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IDENTIFYING INDIVIDUAL VESSELS WITH X-RADIOGRAPHY

Christopher Carr

The individual vessel, rather than the sherd, is the relevant unit of analysis in many kinds of behavioral studies. Economical methods for assigning the sherds of multiple vessels to their vessels of origin are introduced for household-made ceramics. The methods employ visible surface indicators of vessel individuality as well as radiographically detectable ones such as temper quantity, size distribution, spatial distribution, and material type, void spaces, and fracture systems. A hierarchical, sequential sorting strategy and certain radiographic methods, which are optimal for revealing the internal features of ceramics, make this application possible.

La vasija individual, en vez de los pedazos de vasija, es la unidad de análisis pertinente en muchas clases de estudios de conducta humana. En este trabajo, se introducen métodos económicos para designar los pedazos de vasijas múltiples a sus vasijas de origen en cuanto se refiere a la cerámica fabricada domésticamente. Los métodos utilizan indicadores visibles de superficie de la individualidad de las vasijas así como indicadores detactables radiográficamente como cantidad de degrasante, distribución de tamaño, distribución espacial, y tipo de material, espacios vacíos, y sistemas de fractura. Una estrategia jerárquica y secuencial de clasificación y ciertos métodos radiográficos, los cuales son óptimos para revelar los rasgos internos de la cerámica, hacen posible esta aplicación.

Archaeologists use ceramics to reconstruct many kinds of past behaviors and ideas. Community occupation span, household size, culinary and other processing activities, subsistence change, mobility patterns, the frequency of trade and social interaction between communities, community social

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organization, population movements, and worldview each have been assessed through ceramic analysis (e.g., Arnold 1985; Braithwaite 1982; Braun 1987; Braun and Plog 1982; Hally 1986; Hill 1970; Hodder 1982; Plog 1980; Rice 1984; Schiffer 1975; Steponaitis 1982; Turner and Lofgren 1966; van der Leeuw and Pritchard 1984). In most cases, the sherd rather than the vessel is taken as the unit of analysis. Usually sherds are described, typed in some way, and counted or weighed. Behavioral inferences are derived from these data and contextual information. This analytical tradition has developed largely as a matter of practicality, reflecting both the availability of sherds for direct observation and the inability to easily sort sherds by their vessels of origin. Only occasionally are minimum numbers of vessels within a ceramic collection estimated from total sherd weights or counts, or through tedious reconstruction.

This report has two purposes. First, it reemphasizes, in contrast to current practice, that many kinds of ceramic studies can be made more relevant to past behavior and more accurate when the vessel rather than the sherd is taken as the unit of analysis. There are obvious descriptive advantages to working with whole or partially reconstructible vessels. However, there are also more subtle analytical problems that can be overcome when one knows the number of vessels that are represented in a collection of sherds and which sherds derive from which parent vessels, regardless of sherd conjoinability. These problems are clarified and addressed here. Second, to help archaeologists achieve the vessel as a unit of analysis, this article introduces simple x-radiographic procedures that usually allow sherds to be sorted by vessel for household-made ceramics. The methods are adapted from standard and new industrial and medical radiographic procedures. Both goals of this article result from insights obtained while working with 500+ experimental radiographs of 3,500 sherds, vessel sections, and/or whole vessels from 24 Ohio Woodland and Fort Ancient period sites.

THE INDIVIDUAL VESSEL AS THE UNIT OF ANALYSIS

Behaviorally relevant, accurate, and meaningful studies require that analytic units and procedures be "logically concordant" with both higher-level theoretical constructs and the empirical phenomena under investigation (Carr, ed. 1985). In many kinds of studies of archaeological ceramics, analytic concordance is encouraged when the vessel rather than the sherd is taken as the unit of analysis (Carr 1987).

This position can be argued in at least three ways. First, from a theoretical viewpoint, it is the whole vessel, not the sherd, that is the technological, functioning system that interfaces the material world, people, and culture and that is subject to physical and cultural selection. Braun (1983) has made this point with many supporting bridging arguments.

Second, from an analytical viewpoint, vessels can provide more accurate measures of some kinds of past behaviors than sherds can. This follows from the potential for systematic, differential breakage of ceramics of different analytical classes. Vessels that differ in their technology, function, style, locations of manufacture, and/or time periods need not break on the average into similar numbers of sherds. As a consequence, when sherd counts are analyzed, certain vessels and vessel categories may be unequally weighted analytically and skewed estimates of past behavioral phenomena may be derived, without the researcher knowing it. For example, exotic and locally made vessels of one function might differ systematically in their durability and tend to break into different numbers of sherds. Trade frequencies estimated by proportions of exotic to local sherds rather than vessels would be biased by this breakage pattern.

Estimates of other behavioral parameters can also be affected by differential breakage and assessing sherd rather than vessel counts. These include: (1) the intensity of interaction between social units, as measured by the relative frequency of sherds that share similar design elements or grammatical features (Plog 1980; Washburn 1983); (2–4) the occupation span, household number, and the total population of a community, based on the frequency or weight of deposited sherds, vessel use life, the number of sherds into which an average vessel breaks, and the number of vessels in simultaneous use per household (Claassen 1977; Schiffer 1975:265–267); and (5) technological or stylistic time series used as chronometric scales for dating archaeological proveniences (Braun 1985) or as measures of dietary and social evolution (Braun 1987).

Table 1. Degree of Vessel Breakage as a Function of Vessel Thickness: Sherd Size Vs. Sherd Thickness.

Statistic	<1.8-cm Diameter		1.8–2.1-cm Diameter		2.2–2.5-cm Diameter		>2.5-cm Diameter
Mean thickness (mm)	5.70	<	6.39	<	6.54	<	7.11
Standard deviation of thickness	1.41		1.87		1.83		1.58
Sample size	118		54		38		38

Note: Sherds are a random sample from a midden within an early Late Woodland village, Scioto Trails, Square 3L3, Feature 5, accession no. A4804/866, Ohio Historical Center, Columbus.

The case of chronometric scales illustrates the subtlety of the problems that can arise when analyzing sherds rather than vessels. Braun (1985) constructed a time-series regression model that relates the average thicknesses of sets of sherds from individual archaeological deposits to the dates of those deposits for a circumscribed region of Illinois during the Woodland period. The model can be used to establish the approximate date of a collection of undated sherds from their average thickness. When building the model, the average thickness of *sherds* from a deposit were assumed, for practical limitations, to be an unbiased estimate of the average wall thickness of *vessels*. However, this assumption is probably not true. It is almost certain that thinner-walled vessels broke more frequently and into more and smaller pieces and were more commonly represented and counted than thicker-walled vessels in Braun's samples of deposits. This sample bias is likely because thicker- and thinner-walled vessels were used for a similar range of tasks and subjected to similar functional and postdepositional stresses (Braun 1983), yet differed in wall strength. The likelihood of the bias is exemplified in a simple study of the relation of sherd thickness to sherd size for Ohio Woodland ceramics of a technology comparable to the Illinois Woodland ceramics (Table 1). Moreover, not known for Braun's model are the various degrees to which thinner-walled vessels are disproportionately represented and differentially weighted in various portions of the time curve. Such unsystematic sampling bias would affect the shape and variability of the time curve and, thus, bias its estimates of the dates and the precision of dates of collections of undated sherds to various degrees. This problem could have been minimized had Braun been able to sort sherds within deposits to their parent vessels and build and apply his model with sherd samples representative of vessel thicknesses.

A third, operational reason for identifying sherds to their parent vessels and using the vessel as the unit of analysis is that this allows a more accurate estimation of many ceramic morphological, technological, functional, stylistic, and materials-compositional parameters. The area provided by individual sherds may be too small to estimate such parameters with confidence.

For example, consider the shape, maximum circumference, and volume of vessels. When sherds are small and their specific position and orientation on a vessel is unknown, and when the vessel is not spherical, the radius of curvature of a single body sherd provides an inaccurate estimate of the maximum circumference of the vessel (Braun 1983; Smith 1981). However, if multiple sherds have been shown to belong to the same vessel, if they come from dispersed parts of the vessel's body, and if approximate vessel shape is known, more accurate estimates of the vessel's maximum circumference and volume can be found. This is true even if the sherds do not conjoin and form a reconstructible section. The estimates can be made by comparing the histogram of the sherds' radii of curvature to a set of model histograms of radii of curvature for model vessels of various circumferences and the given shape. The estimates can also be made using the method of Ericson and De Atley (1976). In turn, accurate estimates of vessel shape and volume are essential for reconstructing vessel functions (Hally 1986; Smith 1983, 1988) and estimating household sizes (Turner and Lofgren 1966), upon which in turn subsistence, settlement, economic, and other studies may rely.

