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– ARTICLE –

A New Major Adze Quarry from Nānākuli, Oʻahu: Implications for Interaction Studies in Hawaiʻi

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ABSTRACT

A major new basalt adze quarry at Nānākuli Valley, Hawaiian Islands is described which now ranks as one of the two largest on Oʻahu and aside from the Mauna Kea adze quarry complex on Hawaiʻi island and the Haleakalā source on Maui, is one of the major quarries in the archipelago. We defined the approximate limits of the quarry complex, located the *in situ* geological source of the fine-grained basalt used for adze manufacture, report the petrographic and geochemical variability of the source rock, and describe the adze reduction strategies from analysis of adze blanks and preforms, as well as hammerstones and debitage. The geochemical variation of the nine source rocks and artefacts were defined by a comprehensive array of 10 fully quantitative major element concentrations, 43 trace element abundances, and high-precision Sr-Nd-Pb isotopic ratios obtained using the state-of-the-art Thermal Ionization Mass Spectrometry (TIMS, for Sr isotopes), Multi-Collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS, for Nd-Pb isotopes), quadrupole ICP-MS (for trace elements) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, for major elements), respectively. A piece of branch coral was recovered from the surface of a rockshelter that provided a U-series date of possible quarry use in the mid-13th century. It is advocated that a comprehensive range of major and trace element concentrations and Sr-Nd-Pb isotopic ratios are required for geochemically characterising adze quarries to facilitate the long-term viability of sourcing studies.

Keywords: Hawaiian Islands, basalt adze quarries, sourcing, adze technology, geochemistry

INTRODUCTION

The spatial and temporal parameters of basalt adze materials have been used to delimit prehistoric Polynesian interaction systems (Best *et al.* 1992; Weisler ed. 1997, Weisler 1998), debunk the myth of isolated island societies (Collerson & Weisler 2007; Weisler & Kirch 1996; Weisler & Woodhead 1995) and also signal the abandonment of islands (Weisler 1996). The form and density of basalt debitage and adze blanks and preforms have also been used to document the development of craft specialisation (Cleghorn 1986; Bayman & Nakamura 2001; Lass 1994; Mills *et al.* 2011), delimit the physical boundaries of stone adze production (Bayman *et al.* 2004) – and its intensification (McCoy *et al.* 2012) – and define events leading towards increased social complexity (Kirch *et al.* 2012) Two key factors are fundamental to interaction studies: 1) comprehensive information on the location and geochemical variability of sources or quarries (Weisler & Sinton 1997:187–188; see also Beardsley & Goles 2001 and Johnson *et al.* 2007); and 2) use of appropriate geochemical analytical techniques to adequately characterise quarry rock and artefacts thus facilitating robust source assignments of unknown artefacts.

Because all islands in tropical Polynesia are composed mainly of Oceanic Island Basalt (OIB), raw materials for adze manufacture could be found almost anywhere. Indeed, recent Hawaiian sourcing studies on Maui (Kirch *et al.* 2012), Nihoa and Necker (Lebo & Johnson 2007) and Kauaʻi (Mills *et al.* 2010) have shown that most of the debitage and unfinished tools were made from multiple sources of local basaltic rocks with non-local basalts having a more restricted distribution. While it seems that assigning unknown artefacts to a possible source is a straight-forward process, at least in the Hawaiian archipelago, many adze quarries or sources await discovery, a

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point made by McCoy more than 20 years ago (1990:110). Indeed, in a relatively well-studied area of west Molokaʻi (Summers 1971), a recent comprehensive survey geared towards discovering new sources of fine-grained basalts documented eight new sources, one of which was a major, intensively used quarry (Weisler 2011). If this level of intensive survey was conducted throughout the Hawaiian Islands, the amount of known sources would substantially increase, thus 'confound[ing] our ability to make exclusive associations with specific sources' (Lundblad *et al.* 2011:66), especially when interpreting the geochemical values of only a limited range of elements.

It has become common textbook knowledge among the geochemical research community that basalts of totally unrelated origins from different parts of the world may have identical major element signatures, mainly due to similar partial melting conditions for the generation of basaltic magmas from the mantle. It is therefore vital that a broad range of major and trace element concentrations as well as Sr-Nd-Pb isotopic ratios are used for characterising quarries and sources to reduce the likelihood of overlap of geochemical signatures between known quarries as well as new sources discovered and reported in the future.

In this paper we report a fine-grained basalt source on Oʻahu that now ranks as one of the two largest on that island and, aside from the Mauna Kea adze quarry complex on Hawaiʻi island (McCoy 1977), and the Haleakalā source on Maui (Emory 1921; Mintmier *et al.* 2012), is one of the major quarries in the archipelago. The main objectives of our study are to:1) define the limits of the quarry complex; 2) locate the *in situ* geological source of the fine-grained basalt used for adze manufacture; 3) report the petrographic and geochemical variability of the source rock (n=9) – the latter defined by a comprehensive array of 10 fully quantitative major element concentrations, 43 trace element abundances, and high-precision Sr-Nd-Pb isotopic ratios obtained using the state-of-the-art Thermal Ionization Mass Spectrometry (TIMS, for Sr isotopes), Multi-Collector Inductively Coupled Plasma Mass Spectrometry (MC-ICP-MS, for Nd-Pb isotopes), quadrupole ICP-MS (for trace elements) and Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, for major elements), respectively; and 4) collect data on adze blanks and preforms, including hammerstones and debitage to determine the reduction strategies employed at the complex as well as the size and style of adze preforms produced. Although no excavation was conducted during this phase of research, a piece of branch coral was recovered from the surface of a rockshelter that provided a date of possible quarry use.

ENVIRONMENTAL SETTING

Nānākuli Valley lies within the Waiʻanae District on the western side of the island of Oʻahu (Figure 1). Two shield volcanoes formed Oʻahu between 3.9 and 1.7 million years ago (Ma) (Juvik & Juvik 1998). An older series of eruptions formed the shield lavas of the Waiʻanae Range

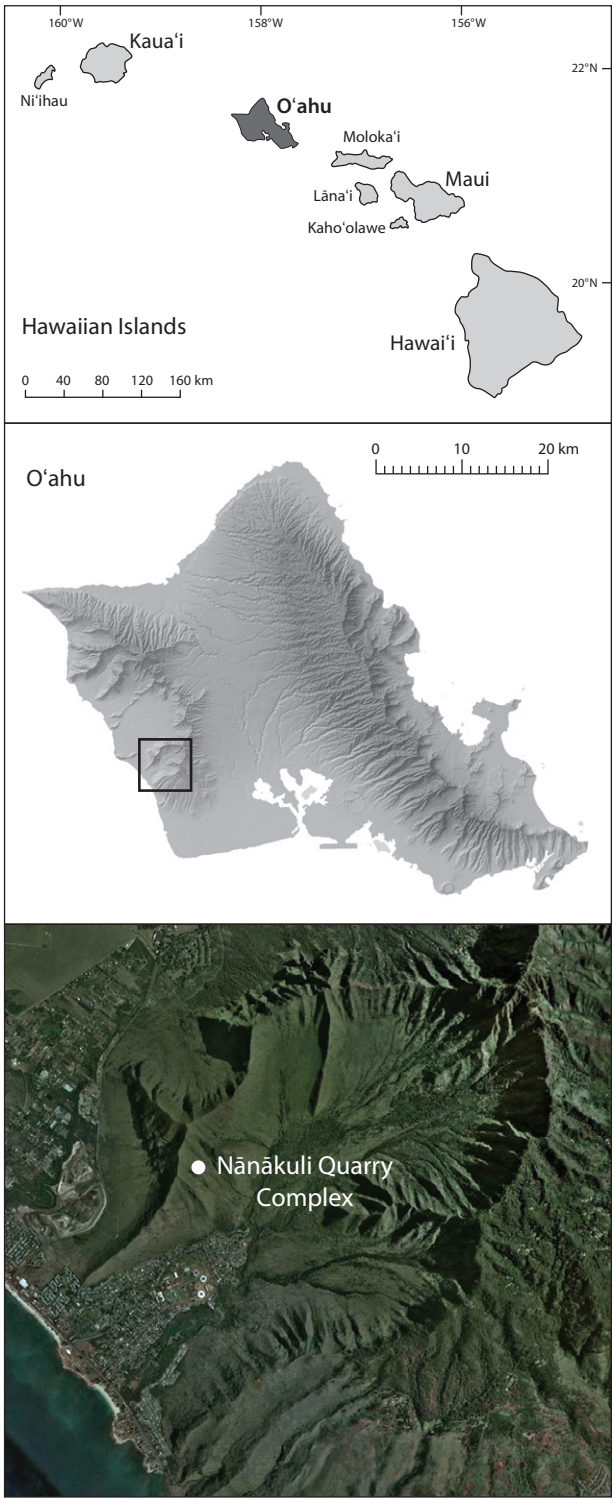

Figure 1. Map of the Hawaiian Islands, with a relief map of Oʻahu showing the location of Nānākuli Valley and a Google Earth view of Nānākuli Valley and the location of the quarry complex (bottom view © 2010 Google; © 2012 TerraMetrics and USGS)

between 3.9–3.5 Ma; they were subsequently overlain by postshield-stage alkalic basalt 3.2–2.5 Ma (Doell & Dalrymple 1973). The large valleys such as Nānākuli that eroded from the shield volcano are a distinctive feature of the Waiʻanae landscape. The project area lies on the north side of Nānākuli Valley approximately 2.2 km inland from the coast, on the slope of the ridgeline of Puʻu Heleakalā.

The Natural Resources Conservation Service (NRCS) Web Soil Survey indicates that soils in the vicinity of the quarry site are Lualualei extremely stony clay (LPE), in the lower portions of the slope, and rock land (rRK) in the upper areas (Soil Survey Staff 2012). LPE soils occur on slopes ranging from 3 to 35 per cent; there are many stones on the surface and runoff is medium to rapid. Rock land occurs in areas where exposed rock covers 25–90 per cent of the ground surface; it is chiefly characterized by rock outcrops and a shallow soil cover. Its slope ranges from nearly level to very steep (Foote *et al.* 1972).

The project area is within a Department of Hawaiian Homelands (DHHL) leasehold that is an active cattle ranch although the site complex is generally at a higher elevation than that accessed by livestock. The vegetation cover primarily consists of exotic grasses and sparse *kiawe* (*Prosopis pallida*) and *koa haole* (*Leucaena leucocephala*) trees which extend upslope into the project area. Rainfall in this part of Oʻahu is sparse, averaging 508–889 millimeters per year (Giambelluca *et al.* 2011). The quarry areas and lithic production sites extend along and adjacent to an unnamed drainage which appears to have an intermittent flow, as indicated on current and historic topographic maps.

PREVIOUS ARCHAEOLOGY IN NĀNĀKULI

From 1988–1991, staff from the State Historic Preservation Division (SHPD) carried out a comprehensive survey of undeveloped lands in Nānākuli owned by the DHHL. The survey work covered much of the upper valley, inland of the existing DHHL subdivision. Although a final report on the survey has not yet been published, the principal investigator for the work, Ross Cordy, summarised the principal findings in his brief study of Waiʻanae (Cordy 2002). The upper valley floor, which lies to the southeast of the current project area, was 'covered with the ruins of dryland agricultural fields' which Cordy suggests date to the 18th century AD (2002: 82). Twenty-six house sites were recorded in association with agricultural complexes; one shrine and a possible *heiau* (temple) were also identified (Cordy 2002).

The 1988–1991 survey of DHHL lands did not include the slope on which the quarry complex is located although one of the survey participants, Moana Lee, had noted the presence of lithic deposits in the area (personal communication, 2011). About 2001,Lee and Eric Komori (then of SHPD) conducted a reconnaissance investigation of that slope and recorded a number of debitage concentrations as well as several potential lithic sources. Their documentation included basic descriptions of features and artifacts, and recordation of Global Positioning System (GPS) coordinates (NAD83, zone 4).

