NEW ZEALAND JOURNAL OF ARCHAEOLOGY

Petrography of Sand Tempers in Prehistoric Watom Sherds and Comparison with Other Temper Suites of the Bismarck Archipelago

William R. Dickinson[1]

ABSTRACT

Tempers in prehistoric potsherds from Watom Island off the Gazelle Peninsula of northeast New Britain include volcanic sands indigenous to Watom and other sands exotic to the island. Indigenous tempers are dominantly hybrid sands composed of varying admixtures of volcanic beach sand with calcareous reef detritus, but variants of Watom temper include volcanic sands with little or no admixture of reef detritus, placer beach sands rich in ferromagnesian minerals, and feldspar-rich sands possibly derived from interior drainages. Terrigenous grain types in the indigenous sands are restricted to plagioclase, pyroxene, opaques, and volcanic rock fragments, among which mafic glassy grains are prominent. Source rocks were evidently basalts and basaltic andesites of the Rabaul Volcanic Series forming the bedrock of Watom.

Subordinate quartzose temper sands in Watom sherds represent sands probably collected along the mainland coast of New Britain not far west of Watom as detritus from the volcanogenic island basement complex intruded by plutons. Similar tempers occur in sherds from Kreslo on the south coast of New Britain. Rarer hornblende-bearing tempers are inferred to reflect the transfer of pottery to Watom from elsewhere within the Bismarck Archipelago or possibly from Bougainville.

Tempers in Lapita sherds from islets off the north coast of central New Britain are sands with higher ratios of orthopyroxene to clinopyroxene than observed at Watom, and evidently represent detritus from the volcanic chain of the main New Britain magmatic arc lying along the north coast. Tempers in Lapita and non-Lapita sherds from sites farther north in the Bismarck Archipelago are typically volcanic sands containing both hornblende and pyroxene in varying proportions, and were probably derived from the volcanogenic basement of Manus or New Hanover-New Ireland. Local tempers from the smaller islands south of Manus in the Admiralty Group are quartz-bearing felsitic sands derived from source rocks of the bimodal basalt-rhyolite assemblage associated with active seafloor spreading within the Bismarck Sea.

Keywords: BISMARCK ARCHIPELAGO, BISMARCK SEA, LAPITA, NEW BRITAIN, PAPUA NEW GUINEA, PETROGRAPHY, TEMPER SAND, WATOM.

[1] Department of Geosciences, University of Arizona, Tucson, Arizona 85718, USA

INTRODUCTION

Prehistoric potsherds from Watom Island off the Gazelle Peninsula of northeast New Britain (Fig. 1) occupy a special niche in the annals of Pacific prehistory because sherds from Watom were the first examples reported, just after the turn of the century by Father Otto Meyer, of the ancient ceramic tradition now termed Lapita, widespread in the Bismarck Archipelago of Near Oceania and dispersed through the island groups of Remote Oceania to the south and east of the Solomon Islands by the earliest inhabitants of island Melanesia and western Polynesia (Green 1979, 1992, 1997). Because of the resulting intrinsic interest in Watom artefacts, three sherds from Watom, provided to me by Richard Shutler Jr. in 1966, were among the first Oceanian potsherds studied in thin section at the outset of my own petrographic investigations of temper sands in Pacific pottery (Dickinson 1998). Twenty more sherds collected on Watom by Jim Specht (1968) were examined in 1973, and recently eight additional thin sections, including slices of fourteen different sherds, were submitted for petrographic analysis by Dimitri Anson because of the anomalous chemical composition of pastes in seven of them in comparison to more standard Watom sherds. An unpublished petrographic report on the temper sands in 76 Watom sherds by Mareshet Yimer at Auckland University was available to me for perusal, although the thin sections themselves were unavailable, and a written petrographic summary of the tempers in 21 other Watom sherds by Yvonne Cook at Otago University was also available.

This paper is a general appraisal of the range of sand tempers observed in sherds from Watom, including inferences about their geologic derivation and comparison with the tempers of Lapita and younger sherds from elsewhere within the Bismarck Archipelago. The Watom materials include dentate-stamped Lapita and associated nail-impressed, applied-relief, and plain sherds. Mean values for elemental compositions from electron microprobe analyses of clay pastes in typical dentate-stamped, nail-incised, and applied-relief sherds overlap in all cases at one standard deviation (Dimitri Anson pers. comm. 1996). Although salient variations in clay chemistry correlate partly with differences in temper, as discussed where appropriate in this paper, the microprobe and petrographic results jointly document a generally homogeneous Watom ceramic assemblage, without consistent contrasts in clays or tempers between sherds of varying typology or from different local sites and stratigraphic horizons. Some temper sands, however, were apparently derived from the nearby coast of New Britain rather than Watom, and there are a few sherds with anomalous tempers of uncertain origin.

WATOM GEOLOGY

The bedrock of Watom, only 4–5 km in diameter, is entirely basalt and basaltic andesite of the Quaternary Rabaul Volcanic Series exposed as interbedded lavas and scoriaceous breccias flanked locally along the coast by emergent exposures of Quaternary reef limestone (Heming 1974). The island lies 15 km due northwest of the rim of the Rabaul Caldera, represents an offshore satellitic cone of the volcanic edifice surrounding the caldera, and is itself capped by a fault-bounded elliptical caldera ≈2 km in diameter. A major eruption from Rabaul Caldera approximately 1400 years ago blanketed Watom with ash that covered the sites from which Lapita pottery has been excavated to depths approaching 40 cm (Green and Anson 1987, 1991). Phenocrysts of sand size (or larger) in basalts and andesites of the Rabaul Volcanic Series include plagioclase feldspar, clinopyroxene, subordinate orthopyroxene, and rare olivine (Heming 1974, 1977), but hydrous ferromagnesian silicates (hornblende, biotite) are notably absent (Wood *et al.* 1995).

WATOM TEMPERS

The most prevalent tempers in Watom sherds form a spectrum of hybrid sands (Zuffa 1979) composed of mixtures, in varying proportions, of calcareous reef detritus and terrigenous volcanic sands. The latter include a severely restricted assemblage of monomineralliс-monocrystalline mineral grains (igneous silicates and oxides) and glassy or polymineralliс-polycrystalline volcanic rock fragments of mafic character. Some tempers seemingly represent the same type of volcanic sand unmixed with calcareous detritus. Although the proportion of calcareous ('carbonaceous') grains in the mixed temper suite tends to decrease upward stratigraphically at some Watom sites, the change is not systematic and both partly

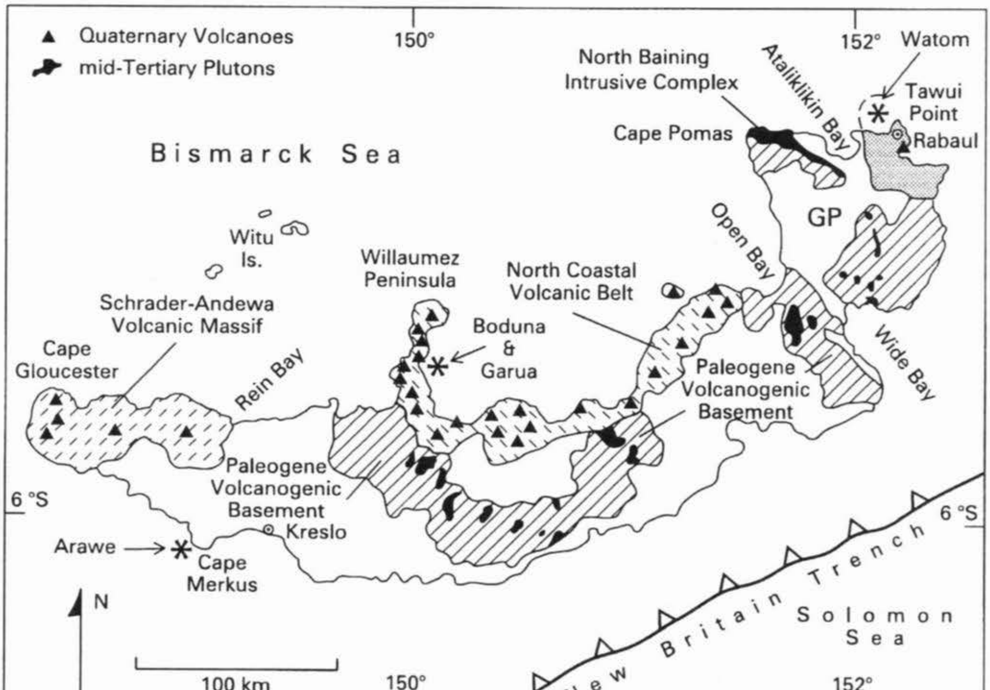

Figure 1: Sketch map of New Britain showing archaeological sites on offshore islets (*) and geological provinces discussed in the text. Geological features after Johnson (1976), Page and Ryburn (1977), Whalen (1985), and Lindley (1988). GP = Gazelle Peninsula, where stipples indicate exposures of Rabaul Volcanic Series (including Watom Is.). Unpatterned areas underlain by Miocene-Pliocene sedimentary strata.

