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Pleistocene Climates and Chronology in Deep-Sea Sediments

Magnetic reversals give a time scale of 2 million years for a complete Pleistocene with four glaciations.

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The Pleistocene epoch was a time of emergent continents, deep ocean basins, active volcanoes, and high mountains; a time of drastic climatic changes marked by repeated spreading of great ice sheets over wide regions; and a time of exceptionally rapid evolution of living things. The Pleistocene has been a battleground for scientists since it was named more than 100 years ago. A reason for great interest and heated controversy regarding the Pleistocene is probably its close connection with the evolution of man. If the climatic and topographical changes of the Pleistocene had not occurred, it is doubtful that *Homo sapiens* could have developed within its short span.

The Pleistocene is known to most people as the great ice age, the epoch of cavemen and woolly mammoths and huge continental ice sheets covering much of northern Europe and North America. Most early glaciologists refused to believe in more than a single glaciation. Explorations around the turn of the century, however, led to the recognition that the Pleistocene was divided into four successive major glaciations separated by long intervals of temperate climate. The view that the base of the Pleistocene coincides approximately with the earliest glacial deposits is generally accepted by gaciologists.

The concept that the Pleistocene is synonymous with glaciation has been widely discussed. Recently Selli (*1*) observed that direct correlation of the Pleistocene with the glacial epochs can no longer be maintained. He suggests that the preglacial Pleistocene appears to have lasted 1 to 1.5 times as long as the glacial Pleistocene. Berggren *et al.* (*2*, *2a*) and Hays and Berggren (*3*) have come to conclusions very similar to Selli's.

Our estimate for the duration of the Pleistocene is about the same as that of these investigators, but instead of including a preglacial interval and subsequent series of glaciations, our results indicate that the entire Pleistocene was divided into four major glaciations separated by three interglacial stages.

Because of the nature of the depositional process—that is, the alternating expansion and melting of the ice sheets—the deposits readily accessible to study that were left on the continents by the ice provide a discontinuous record at best. Then the difficulty of interpreting the record is compounded by the fact that, as each succeeding ice sheet spread over the land, it tended to destroy the evidence left by earlier glaciations. Furthermore, the long interglacial stages are often represented by nothing more than a weathered, or chemically altered, zone on the surface of glacial detritus left by a preceding ice sheet. As if this were not enough, in many regions the alternative to weathering has been total destruction of the record by erosion—the ceaseless washing away of unconsolidated sediment by rainfall, streams, and high winds which, little by little, transfer material from the continents to the ocean basins. Because the record of the Pleistocene on the continents is so nearly illegible, some investigators turned to the sediments of the deep ocean basins.

Deep-sea sediments offer an alternative approach. The extremely slow and continuous rain of fine mineral particles and hard parts of temperature-sensitive microorganisms on the ocean floor provides an ideal recording mechanism.

The pioneer work of Schott (*4*) on sediment cores collected in the equatorial Atlantic by the *Meteor* expedition opened up a new approach to the problem of the Pleistocene climates. Schott concluded that vertical variations in the abundance of the planktonic foraminiferans *Globorotalia menardii* in the cores probably corresponded with the moderating of climate 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.

Lamont Geological Observatory has a unique collection of cores of deep-sea sediment from all the oceans. The collection contains more than 5000 cores, obtained in more than 50 expeditions. In order to cope with this quantity of material, it was necessary to make use of a rapid method of foraminiferal analysis of the climatic record, based on relative numbers of warm-water and cold-water species. We published (*5*) results of an extensive study based on this method and gave a composite climatic record correlated with the glacial and interglacial stages of the Pleistocene. We defined the Pliocene-Pleistocene boundary from changes in species of planktonic foraminiferans and the extinction of Discoasteridae, the organisms responsible for secreting the minute star-shaped objects called dis-

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Table 1. Geographical location, water depth, and core length for the ten cores of our study.

Core*	Latitude	Longitude	Water depth (m)	Core length (cm)
A172-C6	14°59′N	68°51′W	4160	935
A179-C4	16°36′N	74°48′W	2965	690
V9-C11	3°13′S	32°12′W	4120	1207
V12-C18	28°42′S	34°30′W	2935	1080
V12-C122	17°00′N	74°24′W	2730	1090
V16-C39	24°43′S	4°45′W	4510	802
V16-C200	1°58′N	37°04′W	4095	989
V16-C205	15°24′N	43°24′W	4045	1257
V19-C297	2°37′N	12°00′W	4120	1300
V22-C163	26°22′S	00°56′E	4440	1080

* The letter that precedes a core number indicates the research vessel by which the core was taken: (A) *Atlantis*, (V) *Vema*. The number directly following the letter is the number of the expedition; the number that follows the hyphen and is preceded by C is the serial number of the core for the expedition in question.

coasters. Dates determined by the radiocarbon, the protactinium-ionium, and the protactinium methods provided an absolute time scale from the present back to about 175,000 years ago. We established a time scale of about 1.5 million years for the entire Pleistocene epoch by extrapolation beyond 175,000 years ago.

The discovery of paleomagnetic reversals in deep-sea sediments and their correlation with the reversal record of continental rocks is one of the most important recent contributions to marine geology. Significant results of studies made to determine the dates of sediment cores by this new method have been published by Harrison and Funnell (*6*), Fuller *et al.* (*7*), Opdyke *et al.* (*8*), Berggren *et al.* (*2*), Glass *et al.* (*9*), and Hays and Opdyke (*10*). The sequence of reversals provides a long-sought-for means of dating stratigraphical levels as far back as the beginning of the Pleistocene.

The chronology of the glacial Pleistocene is probably the most important because it provides a time scale against which to study the rate of biological and geological development, and it supplies anthropologists with a dated context in which to place the emerging races and cultures of man and his primitive predecessors. With the exception of our earlier estimate of about 1.5 million years for the duration of the glacial Pleistocene (*5*), estimates of its duration range from 300,000 to about 1 million years. Now, with paleomagnetic dates of the deep-sea cores available which give an absolute chronology for the entire Pleistocene and with a different method for interpreting the climatic record, the results indicate that the duration of the glacial Pleistocene was about 2 million years.

