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The Pleistocene Epoch in Deep-Sea Sediments

A complete time scale dates the beginning of the first ice age at about 1½ million years ago.

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A new approach to the study of the Pleistocene epoch opened in 1935 when W. Schott (*1*) found well-defined changes in the abundance of the shells of certain species of planktonic Foraminifera in a series of sediment cores from the equatorial Atlantic. He surmised that the most recent change in the Foraminifera recorded the climatic amelioration at the end of the last ice age. This suggested the probability that a legible record of all the major climatic events of the Pleistocene lay within the deep-sea sediments of the Atlantic Ocean. With the invention of the piston coring tube by Kullenberg (*2*), which made possible the recovery of sediment cores 10 to 15 meters long, this record seemed to be within reach.

However, before such a record could be converted into a chronology in years, some method of determining rates of sediment accumulation in the deep oceans was needed. The development of the radiocarbon method of dating filled this need. It became possible to date a sample of sediment from a core by measuring the amount of radiocarbon remaining in the calcium carbonate shells of the planktonic foraminiferans in the sample. Unfortunately, the method is limited to material no older than about 35,000 years. However, this period is long enough to establish rates of sediment accumulation by which the ages of deeper levels in the sedimentary section can be estimated.

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Since 1947 M. Ewing and his coworkers during 44 oceanographic expeditions have raised more than 3000 cores from sediments in all the oceans and adjacent seas. We have constructed the record of Pleistocene climatic events presented in this article by piecing together correlating and overlapping sections of 26 cores selected from the collection at Lamont Geological Observatory.

Sediment Cores

All but one of the 26 cores were taken with apparatus designed by Ewing on the principle of the piston coring tube of Kullenberg (*2*). The exceptional core, V16-201, was raised with a device designed by Stephen Chelminski, which utilizes hydrostatic pressure to drive the coring tube into the sediment. This core includes a section, between 1180 and 1380 centimeters, in which the sediment was disturbed. This is not due to disturbance of the sediment *in situ,* but to a partial malfunctioning of the coring apparatus, which resulted in stretching out the section somewhat, but not in a break in the continuity of the sediment. The geographical positions of the coring stations, depths of water, and lengths of the cores are shown in Fig. 1.

All the cores included in our composite record consist of foraminiferal lutite, a mixture of fine mineral particles from the continents and particles of calcium carbonate secreted by planktonic organisms, particularly the Coccolithophoridae and the Foraminifera. Except for minor variations in color in some of the cores, the sediment is uniform from top to bottom: the climatic zones are not distinguished by discernible changes in the physical character of the sediment.

The cores we have selected for our interpretation of the climatic history of the Pleistocene contain undisturbed foraminiferans. Investigations by Ericson *et al.* (*3*) have shown that the processes that most often disturb the foraminiferal record are turbidity currents, scour by deep currents, and removal of layers of sediment by slumping. Transportation and emplacement of foraminiferans by turbidity currents or deep oceanic currents give rise to abrupt and easily recognizable changes in texture. In none of the 26 cores selected for our study are there any such changes in texture. Slumping, of course, has no effect on texture. Deletions in the record due to slumping can be detected only by careful cross-correlation between two or more cores. Such cross-correlation has been one of our chief concerns in this study.

The best places on the ocean bottom to core for undisturbed sections are the tops and flanks of gentle rises. Of the 26 cores, those which contain continuous records from some time in the past up to the present were taken on gentle rises. Slumping has been useful to us because it has removed sediment of late Pleistocene age, thereby bringing older sediment within reach of the coring tube. Slumping is confined to relatively steep slopes; the cores containing the middle and early Pleistocene sections were taken on such slopes.

Climatic Record

Living foraminiferans have been collected in various parts of the oceans, and we have a fairly good general picture of the geographical distribution of most of the species. In general, the boundaries of the geographical ranges of the species trend east and west, which suggests that temperature is the most important factor limiting their ranges.

Since 1872, when H.M.S. *Challenger* set out on the first great oceanographic expedition, many samples of sediment have been raised from the floors of the oceans, particularly from the North Atlantic. Various investigators have studied the planktonic foraminiferans in the samples, and from their data have emerged patterns of the areal distribution of the 18 most common species now living in the Atlantic. From the charts of areal distribution, one can divide the planktonic species into three groups: those confined to low latitudes (near the Equator), those abundant in middle latitudes, and those which live most abundantly in high latitudes. The fact that the distribution with respect to latitude is the same both in the northern and in the southern hemispheres lends further weight to the conclusion that water temperature is the controlling factor in the geographical distribution of the species. This is of primary importance in our attempt to decipher the record of past climatic changes. Evidently some species of planktonic foraminiferans are sensitive to temperature, and their geographical distributions are limited accordingly.

Studies by Schott (*1*), Cushman and Henbest (*4*), Phleger (*5*), Ovey (*6*), Parker (*7*), Wiseman (*8*), Ericson *et al.* (*3*), Ericson and Wollin (*9*), and others, of the planktonic foraminiferans in sediment cores have shown that there is a variation, from level to level, in the relative abundance of the species that are sensitive to temperature. It is agreed by these investigators that variations record shifts in the geographical ranges of the species and that these shifts were a consequence of the climatic changes of the late Pleistocene.

In recent years many datings of plant detritus in late Pleistocene continental deposits by the radiocarbon method have shown that rapid retreat of the continental ice sheets set in about 11,000 years ago. At the same time, radiocarbon assays (*10*) of the calcium carbonate shells of planktonic foraminiferans in many samples from the upper parts of sediment cores from the Atlantic prove that the most recent strongly defined change in the geographical ranges of temperature-sensitive species of planktonic foraminiferans occurred about 11,000 years ago. The nature of the faunal change, that is, from cool-water species below to warm-water species above, is in itself strong evidence for a causal association of the two events; the coincidence in time amounts to final proof that they had a common cause. This justifies the conclusion that similar faunal changes lower in the sedimentary section record earlier climatic changes of comparable importance.

Most of the data on the Pleistocene which have come from deep-sea sediments are based on study of the planktonic foraminiferans. This has been essentially the case with our own results, but, though the foraminiferans have provided the climatic record, we believe we could not have obtained reliable results if we had not also carefully examined the physical aspects of the cores. The sea floor is a far more dynamic environment than we realized only a few decades ago; truly quiet areas of the sea floor, where sediment, once having come to rest, can remain undisturbed for millions of years, are exceptional. In view of the prevalence of disturbing processes, we have felt it necessary to check carefully the continuity of our Pleistocene sections by cross-correlation.

Since our first concern was to cross-correlate many cores in order to recognize those with long continuous sections, we developed the method of faunal analysis which has been described by Ericson *et al.* (*3*).

