The Ka'ena Highstand of O'ahu, Hawai'i: Further Evidence of Antarctic Ice Collapse during the Middle Pleistocene[1]

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Abstract: Marine isotope stage (MIS) 11 may well represent one of the most significant interglacial highstand events of the past million years. Ocean volume changes charted from coastal exposures imply partial or complete melting of some of the world's major ice caps during a middle Pleistocene interglacial. The coastal geology of both Bermuda and the Bahamas yields evidence of an MIS 11 highstand 20 m higher than present. Further support for this catastrophic episode in sea-level history is revealed in subtidal and intertidal deposits at $+28 \pm 2$ m in O'ahu, Hawai'i. The stratigraphy, petrology, and uplift history of the Hawaiian deposits strongly suggest a correlation with MIS 11, and a compilation of amino acid racemization, uranium/thorium (alpha and mass spectrometry), and electron spin resonance ages shows a scatter between 300 and 550 kyr. When corrected for uplift, the Ka'ena Highstand succession at Wai'anae Health Center (OWH1) reveals a "stepping up" of sea level through the interglaciation, similar to that described in the Bahamas. Previous studies on O'ahu attributed all 28 m elevation of the Ka'ena Highstand to uplift since 0.5 Ma, but now it appears that only 8 m of that was caused by uplift, and the remaining 20 m by eustatic sea-level rise. These findings from O'ahu strengthen evidence for the complete disintegration of the Greenland and West Antarctic ice sheets and partial melting of the East Antarctic ice sheet during the middle Pleistocene. If the instability of polar ice sheets can be linked to prolonged warm interglaciations as the data suggest, then existing conservative predictions for the magnitude of sea-level change by future "greenhouse" warming are seriously underestimated.

A KEY TO EVALUATING the potential threat of abrupt sea-level rise may be in understanding the behavior of ice sheets during past very warm and/or prolonged interglaciations. Of particular interest in assessing the Holocene climate, because of similar insolation values at that time, is marine isotopic stage (MIS) 11, which the deep-sea oxygen isotope records of ODP Site 677 (Shackleton et al. 1990) and SPECMAP (Imbrie et al. 1984) suggest occurred between 423 and 362 kyr (Figure 1) and lasted for 60 kyr. The deep-sea oceanographic evidence is compelling, yet remains at best an indirect or circumstantial measure of sea-level change during MIS 11. Other than direct studies at or beneath the ice sheet (Sherer et al. 1998), ocean volume changes in response to ice melting are best measured along stable shorelines or at locations where the tectonic element is well understood. Direct dating of MIS 11 tectonically elevated deposits near Rome, Italy, indicate that the interglacial highstand persisted for 15–37 kyr (Karner et al. 1999) and ended around 400 kyr ago (Karner and Renne 1998). A sequence of coral reefs and shoreline deposits of middle Pleistocene age between modern sea level and $+28 \pm 2$ m are well exposed along the west and northwest coasts between Ka'ena Point and Wai'anae town (Figure 2) and at lower

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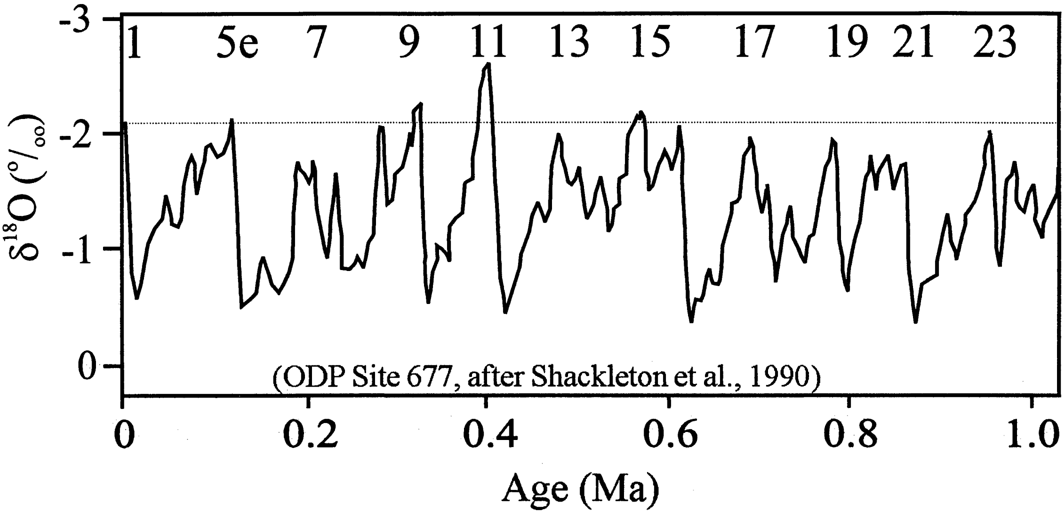

FIGURE 1. Planktonic oxygen isotope data from ODP Site 677 for the past million years (Shackleton et al. 1990). MIS 11 stands out as the isotopically lightest interglaciation over this interval of the Quaternary.

elevations (e.g., Black Point) elsewhere on O'ahu.

Reviews concerning the sea-level, oceanographic, and ice history of MIS 11 are available (Burckle 1993, Oppenheimer 1998, Poore et al. 1999). On the North Slope of Alaska, Kaufman and Brigham-Grette (1993) and Brigham-Grette (1999) identified a +22 to +23 m middle Pleistocene-age shoreline and interpreted it to be associated with the Wainwrightian transgression. Similarly, in southern Britain, Bowen (1999) estimated an uplift-corrected sea-level highstand of +23 m and correlated this with MIS 11 on the basis of amino acid racemization (AAR) age estimates. Outcrops in Bermuda and the Bahamas reveal strong evidence of an important interglacial highstand with a rise of sea level to approximately +20 m during the middle Pleistocene. This "super" interglaciation has been thoroughly documented using a variety of approaches including geomorphology, stratigraphy, sedimentology, petrography, and geochronology by AAR and thermal ionization mass spectrometry (TIMS) uranium-thorium (U/Th) dating techniques (Hearty et al. 1999, Kindler and Hearty 2000).

The objectives of this study were to: (1) evaluate and interpret the sea-level record associated with the Ka'ena Highstand deposits; (2) determine the similarities and differences between this event and coeval deposits from stable carbonate platforms tied to MIS 11 through stratigraphy and dating; and (3) assess the sea-level, glaciological, and tectonic implications for a middle Pleistocene highstand of this magnitude. The methods used are stratigraphic comparisons of sea-level history, and dating of the Ka'ena event by several techniques, including AAR, electron spin resonance (ESR), and TIMS.

SEA-LEVEL INDICATORS FROM MIDDLE PLEISTOCENE DEPOSITS IN WEST O'AHU

A stratigraphic section adjacent to the Wai'anae Health Center (site OWH1 located 350 m south of Pu'u Mā'ili'ili) just on the southern edge of Wai'anae town contains the following sequence of middle and late Pleistocene-age units that reflect sea-level stillstands from oldest to youngest (Figure 3).

