

**TECHNOLOGICAL STUDIES OF PREHISTORIC POTTERY
FROM ALABAMA: PHYSICAL PROPERTIES AND VESSEL
FUNCTION**

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"It can be argued that specific materials and techniques [of pottery manufacture] are selected by cultural pressures ... but such arguments are not valuable unless supported by data delineating the practical limitations of material use. ... If the technological constraints can be identified then we move further to understanding why potters have used specific materials and methods, and why some vessels may be 'superior' to others."

Rye 1976:106

There can be no doubt that pottery vessels reflect, to some extent, the 'mental templates' or cultural norms of the people who made them. This is why we have relied so heavily on pottery in defining archaeological cultures and in assessing the pattern and degree of interaction among sites. Yet it must also be recognized that pottery vessels, like any other utensils, were made to be used, and that function plays a very important rôle in determining a vessel's characteristics (Braun 1981; Linton 1944; Rye 1976, 1981; Shepard 1956).

Numerous studies have investigated vessel shape in relation to function. Considerably less attention, however, has been devoted to how the physical properties of the ceramic material itself can affect a vessel's suitability for various uses. Among the properties that could be considered important in this regard are permeability, which affects a container's fitness for storing liquids; thermal conductivity, which affects a vessel's performance in cooking; and both strength and thermal stress resistance, which are major determinants of ceramic longevity. All of these properties are affected by the materials and techniques of manufacture, and so within certain limits they can be manipulated to the potter's advantage.

The last-mentioned fact presents the archaeologist with a powerful tool for interpretation. To the extent that physical properties are empirically measurable, and their relationship to

fabrication processes is understood, these factors can be used to explain why prehistoric potters made their wares in certain ways and not others. Such an approach, when combined with other lines of evidence, can often lead to a more complete understanding of the ceramic variation which is manifested in the archaeological record.

In this paper, I present two examples of how such an approach can be applied to archaeological data, in both cases dealing with prehistoric pottery from west-central Alabama. The first study is concerned with explaining synchronic differences between ware groups that were produced at a single site. The second example takes a somewhat broader view, and attempts to explain the major changes in tempering practices that occurred throughout the region from 500 B.C. to A.D. 1550.

CASE 1: SYNCHRONIC VARIATION IN PASTE COMPOSITION

The first case we shall consider deals with pottery from Moundville, a late prehistoric site on the Black Warrior River occupied from about A.D. 1000 to 1550 (Peebles 1978, 1979; Steponaitis 1980, 1983). Technological studies were carried out to investigate the relationship between the pottery's composition and its physical properties. In brief, the results strongly suggest that the distinction between coarse and fine shell-tempered wares at Moundville was based on technological factors related to function, and was not simply an arbitrary distinction rooted in aesthetics or cultural convention, as archaeologists have commonly believed.

In order to provide some background on the nature of the assemblage being considered, let us begin with an overview of the materials and techniques of pottery manufacture at the site, as reconstructed from archaeological and other evidence. The account that follows is deliberately brief: most of the detailed evidence on which it is based has been published elsewhere (Steponaitis 1983).

Moundville pottery: materials and manufacturing techniques

All the raw materials required for pottery manufacture at Moundville were easily obtained locally. Numerous outcrops of high-quality clay occur not only in the immediate vicinity of the site itself, but also throughout the entire region. Mineralogical analyses have shown that local clays are predominantly kaolin-illite mixtures, and also contain quartz, hematite, muscovite mica, and plagioclase feldspar as common accessory inclusions (Clarke 1966; Steponaitis 1983:18-20). This range of minerals corresponds closely to those found in Moundville ceramics, indicating that these types of clay were indeed used by Moundville potters (Steponaitis 1983:30-33).

The other major ingredient of Moundville pottery was crushed shell, which was added to the clay as temper. This shell was almost certainly obtained from locally available mussels, as evidenced by the fact that the temper particles, when viewed microscopically in thin sections, commonly exhibit the kinds of internal shell structures that are typical of the family Unionacea - a taxon that subsumes a large portion of the bivalves native to the rivers of the southeastern U.S. (see Taylor et al. 1969: 109-115).

Although direct archaeological evidence of the practice is still lacking at Moundville, it is quite likely that shells were deliberately heated before being added to the paste as temper (Porter 1964:3-4; Million 1975a:218-219). Such heating would have offered the potter two practical advantages. The first and most obvious benefit is that heating whole shells makes them extremely friable, and greatly reduces the effort required to crush them to the appropriate size. The second benefit has to do with certain changes in shell mineralogy which take place at elevated temperatures. Unionid shells in their natural state consist mainly of the mineral aragonite (Taylor et al. 1969:109; Porter 1964:2), which, when heated to about 500° C, alters irreversibly to calcite (Hutchinson 1974:454). Although both these minerals are crystalline forms of calcium carbonate, the shift from one to the other entails an expansion in volume which could cause some damage if it were to occur inside the vessel wall during firing. Pre-heating the shell reduces the risk of such damage, by allowing

the expansion to take place before the shell is added to the paste. Million (1975a:219; 1975b:202) has found conclusive evidence that Mississippian potters in northeast Arkansas used burned shell as temper, and given the cultural similarities between the two regions, there is no reason to believe that the Moundville potters would have done otherwise.

Moundville vessels were invariably constructed by hand, generally by means of a coiling technique (Van der Leeuw 1981; Steponaitis 1983:21-29). Manufacturing traces visible on vessels and sherds indicate that many of the pots were placed on a flat or basin-shaped support while being built. Minimally, such a support probably acted as a rotating device on which the vessel could be turned, as coils were added to the walls; in some cases the support also served as a mould in which the base was formed by squeezing out a lump of clay. Once the basic shaping of the vessel was complete, the secondary shaping and finishing techniques employed depended a great deal on what kind of vessel was being made. Bowls and bottles were usually thinned by scraping, and then burnished. Jars, on the other hand, were generally finished with a paddle and anvil technique, after which the surfaces were scraped and smoothed, but not burnished. Vessels of all shapes were often decorated with incised designs and/or appliquéd appendages.

After the vessel had been thoroughly dried, the last step in the manufacturing process was firing. There is no evidence, archaeological or ethnographic, that the native inhabitants of eastern North America ever used true kilns in firing their wares. The most reasonable assumption, then, is that the Moundville potters relied on some variant of open firing - perhaps using a bonfire or, as Million (1975a:220) has suggested, a shallow pit filled with coals and covered with large sherds. The fact that the vessels were shell-tempered implies that firing temperatures generally remained below 800° C. Higher temperatures would have caused the calcite to decompose, initiating the process called 'lime spalling' which usually results in serious damage to the vessel wall (Rye 1976; Steponaitis 1983:33).

Although much has been learned in recent years about the technical aspects of pottery manufacture at Moundville, consid-

erably less is known about the social context and organization of production. Given the limited number of shapes produced and the relatively low-degree of standardization, it has generally been assumed that most, if not all, Moundville pottery was produced in a domestic context. Admittedly, there does exist some evidence for the presence of specialist potters at Moundville. Excavations have yielded at least one unusually large group of vessels that, on the basis of style, appear to be the work of a single individual (Hardin 1981). The overall rarity of such finds, however, suggests that highly specialized production was not the dominant pattern (cf. Van der Leeuw 1981). The prehistoric situation was probably one in which a few particularly skilled potters consistently produced more vessels than they themselves could use, and distributed their surplus to other members of the community through gift-giving or exchange. Yet production was never fully in the hands of such part-time specialists, since each household probably contained at least some individuals who could, and occasionally did, make their own pots.

The effect of paste composition on physical properties

Now that we have considered the fabrication processes of Moundville wares, let us examine the relationship between physical properties and ceramic composition.

Moundville pottery can be divided into two broad groups, which differ from each other in both function and paste composition. One group consists mostly of bowls and bottles that were used as eating and storage vessels, but were not used for cooking. Typically, these non-cooking vessels are tempered with finely-ground shell, and have a dark surface finish produced by deliberate smudging during the last stages of firing (fig. 1). Indeed, the fact that most of them are 'black-filmed' implies that they were not used for cooking, because contact with a cooking fire would have oxidized the surface and made it lighter.

The second group, the cooking ware, consists of unburnished jars. These vessels, in contrast to the non-cooking wares, are usually tempered with coarse shell. The surface colour tends to be an oxidized reddish brown, and many vessels exhibit a band of soot around the body - exactly the kinds of traces one would expect

to find on a pot used over a fire (Hally 1980) (fig. 2).

One can see the difference in the way these two functional groups are tempered by looking at the histograms shown in fig. 3. These histograms illustrate the frequency distribution of the third largest temper particle visible in the vessel's surface, based on a sample of about 50 vessels in each group. (The third largest particle tends to be more representative of the size of the coarse fraction in the paste, since even a finely tempered vessel is likely to have one or two anomalously large shell particles visible on the surface.) Although the two distributions overlap somewhat, the unburnished jars clearly tend to have larger shell inclusions than the bowls and bottles. The mean size of the coarse particles is about 4 mm for jars (the cooking vessels) as compared to only 2 mm for bowls and bottles (the non-cooking vessels).

