# Radiographic Analysis of Temper in Ceramic Vessels: Goals and Initial Methods


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*Information on several characteristics of temper particles can aid the archaeologist in interpreting details of ceramic vessel use and functional variation. The paper summarizes theoretical reasons and experimental procedures for using X-radiography to obtain rapid, low-cost quantitative measurements of the sizes, shape, density, and orientation of temper particles. The feasibility of this approach is assessed using Woodland period pottery from the central midwestern United States. The paper concludes with a discussion of technical limitations and areas for further investigation and procedural refinement.*


### Introduction

Archaeologists ordinarily analyze the temper, or nonplastic inclusions, in the pastes of ceramic vessels to obtain information on places and methods of vessel manufacture. Where the size, shape, density, or mineralogy of temper particles vary over time or space, this variation provides a basis for the temporal or spatial classification of ceramics. Cultural reasons for the variation, other than for the mineralogical variation, rarely are considered. Studies in ceramic engineering, however, indicate that many temper-particle characteristics affect the mechanical performance characteristics of whole vessels. Variations in these characteristics, therefore, are constrained by the patterns of intended whole-vessel use. The constraints involved provide an as-yet barely explored means for obtaining behavioral information from the remains of ceramic vessels.

Archaeological methods for analyzing temper inclusions range from rapid, superficial classifications based on highly summary criteria, to slow, highly labor-intensive and detailed microscopic examinations.[1] In general, the more quantitative the desired data on each specimen, the greater the amount of time and laboratory preparation required for each specimen. In particular, quantitative data on particle shapes, density, and size distribution usually are acquired only as part of an overall process of microscopic petrographic examination, and minimally require the preparation of flat-cut or ground sections. Because such data are highly useful in studies of ceramic functional engineering, however, it would be useful to have more efficient, inexpensive methods of examination.

This paper summarizes initial work on the development of a rapid, relatively low-cost radiographic method for obtaining quantitative data on the shapes, density, and size distribution of temper particles. The theoretical basis for collecting such data is reviewed, emphasizing the analysis of domestically produced, preindustrial utilitarian vessels. The initial experimental procedures are described and illustrated from an analysis of Woodland ceramic variation in the midwestern U.S. between ca. 1 A.C. and 900 A.C. The paper concludes with a discussion of limitations, and of areas for future investigation for refinement of the method.

### General Framework

The archaeological literature on ceramic-vessel manufacture generally identifies three sets of reasons for the inclusion of temper in ceramic pastes: to control paste plasticity during vessel shaping; to serve as a binder during vessel drying prior to firing; to reduce internal stresses resulting from clay shrinkage; and to improve the green

1. E.g., Henry Hodges, *Artifacts* (John Baker: London 1964) 194–202; Anna O. Shepard, *Ceramics for the Archaeologist* (Carnegie Institution: Washington, D.C. 1965) 95–193; M. S. Tite, *Methods of Physical Examination in Archaeology* (Academic Press: New York 1973); M. Ann Bennett, *Basic Ceramic Analysis, Eastern New Mexico University Contributions in Anthropology* 6–1 (Portales 1974); Sander E. van der Leeuw, *Studies in the Technology of Ancient Pottery* (Univeriteit van Amsterdam 1976); Owen S. Rye, *Pottery Technology* (Taraxacum: Washington, D.C. 1981) 46–53.

mechanical strength of the dried vessels prior to firing.[2] These reasons are recognized by native potters, and their modern industrial validity has been confirmed experimentally.[3]

The binding effect during drying appears to result from two more specific effects. First, the temper particles serve as points of focus for the stresses that develop with shrinkage of the paste, and therefore become the points of focus of microfractures that develop to relieve these stresses. The particles thereby reduce overall crack propagation. Second, the microfracturing around the temper particles makes them relatively mobile and apparently able to relieve some shrinkage stresses also by shifting slightly within the drying matrix.[4] Shrinkage stresses are greater, the larger the vessel and the thicker its walls, and hence in such circumstances the greater will be the need for binding temper. The improvement in the green strength of dried pottery prior to firing, from the inclusion of temper particles, similarly appears to result from an increased resistance to crack propagation. In either case, microfractures developed during drying and handling prior to firing should disappear during firing unless serious structural flaws are present.

Discussions of the effects of temper particles, other than effects on the mineralogy of fired bodies, generally do not consider effects related to vessel use. Considered together with the theoretical literature in ceramic engineering, however, archaeological studies are beginning to reveal the extent to which the shape, orientation, density, and size distribution of temper particles do indeed affect mechanical performance. The effects in this realm are both adverse and beneficial, depending on the kinds of stresses developed during use.[5] As Rye[6] emphasizes, however, the non-archaeological literature in ceramic engineering concerns materials fired to much higher temperatures than the 500–900°C. range typical of our material, with average temper particle sizes well below the range typical of preindustrial products. As a result, expectations for archaeological samples must come from extrapolations of effects and mechanical principles established for more refined conditions. It also must be kept in mind that the effects will vary somewhat with clay chemistry.

