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# Antarctic Radiolaria, Magnetic Reversals, and Climatic Change

## Disappearances of some Radiolaria closely correlate with magnetic reversals during the last 5 million years.

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Earlier (*1*) we reported the magnetic and radiolarian stratigraphy of seven cores from the Antarctic Ocean; the study established a paleomagnetic stratigraphy for antarctic deep-sea cores back to about 3.5 million years ago and verified the previously established (*2*) radiolarian stratigraphy. We now report the results of a study of three long antarctic cores containing records of continuous or nearly continuous sedimentation back to more than 4 million years ago; one of them contains a record probably longer than 5 million years. This longer stratigraphy makes possible the definition and approximate dating of new polarity events and radiolarian zones; it also contains evidence of a major faunal change about 2.5 million years ago that appears to correlate with evidence of cooling in other parts of the world.

Two (E13-3 and E13-17) of the three cores were taken (*3*) from the Bellingshausen basin; one (E14-8), from the western flank of the Mid-Pacific Ridge (Fig. 1 and Table 1). Each core contains an upper layer of siliceous sediment: diatom ooze in E13-17 (0 to 1020 centimeters) and E14-8 (0 to 1710 centimeters), and radiolarian clay in E13-3 (0 to 1000 centimeters). This siliceous sediment overlies a tan clay that is barren in E13-3 (1000 to 1603 centimeters) and E14-8 (1710 to 1830 centimeters) but interbedded in E13-17 with layers of radiolarian and diatomaceous clay (Figs. 2–4).

### Magnetic Stratigraphy

Samples (8 cubic centimeters) were taken from all three cores at 10-centimeter intervals. The lower end of each sample was marked, and all were partially demagnetized in alternating fields (E14-8, 50 oersteds; E13-3 and E13-17, 150 oersteds). The direction and intensity of the remnant magnetism of each sample were measured on a magnetometer (5 cycles per second) described by Foster (*4*).

Inclination versus depth in the cores is shown in Fig. 5; the internal consistency is reasonably good in E13-17 and E13-3, but in E14-8 the quality of the data is poor, especially above 800 centimeters.

Correlation of the magnetic stratigraphy between these three cores and their correlation with the magnetic stratigraphy of Cox, Doell, and Dalrymple (*5*) are evident down to the Gilbert reversed-polarity epoch (Fig. 1 and Table 2).

The magnetic stratigraphy of E13-17 has been reported by Watkins and Goodell (*6*), who determined the inclination only upward or downward, with an astatic magnetometer; the amount of inclination was not determined, and only one specimen in seven was demagnetized in alternating fields. Watkins and Goodell chose the Brunhes-Matuyama boundary at 500 centimeters, which is preceded by a long normal interval that they identified as the Jaramillo event. The inclination plot for this core (Fig. 5a) shows that, at the point chosen by Watkins and Goodell as the Brunhes-Matuyama boundary, the inclination becomes less steep but never crosses the axis to become positive. It is probably because all specimens were not demagnetized that Watkins and Goodell misidentified the Brunhes-Matuyama boundary. We place the boundary at 615 centimeters, which position accords with the paleontologic zonation since the X-Ψ boundary occurs at 690 centimeters (Fig. 4). The relation between the paleontologic and magnetic stratigraphy is well documented (*1*); therefore the Jaramillo event as we identify it is the event that Watkins and Goodell called the Gilsa. Clearly there is in this core no evidence of the Gilsa event as postulated by MacDougall and Wensink (*7*).

Hitherto details of the magnetic stratigraphy within the Gilbert and below have remained unknown. A predominantly reversed section of core, which presumably represents the Gilbert reversed-polarity series, lies below the Gauss normal series in all cores. Within this reversed interval are three prominent normal events in E13-3 and E13-17. The lower two events in E13-17 appear to be split, but the resolution of the data is insufficient for determination of this point without question. In the sediment below the Gauss normal series in E14-8 two distinct normal events are defined, and the upper part of a third is present. The core bottoms at 1830 centimeters, but the magnetic intensity drops to too low

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a level for reliability below 1650 centimeters.

Below the three events in E13-17 is an interval from 2000 to 2070 centimeters that is reversely magnetized. A void in the core extends from 2090 to 2180 centimeters, and the magnetic determinations from the specimens immediately above and below this void must be regarded as suspect. From 2200 to 2500 centimeters the core is predominantly normally magnetized, with one short reversed section at about 2225 centimeters.

These cores provide strong evidence of the existence of three short polarity events in the Gilbert reversed-polarity epoch; their existence has been confirmed in cores from other regions. Below these events in E13-17 are a reversed interval and then a long normal interval of epoch proportions. We propose establishment of the beginning of the Gilbert reversed-polarity series at the base of the reversed section of core that precedes the three newly established events.

The JOIDES deep-sea drilling program will provide for study cores that span significantly longer periods than do cores obtained by piston-coring techniques. Thus the present system of naming epochs of magnetic polarity after great magneticians, and events after geographic localities, will lead to great proliferation of names, since one may obtain a single deep-sea core spanning possibly 60 million years of the earth's magnetic history. It seems reasonable to restrict the present systems of naming (*5*) to epochs and events that have already been defined on the basis of correlation by potassium-argon decay. Barring a major breakthrough in the precision of potassium-argon dating techniques, it seems unlikely that the present system can be extended much beyond the Gilbert reversed-polarity epoch.

