Journal of Archaeological Method and Theory, Vol. 6, No. 3, 1999

Pottery Production, Distribution, and Consumption—The Contribution of the Physical Sciences

M. S. Tite[1]

The study of the life cycle of pottery, from the selection of raw materials and the production stage through distribution and use to ultimate discard, can make a valuable contribution to archaeological research. The aim of the present paper is to provide a summary and critical assessment of the particular contribution of the physical sciences to the reconstruction and interpretation of this life cycle, in large part through the presentation of selected case studies. The topics covered include the reconstruction of the technology used in pottery production, through a combination of microscopy, radiography, and chemical analysis; the investigation of the extent of craft specialization and the organization of pottery production; the reconstruction of pottery distribution from its production center, using thin-section petrography and chemical analysis, and the interpretation of these data in terms of exchange and trade; the reconstruction of the consumption stage or uses to which pottery was put, from the study of surface wear, organic residues, and performance characteristics; and a discussion of the reasons for the introduction of pottery and for the different technological choices made in pottery production. Throughout, the importance of considering the overall environmental, technological, economic, sociopolitical, cultural–ideological and historical context in which the pottery was produced, distributed, and consumed is emphasized. The paper is concerned, almost-exclusively, with unglazed earthenware spanning prehistory through to circa 1500 AD.

KEY WORDS: pottery; production; distribution; consumption.

INTRODUCTION

This paper aims to review the contribution of the physical sciences to the investigation of the life cycle for pottery produced in the past. This life cycle,

[1]Research Laboratory for Archaeology and the History of Art, University of Oxford, 6 Keble Road, Oxford OX1 3QJ, England.

1072-5369/99/0900-0181$16.00/0

which is in many ways similar to the behavioral chain or flow model proposed by Schiffer (1976) and the *chaines operatoires* proposed by Leroi-Gourhan (1993), starts with the production stage, which includes the selection, procurement, and processing of the raw materials together with the forming, surface treatment, and firing of the pottery. It then continues through the distribution of the pottery, to the consumption stage, which includes the use, maintenance, repair, reuse, and ultimate discard of the pottery.

Having first defined the archaeological research question, the next stage in the study of a group of pottery is the reconstruction or description of the relevant aspects of production, distribution, or consumption. These data then need to be interpreted in order to provide a better understanding of the behavior of the people who produced, distributed, or used the pottery and, thus, achieve the final goal of such studies, which is "not to describe microscale prehistoric *activities*, but to understand microscale social *processes*" (Dobres and Hoffman, 1994, p. 213). At this stage, the questions being asked include, typically, how pottery production or distribution was organized and what the reasons were for technological innovation and technological choice.

A starting point for such a study is the materials science paradigm (Kingery, 1996), which states that materials selection and processing lead to particular artifact structures and chemical compositions. The latter, in turn, give rise to properties on which depend the performance characteristics of the artefact in distribution and, more importantly, in use. Thus, in modern materials science, the raw materials and processes are varied in order to achieve a structure and composition which result in the required properties of the finished product. In a prehistoric context, it is rarely, if ever, appropriate to visualize a series of similarly systematic experiments being employed in the development of a production technology. Instead, the materials science paradigm is valuable in providing a basis for making inferences about the raw materials and processes employed in the production of the pottery from the investigation of the structure and composition of the pottery itself. Similarly, inferences regarding use and, to a lesser extent, distribution can sometimes be made from the measurement and assessment of the properties of the pottery. Further information for the reconstruction of the life cycle of pottery is obtained from the study of the surface traces (e.g., tool marks, wear, residues) resulting from its production and use. These physical science data then need to be considered together with information on the dimensions, shape, and surface decoration of the pottery, the archaeological context in which the pottery was found, including its relationship to other artifacts, and the abundance of particular pottery types.

In order to maximize the quality of the data obtained from the collaboration between physical scientists and archaeologists and to try to avoid the tensions that have occurred in the past (Bishop and Lange, 1991), it is important that the physical scientist is actively involved in defining the archaeological research questions. Also, whenever possible, the physical scientist should participate in the associated archaeological fieldwork and excavation and, in order to ensure that the pottery studied is representative of the available assemblage, should assist in the selection of pottery for physical examination.

In the reconstruction of production, distribution, and consumption from the scientific data, the results of fieldwork and excavation are important in helping to define the context in which the pottery was used and ultimately discarded and in providing information on the availability of raw materials and on the technology employed in the production of the pottery. In interpreting the results of the physical examination, full account should be taken of cultural and environmental formation processes which could have affected the pottery both in use and after discard. Experimental replication of the production technology and the use inferred from the physical examination are also important in testing the validity of these inferences. Further assistance in the reconstruction of the production technology and use can come from contemporary ancient writings on and illustrations of pottery production plus other historical documentation and from present-day traditional potters.

At the interpretation stage, archaeological input is again crucial in defining the overall context in which the pottery was produced, distributed and consumed. Thus, in attempting to answer the questions relating to interpretation, it is necessary to consider the full range of contextual aspects from the environmental and technological constraints, through the subsistence and economic base and the social and political organisation, to the religious and belief systems of the people under consideration. That is, one needs to adopt the ceramic ecology approach, first proposed by Matson (1965) and subsequently modified by Arnold (1985, p. 12) and Kolb (1989), which attempts to link pottery production to the environment in *all* its aspects (i.e., physical; biological, including human biology; and sociocultural), the methodology for establishing links with sociocultural processes being, as yet, the least well developed.

Finally, ceramic ethnoarchaeology, which involves the direct observation and study by archaeologists of variability in ceramic production, distribution, and consumption and its relation to human behavior and organization among extant societies, has a potentially very valuable contribution to make at the interpretation stage (Longacre, 1991). In particular, ethnoarchaeological studies are valuable in exposing us to other ways of thinking about the material world and reminding us that pottery is used in creating and expressing social relationships and that rites, myths, and taboos can be associated with its production, distribution, and consumption (Lindahl, 1995). In addition, the application of the methods of physical examination to ethnographic pottery, for which information on production, distribution, and consumption is already available, provides some check on the validity of the results obtained when these same methods are applied in an archaeological context (Gosselain and Livingstone-Smith, 1995).

The following sections of the paper are concerned with the role of the physical sciences, first, in the reconstruction of the technology of pottery production;

second, in the investigation of the extent of craft specialization and the organization of pottery production; third, in the reconstruction of pottery distribution from its production center and the interpretation of these data in terms of exchange and trade; and fourth, in the reconstruction of the consumption stage or uses to which pottery was put. Next, drawing on the results and ideas presented in the previous four sections, the possible reasons for the introduction of pottery (i.e., technological innovation) and for the different technological choices made in pottery production are discussed. In each of these sections, the contribution of the physical sciences are illustrated through the presentation of selected case studies. Finally, future developments required in order to increase the effectiveness of the contribution of the physical sciences to the study of potttery are suggested.

With the exception of two case studies under Distribution, the present paper is concerned exclusively with unglazed earthenwares made from low-refractory clays (i.e., melting in the range 1100–1200°C), which typically fire to a red or buff color in an oxidizing atmosphere, and spanning prehistory through to circa 1500 AD (i.e., the end of the medieval period in Europe). Glazed earthenwares and high-refractory stonewares and porcelains are not considered.

PRODUCTION TECHNOLOGY

The reconstruction of the production technology for pottery involves establishing, first, what raw materials were used and how they were prepared and, second, how the pottery vessels were formed, surface-treated, and fired. Whenever feasible, the reconstruction should start with archaeological fieldwork and excavation to locate the workshops and kilns in which the pottery was produced. However, in many parts of the world, including the American Southwest (Sullivan, 1988), such primary evidence of pottery production is extremely rare, a feature that itself may be telling us something about the intensity and organisation of production.

The pottery, together with any appropriate production debris (e.g., raw clay samples, kiln fragments) that may have survived, is subjected to a range of analytical, microscopy, and radiography techniques, as outlined below. Here, each stage within the production sequence is considered separately. However, even in the case of problem-specific research requiring the investigation of only one aspect of the production technology, the interrelationship among all stages in the production sequence must be taken into account in any interpretation.

Raw Materials

In selecting a clay for pottery production, a primary requirement is to ensure that the clay is sufficiently plastic for forming but that its drying shrinkage is not so great as to result in cracking. This necessitates achieving a balance between the clay mineral and nonplastic inclusion contents. Therefore, as-received clays frequently either were refined to remove excessive quantities of nonplastic inclusions or had temper [e.g., sand, grog (i.e., crushed sherd), organic material (e.g., chaff), crushed flint, shell, or limestone] added to them. Alternatively, clays from more than one source were sometimes mixed together.

As a result of their breakdown (i.e., dehydoxylation) during firing, it is not normally possible to use either x-ray diffraction analysis or infrared spectroscopy to determine which clay minerals were originally present in the clay. However, the use of a more refractory clay, rich in kaolinite, can be inferred from higher alumina (>20% Al_2O_3) and lower alkali (<3% $Na_2O + K_2O$) contents, as determined by chemical analysis of the clay matrix of the pottery using, for example, a scanning electron microscope (SEM) with attached analytical facilities. On the basis of the lime content of the pottery, it is also possible to distinguish between the use of noncalcareous clays and that of calcareous clays, which typically contain 15–25% well-dispersed lime. In the latter, crystalline calcium and calcium–aluminium silicates are formed during firing, and as discussed under Technological Innovation and Choice, this facilitates the firing process as well as conferring other beneficial properties.

The nonplastic inclusions in the pottery can be identified and their particle size distribution estimated by thin-section petrography. Further, it is sometimes possible, in the case of mineral or rock inclusions, to distinguish between inclusions intrinsic to the clay and those added as temper on the basis of whether they are rounded or angular respectively. Alternatively, the addition of temper can sometimes be established as a result of the presence of inclusions with two distinct particle size ranges, one associated with intrinsic inclusions and the other with added temper (Rye, 1981, p. 52). However, neither criterion is necessarily valid, and it is frequently impossible to establish whether the inclusions are intrinsic or added.

Neither the plasticity nor the drying shrinkage of the original clay can be estimated from measurements on the pottery. Such estimates (Bronitsky, 1986, p. 212) are possible only when raw clay samples, which can be shown by chemical analysis and petrography to have been used in the production of the pottery, are available either from the pottery production site itself or from local clay sources.

Forming

A wide range of methods has been used in forming pottery vessels, sometimes with different methods being used for different parts of a vessel or sometimes with two or more methods being used sequentially (Rye, 1981, p. 58, Rice, 1987, p. 124). The primary techniques, which transform the shapeless clay into the basic shape, include modeling from a lump of clay by pinching, drawing, or beating using a paddle and anvil; pressing or pounding into a mold; building up from coils or slabs;

and throwing on a wheel. The secondary techniques, which are subsequently used to modify the basic shape, include scraping, trimming, and, again, beating using a paddle and anvil. In considering the use of a wheel, it is important to distinguish the slowly rotating turntable or *tournette*, which is used to aid hand building and finishing pottery, from the fast wheel, which is used for primary forming. Only in the latter case is the speed of rotation sufficiently fast for the centripetal force to push the clay against the hands of the potter, so that he/she can squeeze the clay and lift it to form the vessel.

With training and practice, it is often possible to infer the method used from visual examination of surface markings, cracks and joins, pore and temper distribution and orientation, and variations in wall thickness. Further information on the methods used can be obtained by investigating void and inclusion orientation using radiography, thin-section petrology, or SEM examination of polished or fracture sections. Xeroradiography, which, through its method of recording the x-ray image, enhances the edges of inclusions, pores, and any joins within the pottery, provides a particularly powerful technique for investigating pottery forming methods (Carr, 1990; Carr and Riddick, 1990; Middleton, 1997). Thus, a thrown vessel can be identified because, in the act of throwing, elongate inclusions and pores in the clay paste are drawn out in a spiral pattern up and around the walls of the vessel. In a xeroradiograph, this spiral pattern is typically revealed as a cross-hatched pattern formed by the oblique elongate inclusions and pores on opposite sides of the vessel. Conversely, coiling techniques tend to produce a horizontal alignment of pores. However, if the vessel wall is further shaped after coiling, then the pores again tend to be aligned at various angles to the horizontal. Xeroradiography can also reveal the joins between the coils and slabs from which the pottery was constructed, together with information on the way in which, for example, handles, spouts, and rims were attached.

Vandiver (1988), in a study of Neolithic storage jars, has used a combination of visual examination and xeroradiography to show that jars from the Near East were built up using overlapping irregular clay slabs, a method referred to as sequential slab construction. In contrast, using mainly xeroradiography, she showed that the jars from China were constructed from coils which were subsequently compacted using the paddle and anvil technique. Leonard *et al.* (1993), in a study of Late Bronze Age stirrup jars from the eastern Mediterranean, have similarly used xeroradiography to identify two distinct techniques for producing the false (i.e., nonfunctional) neck from which the strap handles spring. The first technique involved the production of a solid neck which was luted onto the almost totally closed globular body of the stirrup jar, whereas the second involved drawing up, during throwing of the jar, a hollow neck which was thus integral to the globular body. In both cases the true (i.e., pouring) spout, which was offset on the shoulder of the jar, was luted onto the body rather than being inserted through it.

Courty and Roux (1995) have undertaken a systematic study of the surface markings (e.g., grooves, rilling) and microfabrics resulting from the different methods of forming. Their analysis of microstructure involved the examination of cross sections perpendicular to the vessel wall using both a petrographic microscope with thin sections and a SEM with fracture sections. A particular aim of the investigation was to establish criteria for distinguishing between wheel-thrown pottery and coil-built pottery which was subsequently shaped on a turntable. They show that, because wheel throwing involves shear stresses and coil building involves tensile stresses, subtle differences in the subparallel alignment of clay domains are visible under a petrographic microscope and SEM at magnifications up to ×200 and ×5000, respectively. Further, they show that, although shaping on a turntable obliterates discontinuities between coils, it does not significantly modify the internal arrangement of the clay domains. Similarly, the distinctive surface grooves associated with coil building are not necessarily obliterated entirely by subsequent shaping on a turntable. Using these criteria, they argue that groups of third-millennium BC pottery from Syria, Iran, and India, which were previously thought to have been wheel thrown, could instead have been formed by coiling and then shaping on a turntable.

