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Ultrasonic Disaggregation and Instrumental Neutron Activation Analysis of Textural Fractions of Tucson Basin and Ohio Valley Pottery

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Chemical variation in ceramic pastes may derive in part from textural variation. In order to investigate this possibility, experiments were carried out in which different size fractions of ceramics, temper, and raw clays were characterized by INAA. Fractionation of the samples, archaeological and geological specimens from the Tucson Basin and the Ohio Valley, was accomplished using an ultrasonic disaggregation technique. Results indicate that, under most circumstances, little or no increase in resolution of compositional groups is achieved by analysis of the smallest size fraction.

Compositional analysis of archaeological materials has revolutionized the study of ancient and prehistoric exchange. It provides highly accurate measurements that allows the confident assignment of artifacts to raw material sources (Earle 1982). Provenience studies that use compositional analysis have been able to identify sources of raw materials and locations of production, reconstruct contexts of exchange, and refine artifact taxonomies based on formal/functional attributes (Earle 1982; Rice 1987). Provenience-oriented compositional analysis has been most successful when working with chemically homogeneous materials such as obsidian. Heterogeneous materials, such as ceramics, are more difficult, but can and have been provenienced successfully (see Rice 1987 for a review; also Bishop and Neff 1989).

Gaines and Handy (1977) have suggested that reducing the natural heterogeneity within ceramics by segregating the ceramic into its constituent parts—clay(s) and aplastics—and then analyzing each part separately may improve the resolution of provenience studies. In the present study, instrumental neutron activation analysis of the different size fractions is used to determine: (1) chemical dilution and enrichment patterns of the clay(s) and aplastics composing the ceramic; and (2) differences in chemical patterning between the various size fractions and the bulk ceramic. Data derived from this study are then used to ascertain if more fine-grained discrimination of groups within a collection of ceramics could be accomplished by analyzing either the clay or aplastic fraction instead of the bulk ceramic.

Elemental Heterogeneity in Ceramic Compositional Analysis

The chief objective of ceramic compositional analysis is the identification of mineralogically or chemically homogeneous groups within a given category of ceramics. These patterns are then used to infer production loci and exchange relations and to aid in interpreting the contexts of exchange. One of the major problems in this type of analysis arises from the fact that ceramics are inherently heterogeneous in their chemical and mineralogic composition (Rice 1987; Neff et al. 1988b, 1989). This characteristic stems from two factors: (1) the natural chemical and mineralogic heterogeneity of the raw materials used to construct ceramics; and (2) heterogeneity introduced by the potter during the manufacture of ceramics. The heterogeneity due to these two factors often serves to complicate the formation of compositional groups and may confound identification of the sources of the raw clay or aplastics (Rice 1987; Neff et al. 1988b, 1989; see also Attas et al. 1977; Fillieres et al. 1983; Allen et al. 1987; Kilikoglou 1988).

Several approaches have been used to investigate and/or compensate for the effect of chemical heterogeneity in ceramics. The first involves mathematical simulation of the effects of aplastics in creating or obscuring relationships among ceramic groups that are defined compositionally (Neff et al. 1988b, 1989). These studies have concluded that the effect of aplastics in obfuscating group formation in a ceramic data set depends largely on four factors: (1) the amount of aplastic in a ceramic; (2) chemical homogeneity of the aplastic material; (3) the distinctiveness of the untempered clay compositional groups; and (4) the relative concentrations of elements in the clay vs. the aplastics. The general conclusion reached was that, except in cases of very heterogeneous aplastics with elemental concentrations approaching those in the matrix (e.g., grog temper), the amount of aplastics that is required to confound formation of compositional groups is 75-80% of the total volume of the ceramic. Finally, the authors of these studies emphasize the importance of microscopic examination of sherds in order to form textural classes and identify temper types prior to compositional analysis. From this work, expectations concerning the effects of aplastics can be formulated and tested in order to facilitate formation of compositional groups that have archaeological significance.

Another approach to the aplastic problem has been to look at elemental concentrations in unprocessed aplastics and clays relative to finished ceramics (Arnold et al. 1978; Rice 1978). These studies demonstrated that mixing clay and aplastics to form a ceramic produces an elemental signature that is distinct from either the clay or aplastics and that averages the chemistry of both components. Unfortunately, the studies did not determine whether aplastics attenuated or created groups within a ceramic compositional data set, compared to groups based on clay chemistry alone. Arnold et al. (1991) have since demonstrated that bulk ceramic analyses can be related to analyses of constituent raw materials even though the ceramic does not compositionally match either the clay or the aplastics.

A third approach to the heterogeneity problem in ceramic compositional studies has been to analyze the constituents of the ceramics separately. This requires some method for separating the material into its constituent parts, e.g., clay(s) and aplastics. The individual constituents are then analyzed in an effort to identify differences in their chemical signatures and how these are reflected in the bulk ceramic composition (Attas et al. 1977; Fillieres et al. 1983; Rice 1987). This approach is based on the assumption that analysis of the individual constituents enables isolation, identification, and removal of the constituent that is responsible for introducing chemical heterogeneity (noise) and that attenuates patterning in the data. This assumption has been best articulated by Gaines and Handy (1977), who first developed a method for successfully disaggregating pottery. They state that:

> the trace-element signature of a sherd of sand-tempered pottery will depend not only upon the clay(s) in the paste, but also upon the diverse minerals in the tempering material. It is conceivable that the trace-element content of a sherd may be largely determined by the chance presence (or absence) of a single grain of some minor component (such as zircon, monazite, or sphene) in the sand, resulting in different signatures for adjacent sherds from the same pot. Therefore, detailed studies of heterogeneous substances may require separate analyses of each of the various components as well as determination of their relative proportions and their distribution in the sample (1977:252).

As the quotation indicates, the aplastic component is usually assumed to be the component responsible for chemical heterogeneity of a ceramic.

The basis for the assumption that aplastics are usually responsible for the chemical heterogeneity of a ceramic and represent potential noise in compositional analysis is derived from two observations. First, temper is considered to be inherently more heterogeneous than clay. Second, temper can be introduced and distributed in the clay matrix in a relatively

haphazard fashion during the manufacture of the ceramic. The notion that temper is more heterogeneous than clay derives from the observation that temper can consist of many different materials, including organics, crushed rocks, crushed shell, crushed sherds, or diverse combinations of these. Clays, especially secondary clays, tend to be more homogeneous due to the sorting and reduction effects of mechanical and chemical agents. Additionally, if the clay is processed in some fashion, such as levigation, grinding, winnowing, and/or aging prior to the manufacture of the ceramic, this may result in a more chemically homogeneous material.

The second observation, regarding the variability of ceramic production, is based on ethnographic studies (see Rice 1987, for an overview). Primitive potters have been found to have a variety of recipes for making ceramics, although these are often more ideal than real. Rarely are the recipes followed precisely, and they may be varied quite often. Moreover, aplastics are often introduced on a rather subjective basis, until the potter decides that the paste has the correct feel or workability. Therefore, the assumption that temper is most often the source of noise in the chemical signature of a ceramic is not unreasonable.

In conclusion, analyzing individual constituents of a ceramic is attractive for several reasons. First, it provides an empirical means for testing many of the conclusions reached by the simulation studies summarized above (Neff et al. 1988b, 1989), especially the main conclusion that tempering with aplastics usually poses no serious threat to identifying archaeologically significant groups in a ceramic compositional data set. Second, separation provides a means for empirically investigating the sources of elemental concentrations measured in the paste of a ceramic. Third, separation also provides a method for more precisely characterizing the mineralogy of a ceramic. In sum, constituent separation represents a potential improvement in the ability to identify ceramic compositional groups that have archaeological significance.

Expected Element Distributions in Ceramic Constituents

One key to successful results in ceramic disaggregation and chemical studies is formulating expectations about the nature of element distributions in the ceramic constituents. Without expectations, interpreting results becomes much more difficult. Developing a set of predictions requires two things. First is basic knowledge about the elemental makeup of the clays and aplastics. Second is binocular examination of the ceramics in order to determine the raw material type of the aplastics. This knowledge enables one to predict the concentrations of elements in each constituent.

Expected Element Distributions in Clay

Clays are the products of the decomposition of rocks, most often feldspathic rocks. Decomposition results from environmental forces such as water and wind erosion, temperature fluctuation, and the actions of plants and animals, or more generally, mechanical and chemical weathering. During the process of clay formation, mobile ions are formed, which alter the elemental makeup of a clay compared to its parent rock (Rice 1987). Thus, clays tend to be enriched in some elements and diluted in others. Further, the techniques of a potter may accentuate these differences. This is especially true if the clay is refined by some type of sorting method such as levigation and aplastics are added later.

During the formation of a clay, elements that define the type of parent rock are removed from the clay through the actions of mechanical and chemical agents. The most common minerals in most parent rocks are usually orthoclase and plagioclase feldspars. The Na, Ca, and K of these minerals tend to form mobile cations that are carried away during weathering. Thus, these elements tend to be diluted in a clay relative to its parent feldspathic rocks. In contrast, trace elements such as the lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu), and U and Th tend to concentrate in a clay. However, since clay can be formed from other rocks besides feldspathic rocks, the element concentrations in clay will not always follow this pattern. For example, chlorite clays are derived from ferrous biotites and may be enriched in Fe, Mn, and/or Cr (Rice 1987). Ideally, one would want to know the mineralogic classification of the clay used to make a vessel. However, this may be impossible if suspected clay sources have not been found. Also, firing usually destroys clay minerals, making it impossible to identify the original mineralogy of a clay in a vessel. Consequently, expectations concerning the element distributions in the clay fraction of the paste can usually be formulated only in a rather general fashion.

