

Isotopic Paleotemperatures: Discussion

In a recent review of the application of oxygen-isotope temperature analyses and of cross-correlation methods to deep sea cores, Emiliani (1) proposed (i) a generalized temperature curve for the surface waters of the central Caribbean Sea and (ii), a curve correlating thickness of certain core stages from the Caribbean and the equatorial Atlantic with ages of summer insolation minima at 65°N. The correlation coefficient indicated by this latter curve was calculated to be 0.997. We have given the data and analytical methods involved in the construction of these two curves careful scrutiny, in view of the importance of the validity, or lack of validity, of the curves to the understanding of paleoclimates and to climatic theory, and find Emiliani's climate curve inaccurate and his correlations of core stages with radiation variations untenable.

1) The generalized climate curve in Fig. 1 (Emiliani's Fig. 5 redrawn, with the more recent stages at the right, for better comparison with the curve of Fig. 2) was developed by the use of O^{18}/O^{16} , C^{14} , and Pa^{231}/Th^{230} data and "reasonable extrapolations therefrom." We have shown (2) that the core data on which the climate curve was constructed can be interpreted quite differently. Considerable subjectivity appears to have been involved in the selection of the core stages averaged to give the generalized temperature curve. Thus, in Fig. 1, the depths of all the temperature minima are about equal,

and so the stages are quite prominent, but the primary core data on which the generalized curve is based do not support this interpretation. The boundary between stages 3 and 5 is based on the relatively slight temperature dips at about 200 cm in the core logs of Emiliani's Fig. 4 (1) and on similar features in other core logs (3). What appear to be simple irregularities on a continuous temperature decline have thus been used to establish a full glacial stage equivalent to other glacial stages with better documentation. Figure 2 shows the Milankovitch radiation curve as developed by van Woerkom (4), together with climate stage numbers assigned by Emiliani (3). In Fig. 2 there is a prominent radiation minimum between stages 3 and 5; the corresponding portion of Emiliani's generalized temperature curve (Fig. 1) shows a minimum of equal prominence, although the primary core data show a barely discernible minimum, not a significant stage. Also, according to a report (5) in the same issue of *Science*, faunal analysis of Pacific cores has not indicated Emiliani's stage 3.

Further, Emiliani's climate curve (see Fig. 1) shows a strongly developed glacial or temperature minimum establishing the boundary between stages 11 and 13. But the equivalent stages in the Milankovitch curve (Fig. 2) are separated by a very weak radiation minimum which barely falls below the 65° north latitude level, the value taken by Milankovitch to repre-

sent normal. In the absence of an absolute chronology over the range of the generalized climate curve, one must be careful to avoid the subjective correlations invited by two sets of oscillations of roughly the same frequency.

We have shown in more detail (2) that Emiliani's entire generalized climate curve is based on quite subjective "reasonable extrapolation," and we regard the curve as far from being "established rather firmly with respect to both amplitude and age."

2) If valid, the curve in Emiliani's Fig. 10 and the related correlation coefficient of 0.997 would indicate most strongly a causality between variations in insolation produced by the Milankovitch effect and climatic fluctuations.

Any appraisal of this curve and correlation value must involve consideration of the referenced data (3) on which they are based. First, we note that, instead of comparing thicknesses of individual core stages with estimated corresponding Milankovitch time intervals, which would be the correct procedure, Emiliani compared cumulative values for thicknesses of core stages, from the top of the core down, with cumulative values for time intervals, from the present backward. A procedure of this kind will always give a spurious high correlation. For example, consider two series of numbers, each series made up of a pair of six-digit telephone numbers randomly selected from the phone book: 8,9,1,6,2,-4,0,3,7,2,9,3 and 6,0,4,8,3,0,5,3,2,9,8,3. If these series are correlated number by number, the correlation coefficient is -0.001. But if successive sums in each series are correlated, the coefficient increases to +0.93! A plot of the latter values would give a fairly straight line like that of Emiliani's Fig. 10, whereas a plot of the former values would give a random scatter diagram.