Other things being equal, flexural or mechanical strength (modulus of rupture) generally should decrease with increasing average grain size in a fired paste.[7] This effect appears to result from the tendency for internal grain irregularities, in a polycrystalline matrix, to act as points of focus of mechanical stress and therefore as points of crack initiation.[8]

Under repeated, rather than continuous mechanical stress, however, the potential use-life of a vessel can be increased (presumably within limits) by increasing the average size of tempering inclusions. Fine-grained fired pastes have low resistances to crack propagation despite their higher resistances to fracture initiation. Fractures once begun in such pastes will propagate rapidly, resulting in the mechanical failure of the vessel wall. On the other hand, the presence of particles relatively much larger than the bonded clay particles in a fired paste decreases initial resistance to fracture but increases resistance to crack propagation. Fractures once begun in such coarser pastes will be truncated by a coarse inclusion and will have a lower resulting tendency to propagate during any one episode of mechanical stress. Repeated stress, of course, eventually will lead to mechanical failure.[9]

Other things being equal, resistance to thermally induced stresses also is affected by temper inclusions. Particles of materials whose coefficients of thermal expansion are greater than that of the surrounding fired clay will expand differentially if a vessel is heated. Clearly, temper inclusions must have thermal expansion characteristics at least broadly similar to that of the as-

2. E.g., Shepard, op. cit. (in note 1) 25–27; van der Leeuw, op. cit. (in note 1) 84–85; Owen S. Rye, "Keeping Your Temper under Control: Materials and the Manufacture of Papuan Pottery," *Archaeology and Physical Anthropology in Oceania* 11 (1976) 106–137.

3. E.g., Dean E. Arnold, "Ethnomineralogy of Ticul, Yucatan Potters: Etics and Emics," *AmAnt* 36 (1971) 20–40; Owen S. Rye and Clifford Evans, "Traditional Pottery Techniques of Pakistan," *SmithConAnth* 21 (1976); Owen S. Rye, op. cit. (in note 2) 108–109. Discussions of experimental confirmation include: Paul Rado, *An Introduction to the Technology of Pottery* (Pergamon Press: New York 1969) 4, 23; W. G. Lawrence, *Ceramic Science for the Potter* (Chilton: Philadelphia 1972).

4. Shepard, op. cit. (in note 1) 25–27; Rado, op. cit. (in note 3) 190–191; van der Leeuw, op. cit. (in note 1) 84–85.

5. See especially Rye, op. cit. (in note 2); Vincas P. Steponaitis, "Ceramics, Chronology, and Community Patterns at Moundville, A Late Prehistoric Site in Alabama," unpublished Ph.D. dissertation (University of Michigan 1980) 28–83.

6. Rye, op. cit. (in note 2) 114.

7. Shepard, op. cit. (in note 1) 26–27, 131; Gordon P. K. Chu, "Microstructures of Complex Ceramics," in Richard M. Fulrath and Joseph A. Pask, eds., *Ceramic Microstructures* (John Wiley and Sons: New York 1968) 828–862; Rado, op. cit. (in note 3) 194; W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics* (John Wiley and Sons: New York 1976) 768–813; R. W. Davidge, *Mechanical Behavior of Ceramics* (Cambridge University Press 1979) 64–117; Henry P. Kirchner, *Strengthening of Ceramics* (Marcel Dekker: New York 1979) 1–12.

8. Archaeological examples include Rye, op. cit. (in note 2); and Steponaitis, op. cit. (in note 5) 28–83.

9. Rado, op. cit. (in note 3) 191; Lawrence, op. cit. (in note 3) 181–182; Kingery et al., op. cit. (in note 7) 796.

sociated clay, over the range of 0–900°C., for a vessel to survive initial firing. Under any repeated cycles of reheating, however, differences in thermal expansion characteristics eventually will result in fracture. The greater the difference, the greater the stress to be relieved through fracture.[10] Fractures also can initiate as a result of thermal shock, the rapid generation of a pronounced thermal, and hence expansion or contraction differential between inside and outside wall surfaces.[11]

The particle size of temper inclusions also affects resistance to various thermal stresses. The greater the average size of included particles, the greater will be the stresses, leading to fracture, resulting from any differential thermal expansion of those particles. On the other hand, whatever the specific causes of any thermally induced fracture, resistance to crack propagation will still be subject to the effects of particle size irregularities noted earlier.[12]

Other relationships between temper particle characteristics and vessel mechanical performance, which have been suggested but not yet systematically explored in archaeology, include the effects of particle shape, orientation, homogeneity of arrangement in a vessel body, and overall density.[13] For example, irregular particle surfaces are suspected to have a greater positive binding effect during drying than smooth particle surfaces. Theoretically, however, particle-surface irregularities should tend to be points of origin of fractures during use. For another example, the orientation of flat particle surfaces parallel to the vessel walls should increase transverse rupture strength because of an effect on paste fracture planes, but should decrease resistance to crack propagation along planes parallel to the wall surfaces.