Not only are the two groups distinguished according to the size of the shell inclusions, but they also tend to differ in amount of visible shell they contain. The histogram in fig. 4 illustrates the volume percentage of visible shell found in the small, but fairly representative sample of ten sherds which were examined in thin-section. One can see that the distribution is bimodal, with most of the cooking vessels having relatively abundant shell, and most of the non-cooking vessels having relatively sparse shell.

Quite clearly, Moundville potters tended to use different paste compositions in making vessels designed for different uses. Cooking vessels were usually made with large particles and abundant visible shell, while non-cooking vessels were usually made with finer particles and not as much visible shell (fig. 5). Why should this have been so? Many archaeologists have tended to view this distinction as being purely a matter of aesthetics or cultural convention. That is, the fine paste vessels are often thought of as being the 'ceremonial' or 'nice' ware, while the coarse paste vessels are regarded as the common 'utilitarian' ware (e.g. Goldstein 1980:15). The difference in composition is thus implicitly seen as the result of effort minimization: the utilitarian ware did not need to look as nice, and so the Indians did not take the trouble to grind up the shell as finely.

There is good reason, however, to question such an interpretation, at least insofar as the Moundville materials are concerned.

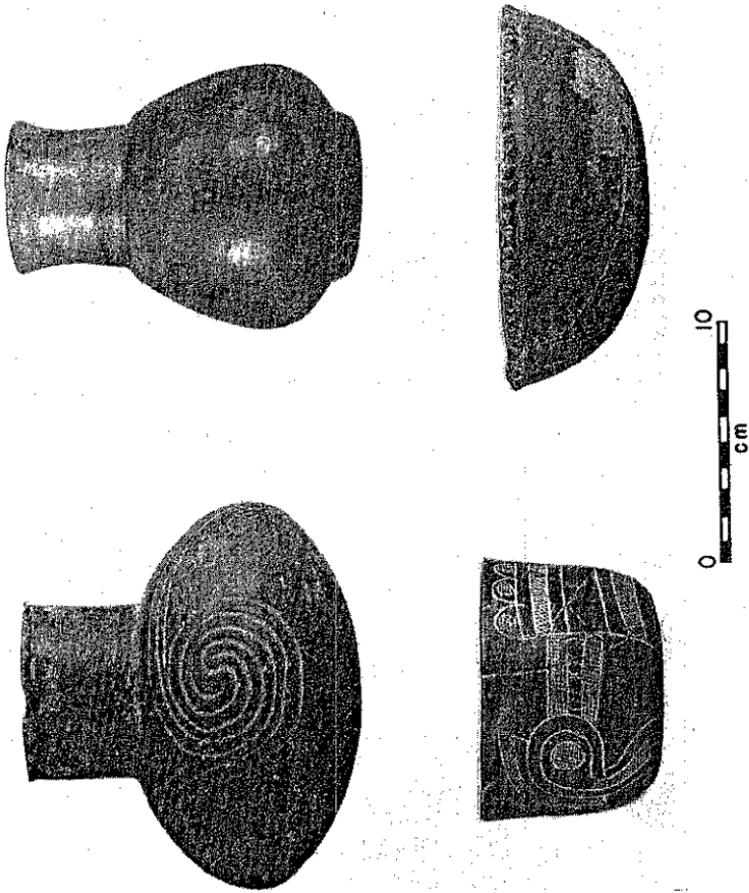


Figure 1 Typical non-cooking vessels from Moundville. Top: Berries; bottom: bowls.

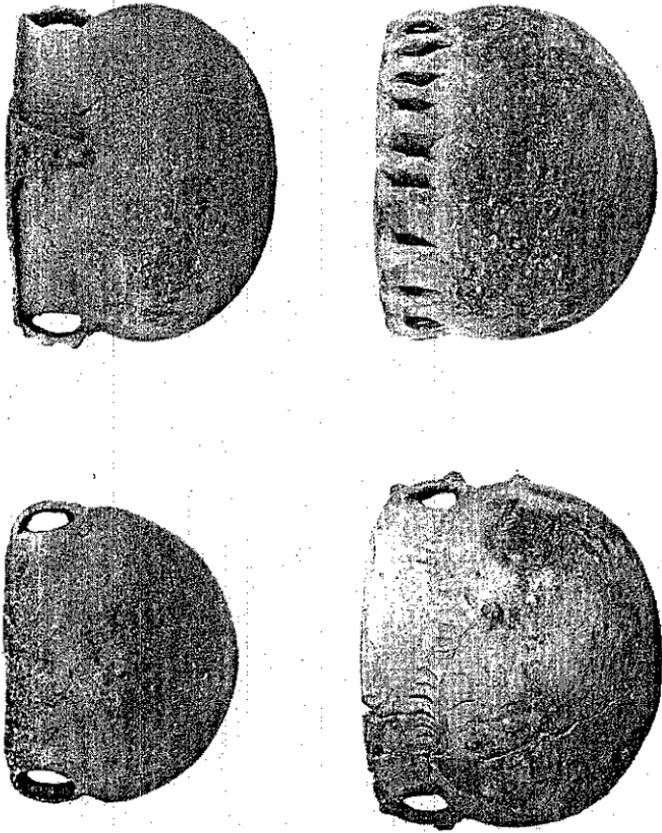


Figure 2 Typical cooking vessels (jars) from Moundville

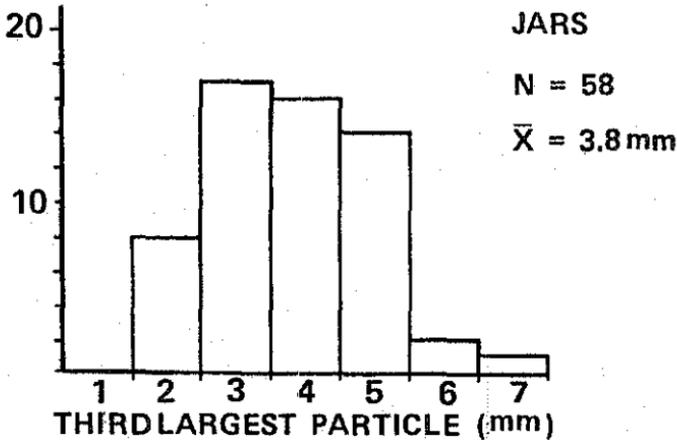
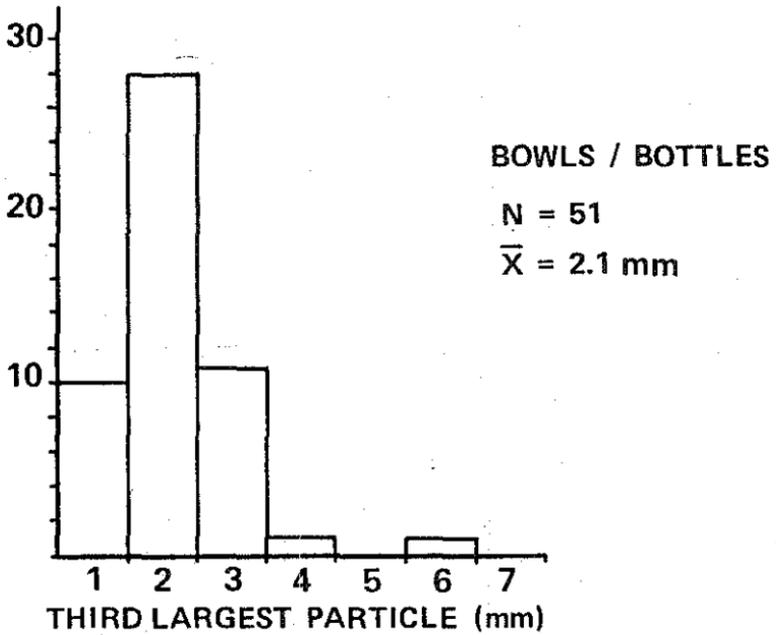


Figure 3 Frequency distribution for the size of the third largest temper particle in Moundville vessels. Top: non-cooking vessels; bottom: cooking vessels.

