Journal of Pacific Archaeology – Vol. 5 · No. 1 · 2014

– ARTICLE –

Non-destructive XRF Analyses of Fine-grained Basalts from Eiao, Marquesas Islands

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ABSTRACT

The Marquesan island of Eiao was an important source of fine-grained basalt in Central East Polynesia, with examples being identified in archaeological assemblages throughout the region. However, compared to many other large-scale Polynesian basalt sources, little has been published about the physical extent and geochemical variability of tool-quality basalt on Eiao; prior to our study, only a single site with evidence of stone extraction had been identified and geochemical information was limited to less than two dozen samples. In this paper we report geochemical data for 225 additional basalt specimens collected on Eiao. Our analyses were conducted non-destructively using three EDXRF instruments: one lab-based unit and two portable analysers. The majority of our sample, identified here as Group 1, possesses geochemical and physical characteristics similar to those reported in previous studies. Group 1 samples were collected from various locations on Eiao suggesting that, rather than being limited to a single quarry site, fine-grained basalt was extracted from multiple sources throughout the island. In addition, we identified a second group (Group 2), which possesses a distinct geochemistry, a coarser grain and often an unusual reddish colour. Evidence from Eiao indicates that Group 2 stone was regularly utilised and our analysis of an adze collected on Hiva Oa Island suggests that this material was distributed at least as far as the southern Marquesas.

Keywords: Eiao, Polynesia, basalt tools, XRF, non-destructive analysis

INTRODUCTION

The geochemical analysis of stone tools has a long history in Polynesian archaeological studies, dating back almost three decades (e.g., Best 1984; Best *et al.* 1992; Weisler 1993). In East Polynesia, fine-grained basalt is one of the few types of materials that has the potential to unambiguously identify the movement of artefacts between locations (see Weisler 1998). For some island groups, particularly Hawai'i (e.g., Mills *et al.* 2008, 2010; Lundblad *et al.* 2008, 2011) and Samoa (e.g., Johnson 2005, 2011; Winterhoff 2007), our knowledge of basalt tool production and distribution has been steadily accumulating over the last decade. However, for several other groups, including the Marquesas Archipelago, information remains limited. Although basalt adzes from several Marquesan sites have been geochemically analysed, stone from the most well-known and widely distributed source in the Marquesas, the island of Eiao, has to date been inadequately characterised. Currently, data for only five specimens with a secure provenance to Eiao have been published (see below), which is insufficient to understand the range of variability that might be expected from this island. Stone tools attributed to Eiao have been identified both within the Marquesas Islands (Rolett *et al.* 1997; Rolett 1998; McAlister 2011; Allen & McAlister 2013) and in several other Polynesian archipelagos, including the Tuamotu group (Collerson & Weisler 2007), the Society Islands (Weisler 1998, 2008), the Line Islands (Di Piazza & Pearthree 2001) and Mangareva (Weisler 1998, 2002; Weisler *et al.* 2004). In this paper we report data for over 200 basalt samples collected on Eiao by Charleux and colleagues and characterised with Energy Dispersive X-ray Fluorescence (EDXRF).

Traditionally, most geochemical analyses of Oceanic basalts have been carried out using Wavelength Dispersive X-ray Fluorescence (WDXRF), a technique that can provide accurate determinations for a wide range of elemental data but usually requires the partial destruction of samples (see Parker & Sheppard 1997; Weisler & Sinton 1997). Recently, the related technology of EDXRF has been increasingly employed by researchers in Polynesia (e.g., Weisler 1993:137–41; Lundblad *et al.* 2008, 2011; Mills *et al.* 2008, 2010; McAlister 2011; Allen & McAlister 2013).

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Submitted 22.5.13, accepted 5.11.13

There are particular strengths and weaknesses associated with each XRF technique, such as analytical accuracy and precision, analysis times and instrument costs (see Weisler & Sinton 1997; Parker & Sheppard 1997; Shackley 2011 for overviews of archaeological XRF applications), but perhaps the most important advantages of EDXRF are that the technique can analyse samples non-destructively and comparatively rapidly, thus allowing for the cost-efficient generation of large datasets. In this study, we present and discuss the results of analyses carried out on basalt samples from Eiao using three EDXRF instruments: one laboratory-based unit and two portable analysers.

PREVIOUS RESEARCH ON EIAO

The Marquesas archipelago is thought to have formed through volcanic hot spot activity, a process postulated for several other Oceanic island groups, including Hawai'i and Samoa (Filmer *et al.* 1994). The islands generally increase in age from southeast to northwest (Figure 1); Fatu Hiva, the southernmost island, is around 1.3 Ma, while Eiao, at the extreme northwest of the archipelago, has an approximate age of 5.8–5.0 Ma (Brousse *et al.* 1990; Desonie *et al.* 1993). Eiao's original caldera, estimated to have been about 25 km in diameter, has undergone major collapse leaving a crescent-shaped island approximately 13 km by 4 km in extent and 39 km² in area (Liotard *et al.* 1984; Caroff *et al.* 1999). The island reaches an elevation of 577 m at its highest point, Mount Mouatiketike (Figure 2). The analysis of stratified rock samples from three 800 m-deep drill holes during the 1972–1973 Bureau de Recherches Géologiques et Minières (BRGM) campaign, indicates that Eiao was formed through a series of comparatively rapid volcanic events resulting in a variety of stone types, with alkalic basalts dominating the upper few hundred metres (Caroff *et al.* 1995, 1999).

