Insolation Changes, Ice Volumes, and the O^{18} Record in Deep-Sea Cores[1]

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Abstract. A detailed curve of ice volume versus time is needed in order to test the validity of the hypothesis that changes in the earth's orbital parameters are the cause of oscillations in Pleistocene climate. Although absolute ages available for glacial moraines and raised coral reefs provide a number of key points, they by no means allow a continuous curve to be drawn. Those points that exist, however, are entirely consistent with the hypothesis that the O^{18}/O^{16} curves from deep-sea cores provide good approximations to the ice volume record. If so, then the primary glacial cycle must be sawtoothed in character; gradual glacial buildups over periods averaging 90,000 years in length are terminated by deglaciations completed in less than one tenth this time. Modulating this primary cycle are secondary oscillations. Those recognized during glacial growth phases average 20,000 years in length and those during the retreats about one thousand years in length. When the ice volume curve obtained in this way is compared with the summer insolation curve for the northern hemisphere, it is seen that the rapid deglaciations occur during times of unusually great seasonal contrast and that the secondary cycles modulating the glacial buildups closely parallel the insolation variations. Although these findings provide convincing evidence for the influence of orbital changes on climate, the cause of the primary sawtoothed cycle is still an open question. In conjunction with this study, we have determined the O^{18}/O^{16} record for Caribbean core V12-122 and find it to be compatible with those given by Emiliani for cores P6304-8 and P6304-9. Our dating of this core by Pa^{231}-Th^{230} and by magnetic reversals, however, strongly suggests that the absolute time scale adopted by Emiliani for deep-sea cores must be increased by 25%.

The causes of the large changes in climate that resulted in the repeated growth and disappearance of ice sheets of continental dimension has intrigued earth scientists for more than a century. Although enormous strides have been made in establishing the scale and chronology of the worldwide effects of these glacial cycles, progress toward understanding the factors responsible for their generation has by comparison been very slow. The purpose of this paper is twofold. The first is to bring attention to the asymmetric sawtoothed character of the major cycle and the second is to show that, at least in part, the climatic changes are caused by insolation changes resulting from periodic variations in the earth's orbital parameters.

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THE SHAPE OF CLIMATIC CYCLES AS SHOWN BY THE O^{18} RECORD

The key to our understanding of the basic shape of the curve of climate versus time comes from *Emiliani's* [1955, 1958, 1964, 1966] O^{18} measurements on deep-sea cores. These sediments, at least in some areas of the ocean, have accumulated at nearly a constant rate over at least five climatic cycles. It is still not clear whether the major factor causing the observed temporal variations in the O^{18}/O^{16} ratio in the shells of planktonic foraminifera found in these cores is change in the water temperature [*Emiliani*, 1955], or in the isotopic composition of sea water in which the shells grew [*Shackleton*, 1967], or an equal combination of both, as was suggested by *Craig* [1965]. In either case a first-order synchroneity between the isotopic composition of the $CaCO_3$ and the extent of continental glaciation might be expected. No other recorder of climate change yields a curve of comparable quality.

Although Emiliani's results have been widely discussed, there is one point that needs clarification. In Figure 1 are reproduced the upper parts of the O^{18}/O^{16} records for nine of the eleven Atlantic and Caribbean cores analyzed by Emiliani. To facilitate comparison, the depth scales have been normalized so that the sharp decreases in O^{18} content, referred to here as termination II, coincide. The idealized curve of *Emiliani* [1966] is given for comparison. The point to be made is that Emiliani's idealized curve for the last 125,000 years is based largely on the record from the single core (280) from the North Atlantic. He has thus obscured the fundamental cycle shown by the O^{18} results. Although the eight cores from the equatorial Atlantic and the Caribbean appear to record the secondary fluctuations that are so prominent in core 280, these fluctuations are clearly subsidiary to a dominant asymmetric sawtoothed cycle. The O^{18} content of foraminifera oscillates between rather uniform limits, the increase in O^{18} content taking place gradually over a long period of time and the decrease abruptly during a relatively short period of time. The record for two of Emiliani's Caribbean cores for the last five O^{18} cycles, given in Figure 2, shows that this sawtoothed shape is not a chance characteristic of just the last cycle.

If the O^{18} record does indeed reflect the extent of the glacial ice, it suggests that glacial periods are characterized by relatively long periods of more or less continuous ice growth followed by short periods during which this ice is destroyed.

Superimposed on this sawtoothed O^{18} cycle are secondary oscillations. Careful examination of Emiliani's curves shows that the departures from the simple sawtoothed pattern, although exaggerated in his idealized curves, are almost certainly real. The change in apparent age of these peaks from core to core is probably an artifact of our assumption of a constant sedimentation rate. As *Broecker et al.* [1958] have shown, in the equatorial Atlantic, deposition was twice as fast during the 15,000-year period before 11,000 years ago than subsequently. This rate change from glacial to interglacial certainly differs in magnitude and perhaps even in sense from area to area of the sea floor. Thus ages obtained by a simple interpolation between the core top and termination II may be systematically different from core to core. As will be shown below in the discus-

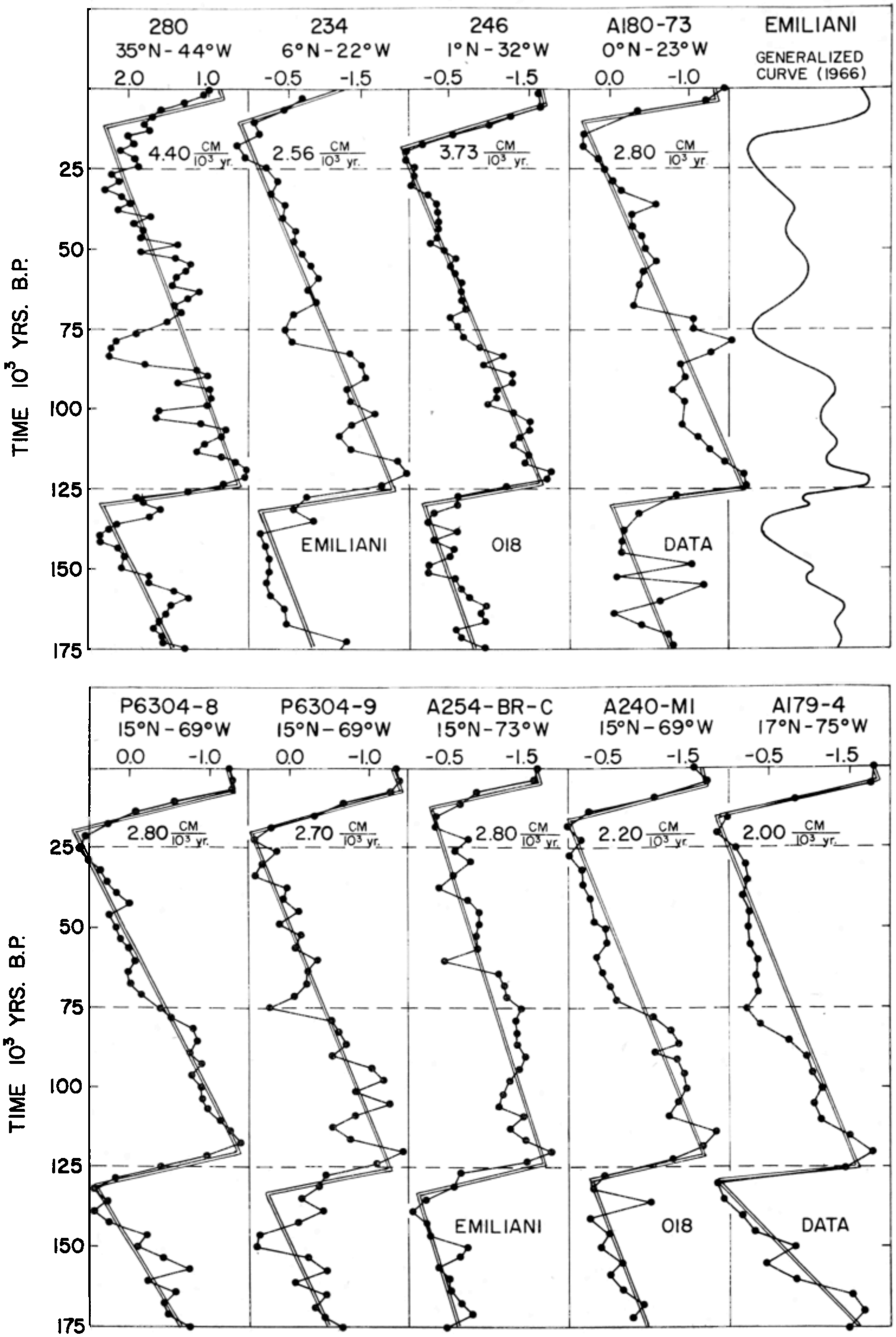


Fig. 1. Plots of δO^{18} versus time, the upper part of nine of the eleven North Atlantic and Caribbean cores analyzed by *Emiliani* [1955, 1964, 1966]. The time scale was obtained by assigning an age of 127,000 years to the midpoint of termination II and assuming the sedimentation rate to be constant. Since sedimentation rates during cold periods (i.e., high δO^{18}) are probably somewhat different from those during warm periods, the age of the point intersected by the dotted line for 75,000 years could be in error by ±10,000 years. The extent of this distortion would vary from core to core. The idealized curve of *Emiliani* [1966] is given for comparison.

sion of direct measurements of ice volume, these secondary fluctuations may well represent times at which the ice was either suffering a temporary setback in growth or undergoing unusually rapid growth in the course of its gradual buildup toward a glacial maximum. Thus, although the fundamental variation requiring explanation is the basic sawtooth cycle, it will also be necessary to understand the significance of the oscillations that modulate this cycle.