The selection of particles for inclusion in a ceramic paste thus not only will follow the requirements of the process of manufacture, but minimally must not interfere with the desired mechanical performance of the resulting vessels. Appropriate selection can, in fact, improve vessel performance under particular circumstances. The potter must establish a compromise in selecting particles for inclusion, balancing the choices according to the risks and benefits of particular materials under particular conditions of manufacture and use. This balancing also involves the consideration of other factors, including the labor and material costs of different choices, intended wall shape and thickness, and whole vessel size and shape. The last four of these also directly relate to vessel intended use and mechanical response characteristics.[14]

It is this process of balancing, finally, that allows us to interpret prehistoric variation in tempering characteristics. Variation in mechanically sensitive temper-particle characteristics, when variation in clay chemistry also has been controlled for, will indicate variation in the relative importance of the factors conditioning the balancing. In theory, then, information on such characteristics as, for example, particle shape, size distributions, and orientation, will provide considerable information on functional variation in ceramic assemblages, in a given cultural context.

## Methods

The method presented here consists of procedures designed primarily to assess the feasibility of measuring temper-particle characteristics from radiographic images of sherds. The procedures are designed for use with relatively low-fired ceramics (firing range less than ca. 900°C.), and so are appropriate for use with all preindustrial utilitarian potteries.

The purpose in using X-radiographic images is to provide a means for rapidly and simultaneously examining temper-particle size, shape, density, and orientation in relatively large numbers of sherds, at a relatively low cost in materials, preparation time, and labor. The use of X-radiography was indirectly suggested for this purpose by Rye,[15] in his research on using radiography to study manufacturing practices. The visibility of many tempering materials in radiographs of pottery has been recognized for a long time, but has not been scientifically

10. Shepard, op. cit. (in note 1) 24–31, 131; Rado, op. cit. (in note 3) 30; Rye, op. cit. (in note 2) 114; Steponaitis, op. cit. (in note 5) 28–83.

11. E.g., D. P. Hasselman, "Unified Theory of Thermal Shock Fracture Initiation and Crack Propagation in Brittle Ceramics," *Journal of the American Ceramic Society* 52 (1969) 600–604; Rado, op. cit. (in note 3) 191–200; Lawrence, op. cit. (in note 3) 174–182; Rye, op. cit. (in note 2) 113–120.

12. Steponaitis, op. cit. (in note 5) 28–83 provides an excellent example of these interactions.

13. E.g., Shepard, op. cit. (in note 1) 24–31, 125–136; Lawrence, op. cit. (in note 3) 102–110, 121–126.

14. Jonathan E. Ericson, Dwight W. Read, and Cheryl Burke, "Research Design: The Relationships Between the Primary Functions and the Physical Properties of Ceramic Vessels," *Anthropology U.C.L.A.* 3 (1972) 84–95; David P. Braun, "Experimental Interpretation of Ceramic Vessel Use on the Basis of Rim and Neck Formal Attributes," in Donald C. Fiero and others, "The Navajo Project," *MNA Research Paper* 11 (Museum of Northern Arizona: Flagstaff 1980) 171–231; David P. Braun, "Pots as Tools," in Arthur Keene and James Moore, eds., *The Hammer Theory of Archaeological Research* (Academic Press: New York in press).

15. Owen S. Rye, "Pottery Manufacturing Techniques: X-Ray Studies," *Archaeometry* 19 (1976) 208.

exploited.[16] Readers are referred to such works as those by Krinitsky, and Christensen et al., as well as by Rye, for information on the relevant principles and mechanics of radiography.[17]

The method separates into four procedural stages: X-radiography; measurement of temper-particle characteristics; recording of certain control data for each sherd; and statistical synthesis.

*X-radiography*

Because the present study aimed only at assessing overall feasibility, no experiment with the details of radiographic technique was pursued, and most of Rye's guidelines were followed.[18] As is discussed in the conclusions below, improvements in the kinds of results obtainable undoubtedly can be achieved through the refinement of radiographic technique. Availability dictated the use of a standard grade of rapid, coarse-grained, medical X-ray film (Kodak RPX-1). Trial runs were conducted both with and without an intensifying screen, with and without high-speed filtering. Greatest particle-image clarity, given the coarseness of the film grain, was obtained in the absence both of screen and filter, with a cost of only moderately longer exposure times.

Sherds must be sorted roughly by thickness, with each film sheet recording only one range of thicknesses (in 5 mm. gradation, in our experiments), to achieve approximate uniformity of exposure of individual sherd images. Sherd curvature did not appear to affect particle image resolution, although in our experiments no sherd had less than a 10 cm.-diameter arc of maximum curvature. Sherds were laid, concave side upward, on a film packet, closely packed but without overlapping edges, generally in a specimen-numerical order to facilitate later analysis. Thirty to 60 sherds ordinarily could fit on a single 14 in. × 17 in. sheet of film, still leaving an area along one edge for recording control information.

Exposures generally were made at 60–65 Kv and 100 mA, varying the exposure time by sherd-thickness grade. This dosage level was chosen over the much lower, slower procedures advocated by Rye,[19] for expediency only. Much finer detail can be obtained with a lower dosage procedure, but was not needed in this initial set of experiments. Exposures were made with hospital X-ray equipment of varying manufacture, with a film-to-source distance of ca. 1.5 m. in all cases. A more rigorous application of the proposed archaeological methods would, of course, require standardization of the radiographic equipment as well.

*Temper Measurement*

Tempering particles appear on radiographs as areas of contrastingly lighter exposure, indicating greater resistance to the penetration of radiation than the surrounding matrix of fired clay. Where the temper has weathered out, as in cases of burned-out organic materials or dissolved crystalline carbonates (e.g., shell, coral, limestone), the resulting holes in the clay show up as areas of contrastingly darker exposure. Figure 1 illustrates the range of particle-image variation observable with pottery from the prehistoric midwestern U.S.

