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Barney J. Szabo
U.S. Geological Survey

Kenneth R. Ludwig
U.S. Geological Survey

Daniel R. Muhs
U.S. Geological Survey, dmuhs@usgs.gov

Kathleen R. Simmons
U.S. Geological Survey, ksimmons@usgs.gov

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Barney J. Szabo,* Kenneth R. Ludwig, Daniel R. Muhs, Kathleen R. Simmons

Thorium-230 ages of emergent marine deposits on Oahu, Hawaii, have a uniform distribution of ages from ~114,000 to ~131,000 years, indicating a duration for the last interglacial sea-level high stand of ~17,000 years, in contrast to a duration of ~8000 years inferred from the orbitally tuned marine oxygen isotope record. Sea level on Oahu rose to ≥1 to 2 meters higher than present by 131,000 years ago or ~6000 years earlier than inferred from the marine record. Although the latter record suggests a shift back to glacial conditions beginning at ~119,000 years ago, the Oahu coral ages indicate a near present sea level until ~114,000 years ago.

The peak of the last interglacial period (marine oxygen isotope substage 5e) has been considered to be a possible analog for a future greenhouse climate resulting from the buildup of CO_2 and other gases (*1*). Estimates for the timing [peak at ~125 thousand years ago (ka)] and duration (~8 × 10^3 years) of the last interglacial have been derived mainly from an orbitally tuned $\delta^{18}O$ chronology of deep-sea cores, SPECMAP (*2–4*). If the oxygen isotopic composition of seawater is controlled principally by changes in global ice volume, the $\delta^{18}O$ variation in foraminifera provides a proxy record for changes in global sea level (*5*). However, from U-series ages of calcite at Devils Hole, Nevada (*6, 7*), Winograd *et al.* (*7*) inferred that the last interglacial began earlier (~140 ka) and lasted longer (~20 × 10^3 years) than the SPECMAP $\delta^{18}O$ record indicates. This result challenges the orbital-forcing theory of Milankovitch as being the primary trigger for major climatic changes that occurred during the Pleistocene (*7*).

Emergent fossil coral reefs on tectonically stable coasts provide a geologic record of a higher-than-present sea level during the last interglaciation. If a coral reef grows vertically, responding to a rising interglacial sea, then high-precision U-series dating of suitable coral samples can potentially reveal the timing of sea-level rise during an interglacial (*8*). In this study, we report ages of fossil corals from Oahu and use these results to ascertain the timing and duration of the last interglacial period.

Well-preserved coral reefs or coral-bearing marine deposits fringe much of Oahu (Fig. 1). We collected and analyzed samples of *Porites* sp. and *Pocillopora* sp. (both frequently found in typical shallow-water habitats of reefs) at 19 localities (Fig. 1) (*9*). Most last interglacial marine deposits on Oahu are gently dipping, generally well-sorted and well- to poorly cemented, coral-bearing conglomerate. We observed and collected corals in growth position only in deposits near Mokapu Point and Kahuku Point and at exposures of a reef east of Kaena Point (Fig. 1) (*10*).

Two tests for the reliability of U-series coral ages are that U concentrations should fall within the range of modern corals and that calculated initial $^{234}U/^{238}U$ activity ratios in fossil corals should be close to that of modern seawater (*8*). Modern seawater has a $^{234}U/^{238}U$ ratio of 1.148 ± 0.002 (*11*). We classify fossil corals with calculated initial $^{234}U/^{238}U$ ratios in this range as category A samples and consider that their $^{230}Th/^{238}U$ ages are reliable (Table 1). Category B samples have initial $^{234}U/^{238}U$ ratios from 1.150 to 1.160 (as much as 1.0% higher than modern seawater) and are moderately reliable (accurate to within <2000 years) (*8, 12, 13*). Ages of samples with $^{234}U/^{238}U$ ratios greater than 1.160 are unreliable because of the likelihood of a significant open-system history for U (and possibly Th). Of the 33 last interglacial samples that we analyzed, 17 are category A, 12 are category B (below the 1.16 curve in Fig. 2), and 4 are unreliable and not discussed further.

