Combining Big Data and Thick Data: Scalar Issues when Integrating Neutron Activation and Petrographic Data as Illustrated through a Ceramic Study from the Southern U.S. Southwest

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Abstract (<200 words)

Recent theoretical approaches in archaeology have focused on "big data", that is the production of large and varied datasets reflective of advances in scientific methods and data science. While such data are now more common, the need for "thick data", that is qualitative and contextual information, has also become significant. Particularly for ceramic research where big data from neutron activation analysis is combined with thick data from petrography, the juxtaposition has revealed issues of interpretation. Through a regional case study of painted and unpainted utility wares from AD 1200 – 1450 settlements in southern Arizona and southwestern New Mexico, three areas of concern were identified. These centered around issues of scale, 1) number of samples (sometimes in the thousands); 2) geographic area (which can be necessarily extensive); and 3) organization of production (that potters can be centralized and/or dispersed on the landscape). Interestingly, only the combined datasets reveal these issues, but that highlights why they work well together and are necessary for a more accurate explanation. Once the specifics of the disjunction between compositional "big data" interpretations and those arrived at through petrographic thick data are accounted for then a more contextual approach can be taken in reconstructing past behavior.

Keywords: big data, thick data, neutron activation analysis (NAA), petrography, Southwest, sample numbers, geographic scale, organization of ceramic production, Salado, ceramic provenance

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Introduction

When Big Data and Thick Data Meet in Archaeology

Archaeology is fundamentally about the study of past people, but more and more often that research is focused on using large-scale data to identify patterns of behavior reflecting migration, cultural interaction/social networks, the development of identity, and the movement of ideas, to name a few. Due to the advances of computing, archaeology is in a "hay-day" of examining large datasets efficiently to address multiple and varied questions. However, sometimes it can be challenging to identify and interpret meaningful patterns in all that hay, or as is more appropriately termed, big data. The definition of big data in archaeology is still being debated, but generally it reflects the intersections of massive information gathering, advanced technology, sophisticated methods to be used on that technology in order to process that information, and the unintentional impact of the collection of this data in other fields and on other research questions (De Mauro et al. 2016:122, et al. 2020; VanValkenburgh and Dufton 2020)

At a basic level big data relies on an information component that is high volume, high velocity, and high variety (Laney 2001). In archaeology, many projects with millions of data points from a diversity of material and non-material attributes can attain high volume and high variety. However, high velocity, defined as "the rate at which data are generated and the speed at which it should be analyzed and acted upon (Gandomi and Haider 2015)" is almost impossible for archaeological data due to the very nature of the research (see Huggett 2015:19; VanValkenburgh and Dufton 2020). Thus, in archaeology the term big data is restricted to the technology and methodology components, or for our purposes what can be termed "big data"[1]. A second challenge with "big data" is the focus on the quantitative without considering contextual findings and other meaningful small-scale distinctions (Cunningham and MacEachern 2016). One possible solution is the integration of so-called "thick data", i.e., qualitative, small scale, and low-resolution data, to clarify the social context of the "big data" (sensu Geertz 1977 and Wang 2013; see also Alles and Vasarhelyi 2014; Bornakke and Due 2018; Latzko-Toth et al. 2017)[2].

[1] Although our current study, discussed below, comprises 1,215 NAA sherds, this would still be considered on the low side for sample numbers for truly big data as are most datasets that are considered big data in archaeology.
[2] In other terms, thick data could be considered as categorical or qualitative with high resolution, while NAA data would be quantitative or continuous data. Such datasets can be combined for integrated data evaluation (see Ownby et al. 2014; Bornakke and Due 2018) or even utilize AI approaches, such as machine learning or pattern recognition

One notable application in archaeology of this combined approach is the integration of ceramic elemental data, often acquired via neutron activation analysis (NAA), with petrographic information. Such an approach has now become common (see Day et al. 1999; Eckert et al. 2015; Falabella et al. 2013; Minc and Sherman 2011; Ownby 2017a; Sahlén 2013; Stoner et al. 2008)[3]. However, most studies have been small in sample size and geographic scope. Several recent projects involved much larger NAA datasets for complex pottery collections sampled over a wide geographic area (Huntley et al. 2016; Ownby et al. 2014). In examining the interpretations derived from the statistical analyses of the NAA data and those born from the petrographic examinations, divergences were noted[4]. By taking a "big data" (a database of quantitative values, geochemical in this case) versus thick data (qualitative information, petrographic paste characterizations) approach, the goal is to explore these divergences and understand more clearly their root cause, while acknowledging analyses from "big data" and thick data will fundamentally produce different results. The principal source for these divergences based on our ceramic case study (described below) are suggested to reflect three different issues of scale.

Issues of Scale Visible with Combined Data

Three scale issues seem to be at the root of interpretive differences between "big data" and thick data, in our case elemental (NAA) data and petrographic data. The first is that large sample sizes are common for NAA data but can be challenging to examine statistically (Bishop et al. 1982). Identifying meaningful groupings of similar ceramics when thousands of samples are analyzed can be problematic as large groupings can obscure smaller scale variability. Further, elemental groups with many samples can result in a loss of meaning and interpretation when such groups are related to ceramic type, time period, and site location. Those considerations are often used to assist in clustering samples into meaningful groups.

(see Bickler 2021; Pawlowicz and Downum 2021). This was not attempted here as the differences in results between the NAA and petrographic data were significant, and the understanding of this divergence is the basis of this article.

[3] While it is common in the Americas to petrographically examine a subsample of sherds with geochemical data, in Europe and other areas projects often examine all the sherds petrographically and with elemental data. Thus, the issues discussed in this paper are mostly relevant to the subsampling approach to scientific ceramic analysis.

[4] Such differences between geochemical and petrographic results have been documented and discussed for years (see Arnold et al. 1991, 2000; Blomster et al. 2005; Neff et al. 2006; Sharer et al. 2006). Our paper aims to suggest a few possible reasons, adding to the many previously proposed, whose investigation could be helpful for clarifying archaeological interpretations.

Concurrently, whereas large sample sizes are common with NAA datasets, small sample sizes are sometimes the norm with petrographic data. This is because if consistent sample groupings are found in the elemental data, petrographic analysis of a few sherds from those groups will often represent the entire group's paste composition. Petrography's qualitative approach is based on examining the inclusions and clay characteristics separately (rather than in bulk as NAA does) and uses their characteristics (especially sand) to provide information on the physical location where raw materials were collected. Petrographic analysis is often used to evaluate whether each elemental group represents raw materials collected from a single location or multiple locations that are similar in chemical composition (Stoltman 2001; Stoltman and Mainfort 2002). Both methods are dependent on geological variation and geographic scope, and the examination of known local resources is particularly helpful.

The second issue of scale is geographic range from which the samples are derived. For projects with a small geographic area, the available raw materials are more limited. At this scale, both elemental and petrographic groups may accurately identify single raw material sources. A larger scale will likely result in more geological variability and the necessity of petrography to separate areas of production on the landscape. Especially within a single basin, subtle petrographic differences may be more easily identified than chemical variations if the statistical analyses have grouped samples within a single area together. Thus, at a larger scale, elemental data would likely indicate group production by region rather than site.