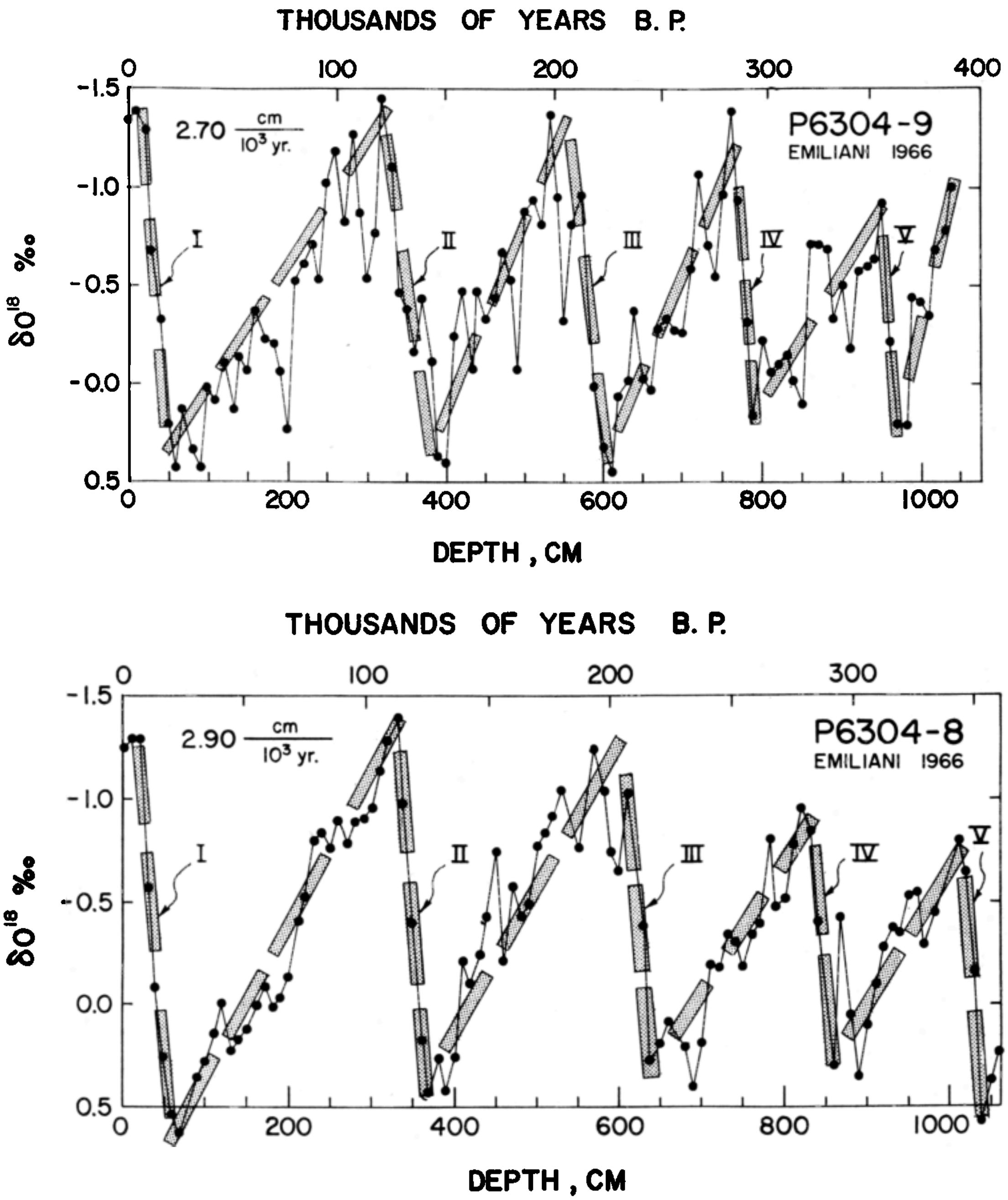


Fig. 2. Plot of δO^{18} versus depth in cores P6304-9 and P6304-8 [*Emiliani,* 1966]. The dots are data points and the heavy dashed line represents the proposed primary sawtoothed cycle. The time scale is that adopted in this paper.

THE CHRONOLOGY OF DEEP-SEA CORES

The first estimates of the time scale of the cycles observed in deep cores were based on radiocarbon dates obtained by *Rubin and Suess* [1955]. Although C^{14} dating is applicable over less than one-half a climatic cycle, it was possible to obtain a good first approximation of the over-all time scale by assuming that the sedimentation rate established for the last 30,000 years is valid for the entire sequence. In this way it was shown that the length of a complete cycle was about 10^5 years. Absolute ages obtained by the Pa^{231}-Th^{230} method [*Rosholt et al.*, 1961] allowed the chronology to be extended to 150,000 years. These results largely confirmed the extrapolations based on C^{14}. They provide the basis for the time scale adopted by *Emiliani* [1966] for his idealized curve. For reasons outlined below, it appears that, beyond the range of C^{14} dating, Emiliani's time scale is generally about 25% too low. Specifically, the age of 100,000 years he assigns to what is designated here as termination II (see Figure 11) should be increased to 125,000 years. The age of 295,000 years he obtains for the paleontologic *U-V* boundary (see Figure 11) of *Ericson et al.* [1961] should be increased to about 400,000 years. The time scale used in Figures 1 and 2 incorporates this revision.

The primary evidence supporting a revision of the Emiliani time scale comes from Pa^{231} and Th^{230} measurements made by *Ku* [1966] on Caribbean core V12-122 (see Table 1). The depth of termination II in this core was initially established at 300 cm by *Ericson et al.* [1961] using paleontologic criteria (i.e., the reappearance of the species *Globorotalia menardii*). O^{18}/O^{16} measurements (see Figure 3) not only confirm this conclusion but also show that the pattern of O^{18}/O^{16} variation in this core closely resembles that shown for the Caribbean cores analyzed by Emiliani. Figure 4 shows plots of depth versus the logarithm of the Th^{230} activity, of the Pa^{231} activity, and of the Pa^{231}/Th^{230} activity ratio. Lines with slopes corresponding to the deposition rate required to yield the time scale adopted by *Emiliani* [1966] and to yield the revised time scale proposed here are shown in each case. Although the lines corresponding to the extended scale clearly provide better fits to the data, enough scatter exists to preclude a highly precise determination of the mean rate of sedimentation.

The data on core V12-122 can be treated in a different way. Instead of all the points, only those just above and just below terminations I and II are considered. Of these, the pairs 12.5, 277.5 cm and 37.5, 312.5 cm are considered the best, since they represent samples taken at similar parts of the climatic cycle (the first pair from the warm intervals just following terminations I and II, and the second pair from the cold intervals immediately preceding these terminations). Table 2 shows that the average rates obtained in this way are, respectively, 2.40 cm/10^3 years and 2.25 cm/10^3 years. Taking 2.35 cm/10^3 years to be the best accumulation rate estimate for this interval, the time elapsed between terminations I and II is 116,000 years. Adding on the 11,000-year age established by C^{14} dating for the mid-point of termination I [*Broecker et al.*, 1960], an age of 127,000 years is obtained for the mid-point of termination II. Taking the uncertainty in the sedimentation rate to be ± 0.10 cm/10^3 years, the uncertainty in this age is 6000 years.

TABLE 1. Analytical Data for Uranium Series Measurements on Caribbean Core V12-122 (17°00'N, 74°24'W)

Depth, cm	$CaCO_3$, %	U, ppm	Th, ppm	U^{234}/U^{238}	Th^{230}/Th^{232}	Excess Th^{230}, dpm/g	Excess Pa^{231}, dpm/g	$Pa^{231}_{ex}/Th^{230}_{ex}$
10–15	75.4	2.76	7.48	1.01 ± 0.04	7.54	2.84 ± 0.10	0.204 ± 0.017	0.072 ± 0.007
20–25	75.0	2.76	7.30	1.06 ± 0.04	7.42	2.70 ± 0.10	0.166 ± 0.009	0.062 ± 0.005
35–40	67.0	2.67	8.91	1.01 ± 0.04	5.11	2.91 ± 0.09	0.171 ± 0.011	0.059 ± 0.004
73–77*	55.5	2.16	8.87	1.09 ± 0.04	3.59	2.77 ± 0.10	—	—
128–131*	67.1	2.31	7.96	1.06 ± 0.04	4.00	1.98 ± 0.08	—	—
180–185	59.0	2.90	11.3	0.90 ± 0.03	2.35	1.83 ± 0.07	0.063 ± 0.006	0.034 ± 0.004
215–220	65.8	2.98	11.1	0.96 ± 0.04	2.35	1.42 ± 0.09	0.038 ± 0.005	0.027 ± 0.004
275–280	67.0	2.73	9.60	0.92 ± 0.04	2.23	1.09 ± 0.08	0.021 ± 0.004	0.019 ± 0.004
310–315	66.7	2.40	10.0	1.04 ± 0.03	1.88	0.93 ± 0.06	0.014 ± 0.001	0.015 ± 0.002
315–320	64.4	2.42	10.1	1.02 ± 0.04	1.82	0.91 ± 0.06	0.020 ± 0.011	0.022 ± 0.013
345–350	53.0	2.62	12.5	0.98 ± 0.03	1.38	1.07 ± 0.07		
365–370	58.1	2.79	13.3	0.90 ± 0.02	1.28	0.94 ± 0.04		
419–421*	56.1	2.17	11.5	0.93 ± 0.03	1.17	0.83 ± 0.05		
477–480*	60.9	2.30	10.1	0.95 ± 0.02	1.28	0.61 ± 0.03		
535–540	71.2	2.33	8.72	1.00 ± 0.04	1.49	0.40 ± 0.04		
612–614*	61.4	2.33	10.2	0.91 ± 0.04	0.90	0.28 ± 0.02		
697–701*	59.6	2.63	10.6	0.96 ± 0.03	0.83	0.13 ± 0.02		
752–758*	62.7	2.55	12.5	0.95 ± 0.04	0.80	0.25 ± 0.02		
780–785	60.0	2.30	11.2	0.92 ± 0.03	0.82	0.26 ± 0.04		
910–915	56.5	2.10	8.14	0.90 ± 0.03	0.84	0.11 ± 0.03		
1061–1065*	64.2	2.26	8.51	0.99 ± 0.04	0.86	0.07 ± 0.02		

Measurements marked by an asterisk were made by this laboratory in 1969 and the remainder by *Ku* [1966]. The uranium and thorium concentrations are calculated on a $CaCO_3$-free basis. Isotope ratios are given in terms of activity. Excess Th^{230} and Pa^{231} activities are calculated by subtracting the U^{238} and U^{235} activities from the total Th^{230} and Pa^{231} activities.

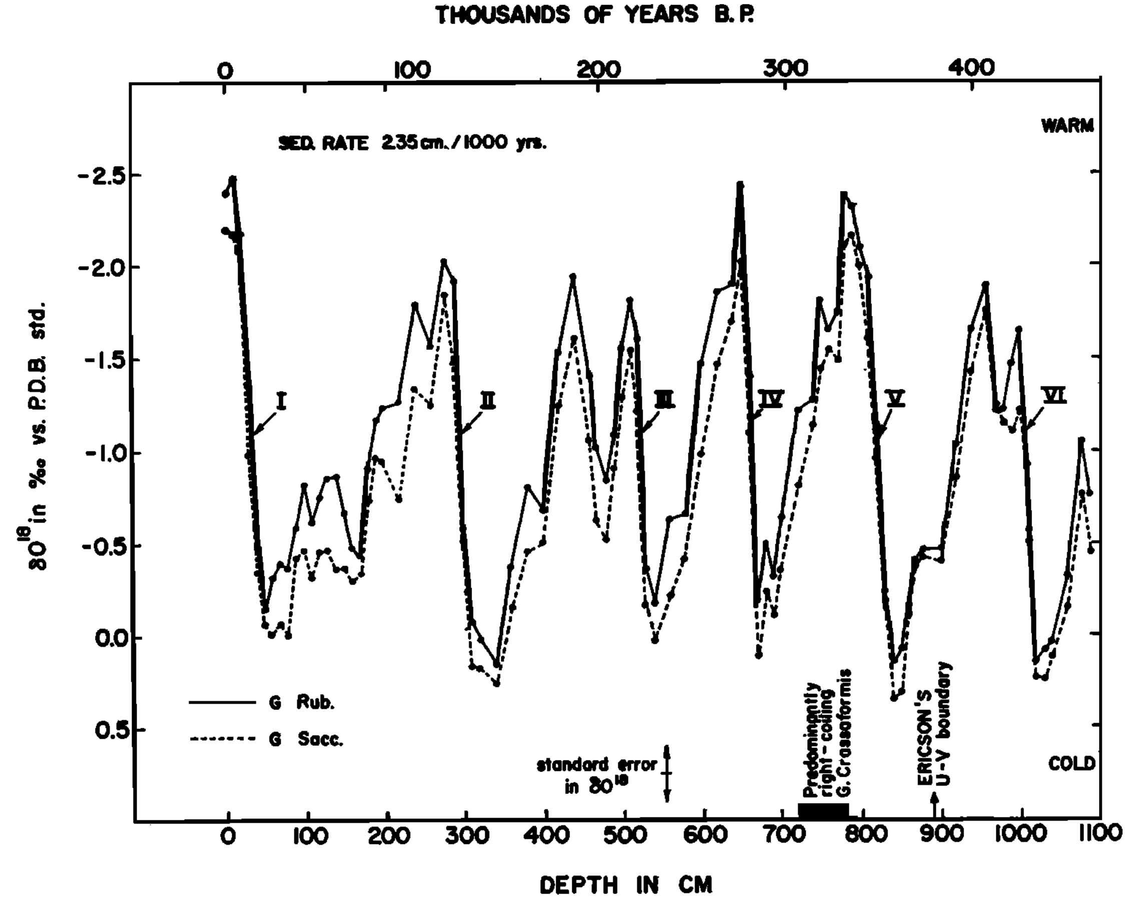
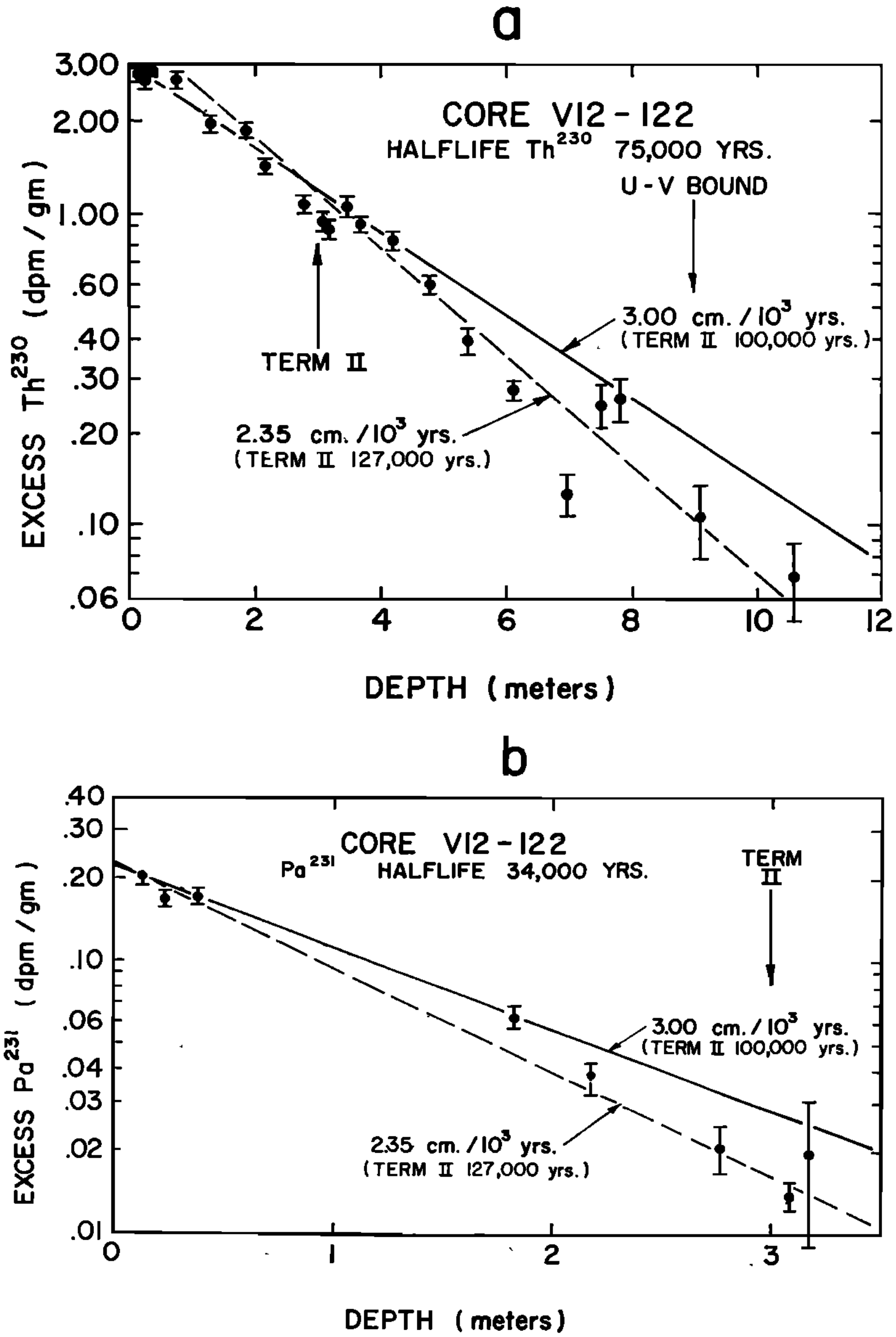


