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Geochemical sourcing of volcanic materials imported into Teti'aroa Atoll shows multiple long-distance interactions in the Windward Society Islands, French Polynesia

AYMERIC HERMANN, GUILLAUME MOLLE, RENÉ MAURY, CÉLINE LIORZOU and ANDREW MCALISTER

AH: Max *Planck Institute for the Science of Human History*; AH, GM: *Unité Mixte de Recherche 7041, Centre National de la Recherche Scientifique*; GM: *Australian National University*; RM, CL: *Université de Bretagne Occidentale*; AM: *University of Auckland*

ABSTRACT

*Teti'aroa, located 28 nautical miles (52 km) north of Tahiti, lies at the periphery of the Windward Society islands. At the end of the eighteenth century, this atoll was presumably controlled by the chiefdom of Porionu'u, which included the districts of Pare and Arue on the north coast of Tahiti. This situation is confirmed by a number of ethnohistorical accounts and oral traditions describing an intense traffic of basic resources between the atoll and Tahiti island as well as the specific function of Teti'aroa for Tahitian social elites visiting the atoll for ceremonial or recreational purposes. However, the prehistory of the atoll remains largely unknown and the time-depth of dominance by Tahitian elites on the atoll is unclear. In this paper, we investigate potential inter-island relationships between Teti'aroa and other islands in the archipelago and beyond. We present geochemical analyses (energy dispersive X-ray fluorescence and inductively coupled plasma-atomic emission spectrometry) of stone tools and elements of ceremonial architecture (*marae*), which were necessarily imported given the complete subsidence of the volcanic substratum of the island. Our results confirm the regional origin of a majority of artefacts, but also indicate several later long-distance relationships maintained by Tahitian chiefs.*

Keywords: provenance analysis, Eastern Polynesia, stone tool, ceremonial architecture, chiefdoms, exchange

RESUME

L'atoll de Teti'aroa, situé à 28 miles nautiques (52 km) au nord de l'île de Tahiti, se trouve à la périphérie des Iles du Vent dans l'archipel de la Société. A la fin du 18ème siècle, cet atoll était intégré au territoire de la chefferie de Porionu'u qui dominait les districts Pare et d'Arue sur la côte nord de Tahiti. Cette situation est confirmée par de nombreux témoignages ethno-historiques et traditions orales décrivant l'intense échange de ressources et de biens entre l'atoll et l'île de Tahiti, ainsi que le rôle de Teti'aroa pour les élites tahitiennes qui y séjournaient pour des durées plus ou moins courtes, dans le cadre de cérémonies particulières ou pour se retirer lors de périodes de conflits.

*Dans cet article, nous traitons des relations interinsulaires qui impliquait Teti'aroa et d'autres îles de l'archipel et au-delà. Nous présentons les analyses des compositions chimiques (ED-XRF et ICP-AES) d'un ensemble d'outils en pierre et éléments d'architecture cérémonielle (*marae*), qui furent nécessairement transportés depuis une île haute, puisque le substrat volcanique de l'île est enfoui par subsidence. Nos résultats conferment l'origine régionale de la plupart des artefacts, et indiquent également plusieurs connexions à très longue distance maintenues par les chefferies tahitiennes à une époque relativement récente.*

Mots-clés: Analyses de provenance, Polynésie orientale, Outils en pierre, Architecture cérémonielle, Chefferie, Échange

Correspondence: Aymeric Hermann, Department of Linguistic and Cultural Evolution, Max Planck Institute for the Science of Human History, D-07745 Jena, Germany. Email: hermann@shh.mpg.de

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BACKGROUND AND HYPOTHESIS

The Windward group of the Society Islands is considered to be the home of some of the most stratified chiefdoms in Polynesia and, as such, has featured prominently in studies of traditional Polynesian society (Oliver 1974). Teti'aroa, the focus of this study, is the only atoll in the group, which is otherwise composed of high islands. Oral traditions mention connections between Teti'aroa and a junior line of chiefs from the Papeno'o valley on the north coast of Tahiti Nui (Henry & Orsmond 1928: 622–3; Oliver 1974: 6189). Early historical records describe permanent occupations of the atoll by small communities under the domination of chiefly lines from the united district of Porionu'u, also on the north coast of Tahiti, with regular exchange of manufactured goods and natural resources between the two islands during the late eighteenth century (Cook 2003; Ellis 1972: 41; Morrison 1966: 167). Tahitian chiefs also used the atoll as a secondary place of residence, and as a remote location for ceremonial practices, such as the fattening of the youngest individuals from chiefly families (*ha'apori*) and as a meeting place for members of the *'arioi* cult (Ellis 1972; Morrison 1966; Oliver 1974, 2002).

Limited excavations on Onetahi islet (see Figure 1) by Sinoto and McCoy (1974) provided several radiocarbon dates indicating that *marae* building may have started by the fifteenth century AD, but no evidence of temporary or permanent occupation prior to that period has yet been identified. However, the proximity and intervisibility with the high islands of Tahiti and Mo'orea, some 52 km distant, suggest that the atoll was known and visited by Polynesian colonizers throughout prehistory, perhaps since the eleventh century AD as indicated by the earliest archaeological and palaeoenvironmental evidence of human presence in the region (Stevenson *et al.* 2017). Despite the current lack of chrono-stratigraphic information, it seems likely that the atoll was connected with Tahitian polities for at least several generations before European contact.

This article provides material evidence of the multiple movements of individuals and goods described in the ethnohistorical literature between Teti'aroa and other islands. Geochemical sourcing of stone materials necessarily imported on the atoll is used here to determine the spatial extent of inter-island connections as represented by the archaeological record.

THE FIELD SITE: ARCHAEOLOGICAL SURVEY AND SAMPLE COLLECTION

Since 2015, we (GM and AH) started the first archaeological investigations on Teti'aroa since Y. Sinoto and P. McCoy's 1972 and 1973 excavations (Lagarde & Molle 2017; Molle & Hermann 2016; Molle *et al.*, 2019). As a first step, we conducted an archaeological survey on 12 islets, recording and mapping 90 structures and surface remains. Although ceremonial *marae* structures represent a large part of our record, we also mapped several round-ended houses (*fare pote'e*), as well as elite-related archery platforms and community meeting platforms, all of which corroborate ethnohistorical sources indicating that the atoll was part of a "royal domain" belonging to the Pōmare chiefs of Tahiti (Robineau 1985). Other structures, including domestic and horticultural features, suggest some degree of permanent settlement by a local population.

Volcanic stone materials occurring on coral atolls are necessarily imported from high islands; we therefore systematically sampled and analysed stone material found in direct association with, or in the close vicinity to, surface sites. These artefacts, from both ceremonial and domestic contexts, include adze fragments and debitage flakes, cobbles, vesicular oven stones and basalt dykes used as upright stones or in other structural elements of *marae* construction (Table 1). We group these items into four different categories: portable artefacts, architectural items used in *marae*, oven stones and non-transformed raw material. These items are unevenly distributed among the different islets, with all the stone architectural elements used in the *marae* of Horoatera and Reiono, and most of the portable artefacts concentrated in Rimatu'u (Figure 1).

