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# Pliocene-Pleistocene Boundary in Deep-Sea Sediments

## Extinctions and evolutionary changes in microfossils clearly define the abrupt onset of the Pleistocene.

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About one hundred years ago scientists made two giant strides toward an understanding of our past environment and our origin—general acceptance of the theory of continental glaciation during the Pleistocene or Anthropogene epoch and recognition that during that epoch man had evolved from some lower primate. Since then geologists and anthropologists have sought a way to measure the duration of the Pleistocene in order to determine man's rate of physical and cultural evolution. Here the crux of the problem has been to find tangible evidence of the beginning of the Pleistocene. Because of the nature of the depositional process, the easily accessible deposits left on the continents by former glaciers provide only a discontinuous record at best. To make matters worse, disturbance by later glaciations has garbled the earlier part of the record.

Deep-sea sediments offer an alternative approach to the problem. 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 collection of sediment cores at Lamont Geological Observatory includes more than 3000 cores raised from all the oceans and adjacent seas during 43 oceanographic expeditions since 1947. The corer used was designed by Ewing on the principle of the piston corer of Kullenberg (*1*). It has the great advantage over pistonless corers that it does not distort the thickness of the lower layers of sediment. We have found, after careful study of all 3000 cores, that eight contain a boundary clearly defined by changes in remains of planktonic organisms. We conclude that this boundary marks the onset of the first ice age of the Pleistocene. To our knowledge no one has ever before defined the Pliocene-Pleistocene boundary by means of planktonic organisms. Because of the broad geographical distribution of planktonic organisms the criteria defining the boundary should be almost universally applicable to marine sediments.

To the best of our knowledge this article presents the first evidence of multiple criteria which can be widely applied for defining the Pliocene-Pleistocene boundary and which indicate that the transition from Pliocene to Pleistocene was abrupt.

The boundary is defined by a faunal change which takes place within a sediment thickness of no more than 10 to 15 centimeters. The type of sediment indicates that an accumulation of this thickness represents no more than about 6000 years. Since vertical mixing of microfossils by mud-feeding burrowers would tend to increase the apparent thickness of the transition zone, the real time interval represented by the transition zone was certainly somewhat shorter, perhaps much shorter than 6000 years.

The contrast between the planktonic assemblages above and below this zone indicates that the climatic change was such as to have had a profound effect upon the evolution of planktonic organisms. Thus, the eight cores provide a rare opportunity to follow the evolutionary reactions of populations of Foraminifera and individual species living at various latitudes during the relatively long climatic deterioration of the late Pliocene and during the sudden and severe onset of Pleistocene climate, and thereby to gain some insight into the process of speciation.

No mineralogical, chemical, or physical change marks the boundary in any of the cores. The purely paleontological criteria defining the boundary are as follows:

1) Extinction of all discoasters.
2) Change in the coiling direction of members of the *Globorotalia menardii* complex from 95 percent dextral coiling below the boundary to 95 percent sinistral coiling above it and at all higher levels in the Pleistocene.
3) Appearance of *Globorotalia truncatulinoides* in abundance above the boundary.
4) Extinction of *Globigerinoides sacculifera fistulosa.*
5) Reduction of the *Globorotalia menardii* complex to a single fairly uniform race above the boundary.
6) Increase in the average diameter of the tests of *G. menardii* and reduction in their number with respect to the total assemblage 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 climatic fluctuations, which apparently occurred continuously during the Pliocene (*2*). We believe that the boundary marks the

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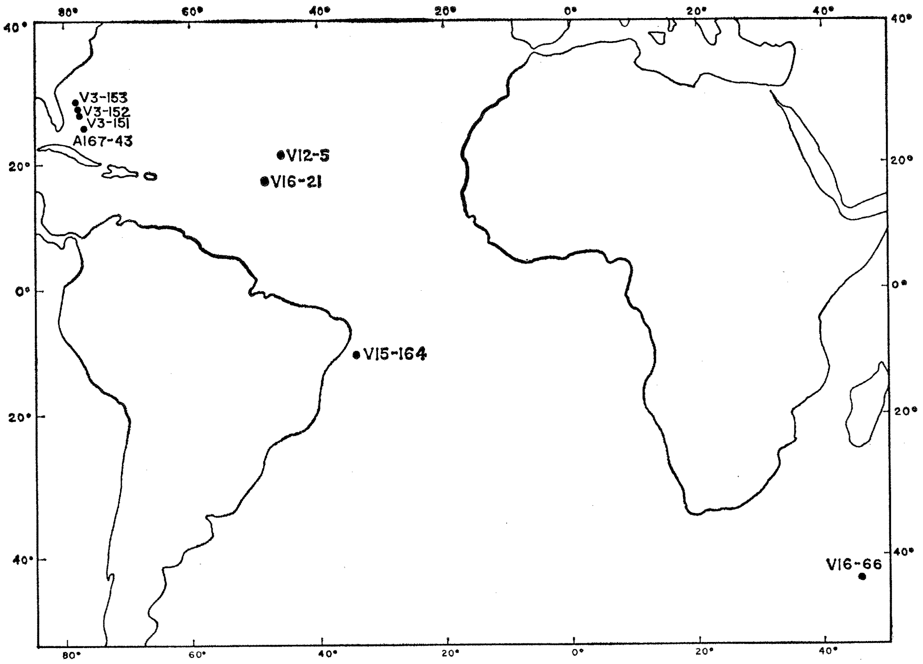


Fig. 1. Locations of cores.

first ice age of the Pleistocene. Whether this was the Günz or a pre-Günz glaciation cannot be determined at present. Since periodic glaciations most clearly distinguish the Pleistocene from the earlier epochs of the Cenozoic era, we suggest that this faunal boundary, recording the first glaciation, be chosen as marking the beginning of the Pleistocene.

The evidence presented in this article of a drastic and relatively abrupt refrigeration superimposed upon the secular climatic deterioration of the late Pliocene has an important bearing on the causation of continental glaciations and may eventually advance our understanding of present and future climates. The minimum extrapolated age of this climatic event, 800,000 years, has important implications for the rate of man's evolution.

## The Pleistocene Epoch

Because glacial climate, more than anything else, sets the Pleistocene apart from the earlier epochs of the Cenozoic, it is logical to define the beginning of the Pleistocene as the onset of the first continental glaciation. Unfortunately, students of the Pleistocene disagree as to the number of continental glaciations that occurred during the Pleistocene, and consequently unanimity regarding the lower stratigraphical boundary even in glaciated regions is still lacking.

Geographical distribution of fossil plants and animals yields evidence of a gradually deteriorating climate during the late Pliocene. Paleo-temperatures determined by the oxygen isotope method show that climatic fluctuations similar to those of the Pleistocene but of less extreme temperature occurred during the late Pliocene. One can envision, under such a climatic regime, a succession of mountain glaciations, each a trifle larger than the preceding one, followed by restricted continental glaciations that gradually expanded into the great continental glaciations of the later Pleistocene. In such a gradually expanding series, "first glaciation" would cease to have meaning.

Table 1. Locations, depths of water, and lengths of cores. 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 the 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.

| Core | Latitude | Longitude | Depth (m) | Length (cm) |
|---|---|---|---|---|
| A167–43 | 25°27′N | 77°03′W | 2605 | 510 |
| V3–151 | 27°58′N | 77°23′W | 1130 | 540 |
| V3–152 | 28°10′N | 77°37′W | 1005 | 562 |
| V3–153 | 28°24′N | 77°56′W | 970 | 545 |
| V12–5 | 21°12′N | 45°21′W | 3000 | 735 |
| V15–164 | 9°45′S | 34°24′W | 3380 | 690 |
| V16–21 | 17°16′N | 48°25′W | 3795 | 702 |
| V16–66 | 42°39′S | 45°40′E | 2995 | 1108 |

Search for a natural boundary in unglaciated regions has also presented difficulties. Vertebrate paleontologists have agreed among themselves to define the beginning of the Pleistocene by the first appearance of the horse, the true elephant, and cattle (*3*). The invertebrate paleontologists have wavered between the first appearance of the cool-water clam, *Cyprina islandica*, and the considerably later first appearance of the benthic foraminifer *Anomalina baltica* in the marine sediments of the Mediterranean region. To end the indecision a commission of the 18th International Geological Congress recommended in 1950 that the Pliocene-Pleistocene boundary be defined by the first appearance of *Anomalina baltica*.

