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# Advances in Ceramic Radiography and Analysis: Applications and Potentials

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X-radiography can be used to study a variety of features of archaeological ceramics in order to solve a broad range of archaeological and anthropological problems. Many of these have only recently become possible with improvements in ceramic radiographic methods. Hidden features that can be detected radiographically include coils, slabs, and their size, morphology, and methods of joining; the material type, approximate mineralogy, size, density, and orientation of aplastic inclusions or voids; fracture systems; paste texture; and hidden vessel parts. Under certain conditions, these features can be used to sort sherds by their vessels of origin, to identify the primary and secondary methods of vessel manufacture, to assess vessel function, to complement petrography when identifying and sourcing trade vessels; and to identify post-depositional alterations. Both the basic data and inferred identities can be useful when reconstructing learning pools, vessel trade networks, and settlement functions; when estimating site occupation spans, population levels, frequencies of vessel trade, and stylistic-based measures of social interaction; and when building chronometric models of ceramic technological change. Bridging arguments that integrate X-radiographic methods, data, and some theoretical agendas of archaeology are made explicit.

*Keywords:* RADIOGRAPHY, CERAMIC TECHNOLOGY, CERAMIC STYLE, CERAMIC EXCHANGE, BEHAVIOURAL ARCHAEOLOGY.

## Introduction

Ceramics are an archaeologist's forte. They can provide information on the subsistence, population, social organization, cultural boundaries, trade networks, alliances, and world views of past peoples (Hill, 1970; Plog, 1980; Braithwaite, 1982; Braun & Plog, 1982; Hodder, 1982; Braun, 1983; Rice, 1984; Arnold, 1985; Smith, 1988). They are also useful for the more basic tasks of reconstructing archaeological formation processes (Schiffer, 1983; Lindauer, 1988; Sullivan, 1988) and establishing chronological sequences (Braun, 1985). Nevertheless, ceramic studies often involve basic problems at the levels of observation, description, and classification which can call their validity into question. Sorting sherds by vessel, discriminating vessels of different functions, and measuring technological parameters are examples.

This article overviews the roles that radiography can play in overcoming many basic problems in ceramic research. It both reviews previous applications and looks ahead to

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new, potential roles that are becoming feasible with recent technical improvements and that are deserving of experimental development. Specific advances in radiographic laboratory procedures and materials, themselves, are reported elsewhere (Carr, 1990; Carr & Riddick, 1990). Finally, this article establishes a suite of bridging arguments that relate ceramic radiographic work and the kinds of data that it can produce to some current theoretical agendas in archaeology. Developing such explicit bridging arguments that bring theory, method, and data into logical concordance is essential to creating successful research designs (Carr, 1985*a*).

Inspiration for the logical linkages and methodologies outlined here come in part from my experimenting with a variety of industrial and medical radiographic methods on Woodland ceramics from the Eastern United States, especially southern Ohio, over the last 7 years. The larger projects of which these experiments are a part include modeling and dating ceramic technological change, identifying previously unrecognized ceramic functional classes, and documenting the evolution of ceramic exchange for Woodland Ohio (Carr, 1985*b*, 1986, 1987, 1990).

## X-Radiography

X-radiography creates a film image of those internal features or parts of an object that differ in their composition, average specific gravity, and/or thickness and, thus, their capability for transmitting X-rays. The varying amounts of X-rays that are transmitted by different portions of a specimen are recorded on film as different grey levels of exposure. In ceramic research, the internal features or part, may be temper particles, voids where temper has been burned or leached out, voids at joins between coils or slabs, fracture systems, thicker or thinner sections, or hidden walls.

X-radiography has been used occasionally by archaeologists to study ceramics since at least the 1930s. Titterington (1935), Digby (1948), and Shepard (1956) defined a limited set of tasks to which radiography is applicable. They focused largely on documenting vessel manufacturing methods and qualitatively overviewing some temper particle characteristics. More recently, X-radiography has caught the attention of others and some methodological improvements have been made (e.g. Braun, 1982; Rye, 1977). Its newer, sister method, xeroradiography, has also been introduced (Glanzman & Fleming, 1986). However, applications have remained infrequent and narrow in scope.

The sporadic use and narrow role of radiography in ceramic research is in part attributable to the nature of ceramics, themselves. Anomalies in ceramics can be subtle in their transmitting characteristics compared to those in other materials. As a consequence, more standard medical radiographic procedures of the kinds used in the above-mentioned studies have not always proven ideal for their purposes and are inadequate for other potential applications to be discussed below. Specifically, both low image contrast and mediocre resolution have been problems.

At this time, it is clear that the problems of contrast and resolution can be largely overcome by using certain industrial and newer medical radiographic methods and materials. These techniques have been tested and used in routine ceramic technological research by myself and radiographers in several medical and industrial laboratories for a variety of Woodland period ceramics from the Midwest United States (Carr, 1985*b*, 1986, 1989, 1990; Carr & Riddick, 1990). Among the most critical parameters of the techniques are: high-contrast, fine-grained industrial films such as Kodak Industrex M or R; certain mammography or high-detail films such as Kodak Ortho M and XTL; industrial X-ray machines with a tungsten tube, small focal spot, beryllium window, no filtration, and built for long exposures at low peak kilovoltages; mammography X-ray machines with a molybdenum tube, small focal spot, beryllium window, and no filtration; minimally penetrating kilo-voltage settings (20–50 kVp) and long exposures; exposures made with a dark balance; and viewing of radiographs with dense incandescent rather than fluorescent light. The particular choice of equipment, materials, and procedures depends on whether a medical or industrial laboratory is available to the ceramicist. For certain applications, more standard xeroradiographic procedures are preferable.

These technical improvements call for a re-examination of the scope of radiographic applications. A broader variety of ceramic features and parameters can now be documented securely. These include: the volumetric density, size distribution, orientation, and shape of temper particles of many materials, for particles down to silt size; the density, size, orientation, and shape of voids; joins between coils or slabs; coil size and morphology; the qualitative degree of paste kneading; paste texture; fracture systems; and hidden vessel morphologies and repair features. The potential for using radiographs in conjunction with petrography to make mineralogical identifications of temper particles remains to be explored. In turn, these diverse data widen the range of archaeological and anthropological problems that can be investigated efficiently with radiographs, as outlined below. Finally, the introduction of new methods, kinds of data, and theoretical areas of application requires their concatenation in a logically concordant manner through the development of bridging arguments which may serve as modular parts of model research designs. Some basic arguments of this nature follow and are summarized in Table 1.

**Documenting Vessel Formation Procedures**

Radiographs can often reveal the primary and/or secondary formation procedures by which a vessel was probably constructed: by pinching, slab-building, drawing, coiling, wheel, molding, or beating. Surface visual evidence of these procedures is usually obliterated by later shaping and finishing steps, making radiographic identification necessary (Rye, 1977: 205; Glanzman & Fleming 1986: 588). This application was first suggested by Shepard (1956: 183–184) and then systematically investigated by Rye (1977, 1981: 66–83), Glanzman & Fleming (1985, 1986), Adler (1983), and Foster (1983).