The third issue of scale is how the manufacture of ceramics took place, particularly the organization and scale of production. For example, if it was dispersed among many potters either in a single community or multiple communities or limited to a few potters in a restricted area (Arnold et al. 1991, 2000; Costin 2005). Presumably, a multitude of non-uniform paste recipes would make it difficult to identify discrete and meaningful compositional groups, even at the level of a valley or basin. Such issues may be less of a problem if pottery is examined from widely separated sites at the regional level, particularly if geological heterogeneity is high and the region has mineralogically distinct raw materials. Thus, for regional studies, both methods can be more definitive if production is specialized and raw materials vary – either due to geological or behavioral factors. On the other hand, if many potters are operating over a similar geological area, i.e., dispersed production, the statistical analysis of elemental data may be able to better separate paste recipes of individual potters or potters within a community of practice than petrographic data due to subtle patterned differences in paste recipes?. The degree to which this scale issue and that of high sample size and large geographic range affects the interpretations of combined petrographic and NAA data is explored through a case study.

Investigated Research Question

In order to examine how sample size, geographic scope, and the organization of production (i.e., centralized vs dispersed) affects the reconstruction of ceramic production groups, we present the results of a study of 1,215 ceramic specimens subjected to NAA. These come from 69 sites dated AD 1200 to 1450 in southern Arizona and southwestern New Mexico of the southwestern portion of the United States. The area covered is around 50,000 square kilometers. The data comprise samples from four principal wares/series, distinguished by paste and inclusions (in this case, primarily sand temper) plus surface features, including specific decorative designs. They are Maverick Mountain Series, Roosevelt Red Ware, Babocomari Painted Ware (mostly Babocomari Polychrome), and Tucson Basin Brown Ware (mostly Tanque Verde Red-on-brown).

These types all overlap temporally during the AD 1300s although Maverick Mountain Series declines sharply in frequency during the early part of that century. Samples of utility ware and undecorated brown and red paste vessels were included as potential markers of local ceramic production. Belford Plain perforated plates, grouped with utility ware, were also examined as they are believed to be associated with the production of Maverick Mountain Series and Roosevelt Red Ware (Lyons 2003; Lyons and Lindsay 2006). Ceramic samples from six valleys and basins were analyzed by NAA and petrography for this study: Safford Basin, San Bernardino Valley, Sulphur Springs Valley, middle San Pedro Valley, Tucson Basin, Lower Salt River Valley, and the Coyote Mountains (Figure 1). Data from a previous study to the east along the Upper Gila River, in the Mule Creek area, and Mimbres Valley in southwestern New Mexico were also included (see Huntley et al. 2016; area not shown in Figure 1).

(Figure 1)

The goal of that study, which lead to a more specific investigation of divergences in interpretations between quantitative "big data" and qualitative thick data, was to examine the southern edge of a social movement linked to Kayenta migrant groups from northeastern Arizona moving southward (Borck 2016; Borck and Clark 2021, in press; VanPool et al. 2007)[5]. The impacts of these migrants and their use of ideology expressed on ceramics to both link them in diaspora and integrate them with local Hohokam and Mogollon communities is particularly important in this region. It appears an inclusive set of beliefs fostered cultural and political hybridity (Borck 2016; Borck and Clark in press, in press; Clark et al. 2013; Crown 1994; Lyons and Clark 2012; VanPool et al. 2007). This phenomenon has been documented by the unique material cultural features of the northern groups when present at southern sites, but also through the production and consumption of specific ceramics. Initially, Maverick Mountain Series pottery was mostly made at dispersed migrant communities with decorative styles reminiscent of wares made in the Kayenta homeland (Tsegi Orange Ware). This reflects the persistence of Kayenta identity in enclaves within resettlement areas (Clark et al. 2013). However, by the mid-14th century AD, a new polychrome tradition (Roosevelt Red Ware or Salado polychrome) dominated painted ceramic assemblages at both immigrant and local communities across much of this broad region despite high variability in mortuary practices, architecture, and other artifact classes. The earliest evidence for Roosevelt Red Ware production is associated with Kayenta enclaves, although this ware was rapidly adopted by nearby local groups (Lyons 2012; Lyons and Clark 2012; Neuzil and Woodson 2014). This suggests an integrative function for Roosevelt Red Ware associated with an inclusive ideology that emerged from intense migrant-local interaction (Borck 2016; Borck and Clark in press, in press; Clark et al. 2013; Crown 1994; Huntley et al. 2016; Lyons 2012).

At some local Hohokam sites, including those associated with Roosevelt Red Ware, indigenous painted wares continued to be produced and exchanged, possibly as a form of opposition to the migrant social movement (Borck 2016; Borck and Mills 2017; Borck and Clark 2021, in press). For example, Tanque Verde Red-on-brown was produced by local Hohokam groups primarily in the Tucson Basin, but also to a limited extent throughout southern Arizona (Wallace 1988). In addition, Babocomari Polychrome is a local type produced in settlements in the middle San Pedro Valley from AD 1150-1450 (Heckman et al. 2000). To further clarify the

[5] These groups likely came from a wide area with diverse cultural identities, practices, and languages. There is no assumption they were a homogenous collective, only that they may have needed a way to come together to support their diaspora and were notably distinct from the peoples living in southern Arizona and southwestern New Mexico.

spread of a migrant-initiated social movement and the possible resistance from local groups, our study investigated the differences between production and distribution of Maverick Mountain Series and Roosevelt Red Ware, examined the local manufacture and limited exchange of Babocomari Polychrome, and further documented the production and dispersion of Tanque Verde Red-on-brown, especially outside the Tucson Basin. A broad geographic scale with a high number of samples was necessary to address those research goals. For the purposes of this article, this large set of data highlights the issues of sample size, geographic extent, and level of specialization in ceramic manufacture when geochemical "big data" and petrographic thick data are combined.

NAA and Petrographic Analysis

The results of the ceramic analysis study described above illustrate how the geochemical "big data" and petrographic thick data were acquired, analyzed, and interpreted, and how this revealed divergences that are investigated in the discussion section. The approach for that study was to select a subsample of sherds from compositional groups identified through the statistical analyses of the elemental data for petrographic examination. The thin-section analysis aimed to clarify if each compositional group represented a set of similar raw materials from a limited area or if the groups contained multiple paste compositions reflecting the combination of a number of production sources. To inform on potential locations of pottery manufacture, sand samples near each site were collected and petrographically analyzed. As all of the examined pottery was sand tempered this was the most effective way to establish ceramic production and distribution patterns. The petrographic data were related back to the elemental compositional groups to provide a more robust and expanded picture of consumption patterns.

NAA Data Analysis

Statistical analysis was conducted on 1,215 specimens from 69 sites in southern Arizona and southwestern New Mexico (Table 1). These data are a combination of those in the study by Huntley et al. (2014, 2016) and the Edge of Salado project (Borck et al. in prep; Borck and Clark 2021, in press). The increased scale of sampling, geography, and ceramic ware/type diversity of this dataset necessitated a slightly different approach to compositional group identification and validation than has been previously used in NAA studies conducted through the Archaeometry

Laboratory at the University of Missouri Research Reactor Center (MURR) (see Duff 2002). The majority of the data formed a large and diffuse cluster that required multiple rounds of group separation using various elemental concentrations, with new groups exhibiting less robust statistical separation with each iteration.

