Milankovitch Hypothesis Supported by Precise Dating of Coral Reefs and Deep-Sea Sediments
Author(s): Wallace S. Broecker, David L. Thurber, John Goddard, Teh-Lung Ku, R. K. Matthews, Kenneth J. Mesolella
Source: *Science*, New Series, Vol. 159, No. 3812 (Jan. 19, 1968), pp. 297-300
Published by: American Association for the Advancement of Science
Stable URL: http://www.jstor.org/stable/1722583
Accessed: 14/05/2009 11:24

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=aaas.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit organization founded in 1995 to build trusted digital archives for scholarship. We work with the scholarly community to preserve their work and the materials they rely upon, and to build a common research platform that promotes the discovery and use of these resources. For more information about JSTOR, please contact support@jstor.org.

American Association for the Advancement of Science is collaborating with JSTOR to digitize, preserve and extend access to *Science.*

http://www.jstor.org

Reports

Milankovitch Hypothesis Supported by Precise Dating of Coral Reefs and Deep-Sea Sediments

Abstract. *Barbados provides a possibly unique opportunity for reconstruction of the times and elevations of late-Pleistocene high stands of the sea. The island appears to be rising from the sea at a uniform rate that is fast enough to separate in elevation coral-reef tracts formed at successive high stands of the sea. Unaltered coral found in the lower terraces enables high-precision* $Th^{230}:U^{234}$ *and* $Pa^{231}:U^{235}$ *dating. Three distinct high stands of the sea are found about 122,000, 103,000, and 82,000 years ago. New* Pa^{231} *and* Th^{230} *dates from a deep-sea core also indicate that Ericson's W-X cold-to-warm climatic change occurred close to 126,000 years ago. These data show a parallelism over the last 150,000 years between changes in Earth's climate and changes in the summer insolation predicted from cycles in the tilt and precession of Earth's axis.*

The Th^{230}-growth method of dating marine carbonates (*1*) has proved to be a highly useful geochronometer for ages between 50,000 and 250,000 years. Many investigators have applied it to the problem of late-Pleistocene fluctuations in sea level (*2–6*); their results suggest that sea level stood somewhat higher about 120,000 years ago than today. The work of Veeh (*6*) in particular documents a sea stand 2 to 6 m above the present level at that time. Stearns and Thurber (*4*) have shown by dating mollusks from cemented terrace deposits in the western Mediterranean and on the Moroccan coasts that, in addition to a 120,000-year high stand, there was a high stand 80,000 years ago. The only coral age supporting this younger event is from an isolated sample from the Berry Islands group, Bahama Banks (*3*). Broecker (*7*) pointed out that these two times correspond to peaks in summer insolation for the Northern Hemisphere, and used these data in support of the Milankovitch theory of glaciation.

Our work on coral samples from Barbados clearly documents the occurrence of 82,000- and 122,000-year high stands of the sea, and also provides compelling evidence of the occurrence of a third high stand 103,000 years ago.

Barbados is the easternmost island in the Lesser Antilles, being approximately 130 km beyond the main volcanic island arc. Unlike its sister islands to the west, Barbados (Fig. 1) is not of volcanic origin. Its oldest rocks are exposed in the Scotland District, where erosion of the coral cap has produced a window into the underlying folded and faulted sediments of varying lithology. The age (*8*) of these rocks is Miocene to Eocene, with exotic blocks of Paleocene to Cretaceous.

Overlying the rocks exposed in the Scotland District is the coral cap, averaging about 80 m in thickness and covering approximately 85 percent of the island. Extensive drilling confirms that the topography of the coral cap generally reflects the topography of the underlying sediments (*9*).

The topography of the coral cap divides into three major highs: the Mount Hillaby–Clermont Nose, the Golden Ridge, and the Christ Church Ridge (Fig. 1). From these high features, the topography drops down through a series of terraces; at least 18 major terraces can be recognized on the island, the face of each of which is an *in situ* coral reef that may on occasion have been modified by subsequent erosion. Coral zonation within the reefs (*10*) and the physical relation between reefs and associated facies confirm the fact that, as a general rule, each successively lower terrace represents a successively younger coral reef. There are some local exceptions to this generality, but they are beyond the scope of this report; here we will restrict discussion to the three youngest coral-reef terraces—to the last 125,000 years. Our results on older terraces, and a complete geologic treatment of the history of the Barbados coral cap, are being reported elsewhere (*11*).

