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Petrographic Temper Provinces of Prehistoric Pottery in Oceania

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ABSTRACT. The mineralogical compositions and petrological character of non-calcareous mineral sand tempers in prehistoric potsherds from Pacific islands are governed by the geographic distribution of geotectonic provinces controlled by patterns of plate tectonics. As sands from different islands are not mingled by sedimentary dispersal systems, each temper sand is a faithful derivative record of parent bedrock exposed on the island of origin. Tempers are dominantly beach and stream sands, but also include dune sand, colluvial debris, reworked volcanic ash, broken rock, and broken pottery (grog). From textural relations with clay pastes, most tempers were manually added to clays collected separately, but naturally tempered clay bodies occur locally. Calcareous temper sands derived from reef detritus are widely distributed, but ancient potters commonly preferred non-calcareous sands for temper. Consequently, beach placer sand tempers rich in diagnostic heavy minerals are typical of many temper suites. Distinctive temper classes include oceanic basalt, andesitic arc, dissected orogen, and tectonic highland tempers characteristic of different geologic settings where contrasting bedrock terranes are exposed. Most Oceanian sherd suites contain exclusively indigenous tempers derived from local island bedrock, but widely distributed occurrences of geologically exotic tempers document limited pottery transfer over varying distances at multiple sites.

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This paper focuses on regional patterns of compositional variation, in terms of mineralogy and petrology, observed for sands contained in prehistoric earthenware pottery of island Oceania. The sands imbedded in the clay bodies are commonly called “temper” because their presence improves the behaviour of the clay during the fabrication of ceramic wares. Conclusions are based on petrographic study, over a span of three decades, of approximately 1200 thin sections made from sherds collected by numerous archaeologists (see acknowledgments) working in island groups of both the southern and western Pacific Ocean

(Fig. 1). Although ceramic petrography is notoriously underutilised in archaeology (Schubert, 1986; Stoltman, 1989), it is a powerful tool for the study of Oceanian tempers (Dickinson & Shutler 1968, 1971, 1979). Generically distinctive temper provinces are both theoretically predictable and empirically definable in terms of the sands available to island potters within different geotectonic realms. Indigenous pottery can be identified from the provenance stamp of local island bedrock as reflected in the nature of temper sand grains. Pottery transfer can be detected from the occurrence of exotic

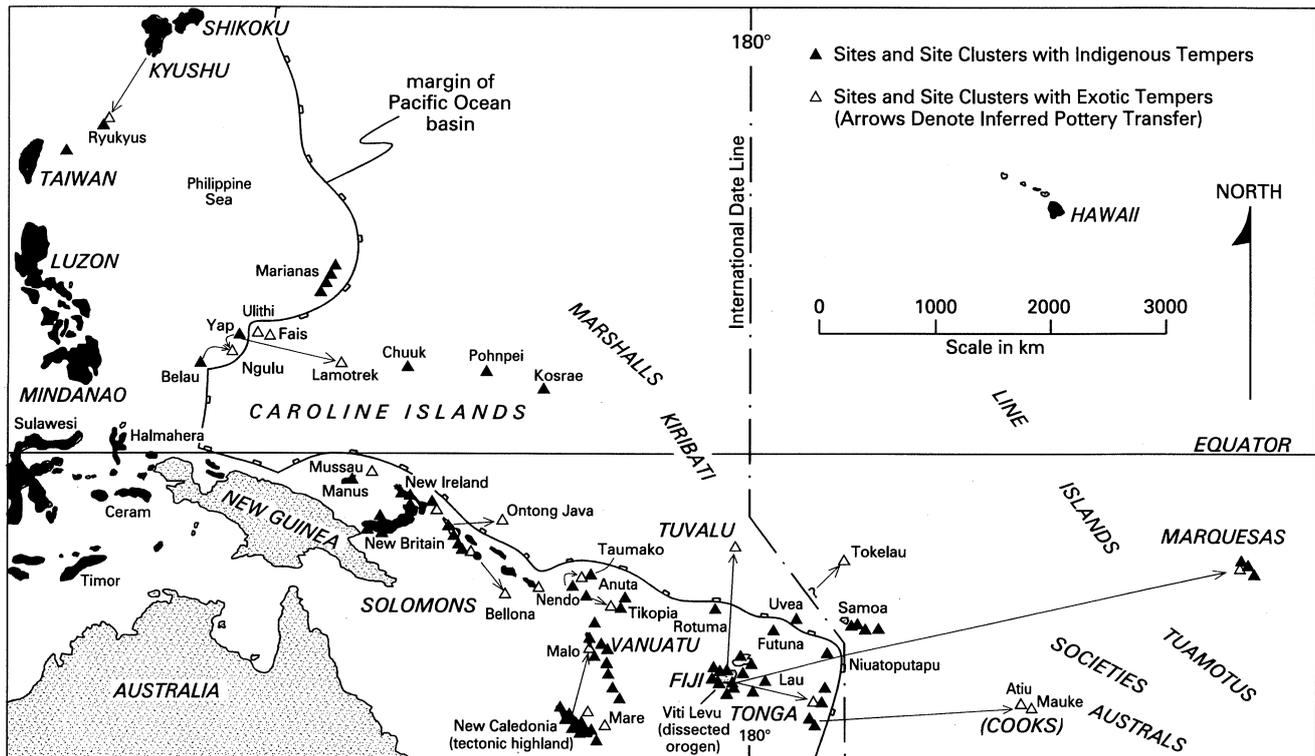


Figure 1. Outline map of island Oceania showing locations of islands and island groups for which temper suites in prehistoric sherds have been studied petrographically. Arrows denote salient prehistoric pottery transfer from sites and site clusters yielding indigenous temper suites (solid triangles) to selected sites yielding exotic temper suites (open triangles).

temper sands that could not have been derived from local island bedrock. Electron microprobe analysis (Freestone, 1982) of selected temper grain types has aided provenance evaluations in selected instances (Dickinson, 1971a; Dickinson *et al.*, 1990).

The success of the regional petrographic reconnaissance reported here stems from the restricted dispersal of sediment in island settings. Each of the small islands within Oceania approximates a point source of local sediment, and sands from different islands never mix, except on the deep sea floor where deposits are inaccessible for collection. Interpretations of sand provenance are consequently less ambiguous than in riverine continental settings, where the mingling of detritus from multiple sources within large drainage basins produces sands of heterogeneous parentage derived from multiple sources (Hays & Hassan, 1974). Elaborate statistical techniques are commonly required to distinguish between temper sands from different continental sites (Mason, 1995), whereas sharp qualitative criteria are typically valid for island settings. This advantage of island sites for temper analysis weakens as the size of islands increases, and the approach used here for island Oceania could not be applied as fruitfully among the larger landmasses of Papua New Guinea, Indonesia, or the Philippines. Other island regions such as the Lesser Antilles are amenable, however, to analogous treatment (Donahue *et al.*, 1990).

The oldest known indigenous pottery in island Oceania dates from 3500–3000 years ago in both the western and southern Pacific regions (Kirch & Weisler, 1994; Rainbird, 1994). In places where earthenware pottery is still made within Oceania, modern products are technologically similar to prehistoric wares, although vessel shapes and decorative styles have varied geographically and through time. Studies of both temporal and areal typology provide a rich context of archaeological interpretation, much of it still incomplete, that is beyond the scope of this paper on the geographic distribution of different temper suites regardless of the ages of the sherds examined. At typical sites, indigenous sherds of varied ages contain similar tempers representing sands that were locally available to resident potters throughout extended intervals of prehistoric time (Dickinson, 1973, 1976; Dye & Dickinson, 1996; Dickinson *et al.*, 1996).

Temper terminology

People who make earthenware pottery need to insure that clay bodies contain an adequate proportion of gritty non-clay constituents, both to enhance workability before firing and to impart strength and durability to fabricated ceramic pieces during and after firing. To achieve the desired consistency, some selected non-clay

aggregate, typically sand, is commonly kneaded by potters into wetted clay prior to the shaping and firing of ceramic wares. This manufacturing technique is commonly described as tempering the clay. In prehistoric potsherds, however, the distinction between manually added grains and analogous grains that may have been imbedded naturally in clay bodies must be derived from inferences based on textural criteria.

