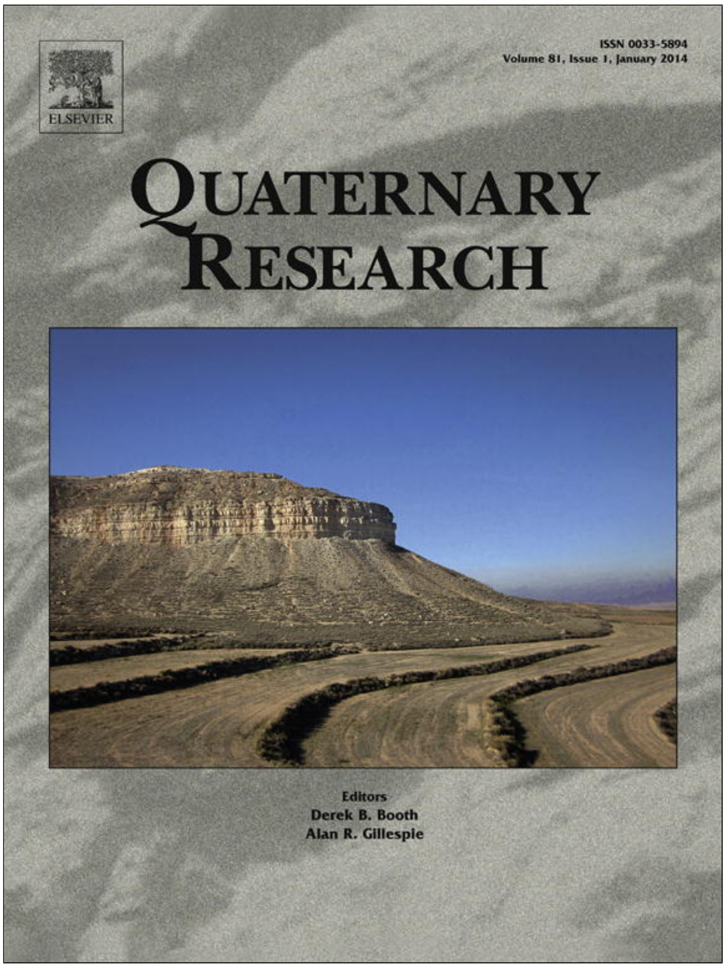
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Sea-level and reef accretion history of Marine Oxygen Isotope Stage 7 and late Stage 5 based on age and facies of submerged late Pleistocene reefs, Oahu, Hawaii

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ABSTRACT

In situ Pleistocene reefs form a gently sloping nearshore terrace around the island of Oahu. TIMS Th–U ages of in situ corals indicate that most of the terrace is composed of reefal limestones correlating to Marine Oxygen Isotope Stage 7 (MIS 7, ~190–245 ka). The position of the in situ MIS 7 reef complex indicates that it formed during periods when local sea level was ~9 to 20 m below present sea level. Its extensiveness and geomorphic prominence as well as a paucity of emergent in situ MIS 7 reef-framework deposits on Oahu suggest that much of MIS 7 was characterized by regional sea levels below present. Later accretion along the seaward front of the terrace occurred during the latter part of MIS 5 (i.e., MIS 5a–5d, ~76–113 ka). The position of the late MIS 5 reefal limestones is consistent with formation during a period when local sea level was below present. The extensiveness of the submerged Pleistocene reefs around Oahu compared to the relative dearth of Holocene accretion is due to the fact that Pleistocene reefs had both more time and more accommodation space available for accretion than their Holocene counterparts.

Introduction

Pleistocene reef formations provide an important record of long-term patterns of reef development, sea-level history and local tectonic and isostatic movements. Not surprisingly, the majority of studies on Pleistocene reefs have focused on emergent deposits elevated above present sea level as a result of either higher sea levels in the past (e.g., the last interglacial period) or local tectonic or isostatic uplift. There has been comparatively much less research on the submerged Pleistocene reef record found on insular and continental shelves. Examining the submerged record is important as it can fill key gaps in the full record resulting in a more complete understanding of late Quaternary reef accretion and sea-level change. In the Hawaiian Islands, detailed studies of submerged Pleistocene reef formations have focused primarily on deep terraces ranging from depths of ~150 to 1200 m around the Big Island of Hawaii (Webster et al., 2009) and along the flanks of the Maui–Nui Complex, which forms the islands of Molokai, Lanai, Maui and Kahoolawe (Faichney et al., 2009, 2011; Webster et al., 2010). These submerged reef systems evolved along subsiding margins, with subsidence caused by lithospheric loading associated with continued volcanism over the Hawaiian hot spot (Faichney et al., 2009, 2011; Webster et al., 2010). While submerged reefs around the island of Hawaii formed over the last 500 ka (Webster et al., 2009), reefs of the Maui–Nui Complex at similar depths are considerably older and range in age from ~0.5 to 1.2 Ma (Webster et al., 2010).

The island of Oahu has been an important locale in Quaternary reef and sea-level studies (e.g., Hearty et al., 2007; Ku et al., 1974; Muhs and Szabo, 1994; Muhs et al., 2002; Szabo et al., 1994; Veeh, 1966). There are two well-documented emergent Pleistocene reefal units on Oahu, the Kaena Formation and the Waimanalo Formation. Both of these units are found island-wide and include an in situ reef framework. There is a broad range of reported ages for the Kaena Formation and it has been variously correlated to Marine Oxygen Isotope Stages (MIS) 11, 13 or 15 (Hearty, 2002a, 2011; McMurtry et al., 2010, 2011; Szabo et al., 1994), though its precise age and MIS correlation remain equivocal. The age of the Waimanalo Formation is well constrained and it is correlated to MIS 5e, the last interglacial period (Ku et al., 1974; Muhs and Szabo, 1994; Muhs et al., 2002; Szabo et al., 1994). Emergent deposits that have been correlated to the intervening highstands between deposition of the Kaena Formation and the Waimanalo Formation (~500 ka to ~125 ka, including MIS 11(?), 9, and 7) are restricted to exposures of coarse carbonate gravels, often interpreted as beach deposits (Brückner and Radtke, 1989; Grigg and Jones, 1997; McMurtry et al., 2010; Szabo et al., 1994). No emergent marine units have been correlated to the intervening period between deposition of the Waimanalo Formation and Holocene reefs (~125 ka to ~8 ka, including MIS 5c, 5a, and 3).

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Sherman et al. (1999) proposed that a nearshore submarine terrace surrounding the island of Oahu is composed mainly of an in situ fossil reef complex formed during MIS 7. They also found evidence for accretion during MIS 5a and 5c. Information regarding these time periods is important on both local and global scales. Globally, the sedimentary database on the timing and position of sea levels associated with MIS 7 (Dutton et al., 2009; Gallup et al., 1994; Muhs et al., 2002, 2011, 2012) 5c, and 5a (Bard et al., 1990; Cutler et al., 2003; Dorale et al., 2010; Gallup et al., 1994; Ludwig et al., 1996; Muhs et al., 2002; Potter et al., 2004; Toscano and Lundberg, 1999; Vacher and Hearty, 1989; Wehmiller et al., 2004) is relatively sparse in comparison to that of MIS 5e. On a local scale, the age and position of additional fossil reefal units on Oahu are important to our understanding of Quaternary reef development, coastal evolution and island tectonics. Here, we present the results of sedimentologic and geochronologic studies of additional cores from the nearshore submarine terrace around Oahu that greatly expand upon our previous results (Sherman et al., 1999) and further document a proposed Pleistocene reefal unit on Oahu, the Waianae Reef (Fletcher et al., 2008; Sherman, 2000). In addition, we discuss the significance of these findings and their implications on our understanding of late Quaternary reef development and sea-level history of Oahu.

Study area

Oahu (21°27′ N, 158° W) is a high volcanic island within the ~6000-km-long Hawaii–Emperor island-seamount chain that spans over 30° of latitude across the Central and North Pacific Ocean (Clague and Dalrymple, 1987). The island is composed mainly of the remnants of two great shield volcanoes, the Koolau Range (~2.6 Ma) and the Waianae Range (~3.7 Ma) (Clague and Dalrymple, 1987). Although dominated by Tertiary volcanics, Quaternary shallow-marine and eolian carbonates also constitute an important aspect of Oahu's geology occurring as a thick cap along the flanks of the extinct volcanoes. Geophysical investigations (Watts and ten Brink, 1989) and analyses of emergent Pleistocene limestones (Grigg and Jones, 1997; Hearty et al., 2000, 2007; McMurtry et al., 2010; Muhs and Szabo, 1994; Szabo et al., 1994) suggest that the island has been undergoing gradual uplift during the late Quaternary. This uplift is attributed to lithospheric flexure associated with volcanic loading and subsidence at the still volcanically active Big Island of Hawaii. Elevations and radiometric ages of emergent reefal limestones indicate that Oahu has experienced nearly 30 m of uplift since ~500 ka at an average rate of 0.02 to 0.06 m per 1000 yr (Grigg and Jones, 1997; Hearty et al., 2000, 2007; McMurtry et al., 2010; Muhs and Szabo, 1994; Szabo et al., 1994).

The shallow bathymetry of Oahu is characterized by a stepped topography consisting of broad shelves separated by steep eroded scarps that bear intertidal notches and other erosional features typically associated with former shorelines (Coulbourn et al., 1974; Fletcher and Sherman, 1995; Stearns, 1974). The present research has focused on the shallowest of these terraces that dips gently seaward from the shoreline out to the ~−20 m contour, where there is a sharp break in slope down to ~−30 m, at the depth of a deeper terrace. The study areas lie on the leeward (western) side of Oahu between Maili and Kepuhi Points and on the windward (eastern) side outside of Kaneohe Bay (Fig. 1). The nearshore terrace is particularly well defined in these areas. The seafloor at these sites consists of well-lithified limestone with a thin veneer of loose carbonate sand and a sparse, patchy distribution of coral and coralline algal growth. This study focuses on cores recovered from the seaward margin of the terrace in these two areas.

