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# Investigating the production and distribution of plain ware pottery in the Samoan archipelago with laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS)

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ABSTRACT

This paper presents a provenance study of 170 ceramic artifacts and 21 ceramic tiles from three islands in the Samoan archipelago using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS). Our analyses confirm that LA-ICP-MS can be used to differentiate between clay formations on a single island. We identify different distribution patterns for pottery recovered from lowland and highland sites on Tutuila Island. We also examine evidence for movement of pottery between islands, and find only limited evidence for such movement. Our findings suggest dynamic patterns of prehistoric interaction and site use that need to be evaluated with further data from across the archipelago.

## 1. Introduction

Pottery production provenance has been of interest to archaeologists studying migration pathways, social and economic interaction, and political organization have all focused on pottery production provenance. Most ceramic provenance studies in the South Pacific have focused on petrographic analyses, which inform primarily on production at the archipelago level (Dickinson, 2006). However, recent work has begun to apply geochemical techniques to ceramic artifacts in an attempt to understand production provenance at the island, and the intra-archipelago, levels (Cochrane and Neff, 2006; Descantes et al., 2001).

The research presented here focuses on plain ware pottery recovered from sites within the Samoan archipelago. The research was designed to accomplish two goals. First, we demonstrate that laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) analyses can differentiate between ceramic materials produced from geologically similar volcanic series on the same island. Second, we examine compositional groups derived from LA-ICP-MS analyses of pottery recovered from sites located on three islands within the Samoan archipelago and relate these groups to intra- and inter-island production organization and distribution. We conclude that LA-ICP-MS can provide the type of data that we seek, however results must be considered using multiple statistical techniques and an understanding of the geological context. Further, more data are necessary from the Samoan archipelago to confirm and interpret the ceramic distribution patterns presented here.

## 2. Geological and cultural background

### 2.1. Geological setting

The Samoan archipelago (Fig. 1) is comprised of six large volcanic islands and numerous small coral islands. Volcanic islands in the archipelago have formed during the westward movement of the Pacific Plate over a hotspot of erupting magma (Nunn, 1998); as a result, islands in the west are geologically older than islands in the east. As the islands moved away from the hotspot, volcanic activity ceased (although see Hawkins and Natland, 1975 for a discussion of anomalous volcanic activity). Over time across the archipelago, volcanoes collapsed forming calderas, these calderas were partially filled through later plutonic activity and erosion, deep valleys and

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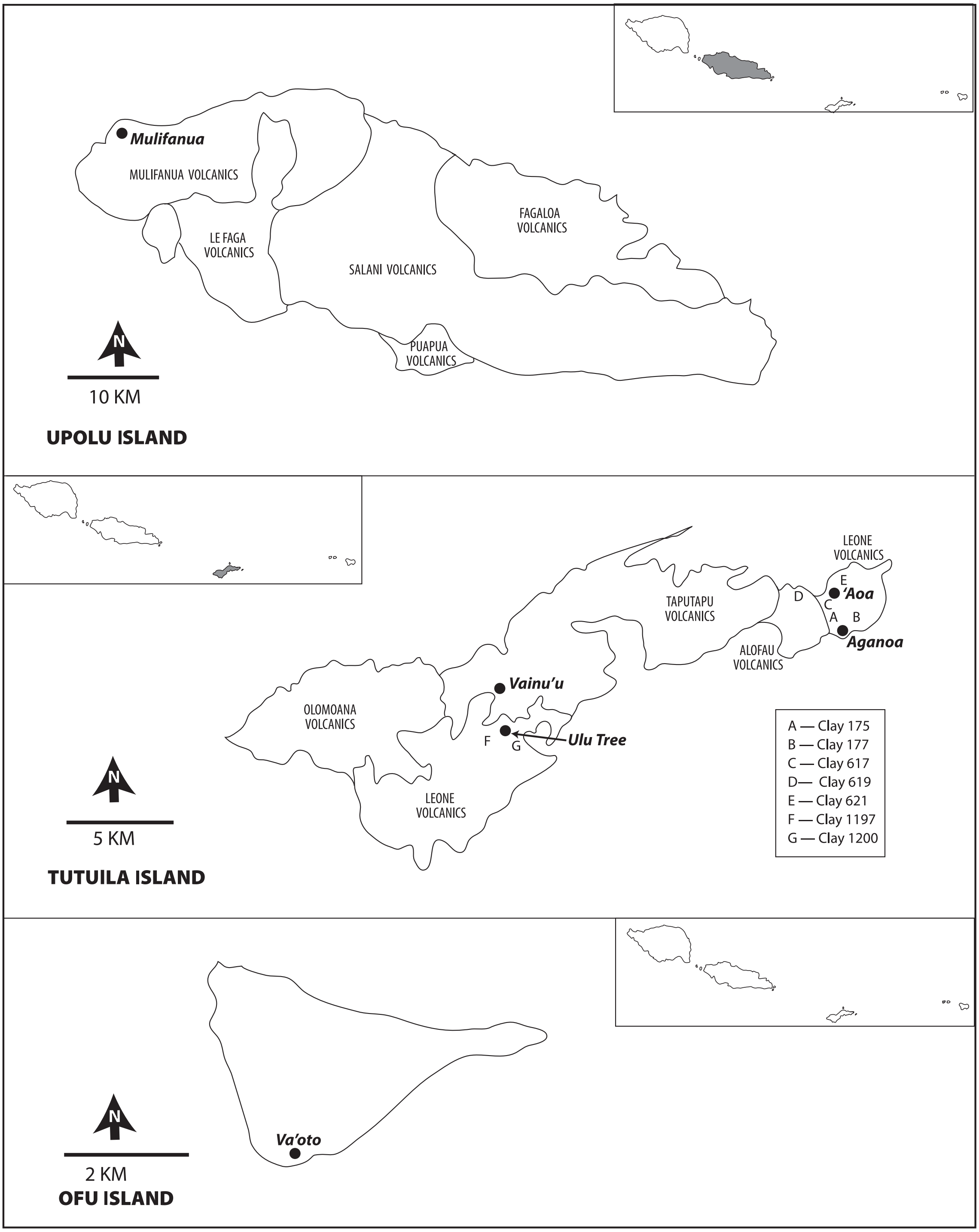

**Fig. 1.** Maps of each island examined in this study showing location of sites and clay collection locations in relation to volcanic series.

high sea cliffs were cut into the landscape, subsidence and coral reef formation changed the coastlines, and sea level rise ca. 20 000 BP filled some valleys and covered early barrier reefs (Stice, 1981).

Archaeological samples in this project come from three islands: Ofu and Tutuila in American Samoa, and Upolu in the independent State of Samoa. Ofu, the smallest island examined in this study, is the most western island of the Manu'u group. The Manu'u group consists of a cluster of three small volcanic islands located on the eastern edge of the archipelago. Ofu Island consists of one shield volcano that formed during the late Pliocene or early Pleistocene (McCoy, 1965) and is dominated by the Tuafanua volcanic series (Stice and McCoy, 1968).

The majority of archaeological samples, as well as clay samples, for this project come from sites on Tutuila Island. Four of the island's main volcanoes and numerous secondary eruptions experienced peak activity during the late Pliocene (McDougall, 1985; Stearns, 1944). This resulted in the formation of four of the island's five distinct volcanic series including Alofau, Olomoana, Pago, and Taputapu. A resurgence of volcanic activity added another 21 square kilometers of land to Tutuila Island known today as the Leone volcanic series (Stearns, 1944). Despite being formed in geologically close succession and from the same magma bed, the five volcanic series on Tutuila Island are mineralogically, chemically and morphologically diverse, partially due to the numerous dikes, plugs, and extra-caldera lavas that transect much of the island (Natland, 1980; Stearns, 1944; Walker and Eyre, 1995).

Upolu Island is also comprised of five volcanic series. The Fagaloa volcanic series formed in the late Pliocene (Kear and Wood, 1959; Natland and Turner, 1985); the Salani and the Mulifanua series both formed during the Last Interglacial (Kear and Wood, 1959); the Lefaga volcanic series formed during the early to middle Holocene; and the Puapua volcanic series formed between 1950 and 750 BP (Kear et al., 1981). This last volcanic series is of especial interest because it occurred after the Samoan archipelago had been settled by pottery-producing groups, and would have had implications for changing subsistence and settlement patterns on the island.

The Samoan archipelago's geologically active environment has serious implications for both site preservation and prehistoric social behavior (Rieth et al., 2008). While volcanic eruptions would affect any site within its blast range, different types of natural processes differentially affect preservation and visibility of coastal and highland sites. Coastal sites are affected by mountain slides, island subsidence, coral reef formation, and sea level changes (Dickinson, 2007; Dickinson and Green, 1998; Rieth et al., 2008). Many highland sites are situated in unstable areas that are subjected to cycles of heavy rainfall, erosion and deposition (Eckert and Welch, 2009). Once prehistoric settlements were abandoned, post-depositional physiogenic, biogenic and chemical agents worked to modify and alter the archaeological debris and the spatial relationships between the remains (Sidle et al., 2006). Although the current study examines only six sites as an initial attempt to trace the movement of pottery, the dynamic geological environment – both past and present – will need to be considered in future studies that attempt to reconstruct past social interactions.

Natural catastrophes brought on by severe weather or geological activity would have provided challenges to past residents of the islands. Human reaction to catastrophic events varies widely (Grattan and Torrence, 2007; Johnson, 2002; Kornbacher, 2002), and depend both on natural and social factors (Dodgshon et al., 2000; Sheets, 2007; Torrence and Doelman, 2007; Torrence et al., 2000). People may move their residence to a different area of the island, move to a different island in the archipelago, or leave the region entirely. If abandoned, the area affected by the event may never be reoccupied, quickly reoccupied, or only eventually reoccupied. Traditional subsistence practices may be reestablished, or changed entirely. Social networks, access to material resources, craft production, subsistence, political organization, and economic organization may remain the same or be substantially altered. With this in mind, it is not unlikely that production and circulation of ceramic vessels changed over the 1500+ years of their production in the Samoan archipelago as people responded to their natural and social environment.

Clearly, human responses to catastrophic events, as well as changes in landscape and site preservation, have implications for any study done in the Samoa archipelago. As with previous research on the islands, we believe that studying the prehistoric record can provide an understanding of the past, however we are cautious in the specifics of our interpretations. In this study, we are careful to select sites that date within 500 years of one another to help control for as few unique natural events effecting prehistoric residents as possible. We do not assume, or even imply, that pottery was moving between the specific sites within our study, but only between the different volcanic zones on which the sites are located. Finally, we recognize that there are clay sources and sites that may have disappeared (or appeared) since the pottery we are studying was produced.

### 2.2. *Plain ware pottery and its cultural setting*

Pottery was produced for approximately the first 1500 years of Samoan occupation, from circa 2800 to 1500+ BP (Addison et al., 2008; Addison and Asaua, 2006; Addison et al., 2006; Rieth and Hunt, 2008). The Mulifanua ferry berth site, located just off the northwest coast of Upolu Island, is the earliest site known in the archipelago (Jennings, 1974; Petchey, 2001). The most reliable radiocarbon dates for this site suggest an occupation of approximately 2800 years ago (Petchey, 2001). Decoration on sherds from Mulifanua includes dentate-stamping on and below the rim (Green, 1974); currently, this is the only known dentate-stamped pottery-bearing site in the archipelago. However, two other sites, To'aga (Kirch and Hunt, 1993) and 'Aoa (Clark et al., 1997; Clark and Michlovic, 1996), have provided radiocarbon dates between 3100 and 2700 BP but no dentate-stamped pottery.

