ELSEVIER

Marine Geology 118 (1994) 315-326

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: Implications for sea level during the last interglacial period

D.R. Muhs, B.J. Szabo

U.S. Geological Survey, MS 974, Box 25046, Federal Center, Denver, CO 80225, USA

(Received February 16, 1993; revision accepted November 15, 1993)

Abstract

The Waimanalo Formation (limestone) of Oahu has been correlated with the last interglacial period based on U-series dating of corals by T.-L. Ku and colleagues. The limestone consists of growth-position corals and overlying coral conglomerate. An apparent bimodal distribution of ages for the growth-position corals (mean age = 133 ka) and the overlying coral conglomerate (mean age = 119 ka) has been interpreted to represent two distinct high stands of sea that occurred within the last interglacial period. Both growth-position corals and overlying, conglomerate coral occur in an outcrop east of Kaena Point and consist mainly of *Pocillopora* and *Porites*. U-series ages of growth-position corals that show closed-system conditons are 120 ± 3 ka and 127 ± 4 ka; overlying conglomerate corals have U-series ages that range from 120 ± 3 ka to 138 ± 4 ka. At Kahe Point, conglomerate corals have ages of 120 ± 3 ka and 134 ± 4 ka. These data show that the growth position corals are not systematically older than the conglomerate corals; thus, there is no evidence for two distinct high stands of sea.

Waimanalo deposits at Kahe Point and Mokapu Point (new U-series ages of 134 ± 4 ka and 127 ± 3 ka) have beach deposits as high as 12.5 m and, at Mokapu Point, growth-position corals as high as 8.5 m. A last-interglacial sea-level stand of +8.5 to +12.5 m conflicts with estimates of +6 m from a number of tectonically stable coastlines and islands in the western Atlantic Ocean. We infer, therefore, that Oahu may be undergoing uplift at a low rate. This uplift may be due to compensatory lithospheric flexure, because the island of Hawaii has been subsiding throughout much of the Quaternary from volcanic loading. Because of this possible uplift, Oahu and islands like it elsewhere in the Pacific cannot be used as reference points for sea level during the last interglacial period.

1. Introduction

The buildup of CO_2 and other greenhouse gases in the atmosphere has led many investigators to hypothesize that significant global warming could take place during the next century. Recent studies of the record of submerged reefs off the island of Barbados show that sea-level rise due to ice sheet melting can be rapid (Fairbanks, 1989). It is therefore important to study periods of the recent geologic past where there may be good analogs to future global warming and understand the timing and magnitude of sea-level rise at those times. The last interglacial period has been specifically compared by modellers to possible future greenhouse climates (Hansen et al., 1988).

The last interglacial period is recorded as emergent coral reefs on many tropical islands and coastlines. On Oahu, the distribution of emergent reef limestones (Fig. 1) was mapped by Stearns

0025-3227/94/$7.00
SSDI 0025-3227(93)E0151-U

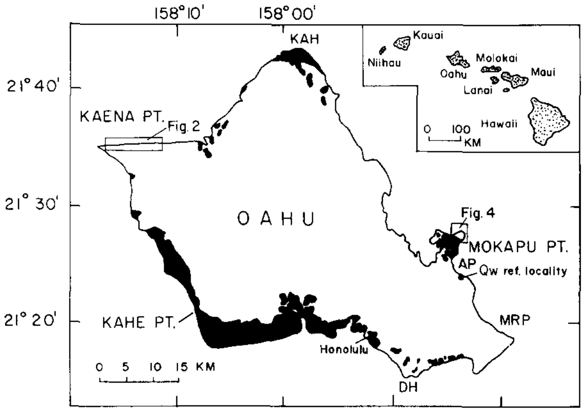

Fig. 1. Distribution of emergent coral reef limestones on the island of Oahu as mapped by Stearns (1974) and localities referred to in the text. *DH* = Diamond Head; *MRP* = Makai Range Pier; *AP* = Alala Point; *KAH* = Kahuku Point.

(1939, 1974, 1978). The youngest reef, limestone of the Waimanalo Formation of Lum and Stearns (1970), has been correlated with the last interglacial period based on $^{230}Th/^{234}U$ ages of corals from a number of localities by Ku et al. (1974). Their reported ages range from 112 ± 6 ka to 137 ± 11 ka. These workers did not provide a detailed stratigraphy of each locality, but described each sample as having come from either a growth-position (or at least cemented) coral or uncemented, wave-deposited coral conglomerate; the latter frequently overlie in situ reefs with corals in growth position.

A recurring theme in Quaternary sea-level studies is a bipartite high sea level during the last interglacial. This concept arose from two observations of reef data. On the Huon Peninsula of New Guinea, an elevated suite of coral reefs is well expressed geomorphically and has been dated by U-series methods (Chappell, 1974; Bloom et al., 1974; Stein et al., 1993). New Guinea reef complex VII of this suite has been correlated with the last interglacial period based on this dating; it is composed of a barrier reef (VIIb), a lagoon, and a fringing reef (VIIa). Chappell (1974), Bloom et al. (1974) and Stein et al. (1993) inferred that a disconformity may exist between reefs VIIb and VIIa. Chappell (1974) and Chappell and Veeh (1978) therefore interpreted the reef complex to represent two distinct high stands of sea during the last interglacial period. Support for the "dual sea-level peak" during the last interglacial period has also been derived from the presence of what has been interpreted to be an apparent age division of Ku et al.'s (1974) U-series data for Oahu (Stearns, 1976; Chappell and Veeh, 1978; Moore, 1982; Chappell, 1983; Chappell and Shackleton, 1986; Smart and Richards, 1992). These workers divided the ages of Ku et al. (1974) into two groups: an "in situ" group (including corals in growth position, or at least cemented in the limestone facies) whose ages average about 133 ka and a "coral conglomerate" group, derived from the uncemented, overlying conglomerate, whose ages average about 119 ka. As pointed out by Chappell and Veeh (1978) and Pillans (1987), a dual sea-level peak during the last interglacial period is not apparent in the foraminiferal oxygen isotope record of deep-sea cores, where the last interglacial period is recorded by deep-sea oxygen isotope substage 5e. The deep-sea oxygen isotope record correlates with orbital forcing models; therefore, a dual sea-level peak during the last interglacial period would be a major challenge to the orbital forcing theory.

We collected corals from most known localities of the Waimanalo Formation for U-series dating. Mapping of the Waimanalo Formation at a previously unstudied locality is presented and new U-series ages that bear on the issue of a bipartite sea level during the last interglacial are reported. We also discuss a mechanism whereby an apparent higher-than-expected sea level on Oahu could have occurred during this time period.