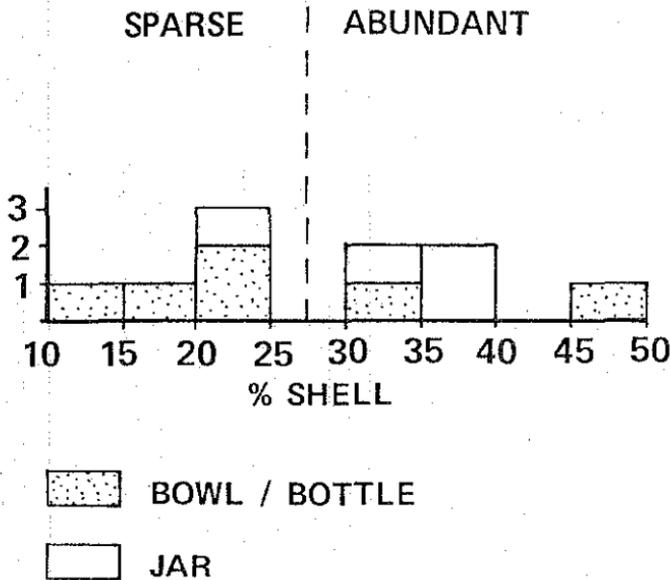
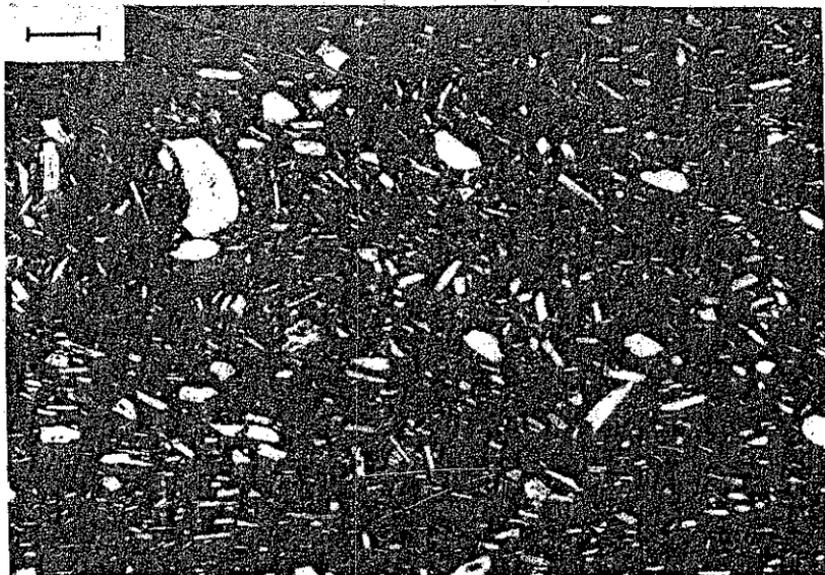


Figure 4 Frequency distribution for the abundance of visible shell temper, expressed as a percentage of total volume (data from Table 1).

Figure 5 (right) High contrast photographs of sherd cross-sections illustrating the difference in paste composition between ware groups. Top: non-cooking vessel (S-7); bottom: cooking vessel (S-6). Shell temper particles appear as light inclusions against a dark background which constitutes the clay matrix. The scale bar in the upper left of each photograph represents 1 mm.



Given that the shell was heated before being crushed, very little extra effort would have been required to make the shell particles fine. Moreover, ethnographers have documented a number of cases in which traditional potters make a conscious distinction between cooking and non-cooking vessels, and use different paste compositions for each (e.g. Thompson 1958; Arnold 1971; Rye & Evans 1976: 28; DeBoer & Lathrap 1979). A number of people have suggested that such customs may well be based on practical considerations, stemming from different physical characteristics required of vessels used for different purposes (Rye 1976; Rye & Evans 1976:8; Van der Leeuw 1977; Hulthén 1977).

It therefore seemed reasonable to investigate the possibility that Moundville potters deliberately manipulated paste composition in order to make some vessels more suitable for cooking, and other vessels more suitable for non-cooking tasks. If this explanation for the paste distinctions observed were indeed correct, then logically one might expect to find evidence of two things: firstly, that the fine paste favoured for non-cooking wares would impart a high resistance to breakage from mechanical stress - the kind of stress that might arise when a vessel is accidentally dropped, kicked, and so on; and secondly, that the coarse paste favoured for cooking wares would impart a high resistance to failure from thermal stress - the kind that arises when a vessel is heated or subjected to rapid changes in temperature.

The various measurements designed to test these hypotheses were carried out on the ten sherds whose temper abundance had already been determined (table 1), along with a few additional sherds on which there was no quantitative information. In order to lessen the possibility of error resulting from post-depositional effects, all the specimens were carefully chosen so as not to be significantly leached or eroded.

The one major difficulty encountered in this work, arose from the fact that all the available sherds were of limited size. Many of the necessary measurements were destructive, and had to be made on a relatively large piece of the specimen. Thus, even on the larger sherds, not very many measurements could be made before a specimen was entirely used up. The fact that certain kinds of measurements were intrinsically susceptible to statisti-

PASTE COMPOSITION AND PHYSICAL PROPERTIES MEASUREMENTS*

Sample Number	Vessel Type	Shell Temper		Tensile		Apparent		Elasticity (kg/cm ²)
		Abundance (% Volume)		Strength (kg/cm ²)		Porosity (% Volume)	Diffusivity (cm ² /sec)	
S-1	Bowl	49.7		126.0		29.2	20.0	12240
S-2	Bottle	14.2		174.4		28.0	16.4	18882
S-3	Jar	33.4		119.2		28.0	14.9	6936
S-4	Bowl	31.6		126.9		27.7	19.0	11904
S-5	Jar	37.2		117.9		26.7	18.5	13200
S-6	Jar	35.7		83.5		31.6	18.6	6978
S-7	Bottle or Bowl	17.9		163.9		30.2	21.0	19092
S-8	Jar	23.5		116.6		27.7	16.2	7626
S-9	Bottle	23.9		147.5		27.4	21.0	12984
S-10	Bowl	20.0		148.6		30.0	16.0	11646

* The values listed for physical properties are the medians of three independent measurements on each sherd.

cal error further compounded the dilemma, because in such cases the same measurement had to be repeated more than once. This problem explains why the number of replications per measurement was kept to a minimum, and also explains why some kinds of measurements, lower in priority, could not be made at all.

Despite these and other minor difficulties encountered along the way, some consistent and rather intriguing results were obtained. The exposition in the sections below will present the substantive findings, but will avoid discussing the intricacies of the measurement techniques employed. An adequate treatment of the latter subject appears elsewhere (Steponaitis 1982:Appendix E).

Resistance to Mechanical Stress

Testing the first part of the hypothesis was relatively straightforward: slabs were cut from each of the ten sherds which had already been thin-sectioned and X-rayed, and their modulus of rupture (S) was measured by means of a three-point bending test (table 1). The modulus of rupture is a measure of tensile strength; the higher the modulus, the more resistant is the material to fracture from mechanical stress. When the modulus was plotted against the volume percentage of shell temper, the expected relationship was found to hold true (fig. 6). The less shell is present in the paste, the higher is the tensile strength. Thus, the finely tempered bowls and bottles (denoted by squares on the diagram) indeed appear to be stronger and more resistant to breakage from mechanical stress than the coarsely tempered jars (denoted by triangles).

Of course, one might legitimately wonder to what extent the strengths measured in the laboratory might have been affected by the kinds of stresses to which the vessels had been subjected when in use. Could it be, for example, that the coarsely tempered jar sherds have lower strengths because they were subjected to thermal shock and weakened in day-to-day cooking, while the bowls and bottles were not? Perhaps, but note that the two coarsely tempered bowls (denoted by circles), neither of which was likely to have been used for cooking, also have low strengths compared to their more finely-tempered counterparts. It there-

fore seems likely that the relationship between strength and paste composition is intrinsic to the material, and is not simply a spurious outcome of differences in thermal history during use.

Resistance to Thermal Stress

When a ceramic body is heated, two kinds of thermal stress can occur. Recognizing the distinction between them is important, not only because they have different causes, but also because the factors that determine a vessel's resistance to each are not the same.

The first results from differences in the intrinsic rate of expansion among the various constituents of the paste. Most minerals expand when heated, and the rate of expansion can be expressed in terms of a coefficient (α), which equals the proportional increase in volume per unit of increase in temperature. If the thermal expansion coefficient of the mineral inclusions is greater than that of the clay matrix in which they are embedded, the inclusions will expand faster than the matrix as the vessel is heated, and stresses within the vessel wall will occur. Up to a point, such stresses can be endured with no damage, but once they exceed a certain value, the vessel will crack and fail.

Other things being equal, the likelihood of failure from inhomogeneous expansion increases with the following variables: (a) the temperature to which the vessel is heated, (b) the difference in the rates of thermal expansion between inclusions and matrix, and (c) the absolute size of the inclusions themselves. A potter can minimize the chances of failure by eliminating any inclusions that have significantly higher expansion rates than the clay. If the undesirable inclusions cannot be eliminated, then the alternative solution is to make them as small and as sparse as possible.