SURVEY METHODS AND RESULTS

In 2010, Weisler and Collins made a brief site visit to relocate features previously identified by Moana Lee and Eric Komori, acquire information on the extent of the site complex and identify the actual source of the fine-grained basalt; this was in preparation for a more comprehensive survey which took place over three days in July 2011. The entire site complex was completely overgrown with dense grass over 1 m high and only constructed shelters, bedrock outcrops and areas of active scree slopes were clearly visible; we therefore consider the surveyed limits of the quarry complex to be the minimum size. The pedestrian survey proceeded slowly over rugged terrain consisting of loose cobbles and boulders obscured by covering grasses, often on 45° slopes as at the inland extent of the complex. The angular shape of the loose source rock observed on the lower slopes and within the drainage suggested the geological source may be a dyke, an *in situ* once sub-surface intrusive flow, or sill above a larger magma chamber. We therefore ascended the broad steep slope en route to the exposed strata at ~320 m elevation, which was barely visible from the bottom of the survey area at ~110 m asl (Figure 2). Adze material was concentrated at structural features and within rockshelters. Sparse adze material and source rock were also found within the drainage and along the broad ridge slope. Some 25+ m on either side of the drainage at the lower elevations, the lithic material decreases markedly. Overall the complex extends ~670 m (straight line distance) from the lower gentle slopes near the road (at ~100 m elevation) to the upper reaches where the rockshelters and the *in situ* source are located at ~320 m elevation. GPS coordinates (NAD83, zone 4) were recorded at a platform/terrace, an exposed section with lithics near the drainage, some rockshelters and at find spots. The most prominent features are briefly described here.

Platform/terrace

Situated at ~196 m elevation (GPS: 0590185/2366166) on the broad ridge slope, we collected four surface flakes for geochemistry at this structure and photographed and recorded dimensions of four adze blanks, three preforms and one hammerstone.

Lithics exposed in eroding bank

On the north side of the drainage and on a level area at the base of a steep rock face (Figure 2, lowest arrow) is a dense concentration of debitage eroding from an intact deposit at ~250 m elevation (GPS: 0590079/2366292). This is one of the few areas within the quarry complex, identified thus

Figure 2. Photo of upper quarry complex from the trail showing the source (B), rockshelters (A, C, D and E) and scree deposits. The solid arrow identifies the debitage scree below rockshelter A. The dotted arrow shows the location of the angular fine-grained rock scree below the *in situ* source. (photo, M. Weisler.)

far, where it might be possible to obtain subsurface dating material in association with debitage. Excavation would be required to determine if this is an *in situ* workshop.

The upper quarry complex (from ~285 to 320 m elevation) consists of four rockshelters and the *in situ* source rock (Figure 3). A detailed compass and tape map was facilitated by setting north-south and east-west baselines with chaining pins every 1 to 5 m depending on vegetation cover and the surface covering of outcrops. The uneven, loose scree surface and 45° ground slope made mapping challenging.

Rockshelter feature A

At the highest and most inland extent of the quarry complex is rockshelter Feature A (Figures 2, 3 and 4a, b). Situated at ~319 m elevation (GPS: 0590021/2366387), it is ~20 m west of the fine-grained rock source (Feature B) which is easily accessible by walking along the same contour. This is significant as the immediate area around rockshelters C and D is on a 45° slope making access to the source from these rockshelters much more difficult. Feature A rockshelter measures 6.20 m wide, ~1.80 m deep and 2.30 m high at the dripline. A scree slope of dense debitage, adze preforms and blanks extends ~30 m steeply downslope (Figure 4g). Data from 17 blanks and preforms was collected here. This rockshelter is in pristine condition with an undisturbed distribution of artefacts and has, by far, the densest concentration of debitage, preforms, hammerstones and hammerstone flakes of any of the rockshelters in the complex (Figures 4b and 5). A single piece of *Pocillopora* sp. branch coral (~35 mm long; lab no. 2011–019) was found at the east end of the rockshelter (Figure 5) and yielded a U/Th date of cal AD 1234 ± 6 (analytical procedures described in Weisler *et al.* 2006). The powdery sediment surface and mounded dense cultural material suggests some depth to subsurface cultural deposits.

Fine-grained basalt source feature B

Situated at the top of the complex at ~318 m elevation (GPS: 0590042/2366381), the rock source is a 2.40 m thick edge of a flow or sill where eroding angular boulders and cobbles form a jumbled pile extending nine m along the exposure (Figure 6a, b). There is no clear evidence of extraction at this particular area, but a continuation of the flow immediately west and outcropping ~0.45 m high (Figure 6d), exhibits flake scars and partially dislodged rock (Figure 6c). A dense scree of angular rock, with few artefacts, begins at the *in situ* source and descends ~35 m. Judging from the amount of angular rock in the drainage below the flow, continuing downslope for nearly 500 m, the source rock has probably been eroding well before the area was settled. It is likely, then, that stone-tool qual-

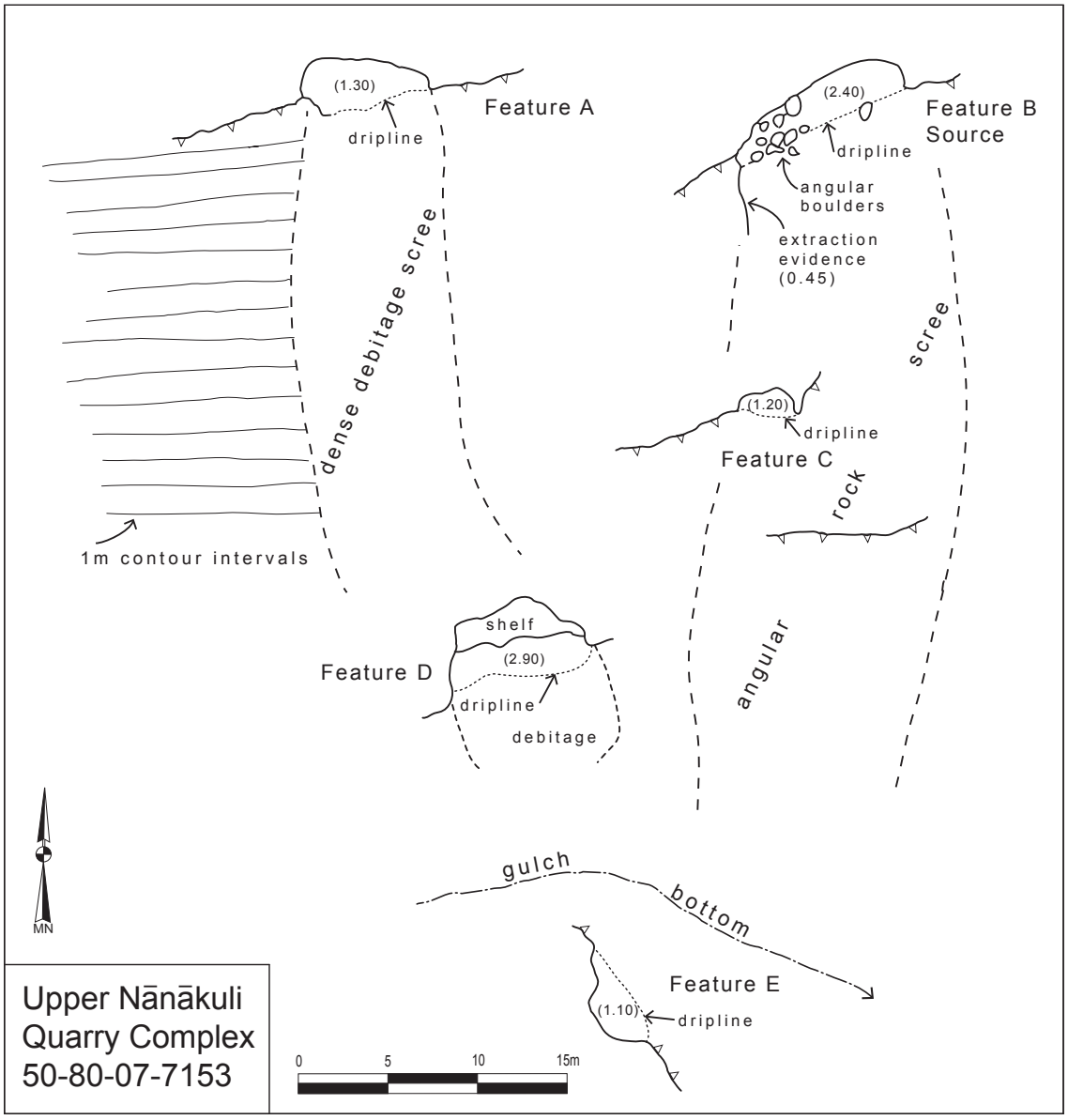

Figure 3. Map of the upper quarry complex showing the source (B), rockshelters (A, C, D and E) and scree deposits. (map, M. Weisler and S. Collins.)

ity rock was most often collected as loose surface cobbles, rather than quarried at the face of the flow. In this regard, an angular, unmodified rock (sample 2011-269) collected at 115 m elevation within the drainage outwash and ~500 m distant from the *in situ* source rock is geochemically identical to the source.

Rockshelter feature C

Located at ~305 m elevation, the rockshelter opening is 3.60 m wide, 1.80 m deep with a maximum ceiling height of 1.40 m (Figures 2, 3 and 4c). A scree of angular rock beginning at the source (Feature B) continues downslope for ~25 m past Feature C (Figure 3). One adze blank and a hammerstone were recorded from the scree. There was much angular unmodified scree rock on the rockshelter surface as well as several secondary flakes and one hammerstone flake (Figure 4d). There is far less debitage here than at rockshelter A. Although there could be subsurface cultural deposits, judging from the quantity of surface debitage, it is unlikely that more than an adze blank or two were made here.

Rockshelter feature D

Near the bottom of the north slope of the quarry complex at ~288 m elevation (GPS: 0590019/2366360), just above the drainage is a rockshelter measuring ~8 m wide, 2 m

Figure 4. Upper Nānākuli quarry rockshelters. a) rockshelter A, view NE with flagging tape at site datum and chaining pins along baseline; scale is 0.5m; b) detail of rockshelter A surface. Note discoidal hammerstone (#A3) left of scale; c) rockshelter C, view NE; d) detail of rockshelter C surface showing debitage and naturally angular rocks; e) W extent of rockshelter D, view W; f) detail of rockshelter D floor with preform (#D1) near scale; g) debitage scree slope ~25 m below entrance to rockshelter A; h) rockshelter E across drainage, view W. (all photos, M. Weisler.)

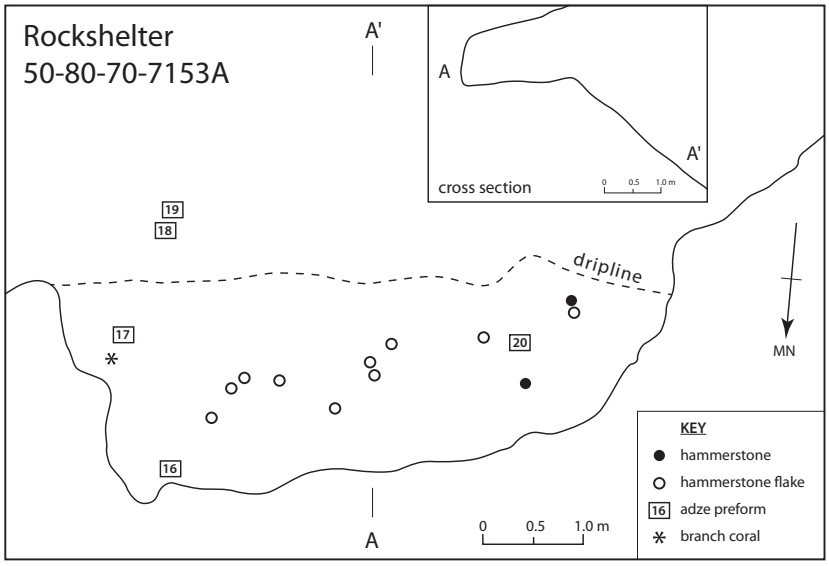

Figure 5. Map of rockshelter A showing the distribution of artefacts other than fine-grained flakes which cover most of the rockshelter floor and extend for >25 m down the 45° slope fronting the entrance. (map, M. Weisler and S. Collins.)