MATERIALS AND METHODS

A total of 83 stone samples were analysed using two analytical techniques. Non-destructive energy dispersive X-ray fluorescence (ED-XRF) was used as a first assessment of the geochemical diversity of the assemblage. These analyses were conducted as part of a larger project aimed primarily at characterising fine-grained basalt adzes (Hermann &McAlister, in prep.). There were some concerns about the suitability of the Teti'aroa assemblage, which consists mainly of coarse-grained and weathered stone, for non-destructive ED-XRF analysis. However, at that time, it was uncertain whether any other types of partially destructive geochemical analysis would be permitted on the assemblage. After this initial analysis, the opportunity arose to conduct inductively coupled plasma-atomic emission spectrometry (ICP-AES) analyses on the majority of the assemblage. Although partially destructive, ICP AES measures a greater range of elements than portable ED-XRF, often with greater accuracy for the major elements and lower detection limits for the trace elements. For these reasons, the results from this method were used as primary data for this study.

ED-XRF

Non-destructive ED-XRF measurements were conducted by AM and AH using a Bruker Tracer III SD portable X-ray fluorescence (pXRF) analyser. The instrument employs an X-ray tube with a Rh target and a 10-mm^2 silicon drift detector with a typical resolution of 145 eV at 100,000 cps. All samples were analysed in an air path through a filter composed of 12 mil (304.8 µm) Al and 1 mil (25.4 µm) Ti (Bruker's "yellow" filter), with an X-ray tube setting of 40 keV at 10.7 µA. The instrument was calibrated using Bruker's S1CalProcess and a set of 24 international and University of Auckland Anthropology lab ''in-house" rock standards BHVO-1, GSP-2, JA-1, JA-2, JA-3, JB-1a, JB-2 and JB-3. Major element concentrations were calculated as oxide percentages and the trace elements as parts-per-million (ppm). Samples were analysed twice, each for 60 seconds per analysis to check for consistency, and the

Figure 1. Location of Teti'aroa in the Society Islands and distribution of stone materials sampled. Conventions as in Figure 2.

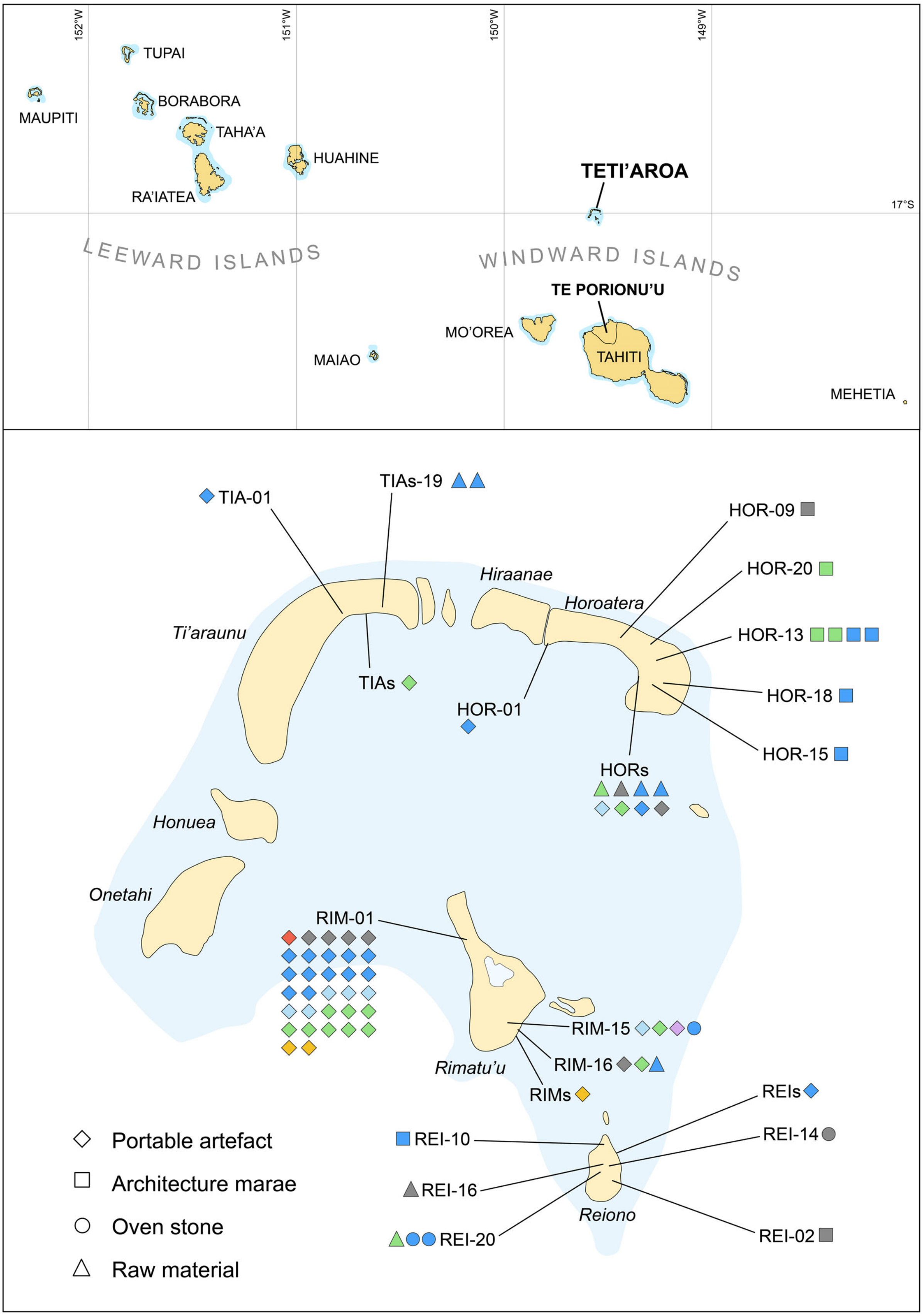


Table 1. Provenance of Teti'aroa materials.