We therefore propose a numbering system that could be tied eventually to classical stratigraphic nomenclature and to the absolute time scale; it has the advantage of simplicity and allows a worker to recognize the positions of events and epochs in the sequence without need to memorize a long list of

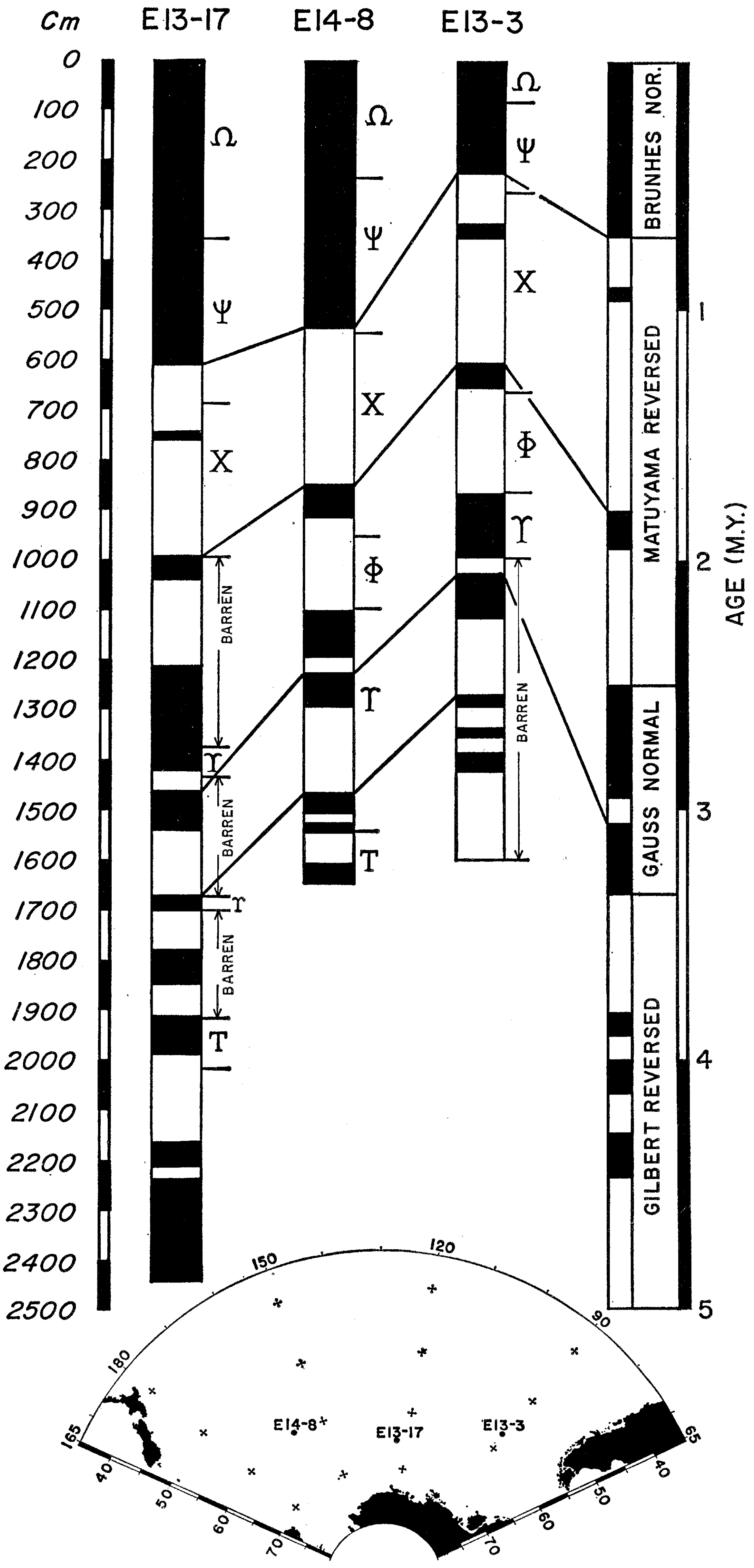


Fig. 1. Correlation of magnetic stratigraphy in three antarctic cores. Solid black represents normally magnetized core: white, reversely magnetized. Greek letters denote faunal zones (*2*). Magnetic stratigraphy, in right-hand column down to the top of the Gilbert reversed, is from Cox *et al.* (*5*). Inset: sources of cores.

names. We propose to label the polarity epochs with Arabic numerals; events are labeled with letters from youngest to oldest within an epoch. By this system, for example, the Brunhes polarity epoch would be 1; the Matuyama, 2; and the Jaramillo and Olduvai events, 2*a* and 2*b*, respectively. If, after the system is established, new events are found, they may be inserted between the established events. If a new event were found between the Jaramillo and Olduvai events it could be designated event 2*a*-*b*. Thus a long set of magnetic stratigraphy can be usefully designated and eventually, through absolute or paleontologic dating, incorporated into normal stratigraphic nomenclature. We do not intend this system to supersede the one now used for the last 3.5 million years of the earth's history, but rather intend it to be used to describe the sequential arrangement of epochs and events that will be found in the near future in oceanic cores. In this article we propose to designate the three new events in the Gilbert *a*, *b*, and *c*, from youngest to oldest, and the long normal interval lying below the Gilbert as magnetic epoch 5.

## Rates of Sedimentation

Rates of sedimentation, with paleomagnetic stratigraphy used as a reference, have been published for seven antarctic cores (*1*). Generally the rates in these cores vary with time. Our E13-3 seems to have a remarkably constant rate of sedimentation. By use of 0.7 million years as the age of the Brunhes-Matuyama boundary, 2.5 million years for the base of the Matuyama, and 3.35 million years for the Gauss-Gilbert boundary (*8*), a time versus depth plot for this core produces