Surface Treatment

Pottery vessels were subjected to a range of surface treatments (Shepard, 1956, p. 65; Rice, 1987, p. 144). As discussed under Technological Innovation and Choice, these treatments serve both as decoration and, in many instances, to reduce the permeability of the vessel to liquids. The surface treatments used include plastic decoration (i.e., impressed or incised patterns, applied decoration), burnishing, application of a slip and/or mineral pigments, and postfiring treatment by sooting or with an organic coating.

The examination of a polished section through the body and surface of a pottery sherd using a SEM with attached analytical facilities provides a powerful technique for studying many of these surface treatments. Burnishing and the application of a slip, both of which can produce a high-gloss surface finish, can be readily distinguished from each other. Whereas burnishing results merely in some compression and alignment of the clay particles at the surface, an applied slip is associated with a clearly visible layer of a more finely textured and less porous clay. Furthermore, by comparing the elemental compositions of the clay matrix of the body with that of the slip, it is sometimes possible to establish whether or not the slip clay was a refined version of the body clay (Tite *et al.*, 1982, p. 124; Kingery, 1991).

The mineral pigments applied to pottery can normally be distinguished from the body on the basis of their textures and, when viewed in the backscattered-electron SEM mode, their atomic number contrast. The actual minerals used can then usually be identified by elemental analysis. Thus, using this approach, Middleton (1987) was able to show that, of a group of some 30 Iron Age pottery sherds from 12 sites in southern England which had been classified as "haematite-coated ware," only some 40% were decorated by the application of powdered haematite to their surfaces. The surface treatment used for the remainder of the pottery was either burnishing or applying a slip.

Similarly, Noll *et al.* (1975), using a combination of optical microscopy and SEM, have established that the mineral pigments applied to pottery in the Near East and eastern Mediterranean in antiquity include hematite for red; manganese oxide, hercynite/magnetite produced by reduction firing, and carbon for black; kaolinite and talc for white; and cobalt aluminate and Egyptian blue for blue. In their studies, particular emphasis was given to tracing the development of the three-stage firing cycle (oxidizing–reducing–oxidizing) required to produce a reduced iron-oxide black pigment on an oxidised red or buff body, the cumulation of which was the production of Greek Attic black- and red-figured wares (Tite *et al.*, 1982).

The postfiring organic coatings applied to pottery can, as discussed under Consumption in the context of organic residue analysis, be investigated using gas chromatography and related techniques.

Firing Procedures

The two basic regimes were normally employed for firing unglazed earthenware. The first, in which the rise in temperature is extremely rapid and the time at maximum temperature is very short, involves an open firing with no permanent structure, such as a bonfire. The second, in which the rise in temperature is much slower and the time at maximum temperature is much longer, involves firing in a closed structure, such as a kiln, sometimes with separation between the fuel and the pottery. Extensive data on the actual temperatures measured during experimental and ethnoarchaeological studies of open firings and kiln firings have been brought together by Gosselain (1992).

These data show that, although partly dependent on whether fast- or slow-burning fuels (e.g., straw or dung, respectively) are used (Shepard, 1956, p. 77), open firings typically reach the maximum temperature in 20–30 min and that the maximum temperature is maintained for only a few minutes. The maximum temperatures reached span the range from 500 to 900°C, with a high proportion in the range 600–800°C. The firing atmosphere in an open firing can change rapidly from reducing to oxidizing. However, the pottery is only very rarely fully oxidized because it is in intimate contact with smoky and sooty fuel and there is insufficient firing time for organic material within the clay to be burned out (Johnson *et al.*, 1988). Because of the very fast heating rates, normally only coarse-textured pottery can be open fired, otherwise steam resulting from loss of absorbed water (a proportion survives drying) and chemically combined water cannot escape, and the vessel will crack. The principal exception is very thin-walled fine-textured pottery, from which the escape of steam is again possible.

Conversely, kiln firings, as a result of the much greater thermal mass and the separation of the fuel from the pottery, typically take an hour or more to reach maximum temperature and this temperature is then maintained for some 30 min. The maximum temperatures reached, in the updraught type kilns normally used for firing earthenware, span the range from 600 to 1000°C, with a high proportion in the range 750–950°C. The firing atmosphere in a kiln can be controlled, by a combination of careful stoking and sealing the openings, to be either oxidizing or reducing. This control, together with the longer firing times and separation of fuel and pottery, means that organic material within the clay can be burned out and fully oxidized pottery can be produced. Alternatively, if the kiln is sealed after the maximum temperature has been reached, reduced pottery is produced. Because of the much slower heating rates, both fine-textured and coarse-textured pottery can be readily fired in a kiln.

Although the ranges for the maximum temperatures reached in open and kiln firings overlap, the techniques used to estimate firing temperatures provide, instead, a measure of the overall heat input, which is a combination of firing temperature plus firing time. When the difference in firing times for open and kiln firings is taken into account (Norton and Hodgdon, 1931), then the range for the "kiln-equivalent" firing temperature (i.e., the firing temperature, which, if maintained for about an hour, is equivalent in its effect on the mineralogy and microstructure of the pottery to the actual firing temperature maintained for only a few minutes) for a high proportion of open firings is reduced to 550–750°C, compared to the 750–950°C range for kiln firings themselves. Consequently, "kiln-equivalent" firing temperatures, when taken together with information on the firing atmosphere (as inferred from the color of the pottery) and on the texture of the pottery (i.e., coarse or fine), can frequently be used to differentiate between open and kiln firings.

Considerable effort has been devoted to determining the firing temperatures employed in antiquity (Heimann and Franklin, 1979; Tite, 1995). The methods used all involve establishing a relationship between the firing temperature and changes in either the mineralogy or the microstructure of the pottery. The mineralogical changes can be followed using, for example, x-ray diffraction (Maggetti, 1982) and, for the iron-bearing phases, Mossbauer spectroscopy (Wagner *et al.*, 1986). The microstructural changes, which involve the progressive sintering and vitrification of the clay matrix of the pottery, can be observed either directly, by examination in section in a SEM (Maniatis and Tite, 1981), or indirectly, through changes in those properties which are dependent on microstructure such as porosity, thermal expansion or shrinkage (i.e., dilatometry), and hardness.

In addition to firing time, the changes in mineralogy and microstructure with firing temperature also depend on the composition of the clay and on the firing atmosphere. A direct estimate of firing temperature from such data is, therefore, not possible, and instead, one of two comparative approaches must be used. The first approach involves refiring samples of the pottery to progressively higher temperatures and determining that temperature at which a change in mineralogy or microstructure occurs. Alternatively, if a locally collected clay can be shown by chemical analysis and petrology to have been used in the production of the pottery, then a sequence of test pieces fired at a range of temperatures can be prepared and compared with the pottery. The choice of the most appropriate refiring/firing atmosphere (i.e., oxidizing or reducing) is based, in the first instance, on the observed color of the pottery under investigation. However, Mossbauer spectra, which provide information on the oxidation states of iron atoms in the pottery, can sometimes help to distinguish between a firing which was oxidizing throughout and one with a reducing stage followed by an oxidizing stage (Wagner *et al.*, 1998). Typically, a refiring/firing time of about an hour is chosen so that "kiln-equivalent" firing temperatures (as defined above) are estimated.

Depending on the method employed and the firing properties of the clay from which the pottery was made, the "kiln-equivalent" firing temperature range estimated for an individual sherd spans as much as 50–200°C (Maniatis and Tite, 1981). However, greater accuracy is rarely appropriate since large temperature differences occur within a single open firing or even a kiln firing (Mayes, 1961, 1962). As a result, the firing temperatures for different parts of a single vessel can vary by as much as 150°C. A consequence of this temperature variation is that firing temperature estimates based on data for a single sherd are of limited value and can be positively misleading. Instead, the distribution of firing temperatures for a selection of sherds from the pottery assemblage under investigation must be determined. Therefore, methods of estimating firing temperatures that are capable of achieving a rapid throughput of samples are particularly valuable.

Tite and Maniatis (1975) used the microstructural changes as observed in a SEM to estimate the firing temperatures for fine-textured pottery from Iraq spanning the period from the Neolithic to the Neo-Assyrian period (ca. 6000–700 BC). They showed, first, that the pottery was all made from calcareous clays and, second, that the great majority was fired in the temperature range 850–1050°C. A more precise estimate was not possible because the microstructure of calcareous clays is stable over this temperature range due to the formation of crystalline silicate phases. The principal exception to this 850–1050°C firing temperature range was the Ubaid ware, produced during the fifth millennium BC, a significant proportion of which was fired at much higher temperatures up to about 1150°C.

Wagner *et al.* (1994, 1998) have used Mossbauer spectroscopy for a detailed study of the firing procedures used in the production of Formative period pottery from Batan Grande in northern Peru dating from the period 800 BC to 400 AD. In this project, Mossbauer measurements were made both on pottery itself and on fired clay samples from the kilns in which some of the pottery had been fired. The resulting firing temperature measurements were then compared with direct temperature measurements made during the experimental firing of both ancient and replicate kilns. Overall, the results obtained suggest that the Formative period pottery from Batan Grande was, typically, fired at temperatures in the range 700–800°C, with some firing temperatures being as low as 600°C and some as high as

900°C. Further, the form of the Mossbauer spectra suggest that the majority of the pottery was first fired in a reducing atmosphere and was then, either intentionally or accidentally, oxidized in air.

SPECIALIZATION AND THE ORGANIZATION OF PRODUCTION

The investigation of the organization of pottery production and the extent of the associated craft specialization is of considerable interest, in part because of the implications for the production of surpluses for exchange and, ultimately, for the rise of complex forms of social and political organization.

Various typologies for the modes of pottery production have been proposed, of which that by Peacock (1982) for Roman pottery is typical and has been much cited. Peacock (1982) defined a sequence involving increasing specialization and size of the work unit, which ranges from household production and household industry, through individual workshops and nucleated workshops, to manufactory and factory. Costin (1991) subsequently proposed four general parameters which can be used to characterize the modes of production defined by the different typologies. In the case of pottery production, the first parameter, context, considers whether the potter worked independently or was attached to an elite group; the second, concentration, considers whether the production facilities in a region were dispersed or concentrated; the third, scale, considers whether the production units were small or large scale (i.e., family or factory based); and the fourth, intensity, considers whether the potters worked part-time or full-time.

Rice (1991), rather than trying to define a typology for the modes of pottery production, suggested four main categories, or archaeological manifestations, of specialization. The first category is resource specialization, where specific raw materials were used in the production of different types of pottery; the second is functional or product specialization, where each group of potters concentrated on one type of vessel; the third is site specialization, where a particular community devoted a large part of its productive energy to pottery production; and the fourth is producer specialization, where the potter became a specialist with an increased reliance on pottery production for livelihood and an increased level of skill. Two of these categories (site specialization and producer specialization) are comparable to two of the parameters (concentration and intensity) proposed by Costin (1991).

The evidence used to reconstruct the organization of production can be either direct or indirect. Direct evidence comes from excavation of actual pottery production workshops and includes unfired clay and other raw materials, molds and other portable tools, and kilns, firing pits, and related structures, together with any firing wasters. When production workshops do not survive or have not been located, then one has to infer the mode of production from the surviving pottery itself. Factors that need to be considered in the latter situation include the degree of standardization, the labor requirements and level of technology, and the pattern of distribution.

A high degree of standardization, or homogeneity, in raw material composition, manufacturing techniques, and vessel shape and dimensions is generally assumed to reflect specialized mass production, whereas variation or relative heterogeneity is taken to indicate household production. For example, Henrickson (1995) has suggested that the observed progressive reduction in the degree of care employed in forming and finishing pottery at Godin Tepe in Iran during the Bronze Age was due to a change from specialist potters employed in a workshop to less skilled potters who were, perhaps, household-based. He further suggests that, in this case, the simpler mode of production, in turn, reflects a reduction in the size of the regional economic units.

A high level of craft skill and complexity in production techniques together with an investment in permanent facilities and in equipment is similarly regarded as evidence for specialised production. Further, the identification of a limited number of production centers combined with evidence of widespread distribution of a particular type of pottery from these centers is again seen as being an indication of specialization.

Standardization Hypothesis

Blackman *et al.* (1993) have used a group of fine-ware stacked kiln wasters from the urban center of Leilan, Syria (ca. 2300 BC), as a starting point for investigating whether or not the degree of standardization provides a valid index for specialization. For the wasters, they observed a high level of homogeneity in the vessel dimensions (rim diameter, wall thickness below rim, vessel height, base diameter, basal thickness), together with a standardization of the procedures followed at each stage in the vessel production. Similarly, a high level of homogeneity in the chemical compositions of the bodies, as determined by NAA, was observed, although this is perhaps less surprising since it seems likely that the entire stack of wasters were made from a single batch of clay. When the study was extended to include sherds of the same vessel type from other contexts at Leilan, the homogeneity became more blurred, with the coefficients of variation for rim diameter being more than two times greater and those for chemical composition three to five times greater than the corresponding values for the stacked kiln wasters.

On the basis of these results, they argued that the standardization hypothesis is clearly valid for pottery which has been mass-produced by a given specialist workshop in a single production event, as in the case of the stacked kiln wasters. Further, even though multiple production events in several workshops resulted in increased variation in clay composition and vessel dimensions, this blurring does not completely obscure the standardization signature associated with specialised mass production. They suggested, therefore, that standardization can be an effective index of craft specialization under conditions of close spatial and chronological control over the pottery under investigation.

