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POTTERY MANUFACTURING TECHNIQUES: X-RAY STUDIES

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Introduction

Pottery typologies are almost universally based on attributes of vessel form and decoration. In attempting to extend the value of excavated pottery in both cultural and technological interpretation, other attributes derived from, for example, material use (Rye 1976) and manufacturing technique can be used. Franken (1969, 1973, 1974) has discussed the problems and implications of broadly based typologies.

The study of pottery manufacturing techniques is relatively straightforward where vessels have been formed on the potter's wheel, as surface markings are often not removed, especially on the interior of closed vessels. Sherds from hand-formed vessels are usually much more difficult to interpret because such techniques commonly produce an initial vessel form which is irregular in wall thickness and shape, requiring extensive smoothing and surface finishing. This removes evidence of earlier forming operations.

While this is true of much pre-wheel formed pottery, I have been working recently with excavated Papuan pottery, which allows some details of forming technique to be reconstructed. Some sherds from large globular vessels show depressions on the interior surface and corresponding paddle markings on the exterior showing clearly that a paddle and anvil technique was used. This is supported by the presence of distinct laminar fracture to the wall of the vessel as a result of strong compression of the fabric. Generally, though, some 90% of the excavated pottery allows no definite statements about forming technique, even with the aid of data gained by ethnographic studies of traditional potters still working in the area. Thus it was decided to experiment with x-ray techniques to determine whether further useful data could be obtained.

The use of radiography generally needs no discussion; it has apparently not been used systematically before in pottery studies. Bertrand *et al.* (1962) report its use in quality control in the ceramic industry. Milanesi (1966) reports microradiographic studies of prehistoric pottery but his work has been available to the writer only in abstract.

Initial studies

In order to establish the relationship between forming process and its evidence on a radiograph, Papuan pottery from Boera and Mailu Island for which the detailed sequence of forming operations is known, has been used. I collected pottery from both these centres and

Table 1 *Cation exchange capacity of refired sherds (m.e./100 g)*

Sherd	*Refiring temp (°C)*		
	100	*750*	*950*
90f1	4.9	3.8	3.3
9 f2	15.1	9.7	4.6

DISCUSSION

The experimental work shows clearly that substantial c.e.c. remains in clays after firing to up to 1000°C. The rather gradual fall off in value over the firing range of interest appears from d.t.a. and x.r.d. work to be associated with the loss of structural water and subsequent disintegration of the lattice structure. Presumably this enables a redistribution of ionic charge, and also reduces access to exchangeable sites.

The uptake of UO_2^{++}/Mg^{++} is approximately in proportion to their concentrations; while this is not unexpected, the possibilities of equilibria operating between various complexes of U(VI), and of the binding of the ion as U^{6+} (which one would expect to be very tight), make its behaviour difficult to predict. At least in large concentrations, the uranyl ion acts similarly to the more common ions in soil ground waters. The situation may be different at very low concentration, since it is likely that in the population of exchangeable sites in the clay there are some specifically favourable for binding this ion. However, this is shown to be only a small proportion of the total available sites.

While the c.e.c. values of the two Roman sherds refired to 950° are consistent with those obtained from firing clay, the two sherds differ greatly at lower refiring temperatures. *90f1* is a Samian fabric, while *9f2* is a common coarse ware type. While some difference may be ascribed to initial firing to different temperatures at which the c.e.c. is partially removed by different amounts, it is more likely that the main difference is due to subsequent 'rehydration' on burial (Kingery 1974). This is supported by d.t.a. curves in which *9f2* shows a large dehydroxylation peak around 320°, whilst *90f1* shows very little evidence of rehydration. The difference in rehydration rate on burial is consistent with the higher firing temperature and lower porosity of Samian ware. Thus not only must we expect pottery to show substantial ion exchange capacity, but at least for lower fired wares this capacity can increase to a value typical of raw clays on burial.

