Holocene Paleoshoreline Record in Tonga: Geomorphic Features and Archaeological Implications

William R. Dickinson‡, David V. Burley‡, and Richard Shutler, Jr.‡

‡Department of Geosciences
University of Arizona
Tucson, AZ 85721, U.S.A.

‡Department of Archaeology
Simon Fraser University
Burnaby, BC, Canada V5A 1S6

ABSTRACT


Coordinated geomorphic and archaeological observations indicate that ancient (c. 3000 years old) archaeological sites in Tonga typically lie inland from present coasts on paleoshorelines associated with a regional mid-Holocene highstand of sea level. Shorelines in Tonga include both seacliffs, which dominate windward coasts, and coral sand beaches, many of which fringe accretionary sand flats on leeward coasts. Seacliffs are characteristically notched at high-tide level by solution and bioerosion. Emergent paleoshoreline notches of mid-Holocene and last-interglacial ages record higher local stands of relative sea level on many Tongan islands. Other indicators of local mid-Holocene sea levels include emergent microatolls, paleobeachrock exposures, beach-ridge berm crests, and fossil beach placers of black sand derived from tephra deposits. Paleoshoreline indicators on Tongatapu and 'Eua, and in the Nomuka and Hahake subgroups of Ha'apai, show that mid-Holocene sea level stood 2.0–2.6 m higher than present sea level, with tectonic changes in island elevations negligible since the last interglacial. By contrast, the Vava'u Group and the Kotu subgroup of Ha'apai have subsided at mean Holocene rates of c. 0.5 mm/yr, enough to counteract the post-mid-Holocene fall in local relative sea level. Elevations and locations of ancient archaeological sites are generally compatible with independent geomorphic evidence for stability or subsidence of individual islands. Parts of Tongatapu were evidently inundated in 1853 by the temporary runup of a local tsunami associated with an earthquake generated by volcanic activity along the nearby volcanic arc.

ADDITIONAL INDEX WORDS: Beachrock, forearc, fringing reef, hydro-isostasy, island arc, Lapita pottery, placer sand, raised reef, shoreline notch, sherd temper, tephra blanket, tsunami, wavecut platform.

INTRODUCTION

Understanding the course of Pacific island prehistory and forecasting future environmental conditions on Pacific islands can be improved by joint archaeological and geological investigations designed to reconstruct the evolution of island settings over the past few millennia (e.g., Dickinson and Green, 1998; Dickinson et al., 1998). This paper describes the results and implications of combined geomorphic and archaeological field work undertaken in Tonga to establish the evolutionary trends of paleoshorelines over the past 3000 years.

Past work within the Ha'apai Group of islands in central Tonga has demonstrated that local settlements represent the offshore sedimentary and lithological characteristics of the Lapita cultural complex (Green, 1973, 1992) in the Hahake subgroup are located on paleo-beaches that now lie well inland from the shoreline and significantly above modern high-tide level (Dickinson et al., 1994; Shutler et al., 1994). The Lapita occupation nearly 3000 years ago was the first human presence in Tonga, but occupation has since been continuous. Lapita sites date from the millenium 1500–500 BC throughout their widespread distribution for nearly 5000 km across the island groups of the southwestern Pacific (Figure 1), from the Bismarck Archipelago on the northwest to Samoa and Tonga on the southeast (Green, 1979; Kirch and Hunt, 1988). The Lapita peoples of western Polynesia were evidently the ancestors of the Polynesians who later spread through the intra-Pacific island groups lying farther east (Kirch, 1997).

The Lapita interval overlaps in time with the latter part of a regional mid-Holocene (glacio-)hydro-isostatic highstand in relative sea level that affected essentially all Pacific islands (Mitrovica and Peltier, 1991). The late Holocene emergence of paleoshorelines with Lapita sites in Tonga is attributed primarily to post-mid-Holocene fall in local relative sea level as the regional hydro-isostatic highstand waned (Woodroffe, 1988; Spenneman, 1989: 66; Dickinson et al., 1994). The potential ancillary influence of tectonism on shoreline history cannot be dismissed, however, because Tonga is an active island arc, with subduction underway at the nearby Tonga Trench (Pelletier and Louat, 1989) and arc volcanism in progress along the associated Tofua (or Tongan) volcanic chain (Scholl et al., 1985). The occupied islands of Tonga lie mostly within the forearc belt between trench and arc.

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Shoreline History

Previous examination of features recording past Quaternary shorelines and relative sea levels on Tongan islands has led to contrasting interpretations of the general tenor of late Quaternary tectonic history within Tonga: (a) Taylor (1978; and Bloom, 1977) concluded that deformation since the last interglacial has been minimal, and that emergent interglacial and mid-Holocene shoreline indicators and reef tracts primarily reflect global or regional highstands in eustatic (interglacial) or hydro-isostatic (mid-Holocene) sea levels; but (b) Nunn and Finau (1995) later concluded that multiple seafloor outcrops, inferred to reflect solution and bioerosion at former relative sea levels, record repetitive events of coseismic forearc uplift at significant net Holocene rates for Tongatapu, the largest island in Tonga.

Resolution of these two contrasting viewpoints is important not only for paleogeomorphic interpretations, and potentially for seismic hazard analysis, but also for archaeological study of Lapita and later settlements in Tonga. Interpreting the paleogeographic context of human settlement, assessing the implications of possibly catastrophic, as opposed to gradual, transformation of relationships between land and sea during human occupation of the islands, and predicting the likely locations of Lapita sites on various islands are dependent upon a proper understanding of shoreline history within Tonga.

We have examined salient features indicative of Holocene shoreline evolution throughout most of Tonga, with the exception of the far-distant outlying islands of Niutatapu, Tafahi, and Niuafo’ou in the north and ‘Ata in the south (Figure 2). Our prime goal was to define the record of the mid-Holocene hydro-isostatic highstand of relative sea level in Tonga, and to detect any additional influence of Holocene tectonism on paleoshoreline relations. As the occupied islands are composed dominantly of raised reef tracts, and would not exist without forearc uplift, the fact of net Neogene uplift is not in doubt, but only its timing and style. Our observations support an interpretation of minimal late Quaternary deformation within Tonga, but also show that Holocene subsidence of parts of the island chain, relative to more stable islands, has locally influenced the paleoshoreline record.

TECTONIC SETTING

The raised coral islands of Tonga are distributed at intervals along the northern part of the Tonga Ridge, a largely submerged bathymetric feature extending NNE-SSW for approximately 750 km along the Tongan arc-trench system (Chase, 1986). The ridge lies within the forearc region, 150–175 km wide, between the active Tongan volcanic arc to the west and the deep Tonga Trench to the east (Figure 2). The segment of the Tonga Ridge where all the raised coral islands occur is an elongate platform 30–50 km wide at depths of 400–600 m or less (<200 m over wide areas). This shallow platform is separated from the volcanic chain to the west by the Tofua Trough, with its floor at 1400–1800 m depth, and from the wall of the Tonga Trench on the east by a sloping bathymetric terrace at depths of 3200 to 5400 m (Clift et al., 1998: Figure 2), still well above the floor of the trench near 9000 m depth.

Exploratory drilling on Tongatapu and seismic profiling offshore indicate that Cenozoic strata including hemipelagic, volcanioclastic, and carbonate deposits (Austin et al., 1989; Tappin, 1993) reach aggregate thicknesses of 2000–4000 m above Eocene volcanogenetic basement underpinning the Tonga Ridge (Herzer and Exon, 1985; Cunningham and Anscome, 1985). On 'Eua, a much thinner sedimentary succession, approximately 300 m thick as exposed above an igneous substratum, is apparently representative of the abbreviated sequences present along the crest of a structural high that rims the eastern edge of the Tonga Ridge (Scholl and Herzer, 1992: figure 6). From Tongatapu well cores, Pliocene and Pleistocene limestones at the top of the forearc sediment pile are only 125–250 m thick (Cunningham and Anscome, 1985; Tappin, 1993; Gatliff et al., 1994; Tappin et al., 1994). This capping reefal association overlies a widespread uncon-
formity and apparently represents a phase of sedimentation triggered by uplift of the Tonga Ridge from a previously deeper forearc belt. The islands and island clusters atop the bathymetric ridge represent local reef tracts that grew higher than the general level of the ridge platform even before emergence placed them at their present elevations above sea level.