Figure 1 summarizes some of the key indicators of primary formation techniques that can be detected radiographically. These diagnostics and others have been found through ethnoarchaeological studies or have been hypothesized by Rye (1981: 61–81), as follows. Rye (1977) demonstrated that Papuan vessels which were produced by coiling, drawing with paddle and anvil beating, and throwing can be distinguished by the shape and orientation of air voids and the orientation of temper grains within them. Coiled vessels have elongated, horizontal voids in their walls and elongated, concentric voids in their bases when viewed normal to the vessel wall. Asymmetrical temper particles are similarly oriented. The direction of voids and temper thus follow coil direction. This orientation is produced when the coil is initially rolled (Rye, 1981: 68; Foster, 1983: 215). Drawn and beaten vessels exhibit flattened, circular air bubbles when viewed normally. In cross section, these parallel the wall and base contours. Asymmetrical temper grains are similarly aligned. This laminar structure arises from the thinning and stretching pressures involved in paddle and anvil shaping more so than the primary formation technique of drawing. Drawing, alone, will usually produce only a random to weakly parallel orientation of voids and temper particles when viewed in cross section (Rye, 1981: 72). Wheel-thrown vessels with asymmetrical inclusions are typified by inclusions that are orientated at an angle to the vertical, parallel to each other in the walls, and in a spiral in the base when viewed normally. These alignments reflect the vertical pressures of lifting and the horizontal pressures of rotation and opening the ball of clay. Rye suggested but did not show that the specific angle of the inclusions reflects the speed of lifting/opening and wheel speed.

Glanzman & Fleming (1986: 591) found that slab-built, paddle and anvil shaped Thai vessels have void and particle alignments like those described by Rye, again reflecting the shaping rather than the primary forming process. Shepard (1956: 184) and Rye (1981: 72)

*Table 1. Tasks to which radiography is suited and optimal techniques for achieving them*

| Problem domain | Operational task | Technique* |
|---|---|---|
| Formation techniques, vessel function. | Identifying coil or slab joins | Xeroradiography |
| Formation techniques, typology reflecting social units, social interaction, chronology. | Documenting coil size and morphology | Xeroradiography |
| Formation techniques. | Documenting stages of primary formation of coiled vessels | Xeroradiography or CAT scan |
| Museum tests of authenticity. | Mapping hidden vessel morphologies and repair features | Xeroradiography |
| Identifying sherds to their vessels of origin, vessel function, chronology, formation techniques. | Estimating rock temper volumetric density, size distribution, orientation, shape | Industrial or mammographic X-radiography |
| Identifying sherds to their vessels of origin, vessel function, chronology, formation techniques. | Estimating shell temper volumetric density, size distribution, orientation, shape | Industrial or mammographic X-radiography or xeroradiography |
| Identifying sherds to their vessels of origin, vessel function, formation techniques. | Estimating void volumetric density, size distribution, orientation, shape | Industrial or mammographic X-radiography or xeroradiography |
| Vessel function (potential), vessel exchange (potential). | Identifying approximate mineralogical classes that differ in specific gravity (e.g. felsic, mafic, opaques, and some finer distinctions), as a complement to more detail petrographic description | Industrial radiography |
| Vessel function, vessel exchange. | Estimating paste texture | Industrial X-radiography for magnification |
| Vessel formation, vessel function (potential), depositional and post-depositional alteration (potential). | Documenting fracture systems | Industrial or mammographic X-radiography |

*Some useful industrial films include Kodak M-2, for unmagnified or low magnification ($<14\times$) work and single coated Kodak R for high magnification work. A useful mammographic film is Kodak Ortho-M. High detail medical specimen film Kodak XTL is also sufficient.

have both hypothesized that voids and inclusions in hand-drawn vessels will show a vertical alignment when viewed normally. However, Rye (1977: 208) found evidence of this only occasionally in the shoulders of Papuan vessels, due to subsequent paddle and anvil shaping.

Coiled ceramics are characterized by elongated voids between coils, in addition to the shape and direction of air voids and temper particles embedded within coils. Coil join voids are more likely to be found in vessels that are secondarily shaped by smearing or

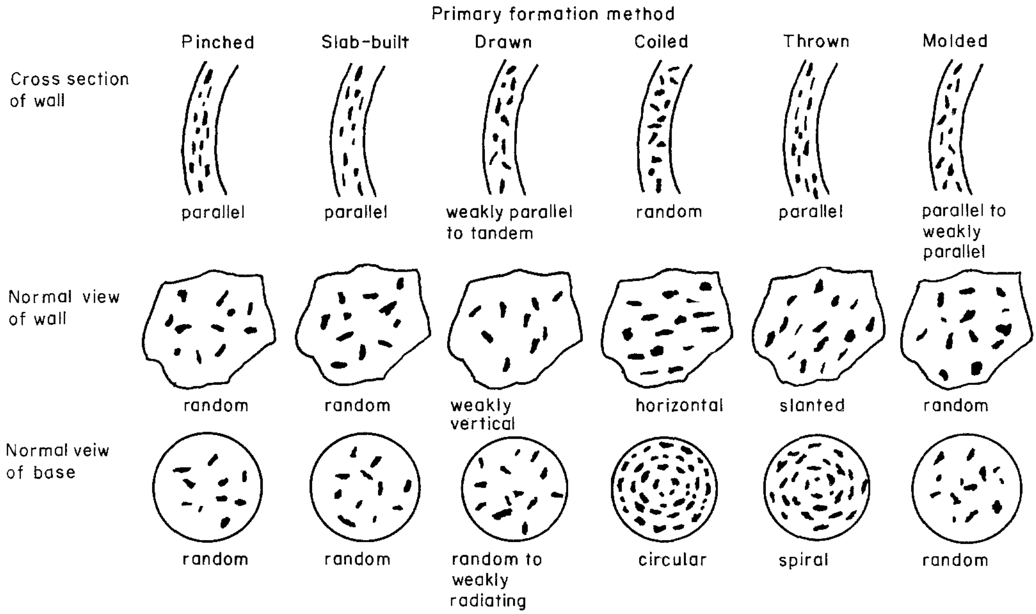



Figure 1. Vessels constructed with different primary formation methods vary in the random or preferred orientation of asymmetrically shaped temper particles in their walls and bases. (Adapted from Rye, 1977; 1981: 61–81).

scraping than in vessels shaped, thinned, and consolidated by beating, which tends to obliterate joins (Rye, 1977). Rye (1977: 207) did not find join voids in his sample of Papuan paddle-and-anvil shaped ceramics. However, residual join voids are occasionally found in beaten ceramics, as documented for paddle-and-anvil shaped vessels from Woodland Ohio (Carr, 1986) and Ban Chiang Thailand (Glanzman & Fleming, 1985), for apparently paddle-and-anvil shaped Mississippian ceramics from Illinois (Adler, 1983), and for Thai tournette shaped vessels (Glanzman & Fleming, 1986: 590). In the Ohio case, coils are distinguishable in approximately 4% of 1000+ vessels. However, they are more often revealed by differences in their temper particle densities, as a result of uneven mixing of temper and clay, than by join voids. Figure 2 illustrates an extreme case.

Documenting ceramic formation techniques need not be limited to broadly classifying vessels as slab-build, coiled, wheel thrown, etc. More detailed aspects of manufacture, which may be significant culturally or chronologically, can also be noted. Examples include the size and morphology of coils, details of how slabs or coils were joined (Glanzman & Fleming, 1985), and tempering differences or coil joins that show a vessel was built in stages (Carr, 1985*b*; Holstein, 1973: 78; Rye, 1981: 21–23).

