Geoarchaeological Context of Holocene Subsidence at the Ferry Berth Lapita Site, Mulifanua, Upolu, Samoa

William R. Dickinson

Department of Geosciences, University of Arizona, Tucson, Arizona 85721

Roger C. Green

Department of Anthropology, University of Auckland, Private Bag 92019, Auckland 1, New Zealand

The 1973 discovery of an underwater archaeological site during dredging for a ferry landing at Mulifanua on Upolu raised important unanswered questions about the prehistory of Samoa, particularly the evolution of Holocene shorelines and relative local sea levels. A cultural horizon yielding Lapita potsherds, the only decorated Lapita assemblage yet found in Samoa and dating to ca. 2.8 ka, lies at a depth of 2.25 m below modern sea level beneath a capping of cemented paleobeachrock. With fluctuating hydro-isostatic sea level taken into account, the sherd occurrence implies subsidence of a former coastline by ca. 4 m at a mean rate of 1.4 mm/yr. Shoreline features on both Upolu and nearby Savai'i are fully compatible with bulk Holocene subsidence. We attribute the observed subsidence to downflexure of the lithosphere from volcano loading centered on the Savai'i locus of historic volcanism, and conclude that any other Lapita sites that may exist in Samoa have subsided by a comparable amount. Although the Samoan linear volcanic chain resembles other Pacific hotspot tracks where active volcano loading is confined to their southeastern ends, the most voluminous Holocene eruptions in Samoa have occurred on Savai'i at the northwestern end of the exposed island chain. Samoan volcanism has evidently been influenced by lateral flexure of the Pacific plate as it moves past the northern extension of the Tonga subduction zone, and the active volcanism is apparently controlled by a longitudinal rift, which transects both Upolu and Savai'i and is superimposed upon older volcanic edifices that may record earlier hotspot volcanism. Early archaeological sites in American Samoa display a variable record of subsidence and possible uplift apparently related to volcano loading in the Manu'a Islands and possibly to the location of Tutuila in a position to be affected by uparching of lithosphere between downflexures beneath more active volcanic islands to the east and west. Bulk subsidence of Upolu and Savai'i may be the fundamental cause of damaging coastal erosion in modern Samoa.   © 1998 John Wiley & Sons, Inc.

INTRODUCTION

In 1973, at Mulifanua on the the northwest tip of Upolu in Samoa (formerly "Western Samoa"), the dredging of a new berth and turning basin for the interisland ferry that plies between Upolu and Sava'i fortuitously recovered abundant prehistoric potsherds from sediment beneath the shallow reef-locked lagoon that borders

much of the coastline of Upolu (Green, 1974a). The sherds are a Lapita assemblage (5% diagnostic decorated sherds), representative of a cultural horizon that extended for 5000 km from the Bismarck Archipelago on the northwest to Tonga and Samoa on the southeast during the millenium 1500–500 B.C. (Figure 1). Makers of Lapita pottery were apparently the first inhabitants of the islands of Remote Oceania lying to the southeast of the Solomon Islands chain (Green, 1992, 1997), but to date no other sites yielding decorated Lapita pottery have been discovered within either Samoa or American Samoa.

The position of the sherd-bearing horizon approximately 2.25 m below modern sea level led archaeologists to infer that the Mulifanua site has been submerged since its Lapita occupation by subsidence of at least part of Upolu (Jennings, 1974; Green and Richards, 1975). If analogous subsidence has affected other parts of Samoa, general submergence of coastlines might account for the failure to find any other Lapita sites where no dredging has been undertaken offshore (Jennings et al., 1976; Davidson, 1979). This viewpoint is in apparent conflict, however, with previous conclusions of geologists, who had interpreted various natural shoreline features as indicative of widespread emergence of islands in both Samoa and American Samoa by approximately 1.5 m since mid-Holocene time (Stearns, 1944; Kear and Wood, 1959). This perspective has led to suggestions that any subsidence affecting the Mulifanua site has been strictly local (Nunn, 1990:131; Clark, 1996:448). Past inferences of emergence, rather than submergence, for Samoan shorelines also raised the possibility (Leach and Green, 1989; Nunn, 1995:316) that the Mulifanua site could be the record of a stilt village built on piles over the lagoon, a settlement type well known for Lapita sites within Near Oceania (Kirch, 1988; Gosden and Webb, 1994; Kirch, 1997:170–175).

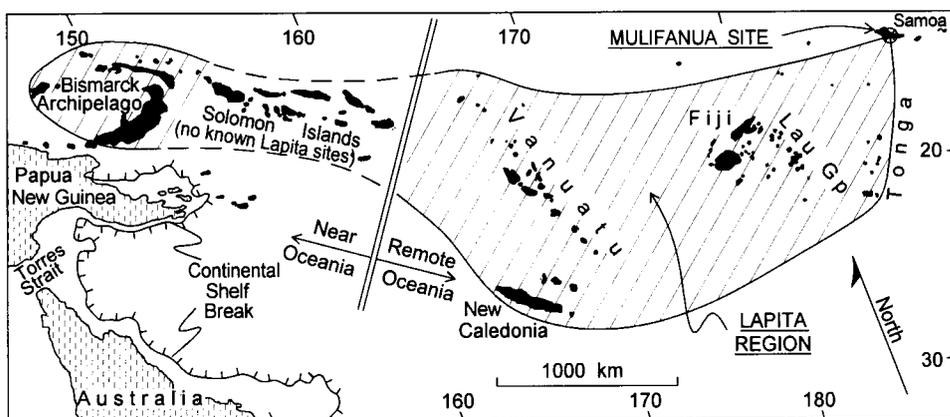Conventions adopted here for age notations are as follows: for geological time,

Figure 1. Location of Mulifanua ferry-berth Lapita site (Upolu, Samoa) at eastern limit of known Lapita region (diagonal rules) in southwest Pacific Oceania.

Ma is millions of years ago and ka is thousands of years ago; for prehistoric time controlled by radiocarbon dates, B.C. and A.D. have their usual connotations and B.P. is before A.D. 1950; radiocarbon dates are uncalibrated.

BACKGROUND

Although the effect of Holocene sea-level changes on Pacific island shorelines has long been considered an important factor for interpreting the environmental settings of Lapita sites (Green, 1979:32,34,50–53), the issue attracted only desultory attention for a number of decades. The subject was once again brought to the fore in a preprinted review paper by Clark (1990), who showed that archaeological data from island Oceania indicate significant changes in relative local sea level over the past few thousand years along many island coastlines. In particular, he noted that a regional mid-Holocene highstand in glacio-hydro-isostatic sea level (quantified by Mitrovica and Peltier [1991]) broadly affected the Oceanian region, and concluded that many early coastal sites are likely to be found well inland from modern strand-lines. He also noted that the submerged Mulifanua ferry berth site on Upolu was apparently a glaring counterexample to the broad pattern of late Holocene coastal emergence within Oceania.

A series of recent studies combining insights from archaeological and geological observations have documented the impact of the mid-Holocene hydro-isostatic highstand on specific Oceanian locales. For the Bismarck Archipelago (Figure 1) in Near Oceania, Allen and Gosden (1996), drawing on the detailed work of Gosden and Webb (1994), argue that the abrupt appearance of Lapita sites during the second millenium B.C. reflects the initial creation of modern-day beach environments as the peak of the mid-Holocene highstand waned. For Tonga (Figure 1) in Remote Oceania, Dickinson et al. (1994) have shown that the cultural remains of several Lapita communities, originally established along the strandline near the end of the second millenium B.C., now occupy backbeach positions well above modern sea level. Effects of late Holocene sea-level change have also been discussed with regard to matters as diverse as evolving coastal landforms in Fiji (Nunn, 1990), plain pottery sites in American Samoa yielding undecorated wares dating to the first millenium B.C. (Kirch, 1993a, 1993b, 1993c; Clark and Michlovic, 1996), the prehistoric exploitation of obsidian sources in the Talasea area of New Britain (Torrence et al., 1996:216–217), and the earliest pottery sites in the Mariana Islands dating to the mid-second millenium B.C. on Saipan (Amesbury et al., 1996:54–58). Kirch (1997:162–165) has provided an overall appraisal of current views on paleoshoreline relations with respect to Lapita sites, and underscores that post-Lapita emergence of island settings is the common context for nearly all known sites. In this regional context, the inundated Mulifanua ferry berth site seems anomalous and therefore problematic (Clark, 1990, 1996).

FOCUS

As interpreting the earliest prehistory of Samoa requires understanding the implications of the submerged Lapita horizon at Mulifanua (Jennings et al., 1976), we

first address that issue directly here. Our reappraisal of the Holocene shoreline history of Upolu and neighboring Savai'i reveals evidence for wholesale subsidence of both islands, owing to the load imposed on the lithosphere by continuing eruption of young lava. Submergence of the mid-Holocene archaeological site at Mulifanua is thus not anomalous, but to be expected. Our geoarchaeological interpretations highlight the necessity for blending observations derived from coordinated archaeological and geomorphic investigations to gain an accurate understanding of prehistoric environmental settings on Pacific islands. In closing, we return to the broader picture of Lapita and related sites elsewhere, within the conceptual framework of a mid-Holocene regional highstand in Oceanian sea level, in an effort to appraise how much local subsidence or uplift may have complicated relations in other island groups.

