Journal of Archaeological Science: Reports 33 (2020) 102542

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Petrographic and chemical analyses of sherds from the Kurin Lapita site (Loyalty Islands, New Caledonia), ca. 3000–2700 BP

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ARTICLE INFO

Keywords:
Lapita pottery
Petrography
INAA
ICP-MS
Loyalty Islands
New Caledonia

ABSTRACT

As part of a wider study of the transfer of Lapita pottery into and within New Caledonia, we studied a sample of Lapita sherds from the site of Kurin on Maré, Loyalty Islands, New Caledonia. The Loyalty Islands lie between the Vanuatu island chain and the rest of New Caledonia, so it has been suggested that they may have been the first part of New Caledonia to have been colonized during the initial Lapita expansion. We examined 28 sherds by optical petrography, and compared these to archived thin sections of Lapita pottery from the islands of Erromango and Efate in Vanuatu. We also made chemical analyses by neutron activation analysis (INAA) of 11 of these 28 sherds, and later reanalyzed these 11, and 12 more, by inductively-coupled plasma (ICP) analysis as part of the analysis of 329 sherds from throughout New Caledonia. We find no evidence in this sample for the transfer of Lapita pottery from Vanuatu to the Loyalty Islands; the only demonstrably exotic pots are 5 sherds from the main island (Grande Terre) of New Caledonia. Our results offer some support to the view that the initial Lapita expansion was not a continuous wave of advance, but a discontinuous "leapfrogging" process that initially bypassed some island chains. We also note evidence for the existence of at least two mutually exclusive networks of exchange of Lapita pottery in New Caledonia after the initial colonization of the region.

1. Introduction

The "Lapita expansion" is the term used for the first colonization of Southern Melanesia and Western Polynesia, a process that began with the occupation of the Bismarck Archipelago around 1350 BCE and ended with the discovery of Samoa and Tonga around 800 BCE (Burley, et al., 2012; Green, 1979; Sheppard, 2019). Until recently, archaeologists tracing the Lapita expansion, and subsequent contacts between Lapita communities, have mainly relied on ceramic vessel typology, and on motif analysis of the characteristic dentate-stamped patterns (for example, Chiu, 2019; Green, 1979). Another valuable source of evidence has been the long-distance transport of some rare, easily sourced rocks like obsidian (for examples, see Best, 1987; Constantine, et al., 2015; Fredericksen, 1997; Galipaud, et al., 2014; Green, 1987; Reepmeyer, et al., 2012; Ross-Sheppard, et al., 2013; Sand and Sheppard, 2000; Summerhayes, 2010; White and Harris, 1997). Petrographic analysis, pioneered by W. Dickinson, has in some cases shown the transfer of Lapita pots between islands (for a summary, see Dickinson, 2006). Chemical compositional analyses have also been employed to try to infer the provenance of Lapita pottery (for example, see Anson, 1983; Buhring, et al., 2015; Chiu, 2003; Falk, 2011; Hunt, 1989; Kennett, et al., 2004; Leclerc, 2015, 2019, 2020; Leclerc, et al., 2019; Shaw, et al., 2016; Summerhayes, 2000).

We employ both ceramic petrography and chemical analysis in studies of pottery from Lapita sites in New Caledonia (Chiu, et al., 2016; Chiu, et al., paper submitted). New Caledonia consists of one very large island (Grande Terre, 420 km by 35–50 km), two offshore island chains (the Belep and Loyalty Islands), the Ile des Pins, and many very small islands – some of which are beyond the borders of our Fig. 1. In this paper we report new data from the Lapita site of Kurin (LPO023) on

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https://doi.org/10.1016/j.jasrep.2020.102542
Received 10 June 2020; Received in revised form 20 August 2020; Accepted 21 August 2020
Available online 12 September 2020

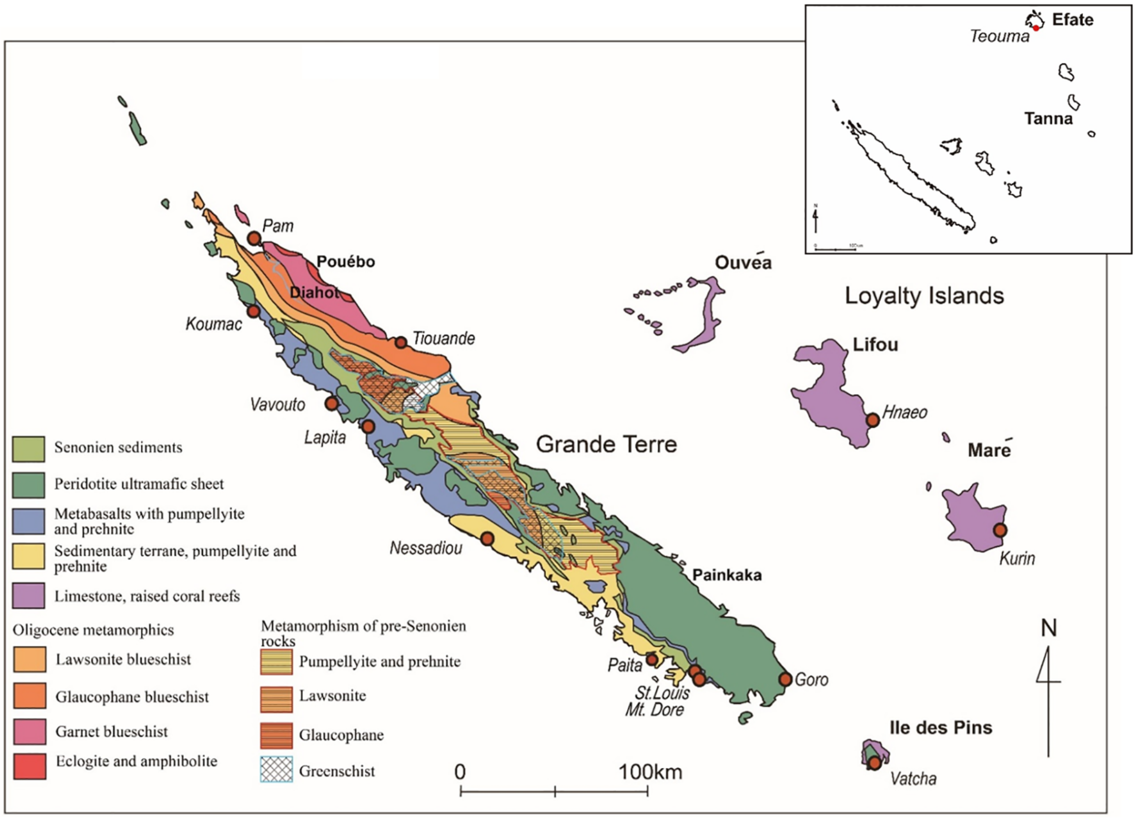

Fig. 1. Simplified geological map of the major islands of New Caledonia. The red circles are the locations of archaeological sites mentioned in the text and figures.

Maré, one of four uplifted coral islands that make up the Loyalty Islands, which are positioned between southern Vanuatu and Grande Terre (Fig. 1). Results obtained from 28 petrographic thin sections and 23 chemical compositional samples from Kurin demonstrate the existence of a weak network linking the Loyalty Islands and the Grande Terre 3000–2800 years ago, but this network probably did not extend towards other islands near the Grande Terre such as Île des Pins, nor to southern Vanuatu islands, as previously suggested (Sand, 2016:360).

2. The Kurin Lapita site and the first settlement of the Loyalty Islands

Archaeological excavations and surveys over the last three decades have revealed sites containing dentate-stamped Lapita sherds on the four inhabited Islands of the Loyalty group. The Lapita site LUV081 is located at Wadrilla, in the center of the semi-atoll of Ouvéa, the early sites, LLI002 of Wassany in Hnaeo and LWT054 of Keny near Nathalo, are located on the east coast of Lifou, and LTD025 of Namara is positioned on the seashore dune forming the northwestern tip of Tiga (Sand, et al., 2010:40). On Maré Island, the southern-most inhabited Island of the Loyalty group, aside from a late-Lapita level discovered on the site of Pakada on the north coast (Wadra pers.com. 2008), all the Lapita occupations cluster on the east coast, between Padawa and Kurin facing a narrow 300 m wide and 4.5 km long lagoon that stretches along the foot of the limestone plateau of the island. Rich marine resources made this location a prime target for incoming settlers, while fresh water was accessible in a cave at the foot of the plateau. The sand dune ridge that restricts access to the hinterland is today under erosion in its southern portion, where site LPO023 (Kurin) is located, but has expanded massively further north in the area over the last 1000 years, partly burying Lapita site LPO020 located on the flat plain between the ocean and the cliffs (Galipaud, 1986; Semah and Galipaud, 1992).

Eight square meters were excavated at Kurin (LPO023) in the locality of Lanjio in 1997 (Sand, et al., 2002a), all on the flat top of the 5 m dune ridge. The stratigraphy is well defined, with five clearly distinguishable layers. The direction of the layers demonstrates that during the first two millennia of human occupation, the dune ridge was expanding upwards towards the ocean, illustrating a larger site surface in the past and the loss of the seaward part of the Lapita occupation layers through erosion. The earliest cultural layer (4) is present between around 80 cm and 50 cm deep and is characterized by a gray sandy fill. A total of 166 potsherds, amongst which 34 were decorated with dentate-stamped and impressed motifs, was unearthed in this layer, mixed with shell and bone remains, and a few non-ceramic items. The main features of this layer were a 60 cm wide stone oven and a post hole. Three dates on unidentified charcoal returned results respectively of 2940 ± 60 BP (Beta 125142), 2900 ± 60 BP (Beta-118335) and 2920 ± 110 BP (Beta-118334), allowing us to date the start of the Lapita occupation between 1100 and 1000 cal BCE (Sand, et al., 2002a: Table 1, pp. 135). These dates make the Kurin site one of the earliest settlements in New Caledonia. The overlying Layer 3 between about 50 cm and 35 cm deep, of brown sandy texture, enclosed a total of 300 potsherds, 71 of which displayed dentate-stamped and stamped decorations, all of a simple motif typology. This layer was dated by one unidentified charcoal sample to 2670 ± 60 BP (Beta-125141), calibrated at 95% confidence to the range 915 to 780 cal BCE. Over a sterile Layer 2, the last occupation (Layer 1) was dated to the middle of the second millennium AD (see Sand:74-6, 2010; Sand, et al., 2002a).