Coral samples for Th^{230} dating (Fig. 1) were selected from *in situ* reef material and were carefully cleaned of adhering sediment, encrusting coralline algae, or diagenetically altered material. The thorium and uranium isotopes were analyzed by alpha spectrometry by use of U^{232} and Th^{228} yield tracers (*2, 12*); pertinent results appear in Table 1.

Table 1. Thorium-230 ages for corals from the three lowest coral-reef terraces. The standard deviation of 3 percent, assigned to individual determinations of the $\mathrm{Th}^{230}:\mathrm{U}^{234}$ ratio, is based on spike-calibration replicates made with an identical procedure; this error is always greater than or equal to the standard deviation determined by use of counting statistics only. Abbreviations: Ma, *Montastria annularis*; Ac, *Acrapora cervicornis*; Ap, *A. palmata.*

Sample (No.)	Elev. (m)	Coral species	U (ppm)	$\mathrm{U}^{234}:\mathrm{U}^{238}$	$\mathrm{Th}^{230}:\mathrm{U}^{234}$	Age ($\times 10^3$ yr)
			Barbados I (average age, 82,000 years)			
1064-A	19.8	Ma	3.03 ± 0.05	1.12 ± 0.01	0.54 ± 0.02	
1064-A	19.8	Ma	2.85 ± .05	1.15 ± .02	.51 ± .02	82 ± 2
1064-C	6.1	Ma	2.53 ± .05	1.12 ± .01	.53 ± .02	82 ± 4
1150-A	12.2	Ac	4.12 ± .08	1.13 ± .02	.54 ± .02	83 ± 4
1152-C	12.2	Ma	2.62 ± .07	1.11 ± .02	.52 ± .02	81 ± 4
			Barbados II (average age, 103,000 years)			
1144-C	21.3	Ma	2.72 ± 0.05	1.11 ± 0.02	0.62 ± 0.02	
1144-C	21.3	Ma	2.75 ± .06	1.12 ± .02	.61 ± .02	102 ± 2
1144-C	21.3	Ma	2.52 ± .06	1.11 ± .02	.61 ± .02	
1150-C	27.4	Ac	3.85 ± .08	1.10 ± .01	.62 ± .02	104 ± 6
			Barbados III (average age, 122,000 years)			
1046-B	24.4	Ma	2.69 ± 0.05	1.13 ± 0.01	0.72 ± 0.02	124 ± 6
1046-B	24.4	Ma	2.62 ± .05	1.12 ± .01	.67 ± .02	
1046-D	39.6	Ma	2.63 ± .03	1.13 ± .01	.68 ± .02	120 ± 6
1150-B	12.2	Ma	2.73 ± .05	1.13 ± .02	.66 ± .02	111 ± 6
1152-B	54.9	Ap	3.25 ± .08	1.11 ± .02	.71 ± .02	
1152-B	54.9	Ap	3.39 ± .05	1.12 ± .02	.68 ± .02	128 ± 6
1160-I	38.1	Ap	3.72 ± .05	1.09 ± .02	.70 ± .02	127 ± 6
1152-E	35.0	Ap	3.31 ± .09	1.12 ± .03	.69 ± .02	124 ± 6

Table 2. Analytical results for uranium, thorium, and protactinium in Caribbean core V12-122. Source of core: 17°00′N,74°24′W; depth of water: 2800 m.