Growth-position corals from ~7.3 m above sea level at Mokapu Point yielded ages of 129.9 ± 1.5 and 131.0 ± 2.7 ka, and corals from ~8.6 m above sea level have ages of 125.0 ± 3.8 and 123.2 ± 2.6 ka (uncertainties are 2σ). Growth-position corals from 1 to 3 m above sea level at Kahuku Point yielded ages of 120.3 ± 2.5, 122.1 ± 1.3, and 121.7 ± 1.5 ka, and two corals from east of Kaena Point, between 1 and 3 m above sea level, yielded ages of 110.5 ± 3.8 and 114.8 ± 2.1 ka. From these age determinations, we estimate that the apparent local paleosea level was at least 7 m higher than at present by ~130 ka and remained higher until at least ~115 ka. Because living *Porites* and *Pocillopora* occupy a considerable depth range (1 to 27 m below sea level), all of our paleosea level estimates on growth-position corals are minima.

The distribution of coral ages between about 131 and 114 ka is fairly uniform (Fig. 3) (*14*). These results indicate that the last interglacial sea-level high stand lasted ~17,000 years, in contrast to a duration of ~8000 years estimated from the SPECMAP record. Six of our coral ages (three category A and three category B samples, including two collected at growth position) are significantly older than the time of a major insolation high at ~127 ka (*15*). These ages imply that the sea-level high predated the insolation maximum by at least 4000 years. Four category A (including two samples in growth position) and two category B corals have ages between ~111 and 115 ka and imply that the last interglacial sea was high at this time. In contrast, the orbital forcing theory predicts a major insolation low at 116 ka (*15, 16*), and the SPECMAP chronology indicates that sea level was 20 to 50 m lower than at present (*2–5*). Thus, the Oahu record implies that

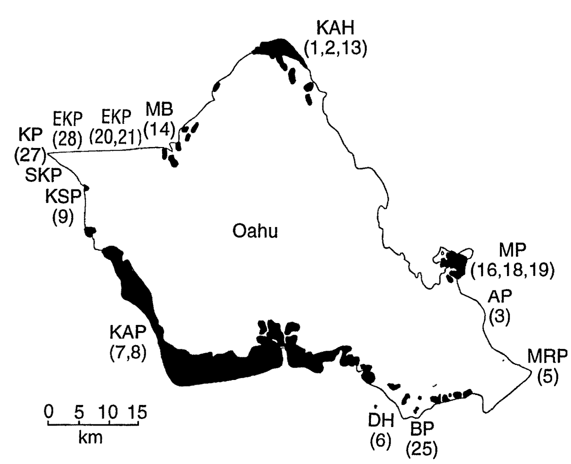

Fig. 1. Distribution of emergent coral reefs of Oahu (darkened areas) from (*25*) [for the east Kaena Point area distribution, see (*10*)], and localities of dated Quaternary deposits referred to in the text. Abbreviations: DH, Diamond Head; BP, Black Point; MRP, Makai Range Pier; AP, Alala Point; MP, Mokapu Point; KAH, Kahuku Point; MB, Mokuleia Beach; EKP, East Kaena Point Reef; KP, Kaena Point; SKP, Southeast Kaena Point Reef; KSP, Kaena Point State Park; and KAP, Kahe Point. Sample localities are shown in parentheses (see Table 1).

U.S. Geological Survey, Denver Federal Center, Mail Stop 963, Box 25046, Denver, CO 80225, USA.

*To whom correspondence should be addressed.

sea-level changes during the last interglacial were not controlled entirely by cyclic variations in insolation parameters (*17*). The U-series ages of fossil coral reefs in the Bahamas, Haiti, Barbados, New Guinea, Vanuatu, and at the margin of southwestern Australia (*8*, *12*, *13*, *18*, *19*) also suggest that last interglacial reefs were well established no later than 131 ka.

We have not observed (*10*) stratigraphic evidence for two episodes of high sea level on Oahu during the last interglacial period, as hypothesized (*20*) on the basis of a bimodal distribution of the previously reported coral ages (*9*) and stratigraphic interpretations supported by a limited number of electron spin resonance and α-spectrometric U-series ages (*21*). If two high sea-level stands had occurred on Oahu, then the intervening decline of the sea could not have lasted significantly longer than ~2000 years, on the basis of the rather uniform distribution of coral age measurements with overlapping analytical uncertainties (Fig. 3).

Table 1. Isotopic and age data for Oahu coral samples. Ratios are activity ratios calculated from the atomic ratios. Errors are shown in parentheses, at the 2σ level, for the least significant digits. We calculated the ages using half-lives from ^{230}Th and ^{234}U of 75,380 and 244,600 years, respectively (*27*); the calculated ages include a negligible to very 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.