Uplift of Tonga is attributed in part to the thermal effects of rifting or arc splitting (TAPPIN et al., 1994; CLIFT et al., 1995) that separated the Lau Ridge of Fiji from the Tonga Ridge, and initiated seafloor spreading within the Lau Basin west of the present Tongan volcanic chain near the end of Miocene time (6-5 myr according to HAWKINS, 1995). More pronounced forearc uplift is attributed, however, to later subduction of the oceanic Louisville Ridge beneath the inner wall of the Tonga Trench (DUPONT and HERZER, 1985; BALLANCE et al., 1989). Analysis of the orientation of the Louisville Ridge with respect to relative plate motions for the Tonga region implies that effects induced by subduction of the Louisville Ridge swept southward along the Tonga Ridge through time, from c. 3 myr (Pliocene) at Vava'u to c. 1.5 myr (Pleistocene) near Tongatapu and 'Eua. From the advent of thicker and coarser ash deposits within the forearc stratigraphic sequence, inception of the modern (Tofua) volcanic arc also occurred at c. 3 myr (CLIFT et al., 1995).

The narrow width (85–115 km; HAWKINS et al., 1987: figure 2) of the Louisville Ridge as a bathymetric feature on the Pacific plate implies that the main pulse of forearc uplift associated with ridge subduction has already ended along the segment of the Tonga Ridge between Vava'u and Tongatapu. Given the effective width (c. 150 km) of the Louisville Ridge parallel to the convergence direction of the Pacific plate as it moves into the trench, and the rate of plate convergence at the trench, the duration of trench-ridge collision effects at any given point along the trend of the Tonga Ridge is predicted to be on the order of only a million years (BALLANCE et al., 1989). If the crustal bulk of the Louisville Ridge is eventually carried into the mantle as part of the subducted slab of oceanic lithosphere descending at the Tonga Trench, relaxational post-uplift forearc subsidence could now be influencing the portion of the Tonga Ridge where the islands of principal archaeological interest are located.

**Forearc Blocks**

Uplift of the Tonga Ridge was influenced by an array of subparallel transverse structures (Figure 3), presumably controlled by faulting at depth, that strike roughly normal to the Tonga Trench and delineate structural blocks arranged like so many separate piano keys along the trend of the arc-trench system (TAYLOR and BLOOM, 1977; TAYLOR, 1978). For at least 750 km along the trend of the forearc belt, transverse structures break the Tonga Ridge into at least a dozen discrete forearc blocks, which average 65 km (range 30–100 km) in longitudinal dimension parallel to the strike of the forearc belt (HERZER and EXON, 1985; TAPPIN, 1993; TAPPIN et al., 1994; GATLIFF et al., 1994). The most prominent of the transverse structural trends are marked by abrupt discontinuities in bathymetry along the Tonga Ridge, and appear as re-entrants in its flanks or as linear passages breaking across its otherwise shallow summit platform. The most notable lineaments (Figure 3) define the block of shoals including Tongatapu and 'Eua on the southwest, three roughly equant segments of the summit platform forming the Nomuka, Kotu, and Hahake subgroups of islands within the Ha'apai Group, and an elongate domain including the south-tilted Vava'u Group farther north. More subdued lineaments subdivide the Vava'u domain north of the Ha'apai Group (Figure 3).

Structural segmentation of the Tonga Ridge implies that the tectonic history of different structural blocks within the forearc belt has been different. Varying magnitudes of relative uplift or subsidence, including subtle patterns of structural tilt, may have affected each island or island cluster separately. Consequently, observations pertaining to changes in relative sea level for any given block cannot be extrapolated
with confidence to other blocks. For reliable interpretations, paleoshoreline indicators must be examined independently within each structural block, and ancient archaeological sites are known to stand at different elevations relative to modern mean sea level in different parts of Tonga.

COASTAL GEOMORPHOLOGY

The present morphology of island coasts within Tonga is the key basis for paleoshoreline analysis because paleoshoreline indicators are best interpreted by analogy with modern shoreline features. There are two fundamental types of strandlines to consider: (a) beaches composed of white calcreous ("coral") sand as loose sediment that is rearranged continuously or intermittently by wave action, and (b) cliffed coasts where the sea at high tide impinges directly upon eroded remnants of uplifted reef-flat limestone forming the cores of raised coral islands.

Beach sediment in Tonga is not derived primarily from wave attack on seaciffs, nor from the rare local streams and ravines, but is washed onshore and longshore by wave and tidal currents from offshore reef flats, which serve as factories for the production of biogenic calcareous detritus. Beach strands include local pocket beaches at the heads of coves between headlands, extensive linear beaches that shield long reaches of island coasts, and pointed or cuspatate spits that form extensions of raised coral islands. Locally, some spits have grown to form tombolos that tie islands together at low tide. Cliffed coasts without beaches are most prevalent on the liku coasts facing east or south into the trade winds, whereas beaches are best developed on sheltered coasts in the lee of the trade winds.

Both types of strandlines are characterized and continually bordered by offshore fringing reefs of varying width. The outer edges of the fringing reefs along liku coasts subject to strong surf action are typically built up by terraced algal ridges that grow within the intertidal zone and form a reef rim enclosing a quasilagoon, which occupies inner parts of the fringing reef with a floor 0.9 m below the outer rim of algal terraces (Nunn, 1993). The algal terraces along the edges of the fringing reefs form picturesque miniature tablelands ("terraces"), washed by surf, that slope gently landward but drop abruptly on their landward sides to the floors of the quasi-lagoons of fringing-reef interiors.

The age of the coralline limestone underpinning the fringing reefs is variable. Although aggradational and progradational growth of visible Holocene coral and other associated calcareous organisms has contributed to the expanse of fringing reefs, much of their morphology stems from erosion of raised reef-flat limestone to form a wavecut shore platform upon which modern coral grows as surficial cover only. The inner margins of fringing reefs where exposed along island shorelines are commonly smooth planar surfaces exposing truncated pre-Holocene coral heads in growth position. On the lee sides of Tongatapu and a number of smaller islands, however, nearshore reefs merge seaward with extensive submerged reef flats that reach far out into adjacent waters in complex areal patterns controlled by active reef growth.

Beach faces of loose sand within the intertidal zone are locally armored by a veneer (0.25-0.75 m) of beachrock (Figure 4A) cemented by Holocene precipitation of calcium carbonate in the interstices between sand grains. Although cementation may extend locally into the lowermost part of the swash zone above high-tide level, or into the uppermost part of the subtidal zone, beachrock is basically an intertidal phenomenon, with precipitation of interstitial cement caused by warming of seawater trapped in the pores between sand grains near the surfaces of wet beaches that are heated by sunshine during exposure at low tide (Ginsburg, 1955). The sand of beachrock is identical in composition and texture to adjacent loose beach sand, and bedding laminae within beachrock dip parallel to beach faces. Consolidated beachrock
Figure 4. Key shoreline features in Tonga: (A) sloping cuesta of beachrock armor within intertidal zone of beach face on west coast of Tungua, Ha'apai Group; (B) sloping surface of modern beachrock (dark), partly buried by loose beach sand, merging downslope with wavecut platform beveled across raised reef-flat limestone (pale), with white beach bag (35 × 35 cm) at discontinuity in slope between beachrock and platform surfaces at Oholei Beach on east coast of Tongatapu; (C) modern shoreline notch at high-tide level (photo at low tide) on eastern liku coast of Lifuka, Ha'apai Group (figure for scale); (D)
is distinguishable from isolated remnants of raised reef-flat limestone exposed on beach fronts because the latter display subhorizontal bedding and coral heads in growth position. Disoriented coral rubble may be present, however, in beachrock where coarse debris occurs as part of the sediment on the beach face. On some strandlines, beachrock ramps merge downslope with wavecut ramps of eroded reef-flat limestone forming the inner edges of wavecut platforms that underpin fringing reefs. In these cases, there is a slight decrease in seaward slope at the contacts between beachrock and the downslope wavecut ramps (Figure 4B).

The most characteristic features of cliffed coasts formed by erosion of raised reef-flat limestone are prominent undercut notches at high-tide level (Figure 4C). Although physical wave attack may contribute to removal of loosened debris from the notches, their origin stems fundamentally from solution of the limestone by seawater, accompanied by effects of bioerosion by littoral organisms. Shoreline notches have formed not only on liku coasts subject to strong wave attack, but are also present at the bases of seafalls that occur locally on sheltered coasts. In the few local instances of sea stacks eroded to form pedestal rocks, notching is roughly uniform around the full periphery of the stacks. The heights and depths of shoreline notches are variable, but dimensions of 1–2 m, both vertically and horizontally, are perhaps typical. In profile, the notches tend to be asymmetric, with flat floors controlled by the position of high tide but sloping visors at angles dependent upon the influence of both spray and mass wasting. The deepest part of each notch provides the closest estimate of high-tide level. This notch level typically stands 1.0–1.2 m, which is the local tidal range, above the flat surfaces of adjacent fringing reefs. On the few cliffed coasts where shoreline notches are absent, low sea cliffs are delimited from the innermost sloping ramps of wavecut platforms by sharp shoreline angles located at high-tide level (Figure 4D).