Fig. 3. Oxygen isotope data on two species of foraminifera from Caribbean core V12-122. The forams were not roasted before acid solution. *Emiliani* [1966] showed that unroasted forams yield O^{18}/O^{16} ratios roughly 0.5 per mil greater than forams pre-roasted in helium at 475°C. The time scale is based on the data reported in this paper. The Roman numerals designate successively older times of sudden O^{18} decrease (i.e., presumably deglaciation).

At this point it is appropriate to ask why this result is more reliable than that obtained by *Rosholt et al.* [1961] using essentially the same method. Rosholt et al. estimated the Pa^{231} content of their sample by measuring the daughter product Th^{227}. Diffusion of the intervening daughter product with a 22-year half-life could cause problems similar to those encountered when Ra^{226} is used as an indicator of its parent Th^{230}. *Ku* [1966] measured Pa^{231} directly. Also in the interval elapsed between Rosholt's and Ku's experimental work, technical advances permitted higher precision and more guarantees that systematic errors were not present. Further, the inconsistency in rates calculated from Rosholt's Th^{230} and from his Pa^{231} results suggest that he had a small Pa^{231} blank. Because Pa^{231}-Th^{230} ages, especially in the range beyond 80,000 years, are extremely sensitive to such a blank, the divergence between his results and Ku's may well be due to this source.

As an example of how this small blank would affect the ages, the results of *Rosholt et al.* [1961] for core A240-M1 are given in Figure 5. Again the logarithms of Th^{230}, Pa^{231}, and Pa^{231}/Th^{230} are plotted separately. Lines whose slopes correspond to the two times scales are again drawn. In addition, the points are



replotted after removing a postulated blank of 0.01 dpm/g for Pa^{231}. It is clear that, in the absence of the blank correction, the Pa^{231} decay suggests a higher sedimentation rate than the Th^{230} decay. An even higher rate is suggested by the Pa^{231}/Th^{230} decay. After the correction is made, the three sets of results consistently point to a common time scale consistent with that obtained here for core V12-122. Thus, on the basis of the criterion that the Pa^{231} and Th^{230} decay patterns must be internally consistent if precise dating is to be done by the uranium series method, Ku's results appear to be more reliable than Rosholt's.

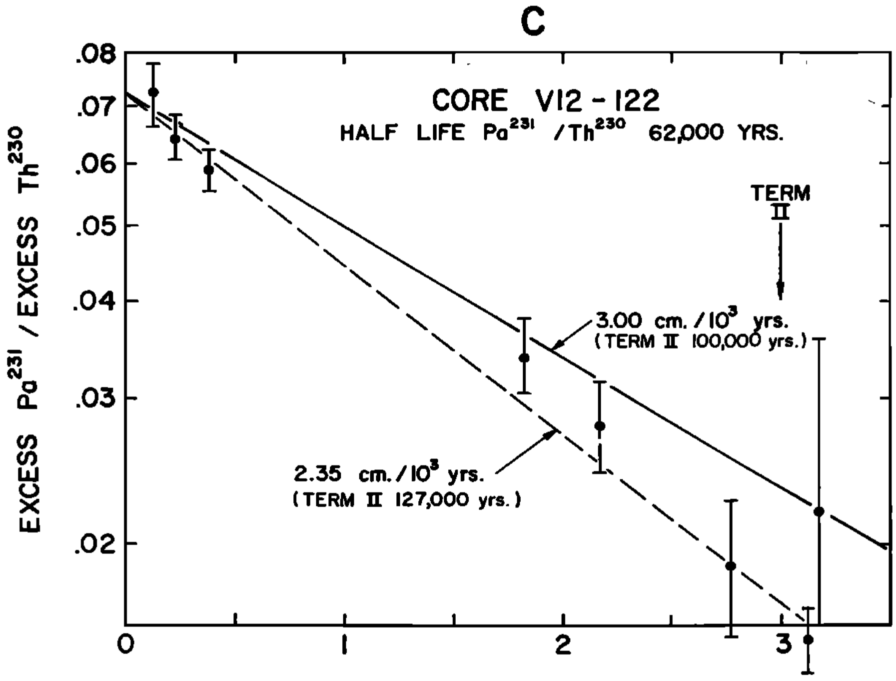


Fig. 4. Plots of logarithms of (*a*) excess Th^{230}, (*b*) excess Pa^{231}, and (*c*) excess Pa^{231} over excess Th^{230} versus depth in core V12-122. On such a plot the points should fall on straight lines if the accumulation rate and the (*a*) initial Th^{230} concentration, (*b*) initial Pa^{231} concentration, and (*c*) initial Pa^{231}/Th^{230} ratio have remained constant. The slope of such a line fixes the sedimentation rate. Two lines are shown in each diagram, one with a slope corresponding to *Emiliani*'s [1966] time scale and one corresponding to the time scale adopted here. The positions of termination II and of the U-V boundary are shown.

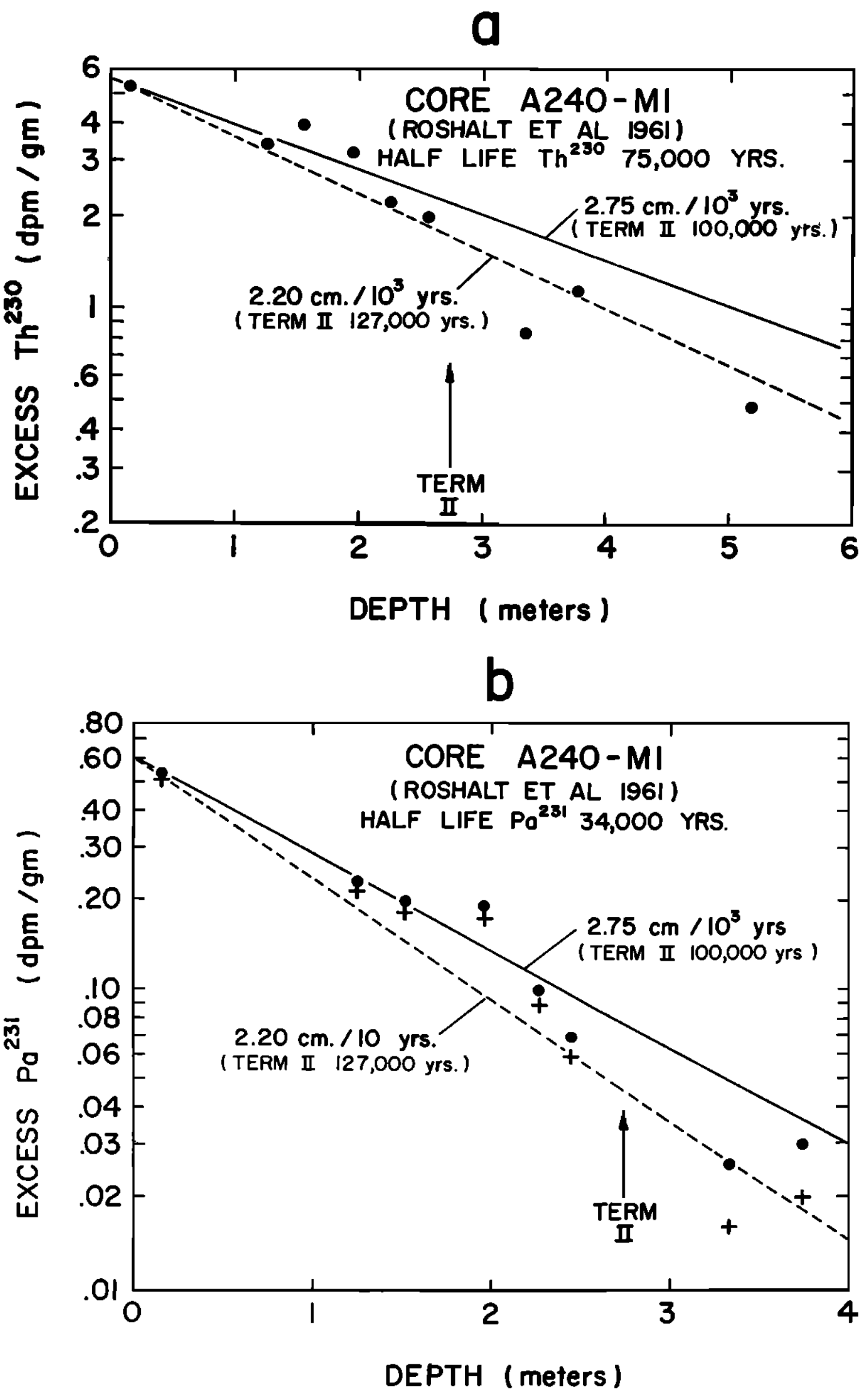
Rona and Emiliani [1969] have recently published Pa^{231}/Th^{230} ages for cores P6304-8 and P6304-9 that agree with the *Rosholt et al.* [1961] time scale. As *Broecker and Ku* [1969] have shown, the measurements upon which these results are based are analytically incorrect. In a recent publication, *Emiliani and Rona* [1969] for the first time point out that their published results were ob-

TABLE 2. Estimates of Average Sedimentation Rates above Termination II in Core V12-122*

Dating Method	12.5 and 277.5 cm (warm periods)	37.5 and 312.5 cm (cold periods)
Pa^{231}†/Th^{230}†	2.25	2.27
Pa^{231}†/g	2.38	2.24
Th^{230}†/g	2.57	2.23

* Based on two pairs of samples, one pair consisting of samples from the cold intervals just preceding terminations I and II and the other of samples from the warm intervals just above these terminations. The rates are given in centimeters per thousand years.

