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INAA of pre-contact basalt quarries on the Samoan Island of Tutuila: a preliminary baseline for an artifact-centered provenance study

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Abstract

This project presents a material-centered instrumental neutron activation analysis (INAA) characterization of 120 geologic samples selected from four fine-grained basalt quarries on the Samoan Island of Tutuila. Previous attempts at definitive differentiation of these Tutuilan quarries have utilized x-ray fluorescence (XRF). In this study, clear differentiation of each analyzed quarry was achieved using INAA. Biplots of canonical discriminant analysis (CDA) scores for the INAA data illustrate clear separation based on the variation in chemical composition between each quarry. The samples analyzed not only define quarry separation, but also provide the ''core group'' for a preliminary baseline necessary for future artifact-centered provenance studies. Inclusion of these ''core group'' samples in the baseline was confirmed by stepwise discriminant analysis. These findings suggest the ability to determine artifact quarry of origin on the island of Tutuila, which can elucidate the importance of individual Tutuilan quarries in the production, distribution and consumption of fine-grained basalt artifacts in Polynesia.

Keywords: INAA; Provenance study; Basalt; Quarry; Samoa; Polynesia

1. Introduction

The Samoan island of Tutuila (Fig. 1) has long been thought of as a prominent source of fine-grained basalt in West Polynesia, as indicated by the missionary Heath in 1840 in a communication to the weekly Honolulu paper *The Polynesian*,

> ''At Tutuila, however is found the hard stone (Trap) of which the Polynesian adzes and other tools were made previously to the introduction of iron. At the other islands the stone is almost uniformly porous of a dull black color. (Heath, 1840)''

Sir Peter Buck (Te Rangi Hiroa) began the investigation of Tutuilan basalt quarries in 1927 with his search for the quarry known as Tataga-matau (Buck, 1930). In his investigation, Buck was told by Leone village elders that, ''people came from all parts of Tutuila to obtain stone adzes at Tataga-matau'' (Buck, 1930:331). Although early research focused primarily on the Tataga-matau quarry complex (Buck, 1930; Leach and Witter, 1987, 1990), more recent investigations have discovered multiple basalt exploitation sites on the island of Tutuila (Clark, 1989).

In fact, Tutuila contains the only known basalt quarries in the Samoan archipelago (Green and Davidson, 1974). These sites range in size and scope from the large quarry complexes of Tataga-matau, Fagasa, and Faga'itua, to smaller less extensive areas of basalt exploitation and tool manufacture (Table 1). The scale and complexity of certain quarry sites and their association with large-scale assemblages of stone tool grinding dishes or whetstones (*fo'aga*) are factors that have led to the proposal of Tutuila as a possible industrial center of basalt tool manufacture for the purpose of exchange

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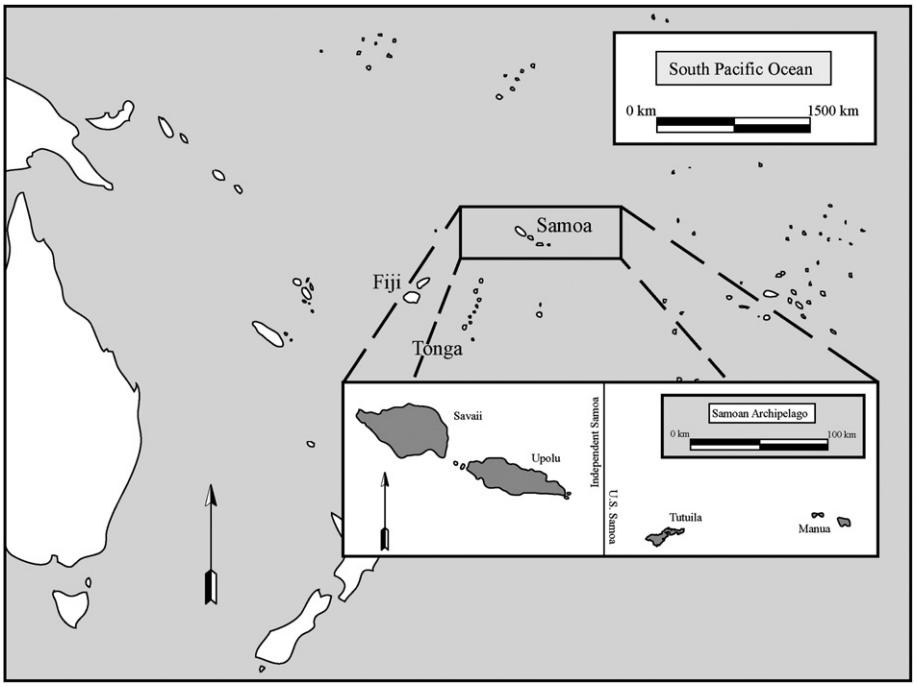

Fig. 1. The Samoan archipelago.