PALEOSHORELINE RECORD

Because beaches are transient features composed of loose sediment subject to easy removal by erosional agents, paleoshoreline notches in seacliffs comparatively resistant to erosion are the most persistent indicators of paleoshoreline positions (Figure 4E–G). The paleoshoreline notches also provide rather accurate estimates of associated sea levels, which are difficult to infer from preserved beach sands unless paleobeachrock is present. Even where present, paleobeachrock exposures must be interpreted with caution because the exact relationship of beachrock cementation to local intertidal ranges is variable (Hopley, 1986). On accretionary coasts, however, where successive beach ridges have added to the areal extent of some islands (Dickinson et al., 1994: figure 9), the successive elevations of the crests of preserved paleo-beach ridges allow qualitative appraisal of former sea levels.

Observations of paleoshoreline indicators on land are inherently restricted to the recognition of past relative high-stands in sea level, whether resulting from subsequent island uplift or from decline in global eustatic or regional hydro-isostatic sea levels. Positive detection of land subsidence or rise in sea level on the basis of paleoshoreline indicators would require underwater investigations, which would encounter the challenge of perceiving paleoshoreline features masked by subsequent reef growth under conditions of higher relative sea level.

Estimates of past relative sea levels from the present elevations of paleoshoreline notches are best made by measuring the vertical differences in elevation between exposed paleoshoreline notches and modern shoreline notches etched into the same seacliffs. This procedure is favored for several reasons:

(a) Foremost is the fact that the position of active shoreline notches with respect to mean sea level is affected by vagaries of exposure to solution and bioerosion governed by the ambient tides, winds, and currents that impinge on each segment of shoreline. Notches are not necessarily formed at the same exact position with respect to mean sea level on all coasts of a given island, but presumably reproduce the same relative positions with respect to mean sea level for different local stands of the sea as recorded at the same localities.

(b) Surveying the elevations of paleoshoreline notches by leveling from monuments of local island datums fails as a viable approach on the many islands in Tonga where local surveys are limited, and is a questionable procedure in any case because the relationship between each local island datum and true modern mean sea level is commonly uncertain.

(c) Attempting to gauge the heights of paleoshoreline notches above the observed sea surface encounters the problem that tidal variations through the lunar cycle are poorly defined for most locales in Tonga, and also meets the even greater difficulty that sea levels on Pacific islands are known to vary interannually by as much 25–50 cm both above and below the long-term regional mean owing to ENSO (El Nino/Southern Oscillation) events (Sherwood and Howorth, 1996: 8).

The positions of archaeological sites inferred to represent coastal settlements can be used as an auxiliary means to estimate paleoshoreline positions, but are not used here as primary evidence. Only by establishing ancient shoreline rela-

modern shoreline angle (at feet of figure for scale) at top of innermost sloping ramp of wavecut platform cut across raised reef-flat limestone on north end of 'Uiha, Ha'apai Group; (E) modern shoreline notch (below) and mid-Holocene paleoshoreline notch (above), each marked by positions of beach bags (35 × 35 cm), on northeast coast of Foa, Ha'apai Group; (F) modern shoreline angle (at feet of figure for scale) at current high-tide level and emergent mid-Holocene paleoshoreline notch (above head of figure) on southwest coast of Foa, Ha'apai Group; (G) modern shoreline notch (near level of feet of figure for scale) and emergent mid-Holocene paleoshoreline notch (near level of head of figure) at Anahulu Beach on east coast of Tongatapu, with subdued and discontinuous notch-like feature present higher on cliff from differential seacliff erosion of raised reef-flat limestone; (H) expanded shoreline notch approximately 2 m high on southwest coast of Kapa, Vava'u Group.
Figure 5. Sketch map of Tongatapu (Figures 2-3) showing uplifted Vaina paleoreef trend (post-mid-Pliocene, pre-mid-Pleistocene). Arrows denote places along coastline where emergent mid-Holocene paleoshoreline notches were observed and measured during this study (figures in parentheses are differential elevations between active modern shoreline notches and fossil mid-Holocene paleoshoreline notches). Solid symbols denote emergent mid-Holocene (triangles) and last-interglacial (square) corals or sediments dated by uranium-series and radiocarbon methods (Taylor and Bloom, 1977; Taylor, 1978; Nunn and Finau, 1995). See text for discussion.

TONGATAPU

The highest elevations on Tongatapu (Figure 5) lie along the curvilinear crest of the uplifted Vaina paleoreef trend of post-mid-Pliocene but pre-mid-Pleistocene age (Taylor and Bloom, 1977; Taylor, 1978; Nunn, 1993; Nunn and Finau, 1995). The maximum elevation of 65-70 m is reached at the southern tip of the island where a paleoisland anchored two wings of paleoreef, which extended leeward to both the northeast and the northwest, and now form coastal ridges standing at elevations of 20-30 m parallel to the southern and eastern coasts of Tongatapu. The crescent-shaped Vaina paleoreef trend enclosed a paleolagoon, which is occupied now by low-lying flatlands in the interior of Tongatapu and can be viewed as the precursor of the present-day Fanga 'Uta Lagoon indenting the northern coast of the island. Patch reefs that grew within the Vaina paleolagoon form isolated hillocks that stand above the lowlands of the island interior at elevations of 20-25 m. A higher hill near Fanga 'Uta Lagoon and the nearby offshore island of 'Euaiki (Figure 2) have summit elevations of 35-45 m and must have formed two small paleoislands prior to uplift of the Vaina paleoreef.

Uplift of the Vaina paleoreef complex tilted the surface of Tongatapu downward to the NNW at a gentle angle of 0.05-0.06 degrees (Taylor, 1978). Views of the profile of Tongatapu from 'Eua to the southeast indicate uniform tilt without internal faulting or flexure within the tilted block, and a com-
bined topographic and bathymetric analysis has shown that the island and the adjacent reef-dotted lagoon to the north jointly form an inclined planar surface over a distance of 25 km (ROY, 1990). Local saddles in the ridges that parallel the southern and eastern coasts represent morphology inherited from ancestral passages through the uplifted Vaima paleoreef trend. The southern and eastern coasts along the uptilted and windward flank of the island are dominated by cliffed shorelines with variable beach development along the bases of the scallifs. The downtilted and leeward northern coast, where sandy beaches or spits and mangrove fringes are prominent (ROY, 1990), passes gradationally offshore into the shoals of an extensive reef platform dotted with small cays (STODDART, 1975). Overall topographic and bathymetric relationships imply net Quaternary erosion of the uptilted windward sides of the island and net accretion to the downtilted northern side of the island through a combination of shoreline progradation and the aggradation of offshore reef flats growing freely in the lee of the island.

**Relative Quaternary Sea Levels**

Uranium-series dating of reefal limestone on Tongatapu provides a framework for understanding local changes in relative sea level during late Quaternary time (TAYLOR and BLOOM, 1977; TAYLOR, 1978). The Utuulu Formation, which has yielded an age of 135,000 ± 15,000 yrs indicative of the last interglacial, underlies coastal terraces standing 6.5-7.5 m above modern high-tide level, and reaches 5.5 m above modern high-tide level in scallifs at seaward terrace margins. Judging from the current tidal range of 1.0 m (neap tide) to 1.2 m (spring tide), reef-flat Utuulu coral heads, assumed to have formed below but near the interglacial low-tide level, are emergent by c. 6.7 m. As the last interglacial sea level evidently stood 6-7 m above modern sea level (BLOOM et al., 1974; NEUMANN and MOORE, 1975; BARD et al., 1990; CHEN et al., 1991; NEUMANN and HEARTY, 1996), the net rate of subsequent forearc uplift has apparently been negligible. The older Niutoua Formation, which locally underlies the Utuulu Formation along a contact 3.0-3.5 m above high-tide level, and elsewhere underpins coastal terraces standing c. 3 m above modern high-tide level, has yielded ages of 200,000-225,000 yrs and apparently reflects an earlier interglacial highstand some 4.5 m above modern sea level.