† Unsupported by uranium.



tained by leaching the core material rather than by totally dissolving it. If the abnormally low uranium contents they report are the result of the failure of their leaching procedure to remove the bulk of the isotopes of interest from the sediment, then the chemical and recoil induced differences among these isotopes must certainly produce a bias in the reported isotope ratios.

Although Pa^{231} cannot be used to date the earlier terminations, the Th^{230}

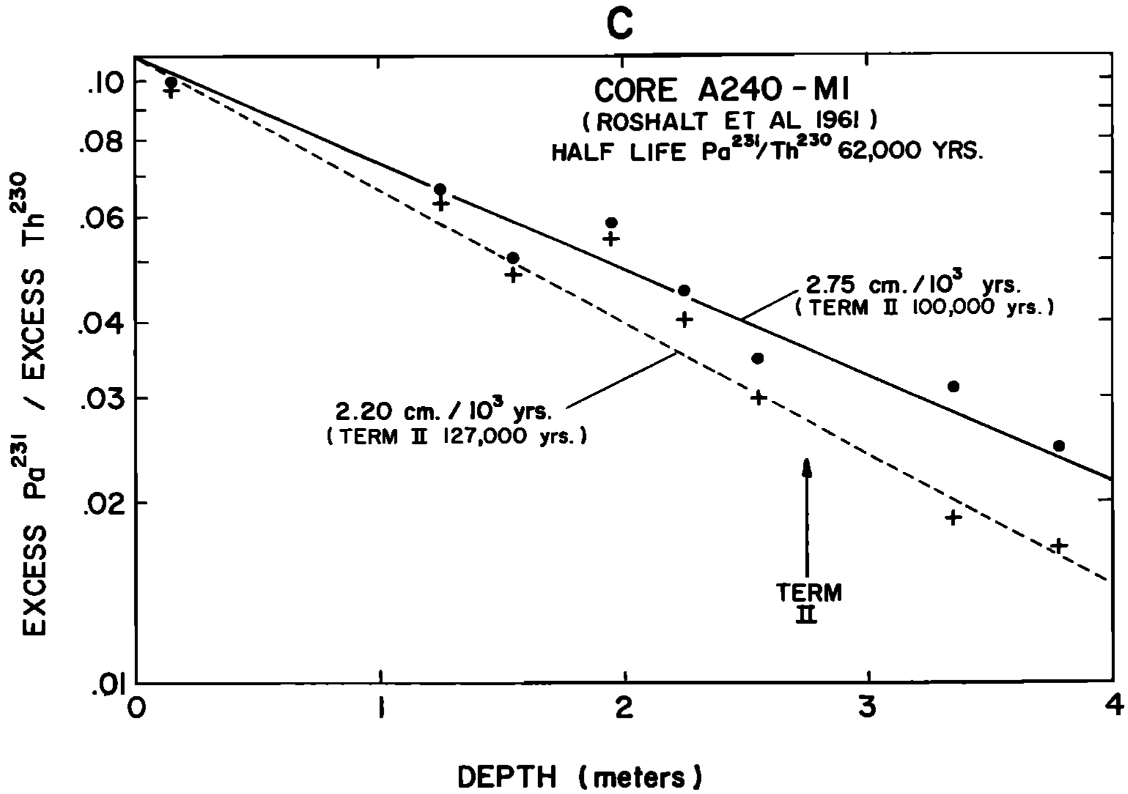


Fig. 5. Plots similar to those shown in Figure 4 for the results on Caribbean core A240-M1 published by *Rosholt et al.* [1961]. Again, lines with slopes corresponding to both the time scale adopted by *Emiliani* [1966] and that adopted here are shown. The plus signs in *b* and *c* show the sensitivity of the Pa^{231} and Pa^{231}/Th^{230} data to a small hypothetical Pa^{231} blank (0.01 dpm/g). The dots are the experimental data corrected for uranium-supported activity.

data on core V12-122 suggests that the time-scale extension must also apply to the time interval between 125,000 and 400,000 years ago. As Figure 4 shows, there is no evidence from the Th^{230} results that the sedimentation rate is significantly different before 125,000 years from after this time. At a depth of 890 cm in this core, a paleontologic boundary occurs that has also been established in the cores studied by Emiliani (i.e., the *U-V* boundary of *Ericson et al.*, 1961). As this boundary is associated not only with the reappearance of *Globorotalia menardii* but also with the characteristic pattern of fluctuation of the coiling directions of *Globorotalia crassaformis* and *truncatulinoides*, its position can be accurately determined. Using the sedimentation rate of 2.35 cm/10^3 years, an age of 380,000 years is obtained for this boundary in core V12-122. This can be compared with an age of 290,000 years obtained by using *Emiliani's* [1966] extended time scale, and of 320,000 years given previously by *Ku and Broecker* [1966] in their analysis of a portion of the data now available for core V12-122. In Table 3 the analyses of three samples from the top of the core are used along with five analyses from between 700 and 1100 cm to establish the mean sedimentation rate over this interval. Using various pairs and methods of normalization, rates

TABLE 3. Mean Sedimentation Rates in Centimeters per Thousand Years Based on Eight Th^{230} Measurements

	12 cm	22 cm	37 cm
699 cm	2.07	2.07	2.03
755 cm	2.83	2.84	2.71
782 cm	2.97	2.99	2.84
912 cm	2.56	2.58	2.48
1063 cm	2.62	2.63	2.54

Each of the 15 rates given is based on a measurement from near the top of the core and one from the region of the *U-V* boundary (890 cm). The average rate obtained in this way is 2.5 ± 0.3 cm/10^3 years.

ranging from 2.03 to 2.99 cm/10^3 years are obtained (i.e., ages of the *U-V* boundary ranging from 450,000 to 300,000 years). Despite the uncertainty in treating these data, an increase of 25% (i.e., to 380,000 years) would seem to be more consistent with the available results than the 290,000-year estimate based on *Emiliani*'s [1966] time scale.

Fortunately another line of evidence is available. Recently *Ericson and Wollin* [1968] have fixed the age of the *U-V* boundary in five cores using magnetic reversal data. The results, as summarized in Table 4, suggest an age of 400,000 ± 20,000 years. This result is obtained by interpolation between the core top and the Brunhes-Matuyama boundary (K-Ar age, 690,000 [*Cox*, 1969]).

In Table 5 the ages of terminations III to VI are estimated in two ways. The first uses the rate established for the interval between terminations II and I and the second uses the rate established for the interval between the *U-V* boundary and termination II. Except for termination VI, the ages established in this way should be correct to within ±8%. As termination VI is reached in only two of the four cores, and as the results are not concordant, no age estimate can be given at this time. The manner in which correlations between the four cores have been established (especially in the region from terminations V to VI) is shown in Figure 6.

TABLE 4. Age of the *U-V* Boundary as Determined by Magnetic Reversals*

Core No.	Latitude	Longitude	Depth to *U-V* boundary, cm	Depth to last magnetic reversal,† cm	Interpolated age of *U-V* boundary, 10^3 years
V16–39	24°43′S	04°45′W	150	270	385
V19–297	02°37′N	12°00′W	270	490	380
V22–163	26°22′S	0°56′E	190	330	395
V12–18	28°42′S	34°30′W	160	270	410
V16–205	15°24′N	43°24′W	250	390	440

* *Ericson and Wollin*, 1968.

† Age 690,000 years [*Cox*, 1969].

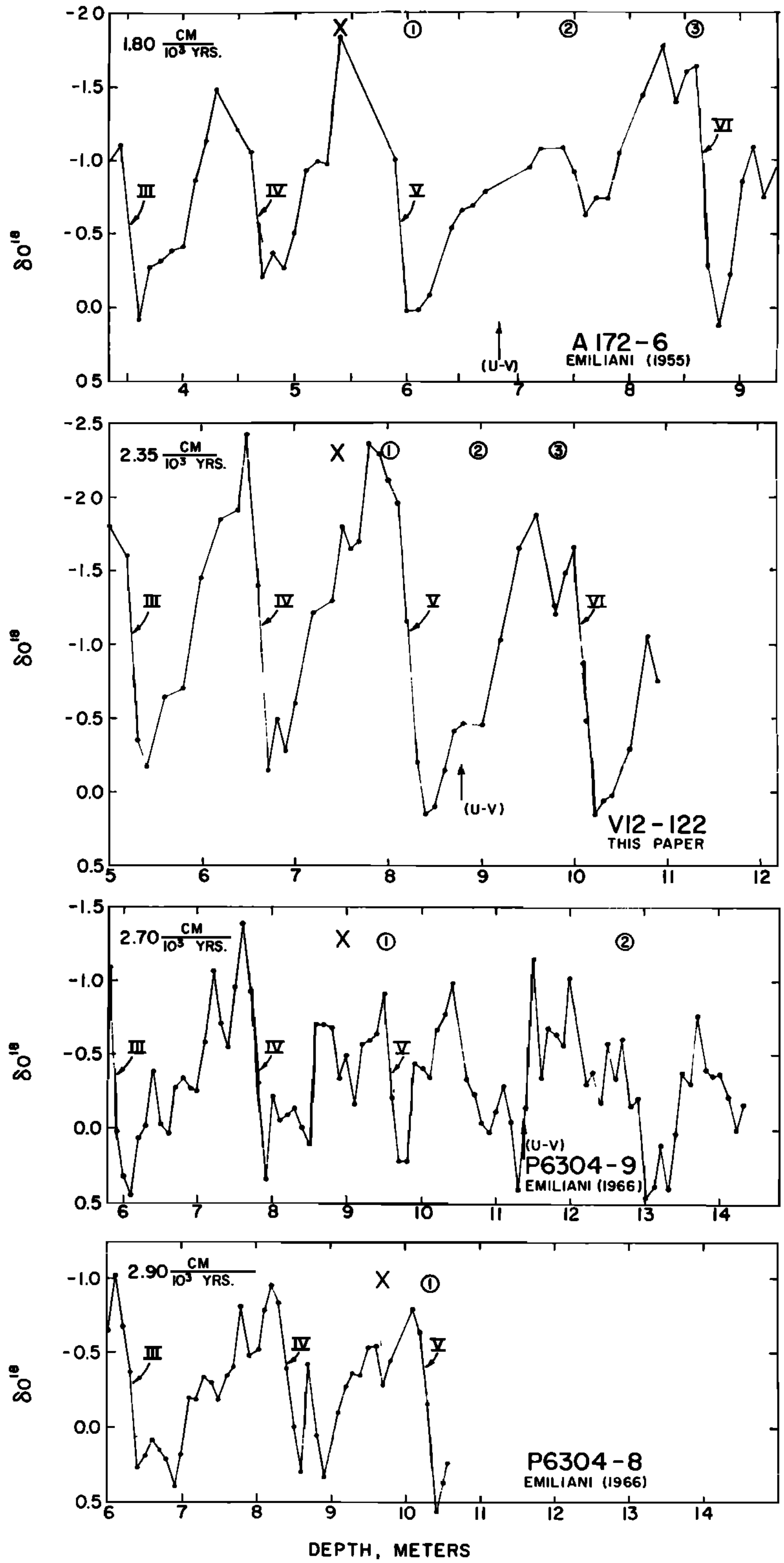
TABLE 5. Ages of Terminations III, IV, V, and VI

	V12–122	A172–6	P6304–9	P6304–8	Best Estimate
Depth to termination I, centimeters	30	30	30	30	
Depth to termination II, centimeters	300	180	340	350	
Depth to *U-V* boundary, centimeters	890	680	1135		
Sedimentation rate between II and I, cm/10^3 years	2.35	1.30	2.67	2.75	
Sedimentation rate between *U-V* and II, cm/10^3 years	2.08	1.76	2.81		
Age of termination III, 10^3 years					
Method 1	225	255	215	230	
Method 2	235	225	200		225 ± 15
Age of termination IV, 10^3 years					
Method 1	280	345	290	305	
Method 2	300	290	280		300 ± 20
Age of termination V, 10^3 years					
Method 1	350	440	410	375	
Method 2	375	360	360		380 ± 25
Age of termination VI, 10^3 years					
Method 1	430	655			
Method 2	470	520			~500

Ages are estimated in four deep sea cores by (1) extrapolation of sedimentation rates established between termination I (11,000 years) and termination II (127,000 years) and (2) by interpolation between the *U-V* boundary (400,000 years) and termination II (127,000 years). In the two cores reaching termination VI, the age of this horizon is calculated by extrapolation from termination II (using the II–I rate) and from the *U-V* boundary (using the *U-V* II rate).