IMPLICATIONS FOR ARCHAEOMETRY

We consider first the effect of residual and re-acquired ion exchange capacity on provenance determination by trace element measurement. Effects which alter the initial clay composition by more than 10% of the trace level can seriously confuse the assignment of likely clay sources. Alteration of the composition of the exchangeable ion population (which for a typical c.e.c. value of 10 milli-equivalents/100 g—a value of 2/3 that found for sherd *9f2*—is 0.5% of the total clay composition) is most likely brought about by a change in the composition of the groundwater environment of the buried sherd from that of the original clay bed. Since groundwaters are largely Na^+, K^+, Ca^{++} and Mg^{++}, which are generally present

in the 1% or greater range in pottery, a major change in, say, the Ca^{++}/Mg^{++} ratio would be required to influence the Ca/Mg ratio in pottery by more than 10%, unless the clay was unusually low in Ca or Mg. For consideration of trace levels it is important to know the proportion of trace element held on exchangeable sites. If we consider the situation for U, a typical concentration of U in natural ground water is $5–10 \times 10^{-6}$ of the total dissolved ion content (Miyake *et al.* 1964). If we assume this fraction is maintained for exchangeable ions, this would amount to 0.1–0.3 p.p.m. of U in the clay for a typical c.e.c. This does not allow for the greater affinity of the clay for UO_2^{++} over the common ions Na^+ and K^+ but nor does it allow for the fact that some of the dissolved U may be in the form of anions. However, since typical U contents of clay or pottery are in the region of 1–3 p.p.m., we might expect that 10% and perhaps more of this is potentially exchangeable. Thus, for example, a sherd buried in groundwaters of twice the U concentration (relative to other ions) from that of its parent clay could experience a 10% increase in U concentration. The same possibilities exist for other trace elements. On the other hand, unless quite unusual situations occur (e.g. burial near corroding bronze) there is unlikely to be greater than a few percent change in trace element level. This is, of course, consistent with the fact that the determination of pottery provenance from trace element compositions is generally successful, and is clearly not usually invalidated by the different soil conditions in which pottery is buried. However, it is worth pointing out the possible source of error.

The major proportion of the radiation dose to buried pottery comes from K^{40}, Th and U in the fabric; the K^{39} concentration is usually 1–2%, while U and Th are present in several p.p.m. Depending on the clay (e.g. the lattice for illites necessarily contains K), a substantial fraction of the 1% or so total quantity of exchangeable ions will be K^+, and the fixation of K^+ from groundwaters is a well-known process. We have shown that an appreciable exchange capacity remains after firing, so that on burial a significant portion of the K^+ is subject to replacement depending on the groundwater composition. The case for U has been discussed above, where it is concluded that alterations of up to 10% are quite possible, and the same argument should apply to Th. Even greater changes may be expected when the pottery is partially rehydrated, since not only is its exchange capacity increased, but the increase is likely to be at different sites from the raw clay, and therefore there is a net increase of exchangeable ion content rather than a replacement. This would occur slowly over time, while the parameters used in estimating the radiation dose are derived from the final composition of the sherd. This potential source of difficulty in TL dating might be hard to detect, but it would be interesting to see if those samples known to give less reliable results also had large residual c.e.c., and it might be possible to measure the extent of exchangeable K^+, UO_2^{++}, Th^{4+}, by replacing all such ions with Ba^{++} and observing the change in K, Th, and U content.

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Results II

The two specific cases discussed above provided initial data to show that x-ray techniques could be used to reconstruct broad elements of manufacturing technique. As with any other identification procedure, it is necessary to have available as many 'standards' as possible with which to compare unknown examples. To this end other vessels from modern ethnographic collections in Melanesia have been radiographed, and a very limited number of samples from other areas of the world. A radiograph of a fifth to sixth century Byzantine store jar sherd from Gaza is shown in plate 2. It is obvious from surface markings on the sherd that it was wheel thrown. Inclusions in the sherd show two simultaneous orientations: one parallel to the interior and exterior walls of the vessel, and another with all inclusions parallel to one another and inclined at roughly 45° to the horizontal.