2. The Waimanalo Formation

We visited most known localities of the Waimanalo Formation on Oahu, based on mapping by Stearns (1939, 1974, 1978) and locality descriptions by Ku et al. (1974). We measured most limestone elevations by hand leveling and tape using sea level as a datum; mean tidal ranges on Oahu are less than 0.5 m, so corrections are not required. Many outcrops reported by previous workers are now obscured by new buildings, removed by construction activities or wave activity,

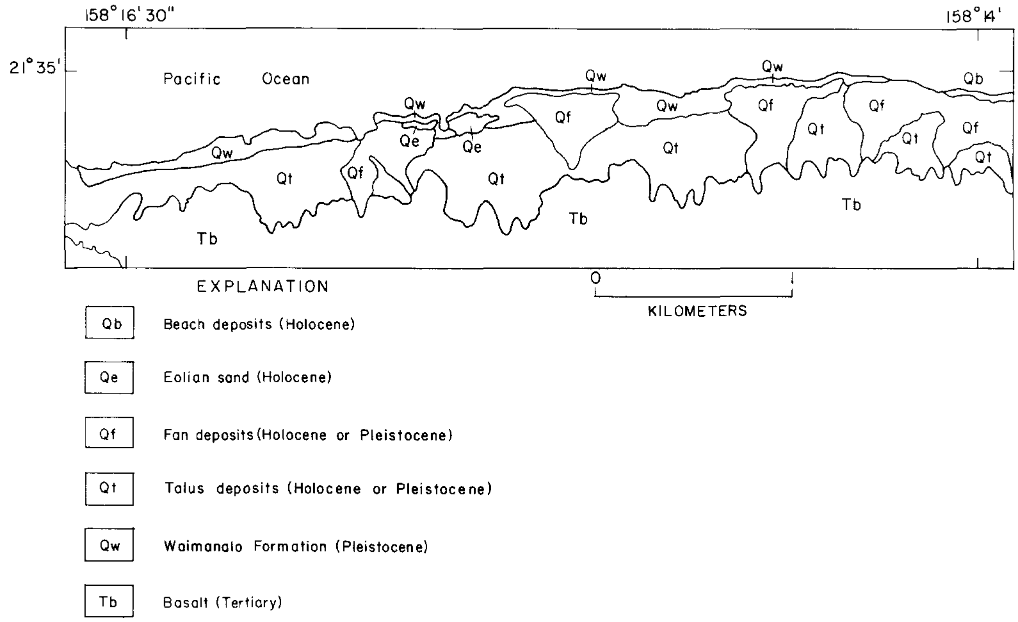

Fig. 2. Geologic map showing distribution of Tertiary and Quaternary deposits on the north shore of Oahu east of Kaena Point.

or are modified such that detailed stratigraphy cannot be described. Other localities have survived but provide only minimum estimates of the elevation of the Waimanalo high sea stand. For example, small reefs crop out at the Makai Range pier at Kaupo Beach Park at +2.5 m, and at Alala Point near Kailua at +3.5. At Diamond Head, near the lighthouse, a small patch of coral-bearing conglomerate is exposed at +3.5 m, but is overlain by ~2 m of eolianite. At Kahuku Point, growth-position corals are exposed, but occur below sea level and up to +2.5 m above sea level, where they are overlain by eolianite. The best exposures are near Mokapu Point, southeast of Kaena Point, and directly east of Kaena Point (Fig. 1). In his 1:62,500 scale map of the geology of Oahu, Stearns (1939) mapped the reef east of Kaena Point, but curiously did not include this in his 1974 and 1978 maps (Fig. 1). We found that the Waimanalo Formation is better exposed and better preserved here than anywhere else on the island. Using 1:12,000-scale aerial photographs as a base, we remapped the Quaternary deposits along the coast just east of Kaena Point (Fig. 2). In this area, there is a nearly continuous exposure of the Waimanalo Formation that extends along the coast for ~4 km. The limestone east of Kaena Point has two facies, a lower facies consisting of coral/algal heads in growth position and an upper facies of uncemented, seaward-dipping conglomerate (Fig. 3). The clasts in the conglomerate are well-rounded pebbles and cobbles composed mostly of the corals *Pocillopora* and *Porites*. We found no evidence of subaerial exposure, such as a paleosol or weathered surface, at the contact

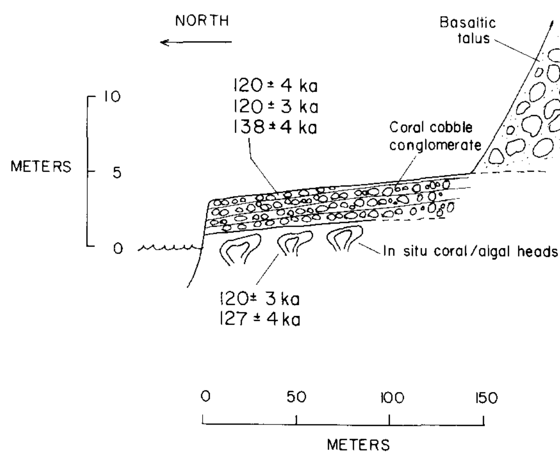

Fig. 3. Cross section of deposits east of Kaena Point, showing stratigraphic relations and U-series ages of corals.

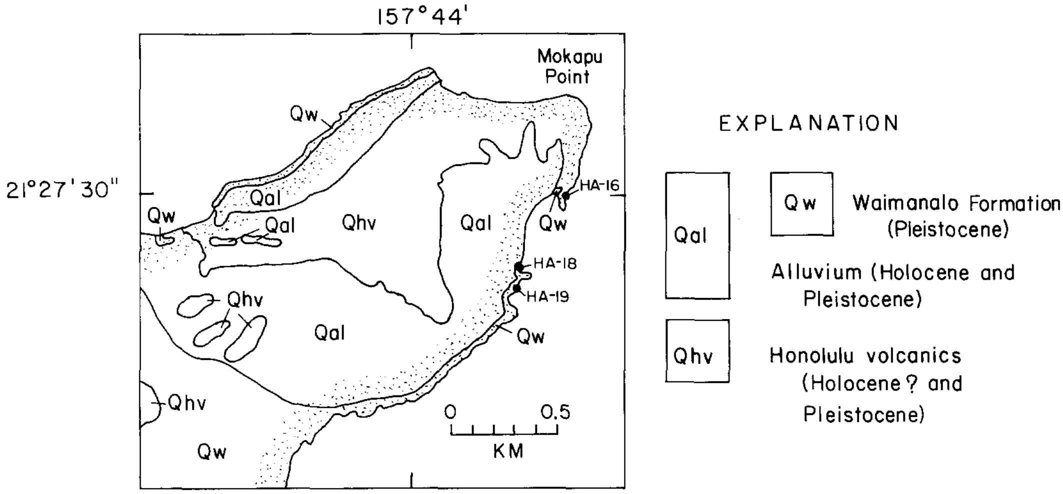

Fig. 4. Geologic map of the area around Mokapu Point, showing fossil localities and localities where elevation measurements were taken. Geologic data modified from Wentworth and Hoffmeister (1939) and Langenheim and Clague (1987).

between the two facies. The maximum exposed elevation of the reef is about 4.5 m, but this is a minimum estimate, because the inner edge of the reef is not exposed, owing to burial by younger talus, fan, and eolian deposits (Fig. 3). Approximately 3.5 km southeast of Kaena Point (Ku et al.'s locality C9), the Waimanalo Formation is also exposed. At this locality, the inner edge of the marine deposits is also covered by colluvium, but we measured 2.5 m of coral-bearing marine conglomerate that overlies a shore platform (cut on basalt) with an elevation of 5–6 m. Thus, marine deposits around Kaena Point have an elevation of at least 7.5 m.