MULIFANUA SITE

The stratigraphy of the Mulifanua site (Figure 2) is known from correlation of the nature of dredged materials with the depth of dredging while excavation was in progress. The lagoon floor at the dredge site lay an average of 1.525 m below modern sea level, and the material just beneath the sediment–water interface was approximately 0.75 m of reef-derived calcareous sand tightly bound together by interstitial calcareous cement. Most sherds were recovered from a thin humus-rich layer just below the cemented layer, although a few, along with unabraded sea-
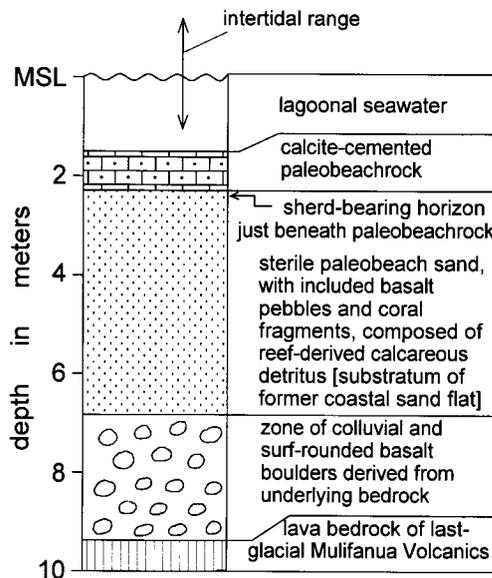

Figure 2. General underwater stratigraphy of the Mulifanua ferry-berth Lapita site (after Jennings, 1974; Green and Richards, 1975; Leach and Green, 1989). MSL = mean sea level.

shells, were incorporated into the base of the overlying cemented crust. The sherd-bearing horizon forms a band with a width of 30–40 m lying at a mean distance of 115 m offshore and extending for at least 110 m longshore (Jennings, 1974). Its extent and coherence argue against any notion that the present offshore occurrence of the sherds stems from scatter by currents from erosion of an onshore site. An average of 4.575 m of sterile calcareous sand, within which larger coralline fragments and pebbles of basaltic bedrock occur sporadically, underlies the sherd-bearing horizon and rests in depositional contact on a rubble zone of basaltic boulders that is approximately 2.75 m thick and grades downward into solid lava that was cored to a depth of at least 10 m below sea level.

The most parsimonious interpretation of the underwater Mulifanua Lapita site is straightforward. The key is the inference (Green, 1979) that the cemented crust overlying the sherd-bearing horizon is paleobeachrock, formed originally within the intertidal zone (Hopley, 1986) but now entirely subtidal. Beachrock is composed of beach sand grains cemented together by precipitation of interstitial calcite in pores between the sand grains when seawater that filters into the sand at high tide is warmed by insolation of the beach surface at low tide (Ginsburg, 1953). The local tidal range is only 1 m (Leach and Green, 1989), whereas the upper surface of the paleobeachrock layer is 1.5 m below mean sea level. Evidence that the cemented layer is not simply a hardground crust atop the fringing reef is provided by the presence of 4.6 m of unconsolidated sand beneath the paleobeachrock. From its position below the paleobeachrock layer, the humus-rich horizon yielding Lapita sherds, shells, and turtlebone is viewed as a midden accumulation on a sandy coastal strand that lay above sea level prior to local subsidence that allowed cementation of beachrock within the intertidal zone. Many modern coastal villages of Upolu are perched upon an analogous modern coastal sand flat, as discussed further below. The beach sand upon which the occupation was established evidently onlapped the basaltic bedrock of the island core.

Evaluation of available bathymetry within the modern lagoon suggests that the beach upon which the site was located lay on a protected lagoon shore opposite a deep passage through an offshore barrier reef and at the head of an elongate canoe passage through a coastal fringing reef (Leach and Green, 1989). Offshore islets along the barrier reef would probably have afforded some additional protection from surf, although the effects of postoccupation reef growth in modifying details of the offshore morphology of reef features cannot be hindcast with any confidence. In any case, the open nature of the lagoon shore, subject to intermittent attack by storm waves, would not have made construction of a stilt village over the lagoon an attractive option for habitation.

Radiocarbon ages for shells from coquina within the paleobeachrock overlying the sherd horizon are difficult to interpret owing to the marine reservoir effect, but date the Mulifanua site to approximately 2750 B.P. (Petchey, 1995), and our unpublished radiocarbon ages for turtlebone within the humus-rich layer underlying the paleobeachrock confirm the estimate. From knowledge of the age range of Lapita assemblages elsewhere, the inferred age of the site would be roughly the

same on the basis of its decorated pottery in the absence of any direct dating (Green, 1974b; Petchey, 1995). From the present underwater elevation of the intertidal paleobeachrock, minimum subsidence of 1.8 m can be inferred since its formation. For dry occupation of the underlying humus-rich midden, subsidence in excess of 2.8 m is more likely. These figures imply an average subsidence rate of at least 0.8 ($\pm$ 0.2) mm/yr since 2.8 ka.

Both these figures, however, are derived with respect to modern sea level and do not take into account estimates of the position of regional sea level at 2.8 ka from hydro-isostatic theory. The transfer of crustal load from Pleistocene ice concentrated in the polar regions to ocean water widely distributed across the Earth's surface led not only to the well-known eustatic rise in global sea level but also to slow Holocene deformation of the Earth's mantle that caused relative sea level to fluctuate through time in various patterns in different regions. Although the latter effect is nearly two orders of magnitude less than the former, a mid-Holocene (4–5 ka) highstand in relative sea level, somewhat variable geographically, is retrodicted for the equatorial Pacific region (Dickinson et al., 1994). The current best estimate for the magnitude of the residual highstand in Samoa at 2.8 ka is 0.8–1.6 m with respect to modern sea level (Mitrovica and Peltier, 1991:Figure 8j). Addition of this estimate to figures for post-2.8 ka subsidence of the Mulifanua site with respect to present sea level would carry the estimate of minimum net subsidence into the range of 2.6–4.4 m.

For purposes of discussion here we adopt a figure of 4 m (1.4 mm/yr), obtained by adding the mean estimate (1.2 m) for the regional hydro-isostatic highstand to the minimum required to place the site on dry land with respect to modern sea level. Before discussing archaeological implications of the late Holocene subsidence at Mulifanua, we next outline our reasons for concluding that the local subsidence inferred for Mulifanua is fully compatible with overall geologic relations in Samoa.

BEDROCK UNITS

Bedrock exposures on Upolu and nearby Savai'i (Figure 3) are exclusively post-mid-Pliocene (largely Quaternary) lavas of generally basaltic composition, together with associated cinder cones and local feeder dikes (Kear and Wood, 1959; Keating, 1992). Key units include (a) late Pliocene to early Pleistocene Fagaloa Volcanics (termed Vanu Volcanics on Savai'i by Natland and Turner [1985]), (b) Salani Volcanics erupted largely during the last interglacial, (c) Mulifanua Volcanics erupted during the last glacial, (d) early Holocene Lefaga Volcanics, (e) late Holocene Puapua Volcanics, and (f) historic Aopo Volcanics. Relative ages are based mainly on degree of weathering and extent of erosional dissection (Wright, 1963).

All units except the oldest display uniformly normal geomagnetic polarity indicative of eruption since 780 ka during the Brunhes normal polarity chron (Tarling, 1965; Keating, 1985). The Fagaloa Volcanics, however, have mixed polarity, and isotopic ages of 1.7–2.8 Ma (Matsuda et al., 1984:149; McDougall, 1985:319; Natland
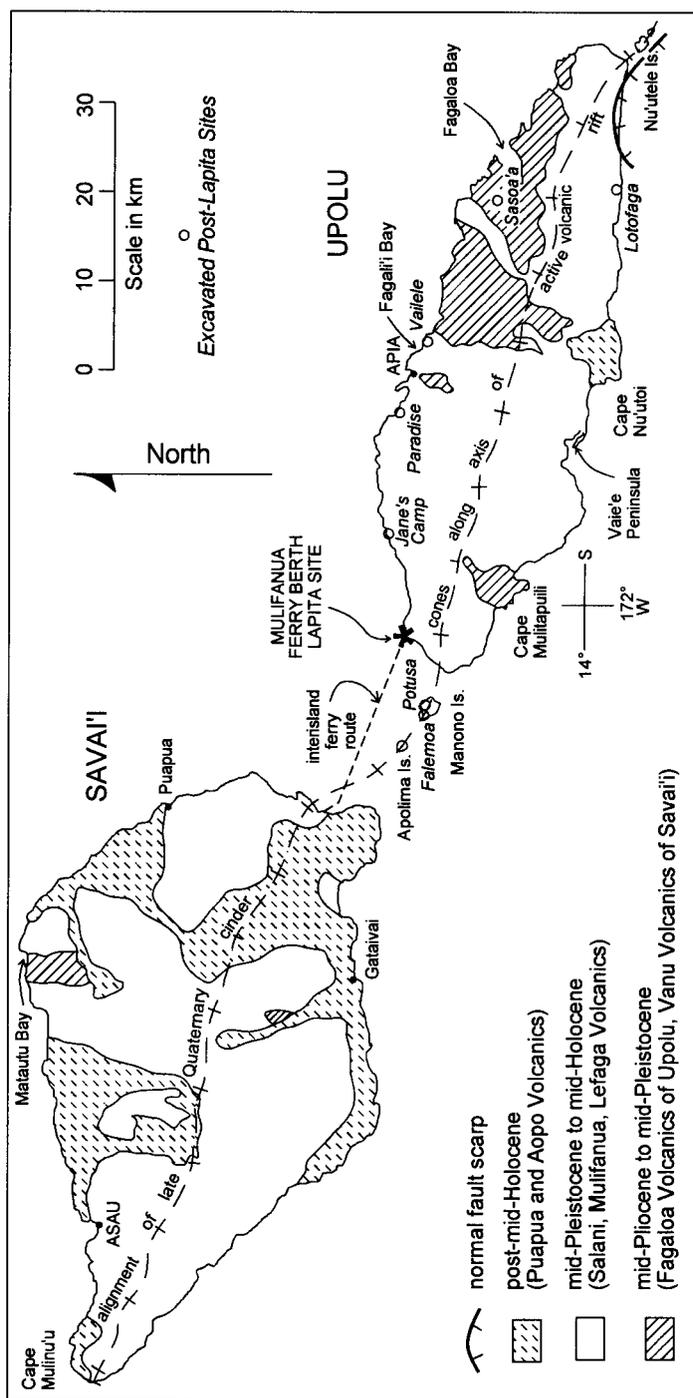
Figure 3. Sketch map of Upolu and Savai'i showing distribution of lavas of different ages (Kear and Wood, 1959) and locations of key sites discussed in text.

and Turner, 1985) reflect eruption during the preceding Matuyama reversed and Gauss normal polarity chrons (Natland, 1980). Fagaloa exposures, marked by steep coastal slopes and deeply incised interior valleys, are limited mainly to northeastern Upolu, although local outcrops occur around Cape Mulitapuili in southwestern Upolu, and the comparably dissected Vanu Volcanics lie inland from Matautu Bay on the north coast of Savai'i (Figure 3). Although the polarity of the Vanu Volcanics is normal, they were probably erupted during the Gauss polarity chron (2.58–3.58 Ma) rather than during the Brunhes polarity chron (Keating, 1985), as inferred initially (Kear, 1967).