This is consistent with the pressure applied by the potter's fingers in throwing on the wheel, the action between the hand inside the vessel and that outside being to both compress and lift the clay at the same time. Study of x-rays of various thrown vessels suggests that the rapidity of the lifting action is reflected in radiographs by the angle which inclusions take to the horizontal. With slow lifting action the angle is smaller (say 20–30°) and with a faster lifting action the angle approaches 45°. The angle may also partially be a function of wheel speed, and this could be tested empirically. It is concluded that the x-ray techniques can be used to distinguish wheel thrown sherds from others where there is no surface evidence, and that it may be possible to specify details of the throwing process.

A limitation which may be insoluble is that it is still not possible to reconstruct the entire forming sequence with many handbuilt pots. For example in the Boera case discussed above there is no evidence on radiographs of the initial forming process of forming a lump of clay and little evidence of drawing up the thick walls; occasional sherds show a vertical orientation of organic fragments near the shoulder of the vessel resulting from the drawing upwards of the thick walls. In many cases relatively minor differences between initial forming techniques for vessels will not be recovered.

A further limitation is that sherds used for x-ray analysis could not subsequently be used for thermoluminescence dating.

An unforeseen advantage of the technique is that the radiographs give a rapid visual estimate of the amount, and particle size distribution, of inclusions. Thus unusual sherds can be rapidly recognized and selected for thin-section study or other material analysis.

Conclusions

Straightforward x-ray techniques can be applied with pottery sherds to analyse and reconstruct forming techniques used in the manufacture of vessels. The method relies on the basic principle that different forming techniques involve different and characteristic applications of pressure to plastic clay, and that inclusions in the clay take up preferred orientations which are characteristic of the forming operations. In order to establish criteria for recognition of specific forming techniques it is necessary to work from pottery where the sequence of forming operations is clearly recorded, such as pottery collected in ethnographic studies.

In addition to providing data on manufacturing techniques, the radiographs can be used to study variations in temper quantity and particle size range, and to select representative or unusual specimens for thin section studies of sherd mineralogy.

The method has several prerequisites: that inclusions in the pottery are not equiaxial, and are of sufficient size to be visible without magnification; that the largest possible sherds

