to negate such an explanation. Similar crystalline growth has been observed on electrodes following studies of exploding wire (*3*). In this type of experiment, a copper wire, supported between two large electrodes, is subjected to a high current, fast-rise pulse and "exploded," producing hypervelocity copper fragments (and copper vapor).

No analytical studies of the composition of the whiskers were made. Several repeated attempts at reproducing the phenomenon have met with limited success in that the whiskers are considerably shorter and of a larger diameter. If attempts to reproduce longer crystals succeed, composition and better correlation of projectile size and velocity and the filamentary growth may be determined.

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Pleistocene Paleotemperatures

Abstract. *The generalized isotopic paleotemperature curve reproduces absolute temperatures to within 1°C; it closely reflects faunal changes; and its time scale is correct to within a very few percent back to at least 175,000 years. The average oxygen isotopic composition of the North American and European ice caps was about −9 per mil.*

The generalized paleotemperature curve (Fig. 1), based on oxygen isotopic analysis of planktonic Foraminifera from deep-sea cores, was proposed in 1955 (*1*), and extended in 1966 (*2*), as a representation of surface temperatures at low latitudes in the Atlantic Ocean and adjacent seas during the past 425,000 years.

Some authors have maintained that this curve is not in accord with the foraminiferal evidence (*3, 4*); that it represents not temperatures but, largely or even totally, isotopic variations of the seawater (*5–7*); and that its time scale is not accurate but should be stretched by 25 percent (*8, 9*). The purpose of the present report is to review the evidence upon which these contentions are based and to demonstrate the validity of the curve as originally proposed. In the process, a close estimate is derived for the average oxygen isotopic composition of the North American and European ice caps.

The contention that the foraminiferal evidence is not in accord with the isotopic evidence stems solely from Ericson and Wollin's choice of *Globorotalia menardii* as the best temperature indicator and from the artificial boundary condition that they used in estimating the foraminiferal abundances (*10*). *Globorotalia menardii* is a highly polytypic species which produced at least three distinct subspecies during the past 425,000 years, each having different temperature tolerances (*11, 12*). On the basis of the choice of this species as the best temperature indicator, core layers in which *G. menardii* is absent but other species even more restricted to warm waters (*Pulleniatina obliquiloculata, Sphaeroidinella dehiscens*) are abundant have been consistently defined as "cold" and presented as an example of discordance between evidence derived from isotopes and that derived from micropaleontology. By labeling this species as "very abundant" if more than "100 specimens per tray spread" were noticed (*10*), Ericson and Wollin saw none of the abundance variations above the "100 specimens per tray spread" level; this resulted in published "climatic" curves [for example, figure 3 in (*3*); figure 2 in (*13*)] containing only a vastly truncated portion of the available evidence (blackened section of Fig. 2B). It is upon these truncated curves that a "climatic" curve claimed to represent the entire Pleistocene has been constructed [figure 5 in (*13*)].

The artificial boundary condition mentioned restricts the application of Ericson and Wollin's visual method to those foraminiferal species whose abundances range from 0 to 100 specimens per tray spread. In these cases (Fig. 3C) a good correlation with the paleotemperature curve (Fig. 3A) is observed. An even better correlation is obtained if ratios of warm to cold species are used because the temperature signal is thus amplified (Fig. 3B).

Using accurate countings (516 specimens or more) instead of visual appreciation, Lidz (*14*) studied in detail foraminiferal abundances in a long and undisturbed deep-sea core from the Caribbean. His results (Fig. 4, A through I) show such a close relationship with the isotopic curve (Fig. 4J) that the foraminiferal abundance curves can be used in lieu of the isotopic curve for both temperature estimates and spectral analysis. An intimate relationship between isotopic temperature and foraminiferal parameters has also been found by Imbrie (*15*), who used factor analysis on different latitudinal assemblages, and by Ruddiman (*16*), who used the net excess of warm or cold species (Fig. 5). Finally, I demonstrated the excellent relationship between major and minor isotopic temperature variations and shell morphology of monospecific populations of pelagic Foraminifera (*11*).

