Crustal subsidence rate off Hawaii determined from $^{234}U/^{238}U$ ages of drowned coral reefs

K. R. Ludwig, B. J. Szabo
U.S. Geological Survey, P.O. Box 25046, Denver, Colorado 80225
J. G. Moore
U.S. Geological Survey, Menlo Park, California 94025
K. R. Simmons
U.S. Geological Survey, P.O. Box 25046, Denver, Colorado 80225

ABSTRACT

A series of submerged coral reefs off northwestern Hawaii was formed during (largely glacial) intervals when the rate of local sea-level rise was less than the maximum upward growth rate of the reefs. Mass-spectrometric $^{234}U/^{238}U$ ages for samples from six such reefs range from 17 to 475 ka and indicate that this part of the Hawaiian Ridge has been subsiding at a roughly uniform rate of 2.6 mm/yr for the past 475 ka. The $^{234}U/^{238}U$ ages are in general agreement with model ages of reef drowning (based on estimates of paleo-sea-level stands derived from oxygen-isotope ratios of deep-sea sediments), but there are disagreements in detail. The high attainable precision (±10 ka or better on samples younger than ~800 ka), large applicable age range, relative robustness against open-system behavior, and ease of analysis for this technique hold great promise for future applications of dating of 50–1000 ka coral.

INTRODUCTION

The accumulation of erupted volcanic material on the crest of the Hawaiian ridge downwarps the lithosphere beneath the ridge and causes rapid subsidence during times of peak volcanism. During the Pleistocene, this subsidence, coupled with the eustatic rise and fall of sea level caused by wasting and growth of glacial ice sheets on the continents, resulted in the formation of a series of drowned coral reefs. Each reef grew in shallow water, but was drowned by the combined effects of sea-level rise at the end of a glacial period and ongoing lithospheric subsidence (Moore and Fornari, 1984; Moore and Campbell, 1987). We have determined mass-spectrometric $^{234}U/^{238}U$ ages for coral samples from a series of progressively deeper reefs of this type in order to address the question of the time interval over which the local crust has been subsiding, and to what degree this subsidence has been continuous. Our samples come from six well-preserved submerged reefs on a broad platform off the northwestern coast of the island of Hawaii (Table 1, Fig. 1).

Two of the reefs have been radiometrically dated previously: 13 ka by ^{14}C (Moore and Fornari, 1984) for the -150 m reef west of Kealakekua Bay, and 120 ka by alpha-spectrometric $^{230}Th/^{234}U$ (Szabo and Moore, 1986) for the -360 m reef northwest of Kohala. These ages and reef depths, as well as the present-day subsidence rate measured at the Hilo tide gauge, suggest a long-term crustal subsidence rate of 2–3 mm/yr. Using this rate, together with paleo-sea-level curves constructed from deep-sea sediment oxygen-isotope data, Moore and Campbell (1987) constructed a general model that predicts the ages of reef formation on the basis of estimated times of locally stable sea levels. The data we report here provide a quantitative test of that model.

U-SERIES DATING OF CORALS

U-series dating with the $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ decay schemes are the only extensively tested and reliable methods of dating corals formed before 50 ka. However, the precision of conventional (alpha-spectrometric) $^{230}Th/^{234}U$ age determinations on samples older than ca. 200 ka becomes increasingly poor, and vulnerable to open-system behavior for Th or U. Mass-spectrometric $^{230}Th/^{234}U$ determinations (Edwards et al., 1986) offer dramatically improved precision for corals younger than 150–200 ka, but remain dependent on closed systems for Th and U. Though the $^{234}U/^{238}U$ method of marine-carbonate dating requires only that samples have neither gained U nor undergone mid-life loss of U (and that seawater $^{234}U/^{238}U$ has been constant), alpha-spectrometric measurements yield poor precision for all ages, and so have been of limited use for marine-carbonate dating. Mass-spectrometric $^{234}U/^{238}U$ analyses, however, are at least an order of magnitude more precise than alpha-spectrometric analyses (Chen et al., 1986) so adequate geochronologic precision can be attained for samples up to at least 800 ka.

