Petrographic and Qualitative Analyses of Sands and Sherds from the Lower Verde River Area

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Ceramic vessels produced in the prehistoric American Southwest often contain abundant temper such as sand, disaggregated rock, and crushed sherd. Both sand and disaggregated rock tempers can be used as indicators of the provenance of archaeological ceramics when their geological sources are identified (Arnold 1985; Miksa 1995; Miksa and Heidke 1995; Schaller 1994).

The goal of the present study is to identify the provenance of ceramics recovered from the Lower Verde Archaeological Project (LVAP) sites on the basis of the temper found within them (Ciolek-Torrello et al. 1992:III-75 to III-85). The focus of this study is on sand temper. Ceramic wares and/or types produced within the study area are distinguished from those imported from other areas. A reconnaissance sample of wash sands from the lower Verde River area was collected and analyzed to provide the information on geological sources necessary to reach this goal.

ESTABLISHING THE PETROFACIES

Petrographic modal analysis, or point counting, is a quantitative technique that provides data for the evaluation of samples on the basis of the quantity and composition of sand grains present in each sample. Samples can then be grouped based on numerical abundances of the sand-sized rock and mineral grains. This technique was selected for the LVAP because it allows sand samples from the lower Verde River area to be compared directly to sand-size tempering material found in ceramics from study area sites. This section describes how sands were collected, processed, and point counted in thin-section to provide the basis for an actualistic petrofacies model, or map of modern sand composition zones (Ingersoll 1990; Ingersoll et. al. 1993). Subsequent sections detail the statistical techniques used in the derivation of the petrofacies model, how the thin-section-based petrofacies model was used to define expected characteristics of the sand in hand sample as viewed through a binocular microscope, and how the hand sample model was applied to the sand temper in the pottery sherds and verified.
Stark and Heidke (1992:Figure 13.14) developed an analytical procedures flow chart as a means of elucidating the procedures used in conducting a quantitative petrofacies analysis of sands as source materials. This flow chart has been updated and improved (Miksa and Heidke 1995:Figure 9.3); it is presented here as an outline of our analytical process (Figure 1).

**Geology of the Lower Verde River Area**

Much of the lower Verde River area is located in the Transition Zone of Arizona. This zone is transitional between the Basin and Range physiographic province to the south and west, and the Colorado Plateau to the northeast (Peirce 1985). This zone is marked by north to north-west-trending mountain ranges separated by basins or valleys. Geologically the transition zone contains rock types present in both the Basin and Range and Colorado Plateau regions.

The Verde Basin and other basins in this region, such as the Tonto Basin, are part of the extremely geologically complex Mazatzal orogenic province in the Transition Zone (Karlstrom et al. 1990:114). This province is a fault-bounded area of Proterozoic and later rock spanning the time from approximately 1.75 billion years ago (Ga) to the present. In the Proterozoic, the lower Verde River area was part of the developing continental margin (Bowring and Karlstrom 1990; Dickinson 1989; Silver 1978). Rocks from this time period include quartzites, schists, greenstones, phyllites, metavolcanics, shales, conglomerates, granites (and granite family rocks), diorite, and rhyolites. There were several mountain building events (orogenies), but the culminating event was the Mazatzal Orogeny at 1.60 Ga.

After this orogeny, southwestern North America was relatively undisturbed for about 200 million years. This quiet time allowed sediments to deposit over much of the region (Peirce 1976). Most of these sedimentary rocks have been removed from the lower Verde River area by weathering and erosion. The lack of tectonic activity throughout this time suggests that the Mazatzal Orogeny might have involved collision with a relatively large landmass to the south which insulated the southwest from plate margin activities (Karlstrom et al 1990:114).

From the late Mesozoic Era to the early Tertiary Period (80 Ma to 40 Ma) resumption of subduction along the Pacific coast led to extensive magmatism in Western North America. In the
lower Verde River area, this resulted in the extrusion of basalt, dacite, and andesite, and in the emplacement of some granites (Coney 1978; Dickinson 1989; Drewes 1981).

Finally, uplift of the Colorado Plateau (8 Ma to 4 Ma) led to extensive erosion along the Mogollon rim in Central Arizona, leaving the complex rocks of the Mazatzal Mountains exposed (Dickinson 1989). The erosion was accompanied by development of pediments, alluvial fans, and stream terraces from the late Tertiary Period (ca. 3 Ma) to the present along the lower Verde River. There are many generations of these more recent landforms, most of which have extensive soil profiles developed on them (Piety and Anderson 1988). Most of the archaeological sites along the lower Verde River are found on these more recent landforms.

There are several very striking rock types in the highlands draining into the lower Verde River, so several of the petrofacies are unique and should be easy to match with sand temper. However, there are also some areas where the same bedrock type (or range of rock types) is widely exposed. This results in the sands of one petrofacies resembling the sands of another.

**Petrofacies Modeling**

Several people have worked to establish sand-composition zones in Southern Arizona. For examples, see the studies of the Tucson Basin and Avra Valley (Heidke 1993; Kamilli 1994; Lombard 1986, 1987) and Tonto Basin (Miksa 1992; Miksa and Heidke 1995; Stark and Heidke 1992). See also Dickinson (1970) and Miksa (1992) for general discussions of the method applied here.

Sands derived from similar source rocks under similar conditions will have similar compositions. When we study sands within a well-defined region and determine that those sands can be broken into subsets on the basis of composition and spatial contiguity, we have defined petrofacies, or sand composition zones. The petrofacies concept was originally introduced for the study of sand provenance in sandstones. Petrofacies in ancient sedimentary deposits have both lateral (spatial) and vertical (time) components. In modern sands, we deal only with the spatial component. The time component is effectively held constant, barring major climatic and/or tectonic changes within the time scale under study. For the purposes of archaeology, we can think
of the petrofacies as temper resource procurement zones whose sand compositions are distinct from one another. The petrofacies concept is much like the cultural phase concept: both are heuristic tools that allow us to discuss a dimension of ceramic production. A petrofacies bounds a unit of ceramic production space, whereas a phase bounds a unit of ceramic production time.

Drainage basins rarely coincide exactly with rock units, yet they are the geomorphological unit in which sands are created and transported. A preliminary petrofacies map is created by comparing bedrock geology to the geomorphology and drainage pattern in a region. The preliminary petrofacies map is tested by sampling sands and characterizing their composition. Resolution of the petrofacies boundaries depends on the scale of variability in the source rocks, the scale at which samples are collected, the resolution of the analytical technique, and the statistical techniques employed.

Petrofacies are identified in several steps. Geologists use geologic maps of the nearby mountains and alluvial fans, and note which washes drain which rock types. From this they draw in zones of valley sand that should have the same composition. They then go out and collect sands from several washes within each zone and prepare each sand sample for viewing under a microscope. Numerical point counts of the minerals and rock fragments in each sand then can be analyzed statistically. Ideally, the statistical analyses group the numerical information into well-defined petrofacies.

Geologists and ceramists then work together to choose potsherds representative of a problem or site. The potsherds are thin-sectioned and the temper examined in the same manner as the sands. Pottery temper compositions are then compared to the different petrofacies to find compositional matches and, therefore, sources for the materials used in the pot.

**History of the Study**

The underlying purpose of this part of the study is, of course, to group sherds by temper composition, and to assign these sherd groups to known sources (or hypothesized areas). The following steps were taken to reach this end.
The petrofacies study of the lower Verde River area was initiated by Elizabeth Miksa and James Heidke in 1992 for Statistical Research, Inc. As part of this study, Miksa collected the available geologic maps and literature, and constructed a predicted petrofacies map for the basin. Twelve to eighteen petrofacies were predicted at this preliminary stage.

Using this map as a guide, Miksa and Heidke collected 72 sand samples in 1992; an additional 17 sands were collected in 1993. Several areas are undersampled because they were submerged by the winter floods of 1993. This is especially true of areas in petrofacies B, M, and N, where Verde River trunk stream sands had buried all tributary sands. Miksa and Heidke also collected metamorphic rock samples from several washes. Nine of these were chosen for thin-sectioning (eight of these proved to be metamorphic rocks, while one was a carbonate).

Diana Kamilli continued the study in 1993 by point counting the 89 sand sample thin-sections and examining the rock thin-sections. At the same time, she described the sands in hand sample and assembled grain boxes with representative sand-sized rock and mineral specimens for each petrofacies.

The information from the point counts allowed refinement of petrofacies boundaries and reduced the final number of petrofacies to 13 (Figure 2). Figure 2 shows the petrofacies boundaries and the sand sample numbers and locations. Sampling in several of these areas is sparse, and several boundaries are uncertain. Therefore, this map should be considered conditional. Short descriptions of each petrofacies are given in Table 1.

In 1994, Heidke characterized the composition of 984 LVAP vessels using Kamilli’s descriptive guidelines as well as observations of other characteristics. From these he selected 71 LVAP sherds for thin-section analysis, after assigning them to lower Verde River petrofacies or extrabasinal sources (i.e., compositions unlike those documented in sand samples collected for this study). These represented approximately seven percent of the characterized LVAP sherds. In addition, Heidke characterized the temper in 24 vessels recovered from Azatlan.
Kamilli point counted the 71 LVAP thin-sections and also assigned provisional petrofacies (or extrabasinal) designations. In addition, she examined 24 sherds in thin-section from the Azatlan site, located in Petrofacies M, and point counted 13 of them.

Based on her petrographic analysis, Kamilli grouped the sherds into sets of similar composition. She assigned these sherd groups to sand composition zones, when appropriate. This serves as her assessment of whether or not each of the sherds in each group was made from materials available in the lower Verde River area. Finally, Kamilli gave the raw point-count data to Heidke for quantitative correspondence analysis and discriminant analysis. Heidke evaluated the relationship between his (original) characterization and Kamilli’s qualitative petrographic grouping and the statistical clustering.

Heidke and Kamilli used the sum of the qualitative, quantitative, and statistical data to arrive at petrofacies assignments or extrabasinal assignments for each of the point-counted sherd samples. Heidke then related this information to the greater set of characterized sherds, site location, ceramic ware, and time.

**ANALYSIS OF THE SANDS**

**Collection Technique**

In the present study, most the sands were collected from locations where streams and intermittent washes drain out from mountain sources and enter the lower Verde River. Some of the intermittent streams are very close to the highland bedrock sources and, therefore, show little mixing of bedrock types. Other streams drain areas of mixed bedrock. Sand samples were collected from tributaries to the lower Verde River from Ister Flat on the north to the Verde River’s confluence with the Salt River on the south (see Figure 2). Table A.1 gives the UTM coordinates of all the sand samples; they are plotted on U.S.G.S. 7.5’ topographic maps (on file at Desert Archaeology, Inc.).
The 89 sand samples were collected using the following methodology which was designed to ensure that the collected sand was a random, representative sample of each stream (Folk, 1974:15–16):

1. A channel made by recent stream flow was chosen for sampling. In smaller drainages, a single channel with low banks is usually present within the arroyo bottom. In larger washes, there may be multiple channels present. In each case, a sketch was drawn illustrating the relationship of the sampled channel to the wash.

2. A plastic tarp was laid out in the channel, and sand was collected from a transect perpendicular to the channel flow and placed on the tarp. If the sampled channel was small (<~4 m wide) a trench one shovelful deep and ~20 cm wide was dug across the transect. For larger channels, a shovelful was collected every 25 cm to 30 cm. Some of the largest channels (> 15 m wide) required sampling a shovelful of sand every 50 cm to 60 cm. Grab samples of Verde River sand were collected from sand bars for comparative purposes. No attempt was made to homogenize the trunk stream samples by collecting more than one sand bar.

3. The sand was mixed thoroughly and uniformly by shovel.

4. The resultant sand pile was quartered and subquartered until a pile of approximately 2–3 kg remained.

5. The quartered section was screened through a 2 mm mesh screen into a collecting pan to remove all material coarser than sand size. The coarse material was examined, its grain sizes and lithology were recorded, and it was discarded. A Munsell color was recorded for the screened sand and it was placed in a soil sample bag. In some cases, a close-up photograph was taken of the coarse and fine fractions to show relative colors, grain size, and lithology.

6. The geomorphology of the collection site was recorded, especially noting the degree of soil development and the cohesiveness of the drainage’s banks. A photo was taken of the
wash to further document its size and shape and the relationship of the sampled transect to the overall wash.

**Sand Sample Preparation and Thin-Sectioning**

The collected sands were split and cleaned at Desert Archaeology’s lab before being used for hand samples or thin-sections. To prepare the samples, each one was repeatedly halved using a riffle style sample splitter until it was small enough to fill a 30 dram vial, about 130 grams. The sample splitter was used to ensure that the small samples would be random representations of the larger samples without sorting or settling biases.