It is apparent that all foraminiferal evidence now available, including the evidence provided by Ericson and Wollin (*3, 4, 10*) if the artificial boundary condition mentioned above is eliminated, is in complete agreement, usually down to minor details, with the results obtained by the application of Urey's method of paleotemperature analysis to pelagic Foraminifera from deep-sea cores. Anyone wishing to question this conclusion must first demolish all foraminiferal evidence mentioned above.

The glacial/interglacial range of the O^{18}/O^{16} composition of planktonic Foraminifera of shallow habitat (*Globigerinoides sacculifera* and *G. rubra*) from Caribbean and equatorial Atlantic deep-sea cores is 1.8 per mil for the more recent temperature stages (stages 1 to 6) and decreases to 1.6 per mil for the earlier stages (*2*). This isotopic amplitude, if entirely due to temperature, would represent a glacial/interglacial temperature range of 7° to 8°C. However, a portion of this range [about 30

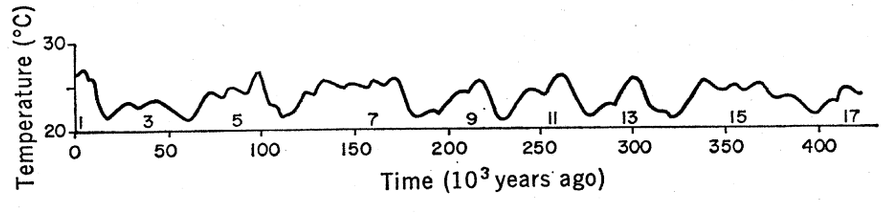
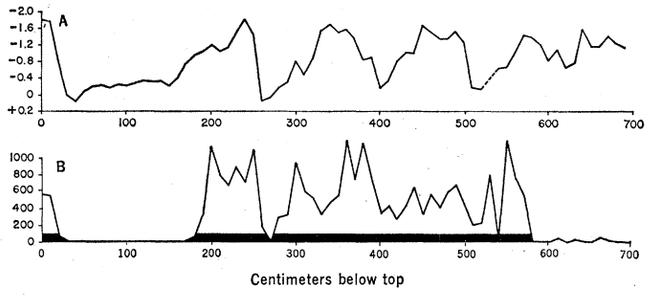


Fig. 1. Generalized paleotemperature curve (from *2*). Odd integers above the abscissa identify warm temperature stages.



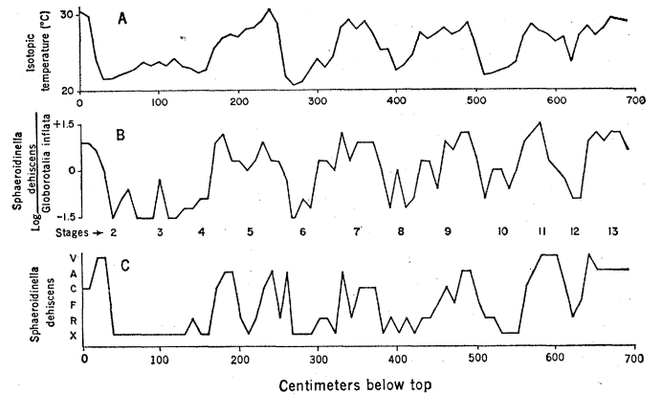


Fig. 2 (left). Core A179-4. (A) Ratios of O^{18} to O^{16} in *Globigerinoides sacculifera* (data from *1*); (B) abundance variations of *Globorotalia menardii* in number of specimens per tray spread (data from *3*). The boundary condition mentioned in the text limits the published information (for example, *13*, figures 2, 4, and *5*) to the blackened section. Fig. 3 (right). Core A179-4. (A) Isotopic paleotemperature curve for *Globigerinoides rubra* (from *1*); (B) abundance ratio of *Sphaeroidinella dehiscens* to *Globorotalia inflata* (from *23*); (C) abundance of *S. dehiscens* (from *24*); *V*, very abundant; *A*, abundant; *C*, common; *F*, frequent; *R*, rare; *X*, absent.

percent, according to my estimates (*1*, *2*)] must be due to the change in the oxygen isotopic composition of seawater which is related to the accumulation of ice on land during glacial ages. From a glacial decrease of sea level of 130 m (probably an overestimate), I calculated that the average oxygen isotopic composition of glacial ice is about −15 per mil and that of the ocean during glacial ages is +0.5 per mil (*2*). A value of −17 per mil for glacial ice was obtained by Craig (*17*) using estimates for its amount and isotopic composition.

