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Hydro-Isostatic and Tectonic Influences on Emergent Holocene Paleoshorelines in the Mariana Islands, Western Pacific Ocean

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ABSTRACT

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Emergent paleoreef flats and paleoshoreline notches in the Mariana Islands document the effects of a mid-Holocene highstand in regional hydro-isostatic sea level and post-mid-Holocene forearc uplift of selected islands. Global hydro-isostatic calculations imply for Micronesia an areally variable magnitude of 0.6–2.7 m for the mid-Holocene highstand, relative to modern sea level, and radiocarbon ages for emergent reef flats and rubble terraces indicate a peak during the interval 4750–2250 yrs BP. In the tectonically stable region of Micronesia southeast of the Mariana Islands, emergences of paleoshorelines by 1.1–2.4 m closely match hydro-isostatic expectations for each island group. In the Mariana Islands, Saipan, Tinian, and southern Guam display emergent mid-Holocene paleoreef flats and paleoshoreline notches standing 1.2–2.0 m above modern counterparts, within the range of 0.8–2.1 m expected from hydro-isostatic theory. With allowance for minor tectonic subsidence locally, average hydro-isostatic emergence for the Mariana Islands is estimated as 1.8 m. Northern Guam and Rota display paleoshoreline emergences in excess of hydro-isostatic expectation, implying 0.8 m and 1.2 m of post-mid-Holocene tectonic uplift, respectively. Subduction of an oceanic seamount chain beneath the segment of the forearc belt beneath Rota and northern Guam probably accounts for subregional tectonic uplift, and also for enhanced interplate coupling responsible for anomalous seismicity. Post-mid-Holocene drawdown in relative sea level influenced the development of attractive environments for human settlement, which began in the Mariana Islands *c.* 3500 yrs BP.

ADDITIONAL INDEX WORDS: *Algal rim, forearc, fringing reef, Guam, island arc, paleoreef, Rota, Saipan, seismicity, shoreline notch, Tinian.*

INTRODUCTION

Emergent remnants of mid-Holocene reef flats that are prominent along the coasts of the Mariana Islands (Figure 1) within Micronesia have been widely interpreted as evidence for forearc tectonic uplift (Curray *et al.,* 1970; Easton *et al.,* 1978; Kayanne *et al.,* 1993; Butler, 1995). Consideration of the effects of Holocene hydro-isostasy on Pacific islands (Mitrovica and Peltier, 1991) suggests the possibility that at least some of the observed post-mid-Holocene emergence of coastal sites can be attributed instead to a regional drawdown in relative sea level (Randall *et al.,* 1984; Siegrist *et al.,* 1984; Randall and Siegrist, 1988; Kayanne *et al.,* 1993; Butler, 1994, 1995). In February of 1998, emergent features along the coasts of all the inhabited islands (Guam, Rota, Tinian, Saipan) were examined systematically in an effort to resolve the issue island by island. Comparative study of paleoshoreline features on all four islands augments the insights gained in the past from specific study sites, and reveals the pattern of emergence for the island group as a whole. Correlation of paleoshoreline features that have been isotopically dated with analogous features exposed elsewhere significantly expands the geographic reach of past work.

Previous reconnaissance of paleoshoreline features among other islands and atolls of Micronesia unaffected by arc-trench tectonism (Dickinson, 1999) allows comparison of data from the Mariana Islands with the broader record of a mid-Holocene hydro-isostatic sea-level highstand within the western Pacific region as a whole. Whereas previous geological (Kayanne *et al.,* 1993) and archaeological (Butler, 1995) analysis has tended to infer that all observed post-mid-Holocene shoreline emergence in the Mariana Islands stems from tectonic uplift, this study concludes that significant Holocene tectonic uplift has affected only selected islands, with the tectonic uplift superimposed on uniform hydro-isostatic emergence that affected all the islands to a consistent degree.

HOLOCENE HYDRO-ISOSTASY

Slow deformation of the mantle in response to postglacial transfer of mass from circumpolar ice caps to ocean waters distributed widely over the globe has influenced relative Holocene sea levels in various ways around the world (Walcott, 1972; Chappell, 1974; Farrell and Clark, 1976). Unlike eustatic sea-level fluctuations, which are uniform

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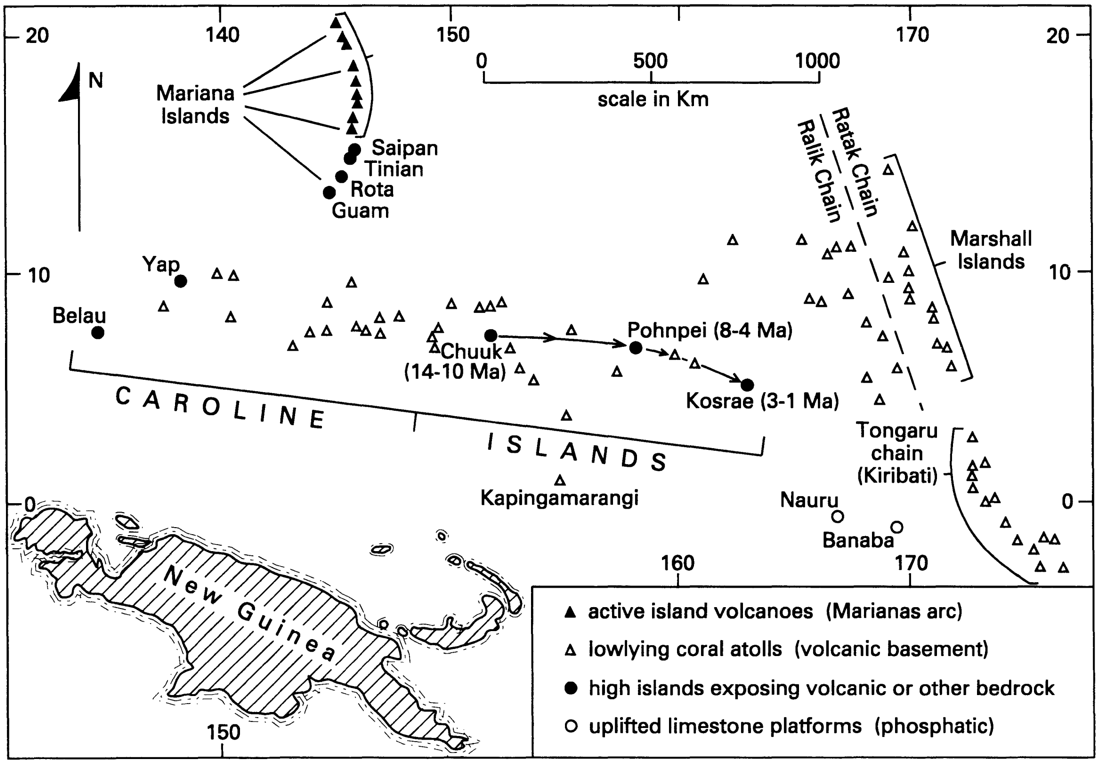

Figure 1. Location of the Mariana Islands in relation to other island groups of Micronesia (north and northeast of New Guinea). Ages of volcanic edifices (Chuuk, Pohnpei, Kosrae) along Caroline hotspot track after KEATING *et al.* (1984a, 1984b), DIXON *et al.* (1984), and SAKAMOTO (1994); younger, more alkalic (feldspathoidal) lavas (MATTEY, 1982) are also present (Chuuk, 4–5 Ma; Pohnpei, 1–3 Ma; Kosrae, 0.5–1.0 Ma).

worldwide in response to changing global volumes of ocean water, hydro-isostatic effects vary regionally, as do the coeval glacio-isostatic effects. Analysis of global glacio-hydro-isostasy indicates that a mid-Holocene highstand in local relative sea levels affected shoreline evolution throughout the central span of the Pacific basin, from as far south as New Zealand to as far north as Japan (NAKADA and LAMBECK, 1988), as the result of a process termed equatorial ocean syphoning (MITROVICA and PELTIER, 1991).