These conclusions are entirely consistent with the results of ethnoarchaeological studies. For example, Longacre *et al.* (1988) have shown that, in the production of cooking vessels in the Philippines, specialist producers achieve a higher degree of dimensional standardization than did household producers. However, they have also emphasized that, in order to obtain meaningful results in such studies, it is crucial to restrict the shape, the function, and the size range of the vessels selected for analysis from the available assemblage, whether ethnographic or archaeological.

Two Case Studies

Andrews (1993, 1997) has reconstructed the production technology employed for three types of late Iron Age pottery from the Auvergne region in France, and then, through consideration of the raw materials, labor requirements, and level of technology, he has attempted to infer the mode of production, as defined in the typology proposed by Peacock (1982). The most sophisticated of the three types was the "painted" pottery, which was decorated with red, cream, white, gray, and black pigments or slips (Andrews, 1991). Its production required a wide range of raw materials, a complex sequence of procedures for processing, forming, and decorating, together with the associated investment in equipment, and a kiln firing in which the atmosphere was varied between semireducing and strongly oxidizing. Andrews (1993, 1997) therefore argued that the mode of production for "painted" pottery was a nucleated workshop in which a team of specialist artisans was employed. In contrast, the production of the black burnished ware required only a single clay for both body and slip, with a wheel for forming as the principal investment in equipment and with firing only in a reducing atmosphere for which a bonfire would have been sufficient. Because of the use of a wheel, production in an individual workshop, rather than household production, was proposed for the black burnished ware. Finally, the white slipped flagons exhibit evidence for "assembly line" production. First, the handles are frequently detached, implying drying-out between construction of the vessel and application of the handle, and second, drips of slip are found on internal uncoated surfaces, implying mass production techniques rather than the care displayed by individual potters. Production in a manufactory was, therefore, suggested.

Day *et al.* (1997) have reassessed the evidence for specialisation in pottery production in Crete during the Prepalatial period. In this case, rather than trying to identify the particular mode of production, they have considered whether or not Prepalatial Cretan pottery production conforms to the four types of specialization defined by Rice (1991). Thus, they have argued, first, that the use of specific raw materials in the production of different types of pottery (e.g., cooking vessels, dark-on-white painted wares, storage jars) provides evidence for resource specialization and, second, that the large-scale and wide-ranging distribution over the island of pottery from identified production centers is evidence of site specialization.

Further, the fact that certain ware categories, defined largely on the basis of surface decoration, have only a limited number of shapes and only one type of fabric suggests product specialization by different groups of potters. Finally, they argue that the skills, technological competence, and investment in equipment, particularly in achieving the three-stage oxidizing–reducing–oxidizing firing cycle required to produce a reduced iron-oxide black pigment, is evidence of producer specialization.

On the basis of these data, they concluded that pottery, as a specialized craft activity, did not start in Crete with the advent of palaces, as has frequently been suggested, but was already well established by the Prepalatial period. Further, they suggested that, even during the Neolithic period, pottery was produced by specialists, rather than within the household production mode, and that ethnoarchaeological studies in Africa, with their emphasis on the evolution from household to specialist pottery production, may have limited applicability to the early Aegean world. Rather, it seems possible that the converse situation prevails, with less highly decorated, more functional pottery being produced in a household setting in the later Neolithic.

DISTRIBUTION

The investigation of the exchange and trade in pottery starts with identifying the production center or centers from which an assemblage of pottery originated. The first step toward this identification is to group together pottery made from the same combination of clay and temper, using either thin-section petrography or chemical analysis for major, minor, and trace elements. Next, one tries to establish for each group of pottery, thus defined, whether it was locally produced or imported, and if the latter, one then tries to identify its actual production center and/or the sources of clay and temper used. This is attempted through a combination of archaeological criteria such as the abundances of particular pottery types, geological knowledge of the region under investigation, and direct comparison of the petrography or the chemical compositions for the pottery groups with those of either raw materials from possible clay and temper sources or pottery samples from known production centers. The success of direct comparison with the raw materials depends, of course, on the between-source variation exceeding the within-source variation, as specified in the so-called "provenance postulate" (Weigand *et al.*, 1977). In addition, such an approach is feasible only for areas of the world where extensive sampling of available clay sources is feasible and where those sources used in antiquity were not completely depleted.

In interpreting the data from such distribution or provenance studies, it is also crucial to remember that the petrography and chemical composition of the pottery does not just reflect those of some specific raw material source but is determined in part by cultural practices in paste preparation. Thus, the potters usually first process the clay, by refining to remove unwanted nonplastic inclusions, by mixing together more than one clay, or by adding further nonplastic inclusions as temper. Furthermore, although the observed distribution is, in the great majority of cases, the result of the movement of pottery, either as a commodity in its own right or as a container for some other commodity, it must always be borne in mind that the observed distribution could alternatively be due to the movement of either raw materials or people bringing pottery with them.

Having established whether a class of pottery was made locally or was imported and, in the latter case, having identified its actual production center, then, in order to realize the full potential of the data, the exchange or trade in the pottery needs to be considered within the overall environmental, technological, economic, sociopolitical, cultural–ideological, and historical context in which it was produced. For example, consideration should be given to the role of exchange or trade in pottery in establishing contacts between people and thus contributing towards changes in technology, subsistence, social organisation and ideology.

In the following, the principal methods used in distribution or provenance studies, that is, thin-section petrography and chemical analysis, are first described, together with proposals for an integrated methodology. The general interpretation, in terms of exchange and trade, of the data thus obtained is then discussed and the results of a selection of representative case studies are outlined.

Thin-Section Petrography

Thin-section petrography is used to identify the monomineralic or rock fragment inclusions present within the clay matrix of a pottery body. Typically, the fine sand or larger particles, greater than 60 μm (0.06 mm) in diameter, are treated as nonplastic inclusions, the silt particles in the range 20–60 μm being treated as part of the clay matrix (Bishop, 1980, p. 49). Depending on whether these inclusions were intrinsic to the clay or were added deliberately as temper, they reflect the geology of the region from which the clay or the added temper, respectively, was obtained.

Therefore, when the inclusions derive from distinctive igneous and metamorphic rocks, thin-section petrography of coarse-textured pottery provides a predictive method for identifying the source of the raw materials used in the production of the pottery. Very occasionally, a particular "key" inclusion type allows one to identify the precise source of the raw materials. This was the situation for a type of Neolithic pottery, known as Hembury ware, which is found within an area in Southwest England, some 300 km across and stretching from Cornwall to Wiltshire. This pottery contains fragments of a metamorphised igneous rock, known as gabbro, which, within the distribution zone of the pottery, is found only on the Lizard Peninsula in Cornwall (Peacock, 1969, 1988). However, it is extremely rare to be able to identify a clay or temper source on the basis of a particular "key" inclusion type, and instead, a more complete petrographic description of the inclusions present in the pottery under investigation is normally essential.

Miksa and Heidke (1995) have developed a systematic procedure for identifying the sources of the sand temper added to pottery and have applied this procedure to prehistoric pottery from the Tonto Basin in Arizona. First, following the procedures established by Lombard (1987), they undertook thin-section petrographic modal analysis or point counting on some 200 sand samples collected from the Tonto Basin, over an area of some 700 km^2. On the basis of the relative proportions of the different monomineralic or rock fragment grains, they defined 17 sand petrofacies associated with different zones within the Basin. Hand-sample descriptions under a low-power binocular microscope were next prepared for each petrofacies and these were then used to create a flowchart which provided a logical step-by-step procedure for identifying sand petrofacies in hand sample. Next, this procedure was applied to all the rim sherds and reconstructed vessels (about 2000) from the complete pottery assemblage, fresh fracture sections being examined under a binocular microscope. Confirmation of the validity of the different petrofacies or temper groups thus defined in hand sample was then achieved by means of thin-section petrographic modal analysis on some 5% of the samples. On the basis of these data, Miksa and Heidke (1995) were able to assign the sand temper in some 70% of the pottery to the different petrofacies zones within the Tonto Basin, the remainder being from unidentified sources outside the Basin.

Such a comprehensive analysis of the sand tempers available in the pottery production region under investigation is not always feasible or appropriate. However, in regions with a relatively complex igneous and metamorphic geology, it is often possible, in the case of coarse-textured pottery, to suggest the general area (or areas) from which the temper could have originated on the basis of the petrographic description of the pottery fabric itself. In contrast, within a more homogeneous geological region, dominated by sedimentary rocks, it is much more difficult to suggest source areas for the temper, since the quartz sand, limestone, flint, and shell, which are typically used as temper, are widely available. In the case of quartz sand temper, either grain size analysis of the quartz inclusions (Streeten, 1982) or heavy mineral analysis (Peacock, 1967) can sometimes help in identifying the source of the temper. However, such quantitative methods are not always successful and are, in any case, very time-consuming, with heavy mineral analysis requiring expertise which is in short supply. Therefore, chemical analysis is often the more appropriate technique for such pottery.

In fine-textured pottery, the polymineralic rock fragment inclusions which provide the best evidence for source geology do not generally survive. Therefore, minor and trace element analysis is, again, normally the favored technique. However, in the case of the fine-textured pottery produced in some volcanic regions, such as southern Italy, the presence of very fine fragments of volcanic glass can be diagnostic of the source geology (Freestone, 1995, p. 113).

Chemical Analysis

Chemical analysis of pottery for major, minor, and trace elements provides a compositional "fingerprint" for grouping together pottery made from the same raw materials and for distinguishing between groups of pottery made from different raw materials. Because of the variability in chemical compositions within an individual clay or temper source and the possible similarity in composition of different sources, provenance studies based on chemical compositions involve the analysis of a large number of samples, which are then grouped together using statistical methods. In selecting pottery samples for analysis, it is important that, as far as is possible, each group (ideally 15–20 samples) is made up of pottery of a single type, from a single period, and from a single site.

As in the case of thin-section petrography of pottery containing coarse inclusions derived from igneous and metamorphic rocks, chemical compositions can also often be used to predict the general area of production on the basis of geochemical considerations. Thus, high concentrations of chromium and cobalt indicate the presence of mafic mineral inclusions, whereas high concentrations of the rare earth elements suggest association with acid igneous rocks (Blackman *et al.*, 1989, p. 69).

In the early days of provenance studies using chemical analysis, the principal analytical techniques were optical emission spectroscopy (OES), instrumental neutron activation analysis (INAA), and x-ray fluorescence spectrometry (XRF). OES was superseded, first, by atomic absorption spectrometry (AAS) and, more recently, by inductively coupled plasma spectrometry (ICPS), either alone or in combination with mass spectrometry (ICPS-MS). INAA and XRF have continued to be used, and of the other new techniques introduced, proton-induced x-ray emission analysis (PIXE) has found the widest application.

In selecting the method of analysis to be used for provenance studies, the principal criteria, in addition to availability of equipment, are the range of elements that can be analyzed; the concentration range covered (i.e., from major through minor to trace element concentrations); the accuracy and, perhaps more important, the precision of the analyses; the ease of sample preparation and the speed of analysis; and finally, the cost per sample analyzed. Because abundant pottery sherds are normally available for analysis, minimizing the sample size and thus the extent of damage is rarely necessary. Instead, it is more important to ensure that the sample size is sufficiently large for the analysis to be representative of the pottery, which can exhibit considerable inhomogeneity.

INAA is, up to the present day, the analytical technique that has been most widely and successfully used for pottery provenance studies. The method can analyze for more than 30 elements at the minor and trace concentration level, down to less than 1 ppm, with a high precision and accuracy. In part because all element concentrations are normally determined against a standard sample, which is included with each batch, analytical data can be readily exchanged between laboratories. Powdered samples are used, and therefore, sample preparation is comparatively easy. A possible disadvantage of the method is that, because of the short associated half-lives, the concentrations of some major and minor elements (e.g., aluminium, magnesium, titanium), including those that influence the firing properties of the clay, are not routinely determined in all laboratories. In Europe, a potentially more serious problem is the fact that access to nuclear reactors for irradiation of the samples is becoming increasingly difficult, as existing reactors in many countries are being closed down and are not being replaced. However, this is much less of a problem in the United States, where several reactor centers are actively engaged in the analysis of archaeological ceramics. Of particular importance in this context is the Research Reactor Center at the University of Missouri, which, through its NSF-supported program, provides access to INAA facilities to archaeologists throughout the United States.

XRF can analyze for some 15–20 elements, including all the major elements. Powdered, pelleted samples are used, and, in principle, it should again be possible to exchange data between laboratories. In spite of the matrix effect on x-ray absorption, the precision and accuracy are greater than those achieved with INAA for some elements, although less for others. However, the detection limits are rarely better than about 10–20 ppm. With PIXE, using a highly focused proton beam, many elements can be analyzed down to concentrations of 1 ppm or less. However, to achieve a representative bulk analysis, the beam must be defocused, with a consequent increase in the detection limits. Therefore, it is not obvious whether the greatly increased cost of operating a PIXE accelerator, compared to a standard XRF spectrometry, is normally justified.

ICPS, also, has the capacity to analyze a total of up to some 30 major, minor, and trace elements with detection limits of the order of 1 ppm and, once procedures for sample dissolution and for taking into account interferences between elements have been established, with a high precision and accuracy. Sample preparation is more time-consuming than for INAA or XRF since the powdered samples must be dissolved in concentrated acids. However, sample analysis is again rapid since all the element concentrations are measured simultaneously, whereas with AAS, which ICPS has effectively superseded, each element concentration is measured sequentially. When ICPS is combined with mass spectrometry (MS), a wider range of elements, including the rare earths, can be analyzed with 1-ppm detection limits and the resulting isotopic data may also be helpful in distinguishing between pottery produced from different raw materials.