Site comments	Latitude	Longitude	Sample name	Texture	Artefact category	Artefact description	ED-XRF	ICP-AES
Marae	–16.991117	–149.55228	HOR-01-24	Coarse grained	Adze preform	Water-worned dyke	Yes	Yes
Enclosures filled with 'iri'iri	–16.990683	–149.54888	HOR-04-14	Coarse grained	Cobble	Flaked	Yes	No
Marae	–16.9904	–149.54395	HOR-09-16-1	Fine grained	Architectural	Fragment of dyke	Yes	Yes
Marae	–16.9904	–149.54395	HOR-09-16-2	Coarse grained	Cobble	Cobble fragment	Yes	No
Beach (intertidal)	–16.995	–149.5415	HORs-09b-a	Fine grained	Geological	Fragment of flaked dyke	Yes	Yes
Beach (intertidal)	–16.991339	–149.54419	HORs-09b-b	Fine grained, weathered surface	Cobble	Fragment of weathered and fire-cracked boulder	Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-c	Fine grained	Flake	Water worned	Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-d	Coarse grained	Adze preform	Flaked prism (Water worned)	Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-e	Fine grained, weathered surface	Cobble		Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-f	Fine grained, weathered surface	Cobble	Unflaked cobble fragment (Water worned)	Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-g	Coarse grained	Flake		Yes	Yes
Beach (intertidal)	–16.995	–149.5415	HORs-09b-h	Fine grained	Flake	Water worned	Yes	Yes
Marae	–16.992733	–149.53985	HOR-13-08-1	Fine grained	Architectural	Fragment of flaked dyke	Yes	Yes
Marae	–16.992733	–149.53985	HOR-13-08-2	Fine grained	Architectural	Fragment of flaked dyke	Yes	Yes
Marae	–16.992733	–149.53985	HOR-13-08-3	Coarse grained	Cobble	Fragment of weathered boulder	Yes	Yes
Marae	–16.992733	–149.53985	HOR-13-08-4	Coarse grained	Cobble		Yes	No
Marae	–16.992733	–149.53985	HOR-13-08-5	Coarse grained	Cobble	Fragment of weathered boulder	Yes	Yes
Marae	–16.995383	–149.54022	HOR-15-2	Coarse grained	Cobble	Unflaked cobble	Yes	Yes
Marae	–16.995217	–149.53922	HOR-18-17-2	Fine grained	Architectural	Weathered dyke partially worked (upright stone)	No	Yes
Stone plateform	–16.991083	–149.54042	HOR-20-25	Fine grained	Architectural	Fragment of flaked dyke	Yes	Yes
Marae	–17.047667	–149.54498	REI-02-02	Coarse grained	Architectural	Fragment of flaked dyke	Yes	Yes
Marae	–17.043717	–149.54597	REI-10-01	Coarse grained	Architectural	Fragment of burnt boulder, not flaked	Yes	Yes
Alignment of coral slabs on edge	–17.0464	–149.54583	REI-13-03	Coarse grained	Cobble	Unflaked cobble	Yes	No
Oven stones	–17.046083	–149.5454	REI-14-04	Coarse grained	Oven stone	Unflaked cobble (vesicular basalt) found in a small heap	No	Yes

(*Continued*)

Table 1. Continued.

Site comments	Latitude	Longitude	Sample name	Texture	Artefact category	Artefact description	ED-XRF	ICP-AES
Fare pote'e	–17.045967	–149.54597	REI-16-05	Coarse grained	Geological	Fragment of flaked dyke (Water worned)	Yes	Yes
Fare pote'e	–17.04675	–149.54622	REI-20-06-3	Fine grained	Geological	Fragment of flaked dyke	Yes	Yes
Fare pote'e	–17.04675	–149.54622	REI-20-06-4	Coarse grained	Cobble	Unflaked cobble	Yes	Yes
Fare pote'e	–17.04675	–149.54622	REI-20-06-5	Coarse grained	Cobble	Unflaked cobble fragment (Water worned)	Yes	Yes
Beach (intertidal)	–17.04364	–149.54514	REIs-07	Fine grained	Core	Flaked cobble (Water worned)	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-a	Fine grained	Flake		No	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-b	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-c	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-d	Coarse grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-e	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-f	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-g	Fine grained, weathered surface	Adze preform		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-h	Fine grained	Flake (Adze blank)		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10a-i	Fine grained	Adze preform		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-a	Fine grained	Flake	From natural prism used in architecture	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-b	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-c	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-d	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-e	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-f	Coarse grained	Cobble		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-10b-g	Fine grained	Cobble		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-21-1	Fine grained	Flake		Yes	No
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-21-2	Fine grained	Flake		Yes	No
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-21-3	Fine grained	Flake		Yes	No

(*Continued*)

Table 1. Continued.

Site comments	Latitude	Longitude	Sample name	Texture	Artefact category	Artefact description	ED-XRF	ICP-AES
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-1	Coarse grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-2	Fine grained	Flake	Water worned	Yes	No
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-3	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-4	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-5	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-6	Fine grained	Flake	Water worned	No	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-7	Coarse grained	Cobble	Cobble fragment	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-8	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-9	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-10	Fine grained	Flake (retouched)		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-11	Fine grained	Flake	Water worned	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-12	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-13	Coarse grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-14	Coarse grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-15	Fine grained	Flake		Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-16	Fine grained	Flake	From natural prism used in architecture	Yes	Yes
Dancing/meeting platform	–17.022817	–149.56097	RIM-01-23-17	Fine grained	Flake		Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-11-a	Coarse grained	Flake		Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-11-b	Fine grained	Flake		Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-11-c	Fine grained	Flake		Yes	No
Taro pits	–17.031583	–149.55648	RIM-15-11-d	Coarse grained	Cobble	Cobble fragment	Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-22-a	Fine grained	Flake (retouched)		Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-22-b	Coarse grained	Flake (retouched)		Yes	Yes
Taro pits	–17.031583	–149.55648	RIM-15-22-c	Fine grained	Flake		Yes	Yes
Beach (intertidal)	–17.032	–149.55527	RIM-16-12-1	Fine grained	Geological	Fragment of flaked dyke	Yes	Yes
Beach (intertidal)	–17.032	–149.55527	RIM-16-12-2	Fine grained	Flake		Yes	Yes
Beach (intertidal)	–17.032	–149.55527	RIM-16-12-3	Coarse grained	Flake	From cobble used in architecture	Yes	Yes
Beach (intertidal)	–17.032402	–149.55567	RIMs-13	Fine grained	Flake	Water worned	Yes	Yes
Archery platform\	–16.9883	–149.5747	TIA-01-20	Coarse grained	Flake		Yes	Yes
Beach (intertidal)	–16.987819	–149.57208	TIAs-09a	Fine grained	Adze preform		Yes	Yes
Beach (intertidal)	–16.9876	–149.5703	TIAs-19-1	Coarse grained	Geological	Fragment of dyke (Water worned)	Yes	Yes
Beach (intertidal)	–16.9876	–149.5703	TIAs-19-2	Coarse grained	Geological	Fragment of dyke	Yes	Yes

results were averaged. Only 75 samples could be analysed among the 83 collected, because the surface of eight coarse-grained crystalized basalt rocks reflected the X-rays unpredictably and cause errors, particularly for the lighter elements.

Results of the ED-XRF analyses are presented in the Supporting Information (Table S2) and provide compositions of six major elements (SiO_2, TiO_2, Fe_2O_3, MnO, CaO, K_2O) and 13 trace elements (V, Cr, Ni, Cu, Zn, Ga, Pb, Th, Rb, Sr, Y, Zr, Nb).