As formerly glaciated regions at high latitudes rebounded isostatically after Pleistocene ice was removed, flexurally uplifted glacial forebulges surrounding areas previously weighted down by glacial ice decayed through time. Continental shelves were also flexed downward as continental margins were tilted oceanward by the weight of augmented seawater in the ocean basins offshore. Because the drowned continental margins and large portions of the upflexed forebulges lay below sea level prior to hydro-isostatic adjustments, shelf downflexure and forebulge decay drew ocean water away from the equatorial oceans to cover the subsiding shelves and decaying forebulges. At low latitudes within ocean basins, the postglacial eustatic rise in global sea level during early Holocene time was therefore succeeded in late Holocene time by a hydro-isostatic drawdown in sea level. The net effects of combined eustasy and hydro-isostasy produced a mid-Holocene highstand in sea level throughout the equatorial Pacific region (MITROVICA and PELTIER, 1991:Figure 8). Except where local island subsidence has counteracted the hydro-isostatic drop in sea level (DICKINSON and GREEN, 1998; DICKINSON *et al.,* 1998, 1999), the result for widespread island groups was a mid-Holocene highstand in relative sea level followed later by a post-mid-Holocene decline in relative sea level (MCLEAN and WOODROFFE, 1994:Figure 7.5; NUNN, 1995).

Initial calculations of global hydro-isostatic effects implied that a mid-Holocene highstand affected the southern but not the central and western Pacific regions (PELTIER *et al.,* 1978; CLARK *et al.,* 1978; CLARK and LINGLE, 1979; CLARK, 1980a, 1980b), where only an inflection point in a monotonically rising sea-level curve was inferred for mid-Holocene time. This result apparently confirmed the conclusion of the 1967 CARMARSEL Expedition that Holocene sea levels have never stood significantly higher than today within Micronesia (CURRAY *et al.,* 1970). More refined calculations, based on improved budgets for deglaciation and incorporating pseudospectral treatment of the relevant sea-level equations now retrodict, however, relative mid-Holocene sea-level highstands on islands of the central and western as well as the southern Pacific region (NAKIBOGLU *et al.,* 1983; MITROVICA and PELTIER, 1991).

Extant global hydro-isostatic theory is based on multiple mantle models, including an isoviscous mantle and more complex models in which the viscosity of the lower mantle exceeds that of the upper mantle by as much as an order of magnitude (MITROVICA and PELTIER, 1991). The range of mantle models used for hydro-isostatic calculations thereby includes the full range of mantle rheology that is compatible with other known geodynamic processes. The resulting calculations consequently produce a range of estimates for the magnitude of the mid-Holocene highstand within any given island group (±0.1 m to ±0.9 m, depending upon geographic location). In each case, however, the median estimate (n = 17) for the highstand exceeds the uncertainty associated with alternate mantle models by 0.6 m to 2.3 m, indicating that the prediction of a mid-Holocene highstand of *c.* 1.5 m (±1 m) is robust throughout the equatorial Pacific region (25° South to 25° North Latitudes). Potentially detectable effects of local mid-Holocene sea-level highstands of geographically variable but theoretically predictable magnitudes must therefore be taken into account for analyses of evolving Holocene shorelines within all tropical Pacific island groups.

MID-HOLOCENE HIGHSTAND

The Pacific highstand peaked nominally at *c.* 4000 yrs BP (MITROVICA and PELTIER, 1991:Figure 8), although alternate assumptions of mantle viscosity and the melting budget for deglaciation allow for an earlier peak during the interval 6000–4000 BP (NAKIBOGLU *et al.,* 1983), and empirical paleoshoreline data for French Polynesia imply persistence of the highstand throughout the interval 4000–2000 BP (PIRAZZOLI and MONTAGGIONI, 1988). Available radiocarbon ages from mid-Holocene reef flats emergent above modern low-tide level within Micronesia lie within the interval 4750–2250 BP (Figure 2), coincident with or close on the heels of the inferred regional highstand. The data plotted are inadequate to test for possible areal variations in the timing of the highstand, although there is a hint that it may have peaked earlier at higher latitudes. In detail, elevations of emergent coralline materials of different ages are inconsistent, and evidently reflect the vagaries of coral growth on reef flats where lateral as well as vertical expansion of coral colonies is characteristic.

The theoretically calculated magnitude of the mid-Holocene highstand varies considerably within Micronesia (Figure 3), and there are uncertainties in expected magnitude for each island group stemming from alternate assumptions of mantle viscosity. The calculated ranges plotted as open rectangles include results for an isoviscous mantle and for more complex models in which the viscosity of the lower mantle is up to an order of magnitude greater than the viscosity of the upper mantle. For sites on the Pacific plate of oceanic lithosphere southeast of the Mariana Trench, the observed emergence of mid-Holocene reef flats (Funafuti, Tarawa, Majuro) and bedrock paleoshorelines (Kosrae, Chuuk) is within the expected hydro-isostatic range, with complex mantle models generally providing a closer match than the isoviscous model. In the southern Pacific arena, the magnitudes of hydro-isostatic mid-Holocene highstands on tectonically undisturbed islands of Samoa (DICKINSON and GREEN, 1998), Fiji (DICKINSON *et al.,* 1998), and Tonga (DICKINSON *et al.,* 1999) also lie within the limits of theoretical expectation.

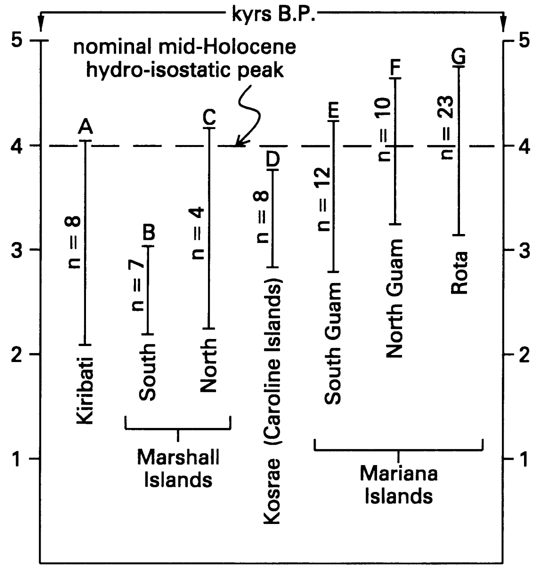

Figure 2. Available radiocarbon ages (conventional ^{14}C yrs BP) for emergent coralline reef and rubble terraces within Micronesia. Sources of data (total n = 72): A, SCHOFIELD (1977); B, CURRAY *et al.* (1970); C, TRACEY and LADD (1974); D, ATHENS (1995) and KAWANA *et al.* (1995); E, TRACEY *et al.* (1964), CURRAY *et al.* (1970), EASTON *et al.* (1978), and KAYANNE *et al.* (1993); F, RANDALL and SIEGRIST (1988, 1996); G, BELL and SIEGRIST (1991) and KAYANNE *et al.* (1993).

From the age of the Pacific seafloor (>145 Ma) in the region southeast of the Mariana Islands, Quaternary thermotectonic subsidence of the underlying lithosphere is not expected to exceed 0.005 mm/yr (SCHROEDER, 1984; STEIN and STEIN, 1992). This rate of regional subsidence would produce less than one inch (0.025 m) of relative sea-level rise since mid-Holocene time, and could not be detected from measurement of paleoshoreline elevations on the islands. If hotspot activity in the Caroline Islands (Figure 1) locally rejuvenated oceanic lithosphere to an equivalent thermal age of *c.* 25 Ma at the time of hotspot volcanism (CROUGH, 1978), then Chuuk, Pohnpei, and Kosrae now may be subsiding at greater rates of 0.02–0.03 mm/yr. Such faster rates, however, would still produce subsidence of only *c.* 0.1 m since the mid-Holocene hydro-isostatic highstand, and this amount lies within the observational uncertainty for estimates of paleoshoreline emergence derived from the present elevations of coastal geomorphic features. However, the lack of emergent mid-Holocene paleoshorelines in the Yap and Belau island arcs south of the Marianas, with mid-Holocene reef flats still subtidal in the latter (EASTON and KU, 1980), suggests late Holocene subsidence of those two volcanically inactive arcs, marginal to the Pacific basin proper, at rates sufficient to counteract the post-mid-Holocene drawdown in regional sea level.