SAMPLE COLLECTION

Coral samples analyzed for this study were collected by dredging from the R/V *Melville* and the M/V *Farnella* and by bottom collecting from the submersibles *Makali'i* and *Pisces V.* Precise sample depths are difficult to determine. The reefs are sediment-covered, gently sloping terraces that have steep rocky faces with heights of up to 100 m or more on the seaward side. For dredge sampling, the dredge is generally dragged upslope near the upper reef face; however, the dredge may contact the bottom through a vertical distance exceeding 100 m. Sample depths (based on the 3.5 kHz echo records) were assigned when a particularly strong grab was recorded on the winch tensionometer. The hydraulic manipulator used to collect samples from submersibles was not strong enough to break off coral samples; hence loose samples

TABLE 1. FIELD DATA FOR CORAL SAMPLES

Sample no.	Field no.	Depth (m)	Location	Vessel*
21	88H-10A	beach	19°35.3'N 155°58.4'W	--
25	M-167-7	20	19°29.2'N 155°56.7'W	Makali'i
3/4	M-170-5	219	19°28.7'N 156°06.1'W	Makali'i
17	P5-78-5	160	18°51.4'N 155°41.3'W	Pisces V
16	P5-70-4A	525	19°51.3'N 156°07.7'W	Pisces V
5/6	Dr-9-A	700-850†	20°02.2'N 156°04.3'W	Melville
9	Dr-9-F	700-850†	20°02.2'N 156°04.3'W	Melville
22	P5-68-2B	750	19°52.9'N 156°07.7'W	Pisces V
18	P5-69-4	980	19°59.4'N 156°07.5'W	Pisces V
23	P5-69-6	960	19°58.9'N 156°07.8'W	Pisces V
14	D-21	1060-1222†	20°06.2'N 156°12.7'W	Farnella
19	P5-73.2	1130	20°04.7'N 156°12.2'W	Pisces V
24	P5-73-1	1110	20°05.1'N 156°12.1'W	Pisces V
20	P5-75-3	1405	19°59.0'N 156°14.6'W	Pisces V

*Years of Cruises: *Makali'i*, 1983; *Pisces V*, 1988; *Farnella*, 1988; *Melville*, 1987.
†Range of depth for dredge hauls; a strong jerk at 835 m depth for Dr-9 probably indicates depth for that dredge haul.

were picked up on ledges or at the base of reef-face scarps, so the samples may have moved significantly downslope from their growth position. The significant depth for the samples is that of the top of the reef face, which, aside from gentle warping, is relatively constant along the reef for tens of kilometres (Fig. 1). We established this depth in the study area by measuring the depth of the average slope break from the best available bathymetry (Moore and Clague, 1987) between lat 19°58′ and 20°06′N.

ANALYTICAL METHODS

Samples for both mass- and alpha-spectrometric analyses were prepared and purified with conventional procedures (Szabo et al., 1981). Mass-spectrometric analyses were done with graphite-doped single Re filaments (Arden and Gale, 1974; Chen et al., 1986) on an automated VG-54E mass spectrometer with an analog-mode Daly detector, normalized for mass discrimination with a ^{233}U + ^{236}U spike. Effects arising from amplifier nonlinearity, amplifier time constants, isobaric interferences, and peak tailing were all determined to be negligible. Precision of $^{234}\mathrm{U}/^{235}\mathrm{U}$ ratios was verified with replicate runs of both samples and the NBS-950a standard. Any remaining biases in the analyses are canceled by reporting $^{234}\mathrm{U}/^{235}\mathrm{U}$ ratios relative to those measured for the HU-1 uraninite, which because of its age (Pb/U isotopic ages are concordant at ~620 Ma; K. R. Ludwig, unpublished data) and $^{234}\mathrm{U}/^{235}\mathrm{U}$ activity ratio of 0.9982 ±0.0088 (2σ; J. N. Rosholt, 1979, written commun.), is believed to be in secular equilibrium. Thus our reported values (Table 2) for the ratio of sample $^{234}\mathrm{U}/^{235}\mathrm{U}$ to HU-1 $^{234}\mathrm{U}/^{235}\mathrm{U}$ are equivalent to $^{234}\mathrm{U}/^{238}\mathrm{U}$ activity ratios. Our weighted mean $^{234}\mathrm{U}/^{235}\mathrm{U}$ for HU-1 was 0.0075678 ±0.0000063 on 11 runs (95% confidence limit). This value implies a ^{234}U half-life of 245.2 ±0.2 ka, which agrees with the 244.6 ±0.7 ka value reported by de Bièvre et al. (1971). Our weighted mean $^{234}\mathrm{U}/^{235}\mathrm{U}$ for NBS-950a was 0.0074408 ±0.0000033 on 19 analyses.

