Gilbert is unlikely to be younger. It is difficult to pick the beginning of the Gilbert in E13-17 because of a gap in the core between 2100 and 2200 centimeters; however, it is definitely normally magnetized below 2200 centimeters. If we extrapolate from the base of the Gauss normal series, using the rate of accumulation within the Gauss, we obtain an age of 5.25 million years for the top of epoch 5, which is probably a maximum age. Therefore an estimated age of 5 million years for the beginning of the Gilbert is reasonable but may be in error by as much as 200,000 years.

Radiolarian Stratigraphy

Four stratigraphic zones have been established in antarctic sediments on the basis of the upward sequential disappearance of species of Radiolaria (2); they have been named \( \Phi \) (oldest), \( \chi, \psi, \) and \( \Omega \) (youngest). The base of the \( \Omega \) zone has been dated radiometrically at about 400,000 years (11). The base of the \( \psi \) zone (0.7 million years) and the base of the \( \chi \) zone (about 2 million years) have been dated paleomagnetically (J), while the base of the \( \Phi \) zone has not yet been defined. Previously the faunal work ended near the top of the \( \Phi \) zone, for in antarctic sediments south of the Antarctic Polar Front the sediments in many areas become barren below the \( \Phi-X \) boundary (2).

The three cores selected for detailed study by us contain Radiolaria older than any previously reported from the floor of the Antarctic Ocean. Cores E13-3 and E14-8 have continuous radiolarian-bearing sequences back to about 3 and 4 million years ago, respectively, while E13-17 contains Radiolaria intermittently back to probably more than 5 million years ago.

In previous work (1, 2) certain species having restricted stratigraphic ranges were selected for study. We include 32 species constituting, in the time period studied, more than 90 percent of radiolarian fauna; the taxonomy of most has been discussed (2), and a report on the others (Larcypyle sp. No. 1, Larcypyle sp. No. 2, and Triceraspis sp.) is in preparation. Altogether 296 slides were examined for Radiolaria; counts of at least 300 (usually 500) individuals were made on the 180 slides bearing sufficient Radiolaria. The results of these counts were reproducible within 6 percent. From these data the stratigraphic ranges of the species were determined (Figs. 2–4), as well as the percentages of individuals in the sample belonging to species not found in the most recent antarctic sediments (Figs. 7–9).

The top four faunal zones in these cores bear the same relation to magnetic reversals as in cores previously reported (Figs. 2–4, Table 4) (I). The bottom of the \( \Omega \) zone falls in the central portion of the Brunhnes series. The \( \chi-\psi \) boundary falls near but below the base of the Brunhnes series, and the \( \chi-\psi \) boundary occurs just below the Olduvai event. The upper limit of the range of Clathroclycas bicornis is near the top of the Olduvai event. Both E13-3 and E14-8 contain a considerable thickness of radiolarian-bearing sediments below the \( \Phi-X \) boundary. The next-older major faunal change occurs at the upper limit of two species (Desmospyris spongiosa and Helotholus vema) having similar upper limits (E13-3, 840 centimeters; E14-8, 1085 centimeters) just above the Gauss-Matuyama boundary (Figs. 2 and 3). This faunal change permits more precise definition of the \( \Phi \) zone as the interval in antarctic deep-sea sediments containing individuals of Clathroclycas bicornis and Eucyrtidium calvertense above the last common occurrence of \( D. \) spongiosa and \( H. \) vema. The sediments underlying the \( \Phi \) zone and commonly containing \( D. \) spongiosa and \( H. \) vema will be designated the upsilon zone (Y). Near the Y-\( \Phi \) boundary there is a sharp upward decrease in the occurrence of species that no longer live in antarctic waters, and a concomitant increase in abundance of species that comprise the Recent Antarctic assemblage, making the \( \Psi-\Phi \) boundary the most striking faunal boundary yet studied. In fact the Y zone in both E13-3 and E14-8 is characterized by high percentages of extinct species (Figs. 7 and 8). Although the \( \Psi-\Phi \) boundary is not present in E13-17, the interval containing Radiolaria within the Gauss normal series (1380 to 1440 centimeters) contains Y-zone species (\( D. \) spongiosa and \( H. \) vema) as well as relatively high percentages of species not found in the most recent antarctic sediments (Fig. 9).

