

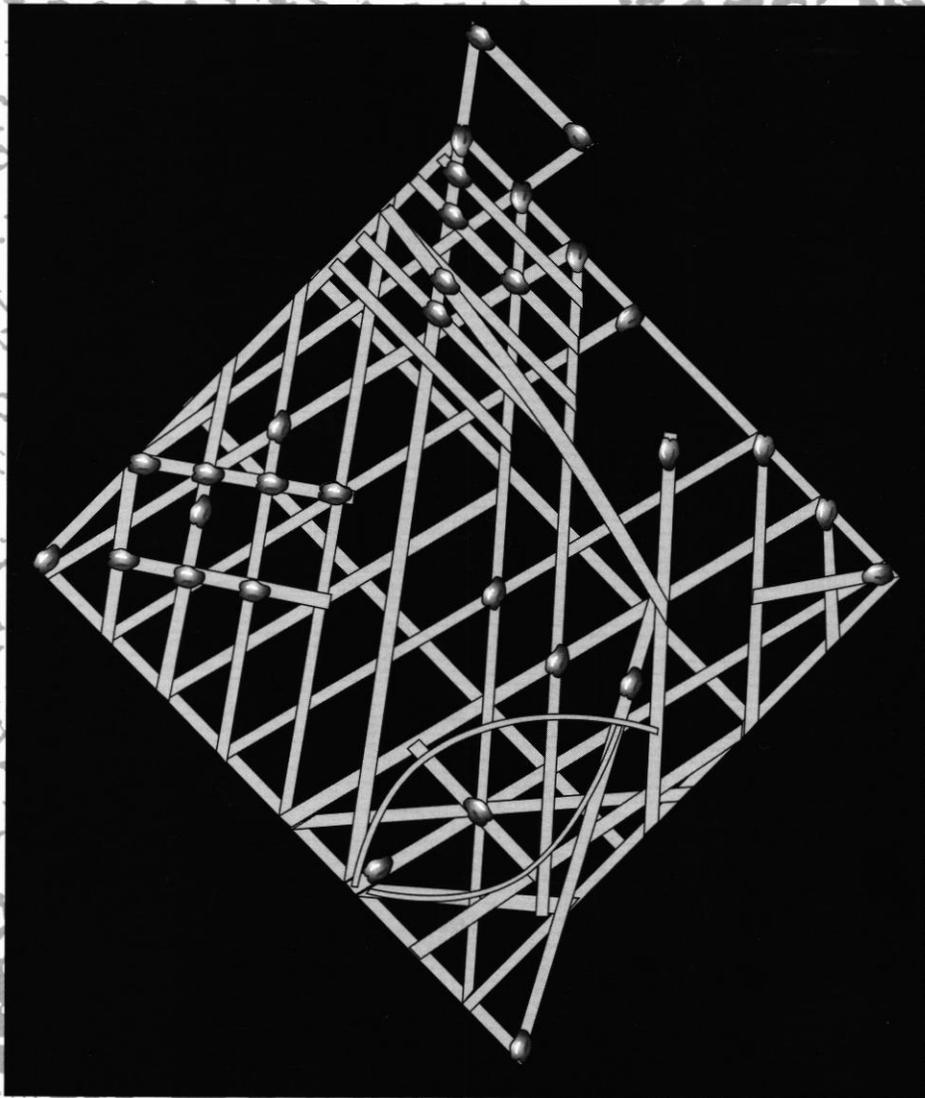


**NEW ZEALAND ARCHAEOLOGICAL ASSOCIATION MONOGRAPH 21:
Marshall I. Weisler (ed.), *Prehistoric Long-Distance Interaction in
Oceania: An Interdisciplinary Approach***



This document is made available by The New Zealand
Archaeological Association under the Creative Commons Attribution-
NonCommercial-ShareAlike 4.0 International License.

To view a copy of this license, visit
<http://creativecommons.org/licenses/by-nc-sa/4.0/>



PREHISTORIC LONG-DISTANCE
INTERACTION IN OCEANIA:
AN INTERDISCIPLINARY APPROACH

Edited by Marshall J. Weisler

21

NEW ZEALAND ARCHAEOLOGICAL ASSOCIATION
MONOGRAPH

TOWARDS IDENTIFYING PREHISTORIC INTERACTION IN POLYNESIA

Marshall I. Weisler and John M. Sinton

Most of Polynesia lies within a geological province composed of Oceanic Island Basalt (OIB) erupted from hotspots deep within the Earth's mantle. Eruptions over several millions of years have coalesced to form island chains spread, in some instances, over several hundred kilometres. These linear arrangements contain geochemical signatures unique at the geographic scale of archipelago and island, and oftentimes to individual volcanoes, and short-term events such as flows or dykes. Geochemical techniques are essential for determining the unique properties of Oceanic islands, thus permitting accurate description of rocks that were fashioned into adzes and other tools. Characterisation of fine-grained basalt artefacts found at distant, and dated, habitation sites form the foundation for examining prehistoric long-distance interaction.

In this paper we present some background information on the geochemical evolution of oceanic island volcanoes, and on analytical techniques in geochemistry. Additionally, we discuss aspects of the available geochemical data on Polynesian sources, with emphasis on using data compiled into a database developed at the University of Hawaii (Chapter 11). These data are used to assess estimates of source variability for certain quarries as well as identify those sources that have not been adequately sampled and/or described. We believe that with the increased interest in geochemical analysis of Polynesian sources and artefacts, it is now timely to establish reporting standards that seek to make different databases comparable (see Weisler 1993a:75-76). We conclude that geochemical techniques are the single most powerful means for understanding prehistoric interaction in Polynesia.

OCEAN ISLAND PETROLOGICAL EVOLUTION

Within Polynesia are two fundamentally different petrological provinces. These provinces are separated by the 'andesite' line, which divides volcanic arc provinces ('continental' islands) associated with convergent plate boundaries, from those intraplate volcanoes making up the

oceanic island association (see, this volume, Chapter 1:Fig 1.1). Polynesian arc provinces include New Zealand and Tonga, where volcanoes are mainly dominated by andesite to rhyolite volcanic rocks typically with high contents of alkalis, Ba (barium) and Sr (strontium), and low contents of TiO₂ (titanium-oxide) and Nb (niobium).

Ocean island evolution can be divided into three volcanic stages (e.g., Clague and Dalrymple 1987; Macdonald *et al.* 1983; Weisler 1993a:64-66; Chapter 8). These include a volumetrically dominant shield-building stage, a post-shield cap of more alkali-rich lavas, and, following a period of volcanic quiescence, a post-erosional, rejuvenation stage. Not all ocean island volcanoes have experienced all three stages, e.g., some volcanoes have not undergone rejuvenation whereas others appear to skip the post-shield stage and then become rejuvenated. Although this volcanic succession was originally determined for Hawaiian volcanoes, it appears to be at least generally applicable to other ocean island volcanoes. For example, rejuvenation volcanism has been recognised on several Marquesan, Samoan and Cook Island volcanoes, where it bears a close chemical resemblance to rejuvenation lavas in Hawaii. Post-shield volcanism, characterised by the eruption of differentiated alkalic lavas ranging from hawaiite to trachyte, is also known from some Samoan, Society, Marquesan and Rapa Nui (Easter Island) volcanoes.

Within Hawaii most known adze quarries are associated with outcrops of moderately differentiated, alkalic post-shield lavas (Weisler 1993a:67). However, tholeiitic lavas also were used, e.g., on O'ahu (Dye *et al.* 1985), Lāna'i (Weisler 1990a) and Kaho'olawe (McCoy *et al.* 1993). Few oceanic islands have erupted silicic rocks broadly similar to those found in volcanic arcs. Notable exceptions are the rhyolites of Rapa Nui, a rhyodacite locality on O'ahu, Hawaii, and dacites from Pitcairn (Weisler and Clague 1997). All these occurrences were used by Polynesians, although typically for the production of bifacial tools (e.g., Rapa Nui *mata'a*) and small flake tools, but rarely for adzes.

THE PETROLOGY OF IGNEOUS ROCKS

The diversity of igneous rocks reflects two primary processes: melting and differentiation. Virtually all terrestrial magmas are the products of partial melting of the source material; in the case of ocean island basalts the source is upper mantle peridotite (an ultramafic, olivine-rich rock). The compositions of primary magmas (those in equilibrium with the residual source rock and unaffected by later differentiation) are mainly controlled by the composition of the source and the extent of partial melting. Both can vary significantly; typically, extents of partial melting giving rise to primary ocean island magmas is from less than ~5% to about 25%. Magmatic differentiation involves cooling and crystallisation of magmas originally formed from melting. As magma progressively crystallises, the composition of the residual, uncrystallised liquid part of the magma is modified because the compositions of the crystallising minerals are different than that of the magma from which they form. A great body of literature on the chemical characteristics of melting and differentiation processes now exists, allowing petrologists to decipher the processes giving rise to a given rock composition. A detailed discussion of those techniques is beyond the scope of this chapter and only cursory mention is given in the following paragraphs. Interested readers can pursue this topic in any modern textbook on igneous petrology (e.g., McBirney 1983).

Elements can be classified according to their behaviour during melting and differentiation processes. The principal parameter describing this behaviour is the relative compatibility of an element for solid phases (minerals) of interest. The ability of an element to substitute into the atomic structure of a mineral is controlled by its size (ionic radius) and electronic charge (valence). For example, igneous olivine contains Mg (magnesium) in combination with Si (silicon) and O (oxygen) in the mineral lattice. Because Ni (nickel) has about the same size as Mg and the same charge (+2) it substitutes readily into olivine. Hence, Mg and Ni are highly compatible in olivine. Similarly Mg, Ni and Cr (chromium) are compatible in pyroxenes, Ca (calcium) and Sr are compatible in plagioclase feldspar, etc. In general incompatible elements form two groups, those with large size (LIL - large ion lithophile elements) and those with high charge (HFSE - high field strength elements). Examples of incompatible LIL elements include the alkali elements Na (sodium), K (potassium) and Rb (rubidium) and the heavy alkaline earths, Sr and Ba. Examples of incompatible HFSE are P (phosphorus), Ti (titanium), Nb and Zr (zirconium).

During mantle melting, the abundance of incompatible elements in the melt is in inverse proportion to the extent of partial melting. Because the upper mantle is relatively uniform mineralogically, mainly consisting of olivine, pyroxene and Cr-rich spinel or Mg-rich garnet, the relative incompatibilities of various elements during mantle melting can generally be determined. From highly incompatible to less incompatible during mantle melting, the elements are arranged in order Rb, Ba, Th (thorium), U (uranium), Nb, K, La (lanthanum), Ce (caesium), Pb (lead), Sr, P, Zr, Ti and Y (yttrium). Although Y is less incompatible than, for example, Rb, it still is incompatible during mantle melting. During differentiation it is important to constrain which minerals have fractionated from the magma. For example, primitive magmas at relatively reducing conditions crystallise only olivine and pyroxene and so only Mg, Ni and Cr are highly compatible, all other elements are incompatible to varying degrees. However, with progressive cooling, first plagioclase and later Ti-rich oxide phases form. Thus Sr is incompatible during olivine and/or pyroxene fractionation but becomes compatible once plagioclase starts to form; similarly Ti is incompatible until Ti-oxide (Ti-magnetite or ilmenite) begin to fractionate.

Petrologists have long used the variable compatibility of elements to decipher melting and differentiation processes giving rise to a particular rock composition, and commonly employ a range of chemical variation diagrams that are designed to 'see through' these processes. For example, variation of one or another element against the most common compatible oxide MgO (magnesium-oxide) allows one to see whether or not two samples can be related by magmatic differentiation. Similarly the ratio of two highly incompatible elements will not be changed significantly by melting or differentiation processes because both elements will be enriched equally during such processes. Hence, differences in the ratios of two highly incompatible elements mainly reflect differences in source compositions.