Figure 6. *In situ* Nānākuli source rock. a) view NE of main exposed layer ~2.5 m thick (scale is 0.5 m long); b) view W showing intact top of formation and jointed nature of source rock near scale; c) detail of extraction area showing bulbs of percussion on some *in situ* source rock,; d) extraction area 5 m downslope of main layer. (all photos, M. Weisler.)

deep with a maximum ceiling height of 2.90 m (Figure 4e). Much of the shelter floor is bedrock and the entire back of the shelter is formed by an outcrop with no sediment accumulation. Debitage and an adze preform are concentrated in the west end of the shelter (Figure 4f), some of which is eroding downslope. The sparse deposits and uneven floor surface suggest that this rockshelter was not used very much.

Rockshelter feature E

The only rockshelter on the south side of the drainage at ~285 m elevation (GPS: 0590019/2366352), this feature measures ~6 m wide, 2.5 m deep and only 1.10 m in height due to sediment accumulation (Figure 4h). The surface is quite uneven and, today, it is only accessible by crawling on one's stomach. There is little debitage and two adze blanks (17 and 30 cm long) and one preform were observed quickly during our final descent from the upper quarry complex.

THE ASSEMBLAGE

Most artefacts were analysed at the quarry while a small sample was collected for further study in the lab. The main objectives were to describe the adze manufacturing process: the hammerstones used, resulting debitage and styles and sizes of adze blanks and preforms. Metric and discrete attributes are reported for five hammerstones, 27 flakes, six adze blanks and 20 preforms (Tables 1–3).

Hammerstones

Of the five fabricators, the two heaviest consisted of fine-grained quarry rock, two were slightly vesicular ('softer' basalt), and a single medium-grained basalt hammerstone was probably collected from the drainage due to its water-rounded shape (Figure 7). Weights ranged from 251–999 g. Selected discrete and continuous attributes are listed in Table 1. Overall shapes were blocky, discoidal and elongate – a similar range of shapes found at other major quarries, such as at Puʻumōiwi on Kahoʻolawe (McCoy *et al.* 1993: 141–45). Found immediately downslope of the *in situ* fine-grained source rock, the largest hammerstone (Table 1: number 9; Figure 7i) may have been used for dislodging large chunks of rock at the source where a heavy blow would be necessary for removing large angular blocks for adze production. The other hammerstone consisting of quarry rock (Table 1: number A10; Figure 7a, b) was made from a discarded adze blank and exhibits intensive battering along two sides. Its weight, at 341 g, suggests that it was used for the latter stages of adze blank/preform production. An elongate hammerstone (Table 1: number 3; Figure 7g, h) weighing 838 g is large enough to have been used for removing large flakes for adze blank production. Made of medium-grained rock this hammerstone is slightly 'softer' than the quarry rock and the rounded, battered end measures 36 × 29 mm. This hammerstone would be ideal for removing long and relatively thin flakes with diffuse bulbs of percussion; an adze preform made from such a flake is illustrated in (Figure 8a). Two slightly vesicular, discoidal hammerstones were found on the surface of rockshelter A in association with secondary flakes and a small adze preform (Figures 4a and 7c-f). Both hammerstones exhibit battering along their entire perimeter; the widths of the used surfaces range from ~75–100 mm. At 251 g, one of these artefacts is the lightest hammerstone recorded and was undoubtedly used for the latter stages of adze production where long, thin flakes, with thin striking platforms and diffuse bulbs of percussion, were struck for reducing blanks into preforms (see also Cleghorn 1982: 215). Discoidal hammerstones with broad areas of contact and made of vesicular basalt which 'catches' the stone as it strikes, are perfect for removing such flakes. This is also supported by the analysis of a sample of debitage associated with these two discoidal hammerstones from rockshelter A.

Debitage

In addition to sampling the intact basalt source, fine-grained basalt flakes were collected from three localities for determining the range of geochemistry present in the rocks that were selected for adze manufacture. These flakes represented the macroscopic variability in phenocrysts and overall grain size. We advocate this geologically-informed protocol for determining the geochemical variability in a source, rather than simply analyzing a large sample of flakes or formed artefacts and assuming that the geochemical variability is defined. Debitage from rockshelter A was collected for indicating the stages of adze manufacture at the site. We acknowledge that this was not a strictly random sample, but the debitage does reflect some of the stages of adze production on the shelter surface. Sixteen flakes were obtained inside rockshelter A and one flake on the adjoining scree slope; five flakes from the floor of rockshelter C; and five flakes from the platform-terrace situated on the broad slope below the main quarry complex. The rockshelter A flakes are summarised here, while discrete and continuous attributes for all debitage are presented in Table 2. This subset of debitage, most of which was collected within 1 m of the two discoidal hammerstones (Figure 4a), consists of generally thin, slightly expanding flakes often resulting from the reduction of adze blanks to preforms (Cleghorn 1982; Williams 1989: 56). In this regard only one of the 16 flakes are primary (with 90 per cent dorsal cortex), while the remaining are secondary flakes. Average complete dimensions are: weight (n=11) 19.7 ± 12.0 g; length (n=16) 37.94 ± 13.52 mm; width (n=15) 39.34 ± 16.70 mm; and thickness (n=16) 6.11 ± 2.45 mm. The striking platforms are broad (n=11; 15.25 ± 5.62 mm) and thin (n=12; 6.05 ± 2.63 mm) suggesting that flakes were removed by 'soft' hammerstones with a wide contact

Table 1. *Metric and discrete attributes for Nānākuli adze blanks and preforms and hammerstones.*

No.	Feature	Type	Condition	Length	Width	Thickness	Weight	Cross-section	Comments
3	platform-terrace	hammer-stone	complete	126	73	63	838	round	elongate, battering on ends, 1 flat used surface 36x29mm.
9	scree below C	hammer-stone	complete	104	99	51	999	quad	~20m downslope of C; made of quarry rock; flat cortex on 2 surfaces.
A1	A	hammer-stone	complete	83	74	29	251	discoidal	slightly vesicular; battering along entire perimeter.
A3	A	hammer-stone	complete	100	97	32	456	discoidal	slightly vesicular (same material as A1); shoulder complete around perimeter.
A10	A	hammer-stone	complete	113	55	40	341	quad	heavy battering on sides.
2	platform-terrace	blank?	complete	218	99	93	>4kg	undetermined	cortex on 2 surfaces.
1	platform-terrace	blank	complete	250	97	195	>4kg	quad	cortex on 2 surfaces, possibly made from a cobble.
7	platform-terrace	blank	incomplete		86	85		undetermined	<10% cortex on 2 surfaces.
8	platform-terrace	blank	complete	304	93	78	7+kg	quad	made from cobble; cortex on 3 surfaces.
10	scree below C	blank	complete	101	60	31	322	quad	~15m downslope; flake series; striking platform at side; ~20% cortex on back & adze front.
A28	A	blank	complete	274	89	57	>4kg	undetermined	made from a cobble; cortex= 60% front, 75% side, 30% back.
4	platform-terrace	preform	complete	158	73	35	1025	quad	bevel flaked, 40% cortex on front face.
5	platform-terrace	preform	blade frag		52	22		quad	cutting edge width=62mm; 100%cortex on front face, 10% cortex on back face; end shock.
6	platform-terrace	preform	butt frag		50	44		square	end shock; tang to poll=97mm; poll W=31mm; poll T=34mm.
9	platform-terrace	preform	complete	221	60	57	1653.2	square	cortex on poll only; slight bevel prep; lump on back reason for discard.
A16	A	preform	midsection		56	36		quad	too well-refined to determine reduction strategy; end shock both ends.
A17	A	preform	complete	110	54	22	205	quad	flake reduction strategy; poll=striking platform; flaked ventral surf=adze front.
A18	A	preform	complete	95	47	32	265	trap	flake series; front wider than back; striking platform=adze poll; ventral face=front.
A19	A	preform	butt frag		56	27		quad	cortex = 100% dorsal, 95% front, end shock; cortex on poll.
A20	A	preform	complete	82	45	14	98.2	quad	flake series; poll=striking platform, bevel prep, flat cortex along half length of 1 lateral margin.
A21	A	preform	complete	224	89	50	2182	quad	lab no. 2011-266; tanged, cortex on front, back, poll and bevel.
A22	A	preform	complete	256	59	70	1851	square	lab number 2011-265; tanged, cortex on front and both sides; bevel preparation.
A23	A	preform	blade frag		58	58		square	end shock; bevel prep.
A24	A	preform	butt frag		54	52		square	reduction strategy undetermined; cortex on back; end shock.
A25	A	preform	butt?		49	51		square	reduction strategy undetermined; tanged, endshock.
A26	A	preform	complete	198	51	55	1115	square	25% cortex on front.
A27	A	preform	complete	153	61	29	464	quad	platform on side; 60% cortex on back.
A29	A	preform	blade frag		59	43		square	80% complete; bevel prep; end shock; 20% cortex on back.
A30	A	preform	complete	163	70	49	980	square	
A31	A	preform	complete	86	34	16	97.4	trap	flake series; diffuse bulb; 100% cortex on striking platform (poll); parallel sides; bevel preparation; 15m south of A.
D1	D	preform	complete	118	55	30	446.3	quad	made from tabular piece; cortex on front and back; bevel prep; lump on front at butt is reason for discard.

Note: measurements and weights provided for complete dimensions only.

Table 2. *Metric and discrete attributes for Nānākuli flakes.*

Feature No.	Weight	Length	Width	Thickness	Platform Width	Platform Thickness	Termination	Cortex	Bulb	Comments
A	26.4	49.23	47.19	8.97	15.46	4.81	feather	0	diffuse	secondary flake
A	34.2	59.81	43.92	7.44	20.18	7.28	hinge	30% dorsal	diffuse	secondary flake
A	31.7	51.53	68.05	6.65	12.64	5.09	hinge	0	diffuse	classic expanding flake
A	29.5	55.71	65.32	5.22	10.50	5.29	feather	5% dorsal	diffuse	expanding flake.
A	5.0	27.84	32.31	4.06	not intact		feather	0	diffuse	collapsed platform
A	19.7	53.23	42.37	6.79	10.57	5.57	feather + hinge	0	salient	
A	7.6	34.23	23.21	5.16	not intact		snap	0	diffuse	broken flake
A	32.9	48.78	54.66	10.51	19.45	5.79	feather	20% dorsal	diffuse	100% platform cortex
A	14.7	26.06	37.75	9.20	26.10	11.63	hinge	0	salient	
A	5.7	35.19	22.81	3.54	17.39	4.93	hinge	0	salient	
A	4.7	29.39		4.39	8.42	2.16	feather	75%	diffuse	flake width incomplete
A	16.9	31.56	45.07	9.21	incomplete	10.37	feather	0	salient	secondary flake
A	2.2	17.28	29.02	3.62	8.64	3.86	feather	0	salient	secondary flake
A	14.7	41.72	49.62	6.93	18.44	5.87	snap	0	diffuse	secondary flake
A	1.5	22.14	13.97	3.18	not intact		feather	5% dorsal	diffuse	secondary broken flake
A	1.3	23.33	14.77	2.96	not intact		feather	90% dorsal	diffuse	primary flake
C	17.8	58.55	18.95	8.99	7.95	2.51	snap	100% 1 edge	diffuse	secondary flake
C	11.3	32.39	26.56	8.97	23.41	14.59	snap	100% plat	diffuse	secondary flake
C	3.6	20.84	28.86	4.28	10.92	3.78	feather	0	diffuse	secondary flake
C	4.9	20.45	35.85	4.67	17.28	5.13	snap	30% dorsal	salient	secondary flake
C	6.5	20.08	32.08	6.85	33.52	8.15	feather	100% plat	salient	100% cortex 1 side; secondary flake
platform	185.5	81.67	75.38	18.82	19.89	6.01	snap & feather	0	diffuse	secondary flake
platform	151.9	93.69	76.28	19.50	19.76	7.45	snap	25% dorsal	diffuse	retouced flake ('scraper')
platform	11.6	35.47	33.17	8.61	not intact		snap	0	diffuse	broken, secondary flake
platform	9.9	26.72	25.08	6.49	not intact		snap	0	diffuse	broken, secondary flake
platform	0.9	11.53	7.40	6.87				yes		volcanic glass nodule
A-scree	65.0	67.90	64.09	10.58	35.91	10.09	feather	0	salient	secondary flake