Almost the entire land surface of Savai'i and fully three-quarters of Upolu are underlain by the post-Fagaloa units of latest Pleistocene and Holocene age (Figure 3). The surfaces of the young lavas form gentle and largely unbroken slopes extending from the seashore to the central spines of Savai'i (max. elev. 1825 m) and Upolu (max. elev. 1150 m) capped by lines of cinder cones cloaked in thick vegetation. As the thicknesses of lavas of various ages are poorly known, Pleistocene–Holocene eruption rates cannot be calculated with any confidence, but the elongate shield volcano of Savai'i is the most active in the Pacific Ocean, apart from the island of Hawai'i. Nearly a third of its surface is underlain by post-mid-Holocene lavas (Figure 3). Voluminous eruptions occurred ca. 1760, in 1902, and during the interval 1905–1911 (Keating, 1992). Based on the number of postglacial cinder cones, the average return time for major eruptions is estimated to be approximately 300 years (Kear and Wood, 1959).

UPOLU SHORELINES

On Upolu, cliffed shorelines occur only on outcrops of the older Fagaloa Volcanics and at the margin of a late Holocene lava delta along the south coast (Figure 3). Elsewhere, a wide fringing reef transitional to a shallow barrier reef fronts a lagoon shore exposing bedrock along both the north coast and the western end of the island, whereas a fringing reef along the southeast coast fronts a narrow coastal strip of carbonate-sand beach ridges built by storm-wave action (Richmond, 1992a, 1992b). Barrier spits blocking coastal swamps also occur locally at stream mouths.

Kear and Wood (1959) inferred that the coastal strip of Holocene sand deposits standing at an elevation of ca.1.5 m (their figure) above modern sea level, and termed by them Tafagamanu Sand, represents the record of a mid-Holocene highstand of relative sea level. These coastal sand deposits are episodically overtopped, however, by storm waves at the present time, and hence do not require the postulate of a higher relative sea level to explain their occurrence (Richmond, 1992a, 1992b). At many localities, moreover, at least the upper levels of the coastal sand accumulations are cultural deposits locally 1–2 m thick (Davidson, 1969:232, 1974: 200). As a radiocarbon age of only 1180 ± 55 B.P. has been obtained from supposedly type "Tafagamanu Sand" (Grant-Taylor and Rafter, 1962), there seems every reason to regard the deposits as submodern storm-beach berms and backbeach washover flats forming embankments and veneers directly overlying lava bedrock.

For centuries, residents of coastal villages have also carried sand up from the beach almost daily to scatter around their houses, thus covering otherwise muddy ground, and traditionally made their house floors of coral rubble and shell also obtained on the shore (Davidson, 1965:65).

Our observations indicate that the coastal beach berms actually reach elevations of as much as 2.5 m above high-tide level, but that figure is within the range observed for modern beach berms on exposed coasts in nearby island groups such as Tonga (Dickinson et al., 1994). Nowhere on the coast of Upolu could we find any prominent erosional benches cut above modern sea level, nor any emergent beachrock exposed above the intertidal zone. Where not masked by a veneer of reef-derived sand deposited by storm waves, shoreline outcrops of lava bedrock are typically bulbous knobs, of irregular shape, washed by the surf as they descend below sea level. We conclude, with Richmond (1992a, 1992b), that shoreline features on Upolu are fully compatible with continuing Holocene subsidence, probably related to volcano loading of the lithosphere.

Three key features regarded by some as contrary to that view require comment. At Lotofaga (Figure 3) on the south coast, Davidson (1969:232) reported supposedly raised reef limestone exposed at low tide on the modern beach. Close examination of that outcrop reveals, however, that it is actually well-cemented modern beach-rock, composed entirely of wave-worn fragmental debris in beds lying parallel to the beach face and within the intertidal zone at a normal elevation with respect to present sea level. In Fagali'i Bay (Figure 3) on the north coast not far east of Apia, a prominent block of reef limestone rises well above the modern high-tide line in an apparently anomalous position with respect to modern sea level. Nunn (1994: 231–232) has shown elegantly, however, by his description and an accompanying photograph, that the exposure is a tilted block of coralline limestone ripped off the reef front and thrown atop the reef by storm waves, to be recemented into the surface of the reef as an upward-projecting appendage after its displacement. Ephemeral storm ramparts composed of transported coral blocks perched on top of the fringing reef are commonly built to elevations of 2–3 m above mean sea level by hurricanes striking the coast of Upolu (Richmond, 1992a). Local evidence for shoreline emergence on Nu'utele Island off the southeast tip of Upolu (Nunn, 1997) may reflect the position of the islet on the upthrown side of an arcuate normal fault that delineates a short segment of the nearby south coast of Upolu (Figure 3).

Cores from mangrove swamps on the south coast of Upolu provide evidence supportive of a regime of bulk Holocene subsidence of the island under volcano loading (Bloom, 1980). Radiocarbon ages for peaty mud deposited slightly below high-tide level increase monotonically with depth. When observed depths are adjusted for inferred hydro-isostatic changes in relative sea level, the internally consistent data imply subsidence at a mean rate of 1.4 mm/yr for the interval 5–1.5 ka (Figure 4). This subsidence rate is the same as the minimum rate we infer since 2.8 ka from stratigraphic relations at Mulifanua. As the subsidence curve derived from mangrove peat projects to a present elevation below the intertidal zone, it
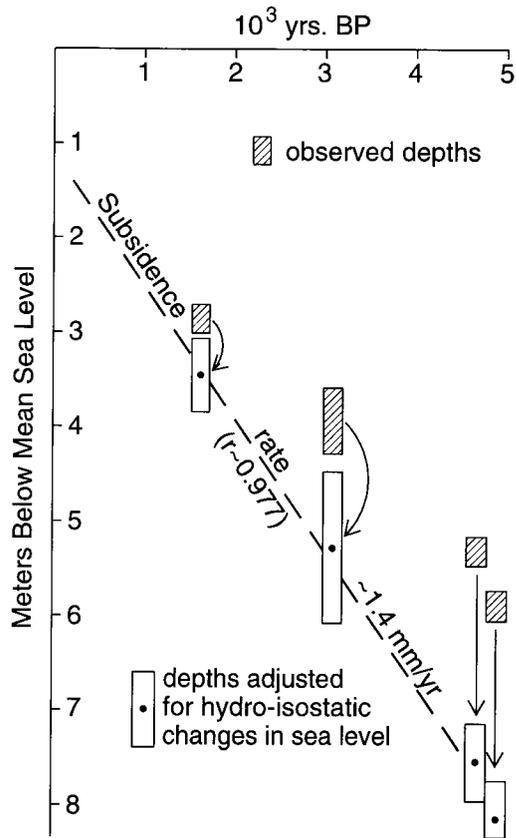
Figure 4. Plot of age-depth relations of peaty mangrove muds on south coast of Upolu after Bloom (1980). Dimensions of blocks show uncertainties in age (±values for radiocarbon B.P.) and depth. Central dots in blocks for hydro-isostatically adjusted depths below mean sea level denote mean estimates. Arrows indicate movement of data points owing to hydro-isostatic depth adjustments. Magnitude of hydro-isostatic adjustments after Mitrovica and Peltier (1991), with the oldest two points adjusted for the peak mid-Holocene highstand (2.0–2.5 m) inferred from theory.

evidently incorporates some systematic error, such as sediment compaction, not corrected by adjustment of observed elevations to account for the hydro-isostatic mid-Holocene highstand in relative sea level.

SAVAI'I SHORELINES

Reconnaissance of Savai'i shorelines also suggests bulk Holocene subsidence of Savai'i, which the concept of subsidence from volcano loading on Upolu would seemingly require, for post-mid-Holocene volcanism has been more widespread on Savai'i than on Upolu (Figure 3). Extensive segments of the Savai'i shoreline where

Holocene lavas have flowed into the sea are so-called "ironbound" coasts, named thus by early European seamen and marked by low but steep rocky cliffs 3–15 m high. The cliffs of the ironbound coasts form when lavas flow off the land surface as lava deltas spanning the width of fringing reefs or lagoons confined behind reef barriers. When the flows, ponded temporarily within lagoons or above fringing reef flats, finally plunge into deep water beyond the reef edge, they spill over abruptly to preserve an almost vertical cliff that persists as an ironbound coast (Kear and Wood, 1959:29). A similar cliff is preserved along the seaward margin of the Holocene lava delta around Cape Nu'utoi on the south coast of Upolu (Figure 3).

Cliffed coasts are comparatively rare where post-Pliocene but pre-Holocene lavas are exposed along the coastline of Savai'i. Instead, irregular bedrock surfaces typically slope gradually into the sea or terminate in irregular ragged seacliffs. This relationship implies subsidence of pre-Holocene ironbound coasts, for wave erosion of seacliffs without a relative rise in sea level would accentuate the height of the seacliffs. No emergent beachrock occurs above the intertidal zone on Savai'i, and emergent wavecut benches and notches observed slightly above modern sea level on some cliffed headlands were eroded out by storm surf along brecciated flow tops or interflow layers of tuff and breccia less resistant to erosion than the massive lava above and below (Rodda, 1988).