The date for the cessation of pottery production throughout the Samoan archipelago is debated: while the conventional view has been that pottery ceased to be produced at 1700 BP (Davidson, 1979), Rieth and Hunt (2008) recently argued for an end date of 1500 BP, Kirch and Hunt (1993) suggest an end date of 1200 BP, and Clark et al. (1997); Clark and Michlovic (1996) have argued that pottery was produced as recently as 400 years ago. The American Samoa Historic Preservation Office (2009) has stated that the inability to adequately date the end of pottery production is a result of the fact that, at the time the chronology was being outlined and refined (Burley et al., 1995; Davidson, 1979; Green and Davidson, 1969, 1974; Kirch, 2000), pottery-bearing sites were all assumed to date to the earliest period of Samoan prehistory; charcoal was rarely collected from these sites to confirm this assumption. As pottery in well-dated contexts begins to be collected, an end date for this period will be more firmly established.

The vast majority of pottery produced on the Samoan Islands is undecorated; where decoration does exist, it is usually simple patterns along the rim. Commonly known as Polynesian Plain Ware, the period in which this pottery is produced is significant because most Oceania archaeologists believe that it is from the pottery-producing culture that all subsequent Polynesian culture springs (Burley et al., 1995; Clark, 1996; Davidson, 1979; Hiroa, 1930; Irwin, 1992; Kirch, 1984, 2000; Kirch and Green, 2001; Pawley, 1966; Pawley and Ross, 1993; Shutler and Shutler, 1975). However, this cultural continuity has yet to be established archaeologically (Smith, 2002); as such, the term "Plain Ware" is used here, so as avoid untested cultural affiliations.

Plain Ware recovered from across the archipelago was slab-built and low-fired. Although pottery can be divided into thick and thin categories, or into fine and coarse categories, the temporal and functional interpretation of these distinctions remain unclear (Clark and Herdrich, 1988; Eckert and Pearl, 2006; Eckert and Welch, 2009; Green, 1974; Jennings and Holmer, 1980; Kirch and Hunt, 1993; Moore and Kennedy 2003: 103–110). Large sherds and rim forms vary within and across sites, but represent primarily wide-mouthed, globular vessels and platters. Ceramic assemblages from various sites show evidence that at least some vessels were used for cooking (Clark and Michlovic, 1996:161; Eckert and Pearl, 2006; Eckert and Welch, 2009; Hunt and Erkelens, 1993:137). The general consensus is that pottery vessels were probably used in a variety of ways including to store, cook, and serve food items.

## 3. Methods

### 3.1. *Ceramic chemical characterization using LA-ICP-MS*

This is a provenance study, an attempt to determine where ceramic vessels were produced. Archaeologists determine

**Table 1**
Provenience and chronological information for samples used in this study.

| Site | Island | Sample size | Volcanic series | Associated dates |
|---|---|---|---|---|
| Mulifanua | Upolu | 8 sherds | Mulifanua | 2880–2750 cal BP (Petchey, 2001) |
| Va'oto | Ofu | 15 sherds | Tuafanua | 2840–2120 cal BP (Hood, 2008) |
| Aganoa | Tutuila | 13 sherds | Olomoana | 2760–2510 cal BP (Hood, 2007a,b) |
| 'Aoa | Tutuila | 48 sherds | Olomoana | 2455–2195 cal BP (Clark and Michlovic, 1996) |
| Ulu Tree | Tutuila | 33 sherds | Leone | n/a |
| Vainu'u | Tutuila | 53 sherds | Taputapu | 2270–2440 cal BP (Eckert and Welch, 2009) |
| Clay 175 | Tutuila | 3 tiles | Olomoana | n/a |
| Clay 177 | Tutuila | 3 tiles | Olomoana | n/a |
| Clay 617 | Tutuila | 3 tiles | Olomoana | n/a |
| Clay 619 | Tutuila | 3 tiles | Alofau | n/a |
| Clay 621 | Tutuila | 3 tiles | Olomoana | n/a |
| Clay 1197 | Tutuila | 3 tiles | Leone | n/a |
| Clay 1200 | Tutuila | 3 tiles | Leone | n/a |

provenance through both direct and indirect evidence of production (Costin, 2005, 2007; Costin and Hagstrum, 1995; Mathien, 2001; Weisler, 1998). Direct evidence of production involves the identification of features (e.g. kilns), tools (e.g. polishing stones), and debris (e.g. waster sherds) associated with the production process. Evidence of this nature has never been found in the Samoan archipelago. As such, archaeologists working in Samoa need to rely on indirect evidence of production, which involves inferences about the raw materials used to produce pottery (Costin, 1991, 2005; Mills and Crown, 1995).

In a perfect world, ceramic chemical data could be statistically clustered into compositional groups that could then be matched with geological sources (Bishop et al., 1982). However, ceramic material is a complex mixture of paste matrix (the fired clay) and temper (non-plastics naturally occurring or intentionally added to the clay). Ceramic resource material is often wide spread with indistinct boundaries (Neff and Glowacki, 2002) and so a one-on-one match with a "quarry source" is actually not a reasonable expectation. Further, the numerous decisions made by a potter during the production process affect the final chemical composition. Potters may collect clays from primary locations eroding from a parent rock, or from secondary locations such as a streambed (Orton et al., 1993). Once clays are collected, they can be seasoned to encourage bacterial growth, they can be mixed with other clays, they can be cleaned of their naturally occurring non-plastics, and/or they can have one or more non-plastics added to them (Orton et al., 1993; Rice, 1987; Shepard, 1956). All of these actions by potters potentially change the chemistry of the final ceramic product.

Although attempts should be made to match wild clays with ceramic material, wild clays and other aspects of regional geology are viewed as supplemental information and should never be solely relied upon (Bishop et al., 1982; Neff and Glowacki, 2002). Rather, researchers rely on inferences made from statistically robust

**Table 2**
Mean and standard deviation of oxide concentrations for each element in Tutuila clays.

| Element | Clay 175 ($n = 3$) | Clay 177 ($n = 3$) | Clay 617 ($n = 3$) | Clay 619 ($n = 3$) | Clay 621 ($n = 3$) | Clay 1197 ($n = 3$) | Clay 1200 ($n = 3$) |
|---|---|---|---|---|---|---|---|
| Na23 | 10.3734 ± 0.8484 | 10.8315 ± 1.5123 | 34.7446 ± 1.5742 | 13.7657 ± 1.7175 | 13.3634 ± 4.5956 | 12.8367 ± 2.4600 | 08.9327 ± 0.4148 |
| Mg24 | 00.9154 ± 0.0388 | 00.7924 ± 0.0299 | 00.8359 ± 0.0792 | 00.9525 ± 0.0820 | 00.9384 ± 0.0447 | 02.5267 ± 1.1665 | 01.2224 ± 0.3475 |
| Al27 | 25.9893 ± 2.0594 | 29.4727 ± 3.3615 | 18.6027 ± 1.4303 | 22.8256 ± 0.4730 | 25.0268 ± 2.5203 | 23.3155 ± 4.3077 | 28.3966 ± 1.3378 |
| Si29 | 32.7335 ± 1.4021 | 32.7305 ± 2.0338 | 22.5842 ± 1.2009 | 33.6206 ± 2.3737 | 34.5053 ± 1.8406 | 31.8417 ± 0.9146 | 31.6169 ± 0.5816 |
| K39 | 00.2697 ± 0.0387 | 00.2308 ± 0.0500 | 00.7513 ± 0.0555 | 00.4547 ± 0.0461 | 00.4775 ± 0.0730 | 00.2900 ± 0.2395 | 00.0756 ± 0.0007 |
| Ca44 | 00.9967 ± 0.0575 | 00.3168 ± 0.0241 | 01.3545 ± 0.0672 | 01.3738 ± 0.2464 | 00.6630 ± 0.0900 | 03.0186 ± 2.4773 | 00.3712 ± 0.0174 |
| Sc45 | 00.0051 ± 0.0041 | 00.0051 ± 0.0032 | 00.0037 ± 0.0014 | 00.0304 ± 0.0005 | 00.0270 ± 0.0012 | 00.0275 ± 0.0029 | 00.0343 ± 0.0009 |
| Ti47 | 03.6413 ± 0.2986 | 03.5900 ± 0.2106 | 03.2389 ± 0.1392 | 04.8012 ± 0.2038 | 04.6202 ± 0.2736 | 04.4204 ± 0.4147 | 04.8683 ± 0.1279 |
| V51 | 00.1588 ± 0.0038 | 00.1756 ± 0.0106 | 00.1706 ± 0.0116 | 00.2443 ± 0.0150 | 00.2452 ± 0.0127 | 00.2722 ± 0.0221 | 00.3097 ± 0.0082 |
| Cr52 | 00.0090 ± 0.0023 | 00.0087 ± 0.0027 | 00.0953 ± 0.0217 | 00.1663 ± 0.0134 | 00.0777 ± 0.0242 | 00.2043 ± 0.0108 | 00.2568 ± 0.0536 |
| Mn55 | 03.5536 ± 0.1766 | 05.4690 ± 7.0895 | 01.9029 ± 0.0181 | 02.5461 ± 0.3084 | 02.3108 ± 0.2372 | 02.1441 ± 0.1063 | 01.8639 ± 0.0835 |
| Fe57 | 19.1539 ± 1.2212 | 14.9532 ± 0.9067 | 14.2110 ± 1.2481 | 17.5626 ± 0.1401 | 16.0426 ± 0.8870 | 17.2975 ± 2.0249 | 20.2816 ± 0.5884 |
| Co59 | 00.0383 ± 0.0029 | 00.0359 ± 0.0013 | 00.0439 ± 0.0038 | 00.0579 ± 0.0083 | 00.0400 ± 0.0024 | 00.0586 ± 0.0041 | 00.0630 ± 0.0025 |
| Ni60 | 00.0113 ± 0.0015 | 00.0265 ± 0.0017 | 00.0457 ± 0.0040 | 00.1126 ± 0.0132 | 00.0326 ± 0.0021 | 00.1545 ± 0.0182 | 00.1487 ± 0.0030 |
| Cu65 | 00.0047 ± 0.0002 | 00.0111 ± 0.0015 | 00.0153 ± 0.0007 | 00.0137 ± 0.0014 | 00.0046 ± 0.0003 | 00.0381 ± 0.0092 | 00.0123 ± 0.0005 |
| Zn66 | 00.1330 ± 0.0084 | 00.0952 ± 0.0017 | 00.1339 ± 0.0127 | 00.0879 ± 0.0041 | 00.0709 ± 0.0050 | 00.1898 ± 0.0356 | 00.0997 ± 0.0010 |
| Rb85 | 00.0042 ± 0.0004 | 00.0023 ± 0.0001 | 00.0251 ± 0.0011 | 00.0186 ± 0.0019 | 00.0154 ± 0.0020 | 00.0126 ± 0.0050 | 00.0059 ± 0.0003 |
| Sr88 | 00.1234 ± 0.0088 | 00.0803 ± 0.0080 | 00.0987 ± 0.0012 | 00.1117 ± 0.0076 | 00.0969 ± 0.0030 | 00.1397 ± 0.0690 | 00.0824 ± 0.0045 |
| Zr90 | 00.7744 ± 0.0615 | 00.5309 ± 0.0681 | 00.5004 ± 0.0258 | 00.5874 ± 0.0211 | 00.7382 ± 0.0858 | 00.4669 ± 0.0614 | 00.6272 ± 0.0315 |
| Ba138 | 00.6359 ± 0.0178 | 00.3255 ± 0.1272 | 00.2496 ± 0.0043 | 00.2742 ± 0.0226 | 00.2522 ± 0.0055 | 00.4008 ± 0.0730 | 00.3403 ± 0.0042 |
| La139 | 00.0733 ± 0.0085 | 00.0470 ± 0.0061 | 00.0542 ± 0.0011 | 00.0604 ± 0.0094 | 00.0678 ± 0.0036 | 00.0550 ± 0.0127 | 00.0604 ± 0.0055 |
| Ce140 | 00.1790 ± 0.0102 | 00.1084 ± 0.0078 | 00.1446 ± 0.0079 | 00.1503 ± 0.0113 | 00.1686 ± 0.0031 | 00.1324 ± 0.0267 | 00.1465 ± 0.0073 |
| Pr141 | 00.0169 ± 0.0059 | 00.0133 ± 0.0016 | 00.0159 ± 0.0013 | 00.0164 ± 0.0014 | 00.0186 ± 0.0005 | 00.0142 ± 0.0039 | 00.0160 ± 0.0010 |
| Nd142 | 00.0991 ± 0.0109 | 00.0673 ± 0.0080 | 00.0744 ± 0.0071 | 00.0793 ± 0.0085 | 00.0923 ± 0.0054 | 00.0664 ± 0.0172 | 00.0769 ± 0.0053 |
| Sm152 | 00.0204 ± 0.0018 | 00.0150 ± 0.0019 | 00.0169 ± 0.0009 | 00.0170 ± 0.0011 | 00.0205 ± 0.0013 | 00.0140 ± 0.0037 | 00.0167 ± 0.0014 |
| Eu153 | 00.0063 ± 0.0006 | 00.0047 ± 0.0006 | 00.0053 ± 0.0002 | 00.0052 ± 0.0003 | 00.0062 ± 0.0003 | 00.0045 ± 0.0011 | 00.0052 ± 0.0004 |
| Gd158 | 00.0183 ± 0.0023 | 00.0135 ± 0.0017 | 00.0155 ± 0.0010 | 00.0154 ± 0.0007 | 00.0188 ± 0.0005 | 00.0127 ± 0.0027 | 00.0159 ± 0.0010 |
| Tb159 | 00.0028 ± 0.0004 | 00.0020 ± 0.0003 | 00.0025 ± 0.0001 | 00.0023 ± 0.0002 | 00.0029 ± 0.0001 | 00.0019 ± 0.0003 | 00.0024 ± 0.0001 |
| Dy164 | 00.0136 ± 0.0014 | 00.0092 ± 0.0011 | 00.0117 ± 0.0010 | 00.0114 ± 0.0006 | 00.0141 ± 0.0005 | 00.0093 ± 0.0016 | 00.0122 ± 0.0009 |
| Ho165 | 00.0023 ± 0.0003 | 00.0015 ± 0.0001 | 00.0021 ± 0.0001 | 00.0020 ± 0.0001 | 00.0025 ± 0.0001 | 00.0017 ± 0.0003 | 00.0022 ± 0.0001 |
| Er166 | 00.0049 ± 0.0005 | 00.0030 ± 0.0002 | 00.0048 ± 0.0003 | 00.0044 ± 0.0003 | 00.0053 ± 0.0001 | 00.0038 ± 0.0004 | 00.0051 ± 0.0003 |
| Tm169 | 00.0006 ± 0.0001 | 00.0005 ± 0.0001 | 00.0008 ± 0.0001 | 00.0006 ± 0.0001 | 00.0007 ± 0.0001 | 00.0005 ± 0.0001 | 00.0007 ± 0.0001 |
| Yb174 | 00.0044 ± 0.0006 | 00.0028 ± 0.0002 | 00.0048 ± 0.0005 | 00.0042 ± 0.0004 | 00.0050 ± 0.0001 | 00.0037 ± 0.0007 | 00.0048 ± 0.0002 |
| Lu175 | 00.0005 ± 0.0001 | 00.0004 ± 0.0002 | 00.0007 ± 0.0001 | 00.0005 ± 0.0001 | 00.0006 ± 0.0001 | 00.0004 ± 0.0001 | 00.0006 ± 0.0001 |
| Hf180 | 00.0135 ± 0.0015 | 00.0107 ± 0.0014 | 00.0097 ± 0.0007 | 00.0111 ± 0.0004 | 00.0141 ± 0.0017 | 00.0088 ± 0.0016 | 00.0124 ± 0.0003 |
| Ta181 | 00.0038 ± 0.0003 | 00.0023 ± 0.0003 | 00.0025 ± 0.0002 | 00.0029 ± 0.0001 | 00.0034 ± 0.0002 | 00.0027 ± 0.0002 | 00.0032 ± 0.0001 |
| Pb208 | 00.0055 ± 0.0013 | 00.0079 ± 0.0017 | 00.0097 ± 0.0013 | 00.0006 ± 0.0001 | 00.0006 ± 0.0001 | 00.0050 ± 0.0024 | 00.0005 ± 0.0001 |
| Th232 | 00.0071 ± 0.0008 | 00.0047 ± 0.0006 | 00.0056 ± 0.0005 | 00.0059 ± 0.0002 | 00.0068 ± 0.0003 | 00.0053 ± 0.0006 | 00.0066 ± 0.0005 |
| U238 | 00.0019 ± 0.0001 | 00.0013 ± 0.0002 | 00.0019 ± 0.0002 | 00.0018 ± 0.0003 | 00.0023 ± 0.0004 | 00.0014 ± 0.0001 | 00.0017 ± 0.0001 |