ICP-AES

Partially destructive ICP-AES analyses were conducted by CL at PSO/IUEM (Plouzané, France). Elemental compositions of 71 powdered samples were obtained using an ICP-AES Jobin Yvon Ultima 2 at the University of Brest, after a HF-HNO_3 digestion, boric acid neutralisation and dilution in nitric acid, as described in Cotten *et al.* (1995). Repeated analysis of the international standards JB-2, AC-E, WSE and BELC and internal standards MORB-E, CB2, CB15 and CB18 demonstrated external reproducibility better than 5–10% depending on the element and concentration (Table S3 in the Supporting Information). Results of the ICP-AES analyses are presented in the Supporting Information (Table S4) and provide compositions of major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, MnO, K_2O, Na_2O, P_2O_5) and 17 incompatible trace elements (Sc, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, Th).

Comparison of methods

Overall, the analyses of the samples’ surfaces with pXRF provided comparable results with those using ICP-AES, especially when analysing the fine- to medium-grained volcanic rocks and averaging multiple measurements on different spots of a clean surface of the artefact. These results are in agreement with other assessments of the analytical accuracy of this technique (Bourke & Ross 2016). However, the analyses of coarse-grained material and/or weathered surfaces are more divergent (especially in the measurement of MnO, Sr and Y), which is probably related to textural variation and chemical weathering as shown in the online Supporting Information Figure S1.

Provenance analysis

The reliability of geochemical sourcing in archaeology depends on the body of reference data available in order to discriminate regions, sub-regions and specific geological features among a well-defined set of possible provenance locations. The reference data used for inferring geological provenance of the Teti’aroa samples builds on a combination of the online GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/) and data deriving from geological survey and mapping conducted in French Polynesia by the Bureau de Recherches Géologiques et Minières (BRGM, France).

RESULTS

Major element data

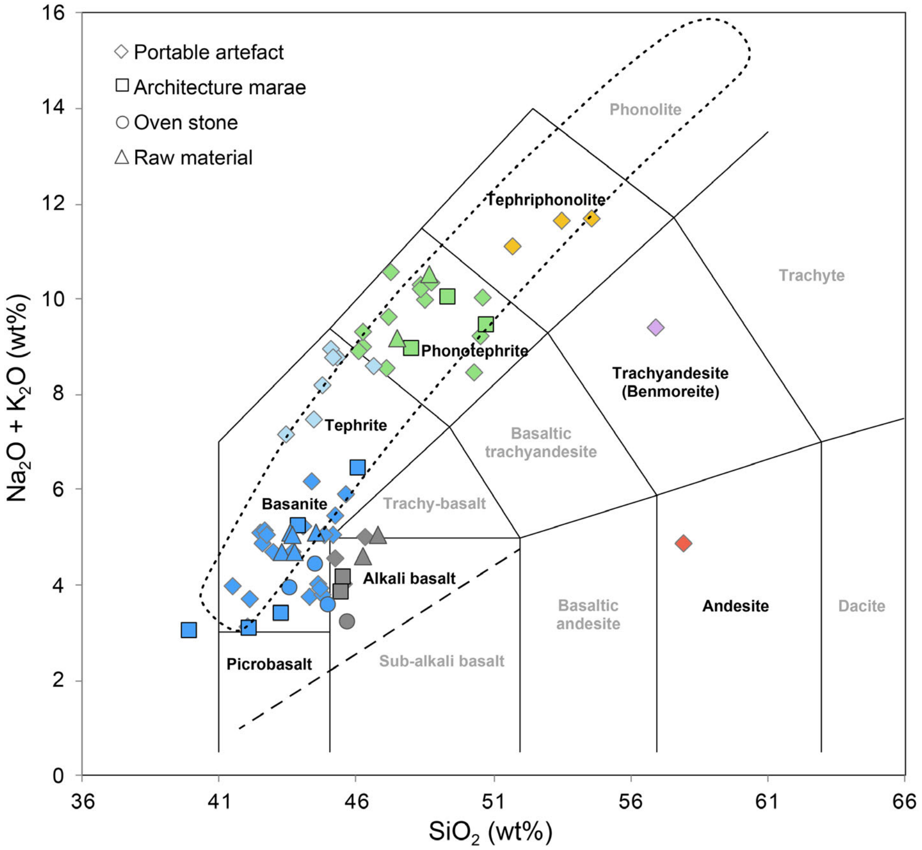
Loss on ignition (LOI) ranges from negative values to 4.5 wt%. They are lower than 1.5 wt% for 40% of our sample set, between 1.5 and 3 wt% for 50% of it and between 3 and 4.5 wt% for the remaining 10% of our samples (Table S4 in the Supporting Information). Therefore, the Teti’aroa archaeological samples can be considered fresh to moderately altered volcanic rocks, with elemental compositions consistent with those of geological samples collected in the volcanic islands of East Polynesia.

The studied sample set displays a wide range of silica contents, from c. 40–58 wt% (Table S4 in the Supporting Information). A total alkali versus silica plot (Figure 2) indicates that all the samples but one (andesite RIM-01-10a-a) plot in the alkaline rock field, that is above the alkaline–subalkaline boundary proposed by Macdonald and Katsura (1964) for Hawaiian lavas. Again, with one exception (benmoreite RIM-15-22b), they define a continuous range from basanites and alkali basalts to tephriphonolites and are characterised by a progressive decrease of MgO with increasing SiO_2 contents (Figure S6 in the Supporting Information), while alkali basalts define a slightly different trend. Only three samples (HORS-09b-h, HORS-13-08-3 and HORS-18-17-12) can be termed picritic basanites as they display MgO contents higher than 12 wt% (from 20.49 to 14.23 wt%; Table S4 and Figure S6 in the Supporting Information). The other mafic samples are mainly basanites, with subordinate alkali basalts (Figure 2). Basanites, tephrites, phonotephrites and tephriphonolites form a well-defined series that closely matches the strongly alkaline basanite–phonolite series (C series of Cheng *et al.* 1993) defined by authors of previous studies of Tahiti lavas (Cheng *et al.* 1993; Duncan *et al.* 1994; Hildenbrand *et al.* 2004; Lacroix 1927, 1910; McBirney & Aoki 1968). They are silica-undersaturated and contain high amounts of alkalies, TiO_2 and P_2O_5 (Table S5 in the Supporting Information). Alkali basalts and basanites display major element features typical of Society Islands basaltic lavas (Dostal *et al.* 1982).

Sample RIM-15-22b, a benmoreite, is more silicic and less rich in Na_2O than the tephriphonolites, although it is still a slightly silica-undersaturated intermediate alkaline lava. Its rather low TiO_2, MgO and P_2O_5 contents are consistent with its derivation from alkali basaltic magmas by crystal fractionation processes.