RESULTS

Except for one sample, the $^{230}\mathrm{Th}/^{234}\mathrm{U}$ ages from alpha-spectrometric measurements agree with the mass-spectrometric $^{234}\mathrm{U}/^{238}\mathrm{U}$ ages to within twice the assigned errors (Table 2). For sample 22, the discrepancy is significant and is evidently the result of an open-system history in the U-Th system. For this reason, the mass-spectrometric $^{234}\mathrm{U}/^{238}\mathrm{U}$ age for sample 22 must be regarded as possibly biased.

A linear regression of the $^{234}\mathrm{U}/^{238}\mathrm{U}$ ages against the average terrace depths shows that average subsidence has been approximately uniform at 2.6 ±0.4 mm/yr for at least the past 460 ka (Fig. 2B). This rate is consistent with values previously estimated from present-day subsidence, from subsidence over historical time, and from subsidence calculated from previous age determinations of the −150 and −360 m reefs (average depths, correlative with the −430 m reef off northern Hawaii). Measured ages suggest that the subsidence rate may have been slightly greater prior to 300 ka (Fig. 2B), but the greater scatter of the older ages makes this difficult to quantify.

The model for terrace formation on a subsiding volcano (Moore and Fornari, 1984; Moore and Campbell, 1987) predicts that reef growth begins during episodes of major eustatic sea-level fall when relative sea-level change is small. Conversely, reef growth should end when the rate of local sea-level rise (due to the sum of eustatic sea-level rise plus local crustal subsi-