(Best et al., 1992; Clark et al., 1997). Provenance study of Tutuilan material has often tested the possibility of long-distance inter-island exchange (Best et al., 1992; Weisler, 1993a; Weisler and Kirch, 1996). Chemical characterization has identified basalts of Tutuilan origin as far as 1600 km from their source, on Mangaia (Weisler and Kirch, 1996), and several provenance studies have linked Tutuila with stone tools recovered throughout the Pacific (Allen and Johnson, 1997; Best et al., 1992; Weisler, 1993a).

Although Tutuilan basalts have been identified on other Pacific islands they were not always confidently traced to an individual quarry of origin (Allen and Johnson, 1997; Best et al., 1992; Clark et al., 1997). One factor that may have limited confident quarry-level artifact assignment is that Tutuilan provenance studies have primarily focused on artifacts and artifact assignment, not on the definition of quarry source geological variability. Initial attempts to distinguish intra-island quarry signatures did not achieve confident differentiation between multiple Tutuilan quarries (Best et al., 1992; Clark et al., 1997). In 1993, Marshall Weisler addressed this issue stating, ''until most of the major sources of adze material in Polynesia (or a particular study area) have been identified and their chemical variability understood, specifying a particular quarry for each artifact may not be possible'' Weisler (1993b:68). Before an artifact can be confidently sourced to the Tutuilan quarry of its origin, a comprehensive analysis of each known Tutuilan quarry must be completed to properly define the study area. In order to achieve that goal, the rubric of Samoan provenance study must shift.

To that end, the primary focus of this research is the definition of the geological variability of individual Tutuilan basalt quarries, not the investigation of artifact assignment. Only geologic samples were considered for this project, as the immediate goal was to establish preliminary baseline data for select Tutuilan basalt quarries. To do this, we must meet two objectives. First, we must determine whether geochemical variation in Tutuilan basalts is detectable using instrumental neutron activation analysis (INAA) as the analytical approach. Second, any detected variation using INAA must be sufficient to differentiate between intra-island quarries. Successful

Table 1
Tutuilan basalt quarries

Quarry	Site no.	Size (m^2)	References
Alega 1	AS-23-022	123	Clark (1992) and Clark et al. (1997)
Alega 2	AS-23-023	495	Clark (1992) and Clark et al. (1997)
Alega 3	AS-23-029	250	Clark (1992) and Clark et al. (1997)
Asiapa	AS-23-031	205	Clark (1989) and Clark et al. (1997)
Fagasa 1	AS-26-010	27000	Best (1993) and Clark et al. (1997)
Fagasa 2	AS-26-011	525	Best (1993) and Clark et al. (1997)
Faga'itua	–	16000	Clark (1989) and Clark et al. (1997)
Lau'agae	AS-21-100	10000	Clark (1989), Clark et al. (1997) and Moore and Kennedy (1996)
Le'aeno	AS-21-110	50	Clark (1989) and Clark et al. (1997)
Leafu	–	123	Best et al. (1992) and Leach and Witter (1985, 1987)
Masui's	AS-25-071	–	Report on file at ASHPO
Tataga-Ml	AS-34-010	–	Best et al. (1992), Best et al. (1998) and Leach and Witter (1985, 1987)
Tataga-M2	AS-34-010	–	Best et al. (1992), Best et al. (1998) and Leach and Witter (1985, 1987)
Tataga-M3	AS-34-010	–	Best et al. (1992), Best et al. (1998) and Leach and Witter (1985, 1987)
Usi 1	AS-23-012	70	Clark (1989) and Clark et al. (1997)
Usi2	AS-23-014	300	Clark (1989) and Clark et al. (1997)
Vai's	AS-25-072	–	Report on file at ASHPO

completion of these two objectives stands to create the foundation for INAA provenance studies of Samoan basalt. With the continued progress of chemical characterization in Polynesia (Weisler, 2002, 2003) and the complexity of questions centered on Samoan involvement in Polynesian basalt trade networks, this level of analysis will be a valuable contribution to Polynesian archaeological research.