(Table 1)

Compositional groups were initially identified through visual inspection of numerous elemental scatterplots (Table 2). Groups 1, 2, 3, 4, 5, 7, and 8 were generally small (only Group 4 had more than 30 specimens) and were visually distinct from the main cluster of data (Figure 2). The groups were separated and evaluated for internal compositional consistency and separation from other data. After the identification of the first seven groups by visual inspection, the remaining data were separated into five large clusters (Groups 10, 20, 30, 40, and 50) using a combination of elemental plots and hierarchical cluster analyses. While some specimens remained unassigned, the goal was to further subdivide these large groups. Groups 10 and 20 were slightly refined but no further subdivision was possible (Figure 3). Group 30 was determined to be too variable to represent a viable compositional group and all members were reclassified as unassigned. Group 40 was divided into five subgroups (Groups 41, 42, 43, 44, 45, and 46) and the remaining specimens were reclassified as unassigned (Figure 4). Only one group (Group 51) was identified from the initial Group 50 and the rest were returned to the unassigned category.

(Table 2) (Figures 2, 3, and 4)

After the removal of a few outliers, all of the unclassified samples were recombined and reexamined. Most specimens in a new Group 60 were subdivided into six further groups (61, 62, 63, 63b, 64, and 65) based on visual separation in scatterplots with the remainder moved back to unassigned. The large remaining cluster of unassigned samples was divided into two main groups (70 and 80) primarily based on calcium concentrations (Figure 5). A sizable portion of Group 80 was separated into Group 81, leaving three large groups. Numerous rounds of group refinement, primarily using group membership probabilities based on Mahalanobis distance, resulted in three stable groups and many specimens removed and returned to unclassified status. Substantial overlap exists between Groups 70, 80, and 81 and some specimens were assigned to intermediate groups if they had high probabilities of membership in more than one.

After removing the 70, 80, and 81 groups, along with their intermediate groups, there was still a large dataset remaining unassigned. Group 90 was identified and appears to represent a group composed primarily of Tanque Verde Red-on-brown samples (Figure 6). Groups 91, 92, and 93 were established, but the separation and validity of these groups was problematic. The lack of apparent spatial pattern of the sherd samples of each of these three groups (all including a variety of wares) casts further doubt on group validity. These last three groups include a wide variety of sherds from forty-two sites that cover the entire project area and a few locations in central Arizona. This suggests statistical issues more than true patterns of ceramic exchange. In one final attempt to generate compositional groups, the remaining specimens were split into two clusters (Unassigned 2 and Unassigned 3) based on a cluster diagram with a very broad spatial patterning and many wares included.

(Figures 5 and 6)

The repeated attempts to divide the remaining dataset, after the removal of better-defined groups, resulted in a large number of compositional groups with highly variable statistical validity. In general, the lower the group number, the higher the confidence in the group. Ultimately, this statistical approach identified 27 groups, some outlier samples, and two unassigned groups.

Petrographic Analysis

Sample selection was based on NAA group membership with most groups being sampled. Further considerations were ware assignments within and among NAA groups, spatial patterning (i.e., site location) within and among NAA groups, known geological diversity in the project area, and available existing petrographic data. The 67 petrographic samples were selected from 16 NAA groups along with some outliers. Sherds were typically not selected from NAA groups with less than five samples such as 5, 45, 61, 64, 91, 93, 98, and 99, or from the two unassigned groups. Variability in geological deposits in southern Arizona is significant and incorporates almost a dozen different mountain ranges with differing outcrops. A number of sites were clustered around the Chiricahua Mountains in southeastern Arizona that are largely rhyolite, and the Coyote Mountains in southwestern Arizona that are predominantly granitic (Beikman et al. 1995; Drewes 1996). To identify possible locales of raw material procurement, especially sand temper, 30 sand samples were collected near most of the sites of interest, except those in the Tucson and Phoenix Basins where sand compositions are well-defined (cf. Miksa 2011; Miksa et al. 2004).

Petrographic analysis was qualitative, providing full descriptions of the mineral and rock fragments, their relative amounts, and technological features observed in thin sections[6]. Other recorded characteristics included the color of the sections in both plane and cross polarized light and an indication of the optical activity of the matrix, i.e., fired clay and inclusions. This information is important for a general estimate of firing temperature, as typically above 850°C the matrix will become vitrified and be optically inactive (Rice 1987:431). Along with temper type, the percentage of inclusions, their sorting (based on Matthew et al. 1991), size range (Wentworth 1922 scale), and shape range was noted for the inclusions (Powers' 1953 scale of roundness). This information characterizes the sands used to make the pottery such as extent of transport along with describing some paste features. The sherd thin sections were compared to each other and to the collected and available sand sample thin sections. All samples were determined to contain sand temper reflecting the intentional addition of sand to the clay body, making such comparisons helpful for provenance determinations. While the petrographic results are related to the NAA groups to assess their consistency and clarify the ceramic trends they represent, this thick data also provides independent information on clay choices, recipes, and firing practices.

Results

The statistical analysis of the NAA elemental data revealed that some groups have distinct signatures, presumably because potters were consistent in the raw materials they selected

[6] Petrographic research in Arizona has employed quantitative point-counting in areas where sand sources are well-characterized through discriminant models of sand compositions (also based on petrographic point-counting). However, the region of the current study only contained a few of these areas, so the methodology was focused on a qualitative study.

and the recipes they used to produce pottery. Other groups are more heterogenous and statistically dispersed likely because members were made from diverse raw materials or with more variable paste recipes. This resulted in a larger statistical dispersion of sherds and thus a reduced separation between them and other groups. This pattern was initially suggested to be the result of different organizations of production for decorated and undecorated wares, as previous research had indicated undecorated wares were likely locally made and used, while decorated wares were more widely dispersed (Huntley et al. 2014; although see Abbott 2000). Such an assumption was supported by the petrographic data when related to the compositional groups and sampled raw materials. The thin section analysis also suggested the acquisition of pottery from non-local sources. Local production is defined as within 7 km of a site based on ethnographic information for the distance potters travel for clay and sand temper (Arnold 1985:Table 2.1 and 2.2). Thus, our results are presented by the interpretated mode for pottery manufacture: centralized or decentralized, and distribution: limited, mixed, or highly dispersed (Figure 7; see Arnold et al. 1991, 2000; Costin 2005) [7]. In some cases, a mixed centralized/decentralized production model is suggested for a single ware based on the data. We term this heterarchical based on the centralized/decentralized neurological structures that McCulloch (1945) had originally used the term to define. As always, it should be emphasized that analysis of additional samples could change the interpretations offered here. Full petrographic details can be found in Ownby (2017b).

(Figure 7)

Centralized Production and Limited Dispersal (Babocomari Polychrome)

The 12 Babocomari Polychrome sherds analyzed were mostly in Group 3, including 3b (see Figure 2). Petrographic analysis of a utility ware and three Babocomari Polychrome sherds indicated all contained decomposed granite with microcline and muscovite. Such granite was identified in sand samples from the Huachuca (Cc) Petrofacies[8], at the northern end of the Huachuca Mountains adjacent to Babocomari Village (Hayes and Raup 1968; Miksa et al. 2003).