Mid-Holocene reef-flat limestone of the Nuku’alofa Formation is also emergent up to a meter above modern high-tide level, implying a post-mid-Holocene drop in local relative sea level by c. 2.2 m. Survey leveling from the tops of mid-Holocene coral heads exposed in excavated ditches within downtown Nuku’alofa (Figure 5) to the tops of living coral heads on the nearby offshore reef flat in front of Nuku’alofa directly documents an elevation difference of 2.15 m (F. W. Taylor, personal communication, 1995). Generally concordant uranium-series and radiocarbon ages (n = 5 total) suggest an age of 6000 to 6250 yrs (TAYLOR, 1978) for emergent Nuku’alofa coral heads, but radiocarbon ages as young as 5650 ± 80 BP on mangrove peat which underlies shelly marine lagoon deposits beneath Fanga ‘Uta Lagoon (ELLISON, 1989) imply that the peak mid-Holocene highstand may have been slightly younger than any of the dated coral heads. An even younger radiocarbon age of 5050 ± 150 BP (NUNN and FINAU, 1995) has been reported from calcarenite representing coral sand that prograded across the mid-Holocene reef flat at Kolonga (Figure 5) near the northeast tip of Tongatapu. The amount of post-mid-Holocene emergence documented for Tongatapu by isotopic dating of reef-flat coral heads is fully compatible with the inferred magnitude of a hydro-isostatic mid-Holocene highstand in regional sea level (TAYLOR and BLOOM, 1977; DICKINSON et al., 1994), and requires no Holocene uplift of the island to explain originally coastal archaeological sites on Tongatapu that have yielded Lapita artifacts dating to c. 3000 yrs ago (POULSEN, 1987; SPENNEMAN, 1989) lie inland from the present shoreline at elevations compatible with the postulated bulk emergence of the island through late Holocene time (SPENNEMAN, 1988), but were not re-investigated during the present study.

**Alternate Uplift Hypothesis**

Analysis of the heights and inferred ages of multiple scalliff notches on Tongatapu has suggested the alternate hypothesis that discrete coseismic uplift events during Holocene time left a significant imprint on the shoreline record (NUNN and FINAU, 1995). The lowest and most prominent notches standing above modern high-tide level in scalliffs of Tongatapu are interpreted here, however, as the record of the mid-Holocene highstand in regional sea level (Figure 4G). Our observations indicate that the average height of those notches (Figure 5) above modern high-tide level, as recorded by comparable modern notches, is 2.2 ± 0.4 m (n = 8, range 1.8-2.8). More voluminous data from NUNN and FINAU (1995), interpreted here as measured from the same assemblage of paleoshoreline notches, yield the same mean value of 2.2 ± 0.4 m (n = 16, range 1.6-2.9). High-standing paleoshoreline indicators of mid-Holocene high-tide level (paleoshoreline notches) and low-tide level (raised coral heads) thus jointly indicate 2.2 m of post-mid-Holocene emergence for Tongatapu. In our judgment, numerous higher scalliff notches and a few poorly developed lower ones reflect differential erosion of scalliffs along lithologic inhomogeneities. Uplifted reef-flat limestones are composed of alternating layers of relatively resistant biothermal strata, composed of linked coral heads in growth position, and more readily erodible layers of cemented but fragmental calcarenite and displaced coral rubble. Interpretation of essentially all the scalliff notches as paleoshoreline features led NUNN and FINAU (1995) to their postulate of multiple coseismic uplift events during Holocene time, but this viewpoint is unnecessary in our view to explain the complex morphology of the eroding scalliffs (Figure 4G).

To reach their alternate interpretation, NUNN and FINAU (1995) relied heavily upon a single radiocarbon age of 5310 ± 110 BP on shell cemented firmly into a scalliff notch 7.25 m above modern high-tide level at Nakolo (Figure 5) on the southeast tip of Tongatapu. Acceptance of this age as a valid measure of the antiquity of the high shoreline notch requires the postulate of post-mid-Holocene forearc uplift on the windward coast of Tongatapu at a rapid mean rate on the order of 1 mm/yr. If projected back in time, such an uplift rate
would have carried the Vaina paleoreef trend to an elevation of 120–150 m just since interglacial time, whereas its observed elevation is only 25–65 m, and the maximum elevation of interglacial reef-flat terraces along the windward coast is no more than 7.5 m. Post-mid-Holocene uplift of the anomalous site at a mean Holocene rate of 1 mm/yr would also spoil the apparently congruent measures of post-mid-Holocene Tongatapu emergence, by a quasi-uniform 2.2 m, provided by paleoshoreline notches recording mid-Holocene high-tide levels along the windward coast and raised coral heads recording mid-Holocene low-tide levels along the leeward coast. The locality which yielded the anomalous age lies at the most windward point of Tongatapu, and it seems possible that heavy storm surf could transport Holocene shell debris well up the cliff face into positions wholly out of place with respect to its site of origin.

The alternate hypothesis of multiple coseismic Holocene uplift events along the cliffed windward coast would require two associated postulates: (a) key paleoshoreline notches along the uptilted windward coast are not as old as mid-Holocene, even though their elevations are congruent with the elevations of emergent mid-Holocene coral heads along the leeward northern coast; and (b) differential Holocene uplift accounts for the absence of any indication of marked Holocene emergence along the downtilted northern coast. Coseismic downwarping of the northern coast during the mid-nineteenth century was inferred by Ellison (1989) to account for the vertical distribution of historic guava pollen throughout mid-Holocene low-tide levels along the leeward coast. The spatial pattern of postseismic flooding seems fully compatible with the effects of a volcanogenic tsunami triggered by nearby volcanic activity to the west of Tongatapu. In our judgment, residents of Tonga need not fear coseismic deformation of Tongan islands sufficient to modify their configuration and morphology, but events that followed the 1853 Christmas Eve earthquake are a sobering reminder of the risk of tsunamis generated by submarine volcanism along the active volcanic chain west of the inhabited islands.

**EUA**

`Eua (Figure 6), the highest non-volcanic island in Tonga, is an elongate tilt-block, bounded by a submerged offshore fault on the east and inclined downward gently toward the west, with a crestal elevation just above 300 m. Its bedrock stratigraphic succession of mid-Eocene to Oligocene and Pliocene limestone, with intervening Miocene volcanoclastic turbidites, rests unconformably on a volcanic complex, exposed only along the east coast and representative of the igneous basement beneath the Tonga Ridge (Cunningham and Anscobie, 1985; Tappin and Ballance, 1994). The profile of the island is markedly asymmetric, with steep cliffs along its eastern side leading directly down to the seashore or to coves largely inaccessible from land. Its western flank is scored by multiple limestone terraces that step downward from the crest of the island to a less rugged but still partly cliffed shoreline. Pre-Pliocene strata dipping 12° west are overlain along a buttress unconformity by Pliocene and Quaternary limestones that display seaward-dipping foreset beds, deposited on progradational reef flanks and inclined as steeply as 25°–30°, but are otherwise flat-lying (Tappin and Ballance, 1994).

The elevations of coastal interglacial and mid-Holocene coral terraces on `Eua are comparable to those of counterparts on Tongatapu (Taylor and Bloom, 1977; Taylor, 1978), as expected because both islands lie within the same forearc structural block (Figure 3). Reef-flat limestone forming the Lakatoka Formation of interglacial age (133,000 ± 12,000 yrs) reaches 5.5 m above modern high-tide level and underlies prominent terraces standing 7 m above high-tide level along the western side of the island. From the local tidal range, the interglacial sea level on `Eua, as on Tonagatapu, stood c. 6.7 m above modern sea level. Locally on both eastern and western coasts of `Eua, a slightly emergent and variability...
eroded fringing reef, termed Ohonua Formation, stands at lower elevations up to a meter above modern high-tide level. Two radiometric ages (uranium-series and radiocarbon) suggest an age of 6000–6250 yrs, the same as mid-Holocene counterparts on Tongatapu. A comparable mid-Holocene sea-level highstand of c. 2.2 m above modern sea level is indicated. The mid-Holocene reef-flat surface capping limestone of the Ohonua Formation is intricately eroded in most exposures into jagged pinnacles and undercut table rocks projecting above the surface of the modern fringing reef, and modern beachrock locally downlaps unconformably against the inland flanks of local erosional remnants of the mid-Holocene fringing reef. Exposures at Ha'aluma Beach (Figure 6) on the southwest coast show that the modern shoreline notch, marking the modern high-tide level, stands approximately a meter above the adjacent fringing reef flat, with remnants of the degraded mid-Holocene reef flat rising to a little more than a meter higher.

Both interglacial and mid-Holocene paleoshoreline notches are preserved locally on 'Eua. The most informative exposure of the mid-Holocene notch lies within Ohonua town where a paleoseafloor composed of interglacial Lakatoha Formation rises above the mid-Holocene notch, which is located at the inner edge of a broad (25–75 m) terrace that represents the mid-Holocene fringing reef flat mantled by semiconsolidated calcarenite 2.5 m thick. The uppermost surface of the terrace stands approximately 3.5 m above modern high-tide level, and the terrace sediment cover presumably represents mid-Holocene beach sand overlying reef-flat limestone. Elsewhere on both the northwest and northeast coasts of 'Eua (Figure 6), mid-Holocene and interglacial paleoshoreline notches stand an estimated 2–3 m (n = 6, mean 2.6 ± 0.4 m) and 6.0–6.5 m (n = 3), respectively, above modern high-tide level. With allowance for minor variability in the elevations of paleoshoreline notches relative to emergent reef flats at sites subject to varying intensities of wave attack from surf action on coasts of different orientation and exposure to storm surf, relationships on 'Eua, as on Tongatapu, imply negligible deformation of the island since interglacial time.

