

Thorium-230 Ages of Corals and Duration of the Last Interglacial Sea-Level High Stand on Oahu, Hawaii

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 CO₂ and other gases (1). Estimates for the timing [peak at ~125 thousand years ago (ka)] and duration (~8 $\times 10^3$ years) of the last interglacial have been derived mainly from an orbitally tuned $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ 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 $\times 10^3$ years) than the SPECMAP $\delta^{18}\text{O}$ 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).

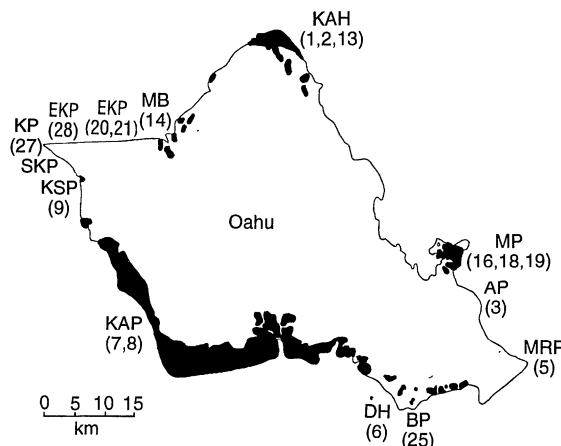
Two tests for the reliability of U-series coral ages are that U concentrations should fall within the range of modern corals and that calculated initial $^{234}\text{U}/^{238}\text{U}$ activity ratios in fossil corals should be close to that of modern seawater (8). Modern seawater has a $^{234}\text{U}/^{238}\text{U}$ ratio of 1.148 ± 0.002 (11). We classify fossil corals with calculated initial $^{234}\text{U}/^{238}\text{U}$ ratios in this range as category A samples and consider that their $^{230}\text{Th}/^{238}\text{U}$ ages are reliable (Table 1). Category B samples have initial $^{234}\text{U}/^{238}\text{U}$ 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 $^{234}\text{U}/^{238}\text{U}$ 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 2 σ 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 $^{234}\text{U}/^{238}\text{U}$, $^{230}\text{Th}/^{238}\text{U}$, and $^{232}\text{Th}/^{238}\text{U}$ of 1.0 ± 0.3 , 1.0 ± 0.3 , and 1.21 ± 0.64 , respectively.

Sample*	$^{230}\text{Th}/^{232}\text{Th}$	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{238}\text{U}$	$^{230}\text{Th}/^{238}\text{U}$ age (ka)†	$^{234}\text{U}/^{238}\text{U}$ initial
<i>Modern corals</i>						
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)
<i>Last interglacial corals</i>						
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)
<i>Middle Pleistocene corals</i>						
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 $\geq 99\%$ 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 $^{234}\text{U}/^{238}\text{U}$ 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 sup-

ported 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 $^{230}\text{Th}/^{238}\text{U}$ ages and acceptable back-calculated initial $^{234}\text{U}/^{238}\text{U}$ 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 $^{234}\text{U}/^{238}\text{U}$ values ($= \gamma_0$). 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 $^{234}\text{U}/^{238}\text{U} > 1.160$ are considered unreliable (see text). Oblique dotted lines are isochrons in thousands of years.

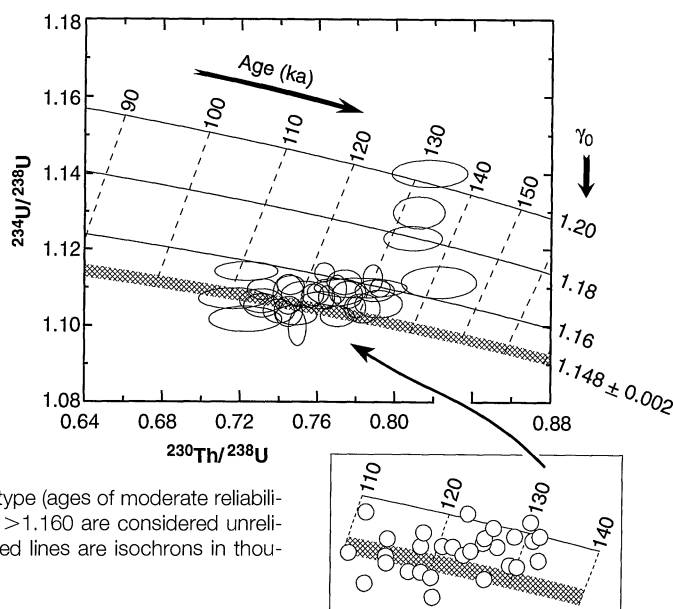
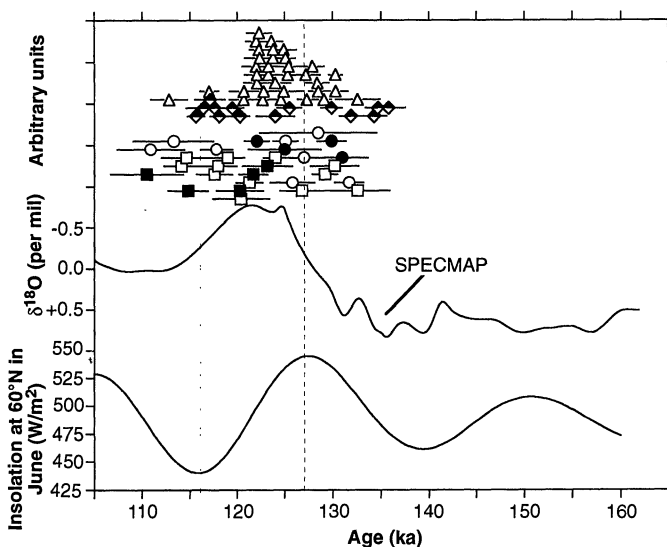