Hagstrum and Hildebrand's (1990) method for estimating vessel shape, circumference, and volume is likewise enhanced when sherds from individual vessels can be recognized and broad areas from each vessel become available for estimation. The method was designed initially for application to

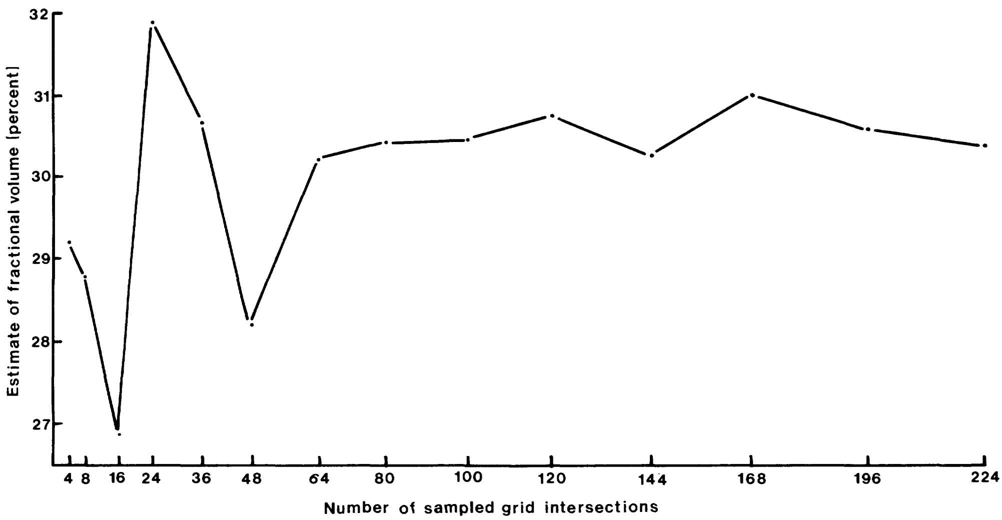

Figure 1. The point-count estimate of temper particle fractional volume for an Ohio early Late Woodland vessel stabilizes as the number of sampled grid intersections and area increases. The grid interval is .5 cm, just larger than the diameter of the vessel's largest common particle, and the grid size for which stability is found is about 80 grid intersections, or 4 x 5 cm.

collections of sherds from multiple vessels, but estimates can be improved significantly when the sherds of individual vessels are analyzed separately (compare Hagstrum and Hildebrand 1990: Figures 3–6 vs. Figure 8).

Similarly, the broadest levels of ceramic design organization, such as symmetry patterns and grammatical relations, become documentable when multiple sherds from single vessels are identified (Washburn 1983:149), be they conjoinable or not. These aspects of design, rather than smaller motifs which can be identifiable on single sherds, are among the "nuances" of style that are often the appropriate measures of social interaction (Friedrich 1970).

Other parameters that can be estimated better with the broader areas of multiple sherds include abrasion and residue patterns and many technological features that can be determined radiographically and/or petrographically. These features include temper-to-paste fractional volume, temper size distribution, the mineralogical families of temper particles, fracture patterns, and certain indicators of vessel-manufacturing procedures (Carr 1986, 1989a, 1990; Carr and Komorowski 1991, 1992; Carr and Riddick 1990). For example, temper particles can be distributed within a vessel in clusters, or vary in their average fractional volume from coil to coil, slab to slab, or built section to built section, possibly due to poor kneading. As a result, a piece of vessel spanning several coils or slabs, or multiple unconjoined sherds that have been identified to one vessel, may be required to accurately estimate the vessel's average temper fractional volume.

Radiographic studies of Ohio Woodland vessels (Carr 1985, 1989a, 1989b) illustrate this circumstance. Radiographs reveal that clustered temper distributions and coil-to-coil differences in temper fractional volume were common in utilitarian wares from the Middle Woodland period, onward. Figure 1 illustrates how such temper clustering can cause inaccurate estimation of the average temper fractional volume of a vessel when the estimate is based on the temper fractional volume of a sherd. A series of estimates of average temper fractional volume were made for a typical, early Late Woodland vessel over a series of concentric areas of increasing size. Standard point counting methods (Chayes 1956) were used. The vessel's temper particles were subangular in shape and clustered in distribution. The data show that a radiographic area of about 20 sq cm is necessary to obtain a stable estimate of average temper fractional volume with ±2 percent accuracy for this vessel. This area is about double the size of most Ohio Middle Woodland sherds in extant collections. To accurately estimate vessel average temper fractional volume with petrographic thin sections, a sample area several times larger would have been required, given the single-plane, low-volume coverage of a thin section compared to a radiograph. A very large area also would have been necessary to partition a radiographic or petrographic estimate of average temper fractional volume into stable estimates of the fractional volumes of particles of different mineralogical families or size classes.

Identifying multiple sherds as constituents of a parent vessel can also ensure the adequate and representative sampling of a vessel for bulk or clay-extract (Elam et al. 1992) compositional analyses by X-ray diffraction, X-ray fluorescence, atomic absorption, neutron activation, proton-induced X-ray emission analysis, inductively coupled plasma emission spectroscopy, etc. Although these methods require only minute samples of ca. 2 mg to 2 g (Rice 1987:374–375), each of them can estimate a vessel's average composition better from an areally diversified sample.

Similarly, accelerator-mass-spectrometry (AMS) radiocarbon dating of food residues on cooking vessels (Haas et al. 1988; Lovis 1990) can require samples that span multiple sherds of a vessel. Of the 30+ cases of Ohio Woodland ceramics with carbonized food residues in sufficient mass for AMS dating that I found in museum collections (Carr 1985:Table 2), all but three involved vessel areas spanning two or more average Woodland sherd areas.

In sum, for theoretical, analytical, and operational reasons it can be important to identify sherds that belong to the same vessel and to use the vessel rather than the sherd as the unit of analysis. It is true that there are certain kinds of studies in which the sherd is the more appropriate unit. Most common are studies that focus on vessel breakdown, the spatial scattering of vessel parts, and/or refitting patterns in order to reconstruct archaeological formation processes, vessel function, or the role of vessels in tool kits (Lindauer 1988; Mills et al. 1988; Sullivan 1988; Villa 1982). However, even in these instances, it is helpful or essential to recognize sherds that have the same parent vessel.

THE DIFFICULTY OF USING THE INDIVIDUAL VESSEL AS A UNIT OF ANALYSIS

Archaeologists are often prevented from using the vessel as the unit of ceramic analysis, despite its benefits, because the archaeological record is dominated by deposits that contain mixtures of sherds from multiple vessels. This situation arises commonly because, in the broad outlines of human prehistory, the origins and spread of ceramic technologies correlate with increasing sedentism. The latter, in turn, correlates with increasing regional and community population and the development of extensive secondary rather than primary trash deposits (Schiffer 1972).

Under some conditions, the archaeologist can segregate sherds from individual vessels within a deposit of multiple vessels by their surface visual features, alone. Rye (1981) and Rice (1987) review a broad array of attributes that can be used for this purpose. However, when vessels are not decorated, or are decorated similarly, or as the number of vessels per deposit rises, the task quickly becomes empirically impossible or economically impractical. In these more typical circumstances, it is often possible to turn to the techniques of industrial and medical x-radiography to help segregate sherds by vessel.

THE POSSIBILITY OF USING THE INDIVIDUAL VESSEL AS A UNIT OF ANALYSIS

X-radiography can be used to document several kinds of internal features of household-made ceramics that may vary significantly among vessels, even when they are made by the same potter for the same function and used similarly. These parameters are: the average fractional volume of tempering inclusions, their size distribution, their material types, the frequency of large void spaces, the degree of temper particle clustering, and/or the kind and degree of vessel fracturing. Often, differences in these traits among vessels can be combined with variation in form, decoration, and other surficial features in order to distinguish sherds from different parent vessels. Let us consider how each of these internal traits can come to vary between vessels.

Temper Fractional Volume

In traditional technologies where a standardized container is not used to measure the proportion of clay and temper for preparing the paste, potters control the amounts of temper that they add to a clay only approximately. A. E. Dittert (personal communication 1989) petrographically observed a 5–10 percent variation in temper fractional volume for vessels made by individual potters in the southwestern United States during the early 1900s (N = 60+ potters). Rye (1981:39) concluded from ethnographic work in several areas that temper fractional volume is often controlled only approximately by monitoring the workability and "feel" of the clay. Thus, different vessels made by the same potter using different batches of clay may be distinguishable by their temper fractional volumes.

Temper Size Distribution

Vessels made by a potter with different batches of clay may also differ in the size distribution of their temper particles. This is especially true if the temper is composed of crushed rocks, shells, or sherds. These materials must be reduced to a technologically appropriate size, which may be judged only by eye and may vary from batch to batch (Rye 1981:37). Even when a single basket or net sieve is used, sorting is only partially effective. Only the upper limit on particle size, not the entire size distribution, is controlled. When temper is water sorted, typically either the lower or upper limit on particle size, but not both, is controlled, and control is only approximate.