Expected Element Distributions in Aplastics

The situation with aplastics is somewhat clearer since their raw material type can usually be identified by simple binocular examination. Obviously, the elements found in the aplastics will depend upon their

raw material type (Neff et al. 1988b, 1989). Sand is primarily composed of SiO_2, generally with an insignificant amount of trace element contaminants. Therefore, its presence in a ceramic usually dilutes the elements in the bulk paste relative to the raw clay (Allen et al. 1989). However, if a significant amount of the mineral zircon is present in the sand, the sand and the bulk paste will tend to be enriched in Zr and Hf relative to the raw clay. Shell temper tends to enrich a paste in Ca and Sr relative to its raw clay. Mafic rock tempers, such as volcanic sands, tend to enrich elements such as Mn, Fe, Cr, and Ni. Organic tempers may contribute little to element signature of the sherd since they are composed primarily of H, O, C, and N, which are usually driven off during firing. None of these tempers have high concentrations of many elements, and therefore none is expected to attenuate severely the determination of compositional groups (Neff et al. 1989). In contrast, grog temper may significantly contribute a variety of elements to the paste. Because of its heterogeneity and because its trace element concentrations will be similar to those in the clay, grog temper has the potential to destroy grouping tendencies completely (Neff et al. 1988b, 1989).

Finally, some brief mention should be made of naturally occurring as opposed to deliberately introduced aplastics in the paste. It has been noted in ethnographic studies of ceramic manufacture that many primitive potters minimally process the clay prior to vessel fabrication (Rice 1987). Consequently, a significant amount of naturally occurring aplastic material may be left in the clay. However, in compositional analyses, the origin of aplastics in the paste is largely irrelevant. They can be treated equivalent to deliberately introduced tempers, since they may serve the same function. Thus, they can be characterized in terms of their mineralogic and chemical heterogeneity, and predictions about their elemental makeup and effect upon the chemistry of the clay body can be formulated. On the other hand, if one were to compare "naturally tempered" pottery to raw analyzed clays, one obviously would not want to remove aplastics from the pottery unless the same size fractions were also being removed from the clays.

Element Distributions and Ceramic Disaggregation

Testing the above predictions, as well as the underlying assumption that aplastics are largely responsible for the chemical heterogeneity of a ceramic, requires that the ceramic be separated into its constituent parts and that each part be analyzed separately. Chemical results can then be compared to the formulated expectations. As long as enrichment/dilution patterns are present and can be identified, it is possible to compare the groupings produced by the separate fractions to each other and to those of the bulk sample to determine what effect the aplastics have on group formation and whether their removal would improve patterning in the compositional data set. Thus, it can be determined whether or not the clay fraction data improves the resolution of compositional groups.

As mentioned above, the clay fraction may, in some circumstances, provide the finest resolution of the data into archaeologically meaningful groups. However, three situations may render this assumption invalid on *a priori* grounds. The first two relate to the level of technological sophistication of the potters who made the ceramics. First, if a single clay was used in production, if it was prepared in a uniform fashion, and if aplastics were added systematically, it is possible that the temper will be the main discriminating feature of groups in the compositional data. This will be true if different groups are characterized by different kinds of tempers or different amounts of the same kind(s) of tempers (Neff et al. 1988a). Ceramics of this nature tend to be found where the techniques of production have reached a level of sophistication similar to those of industrial societies. For example, the amphorae produced by the Classical Mediterranean civilizations were made in factories using very standardized methods. Identification of compositional groups in these ceramics likely depends at least as much on the aplastics as the clays.

Second, if the potters have achieved a level of technical expertise in selecting and preparing clays that minimizes the need for adding aplastics, it is unlikely that separation of the components in this type of pottery will yield much improvement in patterning. Some examples of this type of pottery include the sigillatas of the Hellenistic and Roman periods and the finewares of neolithic Mesopotamia (e.g., Halafian ware, Metallic ware).

Third, separation of components is not necessary, and may actually reduce the statistical resolution of compositional groups, when samples source to geologically distinct regions that differ in their clays, natural aplastics, and tempering agents. In this case, covariation between the elemental compositions of the clays, natural aplastics, and tempers among regions will strengthen multivariate group definition.

In sum, the separation of ceramic components and analysis of the fine fraction will most likely afford an advantage when applied to pottery that (1) has been produced on a small scale with fairly primitive techniques and (2) comes from locales that are distinguished geologically in their clay deposits and less so in their available tempering agents. Woodland

pottery from the glacial till plains of the midwestern United States is one example that meets these criteria.

Materials and Methods

Two sets of ceramics were used to investigate enrichment-dilution patterns and compositional group formation for textural fractions. The first set consisted of 40 Tanque Verde Red-on-Brown sherds from the Marana archaeological site in southern Arizona. The second set consisted of 55 Woodland period ceramics from a number of sites located in central Ohio. Two different sets of materials were chosen because we felt it important to look at two different geochemical systems and ceramic technologies.

Disintegration and compositional analysis of the Tanque Verde sherds were undertaken at the Archaeometry Laboratory at the Missouri University Research Reactor (MURR). The Ohio ceramics were disaggregated at the Archaeology Laboratory at Arizona State University and the constituents sent to MURR for compositional analysis. There were some differences in sample preparation and disaggregation techniques. These are noted where relevant.

Twelve artificial sherds, which we refer to as "cookies," were prepared from clays and sands of the Tucson basin which were suspected to be potential source materials for the Tanque Verde ware. Each cookie represented a different potential source. The cookies were made for three reasons. First was to test the efficacy of the sonication technique for disaggregating ceramics. Second was to introduce grouping within the Tanque Verde sherds since it was suspected, and later borne out, that these sherds represented a single compositional group. Third was to assess which, if any, of the clays and sands were indeed source materials for the Tanque Verde pottery. Preparation of the cookies took place at the MURR lab.

Preparation of the Sherds and Cookies

The Tanque Verde sherds were initially prepared for analysis by removing the surface of each to a depth of roughly 0.5 mm. This ensured removal of contamination due to surface treatment, soil adherents, or leaching. Each sherd was then partitioned into two pieces. One was used for bulk compositional analysis and the other was disaggregated for the separate analysis of its clays and aplastics. The Ohio ceramics were washed and wire-brushed until surface clean. Each sherd was then disaggregated for separate analysis of its clays and aplastics.

Preparation of the Tanque Verde bulk analysis portion involved crushing the sherd into a fine powder using an agate mortar and pestle. The powder was then placed in a clean glass vial and placed in an oven stabilized at 80° C for 24 hours in order to drive off free water in the paste powder. The vials were then capped and placed in a desiccator until the samples were weighed for neutron activation analysis.

The cookies were prepared by wetting the 12 clays until they reached a good plasticity. After aging for two weeks, these were worked and temper was added. No set quantitative amount of temper was added because the quantitative proportions of temper to clay in the Tanque Verde sherds was unknown.

After the cookies had been formed, they were allowed to air dry to leather hardness between 24 and 48 hours. They were then fired in a muffle furnace at a peak temperature of 650° C for roughly ten hours. The cookies were then removed, allowed to cool and prepared in the same manner as the Tanque Verde sherds.

Ultrasonic Disaggregation Procedure

The main obstacle to be overcome in analyzing individual ceramic constituents is finding a method that will successfully disaggregate the ceramic into its textural constituents. Further, the technique must not introduce any contaminants into the separated fractions. These difficulties, as well as labor costs, are the main reasons why this approach has not been used frequently.

The few studies that have attempted to analyze the constituents of ceramics have employed a rather crude levigation method (see Attas et al. 1977; Fillieres et al. 1983). The ceramic or raw clay is crushed and added to distilled or deionized water to create a slurry. The slurry is then allowed to settle for a brief period of time so that the larger particles drop out. The suspension containing the clay particles is then poured off and the water is allowed to evaporate, leaving the clay fraction behind.

Unfortunately, this approach requires that the sherd body be crushed to a fairly fine powder, which may result in crushing some portion of the aplastic inclusions as well. The result is an uneven separation of clays and aplastics; some aplastics are included with the clays. This outcome precludes testing whether complete separation would improve compositional resolution.

Gaines and Handy (1977) developed a method for disaggregating ceramics with ultrasonic energy. This method, known as sonication or ultrasoneration, has the advantage of requiring a minimum of precrushing of the sherd. It thereby prevents reduction of aplastic inclusions to the size of clay particles. The method requires that the sherd first be reduced manually to fragments 2-5 mm in size. The fragments are

then soaked in water for several hours prior to disaggregation. Afterwards, the material is bombarded by ultrasonic energy for several minutes. The resultant slurry is then fractionally separated by settling, the supernate is poured off into centrifuge tubes, and the fine clay fraction is spun out. The coarse fraction of silt and sand-sized particles is then dried and may be further separated by either sieving or magnetic separation. The textural separates are then analyzed individually for their composition.

The method employed at MURR was a variation of Gaines and Handy's (1977) method. It involved 6 steps, as follows.

1. The sherd was crushed into 2-5 mm fragments. Fragments of 2-3 mm were found to work better. An agate mortar and pestle was used to crush the sherd. Care was taken to gently crush rather than grind the sherd. This helped to ensure that the aplastics were not ground into a fine powder during this step. After the sherd had been crushed, it was weighed. The crushed sherd was stored in a clean glass vial until sonication.

2. The crushed sherd was placed in a 100 ml tall form beaker and 50 ml of deionized water was added. The water/sherd mixture is then allowed to sit for a few minutes to ensure that the sherd was adequately hydrated.

3. The material was then bombarded with ultrasonic energy for six minutes using a Heat Systems-Ultrasonics Inc. model W-385 Sonicator with a cup horn attachment. The resultant slurry was then stirred and decanted into a flask. The remaining aggregate sherd fragments were gently recrushed and the procedure was repeated until a large amount of clay slurry was produced. Normally, four sonications were required.

4. Once an adequate amount of slurry was obtained (usually about 200 ml), it was gently stirred and then poured into a custom-designed sedimentation column. The length of the column of slurry and sedimentation time were set so as to allow the settling out of all particles greater than clay (~4 microns) in size and the retention of clay-sized particles in the slurry, in accordance with Stoke's law. The typical sedimentation involved a column of slurry 2.5 cm in diameter and 30 cm tall, and a settling time of 60 seconds. Before sedimentation, the column was inverted three times to ensure adequate mixing. After sedimentation, the supernate containing the clay fraction was drained into a flask.

5. The supernate was stirred one final time and then carefully decanted into 50 ml centrifuge tubes. The tubes were then placed in a centrifuge and spun until essentially all particulates were settled and the liquid was clear. The water was then decanted, leaving the clay fraction at the bottom of the tube. They were then dried in an oven stabilized at 70° C for 24 hours. This procedure yielded about 500-750 mg of clay per sherd.