facing page 208

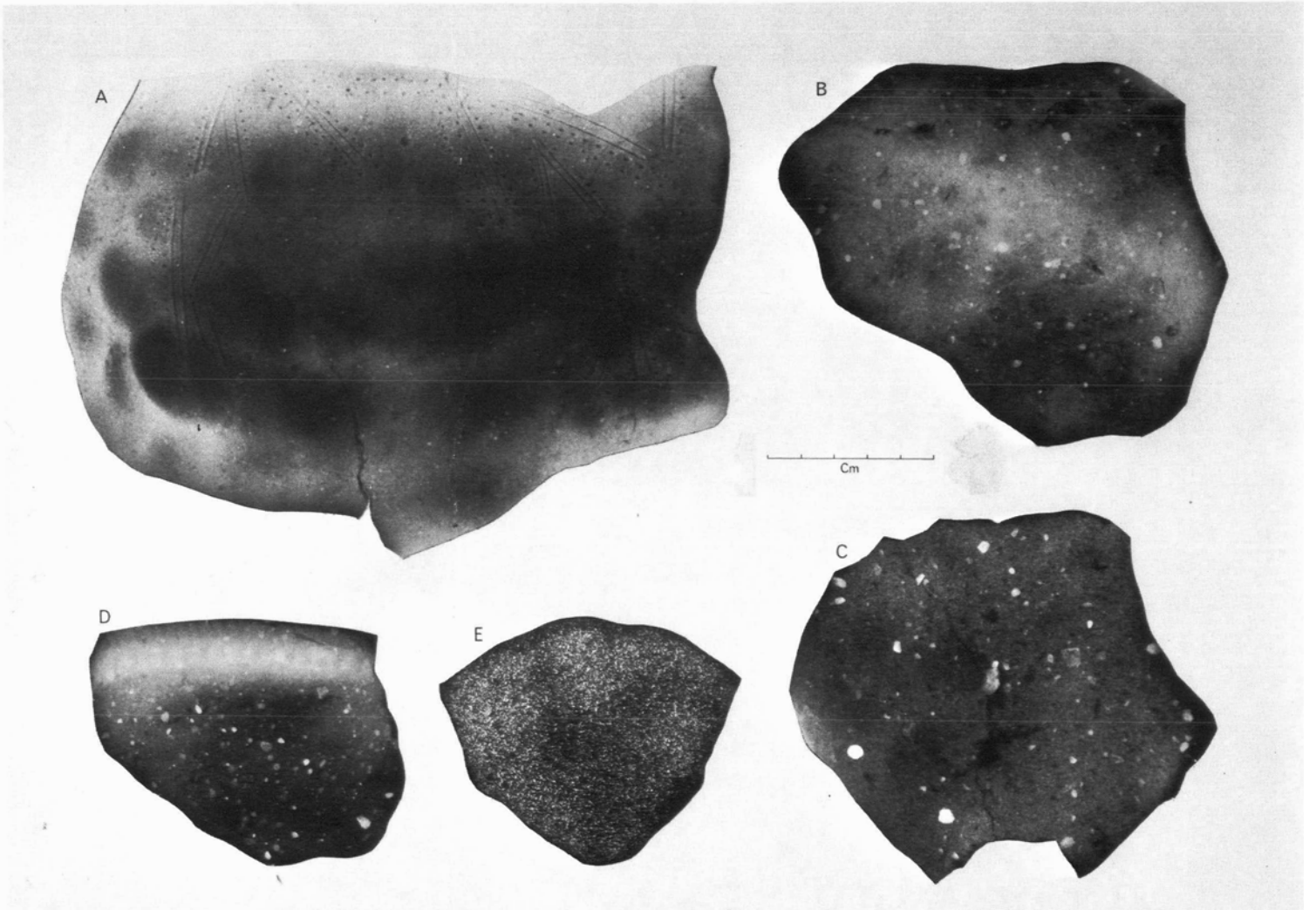

Plate 1 *Radiographs of Papuan sherds (Kodirex film)*
(a) *Upper wall of modern Boera vessel. Note even rows of anvil depressions on interior wall, and incised decoration on exterior.* (b) (c) *Prehistoric sherds from Motupore Island (paddle and anvil technique).* (d) *Prehistoric sherd from Motupore Island (bowl form produced by pinching out clay between fingers).* (e) *Prehistoric sherd from Motupore Island. Note distinctive temper particle size range compared to sherds* (b), (c) *and* (d).