RELATIONSHIP BETWEEN GLACIAL FLUCTUATIONS AND THE O^{18} RECORD IN DEEP-SEA CORES

Radio-carbon dating has clearly established that the continental ice sheets achieved one of their four or so most prominent Pleistocene maxima 18,000 ± 1000 years ago [*Flint*, 1955]. Studies of sea level (see *Jelgersma* [1966] for summary) indicate that at least 90% of the water necessary to form these ice sheets had been returned to the sea by 6000 years ago. The period from 16,000 to 6000 years ago was clearly one of major deglaciation. As was stated above, the mid-point of the sharp O^{18}-O^{16} decrease which constitutes termination I in deep-sea cores falls in the middle of this interval (i.e., at 11,000 ± 500 years ago) [*Broecker et al.*, 1960]. Since the shape of the sea-level rise is not known with adequate precision, the degree to which the ice volume and O^{18} change paralleled one another cannot be established. It is clear, however, that the dates of the mid-point of the sea level rise and of the O^{18} increase coincide. As absolute



1.80 CM/10³ YRS.
X ① ② ③
III IV V VI
(U-V)
A 172-6
EMILIANI (1955)
2.35 CM/10³ YRS.
X ① ② ③
III IV V VI
(U-V)
V12-122
THIS PAPER
2.70 CM/10³ YRS.
X ① ②
III IV V
(U-V)
P6304-9
EMILIANI (1966)
2.90 CM/10³ YRS.
X ①
III IV V
P6304-8
EMILIANI (1966)
δO¹⁸
DEPTH, METERS

TABLE 6. Summary of Evidence for a Higher than Present Sea Stand about 124,000 Years Ago*

Location	Elevation, meters	No. of Samples	Average Age, 10^3 yr	Reference
Atlantic Ocean				
Bermuda	4	3	123 ± 10	*Land et al.*, 1967
Bahamas	3	1	127 ± 7	Goddard (pers. comm.)†
Indian Ocean				
W. Australia	2–4	2	120 ± 20	*Veeh*, 1966
Mauritius	2	1	160 ± 40	*Veeh*, 1966
Seychelles	6–9	2	140 ± 30	*Veeh*, 1966
Pacific Ocean				
Hawaiian Is.	2–3	4	120 ± 15	*Veeh*, 1966
Cook Is.	2	2	100 ± 20	*Veeh*, 1966
Tuamoto Is.	2–4	7	130 ± 20	*Veeh*, 1966

* Corals used for dating showed no evidence of recrystallization and were collected in growth position.

† An error was found in the Th^{230}/U^{234} ratio calculated by *Broecker and Thurber* [1965]; the value should be 0.65 ± 0.04 instead of 0.56 ± 0.04. The corrected age is 113,000 ± 12,000 rather than 80,000 ± 8,000 years. The value reported here is based on a rerun of this sample.

dates are not now available for any of the previous periods of deglaciation, this relationship cannot be tested for earlier terminations.

Th^{230} dating of corals from raised reefs consistently indicates that the last time at which the sea stood higher than it does today was about 125,000 years ago (the evidence is summarized in Table 6). If the revised time scale for deep-sea cores is correct, this high stand closely followed termination II just as the present high stand follows termination I. From their study of the raised coral reefs on the island of Barbados, *Mesolella et al.* [1969] conclude that the next earlier period of positive or near-positive sea stands was 200,000 ± 20,000 years ago. Termination III in deep-sea cores has an age of 225,000 ± 25,000 years. Thus it appears that each of the last three terminations in the O^{18} record was

Fig. 6. (*Opposite*) Correlation of the O^{18} records below termination III in four long cores from the Caribbean Sea. The X indicates the point in each core where the dominantly left-coiled species *G. crassaformis* shows a temporary shift to right coiling. The circles numbered 1, 2, and 3 represent points below this *G. crassaformis* peak where the dominantly right-coiled species *G. truncatulinoides* shows temporary shifts to left coiling. The U-V boundary of Ericson is the level at which the species *Globorotalia menardii* reappears after a zone of absence. The *G. crassaformis* data for cores P6304-8, P6304-9, and A172-6 are from *Emiliani* [1966] and that for V12-122 from J. Imbrie (personal communication, 1969). The *G. truncatulinoides* data for cores A172-6 and V12-122 is from *Ericson and Wollin* [1968] and for P6304-8 and P6304-9 from *Emiliani* [1966]. The locations of the *U-V* boundary in cores A172-6 and V12-122 are from *Ericson and Wollin* [1968] and that for P6304-9 from *Rona and Emiliani* [1969]. Core P6304-8 does not quite reach the *U-V* boundary.

closely followed by a period of maximum deglaciation (i.e., of high sea level). The one dated glacial maximum (18,000 years ago) falls just before the last termination. These data are thus consistent with the idea that glacial fluctuations follow the sawtoothed pattern shown by the O^{18} curves, i.e., a gradual glacial buildup is followed by rapid deglaciation.

Some authors have suggested that sea level returned to its present level between 35,000 and 45,000 years ago [*Curray*, 1965; *Milliman and Emery*, 1968]. This conclusion is largely based on C^{14} ages of carbonates. As *Olson* [1963] and *Olsson et al.* [1968] showed, finite C^{14} ages beyond 35,000 years cannot be accepted in the absence of careful sample pretreatment and concordant cross-checks between samples.

Evidence from the position of both the Laurentide [*Dreimanis and Vogel,*

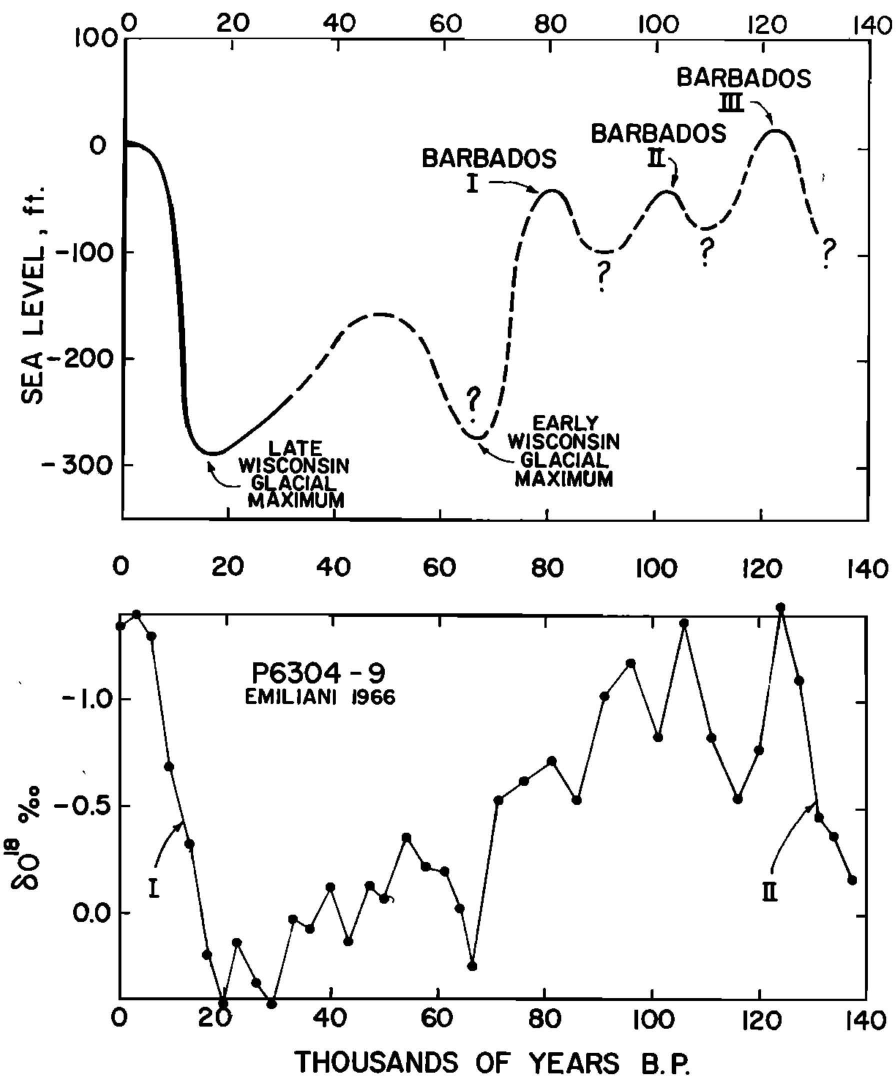


Fig. 7. Comparison of ice volume and δO^{18} chronologies. Upper curve shows the major features of the ice volume curve based on absolute dating of marine shorelines and of glacial tills (see text). The lower curve is based on the O^{18} records given in Figure 1. If termination II has an age of about 125,000, the two records are compatible.

1965] and the Irish Sea ice [*Shotton,* 1967] suggest that both these ice sheets were in existence and more than half their maximum size between 35,000 and 45,000 years ago. Furthermore, no peat deposits of this age in the mid-continent of North America or in Europe have been reported to show pollen assemblages similar to those expected were enough ice to have melted to bring the sea to its present level. We conclude that it is quite unlikely that sea level reached within 60 feet of its present level during this time interval.

There is evidence (see Figure 7) that the oscillations which modulate the sawtoothed cycles found in deep-sea cores also show up in the record of continental ice sheets. As *Broecker et al.* [1968] have shown, the prominent high sea stand at 124,000 ± 5000 was followed by two secondary maxima, one at 103,000 and one at 82,000 years ago (see Table 7). During each of these periods sea level rose to within 40 feet of its present level. These two warm maxima and that at 124,000 years ago may well be equivalent to the three warm peaks shown in Emiliani's idealized curve above termination II.

The following ice volume record is suggested. The ice sheets present 130,000 years ago were largely destroyed during termination II. When they began to grow anew after the maximum deglaciation 124,000 ± 5000 years ago, this growth

TABLE 7. Th^{230} and Pa^{231} Ages for Lowest Four Coral Reefs on Island of Barbados

Sample No.	Elevation, meters	Pa^{231} Age,* 10^3 yr	Th^{230} Age,† 10^3 yr
		Terrace I	
1046-*A*	20		82 ± 2
1046-*C*	6		82 ± 4
1150-*A*	12		82 ± 2
1152-*C*	12	79 ± 4	82 ± 4
		Terrace II	
1144-*C*	21	104 ± 8	100 ± 3
1150-*C*	27		104 ± 6
1152-*A*	7		104 ± 3
		Terrace III	
1046-*B*	24		124 ± 4
1046-*D*	40		120 ± 6
1152-*B*	50		124 ± 4
1160-*I*	38		127 ± 6
1152-*E*	35	120 ± 10	124 ± 6
		Terrace IV	
1144-*A*	47		200 ± 10
1150-*D*	71		210 ± 25
1152-*D*	55		210 ± 30
1144-*B*	32	>170	180 ± 10‡

* *Ku,* 1968.