A recent development, introduced to reduce the cost per analysis, has been to analyze, using ICPS, the solution resulting from weak-acid extraction from a pottery sherd rather than the solution of the bulk sherd in concentrated acids (Burton and Simon, 1993). It is argued that the weak-acid solution comes more from the clay matrix of the pottery than from the nonplastic inclusions. However, there will certainly also be a contribution from any calcite inclusions, as well as possibly from some feldspar inclusions, and from postmanufacture additions from use and the depositional environment. Furthermore, the composition of the weak-acid solution is dependent on the firing temperature, time, and atmosphere used in the production of the pottery. Therefore, it is perhaps not surprising that the results of such an analysis do not agree with the bulk analyses obtained using INAA (Neff *et al.*, 1996; Triadan *et al.*, 1997). However, in spite of these obvious discrepancies, Burton and Simon (1996) continue to argue that, because weak-acid extraction analyses reflect behavioral factors such as the potter's choice of clay, temper, and firing conditions, they provide valuable additional information for investigating technological choice in pottery production. The weakness of this argument is that there is no obvious way of separating out the different behavioral factors. Therefore, it is difficult to see how weak-acid extraction analyses can make a meaningful contribution to our understanding of either the production technology or the provenance of the pottery under investigation.

Because the chemical composition of pottery depends, in part, on cultural practices in clay preparation (Blackman, 1992), the compositional data obtained for pottery cannot be used in a simple-minded search for the clay source exploited by the ancient potters. Instead, a first step is to search for structure in the data for the pottery assemblage from a particular site or cluster of sites, using principal-components analysis and/or cluster analysis (Bishop and Neff, 1989; Baxter, 1994a). In principal-components analysis, which permits the compression of multivariate compositional data into a few dimensions, the first principal component accounts for the direction of maximum variance through the data, with each successive component accounting for the maximum of the remaining variation. In cluster analysis, the compositional resemblance between pairs of samples is assessed using a range of different similarity measures, and a dendrogram, in which samples with greatest similarity are linked together, is thus built up. In using cluster analysis, one must remember that, although providing a useful method of obtaining an overview of compositionally based similarities, it will, by its very nature, produce "groups" out of almost any data. Also, a two-dimensional representation of the n-dimensional data results in considerable distortion.

Having defined hypothetical pottery groups by principal-components or cluster analysis, the next stage is to evaluate their validity both subjectively, by inspecting, for example, bivariate (i.e., two-element) plots, and statistically. A commonly used statistical method (Bishop and Neff, 1989) is to determine the probability of each individual sample belonging to the hypothetical group to which it was previously assigned by calculating the Mahalanobis distance from the sample point to that group centroid. An alternative approach is to take the hypothetical groups defined by principal-components or cluster analysis and to apply to them discriminant analysis (Baxter, 1994b) in which the multivariate compositional data are combined to produce a two-dimensional plot (first two discriminant functions) in which the within-group distances are minimized and the between-group distances are maximized. The probabilities of individual samples belonging to the hypothetical groups to which they were previously assigned are then determined by calculating the Mahalanobis distances from the sample points to each of the new discriminant analysis group centroids. Statistical methods are also available (Beier and Mommsen, 1994) to bring together into a single group samples whose chemical compositions differ only because of the presence of different amounts of chemically pure temper inclusions, such as quartz, which act as a "dilutant." Otherwise, the addition of different amounts of "diluting" temper to the same clay could result in the formation of two or more compositional groups. However, since the use of different amounts of temper could itself be of cultural significance, it is important that this information is not lost.

Finally, an attempt must be made to infer, for each group, whether it was produced locally at the site at which it was found, whether it was produced within the immediate region (i.e., intraregional exchange), or whether it was imported through long-distance interregional exchange or trade. In making these inferences, archaeological criteria, in particular, the relative abundance of different pottery types, are used first. Thus, an initial assumption is that a pottery type strongly represented at a site has been produced locally and that sparsely represented pottery has a nonlocal origin. Similarly, large and heavy vessels, such as large storage jars, are likely to have been made relatively near to where they were used. Second, confirmation of the feasibility of local or intraregional production is sought by checking whether the temper inclusions present in the pottery, as identified by thin-section petrography, could have derived from the local geology and whether the chemical composition of the pottery is, at least, consistent with those of local clay sources. In the latter context, in addition to the collection and chemical analysis of local clay samples, full use should be made of available published geochemical data. Third, on those rare occasions when production debris in the form of kiln wasters is available, comparison of the chemical compositions of the wasters with those of the pottery can provide further confirmation as to whether or not the latter was locally produced. However, even in this situation, if the kiln wasters are of a different vessel type from the pottery group under investigation, it is still possible that different clay sources or clay preparation procedures were employed.

Other factors that need to be considered in interpreting chemical composition data are possible changes in composition either during firing or during burial subsequent to discard. However, it seems very unlikely that firing will have caused a problem, since Cogswell *et al.* (1996) have shown that, with the possible exception of bromine, no volatilization of 34 elements occurred when clay tiles were fired to temperatures in the range 100–1100°C. Similarly, although major/minor elements such as sodium, potassium, magnesium, and calcium can be readily leached from or deposited within pottery during burial in a range of environmental conditions (Freeth, 1967), the transition and rare earth elements, which are of particular importance in defining compositional groups, tend to be immobile (Bishop *et al.*, 1982, p. 296).

An Integrated Methodology

The details of the sampling strategy for a specific distribution or provenance study will obviously depend on its particular objectives. However, in all cases, it is important that as large a proportion of the total relevant ceramic assemblage as is realistic is used to define, and to establish the relative proportions of, the different types of pottery available for further examination. In addition, it is essential to investigate the geology of the region from which the pottery originated and, as far as is possible, to collect samples of the locally available raw materials (i.e., both clays and sands, which could have been used for temper).

In defining the pottery types, the first step is to divide the assemblage according to the different chronological periods represented. Next, for each period, the pottery types are defined, first, in terms of shape, size, and surface decoration and, second, according to fabric or temper type, the latter involving examination of fresh fracture sections with a low-power binocular microscope. Having thus selected the pottery types, representative sherds of each type should next be examined using thin-section petrography. The first aim is to establish the validity of the temper types defined by low-power binocular microscopy. However, thin-section petrography also provides the detailed petrographic description required for comparison with data on both the local geology and the petrography of the collected samples of locally available clays and sands. In this way, it should be possible to predict, at least in the case of regions with a distinctive igneous or metamorphic geology, the general area from which the raw materials used to produce the pottery were obtained.

In the case of coarse-textured pottery without diagnostic inclusions or most fine-textured pottery, thin-section petrography is of limited value for establishing provenance. Therefore, at this stage in the study, one should move on to the application of chemical analysis, some 15–20 sherds of each pottery type being selected together with the collected samples of locally available clays. However, the results of the thin-section petrography are still potentially valuable in that they provide information on variations in temper types and temper concentrations which is crucial for the successful interpretation of the chemical analysis data.

The potential of an integrated approach is illustrated by the classic study of pottery produced on Hopi mesas in Arizona between 1300 and 1600 AD, undertaken by Bishop *et al.* (1988). In this study, it was possible to distinguish, on the basis of chemical composition together with technological and stylistic analysis, between the pottery produced by potters from different villages on the same mesa only 8 km apart, as well as between that produced by different groups of potters working in the same village.

Exchange and Trade

Crucial to the satisfactory interpretation of the petrographic and chemical analysis data is the quantification of the trends in the distribution patterns of the pottery away from the various production centers. Thus, as discussed by Plog (1977), one needs to establish the scale or intensity, the directionality and symmetry, and the duration of the associated exchange or trade. Further, it is important, when considering the exchange or trade in pottery, to bear in mind that pottery is probably only one of a range of artifacts and subsistence products included within the exchange or trade system. Although exchange and trade are often used interchangeably (Renfrew, 1975, p. 4), in the present paper, the distinction recently proposed for use in archaeological contexts by Zedeno (1994, p. 16) is employed. Thus exchange refers to recurrent, independent, symmetrical, and small-scale material transactions that did not have the organizational requirements or the economic impact of trade networks but that served to reinforce intercommunity relationships. Conversely, trade refers to organized, large-scale material transactions that took place regularly over relatively long periods of time and involved the flow of significant quantities of goods.

The possible modes of exchange or trade, as defined by Renfrew (1975), include reciprocity, which involves exchange between two individuals; down-the-line reciprocity, which involves a succession of exchanges between individuals; redistribution from a central place; and middleman trading. The fall-off in the quantity of a particular type of pottery with increasing distance from the source can, in principle, assist in distinguishing between the different modes of exchange or trade. For example, the fall-off with distance from the source will tend to be more rapid in the case of down-the-line reciprocity compared to middleman trading. Similarly, redistribution from a central place is likely to produce localized regions of higher concentration along the fall-off curve. However, in attempting to infer the mode of exchange from the fall-off data, it is necessary also to consider the means of transport available and the uses, as defined under Consumption, to which the pottery would have been put, both of which can affect the distance traveled by the pottery away from source. Thus, the distances associated with transport by sea or river will tend to have been greater than those by land, and on land, the distances associated with transport involving wheeled vehicles or animals will tend to have been greater than those involving only man. Similarly, pottery used for sociopolitical or ideological/ritual purposes will tend to have traveled greater distances than that used for utilitarian purposes. Therefore, it is rarely possible to identify unambiguously the mode of exchange or trade from the fall-off data.

In practice, there do not appear to have been any major fall-off studies based on the distribution of pottery as determined by either thin-section petrography or chemical analysis. This deficiency is due, at least in part, to the difficulty of obtaining the necessary quantitative data for the very large pottery assemblages which are typically involved. However, the potential of such an approach is illustrated by fall-off studies in which the pottery type under investigation is identified on the basis of style. Thus, in a study of Roman pottery produced in the Oxford region in England, Fulford and Hodder (1975) established the importance of water transport as a method of distribution, in that the fall-off in the percentage of this pottery with distance from Oxford was significantly less rapid for sites with good access to Oxford by water than for those without such easy access. They also showed that the percentage of pottery produced in the Oxford region was further reduced in the New Forest region, where the competition from pottery produced at the local kilns was presumably too great for the Oxford wares to make much impact. Similarly, Fry (1980) has used fall-off curves for a range of vessel types, identified on the basis of their micaceous fabrics, to investigate the complex pottery distribution system around Tikal, Guatemala, during the Late Classic Maya period.

More recently, Osborne (1996) has summarized the data for the distribution within the Classical world of fine red- and black-figure ware produced in Athens during the period from 600 to 500 BC. In this case, the products of different workshops and painters could be distinguished on the basis of the stylistic attributes of the painted decoration. The observed distribution strongly suggested that the different workshops in Athens were producing pottery specifically designed to meet the demands of particular markets. For example, some 96% of the products of the "Nikosthenic" workshop, operating during the second half of the sixth century BC, were found in the Etruscan region, with the majority of the amphorae being found at Cerveteri and the majority of the small *kyathoi* at Vulci and Orvieto. Similarly, the majority of the *skyphoi* from the workshop of the Theseus and Athena Painters, operating around 500 BC, was found in the region around Athens, whereas the majority of the *oinochoai* from the same workshop was found in East Greece and Etruria. On the basis of these data, Osborne argued that the exchange of goods within the archaic Greek world was not the result of the need to meet occasional shortfalls in agricultural products. Instead, it involved a regular network of trading links between Athens and individual ports around the Mediterranean. Thus, one needs to envisage a conglomeration of interdependent markets in which production and prices in producing and consuming cities were linked.

A selection of pottery distribution studies, illustrating the range of information that can be obtained for archaeological contexts involving different modes of exchange or trade, are presented below. In each of these case studies, chemical element analysis has been the primary method employed to discriminate between pottery from different production centers, with the integrated methodology being followed to varying degrees. The first case study (i.e., Mayan pottery from the Palenque region in Mexico) is intraregional in range, the aim being to investigate the relationship between pottery production and distribution within a comparatively restricted region. The second case study (i.e., stoneware bangles from the Indus Valley Harappan civilization) should also probably be regarded as intraregional, even though the distances over which the stoneware bangles are distributed are very significantly greater than those involved in the Mayan pottery study. In contrast, the final two case studies (i.e., Hispano-Moresque lusterware and Roman terracotta lamps) are certainly interregional in range, their aim being to obtain information on pottery being traded on a more global scale. All four studies relate to pottery produced within complex urban societies, most probably by specialist potters operating in workshops, manufactories, or factories. However, it should be remembered that pottery produced within a household setting is also frequently exchanged or traded, at least on an intraregional scale. For example, as already discussed, Neolithic Hembury ware was distributed throughout Southwest England over distances of some 300 km, probably as part of a gift exchange system (Peacock, 1969, 1988).

Case Studies

Since the early 1970s, a massive program of analysis of Mayan pottery, using INAA, has been undertaken in the United States, first, at the Brookhaven National Laboratory and, subsequently, at the Conservation Analytical Laboratory at the Smithsonian Institution. A total of some 12,000 pottery samples has been analyzed to date (Bishop, 1994). One project within this overall program has been the Greater Palenque Survey involving the study of pottery from the major civic-ceremonial center of Palenque and from sites in the surrounding region up to distances of about 70 km, spanning the period from the Early to Late Classic (150–800 AD). For this project, an integrated methodology has been employed, with some 100,000 fabric characterizations by binocular microscopy, some 1500 thin-section petrographic examinations, and some 2300 analyses by INAA. A primary aim of the project was to define the pattern of pottery production, consumption, and exchange at an intraregional level and, thus, to contribute to the documentation of the ceremonial and economic development of Palenque, and of its changing relationship with its satellite sites.

The results of the combined scientific examinations indicated that, during the Early Classic period (150–500 AD), there was a change from predominantly local production of pottery at Palenque to a situation where some of the pottery was imported from the southern Usumacinta zone, which was outside the region of Palenque's subsequent influence. This change was consistent with the evolution of Palenque from a locally oriented village on the Maya periphery toward a more hierarchically organized society. During the Middle Classic period (500–600 AD), pottery was imported from a larger number of sources and there was less emphasis on imports from southern Usumacinta. Finally, during the Late Classic period (600–800 AD), when there was very extensive building activity and Palenque became a major civic-ceremonial center, a complex and changing pattern of pottery import and export between Palenque and its satellites was observed. Thus, Bishop (1994, p. 34), has argued that locally produced Palenque pottery with a ritual function served to reinforce the individual status or power of the ruling elite. Further, the export of such ritual pottery from Palenque to nearby localities reflected an interest in integrating different regions into the Palenque polity—a linkage that was reinforced by the export to Palenque of certain types of utilitarian pottery from particular satellite sites.