The feasibility of deriving useful quantitative data from radiographs was assessed in the present experiments by attempting to measure the maximum densities of particles of different average size grades. Clearly, measurements of particle shape and orientation also should be readily obtainable from the same images. Maximum densities were examined because of the variation present in the density of observable particles even within a single sherd's image. Given this variation, greater consistency among laboratory workers was found in identifying the region of the greatest, rather than the average or lowest, particle-image density. Particle size was scaled by minimum diameter, and estimated using a comparative gauge of idealized particle images. Laboratory experience showed that the size increments on the gauge should be relatively small (0.1 mm., in our case), to reduce the problem of interpolation errors.

The measurement of particle densities was treated as a sampling problem, in which a unit of area of a sherd's image would be treated as a sample of its overall image area. Counting all the particle images in a unit, such as a square inch of each sherd's image, proved highly time-consuming. Following standard procedures in, for example, petrography and pedology, a Point Count procedure was adopted instead.[20] This procedure estimates the *percent of a given unit of area* occupied by different categories of materials, by recording category presence/absences for each point in a regular grid of points placed over the area. The procedure generates estimates of the *percent* of area occupied by each category, in the present

16. One example of the informal use of X-rays on pottery is Paul F. Titterington, "Certain Bluff Mounds of Western Jersey County, Illinois," *AmAnt* 1 (1935) Plate 7.

17. E. L. Krinitzsky, *Radiography in the Earth Sciences and Soil Mechanics* (Plenum Press: New York 1970); Edward E. Christensen, Thomas S. Curry, III, and James Nunnally, *An Introduction to the Physics of Diagnostic Radiology* (Lea and Febiger: Philadelphia 1972); Rye, op. cit. (in note 15).

18. Rye, op. cit. (in note 15) 209–211.

19. Ibid.

20. R. B. Daniels, E. E. Gamble, L. J. Bartelli, and L. A. Nelson, "Application of the Point Count Method to Problems of Soil Morphology," *Soil Science* 106 (1968) 149–152.

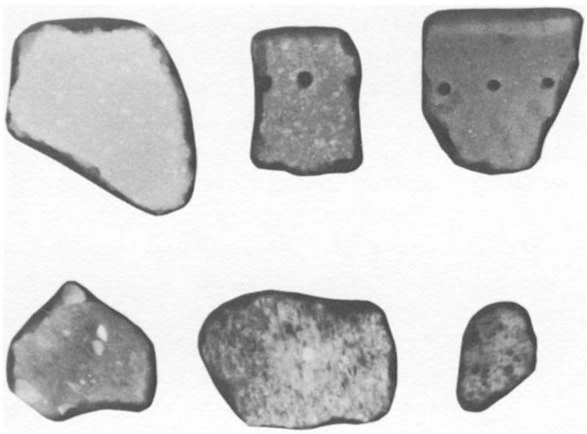

Figure 1. Examples of x-radiographs of pottery from the prehistoric midwestern U.S. Clockwise from upper left (scale 1:1): thick sherd, coarse crushed quartz-rich rock temper; rim sherd with punched decoration, moderate temper; rim sherd with punched decoration, fine temper; leached-out crushed limestone tempering; leached-out fine shell tempering (Mississippian); extremely coarse rock temper.

case images of particles of different size grades, within a known theoretical sampling error. In the present case an area of 1 square inch was converted to a grid of 100 points. Recording times, including counting time, among workers experienced with this procedure, rarely exceeded 10 minutes each for even the most densely tempered sherds.

The laboratory procedure used for point counting was as follows (using a light table).

1. Place grid over sherd image, covering area of highest overall particle-image density, but also so that the largest particle in that field is intersected by as many points as possible. Where a 100-point grid cannot fit, use a smaller standard area of 50 points (FIG. 2).
2. Examine each grid point and, where a point intersects a particle image, record a ''presence'' for that particle's size grade. Because the procedure estimates only the percent of area of a sherd's image occupied by each size grade, it does not matter that larger particles may intersect more than one grid point. Care must be taken to identify those larger particle images created by the radiographic superimposition of images of smaller particles. Care also must be taken to identify the images of weathered-out particles, and to distinguish between these and the images of microcracks or of decorative indentations.
3. Convert tabulations by grid point to total point counts (0–100) for each particle size grade, and record.

### *Analytical Controls*

Statistical analysis of the point-count measurements requires the recording of several control variables for each sherd, in addition to item number, archaeological provenience, and film sheet references. First, the area and number of grid points used for obtaining the point-count measurements must be recorded. Second, sherd thickness must be recorded. Because each radiographic image collapses a three-dimensional field of particles into two dimensions, the effects of thickness both on individual particle visibility and apparent overall particle density on the exposed film must be controlled mathematically.