The Cores

Figure 1 shows the geographical locations of the coring stations, and Table 1 gives geographical locations, depths of water, and lengths of the cores, chosen because they contained correlatable faunal zones for which dates were available.

Our studies of thousands of cores have shown that two main classes of deep-sea sediments are (i) sediments that accumulate slowly and continuously and (ii) sediments that are laid down almost instantaneously by intermittent turbidity currents. We have found that there are three main processes that may cause confusion in the interpretation of the sediment record. Turbidity currents may deposit, almost instantaneously, layers of sediment several meters deep; slumping and submarine erosion due to deep currents may remove parts of the section; and deep-current scour may transport and redeposit both organic and inorganic components of older sediments. More often than not, cores from the deep ocean basins contain evidence of the effect of one or more of these disturbing processes. 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.

The correlation of the variation in the abundance of the *Globorotalia menardii* complex, of changes in coiling direction of *G. truncatulinoides*, of paleontological boundaries, and of the paleomagnetic stratigraphy of the cores used in this study indicates that they contain a continuous sediment record.

All the cores consist of foraminiferal lutite, a mixture of fine mineral particles from the continents and particles of calcium carbonate secreted by planktonic organisms. Except for minor variations in color in some of the cores, the sediment is uniform from top to bottom.

Frequency-to-Weight-Ratio Method

The method generally employed in foraminiferal studies is a determination of percentages of species in the total number of tests in the sample. This is time-consuming and, in the case of climatic studies, to some extent wasteful, in that it necessarily involves counting all species, even though some of the most abundant are of little or no significance from the standpoint of climate.

In deep-sea sediments of normal particle-by-particle deposition, the material coarser than 74 micrometers in particle diameter consists almost entirely of the tests of planktonic foraminifera. Therefore, the ratio of the number of tests of a particular species to the weight of the material coarser than 74 micrometers may be substituted for percentages (see *10a*). Experience shows that plots of variation in this ratio from level to level in sediment cores closely parallel curves for variation in percentages of species calculated in the conventional way. The new method has several advantages: (i) it results in a great saving of time; (ii) it makes it possible to plot

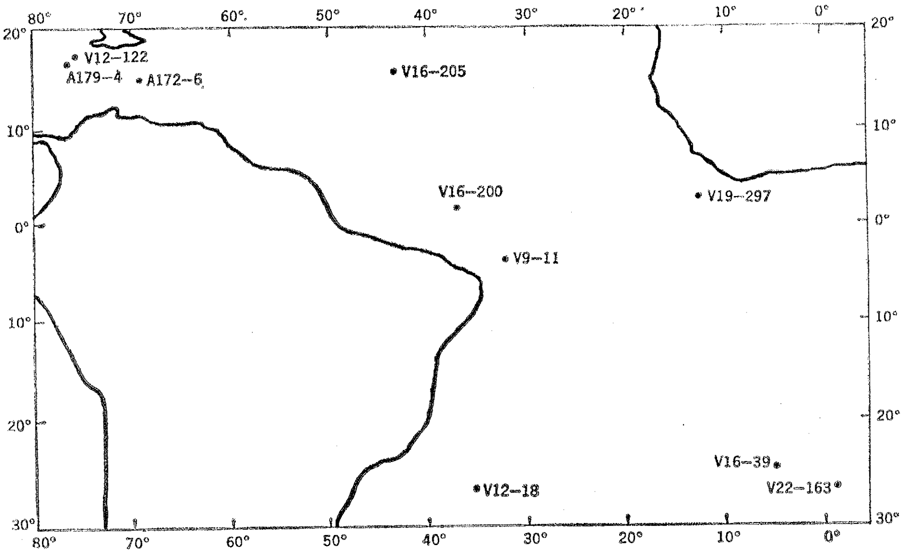


Fig. 1. Coring stations where the cores of Table 1 were obtained.

variations in the relative abundance of particular climatically sensitive species without having to count other species; and (iii) this, in turn, makes it possible to count larger samples, thereby increasing the statistical validity of the data.

The first step is to weigh to the nearest milligram the washed sample to be analyzed. Then the tests of the particular species to be studied are counted, and the ratio of the count to the weight (in milligrams) of the washed sample is calculated. This ratio, which may be called the "frequency" of the species, is, then, an index of its productivity with respect to the total productivity of all planktonic species at the particular core level being studied.

Our counts of the *Globorotalia menardii* complex and of *G. truncatulinoides, G. scitula, Globigerina inflata, Pulleniatina obliquiloculata, Sphaeroidinella dehiscens,* and *Globigerinella aequilateralis* indicate that the *Globorotalia menardii* complex is the most sensitive climatic indicator in the cores. This complex, which includes the three subspecies *Globorotalia menardii, G. m. tumida,* and *G. m. flexuosa,* was chosen because it characterizes certain well-defined faunal zones that are widespread in the equatorial Atlantic and in the Caribbean and the Gulf of Mexico. In addition, the frequency is highly variable from sample to sample, and this suggests that the complex is especially sensitive to changes in the environment. In the cores discussed here, the number of specimens counted in each sample varies from zero to over 2000. Samples were taken at 10-centimeter intervals in the cores.

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.* (*11*), is especially useful as a check on other methods, for it permits identification and cross correlation of layers no more than a few centimeters thick. Such precise correlations provide a valuable test of continuity of accumulation.