A set of rather unusual Lapita motifs, usually made by rocking a bivalve shell's edge on the surface of the vessel to create curved zigzag lines (see Sand, et al., 2002a: Fig. 10c, pp.139), has been observed mainly in the Lapita assemblages of the Loyalties. This has been noted at Kurin on Maré, Hnajoisisi and Keny on Lifou, and Wadrilla on Ouvéa, indicating a local development of Lapita motif preference that is different from contemporary Lapita communities located on the Grande Terre (Sand, et al., 2002a:138). Given the fact that Lapita 13A (WKO013A) on the northwestern coast of the Grande Terre has been dated to around 1100–1000 cal BCE (Sand, 1997; Sand, et al., 1998, 2002b), and Goro (SGO015) on the south end of the Grande Terre is dated to about 1000–900 cal BCE (Sand, et al., 2001:97), Sand has thus hypothesized that the first settlers of New Caledonia could have sailed from Vanuatu to the Grande Terre via the Loyalties that lie between these island groups (Sand, 2016:360), while some sites of Grande Terre might have been colonized by people coming directly from the southern Solomon islands or northern Vanuatu as they sailed due south.

3. Geology of the Loyalty Islands

The Loyalty Islands are parallel to Grande Terre and also to the New Hebrides Trench, along which the Indo-Australian tectonic plate, on which all of New Caledonia is situated, is being forced beneath the New Hebrides plate, which hosts the volcanic arc islands of Vanuatu. Flexing of the Indo-Australian plate prior to subduction has produced a fore-bulge that has raised parts of the plate above sea level to form the Loyalty Islands. Each of these consists of a coral atoll wrapped around a volcanic core. Maré in the southeast (Fig. 1) emerged first and currently has a maximum height of 138 m above sea level. Lifou is 104 m, while Ouvéa in the northwest is still emerging and is only 46 m high (Dickinson, 2013; Dubois, et al.:133, 137-8, 1974; Marshall and Launay, 1978). Among all islands of the Loyalty Archipelago, only the center of Maré Island has exposed volcanic rock, with three small outcrops of deeply weathered olivine basalts and dolerite appearing in the floor of the ancient lagoon that now forms the central plateau (Fig. 2). All other rocks exposed on the Loyalty Islands are Neogene limestones, formed originally by living organism such as corals and algae (Baubron, et al.:168-9, 1976; Dickinson, 2008; Dubois, et al.:137, 1974; Marshall and Launay:187, 1978; Paris, 1981).

Maré Island (Fig. 2) consists of a Miocene volcanic basement (Baubron, et al., 1976) surrounded by a thin layer of fringing coral reef, on top of which rests an older stratified and entirely dolomitic Rhodolith limestone platform, composed of calcareous red algae concretions wrapped in bioclastic cement (Maurizot and Lafoy, 2006:14). Another layer of ancient coral reef formed above this platform in the shape of a crown, with more recent coral reef growing around the outside of the island (Carrière, 1987, cited from Maurizot and Lafoy, 2003:23). One of the three outcrops of alkali basalts and dolerite mentioned above is located at Rawa, and consists of a dark doleritic basalt with coarse grains of olivine. The second is located at Ponibok,

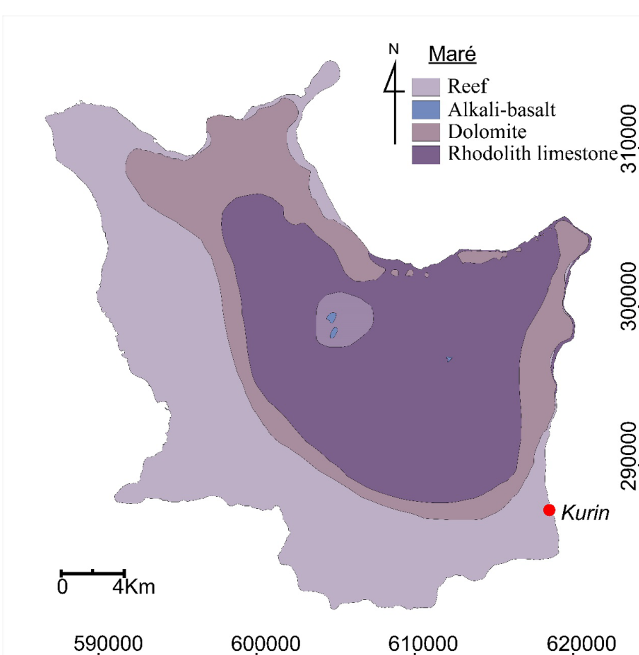

Fig. 2. Geological map of Mare Island (after Maurizot et al., in press:4, Fig. 3).

and is also a doleritic basalt, but with alterations. The last outcrop is located at Péorawa, and consists of a gray-black basalt with olivine phenocrysts, with its eastern part grading into dolerite (Baubron, et al.: 169-70, 1976; Lacroix:122, 1940; Maurizot and Lafoy:25, 2003).

From Baubron's petrographic study of six rock samples collected from both Rawa (n = 1) and Péorawa (n = 5), he was able to show that three samples from Péorawa originated from “a well-defined alkaline group (titaniferous augite, abundance of opaque minerals, presence of a stable olivine, biotite and potassium feldspars in the paste)”, while the rest are less clearly defined (Baubron, et al., 1976: 170).

4. Studies of pottery from the Loyalty Islands

4.1. Prior petrographic studies

Dickinson (2006) and Dickinson (2008) conducted quantitative petrographic analysis on 11 Kurin sherds submitted separately by Sand and Chiu. As 10 out of the 11 samples contain minerals and rock fragments that are generally compatible with the geology of Maré, he concluded that these samples were probably made locally. These sherds contain extremely high amounts of marine calcareous temper (coral and shell) with rare terrigenous grains of feldspar, pyroxene, amphibole, volcanic lithic fragments, and opaque minerals (Dickinson, 2008: Table 273–6). He concluded that “terrigenous volcanic detritus present in the apparently indigenous sherds could be derived from impurities in Maré limestone, which rests on an underpinning of volcanic bedrock” (Dickinson, 2006: 21). He also cautioned that in some cases (samples NC-6, NC-7, NC-8, NC-9, NC-10, and 23–3) “(p)artial or complete dissolution of calcareous grains to form multiple sand-sized vacuoles (Dickinson, 2006:21) has modified the bulk compositions of 70% of the sherds thought to be indigenous to Maré (see Table 273–6 footnotes), and can be expected to affect studies of sherd chemistry” (Dickinson, 2008).

Although this group of sherds are - as Dickinson noted - compatible with the geology of Maré, this does not prove that they were made there. As most of the samples consist mainly of calcareous sands, with only a few terrestrial mineral fragments, it is often not possible to distinguish petrographically between pots made on Maré and those made on other basaltic islands that are also surrounded by ancient and recent coral reefs. Petrographic analyses must therefore be complemented by chemical analysis for more informative analysis of provenance.

One potsherd (#1) contained some chromite (chrome spinel) grains along with marine carbonate clasts (coral and shell), which allowed Dickinson to trace its origin back to the coastline of Grande Terre (Dickinson, 2008). A similar find has been reported by Galipaud from the contemporary Patho Lapita site located just 1 km north of Kurin (Galipaud, 1990: 140). Chromite is a common accessory mineral in the peridotite and dunite sheet that covers many parts of Grande Terre (Dickinson, 2008: Table 273–6).

4.2. Expectations from geochemical analyses of rocks and sediments from Maré

Prior chemical analyses of unweathered basalt samples from Maré (Maurizot and Lafoy, 2003:25-6, Tableau 4–6 in Appendix I, pp. 121–2) show the characteristics of an alkaline basalt composition of the oceanic intraplate basalt (OIB) type that is highly enriched in Light Rare Earth Elements (LREE). They have similar compositions and origins to the OIB samples obtained from the Hawaii hotspot (Maurizot and Lafoy, 2003:25-6; Tableau 4–6 in Appendix I, pp. 121–2, Maurizot and Lafoy, 2006:12). These analyses are not directly relevant to chemical analyses of potsherds, as petrographic analyses show that Lapita potsherds from Kurin are not tempered with unweathered basalt. But LREE are not very soluble, so clays formed by weathering of Maré basalt would be expected to retain the basalt LREE profile - as is observed in deep sea clays derived from basalts elsewhere (Faure, 1998: 50-1, Table 4.5). Geologists note that “(b)oth Maré and Lifou are fully emergent paleoatolls upon which ancient barrier reefs form high standing annular ridges that enclose interior plateaus representing paleolagoon floors" (Dickinson:125, 2013; Maurizot and Lafoy, 2004). The paleolagoon floors are the only possible sources of clay for pottery in the Loyalty Islands, and these clays must derive from weathering of the basaltic cores of the islands. The Grande Terre, on the other hand, is a geologically complex island composed of sediments, metamorphic rocks, basalts and peridotites, and thus is expected to have much more variable concentrations and ratios of rare earth elements (REE) in clays.

Dickinson and Shutler had assumed that most prehistoric Oceanic potters used locally available clay and tempers to make their pots, and that these pots had rarely been transported over long distance to other islands where proper clays and tempers are available (Dickinson and Shutler, 1971, 2000; Dickinson, et al., 1996), but this hypothesis needs to be tested further. Since the concentrations of REE generally reflect the geological formation processes of the region, it is assumed that pots made from a certain geological region may contain REEs that can help us to distinguish them from pots made in other geological regions (for example, see Bishop, et al., 1982; Pollard, et al., 2007; Tite, 2008). Therefore, chemical compositional analyses, at first neutron activation analysis (INAA), and later inductively-coupled plasma mass-spectrometry (ICP-MS) and inductively-coupled plasma atomic emission spectroscopy (ICP-AES) analysis, were also incorporated to address what petrographic analysis alone cannot.