[7] The term "centralized" is preferred to "specialized" as information on number of pots produced per potter is not known. Centralized indicates a more limited regional spread of manufacturing.
[8] Petrofacies are sand composition zones defined by statistical analysis of point-count data from sand thin sections. They also represent specific resource acquisition zones.

Further, the similarity of the Babocomari Polychrome and utility ware sherds from Babocomari Village also suggest this site was probably the sole manufacturer of this ware, i.e., centralized production (see Miksa and Lavayen 2005 for an earlier petrographic study). The Babocomari Polychrome sherd from Garden Canyon (just south of Babocomari Village, but within a different geological environment), and the one from the Reagan site in the Sulphur Springs Valley were identical and indicated limited dispersal of this ware (Table 3; Figure 8) [9].

(Table 3) (Figure 8)

Centralized Production and Moderate Dispersal (Maverick Mountain Series)

Most of the Maverick Mountain Series vessels were found in nine NAA groups. Group 10 appears to represent production in the Point of Pines area in central Arizona (see Figure 3)[10]. This site became an important Kayenta migrant resettlement area as populations moved south (Lindsay 1987; Zedeño 2002). All of the Maverick Mountain Series samples in Group 20, along with the Roosevelt Red Ware in this group, that were examined petrographically featured a remarkably consistent paste of a fine clay with fine-sized volcanic rock fragments along with diverse loose mineral grains (see Figure 3). Such a composition seems to reflect sand from along the Upper Gila River that cuts Oligocene Gila Group sediments in this area (Elston 1965). This river course is long, and the sediments were probably similar in some areas for great distances. As such, though elementally and petrographically the sherds all appear similar, it cannot be proved that only one production area was in operation. Maverick Mountain Series vessels in Group 20 were found at the sites of Ringo, Reagan, Boss Ranch, Noonan Canyon, and Potters Site (Table 3; Figure 9). The six sherds of this ware at Buena Vista may reflect use of local resources.

A few other elemental groups contained Maverick Mountain Series sherds. The thin section analysis of a Maverick Mountain Black-on-red/Polychrome in Group 80 from Spear Ranch in the Safford Basin showed sand temper of broken-down alkali granite with some

[9] Limited in terms of the samples in this study and the investigated sites. The same applies to the other groups where exchange seems restricted. Data from additional sites could change that picture, but as far as the database examined the distribution is limited.

[10] All 52 specimens in Group 10 are Maverick Mountain Series and Roosevelt Red Ware from the Point of Pines area, but detailed discussion is omitted from this paper as no petrographic data were acquired from these samples as the area is located outside southern Arizona, the principal research focus.

gneissic textures (see Figure 5). Spear Ranch is on a wash that drains Early and Middle Proterozoic granitic and gneissic rocks in the Graham Mountains (Drewes et al. 1985). Farther upstream this wash includes the Goat Hill site, a well-established Kayenta enclave (Neuzil and Woodson 2014; Woodson 1999). The granitic composition is compatible with a sand sample from Petrofacies A in the Safford Basin where Spear Ranch is located[11]. In addition, the sand composition is nearly identical to a Belford Plain perforated plate and a Cliff Polychrome (Roosevelt Red Ware) from the site, and a Belford Plain perforated plate from the adjacent site of Krider Kiva previously analyzed (Ownby et al. 2014). Altogether it indicates local production of Maverick Mountain Series and Roosevelt Red Ware.

Production in the Lower (northern) San Pedro Valley is suggested by the analysis of a Tucson Black-on-red or Polychrome from Tres Alamos in Group 65 with volcanic, granitic, and rare sedimentary rock fragments. A source in the Lower San Pedro Valley seems likely, although a good match to sand samples in this area could not be made (Miksa et al. 2003). The sand composition for a Tucson Black-on-red or Polychrome from Babocomari Village (Upper San Pedro Valley), in Group 70, indicated it was not made at the site. It may have been made in the Tombstone (ZA) Petrofacies, 20 kms to the northeast on the other side of the San Pedro River from Babocomari Village (Miksa et al. 2003). Interestingly, the sand of rhyolite, granite, and metamorphic inclusions does not match sand near two well-known Kayenta migrant enclaves: Reeve Ruin in the Little Rincon (OA) Petrofacies and Davis Ranch in the Galiuro (MA) Petrofacies (Clark and Lyons 2012; Di Peso 1958; Gerald 2019). The sample may indicate the presence of an unknown migrant site but is the only known example thus far.

The pattern suggested in the NAA and petrographic data for Maverick Mountain Series is one of centralized production within each valley. The Safford area was served by manufacture at Spear Ranch/Krider Kiva, while a source or sources along the Upper Gila supplied that area and sites in the Sulphur Springs Valley. At least two production areas in the San Pedro Valley, likely one in the south and one in the north, made this ware for consumption in this area. The dispersal pattern indicates a more limited distribution mostly within each valley. As mentioned above, Maverick Mountain Series has been linked with Kayenta migrants based on ceramic design styles and production techniques (Clark and Lyons 2012; Huntley et al. 2010, 2016; Neuzil and

[11] Unpublished work by E. Miksa.

Woodson 2014). These results appear to indicate its movement may have been controlled and served to connect disparate migrant populations within valley areas.

(Figure 9)

Heterarchical Production and Mixed Dispersal (Roosevelt Red Ware)

NAA Group 20, with a high sample number (n=250), contained many Roosevelt Red Ware (80% of the group) samples that, based on petrographic analysis, were likely made along the Upper Gila River (see Figure 3). Multiple production sites could all have utilized similar raw materials from this long river. Sherds in this group were found at sites along the Upper Gila River and in other areas suggesting a complicated exchange network.

A Ninemile Polychrome (a late Roosevelt Red Ware type produced after AD 1375) in Group 7 from the Darnell site (San Bernardino Valley) suggests manufacture in the Chiricahua Mountains (Table 3; Figure 10). The sand temper had common rhyolite inclusions similar to those in a sand sample from near the site and such rocks are present in Tertiary deposits on the east side of the Chiricahua Mountains (du Bray et al. 1997). A Tonto Polychrome in this group found at Mud Springs 2 had a similar sand composition, which was dissimilar to local raw materials. This vessel likely reflects the acquisition at Mud Springs 2 of Roosevelt Red Ware produced in the Chiricahua Mountains, possibly near Darnell. A second production location in this area is attested by a Gila Polychrome from the Bernardino site in Group 81 with sand temper of rhyolite along with granite minerals (see Figure 5). Based on the sand sample near the site and local utility ware, the Gila Polychrome was probably not made at Bernardino, and was not identical to the Darnell vessel, but may have come from another site on the eastern side of the Chiricahua Mountains in the San Bernardino Valley.

Roosevelt Red Ware production in the Sulphur Springs Valley was not confirmed petrographically, although the elemental data suggests that it took place at several sites in the valley. Most of the analyzed vessels from sites in this area appear to have been supplied by production in the Chiricahua Mountains and the Upper Gila River.