2. Background

2.1. Geography and geology

The Samoan archipelago lies east of the andesite line, a boundary that splits the South Pacific into separate geologic divisions. The extrusive rocks found on volcanic islands to the east of the Andesite line are composed of basalt. The Samoan islands are a series of oceanic basalt shield volcanoes that trend easterly at approximately 14° south latitude and 170° west longitude (MacDougall, 1985; Natland, 1980), and Tutuila lies in the center of the archipelago (Fig. 1). The Tutuilan shield-building lavas are mostly alkalic olivine basalts and hawaiities that provide fine-grained material for lithic manufacture (MacDonald, 1944). The Tutuilan landscape is deeply dissected, as a precipitously abrupt montane interior contrasts narrow coastal flats and valleys. The only substantial uninterrupted portion of the island is the broad level Tafuna plain. This area on the southwestern flank of the island was formed in the Holocene by the post-erosional Leone volcanism (MacDougall, 1985; Stearns, 1944).

H.T. Stearns (1944) conducted the definitive geologic survey of Tutuila. Stearns (1944) characterized the island as the end product of four major shield volcanic centers—Alofau, Olomoana, Pago, and Taputapu—as well as the more recent post-erosional Leone Volcanics (Fig. 2). In 1985, Ian MacDougall (1985) argued that the Alofau volcanics are not a discrete shield episode, but in fact the ‘‘eastern flank’’ of the central Pago volcano. For this project, the Alofau volcanics are not designated as a distinct volcanic episode, and in accordance with MacDougall (1985) included in the Pago volcanic province (Fig. 2).

2.2. Tutuilan geochemical characterization studies

The archipelagos of Polynesia stretch great distances across the Pacific. Some islands are isolated by hundreds of kilometers of open water, but Polynesian ocean voyaging tradition allowed for contact and interaction based on inter-island trade networks (Davidson, 1977; Kaeppler, 1978; Weisler, 1997, 1998, 2002). Over the past two decades, provenance studies have become an integral method for investigation of Polynesian seafaring and inter-island interaction (Allen and Johnson, 1997; Best et al., 1992; Clark et al., 1997; Rolett et al., 1997; Sheppard et al., 1997; Smith et al., 1977; Walter and Sheppard, 1996; Weisler, 1993a; 1997; 1998; 2003; Weisler and Kirch, 1996; Weisler and Sinton, 1997; Weisler and Woodhead, 1995; Weisler et al., 1994). In that time, Polynesian provenance studies have been primarily focused on the chemical characterization of basalt artifacts and their sources (Allen and Johnson, 1997; Best et al., 1992; Clark et al., 1997; Moore and Kennedy, 1996; Parker and Sheppard, 1997; Rolett et al., 1997; Sheppard et al., 1997; Walter and Sheppard, 1996; Weisler, 1993a; 1997; 1998; 2002; Weisler and Kirch, 1996; Weisler and Woodhead, 1995; Weisler et al., 1994). Many chemical characterization studies of Polynesian basalt artifacts have included samples from the Samoan island of Tutuila (Allen and Johnson, 1997; Best et al., 1992; Clark et al., 1997; Moore and Kennedy, 1996; Weisler, 1993a; Weisler and Woodhead, 1995).

Prior to this project, geochemical provenance studies attempting to characterize Tutuilan basalts have primarily utilized X-ray fluorescence (XRF) (Allen and Johnson, 1997; Best et al., 1992; Clark et al., 1997; Moore and Kennedy, 1996; Weisler, 1993a,b; Weisler and Kirch, 1996), or isotope analysis (Weisler and Woodhead, 1995). Beardsley and Coles (2001) used INAA to analyze obsidians from Rapa Nui, but this project represents the first application of INAA towards

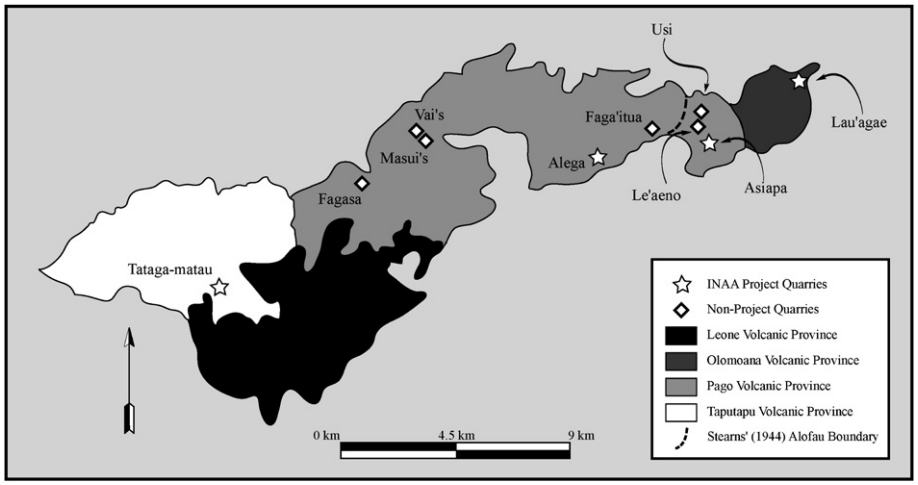

Fig. 2. Samoan Island of Tutuila, adapted from Stearns (1944) and Clark et al. (1997).