In our faunal analyses we note the following species and subspecies:

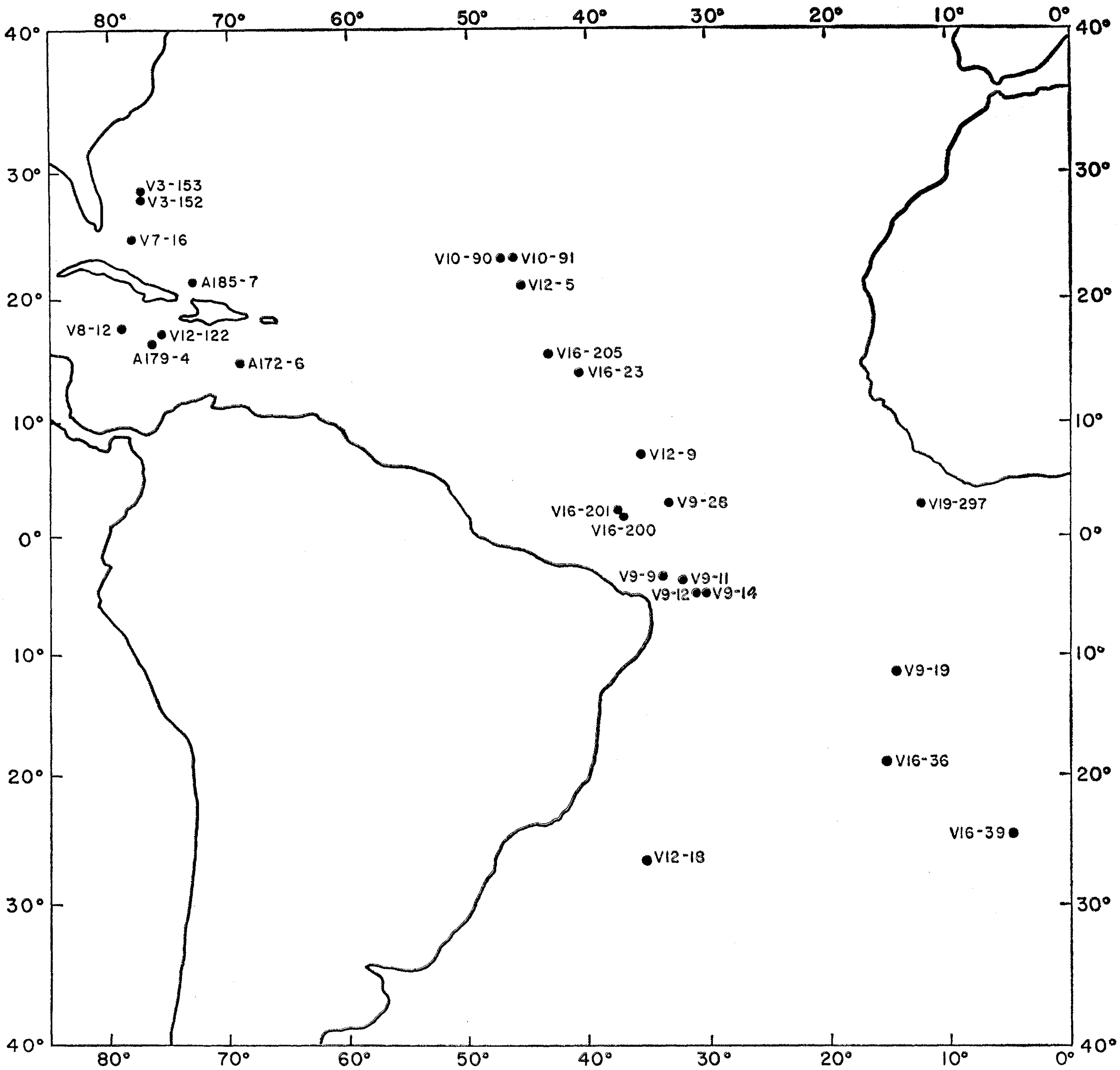
Globorotalia menardii menardii (d'Orbigny)
G. menardii tumida (H. B. Brady)
G. menardii flexuosa (Koch)
G. hirsuta hirsuta (d'Orbigny)
G. hirsuta punctulata (d'Orbigny)
G. truncatulinoides (d'Orbigny)
G. scitula (H. B. Brady)
G. inflata (d'Orbigny)
Globigerina bulloides (d'Orbigny)
G. pachyderma (Ehrenberg)
G. eggeri (Rhumbler)
Globigerinoides rubra (d'Orbigny)
G. sacculifera (H. B. Brady)
G. conglobata (H. B. Brady)
Hastigerina aequilateralis (H. B. Brady)
Orbulina universa (d'Orbigny)
Pulleniatina obliquiloculata (Parker and Jones)
Sphaeroidinella dehiscens (Parker and Jones)

Most of these species have been figured and their taxonomy discussed by Phleger, Parker, and Peirson (*11*), by Loeblich and collaborators (*12*), and by Ericson *et al.* (*3*).

The species of most significance as indicators of climate in equatorial and mid-latitude waters are the races of *Globorotalia menardii,* which are indicative of mild climate, and *Globorotalia inflata,* an indicator of cool climate. In more northerly waters, *Globigerina bulloides, G. pachyderma,* and *Globorotalia hirsuta* are useful.

As reported earlier (*3*), this method has enabled us to identify and correlate faunal zones in hundreds of cores from widely scattered areas in the Atlantic and connected seas, and it has permitted us to select from among more than 3000 cores those which were most likely to contain reliable records of Pleistocene climates and which were best suited for more detailed study. Climate curves based on the relative numbers of warm-water and cold-water species of planktonic foraminiferans found in the 26 cores give a composite climatic record of the Pleistocene (Fig. 2).

