

Th²³⁰/U²³⁸ and U²³⁴/U²³⁸ Ages of Pleistocene High Sea Level Stand

H. HERBERT VEEH¹

*Scripps Institution of Oceanography
University of California, San Diego*

Unrecrystallized fossil corals occurring in their growth positions between 2 and 9 meters above sea level at many locations in the Pacific and Indian oceans have been dated by the Th²³⁰/U²³⁸ and U²³⁴/U²³⁸ methods. Where possible, recent corals were also collected and analyzed for their uranium and thorium isotopes. The uranium contents of the corals were determined fluorimetrically; the U²³⁴/U²³⁸ ratios and the thorium concentrations were ascertained by alpha spectrometry. The Th²³⁰/U²³⁸ ages of the fossil corals range from 90,000 ± 20,000 to 160,000 ± 40,000 years and the U²³⁴/U²³⁸ ages from 80,000 ± 50,000 to 180,000 ± 60,000 years. Absence of Th²³⁰ in the recent corals and absence of Th²³² in both the recent and the fossil corals confirm the assumption that the Th²³⁰ found in the fossil corals resulted solely from radioactive decay of its parent uranium. Control samples of pre-Pleistocene material showed radioactive equilibrium between the various members in the U²³⁸ decay chain. Both the internal consistency of the ages, within experimental error, and the agreement between the Th²³⁰/U²³⁸ and U²³⁴/U²³⁸ ages, strongly support the general validity of these ages. The similarity of the Th²³⁰/U²³⁸ ages of Pleistocene coral reefs to those of like elevations above sea level in many localities suggests a eustatic sea level stand higher than now at about 120,000 ± 20,000 years ago, possibly during an interglacial stage of the Pleistocene.

INTRODUCTION

The principle and the assumptions underlying the Th²³⁰/U²³⁸ dating technique have previously been described [Barnes *et al.*, 1956; Sackett, 1958; Tatsumoto and Goldberg, 1959; Blanchard, 1963; Broecker, 1963; Broecker and Thurber, 1965; Thurber *et al.*, 1965; Osmond *et al.*, 1965]. This method is based on the observation that marine carbonates, in particular reef-building corals and oolites, contain measurable amounts of uranium but are essentially free of its decay product Th²³⁰. The growth of Th²³⁰ toward a state of radioactive equilibrium with its parent U²³⁸ can be used as a measure of age under the following assumptions: (1) No significant amounts of Th²³⁰ are initially present in the carbonate, (2) the carbonate has remained a closed system since its formation, and (3) the U²³⁴/U²³⁸ ratio in the ocean has remained constant throughout the dating period. Because of a 15% excess in the ocean of U²³⁴ over its parent U²³⁸, the re-attainment of radioactive equilibrium between these two isotopes after their removal from the ocean can be used as an approximate age

determination, if assumptions (2) and (3) are valid [Thurber, 1962].

The most promising results have been obtained for reef corals and oolites, where the uranium appears to be of primary origin and where the radiometric ages coincide with the time elapsed since the formation of the carbonate in the marine environment. Since coral reefs also form an ideal marker for former sea level stands [Kuenen, 1955; Russell, 1964], an application of the Th²³⁰/U²³⁸ and U²³⁴/U²³⁸ dating techniques to corals associated with former shorelines in different geographic locations should produce valuable information on the chronology of Pleistocene sea level fluctuations. Maclaren [1842] first postulated that during the Pleistocene period the sea level rose and fell in response to the varying amounts of water tied up on land as ice, and subsequently many workers referred to the widespread occurrence of emerged shorelines of similar elevations in support of this hypothesis [Daly, 1934; Zeuner, 1959; Stearns, 1961; Fairbridge, 1961; Russell, 1964]. In an attempt to test this hypothesis, we have obtained Th²³⁰/U²³⁸ and U²³⁴/U²³⁸ ages for corals occurring in emerged coral reefs of like elevations above sea level in a variety of locations in the Pacific and Indian oceans. The results are reported in this paper.