Middle Pleistocene

UNIT 1. A shallowing-upward, subtidal to intertidal shoreline sequence is exposed at +13.5 m along a SW–NE transect between

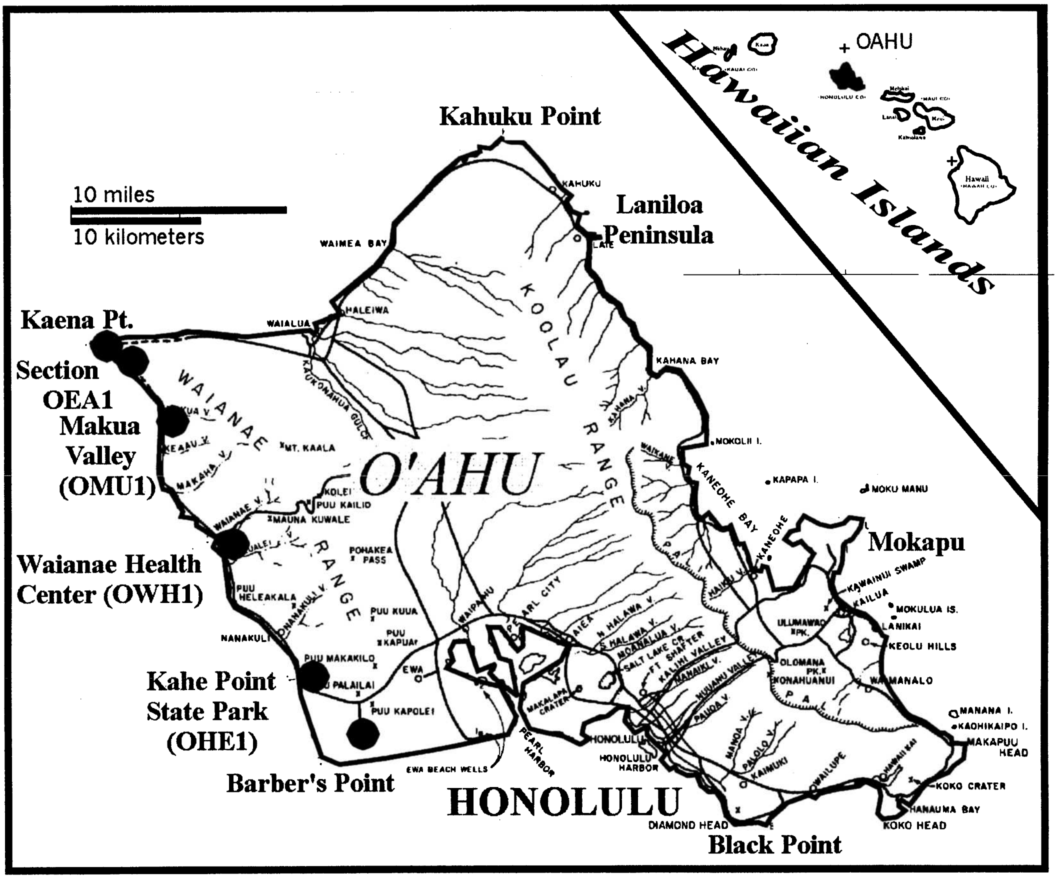

FIGURE 2. Location map of study sites on O'ahu in the Hawaiian Islands.

Pu'u Mā'ili'ili and the mouth of Mā'ili'ili Stream (directly toward the southeast parking lot of the Wai'anae Health Center). Paleosea level is interpreted from the sub- to intertidal facies transition at approximately +5 to +6 m in outcrops along the coastline at the mouth of Mā'ili'ili Stream. Unit 1 is moderately to strongly cemented, presumably in a vadose environment. The coarse, well-sorted carbonate sand is pervasively recrystallized in this unit.

UNIT 2. The upper surface of Unit 1 is truncated by marine bioerosion, presumably in a shallow shoreline environment forming a very flat terrace surface (Unit 2) at +13.5 m (Figure 4). The terrace closely approximates mean low water level, indicating that *relative* sea level was greater than +13.5 m. There is no evidence that soil formation or karst processes acted on this surface, suggesting that it does not represent a prolonged period of sea-level regression (i.e., glacial lowstand), but rather a stillstand of perhaps a few thousand years, followed by erosion in a shallow marine environment.

UNIT 3. Calcareous deposits covered by red alluvium are exposed up to approximately +28 m in the upper, east parking lot at the Health Center. A reefal unit at +26.5 m contains in situ coral heads (*Platygyra* sp., *Pocillopora* sp., and *Porites* sp.) and suggests a minimum relative sea level of +28 to +30 m. The reef terrace at +28 m falls off sharply seaward in a detrital reef debris apron. Con-

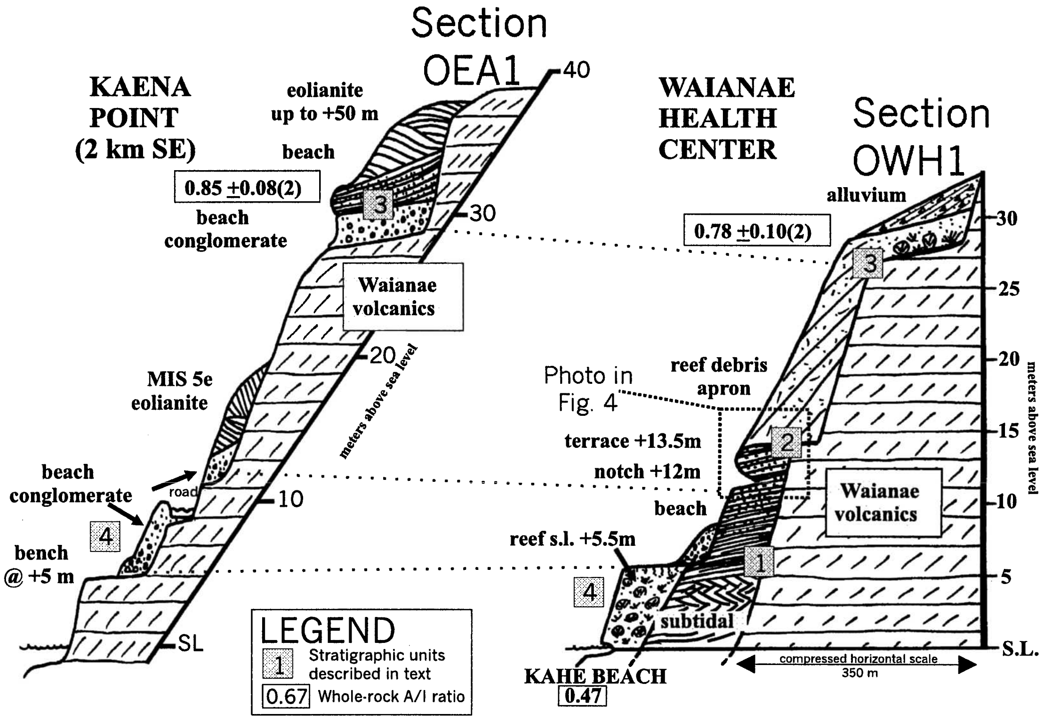

FIGURE 3. Stratigraphic sections of Wai'anae Health Center (OWH1) and Ka'ena Point (OEA1) sections. The latter is located 2 km southeast of Ka'ena Point.

glomerate, reef, beach, and eolianite deposits are also present in outcrops at and above +30 m at several locations at, and just to the southeast of Ka'ena Point (Figure 2).