sample sizes to interpret compositional groups as “recipes” used by ceramic production groups. These compositional groups are then assigned production provenance based on the “criterion of abundance” (Bishop et al., 1982), which assumes that artifacts originate where they are most common.

Previous pottery production provenance studies in the Samoan archipelago have relied upon petrography. The primary tempers reported for pottery recovered from sites in Samoa is igneous rock or beach sand (Clark and Michlovic, 1996; Dickinson, 1969, 1993, 2006; Eckert, 2006; Eckert and Pearl, 2006; Eckert and Welch, 2009). These petrographic analyses indicate production within the Samoan archipelago. These analyses sometimes suggest production on a specific island and occasionally indicate production in a coastal setting. Overall, however, the production provenance of pottery from Samoan sites cannot be determined to a specific volcanic series through petrography. As a result, geochemistry was turned to in an attempt to better identify possible production provenances.

The Samoan archipelago is an ideal setting in which to attempt chemical characterization of pottery as geochemical work on basalts, from which the clays in this study are derived, has successfully differentiated volcanic series on Tutuila Island.

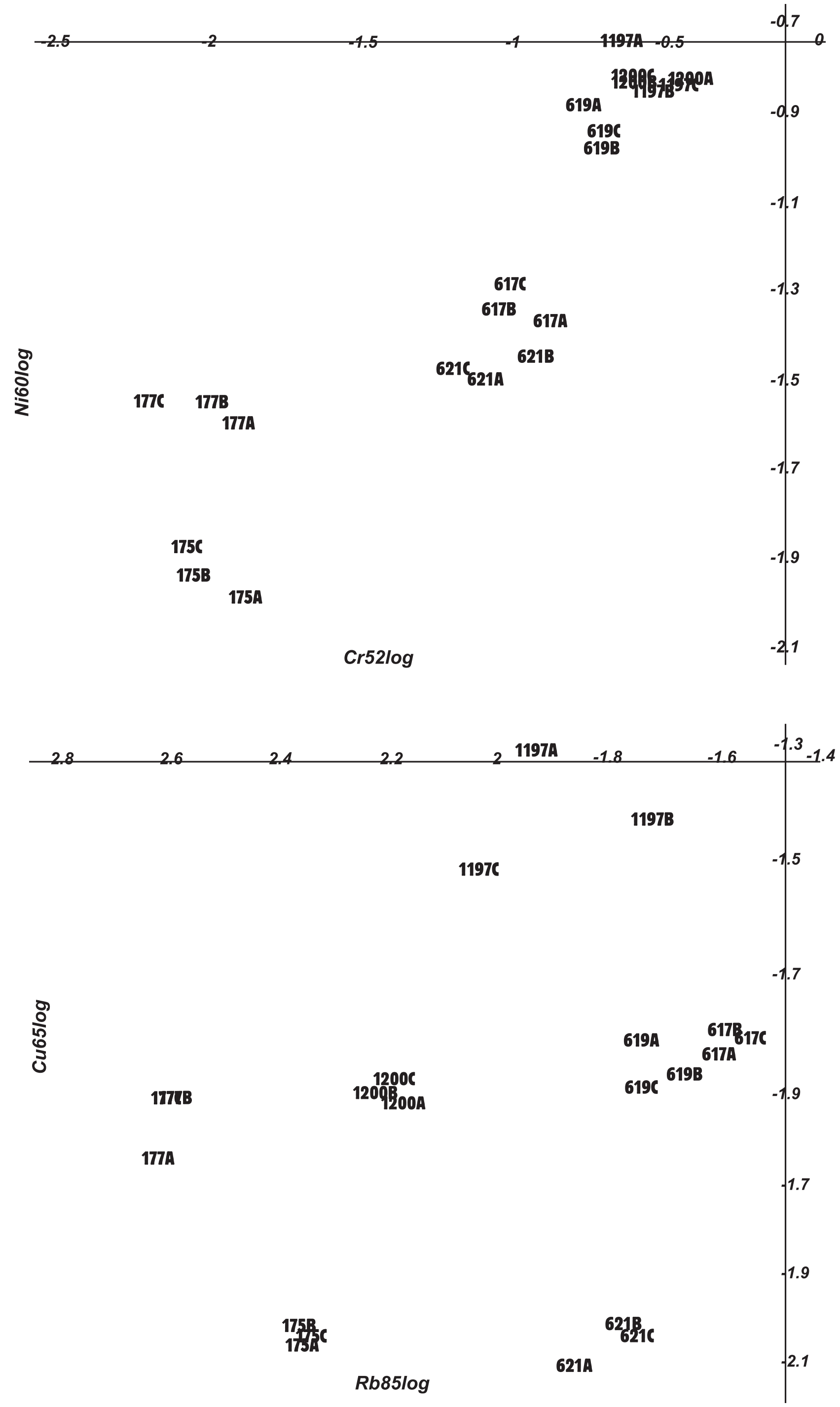

**Fig. 2.** Bivariate plot showing differentiation of clay samples. Values given are log - base 10 oxide concentrations.

Specifically, Johnson et al. (2007) found that basalt rock samples collected from known prehistoric quarries on Tutuila differentiated by quarry using Instrumental Neutron Activation Analysis (INNA). LA-ICP-MS is a microprobe technique determined to be more appropriate than INNA for this study for three reasons. First, it is relatively non-destructive when compared to INAA. Second, previous research in other regions, including Fiji (Cochrane and Neff, 2006), has established that it can successfully differentiate between clays (Larson et al., 2005; Neff, 2003). Third, unlike INAA that is a bulk technique suitable for homogenous materials, LA-ICP-MS allows for characterization of specific components of heterogeneous materials (Cogswell et al., 2005; Neff, 2003), in this case focusing on paste clays rather than temper or pigments.