¹ Now at Department of Geology, Yale University, New Haven, Connecticut.

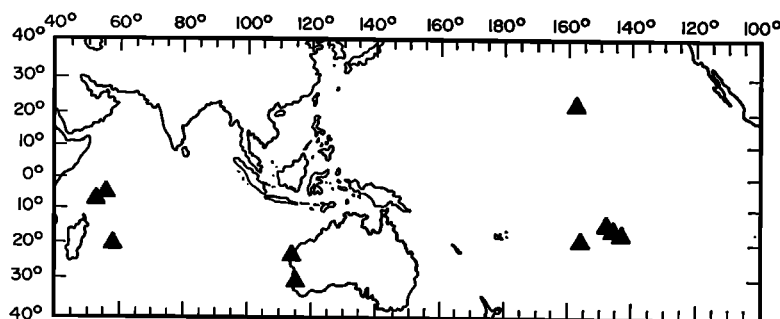


Fig. 1. Map showing location of samples.

SAMPLING PROCEDURE

For the study of the chronology of sea level fluctuations samples are required that represent the former position of sea level as reliably and as accurately as possible and that are taken from diverse localities covering such a wide area that the possibility of any tectonic relationship between these localities is minimized. *Russell* [1964] recommends the contact between reef flat accumulations and overlying encrusting organisms as the best guide to establishing low tide level. By measuring the vertical distance between this contact and its older equivalent, we can determine the position of the former sea level with sufficient accuracy. Because of the uncertainty in relating former sea level stands to emerged coral reefs in some places, measurements made by hand level, rounded off to the nearest meters, are considered to be sufficiently accurate. Since age determinations made on transported material give little information about the time and position of former sea level stands, great care was taken to analyze only corals in their original position of growth.

Emerged coral reefs may indicate uplift of the land due to crustal instability, a drop of sea level, or a combination of the two. In an attempt to separate successfully the effects of both types of movement, we obtained samples from emerged reefs of similar height above sea level in a number of different localities in both the Pacific and Indian oceans (Figure 1). The sample locations include the west coast of Australia, the Seychelles, which cap an ancient crystalline basement, the volcanic islands of Mauritius in the Indian Ocean, Oahu and

Mangaia in the Pacific, and three islands in the Tuamotu archipelago. It seems unlikely that these localities, spread out over two oceans, should be affected identically by tectonic movements. Wherever possible, more than one sample from each location was analyzed in order to obtain an idea of the internal consistency of the ages within the same stratigraphic units. In addition, recent corals were collected from living reefs in a number of places as a check on the general validity of some of the assumptions. A more detailed description of the sample sites is given elsewhere [Veeh, 1965].

EXPERIMENTAL PROCEDURE

The initial sample preparation included the selection of unrecrystallized parts of the aragonite coral skeleton and the mechanical removal of any foreign materials with a standard dentist drill, followed by ultrasonic vibration. As the presence of calcite in any coral sample serves as a criterion for recognizing recrystallized and therefore unsuitable material [Sackett, 1958; *Thurber et al.*, 1965], the fossil corals were analyzed by X-ray diffraction methods,

TABLE 1. Analyses of Uranium in Spergen Limestone Standard

This Study		Other Results	
Method	U, ppm	Method	U, ppm
Fluorimetric	1.09 ± 0.10	Fluorimetric*	1.17
		Alpha spectrometry†	1.08
			1.20

* Sackett (personal communication, 1964).

† Thurber (personal communication, 1965).