Late Pleistocene

UNIT 4. Interglacial deposits of MIS 5e age abound in the area of Ka'ena Point, both in a continuous outcrop for several kilometers along the north shore (Sherman 1992) and at several localities along the west and southwest shore of O'ahu. On the south edge of Mākua Valley, 7 km SE of Ka'ena Point, a Farrington Highway roadcut exposes a section of growth-position corals and subtidal marine deposits up to +9 m (Figure 5). On the seaward edge of the same 400-m-wide terrace section, corals are exposed in a fossil reef, indicating a sea level of approximately +5 m. This interpretation of the Mākua section is significantly revised from that of Stearns (1974; inset on Figure 5).

A section at Kahe Point Beach Park (Muhs and Szabo 1994), located 10.5 km south of Wai'anae, exposes two in situ reef levels like that of Mākua Valley, indicating sea-level stillstands at +5.5 and +9 m (Hearty et al. 2000). A marine conglomerate rises to +12 m at Kahe. U-series ages from the section at Kahe Point correlate with MIS 5e (Easton and Ku 1981, Muhs and Szabo 1994). Numerous studies (e.g., Sherman et al. 1993, Muhs and Szabo 1994) on MIS 5e sites around O'ahu have established similar elevations at +5 and +9 m for the highstand events, indicating the absence of tectonic tilting on the island.

A COMPARISON WITH SEA-LEVEL INDICATORS FROM THE BAHAMAS AND BERMUDA

The most complete section correlated with MIS 11 lies to the north of Goulding Cay (EGC3), Eleuthera, Bahamas (Figure 6)

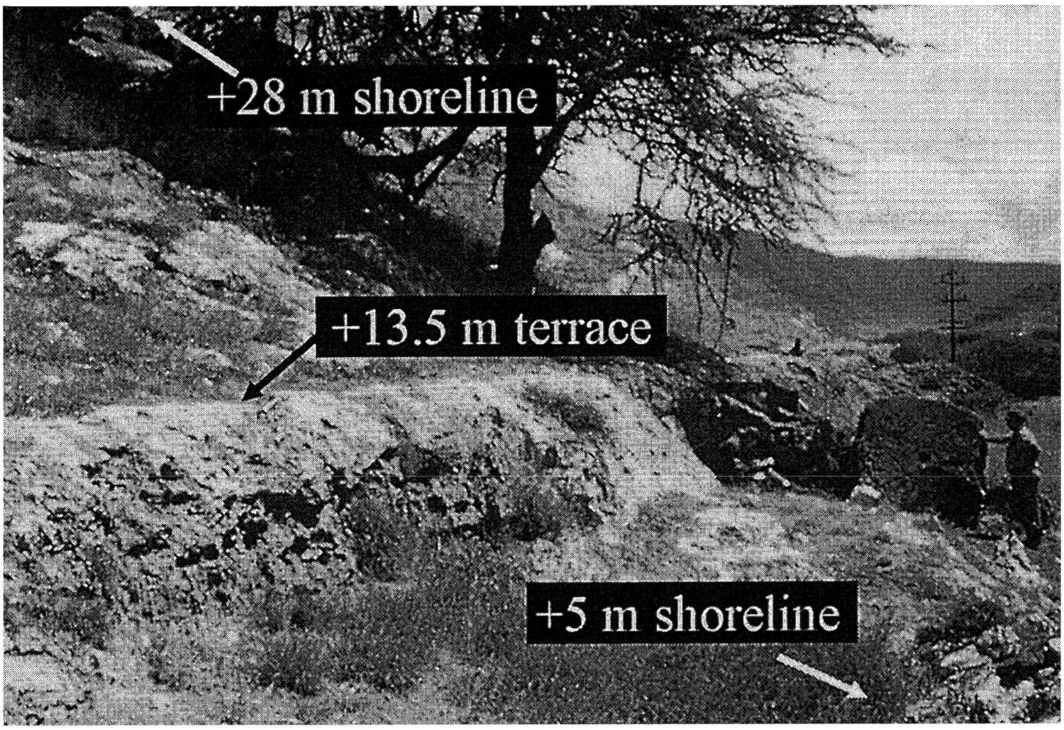

FIGURE 4. Photo of OWH1 showing the distinct +13.5-m terrace. There is no evidence of soil formation or karstification of this surface, suggesting that this unit belongs to the broad interglacial succession between modern sea level and +28 m. The person on the right of the photo is 1.8 m tall.

(Hearty 1998, Hearty et al. 1999, Kindler and Hearty 2000). Other sites in Bermuda similarly preserve the sequence of stillstands during this warm interglaciation (Hearty et al. 1999; unpubl. data). A comparison of equivalent sea-level movements between Bermuda, the Bahamas, and O'ahu are as follows.

Middle Pleistocene

UNIT 1. Deposits at the base of the Goulding Cay section (EGC3) of Eleuthera indicate an initial MIS 11 sea level of approximately 0.5 to +1.5 m (Figure 6). Deposits of this age crop out on Green Island and several other small cays along Castle Harbour, Bermuda (unpubl. data). Sedimentary structures there suggest a sea level of approximately +1 m. A comparison with OWH1 reveals an initial shallowing-upward sequence at +5 to +6 m in O'ahu (Figure 3) compared with the Bermuda and Bahamas level at ca. +1 m, yielding a difference of 5 ± 2 m. Error is calculated from the differences in average measurements from Bermuda and the Bahamas, compared with that in O'ahu.

UNIT 2. A distinct terrace and shoreline deposits at +7.5 m crops out at EGC3 (Figure 6) in northern Eleuthera. Along eastern Front Street in Hamilton, Bermuda (1.0 km east of town center), beach deposits correlated to MIS 11 (Hearty et al. 1992) rise to approximately +9 m, indicating a sea level of perhaps +5 to +7 m. At OWH1, the second stillstand of the interglacial sea-level sequence is represented by an erosional terrace at +13.5 m. This equates with the shallowing-upward sequence in Eleuthera deposited on an erosional surface at +7.5 m (Figure 6). The very precise difference of 6 ± 0.5 m measured between the erosional platforms in O'ahu at +13.5 m and Eleuthera at +7.5 m can be attributed to uplift of the Hawai'i site.