calcareous and apparently non-calcareous tempers are present throughout the local ceramic sequence (Green and Anson 1991). Related variants of the standard Watom temper type include both placer sands formed by beach concentration of ferromagnesian mineral grains of high specific gravity, and feldspar-rich sands relatively depleted in such heavy mineral grains. Subordinate quartzose tempers are unrelated and clearly reflect different source rocks. Rare hornblende-bearing tempers of two distinct types differ in fundamental mineralogy from both the standard and the quartzose Watom tempers.

DATA APPRAISAL

The composition and probable derivation of Watom tempers are discussed below in the order of the apparent relative abundance of each temper type. The proportions of various grain types in the temper sands were established in my own work by frequency counts of the numbers of sand grains present, either within entire thin sections, along traverse bands of consistent widths crossing thin sections at consistent spacings, or within equally sized and evenly spaced fields of microscopic view (area counts or ribbon counts in the sense of Middleton *et al.* 1985). The compositional data of Yimer and Cook are couched in the form of point counts (Chayes 1956), which are generated by counting the grains present beneath the intersection points of a rectilinear grid superimposed on a thin section by moving a traversing stage in equal increments along parallel tracks to bring successive points of the grid beneath the microscope crosshairs. The two counting methods yield similar but not identical results (Dye and Dickinson 1996), with point counts yielding true volumetric proportions of grain types whereas frequency counts, which are less time-consuming, represent a different though equally reproducible measure of grain proportions. In general, as the sorting of grains by transport in water depends upon hydraulic equivalency, which varies by specific gravity, frequency counts have a bias toward higher proportions of heavier (and therefore smaller) grains in comparison with point counts of the same sands.

For the observed contrasts in the compositions of Watom tempers, however, inspection of my frequency counts and the point counts of Yimer and Cook indicates that the two methods yielded generally comparable results. For treatment in parallel with my 37 frequency counts, point-count data were extracted from the tables prepared by Yimer for the 35 of his sherds in which at least 20% of the temper grains are terrigenous minerals and rock fragments, exclusive of calcareous grains, ferruginous clay particles, and unidentified alterites (weathered or otherwise modified bedrock derivatives). This screening eliminated the point counts for which the relative proportions of grain types reflective of bedrock provenance are not precise enough for unambiguous interpretations. The point counts for which no polymineralic rock fragments were reported were also rejected as probably incomplete. The data of Cook were screened in analogous fashion to select the 15 sherds in which at least 30% of the temper grains are terrigenous, exclusive of calcareous grains and oxide particles that represent products of weathering or other alteration of bedrock materials. Grains tabulated by Cook as non-opaque "mafic minerals" are treated here as pyroxene, the dominant ferromagnesian mineral in Watom tempers.

Summaries of temper compositions presented here are thus based on tabulation of results obtained from multi-operator study of 87 Watom sherds. Although this total is a tiny fraction of the sherds recovered on Watom and cannot represent a valid statistical sample of all the sherds available, the careful megascopic culling of sherd collections by Anson, Green, and Specht ensures that all characteristic tempers are represented in the sherds examined and that no clearly anomalous and possibly exotic materials have been overlooked.

WATOM CALCAREOUS-VOLCANIC TEMPERS

The volcanic and related hybrid sands so prevalent in Watom sherds contain varying proportions of the following grain types that are fully compatible with derivation from bedrock lavas and breccias on Watom, together with admixtures of coastal reef detritus (Table 1): (1) plagioclase feldspar mineral grains, some with glass inclusions diagnostic of derivation from volcanic rocks; (2) pyroxene mineral grains, dominantly clinopyroxene (cpx) but also including orthopyroxene (opx); (3) volcanic rock fragments, among which pale brown to red-brown glassy grains, of roughly equant dimensions and in part devitrified to cryptocrystalline alteration products, are prominent; and (4) opaque iron oxide grains. Rare olivine grains, never more than one or two per thin section in my personal experience, are also present. In the thin sections of sherds in my possession provided by Shutler and Specht, the 'pyroxene index', cpx/(cpx + opx), is 0.88–0.94, a value compatible with descriptions of andesitic rocks from the Rabaul Volcanic Series (Heming 1974; Wood *et al.* 1995), which forms the bedrock exposures on Watom. Apart from the characteristic grains of volcanic glass, the volcanic rock fragments are a varied array of partly crystalline types displaying plagioclase microlites in hyalopilitic to intersertal groundmass textures typical of basalts and basaltic andesites. The moderately well sorted and subrounded hybrid sands have textures typical for island beach sands within Oceania (Dickinson 1998).

TABLE 1
Percentages of terrigenous grain types in hybrid calcareous-volcanic sand and related non-calcareous volcanic sand tempers indigenous to Watom

Grain type	**A WRD mean Ave (range) [N = 26]**	**B Yimer mean Ave (range) [N = 22]**	**C Cook mean Ave (range) [N = 12]**	**D Sherd wi8surd (WRD)**	**E Sherd wmm13d (WRD)**
Plagioclase	52 (30–70)	60 (50–70)	38 (20–55)	58	39
Pyroxene	12 (5–25)	13 (0–25)	19 (12–31)	15	2
Opaques	8 (0–20)	13 (5–25)	4 (0–12)	6	3
VRF	28 (18–52)	13 (7–25)	39 (22–65)	21	56

Note: All percentages recalculated exclusive of calcareous grains present in varying amounts in approximately half the sherds. WRD data (cols. A, DE) from frequency counts. Yimer and Cook data (cols.BC) from point counts. Differences between means and ranges (cols. A-C) reflect operator variance. Sherds of columns DE yielded anomalous microprobe analyses for paste but their temper compositions fall within or near the established spectrum for indigenous Watom temper. VRF is total polymineralic and polycrystalline or glassy volcanic rock fragments.

In the hybrid sands, the proportion of calcareous grains ranges upward from a roughly 50–50 mix toward nearly all (≈90%) calcareous grains in sherds examined personally, and downward toward almost none (≈10%) in sherds studied by Yimer and Cook. Proportions of grain types in the terrigenous fractions of hybrid sands and in the non-calcareous volcanic sands are closely comparable in all cases (Table 2). The only systematic difference between typical volcanic sands and hybrid sands is the varying admixture of coastal calcareous detritus present in the latter.

TABLE 2
Comparison of percentages of terrigenous grain types in hybrid calcareous-volcanic sand and non-calcareous volcanic sand tempers indigenous to Watom

	A Cook		B WRD		C Yimer	
Grain type	Calcareous-volcanic Ave (range) [N = 7]	Non-calc (Volcanic) Ave (range) [N = 5]	Calcareous-volcanic Ave (range) [N = 18]	Non-calc (Volcanic) Ave (range) [N = 8]	Calcareous-volcanic Ave (range) [N = 7]	Non-calc (Volcanic) Ave (range) [N = 15]
Plagioclase	38 (30–55)	37 (20–50)	50 (30–60)	54 (35–70)	61 (50–70)	60 (50–70)
Pyroxene	19 (12–30)	20 (15–31)	13 (5–25)	11 (5–20)	11 (4–17)	14 (0–25)
Opaques	4 (0–12)	4 (0–8)	8 (0–20)	9 (0–20)	15 (5–20)	12 (0–25)
VRF	39 (22–56)	39 (30–65)	29 (18–52)	26 (20–35)	13 (7–25)	14 (10–25)

Note: WRD data from frequency counts and Cook-Yimer data from point counts. Percentages for all calcareous-volcanic temper sands are recalculated exclusive of calcareous grains. Operator variance accounts for differences in Cook-WRD-Yimer means (Table 1A-C), but paired means for calcareous-volcanic and non-calcareous (volcanic) subsets of each dataset (Cook-WRD-Yimer) are statistically indistinguishable. VRF is total polymineralic and polycrystalline or glassy volcanic rock fragments.

