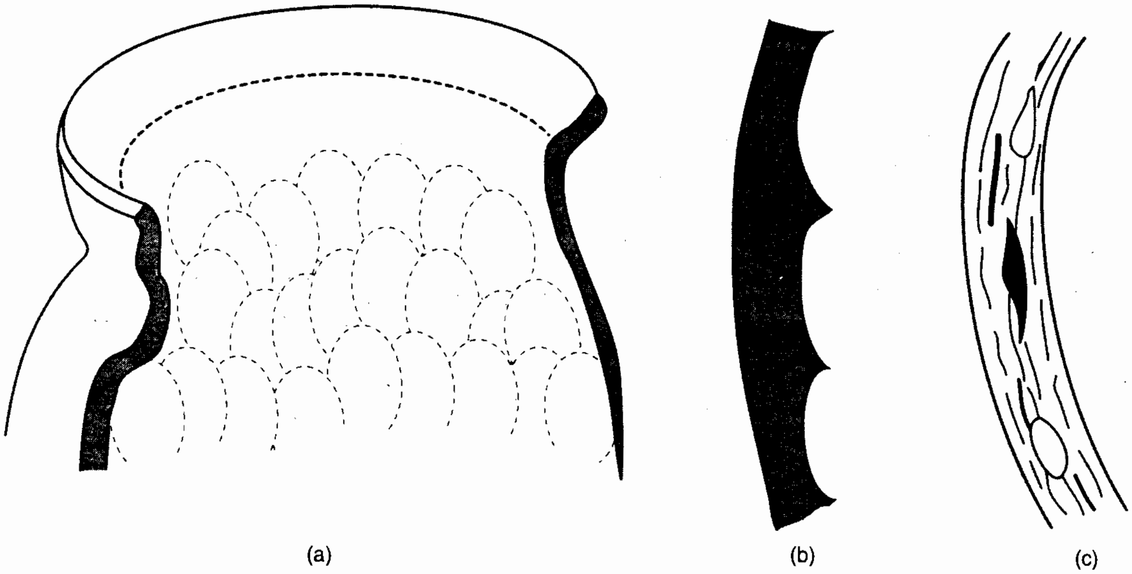


Figure 4.13. *Diagram illustrating some features arising from the use of the 'paddle and anvil' technique: (a) depressions on the interior of the vessel; (b) variations in wall thickness and (c) preferred orientation of particles parallel to vessel walls (after Rye 1981, Figure 70).*

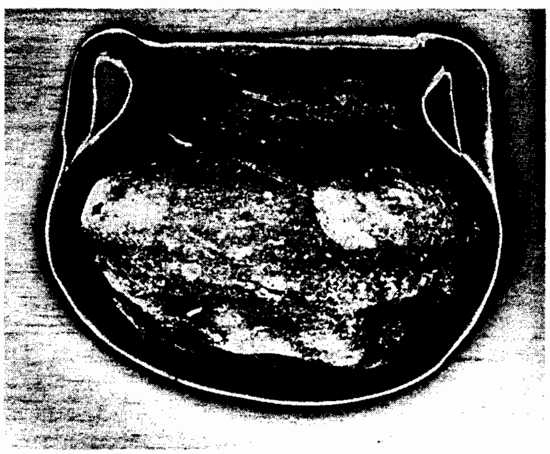


Figure 4.14. *Xeroradiograph of a medieval cooking pot. The lower part of the vessel appears to have been hand-made, perhaps with the aid of a mould, whilst the upper wall and rim were wheel-thrown (note the oblique orientation of the voids) (Museum of London).*

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.