In assessing the resistance of Moundville pottery to failure from this sort of stress, one must first determine whether the principal inclusions differ substantially from the matrix in their rates of expansion, for if they do not, then the amount of thermal stress from this source will be negligible, no matter how large the inclusions or how much the vessel is heated. The shell temper particles found in both cooking and serving vessels consist of

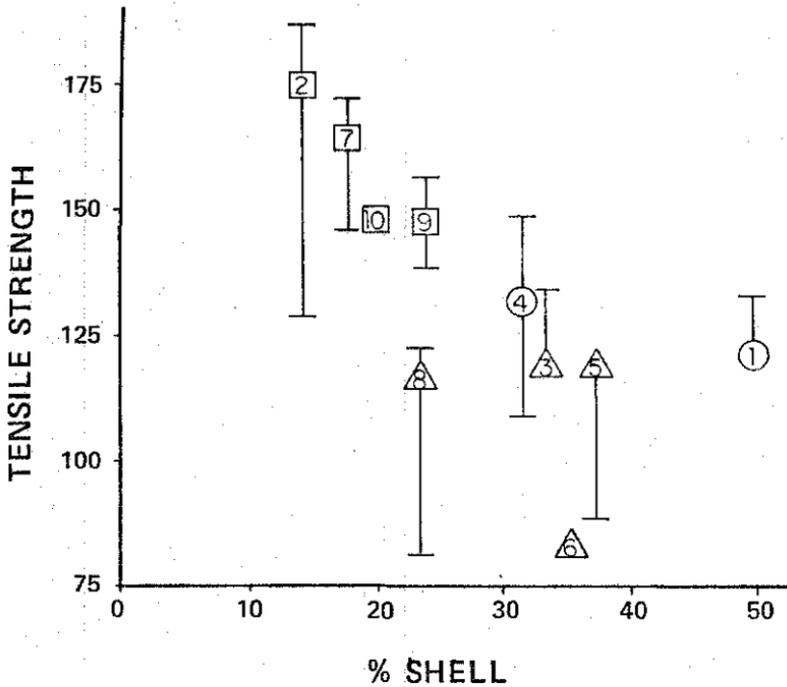


Figure 6 Tensile strength (S) plotted against the percentage of visible shell temper. The median value of S is plotted for each specimen, the error bars indicating the range of values obtained. The squares denote the finely tempered bowls and bottles, the triangles the coarsely tempered jars, and the circles the coarsely tempered bowls. Numbers within the symbols correspond to the sample numbers in Table 1.

calcite, which has a thermal expansion coefficient virtually identical to that of fired clay (Rye 1976:117-118). Thus, Moundville pots would not have been significantly affected by problems stemming from inhomogeneous expansion of paste constituents.

The second kind of temperature-related stress in ceramic vessels results from thermal shock. This occurs when a body is abruptly heated or cooled from one temperature to another. Because ceramics are relatively slow conductors of heat, rapid changes in temperature invariably cause thermal gradients to form within the material. For example, when a cooking pot is suddenly placed over a fire, the exterior surface heats up more rapidly than the interior, since there is always a slight delay as the heat penetrates the wall. The hot exterior expands more than the cool interior, and stress results. Exactly the same process occurs, but in reverse, when a hot vessel is rapidly cooled. The greater the sudden temperature change (ΔT) to which a vessel is subjected, the steeper is the thermal gradient within the material, and the more severe is the thermal shock.

The ability of a body to withstand thermal shock depends a great deal on the size, shape, and distribution of the pores and nonplastic inclusions within the paste. In order to see how such resistance may be measured, we must briefly consider the theory of thermal fracture in ceramics proposed by Hasselman (1969).

The diagram shown in fig. 7 illustrates what happens to the strength of a ceramic material when it is subjected to thermal shock. The vertical axis represents strength, and the horizontal axis denotes the severity of thermal shock (i.e., the temperature difference over which a material is suddenly heated or cooled). The diagram shows that as the severity of thermal shock increases, there is no change in strength until a certain critical temperature difference (ΔT_c) is reached. At that point the material will crack (usually microscopically), and the strength will instantaneously decrease to a lower level. Strength will remain stable at this lower level, until a second critical point is reached ($\Delta T_c'$), after which the strength will decline gradually as ΔT increases.

For present purposes, it is of interest to compare the ware groups at Moundville in terms of two properties, each of which can be taken as a measure of thermal shock resistance. One is

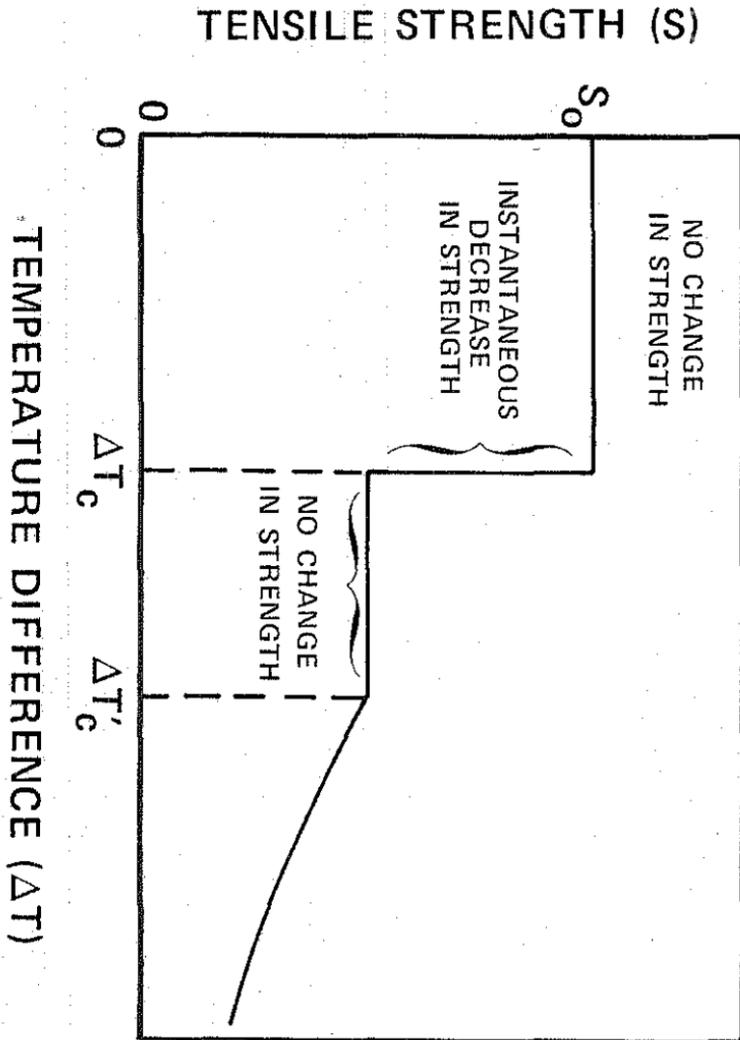


Figure 7 Tensile strength of a ceramic material as a function of thermal history (after Hasselman 1969; fig 2.).

the severity of shock necessary to initiate cracking, i.e., the value of the initial critical temperature difference (ΔT_c). The second is the amount of loss of strength that occurs when the critical temperature difference is reached. A material with high thermal shock resistance either will have a high value of ΔT_c , or else it will exhibit a minimal degradation in strength when ΔT_c is reached.

The ideal approach in measuring these properties would be to determine the shape of such a curve empirically. This would require having lots of slabs of each material, subjecting these slabs to varying degrees of thermal shock, and then measuring their remaining strength. The problem with doing this, however, was the already familiar one of limited specimen size. Each sherd could only be cut into a few slabs, and the strength of each slab could be measured only once. This limitation virtually assured that there would not be enough points to accurately determine the shape of the curve, and so a different approach had to be taken.

The alternative chosen was to measure a number of physical properties that affect thermal shock resistance, and then to use these measurements in calculating a set of thermal shock resistance parameters, by means of which the different paste compositions could be compared. The significant properties examined were apparent porosity, thermal diffusivity (D), elasticity (E), and tensile strength (S) (table 1).

Porosity, defined as the fractional volume of pore space, can have an effect on thermal shock resistance, but the precise nature of the effect is somewhat ambiguous. Although Shepard (1956: 126) and others (Hulthén 1977) have argued that high porosity increases thermal shock resistance, Coble (1958:223) has published evidence to the contrary. One reason for this ambiguity may be that porosity *per se* is often less important in predicting thermal shock resistance than several other closely-related factors - pore shape, density, and the frequency distribution of pore sizes (Hasselmann 1969; Kennedy 1977; cf. Rye 1976). For present purposes, none of these factors had to be assessed directly, since their effect is felt through their influence on other measurable properties which enter into our calculated parameters (e.g.

tensile strength, elasticity, diffusivity). Nevertheless, porosity was measured in our specimens anyway, to see if there were any consistent differences between the ware groups. As shown in fig. 8, the apparent porosity of Moundville pottery stays remarkably constant at about 30%, no matter how much shell is added as temper.

Thermal diffusivity (D) measures the ease with which heat is dissipated through a material. The higher the diffusivity, the faster the heat is dissipated. High diffusivity contributes to thermal shock resistance in that it tends to reduce thermal gradients within the material, hence reducing internal stress. The data obtained on our specimens (fig. 9) show much more scatter than the porosity measurements, but once again no clear pattern is detected in relation to the percentage of shell present.

Elasticity, measured in terms of Young's modulus (E) corresponds roughly to what we think of colloquially as the 'stiffness' of a material. More precisely, it expresses the amount of stress (pressure) produced in a material per unit of tensile strain (deformation). The effect of elasticity on thermal shock resistance varies, and depends on the kind of resistance being measured. In regard to increasing the severity of thermal shock required to initiate cracking (ΔT_c), a low value of E is desirable, because such a material will experience less internal stress for a given amount of thermally-induced strain. Once the critical temperature difference has been reached, however, a high value of E is desirable, because a 'stiffer' material tends to inhibit crack propagation, thereby decreasing the material's degradation in strength. The elasticity measurements obtained on our specimens (fig. 10) reveal a weak, but definite negative correlation with the percentage of shell temper ($r = -0.47$). The less shell, the higher tends to be the value of the elastic modulus. Thus, the finely tempered bowls and bottles tend to be made of stiffer material than the coarsely tempered jars.