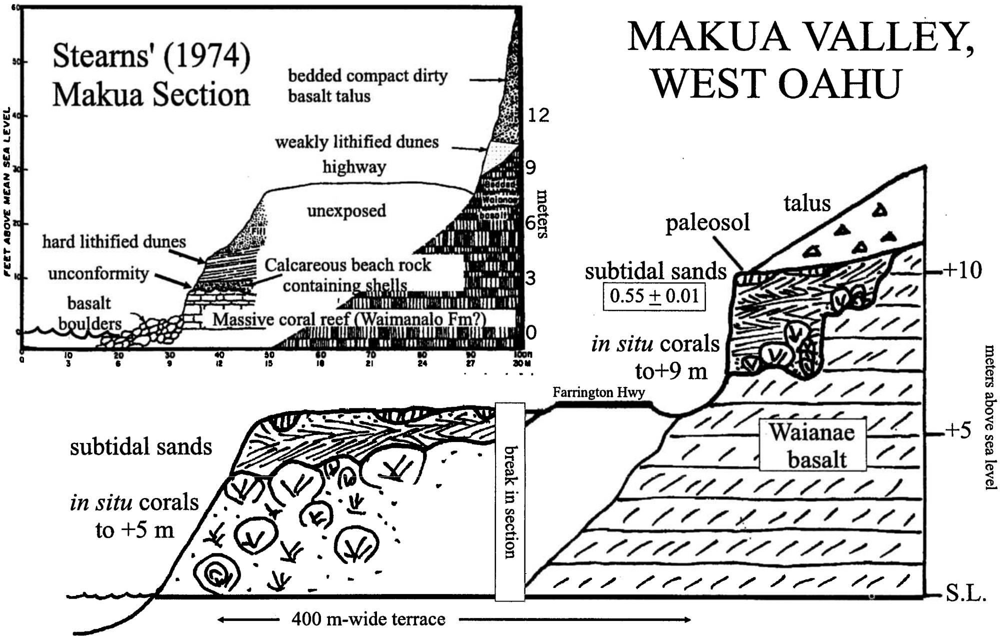

FIGURE 5. The Mākua Valley section located 7 km SE of Ka'ena Point. A 400-m-wide terrace at +5 m was formed or extended early in MIS 5e, but later in the same highstand sea level rose to +9 m or greater, during which the coral heads grew at that elevation. The early-mid level at +5 m and the late +9 m level are typical of MIS 5e for O'ahu (Hearty et al. 2000) and demonstrate no apparent tilting of the island. Stearns' (1974) interpretation of the section is shown in the inset. Stearns saw the +9 to +11 m deposits as a dune. Apparently the growth-position corals were not exposed in his section at the time of that investigation.

UNIT 3. At EGC3, a narrow erosional terrace cut into eolian foresets is covered by thin beach deposits composed predominately of oolite with intertidal fenestrae. Beach deposits vary from 1 to 2 m thick and indicate former sea level between +18 and +20 m. In Bermuda, Land et al. (1967) described a marine terrace with conglomerate and beach sand at 70 ft (+21.3 m) above sea level. These deposits were unfortunately destroyed by quarry expansion; however, more recent surveys have discovered marine deposits in two caves at +18 and +21 m (Hearty et al. 1999), located only tens of meters from the former Land et al. (1967) site.

Unit 3 is characterized at OWH1 by growth-position corals and calcarenite at +27 m, flanked by a debris apron sloping downward onto the +13.5-m terrace (Unit 2). A conglomerate and intertidal sand at +30 m at Ka'ena Point (OEA1), O'ahu, is considered to be coeval to OWH1. At EGC3 in Eleuthera, a narrow terrace with intertidal and subtidal facies between +18 and +20 m record this final and highest sea-level halt of the interglaciation. Equivalent deposits are in the +18 and +21 m caves of Bermuda. The average difference in highstand elevation of Unit 3 between O'ahu (ca. +28 m) and stable localities (+19, +21 m) is 8 ± 1 m.

The Last Interglaciation

UNIT 4. Throughout Bermuda and the Bahamas, MIS 5e deposits have been dated and described at elevations between +2.5 and +3.5 m, which represents the duration of MIS 5e (Neumann and Hearty 1996, Hearty and Kaufman 2000). Late in the period, however, sea level rose to +6 m. Although higher-level notches are recorded (Hearty and Neumann 2001), sea levels of +3 m and +6 m are most representative of, respectively, early-mid and latest MIS 5e. Several MIS 5e

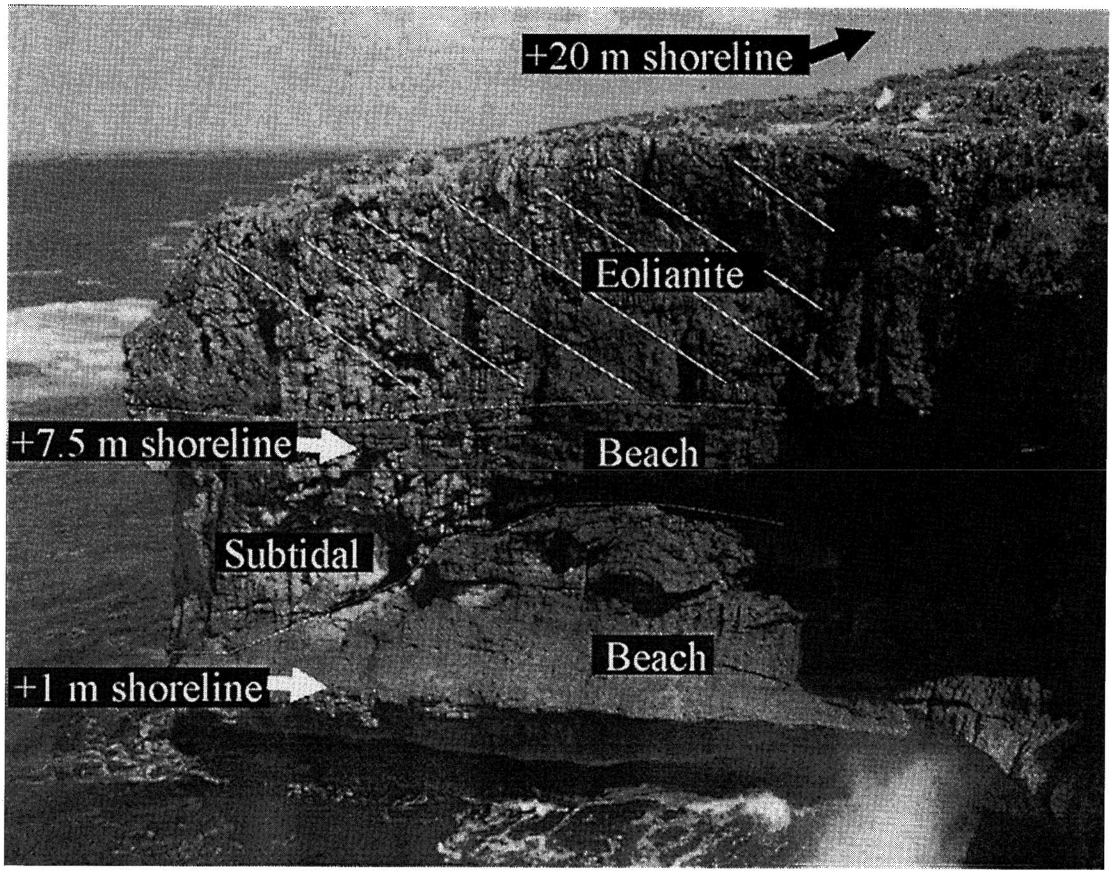

FIGURE 6. Cliff section near Goulding Cay (EGC3), Eleuthera, Bahamas, showing +1 and +7.5 m terraces. These two levels are correlated to the +5.5 and +13.5 m shorelines at OWH1 in O'ahu.

sites in O'ahu (Ku et al. 1974, Sherman et al. 1993, Muhs and Szabo 1994, Szabo et al. 1994, Hearty et al. 2000) expose early MIS 5e growth-position reefs at +5 to +6 m and a subsequent reef at a higher level around +9 m. In general, the reference data for Unit 4 between the study sites for both early-mid and late MIS 5e yield fairly precise and consistent differences of 3 $\pm$ 1 m for both levels.