The amounts of observed emergence of dated mid-Holocene paleoreef flats relative to the surfaces of modern fringing reefs, and of paleoshoreline notches inferred to be of mid-

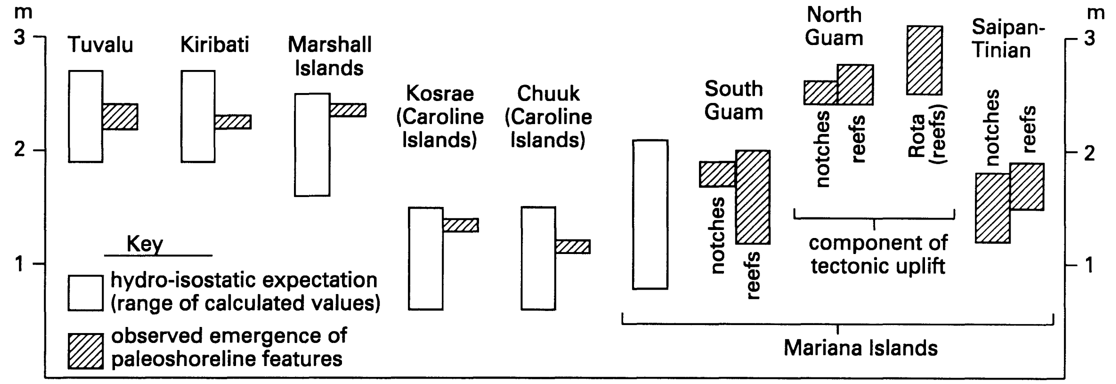

Figure 3. Expected magnitude of hydro-isostatic mid-Holocene highstand in relative sea level on islands of Micronesia (from MITROVICA and PELTIER, 1991:Figure 8b–g) in comparison to observed emergence of mid-Holocene paleoshoreline features (emergent paleoreef flats relative to modern low-tide levels and apices of paleoshoreline notches relative to modern high-tide levels). Observational data for Mariana Islands from this paper (Figures 6–7), for Chuuk from emergent (but undated) wavecut platform incised into volcanic breccia on Yanagi islet, and for other islands from DICKINSON (1999); mid-Holocene paleoshoreline features on Pohnpei (Figure 1), if present at all, are entirely masked by extensive development of coastal mangrove swamps.

Holocene age relative to modern shoreline notches, are within the theoretically expected range for the Mariana Islands on Saipan, Tinian, and southern Guam (Figure 3). For those localities, no tectonic uplift is required to explain observed paleoshoreline emergence. On Rota and northern Guam, however, observed amounts of emergence exceed hydro-isostatic expectation, implying post-mid-Holocene tectonic uplift in addition to hydro-isostatic effects. Discussions of paleoshoreline features within the Mariana Islands serve to clarify those overall inferences, and to provide a tectonic rationale for uplift of selected islands.

MARIANA ISLAND ARC

The Mariana Islands include an active magmatic arc, delineated by a curvilinear chain of Neogene island volcanoes and submerged volcanic seamounts, and a shorter but parallel alignment of Paleogene volcanic edifices now located within the forearc belt between the active island arc and the Mariana Trench (Figure 4). The islands visited during this study are the four largest of the geologically older chain. The Mariana Trough, lying west of the island arc, is an extensional backarc basin separating the active frontal arc of the Mariana arc-trench system from a remnant arc that forms the submerged West Mariana Ridge (FRYER, 1995).

Late Eocene to Early Oligocene volcanism (45–30 Ma) along the paleovolcanic island chain occurred before opening of the Parece Vela Basin (Figure 4) in the eastern Philippine Sea by mid-Oligocene to mid-Miocene (30–15 Ma) seafloor apreading (MROZOWSKI and HAYES, 1979; MEUER *et al.*, 1983; REAGAN and MEIJER, 1984; TAYLOR, 1992). The present frontal arc, including the paleovolcanic chain, was then part of the Palau-Kyushu Ridge, now stranded as a submerged remnant arc midway across the Philippine Sea 1200 km west of the Mariana Islands. Arc rifting that initiated the Parece Vela spreading system interrupted arc volcanism along the present axis of the paleovolcanic chain, and the chief record of Miocene volcanism within the Mariana arc-trench system is preserved along the submerged remnant arc of the West Mariana Ridge. Transient resumption of minor volcanism along the site of the paleovolcanic chain during mid-Miocene time (15–12 Ma), when the Paleogene volcanic edifices were still attached to the West Mariana Ridge, is recorded by sparse lavas and breccias that are interbedded with limestones on both Guam and Saipan (MEIJER *et al.*, 1983). The neovolcanic chain of islands and seamounts has been active since at least early Pleistocene time (MEIJER *et al.*, 1983), and may well have been initiated in Pliocene time.

Paleogene volcanic edifices of the paleovolcanic chain are flanked and locally capped by Neogene limestones including various locally named Miocene units and the widespread Pliocene-Pleistocene Mariana Limestone (CLOUD *et al.*, 1956; DOAN *et al.*, 1960; TRACEY *et al.*, 1964). Neogene uplift of the paleovolcanic islands is indicated by exposures of Mariana Limestone that reach elevations of >50 m on Saipan, >100 m on Tinian, and nearly 200 m on northern Guam, with older Miocene limestones attaining elevations of 175 m on Tinian, 300 m on southern Guam, and nearly 500 m on both Saipan and Rota.

Patches of emergent Holocene reef limestone are mapped as Merizo Limestone on Guam (TRACEY *et al.*, 1964), and as Milencatan Limestone on Rota (KAYANNE *et al.*, 1993), but the partly correlative Tanapag Limestone of Saipan includes both Holocene and Pleistocene strata (CLOUD *et al.*, 1956). Emergent Holocene reef materials are most readily identifiable where Holocene reefs grew upon wavecut platforms cut into volcanic bedrock, which locally flanks the inland margins of exposed Holocene paleoreef flats on southwestern Guam. Holocene limestone can elsewhere be distinguished in the field from Mariana Limestone, and from Pleistocene Tanapag Limestone on Saipan, by its darker color and lack of diagenetic alteration. Holocene radiocarbon ages (Figure 2) for emergent Holocene reef materials confirm the youth implied by field relationships.

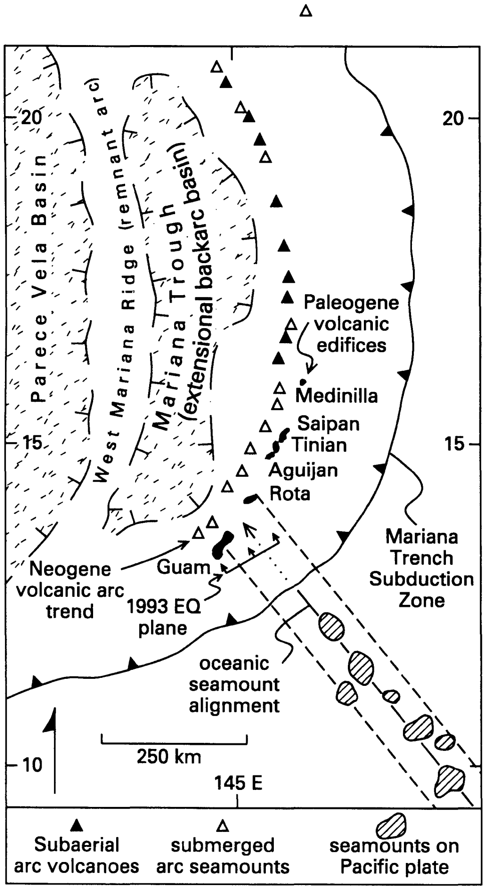

Figure 4. Tectonic setting of Mariana island arc showing active chain of Neogene island volcanoes and submerged seamounts, ancestral chain of Paleogene volcanic edifices (black), and a key alignment of oceanic seamounts being subducted with Pacific seafloor at the Mariana trench; 1993 Guam earthquake seismicity was generated by fault displacement at the plate interface within the forearc region along a seismic plane striking 240° (N60E), as shown by schematic line, and dipping 12.5° (arrows), with a hypocentral depth of 42 km and the slip direction directly down dip (CAMPOS *et al.*, 1996); projection of the seismic plane up dip would intersect the surface at the Mariana Trench.

MARIANA PALEOSHORELINE FEATURES

Two kinds of widely distributed paleoshoreline indicators can be used to estimate amounts of post-mid-Holocene emergence in the Mariana Islands by comparison with the elevations of comparable modern shoreline features exposed nearby: (1) The surfaces of emergent mid-Holocene reef flats (Figure 5AB) with reference to the surfaces of modern fringing reefs forming offshore shoals at modern low-tide level, and (2) emergent paleoshoreline notches with reference to modern shoreline notches ("tidal notches" of PIRAZZOLI, 1996:28–29) incised into limestone seacliffs at modern high-tide level (Figure 5CD).