Roosevelt Red Ware vessel manufacture in the Lower San Pedro Valley was previously documented with Kayenta enclaves as the major production centers and the current study confirms this pattern (Lyons 2012). NAA Group 46 had a Tonto Polychrome from Babocomari

Village with some broken down granite, some gneiss, and very rare volcanic rock fragments. However, this composition does not exactly match the sand composition and brown ware from Babocomari Village (see Figure 4). The vessel could be from the Little Rincon (OA) Petrofacies in the Lower San Pedro Valley that includes Reeve Ruin (Miksa et al. 2003). Also in this group is a Cliff Polychrome from Rillito Fan (Tucson Basin) with a similar sand temper that may indicate it was made in the Little Rincon Petrofacies as well. Production in the Little Rincon Petrofacies may have taken place at the Reeve Ruin migrant enclave, the only major settlement in this zone, as previously suggested (Lyons 2012). Surprisingly, a Gila Polychrome from Noonan Canyon (Sulphur Springs Valley) appeared petrographically similar to those produced in the Little Rincon Petrofacies though placed in NAA Group 70 with vessels from the Sulphur Springs Valley (see Figure 5).

A second location in the Lower San Pedro Valley making Roosevelt Red Ware for distribution was the migrant enclave at Davis Ranch in the Galiuro (MA) Petrofacies (Lyons 2012). Although other possible migrant enclaves are in this petrofacies, Roosevelt Red ware production at Davis Ranch is strongly indicated by large quantities of perforated plates likely used in ceramic production, several with hematite-stained fingerprints, and misfired Roosevelt Red Ware vessels (Gerald 2019). A Gila Polychrome in Group 80 from Ringo (Sulphur Springs Valley) had inclusions mostly of rhyolite and granite minerals (see Figure 5). This is not compatible with the local geology but is similar to sand in the Galiuro Petrofacies. Similarly, two Gila or Cliff Polychrome vessels, both in NAA Group 92, had an analogous sand temper suggesting production in that petrofacies though the vessels were from Tres Alamos and Boquillas Ruin, farther south in the San Pedro Valley (see Figure 6).

Other sites were also probably making Roosevelt Red Ware, but the evidence is less definitive. A Gila Polychrome in Group 65 from Tres Alamos contained a mix of volcanic rock fragments with broken down granite. The vessel may have been made near the Little Dragoon Mountains, to the east of Tres Alamos, which are dominated by such a variety of rocks (Cooper and Silver 1958). A Gila or Cliff Polychrome in the same elemental group but from Babocomari Village had a related sand temper suggesting a source in the San Pedro Valley (either Upper or Lower) but not local to the site.

One of the goals of this research was to determine whether or not production of Roosevelt Red Ware occurred in the Tucson and Phoenix Basins. For the former, a Cliff

Polychrome in Group 41 from AZ AA:12:46 (ASM)[12] contained common rhyolite with loose quartz and feldspars that is similar to sand in the Twin Hills (J2) Petrofacies on the east side of the Tucson Mountains where the site is located (Lipman 1993; Miksa 2011). A Roosevelt Red Ware bowl also in Group 41 from the Shamrock/Dairy site had rhyolite and rare intermediate and mafic volcanic rock fragments (see Figure 4). This unusual composition may come from the Avra Valley, on the west side of the Tucson Mountains, possibly the Recortado (T) Petrofacies (Miksa 2011). A sand with analogous inclusions was noted in a Pinto Polychrome from AZ DD:3:114 (ASM) (Coyote Mountains) in Group 92 (see Figure 6). This likely confirms Roosevelt Red Ware production in the northern Avra Valley to the west of the Tucson Basin[13].

A number of Roosevelt Red Ware and Belford Plain perforated plates, all in Group 70, were analyzed from Los Muertos in the Phoenix Basin (see Figure 5). The petrographic analysis revealed that the plates, a Gila Polychrome, and the Los Muertos Polychrome contained sand of granite minerals, rhyolite, and rare other volcanic rock fragments. This mixed composition compares well with sand samples from the Superstition (L) Petrofacies where the site is located (Miksa et al. 2004). However, two other sherds, a Gila or Tonto Polychrome and a Cliff Polychrome, from Los Muertos had a different sand with quartz, feldspars, and volcanic and metamorphic rock fragments. Based on sand sample comparisons, the temper likely came from the Lower Salt River in the Phoenix Basin. In fact, previous unpublished work on Roosevelt Red Ware in the Phoenix area, from the sites of Las Colinas, Pueblo Salado, Las Acequias, and Pueblo Grande, identified several Roosevelt Red Ware vessels produced from Lower Salt River sand in the Phoenix Basin[14]. Pueblo Grande and Pueblo Salado are located adjacent to the Salt River so could be potential production sites.

These results, in combination, suggest a pattern of Roosevelt Red Ware production with several producers in each valley and distribution within that area and adjacent regions. For example, two production areas were documented in the San Bernardino Valley (eastern Chiricahua Mountains) that mostly supplied this area and the Sulphur Springs Valley (western Chiricahua Mountains). Likewise, at least three production areas in the San Pedro Valley were identified supplying this area, with vessels also reaching the Sulphur Springs Valley and possibly

[12] Some sites are unnamed so the Arizona State Museum site number is employed.
[13] Other petrographic studies have supported Roosevelt Red Ware production in the Tucson Basin (see Ownby et al. 2016, 2011). No NAA data were acquired on those samples.
[14] Data are available upon request from Archaeology Southwest.

the Tucson Basin to a limited extent. A slightly broader distribution pattern was noted for vessels made with Upper Gila raw materials with such pots found in the Safford area, San Bernardino Valley, Sulphur Springs Valley, and a few vessels in the San Pedro Valley. This extended distribution might be linked to the widespread trade of Mule Creek obsidian from the region (Mills et al. 2013). Notably, up to four producers of Roosevelt Red ware were recognized in the Tucson Basin (in petrofacies J2, J3, E1, and E3), with another one in the northern Avra Valley, mostly supplying the Tucson Basin and Avra Valley. This area has extensive research so identifying more producers is possible. The same applies to the Phoenix Basin where at least two and likely four separate areas (petrofacies L, V, F4, and Salt River) were making Roosevelt Red Ware that was consumed within the Phoenix area and possibly the Tucson Basin. Similar intensive research of sites in the other valleys could reveal additional production areas. Nevertheless, the overall impression is more producers for Roosevelt Red ware than for Maverick Mountain Series vessels and with a wider distribution. This probably relates to the expansion of Roosevelt Red ware manufacture outside of Kayenta migrant communities, with local potters making vessels so that their populations could participate in the new social movement (Borck 2016; Borck and Clark 2021, in press; see also Crown 1994; Huntley et al. 2016; Lyons 2012).