APPARENT, ESTIMATED, AND ABSOLUTE AGES OF THE SITES

Stratigraphic Succession of Deposits

There is consensus among the authors mentioned earlier on the MIS 5e age (ca. 125 kyr) of the younger "reference" deposits. Although there are several approaches available to ascertain the age of the middle Pleistocene-age deposits in question, a simple and reliable test is the stratigraphic superposition of the interglacial sequence of units.

The Quaternary stratigraphy of Bermuda, the Bahamas, and Hawai'i consists of a succession of interglacial limestone facies separated by glacial-age terra rossa paleosols. A sequence of stacked limestone-red soils units—the younger superimposed upon the older—is the most fundamental and independent measure of relative age. These reasonably complete glacial-interglacial sequences have been previously documented (Table 1) in Bermuda (Hearty et al. 1992, Hearty and

TABLE 1

Correlation of Marine Isotope Stages (MIS) with Shoreline Deposits in Bermuda, the Bahamas, and Hawaiʻi

MIS Correlation	AZ	Bermuda Site/Fm (Hearty et al. 1992)	Mean W-R A/I Ratio	Eleuthera Site/Fm (Hearty 1998)	Mean W-R A/I Ratio	Hawaiʻi Terrace (Stearns 1978)	Hawaiʻi (Hearty et al. 2000; this study)[a]	Mean W-R A/I Ratio
Modern Recent	A3	Modern beach	0.12 ± 0.01 (2)	Modern beach	0.05[b] ± 0.02 (3)	Present (0 m)	Modern beaches and dunes	0.11 ± 0.03 (6)
Late 1	A2			Singing Sands	0.09 (1)	Kapapa (+1.5 m)	ʻOhikilolo, OA	0.22 (1)
Mid 1	A1			Windermeer Island	0.10 (1)		Makawehi, KA; Moʻomomi, MO	0.27 ± 0.02 (8)
5a	C	Southampton Fm	0.23 ± 0.03 (3)	Whale Point	0.29 ± 0.03 (5)	Lēʻahi Fm (+0.6 m)	Kalani Pt., MO (+2 m)	0.34 ± 0.01 (6)
Late 5e	E2	Rocky Bay Fm	0.32 ± 0.03 (12)	Boiling Hole; Savannah Sound	0.38 ± 0.02 (12)	Waimānalo (+7.5 m)	Mōkapu; Barbers Pt.; Kahe (+9 m)	0.45 ± 0.06 (17)
Mid-Early 5e	E1	Grape Bay Mb (new name)	0.40 ± 0.02 (13)			Kailua (+3.6 m)	Mōkapu; Barbers Pt.; Kahe (+5.5 m)	0.51 ± 0.03 (11)
7/9	F	Belmont eolianite	0.49 ± 0.04 (11)	Goulding Cay, The Cliffs	0.58 ± 0.01 (3)	"Unnamed" ("High")	Laniloa, OA	0.64 (1)
11	G	Upper Town Hill Fm	0.56 ± 0.02 (11)			Kaʻena (+30 m); Lāʻie (+21.5 m)	OWH (+28 m) Kaʻena Pt. (+30 m)	0.81 ± 0.08 (4)
				Goulding Cay	0.67 ± 0.05 (16)	Waiʻalae (+12 m)	OWH (+13.5 m)	?
11	H	Lower Town Hill Fm	0.68 ± 0.03 (9)			PCA (+7.5 m)	OWH1 (+6 m beach?)	?
13	I	?	?	Basal unit	0.74 ± 0.05 (2)			

Note: AAR aminozones (AZ) and whole-rock A/I ratios are included. Data are presented in the format 0.43 ± 0.05 (15) [mean ± 1σ (number of samples analyzed per stratigraphic unit)]. A proposed correlation of Stearns (1978) highstand events with Bermuda and the Bahamas is offered.

[a] OA, Oʻahu; MO, Molokaʻi; KA, Kauaʻi.

[b] Modern ooid shoal samples from Exuma Cays.

Vacher 1994), the Bahamas (Hearty and Kindler 1993*a*,*b*, 1997, Kindler and Hearty 1997, Hearty 1998, Hearty et al. 1999, Hearty and Kaufman 2000), and to a lesser degree Oʻahu (Stearns 1978, Hearty et al. 2000).

On Oʻahu, Stearns (1978) described several highstand events, including the Lāʻie, Waiʻalae, and an unnamed event, postdating the Kaʻena Highstand and preceding the last interglacial Waimānalo Highstand (Table 1). Although Stearns interpreted several shorelines to reflect a single broad, sea-level highstand event, much as we propose here for the Kaʻena, there remain several deposits that could record MIS 9 and 7 highstands. The stratigraphic position and ages of the PCA and Kahuku (and perhaps Lāʻie and Waiʻalae as well) terraces are uncertain in the sequence

(Stearns 1978: table 4) and could also represent interglaciations equal to or younger than MIS 13. Indeed, Stearns' (1978:21) description of the PCA as a "beach sandstone ... in Lualualei Valley" at +7.5 m closely matches the characteristics of Unit 1 at nearby OWH1, and the study reported here indicates a similar sea level at +5.5 m. Given this succession of interglacial-glacial couplets, I interpret that the stratigraphically youngest shoreline unit was deposited during the present interglaciation (MIS 1), that the preceding one correlates with the last interglaciation (MIS 5, which exposes emergent subtidal deposits unlike MIS 3, 5a, or 5c), and that an unnamed unit, the Wai'alae, and the Lā'ie may account for MIS 7 and/or 9. If this interpretation is correct, the interglacial succession is complete back to the Ka'ena sequence, which must then equal or exceed MIS 11.

Aminostratigraphy of O'ahu Deposits

Whole-rock aminostratigraphy has been used to unravel Quaternary stratigraphic questions in Bermuda (Hearty et al. 1992), the Bahamas (Hearty and Kaufman 2000), the Hawaiian Islands (Hearty et al. 2000), and South Australia (Murray-Wallace et al. 2001). In the study reported here, aminostratigraphy is an independent means of confirming the stratigraphic sequence and estimating the ages of the deposits. The underlying theory and various applications of the AAR method are summarized in Rutter and Blackwell (1995). The AAR method is based on the racemization of amino acids preserved in biominerals (Hare and Mitterer 1967). Through time, L-amino acids racemize (or, more specifically in the case of the amino acid isoleucine, epimerize) to their D-isomer form. The ratio of D/L (D-alloisoleucine/L-isoleucine, or A/I) amino acids measures the extent of epimerization. In the epimerization reaction of isoleucine, the A/I ratio is initially zero (0.011 with laboratory preparation) in truly modern organisms and increases to an equilibrium A/I ratio of about 1.3 with time after death of an organism.

Like many chemical reactions, the kinetic rate of racemization/epimerization depends on the ambient temperature of the reaction medium, plus interaction with sediment and water. Thus, sites at lower latitudes and warmer temperatures are expected to yield incrementally higher ratios.

O'ahu is situated in the Tropics at around 21.5° N. Most of the Bahamas' data are from higher latitudes (28 to 22° N). Bermuda lies well north of the Tropics and near the limit of reef growth at 32.3° N. Historical temperature records from the Hawaiian Islands generally yield higher (25°C) mean annual temperatures (MATs) than Bermuda (20°C) or the Bahamas (22–24°C), and significant intraisland MAT differences are also evident in Hawai'i.