Once a 130 gram sample was obtained, each sample was washed in a 10 percent HCl solution for 15 to 30 seconds to remove caliche coatings from the grains. This is not long enough to remove limestone or caliche grains from the sample. The sample was then rinsed at least three times to remove all HCl, and wet screened in a .075 mm sieve to remove grains smaller than silt size. This sieve is slightly larger than the accepted sand-silt break at .0625 mm; however, most samples were so coarse that little information was lost by washing away the very finest sand-sized material.

Washed and screened samples were placed into jars and oven dried. Once dry, they were split again (using the sample splitter) down to a size appropriate for thin-section preparation (approximately 1 tablespoon, or 25 gm). The remainder of the washed sand was retained for use as a hand sample. The remaining unwashed sand was placed into storage in tyvek bags.

Thin-sections were prepared by Quality Thin-Sections of Tucson, Arizona. Each sand sample was mixed with epoxy and set into a small block. Once the blocks hardened, they were treated as rocks and thin-sectioned. All thin-sections were etched with hydrofluoric acid and stained for potassium and calcium so that potassium feldspars and plagioclase feldspars could be readily identified. All thin-sections had permanent cover slips placed on them.
Point-Count Methodology

Point counting is a modal analysis, one that provides information on the relative volume of each mineral in the sample (Chayes 1956:1). Sand thin-sections were point counted using the Gazzi-Dickinson technique (Dickinson 1970; Gazzi 1966), in which all grains that are sand size or larger are counted as individual mineral species regardless of whether or not they occur as free minerals or in rock fragments. Descriptive notes were kept to indicate the circumstances under which each of the mineral types occurred. The advantage of using this technique is that sand maturity effects are minimized, and that sands or sand tempers of different grain sizes can be compared. For example, a very immature granitic sand might contain large numbers of granite grains and very few free minerals. A mature granitic sand would be predominantly free minerals with few granite fragments. The Gazzi-Dickinson technique allows the two sands to be compared, because all sand size mineral grains in the immature sands are counted as minerals not as rocks. This technique is appropriate because we wish to compare data from sands with sand-tempered sherds. It is unlikely that we will sample “the sand” from which prehistoric potters collected their temper, but we have sampled sands derived from the same bedrock in the same geographic units as those available to prehistoric potters. We may have sampled sands that are more or less mature than the prehistoric sands, but the Gazzi-Dickinson method ensures that all data collected from a geographic area can be evaluated as a unit.

Point counts of single minerals and rock grains were made using a high-powered petrographic microscope. Only grains .0625 mm in diameter or larger were counted. The largest stage grid-spacing was chosen that would: (1) allow a count of 400 temper grain points per slide; (2) cover the entire slide; and (3) not count too many grains twice.

Sedimentologists currently prefer to count each grain multiple times if it is large enough to cross more than one grid point, and Kamilli chose this method. In theory, this allows the larger grains that occupy more of the volume of the sand to be counted more accurately. However, it could lead to a misrepresentation of some grains if the sand is very immature with a wide range of grain sizes, or if the grain size distribution is strongly bimodal. For sands with univariate normal grain size distributions, the grid spacing should be large enough for most of the grains to be represented by one grid point. Most of the lower Verde River petrofacies sand samples and potsherds, including
the sherds from the Azatlan site, have unimodal grain-size distributions. The only problem samples encountered in this study were the sherds tempered with coarse phyllite. In any case, it is most important to establish a rigid counting procedure, and to be consistent within the data set (William R. Dickinson, personal communication 1992). Then the data from all counts will be comparable and errors will remain within the counting error estimate (Van der Plas and Tobi 1965).

Single crystal grains larger than .0625 mm in diameter were counted as their mineral name (i.e., quartz) even if they were part of a coarse polycrystalline rock fragment such as granite. Fine-grained polycrystalline rock fragments, those made up of grains that are less than .0625 mm, were given a lithic name based on their texture and mineralogy, following the classification system proposed by Dickinson (1970). With some changes, discussed later, all terminology was brought into conformity with the nomenclature used by Lombard for his studies of the Tucson Basin and Avra Valley (Lombard 1986, 1987, 1990), and Miksa and Heidke in their studies of the Tonto Basin (Miksa and Heidke 1995; Miksa 1992; Stark and Heidke 1992). Excellent discussions of the methods and reasons for the method and terminology may be found in Dickinson (1970), Lombard (1987:98–103), Miksa (1992:159–162), and Stark and Heidke (1992:136–139).

Of the 36 point count parameters used in this study, 17 are lithic fragment parameters and 17 are monomineralic parameters (Table 2). The 35th point-count parameter is sherd temper; it is used only when sherd fragments are found in potsherd thin-sections. A 36th point-count parameter, “unknown,” was also counted. This was done to ensure that the counting was rigorous and that each sand-sized grain which fell under the petrographic microscope’s crosshairs was counted.

Departures from Lombard’s Tucson Basin (Lombard 1987) and Miksa and Heidke’s (1995) Tonto Basin point-count parameters should be noted here. Several mineral species parameters have been added because of their presence in the sands or sherds of the lower Verde River area. The alkali feldspar sanidine occurs in the vitrophyres of the sands of Petrofacies B and is a key mineral for that zone. Plagioclase (PLAG) was divided into NAPLAG (sodic plagioclase; albite to oligoclase) and CAPLAG (andesine and more calcic) because the accurate recording of certain coarse igneous aggregates depends on this distinction. Amphibole and pyroxene have been separated because of the occurrence of intermediate volcanic rocks. Olivine is common in some of the basalts and is
coarse enough to count as a mineral. Sphene was added because it is a key indicator of Petrofacies A sand, although it occurs nowhere else.

Intermediate volcanic rock (LVI) was separated from the mafic volcanic rock category (LVM) because it is quite distinctive in certain areas. Finally, the tempers of several potsherds caused metamorphosed siltstone (LMSS) and metamorphosed felsic volcanic rock (LMVF) parameters to be added because relict textures of some grains allowed them to be identified with assurance. It should be noted, however, that the textures of the porphyritic volcanic rocks grade from obviously volcanic, through relict traces, to totally recrystallized. Amphibolite (LMAMP), a metamorphic amphibole and calcic plagioclase rock, is rare but present in the sand samples from Petrofacies D.

Table A.1 reports the sand point-count data, in order by sample number. Only raw data are presented, so percentages of each parameter have to be computed. An attempt was made to count 400 points per thin-section, but this was not always possible, so the raw data values are not directly comparable without transformation to percentages or logratios. Data transformations and statistical analyses of the sand point-count data are presented below.

STATISTICAL ANALYSES

Multivariate Techniques Used in Analysis

Two multivariate statistical techniques, correspondence analysis and discriminant analysis, were employed to analyze the sand and sherd point-count data. Correspondence analysis was utilized as a method of data reduction and exploration in both data sets. In the sand data it facilitated the refinement of petrofacies boundaries and the assignment of particular sand samples to particular petrofacies. In the sherd data it provided a graphical means to summarize temper composition and facilitated the reassignment of some sherds within the compositional groups. Discriminant analysis was used to demonstrate that the compositions of the sand petrofacies are distinguishable from one another and to determine a set of functions that best discriminates between the petrofacies. The functions derived from the discriminant analyses of the sand data were then used to predict the petrofacies membership of a sample of the sand-tempered sherds (those inferred to have been produced in the lower Verde River area).
Correspondence Analysis of Sand Samples

Correspondence analysis is a principal components analysis method for the display of rows and columns of a two-way contingency table as points in a low-dimensional vector space (Carr 1990). A feature of correspondence analysis that we find especially attractive is its ability to represent both the rows and columns of a data matrix as points on the same plot; this feature allows us to examine the structure in both the rows and columns, as well as their interrelationship (Baxter 1994:100). The geometry of the rows, which in our data set represent the individual sand or sherd samples, is related to the geometry of the columns, which represent the point-count parameters, resulting in a correspondence between the rows and columns (Greenacre 1984). Carr (1990:289) provides a short, but useful, summary of the technique:

A relatively simple transformation is applied to a contingency table to yield a square, symmetric matrix for which eigenvalues and eigenvectors are calculated. From the eigenvalues and eigenvectors, factor loadings are calculated separately for the individuals and the attributes. By combining factor loadings, individuals and attributes can be plotted simultaneously in a two-dimensional plan to yield a clustering pattern.

Although correspondence analysis is statistically based, it is primarily a geometric technique (Greenacre 1984). As Ringrose (1992) has noted, the algebraic technique employed by correspondence analysis is purely deterministic; therefore it provides little indication of the strength of any apparent relationships. For that reason many authors (Baxter 1991, 1994; Escoufier and Junca 1986) emphasize the exploratory, as opposed to confirmatory (Lewis 1986), nature of its results. Melguen (1974) first recognized the usefulness of correspondence analysis as a tool for identifying and characterizing sedimentary facies. We have employed correspondence analysis for that purpose in earlier studies of Tonto Basin (Miksa and Heidke 1995, Stark and Heidke 1992) and Tucson Basin (Heidke 1989) sand composition zones.

One of the primary reasons we choose correspondence analysis as a method of data reduction and exploration is that the technique requires only that all values in the data matrix be positive (zeros are acceptable) and that all row and column totals be greater than zero (Hill 1979:10; Weller and Romney 1990:72). These are important assumptions when one needs to analyze data bases that
contain point-count data gathered from sand samples derived from an extremely heterogeneous set of source rocks, or from sherd samples tempered with a heterogeneous set of materials. In the lower Verde River area, many of the point count parameters recorded are not present in all portions of the study area (see the “Point-Count Methodology” section above). This type of fundamental between-sample compositional variability, necessary to actualistic petrofacies model building, represents one of the greatest differences separating the analytical requirements of petrological analysis from those of instrumental characterization studies of clay chemistry. In instrumental studies there is an expectation that all of the elements and compounds under study will be present in all of the samples; usually only the relative concentrations of elements and compounds exhibit variation between samples. Finally, correspondence analysis was chosen over factor analysis, because, as noted by Baxter (1994:90), factor analysis is a demanding technique from the point of view of the assumptions required to produce results that are, nevertheless, still open to the accusation that they are arbitrary.

Four correspondence analysis trials were run with the sand point-count data over the length of the project. The first trial used the data from all 89 sand samples collected and all 30 point-count parameters recorded (four parameters—LVH, LSA, LSCH, and LMF—were dropped because, during point counting, it was determined that they were not present in any of the sands, sherd temper was not recorded in the sands, and “unknowns,” although present, were deleted). The final trial dropped two sand samples—VB-113 and VB-116—collected from sand bar deposits because the depositional environment they were collected from and their compositionally mixed nature made them unlike any other samples included in the analysis. Four sand samples collected from Petrofacies H—VB-32, VB-35, VB-44, and VB-60—containing amounts of carbonate “far outside” (Velleman and Hoaglin 1981:68) the distribution of all sand samples containing carbonate were also dropped from the final correspondence analysis trial. As noted by Baxter (1991:31), any graphical display may be distorted by the presence of outliers, and sometimes this is the chief feature of a display. If this is the case, reanalysis after omitting the outlying cases is a sensible procedure (Baxter 1991:31).

The final trial utilized a subcomposition of the point-count parameters. A subcomposition can be defined as a subset of a full composition that preserves the ratio relationships between components (Aitchison 1986). As such, it is a means of reducing the dimensionality of a data set
without altering the relationship between the components of that data set. To create the subcomposition utilized for this study, three more parameters—AMPH, MUSC, and LSS—were dropped because of their overall rarity. Other parameters were recalculated by summing the counts for parameters representing rock and mineral types that are found together geologically and that plotted close together in the first three correspondence analysis trials. Table 3 defines the recalculated point-count parameters used in the correspondence analysis. These same parameters were used in the discriminant analyses.

**Figure 3** is a plot of the point-count parameters on the first two correspondence analysis factors. (Note, in order not to obscure the point-count parameter labels, the 83 sand samples included in the fourth correspondence analysis trial are not shown on Figure 3. Instead, a one-standard-deviation ellipse around each of the four major compositional groups present in the lower Verde River sand samples is shown. Like Baxter [1994:102], we find that plots that display both the row and column data can become too “busy.”) The first factor accounts for 34.0 percent of the variation, the second factor accounts for 17.9 percent, and the third factor accounts for 15.1 percent of the variation. These three factors comprise a total of 67.0 percent of the variation and lead us to conclude that the correspondence analysis was highly successful in reducing the dimensionality of the data. Each of the remaining twelve factors accounted for less than 10 percent of the variation.