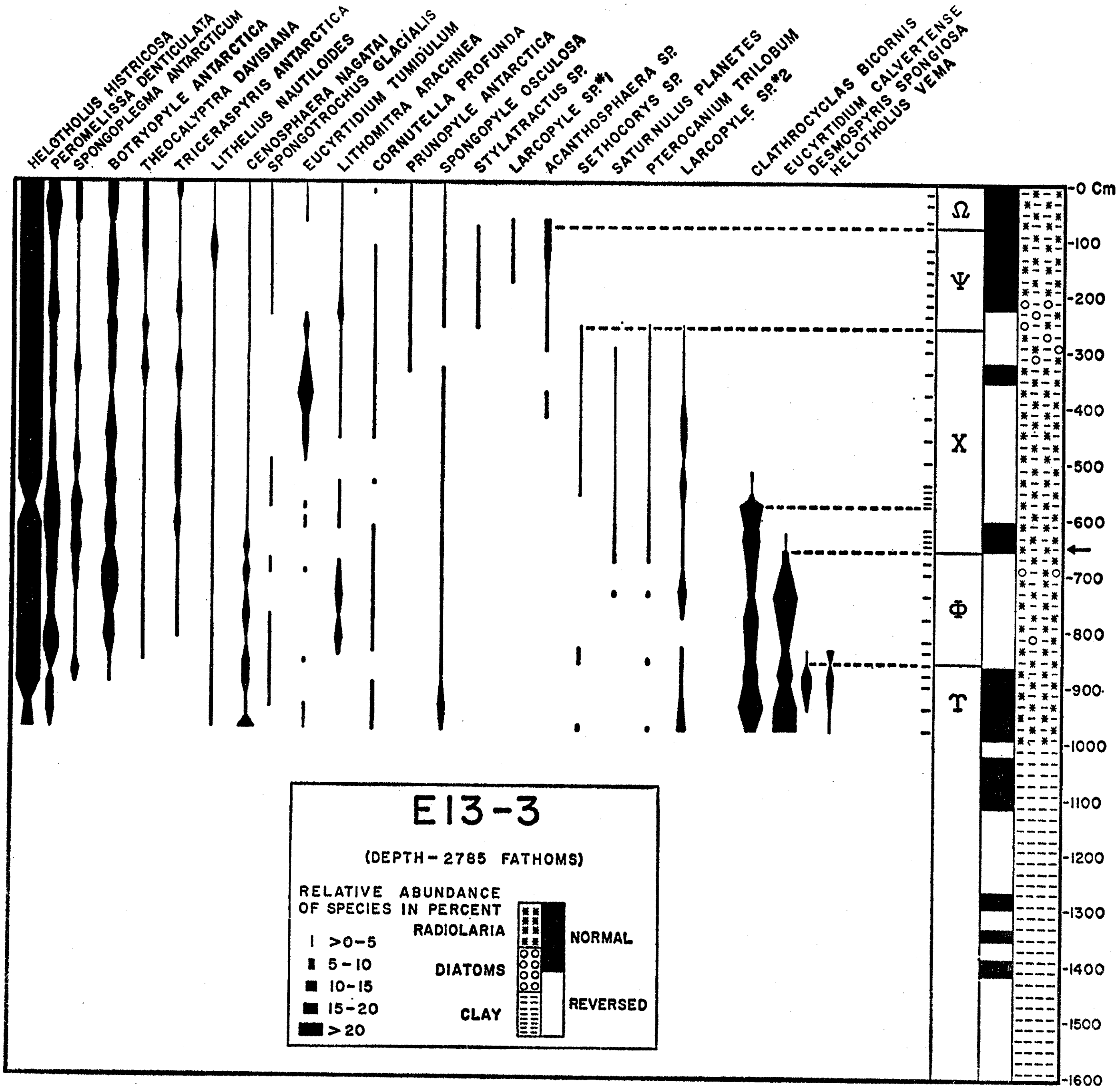


Fig. 2. Ranges of radiolarian species in core E13-3. Right-hand columns show lithology, magnetic stratigraphy, and faunal zones. Graticule at right indicates radiolarian samples. Arrow at far right shows lower limit of ice-rafted material.

a nearly straight line (Fig. 6). The rate of accumulation varies between 2.94 millimeters per 1000 years for the Gauss normal series and 3.56 millimeters per 1000 years for the Matuyama series.

The relative amounts of biogenic silica in these cores can be reliably estimated by inspection of the cores and study of the washed coarse fractions in samples taken at closely spaced intervals. Core E13-3 has a low content of biogenic silica throughout, consisting primarily of the shells of Radiolaria, although diatoms occur in subordinate amounts.

The longest core studied, E13-17, does not have a constant rate of sedimentation (Fig. 6). The rate (millimeters per 1000 years) in the Brunhes series is 8.8; in the Matuyama series,