6. The coarse fraction that was left in the sonication beaker was dried in the oven. The material left in the bottom of the sedimentation column was discarded. This lost portion averaged about 33% of the presonicated weight of the sherd. After drying, the coarse fraction was sieved using a set of separating screens. All particles ranging between 1 mm and 0.25 mm were saved for analysis. Binocular examination of this material revealed it to be largely (approx. 50-80%) quartz sand with a few grains of quartzite, calcite, caliche, or limestone. The remaining portion consisted of bits of the clay body that had not broken up during sonication.

All 40 of the Tanque Verde Red-on-Brown sherds and the 12 cookies were disaggregated in this manner.

The Ohio Woodland sherds were disaggregated in a similar fashion at Arizona State University. Specific differences in the experimental parameters from those used by the MURR are as follows. First, each sherd was entirely disaggregated, leaving no bulk portion for analysis. Sherds about 2.5 cm square were crushed lightly with an iron hammer-piston-cylinder into fragments ranging from powder to 3 mm in diameter. The poor solidity of the ceramics made this level of manual disintegration of the paste simple to achieve. The crushed sherd was placed in a beaker with 1.5 mega-ohm double distilled and deionized (DDD) water, creating a slurry of 250 ml. After settling a few minutes, the slurry was sonicated, one time only, for six minutes with a Heat Systems Ultrasonics Sonicator, Model W225. The sonicator has a titanium

tip, which was submerged about 1 cm into the slurry, and generates waves with a frequency of 20 KHz and a power of about 50-65 watts. A continuous rather than pulsating wave output was used. The entire sonicated slurry was transferred directly to a customized sedimentation column along with enough DDD water to fill its 2.7 cm inside diameter 30 cm high. After inverting the column 3 times, the slurry was allowed to settle one minute and the top 23 cm of supernate were released from a valve appropriately located 7 cm from the column's bottom. Clay and silt-sized particles (particles less than .004 mm in diameter) were thereby isolated in the supernate, whereas the sediment contained primarily sand and larger grade particles. All particulates in the supernate captured by centrifuging and decanting were transferred to storage vials, and then oven dried at 110° C for 24 hours. The coarse fraction in the bottom 7 cm of the sedimentation column was transferred to a beaker and similarly dried. No fraction of the sherd was discarded. The fine-fraction samples ranged between 41 and 2400 mg; coarse-fraction samples ranged between 50 and 1100 mg. Both the fine and coarse fraction samples were submitted to MURR for INAA determinations. The coarse fraction was not sorted by sieving at MURR. Also, as mentioned, no bulk analysis was undertaken on the Ohio Valley specimens.

Neutron Activation Analysis

After the sherds were disaggregated, their elemental composition was measured using INAA. As discussed by Glascock (Chapter 2, this volume), MURR employs two procedures that routinely allow the concentrations of 33 elements to be determined. All of the Tanque Verde pottery and cookie fractions (bulk, coarse, and fine) and the coarse and fine fractions of the Ohio Woodland sherds were analyzed in this manner.

Results and Interpretation

This section discusses the statistical analysis and interpretation of the compositional data derived for the Tanque Verde and Ohio Woodland sherds. Several different statistical techniques were used in order to define the enrichment/dilution effects of the fine and coarse constituents and to assess how the enrichment/dilution effects distorted or enhanced the formation of compositional groups.

Univariate Analysis of Elemental Enrichment and Dilution

The first analytical step was to determine patterns of enrichment and dilution of elements in the fine and coarse fractions relative to each other and the bulk sample. This was accomplished in three ways. The first was by comparing the mean element values of the different fractions to each other in simply a visual manner. This comparison showed that certain elements were indeed enriched or diluted in the various fractions, as anticipated.

In order to better delineate the enrichment/dilution patterns, a second approach was taken. A simple ratio was calculated for each element in a Tanque Verde sherd, as follows:

$$\left(\frac{F-B}{B}\right)100$$

where:
B =concentration in the bulk sherd
F =concentration in the coarse or fine constituent

This equation expresses enrichment/dilution as a percent of the total concentration of each element in the bulk sample. Once enrichment/dilution coefficients were calculated for each constituent and each sherd, they were averaged over all sherds in order to determine an average dilution or enrichment for each element. These were then examined to determine which elements were most diluted or enriched in the coarse and fine fractions. A visual representation of this patterning is depicted in Figure 7.1. Note that the lanthanide elements all tend to be enriched in the fine fraction and diluted in the coarse fraction. Elements such as Na, K, Zr, and Hf tend to be diluted in the fine fraction and enriched in the coarse. This pattern meets the expectations outlined above. The enrichment of Na, K, Zr, and Hf indicates that a significant proportion of the aplastics in the sherd body were feldspars and zircons. This result was confirmed by petrographic analysis, which showed that quartz-feldspar sand comprised the major proportion of aplastics in the Tanque Verde sherds. Zircons, as part of an undifferentiated epidote family, made up a smaller percentage of the aplastics (Lombard 1987).

Because we did not make bulk analyses of the Ohio ceramics, we used a different ratio to characterize elemental dilution and enrichment for these ceramics:

$$\left(\frac{I}{F+C}\right)100$$

where:
I =concentration in the individual constituent (fine or coarse)
F =concentration in the fine constituent
C =concentration in the coarse constituent

The individual ratios were then averaged over all sherds for each element and graphed to assess the enrichment/dilution patterning. Figure 7.2 presents the enrichment/dilution pattern for the Ohio

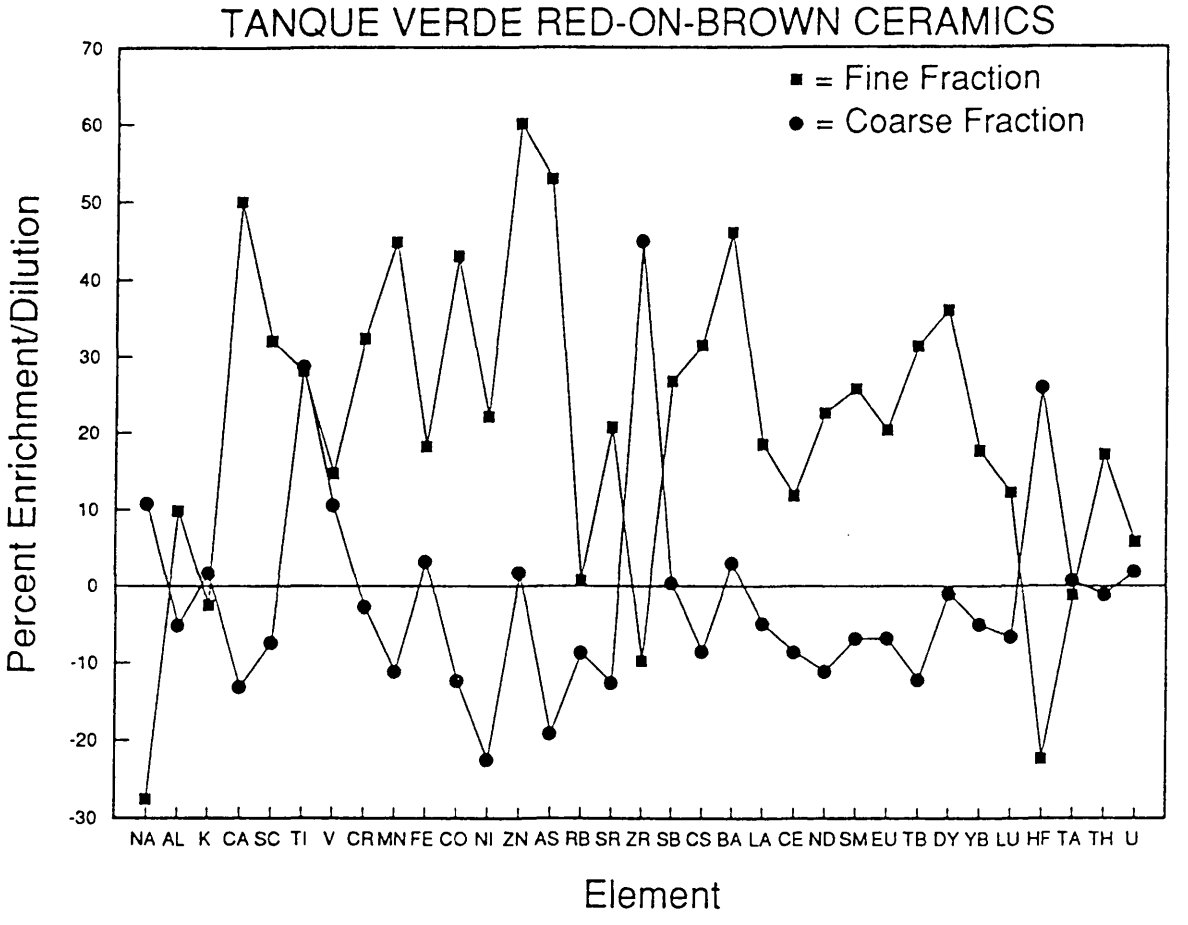

Figure 7.1. Plot of enrichment/dilution coefficients for Tanque Verde Red-on-Brown pottery. See text for definition of the coefficient. Note the dilution of Na, Zr, and Hf, and to a lesser extent K in the clay fraction and their enrichment in the coarse fraction. This concords with a petrographic analysis, which identified aplastics (i.e., the coarse component) as consisting of primarily feldspar sand and zircons.

ceramics. The pattern is similar to that observed in the Tanque Verde sherds. Na, K, Ca, and Sr, which characterize feldspathic rocks, tend to be enriched in the coarse fraction and diluted in the fine fraction. In contrast, the lanthanides are enriched in the fine fraction and diluted in the coarse fraction. Again, this is the pattern that would be expected if most of the sherds had aplastics composed primarily of feldspathic rock fragments. Petrographic analysis of Ohio Woodland ceramics (Carr and Komorowski 1991) concord with this conclusion.