Knowing, from direct measurement, that the oxygen isotopic composition of interglacial (modern) ice (Antarctica and Greenland) is about −30 to −40 per mil, and that of glacial ice is about 10 per mil lighter (*18*), various authors (*5*) concluded that the average oxygen isotopic composition of seawater during glacial ages was +1.2 to +1.6 per mil. If this were the case, the glacial/interglacial range of the oxygen isotopic composition of planktonic Foraminifera would be largely or entirely due to oxygen isotopic variations of the seawater and no glacial/interglacial temperature variation would be permitted (see *6*).

There is a substantial amount of nonisotopic evidence showing that temperature at low latitudes during glacial ages *was* considerably lower than during in-

Table 1. Amplitude of glacial/interglacial temperature variations at low latitudes estimated by methods *other* than oxygen isotope analysis [see *19* and references therein].

Method	Amplitude (°C)
Continental evidence	
Lowering of nivation sculptures on Mount Kenya (Flint)	5° to 10°
Lowering of nivation sculptures in New Guinea (Gentilli)	
Biogeography of East Africa (Moreau)	
Pollen analysis, Colombia (van der Hammen)	
Pollen analysis, Florida (Watts)	
Pollen analysis, Taiwan (Tsukada)	
Oceanic evidence	
Frequency of *Globorotalia menardii, Globorotalia inflata,* and *Globigerinoides sacculifera*, equatorial and North Atlantic cores (Phleger *et al.*)	5° (yearly max.); 3° (yearly min.); 4° (yearly av.)
Frequency of *Pulleniatina obliquiloculata*, equatorial and North Atlantic cores (Phleger *et al.*)	5°
Frequency of *Pulleniatina obliquiloculata*, Caribbean cores (Emiliani)	8°
Latitudinal displacement of Coccolithophoridae (McIntyre)	10° (yearly max.); 5° to 6° (yearly min.); 8° (yearly av.)
Frequency of *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens*, eastern equatorial Pacific, 90° to 94°W (Arrhenius)	$>2°, <5°$
Frequency of *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens*, eastern equatorial Pacific 130° to 135°W (Arrhenius)	$>3°, <9°$
Frequency of *Pulleniatina obliquiloculata*, central Pacific Ocean, 150°W (Brotzen)	$<8°$
Frequency of different pelagic foraminiferal faunas, South Pacific (Blackman)	3° to 4°
Pore concentration in *Globoquadrina eggeri*, Caribbean (Wiles)	6°
Pore concentration in *Globoquadrina eggeri*, equatorial Pacific (Wiles)	3.5°
Conclusions	
Caribbean	7° to 8°
Equatorial Atlantic	5° to 6°
Equatorial Pacific	3° to 4°