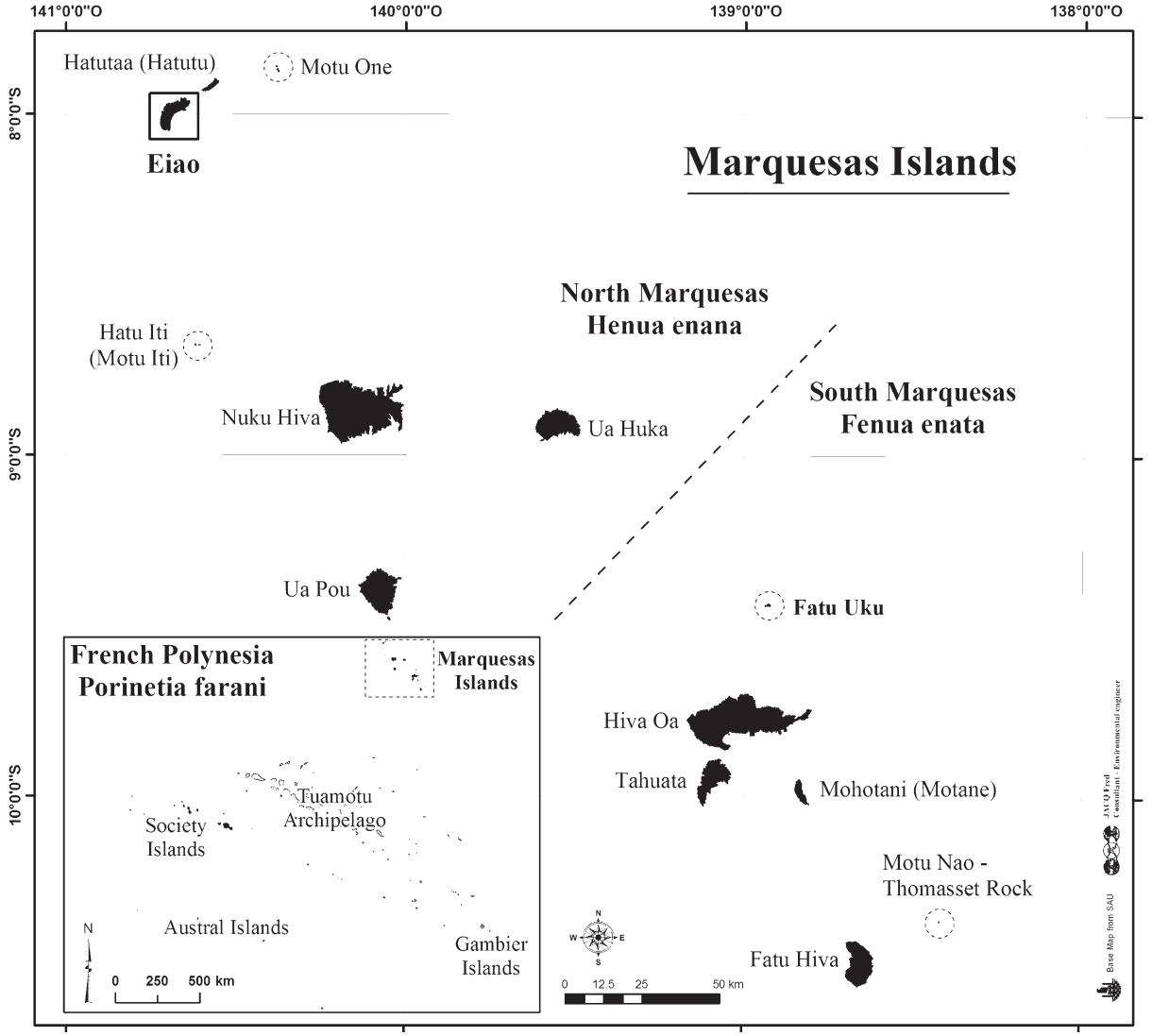

Figure 1. Map of the Marquesas Islands. Inset: French Polynesia.

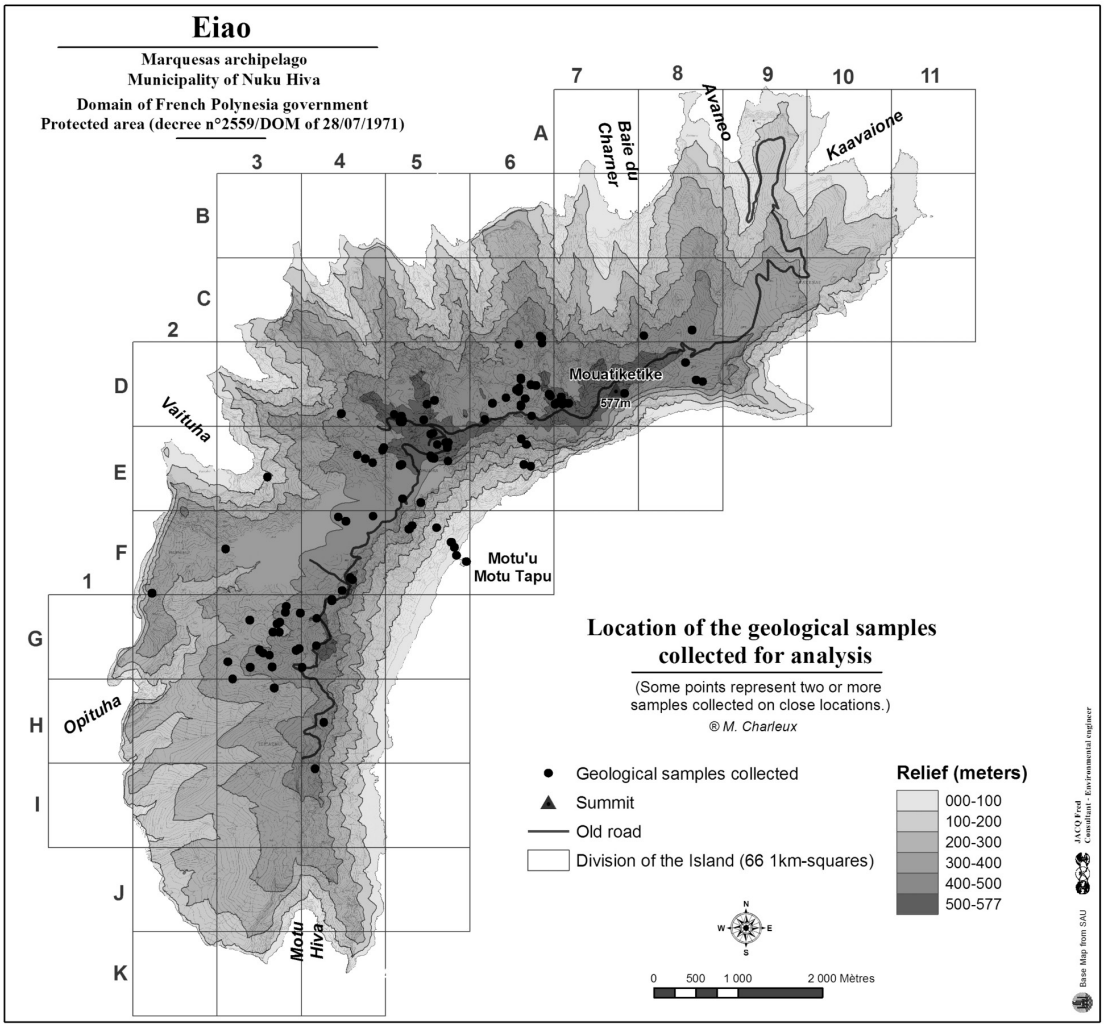

Figure 2. Map of Eiao showing the alpha-numeric grid used for surveying. The collection locations of specimens are indicated with filled circles.

Eiao is currently uninhabited and it is uncertain whether the island ever supported a permanent population (see Linton 1925:106; Handy 1923; Ferdon 1993). Some 20th century authors have suggested (presumably based on oral traditions) that there was once a resident tribe on Eiao, the *Tuametaki*, which was wiped out in the early 1800s by raiders from Nuku Hiva (Christian 1895; Suggs 1962:152). However, the earliest primary sources, dating from 1791, did not directly encounter any inhabitants on Eiao (Ingraham 1793; Marchand 1810). Although Fanning (1834:218) sighted smoke rising from various parts of the island, other visitors noted apparently abandoned dwellings in states of disrepair on the island (Ingraham 1793; Vancouver 1798:94; Vincendon-Dumoulin & Desgraz 1843:190), which suggested to them that Eiao was visited periodically rather than occupied continuously. Accounts from early 19th century Western residents on Nuku Hiva, the closest permanently inhabited landfall, also point to intermittent occupation; Porter (1823) was informed that canoes travelled seasonally to Eiao (and the neighbouring island of Hatuta'a) to collect red feathers from nesting birds, and the missionary Gracia (1843) reported that tribes from the north coast of Nuku Hiva went to Eiao to obtain wild pigs, coconuts and breadfruit in times of emergency. Some writers also stated that Eiao was used as a burial ground for the chiefs of certain Nuku Hiva tribes (Vincendon-Dumoulin & Desgraz 1843:190; Handy 1923:34). Although several 20th century anthropological studies have reported oral traditions of stone tools from Eiao being distributed throughout the Marquesas (Linton 1923, 1925; Handy 1923; Suggs 1961; Maranda 1964), very few primary sources give first-hand accounts of Marquesan stone tools, and none specifically mention Eiao as source of tool-stone.