Temper Material

Vessels made from different batches of clay may also vary in the proportions of temper of different materials that they contain. When heterogeneous materials are used, chance inclusion can dictate the material spectrum of a vessel's temper and differentiate it from that of other vessels. Temper mineralogical variation among rock-tempered vessels is one common example. Environments in which such variation is more likely to occur include glaciated areas where rocks from till plains, moraines, or valley trains are used as temper (e.g., the Midwest United States). Valleys with diverse alluvial components derived from different geological facies or drainage basins provide similar heterogeneity. Moreover, in such environments, different batches of clay deriving from different natural deposits may vary in the fractional volume, size distribution, and mineralogical spectrum of their natural rock inclusions.

Void Spaces and Temper Spatial Distribution

The vessels of a potter may also vary in the frequency of large voids and the degree of clustering of temper particles in their paste. Large voids and temper clustering are more common in vessels made of poorly wedged and kneaded clays. However, these traits are probably less helpful than the above for definitively sorting sherds by their parent vessels in most assemblages of household-made ceramics, and are probably used best as supplementary evidence. Large voids may be rare enough that they are distributed polythetically rather than monothetically among sherds of a vessel. Temper clusters may be larger than the average sherd, obscuring them from the researcher.

Fracture Systems

Vessels made by similar production methods for the same function can nevertheless fracture differently, depending on their idiosyncratic life histories of production, use, and postdepositional stresses. The areal density and relative frequency of two kinds of fracture systems can help to distinguish vessels: (1) systems of fractures that originate at and radiate outward from temper particles and (2) systems of fractures that pass around temper particles or do not spatially associate with them. The first kind is produced by the stresses that arise from heating and cooling cycles when temper particles are thermally more expansive than their clay matrix. These stresses can occur during the initial firing of the vessel, its use for cooking or cremation, or its accidental burning in a house fire, for example. The second kind of fracture system is often produced by mechanical stresses. These stresses can derive from clay shrinkage during vessel drying, impact during transport or other use, or a great variety of postdepositional deformational forces. Both kinds of fracture systems can occur in a single vessel. Radiography is necessary to accurately document and characterize fracture systems because only some cracks will appear on the surface of a vessel.

Unfortunately, fracture patterns, like void spaces and temper spatial distribution, are probably less helpful for sorting sherds by their parent vessels with certainty in most assemblages of household-made ceramics, and are probably used best as supplementary criteria. Fractures in a vessel can be distributed unevenly in occurrence or frequency among its sherds. This can result, for example, from the uneven distribution of thermal stresses over the vessel during its open firing or use in cooking, or from the localization of impact or postdepositional deformation stresses.

In sum, it is expectable for assemblages of household-made ceramics that radiographically detectable distinctions among sherds in the quantity, size distribution, and material type of their temper inclusions can be used with supplementary radiographic information on void spaces, temper clustering, and fracture systems and with morphological and surficial variation in order to sort them by their parent vessels. Commonly, several or more of these traits will vary significantly among vessels compared to their within-vessel variation when the ceramics have been produced by traditional technological methods.

RADIOGRAPHIC METHODS FOR DISTINGUISHING INDIVIDUAL VESSELS

The potential of radiography for studying archaeological ceramics has been known for some time. Titterington (1935), Digby (1948), and Shepard (1956) used it to reveal the quantity and size of temper particles in ceramics and to document vessel manufacturing methods. More recently, Rye (1977), Glanzman and Fleming (1986), and Meyers (1978) have applied it for similar analytical or museum curatorial purposes. Braun (1982, 1985), Snyder (1987), and Carr (1985) have used radiography to document and quantitatively model changes in temper quantity and size through time. Its use with geological petrography to identify the material or mineralogical family of temper inclusions has been suggested and preliminarily tested (Carr 1990; Carr and Komorowski 1991, 1992). The many uses of radiography in ceramic analysis are reviewed by Carr (1990).

The possibility of using radiography specifically to sort sherds by their parent vessels may have originally been recognized by Titterington (1935:29, Plate 7), who documented similarities in the grit tempers of a few common cordmarked prehistoric sherds in Illinois. Rye (1977:20) mentioned the potential but did not pursue it.

The General Approach and An Illustration

The ability of x-radiography to clearly reveal the temper particles within a sherd, and their fractional volume, size, and material type is illustrated in Figure 2. Figures 2a–d show four typical Ohio Woodland sherds that come from the same archaeological site (McGraw) and belong to different vessels. The sherds are tempered with crushed rock in differing fractional volumes and of different size distributions. Differences in the material type or mineralogical family of the temper particles can also be distinguished easily. Both the gray levels of the particle images and their sizes and shapes allow this. Temper materials having mean elemental atomic numbers and specific gravities greater than those of clay, and that consequently have higher "X-ray absorption coefficients" and block more X rays from reaching the film, appear as less exposed, light spots on the film relative to the gray level of the background clay. Particles of igneous, sedimentary, or metamorphic rocks, as well as shell, have this appearance. Different minerals exhibit a wide range of specific gravities and, as a result, their images vary in lightness relative to clays and each other (Figures 2a–d; Carr and Komorowski 1991, 1992). Voids left where limestone or shell particles have weathered out (Figure 2e), or where organics such as grasses or dung have burned out during firing, or where fractures have developed (Figure 2f) transmit more X rays to the film and appear as dark areas. Crushed pottery temper usually is not visible radiographically, even when edge-enhancing xeroradiographic procedures (Adler 1983; Foster 1983:216; Snyder 1987) are used. This limitation arises because