Climatic Interpretation

Studies, by Schott (*4*), Cushman and Henbest (*12*), Phleger (*13*), Ovey (*14*), Parker (*15*), Wiseman (*16*), Ericson *et al.* (*17*), and others, of the planktonic foraminiferans in deep-sea sediment

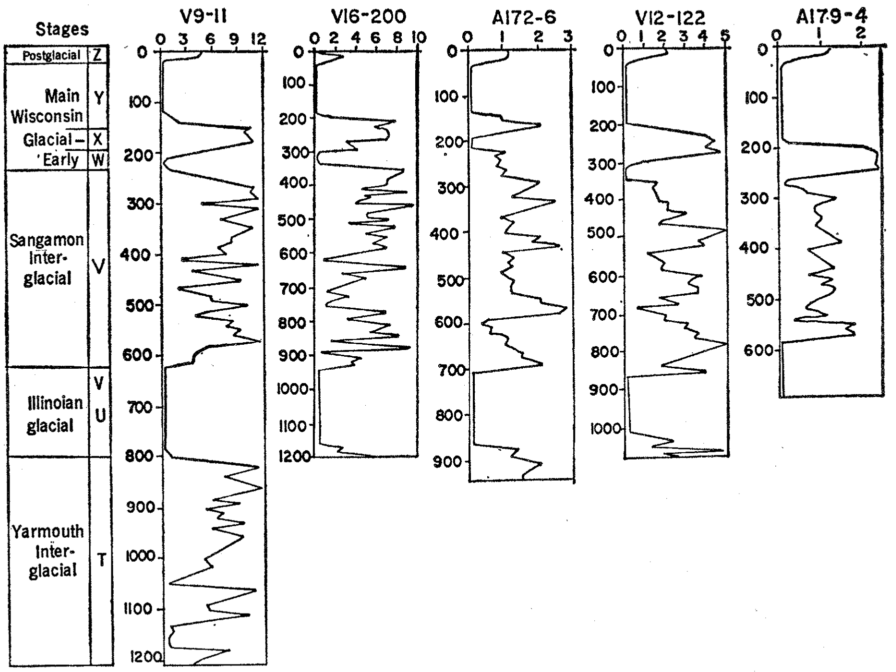


Fig. 2. Frequency curves for the *Globorotalia menardii* complex in five deep-sea sediment cores. Samples were taken at 10-centimeter intervals from top to bottom of the cores. The scales at the tops of the columns are ratios of the number of shells of the *G. menardii* complex to the total population of foraminifera in the samples. Since the magnitudes of these ratios differ consistently from core to core, we have plotted the ratios for each core on a different scale in order to show the climatic zones more clearly. We have correlated the climatic zones indicated by the curves with glacial and interglacial stages. The numbers to the left of the columns are depths in cores, in centimeters.

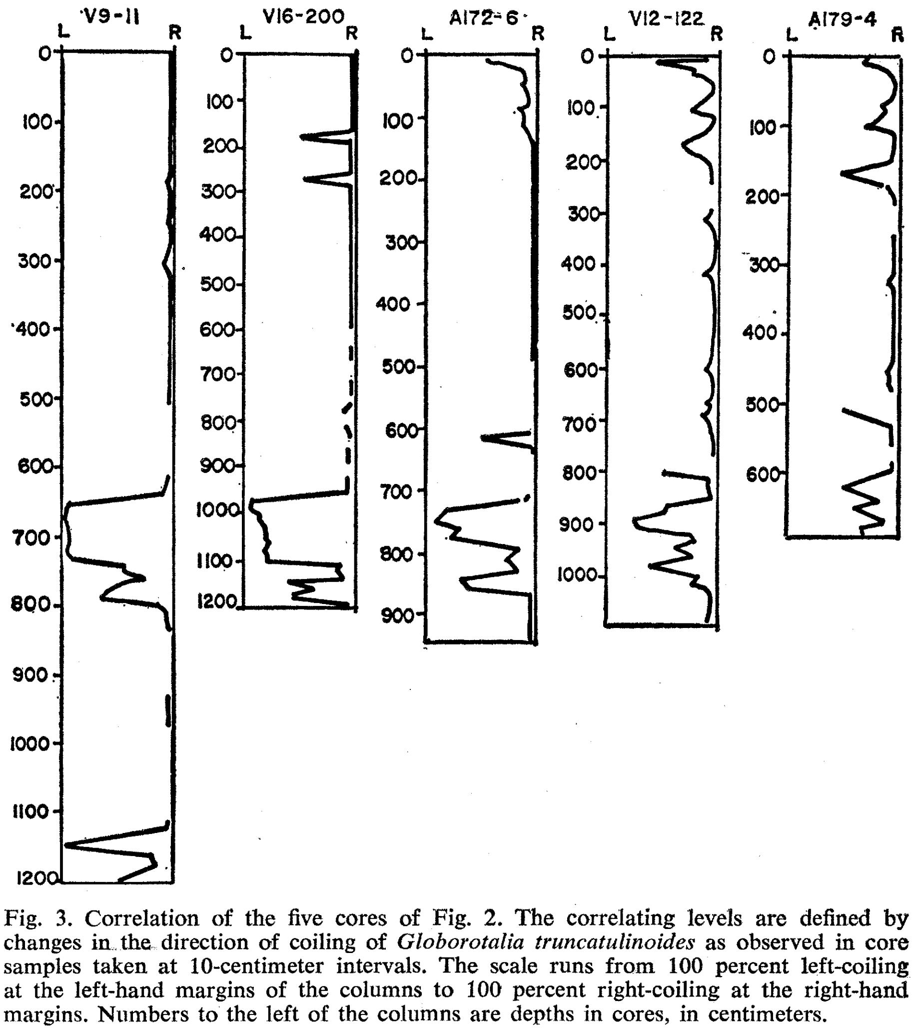


Fig. 3. Correlation of the five cores of Fig. 2. The correlating levels are defined by changes in the direction of coiling of *Globorotalia truncatulinoides* as observed in core samples taken at 10-centimeter intervals. The scale runs from 100 percent left-coiling at the left-hand margins of the columns to 100 percent right-coiling at the right-hand margins. Numbers to the left of the columns are depths in cores, in centimeters.

cores have shown that the relative abundances of the species that are sensitive to temperatures vary from level to level. These investigators agree that the 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. Like Schott, we believe that the *Globorotalia menardii* complex is the most sensitive and reliable of the climatic indicators.

Figure 2 shows the ratios of the number of shells of the *Globorotalia menardii* complex to the total population of foraminifera in the sample, for five cores. We have correlated the climatic zones indicated by the curves with glacial and interglacial stages, and designate them by letters according to the system begun by Ericson (*18*). The correlation of the cores with respect to changes in coiling direction of *G. truncatulinoides* is shown in Fig. 3. Age determinations by the radiocarbon, protactinium-ionium, protactinium, and thorium-230 methods for three of the cores are shown in Fig. 4.