While the enrichment-dilution patterns are similar for the Tanque Verde and Ohio Woodland samples, two differences are noteworthy. First is the lower enrichment of Zr and Hf in the coarse fraction of the Ohio sherds. This indicates the rarity of mineral zircon aplastics in the Ohio sherds. The contrast between the Tanque Verde and Ohio samples in mineral zircon aplastics undoubtedly reflects differences in local geology, clay formation and available tempering materials. Much of the temper material used for the Tanque Verde sherds derived from fluvial sands (Lombard 1987). The tempering materials used in the Ohio ceramics came from glacial tills. Second, Ca tends to be enriched in the clay fraction of the Tanque Verde sherds alone. This is contrary to expectation because Ca, along with Na, is a defining element for feldspathic rocks, specifically plagioclases. However, the Ca enrichment is understandable. Binocular examination of the Tanque Verde sherds revealed large inclusions of either limestone or caliche, both of which are rich in Ca. Caliche deposits may have developed in the sherds as a consequence of their depositional environment. Because the inclusions were very soft and broke apart easily, they were, very likely, fractured into very small grains during sonification and removed with the clay fraction. Thus, the amount of Ca in the clay fraction would have increased significantly.

The enrichment/dilution patterns of the cookies were also examined. Although not presented here, they resembled the pattern of the Tanque Verde sherds, as

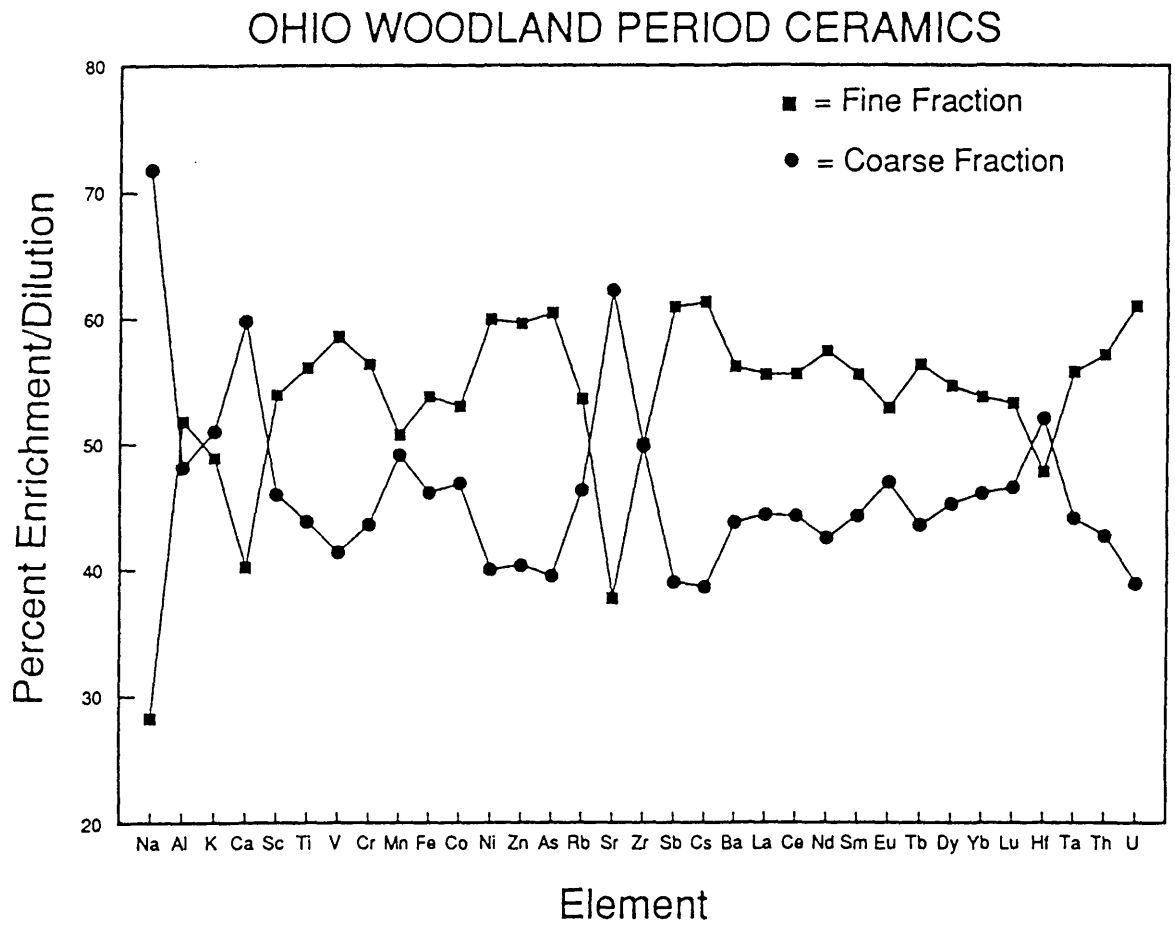

Figure 7.2. Plot of enrichment/dilution coefficients for the Ohio Woodland Period ceramics. See text for definition of the coefficient. Dilution of Na, K, Ca, Sr, and Hf in the fine fraction and their enrichment in the coarse fractionreflect tempering with feldspar sand or crushed feldspathic rock.

one would expect. This provided some initial evidence that the clays and tempers used to manufacture them are good candidates for source materials.

It is also worthwhile to note that our results corroborate results obtained by several other researchers working along similar lines (Kilikoglou et al. 1988; Allen et al. 1989; see also Blackman, Chapter 8, this volume). While these studies focused on analyzing different size fractions of suspected clay sources rather than finished ceramics, the distributional patterns of elements among the size fractions are remarkably consistent. The lanthanide elements tend to be enriched in the clays while the aplastics tend to be enriched in elements characteristic of their specific mineralogy (for example Na, K, and Ca in feldspathic sands; Cr, Co, Fe, in mafic [volcanic] sands, etc.). Perhaps the most interesting result of these studies (including our own) is the consistent enrichment of Hf and Zr in the coarse fraction relative to the clay fraction. This outcome is consistent regardless of the specific geologic environment and occurs in materials from the American southwest and midwest (this report), Crete (Kilikoglou et al. 1988), the Upper Nile Valley (Allen et al. 1989) and the Khabur River Basin of northeastern Syria (Blackman, Chapter 8, this volume). This result probably reflects the resistance of zircons to environmental degradation. Accordingly, Hf and Zr may reflect textural variation in ceramics in many different geological contexts.

Multivariate Analysis of Elemental Enrichment and Dilution

The third approach that was taken to examine enrichment and dilution patterns in the fine and coarse fractions employed principal components analysis. This technique was chosen because major partitions in compositional data are commonly observable on the first few principal components (e.g., Bishop and Neff 1989; Neff et al. 1988b, 1989; Glascock, Chapter 2, this volume).

For the Tanque Verde study, we analyzed the cookie data with the fine and coarse fraction sherd data as one data set in order to ensure that there would be at least two groups (see above). For the Ohio study, we analyzed the fine and coarse fraction data together as one data set. Also, we deleted the element Ni from both data sets as it had a large number of missing values. Tables 7.1 and 7.2 present the first five principal components and associated eigenvalues for the Tanque Verde and Ohio data sets.

The first five principal components accounted for roughly 80% of the variance in both data sets. Examining the components confirms several of the effects identified with the enrichment/dilution coeffi-

Table 7.1. First Five Principal Components for the Tanque Verde Red-on-Brown Bulk Sherds and Fine and Coarse Separates.

ELEMENT	PC #1	PC #2	PC #3	PC #4	PC #5
As	0.4348	-0.4573	-0.1031	0.0076	-0.2180
La	0.1249	0.1423	-0.0368	-0.0052	-0.1409
Lu	0.0948	0.1864	-0.0919	-0.0928	-0.0485
Nd	0.1391	0.1475	0.0150	-0.0437	-0.1360
Sm	0.1462	0.1639	-0.0115	-0.0106	-0.0790
U	0.0827	0.0725	-0.1112	0.0488	0.0872
Yb	0.1123	0.2021	-0.0930	-0.1216	-0.0956
Ce	0.1122	0.1492	-0.0352	0.0030	-0.1033
Co	0.2259	0.2141	0.1527	0.1600	0.2590
Cr	0.1592	0.1949	-0.0306	-0.2132	0.2390
Cs	0.3545	-0.3948	-0.3388	-0.1267	0.2620
Eu	0.1176	0.1149	0.0261	0.0066	-0.0560
Fe	0.0924	0.0843	0.0282	0.0202	0.1121
Hf	-0.1860	0.0443	-0.1792	-0.2361	-0.2035
Rb	0.0841	0.0215	-0.1552	0.0405	0.0704
Sb	0.2508	-0.0804	-0.1996	0.2130	-0.3929
Sc	0.1900	0.1577	-0.0268	-0.0029	0.1428
Sr	0.0868	-0.1639	0.3876	0.4811	-0.1944
Ta	0.0116	0.1965	-0.0858	0.0520	-0.0222
Tb	0.1713	0.1841	-0.0293	-0.0256	-0.0381
Th	0.1286	0.1750	-0.1166	0.0680	-0.1566
Zn	0.2719	0.0944	0.0393	0.1711	0.1254
Zr	-0.1579	0.0900	-0.1278	-0.3113	-0.2995
Al	0.0751	0.0070	-0.0261	0.1085	0.0337
Ba	0.1137	0.1237	0.1316	-0.0197	-0.4879
Ca	0.1956	-0.1292	0.6767	-0.4989	-0.0294
Dy	0.1588	0.2216	-0.0604	-0.1204	-0.0770
K	0.0048	0.0148	-0.1273	-0.0192	-0.0261
Mn	0.2195	0.2158	0.1671	0.0761	0.0535
Na	-0.2434	0.1218	0.0619	0.3548	-0.0204
Ti	0.0533	0.1746	-0.0293	0.0776	0.1197
V	0.0611	0.0696	0.0378	-0.0498	0.1207
Eigenvalues	0.1569	0.0538	0.0516	0.0300	0.0257
% Var. Explained	38.39	13.17	12.64	7.33	6.28
Cumulative Var.	38.39	51.57	64.21	71.54	77.81

cients. For the Tanque Verde data, the first component has high loadings for As, Cs, and to a lesser extent for Na, Sb, and Zn. On the second principal component, both As and Cs have high loadings. On the third component Ca, Cs, and Sr are high. On the fourth component Ca, Sr, and Na have high loadings. On the fifth component Ba, Sb, and Zr have high loadings. The sign of an element's loading indicates its either direct or inverse relationship with most other elements and, thus, to some extent whether it has been enriched or diluted. The magnitude of an element's loading indicates, to some extent, the degree of enrichment or dilution.