Sample No.	Species	Location	U ²³⁸ , ppm	$\frac{U^{234*}}{U^{238}}$	Th ²³⁰ †	Th ²³² , ppm	$\frac{Th^{230}}{U^{238}}$
OAHU L 16	Porites	Oahu, Hawaii	2.6		<0.02	<0.05	<0.01
OAHU L 18	Leptastrea	Oahu, Hawaii	2.7		<0.02	<0.05	<0.01
OAHU L 19	Pocillopora	Oahu, Hawaii	2.5		<0.02	<0.05	<0.01
OAHU L 20	Porites	Oahu, Hawaii	2.6		<0.02	<0.05	<0.01
OAHU L 25	Pocillopora	Oahu, Hawaii	2.4	1.15 ± 0.016	<0.02	<0.05	<0.01
ANAA L 1	Pocillopora	Anaa, Tuamotu Is.	2.5		<0.02	<0.05	<0.01
TAHI L 1	Acropora	Tahiti, Society Is.	2.1	1.16 ± 0.017	<0.02	<0.05	<0.01
TAHI L 2	Porites	Tahiti, Society Is.	2.1		<0.02	<0.05	<0.01
TUTU L 1	Acropora	Tutuila, Samoa	2.0	1.16 ± 0.016	<0.02	<0.05	<0.01
TUTU L 2	Leptoria	Tutuila, Samoa	2.2		<0.02	<0.05	<0.01

* Activity ratio.

† Uranium equivalents.

using a quantitative technique similar to that given by *Lowenstam* [1954]. Fossil corals containing more than 0.5% calcite, the lower limit of detection, were considered unsuitable for dating.

The total uranium content was determined according to a standard fluorimetric procedure [*Grimaldi et al.*, 1954; *Centanni et al.*, 1956] using a ball transmission-type fluorimeter,

model FI-500. Since 99.3% of the uranium in nature consists of U²³⁸ [*Strominger et al.*, 1958], the uranium values thus obtained can be regarded as a measure of U²³⁸. The standard deviation of replicate analyses was 9%. A comparison between the uranium content of a standard determined in this study and by other workers is given in Table 1.

The procedure adopted for the determina-

TABLE 3. Isotopic Uranium and Thorium Content of Fossil Corals Collected in situ between 2 and 9 Meters above Sea Level

Sample No.	Species	Location	U ²³⁸ , ppm	$\frac{U^{234*}}{U^{238}}$	Th ²³⁰ †	Th ²³² , ppm	$\frac{Th^{230}}{U^{238}}$
OAHU 2	Leptastrea	Oahu, Hawaii	3.3		2.51	<0.05	0.76
OAHU 5	Leptastrea	Oahu, Hawaii	3.5		2.54	<0.05	0.73
OAHU 9	Leptastrea	Oahu, Hawaii	2.7		1.97	<0.05	0.73
OAHU 22	Leptastrea	Oahu, Hawaii	3.3	1.10 ± 0.015	2.68	<0.05	0.81
ANAA 5	Leptoria	Anaa, Tuamotu Is.	2.0		1.65	<0.05	0.83
ANAA 15	Leptoria	Anaa, Tuamotu Is.	2.2		1.72	<0.05	0.78
ANAA 16	Leptoria	Anaa, Tuamotu Is.	2.5	1.12 ± 0.015	1.81	<0.05	0.72
NIAU 4	Leptoria	Niau, Tuamotu Is.	2.1		1.81	<0.05	0.86
NIAU 6	Leptoria	Niau, Tuamotu Is.	2.3	1.09 ± 0.015	1.75	<0.05	0.76
MAKA 2	Favia	Makatea, Tuamotu Is.	2.3		1.86	<0.05	0.81
MAKA 3	Leptoria	Makatea, Tuamotu Is.	2.3		1.55	<0.05	0.67
MANG 1	Favia	Mangaia, Cook Is.	3.0		1.88	<0.05	0.63
MANG 2	Leptoria	Mangaia, Cook Is.	2.4	1.11 ± 0.014	1.76	<0.05	0.73
T 63 402‡	Favia (?)	Western Australia	2.5		1.69	<0.05	0.68
I-094§	Porites (?)	Western Australia	3.4	1.11 ± 0.014	2.76	<0.05	0.81
I-176§	Leptoria	Mauritius	2.6	1.11 ± 0.014	2.27	<0.05	0.87
I-267§	Porites	Seychelles	2.1	1.10 ± 0.014	1.69	<0.05	0.80
I-270§	Favia	Seychelles	2.1	1.12 ± 0.015	1.64	<0.05	0.78

* Activity ratio.