Low temperature processes also can affect the chemical composition of a rock through weathering and other alteration processes. Because high temperature igneous minerals and glass are unstable at surface conditions, weathering produces reactions that convert these phases to low-temperature phases such as clay minerals. Weathering and other low-temperature alteration processes mainly introduce water. Other chemical elements most affected by low temperature effects are the alkali elements but, unfortunately, the behaviour of the alkali elements at low temperatures can be highly variable. For example, K can be lost by leaching during subaerial weathering or added if K-rich clay minerals are precipitated. There also can be considerable variability in the behaviour of other elements

at low temperature but the main effects are restricted to water and the alkali elements. For these reasons, the best comparisons are made against relatively unaltered samples. For altered samples, those with high H₂O or LOI values, comparisons using alkali elements should be made with extreme caution.

GEOCHEMICAL ANALYSIS

The identification of minerals and the determination of grain size and texture seen in thin-sections permits rocks to be classified (e.g., Cox *et al.* 1979:176-196) and the techniques were well established almost 150 years ago (Sorby 1858). In some circumstances, petrographic descriptions are a useful adjunct to contemporary sourcing studies but, as a sole technique, they suffer from several problems. First, analytical results are seldom reported in sufficient detail to permit evaluation of precision and accuracy - a vital component to any sourcing study that relies on comparisons of several data sets. Second, there are inaccuracies associated with mineral identifications and measuring average grain size to estimate rock texture. Additionally, thin-sections are essentially a two-dimensional surface used for estimating bulk composition. Comparisons between studies are rendered less useful when methods for determining abundance measures are not reported in detail. While these aspects of petrographic descriptions render the technique problematic for detailed quantitative comparisons that are essential for sourcing studies, geological inferences, based on qualitative assessments, yield important information of petrogenetic value such as magma cooling rates and pyroclastic origins.

Chemical analysis of oceanic island basalt rock has become the preferred method of artefact and source characterisation as the various techniques "provide replicable results between analysts, have a high degree of accuracy and precision, and provide data that are partly or fully quantitative and conducive to computerised statistical manipulations" (Weisler 1993a:71). We describe below the x-ray fluorescence (XRF) analysis of igneous rocks.

The XRF technique

X-ray fluorescence analysis of igneous rocks has gained prominence in the geological literature because it provides a relatively fast and reliable method for the determination of all the major chemical elements present in most igneous materials. The technique exploits the property of characteristic energies associated with electronic decay of excited samples. In practice samples are bombarded with x-rays, which excites electrons in the sample to higher

energy states. Because this excited state is unstable, outer shell electrons fall back to fill the voids left by the excited electrons. As electrons back-fill to inner electron orbitales, an x-ray photon is released (Fig 10.1). This secondary energy associated with backfilling is known as *fluorescent energy*. The energy of the fluorescent x-ray photon is particular to the element of interest and the electron shell involved. For example, when an Fe (iron) electron from the L-shell back-fills to the innermost, K-shell, an Fe Ka x-ray photon with an energy of 6.4 KeV is released. The energies associated with virtually all such fluorescent reactions are well known and can be found in published tables of x-ray energies. In order to determine the amount of an element present it is necessary to determine the number of x-ray photons with a particular energy that are being released. In the simplest case, count rates for a particular x-ray energy (e.g., Fe Ka) in unknowns are simply calibrated against those of standards of known compositions for the same set of analytical conditions.

For quantitative analysis the instrument must be carefully calibrated in order to ensure identical procedures for both standards and unknowns. The amount of energy released for a given x-ray energy is not simply proportional to its composition because some energy is absorbed by the sample. X-ray absorption depends on the bulk sample composition (matrix effects) and on the grain size of the sample. A variety of methods are available for correcting for matrix absorption effects, primarily employing theoretical absorption coefficients and/or various empirical techniques for calibrating absorption for a given set of analytical operating conditions. Correction for absorption assumes that the path of each exiting x-ray photon is identical to all others, i.e., all x-rays have passed through an identical matrix. This is only true if the analysed sample is chemically and texturally homogeneous. Imperfections

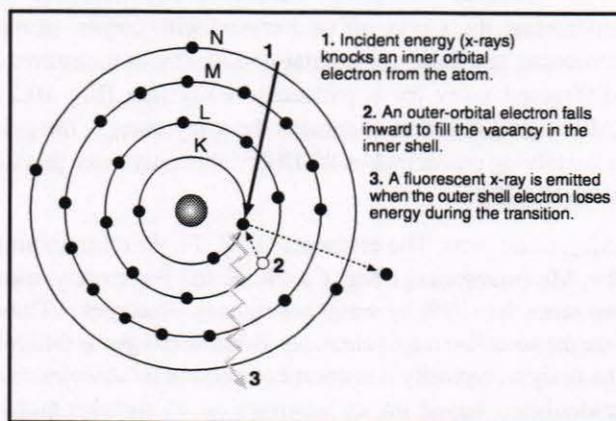


FIGURE 10.1. The process of x-ray fluorescence.

from chemical and textural homogeneity have a greater effect on light elements with low x-ray energies, than on heavier elements.

Grain-size variations typically are minimised either by melting the sample to a homogeneous glass (fused disks) or by grinding the sample to a very fine powder, typically less than 300 mesh. The melting temperatures of most igneous rocks ($> \sim 1100^{\circ}\text{C}$), are above that where the alkali elements, e.g., Na and K, start to be lost by vaporisation. Thus, when fusion is employed in XRF sample preparation, a flux is added to the sample in order to lower the melting temperature below that of alkali volatilisation. A common method for fusing rocks for XRF analysis is described by Norrish and Hutton (1969). This method uses a Li-borate flux that also contains La_2O_3 and Li_2CO_3 . Although fusion produces a homogeneous glass that is ideal for XRF analysis, fluxing the sample with fusion mix also dilutes the original sample. Hence, fusion techniques are particularly well suited to the analysis of elements present in the sample in amounts greater than about 0.1 wt %, which will still be detectable in diluted fused disks. In most labs, fusion is employed for the analysis of so-called major elements whereas trace elements, those present in abundances in parts-per-million (ppm), normally are analysed on undiluted pellets pressed from very fine-grained powders.

Two different types of x-ray fluorescence spectrometers exist. One simply uses electronic filters to measure the amount of energy released for a particular energy window. Instruments employing this method are called energy-dispersive x-ray fluorescence systems (EDXRF). Absorption and line overlap corrections can be applied to the results. EDXRF has rather low resolving power, for example between adjacent and/or overlapping lines, but modern instruments have become increasingly sophisticated and successful in dealing with this inherent limitation. To increase resolution, wavelength-dispersive XRF systems (WDXRF) resolve x-ray energies by diffracting the x-rays off of a crystal with known atomic structure, and using an angular goniometer to measure the diffracted x-ray for a particular x-ray line (Fig 10.2). Although diffraction attenuates the x-ray energy, the gain in resolving power makes WDXRF inherently more precise than EDXRF.

Major elements. The elements O, Si, Ti, Al (aluminium), Fe, Mn (manganese), Mg, Ca, Na, K and P normally make up more than 99% by weight of most igneous rocks. These are the so-called major elements. Because oxygen is difficult to analyse, typically it is not measured and its abundance is calculated based on an assumption of stoichiometric combination with the positively charged cations of known valance (electronic charge). This procedure introduces little

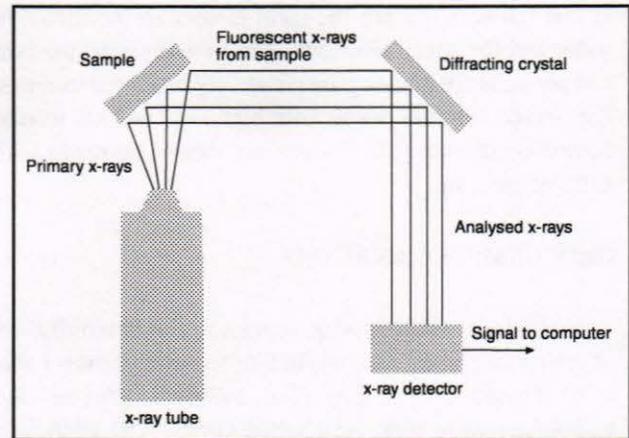


FIGURE 10.2. Basic components of x-ray fluorescence analysis.

ambiguity because the valances for most elements are constant in most igneous rocks. However, Fe typically is present in both reduced (Fe^{2+}) and oxidised (Fe^{3+}) states. Major element abundances are normally reported as oxides, SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3 , FeO , MnO , MgO , CaO , Na_2O , K_2O and P_2O_5 . This list assumes that the amount of Fe in each of its two valance states has independently been analysed. However, many labs pre-oxidise samples prior to fusion (see below), and total elemental Fe is determined during XRF analysis. Thus, many XRF analyses are simply reported with total Fe as either Fe_2O_3^* or FeO^* (the * denotes total iron); which of these reporting conventions is a matter of preference only.

Rock analyses reported in this way account for most of the major components of the sample. Not included in this list is the amount of volatile components in the rock, of which the most important is water. Because hydrogen is too light (x-ray energy too low) to be analysed by XRF, water and other volatiles must be analysed by some independent method. Typically the sample is ignited to a temperature sufficient to drive off the volatile components and the change in weight reported as loss on ignition (LOI). Because oxygen can be gained during oxidation of reduced Fe in the sample, LOI is a complex parameter involving both oxygen gain and volatile loss. In samples with low abundances of volatile components and high amounts of reduced iron, LOI values can be negative (oxygen gain during ignition is greater than volatile loss).

Rock analyses can be reported in various ways as a matter of preference. For example, Fe can be reported with both FeO and Fe_2O_3 , as either FeO^* or Fe_2O_3^* and on a volatile-free basis or with LOI. It is a relatively trivial matter to convert analytical data from one reporting form to another as long as the total elemental abundance of iron and the

analytical total is conserved, but for comparison purposes it is critical that data are compared using the same reporting convention.

The precision of analysis of major elements obtained by WDXRF on fused disks is about 1% relative for most quality laboratories. Hence, the precision of analysis of a rock containing 50 wt % SiO₂ is ± 0.5 wt %. Analytical precision is mainly dependent on the energy of the x-ray line; in general Ka x-ray energy increases with atomic number. Na₂O is the lightest (lowest energy) element typically determined by XRF; its precision is closer to ± 5% relative.

Trace elements. Elements present in ppm normally are analysed on pressed powder pellets and reported simply as elemental abundances. Virtually all chemical elements are present in all rocks but many of these elements are present in abundances below the detection limit of the analytical system. The lower limits of detection depend on the x-ray energy and a number of other variables that are particular to individual laboratories. Analytical precision and detection limits for trace elements analysed at the University of Hawaii are given in Table 10.1.

Element	Detection Limit (ppm)	Absolute Precision (ppm)
Sc	3	2
V	3	3
Cr	3	3
Ni	3	3
Cu	3	3
Zn	3	3
Rb	0.6	1
Sr	1	1
Y	1	1
Zr	1	2
Nb	0.5	1
Ba	8	10
La	8	10
Ce	5	5
Pb	2	1
Th	2	1

TABLE 10.1. University of Hawaii trace element precision and detection limits.

Other analytical techniques

In principle geochemical data collected by any reliable method can be used for comparative purposes in archaeological studies as long as analytical precision and accuracy can be adequately assessed. There are many such methods available besides XRF analysis; each has its own

advantages and disadvantages (e.g., Potts 1987). For example, because volcanic glass typically is relatively homogeneous, large numbers of samples can be analysed rapidly with the electron microprobe (Weisler 1990b). Microprobes also use x-ray fluorescence radiation but the excitation source is an electron beam rather than an x-ray tube. The advantage of an electron beam is that it can be finely focused (to a spot size of less than 10 µm [micron, diameter between .01 and .0001]), but in general only major elements can be determined with much accuracy. Various other methods also give reliable results, including atomic absorption, instrumental neutron activation analysis (INAA) (e.g., Beardsley *et al.* 1990), plasma emission techniques and proton induced x-ray emission and proton induced gamma-ray emission (PIXE-PIGME) (e.g., Duerden *et al.* 1987), analytical quality depending mainly on procedures of the particular laboratory. The principal concerns for which technique to use include selection of a non-destructive or destructive technique, sample size requirements, analytical precision, instrument availability and cost. WDXRF provides a suitable balance of these considerations.