Table 7.2. First five principal components for fine and coarse separates of Ohio Woodland Period sherds.

ELEMENT	PC #1	PC #2	PC #3	PC #4	PC #5
As	0.2368	-0.1895	0.0188	-0.3759	-0.4718
La	0.1255	-0.0540	-0.1686	0.1354	-0.0267
Lu	0.1155	-0.0039	-0.0494	0.1643	0.0517
Nd	0.1602	-0.0436	-0.1767	0.1729	-0.0971
Sm	0.1453	-0.0139	-0.1469	0.1895	-0.0390
U	0.2215	-0.0411	-0.0312	-0.1435	-0.1791
Yb	0.1197	-0.0106	-0.0688	0.1798	0.0586
Ce	0.1255	-0.0409	-0.1931	0.1435	-0.0881
Co	0.1983	0.4494	0.0322	0.1158	-0.0990
Cr	0.1749	0.1439	0.1052	-0.1322	0.2332
Cs	0.2603	-0.0191	-0.2043	-0.1866	-0.0528
Eu	0.0951	0.0436	-0.1397	0.2052	-0.0009
Fe	0.1492	0.1650	0.0967	-0.1303	-0.0395
Hf	-0.0359	-0.1303	0.0461	0.1499	0.0046
Rb	0.1189	-0.0429	-0.2535	-0.0447	-0.0636
Sb	0.2009	-0.0631	0.0326	-0.1630	-0.0898
Sc	0.1377	0.2088	0.0460	-0.1114	0.1616
Sr	-0.3298	0.1014	-0.6381	-0.2282	-0.1988
Ta	0.1275	-0.0847	-0.0291	0.0343	-0.0491
Tb	0.1601	-0.0026	-0.1330	0.2716	0.1186
Th	0.1512	-0.1349	-0.1049	-0.0404	-0.0834
Zn	0.2519	0.0623	-0.0819	0.0257	0.3585
Zr	-0.0074	-0.1141	0.0004	0.1533	0.0712
Al	0.0377	0.0249	-0.0610	-0.0581	-0.0383
Ba	0.1289	-0.1351	-0.3493	0.0441	0.2508
Ca	-0.1909	0.5135	-0.2714	-0.2521	0.2539
Dy	0.1263	0.0033	-0.1052	0.2033	0.0946
K	-0.0014	-0.0381	-0.2360	0.1212	-0.1267
Mn	0.1224	0.5074	0.0885	0.3285	-0.4779
Na	-0.4076	0.0582	0.0170	0.2163	-0.1704
Ti	0.1204	0.0802	0.0324	-0.0793	0.0620
V	0.2051	0.1823	0.0456	-0.2168	0.0373
Eigenvalues	0.2499	0.1327	0.0780	0.0464	0.0282
% Var. Explained	38.16	20.26	11.92	7.08	4.31
Cumulative Var.	38.16	58.42	70.34	77.42	81.73

From the pattern of loadings on the first two principal components, it would appear that at least these components reflect textural differences in enrichment and dilution. Thus, As and Cs are positively loaded on the first component, but negatively loaded on the second. Na also has a negative loading on the first component and a positive, though less significant loading on the second. Zr and Hf also exhibit this patterning, although their loadings are lower.

The situation is similar for the Ohio material. In some regards, the patterning is clearer because there is no contribution to the variance from a bulk sample. High loadings occur for Na, Sr, Cs, and Zn on the first component; Ca, Mn, and Co on the second component; Sr, Ba, Ca, Rb, and to a lesser extent K on the third component; As, Mn, Tb, and Ca on the fourth component; and Mn, As, Zn, and to a lesser extent Ce, Ba, and Cr on the fifth component. As with the Tanque Verde data, the signs and magnitudes of the loadings of elements reflect to some extent their enrichment or dilution and the degree of enrichment or dilution.

Again, at least the first two components probably reflect textural differences in enrichment and dilution. This is evident in that Na and Sr are negatively loaded on the first component, yet positively though less significantly loaded on the second. Ca also exhibits this pattern. In contrast, Cs is positively loaded on the first component and negatively though less significantly loaded on all remaining components.

Since at least the first two components probably reflect textural difference, and since these encompass much of the variation in both data sets, we reasoned that plotting the component scores for the first two components should result in separation of the data into its textural groups: fine, coarse, and bulk in the Tanque Verde case, and fine and coarse in the Ohio case. These plots of component scores are shown in Figures 7.3 and 7.4. In both cases, separation of the textural groups and expression of enrichment and dilution effects occurred along primarily the first principal component. We should point out that we could have achieved greater separation of groups by using discriminant function analysis; however, separating the data into textural groups that we knew existed (for we had created them) was not our goal.

Another thing to point out about the component score plots is the overlap among the textural groups. At least some of this is due to the presence of unseparated clays in the coarse fraction, as well as in the bulk fraction, of course. This pattern is especially exemplified in the case of the Tanque Verde data, where greater overlap occurs between the coarse and bulk

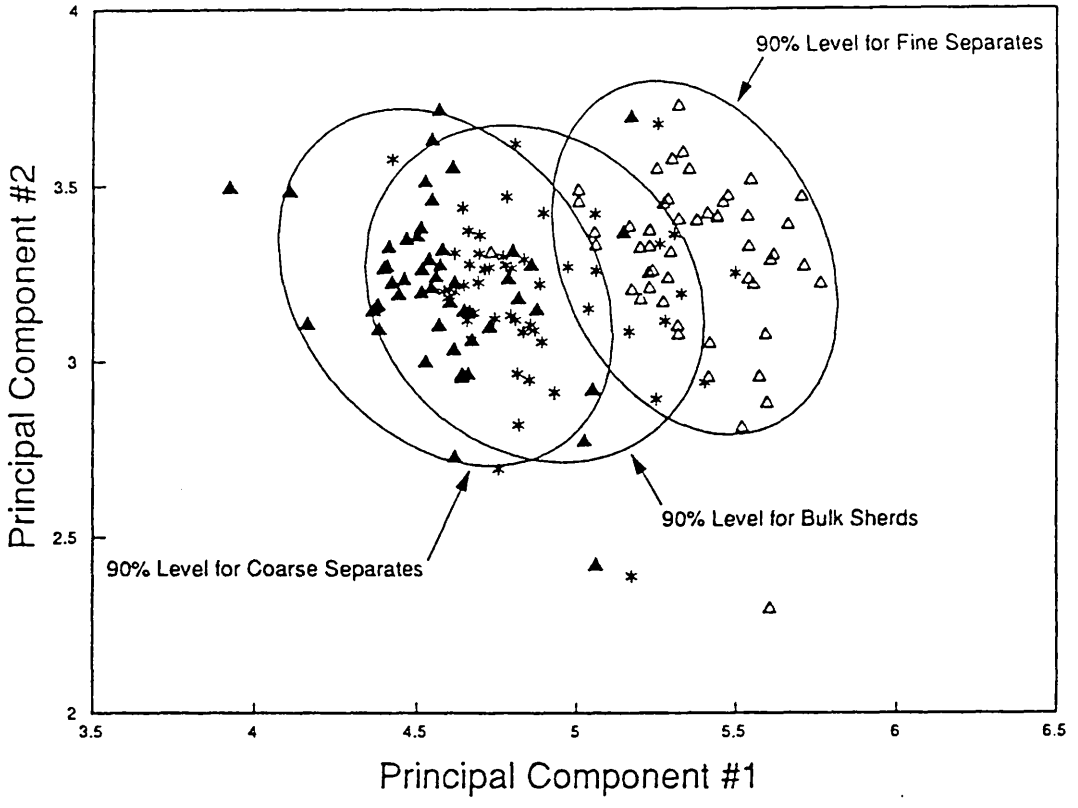

Figure 7.3. Plot of principal component scores of the elemental compositions of Tanque Verde ceramic and cookie fractions.

fractions than between fine and bulk fractions. This result is expectable because the coarse fraction has a significant amount of clay body still in it whereas the clay fraction contains no aplastics.

An additional interesting characteristic of these plots is the smaller confidence ellipses of the fine fractions than the coarse fractions. This is especially evident in the Ohio data, but also pertains to the Tanque Verde data. In the Tanque Verde data, the fine fraction has fewer outliers than either the coarse or the bulk fractions. Examination of the standard deviations of element concentrations revealed that chemical variation of the clay fraction tends to be smaller than that of the other fractions. These facts support the assumption that aplastics are usually more heterogeneous chemically than clays and, thus, may obscure patterning in the data. Indeed, petrographic analyses of the Ohio ceramics have shown that the mineralogy of their glacial till-derived aplastics is very diverse.

At the same time, this position must be qualified. At least some of the greater variability of the coarse fractions is due to analytical error. We were unable to remove all clay from the coarse fraction. This is more true of the Ohio ceramics than the Tanque Verde ceramics and helps explain the wide confidence ellipse for the coarse fraction of the Ohio sherds. Further, simply because the fine fraction is less variable than either the bulk or coarse fractions provides no *a priori* guarantee that group resolution can be improved by analyzing the fine fraction alone. Indeed, if aplastics are responsible for group separation, removing the coarse fraction, while reducing the variance in the data set as a whole, will destroy the archaeologically meaningful compositional patterning in the data.

Analysis of Group Formation by Fraction

Having determined that the effects of aplastics and clays can be isolated in elemental data, we turned to assessing whether improvements in group formation can be accomplished by using the fine fraction. Our initial hypothesis was that using the fine fraction should lead to greater resolution of groups in the data because clays are typically more homogeneous than tempering agents. To assess this proposition, we calculated the principal components for each fraction group separately and then plotted their scores on the first two principal components.

