2 March 1956, Volume 123, Number 3192 SCIENCE

Absolute Chronology of the Last Glaciation

Hans E. Suess

Radiocarbon dating (*1*) has led to a well-established chronology of the Wisconsin stage of glaciation in North America, which was, until recently, considered to be equivalent to the Last or Würm Glaciation of Europe. The first step in this direction was the dating of wood from the Two Creeks forest bed in Wisconsin by W. F. Libby (*2*) which showed, contrary to what had been expected from other evidence such as telecorrelation of varve sequences, that the last major substage of the Wisconsin, the Mankato of North America, was equivalent to the Younger Dryas of Europe.

Since then, more than 60 individual measurements by Suess and by Rubin and Suess (*3*) at the U.S. Geological Survey in Washington, D.C., on samples from a large number of localities in North America have conclusively established the times of the next previous substages, the Cary and the Tazewell. The Tazewell substage represents, at least in the Middle West of the United States, the time of the maximum southward extent of the ice front, which was reached between 17,000 and 18,000 years ago after a more or less continuous advance over a period of more than 10,000 years (*4, 5*). The Washington radiocarbon dates are sufficiently conclusive to allow the calculation of rates of advance and retreat of the ice during that interval of time and thereafter (*6, 8*).

Continental Glacial Chronology

At least four episodes of colder climate with advancing glaciers can be assumed to have followed the Tazewell maximum with decreasing amplitude toward the present time. They are listed in Table 1 on page 356.

It appears that these oscillations have occurred at fairly regular intervals of about 3500 years. Various oscillations of still shorter periods can also be recognized. They seem to become increasingly conspicuous in postglacial time. For two pre-Tazewell substages of the Wisconsin, the Iowan and Farmdale, stratigraphic evidence and radiocarbon dates are less conclusive. Nevertheless, it seems conceivable that these episodes might represent such oscillations immediately preceding the Tazewell substage (*8*).

It can be shown, however, that the Wisconsin glacial stage of North America does not cover the whole period of the Last or Würm Glaciation as understood by European workers. Penck and Brückner (*9*) showed in 1909 that one can estimate from rates of weathering and deposition that the beginning of the Last Glaciation was about 100,000 years ago. Washington radiocarbon measurements also indicate that the last cold period must have begun much earlier than is indicated by the dates on wood from the early Wisconsin Farmdale loess deposits of Leighton (*10*) (samples W-68, W-69, W-79, W-141, and others). Interstadial forest zones in Canada and Alaska (W-100, 121, 157, 189, 76, 77, 174, and so forth) and the base of the interstadial Younger Loess II of Europe (W-173) as well as archeological remains from the Cold Mousterian were found to be older than the present range of the Washington laboratory, which is about 38,000 years.

Deep-Sea Sediments

Further evidence for a long duration of the Last Glaciation comes from the study of deep-sea sediments. The composition of these sediments, in particular their carbonate content, depends strongly on climatic conditions. A series of climatic oscillations during the Pleistocene can be recognized. The extensive work of G. Arrhenius (*11*) on the titanium content of deep-sea sediments of the Pacific Ocean gives an estimated time for the beginning of the last cold period as 100,000 years ago; this agrees with the European estimates of Penck and Brückner. The technique involved determining the titanium sedimentation rate by radiocarbon dating of codeposited carbonate sediments (*12*).

A much more quantitative and direct approach was made by C. Emiliani (*13*), who applied Urey's paleotemperature method (*14*) to a large number of samples from various Atlantic and Caribbean cores. Emiliani identified and separated pelagic Foraminifera tests, usually *Globigerinoides sacculifera* and *Globigerinoides rubra,* from samples taken in 10-centimeter intervals along the cores. The O^{18} to O^{16} ratio in the $CaCO_3$ of these tests was measured by the mass spectrometer group in Urey's laboratory (Toshiko Mayeda, Harmon Craig, and others) at the Enrico Fermi Institute for Nuclear Studies of the University of Chicago. As was shown by Urey (*14*), this ratio is essentially a function of the water temperature at the time of growth of the shells. In this way, the temperature of surface water was obtained as a function of depth below the top of each core.