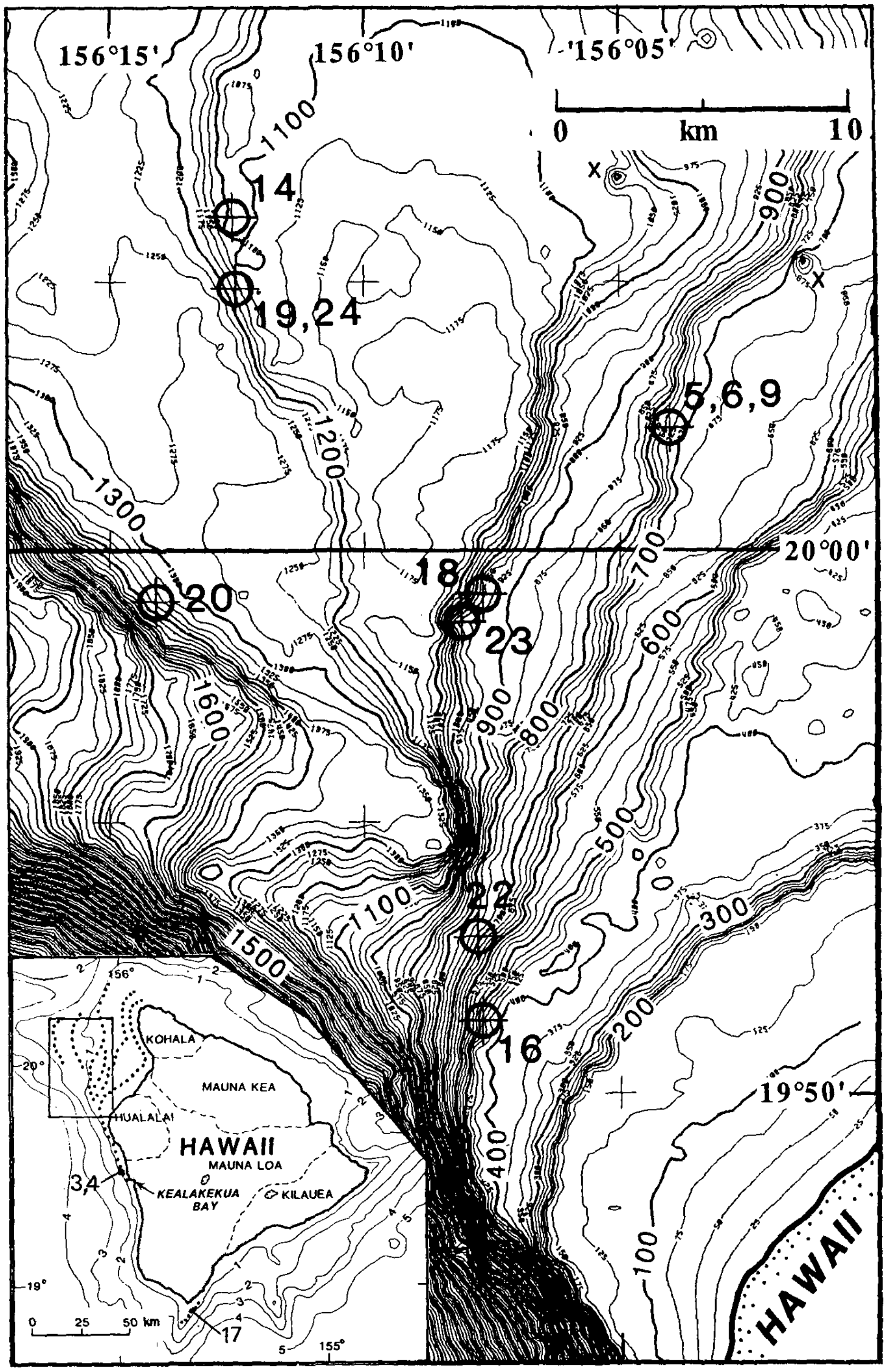

Figure 1. Bathymetry (Campbell, 1987) of sea floor off northwestern Hawaii showing location of dated samples from submerged reefs (see Table 1). Contour interval is 25 m; X indicates possible patch reefs. Index map of island of Hawaii shows boundaries between volcanoes (dashed lines), offshore bathymetry (contour interval 1 km), submerged reefs (dotted lines), detailed map area (box), and location of dated samples outside of detailed map area.

dence) exceeds the maximum sustainable rate of upward reef growth of about 10 mm/yr (Grigg and Epp, 1989).

Assuming that the long-term average subsidence rate is about 2.6 mm/yr, and that oxygen-isotope ratios of deep-sea sediments are a reasonable proxy for eustatic sea-level variations (Shackleton and Opdyke, 1976; Chappell and Shackleton, 1986), we construct a model curve that shows the variations in the past island-submergence rate (Fig. 2C). This curve suggests that during the past 600 ka sea level rose more rapidly than the maximum growth rate of coral about five times, each period lasting less than 10 ka. These five periods, which are the most likely times that major reefs would have drowned, began about 18, 130, 245, 340, and 430 ka (Fig. 2). Reef growth or emergence due to falling sea level would be expected during the long intervals between these periods of rapid submergence and drowning.