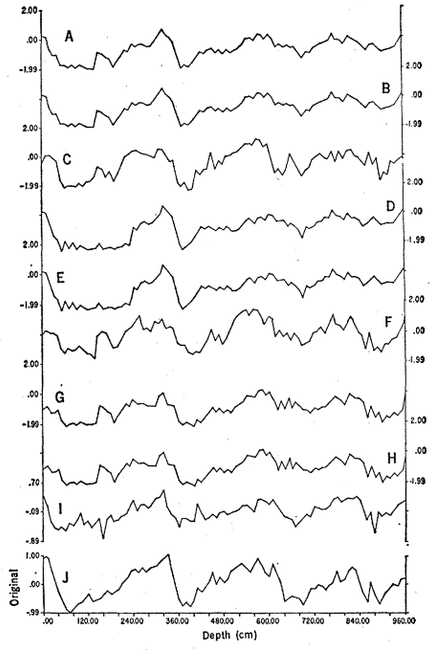


Fig. 4. Core P6304-8. Curves A to I represent ratios of the relative abundance of diagnostic stenothermic planktonic foraminiferal species or groups of species. Curve J represents the ratio of O^{18} to O^{16} in the pelagic foraminiferal species *Globigerinoides triloba sacculifera*. (A) *Globorotalia menardii menardii, Pulleniatina obliquiloculata*, and *Sphaeroidinella dehiscens* to *Globigerinoides rubra* and *Globorotalia inflata*; (B) *Globorotalia menardii menardii, Pulleniatina obliquiloculata*, and *Sphaeroidinella dehiscens* to *Globigerinoides rubra, Globorotalia inflata*, and the *Hastigerina* complex; (C) *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens* to *Globorotalia inflata*; (D) *Globorotalia menardii menardii* to *Globigerinoides rubra*; (E) *Globorotalia menardii menardii, Globigerinoides rubra*, and the *Hastigerina* complex; (F) *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens* to the *Hastigerina* complex; (G) *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens* to the *Hastigerina* complex and *Globigerinoides rubra*; (H) *Pulleniatina obliquiloculata* and *Sphaeroidinella dehiscens* to *Globigerinoides rubra*; and (I) *Globigerinoides triloba sacculifera* and *G. triloba triloba* to *G. rubra*.

terglacial ages. This evidence (lowering of snow lines, pollen changes in lake deposits, latitudinal migrations of planktonic Foraminifera and Coccolithophoridae), recently reviewed (*19*) and summarized here in Table 1, indicates a glacial/interglacial temperature range of 7° to 8°C for the Caribbean, 5° to 6°C for the equatorial Atlantic, and 3° to 4°C for the equatorial Pacific. The amplitude of 6°C adopted for the generalized paleotemperature curve (Fig. 1) appears to be correct to within 1°C for the equatorial Atlantic, as originally proposed.

The above considerations, together with an analysis of the glacial/interglacial range of planktonic versus benthonic Foraminifera from Atlantic, Caribbean, and Pacific deep-sea cores, lead to a close estimate of the glacial/interglacial range of the isotopic composition of seawater. The data (Table 2) indicate that the *average* range was close to the value of 0.5 per mil previously estimated (*1*, *2*). From this value and a glacial lowering of sea level of 130 m, an average isotopic composition of −15 per mil for glacial ice may be calculated.

Table 2. Glacial/interglacial ranges: (A) oxygen isotopic ranges (δ, per mil), as measured in pelagic foraminiferal shells; (B) temperature ranges (°C) estimated from nonisotopic evidence; (C) oxygen isotopic ranges (δ, per mil) of the surface seawater, derived from (A) and (B).

Area	A	B	C
Caribbean	1.8	7° to 8°	0
Equatorial Atlantic	1.6	5° to 6°	0.3
Equatorial Pacific	1.2*	3° to 4°	0.4

* Estimated (see *2*, table 4).

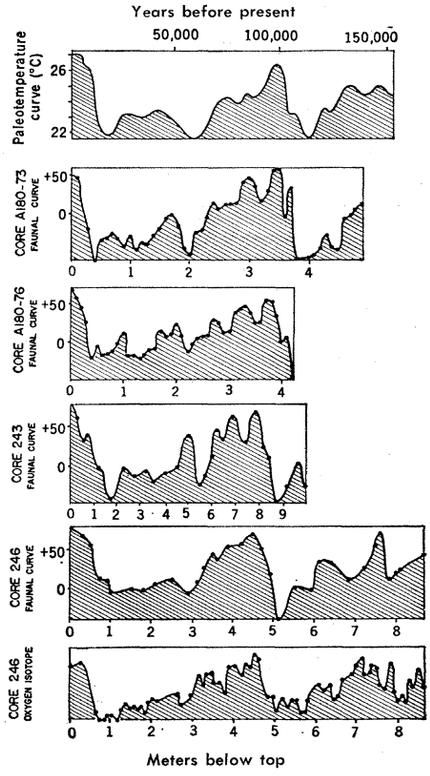


Fig. 5. Equatorial Atlantic paleotemperatures based on oxygen isotope and faunal analysis (from *16*).