In nearly half the hybrid calcareous-volcanic tempers examined personally, some or nearly all the calcareous grains have been dissolved post-depositionally from the sherds by post-burial weathering or subsurface leaching to leave rounded vacuoles of sand size as the only record of their former presence. Particularly revealing are two thin sections in which calcareous grains are fully retained in part of a sherd and wholly removed from another adjacent part, in which the former sites of calcareous grains are marked by vacuoles of exactly the same shape, size range, distribution, and frequency as calcareous grains in the unaltered part of the sherd. Some or all of the 'non-calcareous' volcanic sand tempers reported by Yimer and Cook (but not observed personally) may have had an analogous origin. Close attention to the likelihood that the percentages of calcareous grains in many of the hybrid tempers have been modified by post-depositional sherd alteration may well influence archaeological judgments concerning the stratigraphic and inter-site distributions of different temper variants. Clearcut visual evidence for post-burial loss of calcareous grains by dissolution may be difficult to discern megascopically. As a case in point, sherds from Kosrae were divided megascopically into calcareous-tempered and 'non-tempered' groups until petrographic study revealed that the only difference between the two groups stems from post-depositional removal of calcareous grains from the latter (Dickinson 1995).

The mixed calcareous-volcanic and related non-calcareous volcanic tempers are interpreted to be indigenous to Watom on three grounds: (1) they are the most abundant temper types in Watom sherds, and derivation from elsewhere would have required wholesale importation of temper sands or finished wares for which there is no independent archaeological evidence (Specht 1968; Green and Anson 1987, 1991); (2) although no modern or fossil beach sands from Watom are available for comparative study, the grain types present in the standard

Watom tempers are exactly those expected from Watom bedrock, with no extraneous grain types present; and (3) the occurrence of comparable terrigenous sands derived exclusively from basalt to basaltic andesite bedrock of the Rabaul Volcanic Series from coasts around Tawui Point and the shores of the submerged Rabaul caldera on the nearby mainland of New Britain (Fig.1) is unlikely because mafic lavas comparable to exposures on Watom in the annular uplands surrounding the Rabaul caldera are deeply mantled with more felsic pyroclastic deposits (Heming 1974; Wood *et al.* 1995). The extensive pyroclastic cover probably contributes volcanic sand of a wholly different character as a distinct 'contaminant' to local mainland sands. Watom Island fortuitously exposes the older mafic lavas of the Rabaul Volcanic Series in a distal position where the pyroclastic cover is thin. Indigenous origin of characteristic Watom wares is supported by the similarity of local Watom clay to clay pastes in typical Watom sherds, as confirmed by microprobe analysis (Anson 1983: 166).

Two kinds of closely related volcanic sands are also inferred to be indigenous Watom temper types: (1) placer sands (Table 3) enriched in heavy minerals by intense sedimentary sorting, probably on beach faces, and (2) anomalously feldspar-rich sands (Table 4) interpreted as a local variant of Watom detritus lacking normal proportions of volcanic rock fragments and ferromagnesian mineral grains. The placer tempers include both pyroxene-rich (Table 3A) and opaque-rich (Table 3B) variants. The feldspar-rich tempers, which lack calcareous grains and are more angular aggregates than standard Watom tempers, may be interior sands from small drainages on Watom. Both the placer sands with high contents of ferromagnesian minerals and the feldspar-rich sands, which differ from normal grain aggregates in the opposite sense, contain the same grain types as standard Watom tempers, but in different proportions. One of the sherds containing placer temper has an anomalous paste composition from microprobe analysis (Table 3: note), but is nevertheless regarded here as a compositional outlier of the indigenous Watom ceramic suite.

TABLE 3

Percentages of grain types in placer variants of indigenous Watom temper suite

	A. Pyroxene-rich (N = 3)			**B. Opaque-rich (N = 3)**		
	wi6sur14	**sherd #2**	**sherd #17**	**WI 7/1/15B**	**sherd #10**	**WI 11/43**
Grain type	**(WRD)**	**(Cook)**	**(Yimer)**	**(WRD)**	**(Cook)**	**(WRD)**
Plagioclase	7	42	37	29	22	9
Pyroxene	62	42	35	25	17	33
Opaques	12	10	18	38	46	51
VRF	19	6	10	8	15	7

Note: WRD data from frequency counts and Cook-Yimer data from point counts. VRF = polymínerallic and polycrystalline or glassy volcanic rock fragments. Sherd wi6sur14 has a chemically anomalous paste from microprobe analysis.

Three sherds containing hybrid calcareous-volcanic tempers have also yielded anomalous microprobe results from paste, but the tempers of two (Table 1DE) fall within or close to the standard spectrum of variation displayed by the Watom temper suite. The other (sherd gw17i), a sherd with unique design and finish from the original Meyer collection, differs markedly from all the standard Watom hybrid tempers in the character of its terrigenous sand component (35% together with 65% calcareous grains). The only ferromagnesian grains present in thin section are single grains of pyroxene, hornblende, and epidote. Plagioclase feldspar (≈25% of the terrigenous fraction) is accompanied by volcanic rock fragments (≈75% of the terrigenous fraction) that include none of the characteristic brownish glass grains present in the indigenous hybrid tempers and constitute a varied assemblage unlike those in the indigenous tempers: (1) hyalopilitic grains with plagioclase microlites set in black tachylite, so-called 'ore-charged' volcanic glass darkened by myriads of tiny oxide inclusions; (2) pilotaxitic grains composed of tightly packed plagioclase microlites with little or no interstitial glass; and (3) internally microgranular grains derived from hypabyssal dikes or sills. The provenance of this clearly anomalous temper is indeterminate with present information, but the intrusive detritus and the epidote grain of metamorphic or deuteric origin suggest a possible affinity with the quartzose tempers described next.

TABLE 4

Percentages of grain types in feldspar-rich variants of indigenous Watom temper suite

Grain type	Ave (range) (Yimer, N = 5)	sherd #10 (Cook)	sherd #3371 (WRD)
Plagioclase	82 (76-86)	80	78
Pyroxene	3 (0-7)	10	1
Opaques	6 (2-10)	-	2
VRF	9 (6-14)	10	19

Note: Yimer and Cook data from point counts. WRD data from frequency count. VRF = varied volcanic rock fragments. Pyroxene is entirely clinopyroxene.

QUARTZOSE NEW BRITAIN TEMPERS

Selected sherds studied by Yimer contain quartzose temper sands (Table 5A) that could not have been derived from Watom, but appear suitable for derivation from the prong of the Gazelle Peninsula west of Ataliklikin Bay (Fig. 1), as inferred previously by Green and Anson (1987: 127, 1991: 176). A single sherd with similar quartzose temper (Table 5B) contains paste that is chemically anomalous with respect to the standard Watom sherds that have been microprobed. The temper in the latter sherd is a subangular and poorly sorted aggregate ranging from very fine to coarse sand, and may well be natural temper that was imbedded in a sandy clay body of alluvial origin, for the nonplastic grains grade downward into the silt size range.

Several compositional parameters of the quartzose tempers jointly indicate derivation from intrusive igneous as well as volcanic bedrock. Significant proportions of quartz (≈10%), in company with abundant K-feldspar amounting to 20%–35% of the total feldspar, strongly suggest intrusive as well as volcanic source rocks, and microdioritic to micrograniticrock fragments with granular internal textures confirm the presence of detritus from both coarse plutonic and finer grained hypabyssal intrusive rocks in the sherd with chemically anomalous paste. Yimer also reports the minor presence of sedimentary rock fragments that could reflect detritus from either the wallrocks of intrusive igneous bodies or sedimentary cover above them. The occurrence of hornblende and biotite in the sherd with apparently natural temper and chemically anomalous paste is compatible with the presence of detritus from intrusive rocks.