The archaeological record of 'Eua is poorly known but prehistoric potsherds recovered from inside and near limestone caves in the interior (D. W. Steadman, personal communication, 1995) contain plagioclase-rich temper sands displaying lithic fragments of uralitic gabbro and microgabbro diagnostic of derivation from blocks within the basement igneous complex exposed along the eastern shore of the island (Figure 6), but nowhere else within Tonga. Future exploration for possible Lapita sites on 'Eua should be conducted with the geomorphic evidence for post-mid-Holocene emergence of the coastline in mind.

The numerous small islands of the Ha'apai Group (Figure 7) form three discrete clusters (Dye, 1987), which occupy three different forearc blocks separated by transverse structural trends (Figure 3):

(a) The Nomuka block is equant in shape, approximately 50 km square, with a summit platform less than 100 m deep separated from both the Tongatapu block to the south and the Kotu block to the north by linear passages c. 500 m deep. The scattered small islands of the Nomuka subgroup include several that reach elevations of 15–50 m and expose Miocene volcanioclastic strata and reef limestone (Cunningham and Ansccombe, 1985). Younger limestones within the subgroup locally include raised fringing reefs.

(b) The Kotu block is smaller, 25 km (ENE-SSW) by 40 km (WNW-ESE), with a summit platform also less than 100 m deep. Most of the northern edge of the Kotu block is marked by a bathymetric slope leading down to water depths in excess of 250 m above the submerged western part of the Ha'hake block, but the eastern parts of both blocks are less than 100 m deep, and the boundary between them is marked only by a re-entrant in the eastern flank of the Tonga Ridge immediately south of the islet of Uanukuhahake south of 'Uiha (the transverse structural trend at the block boundary was marked erroneously as lying north of 'Uiha by Dickinson et al., 1994: Figure 1). The structural boundary between the two
blocks is aligned with the position of the island volcano of Tofua along the active volcanic chain to the west, and may help control the position of that major volcanic center. Lowlying islands of the Kotu subgroup typically rise only 5–10 m above sea level, although a few reach elevations of 12–15 m.

(c) The surface of the nearly equant Hahake block, 40–45 km on each side, is tilted distinctly westward away from the Tonga Trench at an angle of approximately 0.70–0.85 degrees down to the WNW. The largest islands of the Hahake subgroup (Figure 8) form a curvilinear chain trending NNE-SSW and standing along the ESE edge of the Hahake block at the lip of a steep bathymetric slope leading downward to the deep terrace on the inner wall of the Tonga Trench. Fringing reefs have prograded several kilometers westward from the island chain, and isolated islands project above water in the central and southwestern parts of the Hahake block, but the surface of the block generally declines westward to depths of 500–600 m along its WNW edge. The NNE edge of the block, marked by a prominent structural trend passing just northeast of Ha'ano and Ofolanga (DICKINSON et al., 1994), is separated from shoals of the Vava'u Group to the north by a segment of the Tonga Ridge with summit depths as great as 400–600 m.

**Nomuka Subgroup**

Observations within the Nomuka subgroup (Figure 7), where no Lapita sites are yet known, were confined to Nomuka, the largest island, where extensive tracts of uplifted Quaternary reef limestone flank and rest unconformably upon an island core of uplifted Miocene reef limestone rising to an elevation of c. 50 m (CUNNINGHAM and ANSCOMBE, 1985: figure 3). The two units are readily distinguishable because pink to buff discoloration from diagenic alteration is characteristic of the densely indurated Miocene limestone, whereas the Quaternary (probably Pleistocene) limestone is uniformly gray with visible coral heads weathering out in growth position.

On the north coast of the northeast cape of Nomuka, a whitened degraded bench cut into cliffs of Quaternary limestone, and backed by a subdued paleoshoreline notch, stands 2.1 m above the modern notch at present high-tide level. By analogy with relations on Tongatapu and 'Eua, this feature is interpreted as the record of a mid-Holocene highstand in local relative sea level. A comparable eroded shoreline bench, lacking a discernible paleoshoreline notch behind it, is also exposed on both sides of the southeast cape of Nomuka at an elevation of approximately 2 m above the modern shoreline notch. We consequently infer post-mid-Holocene emergence of Nomuka by 2.0–2.1 m, and that any Lapita sites on the island are probably located along paleoshorelines lying well inland from the present beaches.

**Kotu Subgroup**

Within the Kotu subgroup (Figure 7), the islands of Ha'afeva, Matuku, and Tungua were examined in detail on foot, and the shorelines of Fetoa and Teaua were observed closely from close offshore by boat. Maximum elevations at the centers of the islands reach only 10–15 m. A consistent geologic feature of the Kotu subgroup is the presence of a thick succession of flat-lying ashfall tuff and lapilli tuff overlying raised reef-flat limestone of presumed Quaternary age. Lapilli clasts reach maximum diameters of 10–20 mm. The dominantly andesitic tephra deposits were doubtless derived from eruptions of Tofua, the island volcano that stands only 40–45 km to the northwest (Figures 2–3). Whereas the tephra layer is only c. 2.5 m thick (WILSON and BEECROFT, 1983) on the larger islands in the Hahake subgroup to the northeast, farther from Tofua, preserved thicknesses within the Kotu subgroup reach at least 7.5 m on Matuku and Ha'afeva, and 10–12.5 m on Tungua. The latter figure is the best estimate of the initial thickness of the Kotu tephra blanket prior to local erosion. On island beaches, local pockets of black mineral sand and scatters of gravel-sized lapilli were evidently derived from erosion of the tephra blanket by some combination of wave attack on sealiffs and runoff from island interiors.

The most informative outcrops of the Kotu tephra blanket occur in a vertical sealiff at the eastern extremity of Matuku (Figure 7). The basal 7 m of the local tephra succession are well exposed, and the immediately underlying raised reef-flat limestone forms discolored outcrops beneath an unconformity exposed on the beach at the southeast tip of the island. The tephra sequence of the sealiff is a generally conformable succession of dominantly andesitic ashfall tuff and lapilli tuff, with multiple lapilli-rich horizons representing the basal lag deposits of graded tephra units, and is capped by brown slopewash deposits overlying a humus-rich paleosol. Lapilli
clasts plucked from the cliff are scoriaceous and petrographically indistinguishable from reworked beach lapilli from nearby Tungua and Ha’a’eva. Individual tephra depositional units, each apparently representing single or clustered eruptive events, are 1.2–1.8 m thick. A discrete layer of white vitroclastic dacitic ash 10 cm thick occurs an estimated 5 m above the base of the tephra section.

No island shorelines visited or observed within the Kotu subgroup display any evidence for local Holocene sea levels higher than at present. On some cliffed shores, coastal benches that somewhat resemble emergent terraces, but display distinct seaward slopes, have developed by storm-wave stripping of erodible tephra cover from underlying, more resistant limestone. Brown slopes of exposed tephra rise above gray limestone outcrops that reach a meter or two above prominent modern shoreline notches and are locally white bleached white below the unconformable contact. The sloped structural benches are features of the modern landscape rather than emergent paleoshoreline indicators. Given widespread evidence elsewhere in Ha’apai (see above and below) for post-mid-Holocene emergence of c. 2 m, relations in the Kotu subgroup imply relative forearc subsidence of the Kotu structural block at a mean rate of c. 0.5 mm/yr. As exposures of the uplifted reef-flat limestones that underlie the tephra cover nowhere reach elevations greater than c. 2.5 m above the modern high-tide line, the islands of the Kotu subgroup could be described aptly as sunken tephra islands, rather than raised coral islands.

On Tungua (Figure 7), coastal limestone outcrops reach elevations of 0.5–2.5 m above modern high-tide line, and are overlain directly by tephra cover along an irregular unconformable contact. The ground surface at the excavated Fakatafenga Lapita site (Dye, 1987), located on the back slope of an accretionary beach ridge along the eastern shore, lies at an elevation only 1.5 m above modern high-tide level, with the Lapita artifacts derived from 0.55–0.85 m below the ground surface. The presently occupied village located farther north along the same beach ridge stands 2–3 m above high tide. Mutual relations of the ancient and modern occupation sites thus confirm the inference from geomorphic features that no post-mid-Holocene emergence has occurred. The postulated subsidence rate of 0.5 mm/yr satisfactorily accounts for the difference in elevation between the Lapita site (c.3000 yrs old) and the modern occupation level.