Appropriate descriptive terminology is not straightforward for the coarser grained, rigid components of earthenware that are not deformed as the surrounding clay is worked. Although long called "temper", such materials have also been termed "nonplastic inclusions" (Shepard, 1965; Rice, 1987), a usage chosen to avoid any connotation of deliberate addition to clay bodies and thus to allow for cases where sufficient aplastic material was imbedded within clays as initially collected. To describe separate grains as "inclusions" is awkward, however, because in mineralogical tradition the word "inclusion" denotes a crystal or crystal cluster wholly enclosed within an individual crystal of another mineral. The usage of "temper" as a non-generic term can be preserved, without turning to the petrographically ambiguous word "inclusion", if "natural temper" is contrasted with manually added temper in cases where the generic distinction can be made.

In general, however, grains of both natural and manually added temper sand may well occur jointly in some earthenware made from sandy clay bodies containing less than the optimal proportion of sand without further manual addition of temper. One may even speculate that sand-poor and "naturally tempered" sand-rich clays could have been mixed together in some instances to achieve the desired proportion of temper. In prehistoric Oceania, however, textural relations between temper sands and surrounding clay pastes in most of the sherds examined for this study show that the typical procedure of island potters, in parallel with the practice of modern studio potters, was to add separately collected temper sands to fine-textured clays lacking, in their natural state, any appreciable fraction of sand.

Temper-paste relations

Clay bodies used for prehistoric ceramic manufacture on Pacific islands were doubtless collected variously from soils, floodplains, and possibly tidal flats. The clay pastes of typical sherds are silty to varying degrees, although grains smaller in diameter than the thickness of a standard thin section (0.03 mm) cannot be discerned individually by optical petrographic methods. In the dominant sherds studied from almost all locales, roughly a quarter to a third of the volume of each sherd is composed of temper sand that forms a distinctly coarser grain population than the silty clay of the paste in which the sand grains are imbedded. Temper grains range in different instances from 0.1 to 1.0 mm in mean diameter, with finer or coarser sand used in irregular patterns throughout the Oceanian region.

The characteristic contrast in grain size between paste and temper implies manual addition of sand to clay by the ancient potters, although sparingly observed gradations in grain size between paste and temper suggest naturally tempered colluvial or alluvial clay bodies in selected instances. Presumed distinctions between natural and manually added temper may be moot if potters exploited some fluvial deposits where alternating clay-rich and sand-rich laminae could be collected jointly and then kneaded together to form mixed material of the appropriate texture and consistency.

Temper textures

As expected from the coastal settings of many island archaeological sites, well sorted beach sands composed of rounded to subrounded grains are the most widespread Oceanian tempers, but only moderately sorted aggregates composed of subangular to subrounded grains and interpreted as stream sands are also common, except in island groups lacking surface drainages. The choice of stream sands for temper on islands with few large drainages may stem partly from the convenience of collecting stream sand near pits dug into floodplains or stream banks to collect clay bodies. Admixtures of calcareous grains derived from offshore fringing or barrier reefs are common in many beach sands, and serve as one signal of coastal origin, but reworked carbonate grains ("limeclasts") derived from erosion of uplifted reef complexes also occur in some stream sands.

Less common Oceanian tempers include poorly sorted aggregates of weathered particles with irregular shapes derived from winnowed slopewash colluvium, well sorted littoral dune sands, slightly reworked volcanic ash, and jagged fragments of volcanic rock perhaps derived from wastage in adze quarries. Rarely, the only temper present in some sherd assemblages is "grog", composed of fragments of previously fired pottery which can be identified only with difficulty in thin section as inhomogeneities within clay pastes (Whitbread, 1986). Grog fragments appear as isolated domains of irregular angular shape having a different texture or fabric than the surrounding clay body. Grog temper is dominant in sherds from Palau, common in sherds from Yap, and present in selected sherds from the famed Nan Madol site on Pohnpei in the central Caroline Islands, and from Ofu in American Samoa (Dickinson, 1993). Grog temper was presumably used where nearby deposits of sand suitable for temper were not readily available, although cultural tradition may well have played a role in the choice of grog for temper.

Calcareous tempers

Locally throughout Oceania, some sherd assemblages or sub-assemblages contain beach sand tempers composed exclusively or dominantly of calcareous reef detritus. The provenance of the calcareous grains is indeterminate on petrographic grounds because reef characteristics are

similar throughout the region. Fortunately for a regional reconnaissance of temper compositions, many ancient potters apparently preferred to use non-calcareous sands as temper, even at sites where nearby white-sand beaches of reef debris are the most abundant readily available source of potential temper sand. The preferential selection of non-calcareous black sand for temper probably stemmed from the tendency for calcareous grains to disintegrate from calcining, which causes spalling of pots within the temperature range achieved by firing earthenware in open bonfires where close control of temperature is not feasible (Rye, 1976; Bronitsky & Hamer, 1986; Intoh, 1990; Hoard *et al.*, 1995).

Placer tempers

Avoidance of calcareous sand was achieved in different instances by seeking black-sand beaches or stream deposits of bedrock detritus, or by collecting placer concentrates of black mineral sand on beaches composed of mixed calcareous and non-calcareous sand (Dickinson, 1994). The use of beach placer concentrates for temper sand, as in Tonga (Dye & Dickinson, 1996; Dickinson *et al.*, 1996), is sure evidence that non-calcareous sand was preferred as temper, for its collection required deliberate avoidance of more abundant associated calcareous sand at some inconvenience to the collectors. The use of placer concentrates, whether collected from beaches or streambeds, may also have served in many places to reduce the proportion of glass-rich volcanic rock fragments in temper. Placer sands are enriched in dense minerals of high specific gravity with respect to polymineralic rock fragments as well as with respect to calcareous grains, and hydrated volcanic glass in the groundmasses of volcanic rock fragments could also be unstable in earthenware if firing promoted dehydration of the glass.

The common occurrence of placer mineral aggregates in Oceanian sherds provides a fortuitous advantage for provenance interpretations, because dense ferromagnesian silicate minerals of high specific gravity are commonly the most diagnostic components of bedrock assemblages, even where present in only accessory or varietal abundances in the source rocks. For studies of sediment provenance, petrographers often separate heavy minerals artificially, using flotation in heavy liquids, from the other, more abundant sand grains present in a given detrital aggregate. The ancient potters of Oceania, for reasons of their own, often achieved an analogous concentration of heavy minerals through their temper-collecting habits. The knowledge that Oceanian sherd tempers reflect various restrictive collections of available sands means, however, that the sherd tempers do not represent statistically valid samples of the full range of local island sands.

Temper-clay sources

The question of how closely temper sands in Oceanian sherds relate to the clay bodies in which they are imbedded

is a vexed one. In the case of natural tempers, the source of the sand and the clay is identical, but the conclusion that a given temper was not manually added is always interpretive in hindsight. In the prevalent cases where textural evidence for manual addition of sand temper is strong, the sources of sand and clay were clearly not identical. For inferences about temper sources, it is immaterial whether natural or manually added temper is involved, except that petrography alone cannot address the question of how far sand or clay may have been transported before the two were mixed together by ancient potters. For detailed provenance studies beyond the scope of this review, it is also useful to distinguish between non-local temper that may nevertheless have been derived from some other part of the same island where the sherds containing it were recovered, and truly exotic temper that is indicative of derivation from a different island or island group.

It seems likely in most cases that the presence of distinctly non-local or exotic temper in sherds from a given site reflects pottery transfer after manufacture, rather than movement of sand as raw material before firing. Given the technological constraints of ancient island cultures, the transport of bulk raw materials for long distances, either on foot or by canoe, would have presented severe challenges, and few sites are located where no sands at all are available nearby. On the other hand, the desire for some special kind of temper, such as placer sand, may have been strong in some instances, and temper is both less fragile and less bulky than finished wares, as well as representing only a fraction of the overall weight of ceramic wares. In general, it is well to bear in mind that petrography alone cannot distinguish between transport of temper and transport of finished wares.