Third, experience showed that the recording of a code rating the quality of visibility of particles aids in dealing with observations of which the recorder is unsure. The code in the present case ranged from acceptable, to mixed, to unacceptable visibility, and varied primarily with the quality of the exposure and the density of very small (D. less than 0.5 mm.) particles present. Finally, it is important to record some overall gross classification of temper mineralogy (e.g., ''sand,'' ''crushed granite,'' ''crushed limestone,'' ''crushed shell'') based on a visual inspection of a breakage face. Such classification, based on whatever rapid-sorting criteria are locally applicable aids the technician in anticipating details of the particle images on the radiographs, and helps control for potential variation in the radiographic visibility (contrasting penetrability) of different raw tempering materials. This latter topic is discussed briefly below, in the conclusions. Other control variables, such as each sherd's position of origin on a whole vessel profile, or the presence of painting or a slip, can be recorded as the researcher may need.

### *Statistical Synthesis*

The reduction of the measurements to a usable form first requires the standardization of all point-counts to the

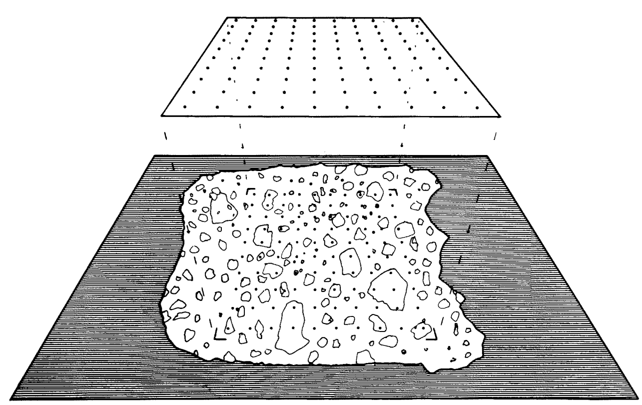

Figure 2. Schematic diagram of the use of a 100-point grid to estimate the percent of area of a sherd image covered by particle images of different size grades. The example has an overall point count of 29. Grid point size is exaggerated for illustration.

same unit of area. The reduction then requires the correction of the point-counts for the fact that they represent a collapsing of three dimensions into two. While the radiographic method deals with the representation of particles by relative *area,* potters generally control the mixing-in of temper by relative *volume.*[21] There are a variety of ways to correct the estimates of image-area percent, for each particle size grade, back to estimates of sherd-volume percent, involving different assumptions about particle shape and the extent of undetected superimposition among particle images. The simplest procedure, entailing the fewest assumptions, multiplies the image-area percent for each particle size grade, by the ratio of the median particle diameter (for that size grade) to sherd thickness. This latter ratio represents an estimate of the percent of sherd thickness that could be occupied by a particle of each size grade. This simplest correction estimates the *minimum* volume percent occupied by each particle size grade in each sherd. If the particle size grades are relatively narrow, e.g., 1 mm. or 0.5 mm. incremental grades, their volume-percent values can be recombined into broader categories as the researcher may need.

### Experimental Results

The above procedures were developed as part of a study of changes in cooking technology during the Woodland period in the central midwestern U.S., ca. 600 B.C.–900 A.C. Materials studied to date and reported upon here fall more specifically between ca. 1 A.C. and 900 A.C. The goals of this study are twofold: to gain information on changes in subsistence practices during the transition from mobile foraging to sedentary food production; and to improve the precision and accuracy of regional ceramic chronometry by taking analytical advantage of any subsistence-related changes in ceramic engineering.[22] Dietary changes during the region's Woodland period include an increasing attention to the harvesting, artificial encouragement, and, eventually, regular cultivation of locally native starchy seed foods, along with an increasing attention overall to the cultivation of introduced starchy and oily seed foods.[23] Associated changes in ceramic engineering include decreasing wall thicknesses in cooking containers, an eventual shift to globular forms of cooking container from early, more cylindrical forms, and an increasing fineness of tempering inclusions.[24]

The trend in tempering particle size, long recognized in the region's literature, has been known only from qualitative assessments, and generally has been used only to help separate pottery into, at best, 200-year "phases" defined by overlapping sorting criteria.[25] The potential functional significance of the trend previously has not been considered. It was hoped that the radiographic methods would allow us both to quantify the changes in temper characteristics, and thereby more precisely to assess their chronometric utility; and also to assess the functional significance of the changes, by providing data on mechanically sensitive particle characteristics.

The data base for the overall project consists of sherds recovered in association with radiocarbon-dated charcoal from pit features at habitation sites in two pilot study areas: the lower Illinois River valley in west-central Illinois, and the combined upper Big Muddy River and upper Saline River basins in south-central Illinois. For the sake of clarity only the results for the Illinois valley are discussed below; similar results have been obtained in both study areas.[26] The radiographic procedures were employed alongside several other laboratory procedures

21. E.g., Arnold, op. cit. (in note 3); Rye, op. cit. (in note 2); Rye and Evans, op. cit. (in note 3); Warren R. DeBoer and Donald W. Lathrap, "The Making and Breaking of Shipibo-Conibo Ceramics," in Carol Kramer, ed., *Ethnoarchaeology: Implications of Ethnography for Archaeology* (Columbia University Press: New York 1979) 102–138.

22. David P. Braun, M. Denise Hutto, and Michael L. Hargrave, "Three Papers on Woodland Ceramic Chronometry," papers presented at the Midwest Archaeological Conference, Chicago 1980; Braun, op. cit. (in note 14, in press).