Sample*	^{230}Th/^{232}Th	U (ppm)	^{234}U/^{238}U	^{230}Th/^{238}U	^{230}Th/^{238}U age (ka)†	^{234}U/^{238}U initial
Modern corals						
1-Pc(U)	7	2.68	1.1477(30)	0.0014(151)	<1.5	1.1480(30)
14-Pr1(U)	‡	2.81	1.1462(34)	‡	<0.01	1.1462(34)
14-Pc1(U)	81	2.83	1.1494(30)	0.0029(13)	0.27(12)	1.1500(30)
Last interglacial corals						
Diamond Head (DH)						
6-Pr1(C)	9,900	2.43	1.1065(25)	0.7309(92)	114.6(2.6) A	1.1473(36)
6-Pc1(C)	15,900	2.79	1.1082(42)	0.7447(65)	118.0(2.0) A	1.1512(60)
Makai Range Pier (MRP)						
5-Pc1(C)	8,150	2.94	1.1057(29)	0.7917(100)	132.6(3.3) A	1.1539(44)
Alala Point (AP)						
3-Pr1(C)§	6,310	2.86	1.1046(31)	0.7832(76)	130.2(2.5) A	1.1513(46)
3-Pc1(C)	5,140	2.60	1.1099(21)	0.7820(198)	128.5(6.1) B	1.1582(41)
Mokapu Point (MP)						
16-Pc1(U)	18,800	2.81	1.1096(30)	0.7705(37)	125.1(1.3) B	1.1563(43)
16-Pc2(U)	16,700	3.46	1.1074(25)	0.7649(34)	124.0(1.2) A	1.1526(36)
18-Pc1(C)	9,140	2.88	1.1114(34)	0.8226(158)	141.2(5.5) U	1.1662(57)
18-Pr2(IS)§	2,090	2.88	1.1067(18)	0.7617(87)	123.2(2.6) A	1.1513(28)
18-Pc2(C)#1	8,440	2.79	1.1049(23)	0.7803(39)	129.2(1.3) A	1.1513(33)
18-Pc2(C)#2	5,030	2.80	1.1081(29)	0.7755(64)	127.0(2.1) B	1.1548(42)
18-Pc3(U)	13,900	2.92	1.1025(22)	0.7704(72)	126.8(2.3) A	1.1468(33)
18-Pc4(U)	6,320	3.02	1.1099(19)	0.7922(43)	131.7(1.5) B	1.1596(28)
19-Pr1(IS)§	9,300	2.62	1.1124(29)	0.7886(41)	129.9(1.5) B	1.1625(42)
19-Pr2(IS)§	6,850	2.67	1.1092(23)	0.7895(83)	131.0(2.7) B	1.1584(35)
19-Pc1(C)	6,250	2.54	1.1298(35)	0.8122(109)	132.8(3.5) U	1.1891(54)
19-Pc2(IS)	6,030	2.70	1.1088(29)	0.7697(126)	125.0(3.8) B	1.1551(44)
19-Pc3(U)	7,740	2.88	1.1114(26)	0.7740(73)	125.8(2.3) B	1.1590(38)
19-Pc4(U)	4,800	2.56	1.1229(26)	0.8091(124)	133.6(4.0) U	1.1795(43)
Kahuku Point (KAH)						
1-Pr1(IS)	18,900	2.78	1.1028(21)	0.7487(87)	120.3(2.5) A	1.1445(31)
2-Pr1(IS)§	10,300	2.76	1.1139(20)	0.7635(44)	122.1(1.3) B	1.1610(29)
2-Pc1(C)	17,600	2.74	1.1095(22)	0.7315(65)	114.1(1.8) A	1.1513(31)
13-Pr1(IS)	4,810	2.70	1.1081(23)	0.7575(49)	121.7(1.5) A	1.1525(33)
East Kaena Point Reef (EKP)						
20-Pr1(IS)	3,830	2.60	1.1071(22)	0.7163(146)	110.5(3.8) A	1.1465(34)
21-Pr1(IS)	3,790	2.67	1.1053(25)	0.7310(75)	114.8(2.1) A	1.1458(35)
26-Pc1(C)	4,400	2.97	1.0994(38)	0.7494(37)	121.3(1.4) A	1.1402(54)
Kaena Point State Park (KSP)						
9-Pr1(C)	7,320	2.72	1.1037(32)	0.7447(59)	119.0(1.8) A	1.1453(45)
9-Pc1(C)	813	2.99	1.1082(28)	0.7535(102)	120.4(3.0) A	1.1522(41)
Kahe Point (KAP)						
8-Pr1(C)§	10,000	2.87	1.1038(25)	0.7398(66)	117.6(1.9) A	1.1449(35)
8-Pc1(C)	4,440	2.77	1.1401(29)	0.8176(159)	131.9(4.9) U	1.2036(50)
7-Pr1(C)	5,270	2.77	1.1017(27)	0.7226(154)	113.3(4.2) B	1.1402(40)
7-Pc1(C)	10,300	2.56	1.1106(20)	0.7458(58)	117.8(1.7) B	1.1544(29)
7-Pc2(C)	4,720	2.86	1.1142(20)	0.7230(133)	110.9(3.5) B	1.1563(32)
Middle Pleistocene corals						
Kaena Point (KP) reef deposits (~30 m maximum elevation)						
27-Pc1(C)	6,160	2.88	1.0295(31)	1.0337(52)	$532(^{+130}_{-70})$	1.133(40)
Black Point (BP) reef deposit (~20 m maximum elevation)						
25-Pc1(C)	1,890	2.31	1.0682(19)	1.0466(223)	$247(^{+66}_{-42})$	1.182(28)