5. Sample selection

Nine hundred and eighty Lapita sherds, excavated from Kurin by Sand and his team (Sand, et al., 2002a), were examined by Chiu through a low-power optical microscope. These were sorted into temper groups according to rough estimates of proportions of light vs dark mineral tempers. A total of 8 temper groups were thus identified. More than 92% of the sherds examined were made of a rather homogeneous temper type that contains large quantities of calcareous sands with only a few light and dark mineral grains. Around 6% of the assemblage contains transparent minerals (probably quartz) that cannot be found on Maré Island (Dickinson, 2002). The remaining 2% is mainly composed of sherds with calcareous sand mixed with a few bits of black sands and red iron oxides.

Petrographic samples were then made from 10% of the sherds that are heavier than 4 g (to allow both petrographic and chemical analysis) in each of the 8 temper groups. Only 235 sherds are heavier than 4 g, but these are unequally distributed between groups, so a 10% sample from each group amounted to 19 petrographic samples. Sub-samples of 11 of these sherds were included in a set of 100 New Caledonian Lapita pottery samples analyzed by INAA at the University of Missouri Research Reactor Center (MURR) in 2008 and 2009 (Ferguson and Glascock, 2009). A total of 329 pottery samples from New Caledonia were analyzed by ICP-AES or ICP-MS at the National Tsing-Hua University (NTHU) from 2008 to 2018 in order to obtain measurements of the REE. These analyses include all 11 samples from Kurin previously analyzed by MURR, the remaining 8 sherds from Chiu's sample of Kurin sherds, and also 4 sherds from the 11 previously sent to Dickinson to make petrographic thin sections. We could not obtain chemical analyses for his other 7 samples because they had been entirely destroyed in making thin sections, or because the remaining portion was too small, or because they could not be located. We therefore have chemical analyses for 23 sherds. Petrographic analyses were made on 21 of these, and on 7 additional samples, giving a total of 28.

6. Analytical methods

6.1. Petrographic analyses

Dickinson had made 28 × 46 mm thin sections of 11 potsherds from Kurin, and reported quantitative (point-counting) data for 100 temper

Table 1
ID Numbers of the Kurin samples with their temper group and stratigraphic information.

ID	Level (cm)	Thin-section ID	Temper type	INAA ID	ICP ID	Possible source
LMA023-PITF-00141	40–50	#1	14235	SCT040	KU01	Grande Terre
LMA023-PITF-00232	60–70	61	14235	SCT039	KU02	Grande Terre
LMA023-PITB-00003	0–10	126	2314	SCT071	KU03	Maré
LMA023-PITB-00004	0–10	127	1423	SCT072	KU04	Maré
LMA023-PITB-00014	10–20	128	1423	SCT073	KU05	Maré
LMA023-PITB-00027	30–40	129	1423	SCT074	KU06	Maré
LMA023-PITB-00033	30–40	130	1423	SCT075	KU07	Maré
LMA023-PITB-00161	50–60	131	1423	SCT076	KU08	Grande Terre
LMA023-PITB-00164	50–60	132	1423	SCT077	KU09	Maré
LMA023-PITB-00229	60–70	133	1423	SCT078	KU10	Grande Terre?
LMA023-PITF-00132	40–50	NC-9	1423	SCT100	KU11	Maré
LMA023-PITF-00007	20–30	KU12	142	x	KU12	unknown
LMA023-PITF-00065	30–40	KU13	142	x	KU13	Maré
LMA023-PITB-00072	40–50	4XK15	142	x	KU14	unknown
LMA023-PITF-00080	40–50	4XK16	142	x	KU15	Maré
LMA023-PITF-00085	40–50	KU16	142	x	KU16	Maré
LMA023-PITF-00134	40–50	x	1425	x	KU17	(no thin section)
LMA023-PITB-00153	50–60	KU18	142	x	KU18	Maré
LMA023-PITF-00182	50–60	4XK17	142	x	KU19	Maré
LMA023-PITF-00186	50–60	KU20	142	x	KU20	Grande Terre?
LMA023-PITF-00231	60–70	x	142	x	KU21	(no thin section)
LMA023-PITF-00190	50–60	NC-10	1425	x	KU22	Maré
LMA023-PITF-00094	40–50	NC-8	142	x	KU23	Maré
LMA023-SURF-00031	Surface	NC-6	2	x	x	Maré
LMA023-SURF-00342	Surface	NC-7	23	x	x	Maré
23–1	unknown	23–1	x	x	x	Maré
23–2	unknown	23–2	x	x	x	Maré
23–3	unknown	23–3	x	x	x	Maré
23–4	unknown	23–4	x	x	x	Maré
23–5	unknown	23–5	x	x	x	Maré

Temper group code: (1 = white light minerals, 2 = black heavy minerals, 3 = transparent minerals, 4 = shell fragment, 5 = red iron oxide or minerals).

particles in each (Dickinson, 2008: Table 273.6). We reproduce these previously unpublished results here as Table 2. We restudied these 11 thin sections (# 1, NC-6, NC-7, NC-8, NC-9, NC-10, 23-1, 23-2, 23-3, 23-4, 23-5 in Table 1) and had 19 new 28 × 46 mm thin sections made. We identified mineral grains in plane- and cross-polarized light with Olympus BH-2 and/or Olympus BX-51 petrographic microscopes at the University of Arizona, and recorded features of interest as digital photomicrographs. We did not point-count the temper grains.

6.2. Chemical analyses

6.2.1. INAA

In order to remove any possible contamination (such as glaze, slip, paint, and adhering soil) from the samples, fragments (about 1 cm^2) from each of the 11 Kurin samples, along with 89 samples from five other Lapita sites, were abraded using a silicon carbide burr and washed in deionized water. Once dried, each sherd was powdered in an agate mortar. For short irradiations, 150 mg of powder from each specimen was weighed and sealed in clean high-density polyethylene vials. Another 200 mg of each sample was weighed and sealed in clean high-purity quartz vials for long irradiations. Standards made from National Institute of Standards and Technology (NIST) certified standard reference materials SRM-1633b (coal fly ash), SRM-688 (basalt rock), and SRM-278, as well as quality control samples (e.g., standards treated as unknowns) of SRM-278 (obsidian rock) and Ohio Red Clay (a standard developed for in-house applications) were similarly prepared.

The analyses at MURR produced elemental concentration values for 33 elements in most of the analyzed samples, but there were ten elements (Ni, U, K, Ba, Zr, Nd, Cs, Rb, Ta, and Tb) with concentrations below detection limits for more than 20% of the samples. Fortunately, these ten elements do not include the elements typically most useful for discriminating compositional groups.

6.2.2. ICP

Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), and inductively coupled plasma atomic emission spectrometry (ICP-AES) were later employed to measure the bulk compositional elements (52 elements) of 23 Kurin samples (including the same 11 samples analyzed with INAA) and 306 samples from 11 other Lapita sites of New Caledonia at the Department of Biomedical Engineering and Environmental Sciences, National Tsing-Hua University, Taiwan. Powdered ceramic samples of around 100 mg were mixed with concentrated HF (1 ml), HCl (2 ml) and HNO_3 (2 ml) and digested in a microwave oven (Mars-5X CEM) for 30 min, then the clear supernatants were diluted for analysis. Commercial standard solutions (E. Merck, Darmstadt, Germany) were used for determination of the concentrations of 52 elements. Eight major elements (Na, Mg, Al, P, K, Ca, Ti, Fe) were measured by the inductively coupled plasma atomic emission spectrometer (Jobin-Yvon JY2000 and later Agilent 725) and the remaining ones (Li, Be, Sc, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, Ge, As, Rb, Sr, Y, Zr, Nb, Mo, Pd, In, Sb, Cs, Ba, Lu, Hf, Ta, Pb, Bi, Th, U, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb) by the inductively coupled plasma mass spectrometer (Agilent 7500ce). Four elements (Pd, In, Pb, and Bi) with concentrations below detection limits for more than 20% of the samples are excluded from the statistical analysis.

7. Results

7.1. Petrographic analyses of Kurin samples

Table 2 is reproduced from an unpublished report by Dickinson (2008: Table 273.6). It shows point-count data for temper grains (100 points per slide) in 11 of the 28 thin-sections listed in Table 1. (We reexamined all of these, and our qualitative descriptions are reported in Supplementary Appendix Table 1). Note that all 11 samples are dominated by calcareous grains, or by vacuoles (voids) that Dickinson inferred were originally calcareous grains. Surviving calcareous grains are rounded and usually have tiny subgrains (micritic texture), but some are whole or fragmentary shells. We agree with Dickinson's inference that these calcareous grains are from beach sands, and also with his conclusion that the vacuoles were produced by post-depositional diagenesis.

The alternative explanation – that calcareous grains were decomposed by firing of the clay – can be rejected, as surviving pieces of shells preserve anatomical fine details. This should prompt readers to ask why the calcareous temper in these sherds is apparently unaffected by firing. Most potters are aware of "lime spalling" in pots tempered with shell or other calcareous materials. This is a consequence of the decomposition of calcium carbonate ($CaCO_3$) when fired above about 620°C (Rye, 1976) to form lime (CaO), which subsequently reacts slowly with water vapor in the air to form crystals of calcium hydroxide ($Ca(OH)_2$. Since this compound has a much larger volume per unit mass than the original carbonate, the pressure exerted by its crystallization cracks the surrounding clay and may cause spalling of the surface, and sometimes complete destruction of the pot.

Rye (1976) noted that some contemporary potters in Melanesia solve the problem of lime spalling by soaking their clays in sea water rather than in fresh water. He also showed by experiment that this raises the temperature at which $CaCO_3$ converts to CaO, in some cases by more than 200 °C. It seems highly likely that this technique was also used in making the Lapita pottery investigated here.