Methods

Cores were collected via a diver-operated Tech 2000 submersible, hydraulic, rotary, coring drill with a 7.6 cm diameter diamond studded bit. Recovered limestones were classified according to Dunham's (1962) scheme as modified by Embry and Klovan (1971). The cores were sampled for radiometric and petrographic analyses, taking care that each facies within a core was sampled. The 'absolute' ages of fossil corals were determined using the ^{230}Th–^{234}U–^{238}U technique at the University of Hawaii SOEST Isotope Lab and at the U.S. Geological Survey, Denver, Colorado. Sample chips were ultrasonically cleaned in ultra-pure reagents and powdered. Mineralogy of coral samples was determined with a Scintag Pad V powder X-ray diffractometer (XRD) with a solid state Ge detector using Cu Kα radiation. Only those samples with <3% calcite were dissolved for Th and U isotopic analyses and spiked with ^{229}Th and ^{233}U. Techniques for Th and U isotopic analyses of corals in the SOEST Isotope Lab are described in Rubin et al. (2000). Total procedural blanks for this chemistry were 1–5 pg U and 5–10 pg Th. Techniques for Th and U isotopic analyses of corals at the U.S. Geological Survey laboratory are described in Ludwig et al. (1992).

Following earlier workers (e.g., Muhs et al., 2002, 2012; Stirling et al., 1998), we use the following criteria to assess the reliability of Th–U ages of Pleistocene corals: (1) little or no evidence of recrystallization of coral skeletal aragonite to calcite as determined by XRD and petrography, (2) U concentrations similar to those in modern corals (~3 ppm (3000 ng/g), cf. Stirling et al., 1998), (3) low concentrations of Th (^{232}Th <1 ppb (1000 pg/g), cf. Stirling et al., 1998) indicating the presence of little or no inherited ^{230}Th, and (4) ^{230}Th-age-corrected ^{234}U/^{238}U (i.e., initial ^{234}U/^{238}U or $\delta^{234}U_i$) values similar to those of modern seawater (δ^{234}U of ~140–155‰; cf. Delanghe et al., 2002; Muhs et al., 2012). Th–U ages of samples that meet these conditions are considered reliable to a first order (shown in bold type in Table 1). Open-system processes can produce notable shifts in sample ages due to recoil redistribution of radionuclides and surface adsorption/desorption effects (Thompson et al., 2003; Villemant and Feuillet, 2003). The potential effects of such processes are discussed below.

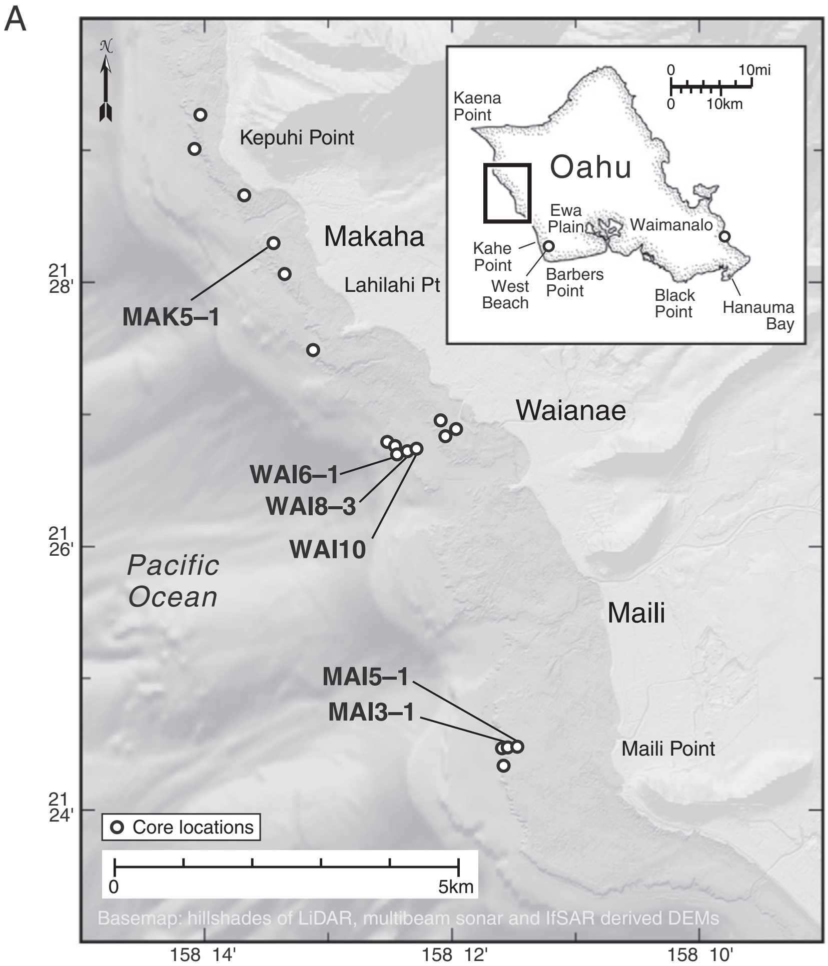
Character, distribution and paleobathymetry of Pleistocene facies

Overview of Pleistocene facies

All limestones sampled are typical of tropical, shallow-marine, reef environments. Skeletal components of these limestones are shallow marine in origin and include coralline algae, coral, mollusks, echinoderms and benthic foraminifers. No deep marine sediments or microfossils (e.g., planktonic foraminifera) were recovered. Terrigenous input is limited to rare volcanic clasts, grain and void coatings of iron-rich clay material and diagenetic products associated with subaerial exposure of carbonate sediments (Sherman et al., 1999). In this and previous coring studies of the Oahu shelf (Sherman et al., 1999), we have identified four distinct Pleistocene facies, a massive-coral facies, branching-coral facies, encrusting-coral facies and encrusting-algae facies. Facies are identified on the basis of their dominant skeletal component and fabric and each includes both an autochthonous (in situ) and allochthonous component. Each facies represents a different depositional environment within a reef complex and may be arranged in order of increasing depositional energy, e.g., the branching-coral facies, massive-coral facies, encrusting-coral facies, and encrusting-algae facies (Fig. 2). The distribution of facies across the nearshore terrace is shown in Figure 3. Paleoenvironmental interpretation of facies with respect to depth and wave energy is shown in Figure 4. Interpretations are based upon the paleoecologic and sedimentologic characteristics of each facies, including dominant skeletal component and growth form, texture and fabric as well as its distribution across the terrace and relationship to adjacent facies.

Branching-coral facies

The branching-coral facies consists of in situ bafflestones and allochthonous floatstones and wackestones formed by delicate branching corals and coralline algae set in a lime–mud matrix. Its mud-supported



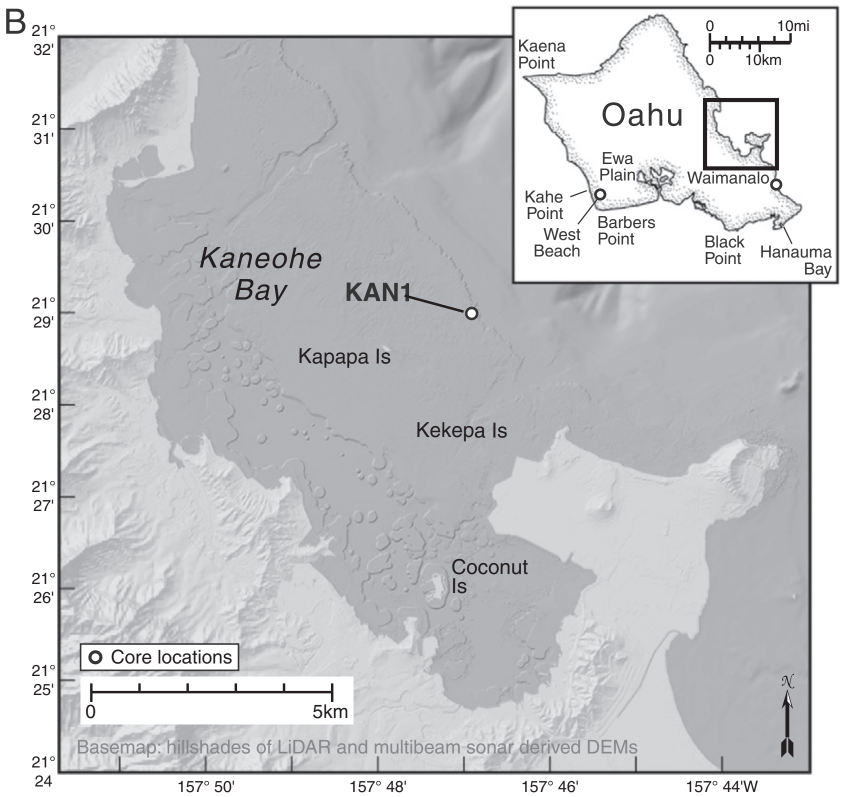


Figure 1. Location maps showing coring sites along leeward (A) and windward (B) Oahu.

Table 1
Uranium and thorium isotopic compositions and ^{230}Th ages of submerged Oahu corals[a]. Samples that meet all closed-system criteria and, therefore, considered to yield reliable ages are shown in bold type.