Mechanical wave action is not instrumental in cutting shoreline notches into limestone seacliffs (PIRAZZOLI, 1996), and they occur on protected as well as exposed coasts. Their origin is attributed to bioerosion by littoral organisms, together with some organically mediated dissolution of carbonate, near the air-sea interface. Shoreline notches are typically V-shaped recumbent recesses, one to two meters in vertical and horizontal dimensions, with definable apices between their floors and roofs or visors. Although the elevation of the apices of modern shoreline notches has been assumed in some places to mark mean sea level (PIRAZZOLI, 1996), all actively forming shoreline notches observed on Pacific islands have apices at high-tide level, along the inner edges of wavecut ramps leading upward through the intertidal zone from the surfaces of fringing reefs positioned at low-tide level. Shoreline notches tend to have gently inclined floors, commonly flat to the eye, but visors inclined at various angles dependent upon the lithology of the limestone into which they are incised and the intensity of wave spray on the limestone seacliffs where they occur.

On some Mariana coastlines, paleobeachrock forms an auxiliary, though more imprecise, measure of shoreline emergence. Within the intertidal zone on tropical coasts, beach sands can be cemented into indurated slabs, up to a meter thick, which locally mantle the beach faces. Beachrock formation stems from precipitation of carbonate interstitially as seawater trapped in pores between sand grains is degassed by warming near the surfaces of wet beaches that are heated by sunshine during exposure at low tide (GINSBURG, 1953). Care must be taken not to confuse *beachrock* with supratidal *cayrock* cemented by other processes (GISCHLER and LOMANDO, 1997), but the generally intertidal origin of true beachrock has been confirmed repeatedly (STODDART and CANN, 1965; HANOR, 1978; SCOFFIN and STODDART, 1983). Nevertheless, the restriction of beachrock formation to the intertidal zone is not absolute (HOPLEY, 1986), in part because alternate wetting and drying of beach faces may extend into the supratidal swash zone where surf that overtops fringing reefs reaches beach faces (DICKINSON and GREEN, 1998), and perhaps in part because seepage of meteoric water (MOORE, 1973) or algal growth (KRUMBEIN, 1979) may promote precipitation of cement in marginally subtidal environments.

As the effective tidal ranges on different coastlines of any island vary somewhat with different exposure to winds and currents, the only reliable estimates of emergence derive from locales where the differential elevations of modern and ancient notches can be measured directly in the same seacliffs, or where modern fringing reefs lie immediately offshore from remnants of emergent paleoreef flats.

MARIANA PALEOSHORELINE POSITIONS

The mid-Holocene age (4750–2750 BP) of emergent paleoreef flats on Guam and Rota is documented directly by previously reported radiocarbon ages for the reef limestone (Figure 2), and the single emergent paleoreef flat exposed on Saipan (Figure 5B) directly underlies a cultural horizon dating to *c.* 3500 BP in an archaeological excavation that reached the paleoreef surface (BUTLER, 1995). The mid-Holocene age of measured paleoshoreline notches is inferred from three consistent relationships: (1) in all cases (n = 10), the mid-Holocene paleonotches are the only prominent seacliff notches present at elevations higher than modern shoreline notch-

Figure 5. Emergent paleoshoreline features in the Mariana Islands: (A) emergent paleoreef flat standing 0.5 m above active shoreline notch incised, with its apex at modern high-tide level, into emergent mid-Holocene reef limestone (hence 1.2 m above surface of modern fringing reef offshore) at Sella Bay (Figure 6A) on Guam, with modern beach sand (in which palm trees are growing) covering the emergent paleoreef flat inland from the shore; (B) emergent paleoreef flat standing, with its upper surface partly masked by trees, 1.3 m above active shoreline notch incised, with its apex at modern high-tide level, into emergent mid-Holocene reef limestone (hence 1.9 m above surface of modern fringing reef offshore) at Achugao Point (Figure 6B) on

es; (2) at several sites (n = 3), the paleoshoreline notches lie along the shoreward edges of wavecut platforms or ramps, of intertidal mid-Holocene origin, which merge seaward with the surfaces of mid-Holocene reef flats (Figure 5EF); and (3) in most cases (n = 8), the amount of shoreline emergence measured for the paleoshoreline notches is coordinate (±0.2 m) with the amount of emergence inferred for mid-Holocene reef flats exposed within 5–10 km of the paleonotch sites (no paleoreef flats are preserved near the other two examples of paleoshoreline notches).

Mid-Holocene paleoshoreline notches were examined, in addition to emergent mid-Holocene reef flats, to expand the available data bearing on the areal pattern of post-mid-Holocene emergence for the Mariana Islands as a whole. At sites where both emergent reef flats and paleoshoreline notches are present, however; the elevations of the latter also serve to show that associated emergent reef flats have not been significantly reduced in elevation by erosional degradation (Figure 5EF). In general, no salient conclusions from this study would be altered if attention were focused exclusively on emergent mid-Holocene reef flats dated by radiocarbon methods.

Measures of emergence are most direct where the differential elevations of mid-Holocene paleoshoreline notches can be scaled in vertical seacliff profiles from modern shoreline notches formed at current high-tide level (Figure 5CD), with measurement in each case between notch apices. The differential elevations of mid-Holocene reef flats above the surfaces of modern fringing reefs, standing at current low-tide level, were determined by measuring directly, in similar fashion, the elevations of the emergent paleoreef flats above the apices of modern shoreline notches at high-tide level (Figure 5AB), and then adding the appropriate tidal range (0.7 m for Guam-Rota; 0.6 m for Saipan-Tinian). The inherent uncertainty in outcrop measurements, stemming from slight irregularities in the morphology of emergent paleoreef flats and paleoshoreline notches at each site, is estimated to be 0.1 m.

HYDRO-ISOSTATIC MARIANA EMERGENCE

Emergent mid-Holocene paleoshoreline features on southern Guam (Figure 6A), Saipan (Figure 6B), and Tinian stand uniformly at elevations within the range inferred for the hydro-isostatic mid-Holocene highstand in regional sea level (Figure 3):

(1) On Saipan, the overall average emergence (n = 9) is 1.65 m, but the range of local estimates (1.2–1.9 m) may reflect Holocene deformation of the island associated with active faulting (BUTLER, 1995). If the sites displaying two anomalously low measures of paleoshoreline emergence (1.2–1.4 m) are discounted as lying within subsided tiltblocks on the downthrown sides of normal faults (Figure 6B), the average emergence is raised to 1.75 m (n = 7). In all cases (n = 5), differential elevations noted on Figure 6B between paleoshoreline notches and modern shoreline notches are within 0.1 m of measurements reported previously by others (IDA *et al.*, 1984).

(2) On Tinian, only 5 km distant from Saipan, paleoshoreline notches standing 1.8 m above modern counterparts at Dangkulo Beach on the eastern coast provide the only discernible measure of post-mid-Holocene emergence. A degraded cuesta of emergent paleobeachrock at Tachogna Beach south of San Jose rises at least a meter above modern high tide-level, to a position compatible with the post-mid-Holocene emergence inferred from Dangkulo Beach, but no maximum measure of emergence can be obtained from the outcrop at Tachogna Beach.

(3) On Guam, apart from two sites near the northern tip of the island discussed in the next section, overall average emergence (n = 8) is 1.7 m, but two sites on the southwest coast display anomalously low (1.2–1.4 m) measures of emergence (Figure 6A). If those two sites are omitted from the average, on grounds that southern Guam may have been tilted toward the west during Holocene time, the average emergence is raised to 1.85 m (n = 6). The amounts of emergence noted on Figure 6A for mid-Holocene reef flats at Aga Point and Agfayan Bay are within 0.1 m of previous inferences (IDA *et al.*, 1984; SIEGRIST and RANDALL, 1985; KAYANNE *et al.*, 1993).