We recalculated the correlation coefficient by the proper method, using Emiliani's original data (4, Table 5), and obtained the much lower value of 0.76, which for eight pairs (stages) of data is barely significant at the 95-percent confidence level, but even this correlation coefficient cannot be considered valid. It is based on core averages for eight core stages, 1,3,5 . . . 15, as found in ten cores, from the Caribbean and the equatorial Atlantic. The averages for some stages are calculated from values for all ten cores, while other averages come from values

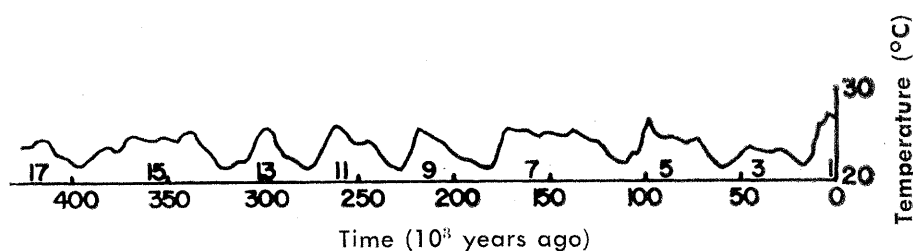


Fig. 1. Emiliani's generalized climate curve (see 1).

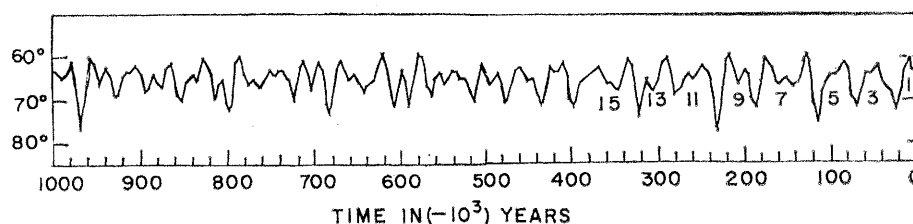


Fig. 2. Variation in summer insolation at 65°N, as constructed by van Woerkom (3) on the basis of the Milankovitch theory of changes in tilt and precession of the earth's axis and eccentricity of the earth's orbit. Insolation variation is given in terms of equivalent latitude in the Northern Hemisphere.

for fewer cores; in some cases the "average" is a value for only one sample. Since the spread of thickness values for the different stages is sometimes as high as 65 percent of the average value, results based on one or a few samples can have little weight. Thus, Emiliani's stage 15 has an "average" thickness of 180 cm, on the basis of a single stage-15 sample 180 cm thick, from core P6304-9. But his core logs also show stage 15 in core A172-6, with a thickness of 108 cm, a value which was not used in his calculations.

Further, a reexamination of the published core records shows that Emiliani did not meet his own criterion (see 4) for selecting core-stage boundaries, and that in many cases considerable subjectivity must be exercised by anyone trying to apply Emiliani's criterion. We made a careful redetermination of thicknesses of individual stages, from published core diagrams and data, and correlated these values with Milankovitch time intervals. The resulting correlation coefficient is 0.60. At the 95-percent confidence level, values below 0.71 are insignificant when the two series of data being correlated have only eight pairs of values (see, for example, 6).

The results of our reworking of Emiliani's data are plotted in Fig. 3. This is similar in form to Emiliani's Fig. 10, but the data points in his Fig. 10 represent cumulative values for core-stage thicknesses and time intervals, whereas the points in our Fig. 3 represent individual stage thicknesses and assumed corresponding Milankovitch intervals. Emiliani's eight points fall on a straight line through the origin; ours clearly do not.

If it is argued that a lower value for confidence level should be used, it is noteworthy that, in Fig. 3, the point for stage 1 (23,000 years and 56 cm) really controls the linear trend that could be drawn through the origin; the remaining points have a fairly random scatter. Since this stage represents only a part of a cycle (the present cycle), if it is to be included in the correlation, some attempt should be made to extrapolate its thickness to the thickness of a full cycle. If this were done, the point would fall in the region of the scatter diagram, and the correlation coefficient would fall much below the value of 0.60. Or, if this point is omitted and the correlation coefficient is determined for the pairs of values represented by the other seven points, the result is only 0.25, ab-

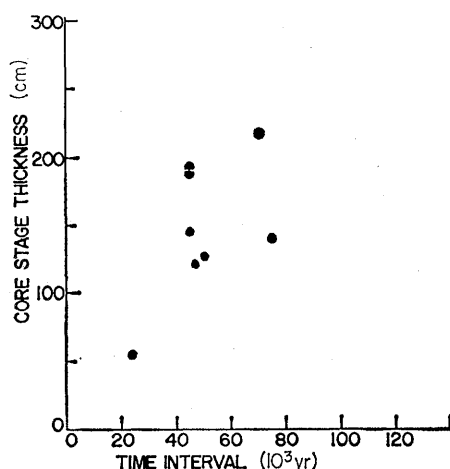


Fig. 3. Plot of individual (rather than cumulative) thicknesses relative to Milankovitch time intervals.

solutely negligible. This calculation emphasizes the hazard in drawing a correlation coefficient from a small sample group, especially when one value is incomplete. Finally, in the event that Emiliani's climate (core) stages are not matched appropriately to the assigned Milankovitch stages, as discussed above, the entire basis for this correlation vanishes.