Exposures of the Waimanalo Formation occur at various places around Mokapu Point (Fig. 4). At the northernmost localities south of the point (e.g. HA-16 on Fig. 4), the deposits are gently dipping, generally well-sorted and poorly cemented, coral-bearing sands with few gravels; we interpret them to be beach or sublittoral sands. The deposits are 2–3 m thick in most places and have maximum elevations of 12.5 m above sea level. Farther south at localities HA-18 and HA-19 (Fig. 4), the beach or sublittoral sands are underlain by a 1–2 m-thick marine conglomerate with growth-position coral heads (*Porites*) and coral and basalt pebbles and cobbles (Fig. 5). The maximum elevation of the upper beach or sublittoral sands here is also about 12.5 m; growth-position corals at these localities occur as high as 8.5 m. Ku et al. (1974) reported an age of 131±8 ka for a *Porites* and an age of 134±7 ka for a *Pocillopora*, both apparently from the lower conglomerate facies of the deposit.

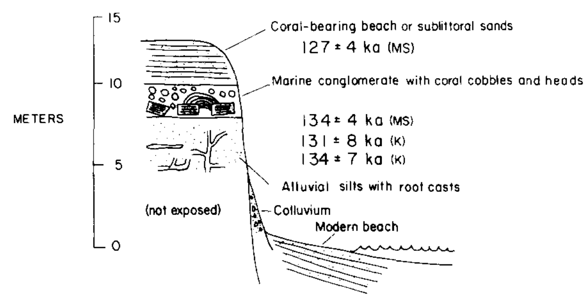

Fig. 5. Cliff exposure of Quaternary deposits at Mokapu Point showing stratigraphic relations, elevations of marine deposits, and U-series ages of corals. U-series ages followed by (*K*) are from Ku et al. (1974); those followed by (*MS*) are from the present study.

At Kahe Point, a patchy marine conglomerate is found on basalt at an elevation of 10.5±1.5 m (Fig. 6). This areally limited deposit consists of rounded cobbles of both coral and basalt weakly cemented by calcium carbonate. No corals in growth position were found in this deposit, and there is no stratigraphic evidence of more than one unit in the conglomerate. Seaward of this

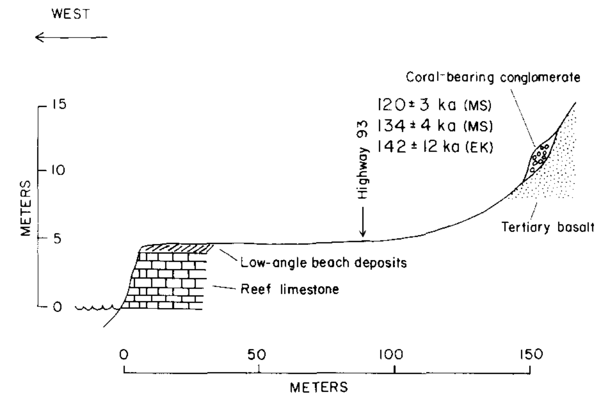

Fig. 6. Cliff and roadcut exposures of marine deposits near Kahe Point, showing elevations of marine units and U-series ages of coral. U-series age followed by (*EK*) is from Easton and Ku (1981); those followed by (*MS*) are from the present study.

deposit, in situ reef limestone is exposed in the modern sea cliff, but available exposures are not sufficient to determine if the in situ limestone is correlative with the conglomerate found higher up on the hillslope (Fig. 6). Easton and Ku (1981) reported a single U-series age of 142±12 ka on a *Porites* clast collected from the higher conglomerate.

3. Uranium-series dating

We collected well-preserved specimens of *Pocillopora* and *Porites* from most exposures of the Waimanalo Formation on Oahu for dating by the uranium-series methods. The results from collections made east of Kaena Point, Mokapu Point, and Kahe Point are reported here. Uranium and thorium concentrations and isotopic activity ratios were determined by isotope-dilution alpha spectrometry using a combined ^{236}U–^{229}Th spike as a yield tracer. All uncertainties given are based on propagated errors from counting statistics and are one sigma.

Modern specimens of *Porites* and *Pocillopora* were collected from Mokuleia Beach, which is ~3 km east of the easternmost exposure of the Waimanalo Formation mapped in Fig. 2 (Table 1). These samples, HA-14(1) and HA-14(2), have U concentrations of 2–3 ppm, no measurable amounts of ^{230}Th, and have $^{234}U/^{238}U$ activity ratios that are, within analytical uncertainty, in the range of values reported for Pacific Ocean water (Chen et al., 1986). The concentrations of U are within the range reported by other workers for modern tropical corals and serve as a criterion

Table 1
Uranium concentrations, isotopic activity ratios, and ages of corals from various lacalities on Oahu

Sample	Loc.[a]	Genus[b]	Calcite (%)	U (ppm)	$^{234}U/^{238}U$ activity ratios	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Age[c] (ka)
HA-14(1)	MB	*Por.*	<2	2.72±0.04	1.13±0.01	>1	<0.001	<0.01
HA-14(2)	MB	*Poc.*	<1	2.77±0.04	1.13±0.01	>2	<0.001	<0.01
HA-3R	MP	Algae[d]	100	0.74±0.01	1.12±0.02	>1	<0.003	<0.3
HA-21(2)	KP	*Por.*[e]	<1	2.77±0.05	1.06±0.02	>300	0.72±0.01	135±4
HA-20(2)	KP	*Por.*[e]	1	2.55±0.03	1.12±0.01	>600	0.68±0.01	120±3
HA-20A	KP	*Por.*[e]	6	2.78±0.03	1.11±0.01	>1000	0.70±0.01	127±4
HA-15(1)	KP	*Por.*	4	2.88±0.06	1.13±0.02	>300	0.74±0.02	140±8
HA-15(4)	KP	*Por.*	<1	2.91±0.04	1.10±0.01	>300	0.73±0.01	138±4
HA-15(2)	KP	*Poc.*	<1	2.57±0.04	1.10±0.01	>600	0.68±0.01	120±4
HA-15(3)	KP	*Poc.*	<1	2.72±0.04	1.11±0.01	>300	0.68±0.01	120±3
HA-18D(1)	MP	*Poc.*	<1	2.95±0.04	1.11±0.01	>300	0.70±0.01	127±4
HA-18A(2)	MP	*Poc.*	<1	2.9±0.4	1.11±0.01	>300	0.72±0.01	134±4
HA-7X	KAP	*Poc.*	<1	2.48±0.03	1.12±0.01	>800	0.68±0.01	120±3
HA-7Y	KAP	*Por.*	1	2.78±0.03	1.11±0.01	>200	0.72±0.01	134±4