### *3.2. LA-ICP-MS methodology and statistical analyses*

LA-ICP-MS analyses were conducted on a Perkin Elmer Elan DRCII housed at the Elemental Analysis Laboratory, Department of Chemistry, Texas A&M University. A New Wave UP-213 laser ablation system with associated software was used for sample induction. At the start of each batch of 10 samples, a series of standards were analyzed: NIST standard SRM 610, NIST standard SRM 612, Glass Buttes obsidian, Pachuca obsidian, and MURR's Ohio Red Clay. A blank was also run prior to each batch. The standards and blank runs were used to calibrate data using the Gratuze method as discussed below (Gratuze, 1999; Neff, 2003; Speakman and Neff, 2005). Each sample had a fresh paste surface exposed and was then placed in the induction chamber with this fresh surface toward the laser system. Prior to the analyses, the following parameters were set: the diameter of the laser beam was adjusted to 30 μm; each pass of the laser over the sample would remove 5 mm of material; the repetition rate of the laser was set to 10 Hz; and the maximum energy of the beam was set to 70%. Ablation rasters were set so that only paste matrix was sampled. After an initial pass to remove possible surface contaminants, two ablation passes were needed to generate abundance data for 39 elements: Al, Ba, Ca, Ce, Co, Cr, Cu, Dy, Er, Eu, Fe, Gd, Hf, Ho, K, La, Lu, Mg, Mn, Na, Nd, Ni, Pb, Pr, Rb, Sc, Si, Sm, Sr, Ta, Tb, Th, Ti, Tm, U, V, Yb, Zn, and Zr.

Once raw count elemental signals were collected from the LA-ICP-MS analyses, the data were quantified using an approach outlined by Gratuze et al. (2001). The formulas for this approach are explained and provided by both Neff (2003) and Speakman and Neff (2005). Briefly put, the approach corrects for background noise, standardizes by calculating a ratio to the counts for a single element (in our case, Al), and converts elemental signals to signals of their oxides. These signals are then converted to oxide concentrations, with a result that the sum of the oxide concentrations within each sample will equal 100. The assumption underlying this quantification is that all elements being measured represent all of the material, other than oxygen, that is ablated from the samples. This assumption may introduce some error for elements that occur in more than one oxidation state and ignores any water that may have been in the sample. Overall, however, experiments on a range of materials, including ceramic, have shown that this approach yields results in reasonable agreement with data generated by other geochemical techniques (Neff, 2003; Speakman and Neff, 2005). Oxide concentrations were then log-base 10 transformed.

Three statistical techniques were used to explore patterning in the data and to assign sherds to compositional groups: bivariate scatter plots, k-means clustering, and principal components analysis (PCA). Bivariate scatter plots provide an easy means to visually examine the relationship between any two elements and helps in determining which elements may be driving separation into compositional groups. K-means cluster analysis (Baxter, 2003) is a non-hierarchical clustering technique used for grouping cases; its advantage over other clustering methods is that as a non-hierarchical technique it minimizes intracluster variation while maximizing intercluster variation.

The cluster solution with the greatest difference between the average sum of the squared distances for randomly generated data and the original data is considered to be the "best" cluster solution (Kintigh and Ammerman, 1982). PCA (Shennan, 1997) compresses a large number of variables into a smaller number of uncorrelated variables called principal components; the first principal component accounts for as much of the variability as possible, and each remaining component accounts for as much of the remaining

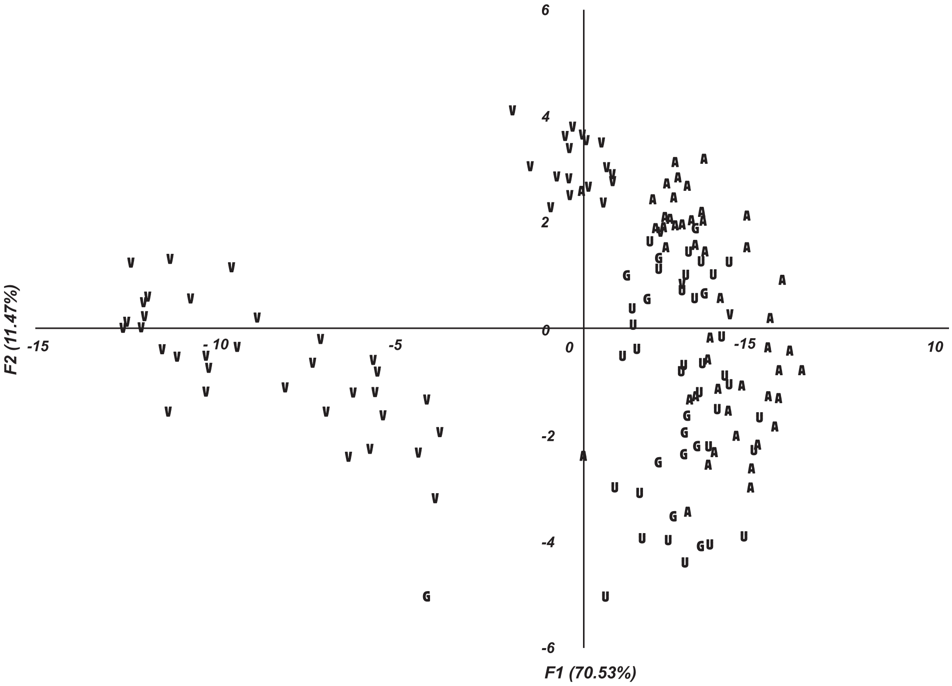

**Fig. 3.** First two components of PCA on log - 10 oxide concentrations for 147 sherds recovered from sites on Tutuila Island: (V) Vainu'u; (A) 'Aoa; (G) Aganoa; (U) Ulu Tree.

**Table 3**
Summary of k-means 5-cluster solution for ceramic sherds recovered from sites on Tutuila Island.

| Cluster | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Objects | 40 | 55 | 15 | 18 | 19 |
| Sum of weights | 40 | 55 | 15 | 18 | 19 |
| Within-class variance | 2.375 | 2.486 | 2.517 | 1.797 | 2.222 |
| Min dist to centroid | 0.626 | 0.883 | 0.752 | 0.658 | 0.702 |
| Ave dist to centroid | 1.487 | 1.503 | 1.422 | 1.229 | 1.387 |
| Max dist to centroid | 2.164 | 2.585 | 3.353 | 2.622 | 2.199 |
| Group members listed by site | ***Aganoa*** | ***Aganoa*** | ***Aganoa*** | ***Vainu'u*** | ***Vainu'u*** |
| | AG001 | AG192 | AG704 | V008.134 | V010.270 |
| | AG194 | AG387 | ***Vainu'u*** | V008.138 | V010.274 |
| | AG396 | AG607 | V010.276 | V008.141 | V010.282 |
| | AG451 | AG631 | V026.458 | V013.82 | V010.284 |
| | AG587 | AG649 | V026.472 | V046.72 | V022.151 |
| | AG634 | ***'Aoa*** | V036.371 | V046.73 | V022.152 |
| | AG641 | Aoa1 | V036.385 | V046.74 | V026.476 |
| | ***'Aoa*** | Aoa2 | V037.252 | V051.31 | V036.383 |
| | Aoa3 | Aoa4 | V037.254 | V057.84 | V037.255 |
| | Aoa7 | Aoa5 | V088.286 | V057.86 | V037.256 |
| | Aoa15 | Aoa6 | V088.300 | V057.87 | V039.158 |
| | Aoa22 | Aoa8 | V096.244 | V057.88 | V039.159 |
| | Aoa25 | Aoa9 | V096.245 | V057.89 | V039.160 |
| | Aoa26 | Aoa10 | V096.246 | V102.91 | V088.299 |
| | Aoa27 | Aoa11 | V096.247 | V102.92 | V088.302 |
| | Aoa29 | Aoa12 | V097.109 | V102.93 | V088.306 |
| | Aoa31 | Aoa13 | | V106.68 | V097.106 |
| | AoaAS1 | Aoa14 | | V106.69 | V097.107 |
| | AoaAS2 | Aoa16 | | | V097.108 |
| | AoaAS12 | Aoa17 | | | |
| | AoaAS13 | Aoa18 | | | |
| | AoaAS14 | Aoa19 | | | |
| | AoaAS16 | Aoa20 | | | |
| | ***Ulu Tree*** | Aoa21 | | | |
| | ULU001 | Aoa23 | | | |
| | ULU003 | Aoa24 | | | |
| | ULU004 | Aoa28 | | | |
| | ULU006 | Aoa30 | | | |
| | ULU010 | AoaAS3 | | | |
| | ULU015 | AoaAS5 | | | |
| | ULU044 | AoaAS6 | | | |
| | ULU053 | AoaAS7 | | | |
| | ULU054 | AoaAS8 | | | |
| | ULU071 | AoaAS9 | | | |
| | ULU081 | AoaAS10 | | | |
| | ULU099 | AoaAS11 | | | |
| | ULU108 | AoaAS15 | | | |
| | ULU109 | AoaAS17 | | | |
| | ULU146 | AoaAS18 | | | |
| | ULU194 | ***Ulu Tree*** | | | |
| | ULU201 | ULU014 | | | |
| | ULU205 | ULU026 | | | |
| | | ULU032 | | | |
| | | ULU052 | | | |
| | | ULU082 | | | |
| | | ULU092 | | | |
| | | ULU100 | | | |
| | | ULU107 | | | |
| | | ULU143 | | | |
| | | ULU147 | | | |
| | | ULU152 | | | |
| | | ULU204 | | | |
| | | ULU216 | | | |
| | | ULU223 | | | |
| | | ULU225 | | | |
| | | ***Vainu'u*** | | | |
| | | V008.140 | | | |
| | | V013.83 | | | |
| Mean and SD of oxide concentrations | | | | | |
| Na23 | 01.0970 ± 0.6826 | 00.3811 ± 0.4217 | 00.1558 ± 0.1124 | 00.0274 ± 0.0135 | 00.0066 ± 0.0002 |
| Mg24 | 00.7690 ± 0.0015 | 01.2399 ± 0.7248 | 00.3690 ± 0.2479 | 00.8774 ± 0.6714 | 00.0936 ± 0.0521 |
| Al27 | 34.7446 ± 8.9980 | 32.8900 ± 6.6889 | 53.4367 ± 7.4355 | 34.7477 ± 3.1049 | 14.7623 ± 0.7482 |
| Si29 | 44.3925 ± 7.3127 | 38.7847 ± 5.7129 | 10.8288 ± 3.0641 | 31.1363 ± 2.9886 | 44.9339 ± 3.9049 |
| K39 | 01.2748 ± 0.1767 | 00.4082 ± 0.3005 | 00.2194 ± 0.1582 | 00.6343 ± 0.4365 | 00.0127 ± 0.0037 |

(*continued on next page*)