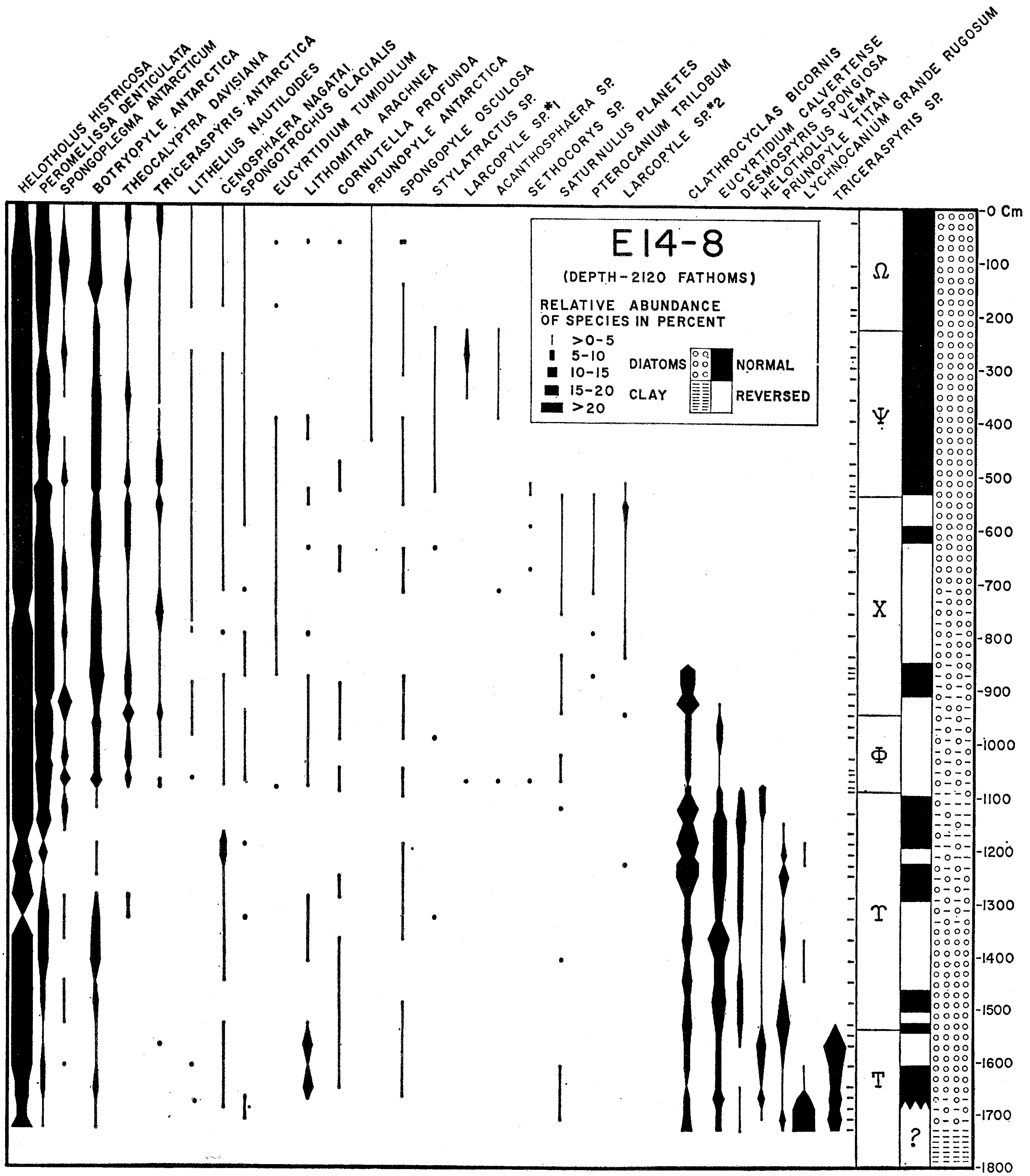
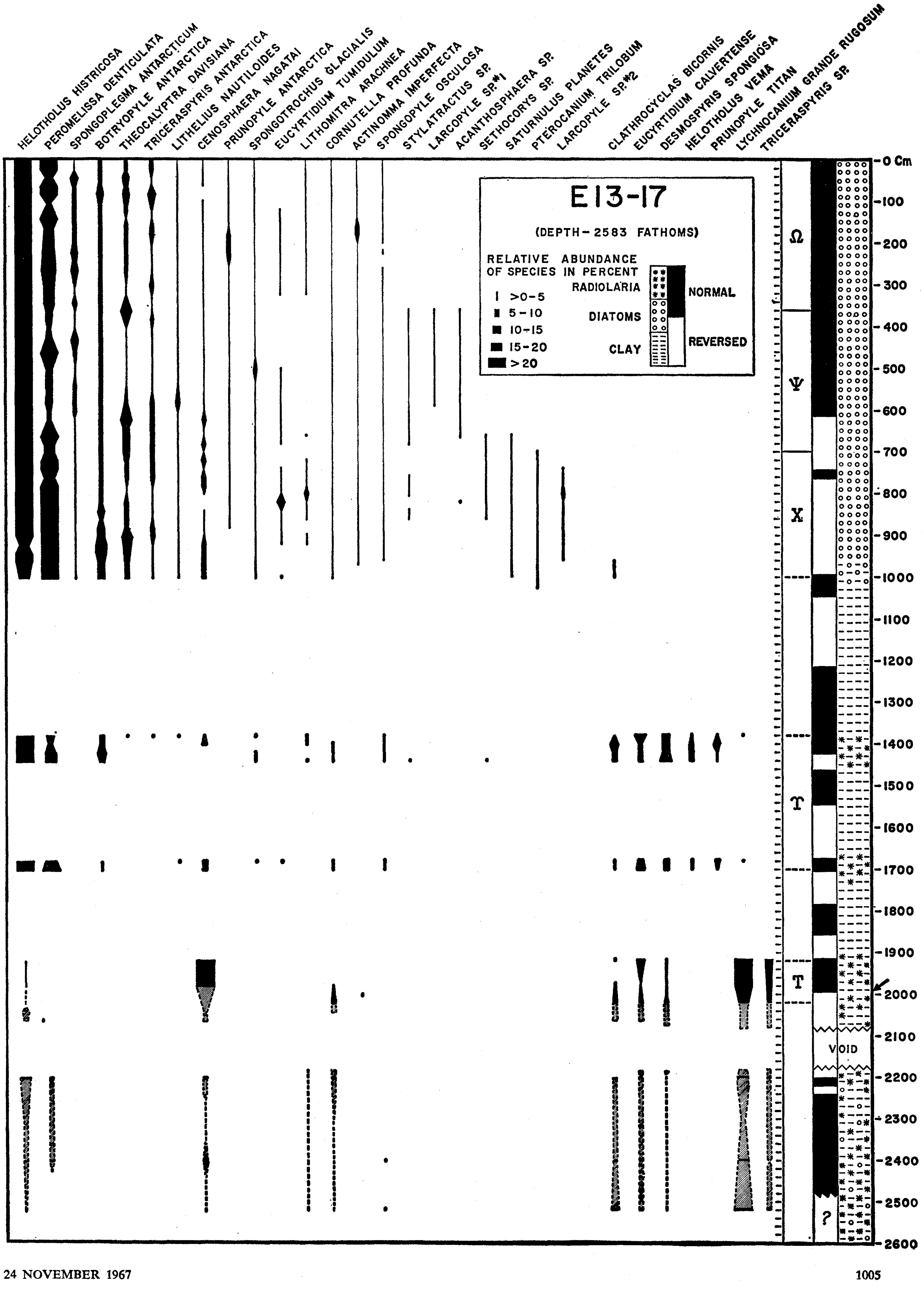


Fig. 3 (above). Ranges of radiolarian species in core E14-8. Right-hand column shows lithology, magnetic stratigraphy, and faunal zones. Graticule at right indicates radiolarian samples. Fig. 4 (right). Ranges of radiolarian species in core E13-17. Right-hand columns show lithology, magnetic stratigraphy, and faunal zones. Graticule at right indicates radiolarian samples. Arrow at far right shows lower limit of ice-rafted material. Hachures show where corrosion makes estimates of abundance difficult.