Official approval notwithstanding, this definition is not fully satisfactory. There is no compelling evidence that the first appearance of *A. baltica* marks the onset of the first glaciation. Neither is it clear that this definition of the Pliocene-Pleistocene boundary coincides with that of the vertebrate paleontologists. In any case, these paleontological criteria, we believe, are valid only locally—that is, within the Mediterranean region. These difficulties have prompted some investigators to search for a natural Pliocene-Pleistocene boundary in deep-sea sediments.

## Earlier Studies of Sediment Cores

Among sediment cores raised in the Pacific by the Swedish Deep-Sea Expedition 1947–1948, G. Arrhenius (*4*) found two which in his opinion included sediment representing all of the Pleistocene epoch and part of the Pliocene. He based his conclusion on variations in carbonate content from layer to layer and the supposition that abundant biogenous carbonate represented times of rapid oceanic circulation which, in turn, corresponded to ice ages. He placed the Pliocene-Pleistocene boundary at a level above which there was a marked increase in carbonate. Thus, his evidence was geochemical rather than paleontological, and it was inapplicable outside of the equatorial Pacific. On the evidence from these cores Arrhenius estimated the duration of the Pleistocene as about 1 million years.

Study by Ericson *et al.* (*5*) of 221 sediment cores raised by Ewing and his co-workers has shown that disturbance and redistribution of sediment by turbidity currents and slumping is far more prevalent than had been previously supposed. The effect of turbidity-current deposition is to increase greatly the rate of sediment accumulation, with the result that even the longest cores rarely reach sediment zones older than the last ice age in areas where turbidity currents have occurred frequently. Fortunately, since turbidity-current deposits are limited to the floors of deep basins and the gentle slopes of the continental rise, one can avoid them by coring on topographical highs.

Slumping of sediment leads to loss of some part of the section. As a rule such hiatuses in the record, particularly when they occur within the Pleistocene section, are not evident from examination of the lithology. The only certain way of detecting them is to cross-correlate, by paleontological methods, several cores from the same region. We reason that, whereas slumping may occur simultaneously (if triggered by a seismic shock, for example) on several isolated rises, the probability of loss of the same stratigraphical thickness at the various stations should approach zero as the number of cross-correlated cores increases and the geographical scatter of the coring stations widens. In this way we believe we have verified beyond reasonable doubt the continuity and completeness of our published (*5*) series of late Pleistocene faunal zones. We have attained this degree of assurance only through applying rapid methods of faunal analysis to the many cores available at the Lamont Geological Observatory.

Because of the difficulty of recovering cores much longer than about 12 meters in calcareous sediment of slow accumulation, we have not yet found any core which in our opinion includes a continuous record of all Pleistocene time. However, in our search for the lower boundary of the Pleistocene section, slumping, normally a nuisance, has proved to be an advantage in that it has reduced the thickness of the late-Pleistocene section at the expense of its continuity and has thus brought its basical boundary within reach of the coring tube. Figure 1 shows the geographical positions of the coring stations, and Table 1 gives latitudes and longitudes of the stations, depths of water, and lengths of cores.

## Lithology of the Cores

The sediment of the seven cores from the Atlantic is a burrow-mottled tan-to-light-tan unsorted foraminiferal lutite. In lithology, these cores are indistinguishable from hundreds of others from the Atlantic and adjacent seas. The sediment of the core from the Indian Ocean (core V16–66) is a silty burrow-mottled lutite, grayish-tan-to-light-buff, containing abundant tests of Foraminifera and Radiolaria. From the top 850 centimeters the sediment contains scattered heterogeneous mineral and rock fragments. This land-derived detritus is indicative of rafting by drifting ice.

With the exception of core A167–43, none of the cores contains any sharply defined lithological discontinuity, or any abrupt increase in state of compaction such as one would expect if a considerable thickness of sediment had been removed by slumping. In core A167–43 a sharply defined color change occurs within the Pleistocene section, 60 centimeters from the top. In spite of the absence of similar clearly defined lithological discontinuities in the other cores, it is evident from the thick-

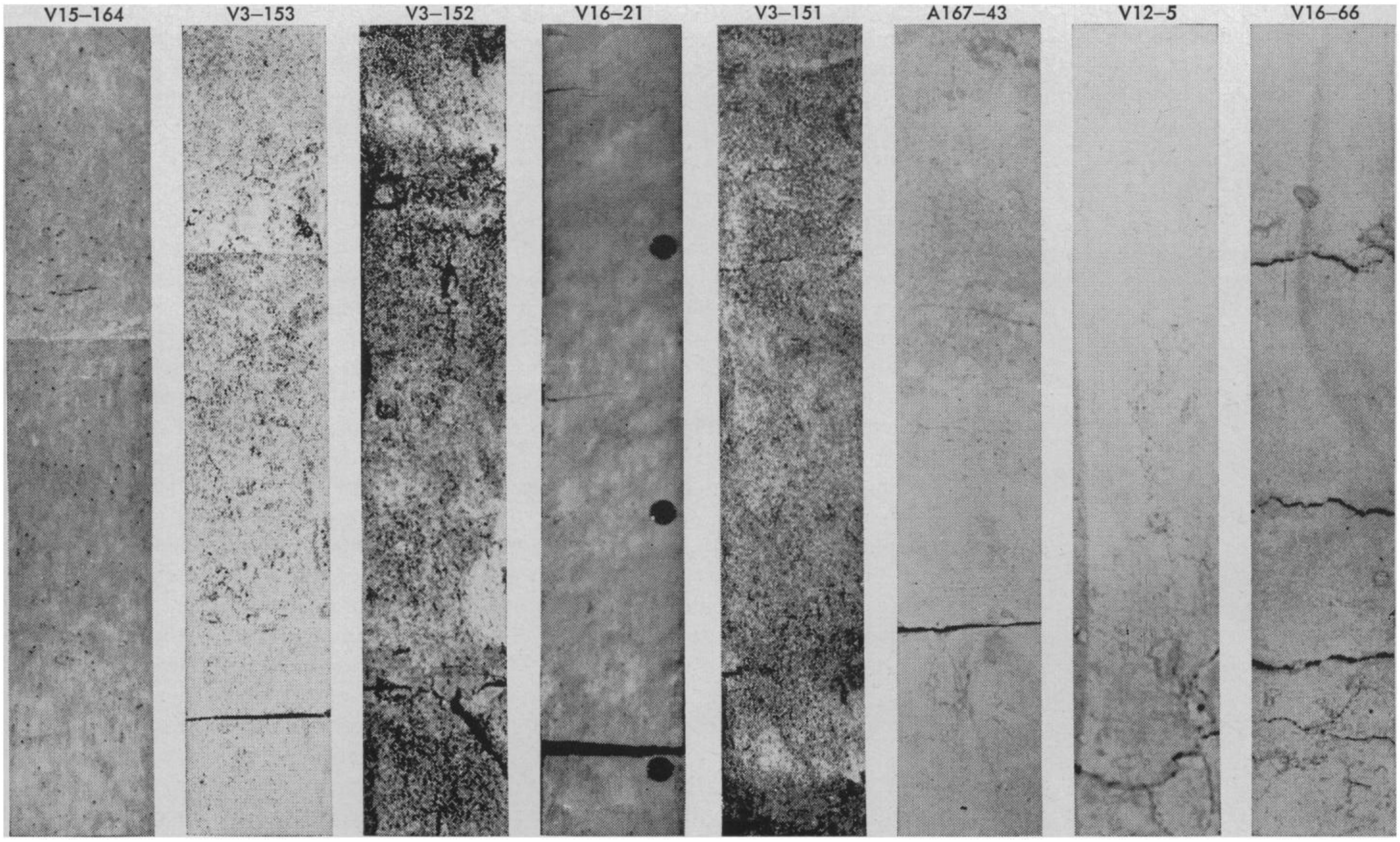


Fig. 2. The core sections which represent the transition from Pliocene to Pleistocene. The midpoint of each section is the midpoint of the Pliocene-Pleistocene boundary. The length of each section is about 25 centimeters. The width of the core section is 6 centimeters.