*Sample names include locality number as shown in Fig. 1 (first number); coral genus (Pr = *Porites* sp., Pc = *Pocillopora* sp.), sample number, and stratigraphic setting (IS = in situ, C = lithified conglomerate, and U = unlithified conglomerate) in parentheses. Samples were ≥99% aragonite unless otherwise noted. †Ages of the last interglacial corals are classified as reliable (A), moderately reliable (B), or unreliable (U), on the basis of their calculated initial ^{234}U/^{238}U ratio (see text). ‡No ^{230}Th resolved; ^{232}Th = 0.74 parts per billion. §Sample was between 95 and 99% aragonite; remainder was calcite.

Stearns (*22*) described emergent marine deposits (~30 m maximum elevation above present sea level) near and southeast of Kaena Point and a marine deposit (~20 m above present sea level) overlain by basalt near Black Point (Fig. 1). He proposed that these deposits are evidence for large glacio-eustatic sea-level fluctuations during the middle Pleistocene. Field studies of tectonically stable coastlines have failed to reveal the presence of any Pleistocene marine deposits higher than ~10 m, and these observations are supported by reasonable estimates of sea-level rise associated with ice-sheet melting (*10*).

We propose instead that Oahu was uplifted during the Quaternary and collected coral samples to determine an average uplift rate (*23*). Of six samples from before the last interglacial, only two yielded finite $^{230}Th/^{238}U$ ages and acceptable back-calculated initial $^{234}U/^{238}U$ values (Table 1). A coral sample from the Kaena Limestone now exposed 24.4 m above sea level gave an age of $532(^{+130}_{-70})$ ka. A probable correlation of the sample is to sea-level high stands recorded as either deep-sea oxygen isotope stage 15 (~550 ka) or stage 13 (~470 ka). From these age estimates and an assumption of a paleosea level close to the present, we calculate long-term average uplift rates of 0.05 to 0.06 m per 10^3 years. A coral from the Black Point Limestone now exposed ~17 m above sea level yielded an age of $347(^{+66}_{-42})$ ka. The K-Ar ages of overlying basalt and an associated dike are 480 ± 160 and 410 ± 80 ka, respectively; the age of the dike is considered to be the best estimate for both the dike and the flow (*24*). A probable correlation of the Black Point deposit is to oxygen isotope stage 11 (~410 ka), yielding an average uplift rate of ~0.05 m per 10^3 years. Assuming that these age estimates are reasonable and that Oahu experienced Quaternary uplift [a possible cause of uplift is discussed in (*10*)], we believe that the uplift-corrected minimum elevation of the last-interglacial sea level, based on the coral ages at Mokapu Point, is between +1 and +3 m.

If our age results are accurate, then the marine oxygen isotope record may not represent an ideal ice volume or sea-level record. Our observations thus are not consistent in any simple way with the orbital-forcing theory of climate change, and they add to a growing body of last-interglacial ages (Fig. 3) that suggest that revision in this theory is required to include consideration of the effects of other physical mechanisms acting in addition to, or coupled with, the orbital-forcing parameters.