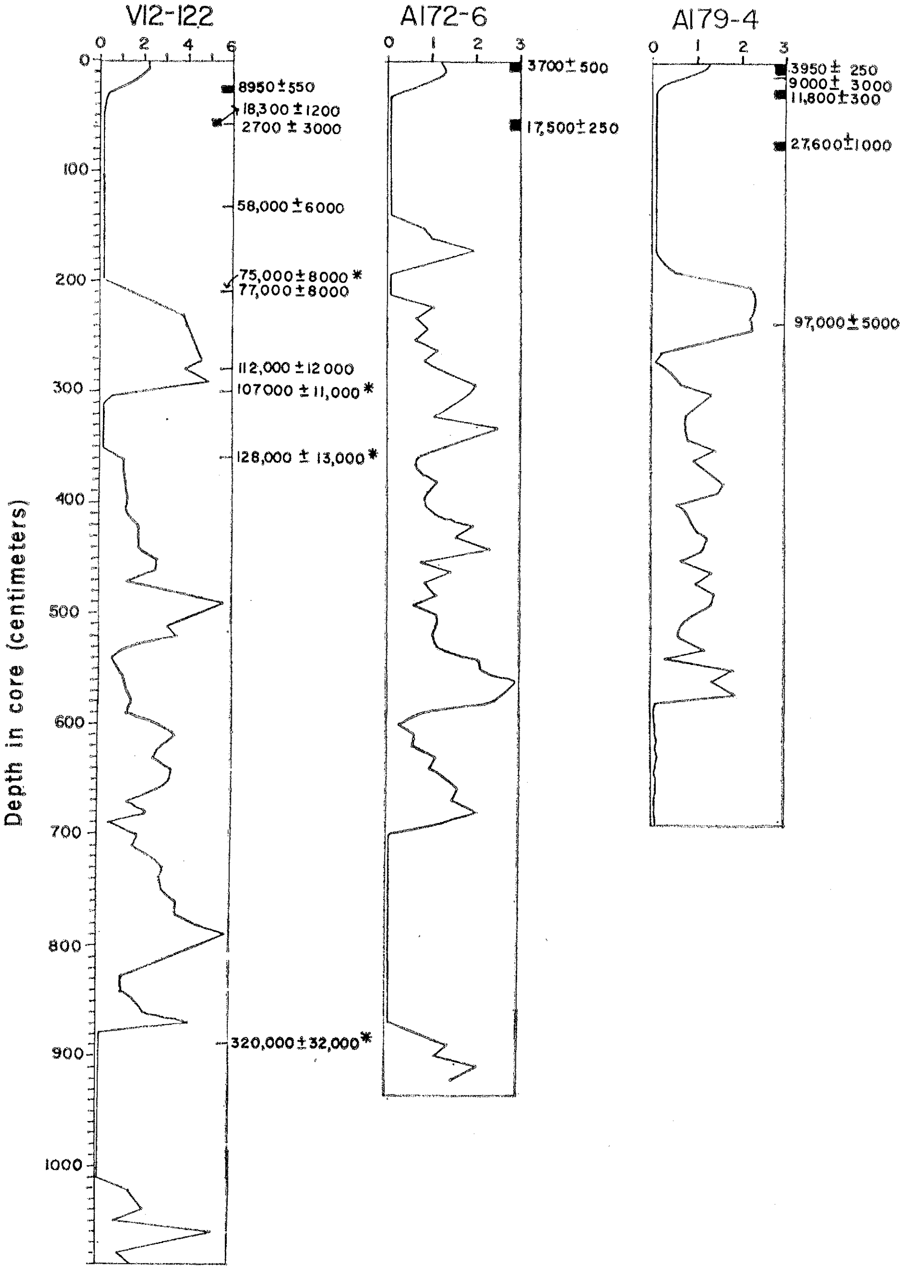


Fig. 4. Radiochemical age determinations and frequency curves for the *Globorotalia menardii* complex in three of the cores of Fig. 2. Numbers to the right of the black squares (sections of cores used for dating) are radiocarbon ages, in years. Numbers to the right of the horizontal lines of core A179-4 are dates determined by Rosholt *et al.* (*32*) by the protactinium-ionium method; those to the right of core V12-122 are dates determined by Sackett (*33*) by the protactinium method, and by Ku and Broecker (*34*) by the thorium-230 method (those obtained by Ku and Broecker are marked with an asterisk). The horizontal lines opposite the dates indicate the mid-depths of the samples used for dating by the three methods.

Several well-defined zones in the frequency curves of the *Globorotalia menardii* complex (Fig. 2) are evident. *Globorotalia menardii* and *G. m. tumida* are very abundant, but *G. m. flexuosa* is absent, in the Z zone, which we believe represents the postglacial section. In the Y zone the *G. menardii* complex is abundant, particularly the subspecies *G. m. flexuosa.* This zone characterized by *G. m. flexuosa* is present in cores from the Gulf of Mexico and the Caribbean, and in many cores from widely scattered stations in the Atlantic. Thus the evidence that the Y zones are equivalent in the five cores is good. In the W zone the *G. menardii* complex is absent or rare. In these five cores from low-latitude stations, this layer is relatively thin. Further north we have found it to be thicker, probably because of more rapid accumulation of the fine terrigenous fraction. The Y, X, and W zones we correlate with the Wisconsin glacial stage.

The *Globorotalia menardii* complex is consistently abundant (although the frequency varies markedly) in the V zone, which we correlate with the Sangamon interglacial stage. *Globorotalia menardii flexuosa* appears in abundance within the lower part of this zone. The *G. menardii* complex is rare or absent in the U zone, which we believe represents the Illinoian glacial stage.

Figure 5 shows the variation in the frequency curves for the *Globorotalia menardii* complex in five cores which penetrate more climatic zones than the cores shown in Fig. 2 do. According to our interpretation, in three of these cores (V12-18, V22-136, and V16-205) the complete Pleistocene section is represented. Core V16-39 almost penetrates the Pliocene-Pleistocene boundary, and core V19-297 reaches the end of the Nebraskan glacial, about 1.8 million years ago. The Jaramillo event was not detectable in V19-297, but the good correlation of that core, with respect to the frequency curve of the *G. menardii* complex, with the other four cores convinces us that absence of evidence of the Jaramillo event in V19-297 must be due to the difficulty of detecting magnetic reversals in unoriented cores from stations near the equator.