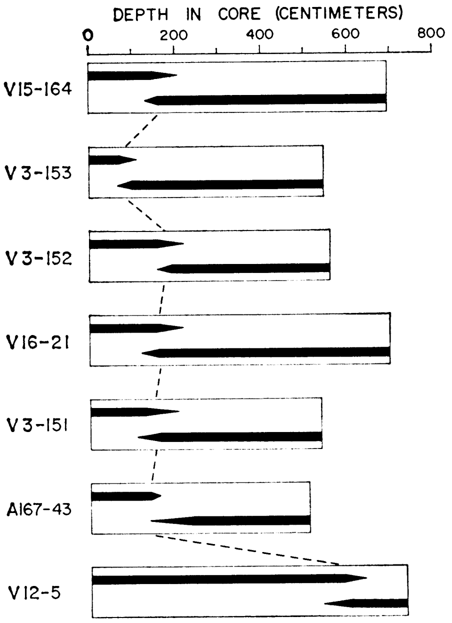


Fig. 3. Pliocene-Pleistocene boundary indicated by abundance of *Globorotalia truncatulinoides* and discoasters in seven deep-sea sediment cores. The dashed lines connect the boundary in the various cores. The core sections to the right of the dashed lines are Pliocene; the sections to the left are Pleistocene. Upper solid zone in each core, *G. truncatulinoides*; lower solid zone, discoasters. Thickness of the solid zones indicates abundance.

ness of the Pleistocene sediment that these sections are incomplete because of loss through slumping.

As Fig. 2 shows, A167–43 is the only core in which there is a lithological change at the boundary. The inconspicuous color change in this core is probably related to the close proximity of the Bahama Islands. Emergence of the islands as a result of the eustatic lowering of the sea level at the onset of the first glaciation would naturally have had some effect upon the kind of sediment that reached this nearby area.

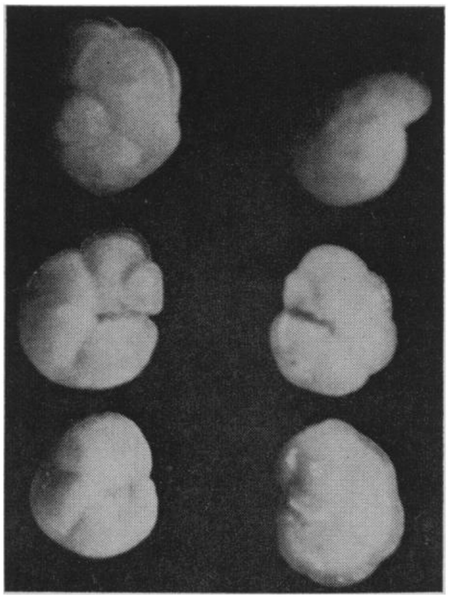


Fig. 4. Left-coiling shells of *Globorotalia menardii* (at left) and right-coiling shells (at right). [About × 27]

The finding that the faunal zones in the upper parts of the eight cores fail to correlate with the standard sequence of late Pleistocene faunal zones described by Ericson *et al.* (*5*) in cores from the equatorial Atlantic, the Caribbean, the Gulf of Mexico, and the western mid-latitude North Atlantic is further evidence of discontinuity of the Pleistocene sections. Radiocarbon assay of a sample taken between 30 and 40 centimeters from the top of core V12–5 proved the sample to be older than 33,000 years. Since samples from about the same depth in cores of similar lithology and containing the standard faunal zones normally have an age of about 15,000 years, as determined by radiocarbon assay, it is clear that a depositional discontinuity in this core occurs somewhere between 30 centimeters and the top.

In four of the cores (V3–153, V15–164, V16–21, and V16–66) a gradual increase upward in the percentage (by weight) of material coarser than 74 microns occurs. In the other cores, irregular minor variations occur, but no secular trend is discernible. Since the measurements were made at 10-centimeter intervals in all cores, it is unlikely that any abrupt change in this parameter was overlooked.

In cores V3–152 and V16–66 a similarly gradual small increase in the percentage of carbonate content is found. Although the carbonate assays were made at wider intervals, it is improbable that any large and abrupt change in carbonate content occurs, because such changes are usually conspicuous as color changes. That there is no such change in color at the faunal boundary is shown by photographs of the core sections which include the boundary. In short, the evidence for an important time boundary in these cores is not lithological or geochemical but purely paleontological.

## Faunal Definition of the Boundary

Extinction of the Discoasteridae (Fig. 3) is probably the most significant termination at the Pliocene-Pleistocene boundary. These organisms are known only from the minute star-shaped calcareous skeletal elements, called discoasters, which occur in enormous numbers in sediments ranging in age from Paleocene to Pliocene. Bramlette and Riedel (*6*) think it probable that the discoasters were secreted by organisms similar to the Coccolithophoridae, a group of algae which abound in the oceans today and which secrete button-like plates of calcium carbonate of about the same size as the discoasters—that is, about 10 microns in diameter. That planktonic organisms secreted the discoasters is fairly certain; only in or near the upper layer of water, where photosynthesis takes place, could the organisms have obtained enough nourishment to swarm in such numbers as the abundance of the little stars indicates. It is also significant that the species of discoasters have a worldwide distribution, a characteristic of planktonic organisms, which are scattered far and wide by surface currents of the oceans. If, as seems likely, they were planktonic organisms floating in or near the layer of water penetrated by light, they must have been exposed to the full rigors of the deteriorating climate of the late Pliocene.

The same, presumably climatic, effect which destroyed the Discoasteridae also put the planktonic Foraminifera to a severe test. The foraminifera are marine protozoa which construct hard shells or tests. The great majority of the species live on the sea floor in fairly shallow water. About 30 species, however, are planktonic. These secrete tests of calcium carbonate which, after death or reproduction of the animals, settle to the bottom and become part of the sediment. Over wide areas of the ocean floor these minute shells make up from 20 to 80 percent, or more, of the sediment. For several reasons they are uniquely useful to the marine geologist and student of past climates. First, since these planktonic animals are wafted about by ocean currents, distribution of the shells is ocean-wide and independent of the nature of the bottom except for the effects of solution at great depths. In consequence, zones in the sedimentary section defined by the presence or absence of certain species can be correlated on a global scale. Second, since the animals live in the upper layer of water penetrated by light, all the species are more or less influenced by climate, and a few species are strongly influenced by the temperature of the upper layer of water—so much so that their presence or absence in a layer of sediment is a good indication of the climatic conditions that prevailed during deposition of the layer. Third, because of the small size (from 0.2 to about 1 mm, in diameter) and the abundance of the tests, samples of sediment weighing no more than 1 gram usually contain thousands of them. Thus, statistical methods may be applied to the study of assemblages in small samples of sediment.

As a group, the planktonic Foraminifera survived the change in conditions which were fatal to the Discoasteridae. Among the individual species, however, abrupt innovations and fatalities occurred. Among the innovations, the abrupt appearance of *Globorotalia truncatulinoides* in abundance above the boundary is an important marker (Fig. 3).

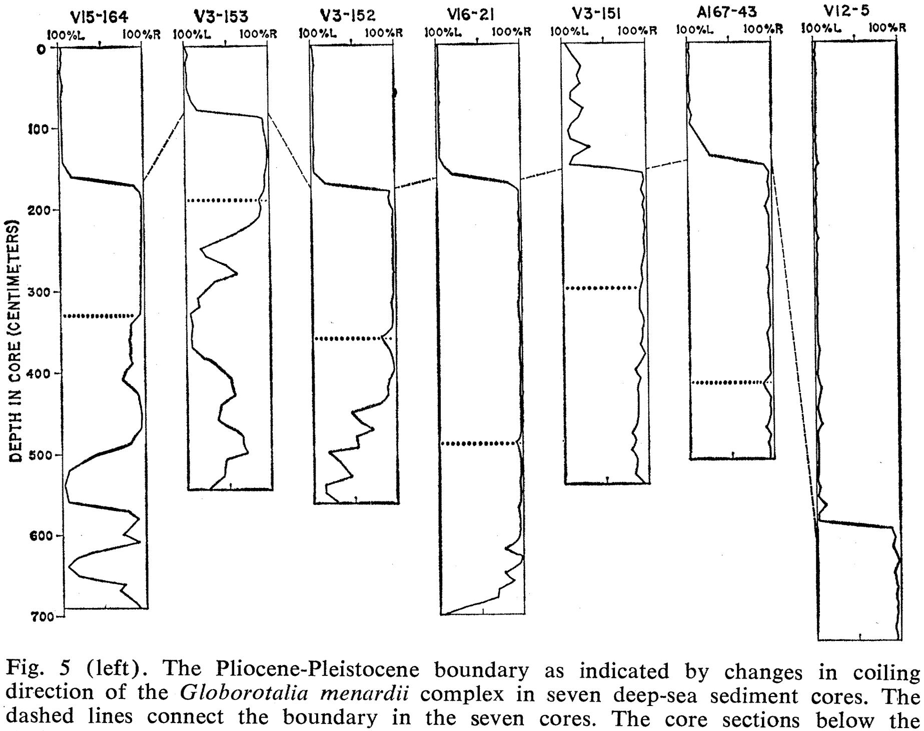
Particularly striking changes occurred within a series of related forms which, for convenience, we call the *Globorotalia menardii* complex. In using this informal grouping we avoid the issue of whether or not the taxonomic units involved ought to be regarded as species or as races of a single species. Taxonomy is not at present our concern. The important point is, rather, that the members of the complex are variations on a single theme which is exemplified by the now very much alive species *G. menardii.* We believe that to insist upon specific distinction among the forms involved is to introduce rigidity into our thinking about populations which must have been unusually fluid at this time of rapid evolutionary change.