Core E13-3 becomes barren shortly below the Y-\( \Phi \) boundary, so only in E14-8 can one determine the upper boundary of the next-lower faunal change. Below 1540 centimeters in

Table 3. Apparent dates (by extrapolation from two cores) of beginnings and ends of three normal-polarity events in Gilbert reversed-polarity epoch.

<table>
<thead>
<tr>
<th>Event</th>
<th>Date (× 10^6 years ago)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beginning</td>
</tr>
<tr>
<td>Core E13-3</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>3.06</td>
</tr>
<tr>
<td>b</td>
<td>4.06</td>
</tr>
<tr>
<td>c</td>
<td>4.25</td>
</tr>
<tr>
<td>Core E13-17</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>3.79</td>
</tr>
<tr>
<td>b</td>
<td>4.08</td>
</tr>
<tr>
<td>c</td>
<td>4.44</td>
</tr>
</tbody>
</table>

E14-8, an undescribed sporyid (Triceraspis sp.) is abundant; it is probably closely related to Desmospyris spongiosa, since the latter is abundant only above the upper limit of Triceraspis sp. Since the upper limit of the range of Triceraspis sp. is based solely on its range in E14-8, only tentatively do we designate the upper limit of this species the base of the Y zone and the top of the T zone. The upper limit of the T zone falls within event a of the Gilbert polarity series.

Relations of Faunal Boundaries to Temperature Changes

The only reliable evidence of past warmer conditions in antarctic sediments is the deep occurrence in cores of species that are normally restricted to Recent sediments north of the Antarctic Polar Front. Evidence (2) has been presented of a change from warmer to cooler conditions across the

Table 4. Depths in two cores to faunal boundaries and nearest reversals.

<table>
<thead>
<tr>
<th>Faunal boundary</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core E13-3</td>
<td></td>
</tr>
<tr>
<td>G-( \Psi )</td>
<td>230</td>
</tr>
<tr>
<td>C-( \Psi )</td>
<td>530–540</td>
</tr>
<tr>
<td>T-( \Psi )</td>
<td>860–870</td>
</tr>
<tr>
<td>T-( \chi )</td>
<td>1065–1095</td>
</tr>
<tr>
<td>T-( \Omega )</td>
<td>1550–1570</td>
</tr>
<tr>
<td>Core E14-8</td>
<td></td>
</tr>
<tr>
<td>G-( \Psi )</td>
<td>50–70</td>
</tr>
<tr>
<td>C-( \Psi )</td>
<td>240–250</td>
</tr>
<tr>
<td>T-( \Psi )</td>
<td>560–570</td>
</tr>
<tr>
<td>T-( \chi )</td>
<td>650–660</td>
</tr>
<tr>
<td>T-( \Omega )</td>
<td>860–870</td>
</tr>
</tbody>
</table>
X-Ψ boundary, but the other faunal boundaries down to the Ψ-X boundary have shown no evidence of change in temperature.

Both E13-17 and E13-3 show definite evidence of warmer conditions at depth. In E13-17, below 2000 centimeters (4.5 million years) are various warm-water radiolarian species, including *Axoprinum stauraxonium* and *Heliodiscus asteriscus*. In all samples below 2180 centimeters (5.0 million years) are fragments of the diatom species *Ethemodiscus rex*; although it has not been reported south of 30°S, Burckle has seen fragments of this distinctive species in samples of Recent sediment from a core raised from the southern part of the Argentine basin (48°08'S, 40°31'W). The occurrence of *E. rex* in E13-17 is therefore nearly 20 degrees farther south than the southernmost known occurrence of this species in Recent sediments.

In E13-3, the northernmost of the three cores, several species of warm-water Radiolaria occur commonly between 860 centimeters (Y-Φ; 2.4 million years) and 980 centimeters, where the core becomes barren.

There is no strong evidence in E14-8 of warmer conditions at depth, but below 1100 centimeters (Y-Φ boundary; 2.4 million years) several warm-water Radiolaria occur intermittently down to the point where the core becomes barren, at 1710 centimeters.

Evidence of change from warmer to cooler conditions exists in all three cores; the change took place approximately 2 million years earlier in E13-17 than in the two northern cores.