The single andesite specimen, RIM-01-10a-a, is the most silica rich and the only strongly silica-oversaturated lava of our set. Although relatively rich in MgO and CaO, it is clearly depleted in TiO_2, MgO and P_2O_5 with respect to the tephriphonolites and bemoreite of our set (Table S5 in the Supporting Information). It plots within the field of medium-K calc-alkaline andesites in the K_2O–SiO_2 plot (not shown) of Peccerillo and Taylor (1976), and its composition is rather close to that of the average of island arc lavas (Gill 1981; Sun & McDonough 1989).

Figure 2. Total alkali silica plot for Teti'aroa materials, adapted from Le Bas *et al.* (1986). The dashed line (Macdonald & Katsura 1964) separates alkaline lavas (above) from subalkaline lavas (below). The dotted envelop delineated the field of the C series (basanite-phonolite) from Tahiti, according to Cheng *et al.* (1993). Picritic basanites (Group E) and basanites (Group F and H) are shown in deep blue, alkali basalts (Group G) in grey, tephrites (Group I) in light blue, phonotephrites (Group C) in green, tephriphonolites (Group D) in orange, benmoreite (Group B) in purple and andesite (Group A) in red.



Trace element data

The primitive mantle-normalised incompatible multi-element pattern of andesite RIM-01-10a-a is shown in Figure 3a. It displays numerous features considered as typical of medium-K calc-alkaline arc lavas: moderately enriched rare earth element (REE) patterns; high contents in large ion lithophile elements (LILE: Rb, Ba, K, Sr) generating positive anomalies with respect to neighbouring elements; conversely, low contents in high field strength elements (HFSE: Nb, P, Zr, Ti) generating negative anomalies. These characteristics are generally attributed to enrichments of the mantle sources of arc magmas by aqueous fluids rich in LILE but depleted in HFSE, derived from the dehydration of the subducting oceanic lithosphere (Kogiso *et al.* 1997; Tatsumi *et al.* 1986; Wilson 1989). The multi-element pattern of the average of arc lavas (ARC in Figure 3a) is indeed rather similar to that of andesite RIM-01-10a-a.

The multi-element patterns of the other Teti'aroa samples (Figure 3b) are rather different, although they also show moderately to fairly enriched REE patterns. Indeed, most of them display high contents (occasionally generating positive anomalies) in HFSE, especially in Nb, Zr and sometimes in Ti, typical of enriched (alkaline) ocean island basalt series (Hofmann 1997; Hoefs 2010). However, the most evolved lavas (tephriphonolite and benmoreite) are characterised by strong negative anomalies in P and Ti that are commonly ascribed to fractionation of apatite and iron-titanium oxides during a differentiation process. In addition, the pattern of benmoreite RIM-15-22b exhibits strong negative anomalies in Ba and Sr, that are usually attributed to the fractionation of alkali feldspar and plagioclase, respectively. Besides these specific anomalies, the samples ranging in composition from basalts to tepriphonolites display smooth and subparallel enriched trends with progressive increase of incompatible elements with SiO_2 contents. Such features are commonly observed in alkaline series evolving mostly by fractional crystallization, that are common in Tahiti (Cheng *et al.* 1993; Duncan *et al.* 1994) and other French Polynesian islands such as Mo'orea, Society (Le Dez *et al.* 1998) or Nuku Hiva, Marquesas (Legendre *et al.* 2005a). However, in Figure 3b, Teti'aroa representative alkali basalt and basanite display a "crossed pattern" feature at the level of

Figure 3. Multi-element plots normalised to the Primitive mantle (Sun & McDonough 1989) for selected Teti'aroa samples and comparable geological samples. Conventions as in Figure 2. (a) RIM-01-10a-a andesite and ARC for the average composition of modern arc lavas. (b) Selected Teti'aroa samples. (c) RIM-15-22-b benmoreite and selected benmoreites from Mo'orea (Le Dez *et al.* 1998). (d) Teti'aroa tephriphonolites and selected tephriphonolites from Tahiti, Ua Pou and Tahuata.

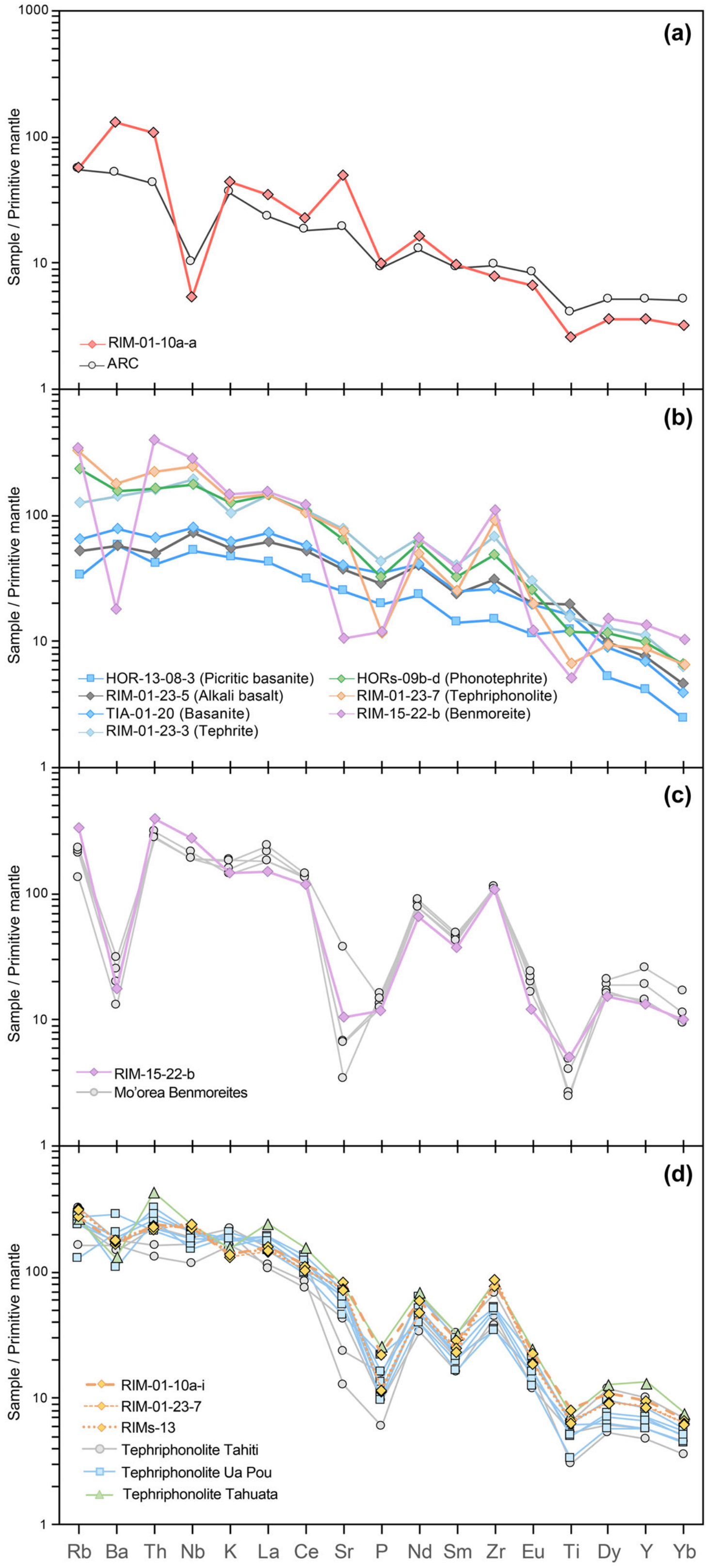


Table 2. Summary of the sourcing results.