23. David L. Asch, Kenneth B. Farnsworth, and Nancy B. Asch, "Woodland Subsistence and Settlement in West Central Illinois," in David Brose and N'omi Greber, eds., *Hopewell Archaeology: The Chillicothe Conference* (Kent State University Press: Kent, Ohio 1979) 80–85.

24. E.g., David P. Braun, "On the Appropriateness of the Woodland Concept in Northeastern Archaeology," in James A. Moore, ed., "Proceedings of the Conference on Northeastern Archaeology," *University of Massachusetts, Amherst, Department of Anthropology, Research Reports* 19 (1980) 93–108.

25. E.g., James B. Griffin, "Some Early and Middle Woodland Pottery Types in Illinois," in Thorne Deuel, ed., *Hopewellian Communities in Illinois, Illinois State Museum, Scientific Papers* 5 (1952) 93–130; Stuart Struever, "Middle Woodland Culture History in the Great Lakes Riverine Area," *AmAnt* 31 (1965) 211–223; Stuart Struever, "A Re-examination of Hopewell in Eastern North America," unpublished Ph.D. dissertation (University of Chicago 1968) 140–172; James B. Griffin, Richard E. Flanders, and Paul F. Titterington, "The Burial Complexes of the Knight and Norton Mounds in Illinois and Michigan," *MMichMusAnth* 2 (1970) 1–10; Marvin Kay and Alfred E. Johnson, "Havana Tradition Chronology of Central Missouri," *MCJA* 2 (1977) 195–217; David W. Benn, "The Woodland Ceramic Sequence in the Culture History of Northeastern Iowa," *MCJA* 3 (1978) 215–283.

26. See also Michael L. Hargrave, "Ceramic Materials from the Carrier Mills Archaeological District," manuscript in preparation (n.d.).

Table 1. Control data for pottery samples used in evaluation of radiographic methods.

| *Pottery Sample Provenience* | *Total N* | *Meas.* N* | *Radiocarbon Association Lab. No.* | *Date B.P.* | *Radiocarbon reference* | *Comments* |
|---|---|---|---|---|---|---|
| Apple Creek Fea. 451 | 50 | 28 | M–1997 | 1030 +/– 120 | 12:168 | |
| Bridgewater Fea. 1 | 24 | 17 | M–1999 | 1050 +/– 200 | 12:168 | |
| Apple Creek Fea. 203c | 59 | 54 | M–1407 | 1160 +/– 120 | 8:266 | |
| Newbridge Fea. 6 | 18 | 14 | M–2000 | 1290 +/– 130 | 12:169 | |
| Apple Creek Fea. 84c | 55 | 49 | M–1406 | 1310 +/– 100 | 8:266 | mixed deposit |
| Stilwell Fea. 9 | 60 | 54 | M–1262 | 1330 +/– 120 | 6:4 | |
| Newbridge Fea. 2 | 50 | 26 | M–2002 | 1330 +/– 400 | 12:169 | large $^{14}C$ error |
| Bridgewater Fea. 2 | 10 | 8 | M–1998 | 1470 +/– 130 | 12:168 | small sample size |
| Apple Creek Fea. 367 | 7 | 6 | OWU-105b | | 9:326 | small sample size, |
| | | | M–1721 | 1490 +/– 104 | 10:76 | averaged date |
| Stilwell Fea. 14 | 55 | 51 | M–1263 | 1550 +/– 120 | 6:4 | |
| Snyders Fea. 8d | 78 | 38 | M–1155 | 1720 +/– 75 | 5:231 | 21 sherds not x-rayed |
| Snyders Fea. 8c | 60 | 58 | M–1154 | 1890 +/– 75 | 5:231 | |
| Macoupin Fea. 173 | 50 | 49 | M–2243 | 1900 +/– 140 | 14:207 | |
| Macoupin Fea. 127 | 15 | 10 | M–2229 | 1950 +/– 200 | 14:207 | |
| Macoupin Fea. 23 | 15 | 12 | M–2225 | 2020 +/– 200 | 14:207 | |

*Number of sherds yielding a usable radiographic image

measuring a variety of properties of ceramic vessel shape and engineering.[27]

Analyses have been completed to date on the pottery from 15 radiocarbon-dated features from the lower Illinois valley, spanning the period from 70 B.C. ± 200 to 920 ± 120 A.C. (uncalibrated) (TABLE 1). Of the 585 sherds examined so far, 474 (80%) were large enough and produced radiographic images of sufficient clarity to permit their complete measurement. Figure 3 illustrates the dominant trend in temper-particle density, using those features with acceptable cultural depositional integrity and sample sizes of 10 or more measurable sherd images. A trend of decreasing particle density overall, for particles 1 mm. or more in minimum diameter, is apparent, despite the overlap in radiocarbon error values. This trend in turn can be broken up into the component trends of narrower particle-size ranges (FIG. 4). Systematic relationships between each sherd's temper-particle size distribution and other technological variables, such as originating vessel size and shape, may account for some of the differences between approximately contemporary feature samples. These possible relationships will be explored in the near future.