(Figure 10)

Decentralized Production and Moderate Dispersal (Tanque Verde Red-on-brown)

Tanque Verde Red-on-brown vessels are most commonly found in the Tucson Basin. Previous petrographic analyses indicated such vessels were produced at Yuma Wash, AZ AA:12:46 (ASM), and at least one site at the northern end of the Tucson Mountains (Ownby 2017a). Petrographic analysis of several samples from Group 44 with a distinctive hypabyssal volcanic rock confirmed production in the Black Mountain (K) Petrofacies in southwestern Tucson (see Figure 4; Miksa 2011). Group 44 has only Tanque Verde Red-on-brown sherds mostly from Zanardelli, a site located on the edge of the Black Mountain Petrofacies and possibly the source of these pots. Petrographic analysis of a Tanque Verde Red-on-brown from the Shamrock/Dairy site in Group 8 revealed a paste with granite, gneiss, and notable garnet. The composition is similar to sands in the Rincon (A) Petrofacies in the southern section of the

Tucson Basin, although the site is located in the Eastern Tortolita (E3) Petrofacies to the north (Miksa 2011). Both NAA groups are small, Group 44 with 15 sherds and Group 8 with 7 sherds (see Table 2).

Production of this ware in the Avra Valley, west of the Tucson Basin, is now also further supported (Table 3; Figure 11). A Tanque Verde Red-on-brown from AZ DD:3:98 (ASM) (Coyote Mountains) in Group 41 had altered rhyolite with some sedimentary rock fragments similar to that in the Golden Gate (L) Petrofacies in the Avra Valley (see Figure 4; Miksa 2011). The group has 54 samples of Roosevelt Red Ware and Tanque Verde Red-on-brown. A Tanque Verde Red-on-brown in Group 90 from Rillito Fan (Tucson Basin) with granite and rare metamorphic and sedimentary rock fragments is not local to the Jaynes (H) Petrofacies where the site is located (see Figure 6; Miksa 2011). Such a sand is more likely from the Avra Valley, and possibly the Cocoraque (U) Petrofacies (Miksa 2011). Interestingly, these sand compositions are not similar to that utilized for a Roosevelt Red Ware sample from the Shamrock/Dairy site in the Tucson Basin or one from AZ DD:3:114 (ASM) in the Coyote Mountains suggesting different communities of practice for production of these two wares.

Also from Group 90, which includes 24 mostly Tanque Verde Red-on brown sherds, were analyzed three Tanque Verde Red-on-brown samples from sites in the Coyote Mountains, AZ DD:2:42 (ASM), AZ DD:3:97 (ASM), and AZ DD:3:98 (ASM). All contained minerals disassociated from granite and diorite along with highly altered rhyolite. This is not compatible with raw materials available at those sites based on comparison to sand samples. Rather, such a sand was probably available south of the sites on the east side of the Baboquivari Mountains where outcrops of Jurassic Kitt Peak granodiorite and volcanic rocks are found (Beikman et al. 1995). Comparison to sand samples in this area also suggests production likely occurred here (Ownby 2015a). A Tanque Verde Red-on-brown from AZ DD:3:114 (ASM) in Group 92 had the same sand temper and was probably made in this area, although this group has 48 sherds from a number of wares and sites. Along with previous petrographic work in the Coyote and Baboquivari mountains, these results document the production of Tanque Verde Red-on-brown in this area (Ownby 2015b). While three Roosevelt Red Ware sherds from the Coyote Mountains sites were included in the NAA study, and one was examined petrographically, no documented production of that ware occurred in this area.

Of principal interest to this study was the possibly rare manufacture of Tanque Verde Red-on-brown in southeastern Arizona. Group 43 has only five sherds, all Tanque Verde Red-on-brown, and all from the San Bernardino Valley. Analysis of a single probable Tanque Verde Red-on-brown vessel in this group from Boss Ranch revealed a sand temper of volcanic and sedimentary rock fragments (see Figure 4). This composition matches the local geology of the southeastern side of the Pedregosa Mountains with deposits dominated by Tertiary volcanics (Biggs et al. 1999; du Bray et al. 1997). The sand temper shares some affinities with the locally collected sand sample, possibly suggesting this sample was made at a nearby site. A second possible Tanque Verde Red-on-brown from Boss Ranch in Group 65, a heterogenous group with 27 samples, had a nearly identical sand temper further indicating potential production of this ware on the southeastern side of the Pedregosa Mountains. However, as these are the only two petrographically-confirmed examples of locally produced Tanque Verde Red-on-brown vessels this far east and the typing of the sherds was strong but not agreed upon by all, additional research is required to confirm such production and establish that these are not Tanque Verde-esque examples of local styles. The production of Tanque Verde Red-on-brown in the San Pedro Valley has previously been demonstrated, which provides a link between the San Bernardino Valley and the Tucson Basin (Lyons 2012). The NAA elemental data also indicate a few Tanque Verde Red-on-brown from the Tucson Basin exchanged to the site of Bernardino so Tanque Verde pottery was known in the region.

These results corroborate that the Hohokam pottery type Tanque Verde Red-on-brown was made at numerous sites in the Tucson Basin, Avra Valley, Coyote Mountains, and areas to the west. Mostly these vessels were exchanged within this region, i.e., to and from the Tucson Basin, Avra Valley, and Coyote Mountains, with some limited dispersal to areas further east. Outside this main production region, manufacture of Tanque Verde Red-on-brown was reduced and its distribution limited. However, additional study of Tanque Verde Red-on-brown vessels from southeastern Arizona is needed to provide a complete picture. This ware was a hallmark of Hohokam society and was a direct descendent from earlier red-on-brown types (Heidke 2011). In southeastern Arizona, a local tradition had developed that may have served the same purpose as Tanque Verde Red-on-brown in supporting a specific cultural identity (e.g., Heckman et al. 2001).

(Figure 11)

Decentralized Production and Limited Dispersal (Utility Ware)

Compositional analyses of the utility ware vessels confirmed their predominantly local production and use at the sampled sites (Table 3). The sand temper provided good geological links to the outcrops around the sites, as confirmed by the collected sand samples. The analysis of utility ware sherds with similar temper to decorated ceramics greatly assisted in documenting the local production of the latter. Many of the utility ware specimens were placed in groups with decorated ware confirming in a number of cases the production of both with similar paste recipes. One notable exception is Group 20 with no utility ware samples indicating specific production of Maverick Mountain Series and Roosevelt Red Ware with Upper Gila River sand and clay, while utility wares were produced with coarse secondary clays and sand near the sites (see Huntley et al. 2016). The current study also suggests that in some cases decorated ceramics were produced with different pastes, such as Salt River sand and clay, from utility ware. However, there are examples of the same paste employed for both, such as at Los Muertos, also in the Phoenix Basin. This could represent two phenomena. The early production of decorated wares by Kayenta migrants using fine alluvial sand and clay, and the later manufacture of decorated vessels by Hohokam potters using their traditional secondary clays and coarse sand. Examination of forming techniques could confirm this as it is likely migrant potters would continue to use the coil-and-scrape method known for northern pottery types, while Hohokam potters traditionally employed paddle-and-anvil technology.