The first two factors, which account for nearly 52 percent of the variation, are readily interpretable in terms of tectonic origin of the sand sample when the ranked parameter optimal scores are examined (Table 4). The first factor is interpreted as a contrast between rocks and minerals, because the lithic point count parameters generally received the lowest (negative) factor scores while the mineral point count parameters received the highest (positive) factor scores. The second factor is interpreted as representing the felsic-to-mafic continuum present in the study area’s volcanic rocks. From negative to positive loading the volcanic rock point-count parameters are ranked from glassy volcanic (VITRO) to felsic volcanic (LVF) to intermediate volcanic (LVI) to mafic volcanic (BASALT).

**Figure 4** is a plot of the 83 sand samples on the first two correspondence analysis factors. The letters shown refer to each sand sample’s petrofacies designation. One-standard-deviation ellipses
drawn around the distribution of sands containing mafic volcanic, glassy volcanic, metamorphic, and granitic compositions show little overlap, although the one-standard-deviation ellipse around the metamorphic sands overlaps both the glassy volcanic and granitic ellipses. However, those compositions are clearly differentiated by the third factor.

The third factor represents the contrast between SCHIST (negative load) and all other rocks and minerals. Figure 5 is a plot of the point-count parameters on the first and third correspondence analysis factors, with the major compositional groups indicated by their one-standard-deviation ellipses. Figure 6 is a similar plot showing the sand samples. As both figures indicate clearly, the overlap between the metamorphic, glassy volcanic, and granitic compositions seen in the second factor is not present. The third factor, therefore, helps to differentiate those three compositions.

As each correspondence analysis trial was completed we plotted each petrofacies’ sand samples individually on the first two factors, with a one-standard-deviation ellipse drawn around the distribution. We then examined how each sand sample related to its petrofacies, and compared the distributions of adjacent petrofacies. This method of examination led us to reassign the petrofacies’ membership of ten sand samples, and to redefine some petrofacies boundaries.

**Discriminant Analysis of Sand Samples**

Criticism of the method of petrographic analysis begun by Lombard in the Tucson Basin, and continued here, has focused on two issues: (1) the need to evaluate the degree of intra-petrofacies compositional variability (Lindauer 1992:278) and (2) the need for a rigorous test statistic to evaluate sherd membership in a given petrofacies (Cable 1989:8). The use of discriminant function analysis, to evaluate the group membership of sand samples using the point-counted compositional data, allows both issues to be addressed.

Because petrofacies are defined using compositional and geographic criteria, it is expected that some compositional overlap will occur between sand samples collected from different areas in a region. The discriminant analysis permits us to estimate the degree of intra-petrofacies variability by comparing assigned group memberships (based on compositional and geographic knowledge) with the posterior probability of group membership (based on assignment by the discriminant
functions). The discriminant analysis also identifies other source zones with which a given petrofacies' sands may exhibit compositional overlap. Finally, the sand temper point-count data, recorded from sherd thin-sections, can be treated as “unknown” cases, and classified as to petrofacies membership by the discriminant functions. This allows us to make probabilistic assignments of sherd samples to petrofacies, and serves as an independent check on the binocular microscopic characterization of temper composition. Therefore, it does not rely on the subjective assignment of sherds to petrofacies seen in Lombard’s work.

Discriminant analysis is a statistical technique designed to study the differences between two or more groups of objects with respect to several variables simultaneously (Klecka 1980). In our study, the data were grouped by petrofacies. Individual sand and sherd samples are the objects, and point-count parameters are the variables. Discriminant analysis was used to address two distinct problems. The first problem was to determine the set of functions that best discriminate between the sand groups and test the accuracy of the resulting discrimination. That use of discriminant analysis is discussed here. The second problem was to use the discriminant functions to assign sherds, inferred to have originated from one of the lower Verde River petrofacies, to these groups in a probabilistic manner. That use of discriminant analysis is discussed later. Richard and Clarke (1989) have used discriminant analysis to model membership in geochemical groups, while Pingitore and Shotwell (1976) and Ingersoll (1990) have used discriminant analysis to model modern sand composition groups. In addition, discriminant analysis has often been used by archaeologists in the study of clay composition (Arnold et. al. 1991; Rands and Bishop 1980; Stoltman et. al. 1992). We have also employed it in previous studies of Tonto Basin petrofacies and the sand-tempered sherds that can be assigned to them (Miksa and Heidke 1995; Stark and Heidke 1992).

Three discriminant analyses were conducted. Based on the results of the correspondence analysis, the first discriminant analysis tested the assignment of sands to either a mineral-rich group of petrofacies, containing sands of granitic composition, or to a rock-fragment-rich group of petrofacies, containing sands of mafic volcanic, glassy volcanic, or metamorphic composition. The second analysis tested the assignment of mineral-rich sands to their specific petrofacies. The third analysis tested the assignment of rock-fragment-rich sands their to specific petrofacies. Following the lead of Richard and Clarke (1989) and Ingersoll (1990), we applied the logratio
The first discriminant analysis included all 89 sand samples, although the single sample from Sycamore Creek (Petrofacies C, VB-48) and the two samples collected from sand bars (VB-113 and VB-116) were treated as “unknown” cases, and, for that reason, were not included in either the mineral-rich or rock-fragment-rich groups. The average quartz, alkali feldspar, and lithic compositions of the two groups are shown in Figure 7. The mineral-rich sand group contains almost twice as much quartz and alkali feldspar as the rock-fragment-rich group, while the rock-fragment-rich group contains approximately seven times more lithic material than the mineral-rich group. The classification matrix resulting from the discriminant analysis of these two groups is reported in Table 5. Examination of this table shows that only one of the 86 samples was misclassified, resulting in an accuracy of 98.8 percent. The sample of “unknown” composition from Sycamore Creek (Petrofacies C) has a predicted membership in the mineral-rich sand group. The two samples of “unknown” composition collected from Verde River sand bars have a predicted membership in the rock-fragment-rich group.

The 48 sand samples from mineral-rich petrofacies that were assigned to the mineral-rich group were included in the second discriminant analysis. Two additional samples with a predicted membership in the mineral-rich group, sample VB-13 (from rock-fragment-rich Petrofacies D) and the sample from Sycamore Creek (VB-48, Petrofacies C), were also included in the second discriminant analysis as “unknown” cases. Figure 8 utilizes a subcomposition to illustrate the differences between the six mineral-rich petrofacies.

The classification matrix resulting from the second discriminant analysis is shown in Table 6. Thirty-six of the 48 samples were classified correctly, resulting in an accuracy of 75 percent. The sample from rock-fragment-rich Petrofacies D has a predicted membership in the Petrofacies M group. Given that sample VB-13 is the first sample located south of the boundary between Petrofacies D and Petrofacies M, the discriminant analyses suggest that the “real” boundary between these two temper resource zones may lie slightly south of where it is now placed.
The 37 sand samples from rock-fragment-rich petrofacies that were assigned to the rock-fragment-rich group in the first discriminant analysis, as well as the two sand bar samples which also have a predicted membership in that group, were included in the third discriminant analysis. Figure 9 utilizes a subcomposition to illustrate the differences between the six rock-fragment-rich petrofacies. The classification matrix resulting from the third discriminant analysis is shown in Table 7. Thirty-three of the 37 samples were classified correctly, resulting in an accuracy of 86.8 percent. Both of the Verde River sand bar samples have a predicted membership in the Petrofacies H group (note that both of these samples were collected far downstream of Petrofacies H).

The results of the three discriminant analyses are brought together in an overall lower Verde River area petrofacies classification matrix shown in Table 8. Examination of Table 8 shows that the petrofacies membership of 69 sand samples was accurately predicted using the discriminating variables. Thus, the model has an accuracy of 80.2 percent (sum of correct predictions, 69, divided by total prediction of all cases, 86). Klecka (1980:50) notes that while the percentage of cases predicted accurately is the most intuitive measure of discrimination, the magnitude of this percentage should be judged in relation to the expected percentage of correct classifications made by random assignment. A proportional reduction in error statistic, \( \tau \), can be calculated. \( \tau \) gives a standard measure of improvement over a random assignment regardless of the number of groups (Klecka 1980:50–51). The maximum value for \( \tau \) is 1.0; this value represents no errors in prediction. A value of zero indicates no improvement over random assignment. The equation for \( \tau \) is presented here as equation 1:

\[
\tau = \frac{n_c - \sum_{i=1}^{g} p_i n_i}{n_{tot} - \sum_{i=1}^{g} p_i n_i}
\]

(1)

\( n_c \) = Number of correctly classified cases
\( n_{tot} \) = Total number of cases
\( p_i \) = Prior probability for each group
\( n_i \) = Number of cases in each group
\( g \) = Number of groups
In the lower Verde River area sand sample data, each of the 12 petrofacies containing more than one sample had a prior probability of 0.083 (i.e., 1 petrofacies/12 total petrofacies = 0.083). Consequently, the summation used for tau is (0.083 × 8) + (0.083 × 8) + (0.083 × 3) + (0.083 × 5) + (0.083 × 23) + (0.083 × 4) + (0.083 × 14) + (0.083 × 4) + (0.083 × 4) + (0.083 × 8) + (0.083 × 3) + (0.083 × 2) = 7.17. With 69 correct predictions out of 86 total cases, \[ \tau = \frac{(69 - 7.17)}{(86 - 7.17)} = 61.83 \div 78.83 = 0.784. \]
This means that classification based on the discriminant model made 78.4 percent fewer errors than would be expected by random assignment (i.e., 17 actual errors versus 78.83 expected by chance). We feel, therefore, that the results of the discriminant function analyses support the validity of our actualistic petrofacies model.

THE ACTUALISTIC LOWER VERDE RIVER PETROFACIES

Relationship of Petrofacies to the Local Bedrock Geology

Of the 13 petrofacies identified, seven are rich in granite aggregates or derived materials (Petrofacies A, C, F, J, M, N and P), two are rich in basalt (Petrofacies E and H), and two are a mix of basalt and granite products (Petrofacies G and L). In addition, one contains abundant felsic vitrophyric tuff (Petrofacies B), and one contains metamorphic grains along with granite products (Petrofacies D). See Figure 2 (above) for the locations of these petrofacies. The actualistic petrofacies map was compared to published maps (Skotnicki 1995, Karlstrom et al. 1990, Anderson 1989, Marsh 1983, and Christenson et al. 1978) to match bedrock sources to the sands.

Petrographic analysis showed the granites of Petrofacies F, J, and A to be distinct. Petrofacies F has abundant microcline feldspar and biotite. Petrofacies J has perthite feldspar dominant and little biotite. Petrofacies A has mixed alkali feldspars and abundant sphene. Both Marsh (1983) and Karlstrom et al. (1990) map the granite just north of Horseshoe Reservoir (Petrofacies J) as Precambrian (Proterozoic) Payson Granite and date it at 1700 Ma, older than the granite around Bartlett Reservoir (Petrofacies F). According to the literature, the Payson Granite appears to be related to a granophyric phase in the Tonto Basin and elsewhere. This may explain the grains of granophyre found with the Tertiary basalt grains in the sands of Petrofacies G to the northeast of Petrofacies F (see Karlstrom et al. 1990; Marsh 1983; Wrucke and Conway 1987). The Petrofacies F granite source, according to Wrucke and Conway (1987:6), is:
Coarse-grained porphyritic quartz monzonite intruded... at Bartlett Reservoir... This plutonic body resembles coarse-grained porphyritic granitic rock widespread to the south (e.g., Ruin Granite, Oracle Granite), and is therefore assumed to be of the anorogenic 1410 - 1430 Ma suite (Silver 1969).

This agrees with the composite map of Karlstrom et al. (1990:116). Unfortunately none of these references specifically names alkali feldspar texture or biotite abundance. It should be noted that this granitic material has been variously called granite, quartz monzonite, and monzogranite.

The map of Karlstrom et al. (1990:116) continues this granite down to the southwest of this study’s Petrofacies M and Petrofacies P, west of the lower Verde River, and stops it at the McDowell Mountains. Karlstrom et al. (1990) show it again as a patch just west of the confluence of the Verde River and the Salt River. However, Skotnicki’s (1995:27) more recent map shows this area as Late Proterozoic “medium-to-coarse-grained granitoid.” Both Skotnicki’s granitoid and the granite aggregates of Petrofacies A sands have similar mineralogy, including the distinctive grains of sphene. This granitoid is undoubtedly the source of granites in Petrofacies A sands.