Another feature of igneous rocks is the isotopic composition of individual elements. For example, it is known that particular isotopic ratios, especially those of Pb, Sr, Nd (neodymium) and He (helium) are characteristic of certain archipelagoes (Weisler and Woodhead 1995:1883-1884). The determination of isotopic abundances, however, requires laborious chemical separation and mass spectrometric techniques, both of which add to analytical time and cost per analysis. It is, however, a good technique for provenance studies where there is difficulty in discriminating sources or determining artefact origin, based solely on XRF data, or evaluating geochemical groups based on less powerful measures (Chapter 13). Another feature of igneous rocks that can be determined from mass spectrometric isotopic analyses, e.g., using Rb-Sr, K-Ar (argon), Ar-Ar or U-Th techniques, is the radiometric age of the sample. This is especially helpful for linear island chains that are time progressive from the hot spot (e.g., Hawaiian Islands).

POLYNESIAN QUARRY GEOCHEMICAL DATA

In order to positively identify sources of individual artefacts using geochemical data, it is necessary for all potential sources to have been described and analysed. Unfortunately, we are far from realising this goal. Nevertheless a substantial amount of data are now available for comparison, and of the 184 artefact samples analysed in the University of Hawaii database (Chapter 11) many can be confidently assigned to a particular source; other

samples apparently were acquired from sources that have not yet been identified through archaeological studies. When geochemical data for a particular province are abundant it commonly is possible to identify the island or volcano for a particular artefact, even if quarries or sources have not been identified for that volcano; in some cases, particular flows or dykes have been identified (Weisler 1993b, 1995). For the most part, however, only in Hawaii is there sufficient data in the geological literature for this to be possible.

Table 10.2 lists identified sources from throughout Polynesian oceanic island provinces. The information was

compiled from Best *et al.* (1992), Weisler (1990a, 1993b, c, 1996a, *et al.* 1994) and from material curated at the University of Hawaii at Mānoa, Bernice P. Bishop Museum (Honolulu, Hawaii), and at the University of Otago, Dunedin, New Zealand. We do not aim to provide a complete listing of samples that we do not have easy access to at time of this writing. However, examination of Table 10.2 does permit a general indication of the relative abundance of source samples. It is apparent from this listing that few quarries and sources have been analysed in much detail and also that many island provinces are as yet

Location: Quarry, Island, Archipelago	Number of Source Samples	Petrographic Data: Number of Slides	Geochemical Data: Number of Analyses	Additional Samples Needed
Tautama, Pitcairn, Pitcairn	25+	1	21	low
Various, Various, Mangareva	47	8	8	low
Mata'are, Mangaia, Cook Islands	10	0	3	low
Various, Mangaia, Cook Islands	Samples from potential basalt sources have been collected from all stream drainages on the island.			
Veitatei, Mangaia, Cook Islands	2	0	2	low
Keia, Mangaia, Cook Islands	2	0	2	low
Black Rock, Rarotonga, Cook Islands	7	0	1	low
Moturakau, Aitutaki, Cook Islands	?	?	3	low
Rapota, Aitutaki, Cook Islands	?	?	?	low
Tataga-matau, Tutuila, A. Samoa	10+	1+	31	high
Fagasā, Tutuila, A. Samoa	?	?	?	high
Sm. Sources, Tutuila, A. Samoa	?	?	?	high
Mako Ridge, Ofu, A. Samoa	4	0	4	low
Fa'ala'aga, Ofu, A. Samoa	3	0	3	low
Ha'a'upa'upa, Nuku Hiva, Marquesas	4	0	4	high
Unknown, Eiao, Marquesas	0	1+	19	high
Papeno'o, Tahiti, Society Islands	1	0	1	high
Vaitopatapata, Ra'iatea, Society Islands	2	0	2?	high
Unknown, Ra'ivavae, Australs	0	0	0	high
Workshops, Rurutu, Australs	0	0	0	high
? Rapa	0	0	0	high
Mauna, Ke'a Hawai'i, Hawaii	10,000+	25	5	medium
Pololū, Hawai'i, Hawaii	10+	9	2	medium
Haleakalā, Maui, Hawaii	?	2	3	high
Pu'umōiwi, Kaho'olawe, Hawaii	?	5	1+	high
Mo'omomi, Moloka'i, Hawaii	100+	7	10	low
'Amikopala, Moloka'i, Hawaii	10+	16	4	medium
Kapohaku, Lāna'i, Hawaii	10+	2	2	medium
Waihole, O'ahu, Hawaii	10+	2	1	medium
Kailua, O'ahu, Hawaii	?	1	1	destroyed
Waimea, Kaua'i, Hawaii	?	?	0	medium
Maungo Otu, Rapa Nui, Rapa Nui	?	?	?	high
Rano Raraku, Rapa Nui, Rapa Nui	?	?	?	high

Data from Best *et al.* 1992; Cleghorn *et al.* 1985; Lass 1994; Weisler 1990a, 1993a, c, 1996a, *et al.* 1994 and from material curated at the University of Hawaii at Mānoa, Bernice P. Bishop Museum, Honolulu, Hawaii, and the University of Otago, Dunedin, New Zealand. Note: All samples collected from Mangareva are from potential sources; no sources have been documented archaeologically.

TABLE 10.2 Basalt source data from Oceanic islands in Polynesia.

relatively unstudied geochemically. Especially lacking are samples from known basalt sources throughout French Polynesia.

Local variability

One factor affecting the degree of confidence with which a source can be identified is the variability within the source itself. Although statistical techniques have been devised for investigating intra-source variability for Pacific obsidians (Leach 1996; Leach and Manly 1982; see also Smith *et al.* 1977:188), few basalt quarries and sources have been analysed sufficiently so that a reasonable assessment of the local variability can be made. Table 10.3 shows the analytical ranges, means and standard deviations of data for sources for which the most analytical values are presently available. In addition, the column labelled variation (%) shows the relative variation for each element or oxide. From these data it is apparent that most major elements vary by about 1-3% of the amount present, with Na and P showing greater variation. LOI shows extremely high variation, owing to variable low temperature alteration effects, but this is not a concern because it is easy to correct analyses for LOI. Most trace elements show variations from less than 1% relative (Sr) to about 5%, with Sc, Cr, Cu (copper), Rb and Nb showing more extreme variation. Of the three locales

listed, the Tataga-matau quarry data show the greatest variation for all trace elements listed except Nb. Tataga-matau data mainly come from Best *et al.* (1992) and Weisler (1993c), and for most elements much of the variation can be ascribed to inter-laboratory biases between Washington State University (Weisler) and Auckland (Best). For example, Weisler reports Zr in eight Tataga-matau samples of 348-362 ppm, whereas the Zr values of nine samples reported by Best *et al.* range from 395-406. Similar biases are clearly apparent in the Tataga-matau data for Zn (zinc), Sr and Nb. The conclusion that can be drawn from Table 10.3 is that the elements least affected by the combination of real, local source variability, and analytical uncertainty are Si, Ti, Al, Fe, Mg, Ca, K, V (vanadium), Sr, Y, Zr and Ba.

THE 'SOURCING' OF POLYNESIAN VOLCANIC ARTEFACTS

Definitions

The 'sourcing' of volcanic artefacts can be accomplished by determining their geological origin. The present sophistication of sourcing studies in Polynesia cannot determine movement of exotic artefacts from one habitation site to another, such as down-the-line exchange.

Quarry	Tataga-matau		Tautama		Eiao		Variation (%)	
	range	mean ± 1s	range	mean ± 1s	range	mean ± 1s	range	mean
<i>n</i>	31		21		19			
SiO ₂	47.78-49.71	48.52 ± 0.56	49.21-50.93	49.93 ± 0.36	46.56-47.28	46.95 ± 0.21	0.4-1.2	0.8
TiO ₂	3.28-3.60	3.42 ± 0.07	2.61-2.78	2.68 ± 0.04	3.79-3.91	3.90 ± 0.11	1.5-2.8	2.1
Al ₂ O ₃	15.13-15.81	15.51 ± 0.19	15.28-15.69	15.57 ± 0.21	14.80-15.35	15.23 ± 0.14	0.9-1.3	1.2
Fe ₂ O ₃ *	13.12-14.13	13.66 ± 0.24	13.20-13.68	13.45 ± 0.13	13.34-13.73	13.53 ± 0.10	0.7-1.8	1.2
MnO	0.16-0.20	0.18 ± 0.01	0.19-0.25	0.22 ± 0.02	0.15-0.18	0.16 ± 0.01	5.6-9.3	7.0
MgO	4.49-5.06	4.79 ± 0.14	3.33-3.73	3.49 ± 0.11	6.23-6.79	6.47 ± 0.13	2.0-3.2	2.7
CaO	7.42-7.68	7.54 ± 0.08	6.93-7.19	7.09 ± 0.10	9.24-9.45	9.32 ± 0.05	0.5-1.4	1.0
Na ₂ O	3.48-4.04	3.76 ± 0.17	4.17-4.80	4.55 ± 0.20	3.07-3.52	3.18 ± 0.11	3.5-4.5	4.1
K ₂ O	1.47-1.64	1.55 ± 0.04	1.93-2.14	1.99 ± 0.05	0.95-1.03	1.00 ± 0.03	2.5-3.0	2.7
P ₂ O ₅	0.74-0.80	0.78 ± 0.02	1.15-1.39	1.25 ± 0.07	0.45-0.68	0.54 ± 0.04	2.6-7.4	5.2
LOI	-0.44-0.43	-0.10 ± 0.24	-0.43-0.36	-0.11 ± 0.25	-0.34-0.27	-0.12 ± 0.15	125-240	197
<i>n</i>	18		6		3			
Sc	15-22	19 ± 3	13-15	14 ± 1	22-25	24 ± 1	4.2-15.8	9.0
V	200-226	210 ± 8	108-114	109 ± 2	287-307	297 ± 8	1.8-3.8	2.8
Cr	<4-7	1 ± 2	6-10	8 ± 1	81-93	87 ± 5	5.7-12.5	9.1
Ni	<4-6	<4 ± 1	<4-5	<4 ± 2	96-103	100 ± 3		3.0
Cu	<4-15	5 ± 5	12-19	15 ± 2	42-53	47 ± 5	10.6-13.3	12.0
Zn	165-198	182 ± 11	162-178	171 ± 5	122-137	130 ± 6	2.9-6.0	4.5
Rb	34-49	42 ± 3	36-41	39 ± 2	17-21	18 ± 2	5.1-11.1	7.8
Sr	694-721	708 ± 7	587-591	589 ± 1	588-593	591 ± 2	0.2-1.0	0.5
Y	45-52	49 ± 2	46-50	48 ± 1	37-37	37 ± 0	0.0-4.1	2.1
Zr	348-419	383 ± 26	414-418	417 ± 2	304-308	306 ± 1	0.3-6.8	2.5
Nb	42-56	49 ± 6	69-116	89 ± 16	28-29	28 ± 0	0.0-180	10.1
Ba	268-333	305 ± 17	443-471	458 ± 9			2.0-5.6	3.8

Source: (Chapter 11).

TABLE 10.3. Geochemical variability of well known quarries.

Future studies could take a more comprehensive examination of the stages of lithic reduction represented by assemblages from well-dated sites in a study region (e.g., Ammermann 1979; Sheppard 1993). In this way, we may come to understand the extraction (and primary reduction), transport, use and deposition of exotic artefacts in relation to long-distance interaction. At present, however, we can distinguish three basic site types whose artefacts play a vital role in sourcing studies.

Quarries. These are most important since they may represent both collection and reduction of source rock at a primary geological locale. Quarry samples provide the best data with which artefacts can be compared. We use the term 'quarry' in a broad sense since raw material at many Polynesian basalt sources was merely surface collected and not extracted by excavation. In fact, the Tataga-matau, Samoa source (Leach and Witter 1987:39), the Papeno'o 'mine' in the Societies (Orliac 1986) and a Rapa Nui fine-grained basalt source may be the only Polynesian quarries where at least some material was extracted from subsurface deposits. Tabular basalt was broken from exposed flows atop Mauna Kea, Hawai'i (McCoy 1990:93), and large flakes may have been removed from outcrops on other sources but, most often, raw material is merely collected as surface erosional products near the geological source such as a flow or dyke.