The highlands of central and eastern New Britain from the Rabaul caldera complex west past the root of the Willaumez Peninsula are underlain by Upper Eocene (Baining Volcanics) to Upper Oligocene (Merai Volcanics) andesitic to basaltic volcanic and volcaniclastic rocks, intruded locally by Oligocene-Miocene dioritic plutons and overlain irregularly by Miocene sedimentary strata (Page and Ryburn 1977; Whalen and McDougall 1980; Whalen 1985). The North Baining intrusive complex, and its wallrocks, occupying the interior of the Cape Pomas sub-peninsula (Fig. 1), only 30–60 km west of Watom, is the nearest exposure of this geologically varied basement terrane (Lindley 1988), and was the most likely source of the quartzose temper in sherds from Watom. The presence of subordinate calcareous grains (10%–30%) in two-thirds of the quartzose tempers studied by Yimer suggests that at least some of the quartzose tempers represent coastal sands collected on beaches around the sub-peninsula. Whether temper or finished wares were imported to Watom cannot be determined from temper petrography alone, but the chemically anomalous paste in one of the quartzose sherds suggests that finished wares containing the quartzose tempers were brought to Watom from the New Britain mainland.

TABLE 5

Percentages of terrigenous grain types in quartzose temper sands of Watom sherds (Cols. A-B) and comparably feldspathic temper sands in sherds from Kreslo (Col. C)

Grain type	A Ave (range) of 7 Watom sherds	B Watom sherd wi81591	C Ave (range) of 8 Kreslo sherds
Quartz	9 (7-11)	2	8 (2-12)
Feldspar	59 (46-71)	63	50 (42-59)
Clinopyroxene	15 (7-18)	2	10 (0-20)
Orthopyroxene	-	-	1 (0-3)
Hornblende	-	4	2 (0-7)
Biotite	-	1	-
Opaques	7 (0-12)	5	5 (0-14)
Rock fragments	10 (6-15)	23	24 (6-42)

Note: Col. A from Yimer point counts. Cols. B-C from WRD frequency counts. Yimer percentages recalculated free of 10%-30% (ave ≈15%) calcareous grains. All feldspar in WRD Watom count is plagioclase but 22%-35% (ave 30%) of feldspar in Yimer counts is K-feldspar. Most rock fragments in Yimer counts are volcanic (plus subordinate sedimentary), but sub-percentages in WRD Watom count are as follows: microgranitic intrusive, 9%; microlitic volcanic, 8%; glassy volcanic, 6%. In Kreslo sherds, feldspar is plagioclase and rock fragments are predominantly volcanic.

Analogous quartz-bearing feldspathic tempers occur in Lapita sherds from Kreslo (Table 5C), located on the south coast of New Britain (Specht 1991), where detritus from the pre-mid-Miocene volcanogenic basement terrane of New Britain is evidently carried by mountainous streams to the coast (Fig. 1). Admixtures of calcareous sand (2%–32%) are also present in Kreslo sherds. The spectrum of tempers observed to date in Kreslo sherds includes more feldspar-rich (n=1), lithic-rich (n=1), pyroxene-rich (n=2), and opaque-rich (n=3) variants, with the latter two representing local placer sands. Nevertheless, the close similarity of quartz-bearing Watom tempers to the most prevalent (n=8) Kreslo temper type (Table 5) provides petrographic comfirmation that the former represent sands from nearby New Britain.

EXOTIC HORNBLENDE-BEARING TEMPERS

Three unusual sherds (Table 6A–C), two of which have yielded anomalous microprobe results from paste, contain hornblende-bearing temper sands lacking any calcareous grains, and are unlikely to have been derived from either Watom or New Britain. All three tempers are moderately well sorted and medium-grained sand, but are composed of generally subangular grains, and most probably represent fluvial channel sands. The two microprobed sherds (Table 6AB) contain no pyroxene at all, and in that respect their tempers differ from all those examined to date in sherds from anywhere within the Bismarck Archipelago, the Solomon Islands, or Vanuatu. With available information, their origin is a petrographic mystery. Their gross composition in terms of generic grain types resembles the feldspar-rich indigenous tempers (Table 4), but the presence of hornblende instead of pyroxene as the predominant ferromagnesian silicate mineral sets them apart from all the indigenous Watom tempers.

TABLE 6

Percentages of grain types in hornblende-bearing temper sands in Watom sherds and comparative tempers from the Admiralty Islands and Bouganville

Grain type	A wi67412I (WRD)	B wi6sur21I (WRD)	C WI/6/2947 (WRD)	D Bougainville (Paubake)	E Admiralty Islands
Plagioclase	76	65	24	29	33
Pyroxene	-	-	30	34	25
Hornblende	3	8	32	26	27
Opaques	2	15	6	6	5
VRF	19	12	8	5	10

Note: All data from frequency counts by WRD. Column D is placer temper in Paubake (Bougainville) sherd 4473/BS-6 (Dickinson 1973: Table 49-1). Column E is average of eight andesitic tempers (unpublished data) in sherds inferred to be indigenous to Manus but in part transported to outlying islands of the Admiralty Group.

The third sherd (Table 6C), from the Specht collection, contains both pyroxene (pyx) and hornblende (hbl) in subequal proportions and could represent ware from either the Admiralty Islands or Bougainville, but Table 6DE shows that presumptive temper matches can be proposed for either option in terms of overall grain proportions. The 'pyribole index', pyx/(pyx + hbl), of 0.48 is matched by the average pyribole index of andesitic Admiralty tempers (Table 6E), but its value ranges widely (0.32–0.87) for individual Admiralty sherds, even though the sum of pyroxene and hornblende in them is quasi-constant at 52 ± 9% (std. dev.). As a closer match of temper and paste textures is provided by the Bougainville sherd (Table 6D), no specific provenance can be inferred with confidence on strictly geologic grounds. On archaeological grounds, however, the occurrence on Watom of associated obsidian artefacts sourced in part to the Admiralty Islands (Green and Anson 1987: 127–28, 1991: 177–78) makes an Admiralty origin seem more likely than a Bougainville origin. Derivation of any of the exotic hornblende-bearing tempers from New Britain seems unlikely with present information, but derivation from nearby New Ireland is not precluded by available data.

OTHER BISMARCK ARCHIPELAGO TEMPERS

Indigenous Watom tempers differ mineralogically in various ways from tempers in prehistoric sherds from sites on other islets of offshore New Britain (Table 7), and from known New Ireland and Admiralty tempers (Table 8). Differences between Watom and other tempers of the Bismarck Archipelago (Fig. 2) are understandable in terms of regional geologic history and its control on the distribution of petrotectonic assemblages with contrasting volcanic mineralogy. A brief overview of known areal variations in temper composition sets the stage for a succeeding geologic appraisal of generic temper types within the region.

TABLE 7

Average percentages of terrigenous grain types in Lapita temper sands from selected islets of offshore New Britain

Grain type	**A** **Boduna Island** **(N = 2)**	**B** **Garua Island** **(N = 2)**	**C** **Watom Volcanic** **(N = 26)**	**D** **Arawe (Apalo)** **(N = 3)**	**E** **Watom Placer** **(N = 1)**	**F** **Arawe (Adwe)** **(N = 4)**
Quartz	tr	1	-	-	-	-
Plagioclase	43	56	52	2	9	16
Clinopyroxene	17	9	11	32	30	35
Orthopyroxene	9	4	1	2	3	5
Hornblende	2	2	-	-	-	tr
Olivine	1	1	tr	tr	tr	tr
Opaques	16	5	8	59	51	32
VRF	12	22	28	5	7	12

Note: All percentages from WRD frequency counts. VRF = volcanic rock fragments. Average Watom volcanic temper (col. C) from Table 1A (=Table 2B). Average Arawe placer temper (col. D) recalculated to exclude up to 12% calcareous grains. Selected Watom placer temper (col. E) from Table 3 (sherd WI 11/43). Less placered Arawe temper (col. F) included for comparison.