The coiling of *Globorotalia truncatulinoides* is also a valuable indicator of climate in the earlier zones of the Pleistocene, left coiling being dominant during times of cold climate, and vice versa.

The correlation of the three cores of this study from the South Atlantic (Fig. 1) with respect to changes in coiling direction of *Globorotalia truncatulinoides* is shown in Fig. 6. The species was too infrequent in one of the cores, V19-297, to yield meaningful counts. The coiling curve of core V16-205 from the North Atlantic is not shown in Fig. 6 because correlation is poor between this core and the three cores from the South Atlantic. Since, as has been shown by Ericson *et al.* (*11*), coiling of the living populations of *G. truncatulinoides* varies with latitude, similar variations probably occurred, at least at some periods, in the past. Therefore, close correlation of coiling curves in cores from stations widely separated in latitude is not to be expected.

As shown in Fig. 5, the T zone, which we correlate with the Yarmouth section, is somewhat different from the V zone, and from the R zone, which, we believe, represents the Aftonian section. The population of the *Globorotalia menardii* complex in the T zone makes up, on the average, a smaller proportion of the total assemblage of planktonic foraminiferans. Especially in the three cores from the South Atlantic (V12-18, V22-163, and V16-39), the Yarmouth sections, as indicated by the frequency curves of the *G. menardii* complex, are not so prominent as they are in cores from the North Atlantic and the equatorial Atlantic (cores V16-205, V19-297, and V9-11) (Fig. 2). The evidence suggests that the climate of the Yarmouth differed from that of the other two interglacials; we infer that the temperature of the water of the Atlantic was lower in Yarmouth time than it was during the other two interglacials. Another difference between the three interglacials is the fact that *G. m. flexuosa* occurs in the major part of the Sangamon section but is absent in the Yarmouth and Aftonian sections.

The *Globorotalia menardii* complex is absent or rare in the S and Q zones, which we correlate, respectively, with the Kansan and Nebraskan glacial stages. These two glacial sections differ in that the Discoasteridae and *Globorotalia* sp. 1 (*5, 19*) become extinct in the Nebraskan, whereas they are, necessarily, quite absent from the Kansan section. Only the lower part of one of the cores, V16-205, contains *Globigerinoides sacculifera fistulosa,* and this species disappears at about the level where the discoasters do. The change from right to left in the coiling direction of the members of the *Globorotalia menardii* complex occurs in two of the cores, at depth of 1030 centimeters in V12-18 and at 1170 centimeters in V16-205. The Pliocene-Pleistocene boundary is indicated by the first appearance of abundant *Globorotalia truncatulinoides.*

The *Globorotalia menardii*-complex curves obtained from cores V12-18 and V16-205 show cold zones extending beyond the Pliocene-Pleistocene bound-