We must conclude that the data on core-stage thicknesses are still too few, and the procedures too subjective, to be of significance in establishing a causal relationship between glacial-interglacial climate change and Milankovitch time intervals. Also, possible variations of sedimentation rate would introduce "noise" that might complicate such correlations. The least ambiguous procedure in correlating climate stages with Milankovitch cycles would, of course, be one based on absolute chronology for sediment cores, a method not yet feasible.

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The foregoing discussion, by Donn and Shaw, of my article (1) rests on a wholly uncritical evaluation of the original analytical data and on questionable statistical arguments. Before replying in detail, I wish to summarize the research under discussion.

Urey and his associates (2) showed that the oxygen-isotope ratio O^{18}/O^{16} in carbonate deposited in equilibrium from a water solution is inversely related to temperature and can be used to determine the temperature at which deposition took place. I applied this method to planktonic Foraminifera in deep-sea cores collected in the equatorial and North Atlantic, the Caribbean, the Mediterranean, and the Pacific. Using planktonic foraminiferal species known, by isotopic analysis and now also by plankton tows, to have grown their shells not more than a few tens of meters from the ocean surface, I obtained paleotemperature curves, for the surface water of the ocean, which showed a number of maxima and minima (see 1, Fig. 4; see also 3, 4). Absolute dating by the C^{14} and Pa^{231}/Th^{230} methods (5) and comparisons with the glacial-interglacial chronology of the continental deposits proved that the minima represent glacial ages and the maxima interglacial ages. Accurate micropaleontological analysis of one of the cores (6) showed a close and direct relationship between the isotopic oscillations and the temperature-induced oscillations in the composition of the microfaunas. I combined the individual isotopic curves into a generalized temperature curve extending from the present to about 425,000 years ago (1, Fig. 5) and, by averaging the thicknesses of the temperature stages of the deep-sea cores, reconstructed an average time-stratigraphic series which I correlated linearly with the time series provided by the insolation variations at the latitude of $65^{\circ}N$ (1, Fig. 9). I obtained a correlation coefficient of 0.997 (1, Fig. 10) and concluded that a causal relationship between the two series was strongly suggested.

In order to obtain the data for the time-stratigraphic series, I determined the thickness of the different temperature stages, using, for each core, the original analytical data (all published), the micropaleontological information (partly published), and the coarse fraction percentages (all published). Donn and Shaw, using only the information contained in the published core diagrams, propose different thicknesses

and present the averages in their Fig. 3. The individual thicknesses used by Donn and Shaw are shown in Table 3 of a communication appearing in the *Journal of Geology* (7). Of the 44 individual values presented in that table, 42 are simply without basis: no analyses have ever been made at the depths indicated, and, in fact, the pertinent core layers lie undisturbed in our core repositories. Donn and Shaw give no justification for their choices.

Figure 1 shows some examples of the core levels where Donn and Shaw have placed their minima in order to divide the cores into stages; clearly, they have not chosen the minima at all, and the thicknesses of the core stages thus derived are incorrect. The errors range up to a thickness of 66

cm, representing a time interval of about 20,000 years, or about half the wavelength of the major oscillation. Furthermore, each error is in fact a double error because, by increasing or decreasing the thickness of a core stage, the thickness of the adjacent stage is automatically decreased or increased. Stage 15 of core A172-6 is included in their table in spite of the incompleteness of the stage in that core, further invalidating the average proposed by Donn and Shaw for stage 15, and core A180-73 is altogether omitted. Finally, the three values for core 234 have been transposed downward by one row, so that the thickness of stage 1 is assigned to stage 3; that of stage 3 to stage 5; and that of stage 5 to stage 7 (the real stage 7 of core

234 has been left out). All the above combine to invalidate every single average for deep-sea-core stage thicknesses presented by Donn and Shaw in Table 3 of their communication (7). As a necessary consequence, all points in Fig. 3 of the foregoing discussion by Donn and Shaw, and all pertinent correlation coefficients, are also invalid.