The results for the Tanque Verde fine, coarse, and bulk samples of sherds and cookies, respectively, are presented in Figures 7.5, 7.6, and 7.7. All three plots exhibit basically the same pattern. There is slight

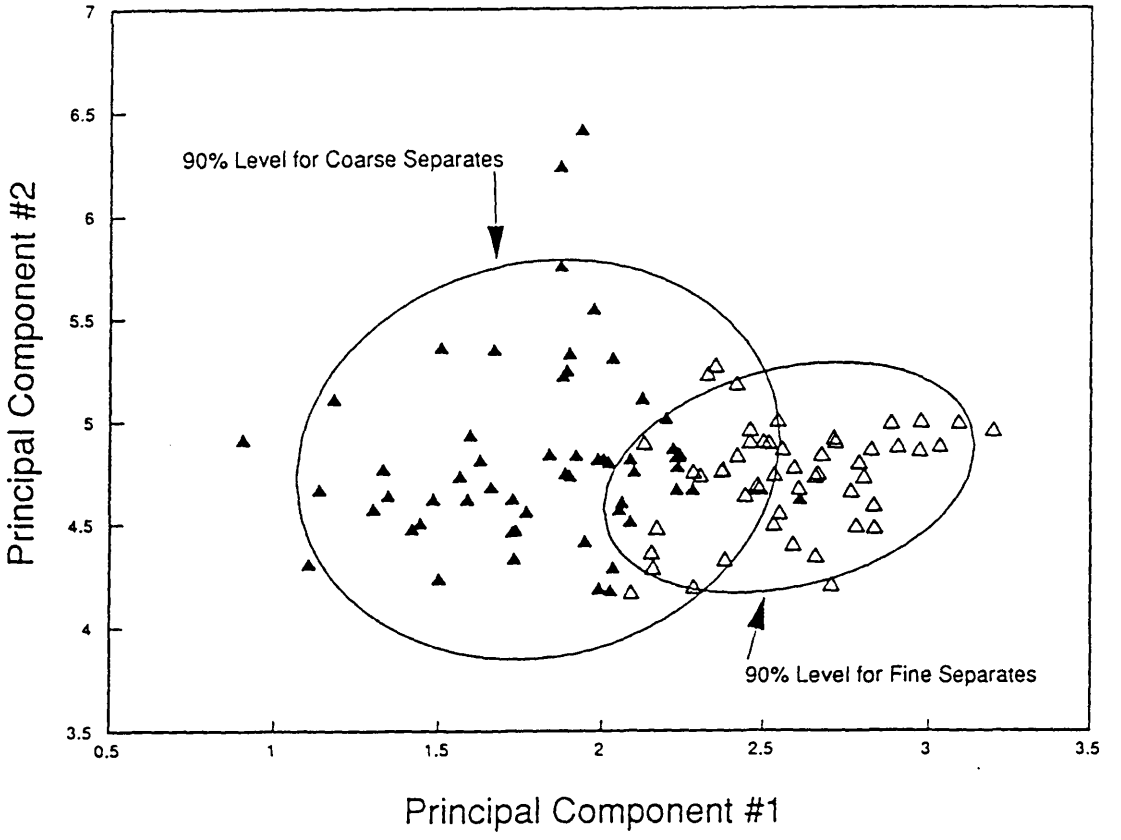

Figure 7.4. Plot of principal component scores of the elemental compositions of Ohio Woodland ceramic fractions.

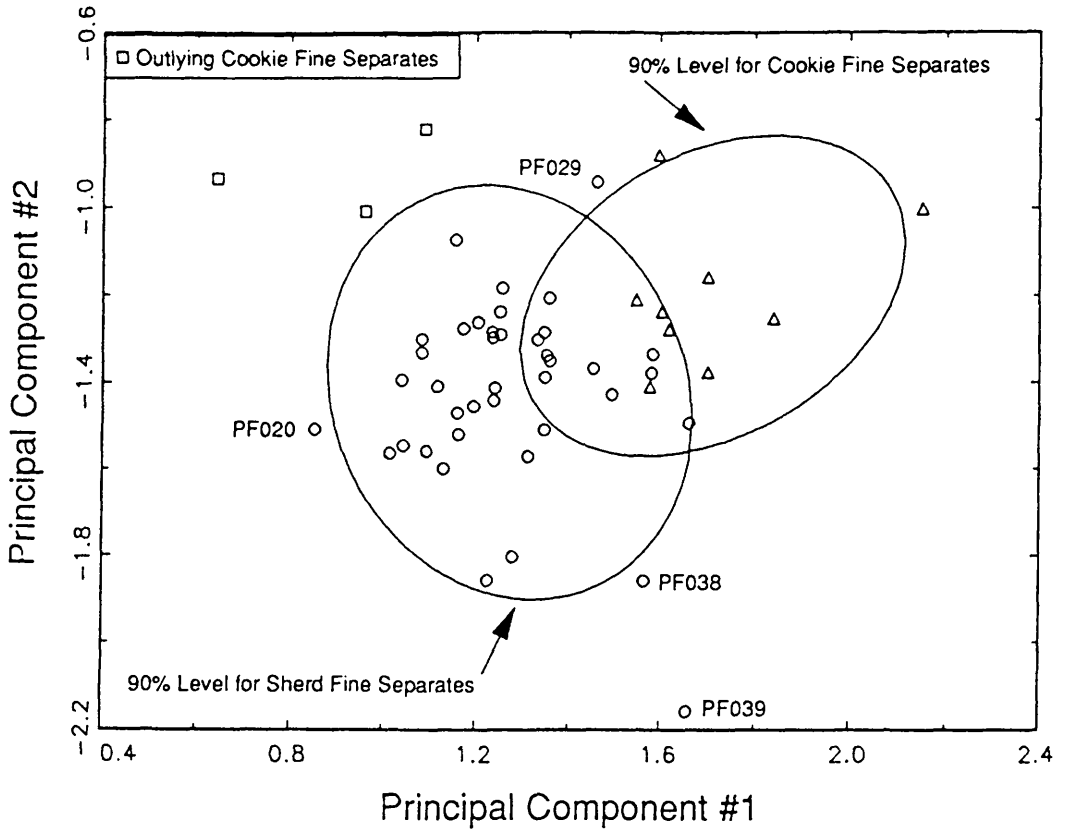

Figure 7.5. Plot of the principal component scores of the elemental compositions of the fine fractions of Tanque Verde ceramics and cookie specimens.

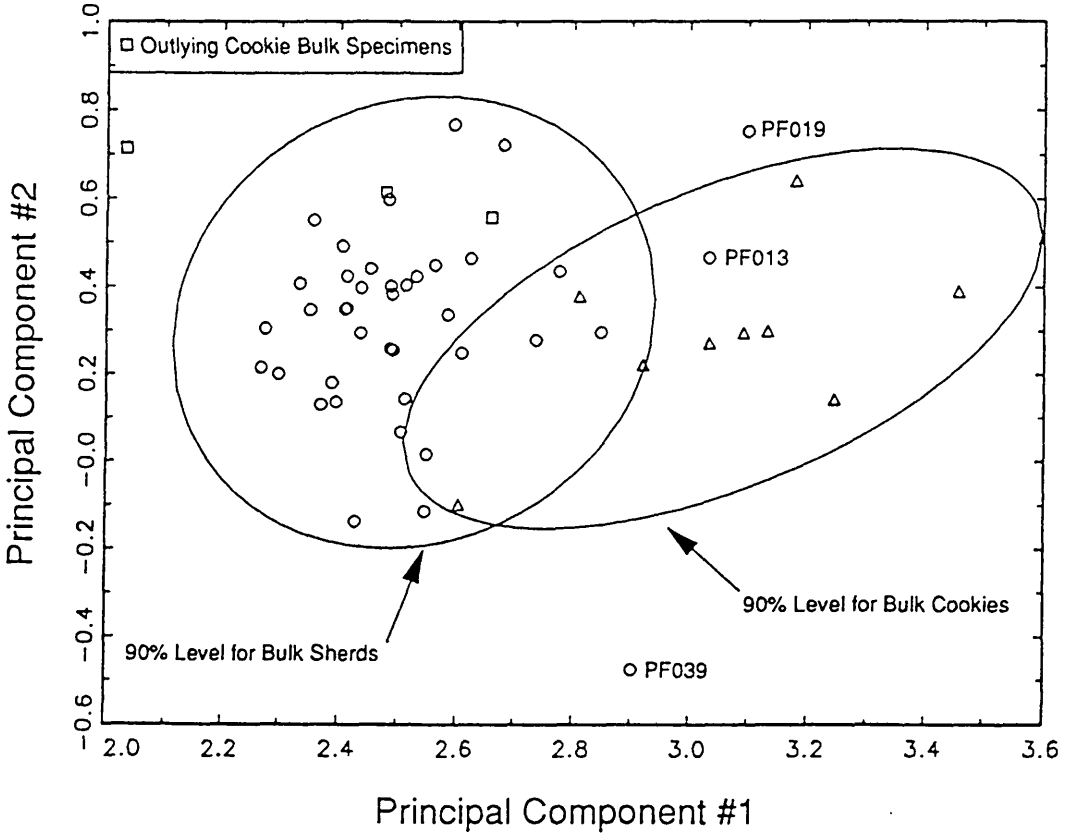

Figure 7.6. Plot of the principal component scores of the elemental compositions of the coarse fractions of Tanque Verde ceramics and cookie specimens.