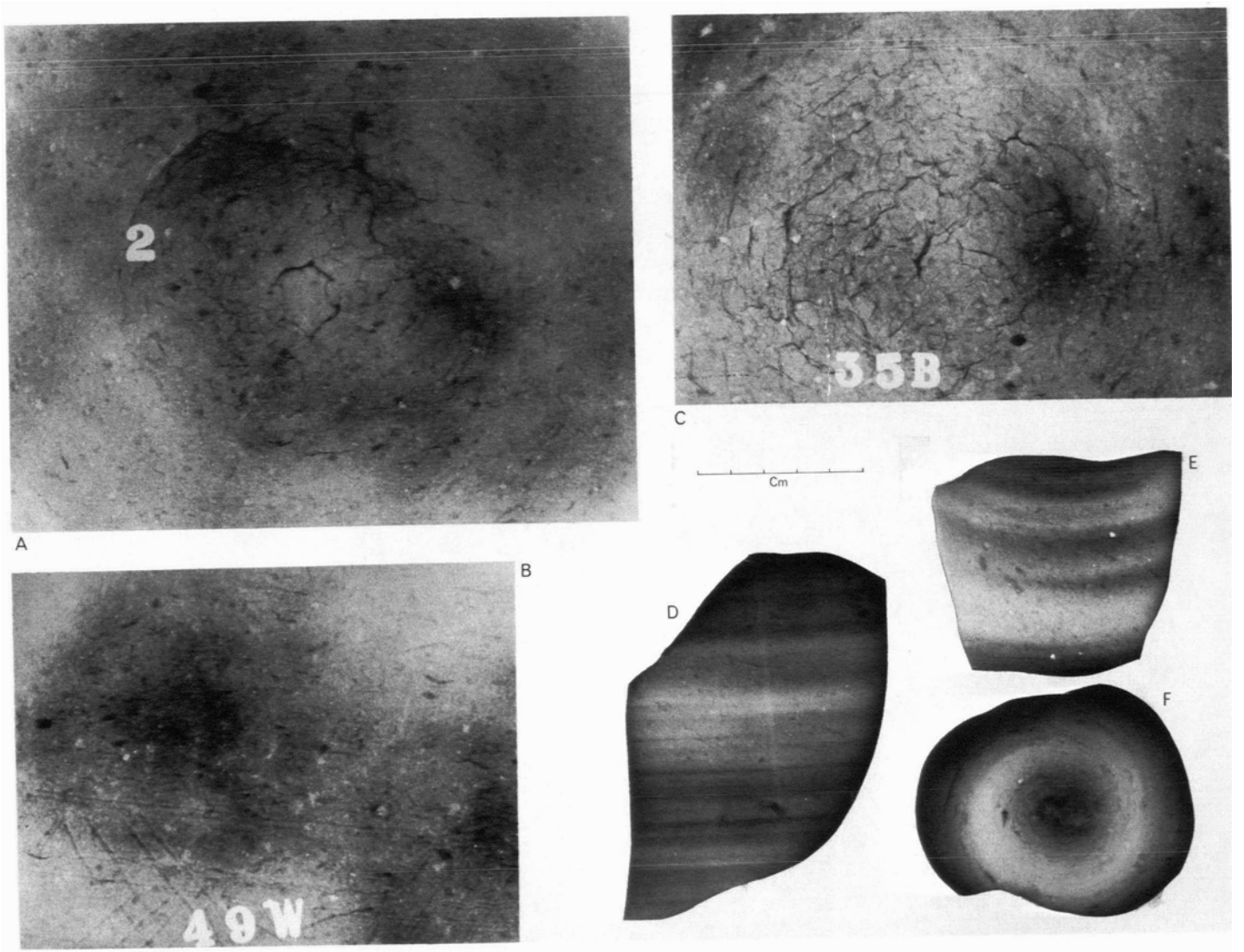

Plate 2 *Radiographs of coil-made and wheel-thrown pottery (Kodirex film)*
(a) *Base of modern Mailu Island cooking pot. Note central plug, circular area of base formed in coconut shell, and circular orientation of voids (dark).* (b) *Base of modern Mailu cooking pot made contemporaneously with* (a), *by a different potter.* (c) *Side wall of Mailu cooking pot (rim to bottom of page). Note parallel, horizontal orientation of voids.* (d), (e) *Wheel-thrown vessels. Note ridges from potter's fingers, and voids oriented parallel to one another at about* 30° *to throwing ridges, wheel rotation clockwise.* (f) *Base of wheel-thrown vessel, with spiral orientation of voids.*