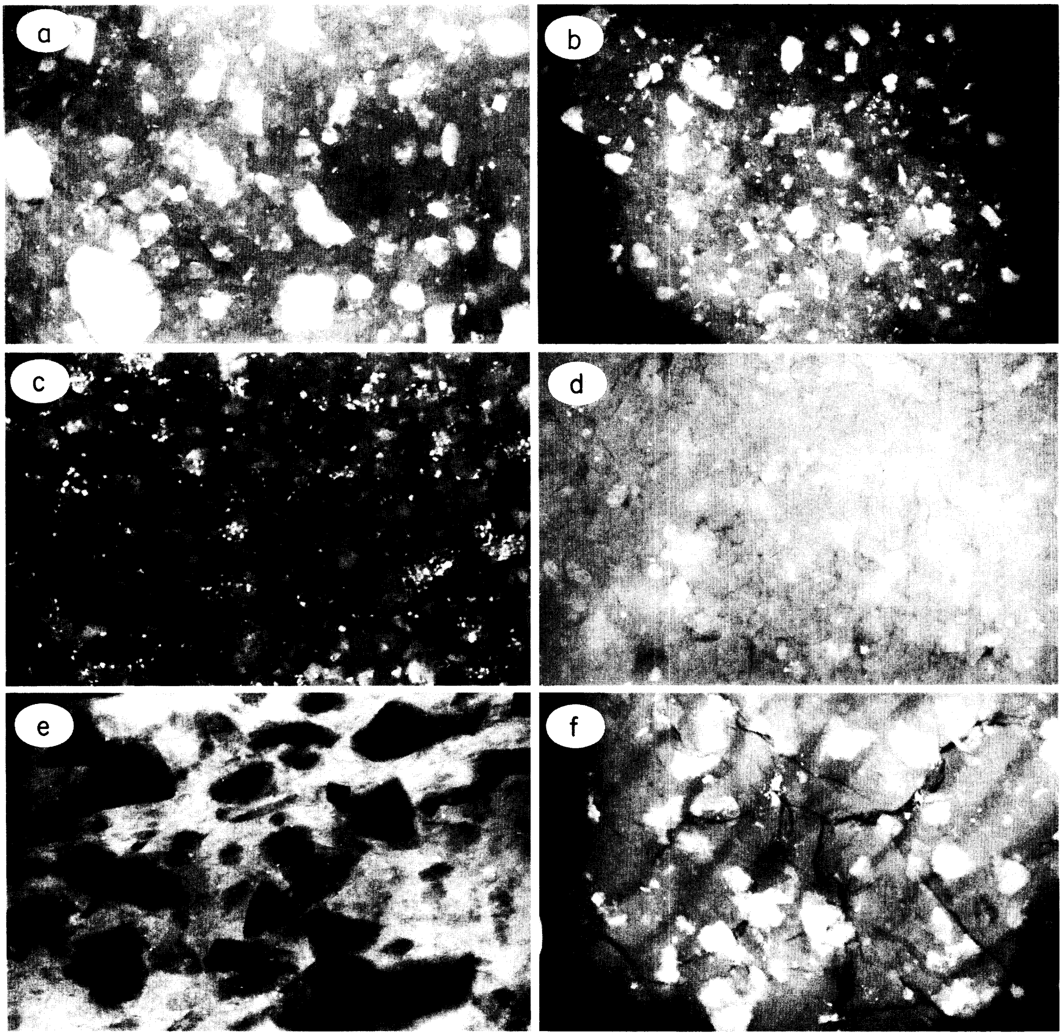

Figure 2. (*a–d*) Four sherds from the McGraw site, Ohio, differ in the fractional volumes, size distributions, and mineralogy of their temper particles. They clearly belong to different vessels. The minerals of sherds (*a–c*) contrast well in the gray levels of their images with that of the background clay. The temper in sherd (*a*) is composed of very large, 2-7 mm, bright, polymineral mafic rock assemblages, predominated by pyroxene or amphibole, and smaller, < 2 mm, grayer felsic minerals, primarily plagioclase and/or feldspar. Some very small, < 1 mm, equant, bright opaques, probably ilmenite or magnetite, and a few very small, < 1 mm, platy, semibright grains, probably mica, also occur. The temper in sherd b is smaller and has a bimodal size distribution. It is comprised of 1-2 mm, semibright particles of pyroxene and/or amphibole; 1-2 mm grayer quartz, plagioclase, and/or feldspar particles; and < 1 mm, equant bright opaques. The opaques are both scattered individually and clustered within larger felsic rock fragments. There are also a few needle-to-platy-shaped, semibright micas and semibright fibrous amphiboles. The temper in sherd (*c*) is characterized by numerous, small, < 1 mm bright opaques, which are scattered individually and in clusters within larger, 1-3 mm, grayer, quartz, feldspar, and/or plagioclase rock assemblages. These particles probably derive from fine-grained sedimentary rock. Some small, 1 mm, platy, semibright particles, probably micas, are also present. The temper in sherd (*d*) is sparse and comprised of minerals that contrast little in the gray levels of their images from that of the background clay. The particles are 1-2 mm, rounded, and probably composed mainly of quartz from stream sediments. A few may be felsic rock assemblages of quartz, feldspar, and/or plagioclase. Occasional, small, < 1 mm, equant, bright opaques are scattered through the specimen. Dark spots in sherd (*e*) from the C+ site, Ohio, are voids where limestone temper has been weathered out. Microcracks, hidden from the eye but detectable radiographically, are illustrated in sherd (*f*) from the McGraw site, Ohio.

clays vary little in their specific gravities and X-ray adsorption coefficients. However, if the clay used to make a vessel has not been vigorously wedged or slaked, detectable air pockets may occur on the sides of some grog particles, indicating their presence (Foster 1983:216).

Using these kinds of qualitative, radiographically detectable features along with visible surficial characteristics, and subject to certain limitations (see below), it is usually possible to identify sherds that derive from the same or different vessels made by traditional technological methods. Furthermore, radiographic information may allow accurate sorting when surficial indicators are ambiguous, as with plain or minimally decorated wares. Figure 3 exemplifies these potentials. A partially reconstructed early Late Woodland vessel from Ohio is shown on the left in Figure 3a. The reconstruction is composed of a number of large, refitted sherds that were found in a midden within a few centimeters of each other. On the right is another sherd that was found in the same deposit. It is similar to the others in color, cord marking, thickness, and circumference. A number of archaeologists, including myself, thought that it might belong to the same vessel as the reconstructed section, although some subtle details in cordmarking hinted otherwise. We attempted to fit the sherd and section together without luck. The situation was ambiguous. However, radiographs of the partial vessel and unjoined sherd showed that they differ significantly in the fractional volume, size, and mineralogy of their tempers (Figure 3b, c) relative to known within-vessel variation of these parameters for Woodland ceramics. The vessel and sherd clearly belong to different vessels.

I have used this strength of x-radiography, along with visual ceramic traits, to sort more than 3,500 prehistoric sherds and vessel sections from Ohio into groups that, from all available evidence, represent individual vessels with great accuracy. The sherds came from 85 proveniences in 24 archaeological components, which date to the Early Woodland through Fort Ancient periods (500 B.C.–A.D. 1400). Approximately 1,000 vessels were discriminated, varying in areal representation from ca. 30 sq cm to nearly complete vessels. All sherds were greater than ca. 9 sq cm.

Several kinds of evidence point to the accuracy of the sherd groups and the reliability of the general method. First, detailed x-radiographic studies of 35 whole Early Woodland through Fort Ancient period vessels from Ohio (Carr 1985) indicated their great internal homogeneity yet noticeable differences from each other in temper size distribution, fractional volume, clustering patterns, and mineralogy. These differences correlated moderately with the dates, archaeological components, river-drainage proveniences, functions, and/or styles of vessels, but also distinguished individual vessels within these analytical categories.

Second, tests of the reliability of the sorting procedures were made using conjoinable sherds, sherds from vessels bearing rare surface features, and sherds from single vessels in unmixed archaeological deposits, whenever these were found. In more than 150 cases where the vessel identity of a group of sherds was almost certain by these criteria, and where expectable limitations on the method did not apply (see below), visually and radiographically based assessments of vessel identity were found accurate in nearly all instances. Approximately half of these tests were made blind; sherds that conjoined or bore similar rare features were recognized to match only after their radiographic imaging and sorting. In contrast, without the benefit of radiography and using visual criteria, alone, I was unsuccessful about 50 percent of the time in identifying sherds that almost certainly had the same parent vessel by radiographic and visual criteria combined. The visual misidentifications occurred despite the careful attention I gave to the details of sherd morphology, cord marking, color, use marks and residues, and fracturing when making the assessments. Both lumping and splitting errors resulted from visual inspection, alone.

Finally, the promise of the method is suggested by the fact that it was not developed deductively, prior to working with the Ohio ceramic collections. Instead, the method repeatedly revealed itself and its reliability during initial explorations of the ceramic collections radiographically for other purposes.

These data do not prove that the method works universally for household-made ceramic assemblages. One can expect the method to vary in its accuracy with varying ceramic technological conditions (see below). However, it is evident that the strategy is highly accurate when applied to unstandardized, heterogeneous ceramic assemblages, such as those of the Ohio Woodland and probably the Woodland ceramics of the Eastern United States in general.

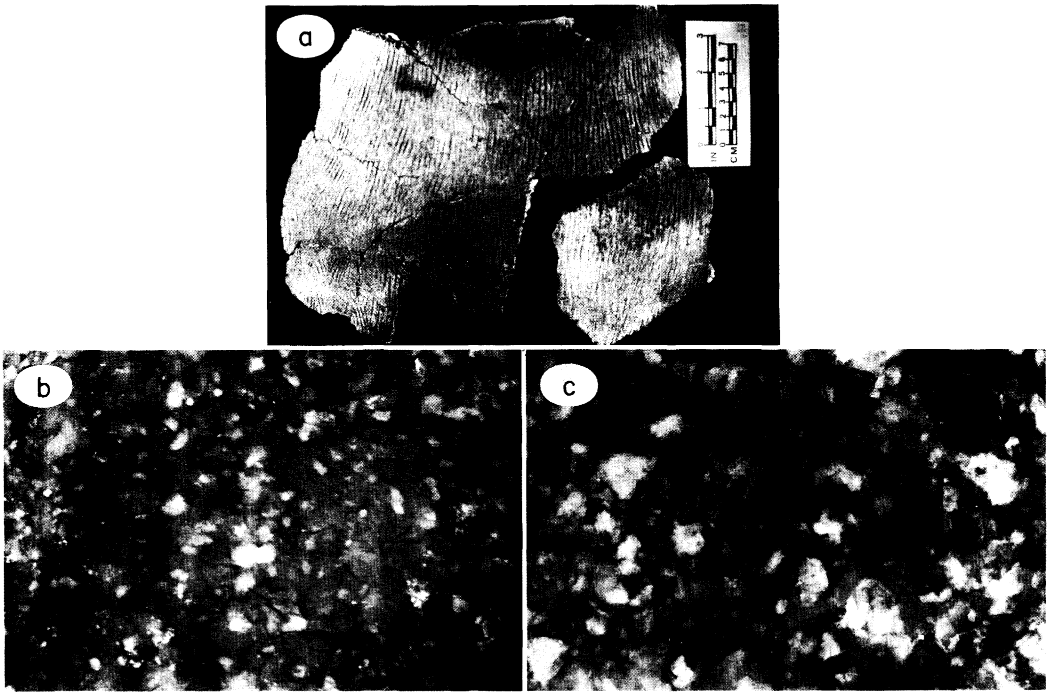

Figure 3. Two large sections of an early Late Woodland vessel from the Scioto Trails site, Ohio, are illustrated in (*a*). From visual and locational evidence, they were thought to belong to one vessel. Radiographs shown in (*b*) and (*c*) clearly indicate that the size, fractional volume, and mineralogical family of temper particles in the two sections differ and that they belong to different vessels. Reprinted with permission from the *Journal of Archaeological Science* (from Carr 1990:Figure 4a-c [respectively]).