Sample	Depth[b] (m)	U (ng/g)	Th (pg/g)	^{232}Th/^{238}U (atomic ratio)	[^{230}Th/^{238}U] activity	Age (ka)	δ^{234}U measured[c]	δ^{234}U initial[c]	Open-system age[d] (ka)
MIS 5									
WAI10-S2[e]	**25**	**3470 ± 10**	**186.0 ± 0.4**	**5.540 ± 0.019**	**0.6913 ± 0.0034**	**104.6 ± 1.1**	**107.4 ± 4.3**	**144 ± 6**	105 ± 3.2
WAI10-S3[e]	**26**	**3209 ± 9**	**39.8 ± 0.2**	**1.283 ± 0.007**	**0.7132 ± 0.0034**	**110.3 ± 1.1**	**106.4 ± 3.4**	**145 ± 5**	110 ± 2.7
WAI8-3S1A[e,f]	**27**	**2709 ± 7**	**77.5 ± 0.3**	**2.957 ± 0.016**	**0.6658 ± 0.0047**	**97.0 ± 1.2**	**116.0 ± 2.9**	**153 ± 6**	94 ± 2.1
WAI6-1S1[e,f]	**30**	**3100 ± 8**	**257.7 ± 0.8**	**8.591 ± 0.034**	**0.6011 ± 0.0028**	**83.0 ± 0.7**	**116.5 ± 3.4**	**147 ± 4**	82 ± 2.1
MIS 7									
MAI5-1S1[e,f]	**10**	**2779 ± 7**	**82.0 ± 0.3**	**3.048 ± 0.013**	**0.9541 ± 0.0049**	**223.7 ± 4.3**	**75.8 ± 2.7**	**143 ± 5**	225 ± 5.5
MAI5-1S2[e,f]	10	2720 ± 7	577.8 ± 1.6	21.954 ± 0.083	0.9881 ± 0.0046	247.5 ± 5.3	80.2 ± 3.0	161 ± 6	239 ± 6.4
MAI3-1S4[e,f,g]	**13**	**2885 ± 7**	**96.8 ± 0.2**	**3.466 ± 0.012**	**0.9437 ± 0.0046**	**209.1 ± 3.6**	**85.8 ± 2.8**	**155 ± 5**	204 ± 4.6
MAI3-1S5[e,f,g]	**13**	**2969 ± 8**	**121.2 ± 0.3**	**4.218 ± 0.015**	**0.9354 ± 0.0043**	**204.0 ± 3.5**	**85.6 ± 2.9**	**152 ± 5**	200 ± 4.5
KAN1-S1[e]	**18**	**2850 ± 7**	**30.2 ± 0.2**	**1.096 ± 0.007**	**0.9820 ± 0.0042**	**249.4 ± 4.8**	**73.1 ± 2.4**	**148 ± 5**	248 ± 5.7
KAN4-1S4[h]	17	2650 ± 3	<100	1.645 ± 0.041	0.9531 ± 0.0025	210.5 ± 2.1	91.4 ± 1.8	166 ± 3	201 ± 2.8
KAN4-1S5[h]	17	2760 ± 3	<100	6.820 ± 0.022	0.9888 ± 0.0024	239.4 ± 2.8	88.0 ± 2.0	174 ± 3	225 ± 3.7
KAN4-2S2[h]	18	2665 ± 3	<100	2.475 ± 0.033	0.9579 ± 0.0023	213.7 ± 1.8	91.6 ± 1.4	168 ± 2	203 ± 2.2
KAN4-2S5[h]	18	2655 ± 3	<100	2.960 ± 0.01	0.9571 ± 0.0022	211.9 ± 2.0	93.2 ± 2.0	170 ± 3	200 ± 2.9
Highly compromised									
WAI10-S4[e]	27	3435 ± 9	143.9 ± 0.4	4.329 ± 0.017	0.8723 ± 0.0045	152.5 ± 1.9	133.7 ± 3.0	206 ± 5	127 ± 2.8
WAI10-S5[e]	28	2921 ± 7	129.4 ± 1.1	4.579 ± 0.040	0.8863 ± 0.0059	158.1 ± 2.5	132.6 ± 2.6	207 ± 4	132 ± 2.8

[a] Activities are calculated using the following: $\lambda_{230} = 9.1577 \times 10^{-6}$ yr^{-1} (Cheng et al., 2000), $\lambda_{234} = 2.8263 \times 10^{-6}$ yr^{-1} (Cheng et al., 2000), and $\lambda_{238} = 1.551 \times 10^{-10}$ yr^{-1} (Jaffey et al., 1971). Analyses conducted on 0.2 to 0.3 g of material. Data are corrected for procedural blanks (<6 pg each for Th and U). Reported errors are 2σ and include errors in λ values where applicable.
[b] Depth = water depth + depth in core.
[c] δ^{234}U = [^{234}U/^{238}U activity ratio − 1] × 1000.
[d] Open-system ages calculated using the model of Thompson et al. (2003).
[e] Analyses done at the University of Hawaii.
[f] Data from Sherman et al. (1999) recalculated for new lambdas.
[g] Data from Sherman et al. (1999) corrected for spike weight errors.
[h] Analyses done at the USGS, Denver, Colorado. Calculated ages include a small correction for initial detrital Th and U with assumed activity ratios for ^{234}U/^{238}U, ^{230}Th/^{238}U, and ^{232}Th/^{238}U of 1.0 ± 0.3, 1.0 ± 0.3, and 1.21 ± 0.64, respectively. Data reported are averages of each parameter measured in duplicate, except for KAN4-1S5, where spread was much larger, so only the more realistic of the two duplicates is reported.

fabric and the dominance of delicate branching corals differentiate this facies from all of the others. Branching corals, e.g., *Pocillopora damicornis*, and coralline algae in upright growth position form the in situ bafflestones. The floatstones and wackestones consist of skeletal grains and peloids supported by a lime–mud matrix. Fragments of branching corals and coralline algae are the dominant skeletal grains, but mollusk, foraminifer, and echinoderm fragments are also common. Grains account for only about 10–20% of these limestones. Lime–mud matrix accounts for the remaining portions. Boring, micritization and micrite envelopes are common. Sherman et al. (1999) found the branching-

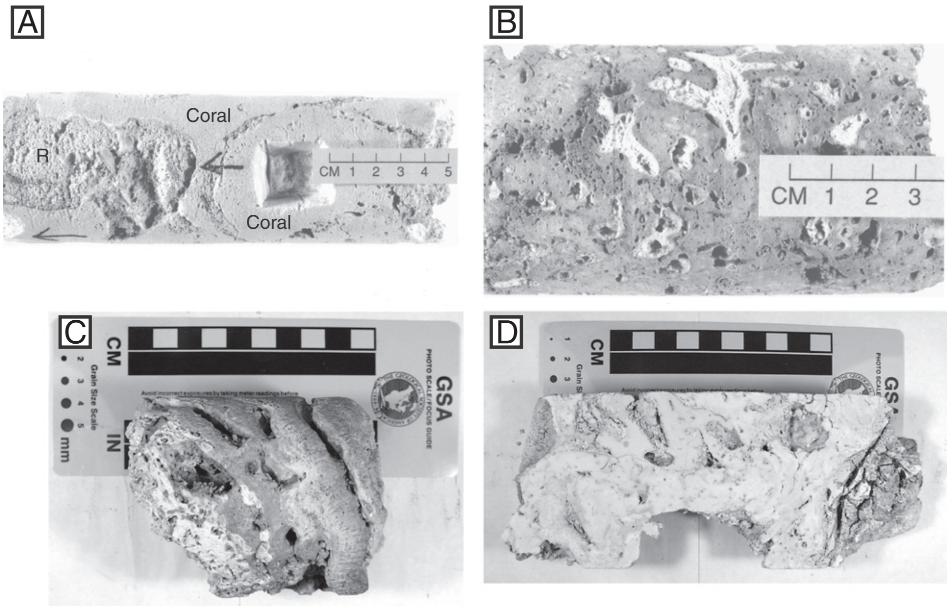


Figure 2. Pleistocene reef facies found in the nearshore terrace. (A) Massive-coral facies composed of in situ framework of massive corals (*Porites lobata*) and a skeletal rudstone (R) filling framework voids. (B) Branching-coral facies composed of delicate-branching corals (*Pocillopora damicornis*) in a lime–mud matrix. (C) Encrusting-coral facies composed of encrusting-coral (*Montipora*, *Cyphastrea*, and *Porites*) bindstone and rudstone. (D) Encrusting-algae facies composed of in situ framework of encrusting coralline algae (*Porolithon* (*Hydrolithon*) *onkodes*).

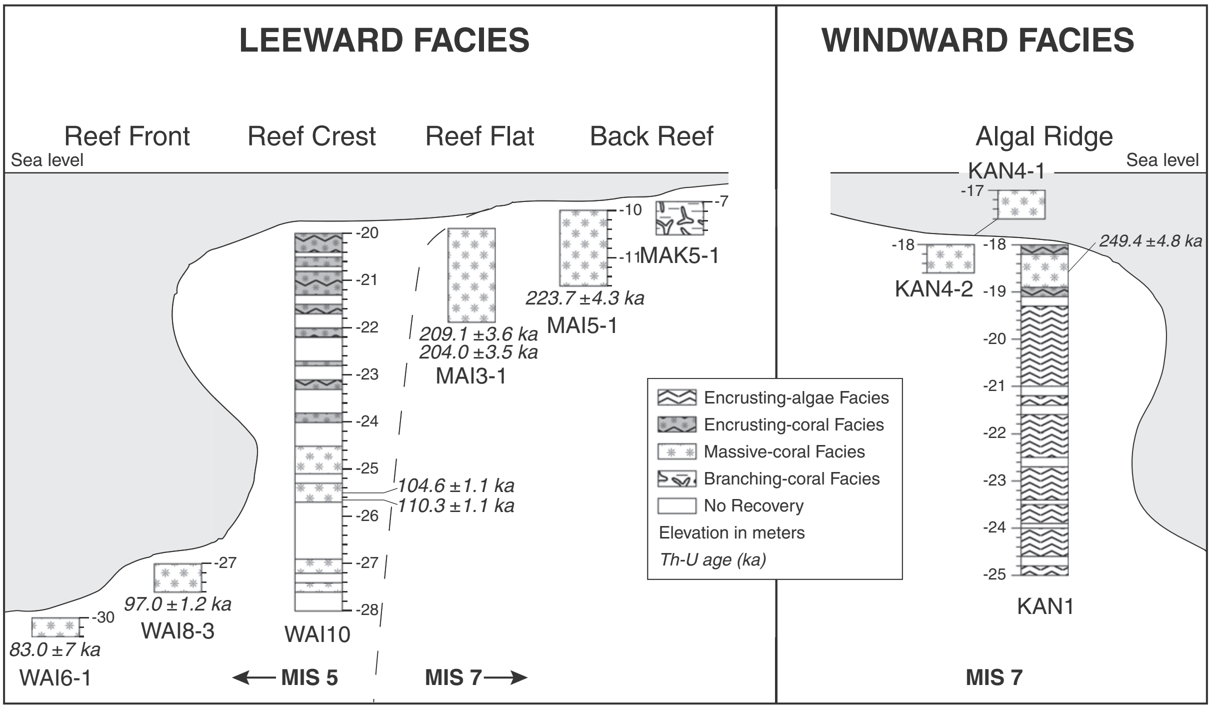


Figure 3. Results of coring showing distribution of Pleistocene reef facies. Depth in meters given on the side of cores. Reliable Th–U ages (ka) of fossil corals shown below or alongside of core where available.