Table 2 is a comparison of correlated MIS 5e and 11 whole-rock A/I ratios from the three study areas. A thorough investigation of whole-rock aminostratigraphy of the Hawaiian Islands is available in Hearty et al. (2000). Age estimates based on whole-rock ratios using a model of apparent parabolic kinetics (APK) (Mitterer and Kriausakul 1989) range from 370 to 565 kyr (Table 2; Figure 7).

Mean A/I ratios from Unit 3 at +27 m at Wai'anae Health Center and +30 m from Ka'ena Point are 0.78 ± 0.10 ($n = 2$) and 0.85 ± 0.08 ($n = 2$), respectively. Absolute age calibration, which allows age estimates on the basis of the APK model, is provided by a 0.47 ± 0.05 ($n = 28$) mean A/I ratio, equivalent to MIS 5e, 125 kyr on O'ahu (Hearty et al. 2000). APK predicts ages of 340 ± 85 kyr and 408 ± 76 kyr (Table 2) for Wai'anae and Ka'ena Point deposits, respectively, averaging 374 ± 114 kyr.

Electron Spin Resonance (ESR) Dating

In the 1980s, because of analytical limitations of the U/Th method, ESR was attempted on corals from uplifted terraces because of its longer effective age range (Radtke and Grün 1988). However, with the advent of TIMS methods (Edwards et al. 1987), the dating range of the U/Th method effectively doubled to nearly 600 kyr. In regard to the Ka'ena Highstand deposits, it appears that the two methods yield comparable results (Tables 3 and 4).

TABLE 2

Apparent Parabolic Kinetics (APK) Age Estimates of MIS 11(?) Deposits in Hawai'i (Hearty et al. 2000; this study), Bahamas (Hearty 1998, Hearty and Kaufman 2000), and Bermuda (Hearty et al. 1992, Hearty and Vacher 1994) Based on Whole-Rock, *Glycymeris*, and *Poecilozonites* A/I Ratios

Locality (Sample Material)	MIS 5e Whole-Rock	MIS 11 Whole-Rock	APK Age Estimate (ka)[a]	Independent Deposit Ages (ka)[b]
Hawai'i (Whole-rock)	0.47 ± 0.05 ($n = 28$)	0.81 ± 0.08 ($n = 4$)	371 ± 74	TIMS: 529 ± 45; 530 ± 45 ESR: 486 ± 136
Eleuthera, Bahamas (Whole-rock)	0.38 ± 0.03 ($n = 16$)	0.66 ± 0.05 ($n = 16$)	377 ± 57	TIMS: <550
Bermuda (Whole-rock)	0.32 ± 0.05 ($n = 43$)	0.56 ± 0.02 ($n = 11$)	383 ± 73	ESR: 373 ± 40
Bermuda (Whole-rock)	0.32 ± 0.05 ($n = 43$)	0.68 ± 0.03 ($n = 9$)	565 ± 113	TIMS: 420 ± 30; 525 ± 30 ESR: 490 ± 50
Bermuda (*Glycymeris*)	0.57 ± 0.03 ($n = 21$)	0.99 ± 0.02 ($n = 2$)	380 ± 27	"
Bermuda (*Poecilozonites*)	0.51 ± 0.04 ($n = 32$)	0.91 ± 0.03 ($n = 10$)	412 ± 45	"

[a] Cumulative error of APK age estimate is the sum of the combined error of the MIS 5e calibration ratio, plus the error associated with the inferred MIS 11 A/I ratio.

[b] See text and tables for independent age references.

Brückner and Radtke (1989) attempted ESR dating of the uplifted marine terraces of O'ahu. From Ka'ena Highstand deposits, including those at Black Point (Stearns and Dalrymple 1978), east of Honolulu, they determined ages ranging between 406 and 547 kyr, with an average and standard deviation of 482 ± 58 kyr. Two replicate ESR samples were tested using U/Th, producing nominal ages of >287 kyr and >225 kyr (Table 4). Jones (1993) added ESR ages of 547 ± 82 kyr from the Ka'ena Point deposits and 468 ± 136 kyr from the Wai'anae Health Center deposits. In Bermuda, Hearty and Vacher (1994) determined whole-rock ESR ages for suspected MIS 11 deposits of 373 ± 40 kyr and 490 ± 50 kyr that correspond with whole-rock A/I ratios of 0.56 ± 0.02 ($n = 11$) and 0.68 ± 0.03 ($n = 9$).

Uranium-Series Dating

Veeh, in Stearns (1974), determined an infinite > 200 kyr U-series age of the Ka'ena deposits, but added, on the basis of a $^{234}U/^{238}U$ value of 1.03, that the deposits are on the order of 600 kyr. Szabo et al. (1994) later determined a TIMS age of $532\ ^{+130}/_{-70}$ kyr for the Ka'ena Point deposits and correlated the deposits (unequivocally) with either MIS 13 or 15, without questioning the accuracy of the dates.

In the study reported here, a sample from an in situ *Platygyra* sp. coral head, the same specimen analyzed by Jones (1993) at +27 m at Wai'anae Health Center, similarly produced a TIMS age of $529^{+47}/_{-35}$ kyr (Table 5). Because of the minor degree of alteration of this sample and perhaps that of Szabo et al.'s (1994) $532^{+130}/_{-70}$ kyr age, the Ka'ena ages are considered to be maxima. To shift from an age of 400 to 530 kyr, the $^{234}U/^{238}U$ ratio would have to increase by only about 1.7% (L. Edwards, pers. comm.). The somewhat larger error associated with the Ka'ena Highstand samples may similarly reflect this minor degree of diagenetic alteration, which, incidentally, would have little or no effect on AAR ratios.

TIMS analyses on samples from +20 m highstand deposits in Bermuda are tabulated in Hearty et al. (1999). From these dates, the chemically most reliable sample was from the lowest 5 mm of a flowstone capping the +20