Immediately below the boundary the complex includes two forms in about equal numbers. One is similar to the form described by Palmer as *Globorotalia menardii* var. *miocenica,* from the middle-to-upper Miocene of Jamaica; the other resembles *G. menardii multicamerata* of Cushman and Jarvis, from the Miocene of Jamaica, but differs from their form in having a thin peripheral keel rather than a "very heavy" one. Above the boundary a single form is strongly dominant; this, except for its smaller size and the somewhat smaller proportion of the final chamber, is essentially similar to the race of *G. menardii* now living in the North Atlantic.

Another change in the *G. menardii* complex at the boundary is a change in the preferred direction of coiling. In almost all species of planktonic Foraminifera the tests grow from the embryonic form to the adult by the addition of progressively larger chambers in a trochospiral series, and thus, like snail shells, coil either to the right or to the left (Fig. 4). In some species (for example, *G. hirsuta*), the dominant coiling direction has varied with time (*5*).

Immediately below the boundary more than 95 percent of the tests of the *Globorotalia menardii* complex coil to the right; above the boundary, more than 95 percent coil to the left. Figure 5 shows graphically the vertical variation in coiling of the complex in the seven cores containing *G. menardii.* The strong dominance of sinistral coiling in the Pleistocene sections of these cores does not conclusively prove that the complex remained sinistral throughout the Pleistocene, because the Pleistocene record in these cores is incomplete. On this point we can only say that we have not yet seen or heard of a Pleistocene population of *G. menardii* in which left-coiling was not strongly dominant. It is probably significant that coiling of the complex appears to have been less stable in the late Pliocene section of four of the cores.

An abrupt increase in the average diameter of the tests of *G. menardii* also occurs at the boundary (Fig. 6).



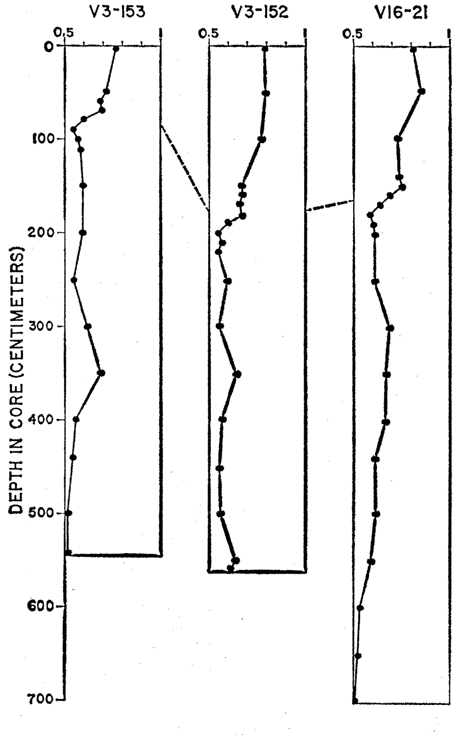


Fig. 5 (left). The Pliocene-Pleistocene boundary as indicated by changes in coiling direction of the *Globorotalia menardii* complex in seven deep-sea sediment cores. The dashed lines connect the boundary in the seven cores. The core sections below the dashed lines are Pliocene; the sections above the lines are Pleistocene. In each diagram the variation is from 100 percent left-coiling shells, at left, to equal numbers in the middle, to 100 percent right-coiling shells, at right. The shells were sampled every 10 centimeters from top to bottom of the cores for study. The dotted lines in six of the cores indicate the level at which *Globigerina nepenthes* became extinct. The core at right did not reach the *G. nepenthes* zone. Fig. 6 (right). The Pliocene-Pleistocene boundary as indicated by increase in the size of *Globorotalia menardii* in three deep-sea sediment cores. The dashed lines connect the boundary in the three cores. The average diameters of the shells are shown (in millimeters) along the abscissa.

*Globigerinoides fistulosa* (Schubert) (see cover), a close relative if not a subspecies of *G. sacculifera*, occurs below the boundary but not above it. Schubert's original material came from the "allerjungstes Pliocän" of British New Guinea.

In general, the assemblage of planktonic Foraminifera above the boundary has a typically Pleistocene aspect.

## Continuity of Sediment Accumulation

Since we regard the Pleistocene sections in these cores as incomplete because of slumping, and indeed, by radiocarbon assay, can prove this to be the case in core V16–21, the continuity of the lower sections, including the faunal boundary, must be questioned. May not the boundary in reality be an unconformity due to loss of some part of the original section by slumping?

In considering the sharpness of definition of faunal boundaries we must take into account the homogenizing effect of mud-feeding burrowing animals. From our experience with the faunal changes of the late Pleistocene in sections of proved continuity we know that a species of Foraminifera absent at one level may occur by the hundreds 10 centimeters higher, and such changes in abundance usually take place where there is unmistakable evidence of burrowing. Except in core V3–151 (Blake Plateau), and core V16–66 (Indian Ocean), the faunal changes marking the boundary are found within a zone from 10 to 15 centimeters thick. If mud-feeders were responsible for mixing of sediment through this thickness, we must suppose that the mud-feeders living at the earlier time represented by the boundary were more capable homogenizers than those of the late Pleistocene. Since we do not know that this was not the case, we submit that the thickness of the transition zone suggests continuity but does not prove it. Absence of change of lithofacies at the boundary in the several cores also suggests continuity of sediment accumulation. This finding, in combination with the evidence of the thickness of the transition zone, is impressive but still falls short of proof.

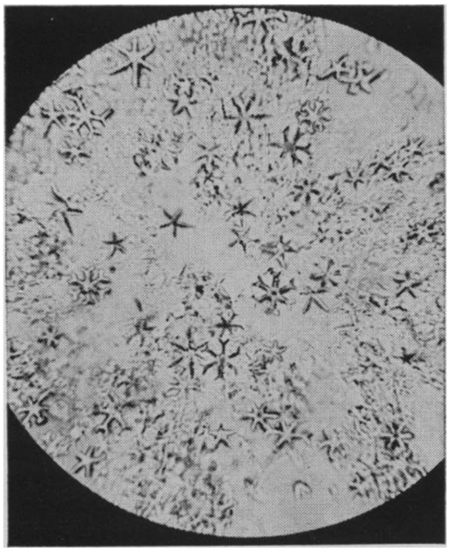


Fig. 7. Discoasters from the 700-centimeter level in deep-sea sediment core V16-21 show the abundant occurrence of *Discoaster challengeri* with its six broad bifurcating rays. [About × 970]

Our conviction that sedimentation has been continuous across the boundary and that, therefore, the faunal changes at the boundary record a nearly isochronous change in ecological conditions is based on clear correlation from core to core of a series of faunal horizons and gradational faunal changes within the Pliocene sections of the cores. The probability that any two cores could correlate so well by mere coincidence is small; the probability of a spurious correlation due to chance resemblance of really unrelated layers becomes virtually zero when the correlation involves a series of zones defined by different kinds of organisms in several cores from widely separated stations.