Sources. These locales represent primary geological sources that have not been archaeologically identified. In these examples, sources may be 'discovered' by the identification of artefacts from geologically well known regions that lack detailed archaeological study. Where there is good geochemical information, artefacts can be potentially assigned to a volcano, flow, dyke, outcrop or secondary deposit such as an alluvial accumulation. Further archaeological survey can confirm the precise location, boundary and lithic reduction activities at the source. Sources also include secondary geological deposits, such as an accumulation of cobbles in a gulch bottom, that bear evidence of lithic reduction.

Sites. This class generally refers to prehistoric habitation locales. Components of these sites may contain reduction activity areas with unmodified raw material, cores and debitage, or finished, recycled, exhausted and discarded artefacts.

Assigning artefacts to source

Although it is a rare occurrence that petrologists can unambiguously determine the unique combination of source composition, extent of partial melting, degree and nature of subsequent differentiation processes, and effects of low temperature alteration that were responsible for the chemical

composition of a particular sample, it is equally true that it is rare for two samples from widely different petrologic provinces, e.g., volcanoes or archipelagoes, to have identical compositions. Because a wide range of variations can occur, each with its own attendant chemical signature, and because it is now possible to analyse a wide range of chemical elements relatively precisely, all with their own peculiar chemical behaviour during igneous processes, XRF analysis is particularly well suited for archaeological provenance studies of stone artefacts. If two rocks have identical compositions for all elements, within analytical uncertainties, then it is highly probable that they indeed are from the same volcano and probably the same lava flow or dyke (that is, source). 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.

Table 10.4 presents three examples of matches of artefacts to well known quarries in Polynesia. Although the prehistoric long-distance movement of fine-grained basalt has now been well documented for the Eiao source in the Marquesas (Chapter 8) and for the Tautama quarry on Pitcairn island (Weisler 1994, 1995; Weisler and Woodhead 1995), we present here the first documentation of inter-island transfer of adze material for the Hawaiian Islands; inter-island transfer of Hawaiian volcanic glass has been documented previously (Weisler 1990). In Table 10.4 the columns labelled (2) denote the absolute differences between the sample data and the average $\pm 2s$ (standard deviation). The way to interpret these data is as follows. Values of (2) = 0 signify that the sample is identical to the quarry average at the 95% confidence level. Values greater than 0 are different at the 95% confidence level. Of the data listed in Table 10.4, only Nb in sample I82N is different from the quarry average at the 2s level of confidence, and in this case by less than 1 ppm. Although this difference is barely significant at the 95% confidence level, at the 99% (4) level, the sample matches the quarry average.

It is worth pointing out that geochemical data can only be used to make consistency arguments in a positive sense, i.e., the data are or are not consistent with having come from a particular quarry within certain confidence limits. The strongest conclusions will always be negative, i.e., one can say with certainty that a sample is unlike a particular quarry composition for a given level of confidence.

Although the best way to determine whether or not a particular sample composition matches that for a particular quarry is to compare the data for all elements, it is possible to devise keys for discriminating quarries using only a few elements. Table 10.5 presents a key to identifying the major quarries in the University of Hawaii database using only

Element	Pu'umōiwi			Eiao			Tautama		
	quarry average	Hiki-2 ^a	(2)	quarry average	I82N ^b	(2)	quarry average	TP-4-99 ^c	(2)
SiO ₂	52.37 ± 0.34	52.52	0	46.95 ± 0.21	47.22	0	49.93 ± 0.36	49.77	0
TiO ₂	2.98 ± 0.04	3.01	0	3.90 ± 0.11	3.80	0	2.68 ± 0.04	2.78	0.02
Al ₂ O ₃	14.02 ± 0.34	13.97	0	15.23 ± 0.14	15.24	0	15.57 ± 0.21	15.44	0
Fe ₂ O ₃ [*]	13.18 ± 0.13	13.03	0	13.53 ± 0.10	13.62	0	13.45 ± 0.13	13.42	0
MnO	0.17 ± 0.01	0.16	0	0.16 ± 0.01	0.15	0	0.22 ± 0.02	0.20	0
MgO	4.60 ± 0.10	4.64	0	6.47 ± 0.13	6.52	0	3.49 ± 0.11	3.52	0
CaO	8.37 ± 0.18	8.46	0	9.32 ± 0.05	9.38	0	7.09 ± 0.10	7.25	0
Na ₂ O	3.00 ± 0.06	3.05	0	3.18 ± 0.11	3.11	0	4.55 ± 0.20	4.51	0
K ₂ O	0.85 ± 0.02	0.86	0	1.00 ± 0.03	1.02	0	1.99 ± 0.05	1.94	0
P ₂ O ₅	0.88 ± 0.04	0.39	0	0.54 ± 0.04	0.52	0	1.25 ± 0.07	1.28	0
LOI	0.27 ± 0.25	0.05	0	-0.12 ± 0.15	-0.04	0	-0.11 ± 0.25	0.25	0
Sc	28 ± 1	28	0	24 ± 1	22	0	14 ± 1		
V	345 ± 8	355	0	297 ± 8	287	0	109 ± 2		
Cr	59 ± 2	59	0	87 ± 5	81	0	8 ± 1		
Ni	60 ± 4	61	0	100 ± 3	96	0	<4 ± 2		
Cu	75 ± 11	72	0	47 ± 5	47	0	15 ± 2		
Zn	145 ± 14	136	0	130 ± 6	122	0	171 ± 5		
Rb	16 ± 1	17	0	18 ± 2	21	0	39 ± 2		
Sr	396 ± 3	397	0	591 ± 2	593	0	589 ± 1		
Y	65 ± 28	66	0	37 ± 0	37	0	48 ± 1		
Zr	228 ± 0	228	0	306 ± 1	307	0	417 ± 2		
Nb	17 ± 0	17	0	28 ± 0.3	29	0.4	89 ± 16		
Ba							458 ± 9		

Quarry averages are from Sinton and Sinoto (Chapter 11).

a - Sample Hiki-2 is a flake from the Hikina'akaia site on Kaua'i.

b - Sample I82N is a flake from the Hane Sand Dune habitation site on Ua Huka, Marquesas.

c - Sample TP4-9 is an adze flake from Layer III in a habitation site (HEN-1, see Chapter 9) on Henderson Island (Sinoto 1983).

TABLE 10.4. Selected sample matches to quarries.

three to four major element oxides. These keys have been found to be 100% effective at discriminating all quarry samples and assigning reasonable matches from the artefact database.

Various geological and statistical procedures have been used to assign artefacts to a source. By 'source' we follow the hierarchical arrangement outlined by Weisler (1993a:63; Fig 10.3) which begins at the most general scale, that of petrologic province (e.g., oceanic island basalt), and leads to more specific, and smaller geographic scales of identification: archipelago, island, volcano, geologic feature (e.g., cone, dyke swarm), or geologic event such as a flow, dyke, or secondary deposit. Consequently, the artefact source does not require reference to a *specific* location to be useful for archaeological purposes. And here we stress the need for an archaeological problem orientation to sourcing studies. For example, White (1987) was able to assign two Tongatapu, Tonga adzes to a source in Samoa or 'Uvea since the artefacts, consisting of oceanic island basalt, were found on the continental side of the Andesite Line in Tonga (Chapter 1: Fig 1.1). While the source was identified only to the scale of archipelago (Samoa), or island, ('Uvea), these adzes were shown to have been imported.

It follows, then, that the notion of 'provenance environment' is useful for assigning artefacts to source.

Here, we refer to the blending of an archaeological problem orientation with geological knowledge of the region of interest. For instance, if we want to determine the provenance of fine-grained basalt artefacts from the Cook Islands, a basic understanding of the island group's geology will be instructive. Furthermore, based on the prehistory of the Cooks, we can place certain limits on the source(s) of artefacts originating from beyond the archipelago. That is, it is most likely that imports may have derived from the closest island groups such as the Australs, Samoa or the Societies, but it is less likely that artefacts sourced to Pitcairn, the Marquesas or Hawaii will be identified. The regional geology and archaeological problem orientation should be factors in any sourcing protocol. Although the case has been made for the Hawaiian archipelago (Weisler 1993a:64-68), we provide a further example from the Cook Islands.

The Cook Islands as a provenance environment

Rising more than 3 km above the ocean floor, the Cook Islands are the northern extent of the Cook-Austral Island chain (Turner and Jarrard 1982), yet do not form a time-progressive linear alignment (Dalrymple *et al.* 1975) typical of many archipelagoes of oceanic island basalt origin. The Cooks are one of the geologically better-studied groups in

Quarry	SiO ₂	TiO ₂	K ₂ O	Other
Hawaiian Islands				
Mauna Kea	46.5-49.0	3.5-4.5	0.9-1.3	15-16 Fe ₂ O ₃
Polulū	48.5-50.5	2.0-3.0	1.5-2.5	> 1.5 P ₂ O ₅
Haleakalā	50.0-52.0	1.9-2.2	2.0-2.5	
Pu'umōiwi	51.5-53.0	2.5-3.5	0.7-1.0	
Kapōhaku	51.0-52.5	2.0-2.5	<0.7	
'Amikopala	50.0-51.5	2.5-3.0	<0.7	
Mo'omomi	43.5-45.0	4.0-4.5	0.7-1.0	
Waihole	52.0-54.0	2.0-2.5	0.6-0.9	
Kailua	52.0-54.0	2.0-2.5	0.6-0.9	11-12 Fe ₂ O ₃
Keāhua I	45.0-46.0	2.0-3.0	<0.7	
Keāhua II	45.0-47.0	2.5-3.5	1.9-2.2	>1.0 P ₂ O ₅
Pitcairn Island				
Down Rope	62.0-63.5	0.4-0.8	>4.5	
Tautama	49.0-51.0	2.5-2.9	1.8-2.2	13-14 Fe ₂ O ₃
Samoa				
Tataga-matau	47.5-50.0	3.0-3.7	1.4-1.9	<5.1 MgO
Le'aeno	47.5-48.5	3.6-4.0	1.2-1.8	>0.6 P ₂ O ₅
Maupau	46.0-47.0	4.0-4.5	1.2-1.6	
Rapa Nui (Easter Island)				
Motu Iti	>70.0	<0.3	>3.5	>3.25 Fe ₂ O ₃
Rano Kau I + Orito	>70.0	<0.3	>3.5	3.0-3.25 Fe ₂ O ₃
Rano Kau II	>70.0	<0.3	>3.5	<3.0 Fe ₂ O ₃
Ovahe	50.0-52.0	2.2-2.6	1.0-1.5	>3.0 MgO
Society Islands				
Vaiopatapata	<45.0	4.0-4.5	1.45-2.0	<13.6 Fe ₂ O ₃
Ra'iatea II	46.0-48.0	3.0-3.5	2.2-2.7	
Tahinu I	<45.0	>4.2	1.45-2.0	13.6-14.0 Fe ₂ O ₃
Tahinu II	<43.5	3.6-4.2	1.8-2.5	
Papeno'o	43.5-45.0	3.5-4.2	1.5-1.8	>0.65
Orofero	46.0-48.0	4.0-5.0	>2.5	
Marquesas Islands				
Eiao	46.0-48.0	3.5-4.5	0.9-1.3	13-14 Fe ₂ O ₃
Cook Islands				
Mata'are	44-45	3.0-3.5	0.5-1.0	

TABLE 10.5. Key to discriminating quarries from the Oceanic Island Basalt province in Polynesia.

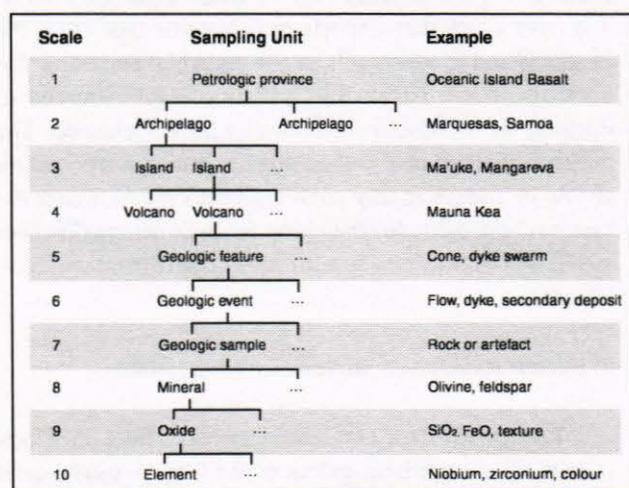


FIGURE 10.3. Hierarchical arrangement of fine-grained basalt sources.