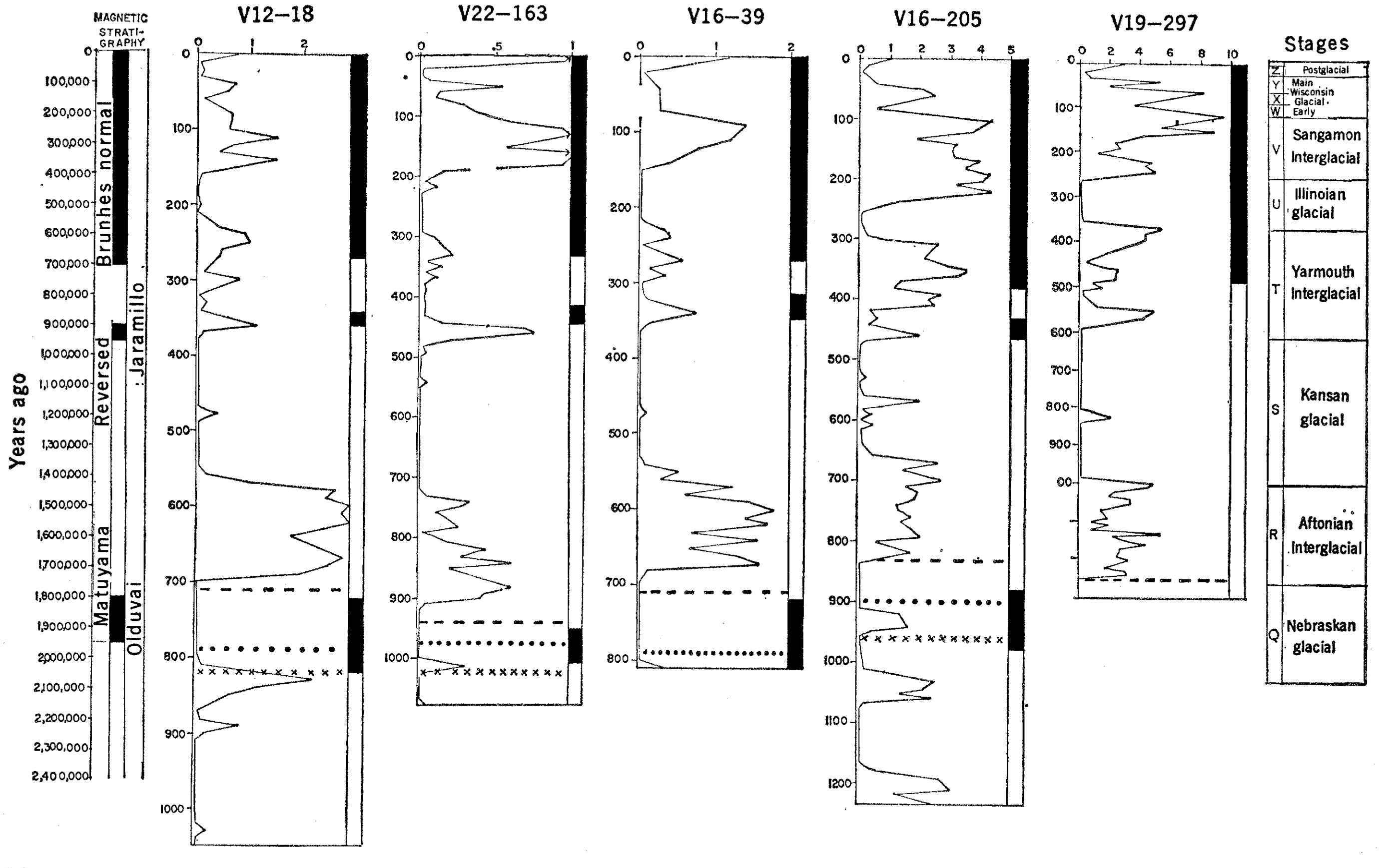


Fig. 5. Frequency curves for the *Globorotalia menardii* complex and magnetic and paleontological stratigraphy in five cores. Samples were taken at 10-centimeter intervals from top to bottom of the cores. The scales at the tops of the columns are ratios of the number of shells of the *G. menardii* complex to the total population of foraminifera in the samples. Since the magnitudes of these ratios differ consistently from core to core, we have plotted the data for each core on a different scale in order to show the climatic zones more clearly. We have correlated the climatic zones indicated by the curves with glacial and interglacial stages. The time scale for the magnetic stratigraphy in the column at left is from Pitman and Heirtzler (*35*). The magnetic stratigraphy for each core is designated by black (normal) and white (reversed) areas to the right of the columns. (Dashed lines) The level at which *Globorotalia* sp. 1 became extinct; (dotted lines) the level at which discoasters became extinct; (X-lines) the first appearance of abundant *G. truncatulinoides*, the criterion used for defining the Pliocene-Pleistocene boundary. Numbers to the left of the columns are depths in cores, in centimeters.

ary, as determined by the first appearance of abundant *G. truncatulinoides*. Thus, it seems that the change toward a colder climate began before the beginning of the Pleistocene.

The fact that the geographical spread of the cores used in this study is from 74°W to 1°E and from 17°N to 26°S is significant. Evidently variations in the frequency curve of the *Globorotalia menardii* complex occurred on a wide scale. Also, zone-by-zone correlation of the major features of the curves shown in Figs. 2 and 5 are continuous over a time interval of more than 1.8 million years. Furthermore, there is nothing in the curves to suggest that evolutionary variation in the *G. menardii* complex has caused an increase in sensitivity to change in ecological conditions; the change from "absent" to "frequent" that occurred about 1.7 million years ago is as clearly defined as later changes in the frequency curve of the complex.

The Pliocene-Pleistocene Boundary

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. The Pliocene-Pleistocene boundary in deep-sea sediments was first defined by Arrhenius (*20*), primarily on the basis of a sharp upward increase in calcium carbonate content in some cores from the eastern equatorial Pacific. On the basis of evidence from the cores, Arrhenius estimated the duration of the Pleistocene to be about 1 million years. Riedel (*21*) suggested that the level of extinction of two radiolarian species (*Pterocanium prismatium* and *Eucyrtidium elongatum peregrinum*) in tropical Pacific cores may serve to mark the "top of Pliocene." Riedel *et al.* (*22*) subsequently found that *P. prismatium* ranged higher than *E. e. peregrinum*.

We established (*5, 23*) the following faunal criteria for defining a Pliocene-Pleistocene boundary in deep-sea sediments: (i) extinction of Discoasteridae; (ii) first appearance of abundant *Globorotalia truncatulinoides*; (iii) change of *G. menardii* complex from diverse below the boundary to a more uniform lineage above it, increase in average test size and reduction in number with respect to total population above the boundary, and change from 95-percent dextrally coiled tests below the boundary to 95-percent sinistrally coiled tests above it; and (iv) extinction of *Globigerinoides sacculifera fistulosa* above the boundary. The thickness of the zone within which these changes occurred differed somewhat in the various cores.

Having examined the coccoliths in seven of the cores we had studied, McIntyre *et al.* (*24*) concluded that the boundary we had defined was the boundary between Aftonian interglacial and Nebraskan glacial. Bandy (*25*) expressed the opinion that the sections in the cores which we believed to be of Pliocene age were actually of latest Miocene age, and that the marked extinction of Discoasteridae in the cores was due to an unconformity, separating Miocene and Pleistocene sediments and representing a gap of some 10 million years of Pliocene time. However, Glass *et al.* (*9*) made paleomagnetic measurements on some of the cores and reported evidence that sediment accumulation across the boundary was continuous in two of the five cores in which meaningful magnetic measurements could be made. Glass *et al.* concluded that the Pliocene-Pleistocene boundary, as indicated by first evolutionary appearance of *Globorotalia truncatulinoides,* occurred at the base of the Olduvai event, about 2 million years ago, instead of about 1.5 million years ago as Ericson *et al.* had estimated.

Emiliani (*26*), on the basis of oxygen isotope analysis of cores, has estimated the base of the glacial Pleistocene variously at 300,000 to 425,000 years ago, and the base of the Pleistocene epoch at 600,000 to 800,000 years ago.

Recently Bolli and his associates (*27*) have identified the faunal changes of the Pliocene-Pleistocene boundary in a sediment section partially cored on the Nicaragua rise in the Caribbean. Because the core recovered included only 40.5 percent of the sediment section, it is perhaps not surprising that these investigators misidentified the magnetic reversal that coincides with the faunal changes as that marking the beginning of the Brunhes Normal Epoch. Accordingly they mistakenly assign an age of 700,000 years to the boundary.

In a study of radiolarians in deep-sea cores from Antarctic seas, Hays (*28*) recognized four faunal zones, the boundary between the lower two being marked by a striking faunal change and by a change from red clay to diatom ooze. He suggested that this boundary coincided approximately with the Pliocene-Pleistocene boundary of Ericson and his associates. Opdyke *et al.* (*8*) determined the paleomagnetic stratigraphy of several Antarctic cores containing Hays's boundary and found that the boundary occurs near the base of the Olduvai event, about 2 million years ago.