It is possible to quantify each of the radiographically detectable characteristics that are useful for sorting sherds (Braun 1982; Carr 1989b; Chayes 1956; Weibel 1979). Quantification is required in radiographic ceramic studies that aim to model technological changes through time, evaluate vessel performance, or perhaps discriminate vessels of different functions. However, to simply identify sherds to their parent vessels, this level of detail was unnecessary in my Woodland ceramic studies. Quick qualitative comparisons of ceramic features by eye sufficed. They can be expected to be adequate for most heterogeneous, household-made ceramic assemblages, within limitations discussed below.

Specific Sorting Procedures

When sorting sherds to parent vessels, a wide range of attributes reflecting at least four, semi-independent dimensions of variation should be used. These dimensions are: primary production, stylistic elaboration, use, and postdepositional alteration. Working with multiple dimensions allows the reliability of sherd matches made with attributes of one dimension to be cross-checked with attributes of other dimensions. When possible, each dimension should be represented by both visible and radiographically detectable attributes, to encourage independent cross-checks.

When attributes vary in their discriminating power, sorting is made easier and more accurate when the attributes are implemented primarily in a sequential, hierarchical, and weighted manner as a decision tree, rather than in a simultaneous, equally weighted manner as with a full paradigmatic classification. Those attributes that vary most among all vessels (i.e., are most discriminating) and that are least variable within vessels (i.e., are reliable discriminators) should be used first in sorting and thus be given most weight. They can be used to divide a collection globally into broad, multivessel or even narrow, vessel-specific groups of sherds. Traits that vary less among vessels or that are more heterogeneous within vessels, but that help to distinguish them in certain groups, should be used secondarily and thus given less weight. They can be used to subdivide multivessel groups or to test and refine vessel-specific groups defined by first-order attributes. This strategy proved effective in my work with Ohio Woodland ceramics.

The decision tree should be established if at all possible by visually and radiographically examining whole or partially reconstructible vessels from the community or regional tradition of interest. Typical intravessel and intervessel variation for each potentially useful attribute should be noted in order to evaluate its relative discriminating power and the relative weight it should be given in the tree. Typical intravessel variation for each attribute must also be noted in order to define the levels of sherd similarity that most likely do or do not constitute a match. If one tries to establish the decison tree using the sherd collection to be sorted rather than whole or partial vessels, reasoning will be circular, and systematic lumping or splitting errors in sherd grouping may result.

An example of a hierarchical, sequential decision tree from my work with Ohio Woodland ceramics is shown in Figure 4. Many whole and partial vessels from each ceramically distinct time period in the Scioto Valley were examined visually and radiographically for variation within and among them in many manufacturing, stylistic, functional, and postdepositionally relevant attributes (Carr 1985). The attributes were ordered into three sets according to their discriminating power. The sets were then used sequentially to divide each site collection of sherds into probable parent vessels. The best discriminators were used first to divide each collection globally into broad, multivessel groups or tentative, narrow, vessel-specific groups of sherds. The best discriminating attributes all turned out to be visually detectable and primarily stylistic or functional. They include oxidized/reduced exterior and interior colors, exterior polish, the details of cordage construction revealed in surface cord marks, relative paste wetness during cord application, and wall thickness. The relative weights that were given to these attributes during sorting were allowed to float from collection to collection, depending on which attributes showed the greatest variation in the collection under study. The second-best discriminating attributes were somewhat less variable among the whole vessels but still homogeneous within vessels. Their intervessel variation tended to crosscut rather than correlate with variation in the first set of attributes. Thus, when sorting sherds into parent vessels, these attributes could be used to test the homogeneity and validity of the initial groups of sherds that were defined with the first set of attributes and, when necessary, to subdivide the groups. Less frequently, they were used to reallocate sherds among groups. The secondary traits all turned out to be radiographically detectable and to pertain primarily to vessel production and function. They include temper volume fraction, size, and mineralogical family, and the degree of temper clustering when observable. The relative weights of these attributes, like the first set, were allowed to float from collection to collection, but also among the tentative sherd groups defined with the first set of attributes. Contextual information on the horizontal and stratigraphic distances between sherds and the functional characters of the deposits in which they were buried was also used at this level, when available, to assess the likelihood of accuracy of potential subdivisions and reallocations. Third-order discriminators often varied significantly within the whole vessels. Thus, these attributes were used only occasionally for sorting, when they were well developed and probably homogeneous within vessels, and then only to subdivide groups produced with the first two sets of attributes, not to reallocate sherds between groups. The traits are all visually detectable and indicate vessel use or postdepositional alteration. They include the presence of cooked food residues on interior surfaces and wall delamination.

For other assemblages, decision trees with different attributes or sequencing of attributes might be more relevant. For instance, certain radiographically detected attributes might be found to be more useful than visible attributes for making initial, global divisions. This was the case in my work with Ohio Early Woodland assemblages (Phillip Smith, Florence, Darby Dan, Dominion Land Company sites), which were predominated by plainwares of similar form and coloration.

When sorting sherds with a decision tree, it is essential to continually test and refine the tentative groups that are initially identified using higher-level attributes with attributes from complementary dimensions at that level or lower, or with contextual information such as provenience. For the Ohio

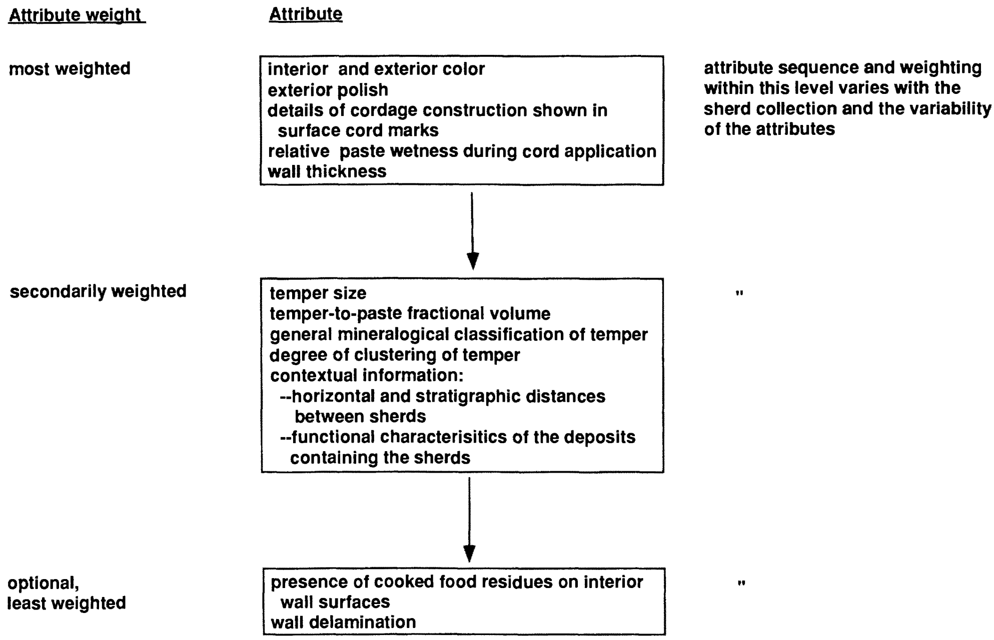

Figure 4. A hierarchical, sequential decision tree of surficially visible and radiographically detectable traits for sorting Ohio Woodland sherds by parent vessel.

ceramics, this was necessary because no one attribute was consistently discriminating of all vessels and no one weighting of attributes within a level was consistently useful for subdividing all initially formed groups.

For collections with hundreds of sherds or more, the number of possible matches that must be considered can quickly rise beyond human cognitive capabilities. Using a hierarchical, sequential approach to sorting greatly reduces the number of possible permutations that are considered compared to those that would be in a simultaneous, fully paradigmatic sorting strategy. However, there are still limits. The largest single collection of Ohio sherds that I sorted confidently with the above procedures (from the McGraw site) had 352 sherds, for which 68 analytically individual vessels were represented by more than one sherd.

This cognitive limitation can be overcome in two ways. First, some additional strategy can be used to initially subdivide a collection into broad, multivessel yet manageable subcollections, each of which contains the most relevant matches within it. Searches for matches can then begin within subcollections to define vessels and later be extended between subcollections using the vessels, rather than individual sherds, as the units to be compared. This can greatly reduce the number of permutations that must be considered. One possible strategy for initially subdividing a collection is to partition it spatially and hierarchically. Searches for matches can begin with sherds from a localized deposit, such as a pit or localized midden. After several such subcollections have been sorted separately, matches can be then be sought between them, focusing on the vessels defined for each subcollection rather than the individual sherds. For this strategy to work well, the collection should constitute a behaviorally relevant depositional unit, such as a cluster of pits or the multiple midden deposits within a house. The largest collection of Ohio ceramics that I analyzed in this way, from the Harness-28 site, had 480 sherds and vessel sections representing 190 vessels from 6 related proveniences.