According to Donn and Shaw, the temperature minimum of stage 4 in my isotopic curves is "a simple irregularity on a continuous temperature decline." Figure 2 shows three cores in which the minimum in question is very clearly exhibited. The significance of this minimum is further enhanced by the fact that the core which has the highest rate of undisturbed sedimentation and which, therefore, contains the

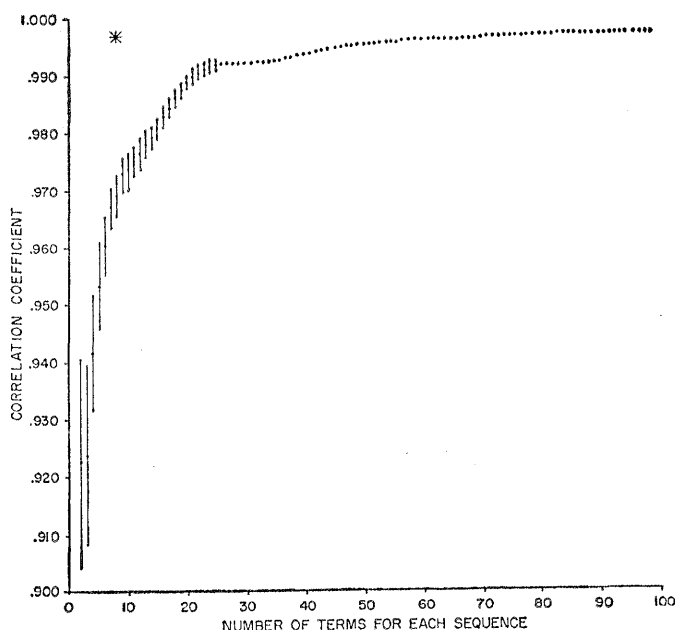
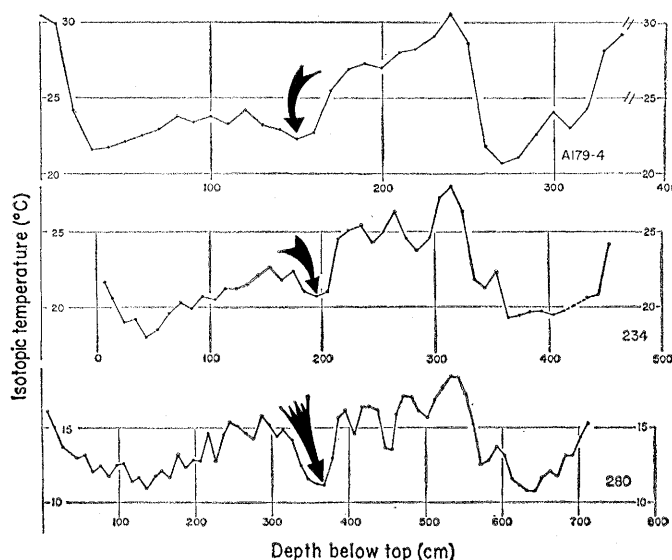
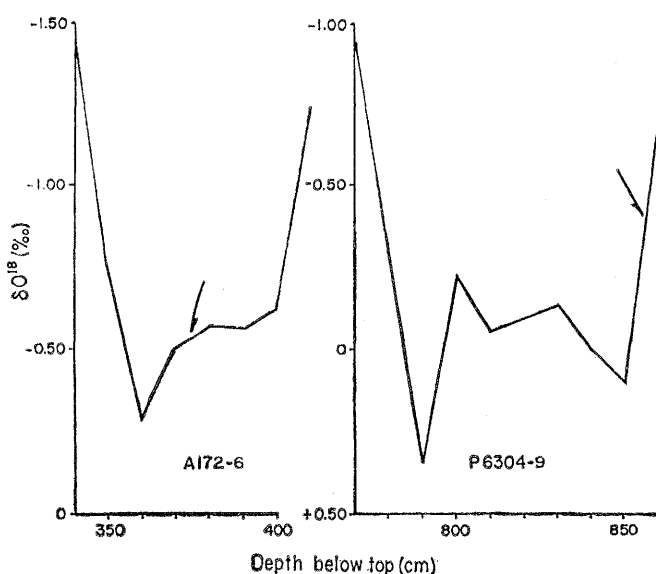


Fig. 1 (top left). Segments of the isotopic curves of two cores, showing the core levels (see arrows) where, according to Donn and Shaw, the minima are located. No analytical data exist for the intervals between the points of inflection.

Fig. 2 (top right). Isotopic curves for three cores showing (see arrows) the stage-4 minimum which, according to Donn and Shaw, does not exist.

Fig. 3 (left). Average correlation coefficient (plus or minus standard error of the mean for the first 25 values) plotted against number of terms for groups of 20 incremental sequences of 2 to 99 random numbers. The asterisk shows the value of the correlation coefficient between the two time series of eight terms each mentioned in the text.

largest amount of information (bottom curve) exhibits the deepest minimum.