Polynesia since initial pursuits by Marshall (1908, 1909, 1912) with subsequent detailed overviews of Mangaia (Marshall 1927), Rarotonga and Atiu (Marshall 1930), followed by an updated archipelago-wide description of the physiography, stratigraphy and petrography of volcanic and sedimentary rocks and features (Wood and Hay 1970; see also Stoddart *et al.* 1990; Woodroffe *et al.* 1991). Detailed accounts of volcanic petrography and geochemistry are provided for all volcanic islands including a general description of the rock types present and rock geochemistry (Dalrymple *et al.* 1975; Marshall 1927, 1930; Palacz and Saunders 1986; Wood 1978a, b; Wood and Hay 1970).

In reference to volcanic provenance studies, a unique aspect of the Cook Islands is the presence of numerous non-volcanic islands such as atolls, cays and the *makatea* regions of the volcanic islands. These non-volcanic islands provide an excellent backdrop for examining the occurrence of imported materials since all volcanic artefacts are of non-

local origin. Also of utility for provenance studies in the Cooks, portions of the volcanic islands are extremely weathered and fresh volcanic rock is limited to few outcrops, to dykes exposed in deeply incised stream drainages and to late-stage eruptions (Marshall 1927:36; Wood 1978a:769; Wood and Hay 1970:27). As an example from Mangaia, geologists have lamented the fact that "volcanic rocks are almost all weathered to a considerable degree...and rock specimens can be obtained in a few places" (Wood and Hay 1970:27). While a problem for geologists, the presence of fresh and fine-grained basalt has a very limited distribution and this fact alone can greatly facilitate determining artefact source.

While it is not necessary here to review the petrology of each volcanic island in the Cooks (see Chapter 6; Weisler 1993b:113-122), it is relevant to summarise a few points. In general, the rocks of the Cook Islands are highly alkaline, undersaturated phonolites and trachytes associated with basic alkaline volcanic rocks with a high content of ferromagnesian minerals (Wood and Hay 1970:53). The youngest flows on Rarotonga - including the putative source at Black Rock (see Chapter 6) - are nepheline sodalite phonolites. There is a striking paucity of olivine-bearing basalts, with a more common distribution of olivine-free basalts (Wood and Hay 1970:53). On present geological evidence, the rocks of Rarotonga and Aitutaki can be separated from other volcanic island rocks in the Cooks by the presence of Sr in abundance of >1000 ppm. Furthermore, the Pb isotope ratios of Mangaian rocks are so unique that they can be separated from any basalt in the Pacific region (Jon Woodhead pers. comm. 1994).

The distribution of lithic resources in the Cook Islands is summarised in Table 10.6. Cook Islands geology has the

following implications for provenance studies of lithic artefacts: (1) the greatest diversity of volcanic rocks are on the largest island of Rarotonga and, secondarily, on Aitutaki at the northern end of the southern group; (2) late stage volcanics, such as the Phonolitic Eruptive flows at Raemaru and Muri, both of Rarotonga, are the largest sources of fresh, fine-grained basalt in the archipelago although use of these rocks has not been demonstrated archaeologically; (3) fresh dyke rock, of medium to fine grain, may be eroded from the upper and middle areas of deeply incised drainages and deposited along the stream courses; (4) only the southern Cooks, excluding Manuae and Takutea, have sources of volcanic oven stones; (5) no volcanic rocks are found naturally occurring in the northern Cooks; (6) chert is present on Mangaia; (7) dense limestone can be found on Atiu, Ma'uke and Mangaia; and (8) most importantly, the largest fine-grained basalt source is at Mata'are, Mangaia (Weisler *et al.* 1994). Smaller basalt sources are found on the *motu* of Rapota and Moturakau in Aitutaki (Chapters 6 and 7).

With this background, Weisler selected 25 polished basalt flakes (presumably the by-products of adze use and reworking) from the Tangatatau (Mangaia) rockshelter (Kirch *et al.* 1995) for non-destructive EDXRF analysis (Weisler and Kirch 1996). (Complete analysis details are described in Weisler 1993b:137-141.)

The mid-z elements chosen for the bivariate plot illustrated in Figure 10.4 were selected because these values are easily detected by the EDXRF technique (Potts 1987:315) and are associated with the highest levels of accuracy and precision. They are also found in sufficient abundances in the source rocks and artefacts. Perhaps, most importantly, these ratios of highly incompatible trace elements (such as Zr and Sr) can be used as discriminants

Island	Type	Fine-grained basalt	Other basalt	Limestone	Chert
Rarotonga	high volcanic	X	X	X	-
Mangaia	<i>makatea</i> + volcanic	X	X	X	X
Atiu	<i>makatea</i> + volcanic	-	X	X	-
Mitiaro	near atoll	-	X	X	-
Ma'uke	<i>makatea</i> + volcanic	-	X	-	-
Aitutaki	almost atoll	X	X	-	-
Manuae	atoll	-	-	-	-
Takutea	cay	-	-	-	-
Penrhyn	atoll	-	-	-	-
Manihiki	atoll	-	-	-	-
Pukapuka	atoll	-	-	-	-
Rakahanga	atoll	-	-	-	-
Palmerston	atoll	-	-	-	-
Suvarrow	atoll	-	-	-	-
Nassau	atoll	-	-	-	-

TABLE 10.6. Distribution of lithic sources in the Cook Islands.

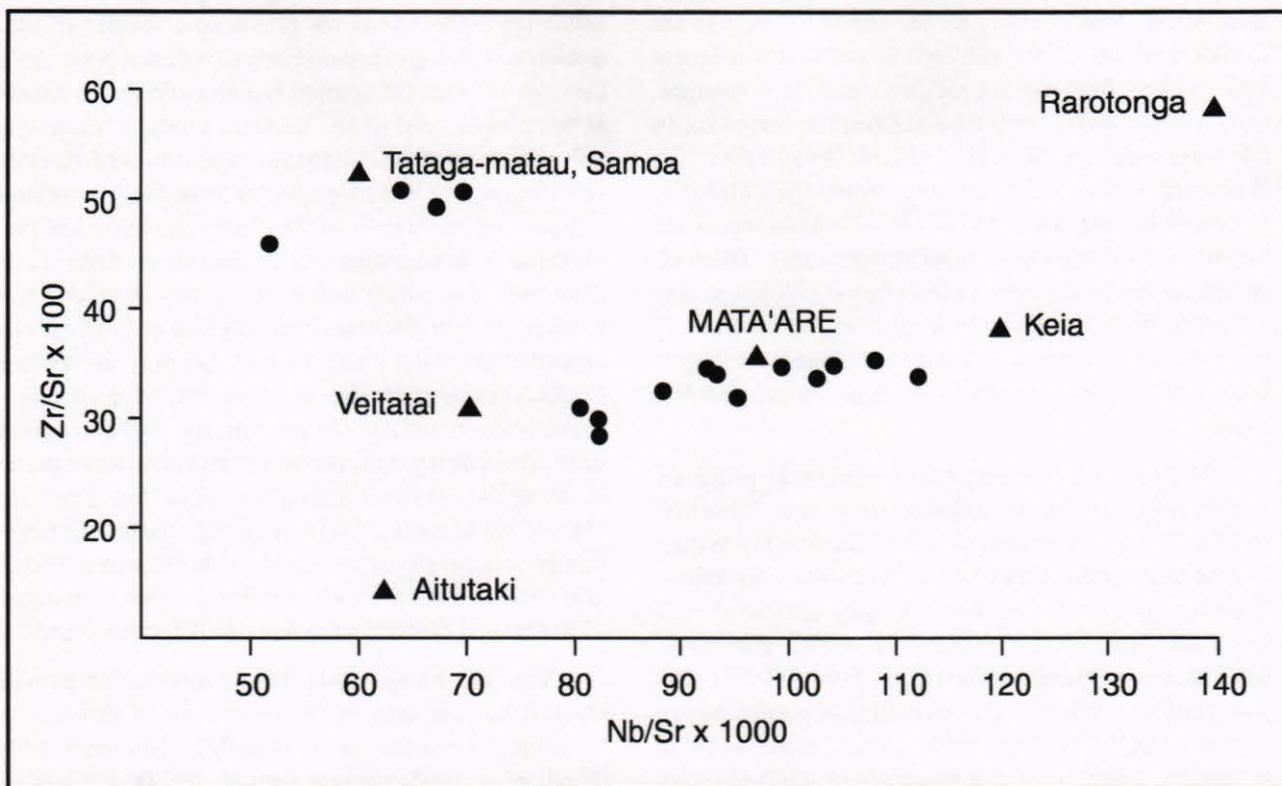


FIGURE 10.4. Bivariate plot of Tangatatau adze flakes analysed by energy-dispersive XRF. The mid-z elements used are Zr, Sr and Nb in parts-per-million (ppm). Triangles represent basalt sources and dots, artefacts. Most artefacts originated from the Mata'are (Mangaia) source, probably four from Tataga-matau (Samoa), and nine with Sr values >1000 ppm, not plotted here, may be from sources on Rarotonga or Aitutaki.

as they are relatively insensitive to near-surface, magma-chamber processes such as crustal assimilation and fractional crystallisation. Best *et al.* (1992:53), however, have found that oxides such as titanium (TiO_2), iron (Fe_2O_3) and phosphorus (P_2O_5) are the most efficient discriminators of basalt source characterisation and artefact provenance, while we have been successful with SiO_2 , TiO_2 and K_2O (see Table 10.5).

Most of the Tangatatau artefacts originated from the Mata'are basalt source, while four specimens probably came from sources on Tutuila, Samoa (Weisler 1993c; Weisler and Kirch 1996). Two flakes from this latter attribution were confirmed by isotope analysis (Chapter 13). Nine other flakes have Sr values >1000 ppm and probably originated from sources on Rarotonga or Aitutaki.

In summary, provenance studies may be facilitated by first delimiting the geographical region of interest. In the example above, the Cook Islands was selected as the *provenance environment* with the assumption that imported basalt artefacts were either from islands within the archipelago or from the closest island groups. We believed, based on *archaeological* information, that it was a low

probability that basalt adze material could have been imported from distant archipelagoes such as the Marquesas, Pitcairn or Hawaii. Indeed, other case studies in this volume have documented inter-archipelago transfer of fine-grained basalt to the Cook Islands from Samoa and possibly from the Societies (Chapters 6 and 7).

A clear understanding the region's geology is essential for assigning artefacts to source. In the case of the Cook Islands, knowing that Rarotonga and Aitutaki have rocks with Sr values in excess of 1000 ppm suggested that nine Tangatatau artefacts (not plotted in Fig 10.4) could have come from sources on those islands. Elements used for artefact discrimination were based on a knowledge of geological principles as well as the strengths and limitations of the geochemical technique used for analysis.

Statistical approaches to basalt sourcing

Statistical approaches begin with the results of the geochemical analyses of source rocks and artefacts, then manipulate these data to identify patterns or structure. Several of these Pacific island studies have been attempted

to date (Best 1989, *et al.* 1992; Walter 1990; Walter and Sheppard 1996) with Best *et al.* (1992) providing the most comprehensive reporting. In one application, major elements (or oxides) were used for analysis of 161 source rocks from the Tataga-matau (Samoa) quarry, most of the major known sources throughout Polynesia and selected artefacts (Best *et al.* 1992). Multivariate analyses, including cluster analysis and stepwise discriminant analysis, were run using all the major elements to rank the efficacy of these oxides for discriminating sources. Green and Bird (1989) have used principal components analysis for sourcing obsidian from the Reef Santa Cruz group.