This strategy can make sorting not only more efficient and feasible, but also more reliable. Once sherds have been grouped by vessel within localized deposits, the range of variation of attributes within each vessel will be better known. Less-probable matches between sherds of different deposits can then be sought and tested with greater confidence.

The second way in which the problem of collection size can be overcome, of course, is by sampling only certain natural depositional units and/or certain sherds within units. When drawing a sample of sherds from within a unit, simple random sampling of the sherds is usually inappropriate. It does not ensure that each vessel for which one or more sherds happens to be drawn is represented by enough area to evaluate the integrity of those sherds as a group. Instead, a stratified, random or purposive sampling design that considers likely matches during sample selection is more appropriate. Specifically, visible diagnostics of individual vessels should be used to very roughly sort sherds into groups that belong to the same or similar vessels. Samples of sherds that would sufficiently represent one or more vessels should then be selected from each group or a sample of the groups, using what insight one has at the time about the vessel identity of sherds and the possible number of vessels in each group. This approach was used, for example, to select the 352 sherds from the 9,946 sherds in the McGraw site collection.

Limitations of the Sorting Procedures

There are several situations in which the sorting procedures just described are not likely to be productive. First is when pottery production is standardized (e.g., fine wares of the Classical eastern Mediterranean civilizations), or when there is little or no functional or stylistic diversification of pots (e.g., some early ceramic industries). In these cases, similar materials, production methods, and decorative elements (if any) may allow the visual and radiographic identification of only broad technological or stylistic classes rather than individual vessels. Plainwares from the Early Woodland of Ohio sometimes pose this problem.

A second problematic situation is when sherds from different portions of a vessel, such as rims or handles vs. body sherds, have been produced with pastes that differ in their tempering characteristics in order to achieve particular functional or aesthetic ends. This can prevent certain sherds of a vessel from being matched, even if the problem is known to exist from studies of whole vessels. For example, the rims of some Ohio Middle and Late Woodland vessels are significantly thinner or thicker than their bodies and have smaller temper particles in lower fractional volumes.

Finally, sorting sherds manually using the above methods may be intractable for ceramic-rich archaeological contexts. Localized deposits within towns or cities may contain tens of thousands of sherds. This limitation may be reduced in the future with the development of semiautomated methods for sorting radiographic images by temper fractional volume, size, and mineralogical family. Currently available line-scanning digitizers, aerial photographic image processing systems such as ERDAS, and geographic information systems such as GRASS provide the basic tool kits that are needed for automation (R. Dorn, J. Feathers, W. F. Limp, personal communications 1989).

X-Radiography Laboratory Procedures for Ceramic Analysis

To be useful for sorting sherds by parent vessel, a radiograph must reveal diagnostic ceramic features with sufficient contrast and resolution. Only some radiographic procedures and materials provide this detail. This section outlines those methods that are best tailored to the ceramic medium.

The primary factors that affect ceramic image contrast, sharpness, and distortion and that must be selected are film type, accelerating kilovoltage, tube target, window material, kind of filtration, film cassette material, whether a diaphragm and screens are used, tube current amperage and exposure time, focal-spot size, focal spot-to-film distance, object-to-film distance, and object-to-film orientation. Optimal choices of these differ for medical vs. industrial laboratory settings because they differ in the design of their X-ray machines. The recommendations made here are based on numerous experiments that I conducted with a medical radiologist, several professional industrial radiographers, and with the guidance of personnel from Eastman Kodak over a seven-year period. More detailed discussions of each of the topics summarized below are given by Carr and Riddick (1990), Eastman Kodak Company (1980, 1981), Bryant and McIntire (1985), Barrett and Swindell (1981), Jenkins and de Vries (1969), Christensen et al. (1978), and Cahoon (1956).

Contrast. One of the principle obstacles to be overcome in ceramic radiography is low "subject contrast." By this is meant the small differences in radiation intensity that are transmitted by different ceramic phases (e.g., temper, voids, paste) and that are available for differentially exposing an X-ray film. This condition, in turn, may result in low "radiographic contrast": small differences in the gray levels of images of those phases on film.

Subject contrast depends most basically on the elemental compositions and specific gravities of the different phases in an object, which determine their X-ray adsorption coefficients. In ceramics, temper particles and clays, for example, may differ only slightly in these properties and, therefore, in their subject contrast (Carr and Komorowski 1991, 1992). Subject contrast is also affected by the radiographic procedures that are used. The radiographic contrast that is obtained for an object with a given subject contrast depends on the selected procedures, alone.

Film. One of the most fundamental ways to compensate for low subject contrast and enhance radiographic contrast, and also to ensure image sharpness, is to select a suitable film type. This factor also affects image sharpness. Braun (1982) used a general purpose medical X-ray film—Kodak XRP-1—in his ground-breaking radiographic study of temper particles. This and other general-purpose, "fast" X-ray films are designed to reduce the patient's exposure to X-rays and are readily available in hospitals. However, they do not enhance radiographic contrast and are moderately coarse grained. Consequently, they are inadequate for ceramic applications for several reasons: (1) Smaller temper particles may not be visible; (2) some larger, overlapping particles may not be discriminable; (3) the morphology, including any facetting, cleavage planes, or interior structural alteration, of larger particles may be too indistinct to help identify their mineralogy; (4) particle images have too restricted a range of gray levels to be useful for distinguishing particle mineralogy or material; and (5) low-contrast, fuzzy images can quickly lead to "eye burn-out" for the researcher (Braun 1982).

Better suited for ceramic research are certain industrial films that are used to inspect metal parts and joints, and mammography films that are used to document subtle anamolies and calcifications within breast tissues. Both kinds of film are designed to compensate for low subject contrast by providing high radiographic contrast. Most are also finer grained, providing sharper images. The specific films that were found very satisfactory for documenting temper particles in Ohio Woodland ceramics are Kodak Industrex M and R for industrial laboratories and mammography film Kodak Ortho M for medical laboratories. Industrex M can be examined under magnification up to 14×, and Industrex R can be examined at much higher magnifications, allowing the identification of temper to mineralogical families (Carr and Komorowski 1991, 1992). Both of the industrial films provide greater contrast. They have steeper characteristic curves, which measure change in image density with exposure. The characteristic curves of the industrial films have an average slope of about 4:1, whereas those of mammography films used without screens have average slopes of approximately 2.5–2.8:1, and those of general-purpose medical films used without screens have average slopes of about 1:1 (W. V. Bowles, Kodak, personal communication 1983). The advantages offered by industrial and mammographic films over general purpose medical films are shown in Figures 5a–d for a typical Ohio Woodland sherd.

Other potentially useful industrial films, such as Kodak MTX, T, and AA, provide high contrast but are increasingly grainy. The advantages they provide in exposure time do not offset their decrease in image sharpness, given that exposure time is minimal compared to specimen setup time in routine ceramic applications. The potentially useful medical films, Kodak XTL high-detail film and Kodak Min-R mammography film, can be eliminated for other reasons (Carr and Riddick 1990).

Kilovoltage. Higher subject contrast, and potentially radiographic contrast, can be obtained by decreasing the peak accelerating kilovoltage (kVp) that is applied to the X-ray tube to generate X rays. Figures 6a and 6b illustrate this for an Ohio Woodland sherd, which was radiographed at 30 kVp and 50 kVp. The gray levels of rock temper particle images contrast with the gray levels of the background clay image more in the lower kilovoltage radiograph than in the higher one.