Banner and Blow (*29*), working in the Calabrian type section in Italy, have shown that *Globorotalia truncatulinoides* evolved from *G. tosaensis* and have suggested that the first appearance of *G. truncatulinoides* may be a suitable criterion for defining the Pliocene-Pleistocene boundary. Their boundary, therefore, is approximately the same as ours (*5, 23*), since we placed the Pliocene-Pleistocene boundary in deep-sea sediment cores at the point where *G. truncatulinoides* first appears in abundance. Thus, deep-sea sediments can be correlated with the continental type Pliocene-Pleistocene section in Italy. Selli (*1*), by extrapolation of sedimentation rates, arrived at a date of 1.8 million years ago for the Pliocene-Pleistocene boundary, on the basis of the first evolutionary appearance of *G. truncatulinoides,* in the Calabrian type section.

In a recent study of deep-sea sediment cores by Berggren *et al.* (*2*), the Pliocene-Pleistocene boundary, as determined by the first evolutionary appearance of *Globorotalia truncatulinoides,* was found to occur within the Olduvai event, about 1.85 million years ago.

As shown in Fig. 5, the Pliocene-Pleistocene boundary in our cores, as indicated by the first appearance of abundant *Globorotalia truncatulinoides,* occurs at the base of the Olduvai event, about 2 million years ago.

Chronology

Paleomagnetic studies of volcanic rocks on land have established the occurrence of a series of reversals of polarity of the earth's magnetic field and have provided dates for these events, obtained by means of the potassium-argon method (*30*). It is known that the earth's field has had its present, or normal, polarity for the last 700,000 years. This period has been named the Brunhes normal epoch. For approximately 1.7 million years before the Brunhes normal epoch the earth's field had an opposite or reversed polarity; this period has been named the Matuyama reversed epoch. Within the Matuyama reversed epoch, two short periods of normal polarity occurred, at about 900,000 and 1.9 million years ago; these have been termed the

Jaramillo and Olduvai events, respectively. It has recently been shown that the remanent magnetism of deep-sea sediments is sufficiently strong and stable that these polarity reversals can be used to date and correlate geological events recorded in these sediments throughout the world during the past 5 million years (*2*, *8–10*, *31*).

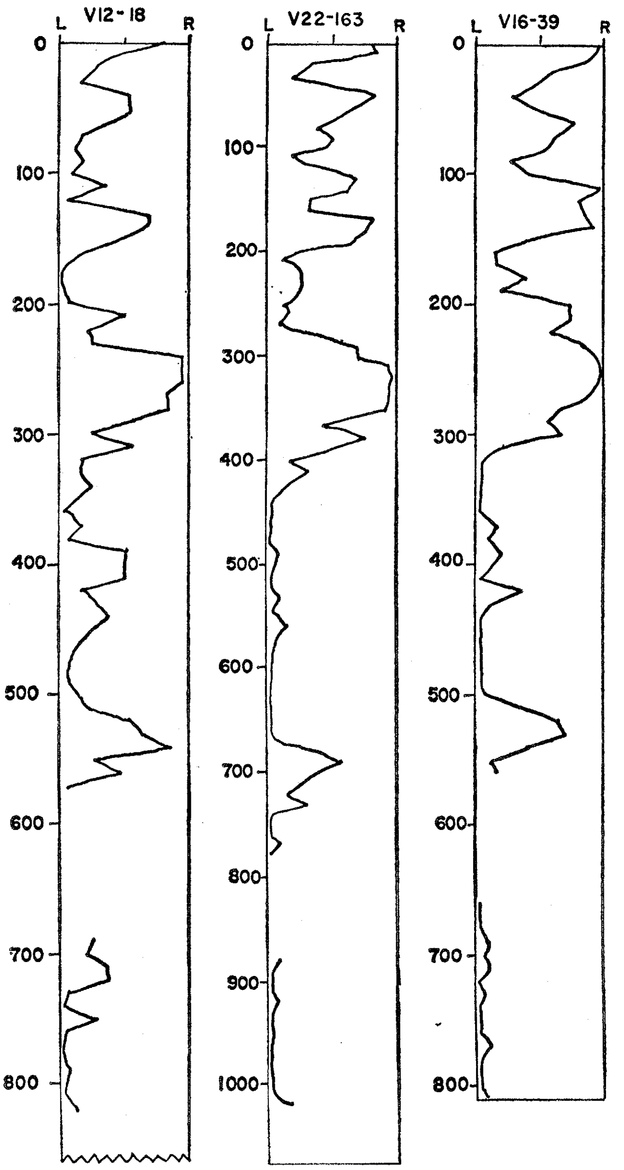
Paleomagnetic studies of four of the cores shown in Fig. 5 have been made by Glass, and the fifth core, V22-163, has been studied by N. D. Opdyke of the Lamont Geological Observatory.

As shown in Fig. 5, the Pliocene-Pleistocene boundary, as defined by the first appearance of *Globorotalia truncatulinoides* in abundance, occurs at or near the base of the Olduvai event, about 2 million years ago. Discoasteridae became extinct within the Olduvai event about 1.9 million years ago, and *Globorotalia* sp. 1 became extinct near the top of the Olduvai event, about 1.8 million years ago.

Figure 7 shows a time scale based on magnetic reversals in the five cores of Fig. 5; our generalized climate curve, based on variation in the frequency of the *Globorotalia menardii* complex in the ten cores used in our study; and our proposed correlation with the stages of the Pleistocene. In comparison with the time scale of 1.5 million years that we had proposed earlier (*5*), this revised Pleistocene time scale of 2 million years increases the durations of the three earliest climatic events, Q, R, and S. The S zone, considered by us to be equivalent to the Kansan glacial stage, now seems to have been of longer duration than the T zone, which we equate with the Yarmouth interglacial.