HELOTHOLUS HISTRICOSA
PEROMELISSA DENTICULATA
SPONGOPLEGMA ANTARCTICUM
BOTRYOPYLE ANTARCTICA
THEOCALYPTRA DAVISIANA
TRICERASPYRIS ANTARCTICA
LITHELIUS NAUTILOIDES
CENOSPHAERA NAGATAI
PRUNOPYLE ANTARCTICA
SPONGOTROCHUS GLACIALIS
EUCYRTIDIUM TUMIDULUM
LITHOMITRA ARACHNEA
CORNUTELLA PROFUNDA
ACTINOMMA IMPERFECTA
SPONGOPYLE OSCULOSA
STYLATRACTUS SP.
LARCOPYLE SP.#1
ACANTHOSPHAERA SP.
SETHOCORYS SP.
SATURNULUS PLANETES
PTEROCANIUM TRILOBUM
LARCOPYLE SP.#2
CLATHROCYCLAS BICORNIS
EUCYRTIDIUM CALVERTENSE
DESMOSPYRIS SPONGIOSA
HELOTHOLUS VEMA
PRUNOPYLE TITAN
LYCHNOCANIUM GRANDE RUGOSUM
TRICERASPYRIS SP.
E13-17
(DEPTH - 2583 FATHOMS)
RELATIVE ABUNDANCE OF SPECIES IN PERCENT
>0-5
5-10
10-15
15-20
>20
RADIOLARIA
DIATOMS
CLAY
NORMAL
REVERSED
Ω
Ψ
X
Τ
T
VOID
?
0 Cm
100
200
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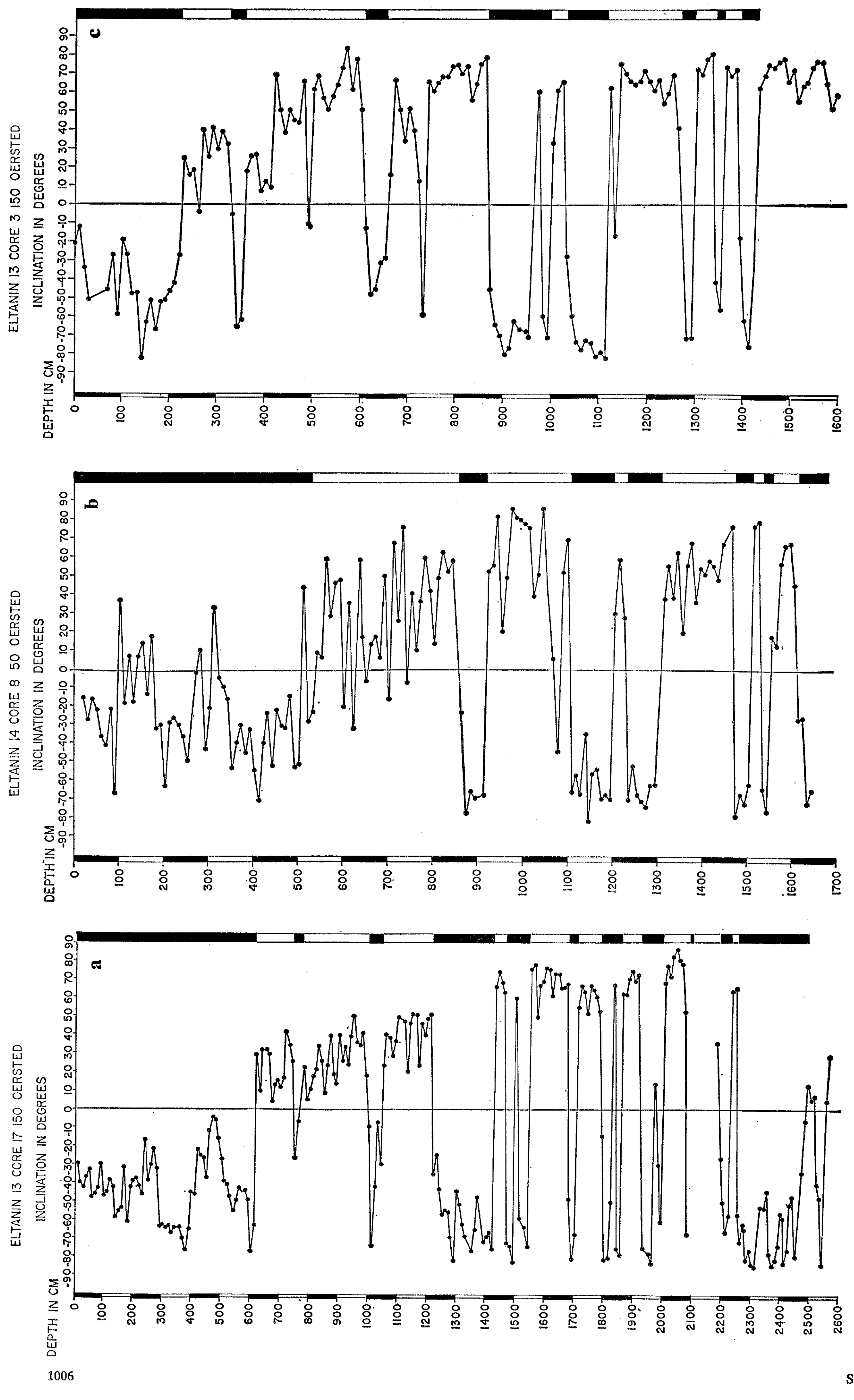


Fig. 5. Plots of inclination versus depth in cores E13-17 (a), E14-8 (b), and E13-3 (c).