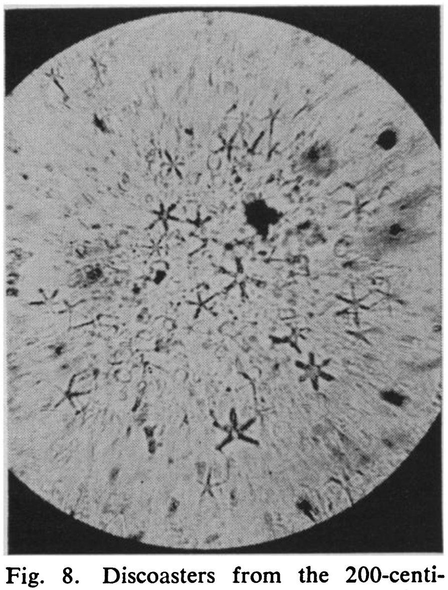


Fig. 8. Discoasters from the 200-centimeter level in deep-sea core V16–21 show the dominance of *Discoaster brouweri* with its five to six slender simple rays. [About × 970]

As already noted, extinction of the Discoasteridae as a group takes place at, or just above, the boundary defined by the change in coiling direction of the *Globorotalia menardii* complex. However, as evidence of continuity of sediment accumulation it is highly significant that in all of the cores, with the exception of V12–5, which penetrated the Pliocene sediment to a depth of only 1½ meters, a gradual extinction of species of discoasters occurs, through sediment thicknesses varying from 1½ to 5 meters and in pace with changes among the planktonic Foraminifera. The discoaster assemblage of the lower part of the Pliocene sections includes *Discoaster challengeri* Bramlette and Riedel, *D. pentaradiatus* Tan, and *D. brouweri* Tan, the first-named species being dominant. From this level the abundance of *D. challengeri* gradually decreases until the species is rare or absent some distance below the boundary.

The abundant occurrence at 700 centimeters in core V16–21 of *D. challengeri,* with its six broad bifurcating rays, is shown in Fig 7; dominance of *D. brouweri,* with five to six slender simple rays, at 200 centimeters in the same core is shown in Fig. 8. Figure 9 shows the secular decrease upward, or in time, of the percentage of *D. challengeri* in the total population of discoasters. We interpret this as an indication of deteriorating conditions during the late Pliocene.

*Discoaster pentaradiatus* also decreases in abundance, but the decrease is less rapid, with rare specimens surviving almost to the boundary. In core V12–5 the Pliocene section is too short to include the lower zone dominated by *D. challengeri,* but V12–5 is in harmony with the other cores in that the section below the boundary contains essentially the single discoaster species *D. brouweri.*

In four of the cores (Fig. 5), shifts to left-coiling dominance of the *Globorotalia menardii* complex define correlating zones in the lower part of the Pliocene sections. Presumably the other cores from the Atlantic were too short to reach the lower levels of left-coiling dominance.

In four cores (V3–152, V3–153, V15–164, and V16–21), the ratio of abundance between members of the *G. menardii* complex varies from level to level and defines correlating zones.

*Globigerinoides fistulosa* does not

occur throughout the Pliocene section but first appears about half a meter below the boundary and disappears above it. Thus, this short-lived species, or race of *G. sacculifera,* defines a relatively thin zone in the Atlantic cores. It is scarcely conceivable that slumping could have occurred at seven scattered stations in such a way as to have left at each the same limited thickness of sediment containing this distinctive species.

In six of the cores (Fig. 5) *Globigerina nepenthes* Todd (Fig. 10) becomes extinct at depths below the boundary which vary from 100 to 325 centimeters. Presumably the Pliocene section in core V12–5 was too short to reach the top of the zone of *G. nepenthes.*

Correlation between the Atlantic cores and core V16–66 from the Indian Ocean rests upon the extinction of the Discoasteridae and the appearance of *Globorotalia truncatulinoides* (see cover) in abundance. *Globorotalia menardii, Globigerina nepenthes,* and *Globigerinoides fistulosa* are absent in this core from a high latitude.

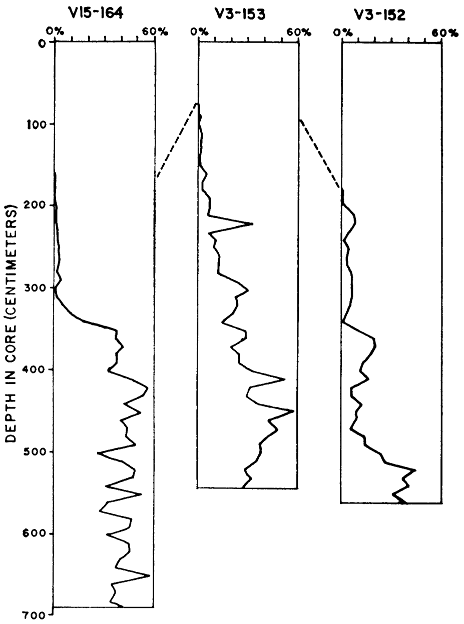


Fig. 9. The secular decrease upward, or in time, of the percentage of *Discoaster challengeri* in the total population of discoasters in three deep-sea sediment cores. The dashed lines connect the Pliocene-Pleistocene boundary in the cores. Core sections below the dashed lines are Pliocene; sections above the lines are Pleistocene. There are no discoasters in the Pleistocene sections. The sediment was sampled at 10-centimeter intervals from top to bottom of the cores.

## "Miocene Aspect" of the Pliocene

Species of Foraminifera which were previously known only from the Miocene but which persist to the Pliocene-Pleistocene boundary are *Globorotalia menardii miocenica* (Fig. 10); *Sphaeroidinella multiloba* (see cover), described by LeRoy as being from the "Late Miocene?" of the Indo-Pacific region; and *Globoquadrina altispira* (Cushman and Jarvis), from the Miocene of Jamaica. Since we feel reasonably certain of the late-Pliocene age of the section below the boundary, we must conclude that these species of planktonic Foraminifera had longer ranges than we had previously supposed. For planktonic organisms living in the open sea, doubtless the most critical environmental condition is temperature. The survival of Miocene species into the Pliocene epoch implies that no abrupt or drastic temperature change occurred at the Miocene-Pliocene time boundary. In contrast, at the Pliocene-Pleistocene time boundary a renovation took place among planktonic organisms on a scale without precedent during the earlier Cenozoic.

Both theory and the evidence from the cores strengthen our belief that when a continuous sequence of deep-sea Cenozoic sediments has been recovered from one or more Moholes, the level of the Pliocene-Pleistocene boundary will be easily recognized, whereas the Miocene-Pliocene boundary may be rather difficult to define.

## Climatic Implications

The succession of extinctions recorded in the Pliocene section of the cores clearly indicates, in our opinion, a gradual deterioration of climate during the last several hundred thousand years of that epoch. The extinction of the Discoasteridae marks its climax. These organisms had swarmed in the world's oceans for about 60 million years. Only a drastic and worldwide deterioration of climate of a severity unprecedented in all the earlier Cenozoic can explain their disappearance. We surmise that their extinction in the equatorial Atlantic coincided with the onset of the first ice age.

In addition to evidence for a gradually deteriorating climate in late Pliocene time there is some indication that there were climatic fluctuations, of about the same period as those that occurred in the Pleistocene but of much smaller amplitude. This is suggested by variation in the frequency-to-weight ratios of the *Globorotalia menardii* complex (Fig. 11). The frequency-to-weight ratio, first used by Ericson and Wollin (*7*), is the ratio of the number of tests of a particular species to the weight, in milligrams, of the sample of coarse fraction containing the species. The coarse fraction (particles of diameter $> 74\ \mu$) is concentrated by washing the sample of sediment on a 200-mesh sieve. The method, which traces variation in the abundance of a single species with respect to the total population of planktonic Foraminifera, yields meaningful data only when applied to pelagic sediments in which the coarse fraction consists almost entirely of the tests of planktonic Foraminifera.