[a]MB = Mokuleia Beach; KP = Kaena Point; MP = Mokupa Point; KAP = Kahe Point. [b]*Por.* = *Porites* sp.; *Poc.* = *Pocillopora* sp. [c]Calculated using half-lives of 244,000 yr (^{234}U) and 75,200 yr (^{230}Th). [d]Unidentified coralline algae. [e]Samples taken from coral heads in growth position.

to assess whether fossil corals from Oahu have lost U during diagenesis. A specimen of modern coralline algae was also collected at Mokapu Point and analyzed. It has a significantly lower concentration of U than coral (Table 1), but has a $^{234}U/^{238}U$ value similar to modern sea water, within analytical uncertainty. It also contains no significant amounts of Th. These data suggest that fossil algae has the potential to be a suitable material for U-series dating.

U-series data for fossil corals can be evaluated by mineralogic, geochemical, and isotopic criteria in order to determine if apparant ages are reliable. Corals should be unrecrystallized, because conversion of primary aragonite to calcite can result in loss of U. X-ray diffraction analyses indicate that all samples but one are 96–100% aragonite; HA-20A originally had only 85% aragonite, but heavy liquid separations resulted in a subsample with 94% aragonite. U concentrations should be in the range found in modern corals (2–3 ppm), and all our samples meet this qualification (Table 1). Samples should be free of inherited ^{230}Th, derived from silicate mineral contaminants; contaminant-free samples are indicated by $^{230}Th/^{232}Th$ values that are greater than about 20. All fossil corals we analyzed have $^{230}Th/^{232}Th$ values well above 200 (Table 1). In recent years, the most serious concern over closed-system conditions in fossil corals has been from apparent high initial $^{234}U/^{238}U$ values (Ku et al., 1990; Bard et al., 1991; Chen et al., 1991; Hamelin et al., 1991; Stein et al., 1993). Corals take up U (but no Th) in isotopic equilibrium with sea water, which has $^{234}U/^{238}U$ values of 1.135–1.155 (Chen et al., 1986). If a fossil coral has been a closed system with respect to ^{238}U, ^{234}U, and ^{230}Th, there is a specific evolutionary pathway that will be followed (Fig. 7). Samples that have experienced closed-system conditions should have $^{234}U/^{238}U$ values that, within analytical error, overlap the pathways shown as dashed subhorizontal lines in Fig. 7. Results indicate that all but two of the samples we analyzed [HA-15(1) and HA-21(2)] meet closed-system conditions and therefore can be regarded as having reliable ages.

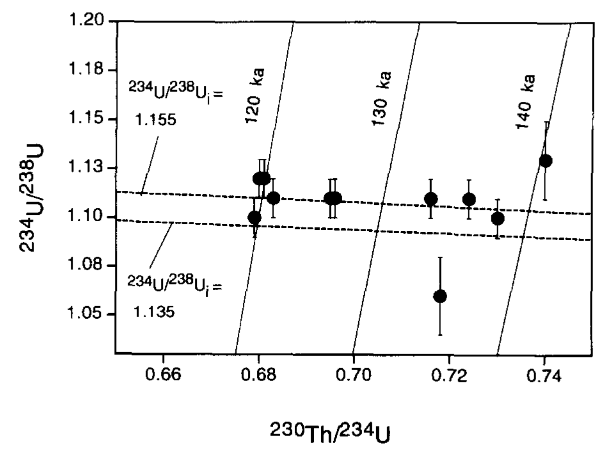

Fig. 7. Isotopic evolution plot showing sympathetic variation of $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ as a function of time for corals with initial $^{234}U/^{238}U$ values of 1.155 (upper dashed line) and 1.135 (lower dashed line). Solid vertical lines are isochrons. Closed circles are samples from the Waimanalo Formation in Table 1; error bars represent one standard deviation. For clarity, error bars for $^{230}Th/^{234}U$ values are not presented.

4. Results and discussion

4.1. The concept of a dual sea-level peak during the last interglacial period

The U-series ages from the Waimanalo Formation do not support the concept of a dual sea-level peak on Oahu during the last interglacial period. At Mokapu Point, our U-series ages agree with those of Ku et al. (1974). One sample of *Pocillopora* from the lower conglomerate facies (that contains growth-position corals) gives an age of 134±4 ka and a *Pocillopora* from the upper beach or sublittoral sand facies gives an age of 127±4 ka (Table 1; Fig. 5). The overlapping analytical uncertainties of these samples do not allow us to interpret these deposits as representing two distinct high stands of sea. At Kahe Point, where we analyzed corals from the upper conglomerate, ages of 120±3 ka and 134±4 were obtained (Table 1; Fig. 6). Closed-system corals in growth position east of Kaena Point have ages of 120±3 ka and 127±4 ka, and ages of closed-system corals from the overlying conglomerate facies range from 120±3 ka to 138±4 ka (Table 1; Fig. 3). Thus, our data indicate that there is no systematically older suite of ages for the in situ facies and no systematically younger suite of ages for the overlying conglomerate facies. We interpret the range of ages found in both facies to represent a single high stand of sea, in agreement with the conclusions of Kaufman (1986) and Chen et al. (1991). A compilation of both our age data and those of Ku et al. (1974) reinforces this conclusion, particularly when compared with the oxygen isotope record, which shows only one peak during substage 5e (Fig. 8).

4.2. *The magnitude of sea-level rise during the last interglacial period*

Islands such as Oahu which are distant from plate boundaries formerly were considered to be the most reliable coastlines from which to obtain absolute data on the magnitude of sea-level high stands (Veeh, 1966). This reasoning is based on the assumption that coastlines on intraplate islands or along passive continental margins are tectonically stable and therefore emergent marine deposits record higher-than-present sea stands. Notches that are thought to represent the Waimanalo high sea stand are frequently quoted as having a +7.6 m elevation, based on data presented in Ruhe et al. (1965), but this figure is really the mean value of a great many measurements, and most are of nickpoints on interfluves measured on topographic maps, rather than wave-cut benches with marine deposits identified in the field. Stearns' (1978) principal reference locality for the Waimanalo high stand of sea (Fig. 1) is actually two undated notches cut into eolianite with reported elevations of 6.7 m and 8.2 m; Stearns did not describe marine deposits associated with the notches. Based on an unsuccessful field search, we conclude that this eolianite with its notches no longer exists.