Our petrographic data for each of the 28 thin sections (Supplementary Appendix Table 1) show that three of them were definitely made on Grande Terre. Section #1 (Fig. 3a) contains chromite (from peridotite) and felsic volcanic glass, which - when found together - point to the area around St Louis, on the southern coast. Section 61

Table 2
Frequency percentages of grain types in calcareous sand tempers of sherds from Kurin, on Maré in the Loyalty Islands. Reproduced from Table 273–6 in Dickinson (2008).

Type	NC10	23–1	23–5	NC-8	NC-9	23–2	23–4	NC-6	NC-7	23–3	#1
feldspar	–	–	–	1	1	–	–	–	–	–	1
pyroxene	–	1	–	–	–	–	–	–	–	–	1
amphibole	–	–	–	–	–	–	1	–	–	–	–
spinel	–	–	–	–	–	–	–	–	–	–	6
opaques	3	4	6	4	3	6	4	8	9	6	9
VLF[1]	–	–	–	1	2	2	3	2	3	8	1
calcareous	97[2]	95[3]	94[3]	94[4]	94[4]	92[2]	92[3]	90[5]	88[5]	86[6]	82[3]

[1] Volcanic lithic fragments
[2] Most calcareous grains dissolved but some relict calcareous grains present within partial vacuoles
[3] All calcareous grains still fully preserved (no vacuoles)
[4] Calcareous grains partly dissolved to form partial vacuoles
[5] All calcareous grains wholly dissolved to form sand-sized vacuoles
[6] Calcareous grains dissolved in parts of sherd to form vacuoles, but still present in other parts of sherd

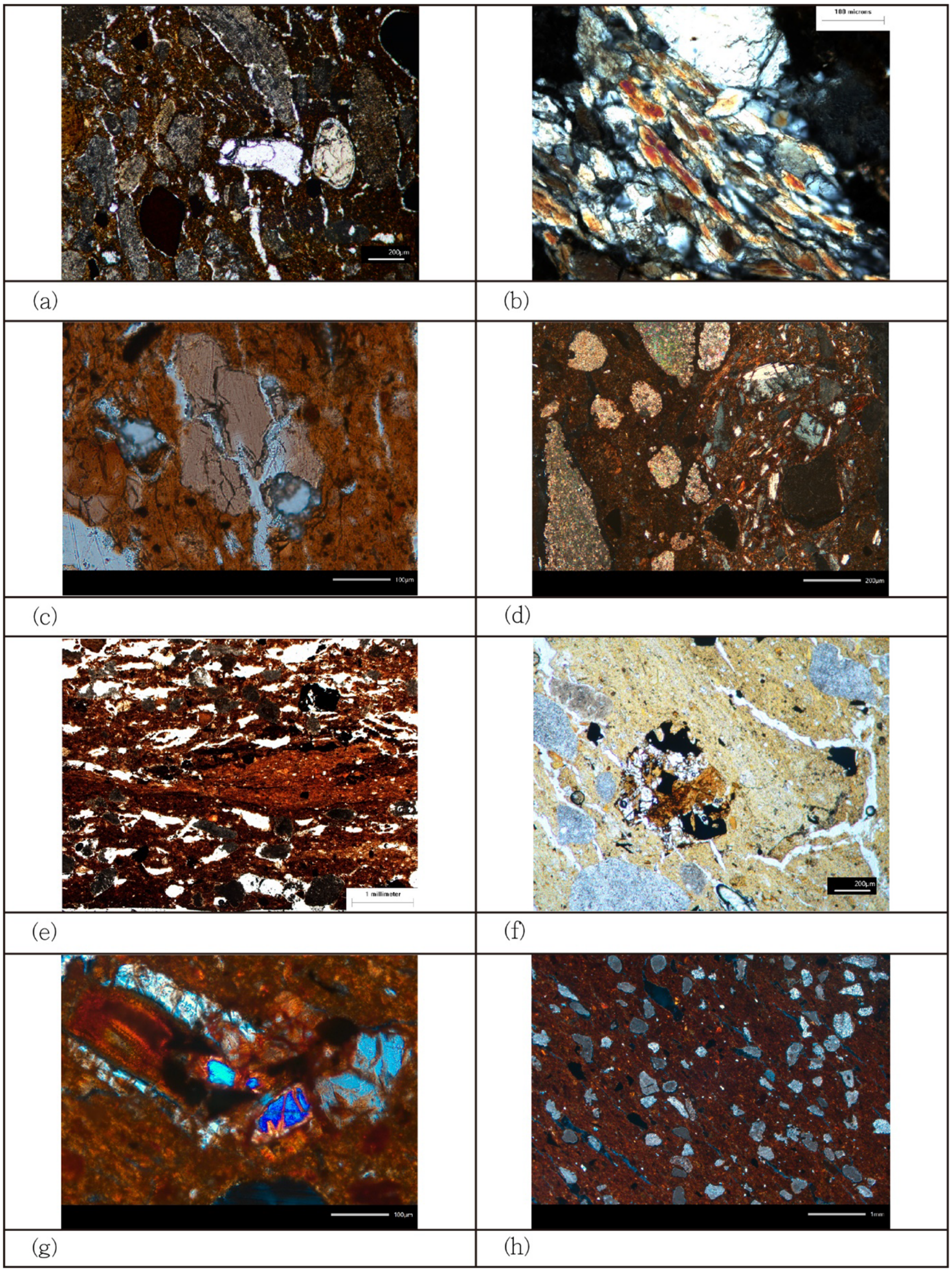

Fig. 3. Photomicrographs of selected petrographic features. For sample contexts see Table 1. (a): Section #1, 50x PPL - chromite, pale glass, basaltic glass and silicate RFA. (b): Section 61, 200x, XPL– amphibolite schist. (c): Section 130, 200x, PPL - tan color glass. (d): Section 131),100x, XPL – rounded coral clasts, two clay colors. (e): Section NC-9, 20x, PPL – poor mixing of clays. (f): Section KU12, 50x, PPL – uniquely pale clay, coral sand, weathered basalt, opaques. (g): Section KU 14/4XK015, 200x, XPL - weathered dolerite/basalt). (h): Section KU15/4XK016, 20x XPL – typical fabric at Kurin (coral sand and scarce terrestrial minerals in red/brown clay).

also contains a grain of chromite, but also a grain with unmistakably metamorphic texture (Fig. 3b). Metamorphic rocks are found in southern Melanesia only in the north of Grande Terre, and they occur with peridotite and beach sands only where the Diahot River reaches the coast. Section 131 contains a single chromite and large crystals of quartz, and so was also made somewhere on Grande Terre.

KU14 has a relatively large amount of weathered basalt (or dolerite; Fig. 3g) and basaltic glass - far more than in the rest of the Kurin samples. This could have been made near one of the many basaltic-doleritic outcrops on south Grande Terre, but basalt is also widely distributed throughout the islands of Vanuatu to the north.

The other 24 samples – 10 of 11 examined by Dickinson (Table 2), and 14 of 19 new samples – are all dominated by coral sand temper and have sparse terrestrial mineral content (Fig. 3h), opaques (magnetite and ilmentite, where specifically identified in polished section) and devitrified (weathered) basaltic glasses, with rare plagioclase and/or clinopyroxene. Dickinson (2008) concluded that the samples he examined were compatible with the basaltic geology of Maré, but they are also potentially compatible with many other basaltic islands in the western Pacific.

The Vanuatu island chain lies to the north of New Caledonia, and Sand (2016) has argued that the Loyalty Islands may have been a stepping-stone for Lapita colonists moving from Vanuatu to Grande Terre. Yet the only evidence so far for movement of Lapita pots between Vanuatu and New Caledonia is in the opposite direction. Dickinson has reported that pots made on Grande Terre have been identified in archaeological assemblages from Santo-Malo (Dickinson:245-6, 1971; Dickinson:108, 2006, Table 25), Efate (Dickinson, et al., 2013), and Erromango (Dickinson, 2006:108, Table 25).

We have therefore paid particular attention to the possibility that some of the pots in our sample from Kurin may have been brought from Vanuatu. Based on Dickinson's summary table for the key supplemental grain parameters for andesitic arc tempers (Dickinson, 2006:54, Table 13), southern Vanuatu tempers (from Efate and Erromango islands) are almost entirely composed of clinopyroxene and opaque minerals, but contain no quartz, hornblende or orthopyroxene, and only rarely olivine. Two Kurin samples (KU13 and KU15) contain tiny pieces of bright green mineral (anisotropic, and thus not chrome garnet). This drew our attention to a description of Erromango tempers that contain a clinopyroxene with a "distinct greenish cast" (Dickinson, 2006:67). In addition, 10 thin sections from Kurin (#1, 126, 129, 130, 131, 132, KU16, KU19/4XK17, KU20, and NC-8) have light brown (pale tan) volcanic glass pieces, that resonated with descriptions of "volcanic lithic fragments that are exclusively pale tan and commonly pumiceous particles of felsic volcanic glass" (Dickinson, 2006: 67) from Efate Island, where all 36 samples had only vitric igneous lithic fragments (Dickinson, 2006:66, Table 14). In the same table, Dickinson reported that eight samples from Erromango had microlitic, lathwork, and/or vitric tempers, often with minor olivine). Yet none of our samples correspond to this description.

We then borrowed (from the Bishop Museum, Hawaii) the thin sections of Erromango and Efate sherds that Dickinson examined. Our restudy of these shows that the greenish clinopyroxene from Erromango tempers does not resemble the unidentified green mineral in the two thin sections from Kurin. Nor do the pale tan volcanic glass and associated minerals and rock fragments from the Efate samples resemble those from Kurin. We conclude that there is still no petrographic evidence of pottery movement from Vanuatu islands into the Loyalty Islands.

We then reexamined our thin sections from Kurin and observed that:

1) the amount of basaltic glasses in all our samples far exceeds that of pale brown volcanic glasses;
2) the pale brown glass (Fig. 3c) is all in very small grains – the largest one observed is 1500 μm, but most are < 250 μm; and
3) while the darker basaltic glasses are heavily weathered (devitrified), the pale tan glass grains are mostly unweathered. (The latter glass shows complete extinction in cross-polarized light.)