Finally, tensile strength (S) is related to thermal shock resistance, and again the nature of the relationship varies with the circumstances. High tensile strength tends to increase the severity of thermal shock that can be withstood before cracking begins, but also tends to increase the degradation in strength which takes

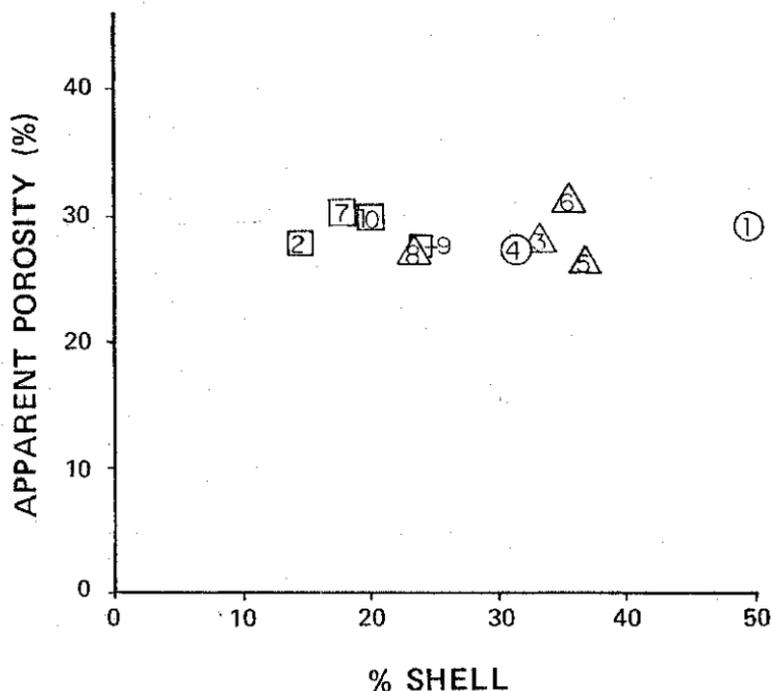


Figure 8 Apparent porosity (% volume) plotted against the percentage of visible shell temper. In every case, the range of values obtained was smaller than the vertical height of the symbol. (See Figure 6 caption for key to symbols used here.)

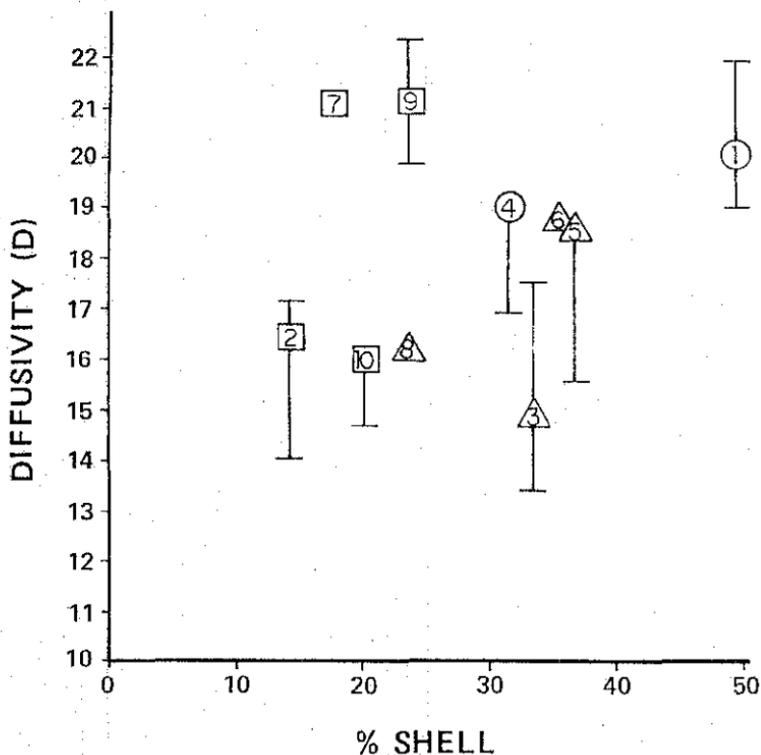


Figure 9 Thermal diffusivity (D) plotted against the percentage of visible shell temper. The median value of D is plotted for each specimen, the error bars indicating the range of values obtained. (See Figure 6 caption for key to symbols used here.)

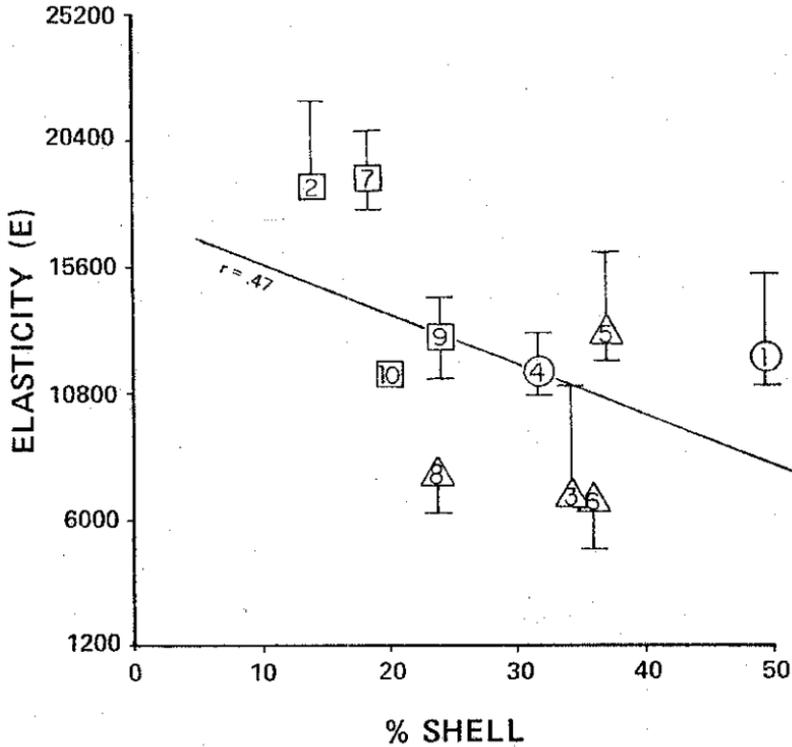


Figure 10 Elasticity (E) plotted against the percentage of visible shell temper. The median value of E is plotted for each specimen, the error bars indicating the range of values obtained. (See Figure 6 caption for key to symbols used here.)

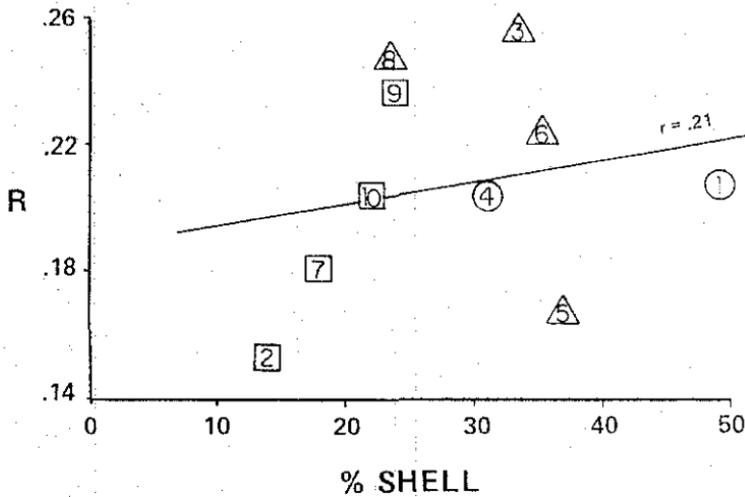


Figure 11 The thermal shock resistance parameter R plotted against the percentage of visible shell temper. (See Figure 6 caption for key to symbols used here.)

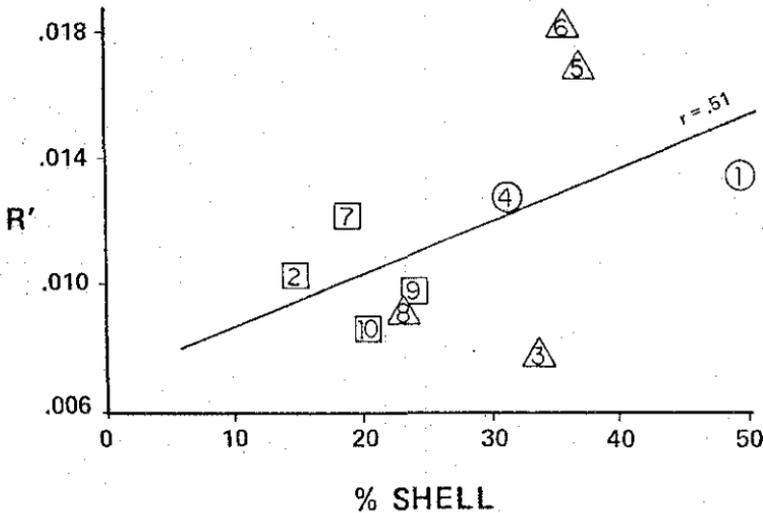


Figure 12 The thermal shock resistance parameter R' plotted against the percentage of visible shell temper. (See Figure 6 caption for key to symbols used here.)

place once cracking has begun (Hasselmann 1969). As shown previously, tensile strength is negatively correlated with the percentage of shell in Moundville pottery, the fine wares generally being stronger than the coarse wares (fig. 6).