Along the east coast of Savai'i and near Cape Mulinu'u at the western tip of the island, coastal deposits of reef-derived calcareous sand ("Tafagamanu Sand") form beach ridges and backbeach washover flats with berm crests standing 1.5–2.5 m above modern high-tide level. As on Upolu, these sand accumulations are regarded here as active or submodern features formed by storm wave attack at present sea level. In settlements around Cape Mulinu'u, waves associated with major hurricanes overtopped the coastal sand ridges and demolished structures well inland from the shoreline during just the past 5 years. Coastal sand lying a meter above present sea level and stratigraphically beneath late Holocene Puapua Volcanics just north of Pu'apu'a on the east coast of Savai'i (Figure 3) has yelded a radiocarbon age of only 1850 ± 80 B.P. (Grant-Taylor and Rafter, 1962).

Problematic outcrops with uncertain implications for relative Holocene sea-level change occur near Gataivai on the south coast of Savai'i (Figure 3) where a prominent coastal bench almost 60 m wide occurs on top of late Holocene Puapua Volcanics (Nunn, 1994:130). Basaltic ash in which coral fragments are imbedded is partially encased in lava at an elevation of 4 m above sea level on top of the bench, and rounded gravel occurs at the base of a low cliff along the inland edge of the bench at an elevation of 5 m above sea level (Kear and Wood, 1959:30). The ash and gravel deposits have yielded overlapping radiocarbon ages of 710–760 (±50) B.P. (Grant-Taylor and Rafter, 1962), and fossil coral on the surface of the underlying lava platform has yielded a slightly older radiocarbon age of 1310 ± 50 B.P. (sample GAT-1, P.D. Nunn, personal communication, 1997). If the sediments and coral formed near sea level, a rapid mean uplift rate of 5 ± 2 mm/yr is implied. Given the lack of evidence for any Holocene uplift elsewhere on Savai'i, we speculate that the emergent ash and gravel may instead have been rafted bodily upward

from the lagoon floor on top of a Holocene lava flow that burrowed beneath unconsolidated lagoon sediment in crossing the lagoon to form an ironbound coast. From work in the northwest United States, it is well known that subaerial flows of lava deltas expanding seaward commonly descend beneath surficial sediment as underflows that spread out to form invasive sills beneath a cover of unconsolidated sediment (Niem et al., 1994). If such a shallow sill ponded within a lagoon until the cliffs of a typical ironbound coast formed offshore, overlying lagoon sediment would be carried upward to a height comparable to the elevation of the coastal bench at Gataivai.

VOLCANO SUBSIDENCE

Subsidence owing to volcano loading is not expected to be episodic in response to intermittent eruptions because deformation of the underlying mantle in response to added loads is not instantaneous. Analysis of crustal rebound following removal of Pleistocene ice and lake-water loads indicates that the relaxation time for mantle deformation driving the uplift is of the order of 10^3–10^4 years (Crittenden, 1963). As subsidence in response to added load is just the inverse of uplift in response to removal of load, and the spacing of major Holocene eruptions on Savai'i is of the order of only 10^2 years, steady gradual subsidence is expected from continuing eruptive activity. Both historic and geologic evidence show that active volcanism on Savai'i has extended throughout Holocene time.

Subsidence of lithosphere under the superposed load of a volcanic edifice does not occur in pistonlike fashion, but in the form of a dimplelike depression created by flexure of the elastic or viscoelastic lithosphere above the weak fluid substratum of the underlying asthenosphere (Watts and Cochran, 1974). The centroid of the volcanic load lies above the deepest part of the dimple, which is surrounded by an upflexed annular arch with more than an order of magnitude less positive relief than the negative relief of the depression. In Pacific island settings, the crest of the arch lies in the range of 200–250 km from the approximate center of the causative volcanic edifice in the case of Rarotonga in the Cook Islands (McNutt and Menard, 1978, 1979; Lambeck, 1981), and in the range of 250–300 km for the island of Hawai'i (Moore, 1970).

Analysis of data from Hawai'i indicates a subsidence rate of 2.2–2.6 mm/yr at Hilo (Moore, 1987; Moore et al., 1996), which lies 40–60 km from the active volcanic centers of Kilauea and Mauna Loa. Mulifanua lies a comparable distance of 50 km from the highest cinder cones on the central spine of Savai'i (Figure 3). The lower subsidence rate of 1.4 mm/yr that we infer here for Mulifanua seems compatible with the lesser eruption rate on Savai'i as compared to Hawai'i. Net volcano subsidence rates cannot be calculated directly from observed eruption rates, which in any case are not well known for Savai'i and Upolu, because the volumetric rate of subsidence of the flexural cone of depression surrounding Hawai'i is several times the known eruption rate (Moore, 1970). Subvolcanic intrusions and unobserved submarine volcanism evidently contribute to the total volcanic load.

The inferred subsidence rate for Upolu and Savai'i cannot be extrapolated to other islands along the Samoan chain. In Hawai'i, the subsidence rate of 2.2–2.6 mm/yr on the active volcanic island declines to 0.75 mm/yr for Maui, at a distance of 175 km but still within the cone of depression. Oahu (350 km) and Kauai (500 km) lie beyond the dimple of subsidence, and both islands preserve paleoshoreline indicators reflecting mid-Holocene (3–5 ka) highstands of relative sea level in the range of 1.4–1.8 m (Jones, 1992; Calhoun and Fletcher, 1996; Fletcher and Jones, 1996). As this amount of emergence closely matches the regional highstand for Hawai'i anticipated from hydro-isostatic theory (Mitrovica and Peltier, 1991:Figure 8q), significant post-mid-Holocene subsidence for either Oahu or Kauai is apparently precluded.

In Samoa (Figure 5), the Manu'a Islands at a distance of 305–330 km would be expected to lie beyond the influence of subsidence owing to volcano loading at Savai'i, but Tutuila at a distance of 200–215 km from the center of Savai'i may lie near the crest of an annular arch surrounding Savai'i. A long gravity profile transverse to the Samoan chain through Upolu seemingly confirms that the crest of the flexural arch produced by volcano loading lies 205–210 km from the volcanic edifice (Robertson, 1987). Analysis of subsidence or uplift for either Tutuila or the Manu'a Islands is complicated, however, by limited Holocene volcanism near Leone on Tutuila and active volcanism in Manu'a, where a submarine eruption occurred between Ta'u and Olosega in 1866 (Stice and McCoy, 1968).

SAMOAN VOLCANIC CHAIN

Our use of analogies between Hawai'i and Savai'i for subsidence analysis requires defense in terms of the overall geologic evolution of linear Pacific island chains, each of which is viewed as a hotspot track formed as the mobile Pacific plate of lithosphere passed northwestward over multiple stationary hotspots in the underlying mantle (Jarrard and Clague, 1977). In Hawai'i, for example, the present position of the mantle hotspot is assumed to underlie the southeastern extremity of the island chain beneath the active Kilauea volcano on land and nearby Loihi seamount, where historic eruptions have occurred offshore.

As typical hotspot volcanic chains evolve, older volcanic edifices tend to subside slowly, as the underlying lithosphere cools in moving away from the hotspot, leaving the highest and bulkiest islands on the southeast above the hotspot, with smaller islands, atolls, and submerged seamounts trailing off toward the northwest along each chain. The progressive thermal subsidence of the successive islands tends to occur, however, at rates one to two orders of magnitude slower than the subsidence under volcano loading inferred for Hawai'i and Savai'i–Upolu. From their positions hundreds of kilometers from a presumed hotspot locus at the southeastern end of the Samoan volcanic chain, hotspot theory would seemingly predict such slow rates of subsidence for Savai'i and Upolu as well.