Hydro-isostatic emergence of mid-Holocene paleoshoreline features in the Mariana Islands can thus be estimated as approximately 1.8 m (±0.2 m), in close accord with theoretical expectation (Figure 3). All measured features (n = 18) on southern Guam, Tinian, and Saipan lie within the range 1.2–2.0 m, with a mean of 1.7 m, and those from sites unaffected

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Saipan; (C) Mid-Holocene paleoshoreline notch (above head of person) incised into Pleistocene Mariana Limestone at a level 1.8 m above active shoreline notch associated with modern high-tide level (near feet of person) at Tumon Bay (Figure 6A) on Guam; (D) Mid-Holocene paleoshoreline notch (marked by beach bags to left of person) incised into Pleistocene Tanapag Limestone at a level 1.4 m above active shoreline notch associated with modern high-tide level (overhanging visor to right of person) at Agingan Beach (Figure 6B) on Saipan; (E) emergent paleoreef flat at Ipan Beach on Guam (Figure 6A) and associated mid-Holocene wavecut platform (both partly grass-covered) terminating inland (near figure) at mid-Holocene paleoshoreline notch incised into Pleistocene Mariana Limestone at a level 1.7 m above active shoreline notch (out of view to right) associated with modern high-tide level; (F) emergent paleoreef flat (left of person) and associated paleoshoreline notch (right of person) at west end of Lau Lau Beach (Figure 6B) on Saipan, with post-mid-Holocene emergence of 1.5 m (paleoreef flat) to 1.7 m (paleoshoreline notch) indicated by present elevations of emergent mid-Holocene features relative to modern low-tide and high-tide levels, respectively; (G) eroded pedestal (person for scale), with active shoreline notch incised into its base (notch apex at modern high-tide level), composed of mid-Holocene Merizo Limestone topped by remnant surface of mid-Holocene paleoreef flat standing an estimated 2.6 m above surface of modern fringing reef offshore at Tarague Beach (Figure 6A) on Guam; (H) erosional mesa-like monument carved by modern surf from emergent mid-Holocene reef limestone at Mochong Beach (Figure 7) on Rota; coralline facies rises to level marked by beach bag (2.1 m above apex of active shoreline notch at base of monument or 2.8 m above surface of modern fringing reef offshore), with a degraded capping of intertidal algal facies reaching a higher elevation.

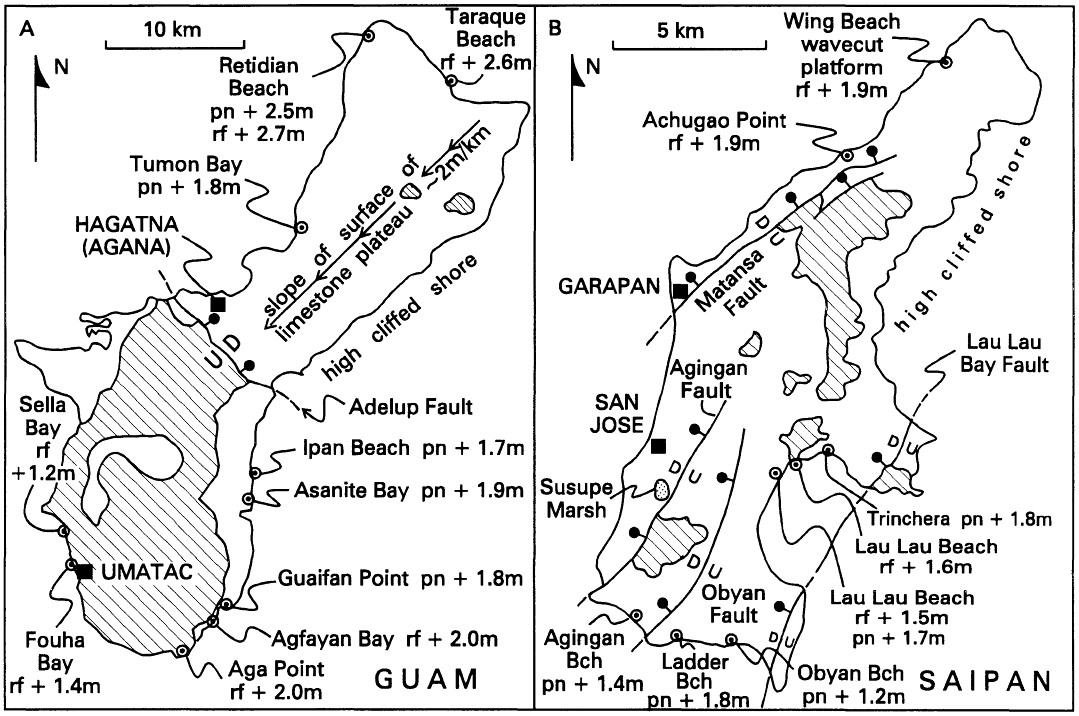

Figure 6. Emergent mid-Holocene paleoshoreline features on Guam (A) and Saipan (B); note different scales. Emergence (+1.2 m to +1.9 m) of paleoshoreline notches (pn), the "tidal notches" of Pirazzoli (1996:28–29), measured relative to elevation of modern shoreline notches incised into the same limestone cliffs at modern high-tide level (measurements made between respective apices of notches). Emergence (+1.2 to +2.7 m) of radiocarbon-dated mid-Holocene paleoreef flats (rf), and of one undated wavecut platform denoted separately, measured relative to surfaces of adjacent modern reef flats built upward to modern low-tide level. Tidal ranges assumed as uniformly 0.7 m for Guam and 0.6 m for Saipan. Ruled areas denote volcanic bedrock (other areas are Neogene limestone cover). Balls denote downthrown sides of Neogene normal faults. Geologic features after CLOUD *et al.* (1956) and TRACEY *et al.* (1964).

by suspected local tectonic subsidence lie within the narrower range of 1.5–2.0 m (n = 14), with a mean of 1.8 m. Although minor tectonic deformation, either uplift or subsidence, may have affected some or all of the sites, there are no grounds to suspect systematic tectonic uplift of Saipan, Tinian, or southern Guam since mid-Holocene time (Figure 3).

ROTA-GUAM TECTONIC UPLIFT

Emergent paleoshoreline features, chiefly mid-Holocene reef flats (Figure 5GH), on northern Guam (Figure 6A) and neighboring Rota (Figure 7) rise to elevations distinctly higher than expected from hydro-isostatic theory (Figure 3). Post-mid-Holocene tectonic uplift of northern Guam by an estimated 0.8 m, and of Rota by as much as 1.2 m, is implied by available data. The net emergence for Rota is indicated by maximum elevations of coralline facies in emergent paleoreef limestone (Figure 7), with overlying algal facies inferred to have extended into or throughout the mid-Holocene intertidal zone (BELL, 1988; BELL and SIEGRIST, 1988; KAYANNE *et al.*, 1993).

Maximum post-mid-Holocene emergence of the north shore of Rota (at Pinatang) by 2.9–3.1 m (Figure 7) is coordinate with the net estimate of 3 m by Bell (1988), and matches the emergence reported for the Pinatang vicinity by KAYANNE *et al.*, (1993, their sites C–E), who reported the elevation of the emergent reef crest as 2.7 m above mean sea level, translating to 3.1 m of emergence above low-tide level (LTL of Figure 7). Farther east at Mochong Beach, however, the emergence of 2.8 m inferred here (Figure 7) is distinctly less than the emergence of 3.5 m inferred by KAYANNE *et al.* (1993, their sites A–B). In my judgment, however, KAYANNE *et al.* (1993) assumed modern mean sea level at Mochong Beach to be approximately 0.7 m below the level indicated by local shoreline morphological features. If an adjustment of that amount is made to their data for Mochong Beach, our results are coordinate. Elsewhere along the north coast of Rota, radiocarbon ages of 3600–4100 yrs BP (n = 4) for coral growing on the floors of paleoshoreline notches document post-mid-Holocene shoreline emergence of 3.0 m (KAYANNE *et al.*, 1993), in accord with the maximum inferred here (Figure 7). Readers should be aware, however, that KAYANNE *et al.* (1993:Figure 10) inferred net emergence of Rota by 3.5 m, or 0.4 m greater than the maximum of 3.1 m inferred here.

On northern Guam, the post-mid-Holocene emergence noted on Figure 6A for Tarague Beach lies within 0.1 m of the maximum emergence reported previously (RANDALL and SIEGRIST, 1988), except for one mid-Holocene coral occurrence of uncertain significance implying local emergence of

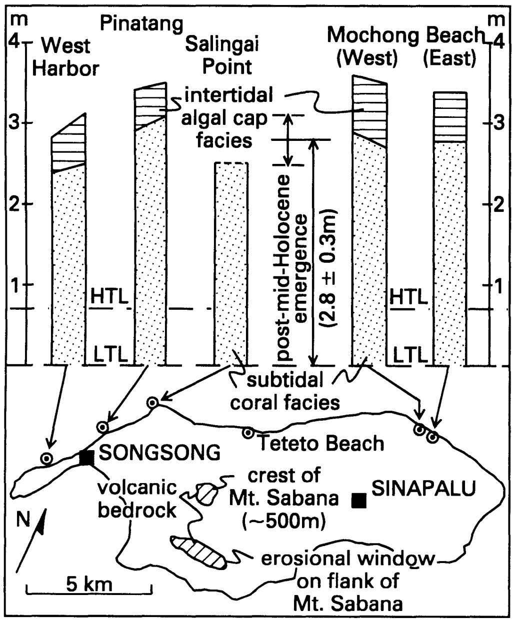

Figure 7. Elevations of emergent mid-Holocene reef features along northwest coast of Rota (Figure 4). LTL = modern low-tide level (surface of modern fringing reef flat); HTL = modern high-tide level (elevation of apex of modern shoreline notch). Volcanic outcrops (beneath limestone cover) after YOUNG (1989).