Conclusion

Our Pleistocene climatic record of four major glaciations and three interglacial stages is the result of our study of variations in the frequency of the *Globorotalia menardii* complex in ten cores from the Atlantic and the Caribbean. Evidence for continuity of the



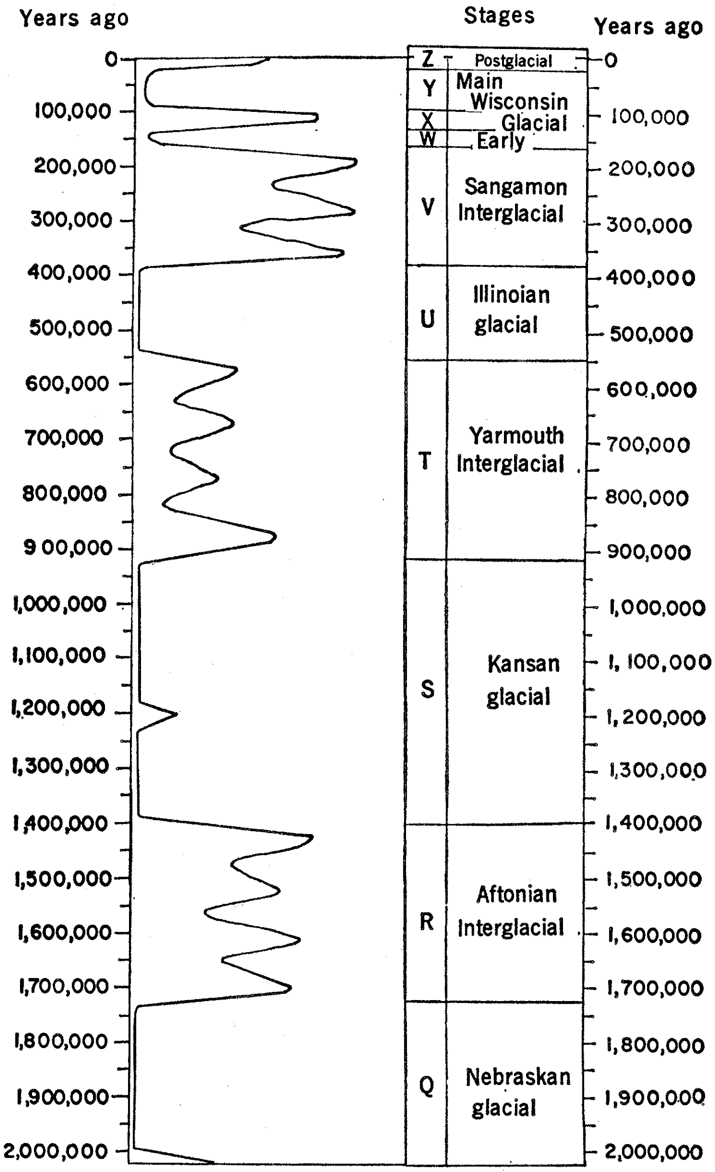


Fig. 6 (left). Correlation of three of the cores of Fig. 5. The correlating levels are defined by changes in the direction of coiling of *Globorotalia truncatulinoides* as observed in core samples taken at 10-centimeter intervals. The scale runs from 100 percent left-coiling at the left-hand margins of the columns to 100 percent right-coiling at the right-hand margins. Numbers to the left of the columns are depths in cores, in centimeters. Fig. 7 (right). Pleistocene time scale, based on magnetic reversals in the five cores of Fig. 5, a generalized climate curve based on variation in the frequency of the *Globorotalia menardii* complex in the ten cores used in this study, and a proposed correlation with the stages of the Pleistocene. The beginning of the Pleistocene is defined by the first appearance of *G. truncatulinoides* in abundance.

Pleistocene record is also provided by changes in the coiling direction of *G. truncatulinoides*.

The most important criteria which distinguish Pleistocene pelagic sediments from sediments of earlier epochs of the Cenozoic Period are the general occurrence of *Globorotalia truncatulinoides* in abundance and the absence of discoasters.

Our time scale, based on magnetic reversals, dates the beginning of the Pleistocene, as defined by the first appearance of *Globorotalia truncatulinoides* in abundance, at about 2 million years ago.

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CURRENT PROBLEMS IN RESEARCH

Clinical and Psychological Effects of Marihuana in Man

Andrew T. Weil, Norman E. Zinberg, Judith M. Nelsen

In the spring of 1968 we conducted a series of pilot experiments on acute marihuana intoxication in human subjects. The study was not undertaken to prove or disprove popularly held convictions about marihuana as an intoxicant, to compare it with other drugs, or to introduce our own opinions. Our concern was simply to collect some long overdue pharmacological data. In this article we describe the primitive state of knowledge of the drug, the research problems encountered in designing a replicable study, and the results of our investigations.

Marihuana is a crude preparation of flowering tops, leaves, seeds, and stems of female plants of Indian hemp *Cannabis sativa* L.; it is usually smoked. The intoxicating constituents of hemp are found in the sticky resin exuded by the tops of the plants, particularly the females. Male plants produce some resin but are grown mainly for hemp fiber, not for marihuana. The resin itself, when prepared for smoking or eating, is known as "hashish." Various *Cannabis* preparations are used as intoxicants throughout the world; their potency varies directly with the amount of resin present (*1*). Samples of American marihuana differ greatly in pharmacological activity, depending on their composition (tops contain most resin; stems, seeds, and lower leaves least) and on the conditions under which the plants were grown. In addition, different varieties of *Cannabis* probably produce resins with different proportions of constituents (*2*). Botanists feel that only one species of hemp exists, but work on the phytochemistry of the varieties of this species is incomplete (*3*). Chronic users claim that samples of marihuana differ in quality of effects as well as in potency; that some types cause a preponderance of physical symptoms, and that other types tend to cause greater distortions of perception or of thought.

Pharmacological studies of *Cannabis* indicate that the tetrahydrocannabinol fraction of the resin is the active portion. In 1965, Mechoulam and Gaoni (*4*) reported the first total synthesis of (—)-Δ^1-*trans*-tetrahydrocannabinol (THC), which they called "the psychotomimeti-

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This work was conducted in the Behavioral Pharmacology Laboratory of the Boston University School of Medicine, sponsored and supported by its division of psychiatry, and at the Boston University Medical Center, Boston, Massachusetts. The present addresses of the authors are: Dr. Weil, Mt. Zion Hospital and Medical Center, San Francisco, California 94115; Dr. Zinberg, Harvard University, Cambridge, Massachusetts; and Miss Nelsen, Department of Pharmacology and Experimental Therapeutics, Boston University School of Medicine, Boston, Massachusetts 02118.