A number of archaeological studies have been conducted on Eiao but most research has been limited to recording surface structures. Linton (1925:106) carried out the first archaeological survey of the island and identified

several sites, including one, located at the southern end of the island, which he described as an adze workshop. Suggs (1961) briefly visited Eiao and collected some basalt adze-flakes, three of which were subsequently geochemically analysed by Weisler (1998; see below). In a study that focused on the island's surface architecture, Candelot (1980, 2007) reported several sites with evidence of stone working. In 1987, Charleux spent a month surveying the island and identified over 70 additional sites, which are summarised in Butaud and Jacq (2007). In 1998, Rolett and Sinton visited Eiao and reported a site they described as a quarry in the northern part of the island (Rolett 2001). More recently, in 2010 and 2011, Charleux has directed three expeditions to Eiao, which are discussed in more detail in the following section.

The chronology of human occupation on Eiao is currently being investigated by Charleux and will be the subject of a forthcoming publication; his initial findings, based on radiocarbon determinations, indicate that the island has been visited since at least the 12th century A.D., a date consistent with the findings of other researchers (e.g., Rolett *et al.* 1997; Rolett 1998; McAlister 2011; Allen & McAlister 2013) who have identified stone from Eiao in the earliest dated contexts in Marquesan sites on Nuku Hiva and Tahuata.

Despite the documented widespread distribution of Eiao basalt in Central Polynesia, relatively little is known about the stone industry on Eiao itself. Although some researchers have conducted physical analyses of stone tools collected on Eiao (e.g., Gérard 1976; West 2000; Charleux 2009), in comparison to most other island groups with extensive stone tool industries, such as the Cook Islands (e.g., Weisler 1993; Walter & Sheppard 1996, 2001; Allen & Johnson 1997; Sheppard *et al.* 1997; Walter 1998), Samoa (e.g., Best *et al.* 1992; Weisler & Kirch 1996; Clark *et al.* 1997; Johnson 2005, 2011; Winterhoff 2007; Crews 2008) and Hawai'i (e.g., Lebo & Johnson 2007; Lundblad *et al.* 2007; Mills *et al.* 2008, 2010; Kahn *et al.* 2009), few archaeological studies have reported geochemical data from the Marquesas Islands in general and Eiao in particular.

In 1997, Sinton and Sinoto published summary data for 19 specimens attributed to Eiao (see Table 3). Their data included specimens reported in other studies (e.g., Best 1984; Rolett *et al.* 1997) as well as samples analysed using WDXRF by Sinton at the Department of Geology and Geophysics, University of Hawai'i at Mānoa (pers. com., J. Sinton 2007). All 19 specimens were analysed for the ten major elements but trace element data were determined for only three (see Table 3). Two other archaeological studies not included in Sinton and Sinoto's (1997) summary also have reported geochemical data for Eiao; McAlister (2011:78) analysed a single artefact collected on Eiao using WDXRF and Weisler (1998) analysed three flakes collected on Eiao in the late 1950s by Suggs (1961) using EDXRF. One of Weisler's samples was subsequently re-analysed by Collerson and Weisler (2007) for major and trace elements and also selected isotopes (Sr, Nd and Pb).

In total, our current knowledge of Eiao adze stone geochemistry is based on only 23 specimens, all of which are derived from artefacts of some form (e.g., adzes and flakes) rather than natural outcrops from identified manufacturing sites. Additionally, at least nine of the specimens summarised by Sinton and Sinoto (1997) were collected on other Marquesan Islands (i.e., Nuku Hiva and Ua Huka) and attributed to Eiao on the basis of geochemical similarities (pers. com., J. Sinton 2007). This study builds on previous research by augmenting the existing sample substantially and including specimens collected from a variety of locations and contexts on Eiao.

FIELD METHODS

This study forms part of a larger research project conducted by Charleux and aimed at understanding various aspects of the mode and chronology of prehistoric life on Eiao (Charleux 2009, in preparation). The lithic samples reported here were collected by Charleux and his field crew over three field seasons between 2010 and 2011. All specimens are from surface contexts and include both artefacts and unmodified stone collected from outcrops and exposures. The main objective of these collections was to gather representative samples from various locations across the island so as to better understand the geochemical and physical variability of the raw materials and to investigate possible spatial links between quarrying sites and workshops.

Because we no longer know most of the place names that Marquesans gave to localities on Eiao, an alpha-numeric grid consisting of 66 quadrants, each 1 km² in area, was laid over a map of the island to aid organisation (see Figure 2). During the field work, each site was identified using the prefix 'MEI' (Marquesas-Eiao) followed by the quadrant identifier and a unique site number (e.g., MEI.D6.029). In addition, the location of each sample was recorded using GPS. Samples were collected from various locations on the island, but preference was given to locations with evidence of lithic exploitation or manufacture (i.e., suspected quarries, worked exposures, workshops and habitation areas). A large concentration of utilised stone was identified at Hanata'aitoki Valley, (Marquesan for 'the valley where adzes were made'), located inside the D6 quadrant (Figure 2), which contains a large concentration of domestic structures (*paepae*) and stone workshops. In total, 229 lithic samples were collected on Eiao and included unfinished adzes (i.e., blanks, preforms and rejects), flakes and samples from natural rock outcrops. From this collection, 225 specimens were selected for geochemical analysis: 165 were analysed at the University of Auckland and 60 and the University of Hawai'i at Hilo.

ANALYTIC METHODS

The samples reported here were analysed at two laboratories using three instruments. The analyses at the University of Hawai'i, Hilo were conducted by Mills and Lundblad with a ThermoNoran QuanX TM EDXRF spectrometer using a rhodium (Rh) target under vacuum. Four sets of operating conditions were used to optimise the response for elements of differing atomic weights: for Na, Mg, Al and Si a setting of 6 kV with no filter and 300 seconds live time was used; 15 kV for 200 seconds through a thin Pd filter was used for K, Ca, Ti, Mn, V, Fe and Ni; 28 kV for 200 seconds and a thick Pd filter was used to analyse Cu, Zn, Rb, Sr, Y, Zr, Nb and Pb. Ba, La and Ce were analysed at 50 kV for 150 seconds using a thick Cu filter. The spectrometer was calibrated empirically using linear regressions derived from a set of 27 geological standards with an emphasis on basalts, following the laboratory's standard approach (see Lundblad *et al.* 2008; Mills *et al.* 2011). A total of 22 major and trace elements were analysed by the ThermoNoran QuanX TM spectrometer (see Table 1).

At the University of Auckland, McAlister and Charleux used two different portable energy dispersive X-ray fluorescence (pXRF) instruments. The first, an Innov-X Alpha, uses a source producing up to 40kV at 20μA, a tungsten (W) target and a 10 mm² Si (PIN) diode detector. The quoted energy resolution is less than 230 eV FWHM at the 5.95 keV Mn Kα line. Analyses were run using the instrument's Soil Mode. Two operating conditions are used in this mode; Standard Mode, which is optimised for the heavier elements (i.e., those heavier than Fe), and the Light Element Analysis Program (LEAP) which uses a lower operating voltage (10 kV) and a different (unspecified) filter setting to increase sensitivity for the lighter elements (i.e., K, Ca, Ti, Cr, Mn and Fe). Samples were run for 120 seconds per mode, giving a total time of 240 seconds per analysis. The live time varied slightly but was generally about 90 percent of the total time. The Innov-X Alpha instrument used for this study was supplied with inbuilt quantification software that employs the Fundamental Parameters (FP) method (see Criss & Birks 1968) and is primarily intended for the analysis of soils. Although other researchers have found this software to be accurate for the analysis of obsidians (e.g., Sheppard *et al.* 2010, 2011), substantial errors have been encountered for the lighter elements when the same software is used with basalts, possibly because of differences in the sample matrices (see McAlister 2011). Instead, the raw spectra data were extracted from the instrument and elemental concentrations were derived empirically using linear regressions based on 21 reference specimens, mostly basalts. These methods are described in detail by McAlister (2011). A total of 13 elements were quantified using the Innov-X Alpha instrument, the lightest being K (Table 1).