Several references note that the basalts of the lower Verde River area are Tertiary (Middle Miocene) and interfinger with conglomerates and sandstones. Little difference was seen in the basalt grains from Petrofacies E, G, H, and L, but more detailed petrography could probably find mineralogical variation.

The limestone of Chalk Mountain, just north of Horseshoe Reservoir, overlies sandstone and is the youngest Tertiary deposit in the lower Verde River area (Wrucke and Conway 1987:12). It would supply the carbonate grains abundant in several of the sands in the Tertiary basalt-rich Petrofacies H (VB-32, VB-35, VB-43, VB-44, and VB-60). This is the only portion of the study area with abundant carbonate material.

Piety and Anderson (1990:53–54) note that a northwest-striking fault is present immediately downstream from Bartlett Dam. This fault places Precambrian granitic rocks on the northeast (Petrofacies F) against Tertiary basalts on the southwest (Petrofacies E). This fault is the reason that
the boundary lines between Petrofacies E and F are displaced as they cross the Verde River (see Figure 2).

During our literature search, we never found a specific, mapped bedrock source located within the boundaries of Petrofacies B for the distinctive felsic vitrophyre of that petrofacies. However, recent geologic mapping of the Fountain Hills - Mount McDowell area by Skotnicki (1995) has revealed an ash flow tuff that crops out near the Verde River drainage basin. The description of this ash flow tuff, unit “Tts” on Skotnicki’s map (1995:sheet 1), is consistent with the felsic vitrophyric grains seen in Petrofacies B sands. We hypothesize, therefore, that Tts crops out within Petrofacies B, either in vertical exposures not mapped at the surface or outside of the recently mapped area.

The two-granite, compositionally mixed sand seen in the single sample from Petrofacies C (VB-48, Sycamore Creek, see Table 1) has clearly been derived from the extensive Sycamore Creek drainage basin. An ongoing petrofacies study of this basin will clarify the sources of Sycamore Creek sand (Miksa et al. 1996).

There are several areas of metamorphic bedrock that drain down into the lower Verde River; however, only one petrofacies (Petrofacies D) has sand that reflects this. The metavolcanics, metasiltstones, amphibole gneiss, schist, and phyllite grains in Petrofacies D sands have clearly washed down from the McDowell Mountains just to the west. Christenson et al. (1978) note that the rocks of the McDowell Mountains are predominantly Precambrian in age and that there appear to be two stages:

- The earlier Precambrian rocks are quartzite, phyllites, greenschists, and metavolcanic rocks of various types. The main type is a metarhyolite and metatuff unit. This unit is underlain by quartz-mica schist (probably metavolcanic rocks of dacite and andesite composition) and greenschists (metabasalts).
These in turn are

. . . underlain by units of quartzite . . . A phyllite-argillite of extreme variability occurs
interbedded with these quartzites and all are interpreted to represent metasedimentary rocks.
This entire sequence of sediments and volcanics has undergone at least one episode of
metamorphism . . . Intrusion of the igneous rocks occurred in later Precambrian time, their
compositions ranging from diorite to granite . . . Tertiary fanglomerates crop out on the
southeast side of the mountains . . .

These are “overlain by Tertiary basalt flows, welded ash-flow tuffs, and various (volcaniclastic)
rocks” (Christenson et al. 1978:map introductory statement).

There are additional bedrock sources of metamorphic rocks to the northwest and northeast of
the lower Verde River area, but they are further away from the river and do not appear to have
shed materials that reached the sampled areas.

Again, it is necessary to stress that there is a singular lack of stream sands containing
metamorphic materials in the lower Verde River area samples. The cobbles collected along with
the sand samples, however, prove that naturally occurring metamorphic rock sources are available
(Table 9). The 46 metamorphic cobbles were collected from washes in Petrofacies A, D, and M, in
the southwest of the study area, and Petrofacies L, northeast of Bartlett Reservoir. (Note, however,
that no cobbles were collected from the area just below Bartlett or Horseshoe Reservoirs, where
non-local materials were dumped during construction of the dams.) The rocks from Petrofacies
A, D, and M are assumed to have come from the McDowell Mountains, while those collected in
Petrofacies L came from the Slate Creek shear zone area of the Mazatzal Mountains. The rock types
represented are gneisses, phyllites, schists, metasiltstones, metavolcanics, quartzites, and
greenstones. Of the 46 cobbles collected, eight metamorphic examples were thin-sectioned. One
metavolcanic rock is from Petrofacies A (VB-3R), two metavolcanic rocks and one coarse schist are
from Petrofacies D (VB-11Ra, VB-11Rb, and VB-13R), and two metavolcanics, one coarse phyllite
and one metasiltstone, are from washes near the boundary between Petrofacies F and L (VB-23Ra,
VB-23Rb, VB-27Ra, and VB-27Rb).
As discussed later, many of the sherds from the Bartlett and Horseshoe Reservoir sites and the Azatlan collection contain temper with abundant phyllite, schist, gneiss, or metavolcanic material. All these materials are available from the McDowell Mountain bedrock sources, but the rock sample information suggests that there are other possibilities. Several parts of the lower Verde River area were only sparsely sampled, and it remains possible that not all of the sources have been identified.

**Qualitative Descriptions of Sands in Thin-Section**

A description of the grain types present in each sample was recorded, as each thin-section was point counted. Commonly, a mineral, a rock type, or a mineral texture is present that is very distinctive, even unique, to a petrofacies. These grains are called “key grains” and may supply the necessary clue to source a potsherd to a specific petrofacies. However, the presence of a “key grain” unique to the sands of individual petrofacies is not amenable to discriminant analysis because of its absence in all other source zones in the region. In those cases the “key grain” criterium is stronger than probabilistic assignment by the discriminant functions. However, such information could be lost for some coarser grained rocks, unless especially noted, because of the Gazzi-Dickinson method of point counting used in this study.

**Qualitative Descriptions of Sands in Hand Sample**

All of the numbers and statistical analyses that result from point counting a thin-sectioned sand sample provide little comfort to the ceramicist, untrained in detailed petrography, when faced with the task of identifying the source of a coarse-grained sand temper. Therefore, descriptions of the loose sands, grouped by petrofacies, were made.

Each of the 89 sands collected were examined under a low power (10X–15X) binocular microscope. The grains in each sample were identified, described, and assigned an estimate of relative abundance (see Miksa and Heidke 1995 for additional explanation). Ideally this process should result in petrofacies descriptions that are clear and comprehensive; descriptions that a ceramicist can use to characterize tempering materials with the aid of a low power microscope.
To make things easier for the ceramicist, a collection of sand-sized mineral and rock specimens representative of each petrofacies was glued into covered match boxes. Each grain type was numbered and identified in a key accompanying each detailed petrofacies description (Table A.2). In this way, Heidke could compare coarse sand grains observed in a sherd with those in a petrofacies box (Kamilli 1994). Grain boxes prepared for this study are on file at Desert Archaeology, Inc. Detailed petrofacies descriptions, derived from examination of hand samples, thin-sections, and geologic maps, are presented in Table A.2. Abbreviated descriptions of each petrofacies are provided in Table 1 above.

Creating the Flow Chart

Once all petrofacies were described and their grain boxes prepared, a flow chart was constructed (Figure 10). The flow chart provides a logical, step-by-step means of evaluating the grain types in a sand or in a sand-tempered sherd. The flow chart is designed to first break out similar petrofacies, then to provide criteria for separating similar petrofacies from one another. For example, the basalt-rich petrofacies occupy the left-most branch of the chart, while granitic petrofacies occupy the right-most branch. The lowest order (most fundamental) differences occupy the highest positions on the chart, followed by increasingly subtle differences.

After the sand descriptions, grain boxes, and initial flow chart were assembled by Kamilli, they were used by Heidke to learn how to identify the sands in hand sample. In his daily examination of the sands, Heidke identified several problem areas in the flow chart. These were areas where following the charted decision-making process led to incorrect sand assignments. Kamilli used problems identified by Heidke to revise sand descriptions where necessary to account for the variation of certain petrofacies, or simply to provide more detail. She then revised the flow chart.

The flow chart revisions are intended to account as well as possible for the nonmodal variations in the natural system. The goal was to devise an “expert system” (Vitali 1989) to account for as many cases as possible without losing accuracy by becoming too vague. To test whether or not we met these goals, we conducted blind sand assignment tests, where unlabelled sand samples were assigned to petrofacies using only the flow chart. Heidke consistently placed 95 to 100 percent of
the sands into their appropriate petrofacies when working with the sands on a daily basis over the five week period during which he characterized the pottery’s temper.

**ANALYSIS OF THE SHERDS**

**Binocular Microscopic Characterization of the Sherds**

Once the flow chart was complete, it was used to characterize the temper composition of a sample of sherds chosen by ceramicists at Statistical Research, Inc. The sample included 299 sherds from Bartlett Reservoir project area sites, and 685 sherds from Horseshoe Reservoir project area sites. Ordered from highest to lowest, the sample prioritized: (1) reconstructible vessels on room floors and burials; (2) reconstructible vessels in other contexts; (3) rim sherds on floors; (4) rim sherds in floor, roof, and general fill; (5) body sherds on floors; and (6) body sherds in floor, roof, and general fill or surface contexts (see Volume 3, Chapter 1 and Appendix A for a detailed discussion of SRI’s sampling strategy). An additional 24 sherds from the site of Azatlan, previously examined by Garrett (1991), were also characterized. Sherds were examined at 10 to 15 power magnification using a Unitron ZSM binocular microscope with a Lite Mite Series 9 circular illuminator. Lower Verde River petrofacies assignments were based on the sand hand sample classification flow chart, descriptive key, and grain boxes.

Three variables were used to characterize temper composition (Figure A.1). The first variable, temper type (TT), was used to characterize whether or not the temper composition was dominated by a micaceous material, such as phyllite, schist, or muscovite mica. The second temper variable, generic temper source (TSG), was used to characterize the geographic and tectonic origin of the temper grains observed. A given sherd was attributed to a generic source based on binocular microscopic observation of the rock fragments and monomineralic grains known to define particular geographic and tectonic settings. The third temper variable, specific temper source (TSS), was used to characterize the petrofacies of origin for the observed temper grains. A given sherd was attributed to a specific source based on the binocular microscopic observation of the distinctive suite of rock fragments and monomineralic grains in the abundances known to define a particular petrofacies. In this way, we used the precise data gained from thin-section studies as a means of assigning tempers to petrofacies without thin-sectioning each sherd.
The difference between the “generic” and “specific” temper source attributes used in this study lies in the finer level of geographic resolution implied by the petrofacies. In practice, the information represented by the “generic” attribute is redundant with the information represented by the “specific” attribute when the sand temper observed in a given sherd permits its assignment to a petrofacies. It is sometimes the case, however, that the temper does not exhibit any or all sand grains necessary for a specific assignment. For example, it is often difficult to characterize the specific temper source of small or badly burned sherds, or those that are sparsely tempered. However, the temper grains that can be observed in small, badly burned, and sparsely tempered sherds are often sufficient to categorize the generic origin of the sand. For instance, a sherd may be assigned a generic code that indicates it has a granitic temper, and a specific code of “indeterminate.” Important compositional and limited provenance information would be lost in those cases if only an attribute recording the petrofacies of origin was required during analysis, because all generic petrofacies assignments would, by definition, have to be recorded as “indeterminate.

A number of unknown or extrabasinal temper compositions were encountered during the binocular microscopic characterization. As these compositions were encountered, a brief note describing each composition was recorded in a sherd’s “comments” field. After all sherds were characterized the “comments” field was reviewed. Ad hoc generic temper source codes were then defined for sets of sherds sharing similar “comments.”