The $^{234}\text{U}/^{238}\text{U}$ ages of the two shallowest reefs (–150 and –430 m) correspond closely to the onset of the last two periods of predicted rapid submergence. The ages of the three samples from the –693 m reef bracket the predicted submergence time: two are slightly (<20 ka) younger, and one is 30 ka older. The $^{234}\text{U}/^{238}\text{U}$ ages for the next two deeper reefs (–945 and –1146 m) differ more from the predicted submergence times. Both samples from the –945 m reef yield ages that are 30 and 60 ka younger than predicted by the model curve. Three samples from the –1146 m reef yield ages that bracket the predicted age; two are 25 ka younger, and one 45 ka older.

The deepest (–1336 m) reef is in a somewhat different class, in that it is not a constructional reef of the same sort as the other terraces. This reef is bounded downslope by a scarp that merges with steep terrain that descends to abyssal depths. The brow of this steep slope probably represents the shoreline at the end of shield building of Mahukona volcano, an older volcano in the Hawaiian Island group that is largely covered by younger volcanoes to the east (Moore and Campbell, 1987); hence the age of this slope break does not correlate with the onset of rapid submergence. The reconstructed sea-level curve does not indicate any such submergence at the depth of the slope break or at the $^{234}\text{U}/^{238}\text{U}$ age of the sample collected from the upper part of this scarp (Fig. 2B). The $^{234}\text{U}/^{238}\text{U}$ age of the –1336 m reef is in reasonable agreement with the age predicted by the sea-level curve at the depth of the slope break, indicating that some carbonate material accumulated, though a sizable reef did not develop.

DISCREPANCIES IN PREDICTED AGES

Coral samples whose $^{234}\text{U}/^{238}\text{U}$ ages are older than the predicted drowning age of a given reef (as on the –693 and –1146 m reefs; Fig. 2) may be the result of sampling the older interior of the reef. Normally, we expect our samples to have been derived from the outer carapace of the reef (including the steeply sloping seaward face of the reef). This part of the reef should have been built last, so that its age should be similar to the drowning age. However, the seaward face of even the youngest submerged reef (–150 m) is known to have sustained up to 50 m of shoreward recession as a result of solution and erosion (Moore and Clague, 1987). Such erosion, as well as landsliding, could expose and permit sampling of reef material older than that of the reef carapace, but no older than the youngest material of the next downslope reef.

It is possible that the $^{234}\text{U}/^{238}\text{U}$ ages (Table 2) that are younger than the predicted drowning age of a given reef (as on the –945 and –1146 m reefs; Fig. 2) are the result of the downslope movement of coral debris from the next higher (more shoreward), younger reef. This seems unlikely, however, because the distance of downslope movement on the nearly horizontal sea floor is 3–10 km for the samples in question. However, younger coral could be derived from collapse of an adjacent high-standing patch reef inside of the outer edge of the reef shelf break. Patch reefs are high-standing coral towers as tall as 100 m (Moore and Campbell, 1987) that somehow are not drowned and, because of very rapid growth, keep up with sea level during submergence. The towers north of dredge sites 5, 6, and 9 (Fig. 1) are probably such patch reefs.

A second possibility is that the $^{234}\text{U}/^{238}\text{U}$ ratios have been altered by diagenetic or other