The Pliocene-Pleistocene boundary

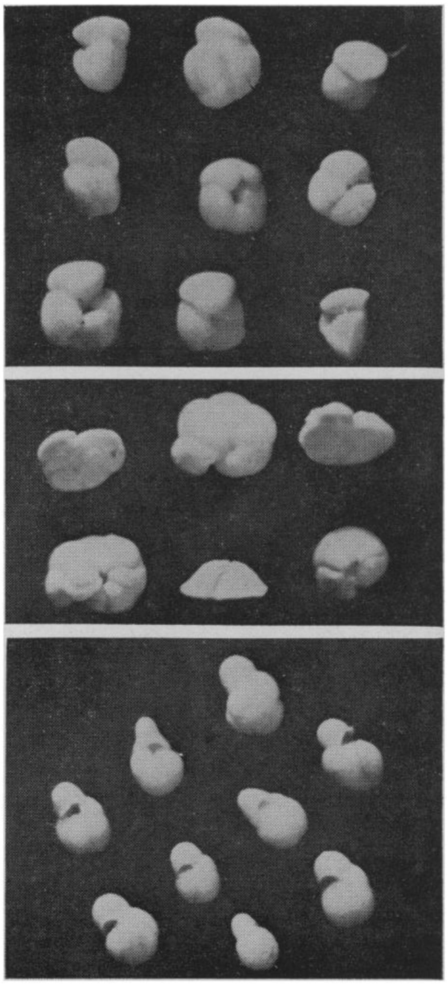


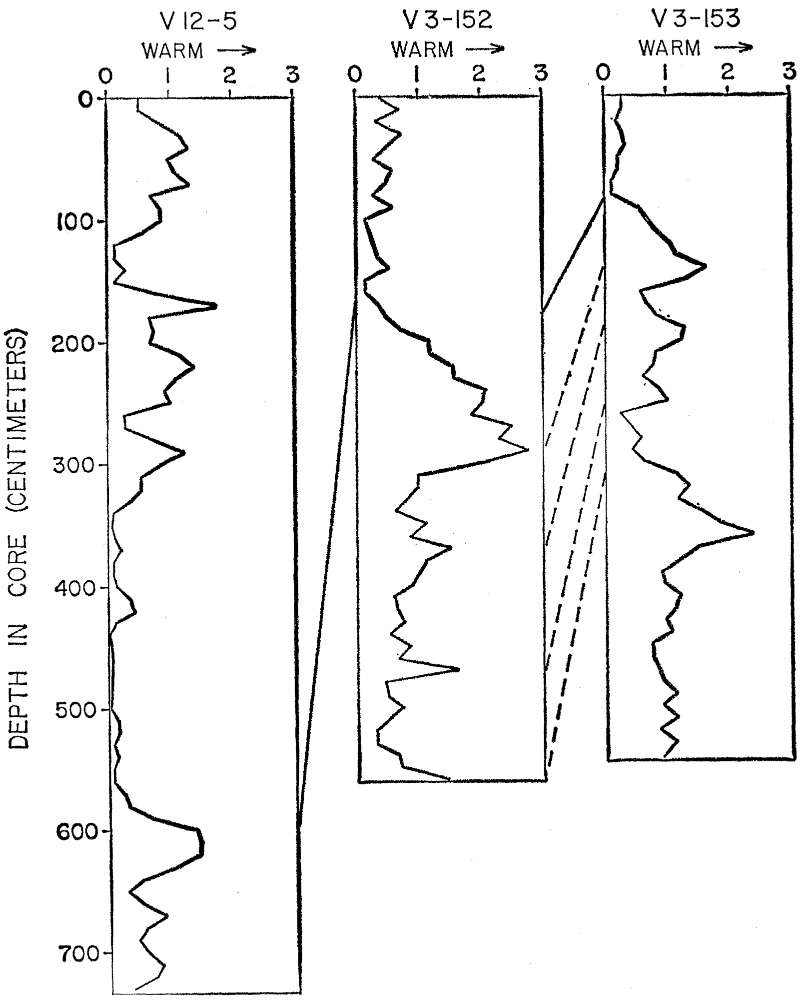
Fig. 10. Three species of planktonic Foraminifera. (Top) *Globorotalia hirsuta punctulata*; (middle) *G. menardii miocenica*; (bottom) *Globigerina nepenthes.*

is indicated by a marked increase downward from the boundary in the frequency-to-weight ratios of *Globorotalia hirsuta* in two cores, as shown in Fig. 12.

The species *Globorotalia menardii* is particularly sensitive to temperature. A marked decrease in the frequency-to-weight ratios of *G. menardii* just above the Pliocene-Pleistocene boundary in three cores is shown in Fig. 11. Its close approach to zero in core V12–5 between 590 and 330 centimeters is particularly striking. Ericson *et al.* (*5*) have observed a similar drop to almost zero in the sediment layer in North Atlantic cores which accumulated during the last ice age, as proved by numerous radiocarbon datings. From this we conclude that the layer from 590 to 330 centimeters in core V12–5 records a time of glacial climate, the first ice age.

Figure 13 shows variation in coiling direction of *Globorotalia truncatulinoides* in the Indian Ocean core, V16–66, and in a core (V12–5) from the equatorial Atlantic. According to Ericson *et al.* (*5*) the areal distribution of dextral and sinistral populations of *G. truncatulinoides* is not temperature-dependent but is controlled by some other, as yet unknown, environmental condition. Whatever the controlling factor may be, we have observed that sudden shifts in coiling direction tend to occur at times of changing climate. It is noteworthy that mixed dextral and sinistral populations occur in both cores at the Pliocene-Pleistocene boundary and that a sudden shift to sinistral population occurs in core V12–5 at 300 centimeters, where, as the frequency-to-weight curve of *Globorotalia menardii* (Fig. 11) shows, the climate was rapidly becoming warmer. Evidently this was a time of environmental instability at the beginning of an interglacial age.

The swings to left-coiling in the *Globorotalia menardii* complex in the Pliocene sections of four cores (Fig. 5) also strongly suggest an unstable environment. It is significant that a race of *G. menardii* similar to the unique form of the Pleistocene section is dominant over *G. menardii miocenica* and *G. m. multicamerata* in these zones of left-coiling. It is scarcely conceivable that direction of coiling could in itself have any direct influence on the temperature-tolerance of a species. Gene linkage may more plausibly explain the



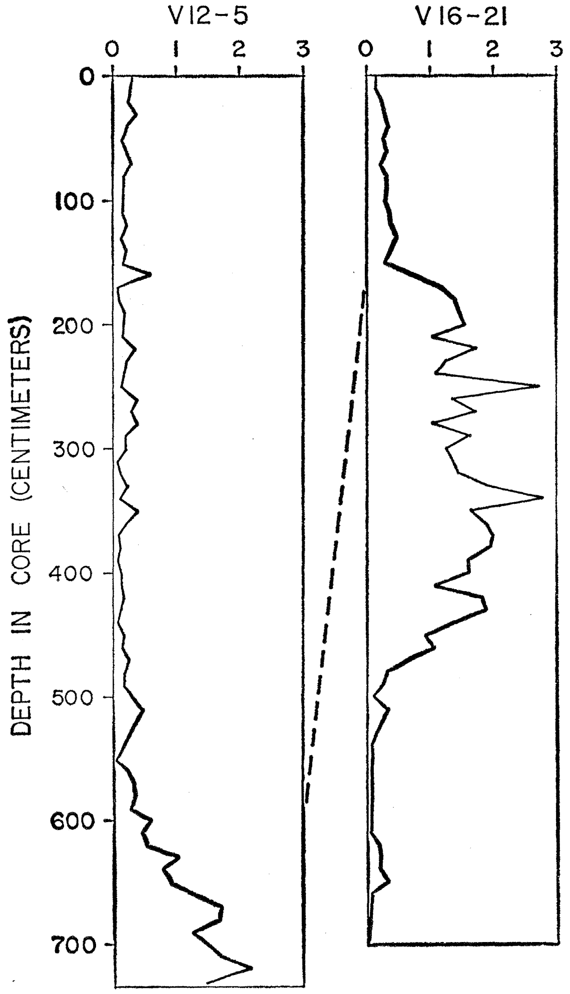


Fig. 11 (left). Variations in the abundance of the *Globorotalia menardii* complex in three deep-sea sediment cores. The curves are based on the ratios of number of shells to weight of material coarser than 250 microns in each sample. Higher ratios indicate warmer waters. The solid lines between the cores connect the Pliocene-Pleistocene boundary. The dashed lines emphasize the correlation of the Pliocene sections in cores V3–152 and V3–153. The sediment was sampled at 10-centimeter intervals from top to bottom of the cores. Fig. 12 (right). Variations in the abundance of *Globorotalia hirsuta* in two deep-sea sediment cores. The curves are based on the ratios of number of shells to weight of material coarser than 250 microns in each sample. The dashed line connects the Pliocene-Pleistocene boundary. Core sections below the dashed line are Pliocene; sections above the line are Pleistocene. The sediment was sampled at 10-centimeter intervals from top to bottom of the cores.