The sourcing of clay bodies in prehistoric sherds presents a different and more difficult problem than the sourcing of sand tempers, and petrographic methods are ineffective because of the submicroscopic grain size of clay particles. Beyond that technical consideration, sand grains are largely unmodified pieces of parent bedrock and carry a clearcut provenance signal, whereas clays are produced by wholesale mineralogical modification of bedrock by weathering (Garrels & Mackenzie, 1971: 142–170). The mineralogy of clays, whether residual in soil or transported and redeposited as alluvium, reflects the local geochemical environment of a weathering horizon, and may be as dependent upon the local climate or microclimate as upon the nature of the parent bedrock (Blatt *et al.*, 1980: 272–273; Blatt, 1982: 42–44). For example, alumino-silicates of the kaolin group, which lack metallic elements other than Al and Si in their crystal lattices, form only where oxidation of iron to the ferric state is strong and rainfall is sufficient for percolation to leach alkalis (Na, K), alkaline earths (Ca, Mg), and appreciable silica (Si) downward from the soil horizon, whereas formation of the smectite group of more complex chemistry requires retention of silica and some combination of alkaline earths (Ca, Mg), alkali metal (Na), and ferrous iron within the soil horizon owing to ineffective leaching, whether from inadequate moisture or poor infiltration that leads to water logging of surficial

layers (Keller, 1970). Clays of varied mineralogy and geochemistry can thus form from the same bedrock in different geomorphic settings, whereas quite similar clays can form in similar geographic settings from a rather wide range of parent bedrock types.

Chemical analysis of clay bodies can be employed in attempts to match sherd pastes with specific potential clay sources, but in general is not an attractive tool for regional reconnaissance of sources for raw materials in the way that temper sands can be studied petrographically for comparison with what is known of potential bedrock sources. For clay analysis, moreover, care must be taken to allow for the effect of associated temper on the bulk chemical compositions of sherds (Schubert, 1986; Neff *et al.*, 1989; Arnold *et al.*, 1991; Ambrose, 1992, 1993). Microprobe analysis of clay paste apart from temper grains is the most direct means to avoid contaminating results from clay analysis with the chemistry of manually added tempers (Summerhayes, 1997).

Geotectonic realms

The generic mineralogical and petrological character of island sands is governed by the irregular distribution of key Pacific geotectonic realms (Fig. 1). The overall geography of different temper provinces is dictated by the pattern of movement of major plates of lithosphere in the geometric dance of plate tectonics (e.g., Oxburgh, 1974; Kearey & Vine, 1990). The Pacific plate of lithosphere including most of the islands of Polynesia and Micronesia is moving toward the northwest, relative to Asia and Australia, and descends beneath the edges of the Eurasian and Indo-Australian plates along subduction zones marked by the deep trenches of the western and southwestern Pacific. Isolated archipelagoes and linear island chains of the Pacific plate were built exclusively by intraoceanic volcanism above hotspots in the underlying mantle, whereas linear and curvilinear island chains along the edges of the adjacent Eurasian and Indo-Australian plates were built by arc magmatism and tectonism influenced by the descent of lithosphere into the mantle beneath the island arcs.

The overall picture is complicated by the existence of island arcs of reversed polarity in Melanesia, where current subduction beneath New Britain, the Solomon Islands, and Vanuatu is downward to the northeast, involving oceanic lithosphere of marginal seas lying to the east of Australia and New Guinea, rather than the Pacific plate (Kroenke, 1984). In the Ryukyu Islands, subduction of normal polarity, downward away from the Pacific basin, nevertheless involves marginal-basin lithosphere of the Philippine Sea (Seno & Maruyama, 1984). Even island arcs of normal polarity in Tonga and the Mariana Islands are backed by marginal seas of oceanic character, and in that sense are intraoceanic, as contrasted with arcs such as the Andes or Sunda (Sumatra-Java) built along the edges of continental blocks (Dickinson, 1975).

The petrology and consequent mineralogy of intraoceanic and island-arc igneous assemblages are

fundamentally different because intraoceanic volcanism is triggered by simple decompression melting of advecting mantle (Jarrard & Clague, 1977), whereas arc magmatism involves more complex processes related to subduction of lithosphere (Anderson *et al.*, 1978). The salient additional factor is probably the release of volatiles, chiefly water, from subducting slabs of lithosphere as they warm during descent into the mantle. The rising volatiles can flux the overlying mantle wedge to produce types of melts unknown from intraoceanic settings, including hydrous magmas capable of generating the explosive eruptions so common along island arcs.

As island arcs evolve above subducting slabs, large bodies of derivative magma are also commonly trapped within island arc crust to form intrusive bodies, including granitic plutons, of a size and composition unlike the subvolcanic dikes and sills of limited volume known from intraoceanic settings (Dickinson, 1970). Along the flanks of island arcs, moreover, the structural effects of subduction include the detachment of seafloor sediment from the surfaces of descending slabs of oceanic lithosphere, and their tectonic stacking into folded and thrust-faulted piles of deformed strata termed subduction complexes (Dickinson, 1972). The subduction complexes in some cases contain fault-bounded slivers of oceanic lithosphere, composed of both crust and mantle horizons jointly termed an ophiolite succession (Moore, 1982), and can be driven beneath analogous ophiolite slabs underpinning interoceanic island arc structures composed of arc igneous assemblages.

Temper classes

Geotectonic relations thus dictate that Oceanian temper suites fall into four broad classes distinguishable on qualitative grounds despite large quantitative variations in temper composition within each class: (a) *oceanic basalt* tempers in clusters and chains of shield volcanoes built by hotspot volcanism piercing the oceanic plate; (b) *andesitic arc* tempers of undissected, though either active or dormant, magmatic arcs fostered by subduction of oceanic lithosphere; (c) *dissected orogen* tempers occurring where deep erosion has bitten into the plutonic roots of magmatic arcs; and (d) *tectonic highland* tempers where seafloor lavas and sediments overlying ultramafic mantle lithosphere have been uplifted by folding and thrust faulting associated with subduction. Oceanic basalt and andesitic arc tempers include exclusively volcanic detritus, augmented locally by minor contributions from injected dikes and sills, but the dissected orogen and tectonic highland classes include detritus in locally varying proportions from plutonic, metamorphic, and sedimentary rocks as well. Preliminary appraisals of the four temper classes by Dickinson & Shuttler (1968, 1971, 1979) are here sharpened and augmented through results and insights from petrographic observations over the past two decades involving sherds from many localities not included in previous analyses.

The designations adopted here for the four generic temper classes should be regarded as convenient labels, rather than as complete descriptions. For example, oceanic basalt tempers, in the usage intended here, include tempers derived from trachyte and other differentiates of intraoceanic basalt magmas, and andesitic arc tempers include tempers composed of basaltic or dacitic debris from the igneous assemblages of island arcs. A brief discussion of each geotectonically defined temper class serves to clarify these and related points. As variable amounts of opaque iron oxide grains (magnetite or ilmenite or both) are present in most tempers, only the non-opaque grain types are discussed in detail.

Oceanic basalt tempers

Oceanic basalt tempers occur in sherds from (a) Chuuk, Pohnpei, and Kosrae in the Caroline Islands; (b) Rotuma and Uvea in the northern Melanesian borderland; (c) Upolu, Tutuila, and Ofu in Samoa; and (d) Hiva Oa, Nuku Hiva, and Ua Huka in the Marquesas Islands. The only grain types are volcanic rock fragments of variable texture and phenocrystic minerals of sand size. Individual temper types vary widely in texture, depending upon the sedimentological nature of the aggregate used as temper, and also vary mineralogically, both in ways that reflect strictly local variations in parent bedrock and in ways that reflect more systematic empirical variations in the volcanic assemblages of different island groups. Rounded beach sands are most common but reworked ash and colluvial debris was also used for temper locally. Homogeneous aggregates of angular sand, evidently produced by crushing volcanic rock, were used locally as temper on both Upolu and Tutuila in Samoa, and may represent wastage from adze quarries.