† Uranium equivalents.

‡ Collected by C. Teichert.

§ Collected by R. J. Russell and Wm. G. McIntire.

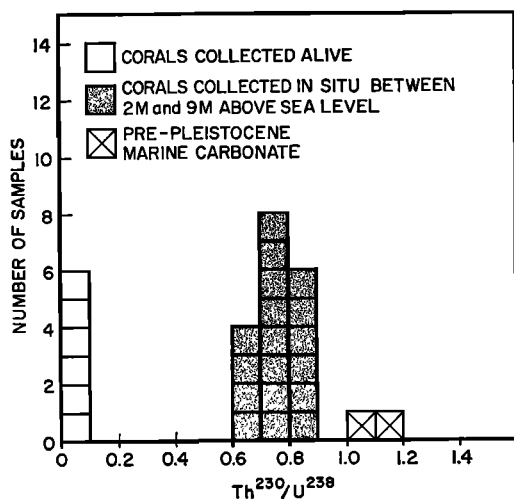


Fig. 2. Histogram of $\text{Th}^{230}/\text{U}^{238}$ ratios. Note how values for corals occurring in emerged reefs between 2 and 9 meters above sea level fall into a narrow range with an average of 0.76. The recent and the pre-Pleistocene material are control samples; they show that no Th^{230} is present in recent corals but that Th^{230} is near equilibrium with its parent uranium in old material.

tion of the $\text{U}^{234}/\text{U}^{238}$ ratio by alpha spectrometry is similar to one reported by Koide and Goldberg [1965], who used an ORTEC silicon diode solid-state detector (Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee) coupled to a Nuclear Data 512-channel pulse height analyzer (Nuclear Data, Inc., Madison, Wisconsin). The alpha resolution of the different detectors used in this study varied from 37 to 45 kev. The efficiency of the procedure for chemically isolating the uranium isotopes from the thorium was checked with Th^{234} as a tracer. A second check was obtained by dissolving several of the final uranium deposits on the counting planchets, recycling them through the anion exchange process, and then replating them. The $\text{U}^{234}/\text{U}^{238}$ ratios of the recycled uranium did not differ within experimental error from the $\text{U}^{234}/\text{U}^{238}$ ratios of the first uranium deposits on the planchets. Hence the activities under the U^{234} peak of the alpha spectrum are solely attributed to U^{234} and not in part to Th^{230} .

A procedure for the isolation and enrichment of thorium from limestones and corals, using Th^{234} as a yield tracer, has been described [Hyde, 1960]. The basic steps include co-pre-

cipitation of thorium with ferric hydroxide and further purification by cation exchange. The purified thorium is electroplated on platinum planchets and the yield determined by counting the beta activity of the Th^{234} tracer under an end-window Geiger counter. The analytical error of this procedure arises mainly from the counting statistics and is less than $\pm 5\%$.

RESULTS AND DISCUSSION

The analytical results are shown in Tables 2 and 3. On the average, the uranium concentration in the fossil corals does not differ significantly from that in the recent corals; therefore most of the uranium in the fossil corals is of primary origin. The insignificant content of Th^{230} in the recent corals and of Th^{232} in the recent as well as in the fossil corals probably reflects the extremely low concentration of these isotopes in seawater [Sackett *et al.*, 1958; Moore and Sackett, 1964]. Absence of significant amounts of Th^{232} in the fossil corals, a requirement imposed on the reliability of the $\text{Th}^{230}/\text{U}^{238}$ ages [Tatsumoto and Goldberg, 1959], shows that contamination by extraneous Th^{230} cannot be responsible for the Th^{230} contents listed in Table 3. Hence the Th^{230} observed in the fossil corals must have resulted solely from radioactive decay of its parent uranium. When the $\text{Th}^{230}/\text{U}^{238}$ and the $\text{U}^{234}/\text{U}^{238}$ ratios are plotted in histograms, a distinct pattern evolves (Figures 2 and 3). The $\text{Th}^{230}/\text{U}^{238}$ ratios of the fossil corals collected from emerged reefs of like elevations between 2 and 9 meters above