The second pXRF instrument, an Innov-X Delta Premium, offers several improvements over the earlier Alpha model, including a more powerful tube, a Rh target and a 25 mm² Large Area Silicon Drift Detector (SDD). The instrument's Soil Mode, which applies three operating conditions, also was used for this analysis; Beams 1 and 2 operate at 40 keV at 90 μA, while Beam 3 operates at 15 keV at 55μA. Different filters are used for each beam but their properties are not specified in the literature. Samples were run for 120 seconds live time per beam giving a total of 360 seconds per analysis. Longer analysis times are possible but it has been found that they offer no measurable improvement in performance. As was the case with the Alpha analyser, the Delta's inbuilt quantification software produced substantial errors for the lighter elements (i.e., K–Fe), Again, matrix effects are suspected to be the likely source of much of the error and for this reason the spectra data were analysed to derive concentration data using a similar procedure to that employed with the Alpha analyser (see McAlister, in preparation). Sixteen elements were quantified using the Innov-X Delta instrument, the same 13 as for the Alpha with the addition of V, Y and Pb (Table 1).

For both pXRF instruments, each sample was run twice on different portions of its surface to check for analytic consistency. In all cases results were within 10% of each other and the two sets of values were averaged for each sample. Prior to pXRF analysis, all samples were scrubbed clean under hot water, immersed in an acid solution (10% HCL) for 30 seconds to remove surface carbonates and placed in an ultrasonic bath with distilled water for 20 minutes. Most specimens were analysed whole. There were, however, a few unmodified flake specimens that were set aside for thin-sectioning (see below); these were ground flat with a diamond lap to provide a better analytic surface. For all three instruments, the smoothest and flattest portions of each whole sample were selected for analysis and placed as close and parallel to the detector as possible. Although occasional phenocrysts were visible in the generally fine-grained matrix of the samples, specimens were positioned over the window so as to avoid obvious inclusions. The averaging of multiple analyses per specimen also helped to minimise the potential of subsurface phenocrysts biasing our results.

Typically, WDXRF analyses of basalt major elements are carried out on glass beads fused from powdered rock samples and are reported as oxide weight percentages to two decimal places (see Weisler & Sinton 1997, Parker & Sheppard 1997). Testing at both Hilo and Auckland indicates that the same level of precision is not possible for non-destructive EDXRF analyses (see Lundblad *et al.* 2008, 2011; McAlister 2011). The four lightest major elements, Na, Mg, Al and Si, (analysed at Hilo but not Auckland) can be quantified to approximately the closest whole percentage when using pressed powder standards (see Table 3). However, the analysis of whole specimens introduces considerable error due to a combination of surface irregularities and weathering (see Lundblad *et al.* 2008, 2011).

Consequently, for analyses of whole specimens, the light elements, Na, Mg, Si and Al, cannot be quantified with the resolution necessary to discriminate among most Polynesian basalt sources.

The major elements, K, Ca, Ti, and Fe, however, can be quantified to within around 0.1 % using pressed powder standards (see Table 3), and approximately 0.2–0.3 % on whole samples, depending on the extent of weathering. In contrast to Na, Mg, Al and Si, these elements often can be usefully employed in conjunction with, but secondary to, the generally better-quantified mid-z elements, Rb, Sr, Y, Zr and Nb. Manganese can be accurately quantified to two decimal places by all three instruments but this element is generally not useful for discriminating among most Oceanic basalts because it occurs in similar concentrations (*ca.* 0.15–0.20 %) throughout the region (see Sinton & Sinoto 1997). Phosphorus, the remaining major element commonly reported in WDXRF analyses, has been found useful for discriminating in some studies (e.g., Best *et al.* 1992; Allen & Johnson 1997). Unfortunately this element generally occurs in low concentrations (i.e., < 1 %) in Oceanic basalts and sample surfaces can be affected by phosphate contamination (see Lundblad *et al.* 2011:72), which, together, make it difficult to obtain accurate values for EDXRF analyses of whole specimens. For these reasons, P is not reported here. In contrast to the major elements, the accuracy and precision of many trace elements analysed using EDXRF approaches that of WDXRF and they are reported to the closest part per million (ppm) here.

RESULTS

Our summary results, separated by instrument, are given in Table 1 and data for individual specimens are available in a supplementary file online.[5] Two distinctive groups, referred to here as Group 1 and Group 2, were identified and are easily distinguished on the basis of all but two of the measured elements (i.e., Zn and Pb). Scatterplots of CaO against TiO_2 (Figure 3) and Sr against Zr (Figure 4) clearly show the separation of the identified groups. Data for a geochemical group of basalt samples from the neighbouring valleys of Ha'ataivea and Anaho on Nuku Hiva Island also are included in the plots for comparative purposes. Nuku Hiva is the closest inhabited island to Eiao (see Figure 1), and stone from both of these valleys is known to have been used for tool manufacture (Suggs 1961; Weisler 1993; Rolett *et al.* 1997; Allen *et al.* 2005; McAlister 2011). The Nuku Hiva samples were destructively analysed by McAlister using WDXRF and are combined in the plots because previous research has found them to be geochemically indistinguishable on the basis of elemental concentrations (see McAlister 2011).

5 hilo.hawaii.edu/depts/geoarchaeology/

Table 1. *Summary data for the two identified Eiao groups, separated by instrument.*

		Eiao Group 1						Eiao Group 2					
Lab		Hawaii		Auckland		Auckland		Hawaii		Auckland		Auckland	
Instrument		QuanX		Innov-X Alpha		Innov-X Delta		QuanX		Innov-X Alpha		Innov-X Delta	
Count		53		119		28		6		13		3	
Element	**Unit**	**mean**	**S.D.**	**mean**	**S.D.**	**mean**	**S.D.**	**mean**	**S.D.**	**mean**	**S.D.**	**mean**	**S.D.**
K_2O	%	1.0	0.1	1.1	0.2	1.1	0.1	1.9	0.2	2.3	0.3	2.0	0.3
CaO	%	8.3	0.5	8.7	0.9	9.4	0.8	6.1	0.8	5.2	0.6	6.4	0.3
TiO_2	%	4.2	0.3	4.4	0.4	4.2	0.2	3.1	0.3	2.7	0.3	2.4	0.2
V	ppm	409	30	–	–	302	52	254	34	–	–	159	63
Cr	ppm	–	–	60	61	63	35	–	–	33	32	22	7
MnO	%	0.17	0.02	0.13	0.03	0.16	0.03	0.27	0.07	0.17	0.02	0.18	0.02
Fe_2O_3T[1]	%	13.3	0.8	13.0	1.5	13.1	0.9	10.1	0.9	9.6	0.8	11.4	0.4
Ni	ppm	71	21	79	29	94	21	3	5	32	17	19	7
Cu	ppm	23	13	21	12	33	15	11	3	19	7	15	12
Zn	ppm	164	15	98	23	106	15	162	11	109	11	133	6
Rb	ppm	26	4	23	4	24	4	52	5	46	3	51	3
Sr	ppm	627	32	603	18	607	15	765	48	739	19	747	14
Y	ppm	37	3	–	–	36	4	58	6	–	–	70	2
Zr	ppm	346	18	309	14	308	10	628	45	536	17	560	13
Nb	ppm	31	2	29	3	29	2	61	5	60	4	63	2
Ba	ppm	295	38	–	–	–	–	613	71	–	–	–	–
Pb	ppm	0	0	–	–	3	1	0	1	–	–	7	1