Temper sands in sherds from Boduna (Ambrose and Gosden 1991) and Garua (Specht 1974; Boyd and Torrence 1996) near the Willaumez Peninsula on the north coast of central New Britain (Fig. 1) are non-calcareous volcanic beach sands (Table 7AB) containing proportions of feldspathic, ferromagnesian, opaque, and lithic grains comparable to the terrigenous fraction of standard Watom tempers (Table 7C). Hornblende and minor quartz are present, however, in both suites, and the 'pyroxene index', cpx/(cpx + opx), is 0.65–0.70, as opposed to ≈0.90 for indigenous Watom tempers. Beach sand tempers from the Apalo site on Kumbun in the Arawe Islands (Gosden 1989, 1991; Gosden and Webb 1994) off the southwest coast of New Britain are placer beach sands, with admixtures of calcareous grains, but the terrigenous fraction (Table 7D) closely resembles the most opaque-rich placer sand observed in Watom sherds (Table 7E). Other Arawe tempers from nearby Adwe (Table 7F) are typically less opaque-rich, but comparable in petrologic character, and also distinctly less feldspathic than standard Watom tempers. The pyroxene index (0.86–0.94) for Arawe temper is closely comparable to the values (0.88–0.94) obtained from Watom sherds. Boduna, Garua, and Arawe sherds were probably brought to the offshore islets from adjacent segments of the New Britain mainland.

TABLE 8

Average percentages of terrigenous grain types in selected temper sands from New Ireland and Admiralty Islands

Grain type	A Lasigi non-placer N = 2	B Lossu (Lesu) N = 2	C Lossu (Lesu) N = 3	D Admiralty felsitic N = 4	E Mussau non-placer N = 4	F Mussau placer N = 2
Quartz	-	-	-	11	-	-
Plagioclase	59	56	56	36	65	40
Pyroxene	12	14	34	3	1	17
Hornblende	9	11	2	3	11	17
Opaques	6	7	2	7	11	10
VRF	14	12	6	39	12	15

Note: All data from frequency counts by WRD. Lossu (Lesu) data from Dickinson (1980), with hornblende-rich (col. B) and hornblende-poor (col. C) sands averaged separately. VRF = volcanic rock fragments. Lasigi (col. A) and Lossu (cols. BC) are non-Lapita sites on New Ireland (see text). Admiralty Islands felsitic tempers (col. D) occur in non-Lapita sherds from Lou, Baluan, and M'Buke (see Fig. 2). Terrigenous tempers in Lapita sherds from Mussau (cols. EF) are exotic to Mussau (Fig. 2), which exposes only calcareous sands. Mussau placer tempers also contain minor biotite (≈1%).

Tempers in prehistoric sherds from Lasigi (Golson 1991) and Lossu or Lesu (White and Downie 1980) on the northeast coast of New Ireland (Fig. 2) contain volcanic sand tempers (Table 8A–C), probably including both beach and stream sands, that are compositionally similar to the terrigenous fraction of standard Watom tempers except for the prominence of hornblende grains. Andesitic tempers from Manus (Kennedy 1982) are comparably rich in hornblende, or even more so (Table 6E). Volcanic sand tempers from the small islands south of Manus are quartz-bearing and contain a population of volcanic rock fragments dominated (50%–75% of VRF) by felsite grains derived from silicic volcanic rocks (Table 8D). The felsite grains are composed of intergrown quartz and feldspar as a microcrystalline mosaic, and represent groundmass fragments of rhyolitic to dacitic lavas or breccia blocks.

Exotic Lapita sherds with non-calcareous tempers from Eloaua islet off Mussau (Fig.2), where abundant calcareous grains are present in all local sands (Kirch *et al.* 1991), typically contain hornblende-rich volcanic sand tempers (Table 8EF). Less abundant exotic tempers so far observed in only two Mussau sherds are pyroxene-rich placer sands composed dominantly of clinopyroxene and plagioclase grains, with only ≈10% volcanic rock fragments and just traces of hornblende present (unpublished data).

Appraisal of geotectonic temper provinces within the Bismarck Archipelago can best be approached in two stages, first with a focus on the diverse volcanic assemblages internal to New Britain, and then by turning attention to broader relations involving other islands within and bordering the Bismarck Sea.

NEW BRITAIN VOLCANIC BELTS

New Britain harbours three distinct post-Miocene volcanic provinces (Fig. 1):

(1) On the far west, the Shrader and Andrews (or Andewa) massifs inland from Cape Gloucester to Rein Bay and Cape Merkus represent a dormant continuation of the Manam-Karkar chain of active volcanic islands (Schouten Islands) extending to the west of New Britain off the coast of the Huon Peninsula of Papua New Guinea (Johnson 1976). Manam and Karkar erupt mainly pyroxene-bearing basalt and basaltic andesite in which orthopyroxene is rare or absent and hornblende is lacking (Palfreyman and Cooke 1976; McKee *et al.* 1976; Johnson *et al.* 1985). Arawe tempers (Table 7D) of southwest New Britain are mineralogically compatible with derivation from source rocks exposed in the Andewa massif inland from the coast. The mineralogical similarity of Arawe tempers to opaque-rich Watom placer temper is an apt reminder of the ambiguities that temper analysis can encounter. Although the analogous Watom placer temper (Table 7E) is finer grained than most Arawe temper sands, and is less abundant relative to enclosing clay paste, its mineralogy could be taken as an indication that the surface sherd containing it was imported from Arawe.

(2) The north coast from the Willaumez Peninsula east to the root of the Gazelle Peninsula is a belt of both active and dormant Quaternary island-arc volcanoes linked genetically to subduction of Solomon Sea oceanic crust downward to the north at the New Britain Trench lying south of New Britain (Johnson 1976). Dominant pyroxene andesite, with associated basalt and dacite-rhyolite, commonly contains both pyroxenes (orthopyroxene and clinopyroxene) in significant abundance (Lowder and Carmichael 1970; Johnson *et al.* 1972; Blake and Ewart 1974; Blake 1976; DePaolo and Johnson 1979; Johnson *et al.* 1983; Machida *et al.* 1996: Table 1). High ratios of orthopyroxene to clinopyroxene in sherds from Boduna and Garua (Table 7AB) are fully compatible with derivation of their tempers from the nearby north-coastal volcanic belt of New Britain.

(3) At the northeastern tip of the bulbous Gazelle Peninsula east of Open Bay and Wide Bay, eruptions around the Rabaul caldera (Wood *et al.* 1995), including the lavas of Watom Island (Heming 1974) and of the slightly older rhyodacites of the Mio-Pliocene Nengmuka Volcanics somewhat farther inland (Lindley 1988), have been linked spatially to incipient rupture of New Britain along fault systems associated with lateral displacement of nearby New Ireland to the northwest with respect to New Britain (Madsen and Lindley 1994). Although some orthopyroxene is present in Quaternary volcanic rocks of the Rabaul caldera complex and Watom, it is much less abundant in the unique geotectonic setting of the Gazelle Peninsula than along the main New Britain magmatic arc lying farther to the west along the north coast of the island.