the characterization of Samoan basalts. Previous studies have successfully characterized individual quarry sources and identified inter-island movement of Polynesian basalts (Best et al. 1992, Clark et al. 1997). In Tutuilan provenance study, XRF has successfully marked the inter-island exchange of Tutuilan basalts; see Allen and Johnson (1997), Walter and Sheppard (1996) and Weisler and Kirch (1996) for analysis of basalt from the Cook Islands; see Best et al. (1992) for analysis of basalt artifacts recovered in Fiji. These studies have succeeded in determining the island of origin for Tutuilan basalts, but no previous projects have confidently differentiated between multiple Tutuilan quarries.

3. Methods

3.1. Sample selection

Following Church (1994), our research is material-centered, and the necessary first step towards properly defining the variation of Tutuilan basalt quarries. While artifact-centered studies attempt to source artifacts to their geological origin, material-centered studies focus on geologic source material and are designed toward gathering baseline information (Church, 1994). Material-centered analysis provides the foundation for confident artifact-centered provenance studies. Sample selection began with the determination of which quarries to include in the analysis. Two criteria were chosen to guide quarry inclusion. The first criterion was that all samples must be selected from quarries that had previously been chemically characterized to allow for the comparison of results with those previous attempts. Tutuilan quarries that had been previously characterized included: Alega, Asiapa, Faga'itua, Fagasa, Lau'agae, Le'aeno, Tataga-matau, and Usi (Best et al., 1992; Clark et al., 1997; Moore and Kennedy, 1996; Weisler, 1993a; Weisler and Kirch, 1996).

The second criterion was to choose quarries that would represent variation within volcanic provinces and between volcanic provinces (Weisler and Sinton, 1997). As stated earlier, for this project the Alofau Volcanics (Stearns, 1944) are considered part of the Pago Volcanics according to MacDougall (1985). For this initial investigation, a single quarry was analyzed from the Olomoana, Pago, and Taputapu volcanics to test inter-province variability, and a second Pago quarry was analyzed to test intra-province variation. No samples were tested from the Leone province because there are no known quarry sources in the Leone volcanics.

Statistical rigor required that the number of samples analyzed per quarry must be greater than the number of elements used in the analysis. The Elemental Analysis Laboratory typically reports 28 or 29 elements (based on their significance) in INAA characterization (Table 2). Rapp (1985) reports that the ideal number of samples to properly characterize a geological source using INAA is between 20 and 40. Considering these guidelines, it was determined that 30 individual samples would be an adequate preliminary amount to characterize each quarry. Phillip Johnson collected samples for this project in November 2004 from four separate quarry sites (Table 1): Alega from the Pago Volcanics ($n = 30$), Asiapa also from the Pago Volcanics ($n = 30$), Lau'agae from the Olomoana Volcanics ($n = 30$), and Tataga-matau from the Taputapu Volcanics ($n = 30$).

Table 2
INAA elements

Element	Isotope produced[a]	Energy (keV)	Half-life
Short count (P-tube)			
Aluminum (AL)	^{28}Al	1779.5	2.24 min
Dysprosium (DY)	^{165}Dy	94.5	2.33 h
Magnesium (Mg)	^{27}Mg	1014.5	9.46 min
Manganese (Mn)	^{56}Mn	1811.4	2.58 h
Titanium (Ti)	^{51}Ti	319.7	5.76 min
Vanadium (V)	^{52}V	1434.1	3.75 min
Intermediate count			
Lanthanum (La)	^{140}La	1596.2	40.27 h
Lutetium (Lu)	^{177}Lu	208.4	6.71 days
Sodium (Na)	^{24}Na	1368.6	14.96 h
Samarium (Sm)	^{153}Sm	103.2	46.27 d
Uranium (U)[b]	^{239}Np	106.1	2.36 d
Ytterbium (Yb)	^{175}Yb	396.3	4.19 d
Long count			
Barium (Ba)	^{131}Ba	496.3	11.80 d
Cerium (Ce)	^{141}Ce	145.4	32.50 d
Chromium (Cr)	^{51}Cr	320.1	27.70 d
Cobalt (Co)	^{60}Co	1332.5	5.72 years
Europium (Eu)	^{152}Eu	1408.0	13.33 years
Hafnium (Hf)	^{181}Hf	482.2	42.39 days
Iron (Fe)	^{59}Fe	1099.2	44.50 days
Neodymium (Nd)	^{147}Nd	91.1	10.98 days
Rubidium (Rb)	^{86}Rb	1076.6	18.66 days
Scandium (Sc)	^{46}Sc	889.3	83.31 days
Strontium (Sr)	^{85}Sr	514.0	64.84 days
Tantalum (Ta)	^{182}Ta	1221.4	114.50 days
Terbium (Tb)	^{160}Tb	879.4	72.30 days
Thorium (Th)[c]	^{233}Pa	312.0	27.00 days
Zinc (Zn)	^{65}Zn	1115.6	243.90 days
Zirconium (Zr)	^{95}Zr	756.7	64.02 days