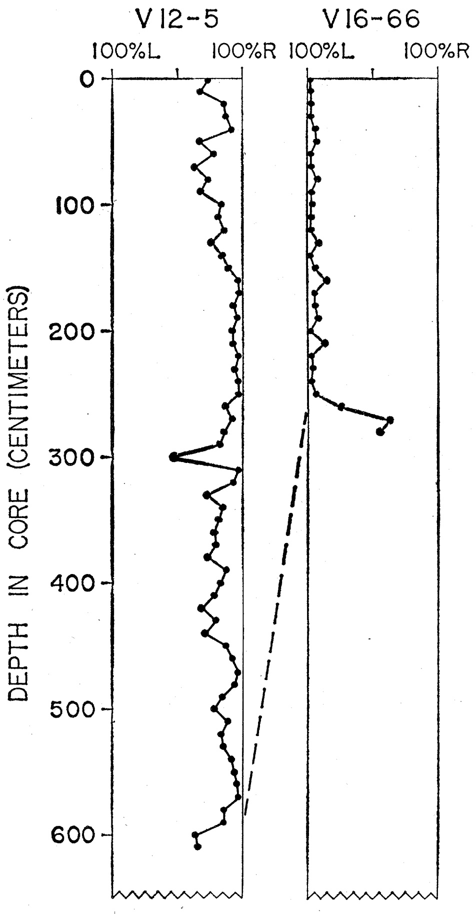
apparent interrelationship between coiling direction and temperature-tolerance. Left-coiling individuals that carried genes conferring tolerance of cooler water would normally be at a disadvantage in competition with the other members of the *G. menardii* complex, but they would enjoy an advantage during times of cooler climate and would tend to dominate the population. Evidently this left-coiling race was the only one to survive the climax of climatic change at the beginning of the Pleistocene.

Bandy (*8*) and Ericson (*9*) have shown that the sinistral race of *Globigerina pachyderma* tolerates temperatures down to the freezing point. With rising temperature the dextral race takes over, to the exclusion of the sinistral. Figure 14 shows the frequency-to-weight curve and the curve for ratio of sinistral to dextral tests of *G. pachyderma* in the Indian Ocean core, V16–66. We have plotted the frequency-to-weight curve with zero at the right in order to make swings to the right correspond to rising temperature and to make this graph more readily comparable with the others.

The frequency curve of *G. pachyderma* indicates a gradual cooling from the 800 centimeter level up to the Pliocene-Pleistocene boundary. This evidence is supported by the gradual disappearance of the discoasters (Fig. 14) between 800 centimeters and the boundary.

Ice-rafted detritus in core V16–66 supports the faunal evidence for climatic deterioration during the final phase of the Pliocene. Presumably the drifting ice originated on the continent of Antarctica. The fact that the detritus first appears in core V16–66 at about 580 centimeters below the Pliocene-Pleistocene boundary (850 centimeters from the top of the core) indicates that the climate of Antarctica had become glacial some 250,000 years before the drastic climatic change that marked the end of the Pliocene epoch.

The curve for coiling indicates a milder climate above the Pliocene-Pleistocene boundary. This surprising evidence is supported by the frequency-to-weight curve. Apparently there was a moderation of climate in this part of the Indian Ocean at the time when, as the Atlantic cores give evidence, there was a general refrigeration elsewhere. This may have been due to some local change in the current pattern. At pres-



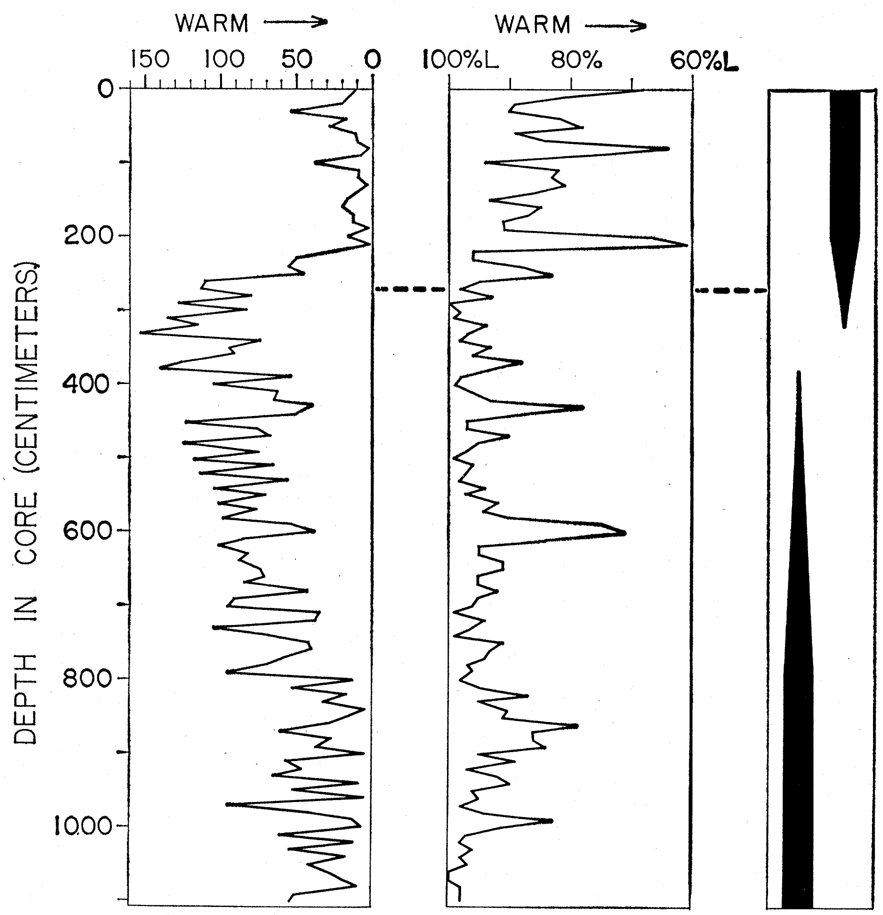


Fig. 13 (left). Changes in coiling direction of *Globorotalia truncatulinoides* in two deep-sea sediment cores. The dashed line connects the Pliocene-Pleistocene boundary. There is no *G. truncatulinoides* in the Pliocene sections. In each diagram the scale of variation is from 100 percent left-coiling shells, at left, to equal numbers in the middle, to 100 percent right-coiling, at right. Fig. 14 (right). The deep-sea sediment core V16–66 from the Indian Ocean. The dashed line indicates the Pliocene-Pleistocene boundary. The core section below the dashed line is Pliocene; the section above the line is Pleistocene. The curve at left shows variation in the abundance of *Globigerina pachyderma*. The curve is based on the ratio of number of shells to weight of material coarser than 250 microns in each sample. Lower ratios indicate warmer waters. The curve at right shows the variation in the coiling direction of *G. pachyderma*. The variation is from 100 percent left-coiling shells, at left, to 60 percent right-coiling shells, at right. Lower percentages of left-coiling shells indicate warmer waters. Upper solid zone in column at right, *Globorotalia truncatulinoides;* lower solid zone, discoasters. Thickness of the solid zones indicates abundance. The sediment was sampled at 10-centimeter intervals from top to bottom of the core.

ent we can offer no better explanation.

The appearance of *Globorotalia truncatulinoides* in abundance above the boundary in core V16–66 is shown in Fig. 14. The disappearance of discoasters (Fig. 14) below the boundary raises a question. If the local climate became less cold at the beginning of the first ice age, why should the Discoasteridae have not survived into the early Pleistocene at least in this part of the Indian Ocean? The answer may well be that they did not at any time reproduce within the region of coring station V16–66 but, instead, were occasionally brought into the area by intermittent currents. This view accords with the fact that discoasters are less abundant by many orders of magnitude in core V16–66 than they are in the Atlantic cores, where they make up an important part of the fine fraction of the sediment.