Depth (cm)	$CaCO_3$ (%)	U* (ppm)	Th* (ppm)	$U^{234}:U^{238}$	Disintegrations per minute per gram: Th^{230}_{ex}†	$:Pa^{231}_{ex}$†	$Th^{230}_{ex}:Pa^{231}_{ex}$†	Climatic zone‡
10–15	75.4	2.76	7.48	1.01 ± 0.04	2.84 ± 0.10	0.204 ± 0.017	13.9 ± 1.2	Z
20–25	75.0	2.76	7.30	1.06 ± .04	2.70 ± .10	.166 ± .009	16.3 ± 1.1	Z
35–40	67.0	2.67	8.91	1.01 ± .04	2.91 ± .09	.171 ± .011	17.0 ± 1.2	Y
180–185	59.0	2.90	11.3	0.90 ± .03	1.83 ± 0.7	.063 ± .006	29.0 ± 3.1	Y
215–220	65.8	2.98	11.1	.96 ± .04	1.42 ± .09	.038 ± .005	37.4 ± 5.4	X
275–280	67.0	2.73	9.60	.92 ± .04	1.09 ± .08	.021 ± .004	51.9 ± 10.3	X
310–315	66.7	2.40	10.0	1.04 ± .03	0.93 ± .06	.014 ± .001	66.4 ± 6.4	W

* On a $CaCO_3$–free basis. † Uranium-unsupported activities. ‡ Designations by Ericson *et al.* (*17*).

The $U^{234}:U^{238}$ ratios (*2*) are consistent with the assumption that late-Pleistocene and Recent corals form with a 15-percent excess of U^{234} activity, and that this excess disappears in accordance with the 250,000-year half-life of U^{234}. The U concentration in any given species of coral remains essentially constant, but existing data suggest a distinct species effect that remains unexplained: *Montastria annularis* (common star coral) averages 2.7 parts per million (ppm); *Acrapora palmata* (moosehorn coral), 3.4 ppm; and *Acrapora cervicornis* (staghorn coral), 4.0 ppm. For any given terrace the $Th^{230}:U^{234}$ results agree within the assigned experimental errors (see legend, Table 1). By use of a half-life of 75,000 years for Th^{230}, one obtains an age of 82,000 ± 2000 years for the youngest terrace (Barbados I), 103,000 ± 3000 years for the second terrace (Barbados II), and 122,000 ± 4000 years for the third terrace (Barbados III).