The general morphology of the linear volcanic chains was known long before the hotspot hypothesis was developed, and the Samoan chain was identified as
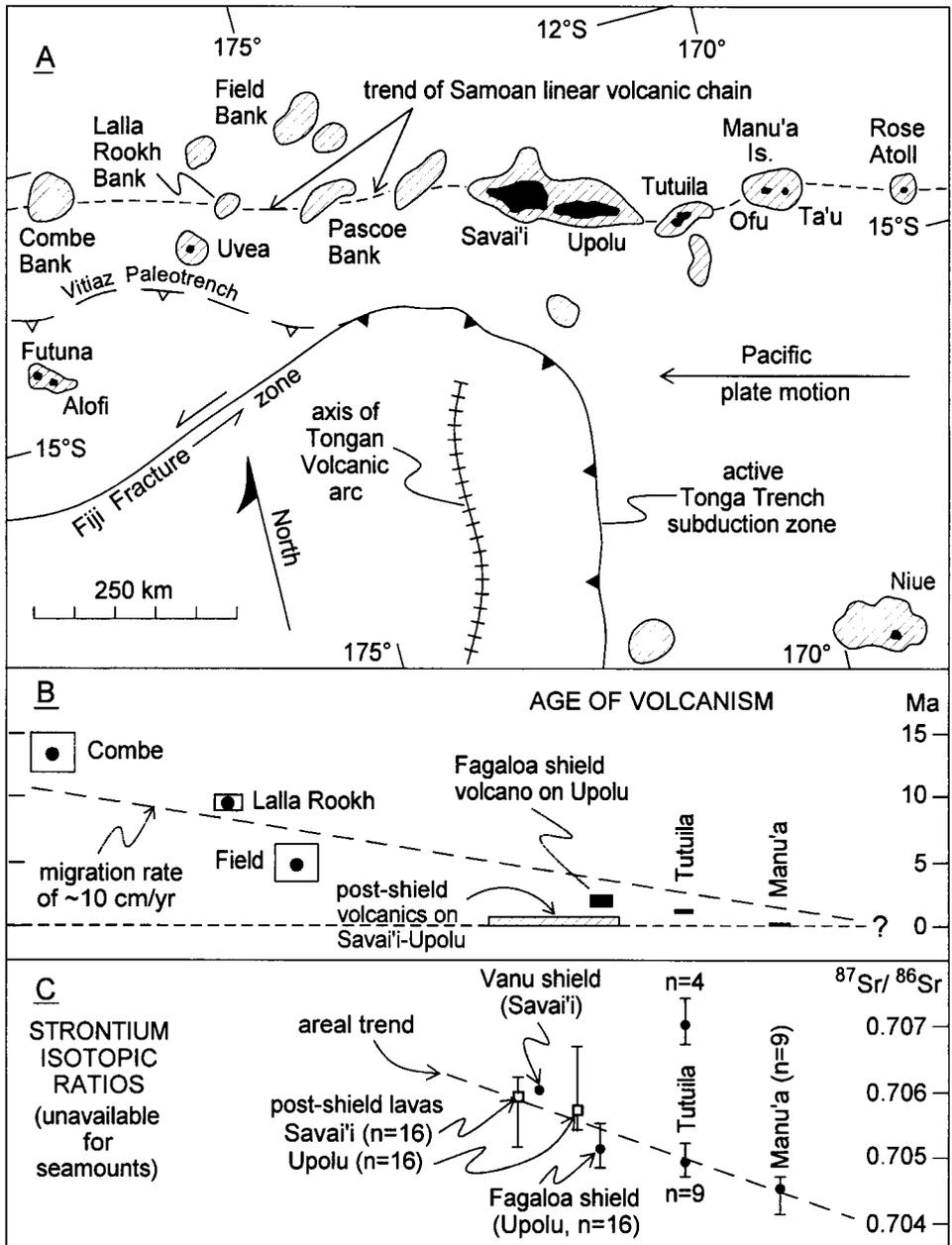
Figure 5. Geography, geochronology, and geochemistry of the Samoan linear volcanic chain: (A) Alignment of islands and seamounts (Brocher, 1985; Johnson et al.,1986); submerged parts of volcanic edifices in diagonal rules with islands in black; Futuna and Alofi (Horne Islands) represent northern extension of ancestral Tongan island arc offset across Fiji Fracture Zone, whereas Uvea (Wallis Island) is a young Pleistocene center related to late volcanism in Fiji but not to Samoan volcanism. (B) Time–distance plot of volcanic rocks from island outcrops and seamount dredge hauls; K-Ar and ^{40}Ar/^{39}Ar ages from Duncan (1985) and McDougall (1985). (C) Geographic and stratigraphic ranges of ^{87}Sr/^{86}Sr ratios (n = 61) from volcanic rocks in Samoa (data from Hedge et al., 1972; Hubbard, 1971; White and Hofmann, 1982; Wright and White, 1986/1987).

anomalous in some respect at least 40 years ago (Chubb, 1957). In Samoa, the largest, highest, and most volcanically active island of Savai'i is located at the northwestern end of the exposed part of the chain, with successively smaller islands to the southeast and Rose Atoll beyond them along the projection of the bedrock island chain (Figure 5A). Despite its resemblance to other hotspot tracks, the linear Samoan volcanic chain may owe its origin to rupture or dilation of the Pacific plate of lithosphere as it is flexed laterally in moving past the curved northern end of the Tonga Trench subduction zone (Figure 5A), or to thermal perturbations induced in the mantle beneath the plate by the flexural deformation of the moving plate (Natland, 1980; Natland and Turner, 1985). Unlike classic hotspot chains, Samoa displays Holocene volcanism of variable intensity along almost the full length of the exposed island chain (Figure 5B).

The hotspot interpretation of Samoan volcanism has been preserved in modified form by close attention to the petrologic evolution of individual volcanic centers. Work in Hawai'i has shown that the initial shield-building phase of island volcanism, during which the bulk of each volcanic edifice is constructed, usually erupts subalkalic (tholeiitic) basalt, which is succeeded later in the history of each volcano by eruption of a veneer of alkalic basalt. The distinction between tholeiitic and alkalic basalt is based upon differences in petrochemistry, and in the nature of associated derivative lavas produced by crystal fractionation or other modification of the parent magmas, and is not readily apparent to nonpetrologists in the field.

Although most exposed Samoan volcanics are alkalic olivine basalts and their differentiates (Macdonald, 1968; Hawkins and Natland, 1975), the pre-mid-Pleistocene lavas of the Fagaloa and Vanu Volcanics on Upolu and Savai'i are transitional in petrochemistry between tholeiitic and alkalic basalt (Natland, 1980). The transitional lavas are viewed as the only exposed record of the shield-building phase of Savai'i-Upolu volcanism, with eroded shields mostly buried by younger alkalic basalts erupted from a linear rift marked by the curvilinear array of cinder cones (Figure 3) extending for 170 km along the aligned crests of Savai'i and Upolu (Natland and Turner, 1985). By reasoning from this perspective, and regarding only the oldest lavas of each volcanic center as the products of hotspot volcanism, the Samoan islands can be interpreted as the eastern segment of a hotspot track composed of seamounts and islands extending for ca. 1000 km parallel to Pacific plate motion (Figure 5A). A monotonic age progression in the normal sense for Pacific hotspot tracks (oldest to the northwest) can be inferred if only the oldest lavas known at each volcanic edifice are used to construct a time-distance curve (Figure 5B). The younger lavas on Upolu and Savai'i have poured over the eroded remnants of older shields (Figure 3).

Even so, petrologic relations are atypical for hotspot chains. In Manu'a, where only eroded late Pleistocene shields are present, all the exposed lavas are alkalic (Stice, 1968). On Tutuila, where a deeply dissected Pleistocene shield volcano is flanked by coalescing satellite cones (McDougall, 1985), all the exposed volcanics are also alkalic (Macdonald, 1944). In fact, no unequivocal tholeiitic basalts occur anywhere in the Samoan Islands (Natland, 1980:720). Moreover, ratios of radiogenic

strontium (Figure 5C), thought to reflect the nature of mantle sources, vary systematically from east to west in Samoan volcanic rocks (Hedge et al., 1972), implying derivation from multiple sources rather than from a single mantle hotspot. Dredged samples from seamounts of the Samoan linear volcanic chain west of Samoa are also dominantly alkalic lavas, although one sample of tholeiitic basalt was recovered from Combe Bank (Sinton et al., 1985; Johnson et al., 1986).

We conclude that subsidence due to volcano loading cannot be restricted in Samoa to some cryptic early shield-building phase of transitional basaltic eruptions, but must continue through the eruptive phase of voluminous alkalic magmas. Regardless of the nature of the largely invisible underpinnings of the Savai'i and Upolu volcanic edifices, eruptions of alkalic magmas from the longitudinal rift zone traversing the two islands have been most voluminous toward the west on Savai'i (Natland, 1980), in a geographic position favorable to drive subsidence at Mulifanua. The lithosphere does not respond flexurally to the petrochemistry of erupted lavas, but to their weight regardless of petrologic affinity.

ARCHAEOLOGICAL IMPLICATIONS

Nearly 4500 sherds have been recovered from the Mulifanua ferry berth site, of which nearly 5% are decorated in distinctive Lapita style (Petchey, 1995). The proportion of decorated sherds is typical of Eastern Lapita assemblages elsewhere, in part because only pot rims and the upper parts of bodies above the shoulders were typically decorated. Petrographic analyses of sand tempers in representative sherds show that the sands are detritus derived from Upolu bedrock units, and could have been collected nearby (Petchey, 1995), although sources elsewhere on northwest Upolu are not precluded (Dickinson, 1974, 1976). The sands resemble in a generic sense tempers from younger Samoan sherd assemblages (Dickinson, 1969, 1993). These observations indicate that the pottery-makers were living at or near Mulifanua, making both their decorated and undecorated ceramics from indigenous materials (Jennings and Holmer, 1980), and preclude the possibility that the decorated fraction of the Mulifanua sherd assemblage represents pottery brought by itinerant travellers, suggested as one possibility by Clark (1993, 1996:450).

Although it is impossible to predict how many early Lapita sites may exist in Samoa, or how many of them harbor decorated wares, it seems unlikely to us that settlers would confine their occupation to only one locale within such a large archipelago for any extended period of time. Our subsidence analysis implies that any other Lapita sites on Upolu or Savai'i now lie below the intertidal zone where sedimentation, surficial coral growth, or formation of beachrock, as at Mulifanua, may have prevented their fortuitous discovery in the absence of dredging. Some Lapita sites could even lie deeply buried under Holocene lava flows.

Recent work in American Samoa (Tutuila and Manu'a Islands of Figure 5A) suggests, however, that Lapita decorative practices either died out rapidly in Samoa following initial settlement, or that decorated pots were made only at certain places for special purposes that are unknown. Earlier work in Samoa had suggested that

a cultural transition from decorated Lapita ware to undecorated Polynesian Plain-ware did not occur until perhaps 300 B.C. (Green, 1974b). This inference initially came under challenge with the excavation of plain pottery sites on Upolu and nearby Manono (Figure 3) dating to early in the first millenium B.C. (Jennings and Holmer, 1980:111–115). In American Samoa, moreover, the deepest cultural levels of sites that have yielded only undecorated sherd assemblages at 'Aoa on Tutuila (Clark and Michlovic, 1996) and at To'aga on Ofu in the Manu'a Islands (Kirch et al., 1989; Kirch, 1993c; Kirch and Hunt, 1993b) date to ca. 1000 B.C.