How then are these properties combined to estimate thermal shock resistance? In the present case, the resistance to initial cracking from thermal stress can be compared by means of the theoretically-derived parameter:

$$R = \frac{S(1-\nu)D}{\alpha E}$$

Given the mineralogical similarity of our specimens, and the fact that calcite temper has about the same thermal expansion characteristics as low-fired clay, it is reasonable to assume that Poisson's ratio (ν) and the thermal expansion coefficient (α) are constant for our wares (for a definition of the variable ν , see Nash 1972: 6-7). Such being the case, this parameter reduces to:

$$R = \frac{S D}{E}$$

The greater the value of this parameter, the higher is the temperature difference that can be endured before any degradation in strength occurs (at least in theory: Hasselmann 1970).

Once cracking has occurred, on the other hand, the resistance to loss in strength should be proportional to:

$$R' = \frac{E}{S^2}$$

Unfortunately, limitations on the size of our specimens precluded measurement of the surface fracture energy (G) - which may or may not be affected as the percentage of shell changes. The only thing we can do for now is to treat G as a constant, in which case the parameter reduces to:

$$R' = \frac{G E}{S^2 (1-\nu)}$$

The greater the value of this parameter, *ceteris paribus*, the less strength should be lost when the critical temperature difference is reached (Hasselmann 1970).

If we plot the values of these parameters against the volume percentage of shell, we can begin to assess the relative effects of paste composition on thermal shock resistance in Moundville pottery. The parameter R , which pertains to fracture initiation, does show a very weak positive correlation with the percentage of shell (fig. 11), but the relationship is so weak that it probably has little significance ($r = .21$; $p = .56$). Thus, the data suggest that there is probably no substantial difference between coarse and fine wares in the level of thermal shock required to bring on a degradation in strength.

The parameter R' , on the other hand, shows a much stronger positive correlation with the percentage of shell (fig. 12). Although the correlation is not strong enough to inspire absolute confidence ($r = .51$; $p = .13$), the relationship is definite enough to suggest that the coarse wares would tend to lose proportionally less strength once cracking had begun.

One can also look at the same relationship in somewhat different terms: we have just seen that the loss in strength after thermal shock should be inversely related to the percentage of shell temper. Also, we have demonstrated that the percentage of shell temper is inversely related to initial strength. Therefore, the drop in strength after quenching should be positively related to initial strength.

Such a relationship can be seen in fig. 13, which shows strength as a function of quenching temperature for three different sherds. Although there are no accurate data on the composition of these specimens, one can see that the amount of drop does seem to be related to initial strength. In looking at these graphs, it is useful to keep in mind that the measured initial strength of the sherds in our overall sample usually falls in the range between 80 and 180 kg/cm^2 . Notice that the sherds with a moderate initial strength (i.e., the uppermost two) lose only about 10-20% of that strength after quenching, and still retain enough strength to remain in the middle of the usual range of values. The sherd which started out with a very high initial strength, on the other hand, lost more than 50% of its strength after quenching, and ended up at the very bottom of the usual range of values.

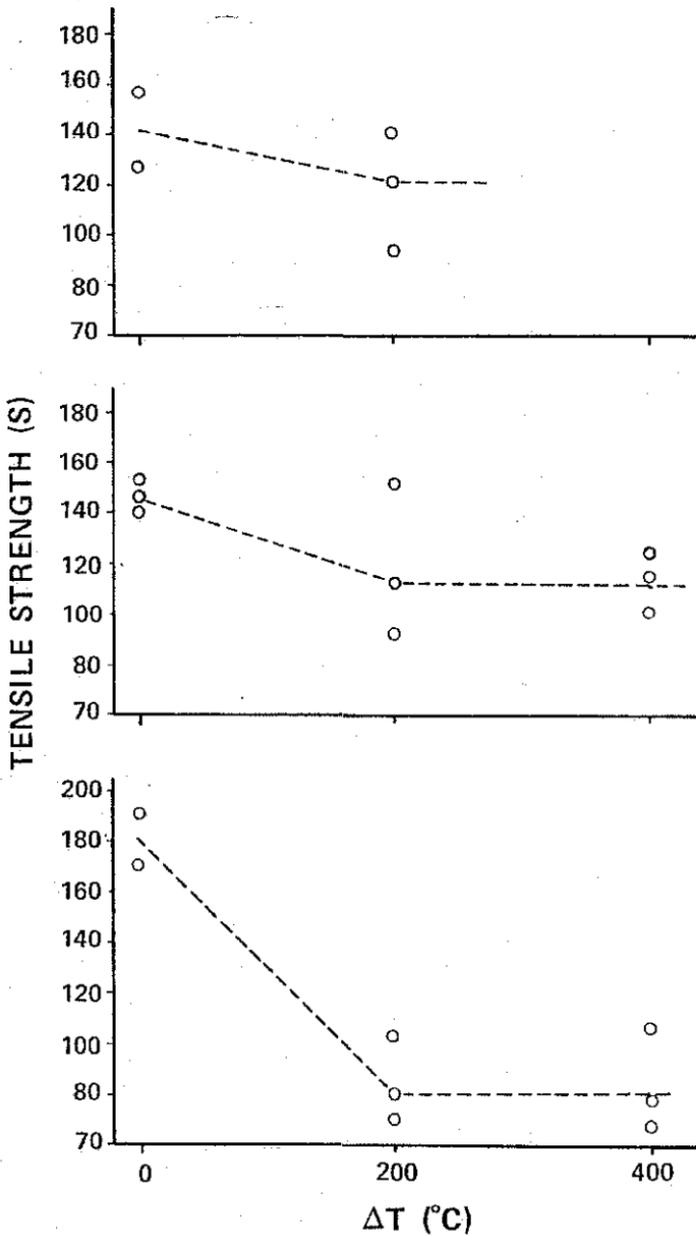


Figure 13 Strength as a function of thermal history for three sherds from Moundville.

All in all, the data suggest that the Moundville potters may have been faced with a trade-off in choosing which paste composition to use. A finely tempered vessel would have a high initial strength, but would lose a very large proportion of that strength if subjected to thermal shock. A coarsely tempered vessel, on the other hand, would have less initial strength, but would retain most of that strength even after a severe thermal shock. This being the case, a coarsely tempered pot would probably have been more resilient and longer-lasting as a cooking vessel. Such findings are perfectly consistent with the notion that Moundville potters maintained the distinction between coarse and fine wares for reasons that were technological, rather than purely aesthetic.

CASE 2: CHANGES IN PASTE COMPOSITION THROUGH TIME

We have just seen how an understanding of physical properties in relation to function, can explain synchronic differences in ceramic composition. In order to illustrate the utility of this approach in understanding diachronic variation, let us now consider the entire prehistoric ceramic sequence in west-central Alabama, leading up to and including to Mississippian ceramics just discussed. For the purposes of illustration, our attention will focus on only one aspect of ceramic development in this region, namely, how the paste composition of cooking vessels - deep, wide-orificed beakers and jars - changed through time. A summary of the relevant changes is presented first, followed by a discussion of their technological significance. The details of the ceramic sequence are drawn largely from the work of Jenkins (1981), and supplemented by my own observations.

The first pottery in the Moundville region appeared around 1000 B.C. These vessels, comprising the so-called Wheeler Series, were generally flat-bottomed beakers or deep bowls, and were made of clay that was deliberately tempered with plant fibres. The fibres, of course, burned up during firing, leaving elongated cavities in the vessel wall. A few centuries after this ware was

introduced, potters began adding quartz-rich sand to the paste in addition to the fibres. Eventually, at about 500 B.C., sand became the only tempering agent used.

The early sand-tempered pottery, known as the Alexander Series, predominantly consisted of beaker forms, often with podal supports on the base. The texture of the ware was typically coarse, with sand inclusions often as large as 1.5 mm in diameter.

By about 100 B.C., the Alexander pottery was replaced by a new set of types called the Baldwin Series. Beakers and jars of the latter ware continued to be tempered with quartz sand, but the size of the inclusions was noticeably finer, with particles rarely over 0.5 mm in diameter.

At about A.D. 400, potters began experimenting with crushed sherds, or 'grog', as a tempering material in addition to the sand. Not long after (ca. A.D. 550), an exclusively grog-tempered ware called Baytown became the dominant type produced. Cooking vessels of this ware were typically deep, wide-mouthed vessels, with rounded bottoms and no podal supports. Notably, the temper inclusions once again became relatively coarse, often 1-3 mm in largest dimension.

The last major change in the sequence occurred at about A.D. 1000. It was then that Mississippian pottery began to appear in the region, and the primary tempering agent for all vessels changed from grog to crushed shell. Although (as discussed previously) the shell in serving vessels was usually rather fine, cooking vessels continued to be tempered with coarse particles, 2-6 mm in maximum dimension.