Table 1. Sources of cores.

| Core | Latitude (S) | Longitude (W) | Water depth (m) | Length (cm) | Region |
|---|---|---|---|---|---|
| E13-3 | 57°00′ | 89°29′ | 5090 | 1603 | Bellingshausen basin |
| E13-17 | 65°41′ | 124°06′ | 4720 | 2642 | Bellingshausen basin |
| E14-8 | 59°40′ | 160°17′ | 3875 | 1830 | Flank of Mid-Pacific Ridge |

Table 2. Intervals of magnetic series and events in three cores.

| Series | Event | Core | | |
|---|---|---|---|---|
| | | E13-17 | E14-8 | E13-3 |
| Brunhes | | 0–615 | 0–535 | 0–225 |
| Matuyama | | 615–1215 | 535–1100 | 225–865 |
| | Jaramillo | 745–765 | ? | 325–355 |
| | Olduvai | 995–1045 | 845–915 | 605–655 |
| Gauss | | 1215–1545 | 1100–1300 | 865–1115 |
| | Mammoth | 1425–1465 | 1195–1225 | 995–1025 |

3.34; and in the Gauss normal series 3.88. The top 950 centimeters of this core is rich in diatoms and Radiolaria, but these fossils are rare below 10 meters, occurring only in thin layers (Fig. 4). The higher rate of accumulation during the Brunhes than during the Matuyama or Gauss can be accounted for by the relatively large number of diatoms and Radiolaria present in the top 1000 centimeters.

Core E14-8, like E13-17, has a higher sedimentation rate (millimeters per 1000 years) in the Brunhes (7.7) than in the Matuyama (3.1) or Gauss (2.4); this variation also can be explained by the content of biogenic silica, which is high in the top 700 centimeters; below this depth, diatoms and Radiolaria decrease in abundance to 1085 centimeters (just above the Gauss normal series). The biogenic silica is least abundant between 1085 and 1230 centimeters, an interval falling within the Gauss normal series. Between 1230 and 1650 centimeters the diatom content increases to a diatom ooze.

Our data indicate that the rate of accumulation of sediment containing little biogenic silica is fairly constant in all three cores, ranging between 2.4 and 3.9 millimeters per 1000 years, and that the high rates occurring in the top portions of E13-17 and E14-8 can be accounted for by the high content of biogenic silica.

In discussing the radiolarian stratigraphy of antarctic cores, Hays (*2*) suggested that the change from highly diatomaceous sediments in the tops of these cores to sediments containing few siliceous fossils below was caused by recently increased productivity in antarctic waters due to intensification of vertical oceanic circulation associated with ice formation around the continent. Our study supports this hypothesis, in showing that the clay sediments represent slow sedimentation rather than rapid clay deposition masking the biogenic silica.

Using the rates of sedimentation determined for the Gauss normal series, one can extrapolate to the three new events in the Gilbert reversed-polarity series to obtain rough estimates of their ages (Table 3). In E13-3, where extrapolation is probably most significant, the three events would span the time between 3.86 and 4.39 million years ago. In E13-17 the three events end at 3.79 million years ago, while they would begin at 4.67 million years. The variable content of biogenic silica in the lower part of E14-8 makes ages extrapolated from this core subject to large errors.

In a recent paper Dalrymple *et al.* (*9*) have dated a reversal which occurs at 3.7 ± 0.1 million years ago (W10R/N). This probably represents the upper boundary of event "*a*," the age of which, by our extrapolation, is very close to the age they obtained. Ozima *et al.* (*10*) record magnetic reversals in New Mexico at 3.7 and 4.5 million years ago which are also probably associated with these events; however, because of the errors involved, exact correspondence is difficult to es-