Knowledge of the relative abundance of different ferromagnesian minerals in the pre-mid-Miocene basement terrane of New Britain is severely limited, but clinopyroxene is probably dominant in the volcanic rocks and hornblende in the plutons that intrude them, with orthopyroxene rare or absent (Whalen 1985). The mixture of subordinate hornblende and clinopyroxene in the quartzose temper sand of a Watom sherd (Table 5B) inferred to have

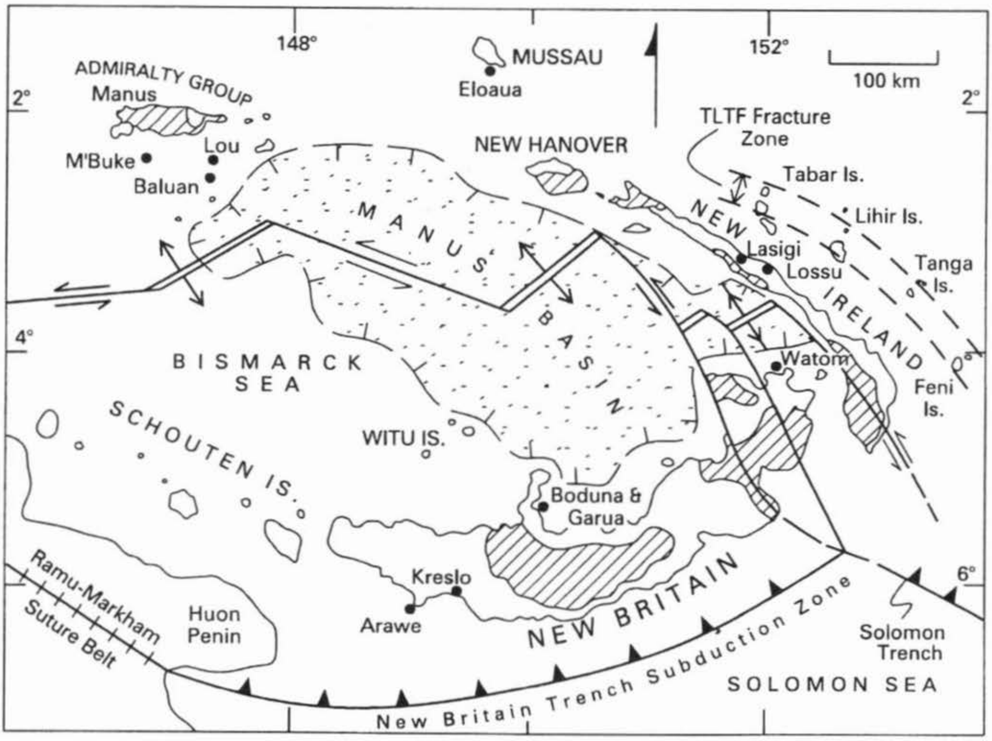

Figure 2: Sketch map of Bismarck Archipelago showing archaeological sites and geological provinces discussed in the text (see Fig. 1 for internal details within New Britain). Geological features after Figure 1, Jaques (1981), Francis (1988), Madsen and Lindley (1994), and Martinez and Taylor (1996). Heavy lines denote microplate boundaries (spreading centres shown as double lines and transform faults with lateral motion as single lines), with arrows indicating relative plate motions. Black dots are pottery sites discussed in text.

been derived from the New Britain basement terrane accords well with expectation, and the predominance of pyroxene over hornblende in Kreslo tempers from the southwest coast is also compatible with derivation of sand from pre-mid-Miocene basement. The pyroxene index (0.78–0.94) of non-placer Kreslo tempers may be a reliable guide to the proportions of clinopyroxene and orthopyroxene in basement detritus. The key indicator of basement derivation for New Britain tempers, however, is the consistent presence of quartz grains derived from intrusive plutons (Table 5).

BISMARCK ARCHIPELAGO GEOTECTONIC HISTORY

Interpretations of tempers derived from pre-Pliocene bedrock of New Britain, New Ireland, New Hanover, and Manus are complicated by the perception that those four main islands of the Bismarck Archipelago were once nearly contiguous, and shared to some extent the same geologic history, prior to post-Miocene seafloor spreading within the Bismarck Sea (Johnson 1979; Martinez and Taylor 1996). The now separate islands are disrupted and displaced segments of the same ancestral island arc (Exon and Marlow 1988), and analogous pre-Pliocene basement terranes of each can be expected to yield broadly similar detritus. Figure 3 shows a speculative mid-Miocene reconstruction of the region with the Bismarck Sea closed. Manus was then tucked close to New Britain, and New Hanover and New Ireland formed a southeasterly continuation of the combined island-arc trend (Weissel *et al.* 1982).

The Upper Eocene Baining Volcanics and Upper Oligocene Merai Volcanics of New Britain have petrogenetic counterparts in the Middle Eocene Tinniwi Volcanics of Manus (Jaques 1980; Francis 1988) and the Lower to Middle Oligocene Jaulu Volcanics of New Ireland (Hohnen 1978; Brown 1982; Stewart and Sandy 1988). The Lower to Middle Miocene Tasikim Agglomerate and Upper Miocene 'Lorengau Basalt' (actually including andesite as well as basalt) of Manus are also analogous to the Upper Miocene Lavongai Volcanics of New Hanover and Lumis River Volcanics of New Ireland. Polymodal but largely dioritic subvolcanic plutons of similar character occur as individually named Oligocene-Miocene and mid-Miocene intrusive complexes on New Britain, the Oligocene and mid-Miocene Lemau Intrusive Complex of New Ireland, and the Middle to Upper Miocene Yirri Intrusive Complex of Manus. Similar Miocene limestones flanking and capping the Paleogene volcanogenic assemblages include the Mundrau Limestone of Manus, the Lelet Limestone of New Ireland, and the Yalam Limestone of New Britain.

The geotectonic reconstruction implies that it may be impossible to distinguish generically between tempers derived from pre-Pliocene basement terranes of the once-connected islands now bordering the Bismarck Sea, although empirical criteria for distinction may prove valid. The significance for interpretation of Watom tempers is simply that the exotic hornblende-bearing tempers, at least one of which appears to show mineralogical affinity with known Manus tempers, may instead have been derived from some as yet untested locale in New Britain or New Ireland, much closer to Watom.

The seafloor spreading system of the Bismarck Sea that carried Manus off to the north of New Britain is bounded to the east by a transform fault system, passing through St George Channel, along which New Ireland has been carried laterally past the east end of New Britain. Subsidiary fault strands of the transform fault system have partly disrupted the Gazelle Peninsula at the eastern end of New Britain to create the unique geotectonic setting responsible for Neogene eruptions at the Rabaul and related calderas near Watom. Close analogues of indigenous Watom tempers are thus not expected on New Ireland, New Hanover, Manus, or the various neighbouring island clusters (Fig. 2).

The small islands south of Manus, and the southwesternmost peninsula of Manus itself, grew during opening of the the Bismarck Sea as a result of bimodal basalt-rhyolite or basalt-rhyodacite eruptive systems, some of which are still active, related to seafloor spreading within the adjacent Manus Basin (Johnson and Smith 1974; Johnson *et al.* 1978; Jaques 1981). Individual islands represent either mafic or felsic phases of the bimodal volcanism, but not both jointly. Quartz-bearing felsitic volcanic tempers of the Admiralty Group (Table 8D), occurring in sherds from Lou, Baluan, and M'Buke (Fig. 2), were evidently derived

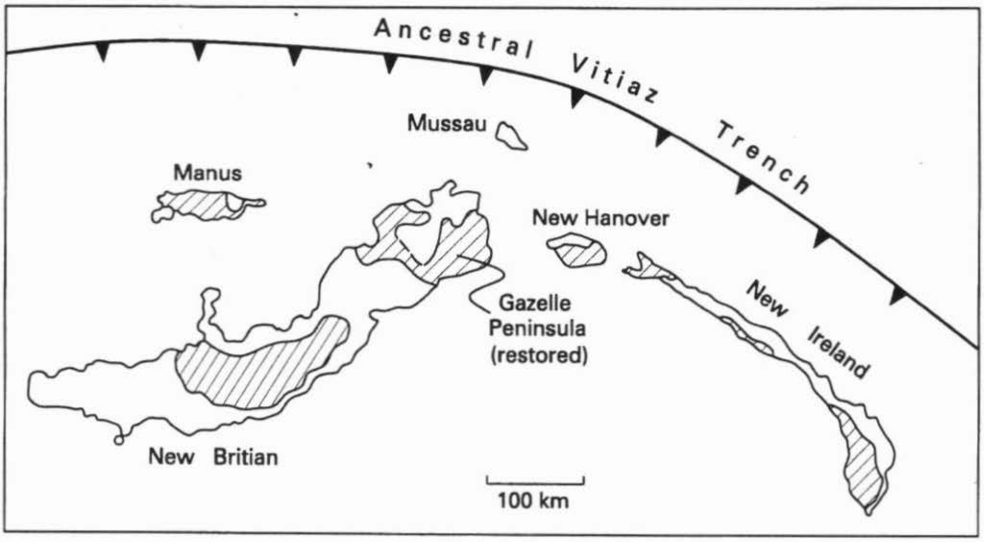

Figure 3: Speculative geotectonic reconstruction of Bismarck Archipelago prior to post-Miocene seafloor spreading within the Bismarck Sea (modified after Weissel *et al.* 1982). Ruled areas are present-day exposures (Fig. 2) of pre-Pliocene (largely Paleogene) volcanogenic Bismarck basement rocks.

from rhyolitic to rhyodacitic end members of the bimodal volcanic assemblage, but basaltic tempers are as yet unknown from the Admiralty Group.