1. Total iron expressed as Fe_2O_3

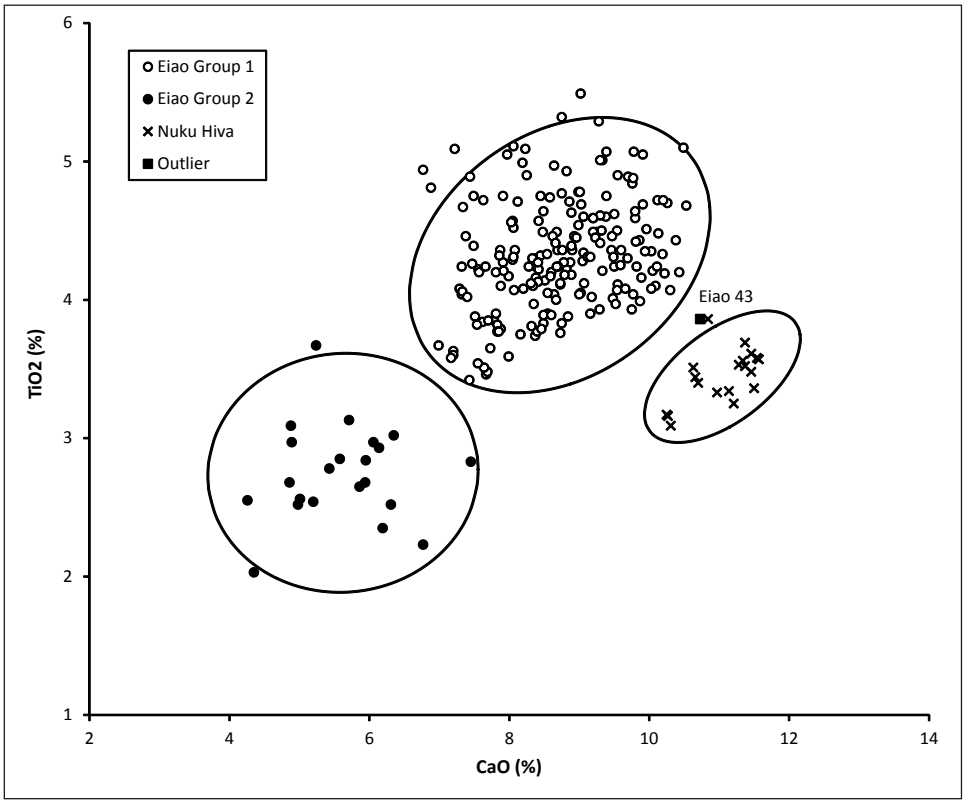

Figure 3. Plot of CaO against TiO_2. The ellipses show 95% confidence intervals. Values are jittered slightly to avoid overprinting.

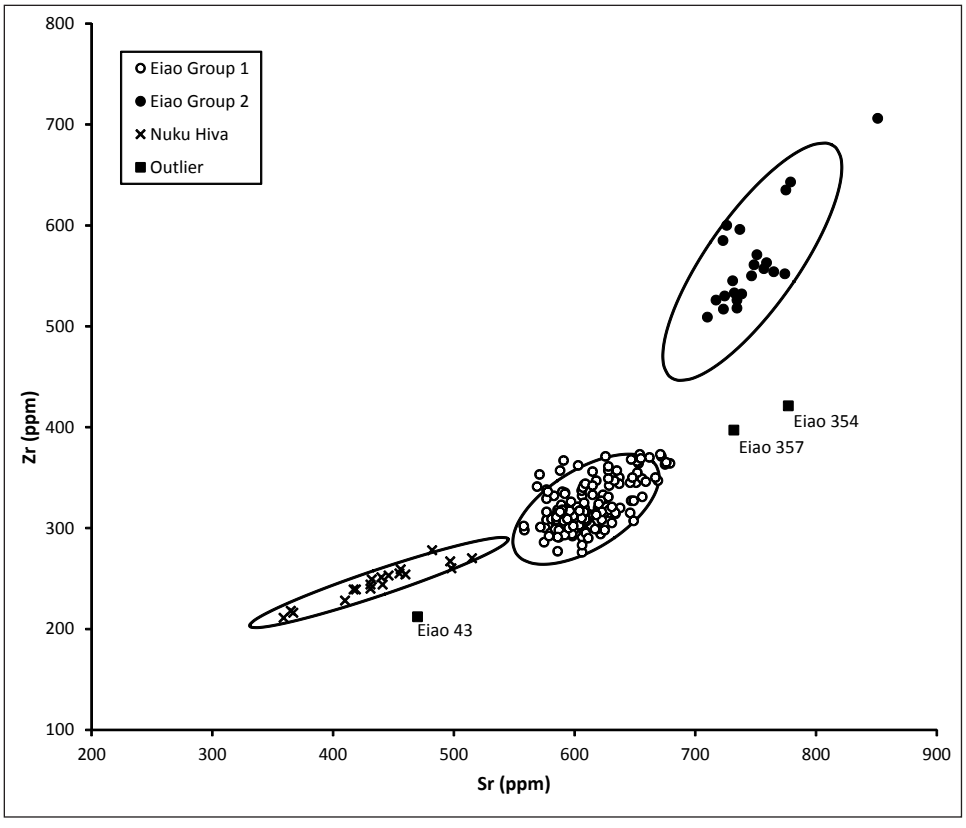

Figure 4. Plot of Sr against Zr. The ellipses show 95% confidence intervals.

Most of our sample falls into the two abovementioned groups. We did, however, identify three outliers; two specimens (Eiao 354 and 357) are close matches to our Group 1 samples apart from having higher concentrations of Sr. The former is a natural prismatic block and the later a flake. The third outlier (Eiao 43) clusters closest to the Nuku Hiva sources in both of the elemental plots. This specimen was struck from a natural outcrop in quadrant F5, indicating that it is not an artefact that was transported to Eiao from elsewhere. Given that our sample includes well over 200 specimens, we would expect to identify a few that do not closely match the main groups.

Principle Components analysis (unrotated) using the elements common to all instruments but not included in the previous plots (i.e., K, Mn, Fe, Cu, Ni, Zn, Rb, Nb) was conducted to examine whether any distinctive patterning not detectable through bivariate scatterplots was observable within the identified groups (Figure 5). As was the case with the elemental scatterplots, Groups 1 and 2 are distinct and the three outlying specimens cluster closest to our Group 1. The sample spread also shows continuous variation within the groups, suggesting that no distinctive sub-groups can be readily identified on the basis of elemental concentrations alone.