Blackman and Vidale (1992) have investigated, using INAA, the production and distribution of stoneware bangles associated with the Indus Valley Harappan civilization. Several factors point to the bangles being luxury artifacts with a unique social function. First, they are relatively rare, with their use apparently being restricted to the two major centers of Mohenjo-Daro and Harappa; second, the associated production technology was complex; and, third, inscriptions are present on both the bangles and the saggars used in their production. The primary aims of the study were to establish whether all the bangles were made at Mohenjo-Daro, where a production workshop had been located, or whether they ware produced at both Mohenjo-Daro and Harappa, and thus to contribute to the discussion on the autonomy or interdependency of these two major centers.

The results of INAA of bangles from Mohenjo-Daro and Harappa, saggars from the Mohenjo-Daro production workshop, and a modern bangle made from local Harappa clay yielded two distinct chemical compositional groups. All the Mohenjo-Daro bangles plus some 30% of the Harappa bangles fell within the first group, which, because it also included the saggars, was almost certainly produced at Mohenjo-Daro. The remaining bangles from Harappa fell within the second group, which, because it included the modern bangle, was almost certainly made at Harappa. These results indicate that, although both centers possessed the technological capability to produce bangles, there was a unidirectional movement of bangles over a distance of some 600 km from Mohenjo-Daro to Harappa. Thus, the results provide the first direct material evidence for interaction between these two major centers. However, the asymmetrical nature of the interaction with respect to the movement of bangles remains unexplained.

The investigation of the trade in Hispano-Moresque lusterware, using both INAA and thin-section petrography, has been reported by Hughes and Vince (1986) and by Hughes (1991). Lusterware was produced at a number of sites in Spain from the 13th century onward and was exported to several other countries in Europe. The two major production centers were Malaga, which was in operation from the mid 13th century until the late 15th century, and Valencia, which did not start production until the late 14th century but then eclipsed Malaga as the major production center during the 15th century. Valencia lusterware was initially produced by Muslim potters from Malaga who moved north, probably as a result of the blockage by Christian ships off the coast of southern Spain. Early Malaga and late Valencia lusterwares are readily distinguished on the basis of style but the late 14th- and early 15th-century products of the two centers are difficult to distinguish.

Samples of lusterware, known to have been produced at these two major centers, were analyzed using INAA, together with samples from two minor production centers at Barcelona and Jerez (Seville). In this case, the products of Malaga and Valencia could be distinguished from each other using scatter plots of pairs of elements (e.g., scandium versus chromium). Using discriminant analysis, it was then possible both to distinguish the products of the four centers and to determine from which production center the lusterware exported to other parts of Europe originated. Thus, it was shown that late medieval London received lusterware from both Malaga and Valencia, with Valencia lusterware becoming progressively more dominant. Further, the results strongly suggest that the lusterware tiles used at the Alhambra at Granada were produced at Malaga rather than at Granada itself.

Schneider and Wirz (1992) have investigated, using XRF, the distribution of a type of Roman terracotta lamp, the so-called *Firmalampen*, which was produced from the first to the third centuries AD. These lamps, which have the maker's name stamped on their bases and which are found in abundance throughout the northern Roman provinces, have been grouped into four main types on the basis of their macroscopic appearance (Loeschcke, 1919). From the archaeological evidence, it is generally assumed that type A was produced near Modena in the Po Valley in northern Italy. The other three types (B, C, and D), which include lamps with the same maker's stamps as found in type A, had previously been thought to be unauthorized copies of imported original lamps from the Po Valley, which were being produced at a number of centers in northern Europe. The aim of the study was to establish whether types B, C, and D were indeed unauthorized copies or whether, instead, they were the product of branch workshops set up from the central production center in the Po Valley.

The results of the XRF analysis on lamps from the legionary camp of Vindonissa in Switzerland showed that nearly all the lamps fall into three compositional groups corresponding to types A plus B, C, and D. From the archaeological evidence, the first chemical group, associated with types A plus B, was assigned to the Po Valley production site. From a combination of archaeological evidence and comparison with the chemical composition of locally produced pottery, the second chemical group, associated with type C, was thought to have been produced near Lyon in France and the third group, associated with type D, in the Trier region of the Rhineland. Thus, nearly 90% of the lamps found at Vindonissa were manufactured at only three major lamp-making centers, all of them very distant from the site. It seems very likely, therefore, that the production centers at Lyon and in the Rhineland were branch workshops of larger firms based in the Po Valley, since it is hard to believe that unauthorized copies were being made nearly exclusively at two large centers far away from the place where they were sold and used. This interpretation is supported by the fact that lamps from a range of sites in the northern provinces, all bearing one of the most commonly found maker's stamp (i.e., FORTIS), fall into the same three compositional groups, corresponding again to types A plus B, C, and D. The existence of large pottery-producing firms with branch workshops is something already known from the study of Roman *terra sigillata*, the products of the firm of ATEIUS, with branches in Arezzo, Pisa, and Lyon, having been similarly studied by chemical analysis (Picon and Garmier, 1974). In the case of both terracotta lamps and *terra sigillata*, the firms appear to have been grouped at a limited number of centers and, on the basis of the chemical analyses, to have made use at each center of the same clay sources.

CONSUMPTION

The uses to which pottery vessels were put range from utilitarian, for example, for storage, food preparation (e.g., soaking, grinding), cooking (e.g., boiling, roasting), serving, and individual eating or drinking, through sociopolitical and ideological or ritual. The latter nonutilitarian functions, which can themselves involve storage, cooking, or eating, include presentation as a gift, which serves to accrue future benefits or to establish bonds between social groups at all levels from families to states, and use as a prestige object to display success or power, for example, as part of competitive or reciprocal feasting.

The first step in investigating the use, or reuse, to which particular pottery vessels were put is a careful assessment of the archaeological contexts in which the vessels were found and of the formation processes that could have affected them. For example, Kolb (1988) has investigated the contexts in which Classic Teotihuacan-period *copoid* ceramics from urban and rural sites in the Teotihuacan Valley in Mexico were found. In addition to being discarded in house middens, some *copoid* ceramics were recovered from kitchens, some from central courtyards, and some from graves, but none from the altar platforms or benches located in the central courtyards. On the basis of these data, together with information on dimensions and shape, he attempted to distinguish among ceramics used for culinary, ceremonial, and ritual purposes.

Next, one looks for and, as appropriate, analyzes the surface traces resulting from vessel usage such as surface wear, soot deposits on the exterior of the pottery, and organic residues either adhering to the interior or absorbed within the body of the pottery. Finally, one tries to infer use from those performance characteristics that are determined by the dimensions and shape of the vessels. A detailed discussion of the full range of performance characteristics required in use is presented under Technological Innovation and Choice in the context of the constraints that they impose on technological choice.

As in the case of production technology and distribution, consumption or use studies should be directed at pottery assemblages that are representative of the pottery in use within an archaeological context at a particular time. However, as indicated by ethnoarchaeological studies of the disposal of broken pottery vessels (DeBoer and Lathrap, 1979; Kramer, 1985; Lindahl, 1995), obtaining such an assemblage is rarely easy. The fragments from a broken vessel can be widely dispersed, so that it is difficult to reconstruct even the form of complete vessels, and only rarely is it possible to obtain the actual complete vessels preferred for the study of surface wear and distribution of organic residues.

Use Alteration

Surface wear or attrition, in the form of scratches, pits, and chips, can provide evidence for the ways in which pottery was used. Ethnoarchaeological studies of groups of pottery, whose use has been observed and recorded, can provide the control data for interpreting the surface wear on pottery from archaeological contexts. Thus, on the basis of the results from a study of an assemblage of pottery in use in a Kalinga village in the Philippines, Skibo (1992) has shown that areas of abrasion on the exterior base are due to contact with the hearth or fire dogs during cooking, that scratches on the lower to midexterior surface are due to abrasion from washing, and that those on the upper exterior surface are due to carrying. Similarly, on the interior surface, scratches are variously due to abrasion from stirring, serving, and washing; and surface spalls, which are associated with the vaporization of water from the vessel wall, are due to the level of the liquid in the vessel falling below that of the spalls while heat was still being applied to the exterior. In the Kalinga context, such spalls are found only on vessels used for cooking rice, which, in the final simmering stage, absorbs into itself the water remaining in the vessel. Spalls are only very rarely found on vegetable or meat cooking vessels, which are normally kept at least half-filled with water.

The nature of the carbon or soot deposit on the exterior of a pottery vessel also provides evidence of the way in which the vessel was used. Again, on the basis of ethnoarchaeological studies, Skibo (1992) has shown that cooking over an open fire results in the formation of several distinct zones of deposited carbon or soot which reflect the distance from the fire and hence the different temperatures reached over the exterior surface. On the base itself, which was closest to the fire, the soot is thinnest and has sometimes been burned away entirely to leave an oxidized patch. Farther from the fire and extending over the lower exterior surface, the soot layer is still thin and is dull black or sometimes gray in appearance. Above this zone and extending more or less to the rim, the temperature of the exterior surface remains relatively low due to a combination of increased distance from the fire and the cooling effect of the liquid in the vessel. As a result resin droplets from the fuel are deposited on the surface to form a thicker layer of glossy black soot.

In an archaeological context, pottery sherds rather than complete vessels are all that are normally available for examination. Therefore, although the presence of abrasion together with a soot deposit can help to establish that a sherd came from a vessel used for cooking, it is generally difficult to explain fully the causes of any observed abrasion and scratches. Instead, in the study of archaeological pottery sherds, it is the analysis of the organic residues, resulting from the food contents of the original vessel or, in some cases, from sealants applied to its inner surface, that has received the greatest attention during the past decade (Evershed *et al.*, 1992; Skibo, 1992; Heron and Evershed, 1993). Such analyses, which are undertaken on residues either adhering to the inner surface or absorbed into the porous body, provide information both on the use of the pottery and on the past diet.

The most useful surviving organic compounds are lipids, which are the constituents of fats, oils, waxes, and resins. Because of their hydrophobic properties, lipids survive on pottery and the migration of lipids from the soil in which the pottery was buried does not normally seem to occur to any significant extent. The lipids are extracted in a solvent and the individual lipids are separated out, typically by gas chromatography. The mass spectra associated with each lipid can then be determined by mass spectrometry. Identification of the lipids is based on a combination of the retention time in gas chromatography and the mass spectra. Alternatively, the pattern of lipids separated out from the archaeological pottery vessel by gas chromatography can be compared with the patterns obtained from modern examples of the different animal and plant species which the vessel could have contained. However, since the animal and plant products are likely to have been chemically altered by oxidation, hydrolysis, and microbiological degradation, either during any cooking process or during subsequent burial, an exact match is only rarely achieved.

Instead, one can, for example, use any sterols present to distinguish animal products (cholesterol) from vegetable products (campesterol or sitosterol). Fatty acids can provide a broad classification into animal fats, dairy products, vegetable oils, or fish oils, but it is not normally possible to identify the actual animal species from the fatty acids alone. However, on the basis of the stable carbon isotopic composition of the fatty acids extracted from pottery, it has been possible to distinguish between fats from ruminant (i.e., ovine and bovine) and nonruminant (i.e., porcine) animals (Evershed *et al.*, 1997) and between milk and adipose fat from ruminant animals (Dudd and Evershed, 1998). Further, the presence of beeswax provides evidence of possible beekeeping, and plant waxes can sometimes provide a basis for identifying different vegetables. However, the need for caution is emphasized by the fact that Evershed (Hedges, 1997) has recently been able to show that a high molecular weight ketone extracted from a wide range of pottery vessels was the product of catalytic condensation of common fatty acids rather than deriving from a ubiquitous and unusual plant wax. Finally, diterpenoid compounds provide information on the nature, origin, and means of production of plant resins and their derivatives (wood tar, pitch) used as pottery sealants.

Using this approach, Roman amphorae have been shown to contain olive oil (Condamin *et al.*, 1976); late Saxon pottery from England has provided evidence of cooking a brassica species, probably cabbage or turnip leaves (Evershed *et al.*, 1991); the use of Corinthian figure vases as containers for oils scented with resins has been confirmed, although it has not been possible to correlate the identified contents with ancient scent recipes (Biers *et al.*, 1994); and Native American pottery from the Great Basin has provided evidence of the use of scale insect resin, or lac, as an adhesive and as a sealant (Fox *et al.*, 1995). In addition, using a combination of Fourier-transform infrared spectroscopy and chemical spot tests, wine and beer have been identified as contents of Early Bronze Age vessels from Iran (Michel *et al.*, 1993), and the Royal Purple indigoid dye as the deposit on Canaanite jars from the Levant (McGovern and Michel, 1990).

When complete vessels are available or can be reconstructed, organic residue analysis for the distribution of the bulk quantities of lipids over the interior of different types of vessel, from rim to base, can provide valuable information on the way in which the vessels were used for cooking. Charters *et al.* (1993), studying reconstructed late Saxon vessels from England, have shown that shallow bowls have accumulated only low concentrations of lipids, suggesting that they were not used for cooking. In contrast, jars have high concentrations of lipids surviving on the upper inner surfaces, whereas "top-hat" vessels have lipids distributed fairly uniformly over the inner surfaces. On the basis of these distributions, it was suggested that the jars were used for boiling food, the lipids rising to the surface of the liquid, and that the "top-hat" vessels were used for roasting meat, the fat from the meat coating the entire inner surface of the vessel. Confirmation of the former hypothesis has been provided by a replication experiment in which cabbage was boiled in a pottery vessel and the accumulation of lipids at the upper surface was observed (Evershed *et al.*, 1995).