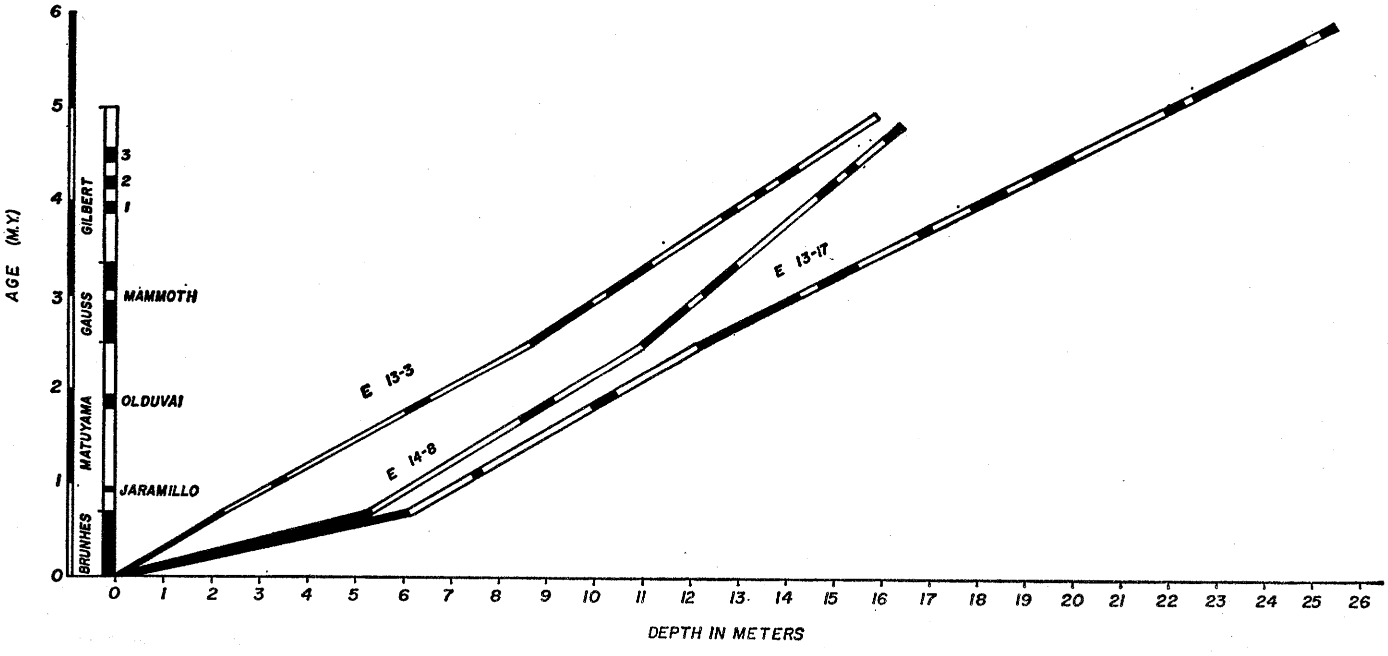
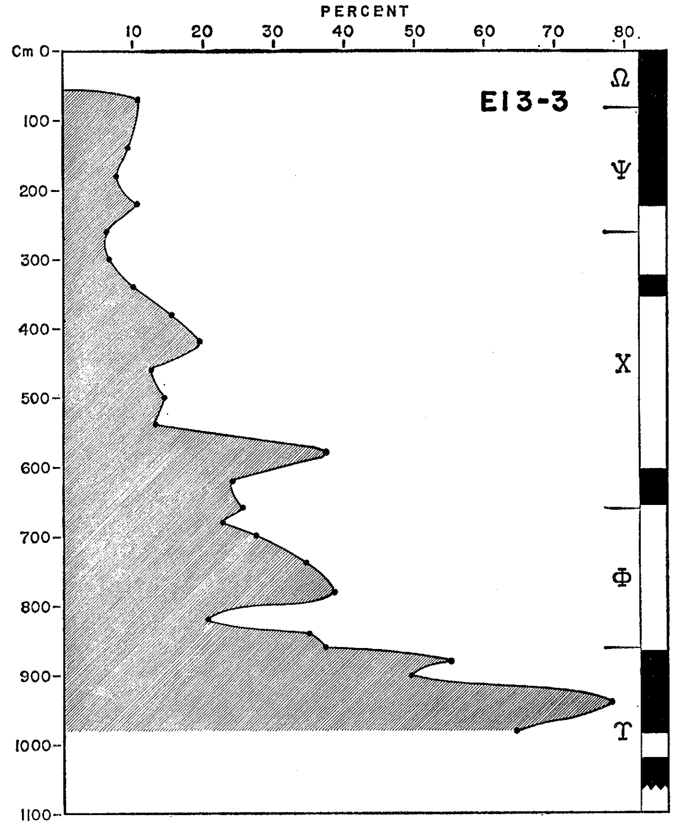
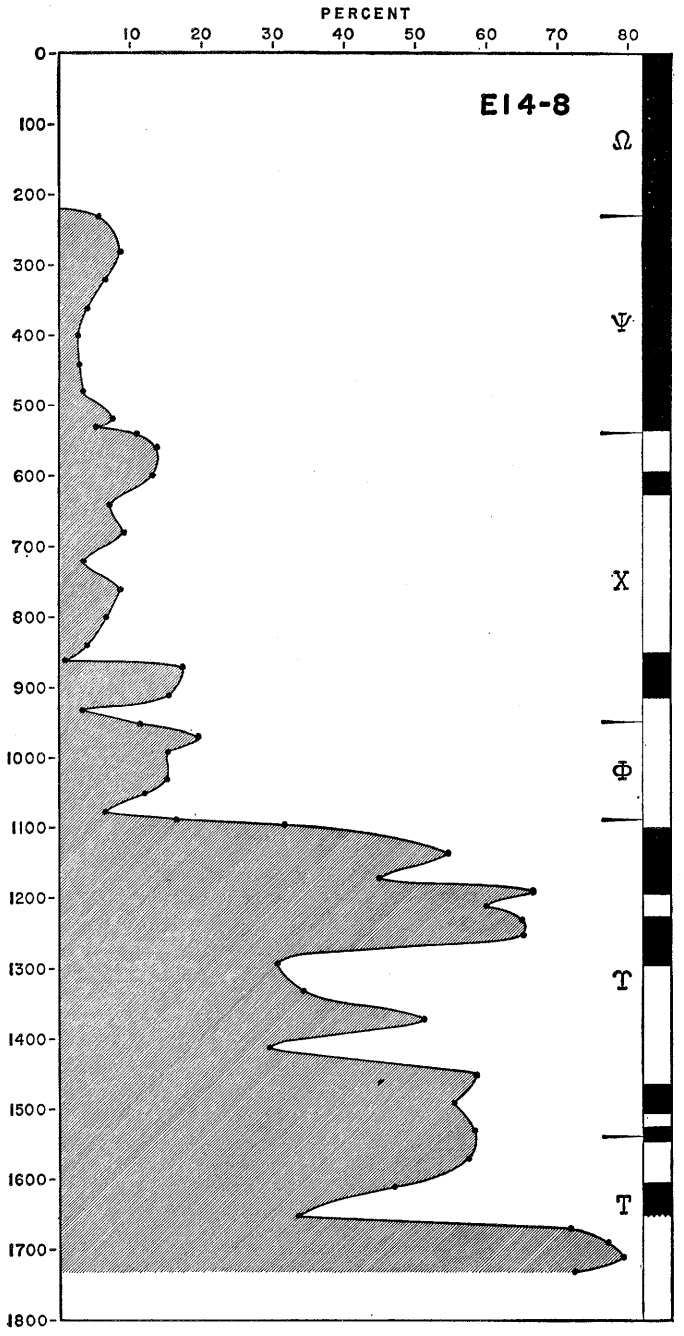


Fig. 6. Time versus depth plots of magnetic stratigraphy for three cores.

tablish. For example, the reversal dated by Cox *et al.* is from reversed polarity below to normal polarity above, at 3.7 million years ago, and the one by Ozima *et al.* is from normal polarity below to reversed polarity above, with the same age. Nevertheless, evidence for the existence of the events is present in lava flows on land.