Overall, all three instruments produced similar results. For most elements, concentrations are within a few percent relative of each other and our most common group, Group 1, compares well to the previously-reported geochemistry of tool-quality basalt from Eiao (i.e., Best 1984; Weisler 1993; Rolett *et al.* 1997; McAlister 2011). Our combined results are shown alongside Sinton and Sinoto's (1997) summary Eiao data (Table 2). There is, however, an average difference of approximately 40 ppm between the Auckland and Hawai'i mean values for Zr (Table 1). We have investigated our results for Zr at length and are unsure of the exact cause of this discrepancy. Nineteen of the samples sent to each laboratory were pairs struck from the same outcrop and presumed to be geochemically similar. The Zr results for these specimens showed variability similar to that of the remainder of our samples and the paired differences appeared random, suggesting no directional systematic biases due to instrument calibration. Moreover, several reference standards are common to both laboratories' calibration sets and these give similar analytical results across all three instruments; an example, BHVO-1, a Hawaiian basalt, is shown below (Table 3). For this reason, we suspect that our differences for Zr averages are related to sample surface variability, differences in sample positioning, and subtle differences in our calibration lines. Despite these differences, we note that our Group 1 average values for Zr are within 12 % relative across all three instruments, which is sufficient to discriminate between the two Eiao groups as well as the Nuku Hiva specimens included in Figure 4.

Our results also show that the spread of concentrations for many elements is considerably higher than in previous studies. Although this is undoubtedly due in part to the lower overall precision of the EDXRF instruments used for this study, particularly the pXRF analysers, our reported concentration ranges likely provide a more

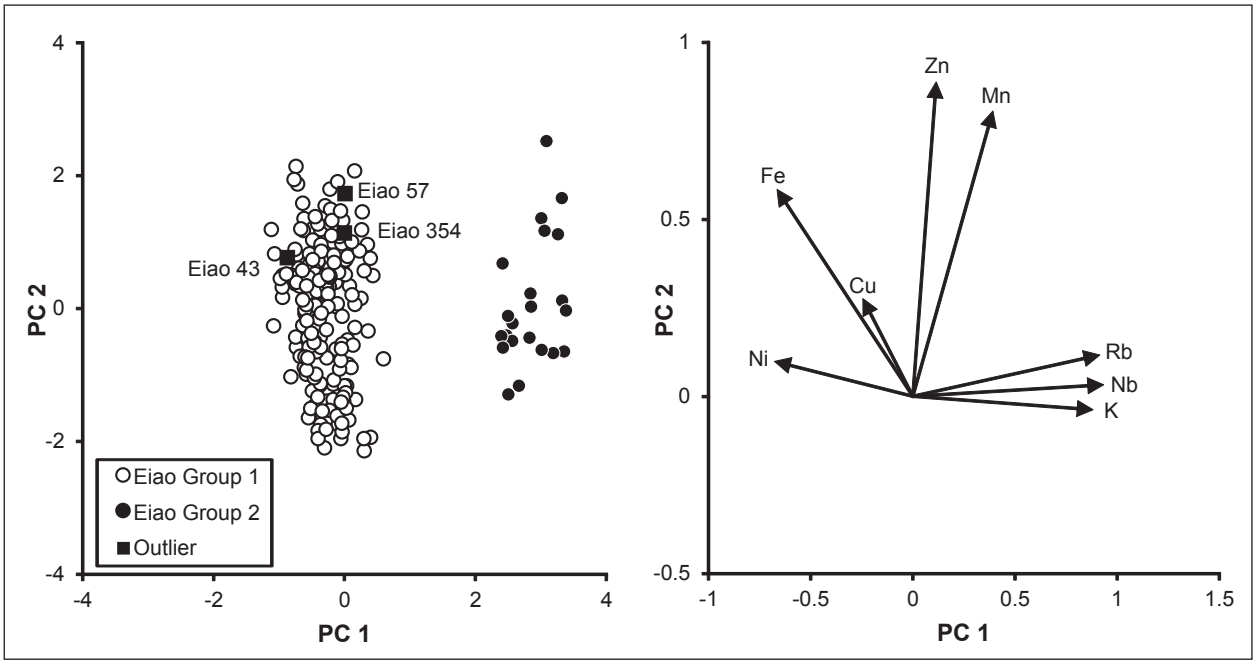

Figure 5. Principle components analysis of the specimens. The figure in the left shows the first two principle components and that on the right shows their associated eigenvectors.

Table 2. *Combined data from this study compared to other Marquesan lithic data.*

		Eiao			Eiao Group 1			Eiao Group 2			Nuku Hiva		
		Sinton & Sinoto 1997			This study			This study			McAlister 2011		
Element	**Unit**	**n**	**mean**	**S.D.**	**n**	**mean**	**S.D.**	**n**	**mean**	**S.D.**	**n**	**mean**	**S.D.**
K_2O	%	19	1.00	0.03	200	1.1	0.2	22	2.2	0.3	19	0.81	0.14
CaO	%	19	9.32	0.05	200	8.7	0.9	22	5.6	1	19	11.03	0.46
TiO_2	%	19	3.90	0.11	200	4.3	0.4	22	2.8	0.4	19	3.43	0.19
V	ppm	3	297	8	81	372	64	9	222	63	19	329	18
Cr	ppm	3	87	5	147	79	50	9	27	31	19	195	93
MnO	%	19	0.16	0.01	200	0.14	0.03	22	0.20	0.06	19	0.16	0.01
Fe_2O_3T[1]	%	19	13.53	0.10	200	13.1	1.3	22	10.0	1.00	19	12.79	0.38
Ni	ppm	3	100	3	200	79	27	22	22	18	19	100	23
Cu	ppm	3	47	5	200	24	13	22	16	8	19	99	9
Zn	ppm	3	130	6	200	116	35	22	127	26	19	113	4
Rb	ppm	3	18	2	200	24	4	22	48	5	19	20	5
Sr	ppm	3	591	2	200	610	24	22	747	30	19	434	41
Y	ppm	3	37	0	81	37	3	9	62	8	19	34	3
Zr	ppm	3	306	1	200	319	22	22	564	48	19	245	18
Nb	ppm	3	28	0	200	30	3	22	60	4	19	24	3
Ba	ppm	3	187	5	53	295	38	6	613	71	19	120	52
Pb	ppm	–	–	–	81	1	2	9	3	4	19	2	1

1. Total iron expressed as Fe_2O_3

Table 3. *Comparison of instrument results for basalt standard* BHVO-1.

		BHVO-1	Hawaii	Auckland	
Element	**Unit**	**Given value**	**QuanX**	**Innov-X Alpha**	**Innov-X Delta**
Na_2O	%	2.26	2	–	–
MgO	%	7.23	7	–	–
Al_2O_3	%	13.80	14	–	–
SiO_2	%	49.94	50	–	–
K_2O	%	0.52	0.6	0.5	0.5
CaO	%	11.40	11.1	10.8	11.6
TiO_2	%	2.71	2.7	2.6	2.7
V	ppm	317	370	–	351
Cr	ppm	289	–	257	248
MnO	%	0.17	0.16	0.16	0.17
Fe_2O_3T[1]	%	12.23	12.7	12.1	12.3
Ni	ppm	121	86	125	126
Cu	ppm	136	144	139	140
Zn	ppm	105	80	105	101
Rb	ppm	11	11	9	10
Sr	ppm	403	398	392	395
Y	ppm	28	27	–	29
Zr	ppm	179	191	175	180
Nb	ppm	19	20	18	21
Ba	ppm	139	136	–	–
Pb	ppm	3	0	–	2

1. Total iron expressed as Fe_2O_3

representative measure of the diversity of Eiao tool stone, especially for the trace elements, which are represented by only seven samples in the previously-reported data. Moreover, the larger sample sizes presented here demonstrate the compositional ranges for artefacts derived from Eiao that might be expected from analyses using other comparable non-destructive EDXRF instruments, regardless of whether or not the variation comes from machine error or sample variability.