[a] Glascock, 1991.
[b] Neptunium (Np) is used to detect uranium.
[c] Protactinium (Pa) is used to detect thorium.

Geologic samples were selected using a stratified random strategy in an attempt to represent the variability of material and texture exploited at each site. Sample selection was restricted to the immediate area containing evidence of basalt exploitation. Artifacts were not selected because this was a material-centered attempt at defining the quarry source variation. Each of the 30 quarry samples were chosen from separate untested surface materials. Surface material was sampled because it is indicative of material exploited prehistorically (Clark et al., 1997; Leach and Witter, 1985; Weisler and Sinton, 1997). The term quarry is somewhat spurious when applied to Tutuilan archaeological sites. In accordance with Clark et al. (1997) we use "quarry" to refer to a prehistoric site of fine-grained basalt exploitation and tool manufacture, and not necessarily to a method of basalt mining. The actual mining of material is not probable for most Tutuilan "quarry" sites, with the possible exception of Tataga-matau (Clark et al., 1997; Leach and Witter, 1985). In fact throughout Polynesia

there is scant evidence to support the extraction of fine-grained basalt for tool making; at most Polynesian quarries the exploited basalt was derived from erosional surface features and dykes (Weisler and Sinton, 1997).

3.2. Chemical characterization

Under the supervision of Dr William D. James, of the Elemental Analysis Laboratory (EAL), all samples included in this project were processed at the Texas A&M University Center for Chemical Characterization and analyzed using instrumental neutron activation analysis at the Texas A&M Nuclear Science Center's 1 MW TRIGA research reactor. Sample preparation and analysis was conducted according to established EAL methods (James et al., 1995). The samples submitted for INAA were comprised of 50 mg of non-cortical material. Control measures included the duplication of every seventh sample as well as inclusion of National Institute for Standards and Technology (NIST) 1633a coal fly ash, and NIST SRM 688 basalt.

3.3. Why INAA?

This is the first application of INAA towards the characterization of Samoan basalts. INAA was chosen as the analytical method for this project because it is one of the most sensitive and accurate tools for chemical characterization available through the Texas A&M Center for Chemical Characterization. INAA has greater analytical sensitivity than previous methods (Neff, 2000; Bishop et al., 1990); Weisler and Kirch (1996:1383) suggest the use of more sensitive methods such as INAA may be necessary when attempting to differentiate, ''Oceanic basalts that are highly similar in geochemical composition.'' According to Bishop et al. (1990:539), '' in comparison to fully quantitative XRF, INAA is more sensitive and can detect some elements having concentrations as low as a few parts per billion.'' This sensitivity has established INAA as a preferred technique in archaeometric sourcing analyses (Bishop et al., 1990; Neff, 2000). It was determined that the sensitivity of INAA over other methods, could be a key factor in the differentiation of Tutuilan basalt quarries.

3.4. Statistical methodology

To explore the possible affiliation of samples based on compositional variability, both canonical discriminant analysis (CDA) and principal component analysis (PCA) were applied to the INAA data (Baxter, 1994; Glascock, 1992). Initially, CDA was applied to test the affiliation of the samples with an assigned quarry of origin. After the application of CDA the samples were treated as of unknown origin and PCA was used to differentiate between the quarries. Prior to statistical analysis, all INAA data were log base-10 transformed (Baxter, 1994; Glascock, 1992). All multivariate statistical methods were applied to INAA results using SPSS version 11 for Mac OSX.

4. Results

The results of the INAA characterization clearly differentiate between the four quarries; and these empirical data strongly support the overarching goals that inspired this project. However preliminary, the level of differentiation produced by this characterization is extremely encouraging for the application of INAA towards future comprehensive definition of Tutuilan quarry variation, and artifact sourcing. The quarry differentiation achieved through CDA provides definitive separation of the analyzed Tutuilan quarry sources. In accomplishing this task CDA has identified a ''core group'' of samples that create the preliminary baseline for future artifact-centered provenance studies; and although the differentiation produced by PCA is less perceptible than CDA, the results are encouraging; and further bolstering of the CDA baseline can be achieved by refining the application of PCA.