Table 3. *Data from scanned adze preforms.*

Aretfact No.	Volume mm^3	Area mm^2	Cortex Area mm^2 (%)	Bevel Angle
A20	33036	8700	1632 (19)	25.3
A21	754632	59296	14898 (25)	83.5
A22	624576	52684	6143 (12)	78.8
A31	32563	7622	0	81.6
D1	150752	20047	5048 (25)	72.8

surface. In this context 'soft' refers to vesicular basalt or hammerstone rock that is less dense than the object piece. Additionally, most (69 per cent) of the flakes exhibit diffuse bulbs of percussion more typical of hammerstones consisting of softer rock than the flakes. Judging from the low percentage of dorsal cortex on the flakes, the high frequency of broad and thin striking platforms and the diffuse bulbs of percussion, it is likely that adze blanks were reduced to preforms inside the rockshelter.

Blanks and preforms

The production of adze preforms include: (1) raw material selection then either (2) reduction of boulders or cobbles directly into blanks; or (3) the production of large flakes which form the basis for blank manufacture. Because adze preform manufacture is on a continuum, it is not always possible to explicitly define where the blank stage ends and preforms begin (see discussions in McCoy *et al*. 1993: 120–124; Weisler 1990: 34). Various authors have grappled with this problem by defining more stages in the continuum. For example, the blank, 'preform?' and preform stages were defined by Dye *et al.* (1985: 11). McCoy *et al.* questioned the usefulness of the blank-preform continuum (1993: 123–24), instead using a 'techno-morphological' approach that proposed four 'types' where type 1 was the least refined and type 4 could be referred to as a preform. Using a slight variation of that proposed by Weisler (1990: 34), the Nānākuli preforms have clearly defined medial and longitudinal cross-sections, while the

medial cross-section of blanks is either indeterminate or refined just sufficiently to propose a likely cross-section form but, overall, the blank is not well refined.

Blanks

Four of the six blanks analysed at the platform-terrace were well downslope from the main quarry and *in situ* source rock, suggesting that eroded angular fine-grained rock located nearby in the drainage and along the broad slope were important sources of raw material. With an average weight exceeding 4 kg, it is less likely that blanks were carried down the steep slope, considerably distant from the source, to be refined into preforms. All blanks exhibited cortex on one or more surfaces. Of the six blanks, three were made from a cobble, one from a flake and two

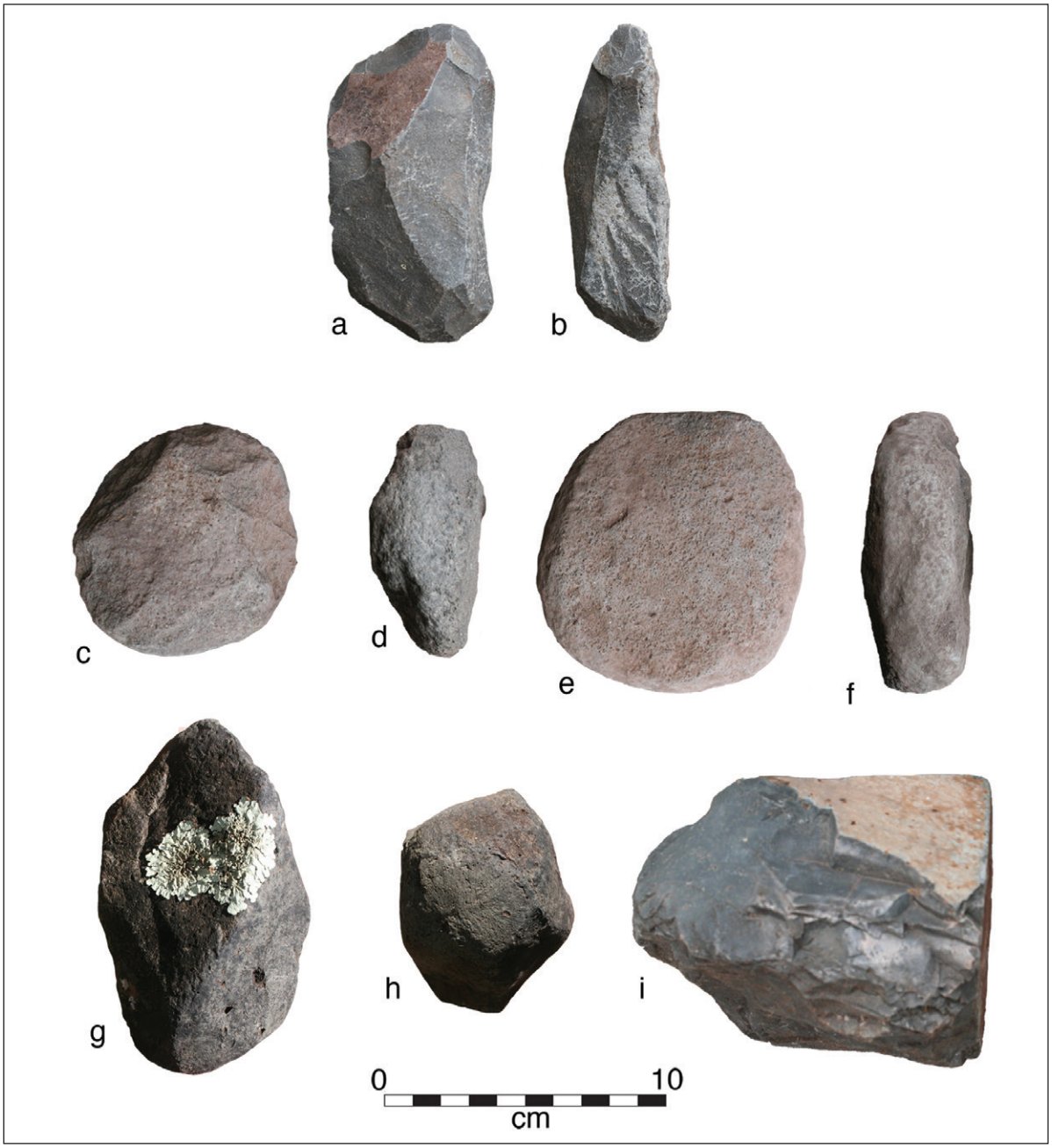

Figure 7. Size, shape and material variation of hammerstones. a) back and b) side, showing intensive battering of specimen A4 made from a rejected adze blank; c) plan and d) side of a discoidal form (specimen A1); e) plan and f) side, exhibiting shouldered use wear along edge of discoidal form (specimen A3); g) side and h) end, showing smoothed area resulting from use of elongate cobble (specimen 3); i) chunk of quarry material used as a hammerstone (specimen 9) possibly to dislodge rock at the source (Feature B). (all photos, M. Weisler; see Table 1 for metrics and additional descriptions.)

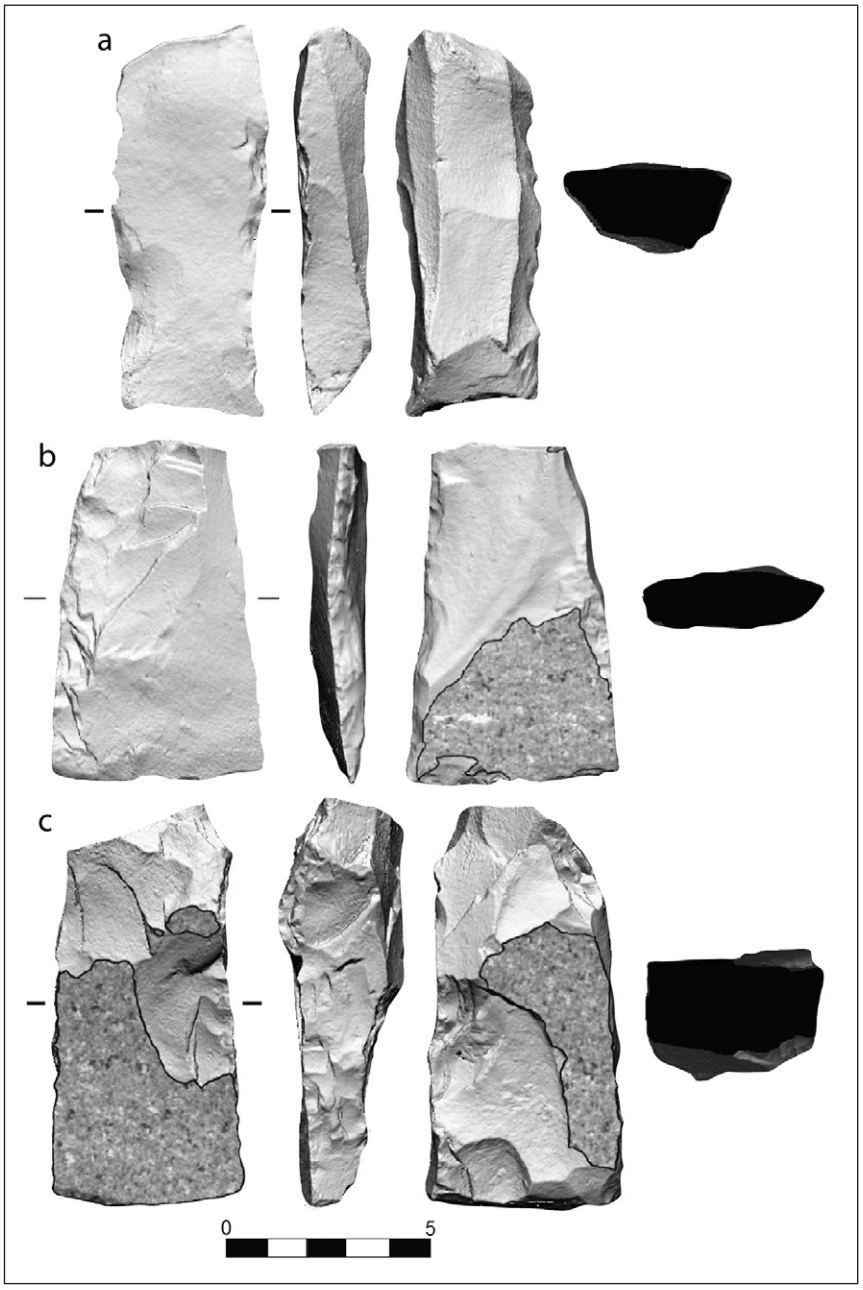

Figure 8. Scans of smaller adze preforms. a) example of an adze preform made from a flake (specimen A31). First view is ventral side of flake or front of adze preform; b) flake series, quadrangular form (specimen A20) with cortex visible on back; c) made from a tabular cobble, specimen D1 exhibits cortex on both front and back. Lump visible on side view (left margin of image) near butt is reason for discard. Note that the cross-section taken at the midpoint is shown darker, while the lighter portion incorporates the view towards the poll. Therefore, D1 gets thicker from the midpoint towards the poll. (see Tables 1 & 3 for additional data; scans by C. Shipton.)

were indeterminable. Three were clearly quadrangular in cross-section although this may not have been their final intended form as the overall longitudinal shape and lack of refinement argued for grouping these specimens as blanks. The average dimensions of these blanks are: length (n=5) 229.4 mm; width (n=6) 87.3 mm; and thickness (n=6) 80.9 mm.