Radiographically documenting the procedures by which vessels were formed and their variation over time and space can be useful to the archaeologist in several ways. (1) The information can indicate networks of prehistoric interaction. Characteristics of a vessel that result from primary forming procedures, unlike those that arise from shaping and finishing methods, are largely invisible to the participants of a culture. They constitute isochrestic technological variation rather than iconographic variation (Sackett, 1982; Carr, in press). Thus, their spatial distributions can reflect the expanse of learning pools (Friedrich, 1970), marriage networks, and/or exchange networks (Plog, 1990), in contrast to active boundary maintenance. Regional distributions of formation methods,

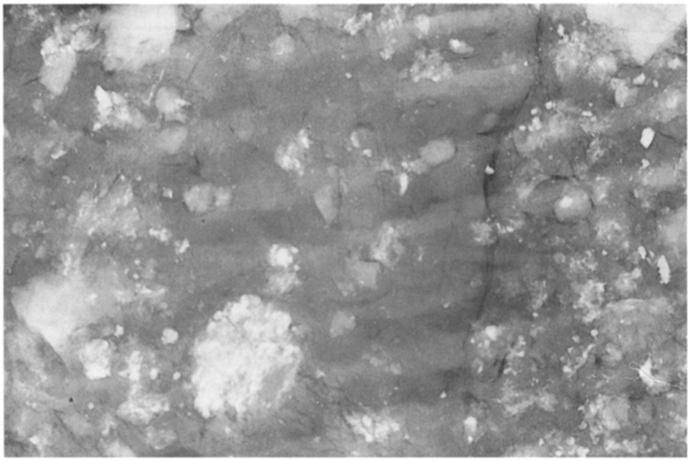


Figure 2. Radiograph of a coiled, paddle-and-anvil shaped early Late Woodland vessel (*c.* AD 650) from the Scioto Trails site, Ohio. Three coils are distinguishable by their different densities or rock temper particles (light spots) as a result of poor mixing of temper and clay. The two coils on the top are separated from the third below by an elongated void (dark), where they were imperfectly joined.

like other isochrestic variation, also have potential use in tracing migration patterns (Maslowski & Carr, 1990). Finally, some construction tasks which can be achieved in a great variety of ways, such as methods for attaching handles, legs, or spouts, can potentially be used to recognize the products of individual potters or small groups of potters and the distribution of their works (Foster, 1983: 214).

(2) In as much as archaeological classifications should reflect the spatial organization of past societies, data on formation techniques can be helpful in building relevant artifact typologies.

(3) Similarly, data on formation techniques can be used to build ceramic chronologies. For examples, Glanzman & Fleming (1985) found with xeroradiography that the details of coil morphology (thinness, height, edge shape) shifted through time in prehistoric vessels from Ban Chiang, Thailand.

(4) Understanding the techniques used to form a vessel may give insight into its relative durability and utility in various mechanical and thermal tasks. An example is the contrast in the eastern United States between Early Woodland slab-built vessels (Haag, 1940; Petersen & Hamilton, 1984) which were not used in hot fires (Ozker, 1982: 143) and some later Woodland, coiled and handled vessels which were probably suspended over flames (Braun, 1983). Relationships between vessel primary formation method and use have not yet been systematically investigated.

## Characterizing Temper Inclusions

Radiographs of a vessel's wall usually allow one to determine the volumetric density, size distribution, shape, material type, and general mineralogy of temper inclusions.

The material type or general mineralogy of temper inclusions can be inferred from their relative grey levels on a radiograph, supplemented with size and shape information. Temper materials with mean elemental atomic numbers and specific gravities greater than those of clay appear as less exposed, light spots on the film relative to the background clay's grey level. Igneous and metamorphic rocks are examples [Figure 3(a)]. Different igneous and metamorphic rocks exhibit a wide range of specific gravities and thus their images vary in their lightness relative to clays and each other. The broad classes of felsic, mafic, and opaque minerals, which differ substantially in their specific gravity (Carr & Riddick, 1990: table 2), can be distinguished in this way [Figure 3(a) versus (b)]. The potential for identifying more specific mineralogical classes is currently beng investigated (see below). In contrast to dense tempers, voids from weathered out limestone or shell or burned out organic tempers appear as more exposed, dark spots [Figure 3(c)]. Crushed pottery temper is inconsistently visible radiographically, even when using edge-enhancement xeroradiographic procedures (Adler, 1983; Foster, 1983: 216). This is so because clays vary little in their specific gravities. Foster (1983: 216) reports that if the clay used to make a vessel has not been vigorously wedged or slaked, detectable air pockets will occur on the sides of at least some the vessel's pottery temper particles. It is probable that cubic voids from crystalized salt water additives, which are sometimes used with shell or calcite tempering, are visible radiographically; they can be seen in petrographic section (Rye, 1977: 136).

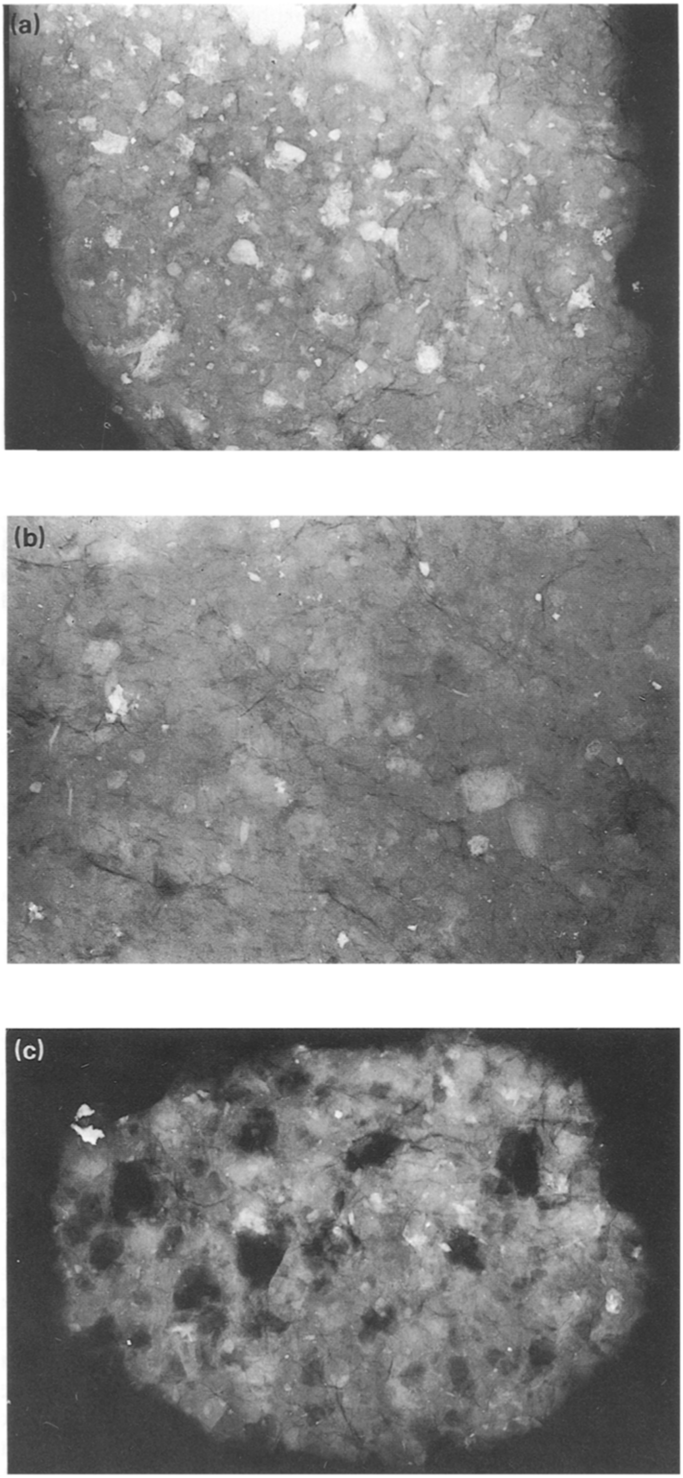
Using improved radiographic techniques which offer high contrast and resolution (Carr, 1990; Carr & Riddick, 1990), it is possible to observe and measure the size of natural and added rock particles down to silt size (0·0625 mm). Industrial films of type M or R, long exposures, and magnification up to 14 × using a back-lit zoom scope are required. Limits on the size of other types of materials and anomalies that can be observed have not been tested.