Testing the Binocular Microscope Characterization

The binocular microscopic temper characterization was tested by classifying a subsample of lower Verde River area sand-tempered sherds’ petrofacies membership using the discriminant functions derived from the sand samples. In order to do this, a set of characterized sherds was selected for point counting. After temper characterization was completed, and the data verified, a list cross-tabulating the three temper variables—temper type, generic source, and specific source—was printed. Forty-one unique temper variable combinations were present (Table 10). A stratified subsample of sherds was selected for petrographic analysis based on that list. The point-counted subsample was stratified by project area, site, time period, ceramic ware, and temper composition (the unique combinations of the temper type, generic temper source, and specific
temper source variables). Twenty-three of the 41 unique temper compositions were selected for detailed petrographic analysis (see Table 10). The 23 sampled groups include all temper variable combinations observed in at least nine sherds (or approximately one percent of the total examined). Although the 23 sampled temper groups represent only about half of all groups present, they contain nearly 95 percent of all characterized sherds (955 sherds in sampled groups ÷ 1008 total sherds = 0.947). In the end, 71 sherds from LVAP sites were selected for thin-sectioning and petrographic analysis, and 13 sherds from Azatlan were also point counted. That number represents an 8.3 percent sample fraction for the entire data set ([71 point counted LVAP sherds + 13 point counted Azatlan sherds] ÷ [984 total LVAP sherds + 24 total Azatlan sherds] = 0.083), and an 8.8 percent sample fraction for the sampled groups ([71 point counted LVAP sherds + 13 point counted Azatlan sherds] ÷ [931 sherds in sampled LVAP groups + 24 sherds in sampled Azatlan groups] = 0.088). The Azatlan sample fraction—54.2 percent—is much larger than the LVAP sample fraction (7.2 percent).

Selection of Sherds for Thin-Sectioning and Their Preparation

Selection of LVAP sherds for thin-sectioning within the 23 temper groups was not random, since only sherds large enough to be thin-sectioned (i.e., ≥ 27 × 46 mm) could be included. A stratified sampling technique was used to select the sherds. The sample was stratified by: (1) project area; (2) site; (3) time period; (4) ceramic ware; and (5) temper composition. The goal of the sampling process was to select a representative analytical subsample from the total population of sherds included in the temper provenance study. A perfect subsample would contain 7.2 percent of the LVAP sherds in each sampled level of the data set (7.2 percent = [71 LVAP point counted sherds ÷ 984 total LVAP sherds] × 100). For example, with 299 total sherds from Bartlett Reservoir sites, 21.6 sherds from that project area should have been thin sectioned (299 × 0.072 = 21.6), while 49.4 sherds from Horseshoe Reservoir sites should have been thin sectioned (685 × 0.072 = 49.4). In actuality, we thin sectioned 17 sherds from Bartlett Reservoir sites and 54 sherds from Horseshoe Reservoir sites.

The crucial question, then, is whether the discrepancies between observed and expected frequencies are small enough to qualify as a probable outcome, given that the null hypothesis—the hypothesis of no difference—is true. If so, the null hypothesis would be retained. If the null
hypothesis is true, then, except for “chance” behaviors in the selection process, the proportion of thin-sectioned sherds in each project area’s subsample should equal the overall proportion of thin-sectioned sherds in both areas. The chi-square test was used to test this hypothesis. Results of that test indicate that there is no statistically significant difference between the observed and expected frequencies \(\chi^2=1.501; df=1; p=0.220\).

The same approach was used to examine each of the four remaining sampling strata (the data that all five chi-square tests are based on is reported in Table A.4). The LVAP sample contains sherds recovered from 16 sites. If the null hypothesis is true, then, except for chance, the proportion of thin-sectioned sherds drawn from each site should equal the overall proportion of thin-sectioned sherds drawn from all 16 sites. Results of that chi-square test indicate that there is no statistically significant difference between the observed and expected frequencies \(\chi^2=14.703; df=15; p=0.473\).

The LVAP sample contains sherds recovered from eight different time periods. If the null hypothesis is true, then, except for chance, the proportion of thin-sectioned sherds drawn from each time period should equal the overall proportion of thin-sectioned sherds drawn from all eight time periods. Results of that chi-square test indicate that there is a statistically significant difference between the observed and expected frequencies \(\chi^2=17.406; df=7; p=0.015\). The Preclassic time periods (i.e., Pioneer, Pioneer-Colonial, Colonial, and Sedentary periods) are over-represented in the sample of thin sectioned sherds, whereas Sedentary-Classic, Classic, historic, and “unknown” time periods are under-represented.

The LVAP sample contains sherds belonging to seven different wares. If the null hypothesis is true, then, except for chance, the proportion of thin-sectioned sherds drawn from each ware should equal the overall proportion of thin-sectioned sherds drawn from all seven wares. Results of that chi-square test indicate that there is no statistically significant difference between the observed and expected frequencies \(\chi^2=3.876; df=6; p=0.693\).

Finally, based on the binocular microscopic characterization, the LVAP sample contains sherds containing 41 different temper compositions. If the null hypothesis is true, then, except for chance, the proportion of thin-sectioned sherds drawn from each temper composition should equal the
Taken together, the results of the five chi-square tests show that the rigorous sampling strategy used to select sherds for thin sectioning and petrographic analysis was, in general, quite successful. No statistically significant differences between observed and expected frequencies are present in the thin-sectioned subsample with regard to project area, site, ceramic ware, and temper composition. However, the thin-sectioned subsample does over-represent Preclassic time periods, and under-represents later time periods as well as sherds drawn from contexts that could not be dated.

The ceramic thin-sections were prepared by Quality Thin-Sections of Tucson, Arizona. The LVAP sherds were saturated with epoxy, then sectioned parallel to the vessel wall to provide a large area for point counting. They were stained for potassium feldspar and plagioclase feldspar, and permanently cover slipped. Sand-sized material in the sherds was then counted using the same methods and parameters as were used for the sand samples except that one additional variable, sherd temper, was included in the point count.

As noted above, 24 sherd thin-sections from the Azatlan collection were also examined. These sherds had been analyzed previously by Garrett (1991) using another petrologic approach and unstained thin-sections. Kamilli recounted 13 of these 24 sherd thin-sections. The reanalyzed sherds included all seven sherds characterized by Heidke as granitic sand-tempered, as well as one sherd each from all of the other temper compositions he observed. Many of these tempers are dominated by metamorphic grains. Kamilli found that, without staining, it was very difficult to distinguish the quartz, unfeatured alkali feldspar, and unfeatured plagioclase in the Azatlan sherds.

Table A.3 reports the point-count data for the thin-sectioned Bartlett Reservoir, Horseshoe Reservoir, and Azatlan sherds.
Correspondence Analysis of Sherd Samples

A single correspondence analysis trial was run with the sherd point-count data. It used data from all 84 point-counted sherds and 27 of the point-count parameters. Eight parameters—SANID, OLIV, SPHENE, CACO, LVH, LVV, LSS, and LMAMPH—were dropped because they occurred at a low frequency in all samples. Table 11 reports the ranked parameter optimal scores derived from the sherd analysis. The first factor accounts for 28.0 percent of the variation, the second factor accounts for 15.1 percent, the third factor accounts for 11.2 percent, and the fourth factor accounts for 10.5 percent of the variation. Each of the remaining 23 factors account for less than ten percent of the variation.

Figure 11 is a plot of the point-count parameters on the first two correspondence analysis factors. (Note, in order not to obscure the point-count parameter labels, the 84 sherd samples are not shown. Instead, a one-standard-deviation ellipse around each of the four major temper compositions identified by Kamilli in the thin-sectioned sherds—phyllite, schist, tonalite, and lower Verde River area granites—is shown.) The first factor is interpreted as a contrast between sherds that are tempered principally with phyllite (LMTP) and metavolcanic (LMVF) materials and sherds containing other tempering agents, because the LMTP and LMVF parameters received the lowest (negative) factor scores while most of the other parameters received positive factor scores. The second factor is interpreted as a contrast between sherds tempered with tonalite and sherds containing other tempering agents, because the two point-count parameters most closely associated with tonalite—CAPLAG and AMPH—received the highest positive factor scores while the other parameters received much lower positive factor scores or negative scores. Figure 12 shows how the sherds assigned to the temper groups plot relative to their group’s one-standard-deviation ellipse.

The third factor is interpreted as a contrast between two of the parameters strongly related to the phyllite-tempered pottery. The two parameters that plotted close together on Factor 1—LMTP and LMVF—are ranked at opposite ends of Factor 3. The metavolcanic parameter (LMVF) received the lowest (negative) factor score, while the phyllite parameter (LMTP) received one of the highest (positive) factor scores. The third correspondence analysis factor is discussed further in the section
on phyllite-tempered pottery below. The fourth factor is interpreted as a contrast between sherd temper, highest (positive) factor score, and all other tempering materials.

Of the 84 point-counted sherds, Kamilli identified 34 (40.5 percent) as having sand tempers that likely originated within the lower Verde River area. Each of these 34 sherds belonged to one of seven temper compositions (the unique concatenations of the temper type, generic temper source, and specific temper source variables discussed above) that resulted from Heidke’s binocular microscopic characterization. Discriminant analysis of the point count data, recorded by Kamilli from all of the thin-sectioned sherds assigned by Heidke to these seven compositions, was used to test his binocular microscopic characterization of sand temper. (The seven granitic sand-tempered sherds from Azatlan are members of one of these compositions.) Point count data for all of these sherds were logratio transformed in the same manner as the sand samples, and classified using the sand discriminant functions. Sherds tempered with phyllite, schist, tonalite, and other indeterminate or extrabasinal materials were not included in the discriminant analysis. They are treated separately in a later section.

Table 12 reports Heidke’s binocular microscopic characterization of all point-counted sherds, their predicted petrofacies membership based on discriminant analysis (where applicable), Kamilli’s petrographic microscopic characterization, and the final inferred analytical group membership of the sherds. Breaks between the rows in Table 12 indicate sets of sherds characterized by Heidke as displaying similar temper compositions (the unique concatenations of the temper type, generic temper source, and specific temper source variables).

Lower Verde River Area Sherds: Interpretation of the Discriminant Analysis Results

The first temper composition to be classified by the discriminant functions was represented in thin section by five point-counted sherds (LVP-7, LVP-8, LVP-16, LVP-17, and LVP-18), only one of which was identified by Kamilli as originating in the lower Verde River area (sample LVP-18), and includes the 32 sherds that were originally characterized by Heidke as “indeterminate sand temper” (TT = 4, TSG = -9, TSS = -9). The discriminant analysis, like Kamilli, assigned LVP-18 to Petrofacies H. Based on Kamilli’s petrographic analysis, each of the four remaining indeterminate
sand-tempered sherds contains a different composition (see the discussions of “Phyllite-tempered Sherds,” “Schist-tempered Sherds,” and “Unique Tempers” below).

The second temper composition, represented by two point-counted sherds (LVP-20 and LVP-21), includes the 30 sherds that were originally characterized by Heidke as “indeterminate Petrofacies F, J, or M sand temper (arkose sand with biotite)” (TT = 4, TSG = 12, TSS = -9). The discriminant analysis, like Kamilli, assigned one of those samples to Petrofacies F and one to Petrofacies J.

The third temper composition, represented by 14 point-counted sherds (LVP-33 through LVP-46), includes the 308 sherds that were originally characterized by Heidke as “Petrofacies F sand temper” (TT = 4, TSG = 13, TSS = F). The discriminant analysis, like Kamilli, assigned 12 of those samples to Petrofacies F. Sample LVP-40 was assigned to Petrofacies L by the discriminant functions and to Petrofacies D by Kamilli. Sample LVP-41 was assigned to Petrofacies J by the discriminant functions and Kamilli.

The fourth temper composition, represented by one point-counted sherd (LVP-52), includes another 12 sherds that were originally characterized by Heidke as “Petrofacies F sand temper” (TT = 4, TSG = 15, TSS = F). The discriminant analysis, like Kamilli, assigned that sample to Petrofacies F.

The fifth temper composition, represented by 11 point-counted sherds from the Bartlett and Horseshoe Reservoir sites (LVP-22 through LVP-32) and seven point-counted sherds from Azatlan (WU-50, WU-51, WU-53, WU-58, WU-60, WU-63, and WU-65), includes 118 sherds that were originally characterized by Heidke as "indeterminate Petrofacies F, J, or M sand temper (arkose sand with biotite and transparent quartz)" (TT = 4, TSG = 13, TSS = -9). The discriminant analysis assigned one of the LVAP samples to Petrofacies A, four of the LVAP samples to Petrofacies F, and six of the LVAP samples to Petrofacies J. The discriminant analysis assigned one of the Azatlan sherds to Petrofacies N, two of the Azatlan sherds to Petrofacies M, and four of the Azatlan sherds to Petrofacies F. Among the LVAP samples, the discriminant function’s petrofacies assignments and Kamilli’s petrofacies assignments are in agreement, except for sample LVP-25. The discriminant functions assigned LVP-25 to Petrofacies A, whereas Kamilli recognized it as a
The differences between the statistical classification of temper provenance and the petrographer’s classification, displayed by this set of point-counted sherds, is to be expected if some of the members of a set are of extrabasinal origin. Discriminant analysis starts from the presumption that a set of objects are known to belong to one of two or more groups (Baxter 1994:185), and each “unknown” case is classified to the group that it most closely resembles (Klecka 1980:9). Therefore, a sherd tempered with an “unknown,” extrabasinal sand composition will be classified by the discriminant functions to the petrofacies group that its composition most closely resembles (in this way the statistical classification procedure resembles the ceramicist’s binocular microscopic characterization). In the end, however, we “know better”: The petrographer’s expertise in the matter of identifying extrabasinal compositions supplants the statistical classification (as well as the ceramicist’s).