TABLE 2. ISOTOPIC DATA FOR CORAL SAMPLES

Sample[*]	Terrace[†] depth (m)	$^{234}\text{U}/^{238}\text{U}$[§] Age (Ka)	[U] (ppm)	$^{234}\text{U}/^{235}\text{U}$[**] /HU-1	Samples[††] /Runs	Alpha[§§] $^{234}\text{U}/^{238}\text{U}$	Alpha[§§] $^{230}\text{Th}/^{234}\text{U}$	Alpha[§§] $^{230}\text{Th}/^{232}\text{Th}$	Alpha[§§] $^{230}\text{Th}/^{234}\text{U}$ Age (Ka)
21	10	0 ±4	2.53	1.1480 ±11	2/4	1.134 ±16	<.002	>3	<0.2
25	10	5 ±10	3.42	1.1458 ±40	1/2	1.138 ±14	<.0006	>3	<0.08
21+25	--	0 ±4	--	1.1479 ±11	3/6	--	--	--	--
3/4	150	17 ±5	2.91	1.1410 ±17	1/2	1.132 ±27	0.136 ±6	180	15.8 ±7
17	150	19 ±5	3.12	1.1403 ±16	1/2	1.134 ±16	0.121 ±4	>50	14.0 ±5
16	430	133 ±10	3.31	1.1015 ±28	1/2	1.133 ±16	0.655 ±20	>250	112 ±6
5/6	693	225 ±12	3.05	1.0782 ±27	1/1	1.089 ±26	0.930 ±43	600	261 +55-38
9	693	226 ±13	2.97	1.0779 ±28	1/1	1.079 ±38	0.992 ±66	800	>260
22	693	276 ±9	2.64	1.0676 ±16	1/2	1.099 ±18	0.820 ±24	>250	177 ±15
18	945	314 ±10	3.16	1.0607 ±16	1/2	1.069 ±14	0.976 ±26	>250	337 +79-46
23	945	287 ±10	2.88	1.0656 ±17	2/4	n.d.	n.d.	n.d.	n.d.
14	1146	406 ±12	3.05	1.0468 ±16	2/4	n.d.	n.d.	n.d.	n.d.
19	1146	360 ±12	2.97	1.0533 ±18	1/2	n.d.	n.d.	n.d.	n.d.
24	1146	475 ±38	3.20	1.0385 ±42	1/2	1.043 ±18	1.083 ±78	110	>320
20	1336	463 ±8	2.92	1.0398 ±8	3/4	n.d.	n.d.	n.d.	n.d.

Note: Uncertainties are 95% confidence-limit for the least-significant digits; errors for samples with replicate analyses are propagated from the individual analyses. n.d. = not determined. Sample 25 = *Porites (Synaræus)*; 21+25 = combined (weighted mean) data; 3/4,9 = *Porites*; 18 = 11% calcite.

[*] All *Porites lobata* and ≥98% aragonite unless otherwise noted.

[†] Average depth of slope break from the best available bathymetry between lat 19°58' and 20°06' N.

[§] Calculated assuming a ^{234}U half life of 244.6 Ka (de Bièvre et al., 1971) and an initial $^{234}\text{U}/^{238}\text{U}$ activity ratio equal to that of the modern reefs (samples 21 and 25).

[**] Ratio of mass-spectrometrically measured $^{234}\text{U}/^{235}\text{U}$ of the sample to the mean $^{234}\text{U}/^{235}\text{U}$ measured for the HU-1 uraninite standard. Because HU-1 is in secular equilibrium, this ratio is equivalent to the $^{234}\text{U}/^{238}\text{U}$ activity ratio.

[††] Samples = number of separately selected and analyzed fractions of coral; runs = number of MS analyses done for these fractions.

[§§] Activity ratio from alpha spectrometry.