We conclude from these observations that the pale brown/tan glasses in Kurin pottery are likely microtephra – tiny particles of volcanic glass produced by the aerial eruption of magma from andesitic volcanos. There are no andesitic volcanos on the Loyalty Islands, while on Grande Terre felsic volcanic glass occurs only as thin lenses stratified within pre-Senonien sediments along the south bank of the Diahot valley in the northwest, and also parallel to the south coast, and to the west of St. Louis. Potsherds including these glasses also contain abundant quartz, and often chert and/or shale; in the Diahot Valley they also include metamorphic minerals, and around the bay of St. Louis they have large feldspar grains from a diorite intrusion (Chiu, et al., 2016). Pottery produced in either of these areas is thus petrographically quite distinct from the thin sections of pottery from Kurin.

The leading candidate for a source of microtephra is Mount Yasur on Tanna Island (Fig. 1) in southern Vanuatu. This is a Stombolian-type volcano that produces basaltic trachyandesite tephra (Kremers, et al.:836, 2012; Oppenheimer, et al.:454, 2006). Mt. Yasur is only 275 km northeast of Maré island. It currently erupts about four times per hour, and has a geological record of eruptions from at least 245,000 years ago to the present (Carney and MacFarlane, 1979; Dugas, et al.:180, 1977; Firth, et al.:837, 2014; Kelley:49, 2008; Nairn, et al., 1988; Robin, et al.:12, 1994). Professor Eric C. Ferré, the Director of the School of Geosciences, University of Louisiana at Lafayette wrote to us as follows:

"Considering that Yasur erupts with violent explosions, the cataclastic process of eruption has, at the very least, to produce microtephra by fragmentation of regular tephra. The height in the troposphere where this microtephra would go is probably not much higher than 3–5 km above the craters based on my direct observation of the plume. Yet even with a low altitude microtephra/dust it would be possible to "push" microtephra 275 km away from the source." (Dr. Eric Ferré, email to SC and DK, 2nd April 2020).

The present-day wind directions indicate that during late March to mid-April, or whenever there is a cyclone nearby, tephra from Mt. Yasur would be blown towards Maré Island (Beccario, 2020). The next nearest active volcanos to Kurin are on Matthew Island (345 km ESE of Kurin) and Hunter Island (425 km ESE). Neither of these erupts continuously, and it is not known whether they were active during the Lapita expansion. On present information Mt. Yasur appears to be the most likely source.

The remaining thin sections are all dominated by coral sand, with small amounts of opaques and weathered minerals and glass of probably basaltic origin, but cannot be assigned to a specific source on petrographic evidence alone. KU12 has a pale yellow clay, unlike the rest of the Kurin samples (Fig. 3f), and also contains devitrified basaltic glasses, chert, angular opaque minerals, a heavily weathered sub-volcanic igneous rock fragment, and a shell fragment completely replaced by silica. On petrographic data alone, we tentatively assigned this to the southern coast of Grande Terre. KU20 has a similar paste to other Kurin samples, yet it has one felsic volcanic rock fragment, pale brown volcanic glasses, and weathered serpentine which is abundant in south Grande Terre, and that sets it apart from local samples.

Chemical data for 23 Kurin sherds by ICP-AES and ICP-MS can be found in the online Supplementary Appendix Table 3. We have extracted the data for Fe, Ti and Cr, and have added the concentrations of each element to the petrographic descriptions in Supplementary Appendix Table 1. Ti and Cr distinguish quite neatly between samples derived from basaltic and ultrabasic terranes. Cr in the crust is largely partitioned into a single mineral (chromite, $FeCr_2O_4$), which in the Pacific is found entirely in dunite and peridotite within ultrabasic ophiolite complexes. The only ophiolite within 2000 km of Kurin is on Grande Terre (Dickinson, 2006). Sherds with more than 1200 ppm Cr and with less than 0.5% Ti (#1, 61 and 131) all contain visible chromite, and are therefore from regions of Grande Terre close to ultrabasic peridotite and or dunite. Sherd 133 lacks visible chromite, but with 766 ppm Cr and only 0.17% Ti it was clearly also made on Grande Terre. KU-20 also lacks visible chromite, but with 252 ppm Cr and 0.82%Ti it would also appear to derive from Grande Terre, though the peridotite signature has apparently been diluted by mixing with sediments derived from other rocks.

The geochemistry of Ti in igneous rocks is well understood (Force, 1976). Low concentrations occur in dunite (mean 0.07%; n = 118), peridotite (0.53; n = 196), granite (0.33; n = 1967), granodiorite (0.63; n = 523) and other acid rocks. The highest mean values are found in oceanic basalt (2.67; n = 148), though alkaline basalts, gabbros and andesites have mean values slightly above this (all values from Force, 1976: Table 2).

The remaining 18 Lapita sherds for which we have chemical analysis contain 1.30% to 1.98% Ti, and 80 to 142 ppm Cr. These narrow ranges of values suggest that the clays from which these pots were made must derive from similar parent rocks. Particles identified as microtephra were also noted in nine of these, and we therefore think that these nine were made on Maré. The other nine can only be assigned to a basaltic geology on these data. Note that one of the sherds in this last group is KU-12, which was assigned on petrographic data alone to the basaltic/sedimentary south coast of Grande Terre.

7.2. Compositional group structure identified by INAA, ICP-AES and ICP-MS data

Concentrations of 33 elements in 11 ceramic samples from Kurin are reported in Supplementary Appendix Table 2. This is a subset of 100 Lapita sherds from New Caledonia that were analyzed by INAA at MURR (Ferguson and Glascock, 2009).

Calcium levels are extremely high in most samples because of the dominant coral sand temper, but some samples show clear sign of postdepositional leaching out of calcareous grains under petrographic examination, as noted above. Thus the elemental data have first been adjusted using the suggested mathematical correction to compensate for the diluting effects of the calcium (Cogswell, et al.:64, 1998; Steponaitis, et al., 1996):

$$e' = \frac{10^6 e}{10^6 - 2.5c}$$

where e' is the corrected concentration of a given element in ppm, e is the measured concentration of that element in ppm, and c is the concentration of elemental calcium in ppm. After the calcium adjustment, concentrations for Ca and Sr which are usually associated with corals and shell fragments, are eliminated from further statistical analysis (Ferguson, et al., 2008; Ferguson and Glascock, 2009). Statistical analyses (Hierarchical Cluster Analysis, Discriminant Analysis, and Principal Component Analysis (PCA)) have all been subsequently carried out on base-10 logarithms for the INAA data, and on Z-scores for the ICP-MS and ICP-AES data of concentrations on the remaining elements.

We identified 8 compositional groups in the 100 ceramic samples from New Caledonia (see Fig. 4 and Table 3). 10 of 11 Kurin samples are clustered into Group 4 (7 samples) and Group 8 (3 samples). Samples in Group 4 correspond to petrographic slides 126 through 132 (see Table 1). Since sherds from group 4 contain the pale glasses identified as likely microtephra from Mt. Yasur, we conclude that Group 4 was probably made on Maré. Group 8 is composed of petrographic samples #1, 61 and 131 (Table 1). These are the three samples containing visible chromite, and thus derive from beaches adjacent to peridotites on Grande Terre. The sample corresponding to thin section 133, which is petrographically assigned to Grande Terre, and is in Group 7 along with samples from both Vatcha of the Île des Pins and Goro of the southern tip of the Grande Terre (Fig. 1).

These same 11 samples were reanalyzed with ICP-AES or ICP-MS analyses, together with 12 more samples from Kurin, as part of a group of 329 Lapita potsherds from New Caledonia. The results for the 23 Kurin samples are reported in Supplementary Appendix Table 3. For multivariate statistical comparison, the calcium correction described above was applied to the entire dataset. Ca and Sr have been excluded from the test after the calcium correction. Pd, In, Pb, and Bi have more than 50% of cases below detection limits, so they are excluded as well. The remaining 46 elements were then transformed to z-scores in SPSS 21. Hierarchical Cluster Analysis (HCA) with Ward's method and Squared Euclidean distance was used first. Stepwise Discriminant Analysis (DA) with Mahalanobis Distance and the leave-one-out classification procedure was then employed to validate HCA results (Baxter, 1994; Shennan, 1988). After several trials, single outliers (13A26, GO24, VA47, EHI001, EHI002, and EHI003) were removed, and two major clusters were recognized. Each of the 46 elements were first run through the Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO), and only data with scores higher than 0.70000 were retained. 17 elements were thus excluded, and a high score of the Bartlett Test of Sphericity with a significance of 0.0000 was achieved with the remaining 29 elements (Al, Ti, Fe, Sc, Co, Ni, Cr, Ga, Ge, As, Y, Zr, Nb, Sb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and U). Principal Components Analysis (PCA) was then conducted and plotted with three factors (Fig. 5).

Fig. 5 shows samples from Kurin plotted together with those for 11 other Lapita sites in New Caledonia (see Fig. 1 for locations). Note that in Fig. 5. most of the Kurin samples (15) separate very clearly from samples from other sites. We have suggested above - on the basis of petrographic and INAA analysis – that most of these were made on Maré. These samples have chemical compositions similar to the average of analyses of deep sea clays (Faure, 1998: 50-1, Table 4.5) with high concentrations of REEs. KU01, KU02, KU08, and KU10 fall within the mass of samples from other sites at the bottom of the plot, while KU09, KU12, KU14 and KU20 lie close to the main group of Kurin samples, but show some overlap with samples from 13A, the Lapita name site (Fig. 1).

Table 4 compares our REE data for Kurin samples with the mean of the Maré basalt samples previously obtained by local geologists (Maurizot and Lafoy, 2003:25-6, Tableau 4–6 in Appendix I, pp. 121–2). It shows that only KU14 has a higher concentration of REE than the basalt samples, while KU07 and KU23 both have REE amounts almost identical to local basalt samples. This may indicate that these two samples are from a local source very close to the small basalt outcrops in the core of the island. KU12 and KU20, with similar inclusions as other Kurin samples but one with a distinctive pale colored clay (KU12) and one with a piece of felsic volcanic rock fragment (KU20) cannot be separated from all other Kurin samples using the concentrations of REEs.