The sixth temper composition, represented by five point-counted sherds (LVP-47 through LVP-51), includes 73 sherds that were originally characterized by Heidke as “indeterminate Petrofacies F or J sand temper (arkose sand with biotite and indeterminate quartz, not Petrofacies M)” (TT = 4, TSG = 15, TSS = -9). The discriminant analysis, like Kamilli, assigned one of those samples to Petrofacies F, and four of those samples to Petrofacies J.

The seventh temper composition, represented by a single point-counted sherd (LVP-53), includes 10 sherds that were originally characterized by Heidke as “Petrofacies J sand temper” (TT = 4, TSG = 15, TSS = J). The discriminant analysis, like Kamilli, assigned that sample to Petrofacies J.

**Interpretation of Sherd Provenance**

The seven temper compositions reviewed above represent 583 vessels, most of which are believed to have been produced in the lower Verde River area. Sherds included in the first temper
composition, “indeterminate sand temper,” display a diversity of tempering materials. Based on Kamilli’s petrographic analysis, this group includes a schist-tempered sherd (LVP-7), a sherd predominantly tempered with quartz (LVP-8), a sherd tempered with phyllite (LVP-16), a sherd containing sand and sherd temper (LVP-17), and a sherd from Petrofacies H (LVP-18). Clearly, most of the sherds in this group were not produced in the lower Verde River area. Five hundred and fifty-one vessels are included in the remaining six temper compositions. With the exception of the muscovite/biotite granite-tempered sherds from Azatlan, most of those vessels are believed to have been produced in the lower Verde River area (all but one of the 34 remaining point-counted sherds included in these six temper compositions was assigned a lower Verde River area provenance by Kamilli).

Examination of Table 12 shows how the results of the discriminant analysis and Kamilli’s classification were used to refine Heidke’s characterization, develop the final temper assignments for those 551 vessels, and assess the accuracy of those assignments. The second temper composition reviewed above contained two point-counted sherds. The discriminant analysis predicted the temper composition of one of these sherds as Petrofacies F and the other as Petrofacies J; Kamilli classified these sherds the same way. Based on those results, their final assignment, and the assignment of all sherds similarly characterized by Heidke, is to a new, analytical temper composition “Petrofacies F or J.”

Discriminant analysis predicted the temper provenance of most of the point-counted sherds in the third and fourth temper compositions as Petrofacies F, as did Kamilli. Based on those results, their final assignment, and the assignment of all sherds similarly characterized by Heidke, is to Petrofacies F. However, two of the 15 point-counted sherds assigned to Petrofacies F were assigned to other sources by the discriminant analysis program (and by Kamilli). Therefore, the inferred accuracy of the final Petrofacies F assignment is 86.6 percent.

The fifth temper composition contained granitic sand-tempered sherds from Azatlan as well as from the Bartlett and Horseshoe Reservoir sites. Discriminant analysis predicted the temper composition of most of the point-counted sherds in this group as either Petrofacies F or Petrofacies J. However, petrographic examination of the point-counted sherds from Azatlan indicates that neither of these petrofacies could be the source for those sherds (see the discussion of
“Muscovite/biotite Granite-tempered Sherds” below). Based on those results, the final assignment of all point-counted sherds in this temper composition, and the assignment of all sherds similarly characterized by Heidke, is to “Petrofacies F, J, or 4 (unknown muscovite/biotite granite).” It must be emphasized, however, that the petrographic analysis shows that the muscovite/biotite granite-tempered pottery only occurred at Azatlan, that Petrofacies F sand-tempered pottery occurred at both the Bartlett Reservoir and Horseshoe Reservoir sites, and that Petrofacies J sand-tempered pottery only occurred at the Horseshoe Reservoir sites.

Discriminant analysis predicted the temper provenance of most of the point-counted sherds in the sixth and seventh temper compositions as Petrofacies J, as did Kamilli. Based on those results, the final assignment of all point-counted sherds in these two temper compositions, and the assignment of all sherds similarly characterized by Heidke, is to Petrofacies J. However, one of the six point-counted sherds in this group was assigned to Petrofacies F by the discriminant analysis (and by Kamilli). Therefore, the inferred accuracy of the Petrofacies J assignment is 83.3 percent.

As the discussion above makes clear, it was not always possible for Heidke to distinguish a Petrofacies F granitic sand temper from a Petrofacies J granitic sand temper. However, the discriminant analysis (and Kamilli) had no problem separating these two granitic lower Verde River petrofacies from one another. The reason why the statistical procedure and Kamilli were able to consistently separate the two sources, and be in agreement, relates to the type of alkali feldspar present in each petrofacies. Sherds assigned a Petrofacies F provenance by discriminant analysis and Kamilli, are tempered with an assemblage that is dominated by quartz, microcline alkali feldspar, lesser amounts of perthite, oligoclase plagioclase, and commonly large grains of biotite mica (but no muscovite). These sherds also contain variable amounts of volcanic rock, and little metamorphic material. Sherds assigned a Petrofacies J provenance by discriminant analysis and Kamilli, are tempered with a composition dominated by perthitic alkali feldspar, quartz, oligoclase plagioclase, and low to moderate amounts of biotite mica (but no muscovite). These sherds contain little metamorphic, sedimentary, or volcanic material.

The difference between microcline alkali feldspar and perthitic alkali feldspar is clearly visible in petrographic thin-section. The percentage of microcline and perthitic alkali feldspar present in all sherds assigned by the discriminant analysis, and Kamilli, to Petrofacies F and J are shown in
Figure 13. The one- and two-standard-deviation sample ellipses shown around the sherds assigned to Petrofacies F are based on the percentage of those minerals in the Petrofacies F sands. Similarly, the one-standard-deviation sample ellipse shown around the sherds assigned to Petrofacies J is based on the percentage of those two minerals in the Petrofacies J sands. (The low number of samples from Petrofacies J precluded us from drawing a meaningful two-standard-deviation ellipse.) As Figure 13 shows, all of the sherds assigned to Petrofacies J by the discriminant functions and Kamilli fall neatly within the one-standard-deviation ellipse of the Petrofacies J sands. Most of the sherds assigned to Petrofacies F by the discriminant functions and Kamilli fall within the two-standard-deviation ellipse for Petrofacies F sand, and those that do not, plot closer to the Petrofacies F distribution than they do to the Petrofacies J distribution. Unfortunately, the difference between microcline alkali feldspar and perthitic alkali feldspar is not visible in hand sample (i.e., under examination with the binocular microscope). Therefore, we expect that there will always be some confusion between these two petrofacies whenever sherds from lower Verde River area sites are characterized with the aid of a binocular microscope.

Having reviewed the final temper composition assignments applied to these 551 vessels, one question remains to be answered: How accurate was the binocular microscopic characterization? The figures reviewed above compare favorably with the overall lower Verde River area sand sample discriminant model’s accuracy of 80.2 percent, and the subset of mineral-rich sand petrofacies that had an accuracy of 75 percent. Clearly, in this study we are working at the maximum level of resolution available, given the region’s geology.

Sherds of Indeterminate and Extrabasinal Provenance

There are several temper compositions documented in this study that, with the information we have, may be either intra- or extrabasinal. As noted above, “extrabasinal” refers to compositions unlike those documented in sand and rock samples collected from tributaries to the lower Verde River from Ister Flat on the north to the Verde River’s confluence with the Salt River on the south. These temper compositions were given designation numbers or letters that are not keyed to the lower Verde River area’s petrofacies model.
Many of the sherds recovered from the Bartlett and Horseshoe Reservoir sites, and Azatlan, contain metamorphic rock-fragment-rich tempers. This presents a problem because no petrofacies established in the lower Verde River area contain compositions with the amounts and types of metamorphic rocks seen in these sherds. Geological references and rock samples collected for this study suggest, however, that there might be unsampled wash sand compositions still to be found. In some cases, the potters may have added disaggregated or crushed rock materials to their clays (Lombard 1987:105; Miksa 1995:15; Schaller 1994:83).

**Phyllite-tempered Sherds**

Twenty-one of the LVAP project sherds and four of the Azatlan sherds are tempered with various mixtures of phyllite (fine and coarse), metavolcanics, schists, and muscovite mica. Based on abundances of these rocks and minerals, reported in Table 13, Kamilli subdivided the point-counted phyllite-tempered sherds into four groups. The four groups are:

Group 7: Phyllite, abundant schist and muscovite mica, and ± minor metavolcanics (LVP-15, LVP-16, LVP-54 through LVP-56; WU-54 and WU-55);

Group 8: Phyllite, minor schist and muscovite mica, and ± minor metavolcanics (LVP-57, LVP-58, LVP-60, LVP-65 through LVP-68; WU-56);

Group 9: Phyllite, minor metavolcanics, and ± minor schist and muscovite mica (LVP-62 through LVP-64; WU-61);

Group 0: Phyllite, abundant metavolcanics, and ± minor schist and muscovite mica (LVP-19, LVP-59, LVP-61, LVP-69 through LVP-71).

As discussed previously, the compositional variability present in the point-counted phyllite-tempered sherds is reflected in the third factor of the sherd point count data correspondence analysis. Figure 14 is a plot of the point-count parameters on the first and third correspondence analysis factors. (Note, in order to clarify compositional subgroups within the phyllite-tempered sherds, only ellipses representing phyllite-tempered pottery “Groups” are shown.) Figure 15
shows how the sherds assigned to the four phyllite subgroups plot relative to their subgroup’s one-standard-deviation ellipse.

In some cases, the different metamorphic textures reflected in the subdivisions of the phyllite-tempered pottery may represent different grades of recrystallization. For instance, wide variations in texture were observed in the metavolcanic rock grains. These textures range from relict porphyritic to completely recrystallized. Therefore, the phyllite group subdivisions likely represent variations of metamorphism within a sedimentary and volcanic province, such as is found in the McDowell Mountains (Christenson et al. 1978). The clustering of such variation may or may not prove to be useful in eventually tracing the specific source of the various phyllitic tempers. In any case, the possibility of a source within the lower Verde River drainage basin can not be ruled out until further work is done.

The four phyllite subgroups were defined during Kamilli’s petrographic analysis. However, after Heidke’s binocular microscopic characterization was completed it was clear that he had consistently identified many members of three of the four subgroups. Six of the seven point-counted sherds assigned by Kamilli to Group 7 are members of four temper compositions identified by Heidke (1st TT = -9, TSG = 25, TSS = -9; 2nd TT = 4, TSG = 21, TSS = -9; 3rd TT = 4, TSG = 25, TSS = -9; and 4th TT = 4, TSG = 26, TSS = -9). Altogether those four temper compositions include 54 vessels (see Table 10). The final assignment of all point-counted sherds in those four temper compositions, and the assignment of all vessels similarly characterized by Heidke, is to Group 7. However, Kamilli classified one of the point-counted sherds (LVP-14) as schist-tempered. Therefore, the inferred accuracy of the Group 7 assignment is 85.7 percent.

Four of five point-counted sherds characterized by Heidke as “phyllite with felsic layering” (TT = 10, TSG = 20, TSS = -9) were assigned by Kamilli to Group 8. Sixty-five vessels were characterized by Heidke as “phyllite with felsic layering” (see Table 10). The final assignment of all point-counted sherds in that temper composition, and the assignment of all vessels similarly characterized by Heidke, is to Group 8. However, Kamilli classified one of the five point-counted sherds (LVP-69) as Group 0. Therefore, the inferred accuracy of the Group 8 assignment is 80 percent.
Three point-counted sherds assigned by Kamilli to Group 0—LVP-19, LVP-70, and LVP-71—are the only members of three temper compositions (1st TT = 4, TSG = 7, TSS = L; 2nd TT = 10, TSG = 22, TSS = -9; and 3rd TT = 10, TSG = 23, TSS = -9) identified by Heidke that were submitted for petrographic analysis. Altogether those three temper compositions include 20 vessels (see Table 10). The final assignment of all point-counted sherds in those three temper compositions, and the assignment of all vessels similarly characterized by Heidke, is to Group 0.