Typical volcanic rock fragments are mafic lava, dominantly olivine basalt or hawaiite but locally including more silica-undersaturated (feldspathoid-bearing) basanite or tephrite, with intergranular to intersertal internal textures displaying twinned plagioclase laths associated with tiny crystals of clinopyroxene and olivine. Minor proportions of coarser grained microgranular dike rocks (dolerite or diabase) are also present in some tempers. Other rock fragments, dominant in some temper types, include hydrated basaltic glass (palagonite), vitrophyric grains with glassy groundmasses in which tiny plagioclase microlites are set, and felsic basaltic differentiates such as trachyte and mugearite in which plagioclase or anorthoclase feldspar is typically the most abundant groundmass mineral.

Mineral grains are dominantly olivine, clinopyroxene, and plagioclase, although hornblende occurs locally in trachytic tempers, known to date only from Samoa. Quartz is characteristically absent, although minor amounts of quartz might well appear in tempers that could potentially be derived from locally exposed quartz-bearing trachytes. The ratio of olivine to clinopyroxene is consistently higher than in andesitic arc tempers (see below), reflecting the generally alkalic

character of intraoceanic basalt magmas throughout the western and southern Pacific regions. In Hawaii, subalkalic tholeiitic basalts, which are less undersaturated with respect to silica, are the dominant shield-building lavas, with alkalic magmas erupted only late in the volcanic history of each island. Tholeiitic basalts are unknown, however, among the archipelagoes that have yielded prehistoric pottery.

Andesitic arc tempers

Andesitic arc tempers occur in sherds from (a) Guam, Rota, Tinian, and Saipan in the Mariana Islands; (b) Belau in the Caroline Islands; (c) Manus, New Britain and New Ireland in the Bismarck Archipelago; (d) Bougainville, the Shortland Islands, the Santa Cruz Islands, the Duff Islands, Vanikolo, Anuta, and Tikopia in the Solomon Islands; (e) the Torres and Banks Islands, Santo, Malo, Malakula, Efate, Erromango, Tanna, and the Shepherd Islands in Vanuatu; (f) Futuna and Alofi in the Horne Islands of the northern Melanesian borderland; (g) the Yasawa Islands, Kadavu and the Lau Group of Fiji; and (h) Niuaotupapu, Vavau, the Haapai Group, and Tongatapu in Tonga. As for oceanic basalt tempers, the only grain types are volcanic rock fragments, including minor dike rocks, and phenocrystic minerals, but the variety of rock fragments and mineral grains is much greater regionally, and locally as well in many instances. Regional variations in the petrologic character of different island arcs is reflected by systematic variations in the mineralogy of derivative temper sands (see section below on temper compositions). Based upon textural criteria, the use of stream sands for temper was as widespread as the use of beach sands along the island arcs of rugged relief.

Typical rock fragments are andesite or basaltic andesite with groundmasses of hyalopilitic to pilotaxitic texture dominated by tiny untwinned plagioclase microlites. Microporphyrific grains, including glassy vitrophyric varieties, some with semiopaque tachylitic groundmasses, are common in many tempers. The variety of volcanic rock fragments is great, however, reflecting the large range of rock types, from basalt to dacite, common along many island arcs. Empirical variations in the textures and compositions of dominant rock fragments provide useful criteria for distinguishing between tempers from different islands in many instances. Microscopic distinctions between andesitic and dacitic rock fragments are inherently intractable, however, unless quartz microphenocrysts are present as an indicator of dacite or rhyodacite. The associated basalts are subalkalic island-arc tholeiites, and contain distinctly less olivine than intraoceanic alkalic basalts and basanites.

Mineral grains are characteristically plagioclase and clinopyroxene or hornblende, or both, but proportions vary widely, and subordinate grains include orthopyroxene, oxyhornblende, and olivine, with variable but typically minor amounts of quartz also present in some tempers. Systematic variations in the content of different ferromagnesian minerals provide multiple criteria for

distinguishing between the tempers of different islands and island groups (see section below on temper compositions).

An unusual island-arc temper rich in rock fragments of metagabbro occurs in sherds from Eua, lying along the front of the Tongan arc where uplift has evidently exposed the ophiolite underpinnings of the arc structure. The rifting of arc structures to form marginal seas can also give rise to volcanic suites indistinguishable from intraoceanic shields. That unusual geotectonic setting is apparently responsible for the presence of oceanic basalt temper at Rotuma, and similar oceanic basalt temper might be characteristic also of Niuafouu, which rises from the floor of the oceanic Lau Basin west of the Tongan arc.

Dissected orogen tempers

Dissected orogen tempers occur in sherd suites studied to date from parts of the Ryukyu Islands and along the southern and western coasts of Viti Levu in Fiji, but could also occur in sherds that might be found in the future on the larger and more geologically varied islands of the Solomons chain, such as Guadalcanal. Grain types reflect derivation from a wide variety of arc volcanic rocks, granitic to dioritic plutons, and both metavolcanic and metasedimentary wallrocks of the plutons. Polymineralic rock fragments include microgranular plutonic and hornfelsic varieties, as well as a range of microlitic to felsitic volcanic-metavolcanic rocks and metasedimentary argillite-slate-phyllite. Mineral grains include abundant quartz and both feldspars (plagioclase, often altered to albite, and K-feldspar), and less abundant ferromagnesian minerals including biotite, hornblende, and clinopyroxene in varying proportions. Along the northern coast of Viti Levu, and on nearby islands of the Fiji platform (Taveuni and Lomaiviti), volcanic sand tempers derived from post-orogenic cover rocks resemble the more basalt-rich tempers of undissected andesitic island arcs.

Tectonic highland tempers

Tectonic highland tempers occur in sherd suites studied to date from Yap and New Caledonia, but might also occur in islands along the eastern fringe of the Solomons chain where uplifted segments of the intraoceanic Ontong Java Plateau have been incorporated tectonically into the flank of the island arc. There are two contrasting subclasses of tectonic highland temper: (a) metasedimentary detritus rich in quartz, quartzite, chert, and foliated tectonite (slate-phyllite-schist) grains; and (b) ophiolitic detritus rich in basalt-metabasalt, serpentinite, and pyroxene grains. Blueschist-facies minerals, such as the amphibole glaucophane, restricted to subduction complexes metamorphosed at high pressure but low temperature, occur in accessory amounts in some temper types from New Caledonia.

Grain counting

To compare tempers of different compositions in more than a qualitative anecdotal fashion, some reproducible measure allowing quantitative representation is needed. For modal analysis of sandstones, sedimentary petrologists use the point-counting method (Chayes, 1956), whereby the grains beneath the intersection points of an equidimensional rectilinear grid superimposed on a thin section are identified and counted, with counts summed to determine overall percentages of different grain types. In practice, the grid is generated by moving the microscope stage in fixed increments, along parallel paths spaced the same fixed distance apart, to place different grains beneath the crosshairs. Point-counting provides a reliable estimate of the true volumetric proportions of different grain types, but is time-consuming and the majority of points for thin sections of potsherds always fall within clay paste, yielding no information about tempers. As there is no systematic statistical relationship between the volumetric proportions of different types of temper grains and their counterparts in parent source rocks, there is no inherent advantage to point-counting sherds that compensates for the excessive time required. Although knowledge of the proportions of clay paste in sherd suites is useful for analyses of ceramic technology, the lack of any systematic regional variations in the respective percentages of clay paste and temper in Oceanian sherd suites means that ratios of temper to paste provide no reliable information about the provenance of temper sands.