Organic residue analyses are comparatively time-consuming and expensive to undertake. As a result, such analyses have, to date, been confined to relatively small groups of pottery, and it seems probable that the method will only occasionally be employed for use studies of large pottery assemblages. Therefore, it is probably most appropriate for future organic residue analyses to be directed toward the investigation of the contents of specific vessel types, such as those resulting from the beginnings of pottery production, as discussed under Technological Innovation and Choice; those associated with the early use of less basic consumables, such as wine, beer, drugs, and perfumes; and those used as containers in the trade of consumables in general. Finally, it should be emphasized that, in the interpretation of the information on diet provided by residue analysis, it is important to take fully into account supplementary data on diet provided by the examination of the faunal and floral remains from the archaeological site on which the pottery was found.

Use Inferred from Performance Characteristics

The performance characteristics most readily employed for inferring use are those based on vessel dimensions and shape. Halley (1986) has used such performance characteristics to investigate the vessel function of 16th-century AD Barnett-phase pottery from Georgia (USA). In this study, some 80 whole or partial vessels were supplemented by some 150 rim sherds (from a total of 4500 sherds) from which vessel shape and orifice diameter could be inferred. Thirteen vessel types were defined and vessel function was inferred from consideration of some 12 performance characteristics. These included vessel capacity, vessel stability, ease of manipulation of vessel contents (e.g., grinding, stirring), ease of removal of vessel contents (e.g., pouring or lifting out), avoidance of spilling of vessel contents, and efficiency in absorbing and retaining heat and in reducing evaporation. The parameters that were considered in assessing these performance characteristics include maximum vessel diameter and height, height of shoulder above base, vessel wall profile, basal diameter, orifice diameter and constriction, rim profile, position and size of any handles, and center of gravity. In addition, evidence of any surface wear and sooting resulting from use and data for the frequency of each vessel type were also taken into account. It was thus hypothesized that four vessels types were used for cooking, four for final heating and serving, four for a combination of storage and serving, and one for transporting and holding fire.

Further comparable studies, based primarily on dimensions and shape, include the investigation of assemblages of Neolithic pottery from Windmill Hill, England (Howard, 1981), and of Late Bronze Age pottery from Mycenae, Greece (Tournavitou, 1992). In both cases, the categories distinguished included vessels for cooking, for eating and drinking, for storage and transport, and for ritual. In these studies, the dimensional and shape data were supplemented by consideration of the surface decoration and the body fabric. Surface decoration can communicate information about the user of a vessel and, therefore, is generally more important in the case of vessels which were used for sociopolitical or ideological/ritual purposes rather than those used for storage or cooking. Also, as discussed under Technological Innovation and Choice, the selection of body fabric can reflect the use to which a vessel was put. Thus, cooking vessels are normally characterised by the abundant temper that they contain.

TECHNOLOGICAL INNOVATION AND CHOICE

The discovery or initial invention of pottery can be readily explained in terms of the fire-hardened clay observed to result from the use of fires many thousands of years before the appearance of pottery itself. In contrast, the reasons for the innovation or adoption stage, in which pottery was accepted and ultimately flourished as a new material, are more complex and tend to vary according to the part of the world under consideration (Barnett and Hoopes, 1995). However, a basic factor in each case was the "demand" for pottery, the existence of a well-perceived requirement for a new material or artifact being the underlying driving force for most technological innovation (Kingery, 1984).

The first extensive use of fired clay appears to have been associated with the Upper Palaeolithic figurine makers at Dolni Vestonice and related sites in Czechoslovakia around 26,000 BP (Vandiver *et al.*, 1989). However, the use of pottery vessels is so far not known to have occurred until after the global changes that accompanied the advent of the Holocene. Although the introduction of pottery was once thought to have been associated with the beginnings of agriculture, it is now known that pottery production preceded agriculture in several instances.

Instead, the basic requirement for the production of pottery is sufficiently long periods of sedentism, spent close to appropriate clay sources and under suitable climatic conditions, to allow time for collecting raw materials and for forming, drying, and firing the vessels. Thus, the earliest pottery in Japan was produced by sedentary Jomon culture fishermen around 12,000 BP, and pottery was utilized by semisedentary Mesolithic cultures in northern Europe before the earliest appearance of domesticates. Conversely, in many parts of the Near East, the beginnings of agriculture preceded pottery production by more than a millennium.

In considering the reasons for the introduction of pottery, one must take into account the use of pottery both for utilitarian purposes, such as the processing of food and the transport and storage of liquids and solids, and for social and ideological purposes. Brown (1989) has argued that the adoption of pottery as a container was "a response to conditions in which the rising demand for watertight, fire-resistant containers is coupled with constraints in meeting this demand." Thus, pottery was adopted when existing containers, such as animal skins, baskets, or hollowed-out wood or stone, failed to meet the increasing demand brought about by new types of food processing, new forms of storage, or the emergence of food presentation as a form of social expression. In this context, a particular feature of pottery production is that it becomes more economical, in terms of the time spent per vessel, as the volume of production increases. In contrast, the alternative technologies of skins, basketry, wood, and stone are not susceptible to the same economies of scale until the advent of machinery. Conversely, Hayden (1995, 1998) puts much greater emphasis on sociopolitical factors, arguing that the principal function of early pottery, with its often elaborate, hand-painted decoration, was as a prestige or elite object which was used to display success and power. And it was only later that pottery, with increasing experience in its production, became sufficiently cheap for it to compete with, or even be less costly than, existing containers and, thus, be used for utilitarian purposes. Similarly, Vitelli (1995) has argued that the earliest Neolithic pottery produced in Greece, which shows no evidence of contact with fire, had an important ideological/ritual function and that the first potters may have been female shamans.

As an example of the initial emergence of pottery, the beginnings of pottery production in the Near East are briefly discussed below. This discussion illustrates both some of the factors that need to be considered and the contribution of the physical sciences, both actual and potential, in providing information, first, on the particular production technology employed and its relationship to preexisting technologies and, second, on the use to which the pottery was put. In the latter context, it should be emphasized that organic residue analyses and the study of surface wear, although having very considerable potential, have not yet been fully exploited.

With the introduction of wheel throwing in the Near East in the fourth millennium BC, the majority of the techniques (i.e., refining and tempering clays, full range of forming methods, slip and painted decoration, kiln firing with controlled temperatures and atmospheres) required for the production of unglazed earthenware was known (Kingery and Vandiver, 1986, p. 8). Subsequently, the major technological innovations in pottery production were associated with the production of glazed earthenwares, stonewares, and porcelains, but these are not relevant to the present paper. Instead, for unglazed earthenwares, the principal concern is the explanation of the different technological choices made in different regions at different periods.

In this context, Schiffer and Skibo (1997) have proposed a theoretical framework in which variability and change in production technology are explained in terms of the constraints imposed by the performance characteristics required for each activity (i.e., procurement of raw materials, manufacture, distribution, use, disposal) within the complete life history of an artifact. The identification of the performance characteristics required is achieved by considering how the situational factors (i.e., environmental, technological, economic, sociopolitical, and cultural–ideological) impinge on the relevant activities. Thus, one attempts to ascertain which situational factors have actually influenced, either directly or indirectly, the particular production sequence chosen for an artifact.

Using these concepts, it is possible to prepare a diagram (Fig. 1) which demonstrates, first, the direct constraints that the situational factors impose on the final technological choices (i.e., clay, temper, forming, surface treatment, firing) in the production of pottery vessels, as a result of either the performance characteristics associated with aspects of the production itself (i.e., raw materials, technology, production mode) or the technological style, as defined below. Second, the diagram demonstrates the indirect constraints that the situational factors impose on technological choice, via the performance characteristics required by the pottery vessels in use and, in turn, the physical properties required to achieve these performance characteristics. Those performance characteristics required in use, that are determined by the dimensions and shape of pottery vessels (e.g., capacity, stability, ease of manipulation and removal of contents) and discussed under Consumption, have been omitted from the diagram. This approach to technological choice is in many ways similar to the design theory approach proposed by Hayden (1998), which again considers the constraints operating in the development of a solution to a functional need.

Following from this diagram, the wide range of factors that influence the technological choices in the production of pottery vessels is discussed below, in terms of the constraints imposed, first, directly by environmental, technological, and economic factors; second, indirectly by the performance characteristics required in use; and third, directly by sociopolitical and cultural–ideological factors.

The Beginnings of Pottery Production in the Near East

In a review of the beginnings of pottery production in the Near East, Moore (1995) notes that the introduction of pottery took place around 8000 BP, long after

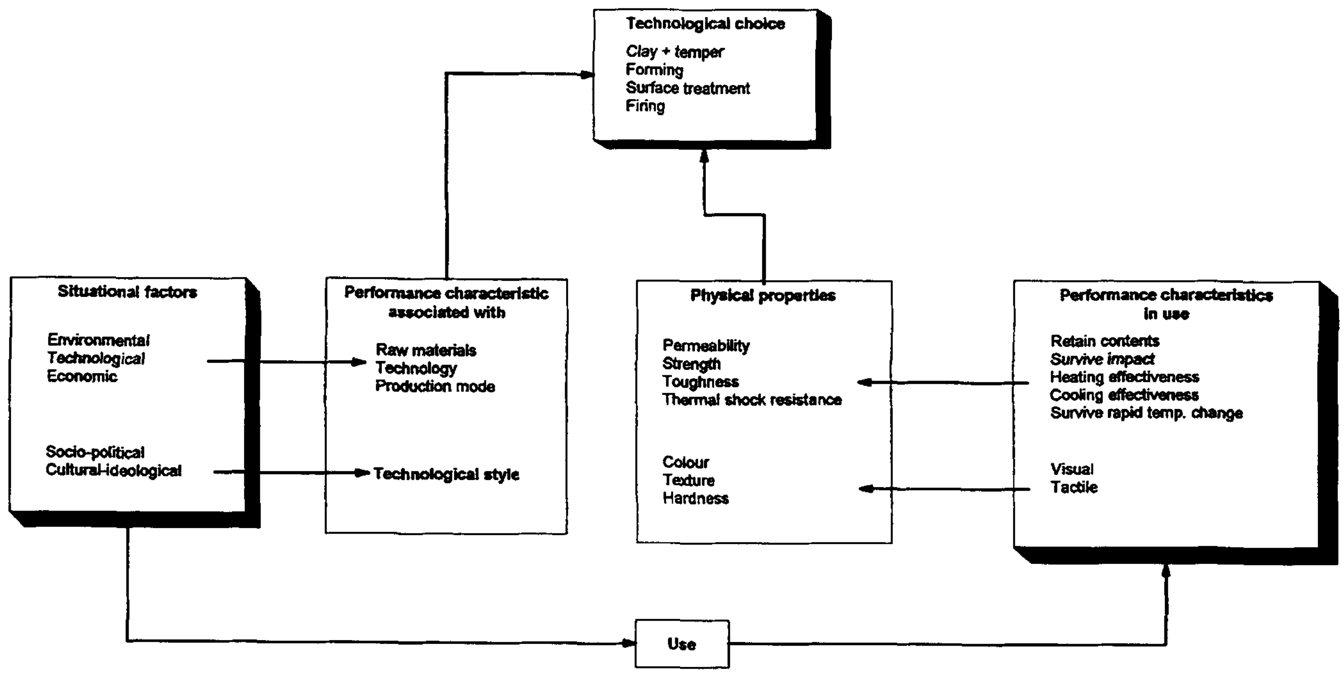

Fig. 1. Block diagram illustrating the interrelationship among the situational factors, the performance characteristics in use, and the technological choices in pottery production. The performance characteristics in use that are determined by the dimensions and shape of the pottery have been omitted.

the inception of the Neolithic farming way of life. These beginnings, which were almost-simultaneous throughout the Near East, appear to have coincided with the change from an economy based on the cultivation of cereals and pulses, combined with some hunting and gathering, to one based on full-time farming including the herding of sheep, goats, and cattle.

The technological antecedents to pottery production start with the making of mud bricks for the construction of houses from about 10,000 BP. However, perhaps more important is the extensive use of gypsum and lime plasters from the ninth millennium BP onward, particularly in the Levant, for the construction of floors for houses, for making white-ware vessels or *vaisselle blanche*, and in ritual contexts, notably to form human faces on skulls and to make models of human figures. As discussed by Kingery *et al.* (1988), the production of lime plaster involved firing to temperatures up to 800–900°C and its use involved the addition of mineral or vegetable fiber tempers and the decoration and burnishing of the surface. Thus, the technology employed in the production and use of lime plaster would have provided much of the technical knowledge required for the production of pottery.

Both coarse-textured and fine-textured pottery was produced from the beginning. The coarse-textured pottery were probably used for storage and, in the case of those vessels with traces of soot on their exterior, for cooking either meat, vegetables, cereals, or pulses. In addition, some vessels could have been used for holding, processing, and serving the dairy products becoming available at this time because of the shift to herding sheep, goats, and cattle. However, in the absence of organic residue analyses for any of these pottery assemblages, it is not possible to be more specific about what was being processed or cooked. Moore (1995), thus, emphasizes the utilitarian functions of the pottery and argues that these were the most important reasons for its development. In contrast, Goren *et al.* (1993) emphasize the dual utilitarian–ideological role of pottery and argue that the decorated fine-textured pottery, which was made from a highly calcareous clay, was produced for ritual use as a replacement for plaster vessels, skulls, and figures.

Constraints Imposed by Environmental, Technological, and Economic Factors

The primary aim in selecting and processing the clay used to make pottery is to obtain a clay with suitable properties, principally plasticity and shrinkage, for forming and firing. However, in ethnoarchaeological studies of procurement distances for clay and temper in traditional societies, Arnold (1985, p. 38) found that, in 33% of the cases, clay within 1 km was exploited, with 84% of the societies obtaining their clay within 7 km. Similarly, in the case of temper, in 52% of the cases the distance traveled was less than 1 km, with 97% of the societies obtaining their temper within 9 km. Hence, it seems probable that, in general, there was considerable flexibility in the choice of raw materials, with the nearest clay source being exploited and with this clay then being modified by refining, adding temper, or mixing with a second clay in order to achieve the required properties.