† *Mesolella et al.,* 1969; *Broecker et al.,* 1968.

‡ Geological evidence for position in terrace sequence is not firm; could be terrace V rather than IV.

suffered the two setbacks documented by the raised coral terraces on the island of Barbados. How much ice growth occurred in the intervals separating these three events is not known.

There is strong evidence for a period of major glaciation predating the 18,000-year glacial maximum and postdating the last period of interglaciation. Radiocarbon data suggest that this glaciation occurred more than 50,000 years ago [*Forsyth,* 1965; *Kempton and Hackett,* 1968]. If the sea level maxima at 82,000, 103,000, and 124,000 years ago represent the last interglacial, then the age of this glaciation must lie between 50,000 and 80,000 years. If so, it could well correspond to the major cold peak following the three warm peaks in Emiliani's O^{18} curve. Thus, it is safe to say that our knowledge of the fluctuation in ice growth during the buildup toward the last major glaciation is compatible with the secondary fluctuations found in the O^{18} record in deep-sea cores.

Because of the short duration of the interval over which the O^{18}/O^{16} ratio changes during times of deglaciation, it is not clear whether fluctuations superimposed on this change would be preserved in deep-sea cores. Burrowing organisms mix deep-sea sediment and tend to average out short-term changes. Thus, although no oscillations are apparent in Emiliani's O^{18} records for termination I (see Figure 8), it cannot be stated that such fluctuations did not occur.

On the other hand, clear-cut evidence is available for re-advances of the continental ice sheets during the period of glacial retreat. The best documented of these is Valders re-advance, which caused the destruction of the forest at Two Creeks, Wisconsin [*Thwaites and Bertrand,* 1957]. Precise radiocarbon dating of the trees from this forest drowned by the rise in Lake Michigan produced by the advancing ice show that this re-advance occurred 11,900 ± 100 years ago [*Broecker and Farrand,* 1963].

The record of climate change as indicated by both pollen profiles and the size of the basin lakes strongly implies that the transition from glacial to interglacial climate was not unidirectional. Pollen profiles in Denmark [see *Barendsen et al.,* 1957] suggest that two complete cycles occurred (the Bolling-Older Dryas 12,000 years ago and the Allerod-Younger Dryas 11,000 years ago). Studies of the sediments deposited by Lakes Lahontan and Bonneville suggest that the desiccation of the pluvial lakes in the Great Basin at the end of the last glacial period was punctuated by two extremely large fluctuations [*Broecker and Orr,* 1958; *Broecker and Kaufman,* 1965]. Partial desiccation of these lakes in progress 13,000 years ago was interrupted by a high lake stand (i.e., a more humid period) 12,000 years ago. Desiccation again largely eliminated these lakes by 11,000 years ago. A second large rise in lake level brought the lakes to near maximum size by 9500 years ago. This last gasp of the lakes was followed by generally arid conditions similar to those existing today.

These relationships are summarized in Figure 8. Clearly, despite its rapidity, the climate change that brought about the termination of the last glacial period resulted in major oscillations in the climate, at least in some regions of the earth's surface. These cycles had periods less than 2000 years in length (compared to a period of about 20,000 years for the recognized cycles modulating the growth of the ice sheets).

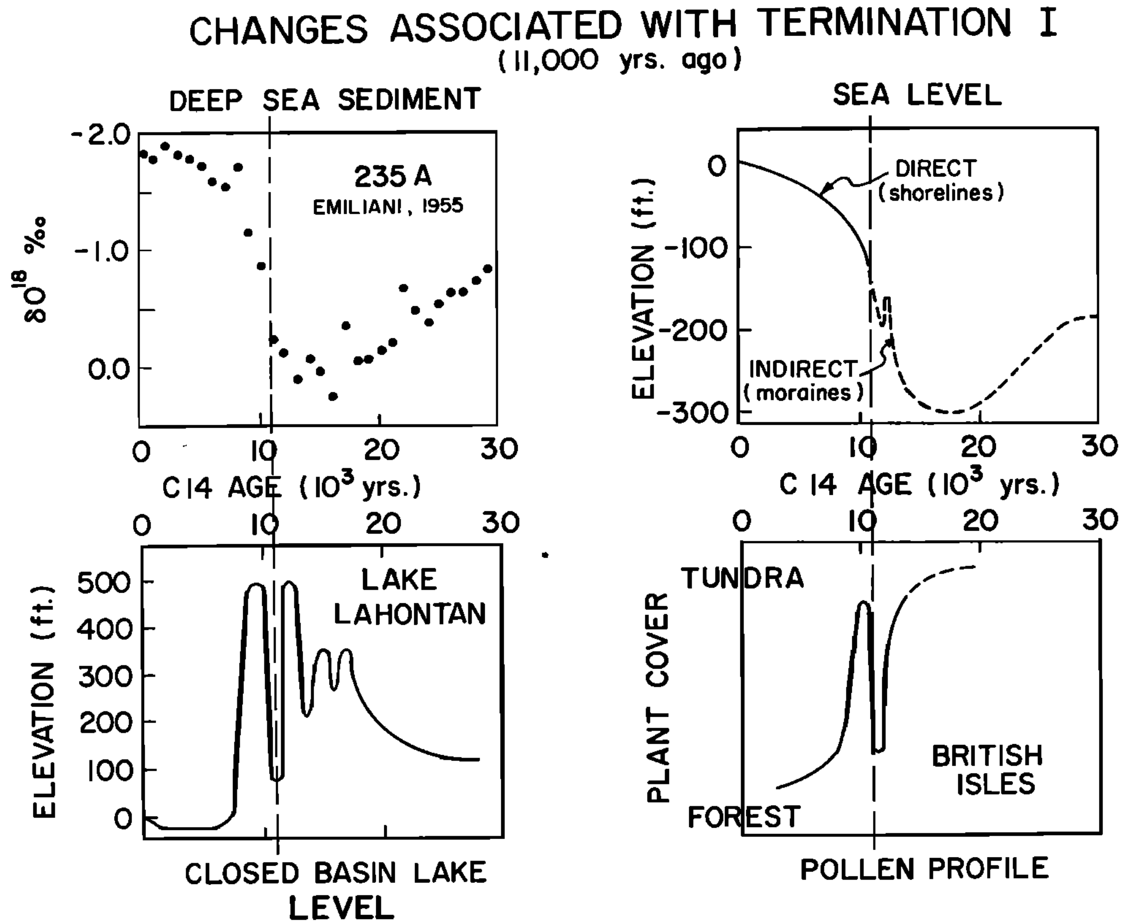


Fig. 8. Changes associated with termination I. Although the O^{18} curves show a unilateral change from cold to warm, glacial deposits, pluvial lake shorelines, and vegetation remains clearly show at least one sharp oscillation between 9000 and 13,000 years ago.

RELATIONSHIP BETWEEN CHANGES IN THE EARTH'S ORBITAL PARAMETERS AND THE CLIMATIC RECORD

The most persistent explanation of the cyclic character of climate during periods of glaciation is that the size of continental ice sheets is strongly influenced by changes in the earth's orbital parameters. Although these changes do not significantly alter the total radiation received by any given part of the earth's surface, they do result in large changes in seasonal contrast. If, as seems reasonable, the equilibrium size of continental ice sheets depends more on the radiation received during the summer than that received during the winter, then the glaciers should prosper during periods of reduced contrast and dwindle during periods of enhanced contrast.

Although variations of this basic hypothesis were proposed by Adhemar in 1842, Croll in 1876, and Koppen and Wegener in 1924, the credit for its establishment is given to Milankovitch, whose rigorous mathematical treatment of the problem put it on a firm theoretical ground [*Milankovitch*, 1938]. The validity of Milankovitch's astronomical calculations was confirmed in the early 1950's by Brouwer and van Woerkom [*Shapley*, 1953] and more recently by *Vernekar* [1968].

The seasonal contrast at any point on the earth's surface changes with time for two reasons. First, the interactions between the earth and other bodies in the solar system leads to a periodic change in the tilt of its axis with respect to the orbital plane (Figure 9). The period of this somewhat irregular cycle averages 41,000 years. Its amplitude averages 2 degrees. During periods of greater tilt the seasonal contrast is enhanced and during periods of smaller tilt the contrast is reduced. The two hemispheres, of course, respond synchronously to these changes. As *Milankovitch* [1938] showed, the changes in contrast are strongly latitude dependent, being almost absent at low latitudes and greatest at the poles. For example, at 45° the mean summer radiation increases by 1.2% for each 1 degree increase in tilt, while at 65° the corresponding change is 2.5%.

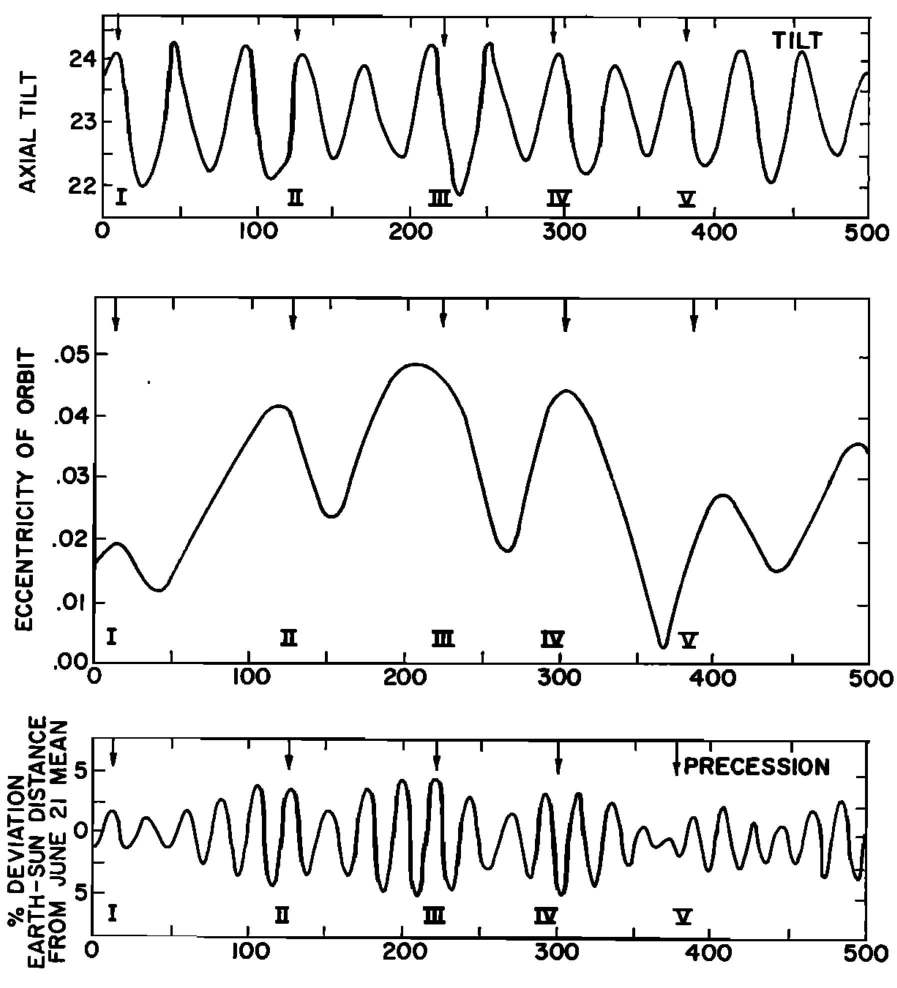


Fig. 9. Variation of the earth's axial tilt (top), orbital eccentricity (middle), and June 21 sun-earth distance (bottom) over the past half-million years (based on the calculations of *Vernekar* [1968]). The arrows and Roman numerals indicate the timing of the sudden terminations seen in the O^{18} record from deep-sea cores.