For quantitative temper study, less time-consuming counts of grain frequency are accordingly adopted here as the basis for compositional comparisons. In practice, different types of temper grains are counted as the microscope stage is traversed across a thin section and grains pass in succession through the field of view. Percentages of grain types are then calculated by summation. As any count represents only a statistical sampling of the total population of temper grains within a sherd, the counting error (one standard deviation) is given by the square root of $p(100 - p)/n$ where p is the percentage of a given grain type as estimated from a frequency count and n is the total number of grains counted (Plas & Tobi, 1965). Fully adequate precision is attained by counting 400 grains, although fewer than this target number may be present in standard thin sections of some sherds containing sparse or coarse temper. Depending on the size of each sherd and the nature of its temper, all temper grains present in the thin section may be counted, or only those grains present within selected bands of appropriate width and spacing across the sherd or within equally sized fields of view spaced evenly within the sherd. The method can be viewed as a blend of area-counting and ribbon-counting, which yield essentially identical frequency values (Middleton *et al.*, 1985). Although frequency counts do not yield the same percentage values as point counts (Dye & Dickinson, 1996), they are equally reproducible and thus equally satisfactory for comparative purposes.

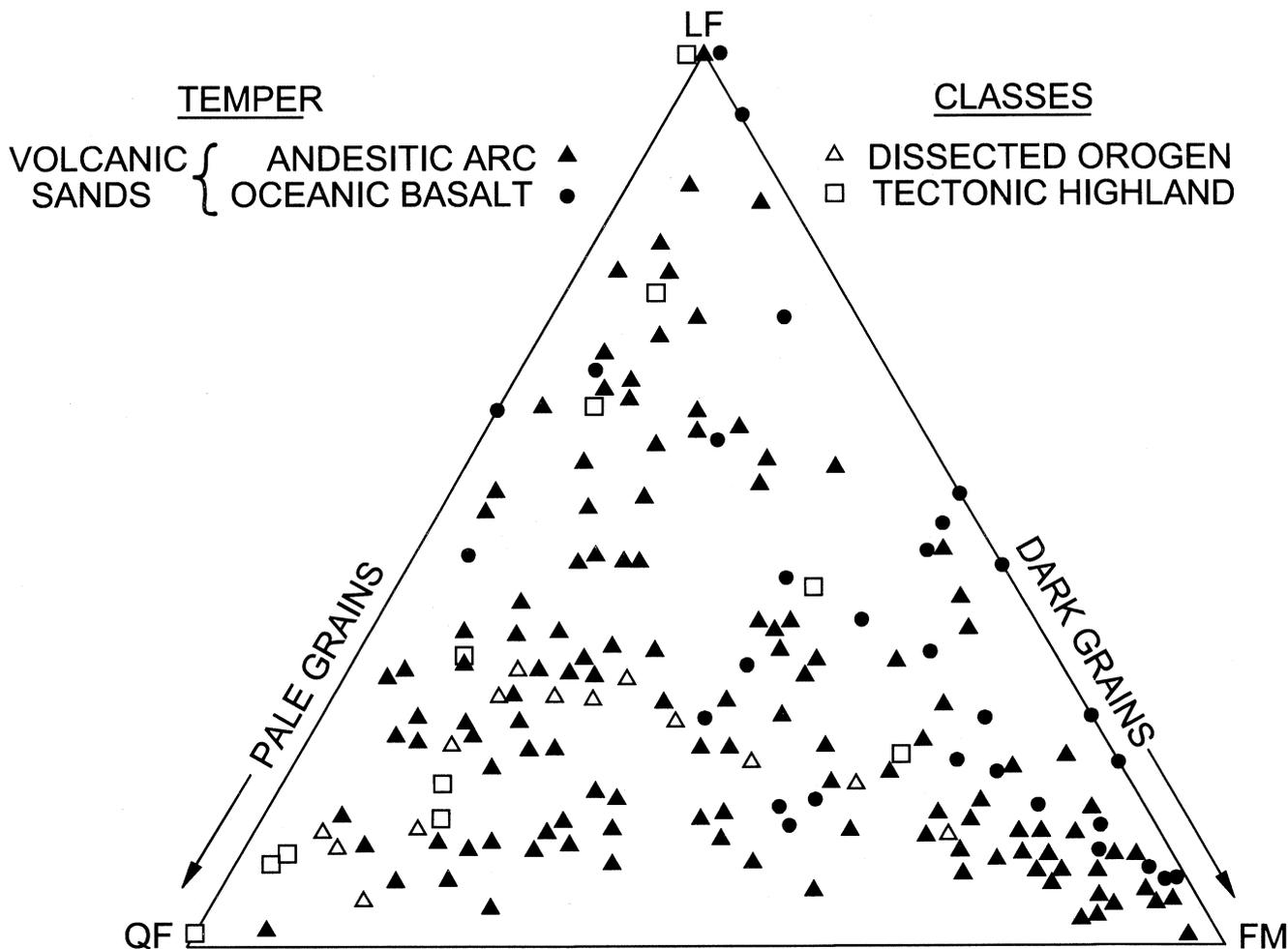


Figure 2. Compositions of Pacific island temper sands in LF-QF-FM space (quantitative triangular diagram) where LF = polycrystalline-polyminerallic lithic fragments (typically shades of grey), QF = quartz and feldspar mineral grains (pale or translucent), FM = ferromagnesian silicate and oxide mineral grains (black or dark green). Plotted points are average compositions of temper types at multiple sites (Fig. 1), but some local temper suites include multiple temper types plotted separately.

Temper compositions

Raw counts may incorporate as many different grain types as desired, based upon mineralogy, internal fabric, and colouration. For the regional comparisons drawn here, grain types are grouped into generic categories to allow depiction of mean temper compositions on triangular plots that represent quantitative graphs of grain frequencies. In tempers that contain non-diagnostic calcareous grains, grain frequencies have been recalculated to 100%, free of calcareous grains. The full non-calcareous grain populations of all studied Oceanian temper types are shown on the LF-QF-FM plot (Fig. 2), which indicates that little or no discrimination between different classes of Oceanian temper is achieved by such simple recalculation of the raw data. This means that even careful megascopic observation of pale grains (QF), greyish grains (LF), and dark grains (FM) in Oceanian tempers has limited scope for provenance determination.

The fundamental reason for the failure of the LF-QF-FM plot to display temper contrasts is the fact that generically related placer and non-placer sand aggregates plot very differently in LF-QF-FM space.

Placer concentration of heavy ferromagnesian mineral grains of high specific gravity moves plotted points for closely related temper types systematically toward the FM pole (Fig. 3). Analogous placer effects are shown by the QF-FS-OO plot (Fig. 4), representing the population of monominerallic mineral grains from which polyminerallic lithic fragments have been excluded (FS + OO = FM). Trends of variation between generically related temper types on this plot trend away from the QF pole for low-density quartz and feldspar grains toward the bottom leg of the triangle connecting the FS pole for ferromagnesian silicates to the OO pole for opaque iron oxides. In several instances, an initial placer concentration of mainly ferromagnesian silicates (FS) is succeeded by further placer concentration of rarer opaque iron oxides (OO) because