One situation in which clays appear to have been specifically chosen was in the very extensive use of calcareous clays (i.e., clays containing 15–25% of well-dispersed lime) for the production of fine-textured pottery in both the Near East and the Mediterranean, in contexts in which noncalcareous clays were being used for the production of more coarse-textured pottery. Due to the formation of crystalline calcium and calcium–aluminium silicates, the microstructure of calcareous clays remains essentially unchanged over the temperature range 850–1050°C. As a result, using such clays, pottery of a consistent quality could be produced with less precise control over the firing temperature than was required when firing pottery produced from noncalcareous clays. In addition, it is possible that the resulting buff-colored bodies were preferred, as a background to decorative treatments, to the red-colored bodies produced when typical iron-rich noncalcareous clays were fired in an oxidizing atmosphere.

Further, there is some evidence that, in the case of hand forming, the methods used were, in part, influenced by the properties of the clays available. For example, Vandiver (1988) has argued that the different methods of construction used for Neolithic storage vessels from the Near East and from China can be explained in terms of differences in the plasticity and drying shrinkage of local clays. Thus, the montmorillonitic clays from the Near East needed to be tempered with vegetable fibers (e.g., chaff or straw) in order to reduce their plasticity and drying shrinkage. As a result of the presence of this fibrous temper, coil construction was not possible and sequential slab construction was used instead. In contrast, the sandy illitic clays from loess deposits in China could be used without the addition of vegetable temper and therefore coil construction was employed. Although this hypothesis almost certainly represents an oversimplification on the geographical and chronological scale proposed, it does illustrate the possible ways in which the properties of the available clays might influence the choice of forming method.

The way in which pottery production was organized and the extent of craft specialization also influence the method of forming, as well as other aspects of the production technology. Thus, coil or slab construction, in which the pottery vessel is progressively built up over a period of time, is ideally suited to part-time household production, in that it can be taken up or left off as other demands allow. Such household production is dominated by women, in part, because pottery making is much more compatible with other household activities than with subsistence activities, which take place away from the home and are undertaken predominantly by men (Arnold, 1985, p. 99; Skibo and Schiffer, 1995).

In contrast, throwing on a wheel, if it is to achieve the significantly higher production rate of which it is capable, requires working for substantial continuous periods of time. Therefore, wheel throwing is normally associated with workshop or factory production, involving the employment of full-time specialists, who are most frequently men. The introduction of wheel throwing can also result in a change in the type of temper used. First, coarse angular temper must be avoided, otherwise the potters will suffer severe abrasion to their hands. Second, to take full advantage of the high production rate that can be achieved with a wheel requires more rapid preparation of the clay. Thus, untempered or sand-tempered clays tends to be favored over clays tempered with, for example, grog or limestone, both of which require prior crushing. An alternative method of achieving a high production rate is the use of preformed molds into which the soft clay is pressed. This method of forming pottery has the additional advantage that, once the molds have been produced, it does not require the highly skilled labor force needed for throwing on a wheel and, therefore, can be undertaken by men and women as well as children.

The introduction of wheel throwing to a region did not, of course, preclude the continued use of coil or slab construction. Thus, in Britain in the Late Iron Age, hand-formed pottery continued to be produced in a household setting, the production of wheel-thrown pottery being associated with the workshop mode (Morris, 1994). In addition, in Roman Britain, cooking pots continued to be hand formed (Williams, 1977) since, as discussed below, they needed to be coarse textured and were therefore difficult to produce by wheel throwing. However, such pottery was traded over fairly large distances and was, therefore, most probably produced in a workshop or manufactory.

The choice of surface treatment reflects both technological knowledge and access to the necessary raw materials. Thus, surface burnishing was widely used from the beginnings of pottery production. In contrast, the application of surface slips and mineral pigments, which required access to suitable clays and minerals, respectively, together with the ability to recognize and prepare them, were used somewhat later. Ethnoarchaeological studies (Arnold, 1985, p. 52) indicate that, in traditional societies, considerable effort can be expended in acquiring such materials, sources that are tens, or even hundreds, of kilometers away often being exploited.

In attempting to explain the choice between open firing with no permanent structure and firing in a kiln, a number of factors must be considered (Pool, 1997). First, because of the investment of time in their construction, firing in kilns is frequently associated with full-time specialist potters based in workshops. However, the quantity of pottery produced in a kiln firing is not necessarily greater than that produced in an open firing, nor is the firing temperature achieved in kilns used to fire earthenware necessarily higher. Also, because of the heat expended in heating the structure, kiln firings tend to be less fuel efficient than open firings. Instead, the principal advantage of kiln firings is the control possible over the rate of heating, the maximum temperature reached, and the firing atmosphere. The slow heating rate achieved in a kiln firing is essential for the production of most fine-textured pottery. Similarly, the ability to control the firing atmosphere facilitates the production of pottery with a uniform surface color and is essential for achieving the three-stage oxidizing–reducing–oxidizing firing cycle required to produce a reduced iron oxide black pigment on an oxidized red body (Tite *et al.*, 1982). Other advantages of kiln firings, over open firings, include the confinement of the flames, and hence the ability to operate in a more restricted space, and the protection that the kiln provides from wind and rain.

Constraints Imposed by Performance Characteristics Required in Use

For pottery vessels used for utilitarian purposes, the performance characteristics that have the greatest potential influence on the choice of production technology are the ability of the vessels to retain their contents and to survive impact without cracking; heating effectiveness and the ability to survive rapid changes in temperature without cracking, in the case of cooking vessels; and cooling effectiveness, in the case of water storage vessels. The associated physical properties (e.g., permeability, strength, toughness, thermal shock resistance) and the production technology choices (e.g., temper type, density, and particle size; surface treatment; firing procedures) required to achieve these properties have been identified through a combination of theory and data provided by the general ceramics literature and the experimental testing of replicate pottery in the laboratory. As yet, systematic measurements of physical properties have been made on only a limited range of clay types and of clay and temper combinations.

In part, because of probable changes in physical properties as a result of use, breakage, and burial, direct measurements are only rarely made on ancient pottery itself. However, Neupert (1994) has developed a ball-on-three-ball tester which can be used to measure the tensile strength in biaxial flexure of irregularly shaped, curved archaeological sherds. Using this system, he has shown that, as a result of a change from the use of sand to grog temper, the strength of Cibola White Ware from the American Southwest increases by about 70% over the period from 700 to 1200 AD.

The influence of surface treatment on pottery permeability, and thus on a range of performance characteristics, has been extensively investigated at the Laboratory of Traditional Technology at the University of Arizona. Thus, Schiffer (1988) has systematically studied the variation in evaporative cooling effectiveness of water storage jars with different interior and exterior surface treatments, ranging from finger smoothing, which allows the greatest permeability, through burnishing, to slipping plus burnishing, which produces the lowest permeability. The results showed that, under the relatively low stress conditions associated with environmental temperatures of about 25°C, the supply of water to the exterior surface was fast enough to maintain the film of water needed for evaporative cooling, with all surface treatments. Only at higher environmental temperatures was the greater permeability resulting from finger smoothing necessary.

Similarly, Schiffer (1990) has studied the heating effectiveness of cooking pots with different surface treatments by measuring the time required to heat water in test vessels to 90°C together with the resulting water loss. The results confirmed that the most effective way to minimize water loss and, thus, energy use was to make the interior surface impermeable by the application of a resin. In this way, water was prevented from permeating to the exterior surface where energy would have been used in boiling it off. The more permeable is the interior surface, the more rapid is the supply of water to the exterior surface. Therefore, the energy used in boiling off this water increases with increasing permeability such that, with a finger-smoothed interior surface, it is often impossible to bring the contents of a vessel to the boil.

A further topic which has been the subject of extensive experimental testing is the role of temper type, density, and particle size in determining the strength, toughness, and thermal shock resistance of pottery and, hence, the ability of the pottery to retain its contents and to survive impact and rapid changes in temperature. Kilikoglou *et al.* (1995, 1998) undertook transverse rupture strength and fracture toughness measurements using, respectively, three-point bending on unnotched test bars and four-point bending on notched test bars. These test bars, which were fired to 950°C, were made from a calcareous clay tempered with varying amounts (0–40%, by volume) and varying particles sizes (100–750 μm in diameter) of quartz sand. As anticipated from theoretical considerations, the transverse rupture strength was observed to decrease progressively with increasing quartz content and, for a given quartz content, also to decrease with increasing size of the quartz particles. Conversely, the fracture toughness increased significantly when the volume fraction of quartz temper was increased from 10 to 20% but was more or less independent of quartz particle size. The explanation proposed was that the differential shrinkage/expansion of the clay and quartz inclusions during drying, firing, and subsequent cooling resulted in the formation of a network of microcracks, as well as in debonding between the quartz grains and the clay matrix. As a result of the formation of microcracks, the probability of crack initiation increases, resulting in the observed decrease in transverse rupture strength with increasing volume fraction of quartz temper. However, this microcrack network also encourages crack deflection and bifurcation, thus increasing the dissipation of energy during fracture. Hence, the probability of crack propagation is decreased, resulting in the observed increase in toughness with increasing volume fraction of quartz temper.

Feathers (1989) and West (1992) have further shown that the increase in toughness resulting from the addition of temper depends critically on the morphology of the temper inclusions. Thus, platy or fibrous temper, such as mica and shell, results in a significantly greater increase in toughness than either angular or rounded temper such as limestone, quartz, and grog. This increase in toughness is due to the increased dissipation of energy resulting from a combination of the increased distance that a crack has to travel in order to pass around platy or fibrous inclusions, the increased friction that must be overcome in pulling such inclusions out from the clay matrix, and the ability of such inclusions to bridge propagating cracks.

The resistance to crack propagation following thermal shock exhibits essentially the same dependence on and variation with temper type, density, and size as that observed for toughness. However, in assessing thermal shock resistance, it is also necessary to consider the driving forces, of which the stresses associated with the differential expansion or contraction of the inner and outer surfaces of a pottery vessel, due to a rapid change in temperature at one surface and the resultant temperature gradients through the wall, are of primary importance. The magnitude of these stresses depends on a combination of the bulk thermal expansion coefficient of the pottery body, the thickness of the vessel wall, its thermal conductivity, and the vessel shape. A possible secondary driving force is the stresses that occur during heating when the thermal expansion of temper particles are greater than that of the clay matrix. However, the associated stresses are probably less severe than sometimes suggested because the greater shrinkage of the temper particles during cooling after firing, compared to the clay matrix, will have created spaces around the particles into which they can expand, at least partially, during subsequent heating.

In contrast to the situation for pottery vessels used for utilitarian purposes, the more important performance characteristics for those used for sociopolitical or ideological/ritual purposes (e.g., prestige pottery presented as a gift or used for competitive feasting) are generally visual and tactile. Such performance characteristics determine, for example, the choice of surface color and decoration, surface texture, hardness, and vessel profile or shape, and these parameters, in turn, can determine the technological choice. Thus, the surface color requirement can determine the type of body clay, surface slips, and mineral pigments used together with the firing atmosphere. A requirement for a highly polished surface can be met either by burnishing or, as in the case of Greek Attic and Roman Samian wares (Tite *et al.*, 1982), by applying a specially selected slip. Similarly, the hardness requirement can again determine the type of body clay used together with the firing temperature and atmosphere, and the required vessel shape can determine the forming method employed. A further factor influencing technological choice in the production of pottery for nonutilitarian purposes is the requirement for it to have a high value, which, in turn, favors the use of raw materials from distant sources and/or high labor costs in production.

In considering the relationship between technological choice and performance characteristics, it is important to remember that several technological choices are usually available for solving a specific performance problem. Conversely, a single technological choice, such as quantity or type of temper, can affect the performance characteristics associated with several aspects of both production and use. Similarly, when a new technological choice is necessary, for example, as a result of a change in the way in which a vessel is used, this can affect many performance characteristics and possibly set in motion a series of changes in production technology. Therefore, a particular technological choice usually represents a compromise in which preference is given to those performance characteristics, associated with either production or use, that are regarded as most important.

For example, Skibo *et al.* (1989) have argued that, in using organics as temper, the potters of the Late Archaic period in the eastern United States sacrificed good abrasion resistance and good heating effectiveness for a vessel that could be transported easily. Also, besides the benefits during use, organic temper improved the workability and wet strength of the clay during vessel manufacture. The results obtained from the study of cooking vessels, which are presented below, provide a further illustration of the range of technological choices available for solving a specific performance problem, together with the compromises that are often necessary. For cooking vessels that are heated directly, rather than indirectly by means of heated stones, the two most important performance characteristics that need to be considered are heating effectiveness and thermal shock resistance.

The Design of Cooking Vessels. The seminal paper by Braun (1983), entitled "Pots as Tools," represents one of the earliest attempts to explain the observed changes in technological choice in the production of cooking vessels in terms of a need for different performance characteristics. He showed that, in Illinois and Missouri during the Woodland period, there were a reduction in the wall thickness of the pottery and a decrease in the density and average size of the quartz sand and crushed rock temper around 400–500 AD. He argued that these changes reflected the increasingly stressful thermal conditions to which pottery was subjected as a result of the longer cooking time associated with the increasing importance of starchy seed foods. Thus, the observed reduction in wall thickness resulted in more rapid conduction of heat from the exterior to the interior and, hence, in an improved heating effectiveness. At the same time, the temperature gradients through the vessel wall were reduced, and therefore, there was less energy available for fracture during thermal shock. On the debit side, the reduction in wall thickness resulted in a decrease in strength. However, this was compensated for by the decrease in the density and average size of temper, which resulted in an increased resistance to crack initiation and, hence, an increase in strength. The decrease in the amount of temper could have resulted in an increased probability of crack propagation and, therefore, a decrease in thermal shock resistance. However, as shown by Kilikoglou *et al.* (1998), provided that the amount of temper does not fall below about 20% (by volume), the fracture toughness remains essentially constant with decreasing temper content. In addition, the reduction in the amount of high-thermal expansion quartz-rich temper also resulted in a decrease in the bulk thermal expansion and, thus, a decrease in the energy available for fracture during thermal shock.