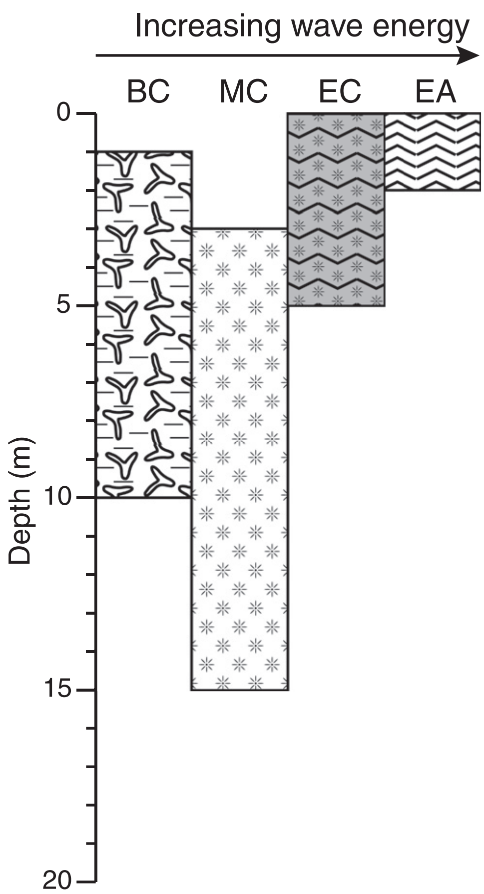


Figure 4. Schematic representation of paleoenvironmental interpretation of Pleistocene reef facies with respect to water depth and wave energy. Interpretations are based upon the paleoecologic and sedimentologic characteristics of each facies, as well as its distribution across the terrace and relationship to adjacent facies.

coral facies only along inner portion of the leeward terrace, such as core MAK5-1 in Figure 3.

The principal coral in the branching-coral facies is the delicate branching coral *P. damicornis*. In Hawaii, this coral is most commonly found within protected bays or upon the inner portions of reef flats away from breaking waves (Maragos, 1977). It seems to be strongly light limited and is rarely reported below depths of 10 m (Maragos, 1977). Sherman et al. (1999) found the branching-coral facies only along the inner portions of the terrace landward of the other facies. This facies was not recovered in our new cores at the seaward margin of the terrace. This distribution is consistent with the expected zonation of lithofacies in a marginal reef complex, where bafflestones and floatstones are most common in back-reef environments (James and Bourque, 1992).

Massive-coral facies

The massive-coral facies consists of in situ coral and coralline-algal framestones and bindstones with coarse skeletal grainstones and rudstones infilling framework voids. Massive colonies of the lobe coral *Porites lobata* form the primary framework. Encrusting corals, including *Montipora* sp., and coralline algae form a secondary component of the framework. Outer portions of the *P. lobata* colonies and intraframework cavities are usually encrusted by a combination of micritic crusts and coralline algae. Vermetid gastropods are also common. Coral colonies are moderately bored and also display irregular cm-scale (possibly solutional) vugs. Semi-friable skeletal grainstones to rudstones partially fill intraframework voids. The massive-coral facies is the most common of the facies identified and is found in both windward and leeward terrace settings. Along the seaward margin of the leeward terrace the massive-coral facies constitutes core MAI5-1, most of MAI3-1 the lower 3.5 m of core WAI10, and all of cores WAI8-3 and WAI6-1. At the seaward margin of the windward terrace, the massive-coral facies forms the upper ~1 m of the KAN1 and KAN4 cores (Fig. 3).

P. lobata is the most widespread and common of Hawaiian corals and can occur anywhere from the intertidal zone down to depths of 40 m.

However, *P. lobata* is most common high on wave-exposed reef slopes just below the area of highest wave action between depths of 3 and 15 m (Gulko, 1998; Maragos, 1977). Grigg (1998) showed that *P. lobata* is the dominant frame builder in habitats exposed to high wave energy. In southwest Molokai, Engels et al. (2004) identified *P. lobata* as a dominant coral type within all three depth zones studied (<5 m, 5–10 m and >10 m). Webster et al. (2009) identified a shallow coral reef facies (Facies 1) from the submerged reefs around the island of Hawaii that was characterized by massive *P. lobata* and branching *Porites compressa*. The facies was interpreted as indicative of depths <20 m and likely depths <10–15 m. The dominance of massive corals (*P. lobata*) along with encrusting algae indicates a shallow high-energy environment of deposition (cf. James and Bourque, 1992). The combination of a grainstone and rudstone matrix with in situ framework is also common in high-energy settings (Bosence, 1985). The massive-coral facies is found along the seaward margin of the terrace. This distribution is consistent with the expected zonation of lithofacies in a marginal reef complex, where rudstones and framestones are most common in reef flat, reef crest, and reef front environments (James and Bourque, 1992).

Encrusting-coral facies

The encrusting-coral facies consists mainly of encrusting colonies of *Montipora patula* and *Cyphastrea ocellina*. These corals are found either as in situ bindstones with a semifriable coarse grainstone to rudstone matrix, or as unconsolidated subround to angular, oblate to bladed, pebble-size clasts. The lobe coral *P. lobata* and the crustose coralline algae *Porolithon* (*Hydrolithon*) *onkodes* are secondary framework components. Unconsolidated clasts are generally abraded and coated by some combination of encrusting coralline algae and dense micritic crusts. Intraframework voids within the bindstone sections are also generally coated by micritic crusts and partially filled by internal sediment. The encrusting-coral facies constitutes the upper 4 m of core WAI10 at the seaward margin of the leeward terrace (Fig. 3).

Although *M. patula* can be found from the intertidal zone down past 15 m on modern Hawaiian reefs, it is most frequently found high on the reef slope or in shallow bays with moderate wave action (Gulko, 1998). In southwest Molokai, Engels et al. (2004) identified *M. patula* as a dominant coral type at depths <10 m. *C. ocellina* is usually found nearshore in shallow water, frequently in areas that have moderate wave action. The co-occurrence of these two species and their encrusting morphologies suggests that they grew in a shallow, moderate-energy environment. A secondary framework of *P.* (*H.*) *onkodes* also supports a shallow moderate-energy setting (cf. Adey et al., 1982; Littler and Doty, 1975). Hagstrom (1979) interpreted a similar assemblage of corals in the emergent Waimanalo Reef as representing a high-energy reef edge environment. This facies is also similar to the coral–algal bindstone facies described by Engels et al. (2004), which was interpreted as indicative of a shallow, high-energy setting.

Encrusting-algae facies

The encrusting-algae facies consists of a dense, well-lithified, in situ bindstone, composed mostly of the encrusting crustose coralline algae *P.* (*H.*) *onkodes* (cf. Adey et al., 1982), along with a coarse grainstone to rudstone matrix. The crustose coralline alga *Tenarea tessellatum* is also common. Encrusting forms of the corals *C. ocellina* and *P. lobata* and the densely branched coralline algae *Porolithon* (*Hydrolithon*) *gardineri* form a secondary component of the bindstone framework. The corals and coralline algae are in growth position. They are right side up and within ~30° of vertical. Micritic crusts, both laminar and knobby, are common either as laminae within the bindstone or, more conspicuously, as dense coatings on intraframework voids (cf. Sherman et al., 1999). In some cases, large, rounded, skeletal clasts are incorporated into the bindstone framework. The grainstone to rudstone matrix is generally semi-friable and composed of abraded skeletal clasts including framework components (algae, coral) as well as mollusks (e.g., bivalves, and the gastropod *Turbo sandwicensis*) and locally abundant spines of the pencil urchin *Heterocentrotus mammillatus*. Clasts are angular to rounded and usually heavily encrusted by algae and/or micritic crusts. The encrusting-algae facies forms a massive in situ framework at the seaward margin of the windward terrace (Core KAN1, Fig. 3). Although recovery was not continuous, over an ~6 m interval in the KAN1 core, only the encrusting-algae facies was recovered.

Because the distribution of many species of coral and coralline algae is largely governed by light levels and wave energy (i.e., water depth) fossil reef assemblages can serve as reliable paleoecologic indicators for the Quaternary (cf. Adey, 1986; Cabioch et al., 1999). Studies by Littler and Doty (1975) on Hawaiian algal ridges showed that *P.* (*H.*) *onkodes* and *P.* (*H.*) *gardineri* dominate the seaward margin of the reef. *P.* (*H.*) *gardineri* dominates subtidal portions of the crest. *P.* (*H.*) *onkodes* dominates intertidal portions of the ridge crest, inshore flat, and seaward front. Algal ridges are common at the seaward margin of reefs throughout the central and eastern Pacific wherever there is a consistent and strong swell pattern (Doty, 1974). Encrusting coralline algae predominate in such settings because they are physically able to withstand high wave energy and because they have a high tolerance to the light levels found in shallow water (Bosence, 1983). Also, the high wave energy minimizes both grazing by fish and invertebrates as well as overgrowth by fleshy algae. The massive nature of the in situ *P.* (*H.*) *onkodes* framework in core KAN1 strongly suggests a very shallow water environment, within ~1 m of mean low water (Adey et al., 1982). The abundance of pencil urchin (*H. mammillatus*) spines and the encrusting morphology of associated corals are also consistent with a shallow reef flat to reef crest setting (cf. Doty, 1974; James and Bourque, 1992). In addition, the location of core KAN1 at the windward margin of the terrace is consistent with the expected location of an algal ridge.

An analogous Holocene feature may be the fringing reef in Hanauma Bay, which has an algal ridge at its seaward margin (Easton and Olson, 1976). In a seaward transect across the reef, corals were most abundant in lower portions of cores. Coralline algae was dominant in the upper portions of the cores, presumably as the reef approached (i.e., caught up with) sea level. Within the Hanauma Reef cores, the ~5–6 m interval dominated by coralline algae represents about 2000 to 3000 yr of growth (Easton and Olson, 1976). Thus, the ~6 m interval of the encrusting-algae facies in the KAN1 core may represent a similar amount of time.