Emiliani (*13, 14*) has criticized our reliance upon *Globorotalia menardii, G. m. tumida,* and *G. m. flexuosa* as indicators of mild climate in preference to *Sphaeroidinella dehiscens* and *Pulleniatina obliquiloculata.* That the above members of the *Globorotalia menardii* complex, by changes of abundance, faithfully record the climatic fluctuations of the late Pleistocene is reasonably certain. Lower in the Pleistocene section, however, and particularly within the section which we believe to represent the Yarmouth interglacial, variations in abundance of the *Globorotalia menardii* complex and *Sphaeroidinella dehiscens* and *Pulleniatina obliquiloculata* are discordant. Emiliani contends that the variations of the latter two species are in better accord with his interpretation of the climatic record, based on oxygen isotope analyses, than with our interpretation. This evidence by itself favors Emiliani's view. However, our studies indicate that, lower in the Pleistocene section, *Sphaeroidinella dehiscens* and *Pulleniatina obliquiloculata* are monotonously abundant throughout. On the evidence of these species alone it would seem that no climatic changes had occurred. Yet variations in the other climate-sensitive species indicate climatic fluctuations of about the same order of magnitude as



Core	Position	Depth	Length	Core	Position	Depth	Length
A172-6	14°59′N, 68°51′W	4160	935	V10-90	23°02′N, 47°03′W	4030	580
A179-4	16°36′N, 74°48′W	2965	690	V10-91	23°23′N, 46°24′W	3540	630
A185-7	21°07′N, 72°51′W	2470	555	V12-5	21°12′N, 45°21′W	3000	735
V3-152	28°10′N, 77°37′W	1005	562	V12-9	6°54′N, 35°28′W	3020	1380
V3-153	28°24′N, 77°56′W	970	545	V12-18	28°42′S, 34°30′W	2935	1080
V7-16	25°20′N, 77°36′W	2635	560	V12-122	17°00′N, 74°24′W	2730	1090
V8-12	17°32′N, 79°28′W	1250	960	V16-23	13°15′N, 40°40′W	4885	1140
V9-9	3°34′S, 33°46′W	3650	1180	V16-36	19°22′S, 11°26′W	3485	830
V9-11	3°13′S, 32°12′W	4120	1207	V16-39	24°43′S, 4°45′W	4510	802
V9-12	3°03′S, 32°38′W	4840	1755	V16-200	1°58′N, 37°04′W	4095	989
V9-14	3°52′S, 30°37′W	4660	1375	V16-201	2°01′N, 37°09′W	4275	2190
V9-19	11°23′S, 14°15′W	3730	730	V16-205	15°24′N, 43°24′W	4045	1257
V9-28	2°54′N, 33°09′W	4305	1190	V19-297	2°37′N, 12°00′W	4120	1300

Fig. 1. Locations of coring stations, depths of water (in meters), and lengths of cores (in centimeters). The letter before a core number indicates the research vessel by which the core was taken: (A) *Atlantis*, research vessel of the Woods Hole Oceanographic Institution; (V) *Vema*, research vessel of Lamont Geological Observatory. The number directly after the letter is the number of the expedition; the number after the hyphen is the number of the station at which the core was taken.

those which occurred during the late Pleistocene.

Furthermore, by cross-correlation and extrapolation of radiocarbon dates, we are reasonably certain that these lower sections accumulated between 300,000 and 1 million years ago, during which time glaciations occurred, as proved by potassium-argon dating (*15*).

Bé (*16*) has found evidence that *Sphaeroidinella dehiscens* is an aberrant terminal form of *Globigerinoides sacculifera*. Apparently this form is achieved by secretion of a thick translucent crust upon the test of *G. sacculifera*. On the

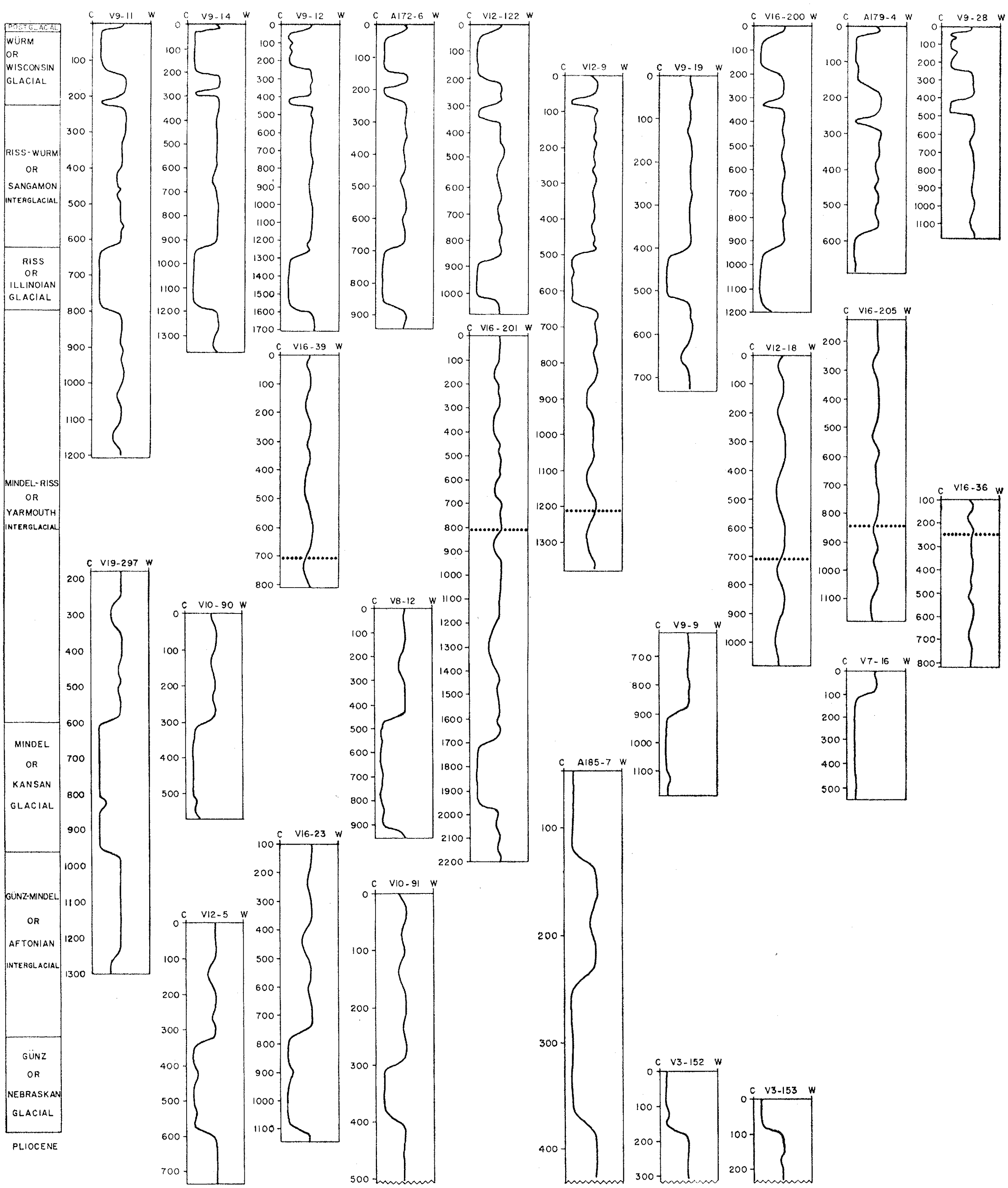


Fig. 2. Climate curves based on study of the planktonic foraminiferans in samples taken at 10-centimeter intervals in 26 cores correlated with the glacial and interglacial ages of the complete Pleistocene. *C*, cold climate; *W*, warm climate. Present climate is plotted midway between *C* and *W*, and inferred past climates are plotted with respect to present climate. Numbers to the left of the columns are depths in the cores in centimeters. The dotted lines indicate the level at which *Globorotalia* sp. 1 became extinct.