Geochemical group	Count	Rock type	Source attribution
A	1	Andesite	IAB: Tonga; or Fiji; or the north island of New Zealand
B	1	Benmoreite	Mo'orea, Society Islands
C	18	Phonotephrites	Probably Tahiti, Society Islands
D	3	Tephriphonolites	Tahiti, Society Islands; or Ua Pou or Tahuata, Marquesas Islands
E	3	Picritic basanites	Probably Tahiti, Society Islands
F	3	Basanites	Austral or Marquesas Islands
G	12	Alkali basalts	Probably Tahiti, Society Islands
H	23	Basanites	Probably Tahiti, Society Islands
I	7	Tephrites	Probably Tahiti, Society Islands

intermediate and heavy REE, which is consistent with their derivation from slightly different mantle sources (Hofmann 1997; Wilson 1989).

Additional ED-XRF data

Nine of the samples could not be analysed using ICP-AES. We therefore used ED-XRF analysis in order to compare them to the rest of the assemblages. A plot of Sr versus Zr shows that two of the specimens (RIM-01-21-3 and RIM-15-11-c) cluster with the tephrites, phonotephrites and tephriphonolite from the IPC-AES data (Figure S4a in the Supporting Information). A further plot of Rb versus Y associates these specimens with the tephrites (Figure S4b in the Supporting Information). Of the remaining samples analysed with pXRF, most are associated with the alkali basalts and basanites (Figure S4c in the Supporting Information).

Synthesis

Our geochemical analysis identified nine distinct groups of artefacts labelled Groups A to I (Table 2, Table S4 in the Supporting Information) according to their plot in the total alkali versus silica diagram (Figure 2) that is widely used for classifying volcanic rocks (Le Bas *et al.* 1986). They include Groups A (andesite), B (benmoreite), C (phonotephrites), D (tephriphonolites), E (picritic basanites), F and H (basanites), G (alkali basalts) and I (tephrites). In addition, incompatible trace element plots (Figure 4) wereelement used to discriminate basanites derived from an HIMU (high $^{238}Pb/^{204}Pb$ ratio)-type source (group F) from those carrying an EM2 imprint typical of Society lavas (Group H).

Group A: andesite

The composition RIM-01-10a-a, a flake of fine-grained calc-alkaline andesite, puts severe constraints on the geographical origin of this sample. Because this type of stone does not naturally occur in Oceanic Islands located east of the Andesite Line, this artefact must have been carried to Teti'aroa from one of the South Pacific island arcs, the most proximate potential sources being Tonga, Fiji or the North Island of New Zealand, which are located between 2500 and 4000 km west or southwest of the Society Islands.

Group B: benmoreite

Sample RIM-15-22-b, a retouched flake, was identified as a benmoreite, which are rather scarce in French Polynesian islands, except for occurrences on Nuku Hiva in the Marquesas (Legendre *et al.* 2005a; Maury *et al.* 2006) and Mo'orea in the Society Islands (Kahn *et al.* 2013; Le Dez *et al.* 1998; Maury *et al.* 2000). In Mo'orea, they cover almost one fifth of the surface of the island (ca. 25 km^2), while other Society islands host only a few known benmoreite exposures: three in Tahiti according to the compilation of Diraison (1991), one in Ra'iatea (Blais *et al.* 1997, 2004) and one in Maupiti (Blais *et al.* 2002, 2006). In addition, Mo'orea benmoreites derive from an unusual combination of petrogenetic processes involving magma differentiation in an upper crustal reservoir (with fractionation of alkali feldspar, plagioclase, apatite and titanomagnetite, generating strong negative anomalies in Ba, Sr, P and Ti) followed by magma mixing (Le Dez *et al.* 1998; Maury *et al.* 2000). The multielement pattern of benmoreite RIM-15-22-b displays these typical features and is most similar to those of Mo'orea benmoreites (Figure 3c). Archaeological research indicates that this material was commonly used in adze production on Mo'orea, where local benmoreites account for around 18% of the 'Opunohu Valley assemblage analysed by Kahn and colleagues (2013). Therefore, we consider Mo'orea, that lies only 60 km SSW of Teti'aroa, as the most likely source for this sample.

Group C: phonotephrites and Group D: tephriphonolites

Twenty-one artefacts are composed of other intermediate lavas (phonotephrites and tephriphonolites), which are present on Tahiti but very uncommon in other Polynesian islands. The Tahitian lavas belong to the strongly alkaline basanite–phonolite "C" series of Cheng *et al.* (1993) indicated by the dotted envelope in Figure 2, which emplaced after the main caldera collapse event, at less than 0.85 Ma (Duncan *et al.* 1994; Hildenbrand *et al.* 2004). Among the rare occurrences elsewhere in Polynesia, the basanite–phonolite series of Rarotonga (Cook Islands) presents a typical "Daly gap" (Thompson *et al.* 2001) with a complete lack of tephriphonolites and only a single phonotephrite. In the Marquesas Islands, Ua Pou contains several tephriphonolites but no phonotephrite (Guille *et al.* 2010; Legendre *et al.* 2005b), while a single

Figure 4. Plots of selected highly incompatible element ratios against Th contents (ppm) for Teti'aroa basanites (Table S4 in the Supporting Information) and Society, Austral–Cook and Marquesas basanites from the GeoRoc database (http://georoc.mpch-mainz.gwdg.de/georoc/). These ratios are thought to be directly inherited from their mantle sources, since Polynesian basanites show little evidence for differentiation or crustal contamination processes.