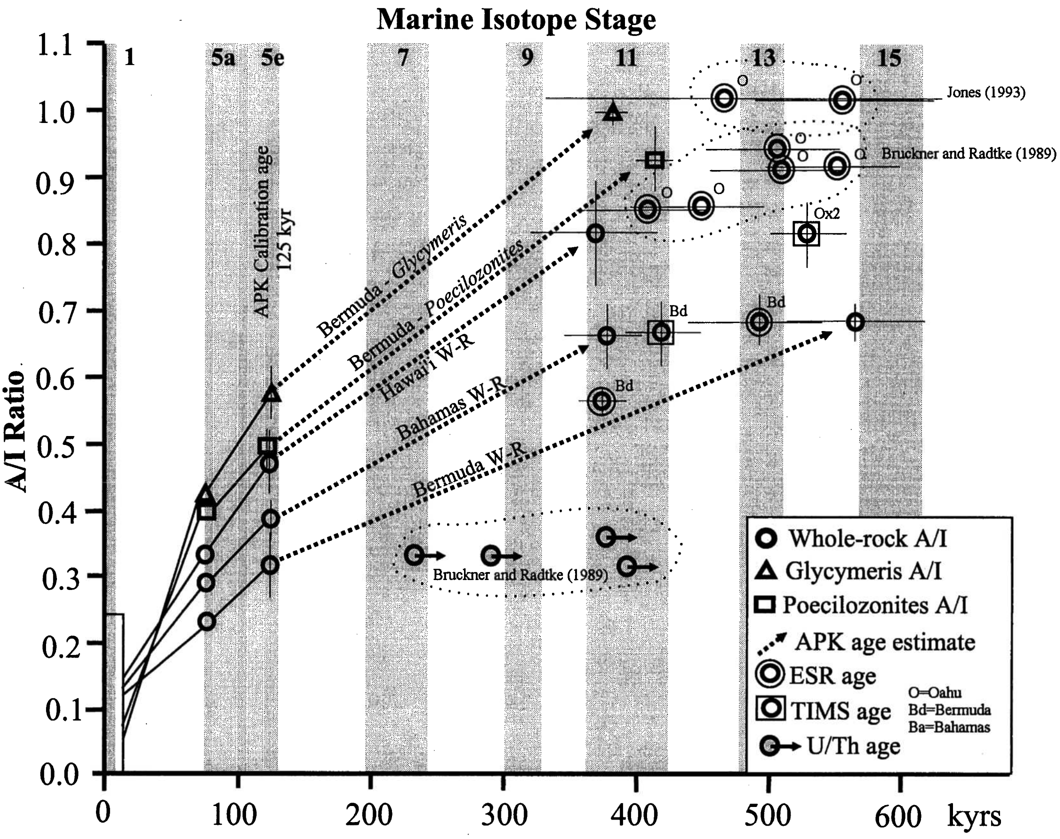

FIGURE 7. Graph showing amino acid age estimates, ESR and TIMS dates from analyses of Ka'ena Highstand deposits, and coeval deposits in Bermuda and the Bahamas.

TABLE 3

Electron Spin Resonance Ages from Correlated MIS 11 and Ka'ena Highstand Sites in Bermuda and Hawai'i

Sample[a]	U (ppm)	Accumulated Dose	Annual Dose	ESR Age (ka)
Bermuda (Hearty and Vacher 1994)				
D-1643	0.87	204.2	0.3984	373 ± 40
D-1644	0.85	274.4	0.4102	490 ± 50
O'ahu, Hawai'i (Brückner and Radtke 1989)				
D-1407	2.17	485.6	0.9577	507 ± 50
D-1437	2.40	503.9	1.0108	499 ± 50
D-1509-1	2.30	445.2	0.9920	449 ± 45
D-1509-2	2.10	358.1	0.8811	406 ± 40
D-1635a	3.00	724.8	1.3240	547 ± 55
O'ahu, Hawai'i (Jones 1993)				
WHC	—	—	—	468 ± 136
Ka'ena	—	—	—	547 ± 82

[a] All "D" samples were analyzed at the University of Düsseldorf (U. Radtke, former director).

TABLE 4

Conventional Uranium-Series (U/Th) Ages from Ka'ena Highstand Deposits, O'ahu, Hawai'i (from Brückner and Radtke 1989)

Sample no.	U (ppm)	$^{234}U/^{238}U$	^{232}Th (ppm)	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Th/U Age (ka)
KP-11	1.88 ± 0.07	1.03 ± 0.05	0.07 ± 0.02	0.98 ± 0.04		>385 (295–∞)
KP-12	2.37 ± 0.05	0.94 ± 0.03	6%	1.09 ± 0.08		>400
KAE-1	2.17 ± 0.05	1.05 ± 0.02	0.15 ± 0.02	1.02 ± 0.03	47,169 ± 6,816	>287
KAE-2	2.40 ± 0.04	1.11 ± 0.03	0.09 ± 0.03	0.90 ± 0.03		>225 (205–255)

TABLE 5

O'ahu, Wai'anae, and Ka'ena TIMS Results (Edwards and Cheng, University of Minnesota) (the error is 2σ)

Sample no.	^{238}U (ppb)	^{232}Th (ppt)	$\delta^{234}U$ (Measured)	$^{230}Th/^{238}U$ (Activity)	^{230}Th Age (ka) (Uncorrected)	^{230}Th Age (ka) (Corrected)	$\delta^{234}U$ (Initial)
OWH-1d	2,869 ± 3	12 ± 8	48.8 ± 1.0	1.0602 ± 0.0032	529 +47/−35	529 +47/−35	218 ± 31
OEA1a(1)	747.8 ± 0.6	1,459 ± 11	27.8 ± 1.9	1.1091 ± 0.0033	—	—	—
OEA1a(2)(I)	711.2 ± 0.8	2,103 ± 12	31.6 ± 3.6	1.1427 ± 0.0035	—	—	—
OEA1a(2)(II)	758.2 ± 0.6	7,725 ± 23	38.6 ± 1.3	1.1625 ± 0.0036	—	—	—

$^{230}Th = 9.1577 \times 10^{-6}$ yr^{-1}, $^{234}U = 2.8263 \times 10^{-6}$ yr^{-1}, $^{238}U = 1.55125 \times 10^{-10}$ yr^{-1}.

m beach deposits. This sample returned a TIMS age of 420 ± 30 kyr, confirming the APK age estimates centered on ~400 kyr (Figure 7).

DISCUSSION

The stratigraphy of coastal sections provides insight into the timing and movements of sea level, periods of stability, and aspects of the environment of deposition during interglaciations. With careful examination, it is possible to document and compare sea-level events within interglaciations between three remote island localities. MIS 5e and 11 are two of the more intricate sequences of the past half million years, with depositional records containing numerous subtidal, intertidal, and supratidal deposits, an indication of multiple oscillations of sea level (Hearty 1998, Hearty and Kaufman 2000) during that interglaciation, and their unique characteristics stand out.

The stratigraphic sequence in Eleuthera, Bahamas, documents two extended periods of terrace formation at +1 and +7.5 m followed by a final rise to +20 m. The +7.5-m highstand resulted in the buildup of a broad and high coastal dune ridge. The stillstand carved a narrow terrace in this dune, upon which beach beds with fenestrae were deposited. In Bermuda, a terrace was also eroded at +20 m (Land et al. 1967), and sea caves were filled with beach sands (Hearty et al. 1999). At Wai'anae Health Center, a comparably complete section reveals the same three movements of sea level, with the addition of a few meters of elevation attributed to upward lithospheric flexure in the forebulge region (Grigg and Jones 1997). Comparable stratigraphies, amino acid ratios, and dates obtained here point toward an event between 300 and 550 kyr.