The temperature records from all the cores show several regular oscillations. Emiliani finds an apparent amplitude of 7° to 8°C temperature variation. By taking into account a slight increase in the O^{18} concentration during glacial times, about 6°C actual variation of the mean temperature of the surface water is found at the locations where the cores were taken. The experiments and interpretation of the results are discussed in detail by Emiliani (*13*).

The author is a research geochemist at the Scripps Institution of Oceanography, La Jolla, California.

Table 1. Approximate time of maximum extent of glaciers in North America as determined from radiocarbon dates (4, 5).

Substage or advance	Time of max. extent before present (yr)	Pertinent samples
Post altithermal advance	3,000?	W-143, W-78
Cochrane	6,500 to 7,500	W-136, W-145
Mankato	10,000 to 11,000	W-42, W-83, W-49
Cary	13,500 to 14,500	W-198, W-33
Tazewell	17,000 to 18,000	W-187, W-165, W-91

Table 2. Apparent radiocarbon ages of carbonate from three deep sea cores determined at the U.S. Geological Survey (5, 6). The sedimentation rate for Core A 179-4 (from samples W-160 and W-159) was 2.78 cm/1000 yr or 1 cm/360 yr; the sedimentation rate for Core A 172-6 (from samples W-236 and W-247) was 3.70 cm/1000 yr or 1 cm/270 yr; the sedimentation rate for Core A 180-73 (from samples W-280 and W-278) was 2.44 cm/1000 yr or 1 cm/410 yr.

Sample No.	Depth (cm)	Material	Apparent age (yr)
Core A 179–4: lat. 16°36′N, long. 74°48′W, depth 2965 m (Caribbean Sea)			
W-160	0– 10	Total carbonate	3,950 ± 250
W-158	23– 30	Fine fraction	13,500 ± 400
W-159	23– 30	Coarse fraction	11,800 ± 300
W-134	30– 35	Total carbonate	15,700 ± 400
W-164	60– 65	Total carbonate	21,300 ± 800
W-162	70– 77	Coarse fraction	27,600 ± 1000
W-135	150–155	Total carbonate	35,000 ± 3000
W-147	260–265	Total carbonate	35,000 ± 3000
Core A 172–6: lat. 14°59′N, long. 68°51′W, depth 4160 m (Caribbean Sea)			
W-236	0– 10	Coarse fraction	3,700 ± 200
W-237	51– 61	Coarse fraction	17,500 ± 500
W-238	114–125	Coarse fraction	36,000 ± 3000
W-239	240–250	Coarse fraction	> 38,000
Core A 180–73: lat. 0°10′N, long. 23°0′W, depth 3749 m (Mid-Atlantic Ocean)			
W-280	0– 8	Coarse fraction	2,960 ± 300
W-278	30– 38	Coarse fraction	15,300 ± 300
W-276	80– 88	Coarse fraction	27,000 ± 1500

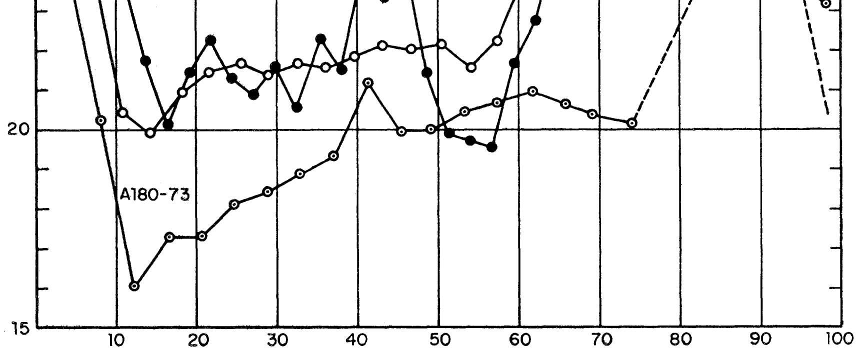

Fig. 1. Paleotemperatures of Foraminifera tests (*Globigerinoides sacculifera*) from O^{18} measurements at the University of Chicago (13) versus their age from C^{14} measurements at the U.S. Geological Survey (5, 6) for three deep-sea cores from the Lamont Geological Observatory, Palisades, New York.