Donn and Shaw obtain a correlation coefficient of 0.93 for two incremental sequences of 12 terms each, taken from the phone book (!) and imply that the value of 0.997 which I obtained is also insignificant. Computer analysis (IBM 7040) of pairs of incremental sequences of 2 to 99 random terms each shows that the correlation coefficient, a function of the number of terms, decreases from 1 (for two sequences of one term each plus the common zero) to about 0.92 for two sequences of a few terms each, and then increases back to 1 for an infinite number of terms (Fig. 3). For two incremental sequences of eight terms each (the number of terms in my two series), a value of 0.970 is not significant. The value of 0.997 which I obtained, lying, as it does, within 10 percent of the upper limit of the entire significance range (0.970 to 1.000), is highly significant and corresponds to a value of 0.900 for nonincremental sets of data. I used the two incremental series, rather than directly correlating stage thicknesses and durations, in order (i) to include correctly the partial stage 1; (ii) to show the relationship between the two parameters not only for single stages but also for their partial and total summations; (iii) to emphasize the long-range trend of the rate of sedimentation; and (iv) to emphasize the absence of small shifts in the same direction, which, if present and summed across a number of stages, would have led to a difference of phase or even to phase opposition.

My generalized temperature curve is based upon 1241 high-precision mass spectrometric analyses and upon 19 absolute age measurements (all published), and not, as Donn and Shaw contend, on "quite subjective extrapolations."

Figure 4 shows a portion of the summer insolation curve for latitude 65°N which includes the insolation minimum at 280,000 years before the present (see arrows), selected by me as corresponding to the boundary between stages 11 and 13. Donn and Shaw chose the curve at left (from 8) as a basis for maintaining that the minimum in question "barely falls below the 65° north latitude level" and,

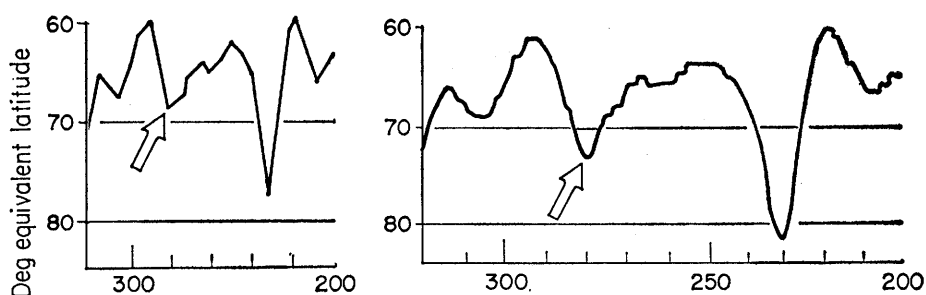


Fig. 4. Portions of the summer insolation curve for latitude 65°N which include the minimum selected by me as representing the boundary between stages 11 and 13 (see arrows). The values on the abscissa represent thousands of years before the present [curve at left, from (8); curve at right, from (3)]. Both curves represent the same set of computer data, originally obtained by van Woerkom (8). The curve at right, an obviously more accurate representation of the data, showing that the minimum in question is highly significant, is ignored by Donn and Shaw.

therefore, cannot correspond to a marked temperature minimum. The curve at right in Fig. 4 (from 3), which is a much more accurate plot of the same original computer data, shows that the minimum in question falls at a much higher equivalent latitude—namely 73°N. It certainly can be related, therefore, to a major temperature minimum.

The fact that a causal relationship between summer-insolation variations at high northern latitudes and the succession of glacial and interglacial ages during the Pleistocene would invalidate the "Theory of Ice Ages" (9), the "Theory of Ice Ages II" (10), and the "Theory of Ice Ages III" (11), which Donn co-authored, is irrelevant because the three theories are invalid in any case, and for a much more fundamental reason: the first two include no impedance whatsoever and cannot possibly explain an oscillatory phenomenon such as the glacial-interglacial succession; and the third includes a questionable impedance which is, at best, several times too small to explain the wavelength of the oscillations. The third theory, stripped to its essentials, is only a replica of an obsolete theory of glaciation which I proposed many years ago (12) and which was later superseded by the theory of glaciation proposed by Geiss and myself (13). The latter is perhaps the only one which is still valid and does not violate either theoretical principles or the vast experimental evidence now at hand. The Fourier analysis by van den Heuvel (14) and the power spectrum analysis by Kemp

and Eger (15) also support this theory.

I regret that the discussion by Donn and Shaw, however inappropriate, will lead uncritical readers to believe that there is ample room for disagreement when, in fact, there is little (if any) such room, due to the wealth of high-precision measurements of various kinds which have been made and published during the past 15 years.

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