basis of material collected by opening and closing plankton nets towed in the Atlantic, he concludes that the process of shell thickening starts in the epipelagic zone (0 to 300 m) and reaches its maximum development between depths of 300 and 2000 meters. However, the "species" is very rare in plankton tows, being present in only 10 out of 800 plankton samples. Full development of the "species" apparently occurs only at a considerable depth, probably below 500 meters and perhaps much deeper. In view of these findings a direct relationship between abundance of *Sphaeroidinella dehiscens* and conditions in the upper layer of water, where conditions would vary most widely during the climatic changes of the Pleistocene, is questionable.

We know less about the habits of *Pulleniatina obliquiloculata*. However, its persistence in abundance across faunal changes defined by other temperature species deprive it of usefulness as an indicator of climate.

Counts of left- and right-coiling shells of *Globorotalia truncatulinoides* have been made and recorded as percentages of shells coiling in the dominant direction in the total count of the species. This method, described in detail by Ericson *et al.* (*17*), is especially useful as a check on other methods, for it permits identification of layers no more than a few centimeters thick in some cases. Figure 3 shows variation in coiling direction of *G. truncatulinoides* in 22 of the 26 cores selected for this study. The species was too infrequent in the other four cores to yield meaningful counts. The strong dominance of right coiling in the post-Illinoian sections is a feature which distinguishes them from the earlier sections—particularly from that which we believe represents the Yarmouth interglacial.

Faunal Definition

The crux of the problem of finding a complete record of the Pleistocene has been to find tangible evidence of the beginning of the epoch. As we have reported earlier (see *18*) the criteria which define the Pliocene-Pleistocene boundary according to our findings from the study of deep-sea sediments are as follows:

1) Extinction of the Discoasteridae

2) Change in the coiling direction of members of the *Globorotalia menardii* complex from 95 percent right-coiling below the boundary to 95 percent left-coiling above it

3) Appearance of *Globorotalia truncatulinoides* in abundance above the boundary

4) Disappearance of *Globigerinoides sacculifera fistulosa* above the boundary in cores from the Atlantic

5) Reduction of the *Globorotalia menardii* complex to a single fairly uniform race above the boundary

6) Increase in the average diameter of the shells of *Globorotalia menardii* and reduction in their number with respect to the total population of Foraminifera above the boundary

From the magnitude of the faunal change at the boundary, we conclude that it records a climatic event of a different order from the fluctuations which seem to have occurred repeatedly during late Pliocene time (*19*). This is why we believe that the boundary marks the beginning of the first ice age of the Pleistocene, the Nebraskan or Günz ice age. Since periodic glaciations most clearly distinguish the Pleistocene from the earlier epochs of the Cenozoic, we suggested in our report (*18*) that this faunal boundary, which records the beginning of the first glaciation, be chosen to denote the beginning of the Pleistocene epoch. Three cores (V3-152, V3-153, and V12-5) of the eight cores included in our study of the Pliocene-Pleistocene boundary are included in this study. Since publication of our paper on the boundary we have found three more cores which include the boundary. These are A185-7, V10-91, and V16-23. We have included these in this study because they contain particularly long sections from the early Pleistocene.

After the publication of our study of the Pliocene-Pleistocene boundary, O. L. Bandy (*20*) expressed the opinion that the faunal change in our cores from the Atlantic represented a depositional hiatus, with Pleistocene sediment lying directly on Miocene, and with all Pliocene sediment absent. He based his opinion on the occurrence of a similar faunal change in the Philippines which he regarded as marking the Miocene-Pliocene boundary. However, after having looked at the foraminiferans in a sample from below the boundary in one of the Atlantic cores, he agreed (personal communication) that the age was Pliocene because of the presence of the subspecies *Sphaeroidinella dehiscens dehiscens*. Since the same subspecies occurs below the boundary in the other cores from the Atlantic, it is evident that the sediment below the boundary in all of the cores is of Pliocene age by Bandy's criterion and as we originally stated in our report.

Our conviction that the faunal change in the Atlantic cores and in the late Cenozoic section of the Philippines records the onset of the first ice age stands on firmer ground than Bandy's presumption that it represents the Miocene-Pliocene boundary, because we have traced the sedimentary section of the Pleistocene downward from a universally recognized level of reference—that is, the layer of sediment recently deposited on the floor of the Atlantic whose age can be verified by radiocarbon dating. Bandy, in contrast, has worked upward from datum levels defined by certain species of planktonic foraminiferans.

As we have pointed out in our report on the boundary, the layer-by-layer cross-correlation between the seven cores from the Atlantic is evidence for continuous deposition across the boundary; loss of some part of the section without destroying the layer-by-layer correspondence could occur only in the event that exactly the same stratigraphical thickness was lost at the same time at the seven widely scattered places on the sea floor where the cores were taken. The probability of such a coincidence is very small. The question of probability is not one of coring seven (now ten) equivalent sections of pre-Pleistocene sediments among the 3000 cores of the Lamont collection. Among the 3000 cores, 96 percent end in Pleistocene sediment and, consequently, we cannot know how many might have included equivalent sections of pre-Pleistocene sediments if the coring tube had penetrated deeper. Therefore, the great majority of the cores in the collection have no bearing on a question of probability which involves a pre-Pleistocene sequence of sediments. Only the 125 cores of the collection which reach pre-Pleistocene sediments enter the question of probability.

Our paper on the boundary was also criticized by Riedel *et al.* (*21*) but on quite opposite grounds. Whereas Bandy felt that the faunal change at the boundary was too important and sharply defined to be explained in any other way than by a depositional hiatus, Riedel *et al.* expressed the opinion that the faunal change was poorly defined, and, therefore, it was doubtful if it could record a marked and abrupt climatic change such as the onset of an ice age. "Thus the relation," they write, "between the boundary defined by Ericson *et al.* and the generally accepted Pliocene-Pleistocene boundary remains uncertain." However, some paragraphs farther on they say, "There is considerable agreement between the horizon proposed by Ericson *et al.* as the Pliocene-Pleistocene boundary and that provisionally used by us to separate 'Tertiary' from 'Quaternary'." Thus their conclusion stands in general agreement with our conclusion that the faunal boundary records the beginning of the Pleistocene.