The kilovoltage setting affects subject contrast by altering the spectrum of X rays emitted from the X-ray tube. As peak kilovoltage increases, X rays of shorter wavelength, and thus higher energy and greater penetrating power, are added to the spectrum; the intensity (percentage) of more penetrating waves compared to all waves in the spectrum increases. This "harder" radiation will pass through both the temper and clay phases of a ceramic sherd to similar extents, because of their

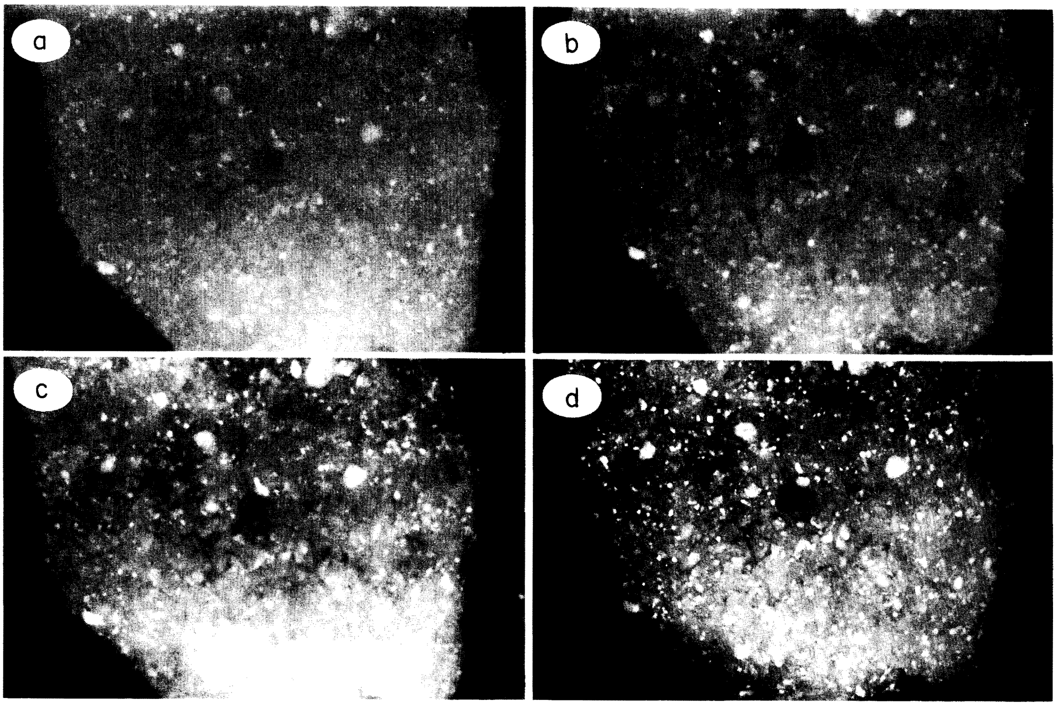

Figure 5. Comparisons of radiographic techniques for their effects on image sharpness and contrast using a Baum phase Fort Ancient, igneous-rock-tempered sherd from Ohio: (*a*) general-purpose medical film Fuji ROXG with a Kodak Lanex Fine screen, 40 kVp, 200 Ma, .025 sec., tungsten target; (*b*) mammography film without a fluorescent screen, tungsten target; (*c*) mammography film without a fluorescent screen, molybdenum target; (*d*) industrial film Kodak Industrex M-2 without a front screen, 50 kVp, 3 Ma, 6 min., tungsten target. Exposures *a–c* were made by Riddick and Carr at Washington Regional Medical Center, Fayetteville, Arkansas. Exposure *d* was made by William V. Bowles, Kodak Research Laboratory, Rochester, New York. Differences in the contrast obtained for exposures made with different films and different X-ray machines only approximate the effect of using different films, alone, with the same machine. Differences among machines in their secondary scattered radiation levels, which is an important contributor to radiographic contrast at low kilovoltages, has not been controlled. Reprinted with permission from the *Journal of Archaeological Science* (from Carr and Riddick 1990: Figure 8a, c–d, f [respectively]).

similar specific gravities, and will expose the film underlying both similarly, producing low subject and radiographic contrast. When a lower peak kilovoltage is used, the generated X-ray spectrum has a greater percentage of longer wavelength and, thus, lower energy, less penetrating "softer" X rays. If these have marginally enough energy to pass through the moderately dense clay phase of the specimen, they will be stopped in significant quantities by denser phases such as temper particles and transmitted in greater quantities by lighter phases such as voids and fractures. This will produce a higher subject contrast between phases and, with appropriate film, higher radiographic contrast.

Minimizing kilovoltage to increase subject contrast does require longer exposure times. However, the time difference is minimal—a few minutes or less per exposure—within the range of kilovoltages that might reasonably be applied in ceramic vessel studies. Kilovoltages between 20 and 50 kVp are recommended for most work. Kilovoltages in the lower end of this range should be used for sherds that more easily transmit X rays, i.e., sherds that are thinner, have rock tempers of low specific gravity, and/or lower fractional volumes of dense temper.

Tube Target. The spectrum of X rays that are emitted from an X-ray machine and contingent subject contrast can be adjusted not only by varying kilovoltage, but also by selecting the tube target. Most tubes that are used to produce radiographs, as opposed to those used in X-ray diffraction or X-ray fluorescence applications, are made with targets of tungsten or molybdenum. Tungsten tubes

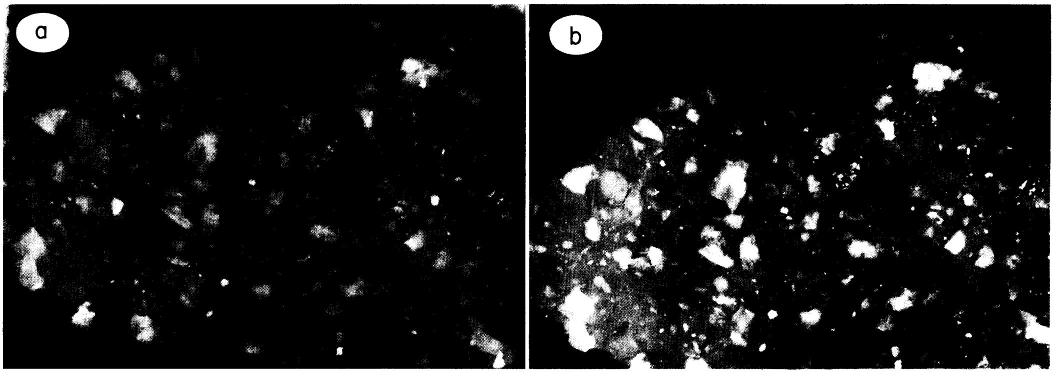

Figure 6. Higher radiographic contrast between phases of a specimen can be obtained by using lower kilovoltages: (*a*) an Ohio Woodland sherd from the W. S. Cole site radiographed at 50 kVp, 3 MaS with Kodak Industrex M-2 film and a tungsten target; (*b*) the same sherd radiographed at 30 kVp, 4 MaS. Radiographic contrast between the gray levels of temper particles and the background clay are greater in the second case. Reprinted with permission from the *Journal of Archaeological Science* (from Carr and Riddick 1990:Figure 5a-b [respectively]).

are most common, being less susceptible to meltdown. They are used in both medical and industrial applications. Molybdenum tubes are used in low-energy mammographic applications.

Molybdenum tubes, unlike tungsten tubes, generate an X-ray spectrum that is dominated by a very large peak of soft radiation at 17 KeV. If the pottery to be studied is less than ca. 5 mm thick and does not have high fractional volumes of temper particles with high specific gravity, this soft radiation can penetrate through the entire thickness of the pottery and significantly increase subject and radiographic contrast. Figures 5b and 5c illustrate this effect for a thin Ohio Woodland sherd, as does work by Rini et al. (1973) and Marshall et al. (1975) with other materials of low specific gravity. This advantage of the molybdenum tube assumes that no spectrum-hardening filters (see below) are used with the X-ray machine (Bernstein et al. 1977). For thicker or more densely tempered sherds that are incapable of transmitting the 17 KeV spike, the molybdenum and tungsten tubes give similar results.

Window Material and Filtration. A third way in which subject contrast can be increased is by choosing an X-ray machine with an appropriate window. In an X-ray machine, the vacuum tube that generates X rays is surrounded by a lead housing with a hole, through which X rays are emitted. Different substances can be used to fill this hole, comprising the "window." These include beryllium, glass, aluminum, and steel. Beryllium allows most radiation that is generated by the tube, both soft and hard, long and short wavelengths, to pass through. Glass, aluminum, and steel increasingly cut out the softer, longer-wavelength, less-penetrating radiation, leaving greater percentages of harder, shorter-wavelength, more-penetrating radiation. This hardening of the spectrum of the emitted radiation affects subject contrast in the same way as hardening the spectrum by increasing kilovoltage: subject contrast is progressively decreased. Consequently, an X-ray machine with a beryllium window, which transmits the most soft radiation, is preferable to one with a glass, aluminum, or steel window.

Many medical X-ray machines with tungsten targets have glass or aluminum windows and, thus, are not optimal for ceramic studies. They are designed, instead, to protect the patient from harmful, softer radiation by absorbing it in the window. In contrast, machines with molybdenum tubes for mammography applications usually have beryllium windows, as do some industrial machines with tungsten tubes. These machines are more appropriate for ceramic studies. Braun (1982) used a medical unit with a more absorbing window, which is one factor that led to less than optimal radiographic contrast in his work.

Similar to windows in their effect on subject contrast are filters. These are sheets of aluminum, molybdenum, or steel of a chosen thickness, which are placed in front of the window. Because all filters harden the spectrum of X rays and thereby reduce subject contrast, they are undesirable in ceramic work. A ceramic researcher working in a medical setting should inquire whether a filter is attached to the X-ray machine to be used because filters, like denser windows, are often used to reduce the exposure of patients to softer radiation.