The point to be emphasized now is the exciting possibility that definitive information on the time of origin of the antarctic ice cap may be gained by means of a few more cores, long enough to reach sediment of late Pliocene age, from stations distributed symmetrically around Antarctica.

As yet only a minimum age can be assigned to the Pliocene-Pleistocene boundary. The longest continuous Pleistocene section so far found among cores of the Lamont collection from the Atlantic measures 1200 centimeters. By estimating the rate of sediment accumulation of the uppermost faunal zones from age determinations, made by radiocarbon assay, for the same zones in other cores, Ericson (*10*) estimated that the 1200-centimeter thickness of sediment represented 600,000 years.

Among the cores from the Atlantic described here, V12–5 contains the thickest Pleistocene section, 600 centimeters thick. Since radiocarbon assay of the 30- to 40-centimeter section showed it to be beyond the range of the method (the range is about 33,000 years), we infer that a depositional elision due to removal of sediment by slumping occurs somewhere above 30 centimeters. The average ratio of the number of tests of planktonic Foraminifera to the amount of fine sediment in the Pleistocene section of core V12–5 is comparable to the ratio for late-Pleistocene sediments from the North Atlantic. The rate of accumulation of such sediments, as determined by radiocarbon dating, is on the order of 3 centimeters per 1000 years (*5*). At that rate, 600 centimeters represents 200,000 years. This estimate disregards the effect of compaction due to the load of overlying sediment presumably recently removed by slumping. Admittedly this introduces a further uncertainty, but we believe that the consistency of the sediment justifies the assumption that the degree of compaction has been small, probably less than 10 percent. Of course, the effect of compaction would be to increase the real age of the boundary beyond our estimate; we concede that our estimate is strictly a minimum.

Comparison of the faunal zones in the 1200-centimeter section with those in the Pleistocene section of core V12–5 indicates absence of duplication of zones or overlap of sections. Thus, the age of the boundary must be at least as great as the sum of the time intervals represented by the two sections, which amounts to about 800,000 years. Since it is very unlikely that the two sections are in direct sequence, it is probable that there is a gap between them and that the real age of the boundary is greater than 800,000 years.

## Conclusion

For a hundred years students of the Pleistocene have looked for evidence of the climatic change which initiated the Pleistocene epoch. Glacial deposits on the continents have been of little help because of their discontinuity and because of the destructive effect of later glaciations. Hence, Pleistocene geologists have turned to the uplifted Pliocene-Pleistocene marine sediments of the Mediterranean region. In the absence of evidence of a single, clearly defined climatic change in this sedimentary section, they have agreed to define the beginning of the Pleistocene by the first appearance of *Anomalina baltica*, a species of benthic Foraminifera tolerant of cool water. This definition leaves much to be desired: It rests on a single benthic species whose areal distribution must have been partly determined by local conditions on the sea floor; it is useless outside of the Mediterranean region; and there is no convincing evidence that the first appearance of *Anomalina baltica* in the Mediterranean coincided with the onset of the first glaciation.

Another approach to the problem is through the remains of temperature-sensitive planktonic organisms—certain species of Foraminifera and the Discoasteridae—preserved in the continuously accumulating sediments of the ocean basins. As dwellers in the uppermost layer of water these organisms are particularly easily influenced by climatic change, especially temperature change, and within certain limiting latitudes their areal distribution is circumglobal.

Among the more than 300 deep-sea sediment cores at the Lamont Geological Observatory eight contain a faunal boundary sharply defined by extinction of the Discoasteridae and by an abrupt change in the planktonic Foraminifera from an assemblage of "Miocene aspect" to one of typically Pleistocene aspect. Evidence from these cores supports the view that a secular deterioration of climate, with superimposed temperature oscillation leading to glaciation in Antarctica, took place during the late Pliocene. We cannot agree, however, that a long interval of gradually deteriorating climate, with expanding minor ice ages, intervened between the nonglacial Pliocene and the time of the great continental glaciations, and that consequently no well-defined natural boundary between the Pliocene and the Pleistocene epochs exists. We believe that the faunal change in the cores is sufficient in degree to justify the conclusion that it records the onset of a "first ice age" in the true sense of the term. Probably this was not the Günz or Nebraskan ice age, but the evidence from the cores convinces us that it was of comparable magnitude.

We have at present no way of knowing whether the boundary as we define it here correlates with the first appearance of *Anomalina baltica* in the Mediterranean, but in any case we believe that our definition of the beginning of the Pleistocene is more logical and can be more useful, than a definition that depends upon the first appearance of *Anomalina baltica*.

Ice-rafted detritus in the Pliocene section of a core from the Indian Ocean shows that at least partial glaciation of Antarctica preceded the time of the faunal change by some 250,000 years. Variations in the abundance and in the degree of dominance of sinistral tests of *Globigerina pachyderma* in this same core indicate that the local climate became milder soon after the extinction of the Discoasteridae and the first appearance of *Globorotalia truncatulinoides*—that is, soon after the faunal change that we believe marks the beginning of the Pleistocene.

As yet, only a minimum age can be assigned the Pliocene-Pleistocene boundary in these cores. From rates of accumulation of late-Pleistocene sediment determined by radiocarbon dating, and from the known thickness of Pleistocene sediment above the boundary, we estimate the age of the boundary to be not less than 800,000 years. Since the Pleistocene section above the boundary is incomplete because of the removal of some part by slumping, the real age of the boundary must be somewhat greater. To our knowledge, these cores provide the first evidence of the nature of the climatic change which opened the Pleistocene epoch and which, by creating an environment of rigorous selection, started a group of primates upon the evolutionary road that led to the emergence of man (*11*).

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# What Are We Looking For?

## Attention to the nature of scientific discovery would produce better information retrieval systems.

Phyllis Allen Richmond

Currently there is a stampede into science information retrieval systems—that is, systems designed to recover factual data from the printed mass—and, to a lesser extent, into document retrieval systems—those designed to disinter a book, article, review, or report, per se, for someone who will then read it to retrieve its information content. There has been too much focusing of attention on ways and means, particularly lucrative ways and means, accompanied by a plethora of silly arguments and downright battles, all obscuring the need to answer the fundamental question: What are we looking for?

The general argument is that we are looking for scientific work that has already been done so that it will not be necessary to do it over again. If we are indeed looking for something like a method of synthesizing a compound, or if we want to know whether such a compound has been made, probably the science information retrieval systems available are as good or bad as we deserve. But suppose we are looking for a new field theory or a scientific approach that will open up new lines of research. Factual retrieval systems will not suffice. Again, what are we looking for?

### Scientific Method

At this point, it would be worth while to consider the nature of scientific method, scientific research, and scientific discovery.

Scientific method may be defined as a means of studying the universe and its contents which is characterized by a critical, systematic process of active investigation and reasoning, leading in general to publicly verifiable conclusions (*1*). The investigational approach may be either observational (direct) or experimental (indirect); it may be based on common-sense procedures or on procedures arising from the acquisition of specialized knowledge. The reasoning from the data produced by either approach may be influenced by hypothesis or theory and may result in generalizations, further theories, predictions, or even quantitative laws (*2*). The requirement for publicly verifiable conclusions eliminates those areas of human knowledge that are characterized by a high reliance on probability, and areas in which "observations" are deduced long after the event.

Scientific method is used in research. Research is defined as "the more or less systematic investigation of phenomena intended to add to the sum total of verifiable knowledge" (*3*). This broad definition excludes experimentation of the trial-and-error type, or pure chance observation. Some degree of planning is involved, certainly mental preparation, although experimentation is not necessarily indicated. Research may be of two main kinds: fundamental and applied. Fundamental research is research motivated by intellectual curiosity rather than by any attempt to solve a specific practical problem. Although fundamental research does undertake to solve particular problems, these are intellectual problems which must be solved in order to bring theoretical structure into line with experimental results, or to suggest new lines of development. Fundamental research ultimately may produce an original theory, or it may elaborate on, prove, or disprove existing theories. Applied research seeks a more limited objective—the production of some well-defined specific scientific occurrence or material. The end product is very often patented; it must be usable, practical, to be eligible for this protection.

The major result of scientific method and scientific research is scientific discovery (*4*); this may come at any time, at any place, and to any man, provided he has the genius to recognize it. A

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