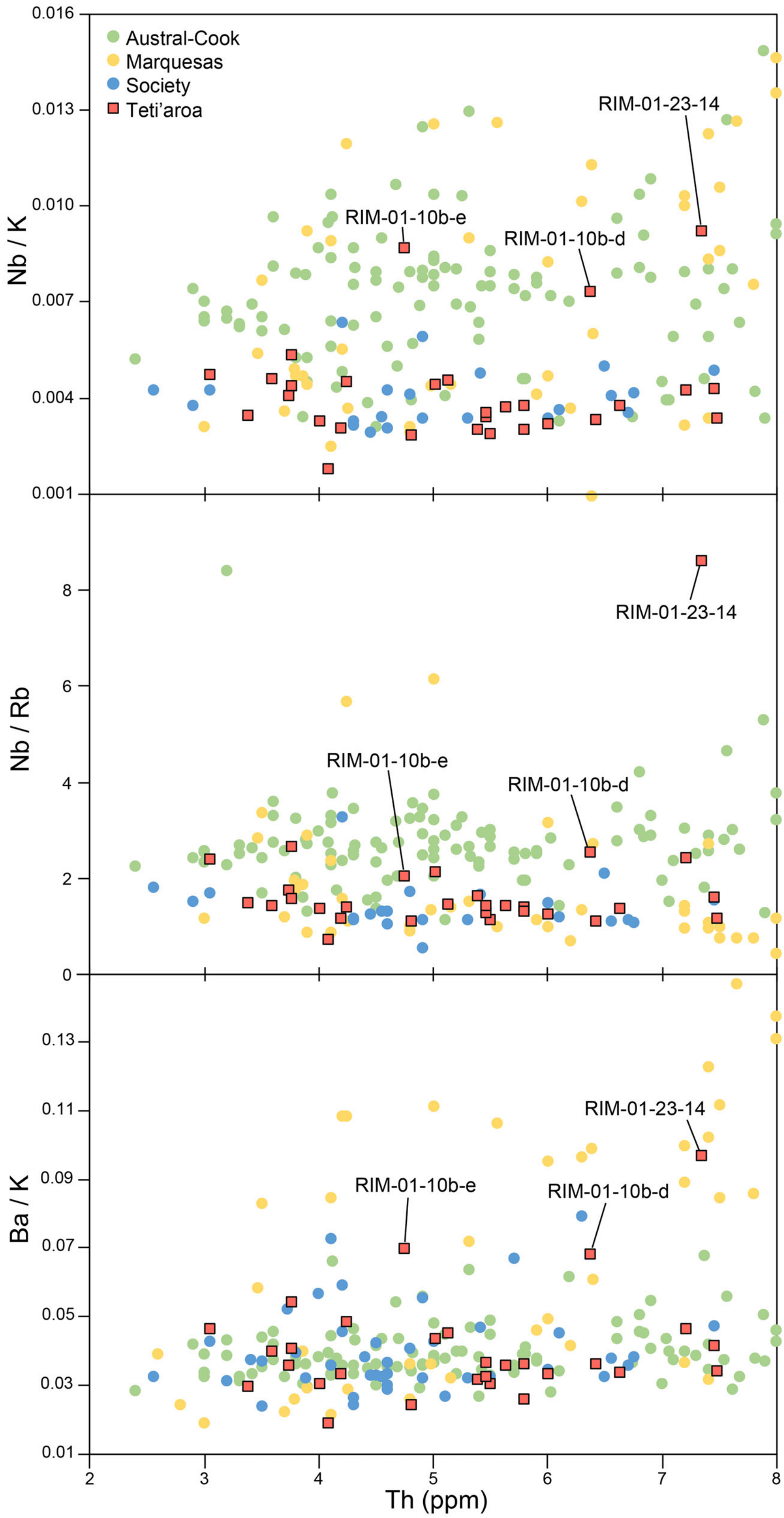


Figure 5. Site RIM-01 from the northern end of the *tahua*. [Colour figure can be viewed at wileyonlinelibrary.com]

tephriphonolitic protrusion has been mapped on Tahuata and a single phonotephritic one in Hiva Oa (Maury *et al.* 2012).

These two rock types have not been identified in other Polynesian islands, and therefore we consider Tahiti as the most likely source for the Teti'aroa materials, especially for the phonotephrites that have not been identified elsewhere in the area (with the exception of the two isolated occurrences in Rarotonga and Hiva Oa noted above). Multielement patterns of tephriphonolites RIM-01-10a-i, RIM-01-23-7 and RIMs-13 (assigned to Group D in our analysis) are shown together with those of tephriphonolites from Tahiti, Ua Pou and Tahuata in Figure 3d. They display rather similar shapes and anomalies, and it is thus difficult to draw conclusions regarding their possible sources from their chemical features, although Ua Pou samples are slightly more depleted in intermediate and heavy REE as well as in Zr and Ti than the Teti'aroa artefacts. The latter are more differentiated (i.e. richer in the most incompatible elements) than the analysed Tahiti tephriphonolites.

Groups E to I: mafic lavas (picritic basanites, basanites, alkali basalts, tephrites)

The sources of Teti'aroa artefacts composed of mafic lavas ($n = 66$) are more difficult to ascertain, because alkali basalts (Group G) and to a lesser extent basanites (Groups F and H) are widespread in Polynesian islands, except in the Gambier archipelago which is exclusively tholeiitic (Caroff *et al.* 1993). Once again, we consider their most likely origin to be Tahiti, where mafics are both very common and define the mildly alkaline (alkali basalt–trachyte) series (B series of Cheng *et al.* 1993) from the main shield and the younger strongly alkaline (basanite–phonolite) series (C series of Cheng *et al.* 1993), respectively (Duncan *et al.* 1994; Hildenbrand *et al.* 2004). Alkali basalts occur in all the other Society Islands, while basanites are only present in Mehetia (Binard *et al.* 1993) and Taha'a (Blais *et al.* 2004). Both types are also found on Rurutu, Tupua'i, Ra'ivavae and Rapa in the Australs (Maury *et al.* 2014a). In the Marquesas, basanites occur in Ua Pou, Ua Huka, Tahuata, Motane and Eiao while alkali basalts are present in all the islands but Hiva Oa and Fatu Hiva (Guillou *et al.* 2014; Maury *et al.* 2014b).

Isotopic (Sr, Nd, Pb, Hf) data are potentially the best tool to discriminate mafic lavas of the Society, which are close to the EM2 mantle end-member (Cordier *et al.* 2016; White & Duncan 1996) from those of the Australs, which contain a strong HIMU component (Chauvel *et al.* 1992, 1997), and those of the Marquesas, which derive from various mixes between DMM, EM2 and HIMU end-members (Chauvel *et al.* 2012). However, some incompatible trace element ratios can be used as proxies to discriminate HIMU-related basanites from those mainly derived from other mantle end-members (Maury *et al.* 2013). Indeed, the former are selectively depleted in K and Rb with respect to the latter (Hoefs 2010), and therefore display higher incompatible element ratios such as Ba/K, Nb/K, Th/K, Ba/Rb, Nb/Rb and Th/Nb. Plots of these ratios against Th contents, which vary according to partial melting and fractionation degrees (Figure 4), show that while most Teti'aroa basanites (Group H) display low ratios consistent with a Society archipelago origin, three of them (samples RIM-01-10b-d, RIM-01-10b-e and RIM-01-23-14 assigned to Group F in our analysis) plot clearly above the others, in the fields of Austral–Cook and Marquesas lavas. These three samples must therefore relate to a remote source, an hypothesis that will need to be verified using other distinctive criteria, such as isotopic compositions and/or geochronological data (Hermann *et al.* 2017).