3.8 m possibly associated with local faulting (RANDALL and SIEGRIST, 1996).

FOREARC UPLIFT MECHANISM

The regional setting of the Mariana Islands (Figure 4) suggests a geodynamic rationale for Holocene uplift of Rota and northern Guam relative to southern Guam and the islands farther north. The northwesterly projection of a linear seamount chain on the subducting Pacific plate passes directly beneath northern Guam and Rota. By analogy with relations in the Vanuatu (TAYLOR *et al.,* 1985, 1987) and Tonga (DICKINSON *et al.,* 1999) forearcs, subduction of the buoyant seamount chain beneath the forearc belt may be the factor inducing local Holocene uplift. The crustal bulk of the subducted seamount chain may also promote a higher degree of coupling between over-riding and under-riding plates of lithosphere in the hypocentral region of the 1993 Guam earthquake (Figure 4), as compared to elsewhere along the Mariana chain. The intensity of the seismic event was unexpected, given the generally low degree of interplate coupling along the Mariana subduction zone (CAMPOS *et al.,* 1996). It is perhaps conceivable that temporary lockage of a fault-plane asperity provided by the underthrust edifice of a subducted seamount may have triggered the anomalous seismicity. Prequake and postquake GPS surveys on Guam reveal coseismic shift of Guam to the southeast by 0.25 m and accompanying subsidence of 0.1 m (BEAVAN *et al.,* 1994), but these movements were presumably part of an earthquake cycle of forearc deformation (CLAGUE, 1997:Figure 3) and provide no information regarding net long-term tectonic behavior of the island.

On Guam, the upper surface of a tilted plateau of uplifted Pliocene-Pleistocene Mariana Limestone, as exposed extensively northeast of the Adelup fault (Figure 6A), is inclined gently (2 m per km) to the southwest, away from the inferred axis of uplift in response to seamount subduction (Figure 4). The elevations of emergent paleoshoreline features of northern Guam (Figure 6A) are compatible with a post-mid-Holocene tilt of approximately 0.05 m per km in the same sense, toward the Adelup fault. As the mid-Holocene paleoshoreline notch at Tumon Bay in central Guam (Figure 5A) is emergent by only the 1.8 m inferred for post-mid-Holocene hydro-isostasy, uplift of northeasternmost Guam is implied. If the indicated rate of post-mid-Holocene tilt has continued unchanged since the last interglacial interval (*c.* 125,000 ka), any last-interglacial terraces preserved on northeasternmost Guam should stand at an elevation approximately 2 m higher than expected. This prediction is seemingly confirmed by an elevation of 8–9 m observed (RANDALL and SIEGRIST, 1996) for the last-interglacial terrace at Tarague Beach (Figure 6A), whereas an elevation of only 6–7 m is expected from global data (MOORE, 1987; CHAPPELL and SHACKLETON, 1986). The westerly tilt of southern Guam, discussed above as an explanation for the divergent measures of paleoshoreline emergence along the southeast and southwest coasts, may also have been approximately 0.05 m per km since mid-Holocene time.

Internal deformation of Rota is also quite possible. Although remnants of uplifted mid-Holocene reefs are present along the coasts of both northeastern and northwestern Rota, more limited preservation of emergent reef in the vicinity of Teteto Beach (Figure 7), near the center of the northern coast, suggests the possibility of differential uplift with a synclinal character, to produce minimum emergence near Teteto Beach. Island-capping limestone plateaus and benchlands of Rota do not, however, display notable tilts in any discernible direction.

ARCHAEOLOGICAL IMPLICATIONS

Pollen and charcoal studies on Guam (ATHENS and WARD, 1995) and Tinian (ATHENS, 1998), as well as radiocarbon dates for the oldest cultural horizons at key archaeological sites on Guam (KURASHINA and CLAYSHULTE, 1983), Tinian (CRAIB, 1993), and Saipan (BUTLER, 1994; AMESBURY *et al.,* 1996), jointly imply initial human occupation of the Mariana Islands *c.* 3500 yrs BP, either coincident with or close on the heels of the mid-Holocene highstand in regional hydro-isostatic sea level (Figure 2). Environmental interpretations for early occupation sites are in harmony with the inference of higher relative sea levels at the time of initial settlement (BUTLER, 1994). For example, Chalan Piao on the southwest coast of Saipan was evidently first established on a narrow sand spit along the seaward side of a saltwater lagoon (AMESBURY *et al.,* 1996:57), whose remnant is now the Susupe Marsh inland from the present coastline (Figure 6B). Farther north at Achugao Point (Figure 6B), initial occupation was located on a small islet or peninsula at the mouth of a shallow lagoon, which has evolved through time into a marshy wetland just inland from the present coast (BUTLER, 1994:20).

From analysis of their radiocarbon ages for emergent mid-Holocene reef materials preserved at different elevations on Guam and Rota, KAYANNE *et al.* (1993) concluded that relative sea level in the Mariana Islands reached its peak by 4200 yrs BP, to decline at still uncertain rates thereafter under combined hydro-isostatic and tectonic influences. As local relative sea level declined, coastal progradation of sediment allowed gradual expansion of human populations as the area of attractive coastal lowlands was enlarged (AMESBURY *et al.*, 1996:65). Complex interplay between sediment progradation and sea-level fall is to be expected, however, and the times that various coastal sites reached environmental stability under conditions similar to their modern guise needs evaluation case by case (BUTLER, 1995).

The prevalent view (KAYANNE *et al.*, 1993; AMESBURY *et al.*, 1996; RANDALL and SIEGRIST, 1996) that a significant fraction of the post-mid-Holocene drawdown in relative sea level on Marianas islands occurred sporadically, in discrete pulses, may be largely invalid. Neither hydro-isostatic sea-level change nor broad forearc uplift is likely to have been episodic. Although preservation of emergent mid-Holocene reef flats on Marianas shorelines might seem most understandable as the result of quick shifts in relative sea level, the necessity for rapid sea-level fluctuations to achieve the observed degree of preservation is denied by the widespread occurrence of analogous emergent paleoreef flats of the same general age on numerous South Pacific islands where there are no grounds to suspect abrupt tectonic movements. Well documented examples occur at multiple localities in the Society Islands (PIRAZZOLI and MONTAGGIONI, 1988), the southern Cook Islands (YONEKURA *et al.*, 1988; DICKINSON, 1998), and perhaps most notably on Tongatapu and 'Eua in Tonga where the elevations of still higher paleoreef surfaces dating from the last interglaciation record the lack of any net post-last-interglacial uplift, either abrupt or gradual (TAYLOR and BLOOM, 1977; WOODROFFE, 1988; DICKINSON *et al.*, 1999).

SUMMARY CONCLUSIONS

Emergent mid-Holocene reef flats and notched or benched paleoshorelines within Micronesia reflect regionally variable post-mid-Holocene drawdown in relative sea level following the peak of the mid-Holocene hydro-isostatic highstand within the equatorial Pacific Ocean basin. Mid-Holocene paleoshoreline features on Saipan, Tinian, and southern Guam are emergent by amounts that lie within the theoretical range retrodicted by hydro-isostatic calculations, and require no ancillary tectonic uplift to explain. Excess post-mid-Holocene emergence of northern Guam (by 0.8 m) and nearby Rota (by 1.2 m) can be attributed to forearc uplift caused by subduction of an oceanic seamount chain at the Mariana Trench. The subducted seamount chain may also induce regionally anomalous seismicity, as reflected by the 1993 Guam earthquake. Initial human settlement of the Mariana Islands was apparently facilitated by the development of attractive coastal environments as local relative sea level declined from its mid-Holocene highstand.