Carbon-14 determinations were carried out at the U.S. Geological Survey radiocarbon laboratory on three of these cores (5, 6), which had been investigated for O^{18} by Emiliani, for the purpose of determining rates of deposition and, from this, the temperatures as a function of time.

The core material was supplied by D. Ericson of the Lamont Geological Observatory, who selected cores that appeared as homogeneous and as free as possible from the effects of turbidity currents, erosion, or slumping. The respective levels for C^{14} dating were selected by Emiliani on the basis of O^{18} trends.

Table 2 lists the results of these C^{14} measurements, expressed in terms of apparent ages, which were obtained by taking for present-day carbonate the C^{14} to C^{12} ratio of modern wood (15) and 5568 years for the C^{14} half-life (1). The true C^{14} to C^{12} ratios of modern sea carbonate are not accurately known, in particular with respect to possible geographic variations, but the uncertainty in the ages will, for this reason, not exceed a few hundred years. For two other reasons, the apparent ages may well deviate from the true ages to a considerably greater degree. (i) The core material may contain redeposited old carbonate incorporated in some way from stirred-up or dissolved older sediments. (ii) It may also contain some modern carbonate as a result of exchange with atmospheric CO_2 during the handling and drying in the laboratory.

The statistical standard error of each measurement is given in the table. It expresses the uncertainty in the C^{14} determination only, and not the uncertainty in age that results from admixture of foreign carbonate. An indication of admixture of old carbonate can be seen from the fact that the total carbonate in the fine fraction has an apparent age sometimes greater by almost 2000 years than the coarse fraction, which consists mainly of Foraminifera tests. All considerations are based on measurements from sieved fractions (greater in size than 74 microns) prepared by Ericson at the Lamont Geological Observatory. The addition of old carbonate, provided that it was constant, only affects absolute age values and not the rates of deposition that are calculated from them. Addition of young carbonate, however, affects the older dates (greater than 20,000 years) to a much greater degree than younger ones. That such an addition has, in some instances, actually taken place can be seen from the measurements for samples W-135 and W-147. The age of these layers was undoubtedly much greater than the apparent age of 35,000 years. Such an addition is insignificant for younger dates (less than 20,000 years); the younger dates were used for calculating rates of deposition.

In Fig. 1, the O^{18} temperatures (derived from *Globigerinoides sacculifera*) as determined at the University of Chicago are plotted as a function of age, which was obtained from the rate of deposition that results from C^{14} determinations at the U.S. Geological Survey. It was assumed that this rate was constant and equal to that at which the upper part of the cores was deposited. Despite the obvious uncertainties of this assumption, it can be seen that the temperature trends as a function of time in the three cores investigated so far agree surprisingly well. If the rate of deposition was different during glacial times from that during the more recent period, then this difference must have been nearly the same in the three cores.

Assuming that this difference was negligible, one finds that a period of decreasing temperatures began about 80,000 years ago. The temperature reached a minimum about 15,000 years ago; this time coincides within the accuracy of the method with the time of the maximum extent of the North American ice sheet. Thereafter, a relatively rapid temperature increase took place, leading to conditions resembling those of the present. Although no indications for fluctuations of a 3500-year period can be recognized, the record from the core material seems to parallel the continental glacial and postglacial events in a crude but unmistakable way. Extrapolating backward in time, we find that the record shows a less pronounced temperature minimum about 55,000 years ago that preceded a relatively moderate period about 45,000 years before the present. The warm period of about 90,000 years ago may be correlated with the Sangamon time of North America, and the moderate period of 45,000 years ago may be correlated with a yet unnamed oscillation that is recognized in Pleistocene stratigraphy of the northern areas of North America (*3*). With respect to European glacial chronology, the sequence resembles that proposed by Zeuner (*16*) if one correlates the temperature interstadial of 45,000 years ago with LG 2/3 and the time about 85,000 years with LG 1/2. Such correlation with the respective Würm phases may well require revision. However, a certain similarity of the temperature record in the core material with the astronomical insolation curve of Milankovitch (*17*), on which Zeuner's chronology is based, cannot be denied. This, at least, is the conclusion that Emiliani (*13*) derives from the combined temperature records of his cores, which in some instances go back to the beginning of the Pleistocene, and from sedimentation rates estimated from various methods of dating. In particular, the 40,000-year period in the obliquity of the earth's axis (*18*) seems to be reflected in these records. The minima in the obliquity, however, precede the temperature minima by nearly 10,000 years.