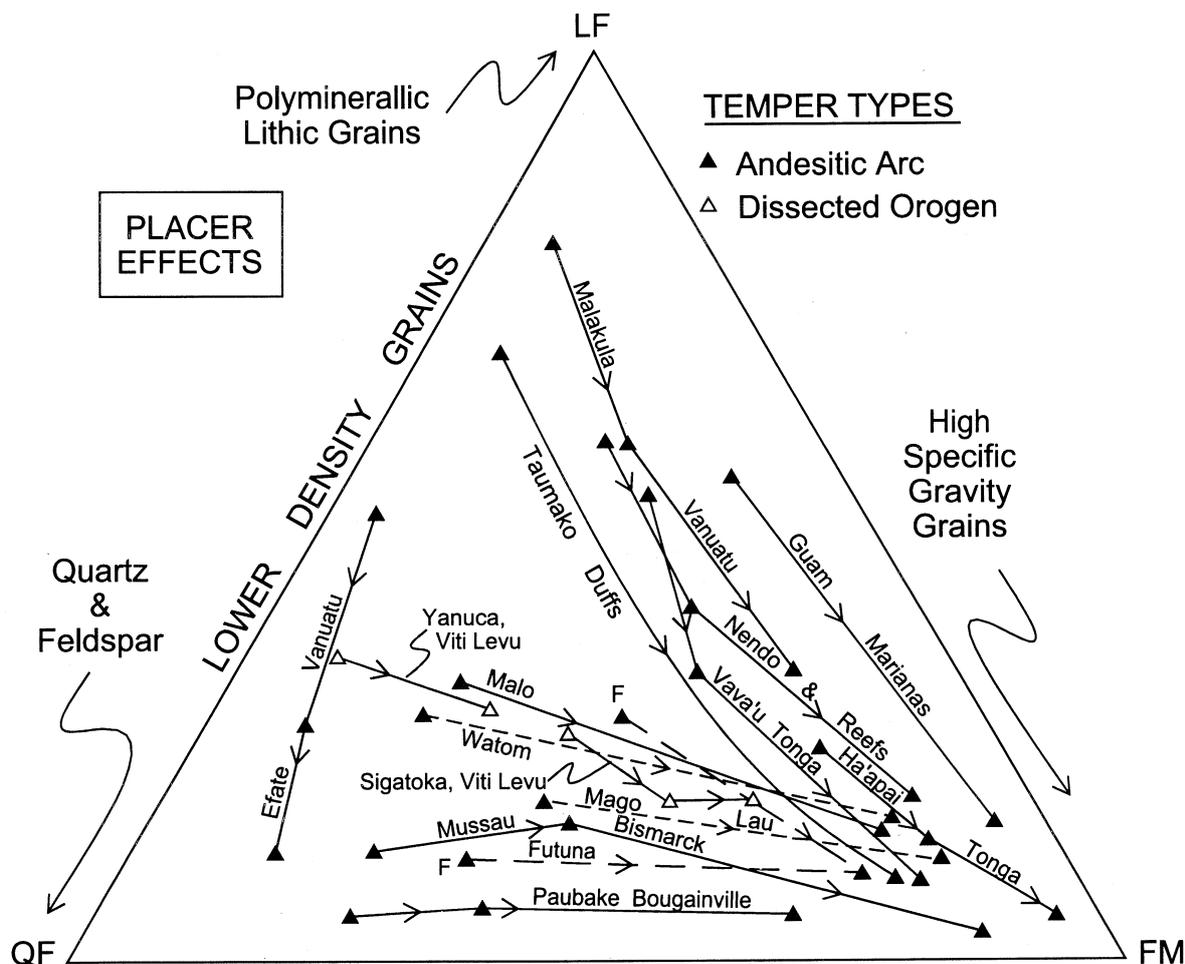


Figure 3. LF-QF-FM plot (see Fig. 2 for poles) showing the effects of fluvial-beach-dune placering (hydraulic concentration of FM grains with higher specific gravity) on temper sand compositions. Plotted points are average compositions of individual temper types, including non-placer and placer aggregates, which form generically related variants of local temper suites and are connected by arrows showing compositional trends governed by progressive placer concentration (in some cases, transitional or intermediate variants are plotted along trends between non-placer and placer end members of temper suites). The seemingly anomalous trend of the Efate temper suite in Vanuatu reflects placer concentration of quartz and feldspar mineral grains (QF) by hydraulic separation from less dense lithic fragments (LF) that are dominantly pumiceous volcanic glass of low specific gravity.

the oxides have inherently greater density than the silicates.

More selective plots reveal differences between Oceanian temper classes more clearly. The Q-F-LF plot (Fig. 5) of quartz and feldspar plus polyminerallitic lithic fragments, with all ferromagnesian grains excluded, successfully achieves separation of dissected orogen and tectonic highland tempers from each other and from undifferentiated volcanic sand tempers of both the oceanic basalt and andesitic arc classes. The general paucity of quartz grains in all volcanic sand tempers of Oceania is well displayed on this plot. The Q-F-FS plot (Fig. 6) of quartz and feldspar plus ferromagnesian silicate mineral grains (non-opaque FM), with both polyminerallitic lithic fragments and opaque grains excluded, achieves an analogous separation.

Plotting the FS population of non-opaque ferromagnesian silicate grains for volcanic sand tempers separately, on the hornblende-pyroxene-olivine graph (Fig. 7), brings oceanic basalt and andesitic arc temper types into different compositional fields, with the abundance of olivine in oceanic basalt tempers as the key discriminant. This plot also shows that different island arcs can be discriminated on the basis of hornblende-to-pyroxene ratio. Relatively primitive island arcs, such as Tonga and the Mariana Islands, have eruptive suites dominated by pyroxene andesites and associated island-arc tholeiites, whereas more evolved arcs, such as Vanuatu and the Solomon Islands, also erupt significant quantities of hornblende-bearing lavas. On strictly empirical grounds, a consistent distinction also emerges on the basis of

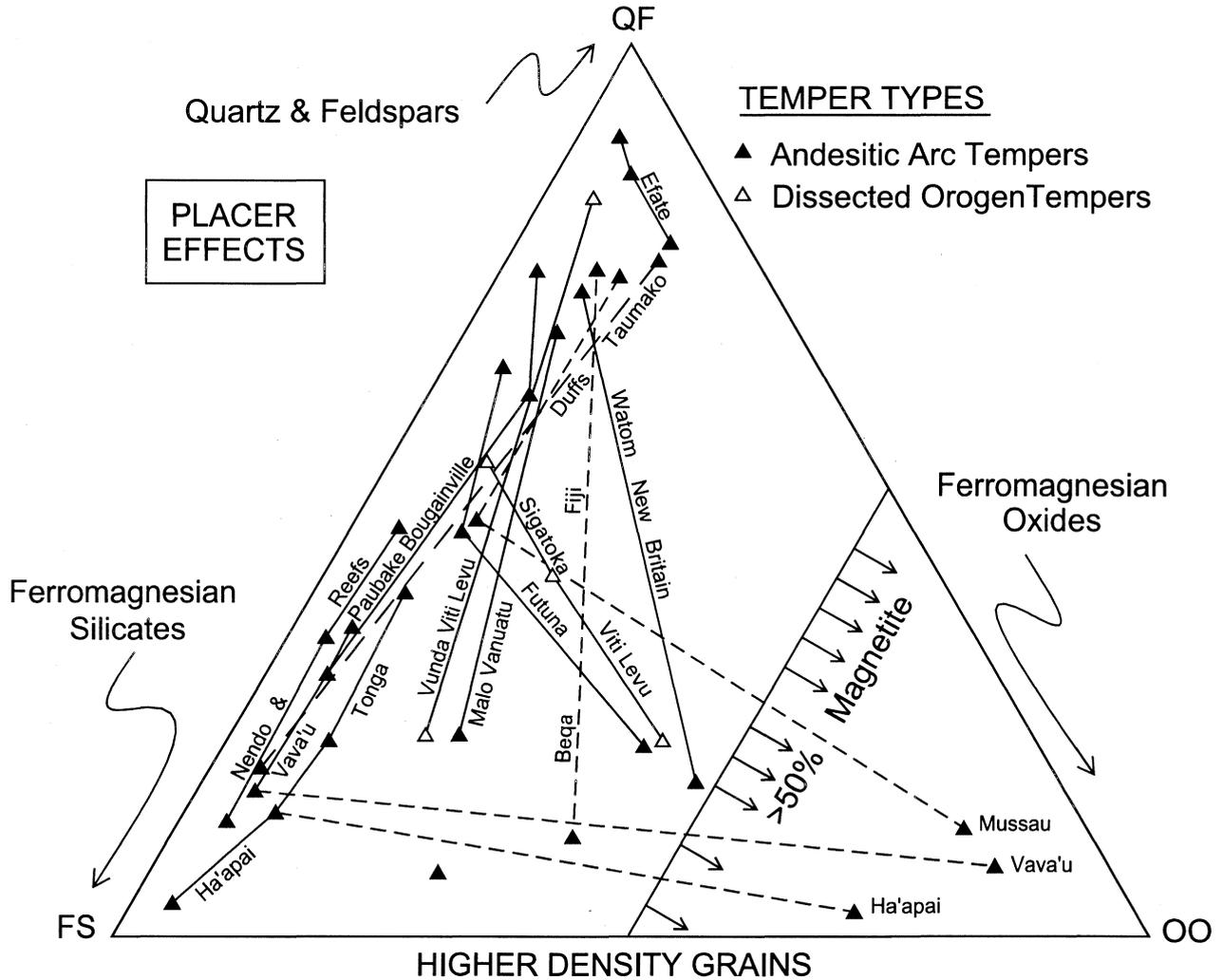


Figure 4. Placing effects (see Fig. 3) on temper sand compositions as displayed on a triangular plot of the QF-FS-OO population, representing mineral grains only (proportions recalculated exclusive of polycrystalline-polyminerallic lithic fragments), where QF = quartz and feldspar, FS = ferromagnesian silicates (clinopyroxene, orthopyroxene, hornblende, oxyhornblende, olivine, biotite, epidote), and OO = opaque iron oxide grains (dominantly magnetite but also including maghemite, ilmenite, hematite, chromite in some cases). Placer concentration proceeds downward from the QF pole (grains of lowest specific gravity) along trends defined by lines connecting non-placer and placer variants of local temper suites, and in some cases pursues further trends toward the OO pole (grains of highest specific gravity).