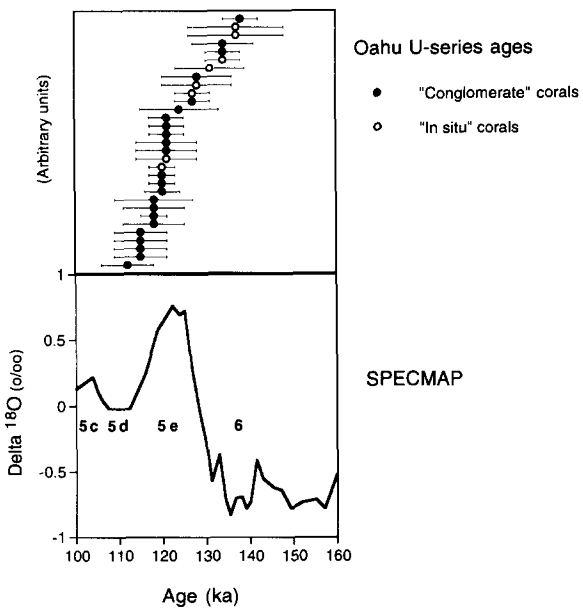

Fig. 8. Plot showing a part of the SPECMAP orbitally-tuned deep-sea oxygen isotope record that covers the last interglacial period (data from Martinson et al., 1987) in comparison to U-series ages of Waimanalo Formation corals from the present study and Ku et al. (1974). Only samples with concordant $^{234}U/^{238}U$ values are presented. Error bars on U-series ages are $\pm 1\sigma$. Bold numbers on lower curve are oxygen isotope stages or substages.

At Kahe Point, *Porites* from the ~11 m deposit gives an age of 134±4 ka and *Pocillopora* gives an age of 120±3 ka (Table 1). Although these ages indicate that the corals grew during the same high stand of sea that is represented by the Waimanalo Formation at Kaena Point and Mokapu Point, the unbedded and poorly sorted character of this deposit do not rule out deposition by storm waves. However, at Mokapu Point we measured three exposures of Waimanalo deposits, with the highest coral-bearing sands at elevations of 12.5, 12.4, and 10 m (locs. HA-16, HA-18, and HA-19, respectively, on Fig. 4) above sea level. Growth-position corals occur at elevations at least up to 8.5 m above sea level (Fig. 5). We emphasize that as far as a paleo-sea level elevation is concerned, the growth-position corals at Mokapu Point give only a minimum estimate. The majority of reef-building corals of the Pacific (including most species of *Pocillopora* and *Porites*) grow in water depths ranging from less than a meter to as much as 27 m, although some grow at much greater depths (Wells, 1954). Because we lack exposures with sufficient detail that would enable us to reconstruct the original reef geomorphology, the growth-position corals at Mokapu Point yield only a *minimum* estimate of paleo-sea level. However, assuming a water depth of at least 1 m, the growth-position corals at Mokapu Point indicate a minimum paleo-sea level of about 9.5 m, relative to present. The coral-bearing sands found up to 12.5 m around Mokapu Point do not appear to have been deposited by storm waves or by a giant wave from a submarine landslide (Moore and Moore, 1984; Moore and Moore, 1988); they are well-sorted, bedded sands that lack significant coral or basalt gravels. We interpret these deposits to be typical beach or sublittoral sands. Overall, the elevations of the growth-position corals give a minimum estimate of paleo-sea level of about 9.5 m, and the beach or sublittoral sands give a maximum estimate of paleo-sea level of about 12.5 m.

In late Quaternary sea-level and coastal tectonic studies, the last interglacial is frequently cited as having a maximum sea level of +6 m relative to present (e.g., Broecker et al., 1968; Bloom et al., 1974; Dodge et al., 1983; Muhs et al., 1992a; Ota and Omura, 1992). The higher-than-present sea level is thought to have been due to a lower ice volume (relative to present) of either the Greenland or West Antarctic ice sheets (Emiliani, 1969; Mercer, 1970, 1978; Koerner, 1989; Johnson, 1991). The magnitude of sea-level rise is based on a rough average of elevations of ~125-ka marine deposits from a variety of what are thought to be tectonically stable intraplate and passive margin localities reported by Veeh (1966) in a pioneering study. More recent studies have in general confirmed Veeh's (1966) earlier conclusions. The best data are from wave-cut notches or emergent reef deposits with shallow-water corals in growth position on tectonically stable islands in the western Atlantic Ocean. On San Salvador and Great Inagua Islands in the Bahamas, Chen et al. (1991) report that last-interglacial, shallow-water corals (e.g. *Acropora palmata*) in growth position record a paleo-sea level of about 6 m above present sea level. This paleo-sea level is supported by the presence of a wave-cut notch, found elsewhere in the Bahamas, at 5.6 m (Neumann and Moore, 1975). On Bermuda, Harmon et al. (1983) report that ~125-ka, shallow-water patch reefs and marine calcarenites are 5 ± 1 m above modern sea level. In a number of other locations, paleo-sea level indicators for the last interglacial period provide only minimum or maximum elevations either because dated corals are not shallow-water species (in which case elevations are minimum estimates), or corals have been reworked into beach deposits (in which case elevations may be maximum estimates). Szabo et al. (1978) report maximum elevations of 2–3 m for 120-to 125-ka corals in growth position on the Yucatan Peninsula. The Key Largo Limestone has growth-position corals of last-interglacial age (Osmond et al., 1965; Broecker and Thurber, 1965; Muhs et al., 1992b) and has a maximum elevation of about 5.5 m on Windley Key, Florida (Hoffmeister and Multer, 1968). Muhs et al. (1992a) report U-series ages of 117–127 ka for corals from a +6 m marine conglomerate on tectonically stable Guadalupe Island off Baja California. In a comprehensive review of last-interglacial shorelines around Australia, Murray-Wallace and Belperio (1991) concluded that in areas thought to be tectonically stable, sea level was never higher than ~6 m and may have been lower. Parts of the Australian coastline that have last-interglacial deposits higher than 6 m are attributed by them to tectonic uplift in the past ~125 kyr. We conclude from all these studies that sea level during the last interglacial period had a maximum elevation of about 6 m, relative to present. Thus, the +8.5 to +12.5 m Waimanalo marine deposits at Mokapu Point and Kahe Point on Oahu differ from the best estimates of paleo-sea level at ~125 ka by 2.5–6.5 m.