In spite of the differences in latitude between these cores and of the corresponding temperature differences, the faunal boundaries occur at about the same time in all three cores. Changes in temperature may have caused the disappearance of some of the species marking faunal boundaries, but this evidence opposes the possibility. Even more convincing is the fact that in a core taken north of the Polar Front (RC8-52; 41°06'S, 101°25'W), in which the vast majority of species are warm-water species, the ranges of *Eucyradium calvertense* and *Clathrocyclas bicornis* are not significantly extended; in fact their upper limits bear a relation to the lower and upper boundaries of the Olduvai event resembling that found in cores taken from beneath the colder waters to the south of the Polar Front (Fig. 10).

**Discussion**

The limited geologic ranges of some planktonic organisms and their widespread distribution have made them excellent guide fossils, yet no completely satisfying explanation of the factor limiting their ranges has been proposed. Our data show with hitherto-unparalleled precision that the upper limits of the ranges of certain radiolarian species are nearly isochronous over a broad area. In fact the magnetic-polarity epochs, down to the base of the Gauss normal-polarity series, can be characterized by their content of Radiolarians.

Of the multitude of factors that may extingush pelagic organisms, only a few leave decipherable records in sediments. One factor that is frequently credited with causing extinctions is change in temperature; our data show that, at least for two species *Eucyradium calvertense* and *Clathrocyclas bicornis*, it is unlikely that change in temperature was responsible. This probability does not preclude the possibility that temperature change was involved in the disappearance from antarctic sediments of other radiolarian species such as those that disappear at the X-Ψ boundary, several of which are still living north of the Polar Front.

It has been suggested (1) that, because some antarctic Radiolaria disappeared near reversals, the reversals in some way influenced their disappearance. The faunal boundaries are drawn at the last common occurrences of the indicator species. The Ψ-Ω boundary has no corresponding reversal, although the other four faunal zones are usually associated with reversals (Table 4). Since nearly all species used in the definition of faunal zones survived a number of reversals before disappearing near one, we can only assume that, if a reversal did affect a species, either the effects of reversals differed or the reversal was a contributor to other environmental stresses that tended to weaken the species. In several instances a faunal boundary and a reversal coincide within the sampling interval (Table 4). The lack of coincidence in other instances may be due to postdeposition-al displacement of either the magnetic or the faunal boundary. It is possible, however, that the reversals and faunal limits are separated by thousands of years. Nevertheless there remain tantalizingly close correlations between four of the five faunal boundaries and reversals (Table 4). We hope that other students of pelagic organisms will examine their data in the light of these results.

**Pliocene-Pleistocene Boundary**

Stratigraphic boundaries traditionally have been drawn on the basis of faunal changes, regardless of whether these changes were climatically induced. It has been recommended (13) that "in order to avoid ambiguities, the Lower Pleistocene should include as its basal member in the type-area the Calabrian formation (marine) together with its terrestrial (continental) equivalent the Villafranchian." [According to evidence given, this usage would place the boundary at the horizon of the first indication of climatic deterioration in the Italian Neogene succession." The cooling trend in the Calabrian, evidenced by the first appearance of several cold-water species, has been taken to signal the initiation of glaciation in the Alps (14).]

While direct faunal comparison between our three cores and the type locality of the Pliocene-Pleistocene boundary is difficult, indirect correlation is now possible. In the Antarctic the base of the Pleistocene was tentatively drawn by Hays (2) at the Ψ-X boundary. Recently Banner and Blow (15) have established a planktonic foraminiferal zonation of the Neogene.
The boundary between their zones N21 and N22, based on the evolutionary transition from Globorotalia (G) tosaensis to Globorotalia (G) truncatulinoides, occurs near the base of the stratotype Calabrian at Santa Maria di Catanzaro (16), the agreed earliest Quaternary (13). Berggren (17) has shown that this same evolutionary transition, marking the boundary between zones N21 and N22, occurs within the Olduvai event in a core from the North Atlantic. Since the Pliocene-Pleistocene boundary falls within the Olduvai event, the Φ-X boundary, falling near the base of the Olduvai event, represents a close approximation of the boundary in Antarctic sediments.

Although the faunal change across the Φ-X boundary is significant, the greatest faunal change in these cores occurs at about 2.5 million years ago; evidence in E13-3 and E14-8 indicates a change from warmer to cooler conditions near this boundary.