Th–U ages of fossil corals

Absolute ^{230}Th–^{234}U–^{238}U ages of nine fossil corals of the species *P. lobata* were determined from high-precision TIMS isotopic composition analyses at the University of Hawaii (UH) and at the USGS in Denver, Colorado. Results are shown in Table 1 and Figure 5, along with TIMS data on six fossil corals from Sherman et al. (1999) for which ages have been recalculated using the ^{234}U and ^{230}Th half-lives of Cheng et al. (2000) and in some cases corrected for previously unrecognized spike weight errors. Ages from Sherman et al. (1999) are also of fossil *P. lobata*. From this combined data set of fifteen corals, eight meet the closed system criteria described in the Methods section and may be considered to have reliable ages (shown in bold type in Table 1). All dated corals are >97% aragonite as determined by XRD, display primary aragonitic skeletal structure both in hand sample and thin section and show no signs of recrystallization, dissolution, or internal sediments. They contain between 2650 and 3470 ng/g U, which is similar to the range of modern Hawaiian corals (2680 to 2830 ng/g; Szabo et al., 1994) and other fossil Hawaiian corals (2180–3010 ng/g) considered as having reliable ages (cf. Hearty et al., 2007; Muhs et al., 2002). Th concentrations are low (typically <260 pg/g) indicating the presence of little or no inherited ^{230}Th. Detrital Th corrections assuming local

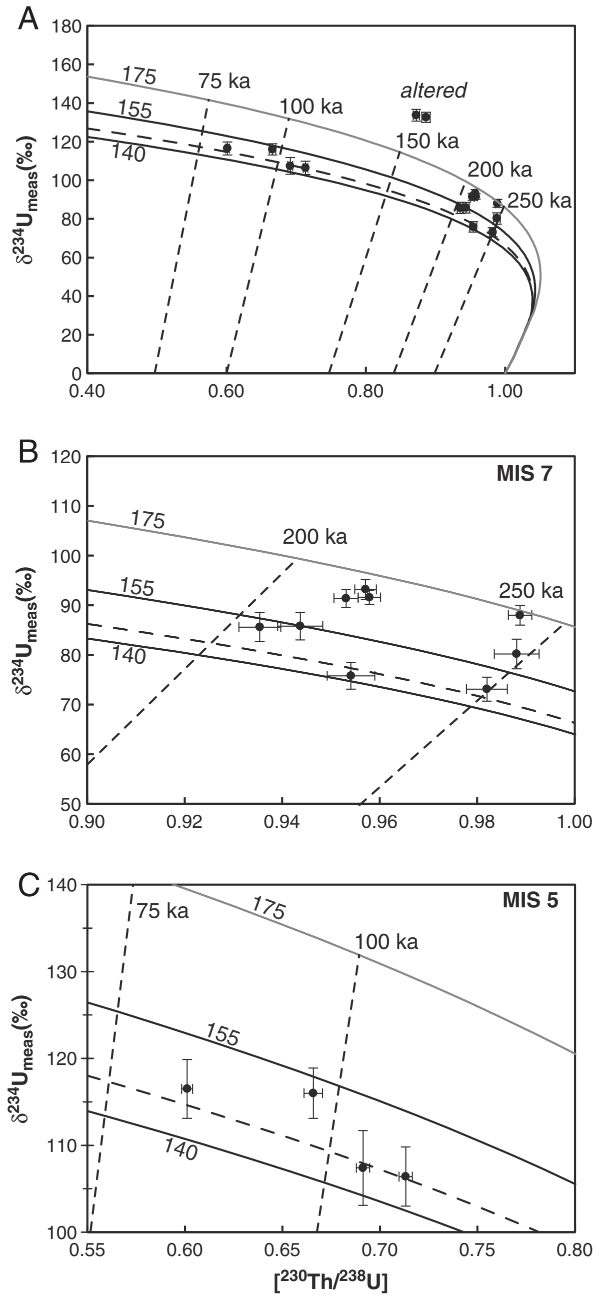


Figure 5. Plot of measured $\delta^{234}U$ versus $^{230}Th/^{238}U$ activity ratio of submerged Oahu corals. $\delta^{234}U$ is the per mil deviation of the $^{234}U/^{238}U$ activity ratio from secular equilibrium. Curved lines are hypothetical isotopic evolution pathways for corals with initial $\delta^{234}U$ ($\delta^{234}U_i$) values of 140‰ (solid black), 145‰ (dashed black), 155‰ (solid black) and 175‰ (solid gray). Dashed diagonal lines are contours of $^{230}Th–^{238}U$ age. The curve for $\delta^{234}U_i$ = 145‰ corresponds to the modern marine value. Data that plot within the range of 140–155‰ are considered reliable ages to a first order (see Methods). Data that plot beyond 175‰ are considered as highly unreliable due to open-system behavior. Error bars represent combined 2σ analytical errors and half-life errors. (A) Entire data set of submerged Oahu corals. (B) MIS-7-age corals. (C) MIS-5-age corals.

volcanic rock compositions are negligible and were therefore not employed for the UH analyses. $\delta^{234}U_i$ values of the closed-system corals range from ~143 to 155‰ (Fig. 5).

As noted above, open-system processes can shift $^{230}Th–^{234}U–^{238}U$ ages to erroneous values. Application of the Thompson et al. (2003) model results in downward age shifts of <1 to ~6% for all but the two corals identified as "highly compromised" in Table 1 (these two samples shift by 16%). Of the eight samples that meet closed-system criteria, five have open- and closed-system ages that agrees to within 1% and the remaining three agree to within 3%, lending further support to the reliability of these ages. Aside from the two highly compromised corals, the open-system age shifts do not change Marine Oxygen Isotope Stage assignments and thus our interpretations of the ages. However, the implications of open-system model results for substage assignments are discussed further below. Notably, the two highly compromised, very altered samples have similar and extremely elevated $^{234}U/^{238}U$ that imply a $^{234}U–^{238}U$ age of just 30 ka, while closed-system $^{230}Th–^{238}U$ ages are 160 ka. Application of the Thompson et al. model returns MIS 5e open-system ages of these two samples, although the extreme nature of the alteration makes this result suspect, so we do not draw conclusions based on these ages in this paper.

Corals that meet all criteria for reliable closed-system U-series histories fall into two age groups: an older group that ranges in age from 204.0 ± 3.5 to 249.4 ± 4.8 ka, and a younger group that ranges from 83.0 ± 0.7 to 110.3 ± 1.1 ka. All sample ages confirm a Pleistocene age for the fossil reefs that constitute the nearshore terrace. Importantly, no Holocene coral samples were recovered in any of the cores. The older group of corals correlates to MIS 7 (Fig. 6; cf. Henderson et al., 2006; Thompson and Goldstein, 2006; Rohling et al., 2009, 2010). The oldest coral of this group comes from core KAN1 collected at the seaward margin of the terrace on the windward side of Oahu and has an age of 249.4 ± 4.8 ka ($\delta^{234}U_i$ = 148 ± 5‰), which corresponds to the timing of the highstand associated with MIS 7e (Dutton et al., 2009). Corals from adjacent cores KAN4-1 and KAN4-2 all have elevated $\delta^{234}U_i$ values (166 ± 3‰ to 174 ± 3‰), indicating probable bias to older ages (Muhs et al., 2012 and references therein). Closed-system ages of these corals range from 210.5 ± 2.1 to 239.4 ± 2.8 ka correlating to the timing of MIS 7 (Dutton et al., 2009). The largest age shifts predicted by the Thompson et al. (2003) open-system model are ~10–15 ka for the KAN4-1 and KAN4-2 corals, supporting their correlation to the latter part of MIS 7 (7a to 7d).

Ages of corals from cores MAI3-1 and MAI5-1 on the leeward side of Oahu were previously reported in Sherman et al. (1999). These data are reported here again with recalculated ages reflecting new half-lives for ^{234}U and ^{230}Th (Cheng et al., 2000) and in the case of samples MAI3-1S4 and MAI3-1S5 corrected for previously unrecognized spike weight errors. Both of these cores were recovered from the inner portion of the terrace. A coral from core MAI5-1 yields a reliable age of 223.7 ± 4.3 ka ($\delta^{234}U_i$ = 143 ± 5‰), correlating to the timing of MIS 7d (Dutton et al., 2009). A second coral from this core has an elevated $\delta^{234}U_i$ value of 161 ± 6‰ and age of 247.5 ± 5.3 ka (MIS 7e). Recalculating these data using the Thompson et al. (2003) model shifts the age to ~238 ka, still correlating to MIS 7e. Core MAI3-1 yielded two corals with reliable ages of 209.1 ± 3.6 ka ($\delta^{234}U_i$ = 155 ± 5‰) and 204.0 ± 3.5 ka ($\delta^{234}U_i$ = 152 ± 5‰), correlating to the timing of MIS 7c and 7b, respectively (Dutton et al., 2009).

Corals in the younger age group were all recovered from the seaward margin of the terrace on the leeward side of Oahu (cores WAI6-1, WAI8-3 and WAI10). Corals from this group range in age from 83.0 ± 0.7 to 110.3 ± 1.1 ka, correlating to the latter part of MIS 5, substages 5a to 5d (Fig. 6; cf. Rohling et al., 2009, 2010). Two corals from core WAI10 collected at the terrace edge have reliable closed-system ages of 110.3 ± 1.1 ka ($\delta^{234}U_i$ = 145 ± 5‰) and 104.6 ± 1.1 ($\delta^{234}U_i$ =144 ± 6‰), which correlate most closely to the timing of MIS 5d and early 5c, respectively (cf. Cutler et al., 2003; Dorale et al., 2010; Potter et al., 2004). Two other corals from core WAI10 (noted as "highly compromised" in Table 1) have $\delta^{234}U_i$ in excess of 205‰ and, thus, have clearly unreliable ^{230}Th-ages. Corals recovered from just seaward of the terrace front in cores WAI8-3 and WAI 6-1 (previously reported in Sherman et al., 1999) have reliable closed-system ages of 97.0 ± 1.2 ka ($\delta^{234}U_i$ = 153 ± 6‰) and 83.0 ± 0.7 ka ($\delta^{234}U_i$ = 147 ± 4‰) and correlate most closely to the timing of late MIS 5c and MIS 5a, respectively (cf. Cutler et al., 2003; Dorale et al., 2010; Potter et al., 2004).