Subsequently, Steponaitis (1984) showed that, in the region around Moundsville, Alabama, during the period from 1000 BC to 1500 AD, the temper type used in cooking vessels changed sequentially from fiber to coarse quartz sand, then to fine quartz sand, to grog, and, finally, to coarse shell during the Mississipian period. He therefore argued that coarsely ground shell provides the most appropriate temper for cooking vessels and that the use of shell temper can be seen as the final stage in a technological development aimed at achieving the "ideal" cooking vessel. The first advantage of shell temper was that, as discussed above, the platy shell particles were more effective at stopping crack propagation than rounded or even angular quartz sand or grog particles and, thus, resulted in a higher thermal shock resistance. The second advantage was that, because the thermal expansion of shell temper was significantly lower than that of quartz, the bulk thermal expansion with a shell-tempered body was lower than that of a quartz-tempered body, and therefore, the stresses resulting from thermal shock were less. Finally, any stresses that occurred during heating, as a result of the differential thermal expansion of the quartz temper and the clay matrix, were absent in the case of shell temper. A potential disadvantage of shell temper is the care required to avoid overfiring (Feathers, 1989). If shell-tempered pottery is fired much above 700°C, the shell will start to decompose to lime, which rapidly hydrates on cooling. The hydration is accompanied by expansion, which causes the pottery to spall and crack.

Contrary to the above studies, Woods (1986) has questioned the emphasis put on the thermal shock resistance of cooking vessels and, in particular, on the importance of shell temper. She showed that, in Britain from the Neolithic through to the medieval period, there is little evidence for the deliberate use of a specific temper type in cooking vessels and that quartz sand was probably more commonly used than shell temper. She, therefore, argued that the crucial characteristic of cooking vessels was that they were coarse textured and that, if they survived the rapid heating and cooling associated with the open firing during their production, they would survive use for cooking. However, the latter argument takes no account of the cumulative effect of the repeated heating and cooling resulting from use in cooking. Thus, conversely, Richard Carlton (personal communication, 1998), in an ethnoarchaeological study of pottery production in the West Balkans, has observed that cooking vessels tempered with limestone survive in use without obvious deterioration for longer periods than those tempered with quartz sand, although both types survived the rapid heating and cooling during their production firing.

Therefore, although thermal shock resistance was clearly one factor influencing the type of temper chosen for cooking vessels, it is important to remember that there were other factors of equal or, perhaps, greater importance that need to be taken into account when attempting to explain the choice of temper type. These other factors include the accessibility of the different temper types and the effect of temper on both the working properties of the clay and on other performance characteristics of the pottery in use. In addition, as discussed below, it is also crucial to consider the sociopolitical and cultural–ideological factors influencing technological choice.

Constraints Imposed by Sociopolitical and Cultural–Ideological Factors

In considering the role of sociopolitical and cultural–ideological factors in influencing technological choice, Lechtman (1977) introduced the concept of technological style. Central to this concept is the idea that "style" resides in every stage of a production process. As a result, a technological style reflects the conscious and unconscious elements of the sum of the technological choices involved in a production process. Lechtman (1977) then goes on to argue that social and ideological factors act as filters and select from the multitude of possible production routes that which is most consistent with prevailing beliefs. Lemonnier (1986), who has also contributed to the development of this concept, similarly relates technological style to a society's worldview.

Much of the pioneering work on technological style was concerned with metals, the classic example being the study of the relationship between pre-Hispanic Andean metallurgy and weaving. In this case, Lechtman (1977) has argued that an inherent similarity existed between the techniques used in metallurgy and weaving in that, for both, the "essential ingredient" was incorporated into the artifact rather than being applied merely to the surface. As a result, a gold or silver surface layer was achieved, not by applying a layer of the desired precious metal to the surface, but by incorporating these metals into the copper alloy of the body and then removing the copper from the surface layer. Similarly, motifs were not embroidered superficially onto Andean textiles but were woven within the fabric itself. Further, in China, as discussed by Franklin (1983), there was an intimate relationship between bronze and ceramic technologies. Thus, from the beginnings of metallurgy in the Shang dynasty, Chinese bronzes were cast in ceramic piece molds rather than being hammered or wrought, as in the case of early metal production in other parts of the world. At the same period, the technique of molding was also used to form some ceramic vessels (Vainker, 1991, p. 27). In addition, some Shang dynasty bronzes and ceramics were similar in terms of both shape and the use of deeply incised decoration. On the basis of these links, Franklin (1982) has suggested that, in China, bronze was regarded and treated as a "fluid ceramic."

In considering the role of technological style in pottery production, the choice of forming method is of particular importance. Thus, Vandiver and Chia (1997) have suggested that, throughout Southeast Asia, a transformational forming technology was employed, involving the expansion of a clay lump using primarily the paddle-and-anvil method. This method is akin to shaping by throwing on a wheel and contrasts with the constructivist technology, involving building up the vessel from slabs or coils, which was employed to the west and east respectively. Similarly, van der Leeuw (1993), on the basis of a detailed assessment of the forming methods employed in three ethnographic and two archaeological contexts, distinguished between invariant and variant elements within a forming tradition. He then went on to argue that the invariant elements are associated with the conceptualization of shape through a combination of the topology of the vessel during forming, the basic entities out of which the vessel is formed (i.e., partonomy), and the sequence in which the vessel is formed and that it is these invariant elements which define the technological style associated with the forming tradition. Conversely, the variant elements within a forming tradition, which are more open to modification than those associated with the conceptualization of shape, are associated with executive functions such as the methods of rotation and support used.

Again, Gosselain and Livingstone (1995), through ethnoarchaeological studies in sub-Saharan Africa, have established close links between ethnolinguistic groupings and the ways in which artisans form their pottery. In contrast, the choices made in most other stages in the manufacturing process (e.g., clay processing, firing) appear to be more randomly distributed. Gosselain (1998) then argued that observed links between linguistic groups and manufacturing methods are the result of potters learning their skills within the nuclear or extended family and that forming methods, because they rely essentially on motor habits, are more resistant to subsequent change than other aspects of the manufacturing process.

The above examples indicate the potential of technological style in pottery production for helping, in combination with the style based on pottery form and decoration, to define social boundaries. Similarly, the identification of changes in technological style can provide additional evidence for the migration of peoples. For example, from the study of the utilitarian plain ware pottery found in the Tonto Valley in Arizona during the Colonial period (700–800 AD), Stark *et al.* (1998) have argued that the methods of forming and surface treatment together with the use of micaceous schist temper, which was not available locally, provide confirmatory evidence for the migration of Hokokam-affiliated groups. The distances involved are such that an explanation in terms of migration of people, rather than exchange or trade of the pottery, is favored since plain ware pottery will most probably circulate in utilitarian exchange spheres within which the travel time from one point to the next rarely exceeds 1 day's journey. Similarly, Rigby and Freestone (1997) have shown that the first wheel-thrown pottery to be produced in Late Iron Age Britain was typologically and, in many respects, technologically identical to contemporary pottery being produced in northern France. However, in this case, the British pottery was made from a local fabric tempered by the addition of grog and vegetal matter. They therefore suggest that the first of these new wheel-thrown wares were produced by immigrant or itinerant potters from Gaul, working in Britain and using local clays.

More generally, in addition to helping to establish the validity of the concept of technological style, ethnoarchaeological studies are valuable in providing examples of choices in raw material selection and vessel production which depend on rites, myths, and taboos rather than on environmental, technological, or economic constraints or on the performance characteristics required in use. For example, in many parts of Africa, the production of pottery is seen as being related to birth

(Barley, 1994, 1997). Thus, the potter is also often the midwife and her husband is the blacksmith, a role similarly involving transformation of material, and also the undertaker. The addition of grog temper to a clay is seen as an act of "rebirth" in which a "reversal of time" is achieved. Similarly, pottery production is seen as being related to the transformation of "wet and smelly" boys to dry, circumcised men. Pottery production is exclusively a dry-season activity and is permitted only after the public inauguration of that season by the rain-chief, who fires grass on the top of his mountain. On the same day, the boys also return from the bush and their heads are "fired" by piling branches over them and setting them alight. In addition, ethnoarchaeological studies can provide insight into the emic dimension, that is, what the potters thought that they were achieving through their choice of a particular production sequence and what the people using the pottery thought were the properties that it had. For example, Aronson *et al.* (1994) interviewed potters and pottery users from the Kalinga area in the Philippines and compared the reasons given for choosing certain clays or purchasing certain pots with laboratory data on the physical properties of the clays and pots. They showed that, in this case, the laboratory data confirmed both the potters' judgments of the clay properties (e.g., good working properties) and the purchasers' judgments of the properties of the pottery (e.g., strong and durable, lightweight).

Overall, therefore, ethnoarchaeological parallels play a valuable role in helping us to understand the influence of sociopolitical and cultural–ideological factors on technological choice. However, in using such parallels, it is crucial to ensure comparability, as far as is possible, between the archaeological and the ethnoarchaeological contexts in terms of the form of the pottery (i.e., dimensions, shape, surface decoration), its distribution in space, its abundance, and its relationship to other artifacts.

In summary, sociopolitical and cultural–ideological factors are clearly of very considerable importance in explaining technological choice. However, even if one accepts the general validity of the statement by van der Leeuw (1993) that "the non-availability of the appropriate raw material(s) turns out to be only very rarely the limiting constraint in the manufacture of pottery," the constraints imposed by environmental, technological, and economic factors and by performance characteristics in use cannot be entirely ignored, as Gosselain (1998) appears to have suggested. First, an understanding of the role of these more practical constraints provides a valuable baseline for the consideration of the overall reasons for technological choice. For example, the knowledge of whether or not the optimum physical properties required by a cooking vessel have been achieved is clearly helpful when trying to establish whether sociopolitical or cultural–ideological factors took precedence over performance characteristics in use in influencing technological choice. Second, it must be remembered that the importance of such practical constraints will tend to increase, relative to sociopolitical and cultural–ideological factors, as the extent of specialization and the scale of pottery production increases from household production to workshop and factory production.

FUTURE DEVELOPMENTS

A primary requirement for the future must be to ensure that an increasing proportion of ceramic studies, making use of the physical sciences, is designed to answer real archaeological questions that go beyond the mere reconstruction or description of the production technology, distribution, and consumption. Such archaeological questions can be problem specific or can require a more holistic approach, in which the complete life cycle, from selection, procurement, and processing of the raw materials through the ultimate discard of the pottery, is investigated. In either case, in interpreting the physical science data, consideration should be given to the overall environmental, technological, economic, sociopolitical, cultural–ideological, and historical context in which the pottery was produced.

In addition to the physical examination, both problem-specific and holistic projects will also variously involve archaeological fieldwork and excavation, experimental archaeology, ethnoarchaeology, and archaeological theory and interpretation. Therefore, interdisciplinary collaboration is essential to success, with the entire group of participants being actively involved at every stage, from the formulation of the archaeological question and the research design, through the fieldwork, excavation, and selection of the samples, to the physical examination, interpretation of the resulting data, and final publication. A further crucial component of any ceramics study is that the samples selected for detailed study are fully representative of the complete ceramic assemblage under investigation. It is therefore important to make full use of low technology methods, such as low-power binocular microscopy, which enable one to undertake a preliminary examination of as high a proportion of the entire assemblage as is realistic.

Regarding the requirements for new techniques of physical examination, it should first be emphasized that an impressive range of techniques is already available and is being utilized in ceramic studies. Therefore, as important as the development of new techniques is the maintenance of quality control over the precision and accuracy of the analytical data generated by existing techniques. In achieving this quality control, the provision of a series of standard samples and the organization of laboratory intercomparisons have an important role to play. However, in the future, one can certainly foresee new developments in organic residue analysis, with more emphasis on the measurement of isotopic compositions in combination with gas chromatography. Furthermore, because of the decreasing access to nuclear reactors, at least in Europe, it seems probable that an alternative to INAA for chemical element analysis will have to be found in the fairly near-future. One possibility which is currently being systematically investigated is ICP-MS. In considering new techniques in general, because of the large size of most pottery assemblages being studied, a high throughput of samples is an important factor in determining choice. However, in order to avoid repetition of the problems encountered with the weak-acid extraction method (Neff *et al.*, 1996; Triadan *et al.*, 1997), it is crucial that the validity of the data provided by the use of simplified and, therefore, more rapid procedures is fully tested before their widescale application. Further, in the context of new methods involving a high level of capital investment, it is important also to ensure that the data that they provide have real archaeological relevance and that they are not merely expensive new "toys" looking for a problem to solve!

Finally, there is clearly scope for more research into some of the basic science on which the interpretation of the results from the physical examination of pottery is based. Of general importance in this context is the investigation of the changes in chemical composition and microstructure that occur as a result of both the use of the ceramics and their weathering during burial, since such alterations can effect the data on which the reconstruction of their production, distribution, and consumption are based. Similarly, further research is required into the chemical alteration of animal and plant residues in pottery, occurring both as a result of cooking and during subsequent burial. Other topics on which a better understanding of the underlying basic science would be of value include the full range of parameters that determine the physical properties (e.g., permeability, strength, toughness, thermal shock resistance) of pottery.

ACKNOWLEDGMENTS

This paper was written, in large part, during a sabbatical spent at the Department of Anthropology, University of Arizona, and at the Conservation Analytical Laboratory, Smithsonian Institution. I thank those two institutions for the excellent hospitality that they provided and, in particular, Professor Michael Schiffer, Professor David Kingery, Dr. Bert van Zelst, Dr. Ron Bishop, and Dr. Pam Vandiver for extremely helpful discussions. I am also very grateful to the various reviewers, who provided both valuable comments and criticisms and a most stimulating further reading list.

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