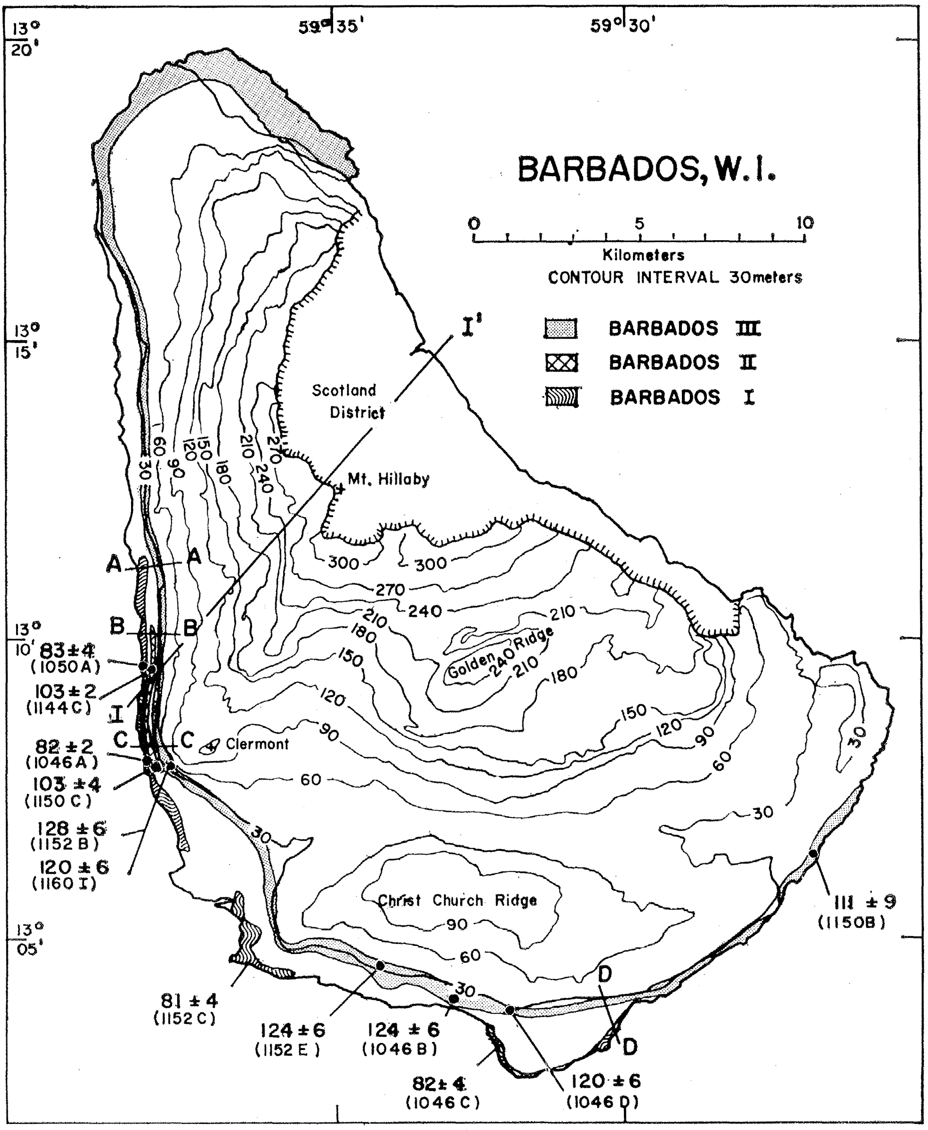

Fig. 1. General geology of Barbados, and topography of the coral cap. The three terraces discussed occur along the north, west, and south coasts of the island. Sources and ages (× 10^3 years) of samples listed in Table 1 are indicated. Letters *A–D* show the locations of traverses used in calculating the paleolevels of the sea (Table 3).

To check the validity of these results, a series of Pa^{231} measurements were made by techniques developed by Sackett (*13*) and modified by Ku (*14*). One sample from each of the three raised coral reefs and one living coral were analyzed. No measurable Pa^{231} was found in the living coral. By use of a half-life of 34,000 years (*14, 15*), an age of 79,000 ± 4000 years was obtained for the sample from the lowest terrace (L 1152-C); 104,000 ± 8000 years, for the sample from the second terrace (L 1144-C); and 120,000 ± 10,000 years, for the sample from the third terrace (L 1152-E). Agreement with the Th^{230} ages is excellent. The analytical results and a discussion of the implications regarding the ratio of the Th^{230} and Pa^{231} half-lives are in preparation (*14*).

Interesting is the question of how these three new ages from Barbados correlate with climate curves for ocean sediments. Both $O^{18}:O^{16}$ measurements (*16*) and Foraminifera population studies (*17*) have been used as indicators of the temperatures of surface waters, and interpretations of this information concur with climatic changes in the Atlantic Ocean during the last 150,000 years. Largely on the basis of the $Pa^{231}:Th^{230}$ measurements of Rosholt *et al.* (*18*), the last oceanic

Table 3. Calculation of heights of sea level for the Barbados I and Barbados II high stands.

Traverse	Terrace	Elevation (m)	Rate of tectonic uplift (m/10^3 yr)	Tectonic correction	Paleolevel of sea (m, relative to present level)
A	III	37	0.24	31	+ 6 (assumed)
	I	6		20	−14
B	III	49	.34	43	+ 6 (assumed)
	II	26		36	−10
	I	12		28	−16
C	III	55	.38	49	+ 6 (assumed)
	II	27		40	−13
	I	18		31	−13
D	III	35	.23	29	+ 6 (assumed)
	I	6		19	−13

warm period was thought to have commenced about 100,000 years ago and to have ended about 65,000 years ago. Before discovery of the 103,000-year high stand of sea level, it seemed possible to maintain agreement between the sea-level and oceanic-temperature data by placing the 82,000-year high stand in this warm zone and the 122,000-year high stand in the preceding warm zone (Ericson's V). On discovery of the 103,000-year high stand, it seems more reasonable to place all three high stands within the last oceanic warm zone [Ericson's X (*17*)].

We have carefully redetermined the Pa^{231} and Th^{230} in Caribbean core V12-122 (Table 2). By comparing the results (that is, by Th^{230}, by Pa^{231}, and by $Pa^{231}:Th^{230}$) on the three points near the core top with the two adjacent to the W-X boundary, we have obtained several estimates of the mean sedimentation rate. All three methods point to a mean value of 2.38 ± 0.10 cm/1000 years, in good agreement with Sackett's (*13*) estimate. This rate yields an age of 126,000 ± 6000 years for the W-X boundary. Use of our results yields satisfactory correlation between high stands of the sea and oceanic warm periods (see Fig. 2). All three high stands noted on Barbados are placed within Ericson's warm X period.