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LITERATURE CITED

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.

ATHENS, J.S., 1995. *Landscape Archaeology: Prehistoric Settlement, Subsistence, and Environment of Kosrae, Eastern Caroline Islands, Micronesia.* Honolulu: International Archaeological Research Institute, 474p.

ATHENS, J.S., 1998. *Paleoenvironment and Prehistoric Landscape Change: A Sediment Core Record from Lake Hagoi, Tinian, CNMI.* Honolulu: International Archaeological Research Institute, 128p.

ATHENS, J.S. and WARD, J.V., 1995. Paleoenvironment of the Orote Peninsula, Guam. *Micronesica,* 28, 51–76.

BEAVAN, K.; MURATA, I.; NAKAO, S.; KATO, T.; HIRAHARA, K.; TANAKA, T.; ABAD, R.; SCHOLZ, C.; ROECKER, S. and DAVIS, D., 1994. Determination of the Philippine Sea plate velocity from Global Positioning System observations, and effects of the 1993 Guam earthquake. *EOS (American Geophysical Union Transactions) Supplement (1994 Fall Meeting),* 75, 59.

BELL, S.C., 1988. Sedimentary history and early diagenesis of Holocene reef limestone on Rota (Mariana Islands). M.S. thesis (unpublished). University of Maryland, College Park, Maryland, 82p.

BELL, S.C. and SIEGRIST, H.G., JR., 1991. Facies development model for emergent Holocene reef limestone: Southern Marianas region. *Micronesica,* 24, 137–157.

BUTLER, B.M., 1994. Early prehistoric settlement in the Mariana Islands: New evidence from Saipan. *Man and Culture in Oceania,* 10, 15–38.

BUTLER, B.M., 1995. Archaeological investigations in the Achugao and Matansa areas of Saipan, Mariana Islands. *Micronesian Archaeological Survey Report* 30, 448p.

CAMPOS, J.; MADARIAGA, R., and SCHOLZ, C., 1996. Faulting process of the August 8, 1993 Guam earthquake: A thrust event in an otherwise weakly coupled subduction zone. *Journal of Geophysical Research,* 101, 17581–17596.

CHAPELL, J., 1974. Late Quaternary glacio-and hydro-isostasy, on a layered Earth. *Quaternary Research,* 4, 405–428.

Chappell, J. and Shackleton, N.J., 1986. Oxygen isotopes and sea level. *Nature,* 324, 137–140.

Clague, J.J., 1997. Evidence for large earthquakes at the Cascadia subduction zone. *Reviews of Geophysics,* 35, 439–460.

Clark, J.A., 1980a. A numerical model of worldwide sea level changes on a viscoelastic Earth. *In:* Morner, N.-A. (ed.), *Earth Rheology, Isostasy and Eustasy.* New York: Wiley, pp. 525–534.

Clark, J.A., 1980b. The reconstruction of the Laurentide ice sheet of North America from sea level data: Method and preliminary results. *Journal of Geophysical Research,* 85, 4307–4323.

Clark, J.A. and Lingle, C.S., 1979. Predicted relative sea-level changes (18,000 years BP to Present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research,* 11, 279–298.

Clark, J.A.; Farrell, W.E., and Peltier, W.R., 1978. Global changes in postglacial sea level: A numerical calculation. *Quaternary Research,* 9, 265–287.

Cloud, P.E.; Schmidt, R.G., and Burke, H.W., 1956. Geology of Saipan, Mariana Islands; Part 1 General geology. *U.S. Geological Survey Professional Paper* 280-A, 123p.

Craib, J.L., 1993. Early occupation at Unai Chulu, Tinian, Commonwealth of the Northern Mariana Islands. *Indo-Pacific Prehistory Association Bulletin,* 13, 116–134.

Crough, S.T., 1978. Thermal regime of mid-plate hotspot swells. *Geophysical Journal of the Royal Astronomical Society,* 55, 451–469.

Curray, J.R.; Shepard, F.P., and Veeh, H.H., 1970. Late Quaternary sea-level studies in Micronesia: CARMARSEL Expedition. *Geological Society of America Bulletin,* 81, 1865–1880.

Doan, D.B.; Burke, H.W.; May, H.G., and Stensland, C.H., 1960. *Military Geology of Tinian, Mariana Islands.* Honolulu: Intelligence Division, Office of the Engineer, Headquarters U.S. Army Pacific, 149p.

Dickinson, W.R., 1998. Geomorphology and geodynamics of the Cook-Austral island-seamount chain in the South Pacific: Implications for hotspots and plumes. *International Geology Review,* 40, 1039–1075.

Dickinson, W.R. and Green, R.C., 1998. Geoarchaeological context of Holocene subsidence at the ferry berth Lapita site, Mulifanua, Upolu, Samoa. *Geoarchaeology,* 13, 239–263.

Dickinson, W.R.; Burley, D.V.; Nunn, P.D.; Anderson, A.; Hope, G.; De Biran, A.; Burke, C., and Matararaba, S., 1998. Geomorphic and archaeological landscapes of the Sigatoka dune site, Viti Levu, Fiji: Interdisciplinary investigations. *Asian Perspectives,* 37, 1–31.

Dickinson, W.R., 1999. Holocene sea-level record on Funafuti and potential impact of global warming on central Pacific atolls. *Quaternary Research,* 51, 124–132.

Dickinson, W.R.; Burley, D.V., and Shutler, R. Jr., 1999. Holocene paleoshoreline record in Tonga: Geomorphic features and archaeological implications. *Journal of Coastal Research,* 15(3), 682–700.

Dixon, T.H.; Batiza, R.; Futa, K., and Martin, D., 1984. Petrochemistry, age, and isotopic composition of alkali basalts from Ponape Island, western pacific. *Chemical Geology,* 43, 1–28.

Easton, W.H. and Ku, T.-L. 1980. Holocene sea-level changes in Palau, west Caroline Islands. *Quaternary Research,* 14, 199–209.

Easton, W.H.; Ku, T.L., and Randall, R.H., 1978. Recent reefs and shore lines of Guam. *Micronesica,* 14, 1–11.

Farrell, W.E. and Clark, J.A., 1976. On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society,* 46, 647–667.

Fryer, P., 1995. Geology of the Mariana Trough. *In:* Taylor, B. (ed.), *Backarc Basins: Tectonics and Magmatism.* New York: Plenum Press, pp. 237–279.

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

Gischler, E. and Lomando, A.J., 1997. Holocene cemented beach deposits in Belize. *Sedimentary Geology,* 110, 277–297.

Hanor, J.S., 1978. Precipitation of beachrock cements: Mixing of marine and meteoric waters *vs.* CO_2 degassing. *Journal of Sedimentary Petrology,* 48, 489–501.

Hopley, D., 1986. Beachrock as a sea-level indicator. *In:* Van Den Plassche, O. (ed.), *Sea Level Research: A Manual for the Collection and Evaluation of Data.* Norwich, UK: Geo Books, pp. 157–173.

Ida, Y.; Yonekura, N., and Kayanne, H., 1984. Holocene sea-level changes in the southern Marianas. *In:* Sugimura, A. (ed.), *Sea Level Changes and Tectonics in the Middle Pacific: Report of the HIPAC Project in 1981, 1982, and 1983.* Kobe, Japan: Department of Earth Sciences, Faculty of Science, Kobe University, pp. 187–204.

Kawana, T.; Miyagi, T.; Fujimoto, K., and Kikuchi, T., 1995. Late Holocene sea-level changes and mangrove development in Kosrae island, the Carolines, Micronesia. *In:* Kikuchi, T. (ed.), *Rapid Sea Level Rise and Mangrove Habitat.* Gifu, Japan: Gifu University Institute for Basin Ecosystems, pp. 1–7.

Kayanne, H.; Ishii, T.; Matsumoto, E., and Yonekura, N., 1993. Late Holocene sea-level change on Rota and Guam, Mariana Islands, and its constraint on geophysical predictions. *Quaternary Research,* 40, 189–200.

Keating, B.H.; Mattey, D.P.; Haughton, J., and Helsley, C.E., 1984a. Age and origin of Truk atoll, eastern Caroline Islands: Geochemical, radiometric-age, and paleomagnetic evidence. *Geological Society of America Bulletin,* 95, 350–356.

Keating, B.H.; Mattey, D.P.; Helsley, C.E.; Naughton, J.J., and Epp, D., 1984b. Evidence for a hot spot origin of the Caroline Islands. *Journal of Geophysical Research,* 89, 9937–9948.