**Table 3** (*continued*)

| Cluster | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Ca44 | 02.6906 ± 0.7620 | 01.5566 ± 1.3871 | 00.3208 ± 0.2168 | 00.1118 ± 0.0612 | 00.0274 ± 0.0048 |
| Sc45 | 00.0307 ± 0.0237 | 00.0588 ± 0.0627 | 00.0054 ± 0.0015 | 00.0373 ± 0.0052 | 00.0051 ± 0.0008 |
| Ti47 | 01.3765 ± 0.0768 | 03.8457 ± 1.4271 | 00.4755 ± 0.1711 | 05.5676 ± 0.6433 | 01.1640 ± 0.7069 |
| V51 | 00.1088 ± 0.0812 | 00.2211 ± 0.0875 | 00.0280 ± 0.0096 | 00.2829 ± 0.0993 | 00.0417 ± 0.0123 |
| Cr52 | 00.0899 ± 0.1069 | 00.3261 ± 0.2189 | 00.0493 ± 0.0357 | 00.2669 ± 0.1280 | 00.0343 ± 0.0175 |
| Mn55 | 00.9094 ± 0.5287 | 01.0256 ± 0.6797 | 00.4107 ± 0.2931 | 01.0699 ± 0.7484 | 00.1465 ± 0.0660 |
| Fe57 | 10.7217 ± 6.3106 | 17.3324 ± 4.7396 | 33.3225 ± 14.9809 | 24.0703 ± 2.3273 | 38.5401 ± 2.4074 |
| Co59 | 00.0210 ± 0.0461 | 00.0370 ± 0.0197 | 00.0067 ± 0.0025 | 00.0520 ± 0.0164 | 00.0080 ± 0.0091 |
| Ni60 | 00.0673 ± 0.0074 | 00.2723 ± 0.2560 | 00.0240 ± 0.0149 | 00.1223 ± 0.0935 | 00.0257 ± 0.0252 |
| Cu65 | 00.0316 ± 0.0256 | 00.0459 ± 0.0307 | 00.0146 ± 0.0110 | 00.0600 ± 0.0406 | 00.0081 ± 0.0073 |
| Zn66 | 00.1733 ± 0.1167 | 00.1706 ± 0.0896 | 00.0567 ± 0.0065 | 00.0941 ± 0.0295 | 00.0146 ± 0.0052 |
| Rb85 | 00.0472 ± 0.0202 | 00.0237 ± 0.0151 | 00.0085 ± 0.0047 | 00.0093 ± 0.0074 | 00.0012 ± 0.0008 |
| Sr88 | 00.1425 ± 0.1400 | 00.1005 ± 0.0920 | 00.0147 ± 0.0026 | 00.0080 ± 0.0063 | 00.0017 ± 0.0012 |
| Zr90 | 00.4617 ± 0.2544 | 00.5422 ± 0.1363 | 00.1343 ± 0.0437 | 00.6061 ± 0.2309 | 00.1355 ± 0.0174 |
| Ba138 | 00.4050 ± 0.2813 | 00.4037 ± 0.3957 | 00.0383 ± 0.0213 | 00.0464 ± 0.0268 | 00.0089 ± 0.0035 |
| La139 | 00.0656 ± 0.0250 | 00.0592 ± 0.0219 | 00.0108 ± 0.0046 | 00.0242 ± 0.0104 | 00.0042 ± 0.0029 |
| Ce140 | 00.1939 ± 0.0743 | 00.1246 ± 0.0496 | 00.0356 ± 0.0186 | 00.0594 ± 0.0265 | 00.0095 ± 0.0057 |
| Pr141 | 00.0166 ± 0.0063 | 00.0140 ± 0.0048 | 00.0027 ± 0.0011 | 00.0065 ± 0.0019 | 00.0010 ± 0.0006 |
| Nd142 | 00.0785 ± 0.0344 | 00.0634 ± 0.0233 | 00.0123 ± 0.0054 | 00.0316 ± 0.0094 | 00.0049 ± 0.0031 |
| Sm152 | 00.0150 ± 0.0052 | 00.0132 ± 0.0042 | 00.0025 ± 0.0011 | 00.0072 ± 0.0021 | 00.0011 ± 0.0007 |
| Eu153 | 00.0034 ± 0.0013 | 00.0038 ± 0.0012 | 00.0006 ± 0.0003 | 00.0023 ± 0.0007 | 00.0003 ± 0.0002 |
| Gd158 | 00.0126 ± 0.0043 | 00.0109 ± 0.0031 | 00.0021 ± 0.0009 | 00.0064 ± 0.0019 | 00.0010 ± 0.0006 |
| Tb159 | 00.0020 ± 0.0007 | 00.0017 ± 0.0005 | 00.0003 ± 0.0001 | 00.0010 ± 0.0002 | 00.0001 ± 0.0001 |
| Dy164 | 00.0100 ± 0.0034 | 00.0081 ± 0.0024 | 00.0017 ± 0.0007 | 00.0050 ± 0.0014 | 00.0007 ± 0.0004 |
| Ho165 | 00.0018 ± 0.0006 | 00.0014 ± 0.0004 | 00.0003 ± 0.0001 | 00.0008 ± 0.0002 | 00.0001 ± 0.0000 |
| Er166 | 00.0042 ± 0.0016 | 00.0032 ± 0.0011 | 00.0007 ± 0.0002 | 00.0019 ± 0.0005 | 00.0002 ± 0.0001 |
| Tm169 | 00.0006 ± 0.0003 | 00.0004 ± 0.0001 | 00.0009 ± 0.0003 | 00.0002 ± 0.0000 | 00.0001 ± 0.0000 |
| Yb174 | 00.0043 ± 0.0017 | 00.0030 ± 0.0011 | 00.0007 ± 0.0002 | 00.0018 ± 0.0006 | 00.0002 ± 0.0001 |
| Lu175 | 00.0005 ± 0.0002 | 00.0004 ± 0.0001 | 00.0008 ± 0.0002 | 00.0002 ± 0.0000 | 00.0001 ± 0.0000 |
| Hf180 | 00.0105 ± 0.0052 | 00.0104 ± 0.0023 | 00.0024 ± 0.0006 | 00.0111 ± 0.0037 | 00.0015 ± 0.0004 |
| Ta181 | 00.0057 ± 0.0026 | 00.0030 ± 0.0012 | 00.0013 ± 0.0007 | 00.0025 ± 0.0009 | 00.0003 ± 0.0001 |
| Pb208 | 00.0057 ± 0.0041 | 00.0037 ± 0.0035 | 00.0010 ± 0.0005 | 00.0013 ± 0.0005 | 00.0003 ± 0.0001 |
| Th232 | 00.0112 ± 0.0047 | 00.0078 ± 0.0023 | 00.0029 ± 0.0015 | 00.0055 ± 0.0020 | 00.0008 ± 0.0002 |
| U238 | 00.0026 ± 0.0015 | 00.0015 ± 0.0006 | 00.0005 ± 0.0001 | 00.0011 ± 0.0006 | 00.0001 ± 0.0000 |

variability as possible. Although not the only statistical methods used in compositional studies (Baxter, 1994; Bishop et al., 1982), these three techniques are commonly used and were selected as the best suite of techniques given our sample size.

### 3.3. The sample

All told, 170 ceramic artifacts and 21 ceramic tiles produced from raw clay samples were chemically characterized through LA-ICP-

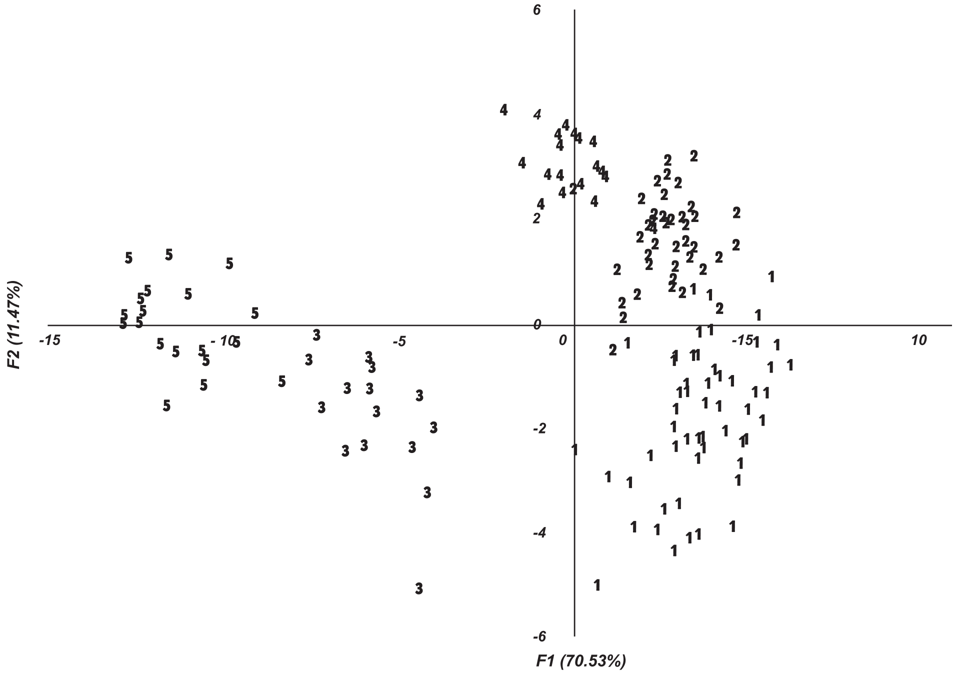

**Fig. 4.** First two components of PCA of log - 10 oxide concentrations for 147 sherds recovered from sites on Tutuila Island plotted by k-means 5-cluster solution: Clusters 3, 4, and 5 are dominated by sherds recovered from the highland site of Vainu'u; Clusters 1 and 2 are dominated by sherds recovered from the lowland sites of Aganoa, ‘Aoa, and the Ulu Tree site.

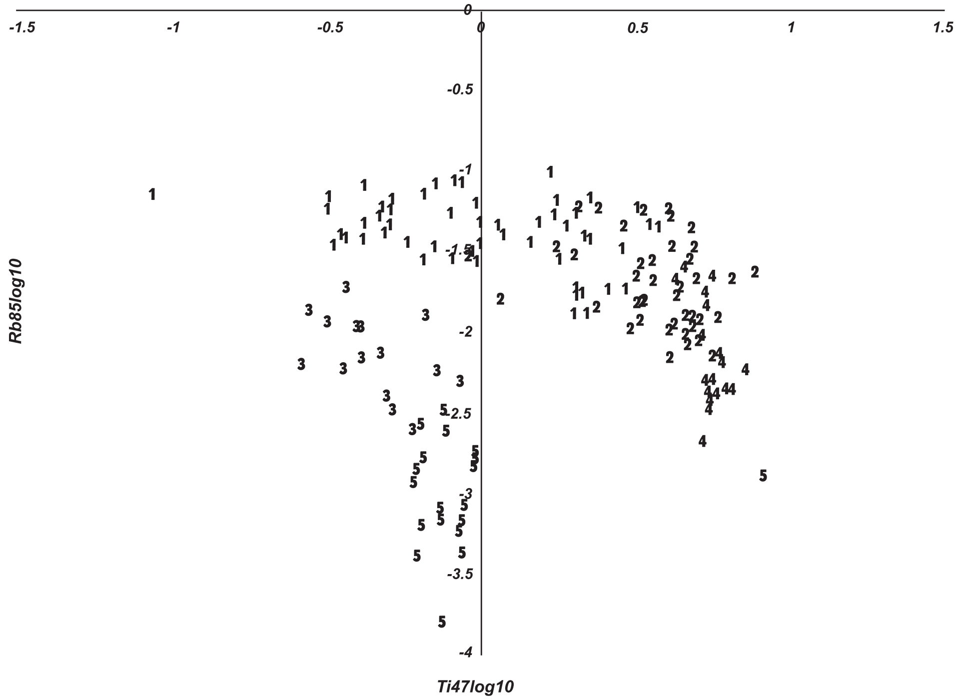

**Fig. 5.** Bivariate plot of log - base 10 oxide concentrations for Ti and Rb showing differentiation of sherds recovered from Tutuila Island by k-means 5-cluster solution.

MS (Table 1). A total of 13 clay samples were collected in 2006 from the vicinity of three ceramic-bearing sites on Tutuila Island (Fig. 1). After various laboratory tests to determine workability, shrinkage rates, and porosity (Rice, 1987), seven of these clays were determined to have sufficient qualities to produce low-firing ceramic vessels. Combined, these seven different clays represent three of Tutuila's volcanic series. Three tiles were produced from each clay for a total of 21 tiles. These tiles measured approximately 3 × 3 × 1 cm and were fired at 700 °C for 30 min. The resulting tiles were similar to ceramic sherds recovered from archaeological sites in terms of paste color, hardness, and texture.