4.1. Canonical discriminant analysis

Overall, the CDA results provide very clear separation between quarries. The first two-discriminant functions created by CDA represent the variability of over 93% of the sample population (Table 3), and a biplot of these first two discriminant functions displays definite differentiation of the quarries (Fig. 3). Quarry membership for each individual sample was set at a confidence of 0.95. Initially, each of the 120 quarry samples was predicted to the proper quarry of origin with confidence of at least 0.99. Only eight of the 120 samples were not predicted to the proper quarry membership with 1.00 confidence, and seven of the remaining eight samples were all predicted with the extremely high confidence of 0.999. Of the 120 samples, sample PJ003 (collected at Lau'agae quarry) had the lowest initial confidence of quarry membership at 0.99747.

After the initial CDA, the INAA data was analyzed using the stepwise or ''jack-knife'' CDA method to determine if the samples were appropriately assigned or if certain samples may be unknown (Duff, 2002). After jack-knifing the data, only one sample's confidence dropped below 0.99. The probability of sample PJ003 belonging to Lau'agae quarry dropped from 0.99747 to 0.90123. This sample was deemed the only unassigned sample due to assignment confidence below 0.95.

4.2. Principal components analysis

After successful differentiation of the quarries using CDA, the INAA results were explored using PCA, as if the samples were of unknown origin. This was done to test the ability to distinguish between Tutuilan basalts of unassigned origin.

Table 3
CDA functions

Function	Eigenvalue	% of Variance	Cumulative %	Canonical correlation
1	38.273	77.8	77.8	0.987
2	7.890	16.0	93.9	0.942
3	3.007	6.1	100.0	0.866

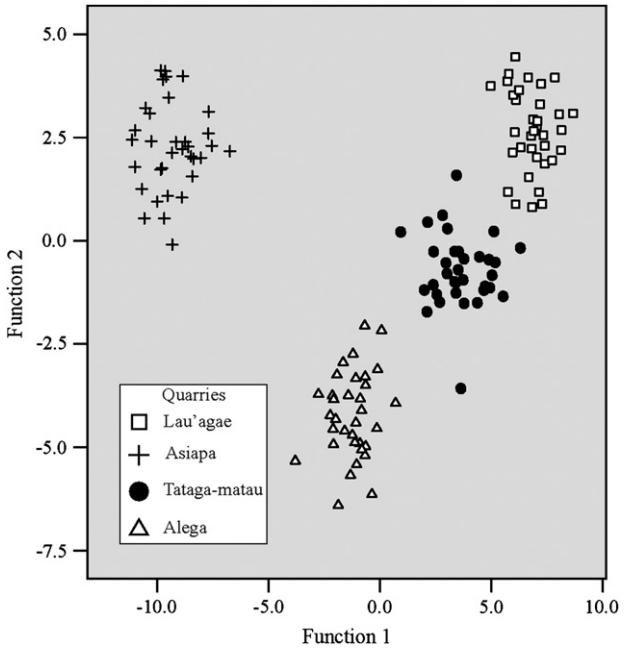

Fig. 3. Biplot of CDA functions 1-2.

Although PCA did differentiate the majority of quarry samples, it was predictably not as successful as CDA. This is apparent in the PCA biplot (Fig. 4). Although most of the intra-quarry samples group together, there is less apparent separation than in the CDA plot. The first two functions created by CDA represent 93% of the variability, while the first two PCA scores only provide 68%. The first two principal component scores simply do not represent enough variation to confidently differentiate between all analyzed quarries. When compared to the CDA results it is evident how the first two discriminant functions differentiate between the populations more successfully than the principal component scores.