Information on the volumetric density, size distribution, and composition of temper particles within vessels can help archaeologists in many ways. These include the tasks of identifying sherds to their vessels of origin, evaluating vessel function, constructing ceramic chronologies, potentially documenting vessel exchange patterns, and evaluating museum reconstructions.

*Identifying individual vessels*

Perhaps most important, radiographed temper characteristics can often be used, along with visible features, to systematically identify sherds that belong to the same or different vessels. This capability becomes especially valuable in the common circumstance where an archaeological deposit has a mixture of sherds from multiple broken vessels which are not reconstructable and which otherwise could not be identified and counted.

Identifying sherds to their parent vessels is often feasible because in traditional technologies, different vessels made by the same potter for the same function can vary detectably in the amounts, size distributions, material types, and degree of clustering of their temper. In particular, in traditional technologies where standardized measuring containers are not used to proportion clay and temper, potters typically can control the amount of temper that they add to a clay within only about 5 to 10% by volume. A.E. Dittert (pers. comm.) has observed this through his examination of vessels made by 60+ potters during the early 1900s in the Southwest United States. Controlling temper volume is often done by feel and approximation during the kneading stage, by monitoring the workability of the clay (Rye, 1981: 39). Thus, different vessels made by the same potter over a short time span may be distinguished by their volumetric densities of temper. Likewise, the size distribution of tempering materials may vary significantly from vessel to vessel, especially if the temper is rocks, shells, or sherds. These need to be crushed to an appropriate size, which may be judged only by eye. Sizing is also accomplished with basket or net sieves (Rye, 1981: 37). These are only partially effective sorting agents, controlling only the upper limit on particle size, not the entire size distribution. Thus, temper size


(a)
(b)
(c)

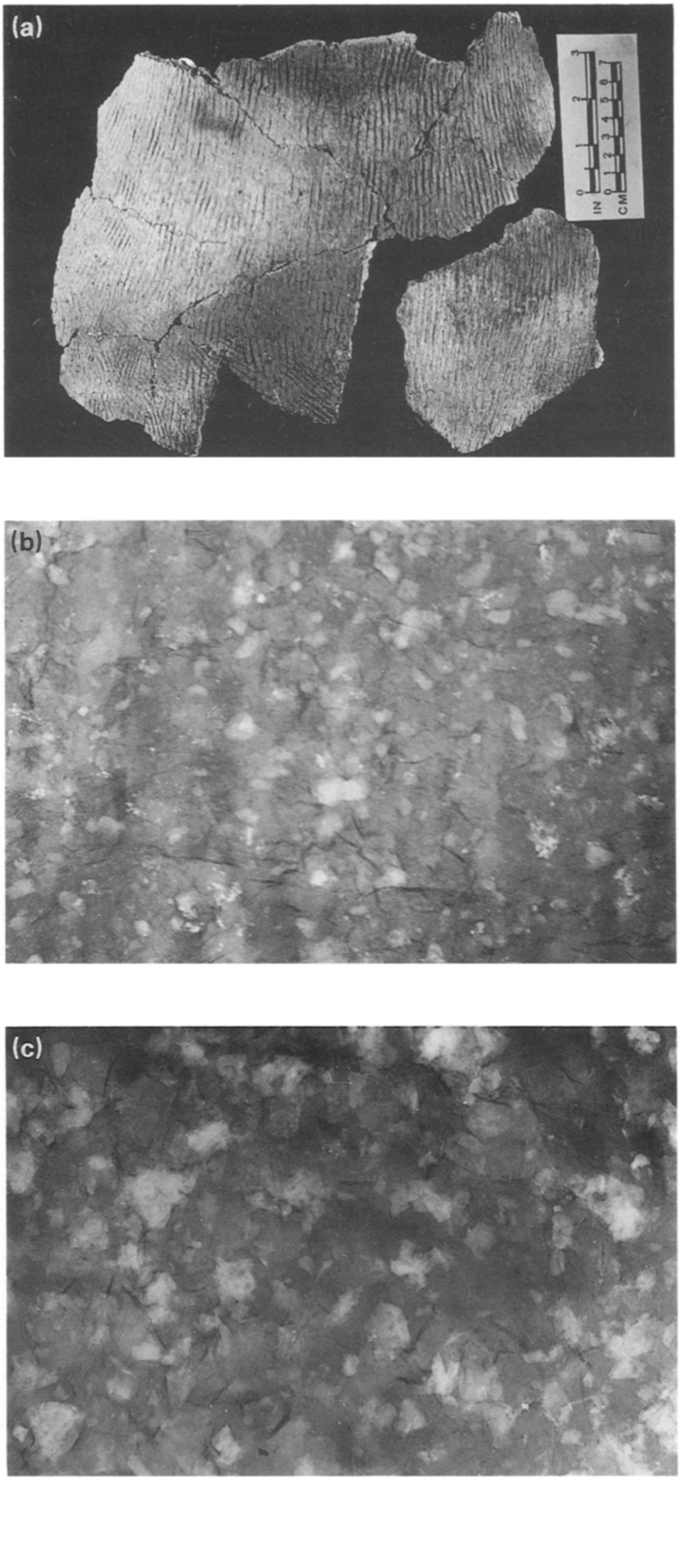
distributions can vary from clay batch to batch and among vessels. In addition, when the tempering material is heterogeneous, different clay batches and vessels may vary in the proportions of temper of different materials that they bear, by chance inclusion. Finally, vessels made of clay-temper mixtures that have been kneaded to different degrees may vary in how uniformly or clustered the temper particles are distributed within the paste. All of these differences are detectable radiographically. When combined with each other, as well as morphological, decorative, and other visible surficial information, and provenience data, they can be used to help sort sherds by their vessels of origin.

A good example of sorting individual vessels with radiography is the following case. Figure 4(a) shows a partially reconstructed Early Late Woodland vessel from southern Ohio. It is composed of a number of large sherds which were found within a few inches of each other and which were successfully fitted back together. Also shown is another sherd—very similar in colour, cord marking, thickness, and circumference—which was found in the same area. A number of archaeologists, including myself, were convinced that the two pieces belonged to the same vessel and tried to fit them together. When radiographed, however, the partial vessel and unjoined sherd differed significantly in the density, size, and mineralogy of their tempers [Figure 4(b), (c)].