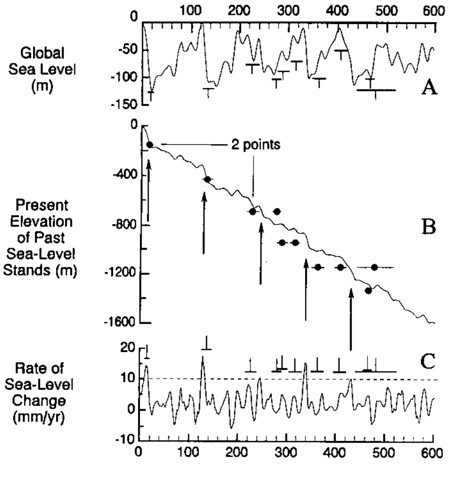

Figure 2. Relation of $^{234}U/^{238}U$-dated corals to subsidence history of reefs and global eustatic sea-level changes. A: Global sea-level variations, based on simple linear transformation of oxygen-isotope record from deep-sea sediments. Vertical lines correspond to $^{234}U/^{238}U$ ages, with uncertainties, of terrace samples. B: Curve shows past sea levels at location of Hawaiian terraces of this study, relative to present-day sea level. Curve was constructed assuming global sea-level history of A superimposed on constant subsidence rate of 2.6 mm/yr for past 460 ka for Hawaiian ridge in study area. Circles with dashes indicate $^{234}U/^{238}U$ ages and analytical uncertainties for terrace samples, plotted at average depth of shelf break of reef; vertical arrows indicate most likely times of reef drowning, projected from C. C: Rate of sea-level change at study area, derived from B (positive values indicate most rapid submergence). T bars in B and C indicate $^{234}U/^{238}U$ ages for terrace samples, with uncertainties. Dashed line indicates approximate maximum upward growth limit of coral reefs.

open-system processes. Such effects have been demonstrated for corals from elevated terraces (Bender et al., 1979), where the corals have been exposed to extensive fresh-water interaction. The 11% calcite content of sample 18 (Table 2) is possibly a result of such alteration, though its $^{234}U/^{238}U$ age is not grossly aberrant. Though we cannot rule out diagenetic effects for the rest of the (calcite-free) samples from the Hawaiian submerged reefs, which have had little exposure to fresh water, we are encouraged by the mass-spectrometric $^{234}U/^{238}U$ age of 750 ±13 ka for a coral from a deep terrace off Maui (Moore et al., 1990). Even though the sensitivity of the $^{234}U/^{238}U$ system to open-system processes at this relatively old age is very high, the 750 ka date is in agreement with the 730 ka age estimated from the depth of the reef and its relation to previously dated reefs.

Despite the complications discussed above, the $^{234}U/^{238}U$ ages from the reefs (Table 2, Fig. 2) seem to support the model of reef drowning at the onset of periods of greatest submergence rate as defined by the oxygen-isotope chronology of deep-sea sediments. The presence of the five similarly sized and spaced reefs supports this model, and can be explained by no other known mechanism. Apparent discrepancies in the $^{234}U/^{238}U$ ages for samples dredged from apparently the same terrace, or from predicted ages of reef drowning, could readily arise from a combination of the sampling difficulties discussed above and uncertainties in the parameters that define the quantitative model of reef drowning. Specifically, it does not seem unreasonable that the value of 10 mm/yr (Grigg and Epp, 1989) that we have used for the rate of maximum upward growth of coral could be in error by as much as a factor of two for these reefs. Also, the calculated trend for the past rates of sea-level change depends critically on both the transformation from oxygen-isotope ratios to sea level and the ages assigned to the curve given in Imbrie et al. (1984). However, the former is known to be an oversimplification, and the latter rely on a time scale derived by a mathematical procedure that forces the timing of the observed deep-sea sediment oxygen-isotope variations to agree with the cyclicity predicted by the Milankovitch model of orbitally induced climate variation. Because of these uncertainties, more work is needed to understand the reasons for the observed $^{234}U/^{238}U$ age variations discussed above.

CONCLUSIONS

Mass-spectrometric $^{234}U/^{238}U$ analysis of corals is a powerful and precise method for dating relatively old Pleistocene reefs that have not been exposed to extensive fresh-water interaction. Dating by this method on corals from submerged reefs suggests that (1) subsidence of the Hawaiian Ridge northwest of Hawaii has been continuous for at least the past 475 ka, at an approximately uniform rate of 2.6 ±0.4 mm/yr; (2) the ages of at least the two youngest terraces (17–19 and 133 ka) match closely the predicted times of reef drowning arising from the rapid rise of sea level at the end of glacial periods; and (3) the ages of samples from the four older terraces are more difficult to correlate precisely with glacial terminations. The difficulty in correlation may arise from (1) minor open-system processes, (2) uncertainties in the parameters used to construct the general quantitative model of reef drowning, or (3) the possibility that some of the samples do not represent the final stages of reef growth for their assigned terraces.