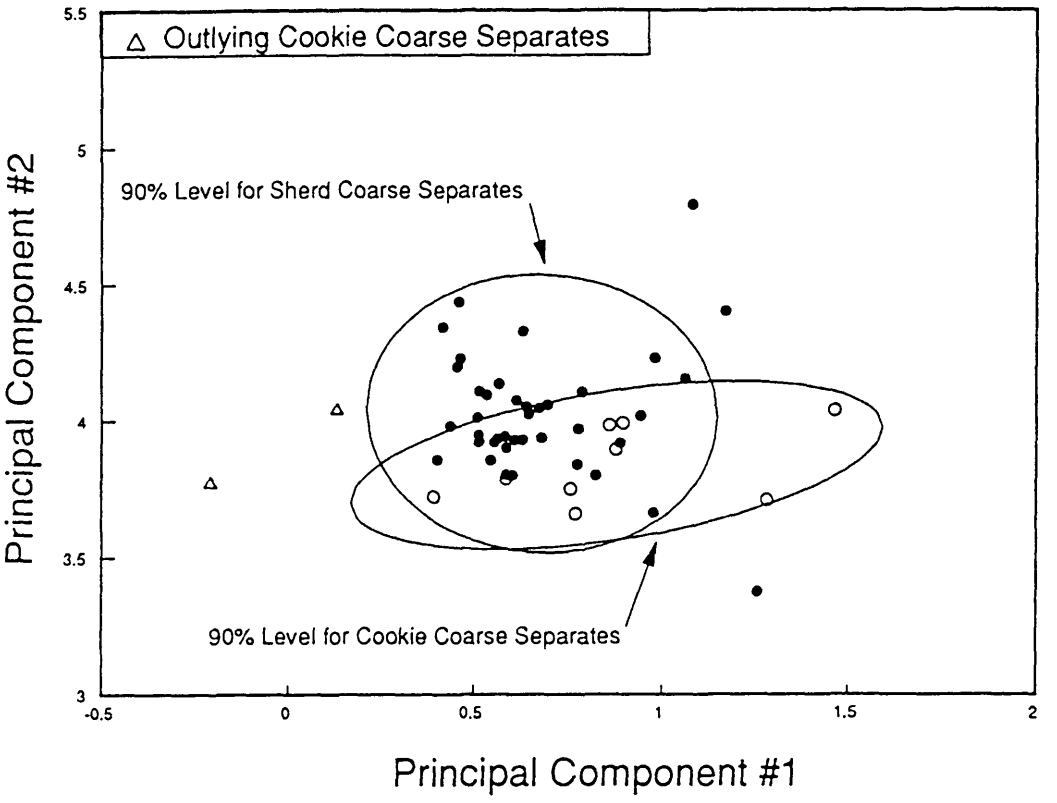

Figure 7.7. Plot of the principal component scores of the elemental compositions of the bulk Tanque Verde ceramics and cookie specimens.

overlap between the sherd and cookie samples, regardless of the fraction considered. Two or three outlier cookie samples and two or three outlier sherd samples are also apparent in each plot. The similarity of these results shows that little or no improvement was gained in defining compositional groups by isolating the fine fraction. In fact, even the coarse fraction served well in resolving groups. This result suggests that in bulk analyses, aplastics obscure the definition of groups only when they are present in overwhelming amounts (Neff et al. 1988b, 1989).

Results of the principal components analysis of the fine and coarse fractions of the Ohio ceramics are shown, respectively, in Figures 7.8 and 7.9. The fine fraction allowed the resolution of one large "Composite Group" and four smaller groups. The four smaller groups are each comprised of sherds that were excavated from one site: either McGraw, Scioto Trails, Harness-28 Late Woodland component, or Howard Baum. The Composite Group consists of specimens from a number of geographically widespread sites. These include Phillip Smith, Mound City, Murphy, Harness-28 Middle Woodland component, and Waterplant. Specimens from different sites in the Composite Group could not be distinguished. The separation between the four small groups and the Composite Group is fairly good. In contrast, the coarse fraction allowed the definition of only three groups, and these overlap considerably. Only the samples from Harness-28 Late Woodland component and Scioto Trails were distinguishable by site. Samples from the remainder of the sites formed one large group, which overlapped with the former two.

We conclude from these results that separating and analyzing the fine fraction did allow significant improvement in the definition of compositional groups for the Ohio ceramics. In a bulk compositional analysis, the chemical heterogeneity of the coarse fraction aplastics, which has been documented petrographically, would obscure to some degree what fine-fraction compositional distinctions do occur.

This conclusion must be qualified in two ways. First, the poor resolution of groups that was obtained with the coarse fraction data is in part due to the noise of sample preparation. Not all fine particles were removed from the coarse fraction, and this contamination varied in amount from sample to sample. This may have confounded the definition of coarse fraction groups to some extent.

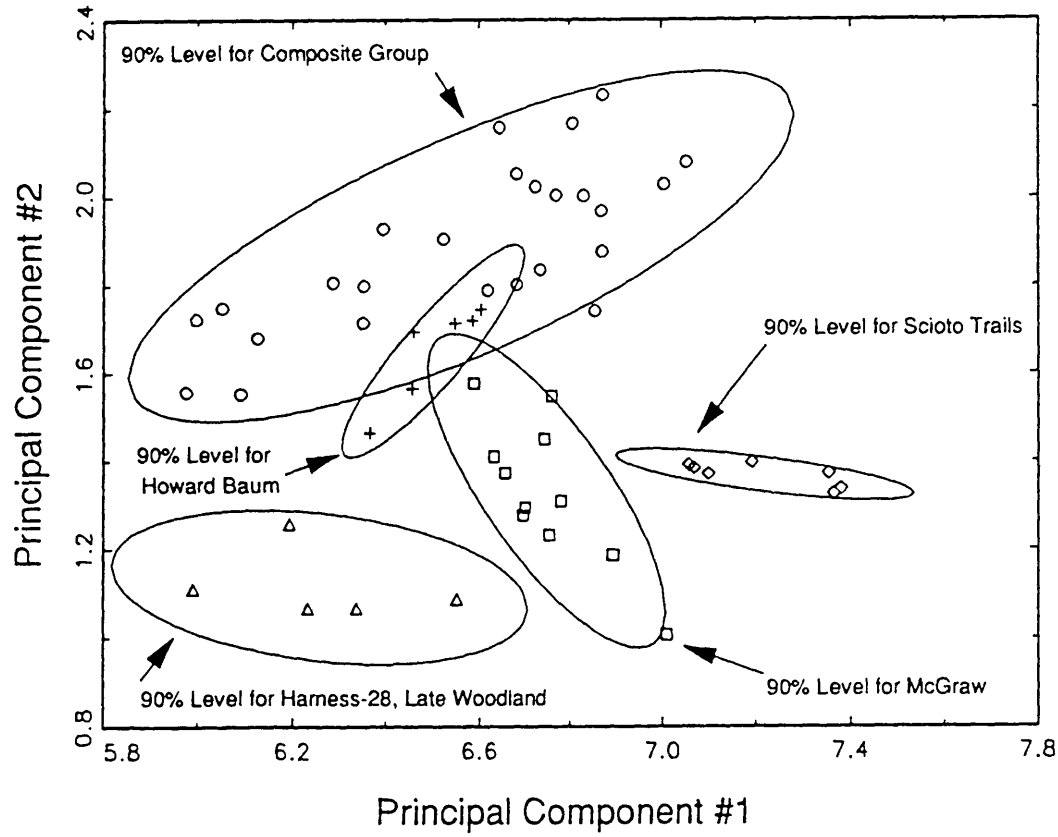

Figure 7.8. Plot of the principal component scores of the elemental compositions of the fine fractions of Ohio Woodland Period ceramics.

Second, the results of the fine fraction analysis are somewhat unsatisfactory in one important way. The sherd groups that were defined only loosely correspond to the drainages from which the sherds come. The Composite Group contains sites from the lower Scioto valley below the confluence of Paint Creek (Harness-28 Middle Woodland component), the lower Scioto Valley above the confluence of Paint Creek (Mound City), the central Scioto Valley (Phillip Smith, Waterplant), and the Licking Valley (Murphy). At the same time, sherds from the Middle Woodland and Late Woodland components of the same site, Harness-28, were distinguished. Also, sherds from the Scioto Trails and Waterplant sites, which are both located in the central Scioto valley only a few miles apart, are distinguished. These patterns are difficult to interpret with the given small sample of pottery. Study of a larger sample of pottery from the region is currently underway.

Conclusions

Several conclusions can be drawn from this study. First is the importance of deriving *a priori* expectations for the amounts of elements in and their distributions among the natural aplastics, added temper materials, and clays of the ceramics to be studied. Such expectations can be based on the known mineralogy of the ceramics and the geological environment of clay formation, or on previous compositional work. Derivation of such expectations is essential to a focused interpretation of the results of multivariate statistical analysis of compositional data (also see Neff et al. 1988b, 1989). In this paper, we derived some very general expectations for elemental amounts and distributions in clays and several kinds of tempering agents (i.e., sands, shell, mafic rocks, organics, grog), as well as specific expectations for the Tanque Verde and Ohio Woodland ceramics.

Second, we showed that ceramic fractions of different textures can vary from each other and from bulk samples in the elements that are enriched or diluted in them. Our studies broadly corroborated *a priori* expectations of elemental amounts and distributions and also corroborated results obtained by researchers pursuing similar lines of investigation (Kilikoglou 1988; Allen et al. 1989; Blackman, Chapter 8, this volume).