Although the foraminiferal assemblages above the Pliocene-Pleistocene boundary maintain their distinctive Pleistocene aspect, some extinctions and evolutionary changes occur within the Pleistocene section.

Globorotalia menardii flexuosa appears in abundance within the lower part of the zone which we correlate with the Sangamon interglacial age. The top of the Sangamon is defined by the disappearance or near disappearance of the three races of the *Globorotalia menardii* complex. All three reappear in abundance in the zone which we believe records the warm interstadial of the last ice age. Apparently, *G. m. flexuosa* became extinct in the Atlantic during the following interval of cold climate. *Globorotalia menardii menardii* and *G. m. tumida* are very abundant in the uppermost layer of sediment deposited during postglacial time, but *G. m. flexuosa* is absent. Since *G. m. flexuosa* does not occur in the Yarmouth and Aftonian sections, it serves as a reliable means of distinguishing between the earlier intervals of mild climate and the major part of the Sangamon section.

Another distinctive form, which seems to be a racial variant of *Globorotalia inflata,* became extinct in the zone which we believe represents the Yarmouth. The level at which it became extinct is shown in Fig. 2. It has been described and figured by Phleger *et al.* (*11*) as *Globorotalia* sp. 1. According to these authors it made up 1 percent of the population of planktonic foraminiferans at 1280 centimeters in core 235. This core was raised by the R/V *Albatross* in the equatorial Atlantic during the Swedish Deep Sea Expedition of 1947–48. According to Phleger *et al.* the fauna associated with *Globorotalia* sp. 1 was intermediate in composition between high and low latitude, or cold- and warm-water assemblages. In our experience, this intermediate character clearly distinguishes the Yarmouth section of the equatorial Atlantic from the sections representing the first and last interglacials. This distinctive aspect of the foraminiferal assemblages in the zone which we correlate with the Yarmouth interglacial has been helpful in fitting together the core sections into a continuous sequence. For example, in four of the cores which include the Pliocene-Pleistocene boundary (Fig. 2) the zone of cold climate directly above the boundary is overlain by a zone containing an assemblage dominated by warm-water species. We believe that this zone represents the Aftonian interglacial. However, may it not, instead, be part of the zone of mild climate which we find in core V16-39? The answer is, no; the zone of mild climate in V16-39 has the distinctive character of the Yarmouth; that in core V16-23 does not. On the other hand, the zone of mild climate in V16-23 is quite different from the zone which we equate with the Sangamon interglacial, because the former does not contain *Globorotalia menardii flexuosa.*

This same distinctive character of the Yarmouth has enabled us to position the shorter cores shown in Fig. 2. The assemblage in these cores is distinctively Yarmouth.

The distinction between the zones corresponding to interglacial and glacial ages is, for the most part, well defined. A striking difference is the abundance of the large and conspicuous forms of the *Globorotalia menardii* complex in the zones that record interglacial ages and their absence or near absence in those which we regard as representing ice ages. However, in this respect, as we mention above, the Yarmouth section is somewhat different from the Sangamon and Aftonian sections. The population of *Globorotalia menardii* in the Yarmouth section shows less variability and makes up on average a smaller proportion of the total assemblage of planktonic foraminiferans. In sum, the typical assemblage of planktonic foraminiferans in this section is a mixture of cold- and warm-water species. However, we have been able to find evidence of four distinct minor cold intervals and one somewhat less distinct minor cold interval within the Yarmouth interglacial. This is interesting because Rózycki (*22*) has reported that he has found evidence of four minor cold intervals in continental deposits in Poland which belonged to the second interglacial or Yarmouth age.

In addition to the minor cold intervals and an anomalous mixture of cold-water and warm-water species in the Yarmouth section, *Globorotalia truncatulinoides,* whose coiling dominance is strongly to the right in the other sections of interglacial age, coils both to the right and left. In the Yarmouth section, the clear-cut segregation between right- and left-coiling populations, so evident especially in the sequence above (Fig. 3), has broken down. The evidence suggests that the climate of the Yarmouth, or Mindell-Riss, differed from that of the other two interglacials.

Rate of Sediment Accumulation

By means of the radiocarbon method of dating we have found that rates of accumulation of foraminiferal lutite vary considerably from place to place. We believe that this variation is due to interaction between deep currents and irregularities of bottom topography. Among many dated samples we have observed that differences in rate of accumulation are accompanied by differences in the textures of the sediments, coarse-grained sediments having accumulated more slowly than fine-grained ones. From this we reason that uniformity of texture from top to bottom in a core is an indication that the rate of accumulation on that particular part of the ocean floor was constant.

In addition, we have the supporting evidence of the dates and chronologies provided by different radiochemical methods. Hence the following principles stand forth: when the texture of a core is uniform from top to bottom, the rate of accumulation of the sediment has remained reasonably constant with time; and among several cores, those with similar textures have accumulated at similar rates. These principles, supported by evidence from more than 100 cores (*3*), have enabled us to translate thicknesses of faunal zones into intervals of time to an extent far beyond the range of any method of dating now available for application to deep-sea sediments.

For our purpose the important relationship is that between texture and rate of accumulation; we have confirmed this relationship by radiocarbon dating of late Pleistocene sections and by precise