I have used radiography and visual characteristics in this manner to sort 3000+ Woodland sherds in 85 archaeological proveniences from Ohio into analytically individual vessels. Rapid qualitative visual assessment of temper density, size, mineralogy, and clustering in the radiographs, rather than their quantitative study, was sufficient for sorting. On the basis of this routine work, as well as detailed studies of temper variation within whole vessels and tests with conjoinable sherds, the method showed itself to be reliable as well as efficient. Specific procedural strategies for sorting sherds by vessel are reported elsewhere (Carr, 1987, unpubl. data). Other researchers who have seen the potential of radiography for this purpose include Titterington (1935: 29, pl. 7), who documented similarities in the grit tempers of a few common cordmarked sherds in Illinois, and Rye (1977: 208), who mentions the possibility.

The method is not likely to be productive in cultural contexts where pottery is produced by at least part-time specialists and is fairly standardized, or where there is little or no functional diversification of pots, as in some early ceramic industries. In these situations, temper and other variation between vessels may be restricted and allow the grouping of sherds into only broad technological/stylistic classes rather than individual vessels. In my Ohio ceramic work, plainwares from the Early Woodland sometimes posed this difficulty. The method also falters when vessel appendages such as rims, lugs, handles, or feet are made with a paste that varies in its tempering characteristics from the paste of the body. This was the case for the rim sherds from some Ohio Middle and Late Woodland vessels that I studied. Some vessels had rims with significantly less and smaller temper particles than their bodies, possibly to allow the rims to be made thinner for aesthetic reasons. Finally, when the number of sherds per deposit rises above several hundred and the number of individual vessels rises to the point where some are fairly similar in most

Figure 3 (opposite page). Different tempering materials vary in their radiographic densities. (a), (b) The different kinds of minerals and rock fragments in two sherds differ in their subject contrast from the paste. The temper in sherd (a) is predominated by moderately contrasting k-spar altered to sericite. A few small, bright, heavy minerals (oxides, zircon) and several large, altered felsic polyminerals are scattered throughout the paste. The temper in sherd (b) is comprised largely of low contrast plagioclase or k-spar; with some low-contrast chlorite or other mica fibers; some low contrast, large quartz crystals, and a few small, bright, heavy minerals (oxides, zircon) scattered throughout the paste. (c) Voids left from weathered out limestone temper.


(a)
IN
CM
(b)
(c)

examined dimensions, sorting becomes difficult. The limits of qualitative assessment and the capacity of human memory in the pattern recognition process are approached. The largest collection of Ohio sherds that I was able to handle confidently had 352 sherds, for which 68 analytically individual vessels represented by more than one sherd were determined. Thus, the method is clearly infeasible manually in ceramic-rich archaeological contexts, such as some from towns and cities in state level societies, which may contain thousands or tens of thousands of sherds.

Under some conditions, it is possible for the archaeologist to segregate the sherds of individual vessels simply by visual inspection. However, when vessels are not decorated, or are decorated quite similarly, or as the number of vessels per deposit rises, this task becomes more arduous and inaccurate, and radiography is required. For example, in my studies of Ohio Woodland ceramics, I was surprised to find that I was unsuccessful at identifying sherds from single vessels using visual criteria, alone, more than 50% of the time. This was despite the careful attention that I gave to details of cord impression morphology and use marks as well as more standard descriptive variables such as sherd thickness, curvature, coloration, and temper.

When it is feasible, the capability to routinely and efficiently identify sherds to their vessels of origin marks a critical advance for those archaeological research designs that aim at fine-grained behavioural resolution. Specifically, it allows a shift in the *fundamental unit of analysis* from the sherd to the vessel in subsequent analytical studies. This is important because it is the vessel, rather than the sherd, that is the behaviourally relevant unit of analysis in most fine-grained archaeological studies and that must be used if analysis is to be fully relevant, accurate, and meaningful. The vessel is the technological and functional system that articulates with culture and the practice of making whole vessels is what is subject to physical and cultural selection (Braun, 1983). This argument pertains whether the ceramics are plain or decorated, ultilitarian or valuable wares.

Analysing vessels rather than sherds is preferable when reconstructing many kinds of past behaviours and conditions. (1) The occupation span of a community, the number of households in it, or its total population, are more accurately estimated when one considers the numbers of vessels that are used and deposited in it, vessel use-life, and the numbers of vessels in simultaneous use per household (Schiffer, 1975: 265–267, 1976: 58–61; Classen, 1977). Numbers or weights of sherds are less relevant unless they can be accurately tied to vessel counts. (2) Accurate estimates of frequencies of ceramic trade between communities and the mechanisms of exchange require the numbers and proportions of exotic vessels found at them (Earle & Ericson, 1977; Renfrew, 1984) rather than sherd counts. (3) The intensity of social interaction within a cultural network is estimated best when the numbers of vessels that have similar or dissimilar design elements or grammatical features are counted along with the number of elements or features (Washburn, 1983), rather then simply the number of sherds with those elements or features. Plog (1990) has recently lamented the theoretical advantage of analysing whole vessels over sherds when measuring social interaction, but the current impracticality of the former without

Figure 4 (opposite page). (a) Two large sections of an early Late Woodland vessel from the Scioto Trails site, Ohio. The sections have very similar cord markings, paste coloration and texture, circumference, thickness, and location within a midden, which initially suggested their belonging to one vessel. (b), (c) Radiographs clearly indicate the different temper particles sizes and densities in the two sections and their belonging to different vessels. The temper in sherd (b) is predominated by chlorite or sericite with some small plagioclase or k-spar crystals and scattered heavy minerals. The temper in sherd (c) is comprised of polymineral grains of mica, amphibole or pyroxene, and some plagioclase or k-spar. Small plagioclase blade-like crystals are also apparent.

methods for identifying individual vessels. (4) More accurate chronometric scales and seriations for dating archaeological proveniences can be developed when vessel-average technological parameters rather than sherd-average technological parameters—such as average wall thickness or average temper size or volumetric density (Braun, 1983; Carr, 1986)—are tracked over time. Similarly, vessel-average parameters are preferable when studying the response of vessel engineering to dietary and social evolution (Braun, 1986). In both cases, it is vessel mean parameters and their variances that are adjusted through time to other systemic conditions and that are best modeled for dating purposes and cultural systems analysis. (5) Reassembling sherds to their vessels of origin can be essential to documenting the broadest levels of design organization, such as symmetry structures and other grammatical forms (Washburn, 1983: 149). These stylistic traits are among the "nuances" of style that are the appropriate focus of studies of social interaction (Friedrich, 1970). (6) Similarly, vessel function can be reconstructed more accurately when sherds from a fair section of a vessel have been identified and joined and vessel morphology, volume, and technology can be described more fully (Hally, 1986; Smith, 1988). Such reconstructions are critical to subsistence, settlement, economic, and other studies. (7) The more accurate estimates of vessel volume that can be obtained with reconstructed vessels compared to sherds can also allow family sizes to be estimated. Turner & Lofgren (1966) did so by comparing the volumes of cooking jars to individual serving bowls over time.

In the first four applications, it is preferable to count or measure vessels rather than sherds because vessels of different kinds—be they vessels of different styles, communities of manufacture, technologies, time periods, or functions—need not break on the average into the same number of sherds and be deposited and excavated in equal proportions. This will consequently weight certain vessels and vessel categories more or less than they should be in any sample and analysis based on sherds. For example, exotic and locally-made pots of one function might nevertheless differ technologically in their durability and break systematically into greater or lesser numbers of sherds. Trade frequencies based on proportions of exotic sherds rather than proportions of exotic vessels would then be biased by this breakage differential.