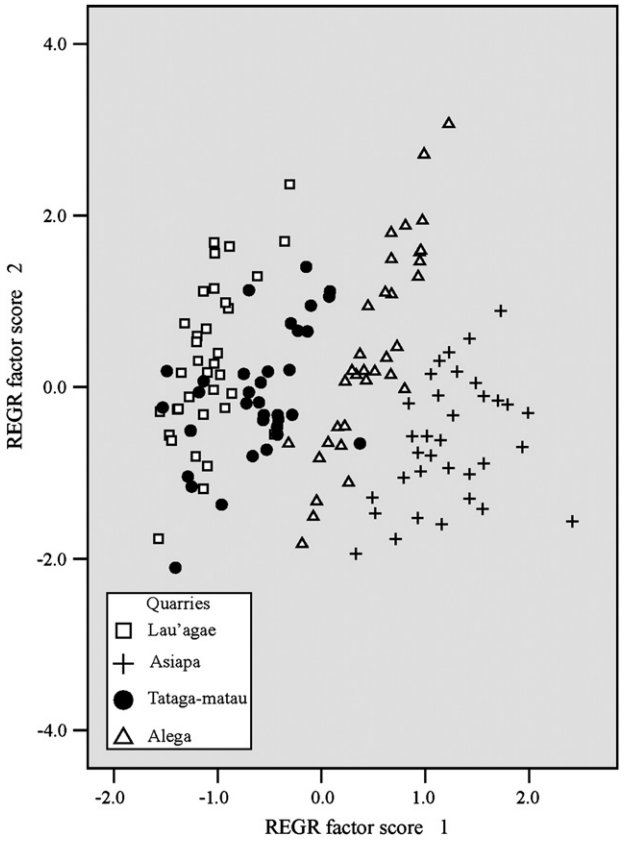

Fig. 4. Biplot of PCA scores 1-2.

4.3. Summary

The differentiation displayed in the INAA data illustrates clear separation of quarries based on inter-quarry chemical composition. The results of CDA on the data provide the unequivocal confidence of 1.00 assignment to proper quarry origin for 112 of the 120 samples. Of the eight samples below 1.00, seven were assigned with extremely high confidence at 0.999, while only sample PJ003 was rejected due to an assignment confidence of 0.90123. The remaining 119 samples create a definitive ''core group'' of geological quarry samples. This ''core group'' not only defines the individual quarries that are represented, but also establishes a preliminary baseline of geological quarry variation that can be used in comparative analysis and artifact provenance studies.

After the differentiation between the tested quarries was achieved, we attempted to determine if any particular elements may be observably driving the differentiation of the four quarries. The CDA structure matrix (Table 4) provided the

Table 4
CDA structure Matrix

	Function 1	Function 2	Function 3
V	0.565	−0.087	0.012
TI	0.340	0.130	−0.029
CO	0.331	−0.055	−0.032
LA	−0.287	−0.081	−0.101
EU	−0.272	−0.084	−0.065
SM	−0.267	−0.090	−0.091
DY	−0.252	−0.084	0.017
CE	−0.247	−0.068	−0.097
YB	−0.232	−0.094	0.057
ND	−0.219	−0.076	−0.103
TB	−0.185	−0.060	−0.045
LU	−0.175	−0.126	−0.012
MG	0.172	0.039	0.135
ZR	−0.150	−0.124	−0.043
UR	−0.115	−0.040	−0.066
NA	−0.081	−0.026	−0.079
RB	−0.078	0.013	−0.050
HF	−0.161	−0.259	−0.191
CR	0.150	0.228	−0.225
SC	0.103	−0.168	0.030
FE	0.101	−0.146	−0.053
ZN	−0.083	−0.115	0.001
TA	−0.074	−0.146	−0.272
AL	−0.009	0.018	−0.216
TH	−0.171	−0.125	−0.205
BA	−0.096	0.011	−0.176
MN	−0.061	0.008	0.168
SR	−0.014	0.131	−0.134

significance for any given individual element in defining the variability between quarry samples. According to the structure matrix, no single element significantly contributed to the variability for any of the three CDA functions. We plotted the most significant element in function 1 (vanadium) against the most significant element in function 2 (hafnium) to display the separation between quarries through individual elements (Fig. 5). These elements alone could not differentiate between all four analyzed quarries. Considering this data, it appears that the combination of multiple major and trace elements is necessary to differentiate between the selected quarry samples.

5. Conclusion and discussion

5.1. Conclusions

Using compositional data generated with INAA we can confidently differentiate these four Tutuilan quarries based on their chemical variability. Unlike the results of prior characterizations, INAA resulted in clear quarry-level differentiation of all analyzed samples. Although successful in differentiating the quarries, data compiled in this project suggests that the chemical composition of the quarries analyzed offers a minute amount of inter-quarry variability. The detectable variability appears limited, but this project clearly displays that Tutuilan intra-island quarry signatures are definable by sensitive methods of analysis such as INAA.