Most particles used in Illinois Woodland pottery are mixtures of quartz-rich sand and crushed, angular quartz-rich rock. Both angular crushed chert and limestone also occur in small numbers of specimens. Based on the theoretical framework discussed earlier, and the recognition that most of the tempering materials do not closely resemble most clays in their thermal expansion characteristics,[28] the trends in temper-particle inclusions indicate

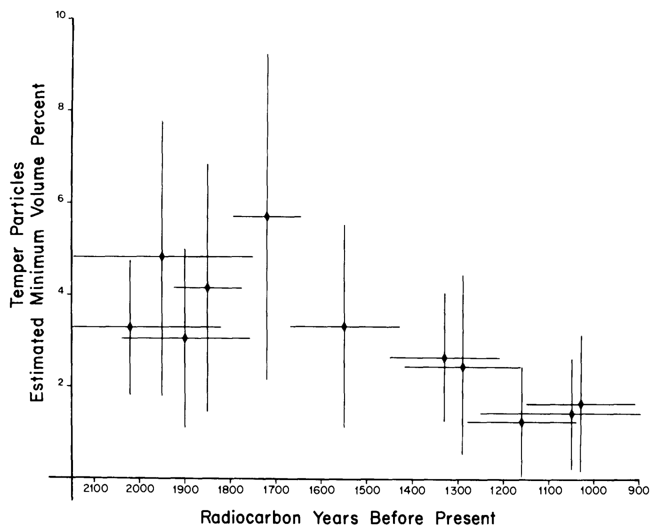


Figure 3. Estimated minimum volume percent (EMVP) for particles equal to or greater than 1 mm. in minimum image diameter, vs. sample radiocarbon date, B.P. uncalibrated (RCBP), for 11 Woodland period sample collections from the lower Illinois River valley. Bars indicate one standard deviation for the determinations of EMVP and RCBP.

27. Braun et al., op. cit. (in note 22); Braun, op. cit. (in note 14, in press).

28. E.g., Rye, op. cit. (in note 2) 116–118.

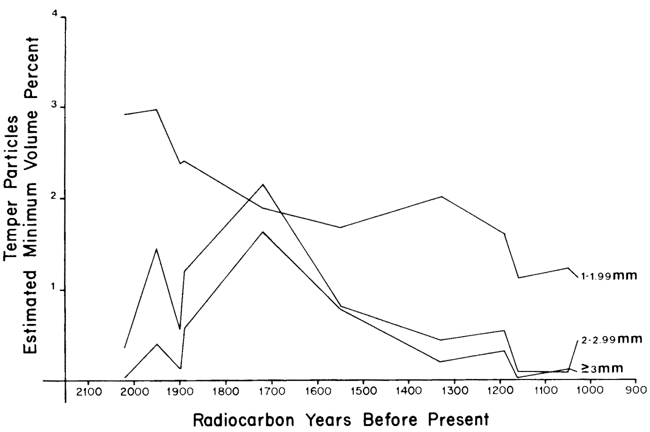


Figure 4. Estimated minimum volume percent for different particle size grades, vs. sample radiocarbon date, B.P., uncalibrated, for 11 Woodland period sample collections from the lower Illinois River valley.

a single overall engineering trend: increasing intended resistance to thermally induced fracture, at increasing levels of thermally induced stress. This interpretation of the changes in temper inclusions parallels information obtained from the analysis of other ceramic properties.[29]

The feasibility of the radiographic method, however, depends not only on whether or not it helps detect meaningful patterns, but on whether or not it accurately and precisely (in a statistical inferential sense) represents the true extent of ceramic variability. How much of the identified variation within or between samples represents technical and measurement error rather than prehistoric cultural variation?

The data summarized here were collected by six different assistants, each fully trained on the same test samples prior to measuring any of the actual research samples. Each assistant analyzed portions of research samples from along the full temporal range represented. The overall temporal changes, therefore, are not thought to result from measurement variation among the laboratory assistants.

Table 2 summarizes the observed and theoretically expected sampling errors for the 11 sample collections represented in Figure 3. The observed error values do not greatly exceed the theoretically expected values, in the nine samples where they do exceed, indicating that no unexpectedly large error effects are present. On the other hand, the observed error values derive from estimates of *minimum,* rather than true volume percent. For this reason, the discrepancies between the observed and expected error values probably do not conversely indicate an especially high level of precision in our experiments, either.

The present data do contain at least one systematic bias. Increasing sherd thickness appears to entail a progressive loss of visibility of increasingly small particles in the radiographic images. This effect appears particularly pronounced, for example, for particles 1 mm. to 1.99 mm. in minimum diameter in sherds 9 mm. or more in thickness (FIG. 5). While this apparent effect partly may result from functional constraints on the selection of temper for thicker-walled vessels or vessel portions, in our case it more probably results primarily from radiological constraints on embedded particle visibility. The use of a more dense, fine-grained grade of film and lower, slower exposure dosages should reduce this effect; as is discussed briefly below, however, additional experiments also are required.

## Conclusions

Initial results indicate that ceramic temper particles can be efficiently analyzed for mechanically sensitive characteristics from X-radiographs. Measurements can be quantitative, and be obtained relatively rapidly for large numbers of sherds. Although the illustration presented involves a study of variation over time in a single functional category of vessels, the relevant concepts would apply equally to studies of synchronic variation among multiple functional categories.