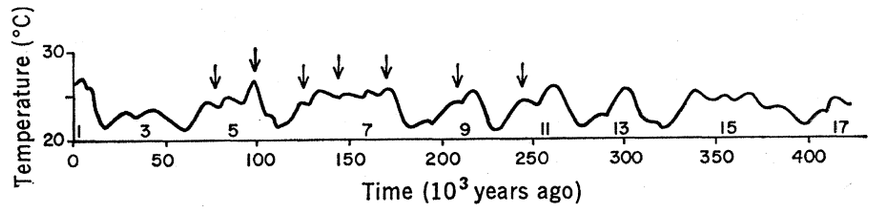


Fig. 6. Relationship between the ages of high interglacial sea levels (arrows) and the generalized paleotemperature curve (from *21*). Odd integers above the abscissa identify warm temperature stages.

Dansgaard *et al.* and Epstein *et al.* (*18*) have found that glacial ice in Greenland and Antarctica has an oxygen isotopic composition about 10 per mil lighter than that of interglacial ice. In addition, Dansgaard and Tauber (*7*) estimated that the total amount of ice in Antarctica and Greenland during the glacial ages was about 2×10^6 km^3 greater than today and that the excess had an isotopic composition 5 per mil lighter than today. On the basis of these values, the value of + 0.5 per mil for the average isotopic composition of seawater during glacial ages, and the assignment of an isotopic composition of −40 per mil to the Siberian ice cap [equivalent to 4×10^6 km^3 of water, according to Dansgaard and Tauber (*7*, table 1)], a value of −9 per mil is obtained for the *average* oxygen isotopic composition of the North American and European ice caps. This value, much heavier than that assumed by Dansgaard and Tauber (*7*, table 1), is not at all unexpected. During glacial ages, in fact, the North American and European ice caps extended well into the middle latitudes and were in close proximity to the oceanic areas supplying moisture (northeastern Pacific, Gulf of Mexico, North Atlantic, Mediterranean). Under these conditions, most of the moisture is expected to have fallen directly on the ice caps as snow without having undergone the extensive process of fractional precipitation so apparent today for the ice masses at high latitudes in Greenland and Antarctica. This contention is supported by the observed aridity of the intervening areas (*20*). An isotopic composition of −30 per mil for the North American and European ice caps, as advocated by Dansgaard and Tauber (*7*), would require a vast amount of precipitation in the intervening areas, an amount for which there is no evidence whatsoever. High glacial lake levels, as in the western United States, are here explained as a result of ice meltwater feeding combined with low evaporation due to prevailing low temperature.

In conclusion, the glacial/interglacial range of the average oxygen isotopic composition of the ocean was about 0.5 per mil and the glacial/interglacial temperature range shown in Fig. 1 is correct to within 1°C.

Broecker and Ku (*9*) suggest that the time scale of Fig. 1 should be lengthened by 25 percent. I showed (*21*) that the present time scale is in excellent agreement with the ages of high sea level carbonates as determined by various authors (*8*, *22*) using methods based on uranium decay series (Fig. 6). The lengthening proposed by Broecker and Ku (*9*), on the other hand, would lead to complete loss of this relationship [figure 2 in (*21*)] and, therefore, must be rejected.

The absolute ages of the high sea level carbonates are not only in full agreement with the time scale of Fig. 1, but also their close relationship to the times of coincidence of northern summer solstice with perihelion (*21*) sets this time scale so rigidly that even a small lengthening or shortening becomes altogether impossible.

The above discussion leads to the following conclusions. (i) The amplitude of the generalized paleotemperature curve as applied to the equatorial Atlantic is correct to within 1°C; (ii) the isotopic temperature curves of the various cores as well as the generalized paleotemperature curve are a very close representation of micropaleontological changes; and (iii) the time scale is correct to within a very few percent back to at least 175,000 years.