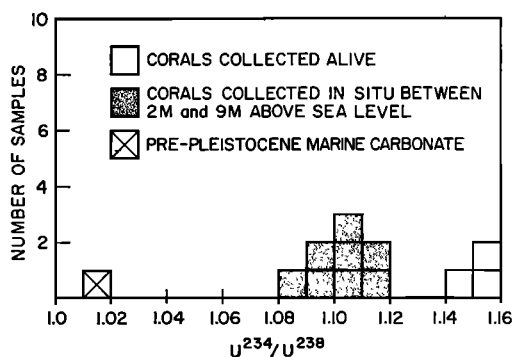


Fig. 3. Histogram of $\text{U}^{234}/\text{U}^{238}$ activity ratios. Note that materials of different ages have different ratios but that the ratios in corals from emerged reefs between 2 and 9 meters above sea level are very similar.

TABLE 4. Ages and Elevations of Fossil Corals Occurring in situ between 2 and 9 Meters above Sea Level

Sample	Location	Elevation above Mean Low Tide, m	Th ²³⁰ age* (× 10 ³ yr)	U ²³⁴ age† (× 10 ³ yr)
Hawaii				
OAHU 2	Oahu	3	120 ± 30	
OAHU 5	Oahu	1.5	110 ± 20	
OAHU 9	Oahu	2	110 ± 20	
OAHU 22	Oahu	1.5	140 ± 30	140 ± 50
Tuamotu Is.				
ANAA 5	Anaa	2	150 ± 40	
ANAA 15	Anaa	4	140 ± 30	
ANAA 16	Anaa	4	110 ± 20	80 ± 50
NIAU 4	Niau	3	160 ± 40	
NIAU 6	Niau	4	120 ± 20	180 ± 60
MAKA 2	Makatea	3	140 ± 30	
MAKA 3	Makatea	3	100 ± 20	
Cook Is.				
MANG 1	Mangaia	2	90 ± 20	
MANG 2	Mangaia	2	110 ± 20	110 ± 50
West Australia				
T 63 402	Rottneest Is.	2	100 ± 20	
I-094	Boundary Beach	4	140 ± 30	110 ± 40
Mauritius				
I-176	Gabriel Is.	1.5	160 ± 40	110 ± 40
Seychelles				
I-267	Mahe Is.	9	140 ± 30	140 ± 50
I-270	Praslin	6	140 ± 30	80 ± 40

* Based on half-life of Th²³⁰ of 7.52×10^4 years [Attree *et al.*, 1962].

† Based on half-life of U²³⁴ of 2.48×10^5 years [Strominger *et al.*, 1958].

sea level are grouped around a value of 0.76. Similarly, the U²³⁴/U²³⁸ ratios in these emerged reefs are centered around a value of 1.11, as compared with a value of 1.15 in modern carbonates and present-day seawater [Thurber, 1962; Koide and Goldberg, 1965]. The low U²³⁴/U²³⁸ ratio in the fossil corals gives support to the assumption that the corals have remained a closed system since their formation in the marine environment.

The Th²³⁰ ages shown in Table 4 have been calculated, using an equation presented by Broecker [1963] and assuming an initial U²³⁴/U²³⁸ ratio of 1.15. The errors quoted correspond to one standard deviation of the Th²³⁰/U²³⁸ ratio, estimated to be 10%. Within the limits of

this error, all the corals from the emerged reefs between 2 and 9 meters above sea level appear to have the same age. Samples taken from the same location display similar variations in age as samples from different geographic locations. If true age differences between these reefs do exist, they cannot be resolved by the techniques employed in this study.