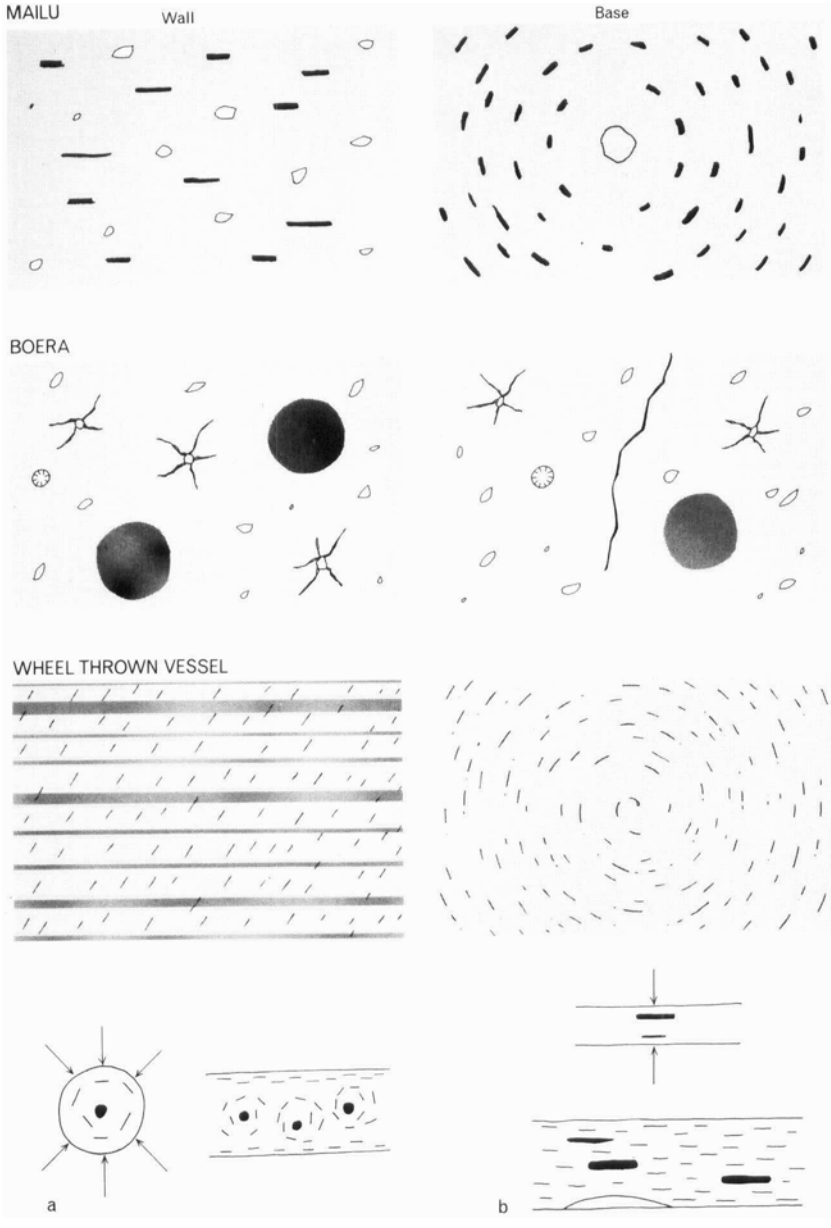

Plate 3 *Schematic appearance of radiographs of Mailu cooking pots (coil-made), Boera vessels (paddle and anvil) and wheel-thrown vessels. At bottom:*
(a) *Pressures involved in rolling a coil and resulting orientation of inclusions in the wall cross-section of a smoothed vessel.* (b) *Pressures involved in pinching or paddle and anvil forming, and consequent orientation of inclusions in the wall cross-section of a vessel.*

should be used to obtain the best assessment of preferred orientation of inclusions; that the radiographs need to be studied in conjunction with surface evidence visible on the sherd; that a full range of sherds including body sherds be included in the study; and that the analysis be applied to enough sherds so that general trends are observed rather than normal individual variations from one vessel to the next.

It should be noted that irradiation of sherds during x-ray studies will render the sherds useless for thermoluminescent dating at any later stage.

ACKNOWLEDGEMENTS

Jim Allen kindly provided sherds excavated at Motupore Island for these studies, and contributed useful discussion. Wal Ambrose assisted with initial thinking about x-ray techniques, and also read the first draft of this paper. Dragi Markovic was responsible for all developing, and advised on exposure problems. Danny Gillespie and Peter Brown assisted with routine work. Drawings are by Win Mumford. Fieldwork in New Guinea was funded by the Australian National University.