Fig. 3. Plot of part of the SPECMAP orbitally tuned deep-sea oxygen isotope record, where peaks in the $\delta^{18}\text{O}$ record indicate interglacial and high sea-level conditions. The lower curve shows the variation of insolation at the top of the atmosphere for June at 60°N (15). The dashed vertical 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 $^{230}\text{Th}/^{238}\text{U}$ 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 $^{234}\text{U}/^{238}\text{U}$ suggesting ages of high reliability) from growth position and conglomerate facies, respectively. Solid and open circles represent category B ages of corals (initial $^{234}\text{U}/^{238}\text{U}$ 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.



REFERENCES AND NOTES

1. J. Hansen *et al.*, *J. Geophys. Res.* **93**, 9341 (1988).
2. J. D. Hays, J. Imbrie, N. J. Shackleton, *Science* **194**, 1121 (1976).
3. J. Imbrie *et al.*, in *Milankovitch and Climate*, A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman, Eds. (Reidel, Boston, 1984), part 1, pp. 269–305.
4. D. F. Williams *et al.*, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **64**, 221 (1988).
5. A change of 0.1 per mil in $\delta^{18}\text{O}$ is considered equivalent to a ~10 m change in sea level [R. G. Fairbanks and R. K. Matthews, *Quat. Res.* **10**, 181 (1978)].
6. K. R. Ludwig *et al.*, *Science* **258**, 284 (1992).
7. I. J. Winograd *et al.*, *ibid.*, p. 255.
8. J. H. Chen, H. A. Curran, B. White, G. J. Wasserburg, *Geol. Soc. Am. Bull.* **103**, 82 (1991).
9. T.-L. Ku, M. A. Kimmel, W. H. Easton, T. J. O'Neill [*Science* **183**, 959 (1974)] reported α -spectrometric U-series ages from Oahu corals and indicated that the last interglacial sea stood apparently ~7.6 m higher than today and occurred about 120 ka. The elevation estimate of this paleoshoreline is based on two undated notches cut in eolianite. An average value of 7.6 m is quoted because the two levels cannot be distinguished in most localities [H. T. Stearns, *Geol. Soc. Am. Bull.* **46**, 178 (1935)]. Mineralogy of the corals was determined by x-ray diffraction analysis. Most of the samples were ~99% aragonite. Six samples had 1 to 5% calcite (Table 1) resulting from the aragonite-to-calcite transformation, but there is no correlation between the unreliable results and calcite impurities. The dense, unrecrystallized parts of selected 3- to 6-g samples were broken into smaller fragments (<0.6 mm) and scrubbed in an ultrasonic water bath. The fragments