The U²³⁴ ages, were derived from the U²³⁴/U²³⁸ ratios in the fossil corals, assuming that this ratio was 1.15 at the time these corals were living. The errors correspond to the uncertainty arising from the counting statistics. Where both the Th²³⁰/U²³⁸ and the U²³⁴/U²³⁸ methods have been applied to the same samples, the ages are in satisfying agreement.

TABLE 5. Characteristics of Control Samples Representing Different Ages

Sample	Age	U ²³⁸ , ppm	Th ²³⁰ *	Th ²³⁰ / U ²³⁸	Th ²³² , ppm	U ²³⁴ †/ U ²³⁸	Th ²³⁰ age (× 10 ³ yr)	U ²³⁴ age (× 10 ³ yr)
KAUA 17 ¹	8370 ± 250 yr C ¹⁴ age (LJ.753)	2.6	0.20	0.08	<0.05		8 ± 1	
MAKA 4 ²	Pleistocene	2.4	2.20	0.92	<0.05	1.05 ± 0.014	≥200	400 ± 100
OAHU 26 ³	Miocene	2.4	2.42	1.01	0.1		>200	
Limestone ⁴	Mississippian	1.1	1.26	1.14	0.1	1.02 ± 0.02	>200	>700

* Uranium equivalents.

† Activity ratio

- (1) Coral (*Porites*) from drowned reef at a depth of 20 m off Kauai, Hawaii (D. L. Inman, personal communication).
- (2) Coral (*Leptoria*) from 15 m above sea level on Makatea, Tuamotu Islands. This coral is stratigraphically older than the emerged reef represented by MAKA 2 and MAKA 3 in Table 4.
- (3) Coral (*Leptastrea*) associated with Miocene fauna from drowned reef at a depth of 500 m south of Oahu, Hawaii [Menard *et al.*, 1962].
- (4) Spargen limestone of Mississippian age from Ste. Genevieve, Missouri.

Further support for the general validity of these ages is provided by the control samples (Table 5). The agreement between the C¹⁴ age and the Th²³⁰ age of sample KAUA 17 is strong evidence for the validity of the assumptions, at least for the last few thousand years. Excellent agreement between C¹⁴ ages and Th²³⁰ ages in coral samples for the last 6000 years has also been obtained by Thurber *et al.* [1965]. The sample MAKA 4 was taken from the remnant of an emerged reef which, by its stratigraphic position, is older than the reef represented by samples MAKA 2 and MAKA 3. This sequence is also reflected in the radiometric ages, demonstrating that two different periods of submergence within the Pleistocene can be resolved by the techniques used in this study. Unpublished results by Lowenstam and Goldberg (personal communication) obtained for two separate coral reefs at different elevations on the island of Bermuda also showed distinctly different Th²³⁰/U²³⁸ ages at about 120,000 years ago and at 200,000 years ago or more. The analyses of the two pre-Pleistocene marine carbonates show the Th²³⁰ to be in radioactive equilibrium with the U²³⁸, which means that these two samples have remained a closed system for at least the last 200,000 years.

These considerations, coupled with the internal consistency of the radiometric ages within the same stratigraphic units and the agreement between the Th²³⁰ and U²³⁴ ages, in-

dicate that the assumptions made are, in general, valid. It is therefore proposed that the apparent ages shown in Table 4 define the time when the sea level was near its present position, although probably somewhat higher than now. The elevations given in column 3 are the measured elevations of the coral samples. They provide a minimum estimate of the former position of sea level but do not, by themselves, give its actual position, which may have been somewhat higher. Furthermore, because of tectonic movements, we do not expect to find former eustatic shorelines at identical elevations everywhere. Hence the actual position of sea level at the time indicated by the ages in Table 4 cannot be determined from the limited number of observations available. However, the similarity of ages of emerged coral reefs at like elevations in the vicinity of the present sea level in many places in the world implies that (1) these reefs were formed during one of the interglacial stages of the Pleistocene, when the climate was similar to that of today, and (2) the age of 120,000 ± 20,000 years marks the peak of that interglacial stage.