The second source of variations in seasonal contrast is the earth's precession (Figure 9). It has long been known that the earth's axis undergoes one complete precessional cycle each 21,000 years. Since the earth's orbit is slightly elliptical, the radiation received by the earth as a whole on any given day depends on the position of the earth in its orbit. If the earth happens to be at the 'long' end of the orbit, less than average radiation will be received, and if at the 'short' end of the orbit, more than average radiation will be received. During periods when summer occurs at the short end of the ellipse, the days will be warmer than during periods when summer occurs at the long end of the ellipse. It is clear that the two hemispheres are exactly out of phase with respect to this effect. When the northern hemisphere is enjoying a reduced seasonal contrast (as it is today), the southern hemisphere will be enduring an enhanced contrast. In contrast to the tilt effect, that due to precession does not show a marked latitude dependence.

The magnitude of the precessional effect depends only on the eccentricity of the earth's orbit. If the orbit were perfectly circular, precession would have no effect on seasonal contrast. Planetary interactions cause the eccentricity of the earth's orbit to undergo periodic changes (Figure 9). Although the period and magnitude of these changes is quite irregular, the time for a complete cycle averages 90,000 years. Over the past million years the eccentricity has varied from 0.00 to 0.06. These changes in eccentricity modulate the amplitude of the 21,000-year precessional cycle (Figure 9).

The resultant change in seasonal contrast is thus the composite of the tilt and precession effects. Since the tilt effect is in phase for the two hemispheres, whereas the precessional effect is not, the resultant for the southern hemisphere will be quite different from that for the northern hemisphere. Because of the latitudinal dependence of the tilt effect, curves drawn for different latitudes will differ in detail. In Figure 10 are shown curves for three different latitudes in the northern hemisphere. The per cent difference from the mean summer radiation is given for the last 500,000 years. The curves were constructed from data given by *Vernekar* [1968].

Shaw and Donn [1968] have used the thermodynamic model of Adem to estimate the summer temperature changes resulting from insolation variations. They find that the difference in June temperature between 127,000 years ago (a period of unusually warm summers) and 22,100 years ago (a period of quite cool summers) was 3.3°C at 45°N, 3.0°C at 55°N, and 2.8°C at 65°N. However, as these authors did not allow such important parameters as cloudiness or snow cover to vary from their present values, these results can only be taken as first approximations to the actual changes. As the temperature changes they obtain are one-third to one-half those generally thought necessary to produce a full-scale glaciation, their statement that 'the Milankovitch effect is rather small to have triggered glacial climates' seems a bit premature.

As is shown above, the fundamental climatic cycle is sawtoothed in character, with sharp terminations spaced at intervals ranging from 70,000 to 115,000 years (see Figure 11). The dominant period of the astronomical cycles is close to 20,000 years. However, both the modulation of this 20,000-year cycle by

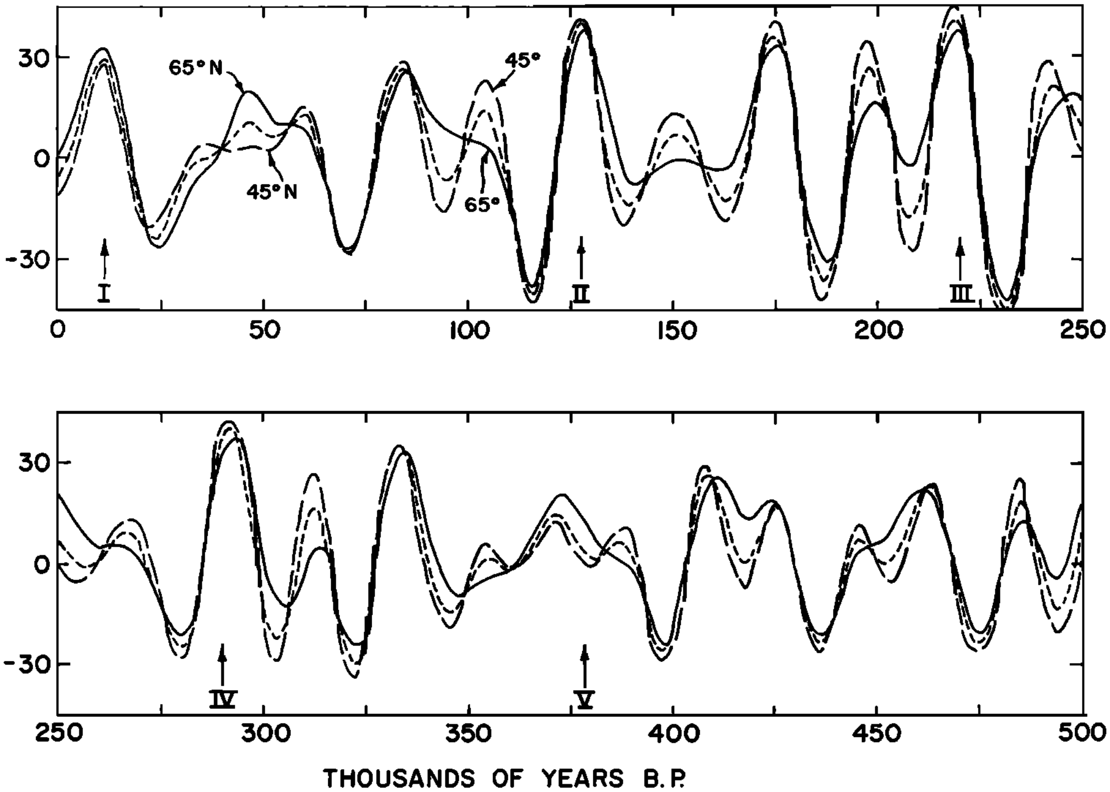


Fig. 10. Summer insolation curves for the past 500,000 years for latitudes 45°N (long dash-short dash), 55°N (dash), and 65°N (solid) based on calculations made by *Vernekar* [1968]. The changes are expressed in units of langleys per day difference from the mean caloric summer radiation at each latitude (900 at 45°N, 845 at 55°N, and 775 at 65°N). The maximum variations are thus about ±5% from the mean summer radiation. The arrows and Roman numerals indicate the times at which sudden terminations occurred in the O^{18} record from deep sea cores.

eccentricity changes (period ~90,000 years) and the varying phase relationship between the tilt (~40,000-year period) and the precessional (~20,000-year period) cycles lead to a supercycle in the amplitude of the precessional peaks with a period averaging 80,000 to 90,000 years in length. As is indicated in Figure 10, the last four terminations appear to have taken place during times of unusually large seasonal contrast in the northern hemisphere. The midpoint of the most recent termination has been dated by radiocarbon at 11,000 ± 600 years [*Broecker et al.*, 1960]. It took place during the only period of strong seasonal contrast during the last 75,000 years (i.e., that 11,000 years ago). Termination II is dated by Pa^{231}/Th^{230} in core V12-122 at 127,000 ± 6000. There are three periods of marked seasonal contrast in the interval between 170,000 and 70,000 years ago; one at 82,000, one at 106,000, and one at 127,000 years ago. If our time scale is correct, termination II coincides with the largest of these three peaks (that at 127,000 years ago). The age of termination III has been estimated to be 225,000 ± 15,000 years ago (Table 5). It appears to correspond to the first of a triad of prominent peaks in seasonal contrast (i.e., those at 220,000, 200,000, and 180,000 years ago).

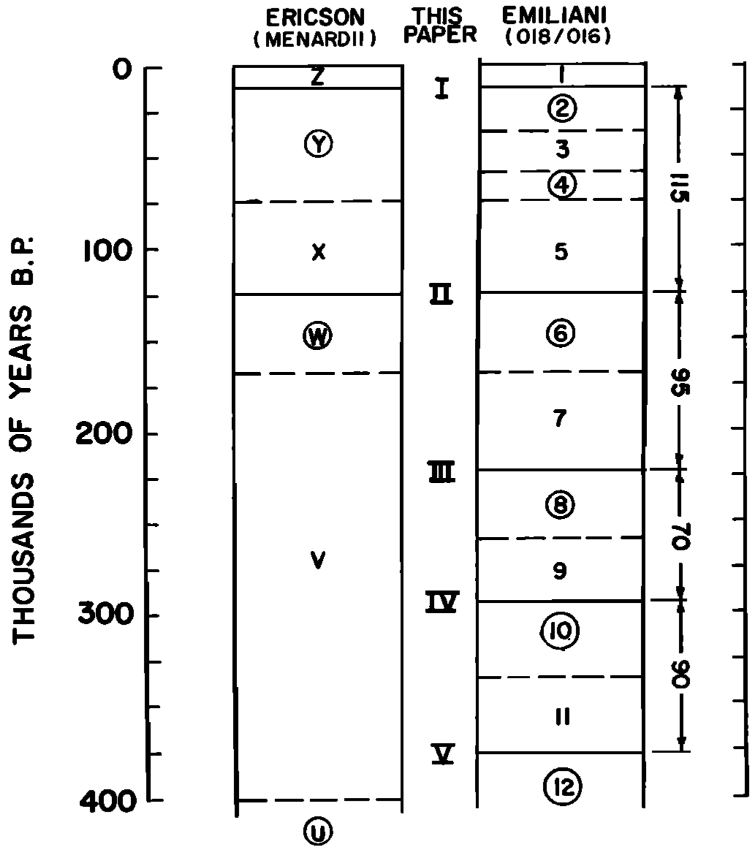


Fig. 11. The stratigraphic relationship between the termination sequence adopted here and the warm and cold zone sequences of *Ericson et al.* [1961] and of *Emiliani* [1955]. The circled letters and numbers represent cold periods (*menardii* absent in Ericson's data and high O^{18} content in Emiliani's data). The uncircled letters and numbers represent warm periods. Except for the presence of warm stage 3 in Emiliani's sequence, the two methods show the same climatic zonation over the last 200,000 years. Beyond 200,000 years the interpretations of the two authors are completely divergent. Except for zone 2-3-4, which we feel is a single cold period, our interpretation is the same as Emiliani's.

Beyond termination III, correlations become more difficult. The age errors encompass more than one precession peak and the possibility that inadequacies in the astronomical calculations have produced improper phasing between the tilt and precession components increases. Termination IV dated at 300,000 ± 20,000 could correspond to the prominent seasonal contrast peak at 291,000 years. Termination V (375,000 years), however, falls in a region where there are no strong insolation peaks.

The phasing problem can be partially surmounted by matching the termination times directly with the eccentricity curve, the point being that the times of greatest seasonal contrast will occur during times of large eccentricity. As is shown in Figure 9, the times of the last five terminations match reasonably well the times of the last five eccentricity maxima. During each major eccentricity maximum, there will be two or three precession maxima. The tilt cycle will cause alternate peaks to be prominent and weak. Back to termination V there have been only four eccentricity cycles. In the same period there have been ten tilt and twenty precessional cycles. The chance that a serious phasing error between precession and tilt occurs during this interval is thus far greater than the chance that the eccentricity curve is in error. Thus revisions of the astronomical calculations, while likely to shift the relative heights of the precession maxima at any given eccentricity maximum, are unlikely to change the time intervals where these maxima are likely to occur. Our dating of terminations I and II is precise enough and the chance of phase shifts small enough that we can demonstrate a correlation with a specific precession peak. For terminations III and IV, the correlation with the eccentricity maxima are quite good, but that with a specific precession peak within the time period encompassed by the peak is quite tenuous. For terminations V and VI, even the correlation with eccentricity peaks becomes tenuous. More precise renditions of the astronomical curves and more accurate dating of deep-sea cores will have to be obtained in order to more rigorously test the correlation.