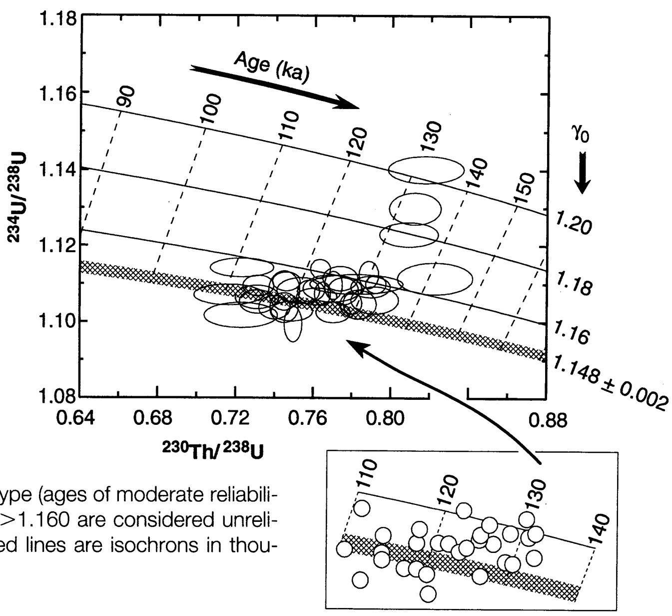

Fig. 2. Diagram showing U-Th evolution for last interglacial corals from Oahu (Table 1). Analyses are shown by their 2σ error ellipses (main diagram) or, without error information, as circles (inset). Curved lines are isotopic evolution paths for various initial $^{234}U/^{238}U$ values (= γ_0). The cross-hatched band (1.148 ± 0.002) denotes the area of category A samples (ages of high reliability). Samples that plot within the range of 1.155 ± 0.005 and sample 7-Pr1(C) are category B type (ages of moderate reliability). Samples with $^{234}U/^{238}U$ >1.160 are considered unreliable (see text). Oblique dotted lines are isochrons in thousands of years.

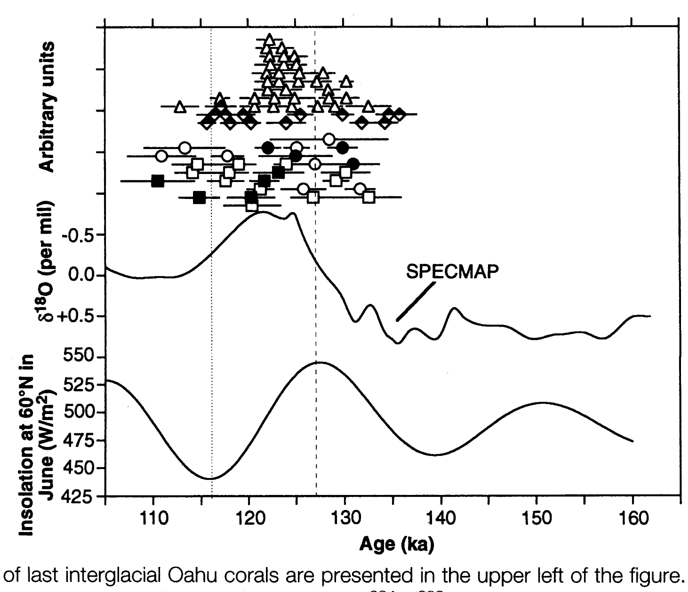

Fig. 3. Plot of part of the SPECMAP orbitally tuned deep-sea oxygen isotope record, where peaks in the $\delta^{18}O$ record indicate interglacial and high sea-level conditions. The lower curve shows the variation of insolation at the top of the atmosphere for June at 60°N (*15*). The dashed vertical line shows the time of a major insolation high at ~128 ka (warm climate and reduction of continental ice volume); the dotted vertical line shows the time of a major insolation low at 116 ka (cold climate and building up of ice volume). The $^{230}Th/^{238}U$ ages of last interglacial Oahu corals are presented in the upper left of the figure. Solid and open squares represent category A ages of corals (initial $^{234}U/^{238}U$ suggesting ages of high reliability) from growth position and conglomerate facies, respectively. Solid and open circles represent category B ages of corals (initial $^{234}U/^{238}U$ suggesting ages of moderate reliability) from growth position and conglomerate facies, respectively. Category A and category B high-precision U-series ages of fossil corals from New Guinea, Vanuatu, and southwestern Australia (partially shaded diamonds) (*12*, *18*, *19*) and from the Bahamas, Haiti, and Barbados (open triangles) (*8*, *13*, *19*, *26*) are also shown. Horizontal bars indicate 2σ uncertainties of each age.

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were inspected under ×10 magnification, and 200 to 300 mg were selected for the mass spectrometric analyses. Details of the chemical and instrumental procedures were reported in (*6*).

10. Stratigraphic sections are presented by D. R. Muhs and B. J. Szabo [*Mar. Geol.* **118**, 315 (1994)]. The normal tidal range of Oahu is <0.8 m, and modern coral reefs in protected bays grow upward to ~0.5 m below low tide level.
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