Preforms

Data were collected from 20 preforms, 15 of which were associated with the steep scree immediately downslope of rockshelter A, attesting that this rockshelter was the main adze manufacturing locale of the upper quarry complex. These refined preforms averaged 865.2 ± 722.3 g in weight;

that is, less than a quarter of the weight of the adze blanks. Importantly, preform weights ranged from just under 100 g to >2 kg demonstrating that a broad array of adze sizes was produced at this quarry. Complete preform dimensions are: length (n=12) 155.3 ± 59.0 mm; width (n=20) 56.6 ± 11.4 mm; and thickness (n=20) 39.6 ± 15.6 mm (see Table 1). A selection of five preforms was scanned using a Next Engine 3D laser scanner (Figures 8 and 9). These scans allow us to take accurate measurements of the volume, surface area and cortex coverage of the preforms (Table 3), variables which could only be previously estimated or measured approximately. Axial dimensions, as though a box were drawn around the artefact and only the relevant sides measured, may be taken more accurately than with calipers after the artefact has been oriented. The illustrations were extracted from the program ScanStudio where the scans were also oriented and the measurements were taken in the program RapidWorks.

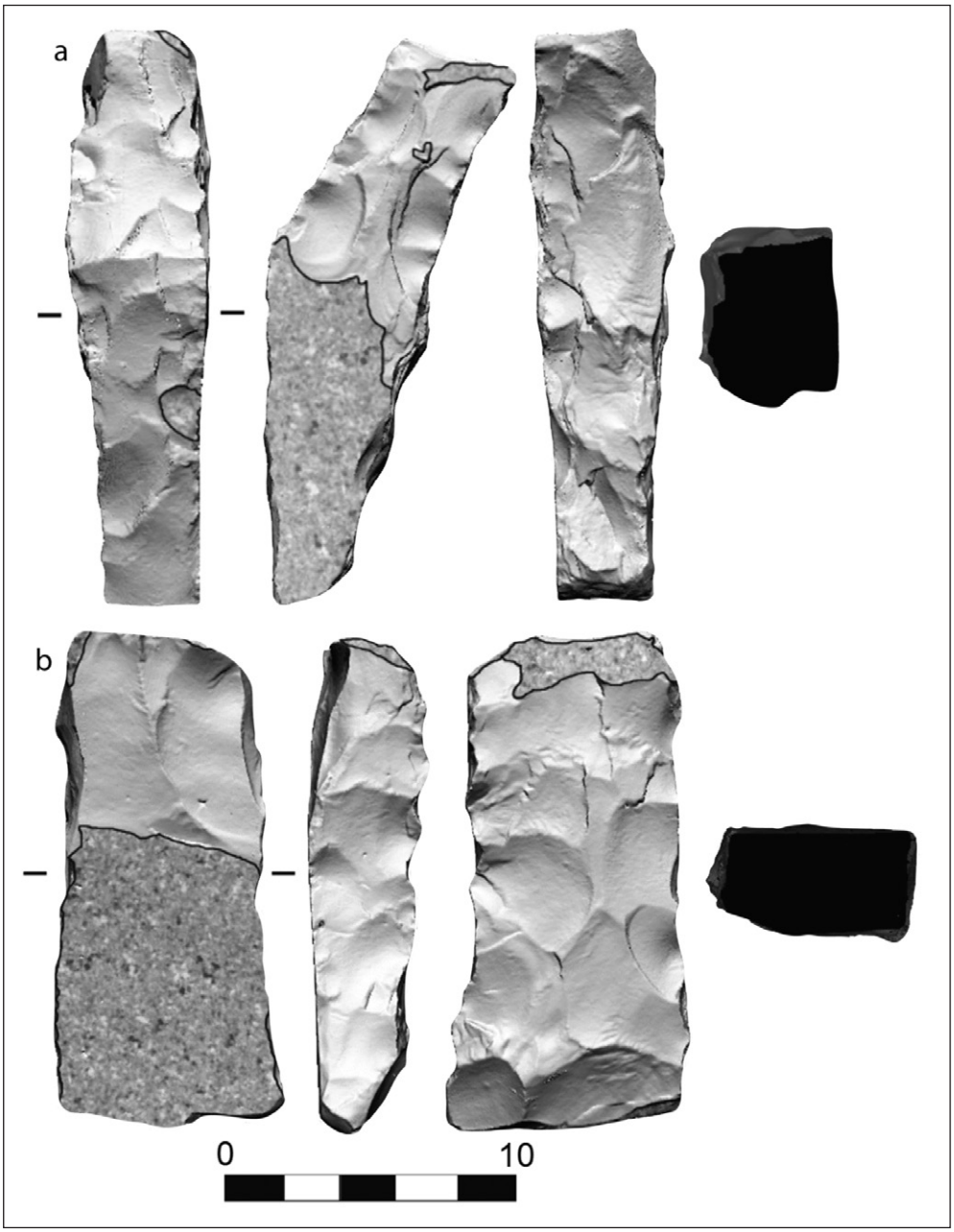

Figure 9. Scans of larger adze preforms. a) tanged, quadrangular preform (specimen A22) with minor cortex on front and both sides; made from a large flake or cobble; b) slightly tanged, quadrangular form (specimen A21) with cortex on front, back, poll and bevel suggesting this preform was made from a cobble. (see Tables 1 & 3 for additional data; scans by C. Shipton.)

From the surface area measurement flake scar density can be calculated. Here, we suggest that adze blanks, from the Nānākuli quarry, may have larger overall flake scars, while preforms have smaller and more flake scars. In the future, scanning technology may facilitate the explicit separation of the stages along the blank-preform continuum. (However, any inter-quarry comparisons of the blank-preform continuum must consider raw material form as a key variable.) As such, experimental evidence indicates that biface reduction intensity can be estimated from the flake scar density measurements taken from scans (Clarkson and Shipton n.d.). Because preforms, by definition, are extensively reduced, it was only possible to determine that two were made from flakes (Figure 8a, b) and one from a tabular cobble with partial cortex on the front and back (Figure 8c). Cross section form was determined through the midsection and, for tanged forms, the transverse section was observed near the tang. Of the 20 preforms: nine are quadrangular (e.g., Figure 9b), nine square (Figure 9a) and two trapezoidal (both with the front wider than the back; Figure 8a). Tanged forms included one quadrangular and three square cross-sectioned specimens (Figure 9a, b). All eight fragmentary preforms were discarded due to end-shock. This is a common problem in the thinning stage of the production of large cutting tools, related to the overuse of force (Edwards, 2001; Shipton *et al.* 2009). Reasons for discard of the whole specimens included a lump – located on the front face at the butt – that couldn't be removed after repeated attempts (Figure 8c middle view), and a very uneven surface resulting from a thick flake removal (Table 1, specimen 9).

Comments on the reduction model

The term 'quarry' is most frequently used when referring to actual 'sources' of fine-grained basalt in the Hawaiian Islands (Weisler and Sinton 1997:180); however, adze rock was most often collected from the surface and not extracted from below the ground or dislodged from outcrops (Dye *et al.* 1985; Kahn *et al.* 2008; McCoy *et al.* 1993; Weisler 1990, 2011). Similar to the Mauna Kea adze quarry complex (McCoy 1977, 1990, *et al.* 2012), raw material at Nānākuli was dislodged from the *in situ* source as well as surface collected at the scree (at Nānākuli, below Feature B), along the broad slopes and within the drainage; raw material is found more than 0.5 km below the *in situ* source.

The Nānākuli raw material is highly jointed (Figure 6) with flat surfaces often intersecting at right angles which probably facilitated adze blank production. There are also loose cobbles with parallel surfaces that could be readily used for the front and back faces of adze blanks and preforms. Consequently, the form of the raw material may have aided blank production, much the same way that tabular layers dislodged from outcrops did at Mauna Kea (Cleghorn 1982). For example, a cobble fashioned into an adze preform required minimal flaking to achieve the desired shape (Figure 8c). The angular shape of the raw material was a somewhat unique feature at Nānākuli (since the use of jointed rock was previously only known from the Mauna Kea quarry complex) and perhaps made the source rock more desirable as a raw material. The adze makers at Nānākuli would have benefited from locating appropriate angular raw material for blank manufacture. While the scree slope below the source (Feature B) has the densest concentration of angular rock, possibly less weathered rock could have been extracted at the *in situ* source. Once the raw material was selected, adze blanks were either reduced from small boulders or cobbles, or flakes were detached from cores and further reduced into blanks. The 'core series' or 'flake series' (after McCoy 1986:12) are typical reduction strategies at all known Hawaiian adze quarries/sources (e.g., Kahn *et al.* 2008:152; Weisler 1990:38–39). Of the Nānākuli adze preforms, one in particular is an excellent example of the flake series reduction strategy. In Figure 8a the flake striking platform is the adze poll, the ventral surface of the flake is the front of the adze, and the distal flake termination shows secondary flaking or bevel preparation for the cutting edge.

Characterisation of the quarry material

Early attempts at characterising fine-grained basalt quarry rock in Hawaiʻi were accomplished by the century-old technique of preparing petrographic thin sections. Rock mounted on thin glass slides, petrographic thin sections ideally measure ~20 by 40 mm and are ground sufficiently thin (~0.03 mm thick) to transmit plain and polarized light allowing the mineralogy of crystals (phenocrysts) to be identified and grain sizes measured. While this technique produced some encouraging results for discriminating several of the well-known Hawaiian sources (Cleghorn *et al.* 1985), it was soon realized that geochemical techniques were necessary to provide a broader range of quantifiable measures (Best *et al.* 1992:50; Weisler 1993:71). Early pursuits by archaeologists at geochemical assay of Hawaiian quarry basalts and artefacts for facilitating sourcing studies used non-destructive energy-dispersive X-ray fluorescence (EDXRF) analysis (Weisler 1993) building on pioneering work in the 1960s at the University of California at Berkeley primarily with obsidian (Shackley 2011; Weisler 1993:74–5). After much trial and error, the 'incompatible' trace elements, also known as the mid-Z elements (rubidium, strontium, yttrium, zirconium and niobium with atomic numbers 37 to 41), or large lithophile elements (former) or high-field-strength elements (latter), collectively prefer the liquid phase over the major silicate mineral phases during partial melting (e.g., Sun & McDonough 1989) and appeared to discriminate basalt quarry sources (Weisler 1993; Weisler and Kirch 1996). As interaction or sourcing studies expanded throughout East Polynesia (summarised in Weisler 1993; see also Best

et al. 1992), it was realised that magma generation and evolution processes responsible for the formation of the Oceanic Island Basalt (OIB) province, and also within the same archipelagos, could yield similar geochemical signatures between islands (Collerson & Weisler 2007:1909; Weisler & Woodhead 1995:1882), especially when only a limited range of oxides and trace elements were used. Consequently, even more discriminating techniques were required to add a larger array of fully quantifiable oxides, trace elements and isotopic ratios for teasing out the geochemical differences between volcanoes thus facilitating sourcing studies.