4.3. *Uplift of Oahu due to lithospheric flexure from volcanic loading*

Lithospheric flexure can explain the higher-than-expected Waimanalo deposits on Oahu because the island of Hawaii (Fig. 1) is active volcanically. Tide gauge data, evidence of subaerial exposure surfaces and soils below sea level, submarine terraces, submarine canyons, and seismic refraction data on crust depths all indicate that volcanic loading on the island of Hawaii is causing subsidence of the Hawaiian Ridge (Moore, 1987). Recent studies of submerged coral reef terraces off Hawaii have documented that the island is subsiding at a rate of about 2–3 m/kyr (Szabo and Moore, 1986; Moore and Campbell, 1987; Ludwig et al., 1991). Subsidence due to volcanic loading on Hawaii could result in an upward lithospheric flexure on distant islands in the Hawaiian chain (Moore, 1970). Using tide gauge data, Moore (1970) showed that the islands of Hawaii and Maui are undergoing subsidence, whereas Kauai and Midway are undergoing uplift. Moore (1987) updated this analysis with additional tide gauge data and reached the same conclusions, although the new data result in lower rates of subsidence for the islands of Hawaii and Maui. A longer-term (1947–1979) sea-level trend for Midway Island is −0.58 mm/yr (Barnett, 1984). This trend, when compared to the global trend, suggests an uplift rate on the order of 2.2 mm/yr, in support of Moore's original (1970) conclusion. An updated long-term (1905–1980) sea-level trend for Oahu, based on tide gauge data, is 1.6 mm/yr (Barnett, 1984). Mean global sea-level rise from 1880–1980 records, obtained from tide gauge stations located away from tectonically active or isostatically rebounding areas, is 1.8 mm/yr (±0.1 mm/yr) (Douglas, 1991). The long-term trend for Oahu, therefore, is not significantly different from the global trend, so a low rate of uplift may not be detectable from tide gauge data. However, if sea level during the last interglacial at ~125 ka was +6 m relative to present, and Waimanalo deposits at Mokapu Point indicate a relative paleo-sea level of +9.5 m (+8.5 m for growth-position corals, plus a minimum of 1 m water depth) to +12.5 m, then a late Quaternary uplift rate for Oahu of 0.028–0.052 m/kyr is implied. This rate is similar to that calculated from last-interglacial coral reef data for the southern Cook Islands where Woodroffe et al. (1991) attributed uplift to lithospheric flexure from volcanic loading.

Older marine deposits at +30 m on Oahu were reported by Stearns (1978) and are the basis for his Kaena high stand of sea. Stearns (1973) reported a single U-series analysis (done by H.H. Veeh) of a coral from +30 m Kaena-age deposits from the Lualualei Valley on the leeward (west) coast of Oahu; the $^{230}Th/^{234}U$ age is reported by Veeh through Stearns (1973) to be >200 ka and a $^{234}U/^{238}U$ value of 1.03 is reported to indicate an age of 600±100 ka. We observed these and other +30 m Kaena high stand deposits on Oahu and confirmed their general elevations. The sedimentology of these deposits and their limited, but similar elevations at at least three localities on Oahu suggest that they are not deposits left by a giant wave from a submarine landslide of the sort that has been documented on Lanai and other islands by Moore and Moore (1984) and Moore and Moore (1988). If they are indeed ~600 ka in age, they provide evidence for long-term uplift of Oahu, because a middle Pleistocene high stand of sea that is 30 m higher than the present one is unlikely, given the present volume of ice sheets that are most likely to be susceptible to melting during an interglacial. The present Greenland ice sheet could cause a rise in sea level of only 7–7.4 m (Reeh, 1985; Warrick and Oerlemans, 1990), and the present West Antarctic ice sheet could cause a rise in sea level of only 5–10 m (Mercer, 1978; Drewry et al., 1982; Lingle, 1985). This interpretation is supported by examination of the oxygen isotope composition of foraminifera in deep-sea cores, because these data record, at least in part, relative ice volumes, and therefore relative sea level. Examination of the record from equatorial Pacific core V28-239 shows that the Kaena high sea stand, if 600±100 ka, could correlate with deep-sea stages 13, 15, or 17 (Fig. 9). None of these interglacial periods shows evidence of a

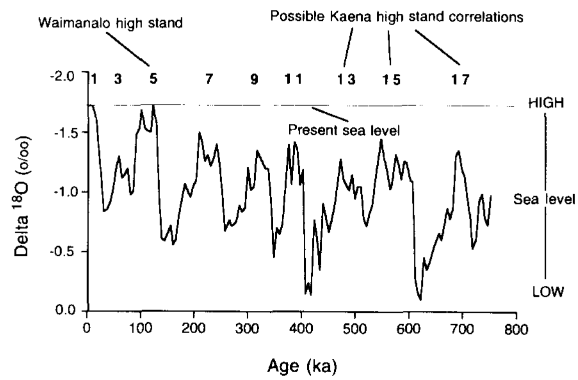

Fig. 9. The record of oxygen isotopic composition of foraminifera in equatorial Pacific core V28-239 as a function of age, and possible correlations of the Kaena sea level high stand of Oahu with interglacial periods (recorded as odd-numbered stages in bold numerals). Age estimates calculated by assumption of a uniform sedimentation rate of 0.93 cm/kyr, based on the Brunhes/Matuyama boundary in the core at 726 cm, and an age for this boundary of 780 ka (Spell and McDougal, 1992). Oxygen isotope data from Shackleton and Opdyke (1976).

significantly higher-than-present sea level. In fact, all three stages may record lower-than-present sea levels, although the oxygen isotope record is to some degree dependent on ocean water temperatures as well as ice volumes. Assuming that sea level was within ± 5 m of the present at the time the Kaena deposits were laid down, and given Veeh's age uncertainties, we calculate a long-term uplift rate of 0.036–0.070 m/kyr, similar to the late Quaternary rate (Fig. 10).

5. Conclusions

Our studies of the Waimanalo Formation on Oahu lead us to several conclusions. There is no compelling stratigraphic or U-series evidence for a bipartite stand of sea levels during the last interglacial period. U-series data for both growth-position corals and overlying coral conglomerate show the same ranges of ages. We conclude that the range of ages represents a single high stand of sea.

Last-interglacial marine deposits, which include corals in growth position, occur at significantly higher elevations at some localities on Oahu than those on tectonically stable coasts and islands elsewhere. A plausible explanation is that lithospheric flexure, in response to late Quaternary volcanic loading on the island of Hawaii, has uplifted Oahu at an average rate of ~0.03–0.05 m/kyr. This hypothesis is supported by the presence of older marine deposits at ~30 m that cannot be explained by a higher-than present sea level during the middle Pleistocene. Existing age data for these older deposits allow calculation of a long-term uplift rate that is similar to the late Quaternary uplift rate.