REFERENCES CITED

Arden, J.W., and Gale, N.H., 1974, Separation of trace amounts of uranium and thorium and their determination by mass spectrometric isotope dilution: Analytical Chemistry, v. 46, p. 687–691.

Bender, M.L., Fairbanks, R.G., Taylor, F.W., Matthews, R.K., Goddard, J.G., and Broecker, W.S., 1979, Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies: Geological Society of America Bulletin, v. 90, p. 577–594.

Campbell, J.G., 1987, Bathymetric atlas of the southeast Hawaiian Islands: Hawaii Institute of Geophysics Technical Report 87-1, 21 p.

Chappell, J., and Shackleton, N.J., 1986, Oxygen isotopes and sea level: Nature, v. 324, p. 137–140.

Chen, J.H., Edwards, R.L., and Wasserburg, G.J., 1986, ^{238}U, ^{234}U, and ^{232}Th in seawater: Earth and Planetary Science Letters, v. 80, p. 241–251.

de Bièvre, P., and eight others, 1971, The half-life of 234-U, *in* Hurrell, M.L., ed., Proceedings of an International Conference on Chemical and Nuclear Data, Measurement and Applications, Canterbury: London, Institute of Civil Engineers, p. 221–225.

Edwards, R.L., Chen, J.H., and Wasserburg, G.J., 1986, ^{238}U-^{234}U-^{230}Th-^{232}Th systematics and the precise measurement of time over the past 500,000 years: Earth and Planetary Science Letters, v. 81, p. 175–192.

Grigg, R.W., and Epp, D., 1989, Critical depth for the survival of coral islands: Effects on the Hawaiian archipelago: Science, v. 243, p. 638–641.

Imbrie, J., and eight others, 1984, The orbital theory of Pleistocene climate: Support from a revised chronology of the marine delta ^{18}O record, *in* Berger, A., et al., eds., Milankovitch and climate, Part I: Boston, D. Reidel, p. 269–305.

Moore, J.D., and Clague, D., 1987, Coastal lava flows from Mauna Loa and Hualalai volcanoes, Kona, Hawaii: Bulletin of Volcanology, v. 49, p. 752–764.

Moore, J.G., and Campbell, J.F., 1987, Age of tilted reefs, Hawaii: Journal of Geophysical Research, v. 92, p. 2641–2646.

Moore, J.G., and Fornari, D.J., 1984, Drowned reefs as indicators of the rate of subsidence of the island of Hawaii: Journal of Geology, v. 92, p. 752–759.

Moore, J.G., Clague, D.A., Ludwig, K.R., and Mark, R.K., 1990, Subsidence and volcanism of the Haleakala Ridge, Hawaii: Journal of Volcanology and Geothermal Research, v. 42, 11 p.

Shackleton, N.J., and Opdyke, N.D., 1976, Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-329, late Pliocene to latest Pleistocene, *in* Cline, R.M., and Hays, J.D., eds., Investigation of late Quaternary paleoceanography and paleoclimatology: Geological Society of America Memoir 145, p. 449–464.

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, v. 14, p. 967–968.

Szabo, B.J., Carr, W.J., and Gottschall, W.C., 1981, Uranium-thorium dating of Quaternary carbonate accumulations in the Nevada Test Site region, southern Nevada: U.S. Geological Survey Open-File Report 81-119, 35 p.

ACKNOWLEDGMENTS

We thank the scientists and crews of several vessels for their valuable service in contributing to the sample collection for this study, particularly D. J. Fornari (1983 *Makali'i* submersible program), J. H. Natland (1987 *Melville* dredging), D. A. Clague and R. B. Halley (1988 *Pisces* submersible program), and Clague, R. Holcomb, P. W. Lipman, and M. Torresan (1988 *Farnella* dredging). John W. Wells kindly determined the species of the coral samples.

Manuscript received July 5, 1990
Revised manuscript received September 10, 1990
Manuscript accepted September 25, 1990