Today the highest analytical precision and accuracy for state-of-the-art geochemical assay (not simply sourcing studies) can be achieved by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for routinely analyzing >40 trace elements and isotopes, by ICP-OES for 10 oxides, and by TIMS or MC-ICP-MS for Sr-Nd-Pb isotopic analyses (e.g., Collerson & Weisler 2007; Li *et al*., 2006; Weisler & Woodhead 1995; Woodhead & Weisler 1997). Characterisation of the Nānākuli source material is made by petrographic thin sections and ICP-MS, ICP-OES, MC-ICP-MS and TIMS to facilitate sourcing studies using a range of techniques. We do not advocate using non-destructive energy-dispersive X-ray fluorescence (EDXRF) for characterising sources or quarry rock as all the results are not fully quantitative and elements routinely used in these sourcing protocols are mostly restricted to the mid-Z elements (specifically, strontium and zirconium); that is, a very small portion of the elements that can be analysed with other techniques. It is advantageous to use a large range of geochemical values especially for characterising sources (see also James *et al.* 2007) but also for assigning unknowns (artefacts) to source. For many archaeologists that are not conversant with the strengths and weaknesses of various geochemical techniques and sourcing protocols, it simply makes good sense that the more unique fully quantitative geochemical values that are used to characterise sources, the better. Furthermore, source assignments of artefacts are more robust when a broad range of fully-quantifiable geochemical values are used. The first step, then, in facilitating robust sourcing studies is the comprehensive characterisation of sources (Weisler & Sinton 1997:180–81). 'It is important to emphasise that the *quality* of the analytical data ultimately controls the confidence with which a particular sample can be assigned to a unique source' (Weisler & Sinton 1997:180; emphasis added).

Petrography

Although petrographic descriptions are no longer used to assign Polynesian artefacts to a particular source, they can be useful for reporting overall grain size (texture), rock structure and basic mineral composition (Weisler 1993:71). The Nānākuli source rock is a fine-grained basalt containing olivine phenocrysts. Typical of basalts, the groundmass (matrix) is composed predominantly of plagioclase, pyroxene and opaque minerals. Locally the plagioclase crystals are euhedral and elongated. We counted the grains along four 500 micron lengths which averaged >100 grains per mm (Figure 10a) and we class the Nānākuli rocks as fine grained; that is, ~100–130 grains/mm (Weisler 2008:538) similar to most Hawaiian quarries (Cleghorn *et al.* 1985: Figure 2).

Geochemistry

We identified the actual *in situ* geological source of the raw material used for adze manufacture and removed two samples for geochemistry. Because the *in situ* source was relatively small, well defined and consisted of a single magmatic unit of a dyke or sill (see Figure 6), it was not necessary to take considerably more *in situ* samples to define the geochemistry of the source. However, we also analysed samples from adzes and flakes in nearby rockshelters to clearly demonstrate the geochemical similarity of rocks used for adze manufacture to the geological source of the material. Tables 4 and 5 list the geochemical data for the Nānākuli source rock, adze preforms and flakes.

All geochemical analyses were performed in two geochemistry laboratories at the University of Queensland (UQ). Analytical procedures for trace elements and Sr isotopes are described in Collerson and Weisler (2007) although, since then, we have extensively experimented with reducing the analytical sample size, especially when working with artefacts. Nd and Pb isotopic ratios were measured using the new multi-collector ICP-MS recently installed in the Radiogenic Isotope Facility at UQ. Only 10 mg for a combination of trace elements and isotopes (Ma *et al.* 2011) were used in our recent analytical protocols. This tiny amount of rock can be removed from most artefacts without leaving a noticeable impression. Major elements were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) using only ~50 mg of rock powder (assuming that the sample is homogeneous like most fine-grained basalts). Our sample sizes are far below wave-length dispersive X-ray fluorescence (WDXRF) which normally uses ~5 g for majors and ~3 g for trace elements.

Figure 11 is a typical bivariate plot of total alkalis of the source rock: sodium oxide (Na_2O) plus potassium oxide (K_2O) against silica oxide (SiO_2) which is a standardised plot used to define rock types (see Cox *et al.* 1979). The Nānākuli source rock is a tholeiitic basalt similar, in some general respects, to the source at Kapōhaku, Lāna'i. Using the key for discriminating basalt sources in the Hawaiian Islands with only oxides of silica (SiO_2), titanium (TiO_2) and potassium (K_2O) (Weisler & Sinton 1997: Table 10.5), the Nānākuli source overlaps with Haleakalā and Kapōhaku with silica, Pololū, Pu'umōiwi, Kapōhaku, 'Amikopala, Waiāhole, Kailua and Keāhua I and II with titanium and is similar to Kapōhaku, 'Amikopala, Waiāhole,

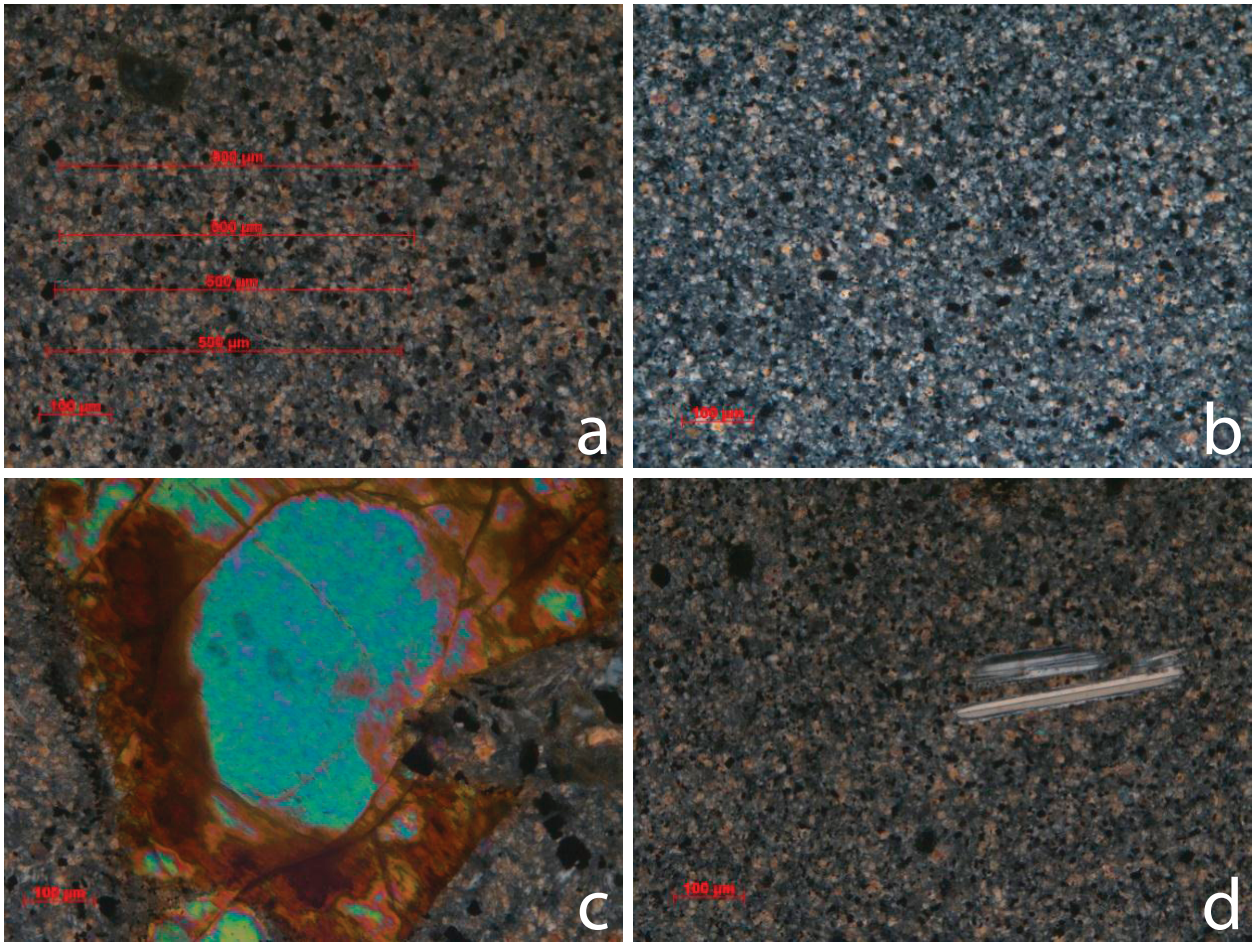

Figure 10. Petrographic thin section images of the Nānākuli source rock and artefacts illustrating the fine-grained groundmass (texture) of the rock. a) source rock, b) flake from rockshelter Feature A; c) source rock with olivine phenocryst and d) elongate plagioclase phenocrysts in a natural cobble at 115 m elevation in the drainage outwash. The scale bars in Figure a shows where the grains were counted for determining rock texture.

Kailua and Keāhua I and II in potassium. Consequently, the use of this key appears outdated with the addition of new quarry data.

We use a selection of 'incompatible' trace elements as well as the rare earth elements (REE) to show the unique signature of the Nānākuli source. Standardised 'spider' diagrams are used routinely in the geological sciences to understand the genesis of rock suites and unravel petrogenetic processes (Rollinson 1993:134) and have only recently been used in sourcing studies (Collerson & Weisler 2007: Figure 3; Li *et al.* 2005: Figure 2; Reepmeyer & Clark 2010: Figure 4). REE concentrations are usually normalized to reference standards, e.g., chondrite, bulk silicate Earth, or primitive mantle, and the resulting REE patterns can be related to the source composition, degree of mantle melting and extent of crystallisation. Figure 12 is a chondrite-normalized REE plot for the Nānākuli source and other quarries with comparable, high-quality geochemical data taken from Collerson and Weisler (2007). Figure 13 is a primitive mantle-normalized 'spider' diagram showing a range of trace elements and REE arranged in the order of decreasing incompatibility with the solid phase during partial melting or crystallisation process (see Sun & McDonough 1989). As expected, the Nānākuli source rock and artefacts form tightly-clustered parallel lines in both figures, clearly differentiated from the Puʻumōiwi (Kahoʻolawe), Haleakalā (Maui), Moʻomomi (Molokaʻi), Kapōhaku (Lānaʻi) and Mauna Kea (Hawaiʻi Island) quarries. It is interesting to note that source rock samples from Puʻumōiwi (Kahoʻolawe) and Kapōhaku (Lānaʻi) are strongly enriched in REE, but relatively depleted in other elements (showing huge negative anomalies), suggesting these source rocks might be derived from strongly evolved (fractionated) magmas. Source rocks from Haleakalā (Maui), Moʻomomi (Molokaʻi), and Mauna Kea (Hawaiʻi Island) quarries display generally more negative slopes than that of the Nānākuli source in this study, suggesting the parental magmas for the other three sources were probably derived from smaller degrees of partial melting at mantle depths than that for Nānākuli source rocks.