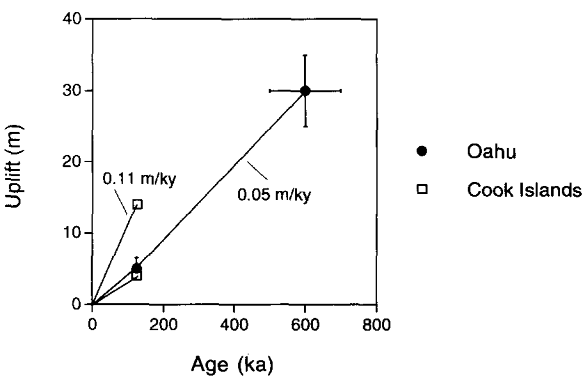

Fig. 10. Plot of inferred uplift as a function of coral U-series age from Oahu and the southern Cook Islands. Older Oahu data from Stearns (1973); Cook Islands data from Woodroffe et al. (1991). Slopes of lines are uplift rates.

If lithospheric flexure is occurring in the Hawaiian Islands, then other Pacific island chains with active hot spots could be similarly affected, as has been documented for the southern Cook Islands by Woodroffe et al. (1991). Examples include the Marquesas Islands, the Society Islands, the Galapagos Islands, and the Tuamotu Archipelago. Elevations of last-interglacial and older marine deposits on these islands should not be used as reference points for the magnitude of sea-level rise.

Acknowledgements

This study was supported by the Global Change and Climate History Program of the U.S. Geological Survey and is a contribution to the Last Interglacial: Timing and Environment (LITE) Project. We thank J. Moore, H. James, and T. Stafford for assistance in the field and helpful discussions. The U.S. Marine Corps kindly gave us access to exposures on Mokapu Point. G. Cebula and J. Groen increased the aragonite content of one of our samples using heavy liquid separations. C. Bush assisted with data processing. D. Clague, C. Naeser, H. Kelsey, and J. Lecompte read an earlier version of the paper and made helpful comments for its improvement.

References

Barnett, T.P., 1984. The estimation of "global" sea level change: A problem of uniqueness. J. Geophys. Res., 89: 7980–7988.

Bard, E., Fairbanks, R.G., Hamelin, B., Zindler, A. and Hoang, C.T., 1991. Uranium-234 anomalies in corals older than 150,000 years. Geochim. Cosmochim. Acta, 55: 2385–2390.

Bloom, A.L., Broecker, W.S., Chappell, J.M.A., Matthews, R.K. and Mesolella, K.J., 1974. Quaternary sea level

fluctuations on a tectonic coast: New $^{230}Th/^{234}U$ dates from the Huon Peninsula, New Guinea. Quat. Res., 4: 185–205.
Broecker, W.S. and Thurber, D.L., 1965. Uranium-series dating of corals and oolites from Bahaman and Florida Key limestones. Science, 149: 58–60.
Broecker, W.S., Thurber, D.L., Goddard, J., Ku, T.-L., Matthews, R.K. and Mesolella, K.J., 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep-sea sediments. Science, 159: 297–300.
Chappell, J., 1974. Geology of coral terraces, Huon Peninsula, New Guinea: A study of Quaternary tectonic movements and sea level changes. Geol. Soc. Am. Bull., 85: 553–570.
Chappell, J., 1983. A revised sea level record for the last 300,000 yrs from Papua New Guinea. Search, 4: 99–101.
Chappell, J. and Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature, 324: 137–140.
Chappell, J. and Veeh, H.H., 1978. Late Quaternary tectonic movements and sea-level changes at Timor and Atauro Island. Geol. Soc. Am. Bull., 89: 356–358.
Chen, J.H., Edwards, R.L. and Wasserburg, G.J., 1986. ^{238}U, ^{234}U and ^{232}Th in seawater: Earth Planet. Sci. Lett., 80: 241–251.
Chen, J.H., Curran, H.A., White, B. and Wasserburg, G.J., 1991. Precise chronology of the last interglacial period: ^{234}U–^{230}Th data from fossil coral reefs in the Bahamas. Geol. Soc. Am. Bull., 103: 82–97.
Dodge, R.E., Fairbanks, R.G., Benninger, L.K. and Maurrasse, F. 1983. Pleistocene sea levels from raised coral reefs of Haiti. Science, 219: 1423–1425.
Douglas, B.C., 1991. Global sea level rise. J. Geophys. Res., 96: 6981–6992.
Drewry, D.J., Jordan, S.R. and Jankowski, E., 1982. Measured properties of the Antarctic ice sheet: Surface configuration, ice thickness, volume and bedrock characteristics. Ann. Glaciol., 3: 83–91.
Easton, W.H. and Ku, T.-L., 1981. $^{230}Th/^{234}U$ dates of Pleistocene deposits on Oahu. Bull. Mar. Sci., 31: 552–557.
Emiliani, C., 1969. Interglacial high sea levels and the control of Greenland ice by the precession of the equinoxes. Science, 166: 1503–1504.
Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature, 342: 637–642.
Hamelin, B., Bard, E., Zindler, A. and Fairbanks, R.G., 1991. $^{234}U/^{238}U$ mass spectrometry of corals: How accurate is the U–Th age of the last interglacial period? Earth Planet. Sci. Lett., 106: 169–180.
Hansen, J., Fung, I., Lacis, A., Rind, D., Lebedeff, S., Ruedy, R. and Russell, G., 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res., 93: 9341–9364.
Harmon, R.S., Mitterer, R.M., Kriausakul, N., Land, L.S., Schwarcz, H.P., Garrett, P., Larson, G.J., Vacher, H.L. and Rowe, M., 1983. U-series and amino-acid racemization geochronology of Bermuda: Implications for eustatic sea-level fluctuation over the past 250,000 years. Palaeogeogr., Palaeoclimatol., Palaeoecol., 44: 41–70.
Hoffmeister, J.E. and Multer, H.G., 1968. Geology and origin of the Florida Keys. Geol. Soc. Am. Bull., 79: 1487–1502.
Johnson, R.G., 1991. Major northern hemisphere deglaciation caused by a moisture deficit 140 ka. Geology, 19: 686–689.
Kaufman, A., 1986. The distribution of $^{230}Th/^{234}U$ ages in corals and the number of last interglacial high-sea stands. Quat. Res., 25: 55–62.
Koerner, R.M., 1989. Ice core evidence for extensive melting of the Greenland ice sheet in the last interglacial. Science, 244: 964–968.
Ku, T.-L., Kimmel, M.A., Easton, W.H. and O'Neil, T.J., 1974. Eustatic sea level 120,000 years ago on Oahu, Hawaii. Science, 183: 959–962.
Ku, T.-L., Ivanovich, M. and Luo, S., 1990. U-series dating of last interglacial high sea stands: Barbados revisited. Quat. Res., 33: 129–147.
Langenheim, V.A.M. and Clague, D.A., 1987. The Hawaiian-Emperor volcanic chain Part II: Stratigraphic framework of volcanic rocks of the Hawaiian Islands. In: R.W. Decker, T.L. Wright and P.H. Stauffer (Editors), Volcanism in Hawaii. U.S. Gov. Print. Off., Washington, U.S. Geol. Surv. Prof. Pap., 1350, pp. 55–84.
Lingle, C.S., 1985. A model of a polar ice stream, and future sea-level rise due to possible drastic retreat of the West Antarctic ice sheet. In: Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-induced Climatic Change. Natl. Res. Counc., Washington, D.C., pp. 317–330.
Ludwig, K.R., Szabo, B.J., Moore, J.G. and Simmons, K.R., 1991. Crustal subsidence rate off Hawaii determined from $^{234}U/^{238}U$ ages of drowned coral reefs. Geology, 19: 171–174.
Lum, D. and Stearns, H.T., 1970. Pleistocene stratigraphy and eustatic history based on cores at Waimanalo, Oahu, Hawaii: Geol. Soc. Am. Bull., 81: 1–16.
Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Jr. and Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Res., 27: 1–29.
Mercer, J.H., 1970. Antarctic ice and interglacial sea levels. Science, 168: 1605–1606.
Mercer, J.H., 1978. West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster. Nature, 271: 321–325.
Mesolella, K.J., Matthews, R.K., Broecker, W.S. and Thurber, D.L., 1969. The astronomical theory of climatic change: Barbados data. J. Geol., 77: 250–274.
Moore, G.W. and Moore, J.G., 1988. Large-scale bedforms in boulder gravel produced by giant waves in Hawaii. Geol. Soc. Am. Spec. Pap., 229: 101–110.
Moore, J.G., 1970. Relationship between subsidence and volcanic load, Hawaii. Bull. Volcanol., 34: 562–576.
Moore, J.G., 1987. Subsidence of the Hawaiian Ridge. In: R.W. Decker, T.L. Wright and P.H. Stauffer (Editors), Volcanism in Hawaii. U.S. Gov. Print. Off., Washington, U.S. Geol. Surv. Prof. Pap., 1350, pp. 85–100.