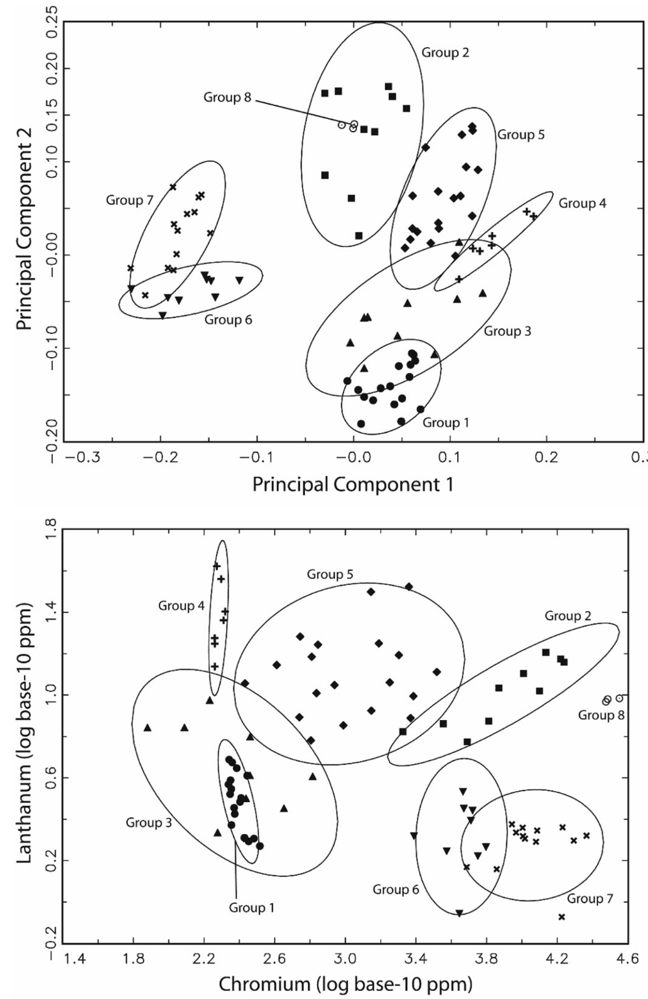

Fig. 4. (Top) Bivariate plot of first two Principal Components from log-10 transformed INAA data (Bottom) Bivariate plot of chromium and lanthanum concentrations (log base-10 of ppm) showing the eight compositional groups based on INAA data. Ellipses in both plots represent the 90% confidence intervals for group membership. Symbols denote group membership.

Table 3
Numbers of samples from 6 Lapita sites in New Caledonia in each of the 8 compositional groups, based on INAA data.

	Compositional Group									
Site	1	2	3	4	5	6	7	8	Unassigned	Total
Kurin				7			1	3		11
Vatcha					6	7	4		3	20
Goro		1	1		1		8		2	13
Nessadiou	12		1		1	1			2	17
Lapita	1	5	6		7	1			2	22
Vavouto	4	4	2		4				3	17
Total	17	10	10	7	19	9	13	3	12	100

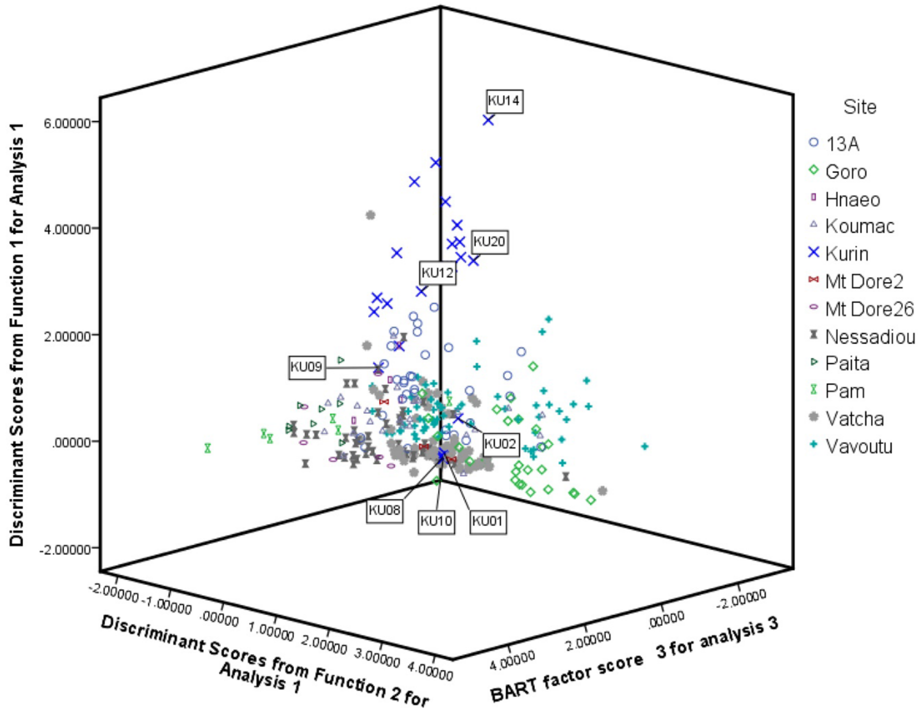

Fig. 5. Plot of Principal Components Analysis (PCA) based on ICP-MS and ICP-AES elements showing local Kurin samples can mostly be separated from other Grande Terre samples.

Fig. 6 shows the chondrite-normalized REE profiles (McDonough and Sun, 1995: 223-253) for Kurin samples. This shows the much higher concentrations of REE in samples that we suspect were made on Maré Island than in the four exotic samples (KU01, KU02, KU08, KU10) which we have already assigned to Grande Terre according to petrographic analysis and/or concentrations of Ti and Cr. We explain the relatively high concentrations of REE in the main (local) group of Kurin samples as follows. Any clay present on Maré (and on the other Loyalty Islands) can only have formed from basalt. As the basaltic core of Maré was raised towards the surface on the forebulge of the New Hebrides Trench (Dickinson, 2013) a coral atoll formed a ring around it, enclosing a lagoon. This formed a basin that prevented the loss of sediments, produced by erosion of the basalt, to the deep sea. As uplift continued, the sediments within this basin were raised above sea level and became accessible to potters. Deep sea clays, to which this group of sherds bears a strong resemblance in trace element chemistry, have high concentrations of REE relative to most igneous rocks because more soluble elements have been removed, thereby concentrating the relatively insoluble REE (Faure, 1998).

Using biplots (Fig. 7), we see again that four exotics (KU01, KU02, KU08, and KU10) can also be separated from the local Kurin samples

Table 4
Log-10 concentrations of Rare Earth Elements, relative to average chrondrite abundances, of local basalt samples and Kurin ceramic samples, ranked by the amount of Ce.

ICP-MS ID	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Possible source
KU14	25.40	86.79	7.50	31.74	7.52	2.82	7.16	1.47	6.27	1.49	3.17	0.81	unknown
Basalt	26.84	55.40	6.67	27.90	6.04	2.09	6.45	0.91	5.26	1.01	2.58	2.26	Maré
KU23	24.34	52.78	6.02	26.66	5.49	1.91	5.90	0.82	4.91	0.88	2.43	0.32	Maré
KU07	24.64	51.41	6.50	28.14	5.65	1.98	6.44	0.91	4.92	1.00	2.57	0.33	Maré
KU15	20.09	45.05	5.21	21.00	4.85	1.93	5.00	1.08	4.26	1.13	2.31	0.65	Maré
KU05	18.33	40.95	4.30	17.70	3.38	1.26	4.36	0.61	3.52	0.68	1.81	0.22	Maré
KU18	15.93	34.67	4.46	18.10	4.35	1.73	4.33	1.00	3.95	1.09	2.24	0.66	Maré
KU12	12.23	33.11	3.02	11.12	2.66	1.20	2.67	0.75	2.36	0.76	1.35	0.52	unknown
KU22	11.01	32.28	3.36	14.13	3.21	1.23	3.42	0.50	3.22	0.57	1.50	0.21	Maré
KU11	18.16	31.04	4.36	18.53	3.52	1.25	4.10	0.60	3.32	0.65	1.72	0.23	Maré
KU17	13.11	29.55	4.06	16.65	4.12	1.67	3.89	0.93	3.40	0.96	1.90	0.61	no thin section)
KU20	14.67	29.51	3.83	15.29	3.37	1.43	3.54	0.87	3.06	0.92	1.77	0.59	Grande Terre?
KU16	13.58	29.02	3.45	13.23	3.16	1.36	3.26	0.83	2.82	0.85	1.54	0.56	Maré
KU13	13.51	26.20	3.44	13.46	3.24	1.42	3.48	0.88	3.16	0.93	1.79	0.59	Maré
KU06	11.51	25.82	2.60	10.62	2.17	0.78	2.60	0.41	2.24	0.43	1.10	0.15	Maré
KU21	11.56	25.60	3.65	14.88	3.74	1.57	3.71	0.91	3.14	0.94	1.76	0.61	(no thin section)
KU19	14.42	24.30	4.01	16.26	3.81	1.54	3.93	0.95	3.34	0.98	1.90	0.62	Maré
KU04	10.80	23.88	2.45	10.12	2.17	0.79	2.55	0.39	2.18	0.43	1.15	0.15	Maré
KU09	6.63	19.59	1.49	6.16	1.29	0.44	1.64	0.25	1.40	0.29	0.79	0.10	Maré
KU03	6.20	17.68	1.60	6.80	1.46	0.57	1.80	0.29	1.58	0.36	0.86	0.12	Maré
KU02	2.09	5.50	0.69	3.16	0.84	0.26	0.98	0.17	1.09	0.22	0.68	0.09	Grande Terre
KU10	0.28	0.91	0.08	0.42	0.09	0.04	0.11	0.02	0.14	0.03	0.10	0.01	Grande Terre?
KU08	0.11	0.32	0.02	0.12	0.03	0.01	0.05	0.00	0.05	0.00	0.03	0.00	Grande Terre
KU01	0.05	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	Grande Terre

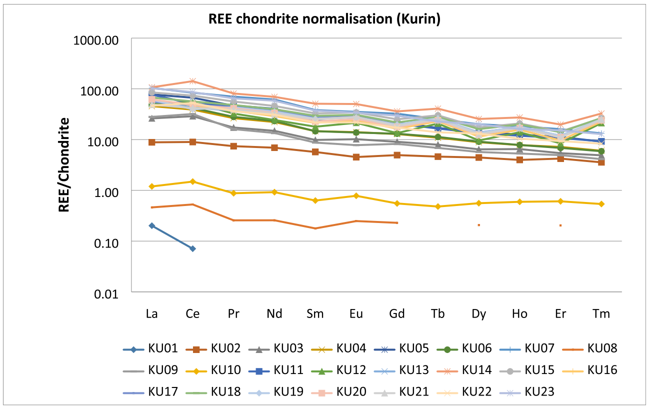

Fig. 6. Histogram showing the concentration of rare earth elements (REE) in the Kurin samples obtained via ICP-MS or ICP-AES.

quite successfully, as they all have much higher concentrations of Cr and Ni, and lower concentrations of V, Fe and Ti than the rest of the Kurin samples. The other three possible exotic samples (KU12, KU14 and KU20) cannot be separated from local Kurin samples as clearly as the above four. KU09, the one that has no sufficient inclusions to determine its source area, also cannot be separated from the local Kurin samples.