Data from multiple excavations suggest that the manufacture of pottery may have ceased throughout most of Samoa during the interval A.D. 250–500 (Green, 1974b; Hunt and Kirch, 1987; Kirch, 1993c; Kirch and Hunt, 1993b), although relations at 'Aoa Valley on Tutuila are permissive of continued local manufacture until the protohistoric interval A.D. 1400–1650 (Clark and Michlovic, 1996). The eventual decline in ceramic usage may stem in part from difficulties that ancient potters experienced in finding usable clay deposits (Claridge, 1984). Widespread ceramic manufacture in Samoa for well over a millenium suggests, however, that restriction in vessel form to bowls and later replacement by wooden bowls were related instead to an increasing dependence on pit ovens for cookery, together with adoption of nonceramic means for food serving and storage (Green, 1974b).

AMERICAN SAMOA SHORELINES

Paleoshoreline analyses of occupation sites in American Samoa yielding only Polynesian Plainware, but contemporaneous with the Mulifanua Lapita site, imply comparable subsidence in the Manu'a Islands, where the prevailing volcanism is recent enough to drive subsidence by volcano loading (Kirch, 1993a; 1993b), but coastal emergence on Tutuila (Clark and Michlovic, 1996), where the principal volcanism occurred more than a million years ago (McDougall, 1985).

The To'aga site on Ofu in the Manu'a Islands (Figure 5) is located at the inner margin of a narrow coastal flat, 75–175 m wide, bordered by a continuous sand beach, which is armored locally by sloping intertidal beachrock cuestas and fronted by an offshore fringing reef (Kirch et al., 1990). Modern beachrock locally extends slightly above high-tide level on both Ofu and nearby Ta'u (Stice and McCoy, 1968: 442, 456), but not above the swash zone of waves that overtop the narrow fringing reef at high tide. Alternate wetting and drying of beach faces influenced by mild surf provides essentially the same local control for beachrock formation as intertidal fluctuation alone on surf-free shorelines.

The To'aga site is backed by a steep slope of colluvium and talus at the foot of towering precipitous cliffs that are nearly 400 m high, and ceramic-bearing horizons dating from approximately 1000 B.C. to A.D. 500 are buried beneath the toe of the slope apron derived from the cliffs (Kirch and Hunt, 1993a). The site is interpreted as a coastal settlement, with the coastal flat now separating it from the shore interpreted as a progressively accreted complex of beach ridges deposited as the beach prograded seaward over the past 2000 years (Kirch and Hunt, 1993a). Subtle

topographic features on the coastal flat may be the record of successive positions of paleobeach ridges along the prograding shoreline. The oldest excavated cultural horizon overlies paleobeach sand at a present elevation within 0.5–1.5 m of the modern high-tide level, although the modern beach berm stands 2.5–3.5 m above the modern high-tide line on the present beach face. Allowing for a hydro-isostatic decline in relative sea level of 0.6–1.8 m since 2–3 ka (Mitrovica and Peltier, 1991), the site has probably subsided 2.6 ($\pm$ 1) m since 2 ka and 3.8 ($\pm$ 1) m since 3 ka, at a mean rate of 1.3 mm/yr, nearly the same rate derived here for Mulifanua. Although the To'aga site is not underwater, it is masked by colluvial cover that hid it as effectively from surface surveys as water could, and points to another possible reason why few sites of comparable age have been found in Samoa (Kirch and Hunt, 1993b).

In 'Aoa Valley on Tutuila (Figure 5), accelerated erosion, reflecting the impact of human settlement on the local landscape, has also buried an ancient occupation site beneath thick sediment cover deposited at the foot of mountainous slopes (Clark and Michlovic, 1996). On Tutuila, however, variably degraded bedrock benches, interpreted as emergent mid-Holocene wavecut platforms (Stearns, 1944; Nunn, 1997), stand distinctly above modern high-tide level on many headlands, offshore islets, and selected seastacks. No comparable features are present in the Manu'a Islands (Stice and McCoy, 1968). An elevation difference of 1.8 ($\pm$ 0.1) m was measured between the best preserved mid-Holocene wavecut bench and its modern counterpart at Ma'ama'a Cove on the islet of Aunu'u (offshore from eastern Tutuila), where both features are cut into inclined beds of tuff forming a local tephra cone of probable early Holocene age. From this observation, late Holocene emergence of Tutuila-Aunu'u lies within the range (1.5–2.6 m) expected for sea-level drawdown following the regional mid-Holocene highstand in hydro-isostatic sea level (Mitrovica and Peltier, 1991:Figure 8j), and thus implies a lack of significant post-mid-Holocene subsidence or uplift. The mid-Holocene highstand in local relative sea level apparently inundated 'Aoa Valley prior to post-mid-Holocene decline in sea level that fostered human settlement of the bayhead valley (Clark and Michlovic, 1996).

Volcano loading by the young (< 0.1 Ma; McDougall, 1985) shield volcano of Ta'u (Figure 5) can account for subsidence of nearby Ofu (0.3 Ma; McDougall, 1985), which lies only 25 km away. Excavation of the only known ceramic-bearing site on Ta'u (Hunt and Kirch, 1988) has been too limited to define its history relative to changing local sea level. Tutuila and nearby Aunu'u, distant 120–150 km from Ta'u, probably lie near the inflection point for the cone of subsidence surrounding Ta'u, meaning that depression of Tutuila–Aunu'u from volcano loading at Ta'u is expected to be negligible or minor. Moreover, Tutuila–Aunu'u may lie along an upflexed arch surrounding the cone of subsidence around the volcanic center of Savai'i, as discussed above, meaning that slight flexural uplift may roughly compensate for any flexural subsidence induced by volcano loading at Ta'u. We conclude that the emergent mid-Holocene paleoshoreline features on Tutuila and Aunu'u faithfully record the approximate height of the regional hydro-isostatic high-

stand within the limits of error inherent for hydro-isostatic and flexural-loading theory. The observed emergence of Tutuila–Aunu'u by ca. 1.8 m since mid-Holocene time is closely matched by the comparable emergence of ca. 1.7 m noted for remnants of raised reef flats at Rose Atoll (Mayor, 1921), which lies 150–160 km east-southeast of Ta'u (Figure 5) and well beyond the influence of Savai'i.

ENVIRONMENTAL IMPLICATIONS

Knowing that Upolu and Savai'i are subsiding influences thoughts not only about prehistoric events, but also about future environmental conditions. Widespread and locally severe coastal beach erosion is a current environmental problem on Upolu (Richmond, 1992a, 1992b). The removal of coastal vegetation, the mining of beach sand for construction, the building of seawalls that alter wave behavior, and the construction of groins and piers that interrupt longshore sediment transport and beach replenishment doubtless exacerbate the problem, but the root cause may be island subsidence (Richmond, 1992a, 1992b:119). The reach and intensity of waves breaking on the coast may be gradually enhanced as subsidence allows slow transgression of the sea over the land surface. Such transgression may be reflected by the occurrence of beachrock cuestas stranded tens of meters offshore within the intertidal zone at selected sites along the north coast of Savai'i, notably in Matautu Bay, and on the south coast of Upolu, notably east of Vaie'e Peninsula (Figure 3). Beachrock that formed originally as a sloping armor on beach faces may have become separated from the shoreline at these and other localities by marine transgression and consequent removal of the seaward edges of coastal flats by wave attack during storms. The actual or potential impact of island subsidence on coastal erosion underscores the relevance of archaeological studies for environmental planning.

CONCLUSIONS

The recent archaeological literature for Oceania has begun to reflect an informed appreciation of the mid-Holocene (ca. 6–3 ka) highstand (ca. 1.5–2.5 m) in regional hydro-isostatic sea level. Its implications for sites of the Lapita horizon (ca. 3.5–2.5 ka) are being discussed in some detail based on studies combining archaeological and geomorphological observations. Emergent beach zones with Lapita artifacts and Lapita sites now stranded well inland are clearly common. The Mulifanua case, however, underscores a point made by Boyd et al. (in press): "detailed local studies are needed before generalised regional models can be proposed for the impact of Holocene sea level changes on Lapita settlements." In particular, the potential for local subsidence or uplift affecting individual sites must be assessed correctly before the impact of the mid-Holocene highstand can be gauged properly from place to place.

The notion of a stilt village built offshore to explain the submerged artifacts at Mulifanua without post-Lapita shoreline submergence seems unlikely for three reasons: (1) Emplacement of piles into shifting unconsolidated sand, which is now

buried beneath the paleobeachrock layer at the site, would present difficulties for construction that were not encountered at typical stilt villages rooted in shallow reef flats of Near Oceania (Gosden and Webb, 1994:40; Kirch, 1988:333); (2) there is no reason to suppose that the Mulifanua site maintained its position relative to sea level as wholesale subsidence of Savai'i and Upolu proceeded; and (3) Lapita stilt villages are common in Near Oceania, and at younger plain pottery sites in Micronesia, but are thus far unknown for Lapita settlements in Remote Oceania, where Lapita house styles apparently lost any tendency for raised floors, to be built directly on the ground surface (Green and Pawley, in press).

Subsidence for Lapita sites, as at Mulifanua, may prove to be a rare phenomenon, although volcano loading of an oceanic plate is not the only mechanism of subsidence that may be operative within Oceania. Tectonic subsidence of segments of the island arcs lying farther west may prove to be a factor, and would tend to hide its effects by removing sites from view by submergence. Better documented thus far is tectonic uplift of segments of the island arcs, as reflected by originally coastal Lapita sites that now stand well above the reach of hydro-isostatic fluctuations in sea level. Salient examples include the Kandrian region along the southwest coast of New Britain, where 2–3 m of post-Lapita tectonic uplift is inferred (Boyd et al., in press), the island of Nendo in the Santa Cruz Group where the Nanggu Lapita site lies 0.5 km inland and 5–6 m above modern sea level (Green, 1976:249–250, 1979:51), and the island of Malo in Vanuatu where Lapita sites are located on a raised reef platform at elevations of 10–12 m above modern sea level (J.D. Hedrick, draft manuscript, 1981). The submergence of the Mulifanua site is an apt reminder, however, that subsidence rather than uplift may affect some Pacific islands.