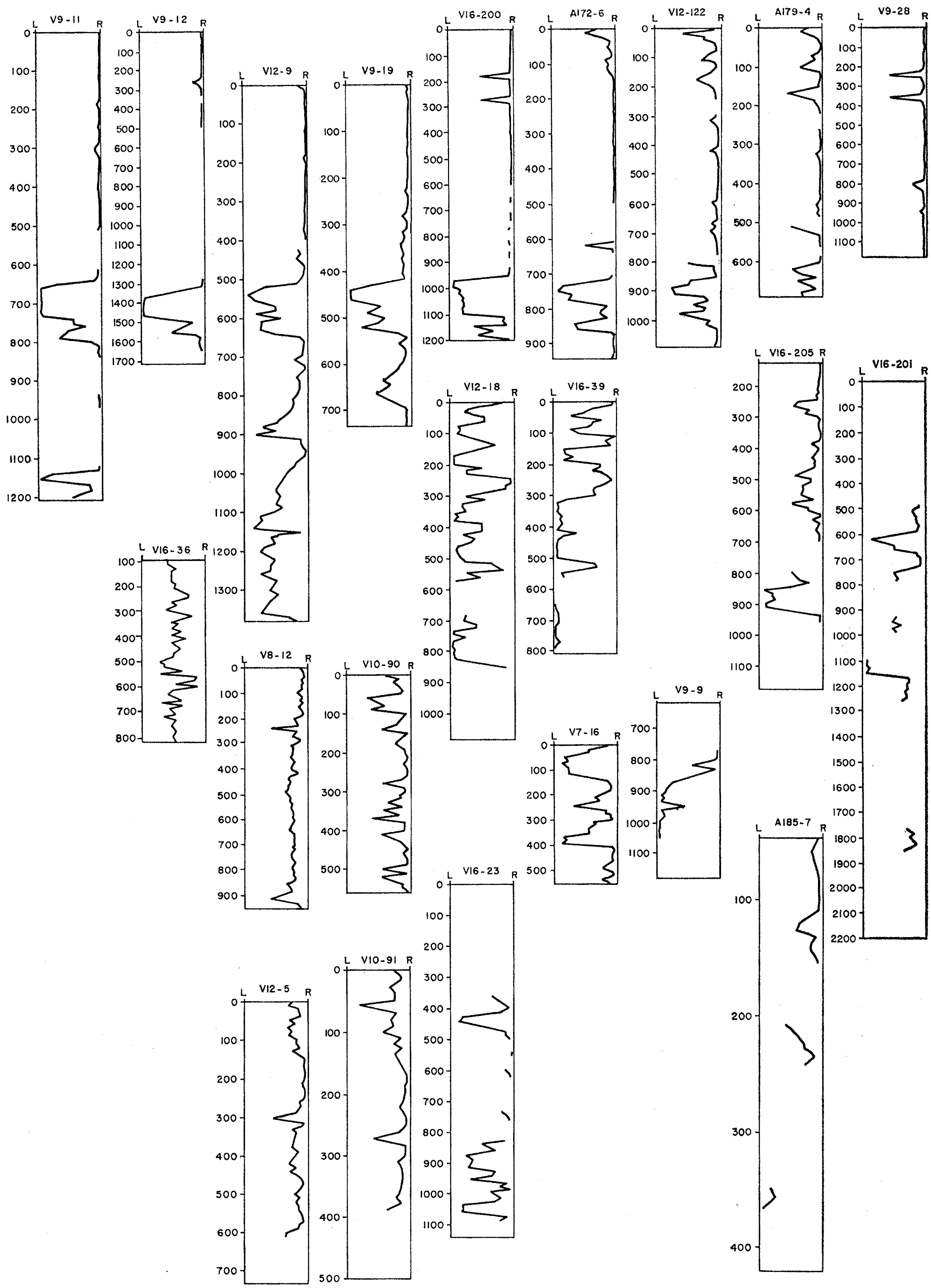


Fig. 3. Correlation of 22 of the 26 deep-sea cores which include the Pleistocene section. The correlating levels are defined by changes in coiling direction of *Globorotalia truncatulinoides* in samples taken at 10-centimeter intervals. The scale of coiling runs from 100 percent left at the left margins of the columns to 100 percent right at the right margins. Numbers to the left of the columns are depths in cores in centimeters.

correlation of earlier sections (*3*). For example, when radiocarbon dates show that the rate of accumulation of the upper part of one core has been twice as fast as that of the upper part of some other core, cross-correlation shows that corresponding layers in the lower part of the one core are consistently twice as thick as those in the other core. In other words, the ratio of two to one between rates of accumulation, as determined by radiocarbon dating of the upper parts, is also true of the lower parts, which are beyond the range of the radiocarbon method. But, and this is a most important "but," we find such consistent relationships only in cores that differ from each other in texture but are individually uniform in texture from top to bottom. When cores contain variations in texture from layer to layer, and the variations are not due to deposition by turbidity currents, cross-correlation with other cores that have vertical uniformity of texture shows that the coarse layers have accumulated more slowly than the finer layers.

The validity of the relationship between vertical uniformity of texture and constant rate of accumulation with time is so well supported by numerous instances and by sound theory that we do not feel misgivings about using it as the basis of our chronology of the Pleistocene.

Chronology of the Pleistocene

Since 1950 a fairly large number of radiocarbon determinations have been made on samples from cores in the Lamont collection. Dates and climate curves based on relative numbers of warm- and cold-water species of planktonic foraminiferans in ten cores are shown in Fig. 4. The reliability of the radiocarbon method of dating as applied to deep-sea sediments is indicated by the consistency of the date of the end of the last ice age, that is, about 11,000 years ago, in spite of the fact that the depth to the climatic change varies, occurring from 15 to 445 centimeters from the tops of the cores. The cores shown in Fig. 4, particularly A180-48, A179-8, A179-15, and R10-10, were selected for dating because they showed considerable variation in depth to the faunal change marking the end of the last ice age. We thought that they would provide not only a good test of the reliability of the radiocarbon method in dating deep-sea sediments but also a test of our method of assessing Pleistocene climates. Detailed descriptions of the cores shown in Fig. 4 have been published by Ericson *et al.* (*3*).

The serious shortcoming of the radiocarbon method is its limitation to material no older than about 35,000 years. To estimate the ages of zones deeper in the cores one must assume a constant rate of accumulation. Our investigations of deep-sea sediments (*3*) have shown that, although there is much variation in the rate of accumulation from place to place (for example, from 1.4 to 41 cm per 1000 years as shown in Fig. 4), these variations are always accompanied by variations in texture. On the other hand, sediments of similar texture show similar rates of accumulation. Since the sediments of the cores selected for this study are uniform in texture from top to bottom, we infer that they have accumulated at rates which have remained uniform through time.

As shown in Fig. 4, one core has been dated by the protactinium-ionium method by Rosholt *et al.* (*23*), and two cores have been dated by the protactinium method by Sackett (*24*); Sackett's method, recently developed, is based on the distribution of unsupported Pa^{231} activity alone. The dates obtained in core A179-4 by the protactinium-ionium method essentially agree with the dates obtained in cores V12-122 and A180-32 by the protactinium method, and the dates obtained from both these methods agree with the radiocarbon dates, as is shown in Fig. 4.