Leaving aside the earliest fibre-tempered pottery, the technology and functions of which are not well understood, it can be seen that cooking wares in the region underwent three major shifts in paste composition: from coarse sand to fine sand at about 100 B.C., from fine sand to coarse grog at about A.D. 550, and from coarse grog to coarse shell shortly after A.D. 1000. These changes are summarized graphically in fig. 14. Although no direct physical properties measurements have as yet been made on the sand- and grog-tempered pottery types, there are good theoretical reasons to believe that this sequence of transformations represents a consistent technological trend toward in-

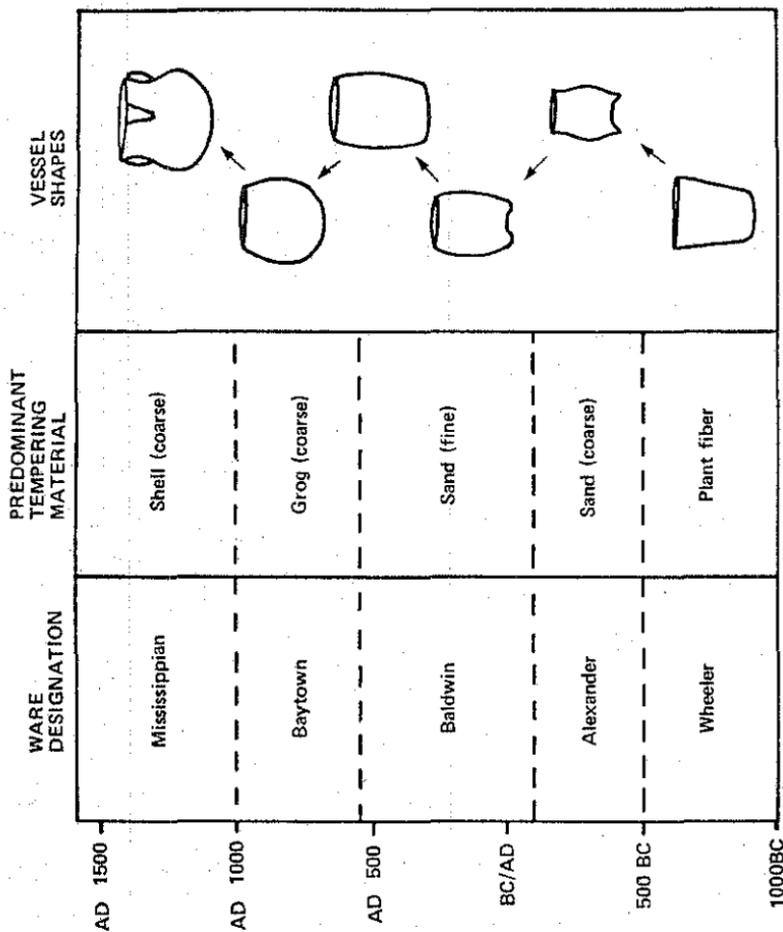


Figure 14 The evolution of cooking vessels in west-central Alabama (source: Jenkins 1981).

creasing the resistance of cooking vessels to thermal stress.

You will recall that there are two forms of thermal stress which can cause a cooking vessel to fail. The first results from inhomogeneous expansion of paste constituents, which occurs when temper or other mineral inclusions have significantly greater expansion rates than the clay matrix. Resistance to failure from this cause is enhanced by making the offending inclusions as fine as possible, or by eliminating them entirely. The second kind of stress results from thermal gradients within the vessel wall, which are brought about by thermal shock. Resistance to failure from the latter, as we have seen, is generally increased by making the temper as coarse as possible. Hence, minimizing the chances of failure from the two forms of stress requires different, and sometimes conflicting strategies. Changes in temper particle size that are advantageous in relation to one form of stress may well be deleterious in relation to the other. In fact, the gradual working-out of such a contradiction seems to be embodied in the ceramic sequence under consideration.

Quartz has a much higher rate of thermal expansion than fired clay (Rye 1976:fig. 3). Thus, in the earliest sand-tempered pottery, inhomogeneous expansion was probably the dominant source of thermal stress, and the potters responded by making the sand temper finer. (For a well-documented parallel case from the Illinois Valley, see Braun [1981, 1982:188-190].)

However, as the sand temper gradually became finer and the problems related to inhomogeneous expansion abated, the susceptibility of the ware to failure from thermal shock actually became greater. The only way the potters could circumvent this technological dilemma was by changing the tempering material entirely. Grog, consisting of fired clay, has thermal expansion characteristics that are identical to that of pottery (Rye 1976: 115). Therefore, the eventual shift to grog as the sole tempering agent totally obviated the problem of inhomogeneous expansion. And because this source of stress was virtually eliminated, the temper particles could once again be made coarse in order to increase resistance to thermal shock. In other words, by changing from sand to grog temper, the potters discovered a way to maximize the resistance of their cooking wares to both forms of ther-

mal stress simultaneously.

Crushed shell ultimately replaced grog as the predominant temper in cooking vessels. Given that the thermal expansion characteristics of shell (calcite) are virtually identical to those of fired clay, it is hardly surprising that the potters continued to make the temper particles coarse. As to the reasons why shell was adopted over grog, the evidence suggests once again that the change presented certain technological advantages. An important difference between grog and shell temper lies in the shape of the particles and their orientation within the vessel wall. Grains of the former are typically equiaxial, and therefore have no preferential orientation. Crushed shell, on the other hand, is platy, and paddle-and-anvil finishing tends to orient the flat grains parallel to the vessel's surface. Other things being equal, ceramics containing oriented, plate-like grains tend to have a much greater fracture toughness, or resistance to crack propagation, than those containing equiaxial grains (Shepard 1956:27; Braun 1982:185; S.W. Freiman, personal communication; see also Lange 1973). The reasons for this are as follows. Cracks brought about by thermal shock or other flexural stresses usually begin at the surface and propagate inward along a path of least resistance (e.g. Lawrence 1972:fig. 14-5). Because cracks require less energy to spread around grains rather than through them, temper particles act as barriers to crack propagation. Flat, overlapping grains oriented parallel to the surface form a particularly effective barrier that makes it more difficult for 'fatal' cracks to find a continuous path from one side of the wall to the other. Hence, the shell-tempered ceramics almost certainly had a greater resistance to thermally-induced failure than the grog-tempered wares which preceded them. And this is not to mention other advantages that shell may have had, such as Million's (1975a:218) finding that calcite acts as a flocculant which greatly improves the plastic working properties of certain clays.

Thus, when viewed in terms of the known effects of paste composition on physical properties, the prehistoric changes in tempering practices become intelligible as a logical progression resulting in the gradual improvement of cooking vessels. It should be noted that the trends discussed were not confined only to

west-central Alabama, but, with some local variations, occurred over a large area of the Eastern Woodlands, including parts of the central and upper Mississippi Valley, and much of the Ohio and Tennessee River drainages. The key elements of this more general trend can be summarized as follows:

1. The earliest cooking pots (with the possible exception of fibre-tempered ware) were tempered with coarse, quartz-rich sand or crushed rock - materials with very high rates of expansion relative to clay (Braun 1981; Griffin 1939; Haag 1942:514-516; Heimlich 1952:9-15; Keel 1976:247-266; Lafferty 1978; Logan 1976:89-110, 128; Mayer-Oakes 1955:184-193; Walthall 1980:95-103). In regions where this sort of temper continued to be used for more than a few centuries, there was often a distinct diminution in the average size of the temper particles through time - a logical response to problems caused by inhomogeneous expansion.
2. Eventually, potters in most regions switched to tempering materials that had better thermal expansion characteristics, such as limestone or grog (Fowler & Hall 1975:2-3; Griffin 1939; Haag 1942:516-519; Heimlich 1952:15-22; Lafferty 1978; Lewis & Kneberg 1946: 80-88, 102-104; Mayer-Oakes 1955:193-196; O'Brien 1972:47-50; Walthall 1980:112-155). Limestone, like shell, is a form of calcite, and therefore has a thermal expansion coefficient very close to that of fired clay. When added to cooking vessels, such materials were virtually always left coarse, so as to maximize resistance to thermal shock.
3. Ultimately, even limestone and grog, which have good expansion characteristics but equiaxial grain shapes, were replaced by crushed shell, which has equally good expansion characteristics and platy grains (Fowler & Hall 1975:3-9; Griffin 1939; Haag 1942:519-520; Heimlich 1952:22-28; Lewis & Kneberg 1946: 88-106; Mayer-Oakes 1955:196-203; O'Brien 1972:50-88; Walthall 1980:196-245). This change further increased the resistance of vessels to thermal failure.

Previous explanations have usually treated these changes in paste composition as being a result of processes of cultural diffusion or migration. Such interpretations, however, have always failed to deal with the trajectory of technological change, or why

certain tempering practices were consistently adopted over others. Understandings of this kind can only be gained through a detailed knowledge of the working characteristics and physical properties of the ceramics in question. This is not to deny that diffusion was important or that migrations sometimes occurred, for it is obvious that these factors played an important role in the spread of innovations. However, a complete explanation of ceramic change can rarely be achieved unless technological factors are given equal consideration.

DISCUSSION

The cases just presented illustrate how physical properties can help to explain both synchronic and diachronic differences in the way that vessels were made. Of course, the differences among the various paste compositions would not have been perceived by prehistoric potters in the same technical terms used here. Instead, the practical advantages of each composition would have been discovered through a gradual process of trial and error, informed by experience and cultural tradition. The potters themselves could observe that certain paste recipes resulted in better pots, ones that could be used for a longer period of time before they broke.