In addition to the correlation between terminations and precession maxima, in the region between terminations II and I there seems to be a relationship between the secondary cycles, which are superimposed on the cooling parts of the sawtoothed cycle, and the insolation changes. As *Broecker et al.* [1968] pointed out, each of the three periods of interglacial sea stands represented by the raised coral reefs on Barbados, dating 124,000, 103,000, and 82,000 years ago, just follows a maximum in summer radiation. The major glacial maximum that took place 18,000 years ago follows a minimum in summer radiation (at 22,000 years). The early Wisconsin glacial maximum, which dated at greater than 50,000 years by radiocarbon and was presumed to postdate the 80,000-year warm period, may well correspond to the prominent cold summer peak 70,000 years ago.

Although both the timing of the terminations and the timing of the oscillations that modulate the glacial buildup may only coincidently correlate with the insolation curve, we choose to interpret this correlation as strong evidence that variations in the orbit of the earth do influence the earth's climate. Whether these variations are the primary cause for the major sawtoothed cycles or whether they merely modulate a cycle due to some other cause is not clear.

In this regard we have one suggestion. Let us assume (1) that in the absence of insolation cycles the earth's climate would not show cyclic variations and that it would be more nearly glacial than interglacial in character, (2) that the time required to grow a full sized continental glacier is several tens of thousands of years, and (3) that the warm summers of periods of large seasonal contrast are capable of destroying large ice sheets. Were this the case, a climate curve similar to that observed could be generated. During periods when no strong peaks in seasonal contrast occurred, the glaciers would grow toward their equilibrium size. Warm summer peaks of moderate size might arrest this growth or even cause the ice to retreat. A strong cold summer peak following one of these periods (as did the one 22,000 years ago) would produce unusually large glaciations. Large warm summer peaks would destroy any existing ice sheets. The ice would begin anew its growth after each prominent peak in seasonal contrast. The extent to which it grew would largely depend on the time elapsed until the next ice-destroying peak took place. Although the eccentricity peaks are fairly evenly spaced, the phase match between tilt and precession required to produce the ice-destroying maxima need not be equally well spaced. This variability of growth time may have led to glacial maxima of quite different magnitude. Thus the four classical glaciations need not match the last four O^{18} minima. They more likely represent four prominent glaciations scattered through a much longer sequence of lesser glaciations. Attempts to match pre-Wisconsin glacial maxima with O^{18} minima in the deep-sea core record are thus highly speculative.

This is certainly not the first attempt that has been made to demonstrate the importance of orbital changes by comparison between insolation and climate chronologies for deep-sea cores. *Emiliani* [1955] pointed out the similarity between the periodicity of the two curves. Two years later *Emiliani and Geiss* [1957] proposed a theory of glaciation using insolation changes to start (but not to end) glacial cycles. In 1966 Emiliani suggested that the timing between O^{18} and insolation peaks yielded a correlation coefficient of 0.994. *Donn and Shaw* [1967] criticize the method used to achieve this correlation, and we show here that the time scale used by Emiliani to obtain this correlation was in error by 25%. *Broecker* [1966] suggested that insolation changes caused the ocean-atmosphere system to jump between two stable states, one glacial and one non-glacial. His conclusions were also based on the incorrect time scale. In addition, the assumption that the basic climatic cycle is rectangular in shape does not appear to be valid. These past claims, if valuable in no other way, at least point up the dangers in playing the game of 'proof by curve matching' indulged in here.

CLIMATE CHANGES IN THE SOUTHERN HEMISPHERE

Although there is good evidence that the antarctic continent was at times in the past even more extensively glaciated than it is today [*Péwé,* 1960] and that the snow cover on the mountains of South America, Africa, and New Zealand once extended far lower than today [*Flint,* 1947], the chronology of these changes has not been well established. If orbital changes are a primary cause of climatic change, their lack of synchroneity between the two hemispheres should lead to different climatic chronologies. In Figure 12 the summer insolation curves for 55°S and 75°S are compared with that for 55°N. As was mentioned above, the tilt component is the same for the two hemispheres and the precession component exactly out of phase. Thus, at times when the tilt and precession contributions reinforce one another to produce major maxima or minima in seasonal contrast in the northern hemisphere (i.e., 127,000, 22,000 years ago), these components are working against one another in the southern hemisphere. Once adequate absolute dating information is available for the southern hemisphere, an additional means of evaluating the role of orbital changes will be possible.

THE PATTERN OF FUTURE CLIMATIC CHANGES

There is no reason to expect that the sawtoothed pattern of climatic changes that is so clearly evident over the past 500,000 years will not continue into the

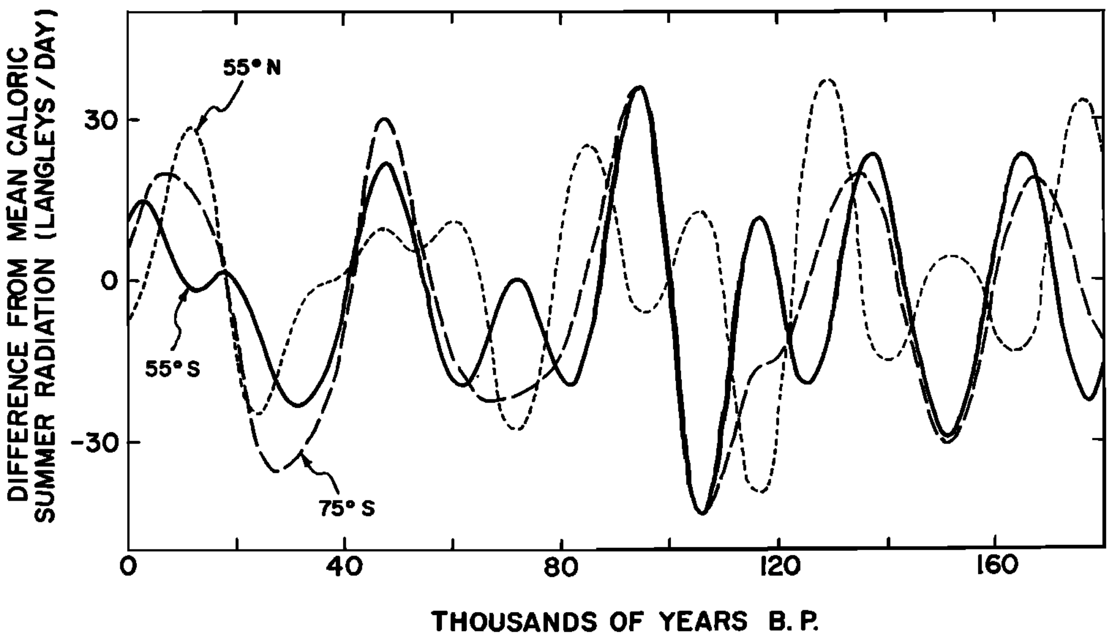


Fig. 12. Comparison of the summer insolation curves for 55°S and 75°S with that for 55°N. Although the tilt effect is the same for the two hemispheres, the precession effect is out of phase. This leads to major differences between the insolation changes in the two hemispheres (based on *Vernekar* [1968]).

future. The glaciers that were destroyed during the termination 11,000 years ago should begin to grow anew. This growth will culminate in another termination 50,000 to 100,000 years in the future. If the main obstacle to the growth of these glaciers is indeed the summer insolation maxima brought about by orbital changes, then the next 50,000 years should see unusually rapid expansion of the continental ice sheets. As is shown in Figure 13, which compares the northern hemisphere summer insolation curve for the coming 150,000 years with that for the past 150,000 years, the curve shows no prominent peaks over this interval (compared, for example, with the large oscillations that followed termination II 125,000 years ago). This absence of change in seasonal contrast is the result of a relatively low orbital eccentricity and of antiphasing between the tilt and precession components. Thus, a repetition of the periods of the near-present sea levels that occurred roughly 20,000 and 40,000 years after termination II is not to be expected. Rather, a more steady and presumably extensive glacial advance can be expected during this time interval.

CONCLUSIONS

1. The O^{18} curves of Emiliani appear to record the extent of continental glaciation. If they do, the major climatic cycles during late Pleistocene time had a sawtoothed character. Gradual glacial buildups over periods averaging 90,000 years in length are abruptly terminated by rapid deglaciations. The time required for deglaciation is no more than one-tenth that for the buildup.

2. The last four major O^{18} terminations occurred 11,000 ± 600, 127,000 ± 6000, 225,000 ± 15,000, and 300,000 ± 20,000 years ago. The most recent of these,

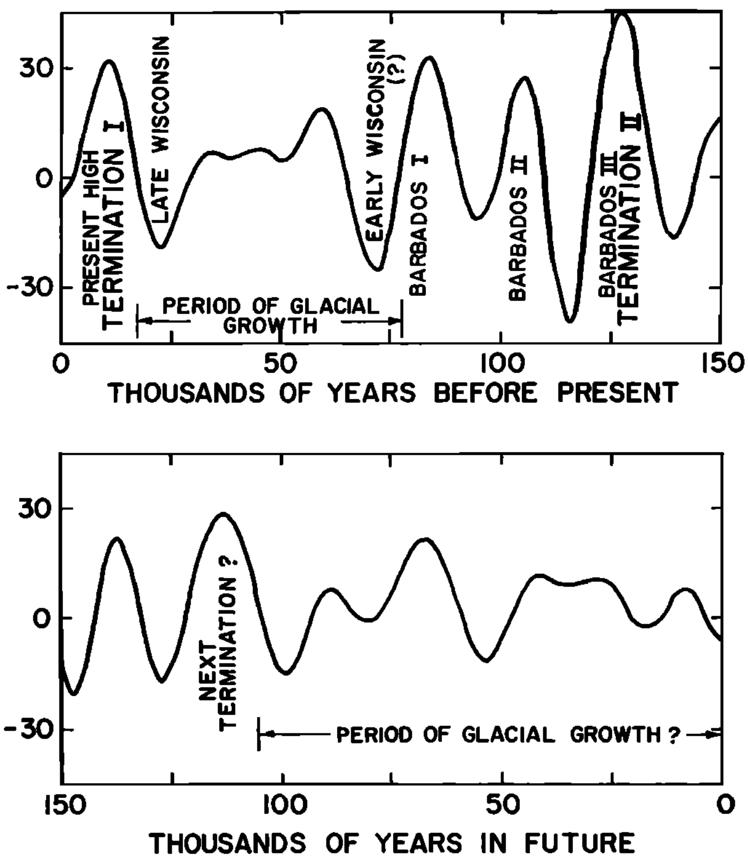


Fig. 13. Comparison of the insolation curve for 45°N over the past 150,000 years with that for the next 150,000 years (based on *Vernekar* [1968]). The low eccentricity of the earth's orbit and the antiphasing of tilt and precession during the next 50,000 years will lead to a low variability similar to that between 60,000 and 30,000 years ago. If our interpretation of the past cycles is correct, sizable continental glaciers should grow during the coming 50 or so thousand years.

termination I, was immediately preceded by a major period of glaciation and followed by a major period of deglaciation. The preceding termination (i.e., II) is known to have been followed by a major period of deglaciation. The next earlier period of near-present sea level has an age close to that of termination III. It seems likely that, as a general rule, major warm intervals (i.e., times of sea level greater than or equal to that of today) occurred just after O^{18} terminations and that periods of major glaciation (i.e., ice cover similar to that 18,000 years ago) occurred just before these terminations.

3. The last two O^{18} terminations (and hence presumably deglaciations) occurred during periods of unusually large northern hemisphere seasonal contrast. The two preceding terminations appear to correlate with times of maximum eccentricity necessary to the generation of precession maxima.

4. The secondary oscillations superimposed on the growth of the ice between terminations II and I closely parallel northern-hemisphere summer insolation changes.

5. Although this dual correspondence strongly supports the hypothesis that changes in the earth's orbital parameters lead to climatic change, it does not require that the major sawtoothed cycle itself be the result of this cause.

6. More precise insolation curves and more extensive and accurate absolute age data are needed in order to further test the match between insolation and climatic changes.

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