Table 4. *Major and trace element data for source (2011-267 & -268) and artefacts.*

Sample name	2011-265	2011-266	2011-267	2011-268	2011-269	2011-270	2011-271	2011-272	2011-273
Major elements (wt%)									
SiO2	51.03	51.03	50.98	51.08	51.33	51.21	51.11	51.13	50.78
Al2O3	13.10	13.23	13.26	13.13	13.37	13.24	13.29	13.26	13.05
TiO2	2.51	2.56	2.58	2.48	2.56	2.58	2.50	2.44	2.47
Fe2O3	12.27	12.32	12.49	12.24	12.51	12.36	12.17	12.04	12.41
MnO	0.16	0.17	0.16	0.16	0.17	0.17	0.16	0.16	0.17
CaO	10.19	10.25	10.16	10.23	9.95	10.15	10.31	10.39	10.24
MgO	7.49	7.21	7.25	7.55	6.94	6.99	7.31	7.43	7.74
K2O	0.56	0.55	0.51	0.49	0.54	0.57	0.50	0.47	0.49
Na2O	2.35	2.33	2.29	2.36	2.32	2.39	2.36	2.39	2.36
P2O5	0.33	0.34	0.31	0.29	0.32	0.34	0.29	0.29	0.29
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Trace elements (parts per million)									
Be	1.11	0.94	1.20	1.01	1.31	1.06	0.98	1.05	1.04
P	1528	1111	1517	1225	1802	1240	1183	1307	1336
Ca	69679	71705	82163	64360	65872	73379	66509	73219	73032
Sc	28.9	29.6	34.9	27.2	28.0	30.3	28.3	30.3	30.2
Ti	14485	14020	16436	13741	14797	14435	13582	14425	14431
V	269	280	335	265	278	294	281	294	292
Cr	271	312	385	408	282	335	587	314	332
Co	40.3	42.6	54.4	39.2	42.9	43.6	48.9	43.1	43.5
Ni	131	134	239	129	148	137	296	134	133
Cu	76.2	55.1	102.6	74.5	108.2	58.8	72.0	82.5	92.3
Zn	109.2	109.9	129.8	104.5	112.4	108.0	113.8	109.2	110.8
Ga	19.3	19.0	22.5	18.2	19.8	20.0	18.7	19.6	19.6
Rb	8.31	5.94	6.90	7.12	10.13	5.77	6.83	6.96	6.98
Sr	354	357	409	330	352	374	340	366	364
Y	26.09	21.20	26.73	24.68	29.32	23.91	22.21	23.64	23.80
Zr	158.3	126.7	159.7	141.7	193.2	136.1	138.3	141.8	144.6
Nb	13.05	10.35	12.88	11.48	15.28	11.03	11.08	11.42	11.77
Mo	0.85	0.61	0.79	0.68	0.95	0.64	0.82	0.72	0.83
Cd	0.09	0.08	0.10	0.09	0.10	0.08	0.09	0.08	0.10
Sn	0.15	0.17	0.56	0.48	0.67	0.46	0.25	0.49	0.50
Cs	0.16	0.05	0.09	0.15	0.23	0.04	0.07	0.12	0.07
Ba	98.1	82.2	106.7	90.0	115.4	92.7	88.6	91.4	91.8
La	12.42	9.00	11.81	11.07	15.42	10.27	9.76	10.48	10.45
Ce	30.04	22.47	29.16	24.89	36.78	25.47	24.03	26.22	26.18
Pr	4.56	3.40	4.47	4.20	5.61	3.85	3.66	3.93	3.90
Nd	21.63	16.23	21.44	20.33	26.32	18.45	17.45	18.69	18.61
Sm	5.82	4.56	5.93	5.55	6.95	5.12	4.86	5.15	5.16
Eu	1.97	1.68	2.06	1.95	2.26	1.86	1.73	1.83	1.81
Gd	6.35	5.06	6.46	6.10	7.41	5.70	5.32	5.75	5.72
Tb	0.97	0.79	1.00	0.93	1.12	0.87	0.83	0.88	0.88
Dy	5.47	4.49	5.70	5.23	6.27	4.96	4.73	5.03	5.03
Ho	1.06	0.88	1.11	1.01	1.20	0.97	0.92	0.97	0.98
Er	2.69	2.21	2.80	2.53	3.02	2.44	2.33	2.48	2.48
Tm	0.364	0.301	0.382	0.340	0.404	0.332	0.314	0.334	0.335
Yb	2.15	1.78	2.25	2.01	2.35	1.96	1.88	2.00	1.98
Lu	0.301	0.250	0.314	0.278	0.327	0.273	0.262	0.278	0.279
Hf	4.02	3.30	4.13	3.64	4.89	3.50	3.58	3.67	3.72
Ta	0.89	n.d.	0.88	0.87	0.92	0.69	1.01	0.70	0.72
W	0.105	0.074	0.101	0.088	0.120	0.083	0.131	0.089	0.112
Tl	0.017	0.012	0.015	0.016	0.027	0.012	0.016	0.015	0.015
Pb	1.44	1.01	1.22	1.16	1.41	1.08	1.17	1.33	1.31
Th	0.769	0.575	0.769	0.684	0.975	0.662	0.655	0.686	0.689
U	0.272	0.197	0.267	0.234	0.338	0.221	0.219	0.237	0.230

Table 5. *Strontium (Sr), neodymium (Nd) and lead (Pb) isotopic data for Nānākuli source rock (2011-267 and -268) and artefacts.*

Sample name	$^{87}Sr/^{86}Sr$	±2σ	$^{143}Nd/^{144}Nd$	±2σ	$^{206}Pb/^{204}Pb$	±2σ	$^{207}Pb/^{204}Pb$	±2σ	$^{208}Pb/^{204}Pb$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	$^{208}Pb/^{206}Pb$	±2σ
2011-265	0.703616	0.000007	0.512951	0.000007	18.0702	0.0014	15.4845	0.0012	37.8205	0.0033	0.85690	0.00001	2.09296	0.00006
2011-266	0.703616	0.000007	0.512964	0.000006	18.0569	0.0019	15.4739	0.0018	37.8184	0.0040	0.85692	0.00002	2.09439	0.00005
2011-267	0.703635	0.000008	0.512957	0.000005	17.9795	0.0015	15.4630	0.0016	37.7357	0.0037	0.86001	0.00001	2.09890	0.00003
2011-268	0.703618	0.000008	0.512960	0.000007	17.9548	0.0012	15.4657	0.0013	37.7309	0.0030	0.86135	0.00001	2.10134	0.00004
2011-269	0.703621	0.000008	0.512966	0.000007	18.0168	0.0011	15.4603	0.0012	37.7795	0.0030	0.85809	0.00001	2.09692	0.00004
2011-270	0.703630	0.000007	0.512955	0.000008	18.0385	0.0024	15.4565	0.0021	37.7894	0.0057	0.85687	0.00002	2.09496	0.00005
2011-271	0.703622	0.000008	0.512958	0.000009	17.9235	0.0012	15.4622	0.0011	37.6677	0.0033	0.86270	0.00001	2.10162	0.00005
2011-272	0.703608	0.000007	0.512957	0.000006	18.1234	0.0013	15.4941	0.0010	37.8643	0.0027	0.85490	0.00001	2.08918	0.00005
2011-273	0.703725	0.000008	0.512960	0.000007	18.1279	0.0016	15.4892	0.0016	37.8708	0.0036	0.85445	0.00002	2.08907	0.00006

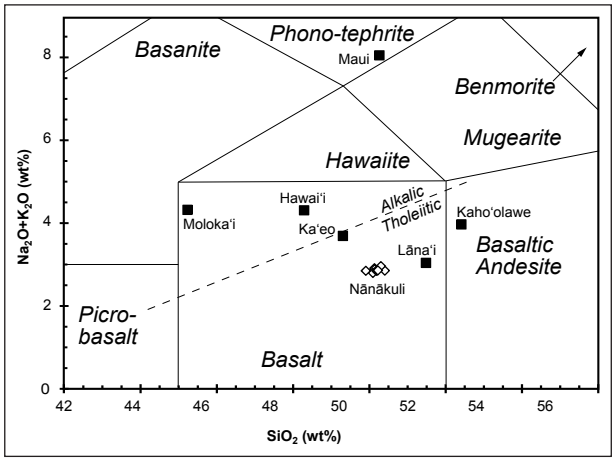

Figure 11. Bivariate plot of silica (SiO_2) and alkalis (Na_2O + K_2O) for the Kaʻeo and Moʻomomi (Molokaʻi), Mauna Kea (Hawaiʻi), Kapōhaku (Lānaʻi), Puʻumōiwi, Kahoʻolawe, Haleakalā (Maui) and Nānākuli, Oʻahu quarries.

There have been few Polynesian sourcing studies incorporating isotopes. Lead (Pb), strontium (Sr) and neodymium (Nd) isotopic ratios can be highly discriminating between sources and their values can be used from the geological literature to assign artefacts to an island or volcano; published values can also be used as a further check on analytical data quality (Weisler & Woodhead 1995:1884). The first applications demonstrated the first two-way transfer of fine-grained basalt and vesicular oven stones within the interaction sphere delimited by the Pitcairn Group and Mangareva (Weisler & Woodhead 1995; Woodhead & Weisler 1997). A more recent study documented the 4,000 km long movement of a Hawaiian adze to the Tuamotus (Collerson & Weisler 2007). When dealing with a large geographic area or 'provenance environment' (Weisler 1993), the number of potential sources increases and so does the geochemical variability, thus making it more difficult to assign artefacts to a probable source. We believe that as the geographic scale increases, so should the sophistication of the geochemical analytical techniques. We, therefore, include isotopic data for the Nānākuli source as early Hawaiian sourcing studies of fine-grained basalts (Weisler & Sinton 1997:180, Table 10.4) as well as volcanic glass (Weisler & Clague 1998:122) have shown that artefacts may originate from distant, off-island sources. Figure 14 plots the isotope ratios of neodymium and strontium for major Hawaiian quarries where there are comparable high-quality published data. In general, there is a tight cluster within their 2-sigma analytical uncertainties (the error bars are smaller than the symbol size) for all nine samples from the Nānākuli source, which is clearly separated from other Hawaiʻi sources. In comparison, the parental magmas for source rocks from Lānaʻi and Kahoʻolawe are clearly derived from a mantle source. It is worthwhile to note the presence of one outlier

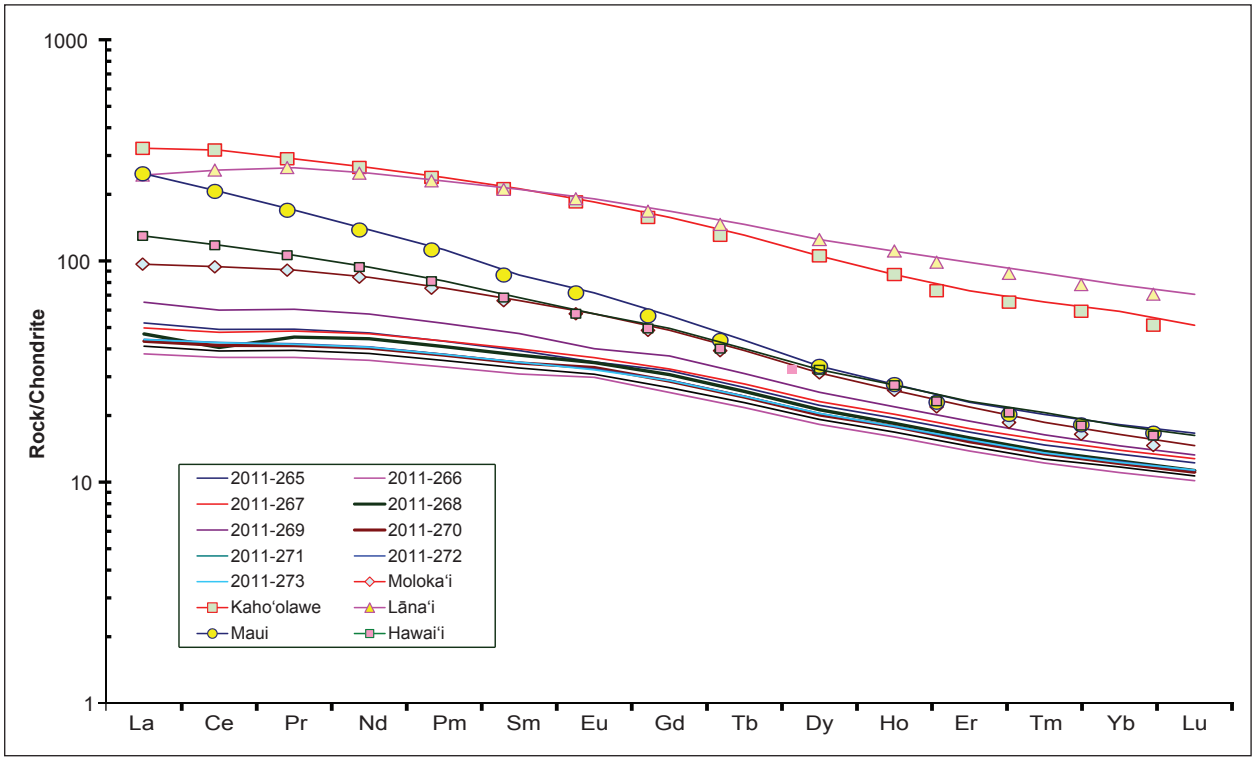

Figure 12. Rock chrondrite and rare earth elements (RRE) for the Nānākuli samples which show internal consistency. The other quarry samples are from Mo'omomi (Moloka'i), Mauna Kea (Hawai'i), Kapōhaku (Lāna'i), Pu'umōiwi (Kaho'olawe) and Haleakalā (Maui). The Nānākuli source is internally consistent and different from the other plotted quarries.