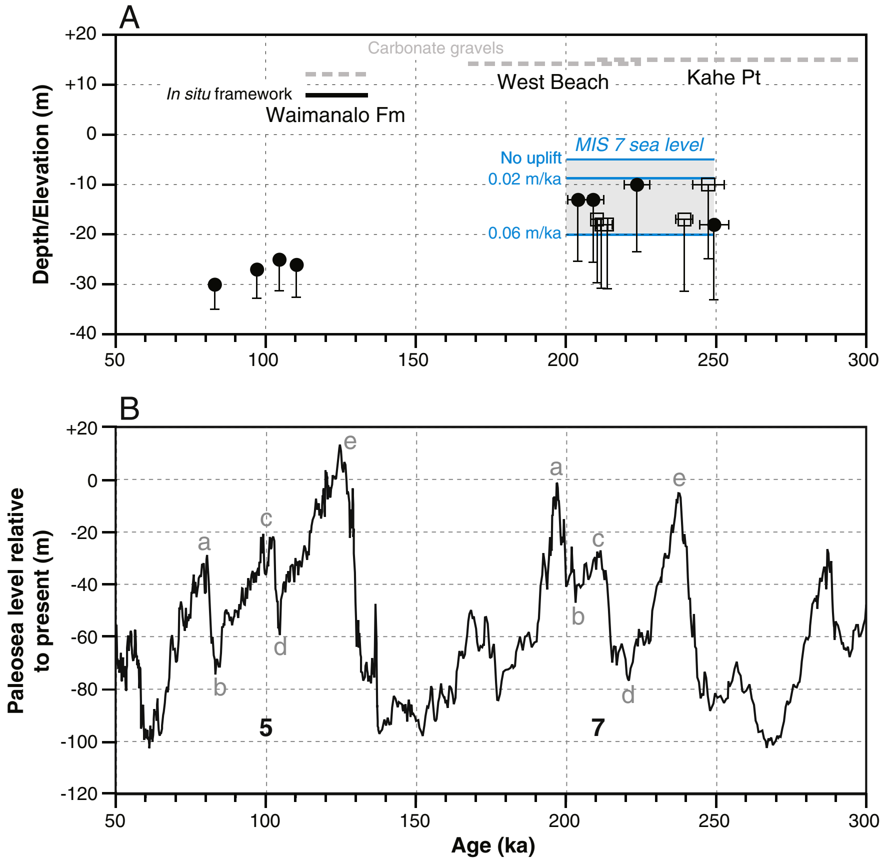


Figure 6. (A) Plot of age versus depth of submerged Oahu corals. Solid circles are reliable ages of corals that meet all criteria for closed-system histories. Open squares are less reliable ages of corals that did not meet all closed-system criteria, most notably $\delta^{234}U_i$ values in excess of 155‰. Highly compromised samples (Table 1) with $\delta^{234}U_i$ values in excess of 175‰ are not displayed in this figure. Vertical error bars indicate range of uplift correction. Black and gray horizontal lines show age and elevation of the emergent MIS-5e Waimanalo Formation (Muhs and Szabo, 1994; Muhs et al., 2002) and possible MIS-7 deposits at West Beach (Grigg and Jones, 1997) and Kahe Point (Brückner and Radtke, 1989). Solid black line indicates in situ reef framework. Dashed gray lines indicate carbonate gravels. Solid gray rectangle indicates range of proposed MIS-7 sea level based on the age, position and paleoenvironmental interpretation of the Waianae Reef. Blue horizontal lines indicate sea level positions with no uplift correction and with corrections for uplift rates of 0.02 m/ka and 0.06 m/ka. (B) The Red Sea relative sea-level record (after Rohling et al., 2009, 2010). Bold numbers below the curve indicate marine isotopic stages. Lowercase gray letters indicate isotopic substages.

Discussion

Timing of reef accretion

Th–U ages of in situ fossil corals indicate that accretion of reefs that form the nearshore terrace occurred during MIS 7 and 5. On the leeward side of Oahu, there is a general trend of decreasing Th–U age of fossil corals moving seaward across the terrace. The shoreward portion of the terrace is composed of reefal material that accreted during MIS 7. Later vertical and lateral accretion occurred along the seaward portions of the terrace during the latter part of MIS 5, substages 5a to 5d. Importantly, reefal units dating to these time periods are not well documented in the emergent Pleistocene record of Oahu. Thus, examination of the accretion history of the nearshore terrace helps to fill these important gaps in the Pleistocene carbonate record of Oahu.

Timing of MIS 7 reef accretion

Sherman et al. (1999) concluded that most of the nearshore terrace was formed by reef accretion during MIS 7. The new TIMS Th–U age data reported here and recalculation of data previously reported in Sherman et al. (1999) supports that conclusion. From the combined data set of Sherman et al. (1999) and this study, four corals of MIS 7 age meet all criteria for closed-system histories and have ages of 204.0 ± 3.5 (MIS 7b), 209.1 ± 3.6 (MIS 7c), 223.7 ± 4.3 (MIS 7d) and 249.4 ± 4.8 ka (MIS 7e). While other corals dated from the same and adjacent cores have elevated $\delta^{234}U_i$ values and, thus, probable bias to older ages, their age range of ~210 to 248 ka still supports an MIS 7 correlation. Additionally, the new data show that the MIS 7 reef is found on both windward and leeward sides of Oahu and extends out and down to the ~−20 m contour on the windward side. In summary, coring on both windward and leeward sides of Oahu has shown that the nearshore terrace consists of in situ reef limestones. Most of these limestones and, therefore, most of the terrace are correlated to MIS 7. It is this in situ MIS 7 reef complex that has been referred to as the Waianae Reef after the locality where it was first examined (Fletcher et al., 2008; Sherman, 2000). Unfortunately, the broad range in Th–U ages of corals from the Waianae Reef makes assigning this unit as a whole to a substage of MIS 7 problematic and, rather, may indicate that it is a complex formed over multiple episodes during MIS 7.

Ages of the MIS 7 Waianae Reef are similar to those determined for MIS 7 reefs at other locales. On Barbados, up to three separate uplifted reef terraces are correlated to MIS 7 (Bender et al., 1979; Schellmann and Radtke, 2004). Based on ESR ages, Schellmann and Radtke (2004) assign these terraces ages of ~222–224 ka. Th–U ages of MIS 7 corals on Barbados determined by Gallup et al. (1994) range from ~193 to 280 ka. However, the majority of these have elevated $\delta^{234}U_i$ values. From this data set, three corals meet closed-system criteria and have ages that range from ~193 to 201 ka, correlating to MIS 7a. On Bermuda, two coral samples from the MIS 7 Belmont Formation have reliable closed-system Th–U ages of ~199 and 201 ka, MIS 7a (Muhs et al., 2002). However, on the basis of field observations and aminostratigraphy, Hearty (2002b) correlates the Belmont Formation to the last interglacial period, MIS 5e. He concludes that the MIS-7 Th–U ages reported for the Belmont Formation represent the age of older reworked cobbles incorporated into the MIS-5e deposits. Corals from the MIS 7 Cortalein unit on Curaçao have ESR ages that range from ~189–226 ka (Schellmann et al., 2004b) and Th–U ages that range from ~190 to 320 ka (Muhs et al., 2012). Th–U ages of older (MIS 7) corals from the Key Largo Limestone in Florida range from ~218 to 262 (Muhs et al., 2011). Unfortunately, in both of these latter cases all samples have elevated $\delta^{234}U_i$ values indicating bias toward older ages. However, plotting these data sets on an isotopic evolution diagram reveals a roughly linear trend that extrapolates toward a closed-system age of ~200 ka, MIS 7a (Muhs et al., 2011, 2012). Vezina et al. (1999) propose an age of ~229 ka for an MIS 7 unit (unit C) within the Ironshore Formation on Grand Cayman based on two Th–U ages of corals of ~226 and 232 ka, both with highly elevated $\delta^{234}U_i$ values. Cores from Mururoa Atoll reveal that MIS 7 is represented by three successive reef units with Th–U ages ranging from ~212 to 264 ka, though most of these samples also have elevated $\delta^{234}U_i$ values and do not meet closed system criteria (Camoin et al., 2001). Those that do meet closed-system criteria have ages of ~212 ka, correlating to MIS 7c. These studies show the broad range of ages reported for MIS 7 reefs as well as demonstrate the difficulty in obtaining corals that meet closed-system criteria and yield reliable ages. Thus, the reliable, closed-system ages reported here represent an important addition to the global data set on the timing of MIS 7 reef accretion.

Timing MIS 5 reef accretion

TIMS Th–U ages of fossil corals reported here and in Sherman et al. (1999) are the first corals on Oahu correlated to late MIS 5 (i.e., post MIS 5e). These corals were collected along the seaward margin of the nearshore terrace on the leeward side of Oahu. The ages range from 110.3 ± 1.1 to 83.0 ± 0.7 ka, corresponding to the timing of MIS 5d to 5a (Fig. 6; cf. Rohling et al., 2009, 2010). All of these samples meet all criteria for closed-system histories. For the most part, these ages do not overlap with any reported ages for emergent reefal deposits on Oahu. A growth position coral from 1 to 3 m above sea level at Kaena Point that yielded an age of 110.5 ka is the youngest sample within the large Szabo et al. (1994) data set. This age is nearly identical to our sample WAI10-S3 collected at ~−26 m (110.3 ± 1.1 ka) and may indicate that some portion of the massive-coral facies at the base of core WAI10 accreted in an offshore environment contemporaneously with deposition of the now emergent MIS 5e Waimanalo reef. However, Szabo et al. (1994) treat this sample as an outlier and restrict the timing of the last interglacial highstand (MIS 5e) to ~131–114 ka. More recently, Muhs et al. (2002) determined new, higher-precision ages of different coral samples from the same Szabo et al. (1994) Oahu localities. These data show a somewhat more restricted range of ages for the Waimanalo Formation, with a youngest age of ~113 ka and most ages between ~125 and ~115 ka. TIMS Th–U ages of fossil corals from the tectonically stable, far-field site of Western Australia indicate that the last interglacial highstand lasted from 128 to 116 ka (Stirling et al., 1998), which corresponds closely to the estimated timing and duration of the highstand based on Oahu data (Muhs, 2002; Muhs et al., 2002; Szabo et al., 1994). Ages of emergent MIS 5e reefs on Curaçao (Muhs et al., 2012) and in south Florida (Muhs et al., 2011) indicate that the last interglacial highstand ended by ~118 ka and 114 ka, respectively. An age of ~110 ka corresponds most closely to the timing of the MIS 5d stadial lowstand (cf. Cutler et al., 2003; Rohling et al., 2009, 2010). Thus, the young (~110 ka) ages reported for the emergent Waimanalo Reef are problematic and the age of our sample reasonable in the context of falling sea level from MIS 5e to 5d.