The Group 1 and 2 samples also differ in physical characteristics. Group 1 specimens possess a particularly fine-grained texture and very dark colour; our sample ranges from black (Munsell Gley 1, 2.5N) for fresh surfaces to gray (5/N) for the most weathered surfaces. In hand specimen, the texture is aphanitic and even in thin section (at 100 x magnification) individual grains are difficult to distinguish and generally measure less than 0.02 mm (Figure 6a). Phenocrysts are extremely rare (estimated to be less than 1%) and are usually small glassy inclusions that do not exceed 0.2 mm.

The specimens assigned to Group 2 are more variable in colour; the majority range from red (2.5 YR 4/6) to dark reddish brown (2.5 YR 2.5/3) depending on the extent of weathering. There are, however a few specimens that are macroscopically similar to the Group 1 samples, both in colour and texture. A representative specimen of the red Group 2 stone was thin-sectioned and found to possess a somewhat coarser grain than Group 1, although the grain is still very fine (*ca.* < 0.1 mm). The groundmass is dominated by partially oriented plagioclase feldspars and phenocrysts are also very rare (Figure 6b).

A thin section of a typical specimen from Ha'ataivea valley on Nuku Hiva also is shown for comparison (Figure 6c). In colour, the Ha'ataivea (and also the Anaho) specimens are lighter than Eiao Group 1, ranging from gray (5YR 6/1) to very dark gray (5YR 6/1). The texture of this Nuku Hiva adze-stone is similar to the Group B specimens although substantially coarser. We note that, despite its coarser grain, stone from Ha'ataivea and Anaho is of a quality suitable for adze manufacture; examples are common throughout sites on Nuku Hiva (see Rolett *et al.* 1997; McAlister 2011; Allen and McAlister 2013).

As noted above, the Group 2 specimens are geochemically distinct for most elements. Adze-stone matching this group has not, to the best of our knowledge, been reported previously. Our Group 2 sample is numerically much smaller than Group 1, and this probably reflects its natural rarity. Adzes made from a reddish stone physically resembling some of our Group 2 material (see below) have been observed in the private collections of residents of the Marquesas by both Charleux and McAlister, and Charleux has identified Group 2 stone in several adze workshops on Eiao. To date, however, only one adze made from this material, a specimen collected on Hiva Oa and currently in the possession of Eric Olivier, has been geochemically analysed (Figure 7). The specimen was analysed at the University of Auckland using an Innov-X Delta instrument and the results are a close match to our Group 2 data (Table 4).

DISCUSSION

The data reported in this study have augmented our knowledge of the stone industry on Eiao. In spite of the relative isolation of Eiao, researchers have found that the fine-grained basalt identified here as Group 1 was widely distributed both within the Marquesas and to other parts of East Polynesia. Moreover, the proportion of stone imported from Eiao is relatively high in Marquesan sites that

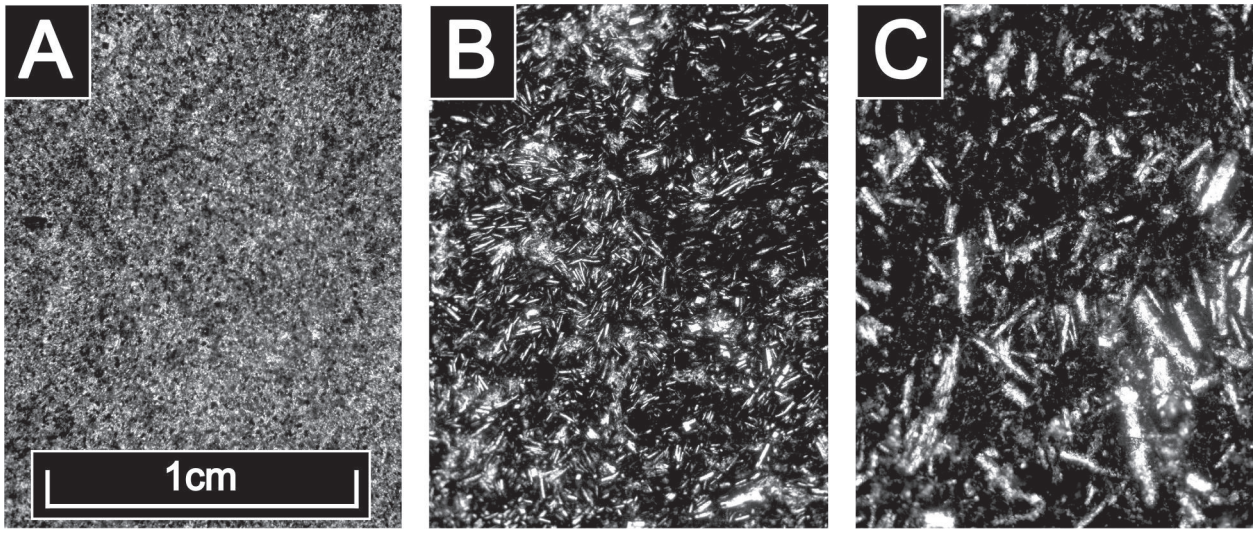

Figure 6. Representative thin sections (100x magnification): A- Eiao Group 1; B- Eiao Group 2; C- Nuku Hiva, Ha'ataivea Valley, Ha'aupaupa quarry.

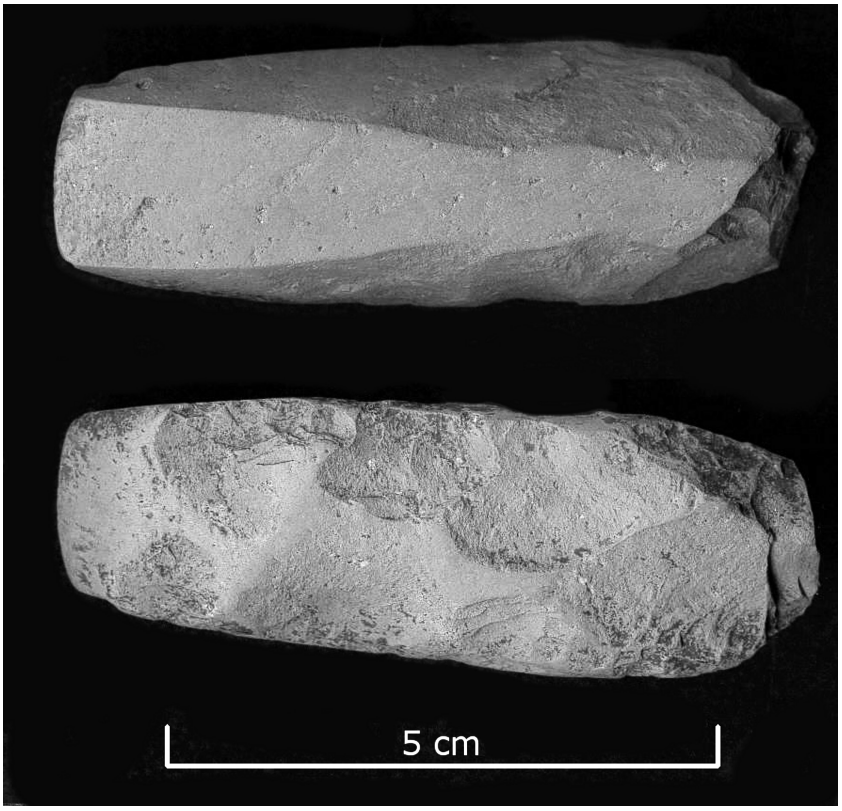

Figure 7. Adze collected on Hiva Oa Island. The upper figure shows the front face and the lower, the back face. Photograph courtesy of E. Olivier.