It may be possible to estimate the levels attained by the Barbados I and Barbados II sea stands as follows. Let us assume that the Barbados III sea stand was 6 m higher than present sea level (*6, 19*), and that for any given local area on Barbados the rate of uplift has been constant during the last 120,000 years. Thus the observed elevations of the other two terraces can be corrected for tectonic uplift, and sea levels at the times of their formation can be estimated. Figure 1 shows the location of four traverses on which such calculations were made, and Table 3 summarizes the results. Note that, although the local rate of tectonic uplift varies from place to place on the island, the calculated elevations of the Barbados I and Barbados II high stands are remarkably consistent from one traverse to the other. This internal consistency leads us to speculate that, whereas the Barbados III high stand 122,000 years ago was about 6 m above the present level of the sea, the next two high stands were each about 13 m below the present level. This speculation would explain why these terraces are less likely to be found in other areas.

It is interesting to compare these times of high stands of the sea with those predicted by the astronomical theory of glaciation. The Milankovitch curve most commonly reproduced is that based on variations in the summer insolation at 65°N latitude. However, as the fractional change in summer radiation, resulting from changes in Earth's tilt, decreases markedly from equator to pole while that for precession remains nearly constant, the character of the resultant curve depends on the latitude for which it is drawn. The tilt component (41,000-year cycle) dominates curves drawn for high latitudes; the precession component (21,000-year cycle), those for low latitudes. For example, a 4-percent eccentricity of Earth's orbit leads to 4.8-percent higher daily summer insolation for the entire Northern Hemisphere when the perihelion is reached on 21 June than when it is reached on 21 March or 21 September. A 1-deg increase in tilt leads to 2.5-percent higher summer insolation at 65°N, 1.2-percent change at 45°N, and 0.8-percent change for the hemisphere as a whole. The curve (see Fig. 2) adopted here corresponds to the change in summer insolation at 45°N (hence it has a smaller tilt component than the usual Milankovitch curve, but a larger tilt component than the curve for the hemisphere as a whole). The amplitude of the curve is expressed as