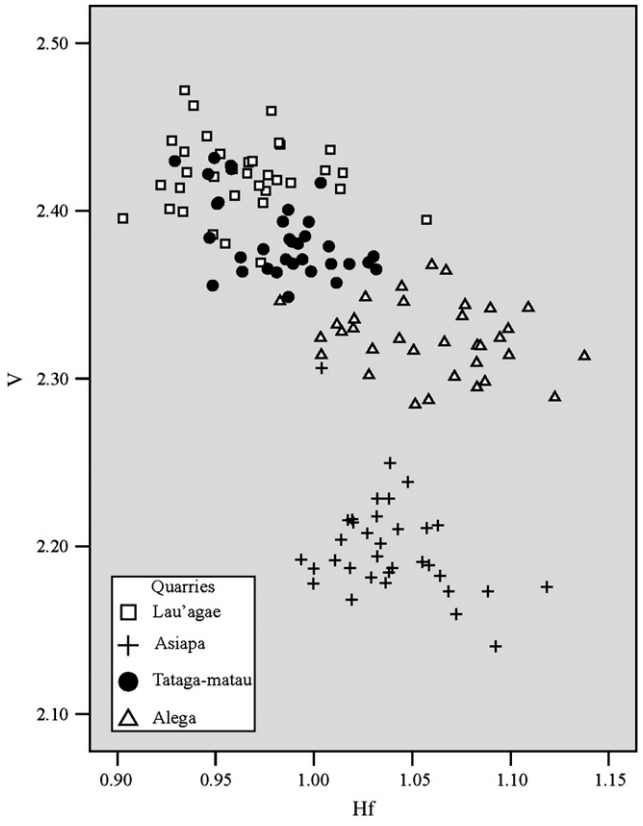

Fig. 5. Biplot of quarry samples for Vanadium-Hafnium.

There were three key factors that allowed for successful differentiation of Tutuilan quarries. The first factor was sampling strategy. This project was designed as a material-centered characterization of quarry variation. Previous Tutuilan studies have included a majority of archaeological flakes; this project was strictly focused on material-centered characterization. This sampling strategy was used to ensure that only material derived at that source was included in the characterization of that source. The high level of cohesion within quarry samples supports this material-centered approach.

A second factor important to the success of this research was sample size. This project analyzed 30 samples per quarry in order to define the variation of each source. Although this number was a marginal amount of samples necessary for proper INAA characterization, it represented a much larger material-centered population than was attempted in any previous single characterization of geologic samples from Tutuilan quarries. The larger sample size allowed a more definitive characterization of quarry composition than previously attained.

The third important factor in the successful characterization of Tutuilan quarries was the use of INAA. Although INAA has been utilized in archaeological provenance studies of Pacific island ceramic vessels (Descantes et al., 2001, 2004) and obsidians (Beardsley and Coles, 2001), it had not been previously utilized in the characterization of Samoan basalts. INAA is one of the most sensitive, precise and accurate methods of chemical characterization available (Bishop et al., 1990; Neff, 2000). When considering the CDA structure matrix (Table 4), this sensitivity appears to be key in differentiation between potentially highly similar samples.

5.2. Discussion

The quarries included in this study were selected to test the ability of INAA to define intra-island variation, not to definitively establish that variation and construct a comprehensive baseline for future reference. As stated earlier there are multiple quarries on the island, the majority of which were not characterized in this analysis; but the results of the analysis were extremely encouraging for the prospect of differentiating individual quarries on Tutuila. As is often the case of any research project, the answers attained have left room for many other avenues of investigation.

Clearly future research needs to include the characterization of quarries not included in this project. To properly define Tutuilan intra-island basalt quarry variation it is necessary to characterize all known quarries as well as conduct surveys for locating more possible unknown quarries. At this point it is especially important to differentiate multiple quarries within the same volcanic province. Addition of more characterized quarries is necessary to increase confidence in the definition of variation among Tutuilan quarries. Our preliminary results display a distinguishable amount of variation between the analyzed quarries; however this trend of clear differentiation may not improve with the addition of future quarries.

Another important avenue of research includes the addition of samples from quarries characterized in this study. This study analyzed a marginal sample size required for rigorous statistical testing. Additional sampling for each quarry will increase the confidence of definitive characterization of a quarry. Further, basalt artifacts present at each quarry should be characterized. Both material-centered and artifact-centered sampling should be employed to confirm the composition of each quarry.

Finally, future source analyses on Tutuila would benefit from a direct comparison of chemical characterization methods including isotopic analysis, XRF, INAA, and ICP-MS. A comparison of material-centered analyses will define which method (if any) is best suited for differentiating the fine-grained basalt quarries of Tutuila. This question is important because not all methods are widely available and some are more destructive than others (Shackley, 1998). Understanding the strengths and limitations of each method's ability to distinguish between quarries would allow for the optimal method to be applied in future provenance studies on Tutuila. This project represents a contribution to the foundation for provenance studies of Tutuilan basalts. The differentiation of multiple intra-island quarries was a necessary step in understanding Tutuilan basalt exploitation. The ability to clearly differentiate between multiple Tutuilan quarries was achieved using INAA, and the continued characterization of fine-grained basalts stands to create a wealth of knowledge and research into Tutuilan pre-contact economy, interaction and exchange.

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