Strong independent evidence supports a correlation of Ka'ena deposits with MIS 11. Numerous deep-sea oxygen isotope records (Oppo et al. 1990, Raymo et al. 1990, Shackleton et al. 1990) generally characterize MIS 11 as a profoundly warm and long interglaciation, in contrast to preceding (MIS 13 and 15) and succeeding (MIS 9 and 7) interglaciations of equivalent or lesser amplitude. The

TABLE 6

Differences in Sea-Level Indicators between O'ahu, Bermuda, and the Bahamas Used to Estimate Uplift Rates Since MIS 11

Isotope Stage	Wai'anae Health Center, O'ahu, Hawai'i	Ka'ena Point, O'ahu, Hawai'i	Bahamas	Bermuda	Average Difference, Hawai'i vs. Bahamas and Bermuda	Uplift Rate (m/kyr)
Late 5e	**+9 to +11 m**	No data	**+6 to 8.5 m**	**+6 to +9.2 m**	**3.0 ± 1.0 m**	0.025 ± 0.005 (120 kyr)
Mid 5e	**+5.5 m**	**+5.5 m**	**+3.0 m**	**+2.5 m**	**3.0 ± 0.5 m**	0.024 ± 0.003 (125 kyr)
Late 11	**+28 m**	**+29 m**	**+21 m**	**+20 m**	**8 ± 1.0 m**	0.020 ± 0.003 (400 kyr)
Mid 11	**+13.5 m**	No data	**+7.5 m**	+5 to +7 m	**6 ± 0.5 m**	0.015 ± 0.001 (410 kyr)
Early 11	+5 to +6 m	No data	**+0 to 1.5 m**	+1 m	5 ± 2.0 m	0.012 ± 0.005 (420 kyr)

Note: These data indicate that a fairly consistent or slightly increasing uplift rate averaging 0.020 m/kyr has affected O'ahu over the past 410 kyr. Uplift rates calculated in previous studies (Muhs and Szabo 1994, Grigg and Jones 1997) were greater by a factor of 2 to 3, attributing all 30-m elevation of the Ka'ena deposits to uplift, rather than only 8 to 10 m, given a global highstand of sea level at 400 kyr at +20 m. Most precise and significant measurements are in **bold** type.

up to 37-kyr duration of the interglaciation (Karner et al. 1999) provides ample time for both minor and major oscillations of sea level, the firm induration and erosion of units, and formation of broad terraces and coral reefs within the succession. The probability is strong, and I thus conclude on the basis of several independent lines of deduction that the +28-m Ka'ena Highstand occurred during MIS 11.

Uplift History of O'ahu

Of critical importance to this discussion is the relative highstand elevations between Ka'ena and Waimānalo (MIS 11 and 5e, respectively) deposits, compared with those of correlative age described in Bermuda (Harmon et al. 1983, Hearty et al. 1992) and the Bahamas (Hearty and Kindler 1995, Neumann and Hearty 1996, Hearty 1998). Well-studied sections at Mōkapu and Kahe, and a new section at Mākua Valley (Figure 5), midway between Wai'anae Health Center and Ka'ena Point, indicate early and late MIS 5e stillstands at +5 and +9 m, respectively. A comparison of early-mid and late MIS 5e highstand deposits from stable locations with those in O'ahu results in a difference of 3 ± 0.5 m over the past 125 kyr, indicating an uplift rate of 0.024 ± 0.003 m/kyr.

Consistent with these rates on O'ahu, the "uplift corrected" terrace positions of MIS 11 yield sea-level records parallel with those from tectonically stable Bermuda and the Bahamas. The most accurately measured middle (Unit 2) and late (Unit 3) MIS 11 units yield average differences in elevation between stable locations and O'ahu of 6 and 8 m, providing uplift rates of 0.015 ± 0.001 and 0.020 ± 0.003 m/kyr, respectively (Table 6). This rate extrapolated over 400 to 410 kyr is consistent with, but marginally slower than, that since MIS 5e. In contrast, Muhs and Szabo (1994) and Szabo et al. (1994) attributed all +30 m elevation of the Ka'ena deposits to uplift and accepted at face value the 532 kyr TIMS age and Veeh's (in Stearns 1974) conventional U-series 600 kyr age estimate, yielding an approximate rate of 0.057 m/kyr. Their calculations imply a substantial decrease in the uplift rate between MIS 11 and 5e. Because so little is known of the tectonic framework of the other Hawaiian Islands, it is uncertain whether accelerating or decelerating uplift rates are more compatible with the movement of the islands over the flexural forebulge area.

Implications for Ice-Melting History

The progressive "stepping up" of sea level through the interglaciation appears to be characteristic of MIS 11, as interpreted from the geology of Bermuda, the Bahamas, and now deposits associated with the Ka'ena Highstand in O'ahu. This progressive rise of sea level is chronologically documented in the Ponte Galeria area near Rome, Italy, with $^{40}Ar/^{39}Ar$ dates of 434 ± 8 kyr, 427 ± 5 kyr, and 406 ± 3 kyr from the base of the MIS 11 sequence to the top (Karner and Renne 1998), respectively. The section at Ponte Galeria documents approximately 40 m of sediment accumulation over this interval of approximately 30 kyr.

Some explanation of the initial rise of sea level is provided by the record of ice-rafted debris (IRD) from ODP Site 982 from the North Atlantic (Stanton-Frazee et al. 1999). Core material from the MIS 12–11 transition (Termination V) shows the highest volume of IRD, followed by 23 kyr (early in the period) *with no IRD deposition*, implying no iceberg discharge and thus that much of the Greenland ice sheet (GIS) must have melted early in MIS 11. This initial rise of sea level of 5 to 7 m caused by the melting GIS may have had a deleterious effect on the marine-based West Antarctic ice sheet (WAIS), which in turn, upon complete disintegration, would have contributed another 5 to 6 m to sea level. The loss of the stabilizing effect of the WAIS on shared ice basins (Radok et al. 1987) in East Antarctica would cause the drawdown of those shared basins and in so doing, generate an additional 8 to 10 m of sea level. These three melting and collapse events would thus account for the net 20 ± 3 m rise of sea level toward the end of MIS 11.

CONCLUSIONS

The middle Pleistocene stratigraphy from the Wai'anae Health Center section in western O'ahu yields a parallel sea-level history when compared with that from Bermuda and the Bahamas with levels at (uplifted O'ahu in parentheses): +1 (+5–6), +7.5 (+13.5), +20 (+28) m. This progressive stepping up of sea level may have occurred over a period of up to 37 kyr (Karner et al. 1999).

The superposition of stratigraphic units together with several dating approaches including AAR, ESR, U-series, and TIMS suggests that the age of the deposits is between 350 and 550 kyr, and deep-sea isotope records (Oppo et al. 1990, Raymo et al. 1990) appear to confirm that MIS 11 was the longest and perhaps one of the warmer interglaciations of the past 0.5 myr. Because the preceding (MIS 13 and 15) and succeeding (MIS 9 and 7) interglaciations show relatively reduced sea level elevation (e.g., Hearty 1998, Hearty and Kaufman 2000), it is reasonable to conclude that the Ka'ena Highstand occurred during MIS 11. The duration and apparent warmth of this middle Pleistocene interglaciation may provide a direct explanation for the great reduction in polar ice volume.

On the basis of comparisons with Bermuda and the Bahamas, an uplift rate of 0.024 ± 0.003 m/kyr is calculated since MIS 5e for O'ahu. If one accepts that 20 m of the +28 m of the MIS 11 Ka'ena Highstand sea level is attributable to eustatic causes, the remaining 8 m can be explained by tectonic motion over the past 400 kyr at a rate of 0.020 ± 0.003 m/kyr, in accordance with our estimate of MIS 5e uplift rates.

The sea-level changes recorded in MIS 11 highstand deposits in Bermuda, the Bahamas, the Hawaiian Islands, and elsewhere reflect the melting history of ice sheets. The association of longer or warmer interglaciations with the partial or complete melting or collapse of some of the world's major ice sheets may be coincidental, but because of the potential significance of this uncertain factor, it should be given due consideration in the formulation of global warming scenarios.

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