Methods for Reducing Scattered Radiation. Radiographic contrast, as distinct from subject contrast, can be increased in several ways. Choice of film type is most important. Procedures that reduce "scattered radiation" are also advantageous. This condition can be explained as follows. The X rays that are emitted from an X-ray machine, called "primary radiation," expand from its focal spot into a larger field that normally encompasses the object of study and its surroundings. Some of this radiation is adsorbed by the object and surroundings, some is transmitted through the object to the film and forms an image, and some is scattered in all directions by the object and surroundings. Any scattered radiation that reaches the film, which is called "undercut" scatter, produces a fog over the film and lessens radiographic contrast among the images of different phases of the object. When low kilovoltages are used, as in ceramic studies, undercut scatter can be large compared to the radiation directly transmitted through the object and must be reduced to ensure radiographic quality.

Four strategies should be used to reduce the effects of scattered radiation. First, a sheet of lead, or layered aluminum and lead, called a "back screen" should be placed behind the object and the film. This will absorb some of the scattered radiation from the object and also prevent what is below the object from scattering radiation. Second, the object and film should be placed as close to the back lead screen as is possible, to ensure its effectiveness. Third, a lead "diaphragm" should be placed on the X-ray machine to restrict the expanse of the X-ray field to the approximate area of the object of study. This will reduce the scattering of radiation by surrounding items. Finally, when the film is held in a cassette rather than a paper "ready-pack," the cassette should be made of plastic rather than metal in order to reduce its scattering of radiation. Plastic cassettes are used commonly and are likely to be available in mammographic laboratories, where kilovoltages are kept low and scattered radiation is usually troublesome. In general-purpose medical radiography settings, where higher kilovoltages and metal cassettes are typically used, the researcher may need to specially request plastic cassettes.

In higher kilovoltage industrial applications, scattered radiation is sometimes reduced by using a "front lead screen"—a sheet of lead that is placed between the object and the film. This is not recommended for low-kilovoltage, ceramic work. The presence of the screen requires that kilovoltage be increased in order to ensure the penetration of radiation through the screen to the film. This reduces subject contrast. In low kilovoltage work, the reduction in subject contrast overshadows the gain in radiographic contrast that is obtained by reducing scattered radiation.

Fluorescent Screens. In many medical applications, fluorescent screens are used. These are plates that are coated with phosphor compounds and placed above and below the X-ray film. They convert some X rays into light, which exposes the film more quickly. They have the benefit in medical work of reducing the dosage of radiation that the patient receives. For ceramic studies, this factor is not critical and screens bring only disadvantages. Screens decrease image sharpness and increase the unevenness of a radiograph's exposure.

Image Filtering and Xeroradiography. The image visibility of different phases in an object can be improved not only by increasing subject contrast and radiographic contrast, but also by enhancing the image boundaries between phases. This can be done by image digitization and filtering methods (Gonzalez and Wintz 1977) after the radiograph is made, or more directly with the technique of xeroradiography (Christensen et al. 1978:308–328; Heinemann 1976). Xeroradiography differs from normal radiography in that a selenium sulfide, electrostatically charged plate is used instead of an ordinary film with a silver halide emulsion. The plate produces edge enhancement, which gives the appearance of high radiographic contrast even though the actual contrast provided by it is very low. The average slope of the characteristic curve of a xeroradiographic plate is approximately only .2:1 (Wagner et al. 1974). Xeroradiography units are available in mammography laboratories, where they are used to detect breast-cancer tissues (Fingerhut and Foutainelle 1974; Wolfe 1972).

Xeroradiography is tailored to the problem of defining boundaries between uniform phases of a specimen. Ideal ceramic applications include documenting the interior wall outlines of hollow closed items (Alexander and Johnston 1982; Foster 1983); delineating voids at the seams between coils or slabs of a vessel (Adler 1983; Glanzman and Fleming 1986); documenting larger cracks (Heinemann 1976); and outlining large, compositionally uniform temper particles such as limestone or shell particles or voids left by these.

The technique is not well suited, however, for (1) documenting small anomalies, (2) providing continuous-image representation, or (3) distinguishing phases with different specific gravities by gray level. All of these drawbacks make xeroradiography a poor choice for documenting the kinds of features that can be used to distinguish individual vessels. The first limitation interferes with identifying small temper particles and fractures (Carr and Riddick 1990:Figure 9) and, thus, with comparing the fractional volume and size distribution of temper particles and the degree of fracturing among sherds. The second and third limitations can make it difficult to resolve overlapping temper particles and to see the integrity of particles with multiple crystal facets. These misperceptions can bias estimates of the temper size distributions of sherds. Also, the second and third limitations, by obscuring the morphology and specific gravity of temper particles, discourage comparing the material type or mineralogical family of particles among sherds.

Tube Current Amperage and Exposure Time. The total amount of radiation that is emitted from an X-ray machine and that partly determines the degree to which radiographic film darkens depends on three parameters. These are the peak kilovoltage applied to the X-ray tube, the amperage of the tube current, and the exposure time. For a given kilovoltage, amperage and exposure time can be adjusted to compensate for each other, similar to f-stop and time in photography. Darkening of the radiographic film also depends on the X-ray absorbancy of the object being radiographed, its composition and thickness, and the amount of the emitted radiation that is transmitted by it.

For sorting sherds by vessel, it is essential to keep the gray level of the background clay as constant as possible from radiograph to radiograph, compensating for differences among sherds in their thickness. When this is done, and because all clays have a similar specific gravity, the overall gray level of a sherd's radiograph becomes a function of the fractional volume and composition of the temper, the frequency of fractures in the sherd, and the thickness of the sherd over which temper particle images and fracture images are created and accumulated on film. When sherds are approximately similar in thickness or have already been sorted by thickness, the last factor is removed, making it easy to recognize in radiographs, at a glance, those sherds that differ significantly in their temper fractional volume and composition and in their fracture frequency, alone. Charts are available (Carr and Riddick 1990) for determining the milliampere seconds that are appropriate for exposing ceramic sherds of varying thickness and rock temper density at 30 and 50 kVp using Kodak Industrex M film, in order to hold constant the background clay gray level.

Image Sharpness. Several procedures help to ensure sharp radiographs. First, an X-ray machine with as small a focal spot as possible should be used. A smaller focal spot more closely approximates a point source of radiation which, as in a pin hole camera, is necessary for image sharpness. Machines used for lower kilovoltage work, such as mammography units, usually are equipped with smaller focal spots. The Ohio Woodland ceramics were radiographed with an actual focal spot (as opposed to an effective focal spot; Carr and Riddick [1990:Figure 4]) of .7 mm.

Second, the distance of the focal spot from the film (ffd) should be kept as large as is practical physically and in relation to exposure time. (Exposure time increases with the ffd.) The larger the ffd, the more the focal spot approximates a point source at an infinite distance. Also, a larger ffd can help to compensate for image blurring that results from any lack of contact between the film and the sherd, due to the sherd's curvature. An ffd of 79 cm was found adequate even with sherd-film separations of a few centimeters in my Ohio ceramic studies.

Finally, the distance of the film from the sherd should be minimized. Small sherds that are to be radiographed together on a single 8 x 10″ sheet of film should be laid directly on the film packet or cassette, convex rather than concave side down. Larger sections or whole vessels can be radiographed with roll film, which can be formed to the vessel's curvature and attached with masking tape.

Image Distortion. Sherds should be oriented as perpendicular to the line of X rays as is possible in order to minimize the foreshortening of images along an axis of tilt or curvature. Distortion can be minimized by laying sherds or vessel sections with their exterior, convex side downward, away from the source, and placing or attaching the film on their exterior. For whole vessels, the film must be placed inside the vessel, on the wall closest to the source. Only a small arc of curvature should be radiographed at a time.

Costs. Routine radiography of the Ohio Woodland sherds, as opposed to whole vessels or large sections that involve more set up time, cost a maximum of ca. 13¢ per sherd in materials and senior technician time without overhead. This figure is based on the use of Kodak Industrex M-2 film, the exposure charts provided by Carr and Riddick (1990), the placing of 40 sherds on each 8 x 10″ or 12 x 10″ piece of sheet film, the setup and exposure of 6 pieces of film per hour (a relaxed pace), and a cost of $250 in supplies and labor per 8 hour day.

CONCLUSIONS

Radiography can clearly play a fundamental role in the descriptive stages of ceramic archaeological research. It can often help the researcher to sort sherds of household-made ceramics into parent vessels more accurately than is possible with visual traits, alone. The vessel is a more relevant analytical unit than the sherd in many common kinds of behavioral studies. Neither cost nor the availability of facilities nor a lack of appropriate methods inhibit the application of radiography in most research settings. Thus, it is important for archaeologists to consider the integration of radiographic methods in their routine work.

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