- were inspected under $\times 10$ 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.
 11. R. L. Edwards *et al.* [*Science* **260**, 962 (1993)] reported that the variation in the initial $^{234}\text{U}/^{238}\text{U}$ activity value in 20 young (1.8 to 13.1 ka) New Guinea corals did not exceed 2 per mil, or 1.150 ± 0.002 (2σ of population). Our measurements of 16 young (modern to 16 ka) Florida and Hawaii corals yield a value of 1.148 ± 0.002 (2σ of the mean) (K. R. Ludwig, K. R. Simmons, D. R. Muhs, B. J. Szabo, unpublished data). For the purpose of this report, we specify an acceptable range of variation for initial $^{234}\text{U}/^{238}\text{U}$ of 1.146 to 1.150. The range of U concentrations of the Oahu corals is 2.31 to 3.96 ppm, and the range of U concentrations in young Hawaiian corals (<15 ka) is 2.39 to 3.15 ppm [K. R. Ludwig, B. J. Szabo, J. G. Moore, K. R. Simmons, *Geology* **19**, 171 (1991); this report]; we do not have large deviations indicative of an open system. All of the fossil Oahu corals have $^{230}\text{Th}/^{232}\text{Th}$ activity ratios of >800 , indicating that the samples should be free of inherited ^{230}Th from detrital materials. However, we cannot rule out the possibility that a minute amount of ^{230}Th , derived from dissolution of existing nearby coral, may have been incorporated into some of our samples, causing the calculated ages to be too old.
 12. M. Stein *et al.*, *Geochim. Cosmochim. Acta* **57**, 2541 (1993).
 13. C. D. Gallup, R. L. Edwards, R. G. Johnson, *Science* **263**, 796 (1994). According to their model, category B equivalent ages are accurate to within <2000 years.
 14. Arbitrary age estimates based on the observation that the apparently sharp cutoff in all category A and category B ages at about 131 and 114 ka, respectively, is about what one would expect for a true range of 131 to 114 ka, allowing for some dispersion at the extremes from analytical error.
 15. A. L. Berger, *Quat. Res.* **9**, 139 (1978); _____ and M. F. Loutre, *Quat. Sci. Rev.* **10**, 297 (1991).
 16. D. Rind, D. Peteet, G. Kukla, *J. Geophys. Res.* **94** (no. D10), 12851 (1989). Climate modeling experiments using the most favorable insolation variations have also failed to predict that snow cover could be maintained or the growth of major ice sheets initiated at northern latitudes, despite the major reduction in insolation culminating at 116 ka.
 17. Unexplained aspects associated with the 10^5 -year cycle responding to the orbital climate forcing are examined by J. Imbrie *et al.* [*Paleoceanography* **8**, 699 (1993)], and the internal response to orbital forcing is discussed by N.-A. Möller [in *Orbital Forcing and Cyclic Sequences*, P. L. de Boer and D. G. Smith, Eds. (Special Publication of the International Association of Sedimentologists, Blackwell Scientific, Oxford, 1994), no. 19, pp. 25–33]. Changes in the Earth's geoid may have affected local paleosea level conditions [K. Lambeck and M. Nakada, *Nature* **357**, 125 (1992); A. Eisenhauer *et al.*, *Earth Planet. Sci. Lett.* **114**, 529 (1993)].
 18. L. B. Collins *et al.*, *Mar. Geol.* **110**, 203 (1993); Z. R. Zhu *et al.*, *Earth Planet. Sci. Lett.* **118**, 281 (1993).
 19. R. L. Edwards, J. H. Chen, T.-L. Ku, G. J. Wasserburg, *Science* **236**, 1547 (1987); B. Hamelin, E. Bard, A. Zindler, R. G. Fairbanks, *Earth Planet. Sci. Lett.* **106**, 169 (1991).
 20. C. E. Stearns, *Quat. Res.* **6**, 445 (1976); J. Chappell and H. H. Veeh, *Geol. Soc. Am. Bull.* **89**, 356 (1978); P. L. Smart and D. A. Richards, *Quat. Sci. Rev.* **11**, 687 (1992).
 21. C. E. Sherman *et al.*, *Geology* **21**, 1079 (1993).
 22. H. T. Stearns, *Bernice P. Bishop Mus. Bull.* **237**, 1 (1978); *Geology of the State of Hawaii* (Pacific Books, Palo Alto, CA, 1966).
 23. Large submarine landslides have been mapped adjacent to the islands of Hawaii including Oahu [J. G. Moore, W. R. Normark, R. T. Holcomb, *Science* **264**, 46 (1994); J. G. Moore *et al.*, *J. Geophys. Res.* **94**, 17465 (1989)]. Some of these debris avalanches may have produced giant wave deposits on the coastal slopes of Molokai and Lanai [J. G. Moore, W. B. Bryan, K. R. Ludwig, *Geol. Soc. Am. Bull.* **106**, 962 (1994); J. G. Moore and G. W. Moore, *Science* **226**, 1312 (1984)]. We studied the exposures of the ~ 30 -m Kaena reef deposits about 3 km southeast of Kaena Point (SKP in Fig. 1) and found no sedimentological characteristics that suggest an origin from a giant wave. Furthermore, morphologic analysis of nick points on interfluvies suggests the existence of a former shoreline with a mean elevation of about 28 m [R. V. Ruhe, J. M. Williams, E. L. Hill, *J. Geol.* **73**, 485 (1965)].
 24. M. A. Lanphere and G. B. Dalrymple, *Am. J. Sci. A* **280**, 736 (1980); H. T. Stearns and G. B. Dalrymple, *Bernice P. Bishop Mus. Occas. Pap.* **24**, 307 (1978).
 25. H. T. Stearns, *Geol. Soc. Am. Bull.* **85**, 795 (1974).
 26. E. Bard, B. Hamelin, R. G. Fairbanks, *Nature* **346**, 456 (1990).
 27. P. de Bièvre *et al.*, in *Proceedings of the International Conference on Chemical and Nuclear Data: Measurements and Applications*, M. L. Hurrell, Ed. (Institute of Civil Engineers, London, 1971), pp. 211–225; J. W. Meadows, R. J. Armani, E. L. Callis, A. M. Essling, *Phys. Rev. C* **22**, 750 (1980).
 28. We thank G. R. Bauer and J. G. Moore, who provided assistance in the sample collection. This report benefited from review comments by I. Winograd and T. McConnaughey. We thank S. Allison for allowing us access to his property. This paper is a contribution to the LITE (Last Interglacial: Timing and Environment) project of the Global Change and Climate History Program of the U.S. Geological Survey.