On Ha’a’eva (Figure 7), no raised reef-flat limestone is exposed beneath the tephra blanket, although occurrences slightly above modern sea level could be masked by the sand veneer of coastal beach ridges and accretionary sand flats that rim the island, banked against the tephra deposits of the interior. Storm berms stand c. 3.5 m above modern high-tide level. Our recovery of Lapita potsherds from a test pit dug in the presently occupied village on the east coast of Ha’a’eva confirms the lack of post-mid-Holocene emergence for Ha’a’eva, and documents shoreline subsidence comparable to that observed for Tungua (Burley, 1996b).

**Hahake Subgroup**

Extensive archaeological investigations throughout the island chain along the eastern edge of the Hahake subgroup (Figure 8) were accompanied by examination of paleoshoreline indicators on all the island coasts. Uplifted island cores of raised reef-flat limestone reaching peak elevations of 10–20 m on ‘Uiha, Lifuka, Foa, and Ha’ano are flanked on selected leeward shores by accretionary beach ridges, spits, and cays of Holocene coral sand deposits, which form the entirety of Tatafa and Uoleva. Summit surfaces of ‘Uiha and Lifuka are tilted downward to the WNW, with western parts of both islands underlain by coral sand deposits of accretionary beach-ridge complexes overlying a hidden reefal substratum, but the summits of Foa and Ha’ano are distinctly less tilted, with peripheral cliffs of raised-reef limestone present locally on all sides. Modern Foa is formed by once separate paleo-islands joined at Faleloa by an emergent mid-Holocene tombolo (Dickinson et al., 1994), and swampy ground near the middle of Foa marks the site of a paleolagoon within the larger paleoisland. The smaller paleoisland was comparable in size...
to the modern islet of Nukunomo (Figure 8), which is separated by a narrow channel from the accretionary sand spit at the northern tip of Foa.

Emergent paleoshoreline notches, in places with associated wavecut benches and interpreted as mid-Holocene in age, uniformly stand c. 2.0 m above modern shoreline notches on the north side of the northeast cape and at the southeast end of 'Uiha, on the south shore of Lifuka, at the southeast end of Ha'ano, and at three localities on Foa: (a) just west of its southwest tip (Figure 4F), (b) just east of its northeast tip (Figure 4E) and (c) on the liku coast at the north end of a beach along the east flank of the tombolo that ties the two segments of Foa together (Figure 8). On southwest Foa, the mid-Holocene paleoshoreline notch is cut into interglacial limestone that has yielded a uranium-series age of 130,000 ± 12,000 yrs (TAYLOR, 1978) and underlies a prominent coastal terrace with its surface c. 7.5 m above modern high-tide level.

On the southeast coast of 'Uiha, a mid-Holocene paleobeach ridge (Figure 8) of fossil placer sand extends for at least a kilometer parallel to the modern beach. At its south end, the depositional base of the paleobeach ridge rests upon a raised wavecut bench, with a slightly karsted surface standing 2 m above modern high-tide level. The face of the paleobeach ridge is subject to storm-wave attack but its crest lies 5 m above modern high-tide level, or 3 m above the inferred mid-Holocene high-tide level. The crest of the modern beach ridge along the west coast of 'Uiha stands a comparable 3 m above modern high-tide level.

Paleoshoreline features thus suggest that post-mid-Holocene internal deformation of the eastern island chain of the Hahake subgroup has been negligible. Specific estimates of the differential elevations, with respect to modern shoreline notches, of inferred mid-Holocene notches at widely distributed multiple localities (n = 7) vary only from 1.9 to 2.1 m (site means) or 1.8 to 2.2 m (site uncertainties). None of the seaciff features interpreted as mid-Holocene paleoshoreline notches occur at lithologic breaks within the raised reef-flat limestone, so none could reflect differential erosion of exposed seaciffs. The offshore positions of emergent mid-Holocene micrattolls that have yielded radiocarbon ages of 5600-5800 BP along the coasts of both Lifuka and Foa (WOODROFFE, 1983) are also generally supportive of island stability through Holocene time. Micratolls are isolated coral colonies with flat tops of dead coral, but living perimeters, and result from restriction of upward coral growth by the air/water interface at low-tide level (SCOFFIN and STODDART, 1978; STODDART and SCOFFIN, 1979).

Ancient archaeological sites in the Hahake subgroup interpreted from excavated stratigraphy as coastal settlements display relations fully compatible with a relative mid-Holocene highstand of sea level c. 2 m above modern sea level. On Lifuka, the Lapita pottery site at Tongoleleka south of Pangai (DYE, 1987; BURLEY, 1996a) and the Polynesian Plainware pottery site at Holopeka north of Pangai (BURLEY et al., 1995), dating respectively to 1000 and 800 BC, lie along or near the crest of the innermost accretionary beach ridge of the island. On 'Uiha, the ground surface at the Vaipuna Lapita site, on an accretionary sand flat inland from the present west coast, lies an estimated 5 m above modern high-tide level, but the Lapita cultural horizon occupies an elevation interval only 1–2 m above the inferred mid-Holocene high-tide level (BURLEY, 1996a). At Faleloa on Foa, a Lapita cultural horizon atop a paleobeach near the west end of the mid-Holocene tombolo that ties the two segments of Foa together occupies a stratigraphic interval lying 1.5–2.3 m above modern high-tide level and 1.0–1.8 m above the crest of the modern beach ridge along the shoreline at the head of Faleloa Bay 150–200 m from the site (DICKINSON et al., 1994; SHUTLER et al., 1994). The initial Lapita occupation apparently occurred either close on the heels of the mid-Holocene peak in local relative sea level, or early during the post-mid-Holocene sea-level decline, when the Faleloa site lay on the shoreline. The Pukotala Lapita site on Ha'ano similarly stands more than 2 m above modern sea level and is located 300 m inland from the coast.

Tatafa and Uoleva are Holocene sand cays separated from accretionary sand flats on 'Uiha and Lifuka, respectively, by tidal channels traversible on foot at low tide. Near the southwest tip of Lifuka, pre-modern but presumably post-mid-Holocene beachrock unconformably overlies a remnant of raised reef-flat limestone exposed at or near modern high-tide level. As the westward tilt of Lifuka implies that pre-till reef-flat limestone projects beneath both accreted beach ridges along the west coast and adjacent modern reef flats offshore, this exposure of exhumed reef-flat limestone apparently marks where the upper surface of the tilted raised-reef flat descends westward below modern sea level and beneath the nearby sand cay of Uoleva.

An annular array of multiple accretionary beach ridges surrounds the island core of Uoleva (DICKINSON et al., 1994), which reaches an elevation in excess of 5 m. A Polynesian Plainware pottery site in the interior indicates that the core of the cay was already in existence by 2400–2800 yrs ago, and the progressive decline in the crestal elevations of successively accreted beach ridges suggests that they were added to the island during a prolonged post-mid-Holocene decline in local relative sea level. Wholesale post-mid-Holocene accretion of coral sand to leeward shores and cays of the Hahake subgroup may have been promoted by any or all of the following influences: (a) expansion of sediment-producing offshore reef flats after peak submergence as a result of the postglacial rise in eustatic sea level, (b) enhanced stripping of sediment from offshore reef flats as a result of the post-mid-Holocene hydro-isostatic decline in regional sea level, or (c) accelerated denudation of local reef tracts as a result of growing human impact on reef ecology.

**VAVA’U**

The Vava’u structural block near the northern extremity of the Tonga Ridge is tilted southward subparallel to the trend of the arc-trench system. Summit elevations of the islands of the Vava’u Group (Figure 9), and the crests of bathymetric banks on the summit platform of the Tonga Ridge immediately to the south, decrease monotonically to the SSW at an average slope of 0.17 degrees for 60 km southward from the top of the high cliffs (c. 200 m) at the northern end of Vava’u.
Stratification in the post-mid-Pliocene limestones (Chaproniere, 1994) underlying both Vava'u and its neighboring islets reflects either uplift of a reef complex composed of multiple reef flats scored by deep channels and passages, or subsidence of an originally more uniform carbonate bank which had its morphology modified by karst erosion during exposure following uplift. Those two influences on modern topography are not mutually exclusive, and numerous sea caves on the shorelines of Vava'u attest to the prevalence of solutional action. The karstic system was presumably breached along seaciffs by subaerial erosion during glacial lowstands in eustatic sea level. Notch-like features within some of the sea caves are solutional irregularities controlled by stratigraphic inhomogeneities within the limestone. The stratigraphic control of cave morphology is best shown by inclined strings of seaciff cave mouths along the western shore of Hunga (Figure 9), where solution has occurred preferentially along selected stratigraphic horizons within packets of dipping foreset strata deposited along uplifted paleo reef flanks.