Heidke characterized as an unspecified type of phyllite temper (TT = 10, TSG = -9, TSS = -9) all four of the sherds assigned by Kamilli to Group 9, as well as four sherds she assigned to Group 8 (LVP-57, LVP-58, LVP-60, and LVP-65) and two sherds she assigned to Group 0 (LVP-59 and LVP-61). That temper composition includes 94 vessels (see Table 10). The final assignment of all ten point-counted sherds in that temper composition, and the assignment of all vessels similarly characterized by Heidke, is to an analytical group that contains members of all three phyllite varieties. Those vessels are reported as Group 8-9-0 in the discussion of “Archaeological Interpretation and Conclusions” below.

Schist-tempered Sherds

Ten point-counted sherds containing coarse schist and variable amounts of granite derivatives (LVP-1 through LVP-7, LVP-14; WU-46 and WU-52) have a higher likelihood of being extrabasinal than the phyllite-tempered vessels, because little coarse schist was seen in the lower Verde River area’s rock samples (and practically none in the sand samples). Some coarse schist has been reported from the McDowell Mountains, but it is also possible that the source was in the Santan Mountains or at Gila Butte.

Heidke characterized schist-tempered pots four different ways (1st TT = 1, TSG = -9, TSS = -9; 2nd TT = 1, TSG = 28, TSS = -9; 3rd TT = 1, TSG = 29, TSS = -9; and 4th TT = 2, TSG = 29, TSS = -9). Altogether those four temper compositions include 98 vessels (see Table 10). The final assignment of all point-counted sherds in those four temper compositions, and the assignment of all vessels similarly characterized by Heidke, is to a schist temper group.
Muscovite/biotite Granite-tempered Sherds

There are two different sets of igneous rock-tempered sherds that cannot be related to a lower Verde River petrofacies, or to known areas of bedrock surrounding the basin.

The first set, referred to as Group 4, was only observed in seven Azatlan sherds (WU-50, WU-51, WU-53, WU-58, WU-60, WU-63, and WU-65). It was not found in any thin-sectioned sherds from the Bartlett Reservoir and Horseshoe Reservoir sites, nor was it found in any of the lower Verde River area’s sand samples. The Group 4 temper is a two-mica granite, one which contains both muscovite and biotite mica. A review of the literature suggests that there may be some sources to the west of the lower Verde River area that are related to the younger Precambrian granite (Anderson 1989). No specific location has been noted and further research should be done. Further sand sampling in the area of Petrofacies M (sparsely sampled) might be of benefit; however, it is possible that these sherds are extrabasinal. These sherds are subsumed under the “Petrofacies F, J, or unknown muscovite/biotite granite (Group 4)” temper category discussed above.

Tonalite-tempered Sherds

Another igneous temper composition was documented in five point-counted sherds from the Bartlett and Horseshoe Reservoir sites (LVP-9 through LVP-13). This temper contains coarse aggregates of a distinctive, deformed, amphibole-biotite, intermediate granitic rock. The plagioclase grains are andesine and commonly strongly zoned. The grains vary from a tonalite to similarly coarse aggregates of an alkali feldspar, biotite-amphibole granite. We are using the term tonalite to identify this grain type as seen in the sand tempers. However, the actual bedrock source could be an intermediate granitic rock of variable composition (i.e. tonalite, granodiorite, quartz monzonite or quartz diorite). It is clear, however, that the temper in these five point-counted sherds came from the same deformed area.

Sample LVP-14 contains this distinctive material, but it also contains a considerable amount of schist, foliated quartz, and felsic volcanic rock. Because of the schist content, it was assigned to the schist group. The assemblage, however, suggests that the deformed tonalite temper sands are from
a source near a metamorphic and volcanic province. Another sherd, Azatlan sample WU-52, also contains some of this deformed tonalite (mostly as free mineral products), along with an abundance of schist. Because of the schist content, it was also placed in the schist group. The presence of the tonalite, a distinctive grain, suggests that the temper could have come from a source where schist and tonalite were associated. Specific reference to such an assemblage was not found in the literature, and more work needs to be done.

Tonalite was not found in any of the sand or rock samples collected, nor was it clearly indicated on maps as being within the drainage of the lower Verde River area. Therefore, the probability exists that these sherds are extrabasinal. However, Christenson et al. (1978) indicate the presence of a granodiorite unit along the ridge line of the McDowell Mountains. The tonalite seen in these sherds could be a variant of that granodiorite. Also, Marsh (1983) shows the presence of a quartz monzonite near Tangle Creek in the Horseshoe Reservoir area.

Heidke characterized these distinctive tonalite sand-tempered pots three different ways (1st TT = 4, TSG = 9, TSS = -9; 2nd TT = 4, TSG = 9, TSS = A; and 3rd TT = 4, TSG = 9, TSS = -9). Altogether those three temper compositions include 41 vessels (see Table 10). The final assignment of all point-counted sherds in those four temper compositions, and the assignment of all vessels similarly characterized by Heidke, is to a tonalite temper group.

Unique Tempers

There remain three temper compositions that are truly unique in the set of point-counted sherds.

The first unique point-counted temper composition is similar to Petrofacies J (LVP-25, Group U). However, this sherd also contains about 12 percent metamorphic grains. Very little metamorphic material was found in the Petrofacies J sand samples. Therefore, this sherd cannot be assigned to Petrofacies J, and is considered extrabasinal. Heidke characterized this sherd as “indeterminate Petrofacies F, J, or M sand temper (arkose sand with biotite and transparent quartz)” (TT = 4, TSG = 13, TSS = -9; see the discussion of “Lower Verde River Area Sherds: Interpretation of the Discriminant Analysis Results” above).
The second unique point-counted temper composition contains approximately 20 percent grog, or sherd, temper (LVP-17, Group Y). This technology was not seen elsewhere in this study. The mineral assemblage in the remaining 80 percent of the temper are unlike anything seen in the lower Verde River area’s sand samples, and the sherd is considered extrabasinal. Heidke characterized this sherd as “indeterminate sand temper” (TT = 4, TSG = -9, and TSS = -9), a correct assessment relative to the lower Verde River area’s petrofacies model.

The third unique point-counted temper composition is dominated by quartz (LVP-8, Group Z). No other temper like this was observed during point counting, and, although the materials could have come from the lower Verde River area, it too is considered extrabasinal. Heidke characterized this sherd as “indeterminate sand temper” (TT = 4, TSG = -9, and TSS = -9), a correct assessment relative to the lower Verde River area’s petrofacies model.

Temper Compositions Not Evaluated through Petrographic Analysis

The preceding sections summarized the results of petrographic provenance studies of 84 thin-sectioned sherds and their relation to 955 vessels characterized with the aid of a binocular microscope. An additional 53 vessels belong to 18 temper compositions that were not evaluated through petrographic analysis. In general, each of these temper compositions contained very few sherds (53 vessels ÷ 18 untested temper compositions = 2.9 vessels/untested temper composition).

The tempers in some of these 53 vessels are related to compositions that were evaluated through petrographic analysis. For example, the temper in two vessels was recorded as “Petrofacies F?” (TT = 4, TSG = 24, TSS = -9). Because 15 sherds characterized by Heidke as Petrofacies F were point-counted and both the discriminant model and Kamilli assigned 13 of these 15 vessels to Petrofacies F, the two vessels characterized as “Petrofacies F?” were assigned a “possible Petrofacies F” designation. Similarly, three vessels were assigned a “possible coarse phyllite with abundant schist and/or muscovite mica (possible Group 7)” designation, and 18 vessels were assigned a “possible schist” designation. During the binocular microscopic temper characterization, Heidke identified one vessel that he believed may have been tempered with Petrofacies D sand and five vessels that may have been tempered with Petrofacies E sand; none of those six vessels were thin sectioned. In the final tallies those vessels have been assigned a
“possible Petrofacies D” and “possible Petrofacies E” provenance respectively. Heidke also identified two vessels containing extrabasinal, diabase sand temper. In a recent study of Tonto Basin ceramic production, all 28 of the point-counted sherds characterized by Heidke as diabase-tempered (Armer/Cline Petrofacies) were shown to contain sand-sized diabase (Miksa and Heidke 1995:Tables 9.14 and 9.20). Therefore, the two LVAP vessels tempered with similar materials are reported as “extrabasinal diabase sand” temper in the final tallies. Lastly, based on Heidke’s (1986, 1990) experience, one sherd is reported as containing a “sand and muscovite mica” temper, while another is reported as containing a “schist and muscovite mica” temper in the final tallies.

With the exception of the 33 sherds discussed here, all of the remaining 20 vessels belonging to untested temper compositions are included in the count of the “indeterminate” temper category reported in the final tallies.

Table A.4 reports the temper characterization data for each Bartlett Reservoir and Horseshoe Reservoir ceramic sample, while Table A.5 reports similar data for the Azatlan sherds.

ARCHAEOLOGICAL INTERPRETATION AND CONCLUSIONS

Temporal Trends in Ceramic Production and Consumption

Temper characterization data for the sample of sherds from the Bartlett Reservoir sites are reported in Table 14, similar data for the sample of sherds from the Horseshoe Reservoir sites are reported in Table 15, while characterization data for the sample of sherds from Azatlan are reported in Table 16. In each of these tables the temper characterization data are reported by time period and ceramic ware. Note that a large percentage of each sample was drawn from undated contexts (39 percent of Bartlett sherds, 22 percent of Horseshoe sherds, and all of the Azatlan sherds). Furthermore, only plainwares, buffwares, and red-on-brown ceramics are well represented throughout. Redwares and sherds typed as “redware or plainware” are absent or rare except in the Classic period sample from the Horseshoe Reservoir sites.

Temporal and compositional patterns within the plainware, buffware, and red-on-brown data are best revealed graphically. In order to simplify the data presentation all four phyllite temper
variants have been collapsed into a single category (i.e., “phyllite”), and lower confidence categories, such as “possible Petrofacies F” and “Petrofacies F or J,” have been deleted. In order to facilitate comparisons between wares the same five (dominant) temper compositions—Phyllite, Petrofacies F, Petrofacies J, Tonalite, and Schist—are shown in each figure, even if they are not present in a given ware, and the sum of the five temper compositions is recalculated to 100%. One word of caution: It cannot be emphasized strongly enough that these graphs are not based on a single sampling strategy, such as all rim sherds and reconstructible vessels (cf. Heidke 1995). Therefore, the relative percentages of each temper composition portrayed in the graphs do not necessarily represent the actual, underlying frequency distribution. Rather, the graphs should be viewed as displaying the presence or absence of specific temper compositions at particular times and places.

Interpretation of the graphs is also contingent upon an understanding of what sand temper resources were locally available to the prehistoric potters residing at the sites. In a recent study we examined the relationship between the distance traditional potters travel to collect tempering materials and the type of material utilized (Miksa and Heidke 1995). We found that potters who crushed rock for temper were willing to travel distances ranging from less than 1 km up to 8 km in order to procure their material, while potters who utilized stream sand as temper exploited nearby resources (.01–3 km).

Seventy-three percent of the potters using sand temper (n = 15) travel no more than 1 km to collect it, and the 3 km distance represents a value that lies “far outside” (Velleman and Hoaglin 1981:68) the overall distribution. From this we conclude that any sand-tempered pottery containing a composition similar to that available in washes located within 3 km of the archaeological site from which the vessel was recovered should, in a behavioral sense, be considered the product of “local” manufacture because some traditional potters do travel that far to collect sand temper. However, the ethnographic evidence also suggests that compositional compatibility between the sand temper in a sherd and the sands in the washes located closest to its recovery site may be a better measure of “local” ceramic production. Sand-tempered pottery displaying compositions that are not available within 3 km of a site are best considered “nonlocal” items.
Table 17 summarizes what the geologically compatible “local” temper resource is at the Bartlett Reservoir and Horseshoe Reservoir sites with well-dated contexts (as well as the undated Azatlan sherds). It also shows whether or not some portion of Petrofacies F or Petrofacies J is located within 3 km of a site, and, therefore, should be considered a behaviorally “local” temper resource.

As Table 17 makes clear, all of the well-dated Bartlett Reservoir contexts are located in Petrofacies E; it is, therefore, the geologically compatible “local” temper resource for these sites. However, washes containing a Petrofacies F composition are located within 3 km of these sites (in fact, site AZ U:2:106/01-316 straddles the divide between Petrofacies E and Petrofacies F); Petrofacies F is, therefore, geologically “local” at site AZ U:2:106/01-316 and behaviorally “local” at sites AZ U:2:95/01-1134 and AZ U:2:107/01-318. Petrofacies J is located more than 3 km from all of the Bartlett Reservoir sites; thus, it is “nonlocal.”