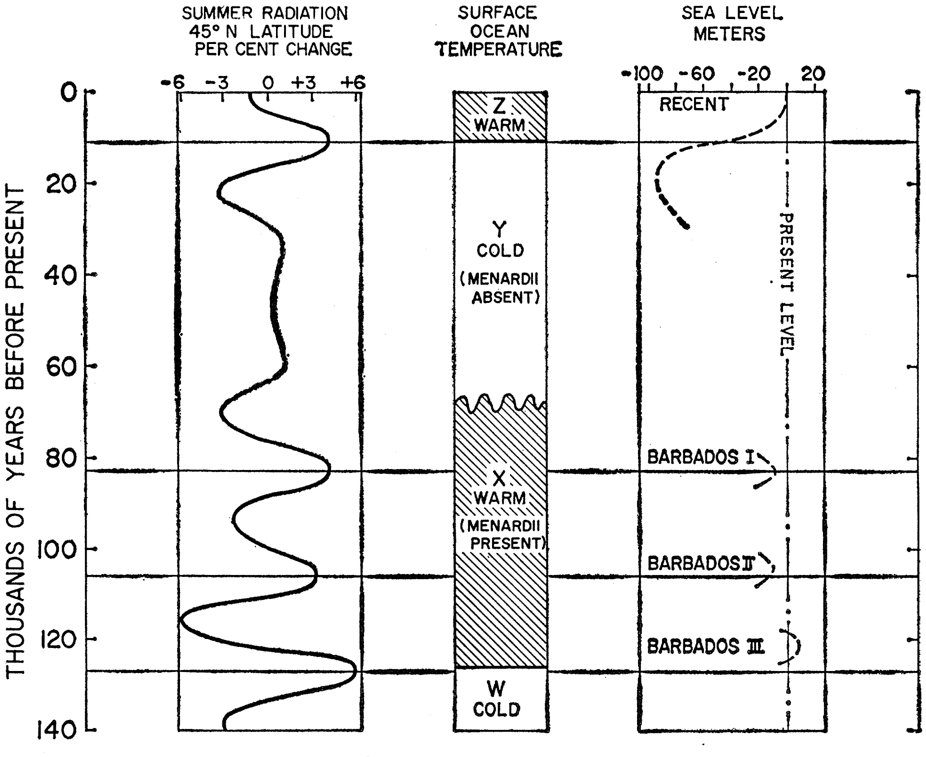

Fig. 2. Correlation of Broecker's (*7*) modified summer-insolation curve for the northern hemisphere with the ocean's surface-temperature record for Atlantic deep-sea cores, and with the record of fluctuations in sea level.

the fraction of the mean summer insolation rather than as a usual equivalent latitude. Whereas the normal presentation may be more useful to a geologist thinking in terms of shifting zones of climate, that adopted by us is far more convenient for scientists thinking in terms of radiation balance.

Whereas the 65°N insolation curve has warm peaks at 11,000, 48,000, 82,000, and 127,000 years, when the precession effect is given more weight than is tilt effect the warm peak at 50,000 years ago is largely removed; those at 127,000, 82,000, and 11,000 years ago persist, and a new peak appears at 106,000 years ago. Our results clearly indicate that the last four high stands of the sea correspond closely in time to the last four prominent warm peaks in the modified curve of summer insolation.

If the "half-response time" for glacial melting is taken to be 3000 years (adopted by Broecker to explain the lag between the present high stand of the sea and the 11,000-year insolation maxima), the high stands associated with the last three insolation maxima should have occurred about 121,000, 100,000, and 76,000 years ago. Since the 6000-year lag time is of the same order of magnitude as the present uncertainty in the absolute ages, the existence of such lags cannot now be demonstrated by radiometric dating.

In addition to demonstrating a remarkable relation between sea level and insolation maxima, we can also show that the last two changes from oceanic cold to warm conditions (11,000 ± 1000 and 126,000 ± 6000 years ago) correspond to the two greatest insolation maxima during the last 140,000 years (that is, those 11,000 and 127,000 years ago). As indicated by results of both faunal (*17*) and $O^{18}:O^{16}$ (*16*) studies, these changes were abrupt (less than 3000 years from full-cold to full-warm); by contrast, the transitions from warm to cold (especially as shown by the oxygen-isotope data) were more gradual. As suggested by Broecker (*7*) these abrupt warmings may well reflect triggering of the ocean-atmosphere system from one mode of operation to another.

Thus, as pointed out by Emiliani and Geiss (*20*), absolute chronologies of climate change certainly support the hypothesis that changes in insolation are the cause of climatic oscillations. As both quantity and precision of our data on absolute age increase, the coincidences become more numerous and exact. Therefore the often-discredited hypothesis of Milankovitch (*21*) must be recognized as the number-one contender in the climatic sweepstakes.

WALLACE S. BROECKER
DAVID L. THURBER
JOHN GODDARD
Lamont Geological Observatory,
Columbia University, Palisades, and
Queens College, Flushing, New York
TEH-LUNG KU
Department of Chemistry, Woods
Hole Oceanographic Institution,
Woods Hole, Massachusetts
R. K. MATTHEWS
KENNETH J. MESOLELLA
Department of Geological Sciences,
Brown University, Providence,
Rhode Island