The methods clearly demand refinement, however, to increase detail and reduce measurement error. Following

Table 2. Comparison of observed and expected error terms, for Estimated Minimum Volume Percent, for particles ≥ 1 mm. minimum diameter.

| *Sample Date** | *Mean E.M.V.P.*** | *Observed s* | *Expected*** s* |
|---|---|---|---|
| 1030 | 1.668 | 1.472 | 1.281 |
| 1050 | 1.427 | 1.205 | 1.186 |
| 1160 | 1.254 | 1.200 | 1.113 |
| 1290 | 2.485 | 1.941 | 1.557 |
| 1330 | 2.660 | 1.407 | 1.609 |
| 1550 | 3.310 | 2.204 | 1.789 |
| 1720 | 5.702 | 3.541 | 2.319 |
| 1890 | 4.150 | 2.709 | 1.994 |
| 1900 | 3.064 | 1.945 | 1.723 |
| 1950 | 4.835 | 3.007 | 2.145 |
| 2020 | 3.296 | 1.464 | 1.785 |

*Radiocarbon years B.P., uncalibrated.
**Estimated Minimum Volume Percent.
***Expected standard deviation, $s = \sqrt{npq}$, where
n = number of points in counting grid;
p = E.M.V.P., expressed as a proportion;
and q = (1 − p) (see footnote 20).

29. Braun, op. cit. (in note 14, in press).

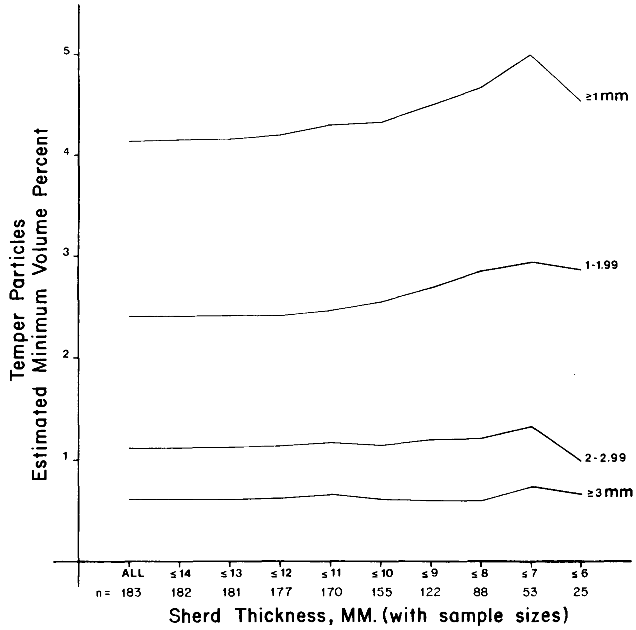


Figure 5. Estimated minimum volume percent for different particle size grades, vs. maximum sherd thickness: (mm.) in a combined sample of 183 Middle Woodland sherds, dating 1720–2020 radiocarbon years B.P. (see Table 1), from the lower Illinois River valley. Sample sizes for each step of the determinations are shown along the horizontal axis.

Rye,[30] I would strongly recommend the use of a more fine-grained, dense, slow-speed industrial film to increase the sharpness of all particle images and particularly those of particles less than 1 mm. in average diameter. The use of fine-grained film also makes it productive to examine the sherd images under enlargement. Informal experiments indicate that appropriately cut film sheets can be examined under enlargement using a microfiche reader, eliminating the problems posed by hand-held magnifiers. I also would recommend the refinement of particle size and shape gauges. The greater the detail given in the gauge, the smaller will be the interpolation error present in the recorded measurements.

The problems of progressive loss of visibility with finer particle size and greater sherd thickness also demand further investigation. Analyses of experimental tiles of varying thickness and temper-size constituency should be used to determine empirically the extent of distortion and interaction effects under controlled conditions. The subject also could be addressed purely mathematically.

The initial methods involved the measurement of particle densities only from the area of greatest apparent density in each radiographic image. As noted, this selectivity helped maintain consistency in the replication of results for single sherds. Variability in tempering characteristics within single vessels could have affected mechanical performance, however, and so may be a worthwhile subject for statistical rather than purely procedural control.

Finally, the initial methods assumed, for mathematical purposes, an approximately three-dimensional symmetry for each particle. In cases where plate-like particles (e.g., mica or laminated shell) occur, somewhat different mathematical procedures will be required.

Beyond these areas demanding refinement, several already known limitations require mention. First, as Rye has noted, exposure to X-rays renders a sherd useless for analyses of thermoluminescence.[31] Second, not all tempering materials will differ in their resistance to radiational penetration from the surrounding fired clay. Tempering inclusions of crushed sherds or simply crushed fired clay, for example, may be no more or less radiographically dense than the surrounding matrix, unless their initial firing or refiring changes their crystalline structure relative to that of the surrounding matrix. In informal trials, the above experimental procedures were unable to detect crushed sherd tempering, present in some of the Woodland pottery from the south-central Illinois pilot study area.

In areas where tempering raw materials do not impose limitations, the use of radiographic methods for analyzing temper appears both feasible and, for several large areas of research, highly desirable. With the suggested refinements, methods similar to those discussed here should help increase our ability to extract useful behavioral information from the archaeological record.

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30. Rye, op. cit. (in note 15) 209–211.

31. Ibid. 208.

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