Third, the results of this study support, qualify, and extend the conclusions reached in Neff et al.'s

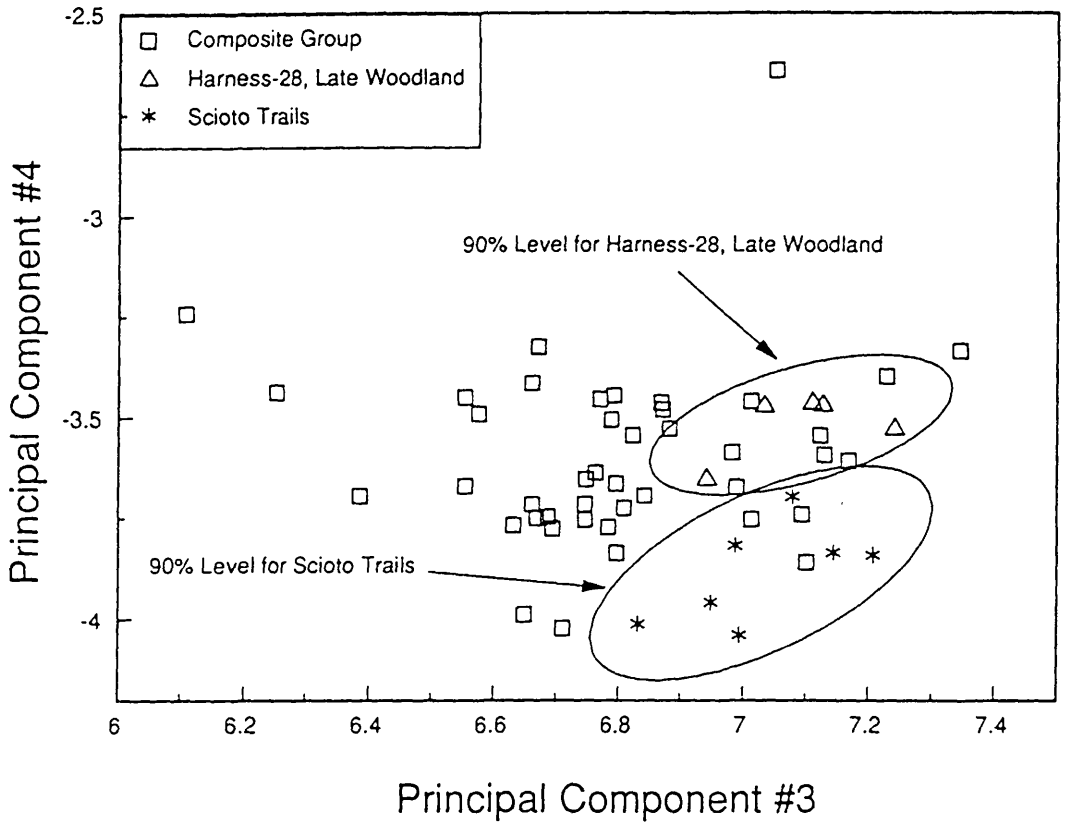

Figure 7.9. Plot of the principal component scores of the elemental compositions of the coarse fractions of Ohio Woodland Period ceramics.

(1988b, 1989) simulation research on the effects of temper in defining compositional groups. Clearly, temper does not obfuscate formation of archaeologically meaningful groups unless it is present in large quantities and is heterogeneous in mineralogy, as these authors have previously concluded. For the Tanque Verde ceramics no improvement was obtained in group formation by analyzing their fine fraction. The bulk samples and even the coarse fraction produced similarly good results. A bulk compositional analysis would be appropriate for research on this data set. In contrast, for the Ohio Woodland ceramics, analysis of the fine fraction yielded significant improvement in group distinctiveness over that achieved with the coarse fraction. Unfortunately, comparison with a true bulk analysis was not possible. However, these sherds were heavily tempered (about 30-40% by volume) with diverse assemblages of felsic and mafic rocks from glacial till, and we believe that separation of textural fractions and focusing on the composition of the fine fraction would be appropriate for research on this data set.

From these analyses and the previous work of Neff et al. (1988b, 1989), we extrapolate some general guidelines for when it is advantageous to separate textural fractions of ceramics for compositional analysis, but also acknowledge the importance of context-specific criteria for making this decision. First, heterogeneity of tempering material may obscure group distinctiveness (Neff et al. 1988b), so separation of textural fractions and focusing on the composition of the fine fraction is useful (1) when temper is present in large quantities, (2) when temper quantity varies significantly from sherd to sherd, (3) when temper particles are mineralogically diverse and represent noise relative to distinguishing clay signals; and, therefore, more generally, (4) when the ceramics are coarse and have been produced with a simpler technology. Compositional homogeneity and distinctiveness of clays relative to tempering agents or a bulk sample can relate to the physical and chemical sorting and weathering of the clays, their preparation by levigation or winnowing, and/or the approximate rather than quantitative manner with which tempers are added to clays. Equally important as the heterogeneity of non-plastics are relative concentrations of elements in the clays versus tempering materials; tempers with elemental concentrations at or above the

corresponding concentrations in clay may easily obscure the distinctiveness of compositional groups, as Neff et al. (1988b, 1989) have demonstrated.

At a more practical level, the major drawback of textural separation and analysis is its labor cost. Approximately one-half hour was required to separate each Ohio Woodland sherd (average over 225 sherds to date). Thus, we recommend textural separation only when exploratory compositional analyses show that bulk samples fail to yield satisfactory groups.

Finally, we conclude that the sonication method presented here is very satisfactory. However, it may not always yield reproducible results, and may vary in effectiveness between labs or samples. This problem arises because extraction of all clay particles from the coarse fraction is difficult. We suspect that this problem can be overcome by magnetic separation, as recommended by Gaines and Handy (1977).

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References Cited

Allen, R.O., H. Hamroush, and M.A. Hoffman
1989 Archaeological Implications of Differences in the Composition of Nile Sediments. In *Archaeological Chemistry IV*, edited by Ralph O. Allen, pp. 33-56. Advances in Chemistry Series 220. American Chemical Society, Washington, D.C.

Arnold, D.E., H. Neff, and R.L. Bishop
1991 Compositional Analysis and "Sources" of Pottery: An Ethnoarchaeological Approach. *American Anthropologist* 93:70-90.

Arnold, D.E., P.M. Rice, W.A. Jester, W.H. Deutsch, B.K. Lee, and R.I. Kirsch
1978 Neutron Activation Analysis of Contemporary Pottery and Pottery Materials from the Valley of Guatemala. In *The Ceramics of Kaminaljuyu, Guatemala*, edited by R.K. Wetherington, pp. 543-586. Pennsylvania State University Monograph Series on Kaminaljuyu, University Park.

Attas, M., L. Yaffe, and J.M. Fossey
1977 Neutron Activation Analysis of Early Bronze Age Pottery from Lake Vougliameni, Perakhora, Central Greece. *Archaeometry* 19:33-43.

Bishop, R.L. and H. Neff
1989 Compositional Data Analysis in Archaeology. In *Archaeological Chemistry, Volume IV*, edited by R.O. Allen, pp. 57-86. Advances in Chemistry Series 220, American Chemical Society, Washington, D.C.

Carr, C. and J.-C. Komorowski
1991 Nondestructive Evaluation of the Mineralogy of Rock Temper in Ceramics Using X-Radiography. *Material Issues in Art and Archaeology, Volume II*, edited by P. Vandiver, J. Druzik and G. Wheeler, pp. 435-440. Materials Research Society, Pittsburgh.

Earle, T.K.
1982 Prehistoric Economics and the Archaeology of Exchange. In *Contexts for Prehistoric Exchange*, edited by J.E. Ericson and T.K. Earle, pp. 1-12. Academic Press, New York.

Fillieres, D., G. Harbottle, and E.V. Sayre
1983 Neutron Activation Study of Figurines, Pottery, and Workshop Material from the Athenian Agora, Greece. *Journal of Field Archaeology* 10:55-69.

Gaines, Alan M. and Julia L. Handy
1977 Ultrasonic Disaggregation of Potsherds for Mineral Separation and Analysis. *American Antiquity* 42:252-254.

Kilikoglou, V., Y. Maniatis, and A.P. Grimanis
1988 The Effect of Purification and Firing of Clays on Trace Element Provenance Studies. *Archaeometry* 30(1):37-46.

Lombard, James
1987 Ceramic Petrography. *The Archaeology of the San Xavier Bridge Site (AZ BB:13:14) Tucson Basin, Southern Arizona*. Archaeological Series 171, Cultural Resource Management Division, Arizona State Museum, University of Arizona, Tucson.

Neff, H., R.L. Bisho,p and D.E. Arnold
1988a Reconstructing Ceramic Production from Ceramic Compositional Data: A Guatemalan Example. *Journal of Field Archaeology* 15:339-48.

Neff, H., R.L. Bishop, and E.V. Sayre
1988b A Simulation Approach to the Problem of Tempering in Compositional Studies of Archaeological Ceramics. *Journal of Archaeological Science* 15:159-172.
1989 More Observations on the Problem of Tempering in Compositional Studies of Archaeological Ceramics. *Journal of Archaeological Science* 16:57-69.

Rice, Prudence
1978 Clear Answers to Vague Questions: Some Assumptions of Provenance Studies of Pottery. In *The Ceramics of Kaminaljuyu, Guatemala*, edited by R.K. Wetherington, pp. 511-542. Pennsylvania State University Monograph Series on Kaminaljuyu, University Park.
1987 *Pottery Analysis: A Sourcebook*. University of Chicago Press, Chicago.

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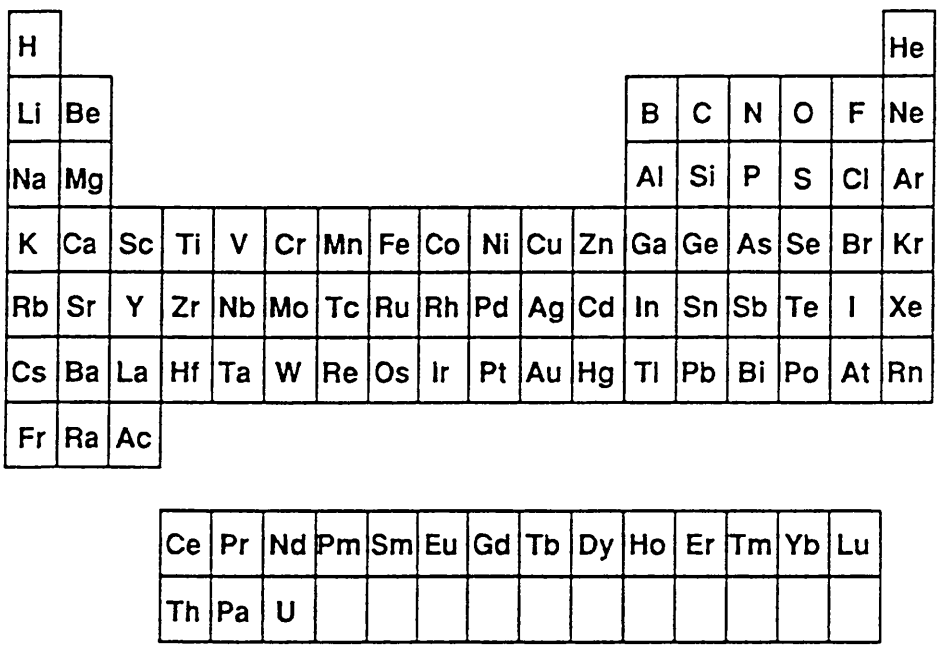

Edited by Hector Neff