Osmond *et al.* [1965], using the Th²³⁰/U²³⁴ technique, obtained an average age of 130,000 years for a number of corals and oolites from the Key Largo limestone and from the Miami oolite banks, both of which are believed to have formed in a sea standing 10 meters higher than now. Broecker and Thurber [1965] analyzed

corals and oolites from the Bahamian and Florida Key limestones and concluded that these areas were submerged at various times between 80,000 and 150,000 years ago. To this may be added a coral collected above sea level on Guadalupe Island off the west coast of Mexico which gave a Th^{230} age of $130,000 \pm 20,000$ years and a U^{234} age of $140,000 \pm 50,000$ years (Goldberg and Koide, personal communication).

Broecker [1965] has given a comparison between various climatic records of the Pleistocene and eustatic sea level stands. His correlation requires that there was also a separate high sea level stand about 80,000 years ago. Results reported for mollusks from emerged shorelines in the Mediterranean seem to support a marine transgression above the present sea level between about 75,000 and 90,000 years ago [Stearns and Thurber, 1965]. These results are based on $\text{Th}^{230}/\text{U}^{234}$ ages for mollusks and thus may be open to dispute because part of the uranium in mollusks is of secondary origin [Broecker, 1963]. So far only one coral from the Bahamas has yielded an age of 80,000 years [Broecker and Thurber, 1965]. This is somewhat puzzling, as one would expect a higher sea level stand at that time to have left many corals above sea level. It should be possible to settle the question by extending this work to other areas, using only corals and concentrating on locations where some stratigraphic control is available.

Acknowledgments. I thank Dr. R. J. Russell and Dr. Wm. G. McIntire of the Coastal Studies Institute, Louisiana State University, and Dr. C. Teichert of the University of Kansas, who kindly supplied some of the samples and valuable information for this study. Dr. E. C. Allison of San Diego State College helped with the identification of the corals. Dr. F. P. Shepard and Dr. E. D. Goldberg of the University of California, San Diego, and Dr. H. Lowenstam of the California Institute of Technology gave helpful advice and criticism.

The experimental part of this work was supported by the Atomic Energy Commission, Division of Biology and Medicine, under contract AT (11-1)-34 No. 84 with the University of California, San Diego. Additional financial support was provided by a grant from the U. S. Steel Foundation, by contract funds (NONR 2216) from the Office of Naval Research, and by a fellowship from the Ford Foundation.