hornblende-to-pyroxene ratio between the Solomons arc and the New Hebrides arc, which includes both Vanuatu and the eastern outliers of the Solomon Islands as a political entity. Local basaltic tempers of the Santa Cruz Group at the northern end of the New Hebrides island arc and tempers derived from the post-orogenic basaltic cover rocks of Fiji plot in a position intermediate between the oceanic basalt and andesitic arc fields.

Pottery transfer

Although limited pottery transfer over comparatively short distances was probably common within complex island groups such as Fiji (Dickinson, 1971b), the transport of

pottery over long distances was apparently not common within Oceania during prehistory (Dickinson *et al.*, 1996). Nevertheless, sherds with tempers exotic to the locales where they were collected provide welcome concrete evidence for pottery transfer in selected instances (Fig. 1). The places of origin of the exotic sherds can be identified with varying degrees of confidence in different cases. The most clearcut evidence for pottery transfer is provided by sherds containing volcanic sand temper that have been found at a number of atolls and raised-coral islands where only calcareous sands are present locally. Distinctive New Caledonian tempers (Galipaud, 1990) have been identified in ancient sherds from both the Loyalty Islands (Huntley *et al.*, 1983) and Vanuatu (Dickinson, 1971a), and sherds of wares apparently

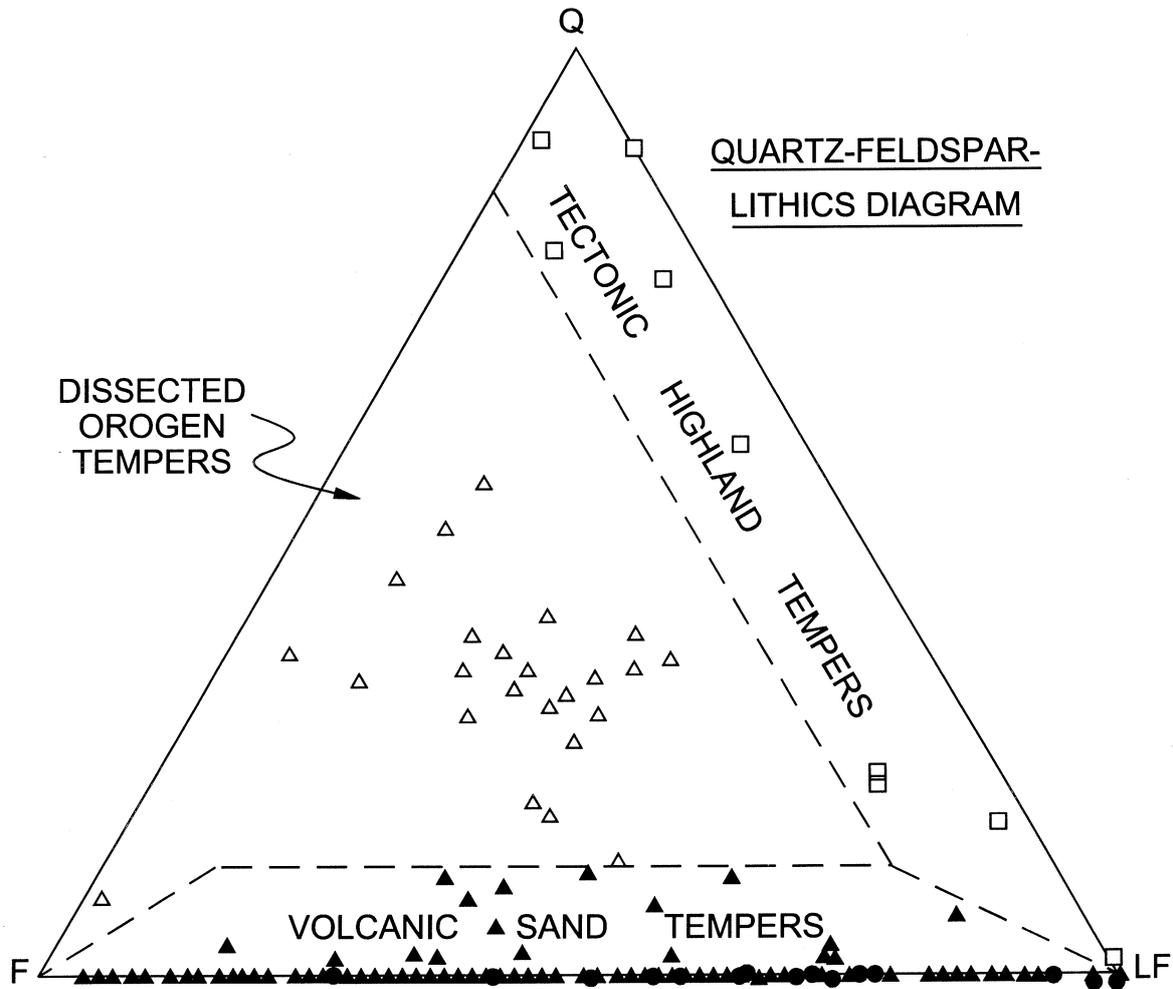


Figure 5. Triangular Q-F-LF plot of partial temper grain populations (all FM constituents of Figs. 2–4 excluded by recalculation), where Q = quartz grains, F = feldspar grains, and LF = polycrystalline-polyminerallic lithic fragments. Plotted points are average compositions of individual temper types, and empirical generic divisions are delineated between fields for dissected orogen, tectonic highland, and volcanic (oceanic basalt and andesitic arc suites undivided) temper classes.

manufactured on the Rewa Delta (Viti Levu, Fiji) have been recovered from protohistoric or uncertain contexts in Lau, Tonga, and the Marquesas (Dickinson & Shutler, 1974; Dye & Dickinson, 1996; Dickinson *et al.*, 1996). Wholly intrusive wares from outside the region are represented by colonial Spanish and Japanese Jomon sherds discovered in the Solomon Islands and Vanuatu, respectively, and contain entirely unfamiliar temper sands (Dickinson & Green, 1974; Sinoto *et al.*, 1996).

General conclusions

Oceanian tempers can be divided into broad classes correlated with geotectonic setting, and empirical differences between tempers from different locales within major temper provinces allow still further subdivision. Recognition of contrasting temper types and suites is not dependent on quantitative mineralogical

differences alone, but rests primarily upon qualitative petrological differences that are evident without statistical manipulation of compositional data. Enough geologic information is now available about most island groups to allow evaluation of temper sources without ancillary collections of modern sands. Although comparative empirical data from modern sands is helpful for the interpretation of ancient tempers, truly exotic tempers can be detected petrographically without specific comparative materials.

Indigenous temper suites from many locales include multiple temper types forming a spectrum of beach and stream, placer and non-placer, or calcareous and non-calcareous sands. The megascopic appearance of closely related tempers may be highly variable as proportions of associated grains of different colouration vary. Only petrographic study can establish unequivocal generic similarities or differences among various indigenous and exotic Oceanian tempers.