Ceramic artifacts examined were recovered from six sites (Fig. 1): Mulifanua on Upolu Island; Va'oto on Ofu Island; and Aganoa, 'Aoa, Ulu Tree Site, and Vainu'u on Tutuila Island. These sites were chosen

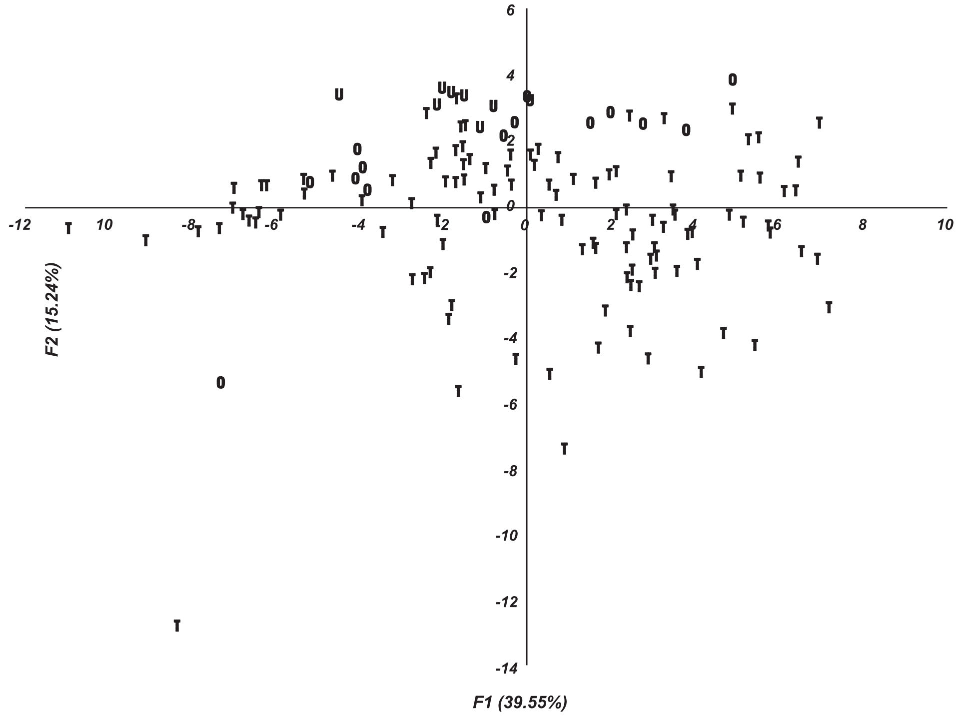

**Fig. 6.** First two components of PCA of log - 10 oxide concentrations for sherds recovered from sites on three different islands in the Samoan Archipelago: (T) Tutuila Island; (O) Ofu Island; (U) Upolu Island.

**Table 4**
Summary of k-means 5-cluster solution for ceramic sherds recovered from sites on three islands in the Samoan archipelago.

| Class | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Objects | 49 | 42 | 24 | 36 | 19 |
| Sum of weights | 49 | 42 | 24 | 36 | 19 |
| Within-class variance | 3.017 | 2.464 | 1.652 | 1.999 | 1.797 |
| Minimum distance to centroid | 0.666 | 0.975 | 0.821 | 0.732 | 0.658 |
| Average distance to centroid | 1.630 | 1.444 | 1.227 | 1.287 | 1.229 |
| Maximum distance to centroid | 4.656 | 3.425 | 1.986 | 2.199 | 2.622 |
| Group members listed by island | ***Tutuila*** | ***Ofu*** | ***Ofu*** | ***Tutuila*** | ***Tutuila*** |
| | AG001 | Vaoto871 | Vaoto869 | Aoa21 | V010.270 |
| | AG194 | ***Tutuila*** | Vaoto876 | Aoa24 | V010.274 |
| | AG396 | AG192 | Vaoto18 | AoaAS18 | V010.282 |
| | AG451 | AG387 | Vaoto864 | AoaAS3 | V010.284 |
| | AG587 | AG607 | Vaoto865 | V008.134 | V022.151 |
| | AG634 | AG631 | Vaoto866 | V008.138 | V022.152 |
| | AG641 | AG649 | Vaoto867 | V008.141 | V026.476 |
| | Aoa1 | Aoa10 | Vaoto868 | V010.276 | V036.383 |
| | Aoa3 | Aoa11 | Vaoto870 | V013.82 | V037.255 |
| | Aoa7 | Aoa12 | Vaoto872 | V026.458 | V037.256 |
| | Aoa14 | Aoa13 | Vaoto 873 | V026.472 | V039.158 |
| | Aoa15 | Aoa17 | Vaoto874 | V036.371 | V039.159 |
| | Aoa16 | Aoa2 | Vaoto875 | V036.385 | V039.160 |
| | Aoa18 | Aoa23 | Vaoto877 | V037.252 | V088.299 |
| | Aoa19 | Aoa30 | ***Tutuila*** | V037.254 | V088.302 |
| | Aoa20 | Aoa4 | AG704 | V046.72 | V088.306 |
| | Aoa22 | Aoa5 | AoaAS11 | V046.73 | V097.106 |
| | Aoa25 | Aoa6 | ***Upolu*** | V046.74 | V097.107 |
| | Aoa26 | Aoa8 | Mulifanua1 | V051.31 | V097.108 |
| | Aoa27 | Aoa9 | Mulifanua2 | V057.84 | |
| | Aoa28 | AoaAS10 | Mulifanua3 | V057.86 | |
| | Aoa29 | AoaAS15 | Mulifanua4 | V057.87 | |
| | Aoa31 | AoaAS17 | Mulifanua5 | V057.88 | |
| | AoaAS1 | AoaAS5 | Mulifanua6 | V057.89 | |
| | AoaAS2 | AoaAS6 | Mulifanua7 | V088.286 | |
| | AoaAS12 | AoaAS7 | Mulifanua8 | V088.300 | |
| | AoaAS13 | AoaAS8 | | V096.244 | |
| | AoaAS14 | AoaAS9 | | V096.245 | |
| | AoaAS16 | ULU026 | | V096.246 | |
| | ULU001 | ULU032 | | V096.247 | |
| | ULU003 | ULU052 | | V097.109 | |
| | ULU004 | ULU082 | | V102.91 | |
| | ULU006 | ULU092 | | V102.92 | |
| | ULU010 | ULU100 | | V102.93 | |
| | ULU014 | ULU143 | | V106.68 | |
| | ULU015 | ULU147 | | V106.69 | |
| | ULU044 | ULU152 | | | |
| | ULU053 | ULU204 | | | |
| | ULU054 | ULU216 | | | |
| | ULU071 | ULU223 | | | |
| | ULU081 | ULU225 | | | |
| | ULU099 | V008.140 | | | |
| | ULU107 | V013.83 | | | |
| | ULU108 | | | | |
| | ULU109 | | | | |
| | ULU146 | | | | |
| | ULU194 | | | | |
| | ULU201 | | | | |
| | ULU205 | | | | |
| Mean and SD of oxide concentrations | | | | | |
| Na23 | 00.8030 ± 0.5822 | 00.2769 ± 0.0304 | 01.2920 ± 0.6551 | 02.3510 ± 1.1343 | 00.2751 ± 0.0563 |
| Mg24 | 01.4646 ± 0.4783 | 00.9792 ± 0.4371 | 01.4132 ± 0.8438 | 02.5625 ± 1.5696 | 00.8728 ± 0.0715 |
| Al27 | 37.6133 ± 14.5828 | 33.6420 ± 7.7371 | 30.0391 ± 7.7336 | 24.6443 ± 9.0198 | 37.6569 ± 4.7306 |
| Si29 | 38.4839 ± 11.5330 | 39.1220 ± 4.2115 | 46.2360 ± 8.2390 | 32.0725 ± 6.9379 | 33.3818 ± 6.8315 |
| K39 | 01.0054 ± 0.9834 | 00.3589 ± 0.3104 | 01.4861 ± 1.2875 | 01.1218 ± 1.8826 | 00.3026 ± 0.0837 |
| Ca44 | 02.0635 ± 1.3360 | 01.3957 ± 0.4573 | 03.0061 ± 0.4716 | 10.7392 ± 4.5730 | 00.7288 ± 0.0978 |
| Sc45 | 00.0241 ± 0.0156 | 00.0427 ± 0.0376 | 00.0441 ± 0.0326 | 00.0946 ± 0.0778 | 00.0350 ± 0.0097 |
| Ti47 | 02.1655 ± 0.1277 | 04.2747 ± 1.6395 | 01.9366 ± 0.0310 | 04.3368 ± 1.4135 | 04.0569 ± 0.8925 |
| V51 | 00.1605 ± 0.2483 | 00.2220 ± 0.1148 | 00.1860 ± 0.1084 | 00.2795 ± 0.0856 | 00.2287 ± 0.1155 |
| Cr52 | 00.1655 ± 0.3033 | 00.3220 ± 0.2451 | 00.1967 ± 0.0668 | 00.2691 ± 0.1427 | 00.2067 ± 0.1360 |
| Mn55 | 01.9603 ± 0.9441 | 00.9955 ± 0.0183 | 00.9111 ± 0.0651 | 01.2380 ± 0.7149 | 00.8599 ± 0.3769 |
| Fe57 | 12.4359 ± 3.6064 | 16.4594 ± 4.5655 | 11.3689 ± 3.2442 | 18.6519 ± 5.3822 | 19.8623 ± 7.2359 |
| Co59 | 00.0229 ± 0.0322 | 00.0302 ± 0.0163 | 00.0353 ± 0.0605 | 00.0501 ± 0.0212 | 00.0387 ± 0.0193 |
| Ni60 | 00.1086 ± 0.1800 | 00.2104 ± 0.1319 | 00.1546 ± 0.2199 | 00.2511 ± 0.0295 | 00.1247 ± 0.0990 |
| Cu65 | 00.0283 ± 0.0261 | 00.0413 ± 0.0199 | 00.0382 ± 0.0266 | 00.0514 ± 0.0423 | 00.0492 ± 0.0302 |
| Zn66 | 00.1298 ± 0.0613 | 00.1586 ± 0.0765 | 00.1940 ± 0.0384 | 00.1257 ± 0.0832 | 00.1354 ± 0.0709 |