Mathews and Curtis (18) have dated a so-called Pliocene-Pleistocene boundary in New Zealand at “more than 2 million years and probably nearer to 2.5 million years ago.” This boundary is placed at the first indication of cooling conditions in a New Zealand pollen sequence (19); such cooling in New Zealand probably correlates with cooling indicated at the Φ boundary in Antarctic cores E13-3 and E14-8.

Rutten and Wensink (20) have found that the first glacial till in Iceland falls in the middle of the Gauss normal-polarity series, so that it is about 3 million years old; this paleomagnetic age has recently been confirmed by potassium-argon dating (7). A similar age of 2.7 million years for a lava flow overlying the oldest till yet found in the Sierra Nevada of California has been reported (21).

Conolly and Ewing (22) determined that the first appearance of ice-rafted debris in severalantarctic cores fell somewhat below the Φ-X boundary; this level was dated (I) at about 2.5 million years ago. Thus it appears that the major faunal change in Antarctic cores during the last 5 million years occurred at about the same time as evidence of deteriorating climatic conditions in other parts of the world. The time between 3 and 2.5 million years ago seems to have been critical in Neogene history and may have been the prelude to widespread glaciation in more temperate regions.

### Antarctic Glaciation

Evidence is now available that glacial conditions existed on Antarctica well before the 3-million-year date reported (20) for Iceland. There is evidence (23) of glacial action probably older than 10 million years in the Jones Mountain area.

Preliminary examination (24) of our three Antarctic cores shows that the age of the lower limit of ice-rafted debris varies from core to core. Core E13-3, the northernmost of the three, has ice-rafted grains in all samples above 650 centimeters (about 2 million years ago). In E13-17, the southernmost ice-rafted debris occurs to a depth of 1970 centimeters (more than 4 million years ago). Core E14-8 has ice-rafted material throughout; the age of its base is uncertain but probably exceeds 4 million years.

In age of its ice-rafted grains, E13-3 resembles nearby cores (22). The earlier appearance of glacial debris in the two western cores (E13-17 and E14-8) may indicate earlier glaciation of East than of West Antarctica. In any event our data indicate widespread glaciation on Antarctica at least 4 million years ago.

### Summary

Our study extends the continuous record of the earth's magnetic field to more than 5 million years ago; it defines three new magnetic normal-polarity events and one new normal-polarity epoch. One core (E13-3) has a sufficiently constant rate of sedimentation to enable one to make reliable estimates of the ages of the three new events. The age of the upper boundary of the new polarity epoch is estimated at 5 million years. Because of the many new magnetic events and epochs that will be found through study of deep-sea sediments, we propose a numbering system that may simplify designation and increase the usefulness of marine magnetic stratigraphy.

The rate of deposition of clay in the cores is relatively constant, fluctuations being largely due to variation in amount of biogenic silica.

The cores contain a radiolarian stratigraphy similar to that reported (1, 2), and they also record disappearances of other species that may make possible the definition of two new faunal zones.

The upper boundary of one of these zones (Y) is the most striking faunal change yet encountered, occurring at about the same time as evidence of climatic deterioration in other parts of the world. All the faunal boundaries are time-dependent; four coincide with reversals, or almost so. Change in temperature may have been responsible for some of the boundaries, but not apparently, for at least one. The close correspondence between reversals and faunal boundaries, whether or not changes in temperature were involved, adds a new dimension to the perplexing question of planktonic extinctions.

### References and Notes

3. The cores were taken by U.S.N.S. Eltanin on cruises of 1960 and 1961.
13. The recommendation was made by the Commission on the Pliocene-Pleistocene Boundary, International Geological Congress, 18th, 1948 (1950).
16. The stratotype is described by M. Gignoux, [Ann. Univ. Lyon 36, 35 (1913)] as typical of his Calabrian stage, as proposed in Compit. Rend., 150, 841 (1910).
24. The examination was made by D. Horn, Lamont Geological Observatory.
25. The work described was supported by grants from the National Science Foundation (GP 4004, GA 824, GA 558, and GA 861) and the Office of Naval Research (NOO004-67-A-0108-0004). We thank M. Ewing and W. Broecker, who read the manuscript and made helpful suggestions, and G. Goodell and N. Watkins, who assisted when the cores were sampled at Florida State University. This article is Lamont Geological Observatory contribution No. 1122.
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