Andesitic volcanic tempers in sherds from Manus (Table 6E) and New Ireland (Table 7A–C), though varied in detail, all contain both clinopyroxene and hornblende, in subequal abundance, to the exclusion of orthopyroxene. Abundance of orthopyroxene in potential source rocks is effectively restricted, within the Bismarck Archipelago, to the active island arc along the north coast of New Britain. Sherds containing Manus andesitic tempers include exotic sherds recovered from Lou, Baluan, and M'Buke south of Manus, where only non-andesitic bimodal volcanic assemblages are present as local bedrock. The most prevalent terrigenous sand tempers in sherds from Mussau (Table 8EF) are also hornblende-bearing andesitic sands with generic resemblance to Manus and New Ireland tempers, although no firm matches have yet been demonstrated for the exotic Mussau tempers.

The extinct Plio-Pleistocene volcanoes forming the Tabar-Lihir-Tanga-Feni (TLTF) island chain northeast of New Ireland (Fig. 2) are unrelated to seafloor spreading, but erupted strongly alkalic lavas of shoshonitic character that may reflect linkage of the volcanism to a fracture system lying subparallel to the transform fault separating New Ireland from young seafloor of the Bismarck Sea to the west (Johnson 1979). The apparently alkalic nature of the green clinopyroxene in hornblende-free but pyroxene-rich placer tempers in two exotic Lapita sherds from Mussau suggests geologically that the wares containing them may come from some locality near the northern end of the TLTF chain. There is at present, however, no archaeological support for the suggestion, and most of the few sherds examined to date from Ambitle in the Feni Islands at the southern end of the TLTF chain (White and Specht 1971) contain varying amounts of hornblende as well as pyroxene (unpublished data).

CONCLUSIONS

1. The most abundant tempers in Watom sherds are hybrid calcareous-volcanic and related volcanic aggregates interpreted as indigenous Watom sands. Post-burial removal of calcareous grains by dissolution is a common but not universal phenomenon affecting the overall proportions of terrigenous and calcareous grains in selected Watom sherds.

2. Subordinate tempers in Watom sherds include (a) quartzose sands probably derived from nearby New Britain and (b) hornblende-bearing tempers from unknown sources, most probably Manus in the Admiralty Islands, but possibly New Ireland-New Hanover or Bougainville in that order of likelihood.

3. Indigenous Watom tempers are distinguishable from tempers in sherds from the north coast of New Britain and its offshore islands by fundamental differences in the ratio of clinopyroxene to orthopyroxene.

4. Tempers from Manus, New Ireland, and nearby smaller islands of the Bismarck Archipelago also differ mineralogically from indigenous Watom tempers, as expected from the geotectonic history of the region.

ACKNOWLEDGEMENTS

I thank Dimitri Anson and Roger Green for providing key Watom sherds for petrographic analysis, and appreciate their encouragement to complete this paper. The work of Mareshet Yimer and Yvonne Cook was instigated by Roger Green and Dimitri Anson, respectively, who provided their data to me. Sherds for comparative study were graciously provided by Wal Ambrose, Jack Golson, Chris Gosden, Jean Kennedy, Pat Kirch, Richard Shutler Jr., Jim Specht, Glenn Summerhayes, John Terrell, Robin Torrence, and Peter White.

REFERENCES

Ambrose, W. and Gosden, C. 1991. Investigations on Boduna island. *In* J. Allen and C. Gosden (Eds), *Report of the Lapita Homeland Project*, pp. 182–88. Australian National University Occasional Papers in Prehistory 20, Canberra.

Anson, D. 1983. Lapita Pottery of the Bismarck Archipelago and its Affinities. Unpublished Ph.D. thesis, University of Sydney.

Blake, D.H. 1976. Pumiceous pyroclastic deposits of Witori volcano, New Britain, Papua New Guinea. *In* R.W. Johnson (Ed.), *Volcanism in Australasia*, pp. 191–200. Elsevier, Amsterdam.

Blake, D. H. and Ewart, A. 1974. Petrography and geochemistry of the Cape Hoskins volcanoes, New Britain, Papua New Guinea. *Geological Society of Australia Journal* 21: 319–31.

Boyd, B. and Torrence, R. 1996. Periodic erosion and human land-use on Garua Island, PNG: a progress report. *Tempus* 6: 265–74.

Brown, C. M. 1982. Kavieng, Papua New Guinea. *Papua New Guinea Geological Survey 1:250,000 Geological Series Explanatory Notes* SA/56-9: 1–19.

Chayes, F. 1956. *Petrographic Modal Analysis*. Wiley, New York.

DePaolo, D.J. and Johnson, R.W. 1979. Magma genesis in the New Britain island-arc: constraints from Nd and Sr isotopes and trace-element patterns. *Contributions to Mineralogy and Petrology* 70: 367–379.

Dickinson, W.R. 1973. Petrographic report on pottery sherds and fired clay samples from the Paubake survey area, south Bougainville. *Field Museum of Natural History Reports of the Bougainville Archaeological Survey* 8, Chicago.

Dickinson, W.R. 1980. Sand tempers in Lesu sherds from New Ireland. *Asian Perspectives* 23: 217–18.

Dickinson, W.R. 1995. Temper sand in prehistoric sherds from Kosrae. *In* J.S. Athens (Ed.), *Landscape Archaeology: Prehistoric Settlement, Subsistence, and Environment of Kosrae, Eastern Caroline Islands, Micronesia*, pp. 271–76. International Archaeological Research Institute, Honolulu.

Dickinson, W.R. 1998. Petrographic temper provinces of prehistoric pottery in Oceania. *Records of the Australian Museum* 50: 263–76.

Dye, T.S. and Dickinson, W.R. 1996. Sources of sand tempers in prehistoric Tongan pottery. *Geoarchaeology* 11: 141–64.

Exon, N.F. and Marlow, M.S. 1988. Tripartite study of the New Ireland-Manus region, Papua New Guinea: an introduction. *In* M.S. Marlow, S.V. Dudisman and N.F. Exon (Eds), *Geology and Offshore Resources of Pacific Island Arcs — New Ireland and Manus Region, Papua New Guinea*, pp. 1–9. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series 9, Houston.

Francis, G. 1988. Stratigraphy of Manus island, western New Ireland basin, Papua New Guinea. *In* M.S. Marlow, S.V. Dudisman and N.F. Exon (Eds), *Geology and Offshore Resources of Pacific Island Arcs — New Ireland and Manus Region, Papua New Guinea*, pp. 31–40. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series 9, Houston.

Golson, J. 1991. Two sites at Lasigi, New Ireland. *In* J. Allen and C. Gosden (Eds), *Report of the Lapita Homeland Project*, pp. 244–59. Australian National University Occasional Papers in Prehistory 20, Canberra.

Gosden, C. 1989. Prehistoric social landscapes of the Arawe Islands, west New Britain Province, Papua New Guinea. *Archaeology in Oceania* 24: 45–58.

Gosden, C. 1991. Towards an understanding of the regional archaeological record from the Arawe Islands, west New Britain, Papua New Guinea. *In* J. Allen and C. Gosden (Eds), *Report of the Lapita Homeland Project*, pp. 205–16. Australian National University Occasional Papers in Prehistory 20, Canberra.

Gosden, C. and Webb, J. 1994. The creation of a Papua New Guinean landscape: archaeological and geomorphological evidence. *Journal of Field Archaeology* 21: 29–51.

Green, R.C. 1979. Lapita. *In* J.D. Jennings (Ed.), *The Prehistory of Polynesia*, pp. 27–60. Harvard University Press, Cambridge.

Green, R.C. 1992. Definitions of the Lapita cultural complex and its non-ceramic component. *In* J.C. Galipaud (Ed.), *Poterie Lapita et Peuplement*, pp. 7–20. ORSTOM, Noumea.