**Table 4** (*continued*)

| Class | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Rb85 | 00.0391 ± 0.0341 | 00.0224 ± 0.0134 | 00.0494 ± 0.0193 | 00.0345 ± 0.0281 | 00.0199 ± 0.0022 |
| Sr88 | 00.1728 ± 0.1847 | 00.1046 ± 0.1002 | 00.1168 ± 0.0045 | 00.1306 ± 0.0134 | 00.0326 ± 0.0047 |
| Zr90 | 00.4379 ± 0.1752 | 00.5809 ± 0.1404 | 00.5065 ± 0.0830 | 00.5551 ± 0.1687 | 00.5514 ± 0.2543 |
| Ba138 | 00.3500 ± 0.3362 | 00.4244 ± 0.4182 | 00.3404 ± 0.0403 | 00.1855 ± 0.0307 | 00.2999 ± 0.0784 |
| La139 | 00.0570 ± 0.0221 | 00.0628 ± 0.0218 | 00.0642 ± 0.0238 | 00.0414 ± 0.0187 | 00.0432 ± 0.0252 |
| Ce140 | 00.1521 ± 0.0803 | 00.1211 ± 0.0474 | 00.1931 ± 0.0748 | 00.0980 ± 0.0506 | 00.1055 ± 0.0745 |
| Pr141 | 00.0147 ± 0.0058 | 00.0143 ± 0.0046 | 00.0159 ± 0.0058 | 00.0097 ± 0.0043 | 00.0116 ± 0.0089 |
| Nd142 | 00.0669 ± 0.0283 | 00.0651 ± 0.0200 | 00.0774 ± 0.0347 | 00.0446 ± 0.0218 | 00.0545 ± 0.0395 |
| Sm152 | 00.0137 ± 0.0054 | 00.0130 ± 0.0038 | 00.0146 ± 0.0046 | 00.0100 ± 0.0044 | 00.0114 ± 0.0071 |
| Eu153 | 00.0036 ± 0.0018 | 00.0037 ± 0.0010 | 00.0032 ± 0.0011 | 00.0030 ± 0.0013 | 00.0031 ± 0.0013 |
| Gd158 | 00.0111 ± 0.0042 | 00.0105 ± 0.0029 | 00.0125 ± 0.0041 | 00.0087 ± 0.0008 | 00.0094 ± 0.0052 |
| Tb159 | 00.0018 ± 0.0006 | 00.0016 ± 0.0004 | 00.0020 ± 0.0006 | 00.0014 ± 0.0005 | 00.0015 ± 0.0008 |
| Dy164 | 00.0086 ± 0.0030 | 00.0077 ± 0.0022 | 00.0102 ± 0.0034 | 00.0066 ± 0.0028 | 00.0071 ± 0.0036 |
| Ho165 | 00.0015 ± 0.0005 | 00.0013 ± 0.0004 | 00.0019 ± 0.0007 | 00.0012 ± 0.0005 | 00.0012 ± 0.0006 |
| Er166 | 00.0033 ± 0.0013 | 00.0030 ± 0.0010 | 00.0044 ± 0.0016 | 00.0028 ± 0.0012 | 00.0027 ± 0.0013 |
| Tm169 | 00.0005 ± 0.0002 | 00.0004 ± 0.0003 | 00.0006 ± 0.0002 | 00.0004 ± 0.0001 | 00.0003 ± 0.0001 |
| Yb174 | 00.0033 ± 0.0013 | 00.0028 ± 0.0011 | 00.0046 ± 0.0019 | 00.0027 ± 0.0011 | 00.0026 ± 0.0012 |
| Lu175 | 00.0004 ± 0.0001 | 00.0003 ± 0.0001 | 00.0005 ± 0.0002 | 00.0003 ± 0.0001 | 00.0003 ± 0.0001 |
| Hf180 | 00.0088 ± 0.0028 | 00.0109 ± 0.0023 | 00.0118 ± 0.0059 | 00.0102 ± 0.0028 | 00.0106 ± 0.0039 |
| Ta181 | 00.0037 ± 0.0017 | 00.0031 ± 0.0009 | 00.0064 ± 0.0028 | 00.0030 ± 0.0013 | 00.0034 ± 0.0019 |
| Pb208 | 00.0034 ± 0.0018 | 00.0039 ± 0.0003 | 00.0072 ± 0.0042 | 00.0027 ± 0.0008 | 00.0020 ± 0.0012 |
| Th232 | 00.0070 ± 0.0025 | 00.0082 ± 0.0020 | 00.0127 ± 0.0048 | 00.0059 ± 0.0017 | 00.0070 ± 0.0033 |
| U238 | 00.0033 ± 0.0004 | 00.0022 ± 0.0009 | 00.0038 ± 0.0030 | 00.0016 ± 0.0007 | 00.0014 ± 0.0008 |

in an attempt to examine pottery that met numerous criteria. First, we wanted to examine pottery from sites located on different volcanic series on Tutuila Island. Second, we wanted to examine pottery from sites located on different islands across the Samoan archipelago. Third, we wanted to examine pottery from sites that were broadly contemporaneous; as such, an attempt was made to examine pottery taken from contexts that dated to between 2800 and 2300 BP, but we recognize that some samples were recovered from much better dated contexts than other samples.

## 4. Results

### 4.1. Tutuila clays

Prior to examining the geochemical variability of ceramic artifacts recovered on Tutuila Island, we needed to determine whether geochemical variation in Samoan clays is detectable using LA-ICP-MS as well as whether any detected variation is sufficient to differentiate between intra-island volcanic series. The results of the LA-ICP-MS characterization clearly differentiate between the seven clays from the three volcanic series (Table 2). Although the number of tile samples does not meet the minimal adequate sample size necessary to perform k-means cluster analysis or PCA, bivariate plots of different elements show that clays and volcanic series can be differentiated (Fig. 2), and that this differentiation is primarily driven by Co, Cr, Cu, Ni, Rb, V, and Zn. Examination of these bivariate plots show that specific elements can be used to distinguish between specific volcanic series; for example, Cu and Rb can be used to distinguish the Alofau series (Clay 619) from the Leone series (Clays 1197 and 1200).

Without studies focused on the clay collection and processing practices of prehistoric Samoan potters, we hesitate to claim that these specific clays were being used to produce the artifacts examined here. However, we are confident that our tile samples begin to represent the range of geological variability present in Tutuilan clays and are sufficient to examine whether or not LA-ICP-MS can be used to distinguish between clays from different volcanic series. The level of differentiation produced by this characterization is extremely encouraging for the application of this LA-ICP-MS toward examining intra-island pottery production provenance on Tutuila Island.

### 4.2. Production and distribution of pottery on Tutuila Island

We next analyzed 147 ceramic artifacts recovered from four archaeological sites on Tutuila Island. The first two principal components explain 82.01% of the variability observed in the LA-ICP-MS analyses. Four groupings can be observed on a bivariate plot of these two components (Fig. 3). The first, most distinct group consists of 32 artifacts from Vainu'u that clearly separate from the remainder of the samples and can be observed on the left side of Fig. 3. A second, less distinct group, observed along the upper *Y*-axis, contains the rest of the Vainu'u samples along with one sample from 'Aoa. A third, also less distinct, group in the lower right hand corner contains samples mainly from Ulu Tree, but also three samples from 'Aoa and two from Aganoa. The largest group, observed along the right side of the graph, contains samples from Ulu Tree, Aganoa, and 'Aoa.

A k-means 5-cluster solution was determined to be the best cluster solution (Kintigh and Ammerman, 1982). This solution groups the assemblage with three clusters dominated by samples from Vainu'u and two clusters both containing samples from Aganoa, 'Aoa, and Ulu Tree (Tables 2 and 3). Samples plotted by k-means cluster using the first two PCA components show comfortable agreement between the two methods (Fig. 4). Finally, bivariate plots suggest that clusters are driven by differences in Co, Cr, Cu, Fe, Rb, Ti, V, and Zn (Fig. 5; see also Fig. 9); for example, cluster 5 samples are relatively low in V and Rb when compared to samples from other clusters. Examination of PCA and k-means cluster results provides two clear patterns: the majority of the ceramic material from the highland site of Vainu'u is compositionally different than material from the other sites, and material from the other three sites cluster together. Each of these patterns is considered in turn.

The data presented here show that the majority of Vainu'u samples cluster together, with limited overlap with coastal site material. This suggests that pottery produced at Vainu'u was not being moved back and forth from Vainu'u to lowland sites. These findings are in agreement with previous investigations at the site. Although no direct evidence of pottery production was recovered from Vainu'u, petrographic data and refired paste color suggest that the pottery recovered was produced from nearby sources (Eckert and Welch, 2009). As such, Eckert and Welch argued that pottery at Vainu'u was being produced for on-site use.

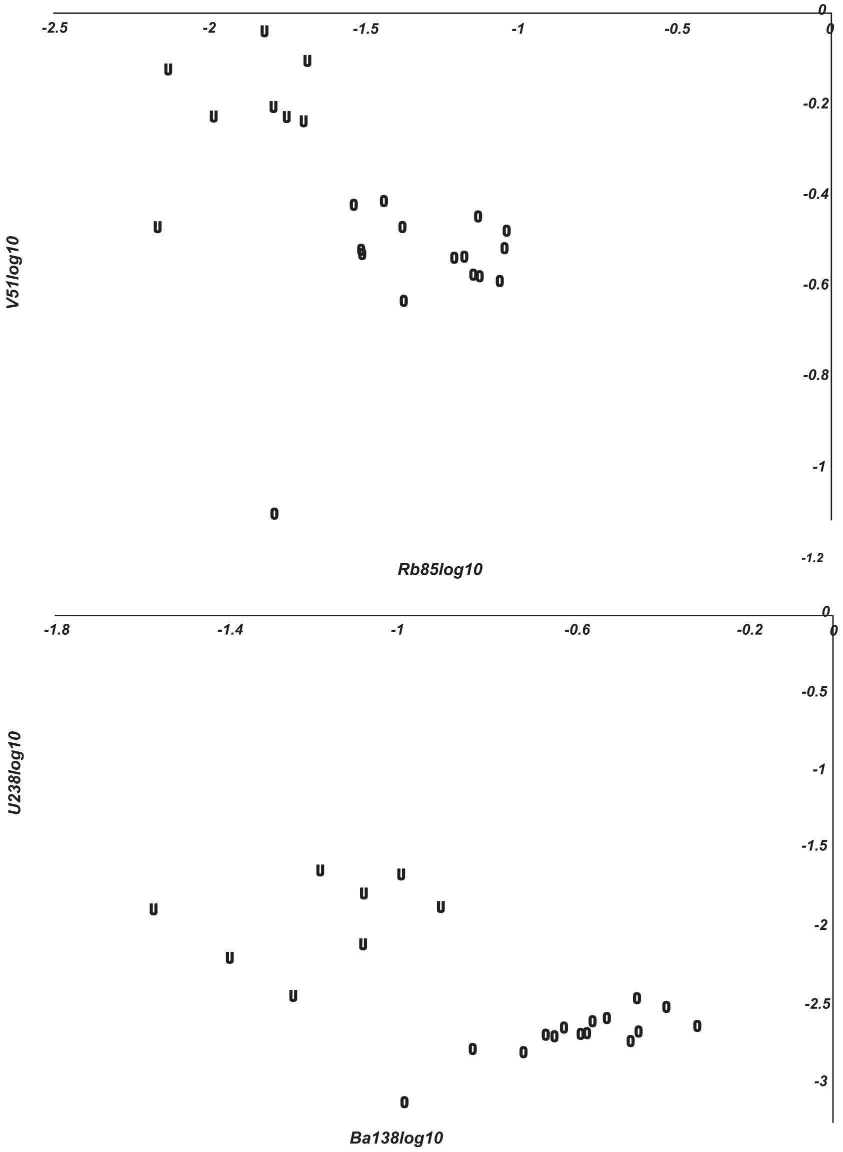

**Fig. 7.** Bivariate plot showing differentiation of sherds by island. Values given are log - 10 oxide concentrations: (O) Ofu Island; (U) Upolu Island.

Two sherds recovered from Vainu'u, V008.140 and V013.83, are grouped in k-means cluster 2 (Table 3). This cluster is dominated by material from the three lowland sites. Examination of these two sherds on the PCA graph as well as on bivariate plots of different elements show that they do not separate out from the lowland material. We interpret this as suggesting that these two samples were made from the same suite of clays that sherds recovered from lowland sites were made. These two sherds may represent vessels that were produced at lowland sites, and were then brought to Vainu'u. If we can eventually trace the production provenance of these vessels with a larger compositional database of Tutuila pottery and raw clays, then we may gain a clearer idea of which lowland villages were associated with activities occurring at Vainu'u.

Pottery recovered from Ulu Tree, Aganoa and 'Aoa all seem to have been produced from the same two clay provinces as reflected by the k-means clusters (Table 3) and PCA graph (Fig. 3). These findings could reflect a variety of different behaviors. On the one hand, potters at different villages may have been using the same clay sources to produce their wares; on the other hand, pottery may have been produced at only one or two villages and then was moved between villages. A third alternative is that pottery was produced at multiple villages, but then moved between villages during feasts, life cycle events, or exchange. Without a larger compositional database of pottery and raw clays, and more detailed technological analyses of artifacts, we currently cannot distinguish between these three possibilities.