Table 4. *Mean values for three analyses of the adze collected on Hiva Oa Island. Our Group 2 mean values are shown for comparison.*

		Hiva Oa Adze		Eiao Group 2	
Element	**Unit**	**mean**	**S.D.**	**mean**	**S.D.**
K_2O	%	2.4	0.2	2.2	0.3
CaO	%	4.9	0.2	5.6	1
TiO_2	%	2.9	0.2	2.8	0.4
V	ppm	253	12	222	63
Cr	ppm	21	7	27	31
MnO	%	0.17	0.03	0.2	0.06
Fe_2O_3T[1]	%	10.8	0.4	10.0	1
Ni	ppm	27	6	22	18
Cu	ppm	18	3	16	8
Zn	ppm	146	7	127	26
Rb	ppm	49	1	48	5
Sr	ppm	763	1	747	30
Y	ppm	61	2	62	8
Zr	ppm	585	4	564	48
Nb	ppm	60	1	60	4
Pb	ppm	10	0.3	3	4

1. Total iron expressed as Fe_2O_3

have been examined in detail, often approaching one half of the total assemblage (e.g., Rolett *et al.* 1997; Rolett 1998; McAlister 2011). We suggest three related reasons for this widespread distribution. First, the Group 1 material is particularly fine-grained and relatively free from large phenocrysts and other flaws, properties which are conducive to the predictable manufacture of high-quality tools with long use-lives (Best 1977; Turner 2000, 2005). Second, our analyses and those of other researchers indicate that the geochemical and physical variability of the Group 1 stone is relatively low, suggesting that careful selection of suitable tool-stone was not crucial to ensuring a comparatively low rate of manufacturing rejects.

Third, in comparison to other stone sources that have been identified in the Marquesas Islands (Suggs 1961; Allen *et al.* 2005; McAlister 2011, Allen & McAlister 2013), adze-quality stone is plentiful on Eiao and occurs in multiple locations. Rolett (2001) identified a single site in the northern end of Eiao, which he describes as 'the prehistoric Eiao quarry' (*la carrière préhistorique d'Eiao*). However, subsequent surveys by Charleux have uncovered evidence of stone exploitation throughout the island. Their locations are shown above (Figure 2) and these sites will be described in more detail by Charleux in a forthcoming article. The analyses reported above show that our Group 1 fine-grained basalt is physically and geochemi-

cally homogenous, indicating that sources of high-quality basalt were not restricted to a single location on Eiao. For this reason we propose that, from an analytic perspective, the Group 1 basalt from the entire island should be considered a single geochemical group, albeit from multiple geographical sources. In combination, these factors make for an abundant and reliable supply of high-quality raw material with predictable working properties.

With the exception of one polished adze fragment (Sample Eiao 83a), all of the worked specimens included in our sample were collected in unfinished condition with no evidence of grinding or polishing (i.e., adze preforms, blanks and rejects; n = 54). Additionally, over the course of his extensive field work on Eiao, Charleux has observed only two adze grindstones and a few polished adze fragments. While it is likely that visiting yacht crews and hunters have collected a small number of particularly attractive complete artefacts (see Rolett at al. 1997: Table 8.4), the overall paucity of finished adzes on Eiao suggests that tools were completed locally only for the immediate needs of the stoneworkers and that the final grinding and polishing of bevels was primarily carried out offshore. These findings concur with traditional accounts, which indicate that Nuku Hiva, the closest permanently inhabited landfall to Eiao, served as a distribution centre for stone adzes; Handy (1923: 23) was told that the inhabitants of Hiva Oa obtained stone from Eiao through trade with Nuku Hiva and Linton's (1925: 107) informants reported that the tribes on Nuku Hiva traded Eiao basalt to several other islands in the group. Rolett *et al.* (1997: 146) and McAlister (2011: 414) have suggested such a scenario might also explain the relatively high frequencies of Eiao basalt they identified at various sites on Nuku Hiva.

Little is currently known about the distribution of tools made from the stone we have identified as here Group 2. This material appears to occur less abundantly than the Group 1 stone but the presence of worked cores and flakes on Eiao and finished adzes made from a similar material elsewhere in the Marquesas indicates that it was routinely, if not commonly, used to make artefacts. We further suggest that implements made from red basalt might have been considered particularly valuable to Polynesians, not only because of the rarity of the material, but possibly also because of a general Polynesian association between the colour red and royalty (Stokes 1925; Beasley 1932; Oliver 2002: 58).

CONCLUSION

This study contributes substantially to our knowledge of basalt use on Eiao. Our geochemical analyses of over 200 samples collected on the island considerably augment existing data. We identified two geochemically and physically distinct groups of stone; the first, our Group 1, matches the fine-grained Eiao basalt widely reported by previous studies while the other, Group 2, often has a unique red colouring. Our analyses have found that at least one adze made from this red basalt was exported to Hiva Oa in the southern Marquesas, but the presence of debitage on Eiao and physically similar adzes observed in private collections on Nuku Hiva suggest that this material was regularly exploited and likely widely distributed. Until recently, little was known about the extent of raw material availability on Eiao; this study demonstrates that multiple sources of geochemically and physically similar fine-grained basalt were worked at several locations on the island and in a variety of contexts. Further field work by Charleux during 2013 examined these sites in more detail.

Our study also highlights some of the strengths and limitations of non-destructive EDXRF technology. The analysis of whole samples can result in substantial errors for several light elements, which our investigations suggest are mainly due to irregular surface morphology and weathering. In contrast, the accuracy and precision of most mid-z element EDXRF determinations on whole samples can approach the levels achieved by destructive WDXRF analyses, provided that instruments are calibrated using appropriate standards. These factors need to be taken into account when using EDXRF data for practical applications, and we recommend giving preference to the better-quantified mid-z elements in studies employing geochemical data derived from whole specimens. Despite these potential limitations, non-destructive XRF analyses can provide a cost-effective means of evaluating the compositional variability of large samples, as demonstrated in this study.

Acknowledgements

The authors would like to thank the following: Charleux would like to thank CIRAP (International Centre for Polynesian Archaeological Research), the Ministry of Culture of French Polynesia, UM 7041-Laboratoire d'Ethnoarchéologie Préhistorique/CNRS and the Marine nationale, for support that made possible his field work on Eiao. Members of Charleux's field crew on Eiao, particularly Jean-François Butaud, Fred Jacq and Gordon Falchetto, assisted with the survey and collections. Georges Teikiehuupoko, President of the Académie Marquisienne, is thanked for providing Charleux with a Marquesan name for Hanata'aitoki Valley in honour of the number of workshops it contains. Eric Olivier graciously allowed the geochemical analysis of an adze from his collection. John Sinton of the Department of Geology and Geophysics, University of Hawai'i at Mānoa, is thanked for providing McAlister with additional information about the Eiao samples summarised in Sinton and Sinoto (1997). John Wilmshurst, of the Department of Geology, University of Auckland, offered practical advice on improving the performance of the pXRF instruments used in this study. Acquisition of the EDXRF spectrometer at the University of Hawai'i at Hilo was supported by a major research instru-

mentation grant from the National Science Foundation (BCS 0317528). Continued funding for analysis is made possible by NSF BCS-Archeology (BCS-0949058). The authors also thank two anonymous reviewers for providing valuable feedback.

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