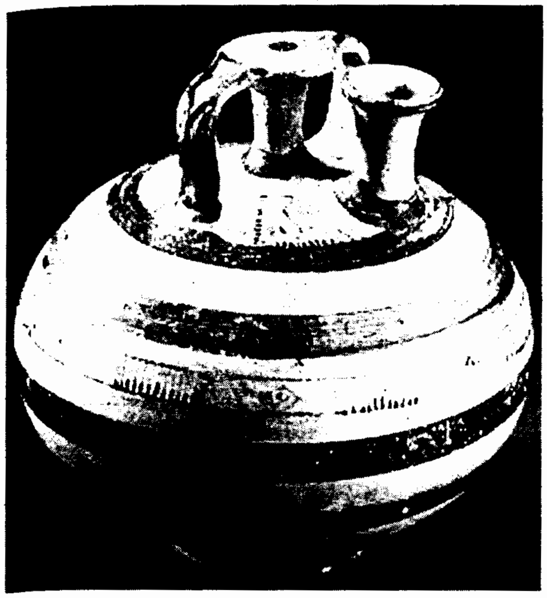
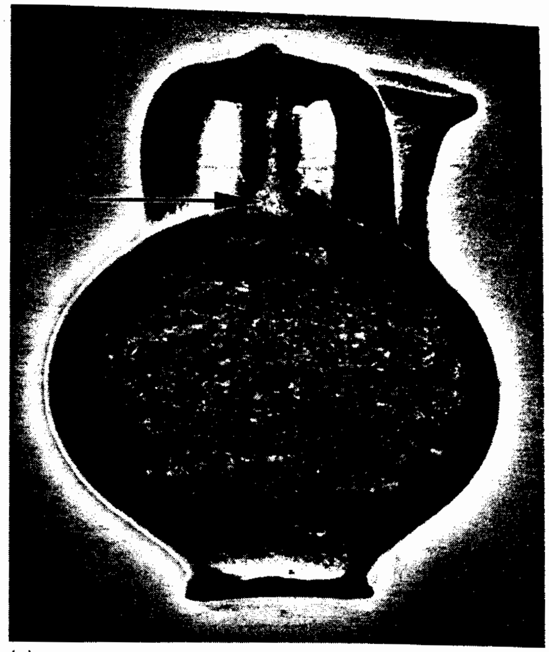
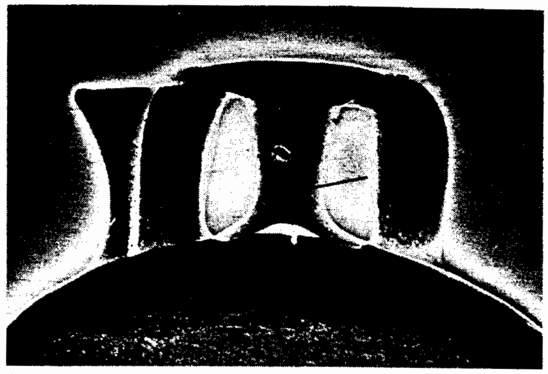


Figure 4.17. *Late Bronze Age stirrup jar from Ialysos, Rhodes (GR 1870-10-8.89).*