Krumbein, W.E., 1979. Photolithotropic and chemoorganotrophic activity of bacteria and algae as related to beachrock formation and degradation (Gulf of Aqaba, Sinai). *Journal of Geomicrobiology,* 1, 139–203.

Kurashina, H. and Clayshulte, R.N., 1983. Site formation processes and cultural sequence at Tarague, Guam. *Indo-Pacific Prehistory Association Bulletin,* 4, 114–122.

Mattey, D.P., 1982. The minor and trace element geochemistry of volcanic rocks from Truk, Ponape and Kusaie, eastern Caroline Islands; the evolution of a young hot spot trace across old Pacific Ocean crust. *Contributions to Mineralogy and Petrology,* 80, 1–13.

McClean, R.F. and Woodroffe, C.D., 1994. Coral atolls. *In:* Carter, R.W.G. and Woodroffe, C.D. (eds.), *Coastal Evolution: Late Quaternary Shoreline Morphodynamics.* Cambridge, U. K., Cambridge University Press, pp. 267–302.

Meijer, A; Reagan, M.; Ellis, H.; Shafiqullah, M.; Sutter, J.; Damon, P., and Kling, S., 1983. Chronology of events in the eastern Philippine Sea. *In:* Hayes, D.E. (ed.), The tectonic and geologic evolution of southeast Asian seas and islands; Part 2. *American Geophysical Union Monograph* 27, pp. 349–359.

Mitrovica, J.X. and Peltier, W.R., 1991. On postglacial geoid subsidence over the equatorial oceans. *Journal of Geophysical Research,* 96, 20053–20071.

Moore, C.H., Jr., 1973. Intertidal carbonate cementation, Grand Cayman, West Indies. *Journal of Secimentary Petrology,* 43, 591–602.

Moore, W.S., 1982. Late Pleistocene sea-level history. *In:* Ivanovich, M. and Harmon, R.S. (eds.), *Uranium Series Disequilibrium: Applications to Environmental Problems.* Oxford: Clarendon Press, pp. 481–496.

Mrozowski, C.L. and Hayes, D.E., 1979. The evolution of the Parece Vela Basin, eastern Philippine Sea. *Earth and Planetary Science Letters,* 46, 49–67.

Nakada, M. and Lambeck, K., 1988. The melting history of the late Pleistocene Antarctic ice sheet. *Nature,* 333, 36–40.

Nakiboglu, S.M.; Lambeck, K., and Aharon, P., 1983. Postglacial sealevels in the Pacific: Implications with respect to deglaciation regime and local tectonics. *Tectonophysics,* 91, 335–358.

Nunn, P.D., 1995. Holocene sea-level changes in the south and west Pacific. *Journal of Coastal Research Special Issue* 17, 311–319.

Peltier, W.R.; Farrell, W.E., and Clark, J.A., 1978. Glacial isostasy and relative sea level: A global finite element model. *Tectonophysics,* 50, 81–110.

Pirazzoli, P.A., 1996. *Sea-Level Changes in the Last 20,000 Years.* New York: Wiley, 211 p.

Pirazzoli, P.A. and Montaggioni, L.F., 1988. Holocene sea-level changes in French Polynesia. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 68, 153–175.

RANDALL, R.H. and SIEGRIST, H.G., Jr., 1988. Geomorphology of the fringing reefs of northern Guam in response to Holocene sea level changes. *Proceedings of the Sixth International Coral Reef Symposium (Australia),* 3, 473–477.

RANDALL, R.H. and SIEGRIST, H.G., Jr., 1996. *The Legacy of Tarague Embayment and its Inhabitants; Volume 3: Geology, Beaches, and Coral Reefs.* Honolulu: International Archaeology, 461 p.

RANDALL, R.H.; SIEGRIST, H.G., Jr., and SIEGRIST, A.W., 1984. Community structure of reef-building corals on a recently raised Holocene reef on Guam, Mariana Islands. *Palaeontographica Americana* 45, 394–398.

REAGAN, M.K. and MEIJER, A., 1984. Geology and geochemistry of early arc-volcanic rocks from Guam. *Geological Society of America Bulletin,* 95, 701–713.

SAKAMOTO, I., 1994. Study of geological characteristics of volcanic rocks from Kosrae Island, eastern Caroline Islands. *Tokai University Journal of the College of Marine Science and Technology,* 38, 185–203.

SCHOFIELD, J.C., 1977. Late Holocene sea level, Gilbert and Ellice Islands, west central Pacific Ocean. *New Zealand Journal of Geology and Geophysics,* 20, 503–529.

SCHROEDER, W., 1984. The empirical age-depth relation and depth anomalies in the Pacific Ocean basin. *Journal of Geophysical Research,* 89, 9873–9883.

SCOFFIN, T.P. and STODDART, D.R., 1978. Beachrock and intertidal cements. *In:* GOUDIE, A.S. and PYE, K. (eds.), *Chemical Sediments and Geomorphology.* London: Academic Press, pp. 401–425.

SIEGRIST, H.G., Jr. and RANDALL, R.H., 1985. Community structure and petrography of an emergent Holocene reef limestone on Guam. *Proceedings of the Fifth International Coral Reef Congress (Tahiti),* 65, 563–568.

SIEGRIST, H.G., Jr.; RANDALL, R.H., and SIEGRIST, A.W., 1984. Petrography of the Merizo Limestone, an emergent Holocene reef, Ylig Point, Guam. *Palaeontographica Americana,* 54, 399–405.

STEIN, C.A. and STEIN, S., 1992. A model for the global variation in oceanic depth and heat flow with age. *Nature,* 359, 123–129.

STODDART, D.R. and CANN, J.R., 1965. Nature and origin of beachrock. *Journal of Sedimentary Petrology,* 35, 243–247.

TAYLOR, B., 1992. Rifting and the volcano-tectonic evolution of the Izu-Bonin-Mariana arc. *Proceedings of the Ocean Drilling Program (Scientific Results),* 126, 627–651.

TAYLOR, F.W., Jr. and BLOOM, A.L., 1977. Coral reefs on tectonic blocks, Tonga island arc. *Third International Coral Reef Symposium (University of Miami) Proceedings,* 2, 275–281.

TAYLOR, F.W.,; Jr. JOUANNIC, C., and BLOOM, A.L., 1985. Quaternary uplift of the Torres Islands, northern New Hebrides frontal arc: Comparison with Santo and Malekula islands, central New Hebrides frontal arc. *Journal of Geology,* 93, 419–438.

TAYLOR, F.W., Jr.; FROEHLICH, C.; LECOLLE, J., and STRECKER, M., 1987. Analysis of partially emerged corals and reef terraces in the central Vanuatu arc: Comparison of contemporary coseismic and nonseismic with Quaternary vertical movements. *Journal of Geophysical Research,* 92, 4905–4933.

TRACEY, J.I., Jr. and LADD, H.S., 1974. Quaternary history of Eniwetok and Bikini atolls, Marshall Islands. *Proceedings of the Second International Symposium on Coral Reefs, Volume 2.* Brisbane, Australia: Great Barrier Reef Committee, pp. 537–550.

TRACEY, J.I., Jr.; SCHLANGER, S.O.; STARK, J.T.; DOAN, D.B., and MAY, H.G., 1964. General geology of Guam. *U.S. Geological Survey Professional Paper* 403-A, A1–A104.

WALCOTT, R.I., 1972. Past sea levels, eustasy and deformation of the Earth. *Quaternary Research,* 2, 1–14.

WOODROFFE, C.D., 1988. Vertical movements of isolated oceanic islands at plate margins: Evidence from emergent reefs in Tonga (Pacific Ocean), Cayman Islands (Caribbean Sea), and Christmas Island (Indian Ocean). *Zeitschrift für Geomorphologie (Supplement-Band),* 69, 17–37.

YONIKURA, Y.; ISHII, T.; SAITO, Y.; MAEDA, Y.; MATSUSHIMA, Y.; MATSUMOTO, E., and KAYANNE, H., 1988. Holocene fringing reefs and sea-level change in Mangaia Island, southern Cook Islands. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 68, 177–188.

YOUNG, F.J., 1989. *Soil Survey of the Islands of Aguijan, Rota, Saipan, and Tinian, Commonwealth of the Northern Mariana Islands.* Washington, D.C.: U.S. Department of Agriculture Soil Conservation Service, 166p.