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APPENDIX

Method

The x-ray source was provided by a Picker–Andrew Model 3002FT instrument. In order to arrive at a routine procedure, empirical trials aimed at standardizing as many variables as possible were made. Variables which were considered in initial trials were film type, film processing, distance from the x-ray source to the film plane, time and exposure, instrument settings for kilovoltage (kV) and miliamperage (mA), sherd thickness, and variations in mineralogy of sherds. All of these variables have a direct effect on exposure and quality of the radiograph.

Film Initially Kodak AA, a fine-grained film, was used but subsequent experience showed that Kodirex medical x-ray film gave satisfactory resolution of detail whilst requiring shorter exposure times than AA film. Because Kodirex film was also readily obtainable it was selected as the standard film type. Two sizes were used, 5 by 7 in. (12.7 × 17.8 cm) for large sherds or radiographs from whole vessels, and 14 by 17 in.

(35.6 × 43.2 cm) which allowed radiographs of several sherds in one exposure, considerably shortening the time required for processing large numbers of sherds. Although Kodirex was selected as the standard working film type, Kodak AA is recommended for applications where the finest quality radiographs are required, such as for publication.

Film processing Standard procedure recommended by Kodak for Kodirex film was used (see Kodak Data Sheet FM 17, available from Kodak). The developer was undiluted D19, and developing time 5 min at 20°C.

Source—film distance This was standardized at 165 cm, which gave full coverage of the 14 by 17 film, and which allowed satisfactory exposures with slightly curved sherds where complete specimen to film contact was not possible. The x-ray source was located at ceiling level, and film could then be placed on a benchtop for exposures. The benchtop was covered with lead sheeting, which was found to significantly reduce backscatter and consequent uneven exposure of the film, especially where the sherds were curved and not in complete contact with the film.

Kilovoltage and milliamperage In the initial trials the kilovoltage was varied between 20 and 35 kV, using 5 mA (the latter being selected because of limitations in the working range of the equipment). It was found that a setting of 25 kV gave usable exposures over a wider range of sherd thickness than other kilovoltages. In other words, using a low kilovoltage setting meant less tendency to over- or under-exposure of the film, while still retaining adequate contrast. These settings (25 kV, 5 mA) have been used as standard in all subsequent work.

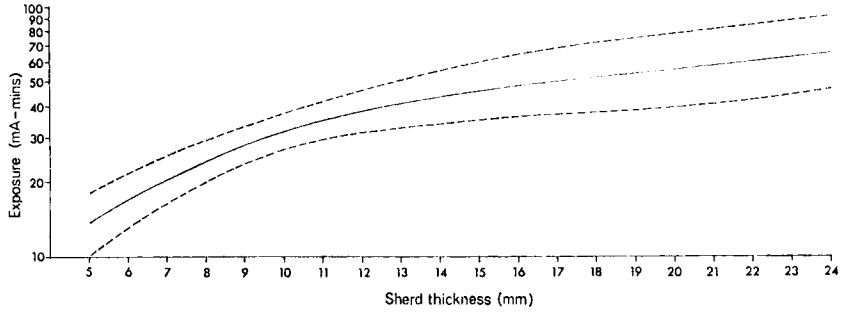

Figure 1 *Exposure times as a function of sherd thickness, for Kodirex film, source to film distance* 165 *cm*, 25 *kV*

Variations in mineralogy It was anticipated that varying clay and temper mixes would have varying opacity to x-rays and that this may have to be taken into account in calculating exposures. Krinitsky (1970, pp. 17–21) provides charts relating exposure time to specimen thickness for various igneous and sedimentary rocks which clearly show that variable mineralogy and porosity necessitate different exposure times at the same specimen thickness.