Much more work needs to be done before the technological aspects of prehistoric pottery in our region are fully understood. As the reader is undoubtedly aware, many of the arguments presented in the foregoing pages are still based on limited evidence. The number of shell-tempered sherds whose properties have been measured is still rather small, and the properties of the sand- and grog-tempered wares have yet to be measured at all. Getting adequate confirmation will require doing repeated tests on a large sample of each material. Because of problems posed by limited sherd size and post-depositional leaching, it is often difficult to obtain large enough samples using archaeological specimens alone. Moreover, the previous thermal history of an archaeological sherd

(was it already subjected to thermal shock?) is a variable that cannot be controlled. The best way to circumvent these problems is to replicate each material in large quantities. Detailed compositional studies have begun to give us a basis for sound replication, and further work with larger and better-controlled samples will be undertaken to confirm these preliminary results.

If there is a general lesson to be learned from the results obtained so far, it is that archaeologists should be much more circumspect about regarding all the variability they see in ceramics as being purely stylistic. The nature of the available raw materials always places certain constraints on the kinds of wares that can be produced, and at the same time, the way these raw materials are combined can place constraints on the range of uses to which the final product may be put. Many times over in the prehistoric record, we see that potters changed the way their vessels were tempered, and changed the techniques by which their vessels were built. I strongly suspect that many of these changes were fundamentally technological, rather than stylistic, in nature. And in order to adequately understand the significance of these changes, archaeologists will have to get into the habit of posing the kinds of technological questions that have been investigated here.

In addition to gaining further empirical support for the ideas already stated, future studies must expand the range of inquiry to include factors that have not as yet been sufficiently considered. First, it will be fruitful to investigate the effects of paste composition on the workability of local clays, and the constraints this imposes on vessel shapes (e.g. Million 1975a; Million & Morse 1978). Second, it will be necessary to take into account how variations in shape and wall thickness affect strength, thermal stress resistance, and other performance characteristics (e.g. Braun 1981). Third, all these lines of inquiry will have to be integrated with studies that examine the economic and social context in which ceramic production took place (e.g. Rice 1981; Feinman et al., this volume). Only then will our approach be truly multidimensional, permitting us to explain the evolution of ceramic traditions in eastern North America, rather than simply describing them.

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DISCUSSION

J. Allen:

Why should people switch to shell, where they have to work with the limitations of the calcium?

V. Steponaitis:

Yes: because limestone also has the same constraint. I have a suspicion that the advantage of shell over white limestone might result from its platy texture. Limestone tends to form in blocky chunks, whereas shell tends to crush up into flat plates; so that might possibly allow one to get a thinner vessel wall, with the same strength of thermoshock resistance. But I am not sure of that.

J.A. Bakker:

If you heat something repeatedly every day beyond normal temperature, what do you get?

V. Steponaitis:

This is a question of thermal fatigue versus thermal shock. I have measured the resistance to very abrupt changes in temperature, and the kind of stress that occurs as a result of that. In theory, according to Hasselman (1970), you can raise and lower the temperature many times, but as long as you stay below that critical temperature difference, then theoretically the material should not lose any strength. However, in practice, one finds that thermal fatigue occurs in ceramics as it does in metal. Repeated cycles of heating and cooling, even at temperatures that are below the critical temperature difference might bring on thermal shock, will cause the material to lose some strength over a period of time. The way to test that is to use cyclical experiments of repeated heating and cooling, testing the strength of each material after each cycle. To do that, you need tremendously large samples, which you can only get by replicating the material in large quantities. Our mineralogical work has given us

space in which to do that: I now have some students who are trying to make briquettes of Moundville pottery in the kiln, which not only supports our study with larger samples, but also allows us to do some thermal fatigue testing.

P. Rice:

Is it wise to generalise about the reduction in temper, or change in temper, for thermal strength on the basis of only two areas, Moundville and Southern Illinois? I do not think you get those sort of changes in Florida, for example. Secondly, you were comparing mechanical strength between the bowls (or serving vessels in general) and the jars. Since, presumably, your jar samples had been used over and over again, are you not really measuring thermal fatigue rather than thermal shock?

V. Steponaitis:

The only way to answer your second question is to re-create material which is identical to the original paste, so that you know it has not been used. Also, I deliberately included one sherd of a serving vessel, with a beautifully white-slipped highly polished surface (not the kind of thing you would expect to use, or to have been used, over a fire), but that was coarsely tempered. I included that for a reason: if the decrease in strength with increase in tempers were simply the result of thermal shock which the vessel had endured while in use, then that one coarsely-tempered vessel which had not been used over a fire, would have a high strength just like all the other vessels. And yet, if we look at the slide again, you will see that that sherd followed exactly the same pattern as the coarsely-tempered cooking vessels. That gives me some reason to believe that the patterns which we have noted are in fact the result of differences in paste composition, and are not due to the fact that some vessels have been used over a fire, and others have not.

P. Rice:

I was wondering. I have heard that calcium acts as a deflocculant, and that it is sometimes used to make pottery become more finely textured (and therefore stronger). If that is true, to what extent might the adding of very fine shell act in the vessels to promote greater strength?

V. Steponaitis:

In Michael Million's work (1975a) in replicating Mississippian pottery from Arkansas (which is essentially contemporary to my pottery), he found that the shell also has the advantage of acting as a deflocculant in the Arkansas clays. It increased the working properties of the clay: it made it more workable. Obviously, I am not trying to say that *everything* is a matter of thermal shock resistance. There are also physical properties related to the workability of the clay and many other things. As I have never made a pot with Moundville clay, and not used Moundville clay mixed with shell, I do not know whether the same thing is true in our area: but elsewhere, shell does have the property of increasing the workability of the clay.

F. Matson:

In measuring the tensile strength, or the modulus of rupture, there are several variables involved. Some of these variables are the curvature of the sherd, the thickness of the sherd and the number of minor cracks that occur in the manufacture of the pottery. So the nature of the sample tested needs close definition. The standard way of testing it, which you cannot always do with ancient pottery, is to have sections of 1 sq. inch, and then measure at least thirty samples. So I would suggest taking clay from Moundville, making slabs of a standard thickness related to the average thickness of the sherds at the site, and testing them under standard conditions. The same thing applies to thermal expansion.

Finally, regarding the change to limestone as a tempering material. Is this associated with people moving to areas where the mountains have limestone debris near their base? In which case, if they were importing limestone for such things, perhaps an ecological evaluation of the tempering material is necessary?

V. Steponaitis:

Ideally, one needs many different measurements of strength of any given material, because strength is a statistical property. We are experimenting with mixing Moundville clay with shell, and with making slabs of the material which will conform precisely to certain standards. In making these measurements, I always used sherds of approximately the same thickness. I chose

them with as little curvature as possible. I was always careful in measuring strength, to measure it parallel to the curve rather than across it.

D. Papousek:

You said at the beginning that the breakage is an important factor for serving vessels. I would like to add that it is also important for cooking vessels: there is no difference between them in that respect. The change from quartz to shell as a temper is not necessary for serving vessels, so cooking vessels could have developed differently from serving vessels. Perhaps this could mark the beginning of technological differentiation or diversification.

Secondly, cooking pots may place different demands on the material; they may need to retain the heat longer than a serving vessel. That may be an explanation for the fact that the material may be coarser.

R. Vossen:

I can confirm that in Spain, cooking vessels generally have a much higher rate of tempering materials than vessels for water. Secondly, the clay is generally a red clay, containing iron, and when we ask the potters why they put more temper materials in these pots, they say that in their experience, these pots therefore last longer.

W. DeBoer:

First, several people have raised the issue of sampling, and the disadvantages of a small sample. On the other hand, good ideas may come from a sample of one: I am thinking of Binford's one reindeer. Secondly, I think you have a phony opposition between technology and everything else, which you attributed to cultural convention, suggesting that these cultural conventions were somehow capricious. I think you created that opposition to serve your purpose: I do not think you really believe in it.

V. Steponaitis:

No, I do not.

W. DeBoer:

My third point concerns the very interesting relationship between thermal constraints and strength. The thing that bothers me is that you have two thousand years of ceramics, and you interpret these in a progressive way, as if potters are almost asymp-

totically approaching the perfect solution. I have a much more creative picture of human behaviour. Instead of viewing this as an approach to an ideal solution, we should consider all the other things which are going on in each stage: the Early Woodland period, the Middle Woodland period, etc. From this perspective, each thing makes sense in its own time, rather than being directed towards any future (shell) solution, which is 2000 years ahead.

V. Steponaitis:

I fully agree with you. I just very hastily sketched out this idea, and I do not think that evolution proceeds to some sort of teleological goal of making perfect pottery. You mentioned that tempering might be connected with changes in culinary practices; Braun (1983) has argued that this trend might be due to changes in subsistence, where people are using more and more corn. He argues that in order to prepare corn, as opposed to nuts, you need more thermally shock-resistant vessels. Instead of a gradual curve, there is an abrupt shift to smaller temper, and that occurs right at the point where people adopt corn-based agriculture. So you are absolutely right, these changes can be linked to changing subsistence patterns.



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VOOR PRAE- EN PROTOHISTORIE

CINGVLA VII

THE MANY DIMENSIONS OF POTTERY

Ceramics in archaeology and anthropology

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