Discussion

For the initial project investigating a migrant-initiated social movement, the combination of petrographic thick data with NAA "big data" has provided results that significantly impact our understanding of Maverick Mountain Series, Roosevelt Red Ware, Babocomari Polychrome, and Tanque Verde Red-on-brown production. This has broader implications for understanding human migration and community interaction during AD 1200 to 1450 in southern Arizona that are discussed in more detail in other publications (Borck 2016; Borck et al in prep; Borck and Clark 2021, in press; Clark et al. 2013; Clark et al. 2019 Lyons and Clark 2012). The statistical analysis of such a large and diverse database with 1,215 ceramic samples - including sherds from five ware groups found across southern Arizona and southwestern New Mexico - identified 27 elemental compositional groups. Some of these groups were small, consistent, and easily understood in terms of production and distribution. Others were statistically dispersed with samples from many wares and numerous sites hindering a clear understanding of manufacturing and consumption patterns. The petrographic analysis confirmed that for those groups, they did in fact represent many diverse paste recipes. Previous research has suggested this discord was attributed to differences in the organization of production for the wares examined (Huntley et al. 2014). Examining the results of the study described above, confirmed that this can be the case and clarified the impact on elemental and petrographic data of each mode of pottery manufacture, centralized or decentralized, and type of distribution, limited, moderate, or highly dispersed (see Arnold et al. 1991, 2000; Costin 2005). The results also indicated two other issues that could be affecting the divergence between the petrographic and NAA data interpretations, the geographic scope of the study and the high sample size. Framing the results in terms of the outcomes of "big data" analysis when in conjunction with qualitative thick data also highlighted these three issues.

Organization of Production

Centralized production with limited distribution is best characterized both elementally and petrographically. The Babocomari Polychrome samples grouped by themselves, and the sand temper characteristics were easily connected to a single source of raw materials located near Babocomari Village.

Centralized production with moderately dispersed vessels could be detected in the elemental data with several groups containing Maverick Mountain Series sherds. These groups also contained some Roosevelt Red Ware and utility ware samples indicating similar raw material sources could be used for all three wares. However, the petrographic data provided a clearer indication that production was more limited for the Maverick Mountain Series sherds with the vessels in the NAA groups representing moderate distribution. Especially for NAA Groups 65 and 70, the diverse array of sites located throughout the project area with sampled sherds did not indicate if they all derived from a specific source, several related sources, or raw materials from different areas with analogous geology. This was clarified petrographically.

A heterarchical mode of production and mixed distribution was identified for Roosevelt Red Ware vessels where several sites produced pottery for distribution within an area and adjacent regions, which modifies our understanding of the similar pattern noted by Crown (1994). This pattern was difficult to distinguish for some of the NAA groups, especially as many contained Roosevelt Red Ware vessels. For those groups, the petrographic data suggested a pot was made in a particular area, while the elemental group from which it came also included samples petrographically linked to other areas. This was particularly true for Groups 70, 81, and 92. Without the petrographic data, it would have likely appeared that all sites may have produced Roosevelt Red Ware with distribution across the project area. The petrographic results suggest more limited manufacture of this ware and a moderate dispersal pattern for consumption. However, in more heavily studied areas such as the Tucson and Phoenix Basins, additional producers were identified suggesting intensive research on this ware in a limited area might indicate decentralized production and moderate dispersal.

Tanque Verde Red-on-brown was produced at many sites, but its dispersal was more limited to within a valley or basin. As such, the NAA data appear to have isolated several production areas, such as the Black Mountain (K) Petrofacies in the Tucson Basin represented by NAA Group 44. The two petrographic samples from this group had identical sand compositions. NAA Group 41 contains vessels that were probably made in several locations of the Tucson Mountains, with vessels consumed by groups in the Tucson Basin and Coyote Mountains. Thus, for decentralized production with moderate dispersal, the NAA data appear to mostly identify individual or closely related paste recipes that can be linked to a production source or area through petrographic analysis.

The local production and consumption of utility wares was marginally clear in the NAA data. Many groups contained these vessels, and in some cases, it indicated the use of similar paste recipes for decorated and undecorated pots. This was clear petrographically and most of the sand compositions were linked to local resources. However, some large NAA groups could contain utility ware and decorated vessels that had varying raw materials, often of similar geological type but not from the same geological deposit. Thus, decentralized production and limited dispersal of sherds can be identified petrographically and elementally, but likely with better success when the research area is restricted so as to pick up the diverse range of pastes.

Geographic Range

Typically, an extended geographic range is helpful for increasing geological diversity that enables individual potting communities to be identified, both elementally and petrographically. However, in investigating the disconnect between some of the interpretations derived from the statistical analyses of the NAA data, and those posited from the petrographic viewpoint, the large research area resulted in unrelated paste recipes being combined. It appeared that at a certain scale, the geographic range then incorporates areas that have similar geology, such as the Tucson Mountains and the Chiricahua Mountains both dominated by rhyolite. For example, in our analysis one elementally defined group had sherds from Los Muertos in the Phoenix Basin but also some from the Safford Basin. Petrographically, they represent distinctly different paste recipes, but some elemental similarity grouped them possibly based on the high amounts of quartz and feldspar grains.

Some paste recipes based on unique raw materials were obvious chemically and petrographically. Such is likely the case for several, mostly small groups with unusual mineral inclusions. NAA Group 7 contained 27 mostly Roosevelt Red Ware and utility ware vessels made in the Chiricahua Mountains and distributed to nearby sites. The unique rhyolite with sanidine temper may have assisted in separating this group along with its limited distribution. An even smaller group of seven samples, Group 8 with one Tanque Verde Red-on-brown sherd analyzed petrographically, likely represents Tanque Verde Red-on-brown and Roosevelt Red Ware made in the Rincon (A) Petrofacies (eastern Tucson Basin) but exchanged to the sites of Shamrock and Rillito Fan in the western Tucson Basin. The garnet mineral signature and a restricted distribution may have led to this group being statistically separate from the others. Breaking out so few samples from a large database indicates they have a unique elemental signature. Thus, a large geographic range can be helpful for clarifying patterns of production and distribution from combined data but can also be a problem especially when many samples are examined over a broad area. Only those with highly unusual signatures maybe isolated into small, easily defined groups.

Sample Size

Examining 1,215 ceramic samples with elemental data statistically is a challenging task. Separating out meaningful groups especially over a broad geographic area where various modes of production and distribution occurred is understandably difficult. As with the other factors influencing the varying interpretations from elemental and petrographic analyses, sample size proved to have a nuanced affect[15]. In some cases, having many samples with a similar paste recipe was beneficial, like for NAA Group 20 that represents Maverick Mountain Series and Roosevelt Red Ware vessels made of Upper Gila River clay and sand. The strong elemental signature for this group was probably due to the 250 samples analyzed and was crucial for the statistical identification of this group. This suggests that having many samples is actually helpful in isolating distinct groups related to the use of specific paste recipes or reflecting a community of practice in a particular area.

However, when the number of sherds in each group is examined, it suggests otherwise. Groups with few samples were noted in the elemental biplots, and they appear to have unique elemental and petrographic signatures along with limited distribution. The difficulty in separating out such groups indicative of a narrow area of production may be due to individual potters producing a few of the analyzed pots while simultaneously there were many producers. The petrographic data supports this to some extent, but it remains challenging to determine those groups that include vessels from diverse manufacturers. Thus, within NAA data, sample size may not greatly impact whether the group is easy to identify. In fact, more analyzed sherds may be needed, but these should be from the same production area to create robust elemental reference groups.