One problem inherent in relying solely on clustering algorithms to determine geochemical groups and facilitate source attribution is that groups are 'forced' by the clustering procedure and outcomes do not necessarily bear a strong correlation to petrogenesis. Consequently, Sheppard *et al.* (Chapter 6) have advocated using Ward's method clustering technique to check the stability of groups formed by average linkage cluster analysis. Certain highly discriminating oxides, such as calcium (CaO), have clear geological reasons why they are of special value for separating sources (see Natland 1980:718; Wright 1986:61), while titanium, iron and phosphorus are deemed most efficient for discriminating fractionation within source areas (Best *et al.* 1992:53). The data, used by Best *et al.* (1992), were displayed using bivariate plots of phosphorous and \log_{10} titanium/iron (see figures in Best *et al.* 1992). Average linkage cluster analysis was then used to group artefacts and source rocks. Artefacts that grouped with specific source rocks were assumed to be from that quarry.

Summary

The use of either a geological or a statistical approach to separating sources and assigning artefacts to quarries is essentially one of choice with no one procedure providing all the answers. The geological procedure begins with a general knowledge of regional geology which predicts where fine-grained basalt sources may be thus complimenting the archaeological data on known quarries. We believe that this geologically-informed procedure facilitates assigning artefacts belonging to unknown sources to actual locations (at various geographic scales). This was shown with the provenance study from the Cook Islands.

Statistical sourcing procedures are quite useful for archaeologists since most researchers are familiar with these kinds of data manipulation and no geological knowledge is required. However, familiarity of geological principles is essential to understanding *why* certain oxides and elements are useful for discriminating sources and assigning artefacts

to source. This additional knowledge may permit greater reliance on the results. We believe that artefact source attribution is most reliable when geological knowledge is used in concert with statistical clustering algorithms.

DIRECTIONS IN POLYNESIAN BASALT SOURCING STUDIES

Towards a sourcing protocol

There is clearly no universal procedure for sourcing all Polynesian basalt artefacts. A protocol must be formulated in reference to the research design, funding, access to analytical equipment and time constraints of each individual project. Here, we do not consider sampling issues at the scale of region or site (see, for example, Redman [1974] for a review of these procedures), but use an artefact assemblage as the starting point. All projects must consider: (1) sampling of the assemblage to be analysed; (2) choice of one or more analytical techniques; (3) procedure for discriminating sources and assigning artefacts (unknowns) to mutually exclusive geochemical groups; and (4) validating source assignment.

Figure 10.5 illustrates the general steps in a sourcing study. In level 1, the entire assemblage is divided into basalt and non-basalt groups, the latter of which may contain artefacts consisting of volcanic glass, chert or other materials. Using the presence or absence of vesicles at level 2, 100% of the basalt artefacts are further divided into vesicular artefacts (e.g., oven stones or fragments of building material) and non-vesicular specimens. Vesicular basalt is not further divided here, but specimens from this class can be analysed by WDXRF at levels 5 and 6, described below. Because vesicular basalt, by definition, has holes throughout the rock matrix and the material is often composed of coarse-grained, mineral-rich rock, it is best analysed by WDXRF using fused disks and crushed pellets. To date, only Weisler (1995:400-401) has conducted geochemical analysis of Polynesian oven stones and sourcing results suggest further studies can be productive.

Using all specimens, relative grain size and the presence of unique characteristics observed macroscopically are used to separate groups at level 3. Geologists consider most non-vesicular artefact basalt as fine grained (i.e., average grain size of <1.0 mm), while archaeologists tend to make further divisions based on rocks that have a 'sugary' appearance (i.e., medium to coarse grained) from those specimens that appear almost without grain. Depending on the detail of information on the regional geology of the study area, unique macroscopic characteristics such as flow banding may be sufficient for determining the source of

some specimens. For example, in southeast Polynesia the largest fine-grained basalt source is located at a hawaiite exposure at Tautama, Pitcairn island. Flow banding is clearly evident in hand specimens and is a distinguishing characteristic of this material *within the context of southeast Polynesia* (Weisler 1996a, b). On Moloka'i, Hawaiian Islands, flow banding is only evident on one of the island's eight known sources and can be used to separate the source at Mo'omomi.

After level 3, there are three options. The first (level 4) is to acquire petrographic descriptions of a sample of the grain size groups. Within this protocol, petrography can be used to determine the range of major rock types present in the sample, but source assignment must await geochemical analysis. The standard size of petrographic thin-sections requires destruction of a relatively large piece of the specimen (about 15 by 35 mm), but information on ground mass, texture, relative abundance of phenocrysts and other distinguishing characteristics such as grain orientation, weathering and presence or absence of opaques are useful for determining major rock classes and, consequently, petrologic provinces (e.g., oceanic islands versus arc volcanic provinces; Hawaiian from Marquesan provinces).

Protocols that do not require petrographic data must then group specimens according to weight which will dictate the specific technique of destructive WDXRF analysis at level 5. Specimens less than 3 g are routinely analysed with an electron microprobe for major elements. If sample weights exceed 3 g, fused disks are prepared for routine XRF of major elements. In many cases, major elements are sufficient for determining sources (Best *et al.* 1992; and papers in this volume), while trace elements (level 6) are analysed from crushed pellets with at least 7 g of sample weight. WDXRF analyses of major and trace elements are relatively expensive and specimens at levels 5 and 6 could be sampled.

Another protocol does not use petrographic descriptions and defers WDXRF for confirmation of geochemical groups and source assignments, or for determining the provenance of problem specimens. After level 3, non-destructive EDXRF analysis is used to characterise the non-vesicular basalt artefacts that have specimen weights in excess of ca 2 g. This is an inexpensive and fast procedure that is cost-effective for analysing 100% of the specimens (description of technique in Weisler 1993a, b, c). Major elements, however, have not been shown to be useful in the characterisation and sourcing of fine-grained basalt artefacts.

In the final level, the isotopes technique is reserved for problems that are encountered in source assignments of

specimens analysed by WDXRF for major and trace elements and for confirming source assignments made with less quantitative techniques (such as EDXRF). The technique is especially useful for provenance studies where WDXRF cannot resolve problems of source overlap such as in the southern Cook Islands (Chapter 6). It may also be useful for separating many sources from a single island. In this regard, Weisler and Woodhead are currently applying the technique of isotope analysis to sources from Tutuila, Samoa and Moloka'i, Hawaiian Islands where many sources are known from a relatively small region and source overlap is a potential problem.

New sources and documenting geochemical variability

With the exception of the Tuamotus (an island group consisting solely of low, coral atolls) most archipelagoes in the oceanic region of Polynesia have sources that await adequate geochemical documentation. Even in island groups with no known quarries, other data suggests that ones should exist. For example, south of the main Australs, Stokes reported various lithic sources for Rapa including Tapuki islet which was "partly composed of very hard and compact stone of dark color which is present on the surface in large boulders" (1930:541). He suggested that it was highly probable that more than 90% of the Rapa adzes were made from (local) dyke rock, the balance being made from flakes or other fragments (Stokes 1930).

Along with the Australs, the Society Islands - integral to any provenance studies in central-eastern Polynesia - is clearly the largest void in the Polynesian basalt source database. Tentative results suggest the Societies were part of an interaction sphere with at least the Cook Islands (Chapters 6 and 7) and it is clear that any resolution for determining the sources of volcanic adzes in the Tuamotus (Emory 1975) will require source data from at least Tahiti where sources are known in the Papeno'o Valley (Orliac 1986).

In addition to finding more quarries, we need to *demonstrate* the geochemical variability of known sources in order to achieve confidence in assigning artefacts to a specific provenance. To date, geochemical variability has been adequately documented at only two small, but important sources. One quarry at Mo'omomi, Moloka'i (Hawaiian Islands) is a hawaiite cone that eroded to form subrounded cobbles and boulders covering about 1.8 ha (hectares) (Weisler 1991:58; geochemical data in Weisler 1990a:45). A second quarry is situated along the south shore of Pitcairn at Tautama where several flows eroded to form talus (geochemical variability discussed in Weisler 1993b). Three key characteristics distinguish data quality of the

Moloka'i and Pitcairn sources from other Polynesian sources: (1) the geological event that formed the fine-grained basalt was clearly identified, thus permitting adequate field sampling for determining the geochemical variability of the stone-tool quality rock; (2) artefacts (e.g., large flakes) and geological material were collected for geochemical characterisation so it was possible to unequivocally link the archaeological material with the geological source. While this may seem an extreme level of caution, this is the one sure way of demonstrating that the archaeological material found at the source is, indeed, from the identified geological event. And (3) the geochemical variability of the quarry has been demonstrated. That is, the addition of new samples does not significantly alter the range of geochemical values.

Defining the geological feature(s) that provide the source rock is especially important for the largest known fine-grained basalt quarry in central Polynesia, Tatagatau, Tutuila, Samoa (Chapter 5; Leach and Witter 1987, 1990). Recent geochemical data (e.g., Weisler 1993c:176 compare sample 89-12 to the others in Table 12.4) clearly points to at least two geological features (i.e., multiple dykes and/or flows) that contributed stone-tool quality rock for prehistoric use. Areal extent (Leach and Witter 1987, 1990) and use of this quarry has been documented (Best *et al.* 1992; Chapter 5), but additional detailed field sampling is clearly warranted to determine the geochemical variability of all the geological features contributing to the source(s) exploited prehistorically.

Field sampling

Sampling lies at the heart of any scientific investigation. Variability in geological sampling and geochemical analysis is introduced at four points: (1) the natural variability of the geological feature being sampled; (2) the variability introduced by the sampling procedure; (3) the variability in preparing the sample for chemical analysis by crushing, splitting, fusing, etc.; and (4) the analytical variability introduced by the geochemical determination of elements in the samples and the operating conditions of the analytical equipment. The first two points are directly relevant to field sampling.

It is important to realise that there is no universal scheme for the design of a sampling programme and the variability of geologic features found at fine-grained basalt sources may require an equal diversity of sampling procedures. Notwithstanding, practical considerations are a real consideration in geological field sampling. The sheer weight of rock samples and costs involved in shipping heavy material from isolated islands are, indeed, very real constraints to acquiring adequate samples.

Several factors influence field sampling such as the size of the rock mass (feature), whether it has a homogeneous matrix composition, the mode of occurrence of the elements for which determinations are sought, presence of weathering, and chilled margins, such as volcanic glass selvages along dykes (see Potts 1987:18).

As discussed above, identifying the geological features that contributed material to the quarry is essential for adequate field sampling. Unless an archaeologist is experienced in recognising geological features, geologists should be part of any field sampling team. Determining the geochemical variability of a source requires identification of how many lava flows, dykes, outcrops, or areas of eroded cobbles and boulders that may have been used prehistorically. Multiple samples should be collected from each worked lithological unit (e.g., flow, dyke). Individual samples should be large enough to allow for multiple XRF analyses and fabrication of petrographic thin sections, preparation of 'splits' or subsamples for other institutions, with sufficient material left for archiving for future analysis by other kinds of techniques. For fine-grained basalt we suggest a minimum individual sample weight of 250 g. A minimum of 10 samples should be collected for each large lithological unit requiring determination of geochemical variation. At the least, this approximates a statistically valid sample which could be used to determine the range of major and trace elements. Large lithological units will probably require more samples than smaller features.

Reporting standards

To facilitate inter-laboratory comparisons of geochemical data, we believe that there are nine areas that should be addressed. (1) The geochemical characterisation technique should be specified. While this is rarely a reporting problem, it is necessary to mention whether the XRF technique used was wavelength or energy dispersive as each are associated with differing levels of accuracy and resolution for detecting certain elements. The make and model numbers of the equipment are also important (e.g., Rigaku 3370 spectrometer; automated Phillips PW 1410 XRF spectrometer). (2) Sample preparation can be destructive (powdered, then pressed pellets; fused disks; saw cut surface) or non-destructive using the whole unaltered specimen. Details of sample preparation could include the equipment used to crush the sample (as certain metals used in the manufacture of these tools can introduce trace elements), use of a sonic cleaner, distilled water, dilute HCl to dissolve carbonate encrustations (Weisler 1993c:172) or acetone used to remove surface contaminants (Sleelenfreund and Bollong 1989:175). (3) The major

elements (oxides) and trace elements should be reported if analysed. Although this seems intuitively obvious, but undetected, elements should be reported as such by listing as 0 and not as a blank entry. This will eliminate the confusion of whether or not an element was actually analysed. Iron (Fe_2O_3) should be reported as total iron. If iron is reported as FeO, it can be converted to Fe_2O_3 by multiplying by 1.11134. Loss-on-ignition (LOI) values should be listed as dry or wet analyses.