Similarly, consider Braun's (1985) pioneering work in which a ceramic technological change—community-average vessel wall thickness—was modeled through time for west-central Illinois during the Middle and Late Woodland. Braun derived a time-series regression that predicts the date of a collection of contemporaneous sherds from their average wall thicknesses (see below). The precision of the date is estimated from the variances of the sherds' wall thicknesses. Means and variances for individual sherds, rather than vessels, were used. Multiple sherds from single vessels were eliminated when this was certainly the case, in order to avoid differential weighting by vessel. However, without information on sherd radiographic signatures, undoubtedly many redundant sherds were retained (D.P. Braun, pers. comm.). Thus, unknown in this research design is the degree to which some thinner walled vessels may have broken more frequently and may have each been represented by more sherds in a sample than some thicker walled vessels. On the other hand, thinner walled vessels may have broken more frequently into smaller sherds below the acceptable size threshold for the study and may have each been represented by fewer sherds in a sample. Consequently, the degree to which thinner and thicker-walled vessels are disproportionately and differentially represented and weighted in different portions of the time curve is unknown.

This source of error could distort both the shape of the time curve and estimates of regression precision in local portions of it and, thus, the predicted date of a collection of sherds. It is conceivable that these effects of a shifting pattern of vessel breakage are pertinent to Braun's regression, given the changes that occurred in Illinois ceramic technology. These include changes in wall strength as a function of temper material, density, and perhaps other manufacturing procedures. The possibility of this problem could have been minimized if vessels rather than sherds had stood as the units of analysis and data points along the time curve.

In the last three applications cited above, identifying sherds by parent vessel provides an advantage not in counting vessels but, rather, in making available a large enough area of a vessel to accurately estimate its various parameters. Vessel shape, circumference, and volume, temper volumetric density, temper size distribution, overall fracture and abrasion patterns, decorative symmetry patterns, and other morphological, technological, and stylistic parameters can usually be estimated with greater confidence when a larger vessel area is available—even if the area is comprised of sherds that cannot be conjoined. Radiographically matching sherds by vessel can provide this necessary area.

Determining vessel maximum circumference, as part of the task of estimating the volume of vessels with simple morphologies, is a prime example of this situation. A single sherd's radius of curvature will produce only an apparent vessel circumference if the vessel has other than a spherical shape (Braun, 1983; Smith, 1981). However, if multiple sherds have been identified as belonging to the same vessel, if they come from different sections of it, and if approximate vessel shape is known, a histogram of the sherds' radii of curvature can be used to estimate vessel maximum circumference and volume more accurately. This is done be comparing the empirical histogram to a suite of model histograms produced for model vessels of different circumferences and the given shape. In addition, the method of Smith (1983) or Ericson & de Atley (1976) for estimating vessel morphology and capacity can be used more productively when multiple sherds have been matched to their parent vessels.

The temper volumetric density of a vessel can also be estimated more accurately when assessed over the broader areas provided by radiographically matched sherds. Temper particles can have a clustered rather than random distribution within the paste of a vessel as a result of poor kneading. Temper volumetric density can vary from coil to coil (Figure 2), slab to slab, or pulled/pinched section to section. In coarse-tempered coiled vessels, clustering can also result from the rolling out of their coils. Coarse particles are driven to the centres of coils. These conditions require a large sherd of several coil widths or slabs in size, which might not be available, to accurately estimate the average temper density for a vessel. However, several smaller sherds, found radiographically to belong to the vessel, might be combined to provide the necessary area.

Temper clustering was found to be a problem in this way for the more sparsely tempered Late Woodland coiled ceramic assemblages from Ohio that I examined. Dimensional analysis of temper volumetric density revealed that stable estimates of this parameter, assessed by point counting methods with a 0·5 mm grid using radiographs, could not be obtained on the average with an area less than 20 $cm^2$. This is larger than most excavated Ohio Late Woodland sherds. A much larger area for assessing volumetric density would have been required had petrographic methods, which examine essentially a plane rather than a volume, been used.

The broader vessel coverage provided by radiographic matching of sherds can also be essential when analysing certain indicators of vessel production, use, failure, and burial that are rare and polythetically distributed among sherds. Colour patterns from initial firing, spalling and delamination from thermal stress, carbonized food residues on the exterior shoulders or interior base of a vessel, use-wear patterns on the sides or bases of vessels, attachments such as handles or legs, base or rim shape, and indicators of vessel kill and cremation are examples. Linking common, ambiguous body sherds that lack such diagnostics to rarer sherds that have them can help one to assess the frequency of certain analytical classes of vessels and the nature of the collection as a whole.

In some studies, sherds are the relevant units of analysis. Certain studies of formation of the archaeological record, vessel function, or vessels' roles in tool kits, which focus on vessel break down and/or spatial scatter, are examples (Villa, 1982; Lindauer, 1988; Mills *et al.*, 1988; Sullivan, 1988). Even in these cases, however, information on sherd "joins" and their spatial distribution, as determined radiographically, can be helpful.

*Evaluating vessel function*

Documenting the size distribution and volumetric density of temper particles within vessels can also be used to assess vessel function (Rye, 1977; Steponaitis, 1982; Braun, 1983) and to segregate vessels or morphologically ambiguous sherds into functional classes. Temper size and density can be used for this purpose because potters often adjust these parameters to adapt vessels to performance or aesthetic requirements. For example, all else equal, a cooking pot can be expected to have lower volumetric densities of temper particles and/or smaller temper particles than a mobile storage vessel when the tempering material has a thermal expansion coefficient much greater than clay (e.g. quartz) and when the cooking pot is subjected to rigorous and cyclical heating and cooling. The lower density and smaller size of particles in a cooking pot help to decrease wall thermal shock whereas the greater density and larger size of particles in a storage vessel help to reduce mechanical breakage (Braun, 1982, 1983, 1987; Bronitsky, 1986; Carr, 1985*b*). On the other hand, when the tempering material has a thermal expansion coefficient similar to clay and a greater thermal conductivity (e.g. some igneous and metamorphic rocks), more and larger particles are useful in a cooking vessel to help reduce thermal gradients in its wall and thermal shock. There may be little or no difference between cooking and storage vessels in the size and density of their temper particles (Carr, 1985*b*). Additional factors that affect decisions about the quantity and size of temper particles in vessels include the desired clay drying time, ease of manufacture, heating and/or cooling efficiency as opposed to shock resistance, and susceptibility to surface abrasion (M. B. Schiffer & J. M. Skibo, unpubl. data). Finally, fine, thin serving wares may have little temper to enhance their surface appearance.

Examples of the operation of these factors can be found in ceramics from the Midwest (Braun, 1982, 1983; Carr, 1985*b*), Southeast (Steponaitis, 1982), and Southwest (J. Stoltman, unpubl. data) United States. For example, Stoltman has documented, with a sample of about 70 thin sections, that Mimbres potters systematically manufactured jars and bowls in different ways. Jars were made on the average with 5 to 10% more grit temper by volume and slightly coarser temper than bowls. Granite was used to temper most jars whereas finer-grained igneous rocks were used almost exclusively for bowls. These differences would be detectable and quantifiable radiographically.

*Constructing ceramic chronologies*

Quantified radiographic descriptions of the size and volumetric density of temper particles within vessels and the shifts in these parameters through time can be used to construct regional chronological frameworks. In particular, it is possible to build a time series regression model that predicts the absolute date of a collection of undated, contemporaneous vessels from their temper characteristics when these shift systematically and at a sufficient rate through time. Vessels with known carbon-14 dates and radiographed temper characteristics are used to build the model and it is applied to undated but radiographed specimens.