17 May 1994; accepted 8 August 1994

Interannual Variability of Temperature at a Depth of 125 Meters in the North Atlantic Ocean

Sydney Levitus,* John I. Antonov,† Timothy P. Boyer

Analyses of historical ocean temperature data at a depth of 125 meters in the North Atlantic Ocean indicate that from 1950 to 1990 the subtropical and subarctic gyres exhibited linear trends that were opposite in phase. In addition, multivariate analyses of yearly mean temperature anomaly fields between 20°N and 70°N in the North Atlantic show a characteristic space-time temperature oscillation from 1947 to 1990. A quasidecadal oscillation, first identified at Ocean Weather Station C, is part of a basin-wide feature. Gyre and basin-scale variations such as these provide the observational basis for climate diagnostic and modeling studies.

Levitus *et al.* (1) presented analyses of temperature time series data at Ocean Weather Station C (OWS C) that indicated the interannual variability of upper ocean thermal structure at this location during the period from 1947 through 1990. The presence of two distinct signals in the data, a temperature oscillation with a quasidecadal time scale and a linear decrease in the data from 1956 through 1985 (Fig. 1), raised the question of the geographical extent and temporal variability of these features. In this report we address these questions by analyzing data collected in the North Atlantic from 20°N to 70°N .

There is little observational evidence of basin- and gyre-scale temperature variability at subsurface depths for any part of the world ocean for interannual to decadal time scales. Such variability, as we identify in this report, is important to the understanding of climate change because of air-sea interactions that may be involved in this variability. The identification of such vari-

ability can provide the basis for diagnostic studies and modeling simulations, as well as for the development of a monitoring strategy for the ocean. With present concern about the possibility of global warming, the identification and understanding of thermal variability in the ocean, whether natural or anthropogenic, is an important subject of study.

We have used historical oceanographic measurements of temperature to analyze the variability of temperature (2) at a depth of 125 m in the North Atlantic Ocean. These data include both time series data from OWS C (3) and historical data from the entire North Atlantic. We analyzed data at a depth of 125 m because this is the deepest standard observation level for which data exist as far back as 1947 for the North Atlantic between 20°N and 70°N . These early data are primarily mechanical bathythermograph (MBT) observations. In addition, the annual cycle of temperature at this depth is relatively small compared to that at the sea surface. Thus, we can expect that the greater part of variability at this depth is associated with temperature variations at periods of more than a year. Yearly data distributions at a depth of 125 m show the data to be variable in space and time; more data are available along the boundary of the Atlantic than in the interior region, and more data are

S. Levitus and T. P. Boyer, National Oceanographic Data Center, E/OC5, Universal Building, 1825 Connecticut Avenue, NW, Washington, DC 20235, USA.

J. I. Antonov, State Hydrological Institute, 23 Second Lane, B.O., St. Petersburg, Russia 199053.

*To whom correspondence should be addressed.

†Present address: National Oceanic and Atmospheric Administration–National Oceanographic Data Center, Ocean Climate Laboratory, Universal Building, 1825 Connecticut Avenue, NW, Washington, DC 20235, USA.