All of the other Th–U ages of corals from the leeward margin reported here are <110 ka and do not overlap with any reported ages of emergent deposits on Oahu. These corals have ages of 104.6 ± 1.1 ka and 97.0 ± 1.2 ka, which bracket the timing of MIS 5c, and 83.0 ± 0.7 ka, which correlates to MIS 5a (Dorale et al., 2010; Potter et al., 2004; Rohling et al., 2009, 2010). Thus, the nearshore terrace contains an important record of the early transition from interglacial to glacial conditions. Following the nomenclature of Stearns (1974) this late MIS 5 reef unit has been referred to as the Leahi Reef (Fletcher et al., 2008).

Late Pleistocene sea levels on Oahu

MIS 7 sea levels

Previous workers have concluded that over the last 500 ka Oahu has been gradually uplifting at a rate of ~0.02 to 0.06 m/ka (Grigg and Jones, 1997; McMurtry et al., 2010; Muhs and Szabo, 1994; Szabo et al., 1994). This conclusion is based on the age and elevation of emergent marine deposits on Oahu and the general progression of increasing age with elevation. Given the current models of uplift, an MIS 7 reef that formed near present sea level should be found at ~9–12 m above sea level and between the current position of the last interglacial Waimanalo Reef and the much older Kaena Reef. However, the Waianae Reef is situated some 10 to 20 m below the position of the last interglacial (MIS 5e) Waimanalo Reef.

Limited emergent deposits at West Beach (+14 m) and Kahe Point (+15 m) may correlate to MIS 7. However, radiometric and paleoenvironmental data from these deposits are problematic. The deposit at West Beach is described as containing in situ corals by Jones (1993) and as a beach deposit by Grigg and Jones (1997). It is correlated to MIS 7 based on one electron spin resonance (ESR) age of a fossil coral of 196 ± 29 ka. Unfortunately, this locale has been destroyed due to construction of a hotel and no additional descriptions or dating of this deposit exist. The +15 m deposit at Kahe Point is also described as a beach deposit. On the basis of 6 ESR ages and 3 alpha spectrometry $^{230}Th/^{234}U$ ages of fossil corals, Brückner and Radtke (1989) conclude that the Kahe Point unit was deposited in the Upper Middle Pleistocene (ca. 250 ka). The ESR ages range from 215 to 300 ka. $^{230}Th/^{234}U$ ages of three of these samples range from 210 to >243 ka. A fossil coral from bioclastic sand and conglomerate between 9.8 and 11.6 m at Kahe Point was $^{230}Th–^{234}U$ dated at 142 ± 12 ka by Easton and Ku (1981) using alpha spectrometry. Muhs and Szabo (1994) report two alpha spectrometry U-series dates of 120 ± 3 and 134 ± 4 ka for these deposits. Easton and Ku (1981) also reference a personal communication with Ku, who dated a coral taken from a nearby beach conglomerate exposed from 15.8 to 18.9 m above sea level at >350 ka. Szabo et al. (1994) report high-precision TIMS ^{230}Th-ages of five corals from lithified conglomerate at Kahe Point. All have last interglacial ages. Muhs et al. (2002) reanalyzed a *Porites* sample from the collection of Muhs and Szabo (1994) and report an age of ~119 ka. Hearty et al. (2007) determined an MC-ICPMS-U/Th age of ~119 ka for an in situ coral from the Kahe Point deposit at +9 to +10 m, though deemed unreliable due to an elevated $\delta^{234}U_i$ value. A growth position coral from a nearby deposit exposed at +9 to +11 m yielded a reliable MC-ICPMS-U/Th age of ~123 ka (Hearty et al., 2007). Together these data support a last interglacial age for the deposits. Thus, correlation of the West Beach or Kahe Point deposits to MIS 7 is equivocal at best, especially given that all high-precision ages of Kahe Point samples are last interglacial (MIS 5e) age. In addition, none of the 35 fossil corals from Oahu collected between 1 and 24 m above sea level analyzed by Szabo et al. (1994) have ages corresponding to MIS 7.

The Waianae Reef, which constitutes most of Oahu's nearshore terrace, provides a record of reef accretion and, indirectly, local paleosea level during MIS 7. Its current position suggests that it formed during a period when local sea level was below present. Within the Waianae Reef, the position of the in situ coralline algal framework (encrusting-algae facies) in the KAN1 core at the windward margin of the terrace serves as the most reliable indicator of paleosea level. The ecological specificity of coralline alga makes them excellent paleoecologic indicators for the Quaternary (Adey, 1986). Although there is a gap in core recovery between the two facies, the Th–U ages of the KAN/windward corals provide a best estimate for the age of the underlying algal framework and correlate the framework to MIS 7. There is no evidence for an unconformity (e.g. caliche and paleosol) between the algal framework and the overlying corals. The broad range in Th–U ages of the overlying corals precludes correlation of the algal framework to a specific substage within MIS 7. The algal framework is found from ~−25 to −19 m tracking the position, within ~1 to 2 m, of slowly rising sea level over an ~2000 to 3000 yr span within MIS 7. This framework may have been uplifted by ~4 to 5 m, using a lower uplift rate of 0.02 m/ka, or by as much as 11 to 14 m, using an uplift rate of 0.06 m/ka. The upward change in facies from encrusting algae to massive corals in the KAN1 core may represent a relative increase in the rate of sea-level rise. Thus, the position of the algal framework in core KAN1 may indicate the position of sea level during a stadial within MIS 7. The shallowest dated coral from the Waianae reef is from ~−10 m (Sherman et al., 1999). Corrected for uplift, this coral framework likely formed from ~14 to 24 m below the present datum (Fig. 6). Correlative back-reef limestones extend up to ~−6 m (Sherman et al., 1999) suggesting that sea level on Oahu during MIS 7 could have reached ~−5 m (not corrected for uplift). When corrected for uplift, the position of the Waianae Reef suggests that it formed when local sea level was ~9 to 20 m below present. Because of the considerable depth range of extant examples of the corals recovered in cores, all paleosea level estimates presented here should be regarded as minima.

Although uplift rates as high as 0.05–0.06 m/ka have been proposed for Oahu (e.g., Grigg and Jones, 1997; McMurtry et al., 2010; Muhs and Szabo, 1994; Szabo et al., 1994), these high rates rely heavily on accurate dating and paleoenvironmental interpretation of emergent, pre-last-interglacial (pre-MIS 5e) deposits. As discussed above and in Hearty (2011), radiometric ages of these older deposits are often equivocal and unreliable. Additionally, paleoenvironmental interpretations are open to debate. The last interglacial (MIS 5e) Waimanalo Formation is the best documented Pleistocene unit on Oahu and provides the best benchmark for assessing late Quaternary uplift. When compared to last interglacial records from other locales, the position of the Waimanalo Formation supports slower rates of uplift of ~0.02 m/ka (Hearty, 2002a, 2011; Hearty et al., 2000, 2007). This, in turn, supports local MIS-7 sea levels closer to ~9 m below present. Lower than present sea levels during MIS 7 are consistent with marine oxygen isotope records (cf. Lisiecki and Raymo, 2005; Rohling et al., 2009 and Fig. 6). Shackleton (1987) includes MIS 7 among those interglacial stages that did not attain Holocene oxygen isotope values, and, thus, the sea may not have reached its present level. In addition, continental isotope records suggest that the stage 7 interglacial was the coolest of the last four interglacials (Winograd et al., 1997).

Sea-level estimates for MIS 7 based on shallow-marine carbonate records at other locales vary from approximately −20 m to +9 m relative to modern sea level. Records indicating MIS 7 sea levels well below present include cores from Mururoa Atoll (French Polynesia) where MIS 7 sea levels are estimated to have been ~10 to 20 m below present (Camoin et al., 2001). Correlation between the uplifted reef terrace record of the Huon Peninsula, Papua New Guinea and the marine oxygen isotope record suggests MIS 7 sea levels of ~−20 m to near the present level (Chappell and Shackleton, 1986). Similarly, the raised terraces of Barbados suggest MIS 7 sea levels of ~−20 m to +9 m (Gallup et al., 1994; Schellmann and Radtke, 2004). On Curaçao, an island with estimated late Quaternary uplift rates similar to those of Oahu, MIS 7 sea levels are estimated to have been from approximately −3 to +2 m (Muhs et al., 2012). Several records from tectonically stable settings such as Bermuda, south Florida/Florida Keys and Grand Cayman indicate MIS 7 sea levels close to present, within ±2 m (Harmon et al., 1983; Muhs et al., 2002, 2011; Vezina et al., 1999).

The position of the Waianae Reef on Oahu supports lower than present central North Pacific sea levels during much of MIS 7 though does not preclude higher MIS 7 sea levels. However, the paucity of emergent MIS 7 deposits and apparent lack of an emergent in situ MIS 7 reef framework versus the extensiveness and geomorphic prominence of the submerged Waianae Reef make it clear that the principal locus of reef accretion on Oahu during MIS 7 was some 10 to 20+ m below present sea level. This may provide an indication of the structure and relative duration of MIS 7 sea stands. Perhaps maximum sea levels, near the present datum, occurred as short-lived events leaving only scattered beach deposits behind on Oahu. Sea levels below present may have been of much longer duration allowing for formation of the prominent and extensive Waianae Reef.