(4) To facilitate further inter-laboratory comparisons, the detection limits or sensitivity of commonly determined elements should be stated. Detection limits are important since they dictate the level at which elements should be reported. For example, in basalt, mid-z elements can be detected with an accuracy of $\pm 2-5\%$ (Parks 1986:153) which should be taken into consideration when comparing data from different labs. While oxides are commonly reported as weight % to two decimal places, trace elements should be reported to the nearest whole number. The limits of significant digits in reporting data depends on the precision of the particular lab. As such there is no absolute value. For example, labs with a precision of 1% relative technically should only report oxides to one decimal place for abundances greater than 10%. With respect to the trace elements, the normal convention is to report values to the nearest 1 ppm. In some cases the precision is greater, e.g., the University of Hawaii lab for Nb, where the precision is closer to 0.1-0.2 ppm. In any case, we recommend reporting data only to the precision of the analysis, which is technique and laboratory dependent.

(5) It is also necessary to report the standards used for instrument calibration (e.g., Best *et al.* 1992:52). Common international standards are produced by the U. S. Geological Survey, Japan and Canada. Institution-specific standards are also used to monitor machine accuracy and precision. The University of Hawaii lab uses a set of internal standards (e.g., UH-1, 2 and 3) which have been made available to the University of California at Berkeley lab for evaluating machine comparability. (6) It follows that analytical accuracy and precision should be reported for international standards and compared with published 'working' values (Govindaraju 1984, 1989, 1994; for example, see Weisler 1993c:173; Chapter 7). This provides a further evaluation of the analysis of all unknowns (artefacts and source rocks) as well as reporting the overall quality of the analysis. (7) Coupled with analytical accuracy and precision is the length of the 'lifetime' or analysis time of each unknown. In the analysis of lighter elements, accuracy and precision will be dependent on the length of time spent in detecting and counting the abundance of each element.

(8) Once the analyses are complete, it is worthwhile to report if there is source rock remaining (in the case of quarry samples) and where it is curated. Making these samples available to other investigators can only improve inter-laboratory comparisons. For example, excellent comparisons of instrument accuracy, precision and detection limits can be assessed when two or more labs analyse subsamples or splits from the same sample.

(9) With all the above in mind, the final result is reporting the source-artefact correlation techniques used to assign unknowns to sources. As we described previously, statistical techniques such as clustering analysis and step-wise discriminant analysis have been used, as well as more geologically-oriented procedures. Whatever techniques are used to assign artefacts to source, they should be described in sufficient detail so others can replicate the results.

The above standards should be reported for each published analysis of source rocks and artefacts. We do not advocate reporting this information each time a new analysis is performed but, rather, suggest labs that routinely analyse material should make a document available that can be referenced by the archaeologist. Alternatively, the archaeologist reporting data for the first time can report the above details, then cite that document when reporting future analyses.

CONCLUSIONS

Understanding the details of prehistoric long-distance interaction across Polynesia and within island groups is best achieved with a basic knowledge of Oceanic island petrological evolution and the general aspects of the petrology of igneous rocks. Armed with this background, the non-specialist can begin to see how it is possible to identify geochemically-distinct rocks and artefacts found distant from their geological sources.

No single analytical protocol is appropriate for every sourcing study. Rather, characterisation techniques that range from simple macroscopic observations to sophisticated procedures such as x-ray fluorescence and isotope analysis that require expensive equipment and complex sample preparation all may be necessary for determining the sources of artefacts in an assemblage (Fig 10.7). Consequently, we have advocated a range of techniques to be used for a single sourcing program where simple, non-destructive analyses lead to more powerful techniques as required for unambiguous characterisation, source assignment and confirmation.

Source assignment is best achieved with the notion of 'provenance environment' (Weisler 1993a) that considers

Technique	Specimen Preparation	Analytical Sample Size	Cost
Visual-macroscopic	non-destructive	large	low
Petrographic	destructive	small	low
Energy-dispersive XRF	non-destructive	large	low
Wavelength-dispersive XRF	destructive	small	high
Isotopes	destructive	small	high

TABLE 10.7. Attributes of analytical techniques.

an archaeological problem orientation, geological knowledge of the study region, principles of petrogenesis, and, perhaps, statistical clustering techniques to assign artefacts to specific or general sources. Statistical clustering algorithms by themselves cannot explain *why* groups are formed - only geological principles have the ability to provide reasons why certain artefacts and source rocks are geochemically similar.

Standardisation of definitions is also necessary for continued success in sourcing studies. To this end, we have provided some fundamental definitions for 'quarry', 'source' and 'site' in hopes of reducing ambiguity. For example, 'quarry' is an often used but, ill-defined term. In Polynesia, at least, the actual quarrying of rock, that is, excavation to acquire stone-tool quality material, is rarely documented at sources, while most raw material is merely collected from the surface. We have retained the term 'quarry' in a broad sense to mean both collection and reduction of source rock at a primary geological locale. 'Sources' represent primary deposits that have not been archaeologically identified or secondary geological accumulations, such as stone-tool quality cobbles in a gulch bottom that evidence prehistoric lithic reduction.

Polynesian adze databases (including regional case studies) that contain hundreds of quarry, source and site (artefact) geochemical characterisations are fast accumulating as papers in this volume attest. Rigorous reporting standards are vital for facilitating inter-laboratory comparisons (Weisler 1993a:75-76) and we have outlined above nine points that should be considered. Perhaps the most important component of any study is an evaluation of analytical precision and accuracy for internationally-recognised standards and published working values. A simple table comparing these values could be included with any case study (see Weisler 1993b, c; Chapter 10).

Further sourcing pursuits will be advanced by archaeologically recording new quarries and understanding the geochemical variability of these locales. To this end, increased emphasis on field sampling with archaeologists and geologists will be necessary to achieve this goal.

Additional field sampling should follow geochemical analysis of museum specimens and other curated artefacts to determine the artefact geochemical groups present for each archipelago (see, for example, Chapter 6). We could then know the relationship between the geochemical groups represented by the adze material to the geology of the archipelago. This information could be essential for formulating future field sampling and also in helping to locate new sources and quarries.

As papers in this volume demonstrate, sourcing studies of fine-grained basalt are providing new and exciting insights into the role of prehistoric long-distance interaction in the evolution and transformation of prehistoric Polynesian societies. We stress that inter-laboratory cooperation is fundamental to continued success in Polynesian sourcing studies.

REFERENCES

- Allen, J. 1984. In search of the Lapita homeland. *Journal of Pacific History* 19:186-201.
- Ammermann, A.J. 1979. A study of obsidian exchange networks in Calabria. *World Archaeology* 11:95-110.
- Beaglehole, E. and P. Beaglehole. 1938. Ethnology of Pukapuka. *Bernice P. Bishop Museum Bulletin* 150. Honolulu.
- Beardsley, F.R., W.S. Ayres and G.G. Goles. 1990. Characterisation of Easter Island Obsidian Sources. *Indo-Pacific Prehistory Association* 11:179-187.
- Bellwood, P. 1978. Archaeological Research in the Cook Islands. *Pacific Anthropological Records* 27. Honolulu, Bernice P. Bishop Museum.
- Best, S. 1987. Long distance obsidian travel and possible implications for the settlement of Fiji. *Archaeology in Oceania* 22:31-32.
- Best, S. 1989. Lakeba: The Prehistory of a Fijian Island. Ann Arbor, Michigan, University Microfilms.
- Best, S., P. Sheppard, R. Green and R. Parker. 1992. Necromancing the stone: archaeologists and adzes in Samoa. *Journal of the Polynesian Society* 101:45-85.
- Buck, P.H. (Te Rangi Hiroa). 1932. Ethnology of Manihiki and Rakahanga. *Bernice P. Bishop Museum Bulletin* 99. Honolulu.
- Buck, P.H. 1944. Arts and Crafts of the Cook Islands. *Bernice P. Bishop Museum Bulletin* 179. Honolulu.

- Clague, D. and G. Dalrymple. 1987. The Hawaiian-Emperor volcanic chain, part 1 geologic evolution. In R. Decker, T. Wright and R. Stauffer (eds), *Volcanism in Hawaii, U.S. Geological Survey Professional Paper* 1350:5-54.
- Cleghorn, P.L., T. Dye, M. Weisler and J. Sinton. 1985. A preliminary petrographic study of Hawaiian stone adze quarries. *Journal of the Polynesian Society* 94:235-251.
- Cox, K., J. Bell and R. Pankhurst. 1979. *The Interpretation of Igneous Rocks*. George Allen and Unwin, London.
- Dalrymple, G.B., R.D. Jarrard and D.A. Clague. 1975. K-Ar ages of some volcanic rocks from the Cook and Austral Islands. *Geological Society of American Bulletin* 86:1463-1467.
- Davenport, W.H. 1962. Red Feather Money. *Scientific American* 206:94-103.
- Dickinson, W. and R. Shutler. 1974. Probable Fijian origin of quartzose temper sands in prehistoric pottery from Tonga and the Marquesas. *Science* 185:454-457.
- Duerden, P., J.R. Clayton, E. Bird, W. Ambrose and F. Leach. 1987. Artefact composition and computation. In W. Ambrose and J.M.J. Mummery (eds), *Archaeometry: Further Australian Studies*, pp. 232-238. Canberra, Australian National University Press.
- Dye, T.S., M.I. Weisler and M. Riford. 1985. Adz Quarries on Molokai and Oahu, Hawaiian Islands. Report 093085 on file, Department of Anthropology, Honolulu, Bernice P. Bishop Museum.
- Emory, K.P. 1975. Material Culture of the Tuamotu Archipelago. *Pacific Anthropological Records* 22. Honolulu, Bernice P. Bishop Museum.
- Gill, W.W. 1876. *Life in the Southern Isles: or Scenes and Incidences in the South Pacific and New Guinea*. London, The Religious Tract Society.
- Goldman, I. 1970. *Ancient Polynesian Society*. Chicago, University of Chicago Press.
- Govindaraju, K. 1984. 1984 Compilation of Working Values and Sample Description for 170 International Reference Samples of Mainly Silicate Rocks and Minerals. *Geostandards Newsletter* Special Issue 8.
- Govindaraju, K. 1989. 1989 Compilation of Working Values and Sample Description for 272 Geostandards. *Geostandards Newsletter* Special Issue 13:1-113.
- Govindaraju, K. 1994. 1994 Compilation of Working Values and Sample Description for 383 Geostandards. *Geostandards Newsletter* Special Issue 18: 1-158
- Green, R. 1991. Near and Remote Oceania: disestablishing "Melanesia" in culture history. In A. Pawley (ed), *Man and a Half: Essays in Pacific Anthropology and Ethnobiology in Honour of Ralph Bulmer*, pp. 491-502. Auckland, The Polynesian Society.
- Green, R.C. and J.R. Bird. 1989. Fergusson Island obsidian from the D'Entrecasteaux Group in a Lapita site of the Reef Santa Cruz Group. *New Zealand Journal of Archaeology* 11:87-99.
- Green, R. and J.S. Mitchell. 1983. New Caledonian culture history: a review of the archaeological evidence. *New Zealand Journal of Archaeology* 5:19-67.
- Handy, E.S.C. 1932. Houses, Boats, and Fishing in the Society Islands. *Bernice P. Bishop Museum Bulletin* 90. Honolulu.
- Harding, T.G. 1967. *Voyagers of the Vitiaz Strait: A Study of a New Guinea Trade System*. Seattle, University of Washington Press.
- Hjarnø, J. 1979-80. Social reproduction: towards an understanding of aboriginal Samoa. *Folk* 21-22:73-123.
- Irwin, G. 1983. Chieftainship, kula and trade in Massim prehistory. In J. W. Leach and E. Leach (eds), *The Kula: New Perspectives on Massim Exchange*, pp. 29-72. Cambridge, Cambridge University Press.
- Kaeppeler, A.L. 1978. Exchange patterns in goods and spouses: Fiji, Tonga and Samoa. *Mankind* 11:246-252.
- Kirch, P.V. 1984. *The Evolution of the Polynesian Chiefdoms*. Cambridge, Cambridge University Press.
- Kirch, P.V. 1988. Niuaotupapu: The Prehistory of a Polynesian Chiefdom. *Thomas Burke Memorial Washington State Museum Monograph* 5. Seattle.
- Kirch, P.V. 1991. Prehistoric exchange in Western Melanesia. *Annual Review of Anthropology* 20:141-165.
- Kirch, P.V., T.L. Hunt, M.I. Weisler, V. Butler and M.S. Allen. 1991. Mussau Islands Prehistory: Results of the 1985-86 Excavations. In J. Allen and C. Gosden (eds), *Report of the Lapita Homeland Project*, pp. 144-163. *Occasional Papers in Prehistory* 20. Canberra, Department of Prehistory, Research School of Pacific Studies, The Australian National University.
- Kirch, P.V., D.W. Steadman, V.L. Butler, J. Hather and M.I. Weisler. 1995. Prehistory and human ecology in Eastern Polynesia: excavations at Tatagamatau rockshelter: Mangaia, Cook Islands. *Archaeology in Oceania* 30:47-65.
- Kirch, P.V. and D. Yen. 1982. Tikopia: The Prehistory and Ecology of a Polynesian Outlier. *Bernice P. Bishop Museum Bulletin* 238. Honolulu.
- Lass, B. 1994. Hawaiian Adze Production and Distribution: Implications for the Development of Chiefdoms. *Institute of Archaeology, University of California* Monograph 37. Los Angeles.
- Leach, F. 1996. New Zealand and Oceanic obsidians: an archaeological perspectives using neutron activation analysis. *Journal of the Royal Society of New Zealand* 26:79-105.
- Leach, F. and B. Manly. 1982. Minimum Mahalanobis distance function and lithic source characterisation by multi-element analysis. *New Zealand Journal of Archaeology* 4:77-109.
- Leach, H. and D. Witter. 1987. Tataga-matau "rediscovered". *New Zealand Journal of Archaeology* 9:33-54.
- Leach, H. and D. Witter. 1990. Further investigations at the Tataga-matau site, American Samoa. *New Zealand Journal of Archaeology* 12:51-83.
- Lilley, I. 1988. Prehistoric exchange across the Vitiaz Strait, Papua New Guinea. *Current Anthropology* 29:513-516.
- Macdonald, G.A., A-T. Abbott and F.L. Peterson. 1983. *Volcanoes in the Sea*. Second edition. Honolulu, University of Hawaii Press.
- Malinowski, B. 1922. *Argonauts of the Western Pacific*. London, Routledge and Kegan Paul.
- Marshall, P. 1908. Geology of Rarotonga and Atiu. *New Zealand Institute Transactions* 41:98-100.
- Marshall, P. 1909. Note on the geology of Mangaia. *New Zealand Institute Transactions* 42:333.
- Marshall, P. 1912. Alkaline rocks of the Cook and Society Islands. *Australasian Association for the Advancement of Science Report* 13:196-201.
- Marshall, P. 1927. Geology of Mangaia. *Bernice P. Bishop Museum Bulletin* 36. Honolulu.
- Marshall, P. 1930. Geology of Rarotonga and Atiu. *Bernice P. Bishop Museum Bulletin* 72. Honolulu.