All of the well-dated Horseshoe Reservoir contexts are located in Petrofacies H; it is, therefore, the geologically compatible “local” temper resource. Sites AZ U:2:61/01-1152 and AZ U:2:73/01-167 are located within 3 km of washes containing a Petrofacies F composition, but are located more than 3 km from Petrofacies J. At those two sites Petrofacies F is a behaviorally “local” resource, but Petrofacies J is “nonlocal.” Sites AZ U:2:75/01-751 and AZ U:2:80/01-819 are located within 3 km of Petrofacies J, but are located more than 3 km from Petrofacies F. At those two sites Petrofacies J is a behaviorally “local” temper resource, but Petrofacies F is “nonlocal.” Site AZ U:2:85/01-286 lies more than 3 km away from Petrofacies F and Petrofacies J; both of these petrofacies are “nonlocal” temper resources at that site.

Plainwares

The most startling aspect of the plainware data is the absence of pottery tempered with geologically “local” Petrofacies E sand (Bartlett Reservoir sites) and Petrofacies H sand (Horseshoe Reservoir sites). (Note, however, that one of the six “indeterminate” plainwares recovered from a Classic period Horseshoe Reservoir site context was identified by both Kamilli and the discriminant function analysis as Petrofacies H sand temper.) Two temper compositions dominate the sample of plainware ceramics recovered from well-dated contexts at the Bartlett Reservoir sites (Figure 16a) and Horseshoe Reservoir sites (Figure 16b): phyllite temper and Petrofacies F granitic
sand temper. Petrofacies J granitic sand temper is present at all points of time in the Horseshoe Reservoir plainware sample, but sherds tempered with Petrofacies J sand are extremely rare in the Bartlett Reservoir sample. Sherds tempered with tonalite are also present in the Horseshoe Reservoir sample. No schist-tempered plainwares were observed in either of these samples, but two schist-tempered plainwares were observed in the sample from Azatlan.

Two chi-square tests were conducted with the plainware data from the Horseshoe Reservoir sites in order to better understand whether or not the behaviorally “local” Petrofacies F and Petrofacies J sand temper resources were actually used by potters residing at those sites. We hypothesized that if potters utilized behaviorally “local” sand resources, then more of the plainwares recovered from sites AZ U:2:61/01-1152 and AZ U:2:73/01-167, located within 3 km of Petrofacies F, should be tempered with Petrofacies F sand, whereas more of the plainwares recovered from sites AZ U:2:75/01-751 and AZ U:2:80/01-819, located within 3 km of Petrofacies J, should be tempered with Petrofacies J sand. An underlying assumption of this hypothesis is that, with respect to petrofacies, the sample of sherds characterized in this study was drawn randomly.

The first chi-square test used the Preclassic plainware data set (n = 124 sherds). No significant relationship between site location and temper resource was observed ($\chi^2 = 2.38; df = 1; prob = .123$). The second chi-square test used the Classic period plainware data set (n = 82 sherds). No significant relationship between site location and temper resource was observed in the Classic period data set either ($\chi^2 = .046; df = 1; prob = .829$). We draw a number of possible conclusions from these results. Either the sample was not drawn randomly with respect to petrofacies, or exchange in plainware vessels between Horseshoe Reservoir sites randomized the distribution of vessels tempered with different sand resources, or neither of the resources were actually used by potters residing at the Horseshoe Reservoir sites. If the latter were true it suggests that similar levels of interaction occurred between the residents of all four Horseshoe Reservoir sites and potters residing at sites in Petrofacies F as well as those residing at sites in Petrofacies J.

Red-on-brown Wares

Four temper compositions were observed in the sample of red-on-brown ceramics recovered from well-dated contexts. Tonalite was the temper composition observed most frequently in the
red-on-brown pottery (Figure 17a and 17b). Red-on-brown ceramics tempered with Petrofacies F granitic sand were recovered from Colonial period contexts at Bartlett Reservoir and Horseshoe Reservoir. Those sherds provide the best evidence, encountered in this study, for the production of pottery decorated with Hohokam design motifs within the lower Verde River area. A few red-on-brown sherds tempered with phyllite were recovered from the Bartlett Reservoir contexts.

Buffwares

Nearly all of the buffwares included in the sample from well-dated contexts were tempered with schist and varying amounts of granite (Figure 18a and 18b). A few Colonial period buffwares tempered with phyllite were observed in the Bartlett Reservoir and Horseshoe Reservoir samples.

Redwares

Most of the redwares included in the sample from well-dated contexts were recovered from Classic period deposits at the Horseshoe Reservoir sites. The temper compositions represented by those sherds are similar to those seen in the Classic period plainwares from the same sites. However, the proportion of redwares tempered with Petrofacies J sand is greater, while the proportion of redwares tempered with Petrofacies F sand and phyllite is lower. Tonalite-tempered redware sherds were not observed.

Discussion

The robust trends in temper composition observed in this study are most strongly related to ware and recovery site location, not to the time of deposit formation. Table 18 summarizes the presence or absence of the major temper compositions by site and ware. The muscovite/biotite granite temper (Group 4) was only observed in the Azatlan plainwares. Petrofacies J sand temper was only observed in the Bartlett Reservoir plainwares (trace), and in the Horseshoe Reservoir plainwares and redwares (common). Petrofacies F sand temper was observed in the Bartlett Reservoir plainwares and red-on-brown wares, and in the Horseshoe Reservoir plainwares, redwares, and red-on-brown wares. Phyllite temper was observed in the Azatlan plainwares, in the Bartlett Reservoir plainwares, red-on-brown wares, and buffwares, and in the Horseshoe
Reservoir plainwares, redwares, and buffwares. Tonalite was observed in the Bartlett Reservoir red-on-brown wares, and in the Horseshoe Reservoir plainwares and red-on-brown wares. Schist temper was observed in the Azatlan plainwares and buffwares, in the Bartlett Reservoir red-on-brown wares and buffwares, and in the Horseshoe Reservoir buffwares.

The spatial distribution of sand-tempered plainwares appears to have been relatively limited. The muscovite/biotite granite-tempered plainware seen at Azatlan is not present at either the Bartlett Reservoir or Horseshoe Reservoir sites. Petrofacies J sand-tempered plainwares are present throughout the sequence at Horseshoe Reservoir, but are rare at the Bartlett Reservoir sites and absent from Azatlan. Petrofacies F sand-tempered plainwares are present at the Bartlett Reservoir and Horseshoe Reservoir sites, but it too is absent from Azatlan.

Schist-tempered buffwares display no such spatial pattern. Schist-tempered buffwares were recovered from Azatlan, Bartlett Reservoir, and Horseshoe Reservoir sites.

Perhaps the most interesting temper material is the tonalite. We have suggested, based on geological evidence, that the source for this temper could lie in the McDowell Mountains. However, if this is the case it seems unusual to us that tonalite was not observed at Azatlan, that it was present in the red-on-brown wares at Bartlett Reservoir, and was present in both the Horseshoe Reservoir plainwares and red-on-brown wares. Given the limited extent of the other granite-tempered plainwares spatial distribution and the directionality of the tonalite-tempered pottery distribution (absent at the southernmost site and present in two wares at the northern-most sites), the archaeological evidence leads us to suspect that the source for this pottery lies somewhere to the north. For example, Marsh (1983) shows a quartz monzonite, a related rock type, to the north of the area sampled for this study.

Phyllite represents the most problematic temper composition encountered in the LVAP and Azatlan ceramics. Phyllite temper is present in more wares and those wares were recovered from more sites than any other temper composition documented in this study. In addition, phyllite rocks were collected from approximately five percent of the washes sampled, although none of the wash sands collected could be described as phyllite-rich.
The strongest trends in temper composition observed in this study relate to ware and recovery site location, and not to the time of deposit formation. It is possible that the sample analyzed here does not reflect the underlying temper frequency distribution. Ceramicists at Statistical Research classified the temper of all plainwares into four categories: phyllite, sand, schist, and nonlocal. Comparison of their classification with the final classification arrived at in this study indicates that the two classifications are in agreement between 95 and 100 percent of the time. Most of the disagreements relate to SRI’s classification of the Group 7 (phyllite with abundant schist and/or muscovite mica) and Group 0 (phyllite with abundant metavolcanic) phyllite-tempered sherds. Approximately 70 percent of the sherds in those two temper groups were assigned to the “sand” category by SRI ceramicists, rather than to their “phyllite” category (see Volume 3, Chapter 1). This indicates that phyllite temper will be under-represented and sand temper over-represented in their data base. However, the degree of under- and over-representation of these tempering materials should not mask significant temporal trends in their use, like those seen in Lerner’s (1986) study of lower Verde River area ceramics.

Developing Concordance between the Actualistic Petrofacies Model and Other Temper Systematics

The wide variability described by early ceramic typologists makes it virtually impossible to systematically discriminate between Verde, Tonto, and Vosberg plainware and redware types based on published information (Bruder and Ciolek-Torrello 1987:82, 90; Hohman 1985:347; Jeter 1978:74). Jeter (1978:74) and Bruder and Ciolek-Torrello (1987:91) surmised that differences in the temper composition of Tonto Basin pottery may well relate to variation in locally available resources. We agree with the logic of their arguments. Our quantitative study of lower Verde River area wash sands demonstrates that 13 distinct sand temper compositions were available to prehistoric potters.

If one uses a ceramic typology based on temper varieties, such as the one presented by Wood (1987:Figure 2), then some of the lower Verde River area petrofacies’ compositions could produce recognized pottery types. The composition of Petrofacies F, J, M, and N sands, for example, should produce a sherd typed as “Verde,” because they display compositions of “angular to round quartz sand with variable amounts of feldspar (arkosic sand) and variable amounts of free gold/copper
mica (biotite)” (Wood 1987:Figure 2). Sherds manufactured with any one of the nine remaining sand compositions, however, would produce unnamed types according to Wood’s (1987) typology.

Concluding Thoughts and Suggestions for Further Study

Shepard (1942:226) identified three principles underlying a successful technological investigation of ceramics: the necessity of adequate sampling, the need for exact and detailed technological analysis, and the correlation of archaeological and technological data. Adequate sampling relates to the ceramic sample and to the ceramic raw materials. In this study, a sample recovered from well-dated contexts was emphasized, while our raw material sampling strategy focused on the collection of wash sand and metamorphic rock samples from the lower Verde River area. Raw material collection was necessary in order to evaluate whether or not published bedrock geology maps provided an adequate model for ceramic provenance studies. They did not. Exact and detailed technological analysis applies to the sand and sherd samples. In this study the same point-counting method was applied to the sand and sherd samples. Statistical analysis of the sand point-count data led to the development of an actualistic model of lower Verde River area petrofacies’ compositions. The flow chart and accompanying hand sample descriptions, derived from the actualistic model, form an exact and detailed descriptive key for the characterization of hand samples of sand or sand-tempered sherds. Correlation of archaeological and technological data was accomplished by: (1) characterizing the provenance of sand-tempered sherds with the aid of a binocular microscope and the descriptive key; (2) point counting a stratified seven percent sample of the characterized LVAP sherds; (3) classifying the probable petrofacies membership of point-counted sherds with the discriminant functions calculated from the sand samples; and (4) comparing the original characterization with the statistical classification.

Many of the methods used in this analysis were not available to Shepard, either because they had not yet been developed (e.g., the Gazzi-Dickinson point counting technique) or because the computing power and software were insufficient. The fine scale at which ceramic temper provenance studies are now being conducted in central Arizona owes much to these nonarchaeological advances. The actualistic lower Verde River petrofacies model developed here represents a major addition to the regional sand data base currently being compiled for the greater-Hohokam culture area (Figure 19).
The question has arisen whether the coarse schist temper, or for that matter, the phyllite temper, could have been collected, crushed, and added to a clay from a different source. To answer this would require a scan of sherd thin-sections to observe grain size, shape, and comparative compositions. Kamilli did not do this because of time limitations, but it should be considered.

There should be further sampling in the Petrofacies D, M, and P areas to look for possible occurrences of tonalite sands, muscovite/biotite granite sands, or sands with abundant metamorphic material. This part of the lower Verde River area was sparsely sampled in this reconnaissance study.

Finally, one should think about why there are practically no pots made with basalt temper as basalt is abundant around the Bartlett and Horseshoe Reservoir sites. Kamilli has seen many ceramics tempered with basalt from other areas of the world. Further experiments might establish technological, or other, reasons why the prehistoric potters of the lower Verde River chose not to use basalt sand temper.

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