Detailed investigations of MIS 5 show increasing evidence that this period was more complex than originally thought with rapid, suborbital-period sea-level changes occurring within isotopic substages (e.g., Potter et al., 2004; Hearty et al., 2007). MIS 7 could have been equally complex. Submerged speleothem records from the Mediterranean indicate that MIS 7 consisted of three high sea-level stands at ~249 to 231 ka (MIS 7e), 217 to 206 ka (MIS 7c), and 202 to 190 ka (MIS 7a), each of these rising to above −18 m (Dutton et al., 2009). These records also indicate that sea level remained below −18 m from 231 ka to 202 ka (MIS 7d through 7b) and further constrain that sea level remained between −21 and −18 m from 217 to 202 ka, or throughout MIS 7c and 7b. Thus, the position of the Waianae Reef may reflect the position of these lower sea levels within MIS 7, such that the reef was submerged and accreting over multiple substages. Most records of MIS 7 sea levels close to present sea level converge on an age of ~200 ka or MIS 7a (e.g., Gallup et al., 1994; Muhs et al., 2002, 2011, 2012). The Oahu record suggests that such an excursion to sea levels near present during MIS 7a, if it occurred, was either short lived or otherwise not conducive for reef growth. If an MIS 7a highstand near present was of sufficient duration, perhaps there was not adequate accommodation space for reefs to grow as has been the case for Holocene reefs around Oahu (see below).

Differences in MIS 7 sea-level estimates based on reef records from different locales can be due to glacial isostatic adjustment (GIA) effects (e.g., Milne and Mitrovica, 2008; Raymo and Mitrovica, 2012). Spatial variability in past interglacial sea level positions of over 10 m can be expected and depend on factors such as proximity of a site to ice margins, loading and unloading history of ice sheets, duration of the interglacial and Earth's rheological response (Lambeck et al., 2012; Raymo and Mitrovica, 2012). Oahu is considered a far-field location with respect to GIA effects. Accordingly, the local sea-level record should exhibit less GIA-induced deviation from the eustatic signal than more near-field sites such as Florida, the Bahamas and Bermuda. However, in addition to GIA processes, vertical movements associated with volcanic loading at the Big Island of Hawaii must be accounted for when interpreting the Oahu record (see above).

MIS 5 sea levels

Corals dating to late MIS 5 (post-MIS 5e) were recovered from the seaward margin of the terrace on the leeward side of Oahu (cores WAI10, WAI8-3, and WAI6-1, Fig. 3). At the close of the MIS 5e highstand at ~113–115 ka, sea level dropped below present and the Waimanalo reef was abandoned, as indicated by the lack of Waimanalo coral ages less than ~113 ka (Muhs et al., 2002; Szabo et al., 1994). Accretion continued offshore at the seaward margin of the terrace between ~−20 and −30 m (~−24 and −34 m corrected for uplift), as indicated by the ages of samples WAI10-S2, WAI10-S3, WAI8-3S1A, and WAI6-1S1 (~110–83 ka). The antecedent topography of the MIS 7 Waianae Reef provided a suitable substrate for continued reef accretion. There is no evidence of subaerial exposure between samples WAI10-S3 and WAI10-S2, which suggests that sea level stayed above −25 m (~−30 m corrected for uplift) between ~110 and 104 ka (i.e., MIS 5d). This is supported by TIMS Th–U ages of corals from submerged fossil reef tracts in the Florida Keys (Toscano and Lundberg, 1999). At higher stratigraphic levels in the WAI10 core there is a facies change from massive coral to encrusting corals that suggests sea level continued to fall. The encrusting-coral facies is indicative of a relatively shallow, moderate to high-energy environment. Sample WAI10-S2 has an age of ~105 ka. Further offshore sample

WAI8-3S1A has an age of ~97 ka. Together they bracket the age of the highstand associated with MIS 5c (Potter et al., 2004). Continuing seaward, sample WAI6-1S1 has an age of ~83 ka, correlating to MIS 5a (Dorale et al., 2010; Potter et al., 2004). The position of the late MIS 5 corals on Oahu (i.e., the Leahi Reef) and the lack of emergent MIS 5a–5c corals are consistent with local sea levels being below present during this interval. The general trend of decreasing age with distance offshore may suggest that accretion was occurring over a period of general sea-level fall during the latter part of MIS 5.

Sea levels lower than present during MIS 5a and 5c are supported by sea-level estimates based on the deep-sea oxygen isotope record (e.g., Rohling et al., 2009, 2010). Similarly, numerous reef records indicate sea levels of ~10 to 20 m below present for both MIS 5a and 5c. These include uplifted reef terraces of Barbados and New Guinea (Bard et al., 1990; Chappell and Shackleton, 1986; Cutler et al., 2003; Gallup et al., 1994; Potter et al., 2004; Schellmann and Radtke, 2004; Schellmann et al., 2004a) and submerged relict reefs on the more tectonically stable southeast Florida shelf (Toscano and Lundberg, 1999). While there is some evidence for higher sea levels during MIS 5c (e.g., Coyne et al., 2007), most records indicate sea levels well below present. In contrast, MIS 5a sea level positions are much more debated. Although the records cited above indicate MIS 5a sea levels below present, there are numerous sedimentary records from locales including Bermuda, the Bahamas, the U.S. Atlantic Coastal Plain and Grand Cayman that indicate 5a sea levels close to or slightly above the present level (Coyne et al., 2007; Ludwig et al., 1996; Muhs et al., 2002; Vacher and Hearty, 1989; Wehmiller et al., 2004). Additionally, a speleothem record from the western Mediterranean indicates that MIS 5a sea level was ~1 m above modern sea level (Dorale et al., 2010). As with the MIS 7 Waianae Reef, the position of the late MIS 5 Leahi Reef on Oahu does not preclude higher sea levels at this time, but does indicate that, if higher sea levels occurred, conditions were not suitable for extensive reef accretion at this time. Additionally, GIA effects can account for at least some of the spatial variability in late MIS 5 sea-level records.

Holocene versus Pleistocene reef accretion

An interesting outcome of this research lies in what was not found. In 30 separate cores from both windward and leeward settings and ranging between water depths of ~5.5 and 35 m, no evidence of Holocene reef accretion was found. Rather, the seafloor is undergoing extensive biological and physical erosion (cf. Grossman et al., 2006). Signatures of subaerial exposure and meteoric diagenesis are recognized in the upper several centimeters of all cores (cf. Sherman et al., 1999). Holocene accretion is limited to sparse patches of coral and coralline algae. This paucity of Holocene reef accretion over a Pleistocene foundation is similar in some respects to the submerged Pleistocene outlier reefs along the south Florida bank margin (Lidz et al., 1991). Holocene accretion in Hawaii appears to be largely limited by wave forces (Dollar, 1982; Dollar and Tribble, 1993; Fletcher et al., 2008; Grigg, 1983; Grigg, 1998; Grossman and Fletcher, 2004; Grossman et al., 2006; Rooney et al., 2004). Episodic destruction of coral communities by storms and open-ocean swell and the removal of carbonate material from nearshore reef zones prevent cementation, lithification, and reef accretion (Dollar and Tribble, 1993). Why extensive and thick reef sequences were able to develop during the Pleistocene but not during the Holocene at these sites remains an important question.

Thick Pleistocene reefs of Oahu owe their existence to having had more time and more accommodation space than Holocene reefs. The broad range of ages for both Waianae and Leahi Reefs indicates that these are complexes built over long-periods of time (20–40 ka), though perhaps not continuously, and over successive substages within an interglacial. In contrast, Holocene accretion has occurred within the last ~8 ka as sea level rose and flooded the nearshore terrace (Fletcher et al., 2008). Reef accretion in Hawaii occurs within a narrow growth window. The lower limit of positive net accretion is ~−30 m, critical depth (Grigg and Epp, 1989). The upper limit is controlled by wave energy (Grossman and Fletcher, 2004; Rooney et al., 2004). Pleistocene accretion of the MIS 7 Waianae and late MIS 5 Leahi Reefs that constitute the nearshore terrace fills much of the growth window around Oahu. Slow, long-term uplift of Oahu has further reduced accommodation space (Fletcher et al., 2008). In general, Holocene reefs have not had as much accommodation space as their Pleistocene counterparts and therefore, around much of Oahu, are restricted to thin veneers on Pleistocene foundations. Only in protected settings with a shallower wave base or where subaerial erosion of Pleistocene foundations has created accommodation space has significant Holocene reef accretion occurred on Oahu (Fletcher et al., 2008; Grossman and Fletcher, 2004). While early Holocene accretion may have been inhibited by increased turbidity associated with initial flooding of the nearshore terrace (e.g., Adey, 1978), the limited distribution on Holocene reefs and their occurrence only in protected settings point to wave exposure as a primary control. It is important to consider these limitations on Holocene accretion while interpreting the Pleistocene record and reasonable to assume that similar factors affected Pleistocene accretion. Thus, the timing and position of Pleistocene accretion does not necessarily correspond to the timing and position of peak sea levels. Rather, accretion occurs where and when it is favored by the interplay of multiple factors including, but not limited to, sea level, wave climate and accommodation space.

Conclusions

In situ Pleistocene reefs constitute a nearshore terrace around the island of Oahu. The windward margin of the terrace consists of coralline algal bindstones, whereas coral bindstones and framestones dominate the leeward margin. TIMS Th–U ages of in situ corals indicate that much of the terrace on both windward and leeward sides of Oahu is composed of reefal limestones correlating to the penultimate interglacial period, or Marine Oxygen Isotope Stage 7. The position of the MIS 7 reef, referred to as the Waianae Reef, indicates that the principal locus of reef accretion on Oahu during MIS 7 was ~10 to 20+ m below present sea level, suggesting that much of MIS 7 was characterized by sea levels below the present datum. Later accretion along the seaward front of the terrace/Waianae Reef occurred during the latter part of MIS 5 (MIS 5d–5a), referred to as the Leahi Reef. The general trend of decreasing age of the MIS 5d to 5a Leahi corals with distance offshore suggests that accretion along the seaward front of the terrace occurred over a period of general sea-level fall during the latter part of MIS 5. The vertical and lateral extensiveness of the submerged Pleistocene reefs around Oahu compared to the relative dearth of Holocene accretion is due to the fact that the Pleistocene reefs had more time and more accommodation space available for accretion than their Holocene counterparts.

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