In trials a series of bars of various thicknesses were made from three different clays. These bars were fired and x-rayed, and the film showed some variation in density for bars of different material at the same thickness. With the method given below for varying exposure with thickness, however, it was considered that variations in materials could be ignored in calculating exposures for routine work. For best quality radiographs from any given set of pottery materials this variable needs to be taken into account.

Sherd thickness and exposure time Having standardized all other variables for obtaining good exposures, exposure calculation became simplified to considering exposure time as a function of sherd thickness. The relationship between these variables is shown in figure 1. This relationship was determined empirically with our equipment and cannot be taken as absolute. In routine work, sherds are grouped firstly according to thickness in intervals of 0.25 cm. Only sherds from one thickness group are radiographed on any one sheet of film. Normally exposure time is calculated by reading on the graph from the 'thickness group' average thickness, to the middle of the graph range for exposure (shown on the graph in the conventional method of expressing exposure, as mA min).

It will be noted that the graph of sherd thickness versus exposure (mA min) is not a single line but encloses a range of values; this expresses the finding discussed above, that varying mineralogy in the sherds requires

varying exposure. With the pottery studied as a routine part of establishing a pottery typology for a Papuan site, it is found that simply using median values for sherd thickness and time gives readable radiographs in almost all cases. For the few sherds where under- or over-exposure has occurred another exposure is made on a 5 by 7 film using more or less time as required, in other words moving to the extremes of the time range for the thickness of the particular sherd.

To identify specific films lead letters and numerals are used, placed on the film. It is convenient to attach these to a piece of masking tape when a series of exposures with the same basic data on each is required. When a large sherd is to be x-rayed the film (which is supplied, and exposed, in a paper envelope) can be bent to fit the sherd closely, and taped to the sherd with masking tape to ensure close specimen to film contact during exposure. Lead sheeting can also be bent to conform to the shape of the sherd, and placed below the film to reduce backscatter.

RESIDENT MINOAN POTTERS ON THE GREEK MAINLAND? POTTERY COMPOSITION ANALYSES FROM AYIOS STEPHANOS*

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Introduction

Late Middle Bronze Age levels at the site of Ayios Stephanos in southern Lakonia have produced a plethora of visually distinguishable wares among the finer pottery.† Among these wares, there are several which are normally found on central and southern Greek sites of the Middle Bronze Age, namely Dark Minyan and a number of different varieties of Matt-painted ware. In addition, there are at least three wares which, as a group, closely resemble Cretan painted wares of the Middle Minoan III period and which have been termed 'Minoanizing'. The primary purpose of the clay analyses described below was to establish whether these Minoanizing wares were local products or whether they were imports, either from Crete itself or from the Minoan colony at Kastri on the island of Kythera (Coldstream and Huxley 1972). In addition, we wanted to know which of the several typically mainland, or Middle Helladic, wares were locally made and which were likely to be imports from other areas of mainland Greece. Finally, we wanted to know if the clay composition pattern of the wares determined on grounds of probability to be local remained constant or differed as a function of time.

The sherds and vases sampled came from a stratified sequence in Area N spanning the ceramic periods from Middle Helladic II (Middle Minoan IIIA in Cretan terms) to Late

* Most of the results discussed in this article were included in a paper entitled 'Resident Minoan potters on the Greek Mainland? Clay composition analyses from Ayios Stephanos' delivered in December 1975 at the annual convention of the Archaeological Institute of America in Washington D.C.

† The pottery to be discussed in this article was recovered from Area N at Ayios Stephanos during the 1973 and 1974 excavation seasons. For the full publication of the Middle and Late Helladic pottery from Area N, see J. and S. Rutter, *A Stratified Middle Helladic II to Late Helladic IIA Pottery Sequence from Ayios Stephanos in Laconia* (Los Angeles 1977). For a preliminary publication of the 1959, 1960 and 1963 excavations at the site, see W. D. Taylour, 1972, Excavation at Ayios Stephanos, *BSA* 67, 205–263.