REFERENCES

Allen, J., and Gosden, C. (1996). Spheres of Interaction and Integration: Modelling the Culture History of the Bismarck Archipelago. *In* J. Davidson, G. Irwin, F. Leach, A. Pawley and D. Brown, Eds., *Oceanic Culture History: Essays in Honor of Roger Green,* pp. 183–197. Special Publication. Dunedin: New Zealand Journal of Archaeology.

Amesbury, J.R., Moore, D.R., and Hunter-Anderson, R.L. (1996). Cultural Adaptations and Late Holocene Sea Level Change in the Marianas: Recent Excavations at Chalan Piao, Saipan, Micronesia. *Indo-Pacific Prehistory Association Bulletin* **15,** 53–69.

Bloom, A.L. (1980). Late Quaternary Sea Level Change on South Pacific Coasts: A Study in Tectonic Diversity. *In* N-A. Morner, Ed., *Earth Rheology, Isostasy, and Eustasy,* pp. 505–516. New York: Wiley.

Boyd, W.E., Specht, J., and Webb, J. (in press). Holocene Shoreline Change and Archaeology on the Kandrian Coast of West New Britain, Papua New Guinea. *In* J. Hall and I. McNiven, Eds, *Coastal Archaeology in Australia and the Pacific Islands,* Special Issue of *Tempus*. Brisbane: University of Queensland.

Brocher, T.M. (1985). On the Age Progression of the Seamounts West of the Samoan Islands, SW Pacific. *In* T.M. Brocher, Ed., *Investigations of the Northern Melanesian Borderland,* pp. 173–185. Earth Science Series Vol. 3. Houston: Circum-Pacific Council for Energy and Mineral Resources

Calhoun, R.S., and Fletcher, C.H., III (1996). Late Holocene Coastal Plain Stratigraphy and Sea-Level History at Hanalei, Kauai, Hawaiian islands. *Quaternary Research* **45,** 47–58.

Chubb, L.J. (1957). The Pattern of Some Pacific Island Chains. *Geological Magazine* **94,** 221–228.

Claridge, G.G.C. (1984). Pottery and the Pacific: The Clay Factor. *New Zealand Journal of Archaeology* **6,** 37–46.

Clark, J.T. (1990). Holocene Sea Level Changes in the South Pacific: Implications for Human Settlement. Seattle: Proceedings of 1989 Circum-Pacific Prehistory Conference (Development of Hunting-Fishing-Gathering Maritime Societies of the Pacific).

Clark, J.T. (1993). Radiocarbon Dates from American Samoa. *Radiocarbon* **35,** 323–330.

Clark, J.T. (1996). Samoan Prehistory in Review. *In* J. Davidson, G. Irwin, F. Leach, A. Pawley, and D. Brown, Eds., *Oceanic Culture History: Essays in Honor of Roger Green,* pp. 443–460. Special Publication. Dunedin: New Zealand Journal of Archaeology.

Clark, J.T. and Michlovic, M.G. (1996). An Early Settlement in the Polynesian Homeland: Excavations at 'Aoa Valley, Tutuila Island, American Samoa. *Journal of Field Archaeology* **23,** 151–167.

Crittenden, M.D., Jr. (1963). New Data on the Isostatic Deformation of Lake Bonneville. *United States Geological Survey Professional Paper* **454-E,** E1-E31.

Davidson, J.M. (1965). Archaeology in Samoa and Tonga. *New Zealand Archaeological Association Newsletter* **8,** 59–71.

Davidson, J.M. (1969). Excavation of a Coastal Midden Deposit, SU-LO-1 (Report 15). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. I, pp. 224–252. Bulletin No. 6. Auckland: Auckland Institute and Museum.

Davidson, J.M. (1974), Site Surveys on Upolu (Report 36). *In* R.C. Green and J. M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. II, pp. 181–209. Bulletin No. 7. Auckland: Auckland Institute and Museum.

Davidson, J.M. (1979). Samoa and Tonga. *In* J.D. Jennings, Ed., *The Prehistory of Polynesia,* pp. 82–109. Cambridge: Harvard University Press.

Dickinson, W.R. (1969). Temper Sands in Prehistoric Potsherds from Vailele and Falefa (Report 19). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. I, pp. 271–273. Bulletin No. 6. Auckland: Auckland Institute and Museum.

Dickinson, W.R. (1974). Temper Sands in Sherds from Mulifanua and Comparison with Similar Tempers at Vailele and Sosoa'a (Falefa) (Report 35). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. II, pp. 179–180. Bulletin No. 7. Auckland: Auckland Institute and Museum.

Dickinson, W.R. (1976). Appendix: Mineralogy and Petrology of Sand Tempers in Sherds from the Ferry Berth Site, Paradise Site, and Jane's Camp. *Bishop Museum Pacific Anthropological Records* **32,** 99–103.

Dickinson, W.R. (1993). Sand Temper in Prehistoric Potsherds from the To'aga Site. *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 151–156. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Dickinson, W.R., Burley, D.V., and Shutler, R., Jr. (1994). Impact of Hydro-Isostatic Holocene Sea-Level Change on the Geological Context of Island Archaeological Sites, Northern Ha'apai Group, Kingdom of Tonga. *Geoarchaeology* **9,** 85–111.

Duncan, R.A. (1985). Radiometric Ages from Volcanic Rocks along the New Hebrides-Samoa Lineament. *In* T.M. Brocher, Ed., *Investigations of the Northern Melanesian Borderland,* pp. 67–76. Earth Science Series Vol. 3. Houston: Circum-Pacific Council for Energy and Mineral Resources.

Fletcher, C.H. III, and Jones, A.T. (1996). Sea-Level Highstand Recorded in Holocene Shoreline Deposits on Oahu, Hawaii. *Journal of Sedimentary Research* **66,** 632–641.

Ginsburg, R.N. (1953). Beachrock in South Florida. *Journal of Sedimentary Petrology* **23,** 85–92.

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.

Grant-Taylor, T.L., and Rafter, T.A. (1962). New Zealand Radiocarbon Age Measurements—5. *New Zealand Journal of Geology and Geophysics* **5,** 331–359.

Green, R.C. (1974a). Pottery from the Lagoon at Mulifanua, Upolu (Report 33). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. II, pp. 170–175. Bulletin No. 7. Auckland: Auckland Institute and Museum.

Green, R.C. (1974b). A Review of Portable Artifacts from Western Samoa (Report 40). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. II, pp. 245–275. Bulletin No. 7. Auckland: Auckland Institute and Museum.

Green, R.C. (1976). Lapita Sites in the Santa Cruz Group. *In* R.C. Green and M.M. Cresswell, Eds., *Southeast Solomon Islands Cultural History,* pp. 245–265. Bulletin No. 11. Wellington: Royal Society of New Zealand.

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

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. Noumea: ORSTOM.

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 Pawley, A.K. (in press). Early Oceanic Architectural Forms and Settlement Patterns: Linguistic, Archaeological and Ethnological Perspectives. *In* R. Blench and M. Spriggs, Eds., *Archaeology and Language, Volume 3: Models of Prehistory Drawn from Language.* London: Routledge.

Green, R.C., and Richards, H.G. (1975). Lapita Pottery and a Lower Sea Level in Western Samoa. *Pacific Science* **29,** 309–315.

Hawkins, J.W., Jr., and Natland, J.H. (1975). Nephelinites and Basanites of the Samoan Linear Volcanic Chain: Their Possible Tectonic Significance. *Earth and Planetary Science Letters* **24,** 427–439.

Hedge, C.E., Peterman, Z.E., and Dickinson, W.R. (1972). Petrogenesis of Lavas from Western Samoa. *Geological Society of America Bulletin* **83,** 2709–2714.

Hopley, D. (1986). Beachrock as a Sea-Level Indicator. *In* O. van de Plassche, Ed., *Sea-Level Research,* pp. 157–173. Norwich, United Kingdom: Geo Books.

Hubbard, N.J. (1971). Some Chemical Features of Lavas from the Manu'a Islands, Samoa. *Pacific Science,* **25,** 178–187.

Hunt, T.L., and Kirch, P.V. (1987). Radiocarbon Dates from Two Coastal Sites in the Manu'a Group, American Samoa. *Radiocarbon* **29,** 417–419.

Hunt, T.L., and Kirch, P.V. (1988). An Archaeological Survey of the Manu'a Islands, American Samoa. *Journal of the Polynesian Society* **97,** 153–183.

Jarrard, R.D., and Clague, D.A. (1977). Implications of Pacific Island and Seamount Ages for the Origin of Volcanic Chains. *Reviews of Geophysics and Space Physics* **15,** 57–76.

Jennings, J.D. (1974). The Ferry Berth Site, Mulifanua District, Upolu (Report 34). *In* R.C. Green and J.M. Davidson, Eds., *Archaeology in Western Samoa,* Vol. II, pp. 176–178. Bulletin No. 7. Auckland: Auckland Institute and Museum

Jennings, J.D., and Holmer, R.W. (1980). Archaeological Investigations in Western Samoa. *Bishop Museum Pacific Anthropological Records* **32,** 1–155.

Jennings, J.D., Holmer, R.N., Janetski, J.C., and Smith, H.L. (1976). Excavations on Upolu, Western Samoa. *Bishop Museum Pacific Anthropological Records* **25,** 1–113.

Johnson, K.T.M., Sinton, J.M. and Price, R.C. (1986). Petrology of Seamounts Northwest of Samoa and Their Relation to Samoan Volcanism. *Bulletin of Volcanology* **48,** 225–235.