This may seem counterintuitive when the recent theoretical push towards large-scale data collection in archaeology of this type often comprises dispersed, disparate, and often contextually ambiguous data points (e.g. Huggett 2015). While the methodological approach to this theoretical trend is often to examine connections based on stylistic similarities and consumption patterns (e.g. Borck et al. 2015; Mills et al 2013; Peeples and Haas 2013), when quantitative information on production location is collected, financial constraints generally enforce the selection of a few samples from (likely) many producers to examine widespread patterns of exchange. When this type of light sampling over large regions is used on its own,

[15] Of note, a petrographic group with one sample is acceptable, but for elemental data these would be left unassigned. They may also not be investigated through thin sections, when the priority is clarifying groups of chemically similar pottery.

such an approach may lead to difficulty in identifying clean elemental groups with samples having similar petrographic features.

Issues of Scale with Big and Thick Data

Our case study highlights that combining "big data" with thick data, which dive deep into smaller sections of information, allows us to counter some of the statistically spurious groupings that can arise from analyzing large databases (e.g., Bornakke and Due 2018; Wang 2013). Though one of many methods when using petrography and geochemical data together, subsampling from the NAA groups for the thin section samples did provide good results to assess not just the questions of the ceramic research, but also broader issues with this approach.

Especially in our case with utilizing existing and new NAA data, a pertinent question should be 'how many samples and in what geographic area should be analyzed together?' Since our research questions necessitated examining data on two wares from across a broad area to better understand how these types were distributed at the southern edge of their known extent, a large geographic scale was required. And it was only at this scale that the significant finding of trade of Upper Gila Roosevelt Red Ware south to settlements in southeastern Arizona was identified. The previous Upper Gila project area was not of sufficient geographic scope to make this important connection (Huntley et al. 2016).

Had our research been exclusively focused on the production and distribution of Babocomari Polychrome, a statistical approach of many samples in a restricted geographic area would have been appropriate. But at this geographic scale its wider limited consumption would have been missed. Likewise, if analysis *had* only focused on the central Upper San Pedro with sites only in this area, this analysis might have been able to identify additional paste recipes/communities of practice and provided a clearer picture of exchange within the valley.

Perhaps the most significant issue when compositional data produces some groups that are challenging to interpret is the research design. How were the interactions between sample size, the organization of ceramic production in the region, and geographic area incorporated or dealt with? This may seem unsurprising, but this complex interaction is not often considered during research design and their effect on NAA and petrographic results is often overlooked. Rather than being frustrated by the results, though, researchers should accept some "slop" if the research requires a large geographic scale, numerous samples over this area, and the likelihood of dispersed ceramic production. In our case, this "slop" indicated that multiple factors were influencing our data and those needed to be carefully investigated. In doing so it became apparent that the NAA groups along with petrography provided useful information on the geographic scale of ceramic manufacture and consumption for our different wares, which related directly to our research questions.

Research Question Results

The combined NAA and petrographic data results clarified the centralized production and limited distribution of Babocomari Polychrome. They also highlighted the centralized manufacture and moderate dispersal of Maverick Mountain Series with exchange to the San Bernardino, Sulphur Springs, and Upper San Pedro valleys. This probably reflects production only within Kayenta migrant communities and movement of vessels to connect these groups. The picture for Roosevelt Red Ware proved more complicated. Manufacture of such vessels was clearly more widespread than for Maverick Mountain Series, including pots made in the Phoenix Basin, and distribution extended to adjacent valleys. This likely represents the production of Roosevelt Red Ware by Hohokam communities or communities comprising the descendants of Hohokam locals and migrants as participation in a common social movement that spread across much of the southern Southwest.

Our investigation confirmed that Tanque Verde Red-on-brown vessels were produced at a number of sites in the Tucson Basin. The results indicated that this ware was also made in the Coyote Mountains and, surprisingly, in limited quantities in the southern San Bernardino Valley, areas that also participated in exchange networks for this Hohokam ware. Thus, local decorated wares continued to be produced and exchanged despite these communities also participating in the new social movement. This is interpreted as likely signifying that the ideological practices associated with this movement were less about reorienting worldviews and more the material remains of an inclusive ideological social movement that persisted in tandem with local traditions instead of replacing them (i.e. Borck 2016; Borck and Clark 2021; Borck and Clark in press)

Conclusions

For our research goals, the NAA data were essential for examining many samples, detecting some consistent elemental groupings, and assisting in selecting samples for petrography. Petrography not only indicated if vessels were likely locally made or exchanged, but also identified elemental groups that included samples with different paste recipes. However, petrography, like NAA, depends on geological diversity, and benefits from a knowledge of available raw materials and their variability. The combined results provide the best approach to such research questions as investigated here. By presenting in detail the analysis of a large set of NAA data, “big data”, in conjunction with thick data from petrographic examination, the goal was to highlight how the results of such research can be challenging to interpret. No one issue can be identified as the cause, although the three issues of sample size, organization of production, and geographic scale are certainly key factors. Many of the most successful applications of NAA and petrography have focused on tracking centralized pottery production at a few sites to consumer settlements. However, other research questions such as ours require a large dataset with samples from a sizable area and many different wares. While it is common to carefully consider examined datasets in terms of the samples chosen, additional factors should be the communities of practice investigated along with reasonable interpretive expectations. Perhaps the best way forward is acquiring additional data that can help to create increasingly robust data sets, which will ensure the combined elemental-petrographic approach lives up to the expectations archaeologist have come to hold for such methods.

While this research was mostly successful, the identified challenges are ones encountered by other researchers and will be present in future projects. One way past some of these challenges that we found particularly useful was to place NAA and petrographic analyses into the “big data”/thick data relationship proposed by Wang (2013). This created a perspective in which the NAA data supplied the wider mass of data for petrography and petrography supplied the bridge, or context, to geographic areas. Though this has been the case for many projects combing such datasets, making this approach explicit assists in interpretive challenges and highlighted the three scalar issues that impacted our interpretations. Ethical research should document problematic results instead of only presenting the “good cases” to create a healthier field. Elemental groups that are hard to assess or cases in which the statistical analysis fails to identify meaningful groups should also be presented. This is the case with the current research where meaningful information on migrant communities in diaspora was acquired, while areas for additional data collection have been recognized. We hope that our elucidation of the issues of scale, and their influence, will be helpful to future researchers who can consider them more deeply during both the research design and analysis stages. Doing so may in of itself provide valuable information on ceramic production and distribution.

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Figure Legends

Figure 1: Map of project area showing sites included in the current study

Figure 2: Biplot from NAA data showing Groups 3 and 3b

Figure 3: Biplot from NAA data showing Groups 10 and 20

Figure 4: Biplot from NAA data showing Groups 41, 41a, 41b, 41c, 42, 43, 44, 45, and 46

Figure 5: Biplot from NAA data showing Groups 70, 80, and 81

Figure 6: Biplot from NAA data showing Groups 90, 91, 92, 93, 98 and 99

Figure 7: Diagram of interpreted modes for pottery manufacture and distribution

Figure 8: Map of production and distribution of Babocomari Polychrome pottery

Figure 9: Map of production and distribution of Maverick Mountain Series pottery

Figure 10: Map of production and distribution of Roosevelt Red Ware pottery

Figure 11: Map of production and distribution of Tanque Verde Red-on-brown pottery