- Maziere, F. 1968. *Mysteries of Easter Island*. New York, W.W. Horton and Company.
- McBirney, A.R. 1993. *Igneous Petrology*. 2nd edition. Boston, Jones and Bartlett.
- McCoy, P.C. 1990. Subsistence in a 'non-subsistence' environment: factors of production in a Hawaiian alpine desert adze quarry. In D.E. Yen and J.M.J. Mummery (eds), *Pacific Production Systems: Approaches to Economic Prehistory*, pp. 85-119. *Occasional Papers in Prehistory* 18. Canberra, Department of Prehistory, Research School of Pacific Studies, The Australian National University.
- McCoy, P.C., A. Sinoto and A. Makanani. 1993. Archaeological Investigations of the Pu'u Moiwi Adze Quarry Complex, Kaho'olawe. Report prepared for the Kaho'olawe Island Conveyance Commission, Honolulu, Hawaii.
- Natland, J. 1980. The progression of volcanism in the Samoan linear volcanic chain. *American Journal of Science* 280-A:709-735.
- Norrish, K. and J.T. Hutton. 1969. An accurate x-ray spectrographic method for the analysis of a wide range of geological samples. *Geochimica et Cosmochimica Acta* 33:431-441.
- Orliac, M. 1986. Outils et techniques avant l'arrivée du métal. *Encyclopédie de la Polynésie* 5:9-24. Tahiti, Christian Gleizal, Multipress Edition.
- Palacz, Z.A. and A.D. Saunders. 1986. Coupled trace element and isotope enrichment in the Cook-Austral-Samoa Islands, southwest Pacific. *Earth and Planetary Science Letters* 79:270-280.
- Parkes, P. 1986. *Current Scientific Techniques in Archaeology*. London, Croom Helm.
- Potts, P.J. 1987. *A Handbook of Silicate Rock Analysis*. Chapman and Hall, New York.
- Redman, C.L. 1974. Archaeological Sampling Strategies. *Addison-Wesley Module in Anthropology* No.55.
- Rolett, B.V. 1993. Marquesan prehistory and the origins of East Polynesian culture. *Journal de la Société des Océanistes* 96:29-47.
- Sahlins, M.D. 1958. *Social Stratification in Polynesia*. Seattle, University of Washington Press.
- Sheppard, P.J. 1993. Lapita lithics: trade/exchange and technology. A view from the Reefs/Santa Cruz. *Archaeology in Oceania* 28:121-137.
- Skinner, H.D. 1940. Provenance of the Nassau island adze. *Journal of the Polynesian Society* 49:272-278.
- Sleelenfreund, A. and C. Bollong. 1989. The sourcing of New Zealand archaeological obsidian artefacts using energy dispersive XRF spectroscopy. In D. Sutton (ed.), *Saying So Doesn't Make It So: Papers in Honour of B. Foss Leach*, pp. 168-189. *New Zealand Archaeological Association Monograph* 17. Dunedin.
- Smith, I.E.M., G.K. Ward and W.R. Ambrose. 1977. Geographic distribution and the characterization of volcanic glasses in Oceania. *Archaeology and Physical Anthropology in Oceania* 12:173-201.
- Smith, S.P. (translator). 1919. History and traditions of Rarotonga. *Journal of the Polynesian Society* 28:183-208.
- Sorby, H. 1858. On the microscopic structure of crystals, indicating the origin of minerals and rocks. *Geological Society of London* 14:453-500.
- Stoddart, D.R., C.D. Woodroffe and T. Spencer. 1990. Mauke, Mitiaro, and Atiu: Geomorphology of Makatea Islands in the Southern Cook Islands. *Atoll Research Bulletin* 341. Washington, D.C., Smithsonian Institution.
- Stokes, J.F.G. 1930. Material culture of Rapa. Manuscript, MS. SC. Stokes (Grp. 2, Box 7 and 8) Archives, Honolulu, Bernice P. Bishop Museum.
- Turner, D.L. and R.D. Jarrard. 1982. K-Ar dating of the Cook-Austral Island chain: a test of the hot-spot hypothesis. *Journal of Volcanology and Geothermal Research* 12:187-220.
- Walter, R. 1990. The Southern Cook Islands in Eastern Polynesian Prehistory. Ph.D. thesis, University of Auckland.
- Walter, R. and W. Dickinson. 1989. A ceramic sherd from Ma'uake in the Southern Cook Islands. *Journal of the Polynesian Society* 98:465-470.
- Walter, R. and P.J. Sheppard. 1996. The Ngati Tiare adze cache: further evidence of prehistoric contact between West Polynesia and the Southern Cook Islands. *Archaeology in Oceania* 31:33-39.
- Weisler, M.I. 1990a. A technological, petrographic, and geochemical analysis of the Kapohaku adze quarry, Lana'i, Hawai'ian Islands. *New Zealand Journal of Archaeology* 12:29-50.
- Weisler, M.I. 1990b. Sources and sourcing of volcanic glass in Hawai'i: implications for exchange studies. *Archaeology in Oceania* 25:16-23.
- Weisler, M.I. 1991. The Archaeology of a Hawaiian Dune System: The Nature Conservancy's Mo'omomi Preserve, Moloka'i. Report prepared for The Nature Conservancy of Hawaii, Honolulu.
- Weisler, M.I. 1993a. Provenance studies of Polynesian basalt adze material: a review and suggestions for improving regional data bases. *Asian Perspectives* 32:61-83.
- Weisler, M.I. 1993b. Long-distance Interaction in Prehistoric Polynesia: Three Case Studies. Ph.D. thesis, University of California, Berkeley.
- Weisler, M.I. 1993c. Chemical characterization and provenance of Manu'a adz material using a non-destructive x-ray fluorescence technique. In P.V. Kirch and T.L. Hunt (eds), *The To'aga Site: Three Millennia of Polynesian Occupation in the Manu'a Islands, American Samoa*, pp. 167-187. *University of California Archaeological Research Facility, Contribution* 51. Berkeley.
- Weisler, M.I. 1994. The settlement of marginal Polynesia: new evidence from Henderson Island. *Journal of Field Archaeology* 21:83-102.
- Weisler, M.I. 1995. Henderson Island prehistory: colonization and extinction on a remote Polynesian island. *Biological Journal of the Linnean Society* 56:377-404.
- Weisler, M.I. 1996a. An archaeological survey of Mangareva: implications for regional settlement models and interaction studies. *Man and Culture in Oceania* 12:61-85.
- Weisler, M.I. 1996b. Taking the mystery out of the Polynesian 'mystery' islands: a case study from Mangareva and the Pitcairn Group. In J. Davidson, G. Irwin, F. Leach, A. Pawley and D. Brown (eds), *Pacific Culture History; Essays in Honour of Roger Green*, pp. 615-629. *New Zealand Journal of Archaeology Special Publication*, Dunedin.
- Weisler, M.I. and D.A. Clague. 1997. Characterisation of archaeological volcanic glass from Oceania: the utility of three techniques. In M.S. Shackley (ed), *Archaeological Obsidian Studies: Method and Theory. Advances in Archaeological and Museum Sciences* 3. New York, Plenum Press.
- Weisler, M.I. and P. Kirch. 1996. Interisland and interarchipelago transfer of stone tools in prehistoric Polynesia. *Proceedings of the National Academy of Sciences, U. S. A.* 93:1381-1385.
- Weisler, M.I., P. Kirch and J. Endicott. 1994. The Mata'are basalt source: implications for prehistoric interaction studies in the Cook Islands. *Journal of the Polynesian Society* 103:203-216.

Weisler, M.I. and J. Woodhead. 1995. Basalt Pb isotope analysis and the prehistoric settlement of Polynesia. *Proceedings of the National Academy of Sciences, U. S. A.* 92:1881-1885.

White, A.J.R. 1987. Appendix 7. Petrography of some stone adzes from Tongatapu, Tonga group. In J. Poulsen (ed.), *Early Tongan Prehistory*, pp. 279-281. *Terra Australis* 12. Department of Prehistory, Research School of Pacific Studies. Canberra, The Australian National University.

Wood, C.P. 1978a. Petrology of Aitutaki, Cook Islands. *New Zealand Journal of Geology and Geophysics* 21:761-765.

Wood, C.P. 1978b. Petrology of Atiu and Mangaia, Cook Islands. *New Zealand Journal of Geology and Geophysics* 21:767-771.

Wood, C.P. and R.F. Hay. 1970. Geology of the Cook Islands. *New Zealand Geological Survey Bulletin* 82. Auckland.

Woodroffe, C.D., S.A. Short, D.R. Stoddart, T. Spencer and R.S. Harmon. 1991. Stratigraphy and chronology of Late Pleistocene reefs in the Southern Cook Islands, South Pacific. *Quaternary Research* 35:246-263.

Wright, E. 1986. Petrology and Geochemistry of Shield-building and Post-erosional Lava Series of Samoa: Implications for Mantle Heterogeneity and Magma Genesis. Ph.D. thesis, University of California, San Diego.