Green, R.C. 1997. Linguistic, biological, and cultural origins of the initial inhabitants of Remote Oceania. *New Zealand Journal of Archaeology* 17: 5–27.

Green, R.C. and Anson, D. 1987. The Lapita site of Watom: new evidence from excavations in 1985. *Man and Culture in Oceania* 3 (Special Issue): 121–31.

Green, R.C. and Anson, D. 1991. The Reber-Rakival site on Watom, implications of the 1985 excavations at the SAC and SDI localities. *In* J. Allen and C. Gosden (Eds.), *Report of the Lapita Homeland Project*, pp. 170–81. Australian National University Occasional Papers in Prehistory 20, Canberra.

Heming, R.F. 1974. Geology and petrology of the Rabaul Caldera, Papua New Guinea. *Geological Society of America Bulletin* 85: 1253–64.

Heming, R.F. 1977. Mineralogy and proposed *P-T* paths of basaltic lavas from Rabaul Caldera, Papua New Guinea. *Contributions to Mineralogy and Petrology* 61: 15–33.

Hohnen, P.D. 1978. The geology of New Ireland. *Australian Bureau of Mineral Resources Bulletin* 176: 1–39.

Jaques, A.L. 1980. Admiralty Islands, Papua New Guinea. *Papua New Guinea Geological Survey 1:250,000 Geological Series Explanatory Notes* SA/55-10, SA/55-11: 1–11.

Jaques, A.L., 1981. Quaternary volcanism on Manus and M'Buke Islands. *In* R.W. Johnson (Ed.), *Cooke-Ravian Volume of Volcanological Papers*, pp. 213–19. Papua New Guinea Geological Survey Memoir 10, Port Moresby.

Johnson, R.W. 1976. Late Cainozoic volcanism and plate tectonics at the southern margin of the Bismarck Sea, Papua New Guinea. *In* R.W. Johnson (Ed.), *Volcanism in Australasia*, pp. 101–16. Elsevier, Amsterdam.

Johnson, R.W. 1979. Geotectonics and volcanism in Papua New Guinea: a review of the late Cainozoic. *BMR Journal of Australian Geology and Geophysics* 4: 181–207.

Johnson, R.W. and Smith, I.S.E. 1974. Volcanoes and rocks of St. Andrew Strait, Papua New Guinea. *Geological Society of Australia Journal* 21: 333–51.

Johnson, R.W., Davies, R.A. and White, A.J.R. 1972. Ulawun volcano, New Britain. *Australian Bureau of Mineral Resources, Geology, and Geophysics Bulletin* 142: 1–42.

Johnson, R.W., Smith, I.S.E. and Taylor, S.R. 1978. Hot-spot volcanism in St. Andrew Strait, Papua New Guinea. *BMR Journal of Australian Geology and Geophysics* 3: 55–69.

Johnson, R.W., Macnab, R.P., Ryburn, R.J., Cooke, R.J.S. and Chappell, B.W. 1983. Bamus volcano, Papua New Guinea: dormant neighbor of Ulawun and magnesian andesite locality. *Geologisches Rundschau* 72: 207–37.

Johnson, R. Jaques, A.L., Hickey, R.L., McKee, C.O. and Chappell, B.W. 1985. Manam Island, Papua New Guinea: petrology and geochemistry of a low-TiO_2 basaltic island-arc volcano. *Journal of Petrology* 26: 283–323.

Kennedy, J. 1982. Archaeology in the Admiralty Islands. *Indo-Pacific Prehistory Association Bulletin* 3: 22–35.

Kirch, P.V., Hunt, T.L., Weisler, M., Butler, V. and Allen, M.S. 1991. Mussau Islands prehistory: results of the 1985–86 excavations. *In* J. Allen and C. Gosden (Eds), *Report of the Lapita Homeland Project*, pp. 144–63. Australian National University Occasional Papers in Prehistory 20, Canberra.

Lindley, D. 1988. Early Cainozoic stratigraphy and structure of the Gazelle Peninsula, east New Britain: an example of extensional tectonics in the New Britain arc-trench complex. *Australian Journal of Earth Sciences* 35: 231–44.

Lowder, G.G. and Carmichael, I.S.E. 1970. The volcanoes and caldera of Talasea, New Britain: geology and petrology. *Geological Society of America Bulletin* 81: 17–38.

Machida, H., Blong, R.J., Specht, J., Moriwaki, H., Torrence, R., Hayakawa, Y., Talai, B., Lolok, D. and Pain, C.F. 1996. Holocene explosive eruptions of Witori and Dakataua caldera volcanoes in west New Britain, Papua New Guinea. *Quaternary International* 34–36: 65–78.

McKee, C.O., Cooke, R.J.S. and Wallace, D.A. 1976. 1974–1975 eruption of Karkar volcano, Papua New Guinea. *In* R.W. Johnson (Ed.), *Volcanism in Australasia*, pp. 173–90. Elsevier, Amsterdam.

Madsen, J.A. and Lindley, I.D. 1994. Large-scale structures on Gazelle Peninsula, New Britain: implications for the evolution of the New Britain arc. *Australian Journal of Earth Sciences* 41: 561–69.

Martinez, F. and Taylor, B. 1996. Backarc spreading, rifting, and microplate rotation between transform faults in the Manus Basin. *Marine Geophysical Researches* 18: 203–24.

Middleton, A.P., Freestone, I.C. and Leese, M.N. 1985. Textural analysis of ceramic thin sections: evaluation of grain sampling procedures. *Archaeometry* 27: 64–74.

Page, R.W. and Ryburn, R.J. 1977. K-Ar ages and geological relations of intrusive rocks in New Britain. *Pacific Geology* 12: 99–105.

Palfreyman, W.D. and Cooke, R.J.S. 1976. Eruptive history of Manam volcano, Papua New Guinea. *In* R.W. Johnson (Ed.), *Volcanism in Australasia*, pp. 117–31. Elsevier, Amsterdam.

Specht, J. 1968. Preliminary report of excavations on Watom Island. *Journal of the Polynesian Society* 77: 117–34.

Specht, J. 1974. Lapita pottery at Talasea, west New Britain, Papua New Guinea. *Antiquity* 48: 302–6.

Specht, J. 1991. Kreslo: a Lapita pottery site in southwest New Britain. *In* J. Allen, J. and C. Gosden (Eds), *Report of the Lapita Homeland Project*, pp. 189–204. Australian National University Occasional Papers in Prehistory 20, Canberra.

Stewart, W.D. and Sandy, M.J. 1988. Geology of New Ireland and Djaul Islands, northeastern Papua New Guinea. *In* M.S. Marlow, S.V. Dudisman and N.F. Exon (Eds), *Geology and Offshore Resources of Pacific Island Arcs — New Ireland and Manus Region*, pp. 13–30. Circum-Pacific Council for Energy and Mineral Resources 9, Houston.

Weissel, J.K., Taylor, B. and Karner, G.D. 1982. The opening of the Woodlark Basin, subduction of the Woodlark spreading system, and the evolution of northern Melanesia since mid-Pliocene time. *Tectonophysics* 87: 253–77.

Whalen, J.B. 1985. Geochemistry of an island-arc plutonic suite: the Uasilau-Yau Yau intrusive complex, New Britain, P.N.G. *Journal of Petrology* 26: 603–32.

Whalen, J.B. and McDougall, I. 1980. Geochronology of the Uasilau-Yau Yau porphyry copper prospect, New Britain, Papua New Guinea. *Economic Geology* 75: 566–71.

White, J.P. and Downie, J.E. 1980. Excavations at Lesu, New Ireland. *Asian Perspectives* 23: 193–220.

White, J.P. and Specht, J. 1971. Prehistoric pottery from Ambitle Island, Bismarck Archipelago. *Asian Perspectives* 14: 88–94.

Wood, C.P., Nairn, I.A., McKee, C.O. and Talai, B. 1995. Petrology of the Rabaul Caldera area, Papua New Guinea. *Journal of Volcanology and Geothermal Research* 69: 285–302.

Zuffa, G.G. 1979. Hybrid arenites: their composition and classification. *Journal of Sedimentary Petrology* 50: 21–29.

Received 8 August 1998
Accepted 30 September 1998