Braun (1982; Hargrave & Braun, 1981) began to use this approach to date Illinois Middle and early Late Woodland cooking pots, taking advantage of decreases in the volumetric densities of temper particles over time. Large-scale data collection and model refinement was not pursued, however, for lack of radiographic methods that would provide the clear and high-contrast temper particle images that are necessary to count particles. Braun's chronometric modeling has remained focused on reductions in wall thickness, which associate with the changes in temper density (Braun, 1985). Luedke (1986) continued this line of research for Massachusetts ceramics, but again was limited by the inability to assess the actual volumetric density or size distribution of temper particles. She measured the relative frequency of only surficially visible temper particles of broad size classes (< 1 mm, 1–3 mm, > 3 mm).

In contrast, the improved ceramic radiographic methods that I have applied (Carr, 1990; Carr & Riddick, 1990) are allowing me to study temporal shifts in both the volumetric density, average size, and size distribution of temper particles greater than silt size for Ohio Woodland cooking vessels, in addition to shifts in wall thickness. Tracking several correlated variables such as these makes it possible to construct a multivariate as opposed to simple bivariate regression model, which can opportunize on the correlations among variables and potentially increase the precision of predicted dates. Similarly, D. Snyder (unpubl. data) has tracked and statistically modelled through time the volumetric density and mean particle size of various tempering materials (volcanic sand, coralline sand, iron oxides), along with sherd thickness, for Micronesian pottery. Separate bivariate regression models were built for each predictor variable. Although Snyder used optimal medical films, he encumbered some difficulties in recognizing particles of different materials and identifying all particles because he used high kilovoltages which reduce image contrast.

Modeling shifts in temper characteristics through time is essentially a descriptive pursuit. However, it can shed great light on cultural and ecosystemic evolutionary processes when these affect the demands that are placed on vessels during their use. This potential has been explored by Braun (1987), though using the parameter of vessel wall thickness rather than temper volume or size. Braun decomposed the time series of average vessel wall thicknesses that he built into several overlapping episodes of selection for thicker or thinner walled vessels. These were modelled mathematically as logistic components. They were interpreted to represent the adjustment of known ceramic technological procedures or the invention and spread of new ones which accommodated changing vessel use. These ceramic changes, in turn, were correlated by Braun with several potentially determining ecological factors, including changes in diet and culinary practices that were tied to population trends; changes in diet and culinary practices that were tied to climatic shifts; decreases in residential mobility and constraints on vessel size; perhaps changes in group size and cooked meal volume; and a technological innovation which allowed thinner, more durable vessel walls. Thus, time series models of ceramic technological parameters, including radiographically determined temper characteristics, appear to have potential for tracking cultural and ecological process.

*Documenting vessel exchange patterns*

Radiography can be used with standard petrographic methods (e.g. Porter, 1963; Shepard, 1956; Rose & Fournier, 1981; Williams, 1983) to help efficiently document the mineralogy of vessels, identify vessels made with nonlocal tempers, infer trade vessels, and to reconstruct vessel exchange networks. An X-radiograph records a number of the criteria by which minerals are identified petrographically. These include the particle's angularity or rounding, the equivalency of its dimensions, and the number and angle of planes of crystal cleavage for euhedral crystals. A particle's radiographic grey-level relative to that of the background clay provides information on its average specific gravity, which compensates to some degree for a lack of information on particle opaqueness and colour, birefringence, spatial patterning in birefringence, and other optical properties studied petrographically. Radiographic grey-level is equivalent to the image grey level used in back-scattered electron microscopy work for identifying minerals (Hall & Lloyd, 1981; Pye & Krinsley, 1984), which has been used in an archaeological study of exchange (Burton & Krinsley, 1987). However, the range of radiographic grey levels is more restricted and the mineralogically significant distinctions in grey level that can be made are fewer and coarser.

Radiography allows the consistent identification of only certain broad classes of minerals when grey level and particle morphology are assessed qualitatively. Felsic, mafic, and opaque minerals are easily identified. Within these classes, it is possible to distinguish, for example, quartz versus orthoclase and plagioclase versus sericitic alterations of plagioclase; micas versus pyroxene; green hornblendes versus pyroxene; and oxides versus hematite versus zircon. It does not appear possible to qualitatively discriminate orthoclase from plagioclase; green hornblendes, micas, chlorite, and epidote; and oxides such as ilmenite, magnetite, and spinel. Ambiguity arises because different minerals may have similar shapes and overlap in the range of their specific gravities and grey levels. Also, variation in particle thickness and the thickness of the paste in which the temper is embedded leads to overlapping ranges of grey levels for different minerals. This assessment of the capabilities and limitations of radiography is based on a series of blind tests in which a petrographer attempted to identify the mineralogy of temper particles in a mineralogically diverse sample of Ohio Woodland ceramics from their radiographic images. More definitive tests are now in progress.

D. Snyder (unpubl. data) found similar potentials and limitations for using radiography to discriminate five kinds of temper in Micronesian ceramics and test tiles: crushed sherd, quartz sand, coralline sand, crushed shell, and iron oxides. Particles of all four classes could be discriminated with some degree of success by their image grey level and shape. However, crushed sherd and quartz particles differed little in grey level from the clay matrix and were often difficult to impossible to locate. Moreover, particle overlap and variations in particle size and sherd matrix thickness hindered the identification of particle composition by grey level. To some extent, these problems were a function of the high kilovoltages (70–110 kVp) and moderate-grained medical film (Kodak XTL) that Snyder used to take the radiographs. These techniques certainly reduced image contrast and resolution well below what might have been obtained with optimal techniques (20–50 kVp, Kodak Industrex M or R film).

Under these restrictions, it currently appears that radiography is best used as a complement rather than alternative to petrography. Radiography can be used to broadly survey the approximate mineralogical variation within a very large collection of sherds. On the basis of this information, statistical sampling strata can be devised and samples within strata can be chosen for finer-grained petrographic analysis. Some inferences about the mineralogy of the larger collection of sherds, especially as to their common minerals and the overall petrology of their temper, can then be drawn from the petrographically analysed sample. This approach has worked well in my radiographic and petrographic studies of Ohio Woodland ceramics.

This research design has the advantage of allowing a much larger number of sherds to be investigated than would be the case if petrography were used alone. The cost of preparing a petrographic thin section (*c.* \$10.) is much greater than that of taking a radiograph (*c.* 13¢ per sherd). Obtaining large enough samples to make statistically meaningful statements about temper mineralogical variation is one of the primary limitations of the petrographic method. Both Shepard (1956: 166) and Plog (1990) have emphasized the need for large sample sizes when studying vessel exchange.