We also compared the Kurin ICP data to 26 ICP-MS analyses of Lapita pots from the Teouma cemetery on Efate Island, Vanuatu (data from Leclerc, et al., 2019:Table 2). The same procedures described above were employed to run HCA first in order to recognize possible numbers of clusters, then Discriminant Analysis (DA) was employed to illustrate the most separable clusters. Fig. 8 shows that there is complete separation of local Kurin samples from Teouma samples (the upper right cluster), and also from pots mostly made in northeast Grande Terre (the lower right cluster). Local Kurin samples can still be separated from the rest of the western Grande Terre samples as they cluster at the top right corner of the largest cluster of the three. (TCC03 and TD03, two New Caledonian Lapita pots that were buried at the Teouma site, are also marked in Fig. 8). Then the KMO test was conducted to obtain 15 elements (Ti, Fe, Co, Ni, Cu, Y, Zr, La, Ce, Nd, Sm, Gd, Dy, Er, and Yb) to run PCA (Fig. 9). Here the clusters are not as clearly defined, but at least four larger clusters can be demonstrated (Fig. 9).

8. Discussion

The results presented in this paper shed new light on the diversity of Lapita networks in southern Melanesia. We have not found any evidence to support the suggestion that the Loyalty Islands may have been settled directly from southern Vanuatu (Sand, 2016). Many of the sherds in our sample from Kurin appear to have been made in the Loyalty Islands, probably on Maré Island itself. At least 4 others were imported from Grande Terre, and 7 (for which only petrographic data were obtained) derive from unspecified basaltic islands (but possibly from Maré). We compared our Kurin thin sections directly with Dickinson's sections from Erromango and Efate Islands in southern Vanuatu, and compared the chemistry of samples from Efate with those from Kurin, but found major differences between them. We have yet to identify a pot made in Vanuatu at any site in New Caledonia, even though contact between the two island chains during Lapita times has been demonstrated by Dickinson, who identified pots made on Grande Terre in sites on Efate and Malo (Dickinson, et al., 2013).

In another paper, Chiu et al. (paper submitted) found no pottery made in the Loyalty Islands in a sample of 68 potsherds from the Lapita site of Vatcha, on the Île des Pins off the southern tip of the Grande Terre (Fig. 1). Another striking finding is that while two thirds of the pots from Vatcha were produced near the northern tip of Grande Terre (most of them in the Diahot River valley), there are none at all from this area in our sample of 28 pots from Kurin, which is (at the precision of radiocarbon dating) contemporary with Vatcha.

Although our sample size is small, and this makes our conclusions more tentative, our current samples were selected to cover the range of temper variation in the entire assemblage. Only 6% (980 sherds) of the Kurin assemblage contains transparent minerals that indicate an exotic source, while more than 92% of the sherds examined were made of a rather homogeneous temper group that we identify as probably local to the Loyalty Islands. The clear differences between the Lapita pottery of the Loyalty Islands and of Ile des Pins challenge the hypothesis that Lapita was characterized by a continuous "wave of advance" model for the earliest settlement of Remote Oceania. Our data support instead the "leapfrog" model identified for the Solomon Archipelago, where Austronesian navigators bypassed many large islands during the first phase of Lapita expansion, leaving these to be settled at a later time possibly by a secondary movement out of the Bismarck Archipelago (Sheppard, 2011, 2019). In the southern Melanesian case, we seem to see two mutually exclusive networks functioning apparently side by side, with little interaction. No potsherd manufactured in Vanuatu or in the Loyalty Islands has been discovered to date in Lapita sites on Grande Terre, but there are multiple examples of Grande Terre pottery being shipped to islands in Vanuatu (see Dickinson, 2006: Appendix Table A1, pp. 142, 144, and 146). Moreover, the number of Grande Terre sherds in our sample of Lapita pottery from Kurin is very limited, and these do not include any from the important Lapita pottery production of the Diahot River valley in northern Grande Terre, which is the major supplier of pottery to Île des Pins. Pottery from the Diahot valley is also present in the Teouma Lapita cemetery on Efate of the central Vanuatu, showing that Lapita colonists of northern Grande Terre returned some 400 km to Efate around 3000–2500 years ago (Chiu, et al., 2016, Dickinson, et al., 2013, Petchey, et al., 2015).

9. Conclusion

Petrographic and trace element data have shown the existence of quite separate spheres of ceramic production and exchange within present New Caledonia during the Lapita period. This paper focuses on the Loyalty Islands, which appear to have had much less ceramic exchange with Grande Terre than previously had been expected. We have also been unable to confirm the hypothesis that the Loyalty Islands were colonized from southern Vanuatu, nor (in a separate paper) the suggestion that Île des Pins was colonized from the Loyalties (Chiu et al., paper submitted).

We conclude with some comments on technical methods for studying ceramic provenance in southern Melanesia. Although pots made on Grande Terre are easily distinguished by petrography from those made on basaltic islands when they contain abundant mineral temper, it becomes much harder to distinguish between these when the pottery is tempered with coral sands containing only a small proportion of heavily weathered terrestrial minerals, and when most of these minerals are opaque. Using surface-polished rather than covered thin sections - as we began to do during this study - helps somewhat, as we can identify some opaque minerals in reflected light. But we nevertheless made several initial misclassifications with sherds having only sparse mineral temper. We were able to correct these when we had trace element data for the same sherds. (For example, the color of the clay can be misleading, as in the case of thin section KU-12). Conversely, multivariate statistics were able to define groups in the chemical data, but without the petrographic data it would be hard to understand what these groups mean in terms of provenance.

It has long been cautioned (e.g., Arnold, et al., 1991; Stoltman, et al., 2005) that there is no simple one-to-one relationship between petrographically recognized temper and non-plastic inclusion suites and the chemical compositional clusters of the whole pot. Previous

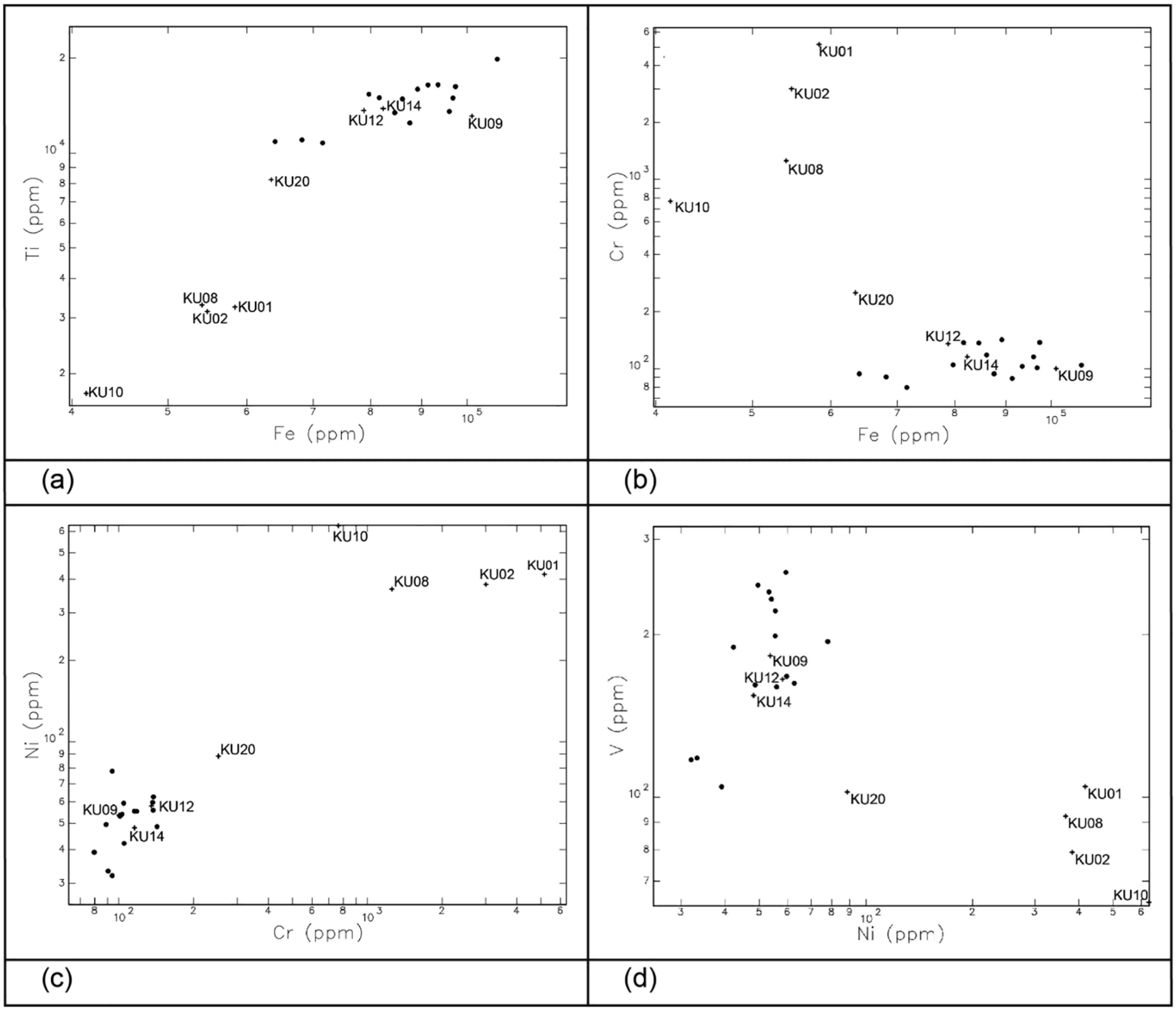

Fig. 7. Bivariate plots showing the separation of four exotic samples (KU01, KU02, KU 08 and KU 10) from local Kurin samples on ICP-MS/ICP-AES data.