The dates obtained by the radiocarbon, the protactinium-ionium, and the protactinium methods provide an absolute time scale from the present back to

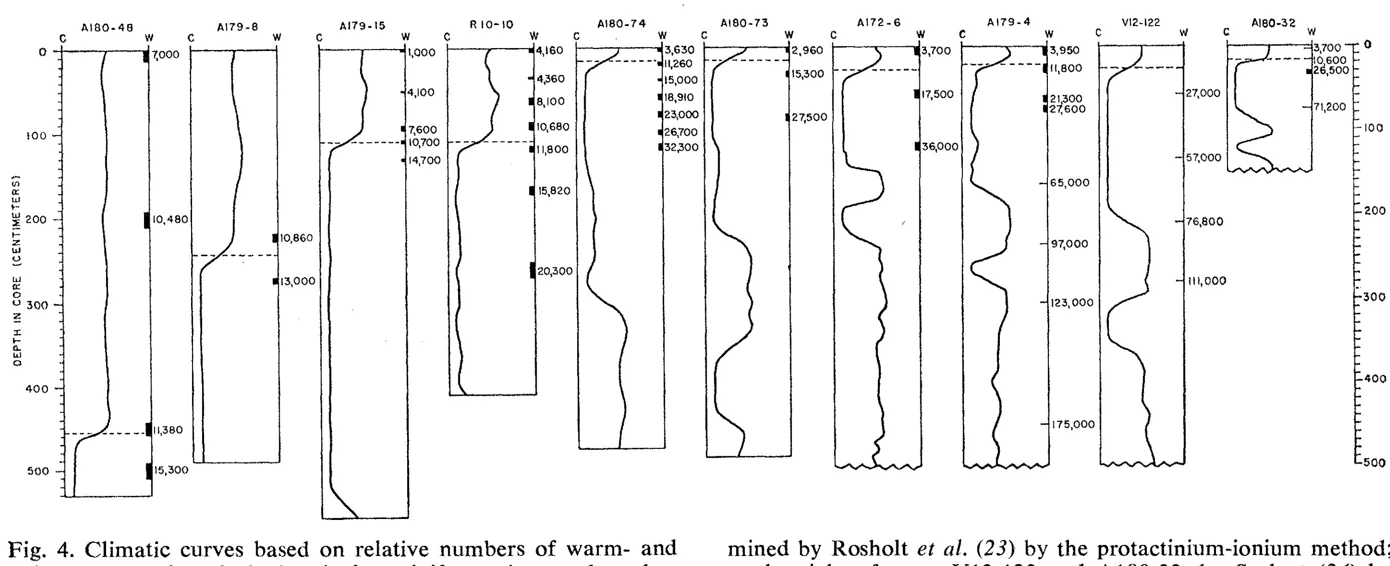


Fig. 4. Climatic curves based on relative numbers of warm- and cold-water species of planktonic foraminiferans in samples taken at 10-centimeter intervals in ten cores. *C*, cold climate; *W*, warm climate. Present climate is plotted on the midpoint between *C* and *W*, and inferred past climate is plotted with respect to it. Dashed lines indicate the end of the last ice age. Numbers to the right of the black boxes are radiocarbon ages in years. Sections of cores used for dating are indicated by the black boxes. Numbers to the right of the lines of core A179-4 are dates determined by Rosholt *et al.* (*23*) by the protactinium-ionium method; to the right of cores V12-122 and A180-32, by Sackett (*24*) by the protactinium method, with the exception of the radiocarbon age of 26,500 years in core A180-32. The midpoint of the samples dated by the protactinium-ionium method and by the protactinium method are indicated by the lines opposite the dates. Three of the cores (A172-6, A179-4, V12-122) are included in the group of 26 cores selected to show the complete record of the Pleistocene.

about 175,000 years ago. These dates indicate that the average rate of accumulation of sediment was on the order of 2.5 centimeters per 1000 years.

By measuring the thickness of the glacial and interglacial sections, we established the average thickness for each of them and the average for the complete Pleistocene. On the basis of the average rate of sediment accumulation of 2.5 centimeters per 1000 years and the fact that the average thickness of the whole Pleistocene section is about 38 meters, we have, by extrapolation beyond 175,000 years, established a time scale for the entire Pleistocene Epoch. As shown in Fig. 5, our time scale dates the beginning of the Pleistocene, as defined by the onset of the first ice age, the Nebraskan or Günz, at about 1.5 million years ago.

Evidence supporting our estimate of 1.5 million years for the duration of the Pleistocene has been published by other investigators in the last few years. This new evidence has come to light through the application of the potassium-argon method of dating to deposits on the continents. A volcanic deposit in the Sierra Nevadas of California has been dated at about 1 million years ago by Evernden *et al.* (*15*), who used the potassium-argon method. The volcanic deposit overlies a glacial till which Blackwelder (*25*) attributed to the Kansan ice age. On the other hand, Emiliani (*14*) cites this same dating as evidence of a long pre-Günzian or pre-Nebraskan Pleistocene, without mentioning Blackwelder's conclusion that this till probably represented glaciation during the Kansan ice age. Since we know of no valid reason for rejecting Blackwelder's assignment of this till to the Kansan ice age, we construe this dating as evidence that the Kansan ice age ended at least 1 million years ago. According to our interpretation of the core record, the Kansan ice age ended 1.06 million years ago.

Evernden *et al.* (*15*) have also determined the age of a "tuff with black pumices" of Volcano Bracciano in Italy as about 430,000 years. Blanc (*26*) assigned the time of deposition of this tuff to the late Mindel-Riss interglacial and shortly before the beginning of the Riss ice age. Blanc regarded his correlation as tentative. However that may be, the potassium-argon date, 430,000 years, and Blanc's tentative correlation are in agreement with our chronology,