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Chemical Composition of the Lunar Surface in a Terra Region near the Crater Tycho

Abstract. *More precise and comprehensive analytical results for lunar surface material in a terra region have been derived from the data of the alpha-scattering experiment on Surveyor 7. The silicon content and the low sodium abundance are close to that of mare material. The abundances of titanium and iron are at least a factor of 2 lower, whereas the abundances of aluminum and calcium are significantly higher. The analytical results provide direct evidence for chemical differentiation in the moon and indicate a lunar crust of appreciably lower density than the whole moon and with lower density and higher albedo than lunar mare material.*

The alpha-scattering experiment on Surveyors 5 and 6 provided data on the chemical composition of the lunar surface at two mare sites: Mare Tranquillitatis (*1, 2*) and Sinus Medii (*3, 4*). The results at the Mare Tranquillitatis site are in adequate agreement with the analyses of the returned lunar samples from Apollo 11 (*5*). Surveyor 7, which landed in the terra region 30 km north of the crater Tycho (*6*), carried the same type of experiment, and preliminary results have been reported (*7, 8*). Processing of data from the Surveyor 7 mission has now been completed. More data have been used than were originally available. Our results are therefore more comprehensive and precise than those given in previous reports.

Earlier reports (*2, 4, 8, 9*) have described the technique of chemical analysis, the checks on instrument performance on the moon, the method of data retrieval and analysis, and the corrections that are applied for small changes in instrument characteristics during the mission, and they have discussed the precision and accuracy of the method. Only the special characteristics of the Surveyor 7 mission will be mentioned here.

Three lunar samples were examined on this mission: undisturbed lunar surface (sample 1), a small lunar rock (sample 2), and a trenched area (sample 3) prepared by the Surface Sampler (*8, 10*). The geometrical relationships of the samples to the instrument were different from those on previous missions (*8*) and therefore required laboratory mock-up studies and special computer analyses to achieve the most detailed interpretation of the lunar data.

Because the ^{242}Cm source strength was greater than on previous missions, there was a higher signal-to-background ratio than in previous experiments. The source quality was, however, somewhat poorer because of the greater thickness of the curium and the presence of a carbon coating used to minimize the transfer of radioactivity by aggregate recoil. The statistical accuracy of the data on each sample was limited by mission constraints and was less than on previous missions. Fortunately, the spacecraft and instrument survived the first lunar night sufficiently well so that additional data in the alpha mode were obtained on sample 3.

As in previous reports (*2, 4*), the energy spectra of the backscattered alpha particles and of protons from (α,p) reactions were analyzed in terms of a library of 13 elements. Table 1 presents the results for the three samples. The atom percent of each element is listed (after substraction of the small biases of the method) together with an estimated accuracy at the 90 percent confidence level. The estimated accuracy was obtained from the statistical error and the error of the method (*4*), with an additional estimated uncertainty for sample 2 included because of its peculiar geometry. The statistical errors were comparable to those on previous missions (*2, 4*). No value is given for carbon because, as this technique was implemented, results on terrestrial samples had been poor. An upper limit of 1 atom percent for carbon can be set for the samples examined on Surveyor 7. The values for sample 1 are well within the errors of the preliminary analysis of the data (*7, 8*).

The results for the two samples of lunar soil (samples 1 and 3) agree even within their statistical errors. This agreement indicates that the chemical composition of the topmost layer at the Surveyor 7 site is identical with the composition of material several centimeters below the surface. The data on the lunar rock (sample 2) give roughly the same composition; the lower magnesium and higher aluminum contents appear to be the outstanding differences. The slightly lower (by 20 percent) iron content is also of interest.

The two samples of lunar soil show significant amounts (0.3 atom percent) of fluorine. Although experience in analysis for fluorine by this technique is more limited than for other elements, similar concentrations of fluorine have been determined with adequate precision in terrestrial rocks. Analysis of the data with an even larger library (20 elements) confirms the results in Table 1 and indicates negligible