(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

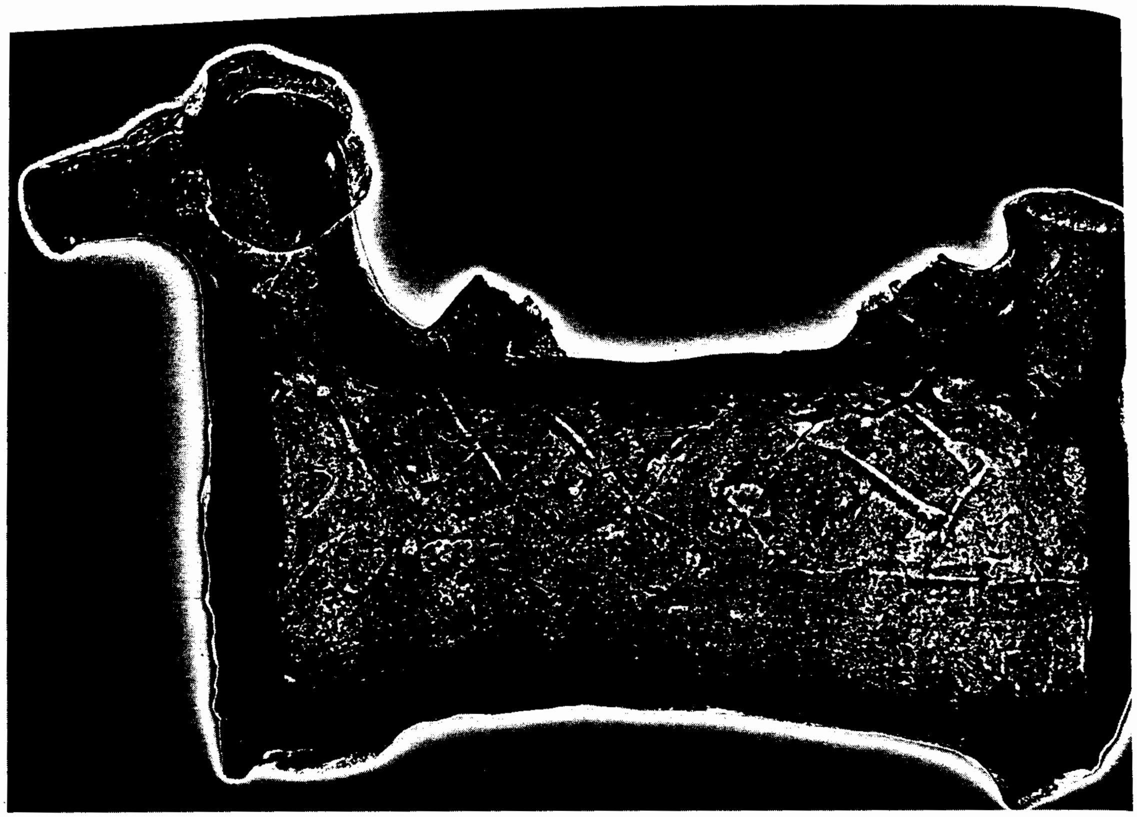


Figure 4.19. *Xeroradiograph of a medieval aquamanile, thought to have been made by coiling. Note the obscuring effect of the lead glaze (ML 1984-6-3.1).*

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

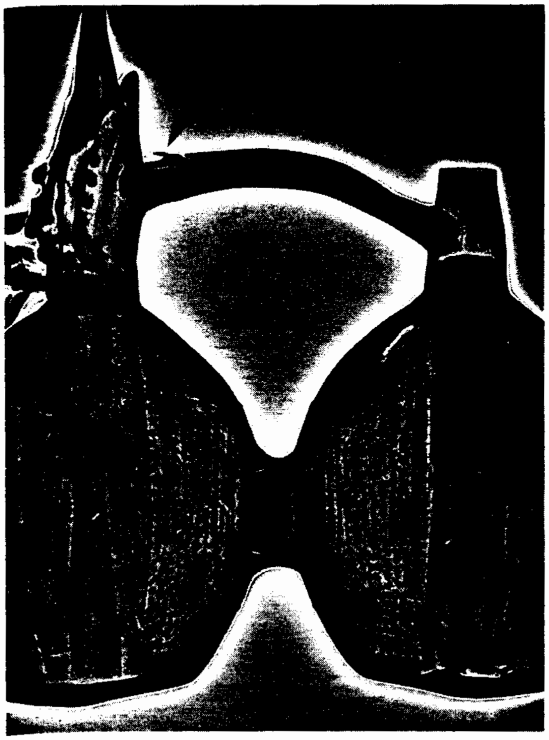


Figure 4.20. *Xeroradiograph of a Peruvian Chimu style double-chambered whistling pot. The radiograph reveals how the various elements were joined together and also the location of the 'whistle', embedded within the handle, close to the head of the figure (arrowed) (ETH 1921-10-27.119).*

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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