Jones, A.T. (1992). Holocene Coral Reef on Kauai, Hawaii: Evidence for a Sea-Level Highstand in the Central Pacific. *In* C.H. Fletcher III and J.F. Wehmiller, Eds., *Quarternary Coasts of the United States: Marine and Lacustrine Systems,* pp. 267–271. Special Publication No. 48. Tulsa: SEPM (Society for Sedimentary Geology).

Kear, D. (1967). Geological Notes on Western Samoa. *New Zealand Journal of Geology and Geophysics* **10,** 1446–1451.

Kear, D., and Wood, B.L. (1959). The Geology and Hydrology of Western Samoa. *New Zealand Geological Survey Bulletin* **63,** 1–92.

Keating, B. (1985). Paleomagnetic Studies of the Samoan Islands: Results from the Islands of Tutuila and Savaii. *In* T.M. Brocher, Ed., *Investigations of the Northern Melanesian Borderland,* pp. 187–199. Earth Science Series Vol. 3. Houston: Circum-Pacific Council for Energy and Mineral Resources.

Keating, B.H. (1992). The Geology of the Samoan Islands. *In* B.H. Keating and B.R. Bolton, Eds., *Geology and Mineral Resources of the Central Pacific Basin* pp. 127–178. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series Vol. 14. New York: Springer-Verlag.

Kirch, P.V. (1988). The Talepakemalai Lapita Site and Oceanic Prehistory. *National Geographic Research* **4,** 328–342.

Kirch, P.V. (1993a). Ofu Island and the To'aga Site: Dynamics of the Natural and Cultural Environment. *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 9–22. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Kirch, P.V. (1993b). The To'aga Site: Modelling the Morphodynamics of the Land-Sea Interface. *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 31–42. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Kirch, P.V. (1993c). Radiocarbon Chronology of the To'aga Site. *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 85–92. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Kirch, P.V. (1997). *The Lapita Peoples: Ancestors of the Oceanic World.* Cambridge: Blackwell.

Kirch, P.V., and Hunt, T.L. (1993a). Excavations at the To'aga Site (AS-13–1). *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 43–83. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Kirch, P.V., and Hunt, T.L. (1993b). Synthesis and Interpretations. *In* P.V. Kirch and T.L. Hunt, Eds., *The To'aga Site: Three Millenia of Polynesian Occupation in the Manu'a Islands, American Samoa,* pp. 229–248. Contribution No. 51. Berkeley: University of California Archaeological Research Facility.

Kirch, P.V., Hunt, T.L., and Tyler, J. (1989). A Radiocarbon Sequence from the Toaga Site, Ofu Island, American Samoa. *Radiocarbon* **31**, 7–13.

Kirch, P.V., Hunt, T.L., Nagaoka, L. and Tyler, J. (1990). An Ancestral Polynesian Occupation Site at To'aga, Ofu Island, American Samoa. *Archaeology in Oceania* **25,** 1–15.

Lambeck, K. (1981). Lithospheric Response to Volcanic Loading in the Southern Cook Islands. *Earth and Planetary Science Letters* **55,** 482–496.

Leach, H.M., and Green, R.C. (1989). New Information for the Ferry Berth Site, Mulifanua, Western Samoa. *Journal of the Polynesian Society* **98,** 319–329.

Macdonald, G.A. (1944). Petrography of the Samoan Islands. *Geological Society of America Bulletin* **55,** 1335–1362.

MacDonald, G.A. (1968). A Contribution to the Petrology of Tutuila, American Samoa. *Geologisches Rundschau* **57,** 821–837.

Matsuda, J.-I., Notsu, K., Okano, J., Yaskawa, K., and Chungue, L. (1984). Geochemical Implications from Sr Isotopes and K-Ar Age Determinations for the Cook-Austral Islands Chain. *Tectonophysics* **104,** 145–154.

Mayor, A.G. (1921). Rose Atoll, American Samoa. *American Philosophical Society Preoceedings* **60,** 62–70.

McDougall, I. (1985). Age and Evolution of the Volcanoes of Tutuila, American Samoa. *Pacific Science* **39,** 311–320.

McNutt, M., and Menard, H.W. (1978). Lithospheric Flexure and Uplifted Atolls. *Journal of Geophysical Research* **83,** 5691–5697.

McNutt, M., and Menard, H.W. (1979). Reply. *Journal of Geophysical Research* **84,** 5695–5697.

Mitrovica, J.X., and Peltier, W.R. (1991). On postglacial geoid subsidence over the equatorial oceans. *Journal of Geophysical Research* **96,** 20,053–20,071.

Moore, J.G. (1970). Relation Between Subsidence and Volcanic Load, Hawaii. *Bulletin of Volcanology* **34,** 562–576.

Moore, J.G. (1987). Subsidence of the Hawaiian Ridge. *U.S. Geological Survey Professional Paper* **1350,** 85–100.

Moore, J.G., Ingram, B.L.,Ludwig, K.R., and Clague, D.A. (1996). Coral Ages and Island Subsidence, Hilo Drill Hole. *Journal of Geophysical Research* **101,** 11,599–11,605.

Natland, J.H. (1980). The Progression of Volcanism in the Samoan Linear Volcanic Chain. *American Journal of Science* **280**-**A,** 709–735.

Natland, J.H., and Turner, D.L. (1985). Age Progression and Petrological Development of Samoan Shield Volcanoes: Evidence from K-Ar Ages, Lava Compositions, and Mineral Studies. *In* T.M. Brocher, Ed., *Investigations of the Northern Melanesian Borderland,* pp. 139–171. Earth Science Series Vol. 3. Houston: Circum-Pacific Council for Energy and Mineral Resources.

Niem, A.R., McKnight, B.K., and Meyer, H.J. (1994). Sedimentary, Volcanic, and Tectonic Framework of Forearc Basins and the Mist Gas Field, Northwest Oregon. *In* D.A. Swanson and R.A. Haugerud, Eds., *Geologic Field Trips in the Pacific Northwest,* pp. 1–42. Geological Society of America Annual Meeting Guidebook. Seattle: University of Washington, Department of Geological Sciences.

Nunn, P.D. (1990). Recent Environmental Changes on Pacific Islands. *Geographical Journal* **156,** 125–140.

Nunn, P.D. (1994). *Oceanic Islands.* Oxford: Blackwell Publishers.

Nunn, P.D. (1995). Holocene Sea-Level Changes in the South and West Pacific. *Journal of Coastal Research Special Issue* **17,** 311–319.

Nunn, P.D. (1997). *Pacific Island Landscapes.* Suva, Fiji: Institute of Pacific Studies, University of the South Pacific.

Petchey, F.J. (1995). The Archaeology of Kudon: Archaeological Analysis of Lapita Ceramics from Mulifanua, Samoa and Sigatoka, Fiji. Master's Thesis, University of Auckland, New Zealand.

Richmond, B.M. (1992a). Holocene Geomorphology and Reef History of Islands in the South and Central Pacific. Ph.D. Thesis, University of California, Santa Cruz.

Richmond, B.M. (1992b). Coastal Geology of Upolu, Western Samoa. *In* B.H. Keating and B.R. Bolton, Eds., *Geology and Mineral Resources of the Central Pacific Basin,* pp. 101–125. Circum-Pacific Council for Energy and Mineral Resources Earth Science Series Vol. 14. New York: Springer-Verlag.

Robertson, E.I. (1987). Gravity Surveys of the Samoan Islands, Southwest Pacific Ocean. *New Zealand Journal of Geology and Geophysics* **30,** 233–240.

Rodda, P. (1988). Visit to Western Samoa with the HIPAC Team. *In* N. Yonekura, Ed., *Sea Level Changes and Tectonics in the Middle Pacific,* pp. 85–90. Report of the HIPAC Project in 1986 and 1987 (Third Research). Tokyo: University of Tokyo.

Sinton, J.M., Johnson, K.T.M., and Price, R.C. (1985). Petrology and Geochemistry of Volcanic Rocks from the Northern Melanesian Borderland. *In* T.M. Brocher, Ed., *Investigations of the Northern Melanesian Borderland,* pp. 35–65. Earth Science Series Vol 3. Houston: Circum-Pacific Council for Energy and Mineral Resources.

Stearns, H.T. (1944). Geology of the Samoan Islands. *Geological Society of America Bulletin* **55,** 1279–1332.

Stice, G.D. (1968). Petrography of the Manu'a Islands, Samoa. *Contributions to Mineralogy and Petrology* **19,** 343–357.

Stice, G.D., and McCoy, F.W., Jr. (1968). The Geology of the Manu'a Islands, Samoa. *Pacific Science* **22,** 427–457.

Tarling, D.H. (1965) The Palaeomagnetism of the Samoan and Tongan Islands. *Geophysical Journal of the Royal Astronomical Society* **10,** 497–513.

Torrence, R., Specht, J., Fullagar, R., and Summerhayes, G.R. (1996). Which Obsidian is Worth It?: A View from the West New Britain Sources. *In* J. Davidson, G. Irwin, F. Leach, A. Pawley and D. Brown, Eds., *Oceanic Culture History: Essays in Honor of Roger Green,* pp. 211–224. Special Publication. Dunedin: New Zealand Journal of Archaeology.

Watts, A.B., and Cochran, J.R. (1974). Gravity Anomalies and Flexure of the Lithosphere along the

Hawaiian-Emperor Seamount Chain. *Geophysical Journal of the Royal Astronomical Society* **38,** 119–141.

White, W.M., and Hofmann, A.W. (1982). Sr and Nd Isotope Geochemistry of Oceanic Basalts and Mantle Evolution. *Nature* **296,** 821–825.

Wright, A.C.S. (1963). Soils and Land Use of Western Samoa. *New Zealand Soil Survey Bulletin* **22,** 1–65.

Wright, E., and White, W.M. (1986/1987). The Origin of Samoa: New Evidence from Sr, Nd, and Pb Isotopes. *Earth and Planetary Science Letters* **81,** 151–162.