REFERENCES

- Attree, R. W., M. J. Cabell, R. L. Cushing, and J. J. Pieroni, A calorimetric determination of the half-life on Th^{230} and a consequent revision to its neutron cross section, *Can. J. Phys.*, **40**, 194-201, 1962.
- Barnes, J. W., E. J. Lang, and H. A. Potratz, Ratio of ionium to uranium in coral limestone, *Science*, **124**, 175-176, 1956.
- Blanchard, R. L., Uranium decay series disequilibrium in age determinations of marine calcium carbonates, Ph.D. thesis, Washington University of St. Louis, 1963.
- Broecker, W. S., A preliminary evaluation of uranium series inequilibrium as a tool for absolute age measurements on marine carbonates, *J. Geophys. Res.*, **68**, 2817-2834, 1963.
- Broecker, W. S., Isotope geochemistry and the Pleistocene climate record, in *The Quaternary of the United States*, pp. 737-753, Princeton University Press, 1965.
- Broecker, W. S., and D. L. Thurber, Uranium series dating of corals and oolites from Bahaman and Florida Key limestones, *Science*, **149**, 55-60, 1965.
- Centanni, F. A., A. M. Ross, and M. A. DeSesa, Fluorimetric determination of uranium, *Anal. Chem.*, **28**, 1651-1657, 1956.
- Daly, R. A., *The Changing World of the Ice Age*, 271 pp., Yale University Press, 1934.
- Fairbridge, R. W., Eustatic changes in sea level, in *Phys. Chem. Earth*, **4**, 99-185, 1961.
- Grimaldi, F. S., I. May, M. H. Fletcher, and J. Titcomb, Collected papers on methods of analysis of uranium and thorium, *U. S. Geol. Surv. Bull.*, **1006**, 184 pp., 1954.
- Hyde, E. K., The radiochemistry of thorium, *Natl. Acad. Sci., Natl. Res. Council, Nuclear Sci. Ser.*, **70** pp., 1960.
- Koide, M., and E. D. Goldberg, $\text{U}^{234}/\text{U}^{238}$ ratios in sea water, *Progr. Oceanog.*, **3**, 173-177, 1965.
- Kuenen, P. H., Sea level and crustal warping, in *Crust of the Earth*, *Geol. Soc. Am. Spec. Paper* **62**, pp. 193-204, 1955.
- Lowenstam, H. A., Factors affecting the aragonite-calcite ratios in carbonate secreting organisms, *J. Geol.*, **62**, 284-321, 1954.
- Maclaren, C., The glacial theory of Professor Agassiz, *Am. J. Sci.*, **42**, 346-365, 1842.
- Menard, H. W., E. C. Allison, and J. W. Durham, A drowned Miocene terrace in the Hawaiian Islands, *Science*, **133**, 896-897, 1962.
- Moore, W. S., and W. M. Sackett, Uranium and thorium series inequilibrium in sea water, *J. Geophys. Res.*, **69**, 5401-5405, 1964.
- Osmond, J. K., J. R. Carpenter, and H. L. Windom, $\text{Th}^{230}/\text{U}^{234}$ age of Pleistocene corals and oolites of Florida, *J. Geophys. Res.*, **70**, 1843-1847, 1965.
- Russell, R. J., Techniques of eustasy studies, *Z. Geomorphol.*, **8**, *Sonderheft*, pp. 25-42, 1964.

- Sackett, W. M., Ionium-uranium ratios in marine deposited calcium carbonates and related materials, Ph.D. thesis, Washington University of St. Louis, 1958.
- Sackett, W. M., H. A. Potratz, and E. D. Goldberg, Thorium content of ocean water, *Science*, **128**, 204–205, 1958.
- Stearns, C. E., and D. L. Thurber, $\text{Th}^{230}/\text{U}^{234}$ dates of late Pleistocene marine fossils from the Mediterranean and Moroccan littorals, *Quaternaria*, **7**, 29–42, 1965.
- Stearns, H. T., Eustatic shorelines on Pacific islands, *Z. Geomorphol., Suppl.*, **3**, 3–16, 1961.
- Strominger, D., J. M. Hollander, and G. T. Seaborg, Table of isotopes, *Rev. Mod. Phys.*, **30**, 585–904, 1958.
- Tatsumoto, M., and E. D. Goldberg, Some aspects of the marine geochemistry of uranium, *Geochim. Cosmochim. Acta*, **17**, 201–208, 1959.
- Thurber, D. L., Anomalous $\text{U}^{234}/\text{U}^{238}$ in nature, *J. Geophys. Res.*, **67**, 4518–4520, 1962.
- Thurber, D. L., W. S. Broecker, H. A. Potratz, and R. L. Blanchard, Uranium series ages of Pacific atoll coral, *Science*, **149**, 55–58, 1965.
- Veeh, H. H., $\text{Th}^{230}/\text{U}^{238}$ and $\text{U}^{234}/\text{U}^{238}$ ages of elevated Pleistocene coral reefs and their geological implications, Ph.D. thesis, University of California, San Diego, 1965.
- Zeuner, R. F., *The Pleistocene Period*, 447 pp., Hutchison, London, 1959.

(Manuscript received January 31, 1966.)