Absence of any limestone on Vava'u young enough to date by uranium-series methods suggests a late Quaternary history dominated by subsidence (Taylor, 1978). Prominent tilted benches on the flanks of Mounts Talau and Mo'ungalafa (Figure 9), with summit elevations of 130 m and 185 m, respectively, have the superficial appearance of uplifted coastal terraces, but are interpreted here as stripped structural surfaces formed by the erosion of exposed limestone strata along lithologic horizons of alternating resistant biostromes and more erodible fragmental limestone. The deep tephra cover of Vava'u, forming a thick reddish soil c. 10 m thick locally (Roy, 1990), is draped over topographic irregularities, with its basal contact only a meter or two above modern sea level on some small offshore islets but at 100–200 m elevation on high plateaus of the island interior.

Reconnaissance by boat of the intricate southern shoreline of Vava'u proper and the shorelines of 40 neighboring islets failed to detect any emergent paleoshoreline notches despite the fact that steep cliffs bare of vegetation typically rise 6–8 m above well-developed modern shoreline notches. Explanation for the lack of emergent paleoshoreline notches by post-mid-Holocene uplift in excess of 6–8 m is not a feasible hypothesis because a site that has yielded Lapita pottery dating to c. 3000 yrs ago near Otea on Kapa (Davidson, 1971) lies only 2–3 m above modern high-tide level. Total removal of emergent paleoshoreline notches by subsequent erosion seems improbable, given the protected nature of many Vava'u shorelines in comparison to shorelines where mid-Holocene paleoshoreline notches are still preserved elsewhere in Tonga.

The only feasible hypothesis for the lack of emergent paleoshoreline notches in the Vava'u Group is the postulate of Holocene subsidence at a rate sufficient to counteract the effects of the regional highstand in hydro-isostatic mid-Holocene sea level. A maximal inferred sea level drop of 2.5 m in approximately 5000 yrs would require net subsidence at a rate on the order of 0.5 mm/yr, which would imply a rise in local relative sea level of only 10 cm since initial European contact and is comparable to the rate of subsidence inferred here for parts of the Ha'apai Group farther south (see above).

As an exact match between subsidence rate and post-mid-Holocene decline in regional sea level cannot be anticipated, minor effects of changing relative sea levels may be present on Vava'u shorelines. Modern shoreline notches, for example, appear in many localities to have a greater height dimension than is typical elsewhere in Tonga. Rather flat notch visors stand as much as 2 m above equally flat floors, with no sharp apices at the deepest parts of many notches (Figure 4H). This somewhat unusual morphology perhaps reflects a "smearing" of solutional action through time because subsidence did not exactly pace decline in relative sea level.

Onetale Bay (Figure 9) on the northeast coast of Vava'u, a wavecut bench that stands perhaps a meter above the present high-tide level, is washed by fairweather surf, might be misinterpreted as the record of a wavecut bench at modern sea level. The stratigraphic control of cave morphology is best shown by inclined strings of seaciff cave mouths along the western shore of Hunga (Figure 9), where solution has occurred preferentially along selected stratigraphic horizons within packets of dipping foreset strata deposited along uplifted paleo reef flanks.

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Figure 9. Sketch map of Vava'u Group (Figures 2-3). Lapita sherds known (to date) only from Otea on Kapa.
notches slope distinctly upward from the points of headlands, where non-breaking waves slosh against sea cliffs, into the heads of small bays where the swash from breaking waves carries seawater well above the high-tide line. Relationships on ‘Umuna and Kenatu indicate that modern shoreline indicators vary slightly in elevation depending upon relative exposure to surf, and reinforce the view that the wave-swept bench at Onetale Bay is a modern geomorphic feature.

**PLACER SANDS**

On selected beaches in Tonga, most notably within the Ha’apai Group but to a lesser extent in eastern and southern parts of the Vava’u Group as well, concentrations of placer sand (Komar and Wang, 1984), composed of ferromagnesian igneous minerals reworked from the tephra cover of raised-coral islands, form pockets and sheets of black sand contrasting with the predominant white beach sands of calcareous composition derived from offshore reef flats. The black volcanic sands are archaeologically significant because ancient potters collected them preferentially to use as temper in ceramic wares (Dye and Dickinson, 1996; Dickinson et al., 1996). They occur not only in Lapita polishes, but also in so-called Lapitoid sherds of Polynesian Plainware, which began to be produced as early as 800–600 BC (Burley et al., 1996). As Tongan cultures had become aceramic by approximately AD 200–400 (Burley, 1994), the use of black sands as temper pertains mainly to the first millenium BC, only a few thousand years after the mid-Holocene highstand in regional hydro-isostatic sea level.

Some of the temper sands in ancient sherds closely resemble modern beach placer sands in mineralogical composition, but others reflect distinctly less placer concentration of heavy minerals. Dye and Dickinson (1996) speculated that the degree of placering displayed by Tongan beach sands derives partly from the duration of the residence time of sands in local beach systems, in addition to the variable intensity of surf action from place to place. By this hypothesis, many black sand grains were delivered to Tongan beach systems during the rapid pre-mid-Holocene rise in postglacial eustatic sea level that flooded parts of islands that had expanded during the last-glacial drawdown in eustatic sea level. Winnowing of tephra deposits that once covered the submerged portions of the enlarged islands is inferred to have swept mineral grains landward onto beach faces, where they were initially piled too rapidly to allow ready development of placer concentrates but have presumably been reworked continuously or intermittently by surf and wind ever since. The slow decline in relative sea level since mid-Holocene time has by inference diminished the supply of fresh volcanic detritus to the beach systems as wave attack on tephra deposits that still blanket the emergent islands has been progressively reduced. Accordingly, modern placer concentration of heavy mineral grains has been promoted by reworking over a longer period of time than the beach placers of the first millennium BC could have experienced.

Confirmation of this scenario is seemingly afforded by the compositions of black sands in the Ha’apai Group forming the mid-Holocene fossil beach ridge on ‘Uiaha in the Hahake sub-group, the innermost beach ridge of the accretionary beach-ridge complex on nearby Lifuka, and interior portions of an accretionary beach-sand belt forming a broad annular coastal flat on Ha’afeta in the Kotu subgroup (Figures 7–8). Although one sample of black volcanic sand from the face of the fossil beach ridge on ‘Uiaha is indistinguishable from modern beach placers in Ha’apai, samples of fossil black sands from near the mid-Holocene berm crest on ‘Uiaha and from the occurrences of fossil black sands on Lifuka and Ha’afeta are somewhat coarser grained sand containing only 34%–42% ferromagnesian silicate and oxide mineral grains. By contrast, modern beach placer sands (n = 25) collected from ten different islands in Ha’apai uniformly contain 92%–100% of those same grain types. The percentages cited derive in each case from grain frequency counts of thin sections made from sand aggregates, and are recalculated free of subordinate calcareous grains. The other non-calcareous grain types present in both modern and fossil beach deposits are monomineralic plagioclase feldspar grains and polymineralic volcanic rock fragments of generally andesitic character but varied textures. The ratio (c. 3:1) of lithic fragments to plagioclase grains in the three anomalous fossil black sands is also reflective of minimal placering.

A systematic search of beaches on Tongatapu (Figure 5) failed to reveal any modern placer concentrates of black mineral sand, even though volcanic sand tempers are common in prehistoric sherds from Tongatapu (Dye and Dickinson, 1996). Three alternatives can be entertained to explain this paradox: (a) the search for black sand on Tongatapu was incomplete; (b) all Tongatapu sherds containing volcanic sand tempers were imported from the Ha’apai Group to the north, or (c) Tongatapu beach placers available for collection during the ceramic periods of Tongan prehistory were depleted by temper collectors then, or have subsequently been removed by modern wave attack. The first alternative is unlikely because we examined many kilometers of beach face on all the shores of the island, and the second seems unlikely because of the sheer volume of the potsherds recovered from Tongatapu (Poulsen, 1987). We are left provisionally with the third explanation as the most likely.

Lapita sherds from Kapa (Figure 9) in the Vava’u Group also contain black sand tempers, many of placer character. Impure beach placer black sands, contaminated by admixtures of white coral sand, occur on the islets of ‘Euakafa, ‘Euaki, Fu’a’amotu, and Kenatu (Figure 9), but no major deposits of black sand have yet been located within the Vava’u Group. The placer tempers in Kapa sherds are nevertheless thought to represent sands from Vava’u because both sherds tempers and modern beach sands in Vava’u display the same characteristic ratio of clinopyroxene to orthopyroxene. The observed proportions of the total pyroxene represented by clinopyroxene are 0.89–0.91 (mean 0.90) for Vava’u tempers and sands, but only 0.84–0.88 (mean 0.86) for Ha’apai tempers and sands. As for Tongatapu, placer sands may have been more voluminous in the past on beaches of the Vava’u Group.