Artefacts analysed with ED-XRF

Of the nine samples analysed only with ED-XRF, two of them (RIM-01-21-3 and RIM-15-11-c) cluster with Group I and display low Nb/Rb and Nb/K ratios, which is consistent with a local origin on Tahiti. Two samples (REI-13-03 and HOR-09-16-2) have unique combinations of Sr and Rb, suggesting they derive from sources not represented in the rest of the assemblage. Again, Nb/Rb and Nb/K ratios are consistent with a Society archipelago origin. The remaining five samples can be associated with the geochemical Groups G and H, which correspond to alkali basalts and basanites of local origin.

DISCUSSION

Our study supports the ethnohistorical accounts describing intense exchange between Teti'aroa and stratified chiefdoms on Tahiti, with 90% of portable artefacts and all other artefacts closely related to Tahitian volcanics. The untransformed material and stones used as elements of *marae* architecture or as oven stones on Horoatera and Reiono indicate that the communities living permanently on Teti'aroa were politically related to Tahitian polities and relied on Tahitian imports for basic domestic activities.

On the other hand, a few samples that correspond to flaked artefacts only found on the *motu* Rimatu'u, indicate other kinds of importations. RIM-15-22-b (our Group B) is a retouched flake clearly associated with similar benmoreites on the neighbouring island of Mo'orea, which were extensively used for adze production, as discussed by Kahn *et al* (2013).The integration of Mo'orea in the same hub of exchange as the Porionu'u suggests an interesting background to the later unification of both territories under Pōmare I in 1788.

The three artefacts in our Group F (RIM-01-10b-e, RIM-01-10b-d and RIM-01-23-14) are unretouched flakes found within a large rectangular platform of 22 m long and 4.5 m wide, standing on the beach crest parallel to the lagoon shoreline (RIM-01), which is also interpreted a place of gathering and meeting (*tahua*) for high-rank individuals descending from chiefly lines, or for the members of the *'arioi* cult (Molle & Hermann 2016; Sinoto & McCoy 1974). The source of these artefacts is likely outside of the Society Islands, and could potentially be located in the Austral–Cook or in the Marquesas Islands. These imported artefacts may represent the maintenance or resharpening of adzes on the site.

RIM-01-10a-a, another flake, was also found on platform RIM-01. Its geological origin west of the Andesite Line implies very long-distance connections beyond tropical East Polynesia. Unfortunately, it is not possible to locate the island source with the elemental data reported here. Isotopic data will provide better constraints to identify the source of this artefact, which potentially derives from Tonga, Fiji, or the North Island of New Zealand. While the possibility of European-induced importations cannot be excluded for such surface archaeological contexts, late contacts between the Tahiti and Tonga have already been suggested based on previous geochemical sourcing of an adze found in the foundation trench of the Lapaha tomb J09 on Tongatapu, which was probably built between 1550 and 1700 AD (Clark 2014; Clark *et al.* 2008, 2014). Interestingly, the composition of this adze is quite similar to the Tahitian tephriphonolites found on Teti'aroa, which reinforces the hypothesis of late bidirectional interactions between the two regions.

CONCLUSION

Polynesian social relations and economic specialization involving the exchange of resources distributed unevenly between inland and coastal environments on high islands (Firth 1929; Maric 2016; Oliver 1989) are, in many respects, similar to relationships between communities from high volcanic islands and those settled on low coral atolls, where resources also are unevenly distributed (Collerson & Weisler 2007; Weisler 1997). The regular interactions between Teti'aroa and Tahiti described in early European records are typical of such relationships. Furthermore, given the political status of Teti'aroa, as part of the "royal domain" (*patu*) of the Pōmare chiefs at the end of the eighteenth century (Robineau 1985: 162), interactions between the atoll and Tahiti are, perhaps, best considered within the framework of political strategies developed by Tahitian elites competing for status in a period of intense political stratification. Therefore, imports of stone materials into the atoll reflect the geographical extent of exchange networks and political relationships within the unified chiefdom of Porionu'u.

The sample of imported stone artefacts reported in this preliminary study lacks the chronological control required to provide nuanced understandings of the specific role played by Teti'aroa in the development of Tahitian social complexity. However, the current evidence points to associations between imported stone resources and elite-related precincts, such as *marae* and *tahua*, suggesting some degree of elite control over importation and possibly subsequent exchange. Although further evidence is needed, such activities might relate to the development of a kind of "wealth economy" similar to those advocated for Mo'orea (Kahn *et al.* 2013) and for the Hawaiian archipelago during the rise of political complexity (Kirch 2010; Kirch *et al.* 2012).

The concentration of artefacts exotic to the Society Islands within site RIM-01 (Figure 5) is revealing of the site's function, interpreted as a place of gathering and meeting for high-ranking individuals descending from chiefly lines, or for the members of the *'arioi* cult. Furthermore, our evidence of the extra-archipelago imports, albeit preliminary, shows that Tahitian polities had established long-distance relationships that likely persisted until late pre-European times. Specifically, the andesite flake RIM-01-10a-a found in the context of a large platform apparently dedicated to ceremonial gathering demonstrates the extent of Ma'ohi politico-religious networks beyond tropical Eastern Polynesia, a potential source region for this item being the Tongan archipelago in West Polynesia, or the North Island of New Zealand. This, along with other evidence of late imports from Samoa into the southern Cook islands (Weisler *et al.* 2016) and from Tahiti into Tonga (Clark *et al.* 2014), would further indicate that interregional contacts indeed existed between West Polynesia and Central East Polynesia, long after the migration period, and possibly after the supposed "collapse" of interisland interaction in the region (Hermann 2015; Rolett 2002; Weisler 1997).

Future investigations involving high-precision and comprehensive geochemical analyses of imported material from well-dated contexts in Teti'aroa and other Society islands will provide more information on the evolution of inter-island relationships within and outside the Windward Islands, and will offer new insights on the role of external contacts in the emergence of the Tahitian stratified chiefdoms.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplementary Figure S1. Comparison of results from ED-XRF and ICP-AES analyses.
Supplementary Table S2. ED-XRF analyses of Teti'aroa materials.
Supplementary Table S3. Measured values of reference material used in ICP-AES analyses.
Supplementary Table S4. ICP-AES analyses of Teti'aroa materials. Fe_2O_3*: total iron as Fe_2O_3; LOI: loss on ignition (wt%). See text for analytical methods. AB: alkali basalt; AN: andesite; BM: benmoreite; BS: basanite; PB: picritic basanite; PT: phonotephrite; TE: tephrite; TP: tephriphonolite.
Supplementary Figure S5. Plots of individual variables showing the association between the samples analyzed with ED-XRF and the geochemical groups identified with the ICP-AES data.
Supplementary Figure S6. Plot of MgO against SiO_2. Conventions as in Figure 2.