Moore, J.G. and Campbell, J.F., 1987. Age of tilted reefs, Hawaii. J. Geophys. Res., 92: 2641–2646.

Moore, J.G. and Moore, G.W., 1984. Deposit from a giant wave on the island of Lanai, Hawaii. Science, 226: 1312–1315.

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

Muhs, D.R., Rockwell, T.K. and Kennedy, G.L., 1992a. Late Quaternary uplift rates of marine terraces on the Pacific coast of North America, southern Oregon to Baja California Sur. Quat. Int., 15/16: 121–133.

Muhs, D.R., Szabo, B.J., McCartan, L., Maat, P.B., Bush, C.A. and Halley, R.B., 1992b. Uranium-series age estimates of corals from Quaternary marine sediments of southern Florida. In: T.M. Scott and W.D. Allmon (Editors), Plio-Pleistocene Stratigraphy and Paleontology of Southern Florida. Fl. Geol. Surv. Spec. Publ., 36: 41–49.

Murray-Wallace, C.V. and Belperio, A.P., 1991. The last interglacial shoreline in Australia—A review. Quat. Sci. Rev., 10: 441–461.

Neumann, A.C. and Moore, W.S., 1975. Sea level events and Pleistocene coral ages in the northern Bahamas. Quat. Res., 5: 215–224.

Osmond, J.K., Carpenter, J.R. and Windom, H.L., 1965. $^{230}Th/^{234}U$ age of the Pleistocene corals and oolites of Florida. J. Geophys. Res., 70: 1843–1847.

Ota, Y. and Omura, A., 1992. Contrasting styles and rates of tectonic uplift of coral reef terraces in the Ryukyu and Daito Islands, southwestern Japan. Quat. Int., 15/16: 17–29.

Pillans, B., 1987. Quaternary sea-level changes: Southern hemisphere data. In: R.J.N. Devoy (Editor) Sea Surface Studies: A Global View. Croom Helm, London, pp. 264–293.

Reeh, N., 1985. Greenland ice-sheet mass balance and sea-level change. In: Glaciers, Ice Sheets, and Sea Level: Effect of a CO_2-induced Climatic Change. Natl. Res. Counc., Washington, D.C., pp. 155–171.

Ruhe, R.V., Williams, J.M. and Hill, E.L., 1965. Shorelines and submarine shelves, Oahu, Hawaii. J. Geol., 73: 485–497.

Shackleton, N.J. and Opdyke, N.D., 1976. Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene. Geol. Soc. Am. Mem., 145: 449–464.

Smart, P.L. and Richards, D.A., 1992. Age estimates for the late Quaternary high sea-stands. Quat. Sci. Rev., 11: 687–696.

Spell, T.L. and McDougall, I., 1992. Revisions to the age of the Brunhes–Matuyama boundary and the Pleistocene geomagnetic polarity timescale. Geophys. Res. Lett., 19: 1181–1184.

Stearns, C.E., 1976. Estimates of the position of sea level between 140,000 and 75,000 years ago. Quat. Res., 6: 445–449.

Stearns, H.T., 1939. Geologic map and guide to the island of Oahu, Hawaii. Territory Hawaii, Div. Hydrogr. Bull., 2: 1–75.

Stearns, H.T., 1966. Geology of the State of Hawaii. Pacific Books, Palo Alto.

Stearns, H.T., 1973. Potassium–argon ages of lavas from the Hawi and Pololu volcanic series, Kohala volcano, Hawaii: Discussion. Geol. Soc. Am. Bull., 84: 3483–3484.

Stearns, H.T., 1974. Submerged shorelines and shelves in the Hawaiian Islands and a revision of some of the eustatic emerged shorelines. Geol. Soc. Am. Bull., 85: 795–804.

Stearns, H.T., 1978. Quaternary shorelines in the Hawaiian Islands. Bernice P. Bishop Mus. Bull., 237: 1–57.

Szabo, B.J. and Moore, J.G., 1986. Age of −360 m reef terrace, Hawaii, and the rate of late Pleistocene subsidence of the island. Geology, 14: 967–968.

Szabo, B.J., Ward, W.C., Weidie, A.E. and Brady, M.J., 1978. Age and magnitude of late Pleistocene sea-level rise on the eastern Yucatan Peninsula. Geology, 6: 713–715.

Veeh, H.H., 1966. Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea-level stand. J. Geophys. Res., 71: 3379–3386.

Warrick, R. and Oerlemans, J., 1990. Sea level rise. In: J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Editors), Climate Change: The IPCC Scientific Assessment. Cambridge Univ. Press, Cambridge, pp. 257–281.

Wells, J.W., 1954. Recent corals of the Marshall Islands. U.S. Geol. Surv. Prof. Pap., 260-I, pp. 385–486.

Wentworth, C.K. and Hoffmeister, J.E., 1939. Geology of Ulupau Head, Oahu. Geol. Soc. Am. Bull., 50: 1553–1572.

Woodroffe, C.D., Short, S.A., Stoddart, D.R., Spencer, T. and Harmon, R.S., 1991. Stratigraphy and chronology of late Pleistocene reefs in the southern Cook Islands, south Pacific. Quat. Res., 35: 246–263.