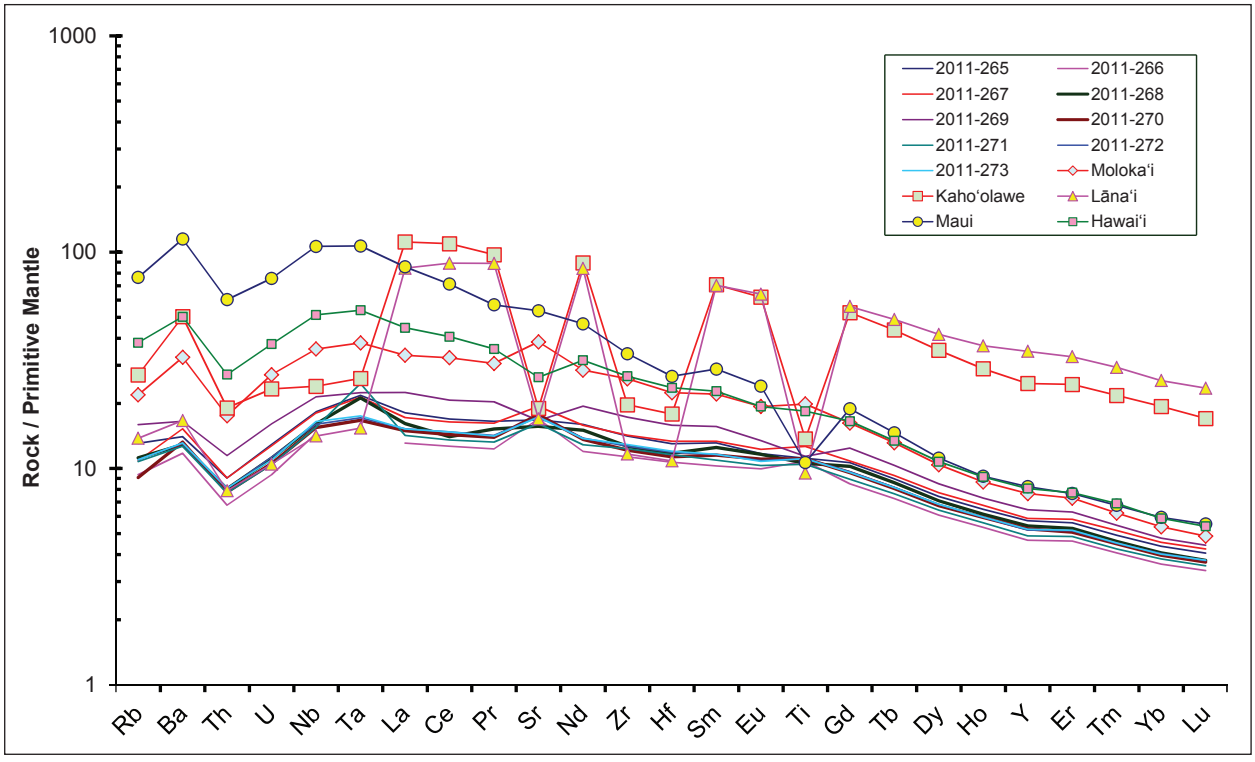

Figure 13. Rock/primitive mantle and rare earth elements (RRE) for the Nānākuli samples which show internal consistency. The other quarry samples are from Mo'omomi (Moloka'i), Mauna Kea (Hawai'i), Kapōhaku (Lāna'i), Pu'umōiwi (Kaho'olawe) and Haleakalā (Maui).

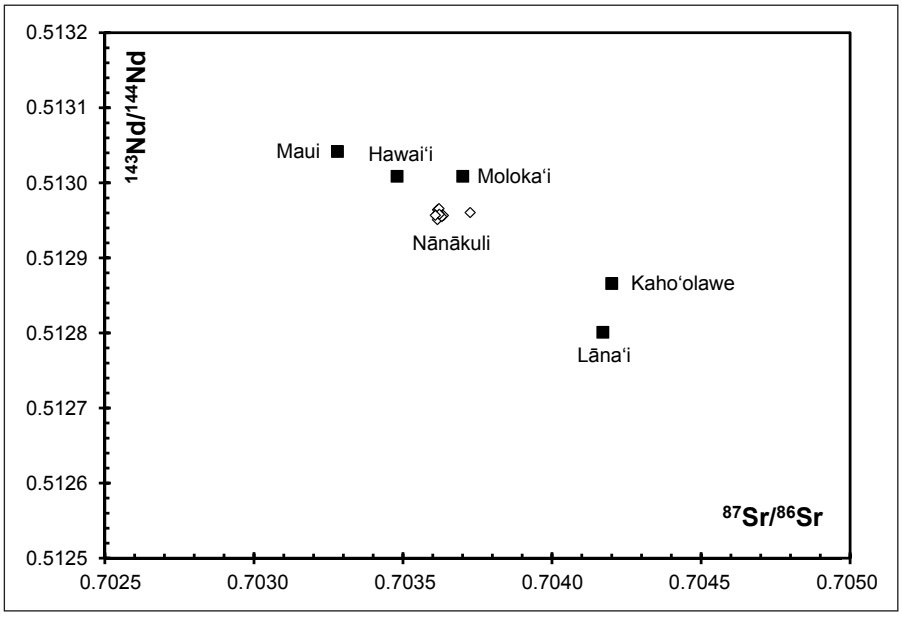

Figure 14. Neodymium (Nd) and strontium (Sr) isotopic ratios showing the differences between Nānākuli and other quarry samples from Moʻomomi (Molokaʻi), Mauna Kea (Hawaiʻi), Kapōhaku (Lānaʻi), Puʻumōiwi (Kahoʻolawe) and Haleakalā (Maui). Two sigma error bars are smaller than the symbols used.

(sample 2011-273), suggesting that there is minor Sr isotopic variability (only a few times larger than its analytical uncertainty). Geochemically, this outlier is most likely related to minor alteration, as only the $^{87}Sr/^{86}Sr$ ratio is slightly deviated from the cluster (its $^{143}Nd/^{144}Nd$ value, on the other hand, is within analytical error of those for the other eight samples). Compared with Nd and other REE elements, Sr is mobile during secondary alteration and weathering processes and its isotopic compositions might be slightly modified during such times.

DISCUSSION AND CONCLUSIONS

The Nānākuli quarry complex extends over at least 0.5 km². Future surveys, preferably during dry conditions with optimal ground visibility, are necessary to precisely record the boundaries of the complex, the variability in debitage concentrations, low architectural features and additional cultural deposits that may be visible in the sides of the main drainage. Rockshelter A is the best site for excavations to obtain dating samples in context with adze material due to its dense surface debitage, hammerstones and preforms that trail downslope for ~25 m. The mid-13th century U-series date from rockshelter A is a surface sample which should be augmented with additional radiocarbon dates from stratified contexts.

The *in situ* source of the Nānākuli raw material is exposed in a dike or sill where material was manually dislodged or raw material was selected from scree accumulations downslope of the source, as well as collected within and along side of the main drainage. There is some evidence that angular pieces with right angles were purposely selected to facilitate adze blank and preform production from a core. However, the dominant reduction strategy was the flake series which is common at many Hawaiian quarries.

Field recording and a comprehensive set of geochemical data for the Nānākuli quarry signal two major concerns for sourcing studies in the archipelago. 1) There is likely to be additional major sources of fine-grained basalt discovered in coming years as surveys are conducted with the express purpose of locating and recording new sources. This is certainly the case when a survey of the relatively well-studied 20,000 hectare area of west Molokaʻi was systematically surveyed for quarries, yielding one major new quarry and several smaller sources effectively doubling the number of known sources for the region (Weisler 2011). How is it that a large quarry at Nānākuli was left unrecorded despite decades of archaeological research on the most populated island in the archipelago? Although not all quarries are highly visible due to sparse scatters of debitage or position high on valley slopes, many quarries are amongst the most visible archaeological sites with dense scatters of adze material spread over large areas (e.g., Figure 4g). 2) Knowing that there are major quarries and perhaps dozens of smaller sources awaiting discovery should force us to rethink our protocols for sourcing studies. As new quarries are geochemically analysed and reported, the likelihood of overlap between sources increases, especially when a restricted number of elements are used to characterise quarries and also to assign artefacts to a source. Given this situation, it is unlikely that

the persistent practice of using strontium (Sr) and zirconium (Zr) to separate sources will be an effective protocol (e.g., Kirch *et al.* 2012: Figure 2; Mills *et al.* 2008: Figures 4 & 5, *et al.* 2010: Figure 5; Mintmier *et al.* 2012: Figures 4 & 6). For instance, in this study, the nine samples of the Nānākuli source have Sr/Zr ratios ranging from 1.8–2.8, overlapping completely with four of the other five sources shown in Fig. 14. Their Sr and Zr concentrations range from 330–409 ppm, and from 127–193 ppm, respectively, overlapping with the Lānaʻi source (358 and 137 ppm, respectively). However, there is a clear unmistakable contrast between Lānaʻi and Nānākuli sources if their REE patterns, trace element spider diagrams, and Sr-Nd isotopic ratios are compared. Because of this, we have advocated using a greater number of oxides, trace element concentrations and isotopic ratios to characterise sources (Figures 12 & 13) and for assigning unknown artefacts to a likely source (e.g., Collerson & Weisler 2007). As we mentioned earlier, source characterisation and assigning unknown artefacts to a particular quarry are more robust when a broader range of major and trace elements and, if necessary, isotopes are used.

In designing any sourcing programme, the issues of time and cost as well as whether specimens can be destructively sampled, will always be important points to consider. Previously, we set out a programmatic approach to sourcing studies that included destructive and non-destructive analytical techniques (Weisler & Sinton 1997). We believe that specific techniques should be used when they are most effective for addressing particular questions, while keeping in mind that source assignments may prove to be inaccurate – when based on a few elements – as new quarry geochemistry becomes known. For example, we would not recommend using EDXRF as the major technique to characterise sources since the procedure can analyse only a limited range of major and trace elements, not all of which are fully quantitative. However, EDXRF can be useful to 'screen' a large number of artefacts to place in tentative groups that should then be subsampled by more precise techniques to evaluate group boundaries and membership (Weisler & Sinton 1997:187). Mintmier et al. (2012) analysed 255 artefacts and source rocks by EDXRF from the huge Haleakalā (Maui) quarry complex. Only five samples (<2 per cent of the analytical assemblage) were then analysed by WDXRF (three for major oxides and two for only 12 trace elements). This is hardly a sufficient number for determining the efficacy of EDXRF and to understand the intra-quarry variability of a source that is several km² in size. We agree with Lundblad *et al.* (2011: 65; Mintmier *et al.* 2012: 622) that EDXRF could be used as a 'first tier' approach, but suggest that a greater number of samples should be analysed by more discriminating techniques whenever EDXRF is the major technique used to group a large assemblage of artefacts into a diverse range of geochemical groups (e.g., Kirch *et al.* 2012) or to provide baseline geochemical data to characterise quarries.

Along with improving the protocols of sourcing programmes, we believe that more effort should be directed towards locating and reporting new quarries and comprehensively analysing their geochemical variability. This will contribute significantly towards understanding the development and importance of prehistoric interaction in island societies.

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