Beyond the analysis of temper particles, radiography has the potential to be used in a manner analogous to petrography (Freestone *et al.*, 1982; Middleton *et al.*, 1985; Stoltman, 1988, unpubl. data) to characterize the texture of the paste of ceramics in

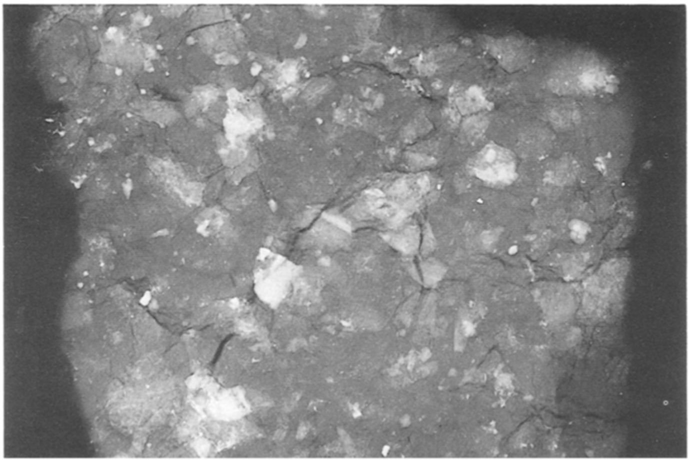


Figure 5. Microcracks in the wall of a vessel from the McGraw site, Ohio. Cracks originate from large quartz or other felsic polymineral grains with thermal expansion coefficients greater than that of clay. This indicates their development more probably from thermal than mechanical stresses.

an effort to detect trade vessels. Standard point counting procedures (Chayes, 1956) can be used to measure texture. However, given restrictions on the resolution and contrast provided by most radiographic films, clays and most silts cannot be consistently discriminated and must be classified together, to be compared with sands and coarser particles of various size classes. Discrimination of fine and coarse silts is possible using Kodak Industrex R type film, which is designed for great magnification. However, long exposure times are required, which may not be practical for routine studies when sherds number are in the thousands.

Radiographic textural analysis becomes especially useful when natural particle inclusions of sand size or larger can be distinguished from added tempers by their size distribution, degree of rounding, and/or broad mineralogical differences. For example, when sandy sedimentary clays have been used as the paste and coarser temper is added, a bimodal particle size distribution can occur, with the lower mode indicating the natural, finer sands and the upper representing the added temper (Rye, 1981: 52). Under such circumstances, the potential arises for isolating the texture of the natural paste and using it to discriminate vessels made of pastes from different sources. Foster (1983: 216) has briefly mentioned her use of xeroradiography and a scanning microdensitometer to characterize the texture of ceramic pastes. I have noticed different bimodal particle distributions which could reflect natural paste variation or variation in tempering methods in Early Woodland vessels from different drainages in Ohio.

*Evaluating museum reconstructions of vessels*

In museum application, radiographically determined temper characteristics can be used to assess whether vessels have been reconstructed properly. For example, Meyer (1978) showed that a reconstructed bowl was composed of unrelated sherds. This use of radiography is fairly common.

**Documenting Fracture Patterns**

Radiography can be used in archaeological studies to reveal microcracks in ceramic vessels (Figure 5), just as it is in industrial nondestructive testing applications. To the

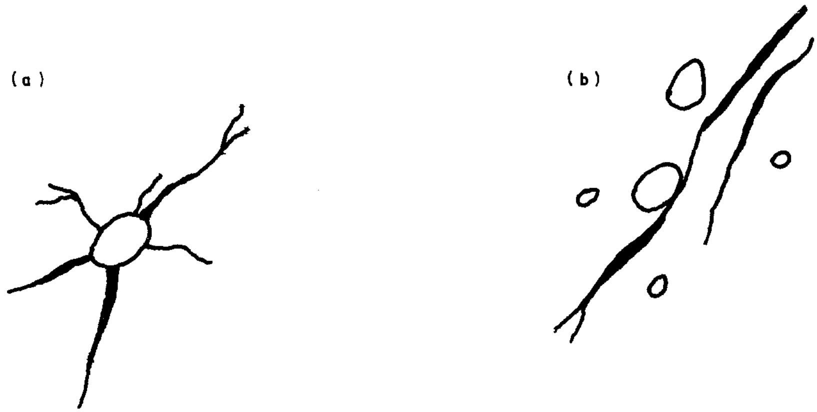



Figure 6. (a) Microcracks that radiate from mineral particle inclusions having thermal expansion coefficients greater than those of clays can indicate thermal stresses. (b) In contrast, microcracks that pass around mineral inclusions or that do not associate with them can indicate mechanical stresses.

extent that different cracking patterns are produced by different kinds of stresses, their detection may have some relevance to archaeological analyses of vessel production, use, and post-depositional disturbance processes (Figure 6). Specifically, it is clear that when thermal stresses build around rock particle inclusions with thermal expansion coefficients greater than those of clays, microcracks are produced which radiate from the inclusions. Firing (Rye, 1981: 107), cooking, or the cremation of a vessel are examples of processes that produce such stresses. In contrast, mechanical stresses are often indicated by cracks that pass around mineral inclusions or do not associate with them. Some examples of factors that produce these stresses include differential clay shrinkage during vessel drying, blows to a vessel during its use, and post-depositional deformation by soil perturbations that arise from physical or biological agents such as freeze-thaw cycles, soil wetting-drying cycles, or rootlet growth. Documenting fracture patterns and frequencies has potential for identifying and assessing these processes.

However, the degree of accuracy with which a morphological typology of ceramic fractures indicates thermal versus mechanical causes of failure has not been tested. Also, quantified studies of fracture lengths, areal densities, and branching patterns and their correlation with various kinds of stresses have yet to be made. These relationships are worthy of investigation, given current archaeological ceramic research on the compromises that potters strike between manufacturing constraints, thermal durability and efficiency, and mechanical durability, and on identifying vessel functions (Braun, 1982; Steponaitis, 1982; Carr, 1985*b*).

For these kinds of tests and more routine documentation of ceramic fracture, there are clear advantages to using radiography in conjunction with physical testing and observation, rather than physical testing and observation, alone. First, experimental destruction of archaeological samples can be minimized and larger samples can consequently be studied. Second, radiographic rather than physical assessments of vessel durability can be more relevant when post-depositional cracking has occurred (Steponaitis, 1982: 38–39) and can be evaluated radiographically.

### Defining Internal Vessel Morphology and Passages

Radiography has long been used by museum conservators and art historians to document and measure the internal morphology and thickness of walls of ceramic vessels and hidden structures within them (Gilardoni *et al.*, 1977). This application has become more attractive with the development of xeroradiography. Xeroradiographic plates define internal wall edges more sharply than normal radiographic emulsions through "edge enhancement," to the point where caliper measurements can be made with precision (Alexander & Johnston, 1982: 149). A critique of the ceramic analytic roles to which xeroradiography is best suited is given elsewhere (Carr, unpubl. data).

The benefits of xeroradiography to ceramic studies were first called to the attention of archaeologists by Heinemann (1976: 110), who examined hidden clay balls in the legs of a Mayan tripod pot and the repair work on a Tlatilco figurine. Alexander & Johnston (1982) used the method to investigate the internal structure of double-chambered pots with hidden tubes. Foster (1983: figures 5–6) examined the internal morphology of join holes in figurines to determine whether the holes were made with a solid or hollow punch or carved with a blade when the clay was leather-hard.

## Conclusion

It is clear that radiography can play standard roles in archaeological research on ceramics that these are fundamental to both description and inference. A few of these roles have been exploited routinely. However, most have been realized only sporadically, examined experimentally, or suggested for their potential here. These possibilities have now been made more feasible with the development of new high contrast, high resolution ceramic radiographic methods and, hopefully, they will be taken advantage of more frequently. Perhaps most basically, radiographic methods provide a low-cost means for investigating ceramics, thereby enabling large samples to be studied and relevant, vessel-based units of observation to be used. Both are essential to the fine-grained, behavioural and ecological studies that characterize American archaeology at this time.

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