Summary

It appears that there is evidence for two main types of climatic fluctuations that have occurred during the Last Glaciation on two different time scales, one of the order of 40,000 years and another of the order of 3500 years. The Last Glaciation embraces at least two of the long periods (Fig. 1) upon which are superimposed oscillations of the short period (Table 1). Apparent contradictions in radiocarbon dates (*19*) are at least in part the result of miscorrelations between events on these two different time scales (*20*).

References and Notes

1. W. F. Libby, *Radiocarbon Dating* (Univ. of Chicago Press, Chicago, 1952).
2. R. F. Flint and E. S. Deevey, Jr., *Am. J. Sci.* 249, 257 (1951).
3. R. F. Flint and M. Rubin, *Science* **121**, 649 (1955).
4. H. E. Suess, *Science* 120, 5 (1954.)
5. M. Rubin and H. E. Suess, *Science* **121**, 481 (1955).
6. ———, *Science*, in press.
7. R. F. Flint, *Am. J. Sci.* 253, 249 (1955).
8. L. Horberg, *J. Geol.* 63, 278 (1955).
9. A. Penck and E. Brückner, *Die Alpen im Eiszeitalter* (Leipzig, 1909).
10. M. M. Leighton, *J. Geol.* 34, 167 (1926).
11. G. Arrhenius, *Report of Swedish Deep-Sea Expedition 1947–48*, Vol. 5, fasc. 1, p. 198.
12. G. Arrhenius, G. Kjellberg, W. F. Libby, *Tellus* 3, 222 (1951).
13. Cesare Emiliani, *J. Geol.* 63, 538 (1955).
14. S. Epstein *et al.*, *Bull. Geol. Soc. Amer.* **62**, 417 (1951); **64**, 1315 (1953).
15. H. E. Suess, *Science* 122, 415 (1955).
16. F. E. Zeuner, *Dating the Past* (Methuen, London, 1952).
17. M. Milankovitch, *Handb. Geophys.* **9**, 593 (1938).
18. A. J. J. Van Woerkom, in *Climatic Change*, H. Shapley, Ed. (Harvard Univ. Press, Cambridge, Mass., 1953).
19. E. Antevs, *J. Geol.* 63, 495 (1955).
20. This article is a contribution from the Scripps Institution of Oceanography, new series, No. 843. Thanks are due to C. Emiliani for making his manuscript (*13*) available to me prior to its publication. The critical comments of R. Rex, M. Rubin, and C. Emiliani are appreciated.

Program of the Gordon Research Conferences

W. George Parks

The Gordon Research Conferences of the American Association for the Advancement of Science for 1956 will be held from 11 June to 31 August at Colby Junior College, New London, N. H.; New Hampton School, New Hampton, N. H.; and Kimball Union Academy, Meriden, N. H.

Purpose. The conferences were established to stimulate research in universities, research foundations, and industrial laboratories. This purpose is achieved by an informal type of meeting consisting of scheduled lectures and discussion groups. Sufficient time is available to stimulate informal discussions among the members of a conference. Meetings are held in the morning and in the evening, Monday through Friday, with the exception of Friday evening. The afternoons are available for recreation, reading, or participation in discussion groups as the individual desires. This type of meeting is a valuable means of disseminating information and ideas that otherwise would not be realized through the normal channels of publication and scientific meetings. In addition, scientists in related fields become acquainted, and valuable associations are formed that often result in collaboration and cooperative efforts between different laboratories.

It is hoped that each conference will extend the frontiers of science by fostering a free and informal exchange of

The author is director of the Gordon Research Conferences and head of the department of chemistry at the University of Rhode Island.