References and Notes

1. J. W. Barnes, E. J. Lang, H. A. Potratz, *Science* **124**, 175 (1956).
2. D. L. Thurber, W. S. Broecker, H. A. Potratz, R. L. Blanchard, *ibid.* **149**, 55 (1965).
3. W. S. Broecker and D. L. Thurber, *ibid.*, p. 58.
4. C. E. Stearns and D. L. Thurber, *Quaternaria* **7**, 29 (1965).
5. J. K. Osmond, J. R. Carpenter, H. L. Windom, *J. Geophys. Res.* **70**, 1843 (1965).
6. M. Sakanoue, K. Konishi, K. Komura, in *Symp. Radioactive Dating and Methods of Low-Level Counting Monaco* (Intern. At. Energy Agency, 1967), vol. SM/28.
7. W. S. Broecker, *Science* **151**, 299 (1966).
8. A. Senn, *Bull. Amer. Assoc. Petrol. Geologists* **24**, 1548 (1940).
9. The coral cap is the main aquifer of the island and has been extensively drilled in connection with groundwater exploration. Thus the major features of the geometry before the coral cap are well known.
10. K. J. Mesolella, *Science* **156**, 638 (1967).
11. ———, R. K. Matthews, W. S. Broecker, D. L. Thurber, in preparation.
12. A. Kaufman, thesis, Columbia Univ., 1964.
13. W. M. Sackett, in *Univ. Rhode Island Occasional Publ. 3* (1965), vol. 29.
14. T. L. Ku, in preparation.
15. The accuracy of a radiometric age depends on knowledge of the half-lives and on sure calibration of analytical procedures. The Th^{230} half-life of R. W. Attree, M. J. Cabell, R. L. Cushing, and J. J. Pieroni [*Can. J. Phys.* **40**, 194 (1962)], 7.52×10^4 years, appears to be accurate. For the sake of consistency in comparison, we use 3.43×10^4 years as the half-life of Pa^{231} [D. Strominger, J. M. Hollander, G. T. Seaborg, *Rev. Mod. Phys.* **30**, 585 (1958)] instead of the newer value of 3.25×10^4 years [H. W. Kirby, *J. Inorg. Nucl. Chem.* **18**, 8 (1961)]. We recognize the possibility of a systematic error in calibration that may have made the ages reported here as much as 8000 years greater than the true ages, but the conclusion that three distinguishable high stands of the sea can be recognized is not affected.
16. C. Emiliani, *J. Geol.* **74**, 109 (1966).
17. D. B. Ericson, M. Ewing, G. Wollin, *Science* **146**, 723 (1964).
18. J. N. Rosholt, C. Emiliani, J. Geiss, F. F. Koczy, P. J. Wangersky, *J. Geol.* **69**, 162 (1961).
19. The choice of sea level is not too critical; +6 m is probably a maximum.
20. C. Emiliani and J. Geiss, *Geol. Rundschau* **46**, 576 (1957).
21. M. Milankovitch, in *Handbuch der Geophysik*, Koppen and Geiger, Eds. (1938), vol. 9, p. 593.
22. Some of the chemical analyses were done by Elaine Lindsey. The studies of physical stratigraphy, facies relations, and carbonate diagenesis were carried out by the Brown group with support from Gulf Oil Corp. and NSF grant GA-306. The dating, done at Lamont Geological Observatory, was supported by NSF grant GA-344 and AEC grant AT(30-1) 3139. Contribution 1139 from Lamont Geological Observatory, Columbia University.

15 August 1967; revised 1 December 1967 ■

Pallasitic Meteorites: Implications Regarding the Deep Structure of Asteroids

Abstract. *Olivine compositions in pallasites exhibit a bimodal distribution and indicate a high degree of internal equilibrium. Cooling rates measured in the metal phases are uniform and consistently lower than those of most iron meteorites. These factors suggest that the pallasites were derived from few parent bodies, and that they crystallized in a highly insulated site—presumably the core of their parent body. Most iron meteorites were derived either from isolated areas closer to the surface or from other parent bodies.*

The pallasites consist of large single crystals of olivine within a metal matrix. They are transitional in composition between the major groups of meteorites: stones and irons. It has long been thought that the pallasites formed at the interface of a stony mantle and a metal core, although other models have been proposed (*1*). We investigated these models by measuring certain critical chemical and physical parameters of a large number of pallasites.

Olivine is the most abundant mineral and the only silicate found in the pallasites. Its composition in meteorites in general is of particular interest; for example, chondrites are classified partly on this basis (*2*). Using an ARL microprobe, we have determined the bulk compositions, compositional gradients, and intercrystalline variations of pallasitic olivine (*3*). At least four and as many as 16 distinct olivine crystals were measured for each pallasite; all crystals were homogeneous (with a variation of less than 2 percent of the amount of Fe present), and only six meteorites displayed compositional variations between olivine crystals. Of these six, only Glorieta Mountain had