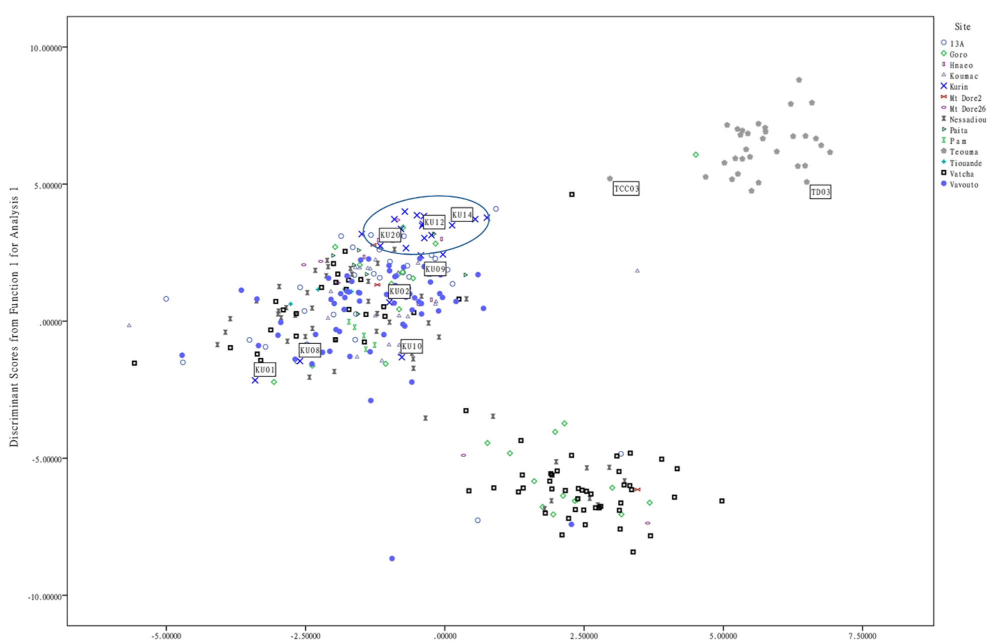

Fig. 8. Discriminant Analysis of ICP-MS/ICP-AES data for all samples from New Caledonia and for those from the Teouma cemetery, Efate Island, Vanuatu. Teouma data are from Leclerc et al. (2019). For locations of the sites corresponding to the symbols, see Fig. 1.

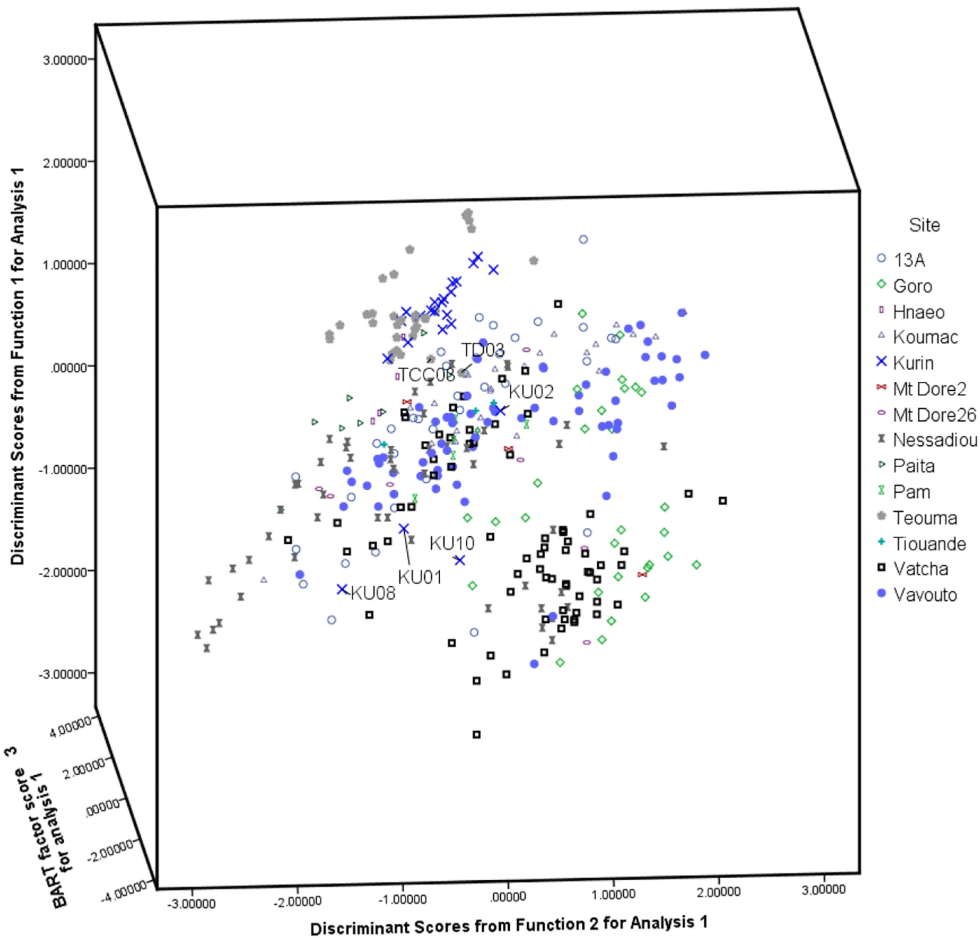

Fig. 9. Principal Components Analysis (PCA) of ICP-MS/ICP-AES data for all samples from New Caledonia and those from the Teouma cemetery, Efate Island, Vanuatu. Teouma data are from Leclerc et al. (2019). For locations of the sites corresponding to the symbols, see Fig. 1.

studies have shown that in some areas, added tempers may obscure chemical distinctions of various clay resources, especially when high proportions of heterogeneous tempers were used. In some cases, sherds that showed chemical compositional similarity may have been made with rather different and distinctive minerals that originated from two geological zones (e.g., Buxeda i Garrigós, et al., 2003; Neff, et al., 2006; Stoner, 2016; Wallis and Kamenov, 2013). In the case of island Melanesia, we have found it necessary to obtain both petrographic and chemical data, and to use each dataset to understand the other. Neither is sufficient in itself, as is clearly demonstrated in this paper. In writing this we certainly do not seek to diminish the achievements of our late colleague Bill Dickinson, whose petrographic studies over 40 years laid the foundation for studies of ceramic provenance in the western Pacific. He himself recognized the limitations of his methods.

We believe that this paper is the first to (tentatively) identify microtephra in ceramic thin sections in the Pacific, and we suggest that the source of these in samples from Kurin is Mount Yasur on Tanna Island in southern Vanuatu. The possibility of airborne and seaborne tempers being mixed in with locally available raw materials should thus be considered and further investigated while conducting future petrographic analysis on Pacific pottery assemblages. Secure matches between volcanic sources of tephra and microtephra in archaeological pots will require analysis of them by microbeam techniques (electron microprobe, laser ablation ICP-MS). In loose sediments microtephra (cryotephra) are concentrated by flotation in heavy liquids (Lane, et al., 2014) but this would not be possible with microtephra in fired potsherds. Analysis would have to be done directly on polished thin sections.

CRediT authorship contribution statement

Scarlett Chiu: Writing - original draft, Writing - review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Funding acquisition, Project administration. **David Killick:** Writing - original draft, Writing - review & editing, Conceptualization, Methodology, Investigation, Data curation, Validation. **Christophe Sand:** Writing - original draft, Writing - review & editing, Funding acquisition, Investigation. **Yu-yin Su:** Data curation, Validation, Visualization, Project administration. **Jeffrey R. Ferguson:** Writing - original draft, Writing - review & editing, Methodology, Data curation. **Jiunn-Hsing Chao:** Methodology, Data curation.

Acknowledgements

We want to express our gratitude to Dr. Pierre Maurizot, who kindly provided us detailed geological maps of New Caledonia, and to Dr. Jon Spencer for providing all of the petrographic reports of the late Prof. William Dickinson. We also thank Miss Charmaine Wong of the Bernice Pauahi Bishop Museum in Honolulu, USA, for loaning us Dr. Dickinson's thin sections of ceramics from Vanuatu. We also want to thank Prof. Eric Ferré for discussing whether Yasur volcanic glasses could have reached Maré in the past, and Miss Jia-Zhun Chang for drawing up the geological map of Kurin for this publication. This project has been funded by the National Science Council (Taiwan, ROC) (NSC-6-2628-H-001-043, NSC-101-2410-H-001-038), the Ministry of Science and Technology (Taiwan, ROC) (104-2628-H-001-006-MY2), and the Chiang Ching-Kuo Foundation for International Scholarly

Exchange (Taiwan, ROC) (RG006-D-14). This project was also supported in part by a National Science Foundation grant (USA) (BCS-1912776) to the Archaeometry Laboratory at the University of Missouri Research Reactor. Scarlett Chiu and Yu-yin Su thank the School of Anthropology, University of Arizona, for hospitality while undertaking the petrographic analyses. The excavation of the Kurin site in 1997 was allowed by the Loyalty Island Province and the local land owners.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2020.102542.

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