**DISCUSSION**

Our goal of blending observations and analysis drawn jointly from archaeology and Quaternary geology to achieve an
improved interpretation of Tongan prehistory requires discussion of the following points: (a) the magnitude and timing of the regional mid-Holocene hydro-isostatic highstand in relative sea level; (b) the differential relative subsidence or uplift of various transverse structural blocks in the Tongan forearc during Holocene time; and (c) the implications of our conclusions on those two points for understanding the locations of ancient archaeological sites in the Kingdom of Tonga.

**Mid-Holocene Highstand**

The most trenchant theoretical analysis of postglacial hydro-isostasy retrodicts a most likely mid-Holocene highstand of approximately 2.5 \(\pm\) 0.2 m peaking 4000 yrs ago for the Fiji-Tonga-Samoa region (MITROVIC and PELTIER, 1991: Figure 8). The post-mid-Holocene drawdown in regional sea level, following the postglacial eustatic rise, stemmed primarily from "equatorial ocean syphoning". By this mechanism, seawater was drawn away from the equatorial Pacific region to fill the void left by the gradually collapsing oceanic portion of the annular peripheral forebulge that surrounded glaciated regions pressed down by the load of superimposed Pleistocene ice sheets. The height of the residual highstand 3000 yrs ago, at the time of initial Lapita settlement in Tonga, is calculated as approximately 1.8 \(\pm\) 0.2 m, declining further to perhaps 0.9 \(\pm\) 0.3 m by 2000 years ago near the beginning of the aceramic period of Tongan prehistory.

The estimated timing and magnitude of the mid-Holocene highstand is subject to revision as information improves about the rheology of the mantle and the melting budget of glacial ice during deglaciation. Previous analyses, for example, have inferred that the peak of the highstand came as early as 5000 years ago (CLARK and LINGLE, 1979), or even 6000 years ago (NACIBOCLU et al., 1983), and the ages of mid-Holocene deposits on Tongatapu are quite compatible with a peak highstand in the range of 5000–6000 years ago. Paleo-shoreline relations on Manganua in the Cook Islands (Figure 1) east of Tonga have been interpreted, however, to indicate a mid-Holocene highstand peaking at approximately 1.7 m above modern sea level during the interval 4000–3400 years ago (YONEKURA et al., 1988). Empirical data from French Polynesia (PIRAZZOLI and MONTAGGIONI, 1988), still farther east, suggest a rather flat peak for the mid-Holocene highstand, extending from 5000–4500 years ago to perhaps 2000–1500 years ago at a maximum height of only a meter above modern sea level. On the south shore of Vanua Levu in Fiji, emergent mid-Holocene paleoshoreline notches and microtolls dating from 6000–3400 years ago (MIYATA et al., 1990) stand a consistent 1.5 \(\pm\) 0.2 m above modern counterparts at multiple localities. The sea-level record in Fiji may be contaminated, however, by Holocene tectonism within the Fiji platform (NUNN, 1990). In sum, empirical observations from the South Pacific region suggest caution with regard to specific retrodiction of mid-Holocene sea levels from theoretical calculations, in terms of either magnitude or timing. Fully valid definition of Holocene sea-level curves will ultimately depend upon iteration between theoretical and empirical estimates.

**Differential Tectonism**

Paleoshoreline notches that are interpreted here as a geomorphic record of the regional hydro-isostatic highstand in mid-Holocene sea level stand at mean elevations of 2.0–2.6 m above modern shoreline notches within the Tongatapu, Nomuka, and Hahake forearc structural blocks (Figure 3). Emergent mid-Holocene coral heads stand at a comparable elevation (2.2 m) above modern low-tide level on both Tongatapu and 'Eua. The indicated elevation interval is intermediate between the emergence calculated from hydro-isostatic theory (2.3–2.7 m) and the emergence empirically observed for Fiji and the Cook Islands (1.5–1.7 m), but is closer to the former. Given the uncertainties in both the theoretical and the empirical estimates of regional post-mid-Holocene emergence, we infer negligible net Holocene tectonic uplift or subsidence (<0.1 mm/yr) for these three structural blocks.

Slight differences in the mean elevations of mid-Holocene paleoshoreline notches within the Hahake (2.0 m) and Nomuka (2.1 m) subgroups of Ha'apai, and on Tongatapu (2.2 m) and 'Eua (2.6 m) could reflect slight differential forearc uplift or subsidence, or tilt, of various forearc domains or sub-domains. Alternatively, the overlap in the ranges of elevations observed for the mid-Holocene paleoshoreline notches from block to block may imply that vagaries of wave attack and spray height introduce enough inherent variability into notch elevations, depending upon the orientations and settings of different coasts, to account for the slight differences in average elevation. All the data lie within the statistical "noise" of the presumed correlation and require no necessary deformation of the forearc belt to explain.

By contrast, observations within the Vava'u Group and the Kotu subgroup of Ha'apai require net forearc subsidence since mid-Holocene time at rates (c. 0.5 mm/yr) sufficient to counteract the effects of the post-mid-Holocene decline in local relative sea level. Observations within the Ha'apai Group jointly suggest the hypothesis that its three blocks (Nomuka, Kotu, Hahake) are foundering differentially, with the Kotu block and western parts of the tilted Hahake block subsiding while the Nomuka block and the high eastern rim of the Hahake block maintain position (Figure 3). The slightly lesser mean emergence observed for mid-Holocene paleoshoreline notches in the Nomuka and Hahake subgroups, in relation to comparable features on Tongatapu and ‘Eua (2.0–2.1 m vs 2.2–2.6 m), could mean that even relatively highstanding parts of the Ha'apai Group have subsided somewhat relative to the Tongatapu block during Holocene time (<0.1 mm/yr).

**Archaeological Implications**

The settlement of Tonga by peoples representative of the Lapita cultural complex was accomplished no later than 3000 yrs ago. The locations of early settlements were highly selective, with Lapita hamlets situated on sandy beaches of leeward coasts facing extensive reef flats or lagoons. The concentrated presence of sea-turtle bone in many of the oldest archaeological horizons suggests that initial settlements may have been chosen near turtle nesting grounds (DYE and STEADMAN, 1990). A possible exception is the cluster of multiple Lapita sites around the inner shore of Fanga 'Uta La-
KiRCH, SHeTLER, FAIRBANK. 2--4 dates from the Huon R, JR. 1995. Rethinking 2L1U (1988) on m above modern high-tide ly lie well inland from present shorelines, and at elevations significantly above modern beach berms. At the best surveyed Lapita site, Faleloa (DICKINSON et al., 1994; SHULTER et al., 1994) on Foa in the Hahake subgroup (Figures 7–8), the top of the Lapita horizon, which occupies the crest of a mid-Holocene beach ridge, stands at just the height (1.8 m) above the crest of the nearby modern beach berm that would be anticipated from global hydro-isostatic analysis (see above). This correspondence encourages us to surmise that above the crest of the nearby modern beach berm that would be anticipated from global hydro-isostatic analysis (see above). This correspondence encourages us to surmise that exploration for Lapita and related archaeological sites elsewhere in Tonga, and in the South Pacific region generally, should be conducted with guidance from hydro-isostatic theory to gauge the expected positions of paleoshorelines. Observations by others (ROGERS, 1975; KIRCH, 1988) on Niutatoputapu (Figure 2), well north of our study area, are relevant for paleoshoreline interpretations in Tonga as a whole. Finds of Lapita pottery dating to c. 3000 years ago are confined to a paleoshoreline that encircles Niutatoputapu at an elevation 3–5 m above the modern fringing reef flat. Allowing for the tidal range in Tonga, this locus of mid-Holocene settlement stands c. 2–4 m above modern high-tide level at an elevation comparable to that of Lapita sites in the Hahake subgroup closely related to inferred mid-Holocene paleoshorelines. Although the elevated position of the Lapita-age paleo-beach on Niutatoputapu was initially attributed to tectonic uplift of the island, decline in local sea level from a regional hydro-isostatic mid-Holocene highstand now appears to be the most parsimonious explanation. The indicated post-mid-Holocene emergence of Niutatoputapu is comparable to that inferred for Tongatapu, 'Eua, and the main islands of the Hahake subgroup.

It is worthy of note that Niutatoputapu lies along the axis of the volcanic arc and would not be affected by forearc uplift or subsidence. Although tectonic movements affecting the volcanic chain itself cannot be excluded in principle, the similar post-mid-Holocene emergence indicated for Tongan islands of different tectonic character, both near the volcanic axis and well out into the forearc belt, argues circumstantially for a common extrinsic cause. A decline in regional sea level following the mid-Holocene hydro-isostatic highstand is the obvious inference.

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