One ceramic sherd, AG704, recovered from Aganoa appears to be an anomaly. Although it clusters with the Vainu'u material in the k-means cluster analysis, it separates out at the central bottom portion of the PCA graph (Fig. 3). Chemically, what separates this sherd from the rest of the samples is a relatively low amount of V, Zn and Cr when compared to sherds from other villages. This sherd may have been produced from the clay on Tutuila Island that is not well represented in the data set, or it may have been produced off island. This latter possibility is explored in the next section.

### 4.3. *Production and distribution of pottery across the Samoan archipelago*

To examine evidence for movement of pottery between islands in the Samoan archipelago, we added 8 sherds from Upolu Island and 15 sherds from Ofu Island to the Tutuila database. The first two

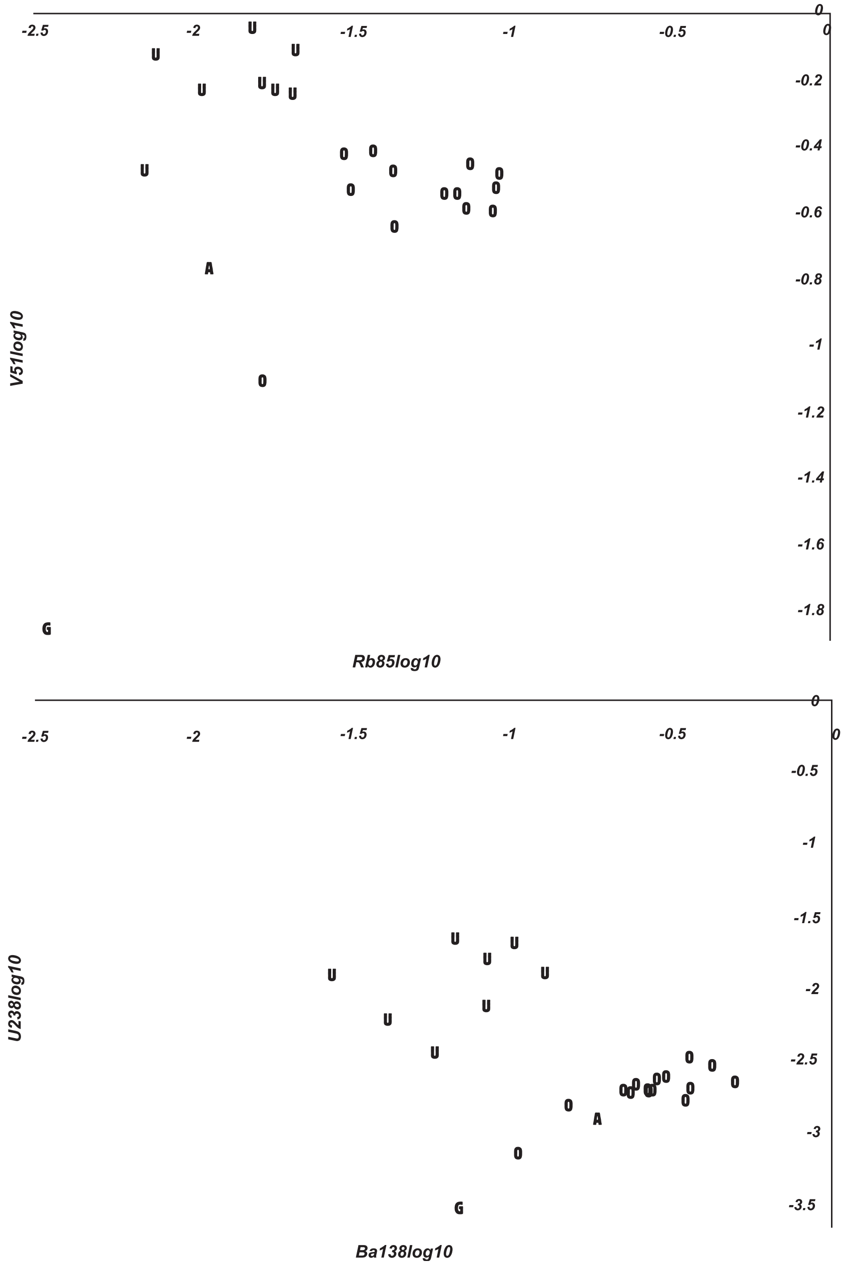

**Fig. 8.** Bivariate plot showing placement of two sherds recovered on Tutuila island but clustered with sherds from Ofu and Upolu islands in the k-means 5-cluster solution. Values given are log - 10 oxide concentrations: (O) Ofu Island; (U) Upolu Island; (A) ‘Aoa site on Tutuila Island; (G) Aganoa site on Tutuila Island.

principal components of the PCA account for only 54.51% of the variability observed in the LA-ICP-MS data, and the first three principal components of the PCA only account for 64.09%. Despite these low percentages, sherds collected from Ofu Island and Upolu Island do group toward the top of a bivariate plot of the first two PCA components (Fig. 6). A k-means 5-cluster solution separates the Ofu and Upolu material from the Tutuila material, but combines these two islands into the same cluster (Table 4). The PCA graph suggests that these two islands may be distinguishable from one another if examined separate from the Tutuila material (Fig. 6). However, if we exclude the Tutuila data, we do not have a sample size large enough to perform k-means analysis or PCA. As such, we examined bivariate plots and found that specific elements can be used to separate Ofu and Upolu ceramic material. For example, material from Ofu is relatively high in Rb and relatively low in V when compared to material from Upolu (Fig. 7a); similarly, material from Ofu is relatively high in Ba and relatively low in U when compared to material from Upolu (Fig. 7b). In other words, these elements can be used to distinguish material from Ofu Island and Upolu Island.

Three anomalous samples need to be addressed: AG704 recovered from Aganoa on Tutuila Island, AoaAS11 recovered from ’Aoa on Tutuila Island, and Vaoto871 recovered from Va’oto on Ofu Island. On the PCA plot, each of these samples lie to the far left of the graph, suggesting that they may be compositionally different than the majority of the material analyzed. The two ceramic samples recovered from sites on Tutuila Island are grouped with the material from Upolu and Ofu in the k-means cluster analysis (Table 4), tentatively suggesting these two sherds may have been produced on one of these two islands. We compared the two

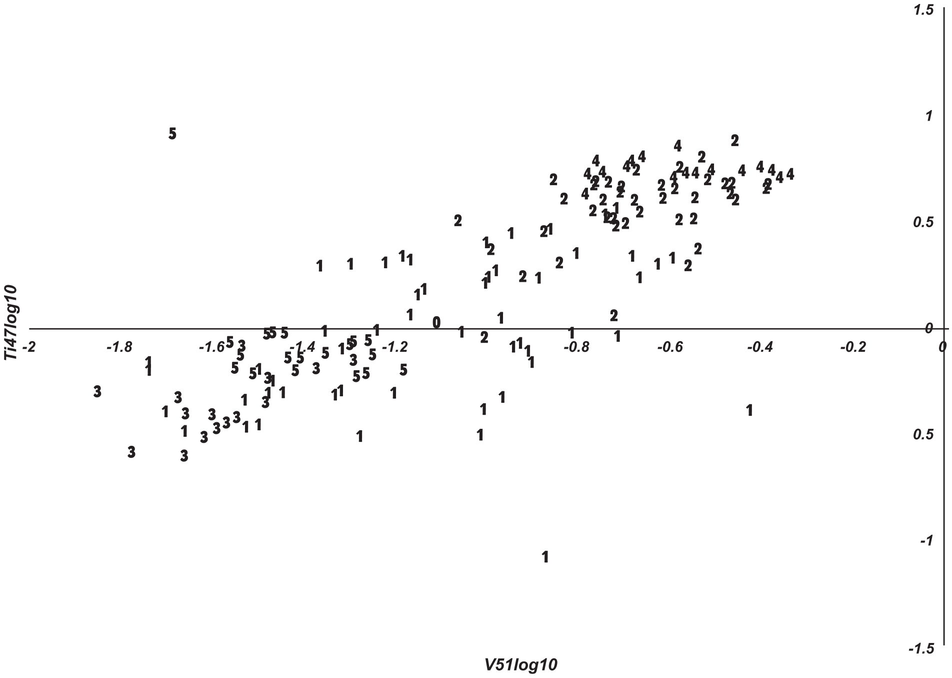

**Fig. 9.** Bivariate plot of log - 10 oxide concentrations for V and Ti showing differentiation of Tutuila sherds by k-means 5-cluster solution along with placement of sherd recovered from the site of Va'oto on Ofu island: (O) sample Vaoto871; (1) cluster 1 dominated by Tutuila coastal sites; (2) cluster 2 dominated by Tutuila coastal sites; (3) cluster 3 dominated by Vainu'u; (4) cluster 4 dominated by Vainu'u; (5) cluster 5 dominated by Vainu'u.

anomalous samples recovered from Tutuila Island on bivariate plots using those elements identified above as distinguishing between material from Ofu Island and Upolu Island (Fig. 8). These plots show that, despite their k-means cluster assignment, these two samples do not group with either the Ofu material or Upolu material and therefore cannot be comfortably identified as having been produced on either of these islands. These two sherds are produced from clays that are not well represented in the data set and, as such, cannot be assigned a production provenance without further data.

Vaoto871, recovered from Ofu Island, is grouped with material from Tutuila Island in the k-means cluster analysis (Table 4). When examined with the Tutuila material using elements identified as those that can distinguish between Vainu'u and lowland sites, this sample clearly groups with the coastal village material (Fig. 9). As such, this sample may represent a vessel that was moved from a coastal village on Tutuila Island to Va'oto on Ofu Island. Although this sample is the only evidence for the movement of pottery between islands, residents from different islands may have been interacting through activities that did not require pottery, or off-islanders were not obligated to bring goods that required pottery for transportation. Due to the availability of workable clay on islands throughout the Samoan archipelago as well as the low level of skill required to produce plain ware vessels, pottery was probably not an exchange good in high demand.

## 5. Discussion and conclusions

Using LA-ICP-MS, we can confidently distinguish between different clay formations on a single island in the Samoan archipelago. The above analysis shows that both experimental tiles made from wild clays and ceramic artifacts recovered from archaeological sites can be differentiated. Pottery recovered from sites on Tutuila Island have different patterns of distribution: pottery from lowland sites were made from the same suite of clays and may have been moving between villages through various social events, while pottery from a highland site was made from a different suite of clays and does not appear to have been distributed far from the site. Despite limitations placed on this study by sample size and chronological control, these findings provide more detail concerning the intra-island production and distribution of pottery than petrography alone. Unfortunately, greater chronological control and more detailed technological analyses are needed to confidently interpret these patterns.

In terms of inter-island interaction, our LA-ICP-MS analyses confirm previous petrographic studies (Clark and Michlovic, 1996; Dickinson, 1969, 1993, 2006; Eckert, 2006; Eckert and Pearl, 2006; Eckert and Welch, 2009) suggesting that pottery was being made on all three Samoan Islands examined here. Further, we found only limited evidence for movement of pottery between islands. One sherd recovered from a site on Ofu shared compositional characteristics with sherds recovered from a site on Tutuila and is interpreted as having been moved between these two islands. Clearly, data from more sites representing the entire 1500+ years of pottery production is necessary to see if this one sherd is evidence of an uncommon event, or if movement of pottery was more common in some periods, or between some islands, than others.

Examination of pottery from multiple islands allow us to conclude that LA-ICP-MS can provide the type of data that we seek, and may be a viable geochemical technique at other volcanic islands in the Pacific. However, results must be considered using multiple statistical techniques and an understanding of the geological context. LA-ICP-MS analyses provide archaeologists with the potential to test hypotheses concerning ceramic manufacture and distribution that has not previously been achieved in Samoan ceramic studies. A larger database of both clays and sherds from multiple sites on multiple islands, along with better chronological control, is necessary to thoroughly take advantage of this potential.

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