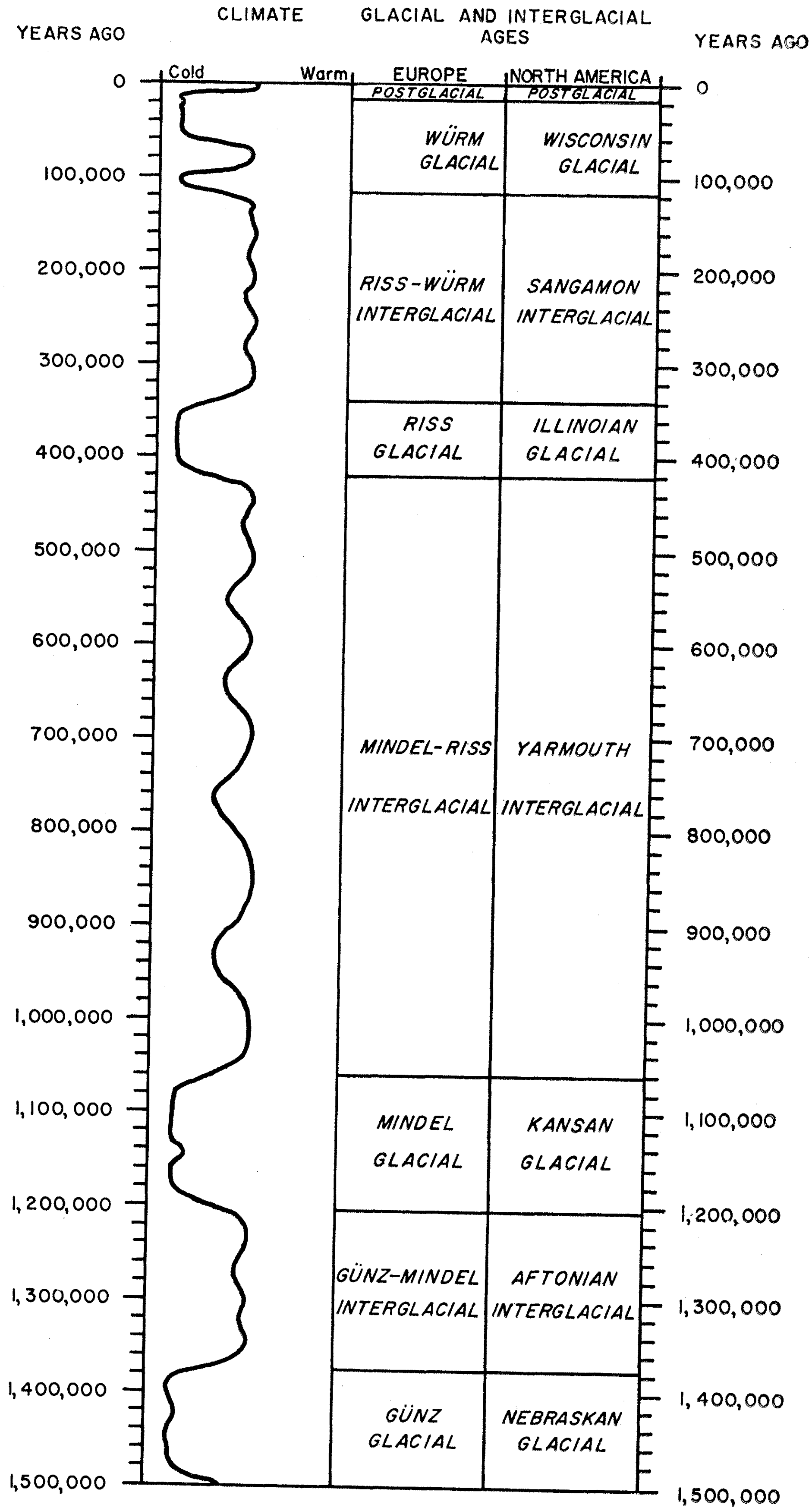


Fig. 5. Pleistocene time scale and generalized climate curve based on the study of deep-sea sediment cores. The beginning of the Pleistocene is considered to be the onset of the first glaciation, the Nebraskan or Günz.

which puts the time boundary between the Yarmouth interglacial and the Illinoian ice age at about 420,000 years before present.

On the negative side, Gentner and Lippolt (*27*) report a potassium-argon age of 350,000 $\pm$ 20,000 years for a terrace of the Rhine valley which has been correlated with the Günz ice age. Because we are not familiar with the terraces of the Rhine, we cannot ourselves impugn the correlation of the dated terrace with the Günz ice age. Neither are we able to assess the reliability of the authors' analytical methods. However, other investigators do not interpret the dating in the same way that Gentner and Lippolt do. Evernden *et al.* (*15*) cite their own dating of the Upper Main Terrace of the Rhine at 360,000 years ago as evidence that "the time scale of the classic four glaciations of the Alps is probably, as suggested by Zeuner, approximately 600,000," which amounts to saying that the Günz ice age began about 600,000 years ago. Of course, this conclusion is also at variance with our chronology; the date falls within what we believe was the Mindel-Riss interglacial. In fairness to our chronology we must point out that Zeuner's (*28*) suggestion that the Günz began 600,000 years ago was not based on radioactive dating; it was based, instead, on the astronomical theory which appeals to periodical perturbations in the orbit of the earth to explain the climatic fluctuations of the Pleistocene. However, the validity of the astronomical theory is far from having been proved. Furthermore, different authors derive disparate chronologies of the Pleistocene from it. Whereas Zeuner, relying on the astronomical theory, put the beginning of the Günz at 600,000 years ago, Emiliani (*29*) concludes that the astronomical theory supports his contention that the Günz began 300,000 years ago.

Perhaps the only valid conclusion to be drawn from these divergent estimates of Pleistocene chronology is that potassium-argon dating has not yet provided a firm chronology of the Pleistocene. This is not surprising; datable Pleistocene deposits are few, and there is sometimes disagreement regarding the positions of those few in the Pleistocene sequence. This is why we think that our chronology, based on a different kind of evidence, deserves consideration.

Figure 5 shows our time scale of the Pleistocene, our generalized climate curve, and our proposed correlation with the classic divisions of the Pleistocene.

Conclusion

Our record of the Pleistocene is the result of piecing together correlating and overlapping sections from 26 cores of deep-sea sediments, ranging in length from 545 to 2190 centimeters. These cores were selected from more than 3000 cores raised from all the oceans. Climate curves based on the relative numbers of warm-water and cold-water species of planktonic foraminiferans found in each of the 26 cores give a composite climatic record which is correlated with the glacial and interglacial ages of the Pleistocene. Additional evidence for continuity of the Pleistocene record is provided by changes in coiling direction of *Globorotalia truncatulinoides*.

Since periodic glaciations most clearly distinguish the Pleistocene from the earlier epochs of the Cenozoic, we consider that the onset of the first ice age, the Nebraskan or Günz, marks the beginning of the Pleistocene. The Pliocene-Pleistocene boundary is sharply defined by extinction of all discoasters and by an abrupt change in the planktonic foraminiferans.

The most important criteria which distinguish Pleistocene pelagic sediments from those of earlier epochs of the Cenozoic Period are absence of discoasters; the dominance of left-coiling, from 95 to 100 percent, in *Globorotalia menardii;* the general occurrence of *Globorotalia truncatulinoides* in abundance; and the absence of certain species or subspecies closely related to *Globorotalia menardii*, with consequent reduction of the *G. menardii* racial complex of the Pliocene to a much more homogeneous group in the Pleistocene.

Dates determined by the radiocarbon, the protactinium-ionium, and the protactinium methods provide an absolute time scale from the present back to about 175,000 years ago. These dates indicate that the average rate of accumulation of sediment was on the order of 2.5 centimeters per 1000 years. On the basis of this average rate of accumulation and the fact that we found the thickness of the whole Pleistocene section to be about 38 meters, we have, by extrapolation beyond 175,000 years, established a time scale for the entire Pleistocene epoch. Our time scale dates the beginning of the Pleistocene, as defined by the onset of the first ice age, the Nebraskan or Günz, at about 1.5 million years ago.

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