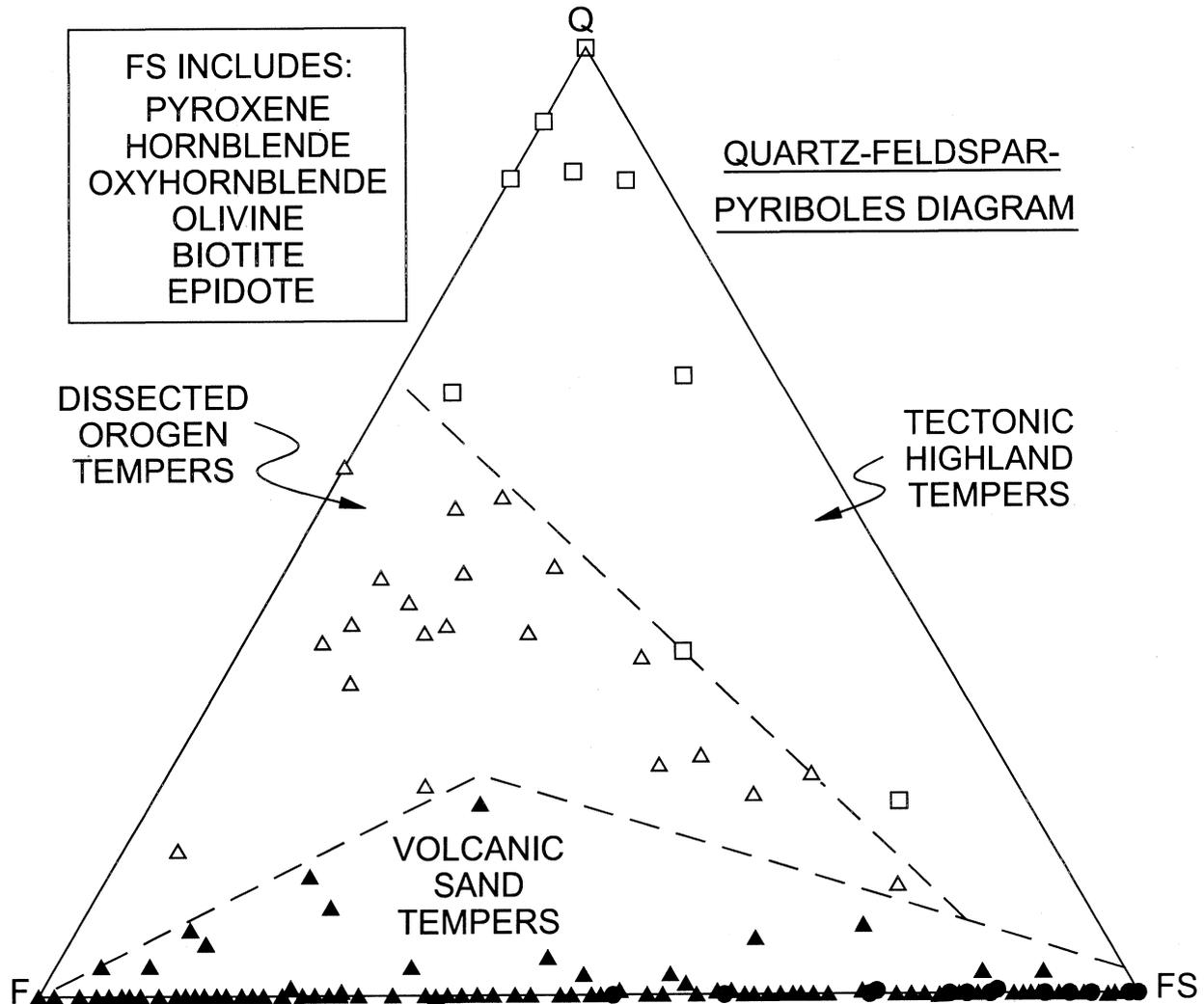


Figure 6. Triangular Q-F-FS plot of partial temper grain populations (recalculated for non-opaque mineral grains only), where Q = quartz grains, F = feldspar grains, and FS = ferromagnesian silicate grains (see Fig. 4 for identity). Plotted points are average compositions of individual temper types, with the compositional space divided into the same generic fields as for Figure 5.

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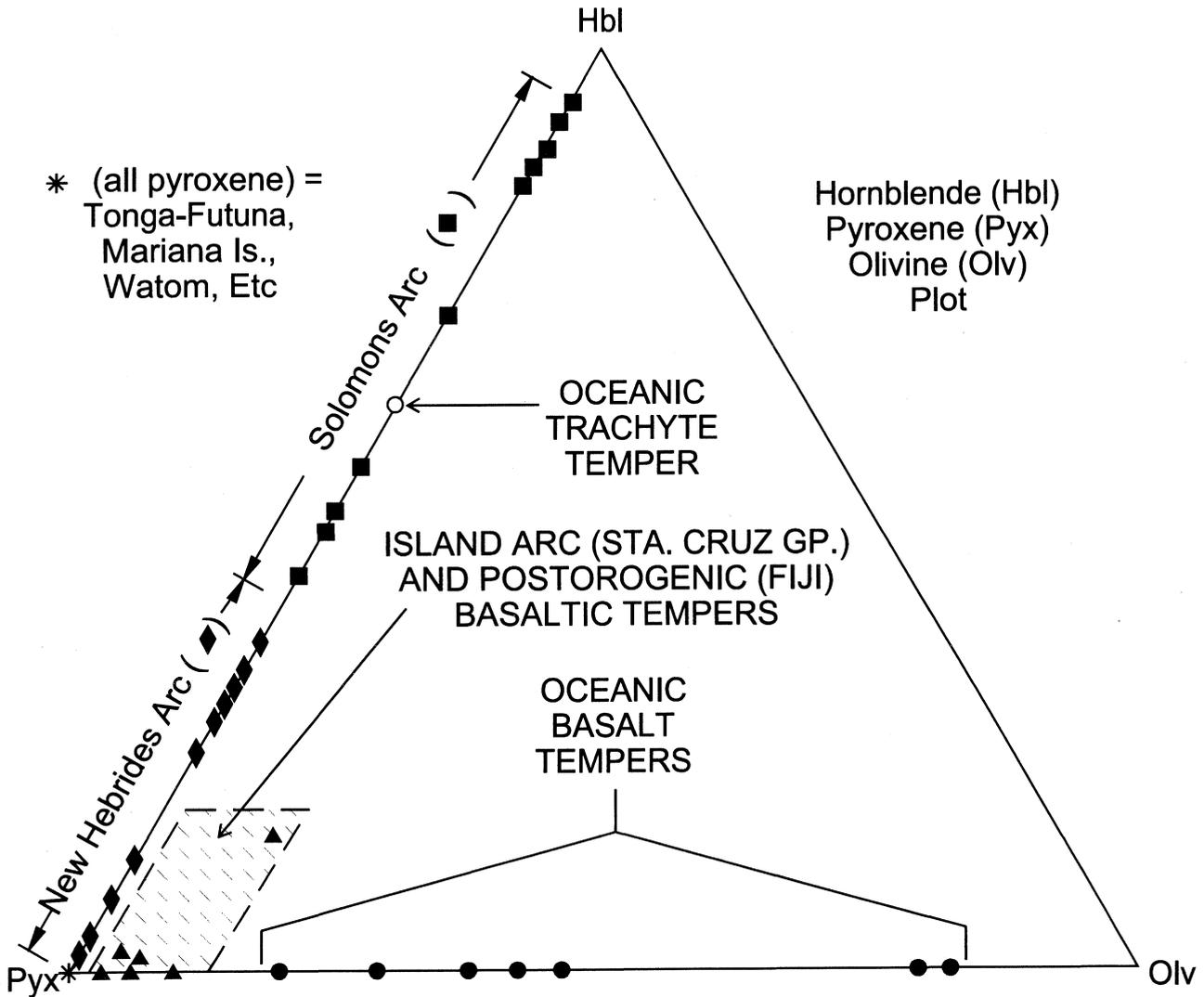


Figure 7. Average proportions of hornblende (hbl), pyroxene (pyx), and olivine (olv) mineral grains in selected oceanic basalt and andesitic arc tempers plotted on a triangular diagram to illustrate generic distinctions in hbl-pyx-olv space.

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