One can also estimate the date of the beginning of the Gilbert epoch. Core E13-3 ends at 1600 centimeters and is reversed to its end; the extrapolated age of its base is 4.8 million years, so the beginning of the





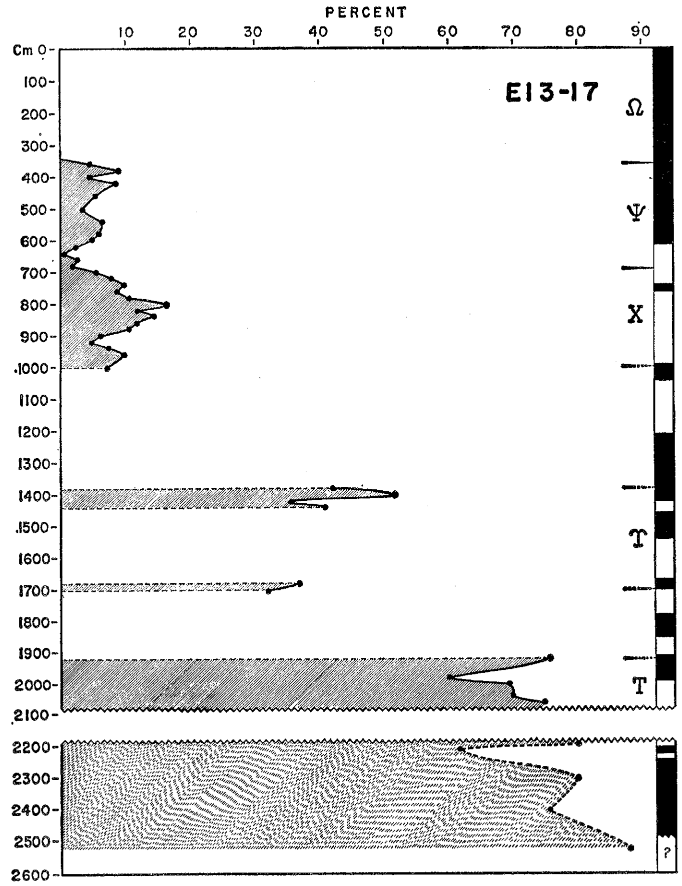


Fig. 7 (top left). Percentages of individuals of species, not found in Recent antarctic sediments, in core E13-3.

Fig. 8 (above). Percentages of individuals of species, not found in Recent antarctic sediments, in core E14-8.

Fig. 9 (left). Percentage of individuals of species, not found in Recent antarctic sediments, in core E13-17. Broken hachures show where corrosion makes estimates of abundance difficult.

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 Φ (oldest), X, Ψ, and Ω (youngest). The base of the Ω zone has been dated radiometrically at about 400,000 years (*11*). The base of the Ψ zone (0.7 million years) and the base of the X zone (about 2 million years) have been dated paleomagnetically (*1*), while the base of the Φ zone has not yet been defined. Previously the faunal work ended near the top of the Φ zone, for in antarctic sediments south of the Antarctic Polar Front the sediments in many areas become barren below the Φ-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 (*Larcopyle* sp. No. 1, *Larcopyle* sp. No. 2, and *Triceraspyris* 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) (*1*). The bottom of the Ω zone falls in the central portion of the Brunhes series. The X-Ψ boundary falls near but below the base of the Brunhes series, and the Φ-X boundary occurs just below the Olduvai event. The upper limit of the range of *Clathrocyclas 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 Φ-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 Φ zone as the interval in antarctic deep-sea sediments containing individuals of *Clathrocyclas bicornis* and *Eucyrtidium calvertense* above the last common occurrence of *D. spongiosa* and *H. vema*. The sediments underlying the Φ zone and commonly containing *D. spongiosa* and *H. vema* will be designated the upsilon zone (Υ). Near the Υ-Φ 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 Υ-Φ boundary the most striking faunal boundary yet studied. In fact the Υ zone in both E13-3 and E14-8 is characterized by high percentages of extinct species (Figs. 7 and 8). Although the Υ-Φ boundary is not present in E13-17, the interval containing Radiolaria within the Gauss normal series (1380 to 1440 centimeters) contains Υ-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 Υ-Φ boundary, so only in E14-8 can one determine the upper boundary of the next-lower faunal change. Below 1540 centimeters in E14-8, an undescribed spyroid (*Triceraspyris* sp.) is abundant; it is probably closely related to *Desmospyris spongiosa*, since the latter is abundant only above the upper limit of *Triceraspyris* sp. Since the upper limit of the range of *Triceraspyris* 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 Υ zone and the top of the T zone. The upper limit of the T zone falls within event *a* of the Gilbert polarity series.

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

| Event | Date (× $10^6$ years ago) | |
|---|---|---|
| | Beginning | End |
| | *Core E13-3* | |
| *a* | 3.86 | 3.95 |
| *b* | 4.08 | 4.15 |
| *c* | 4.25 | 4.39 |
| | *Core E13-17* | |
| *a* | 3.79 | 3.87 |
| *b* | 4.08 | 4.26 |
| *c* | 4.44 | 4.67 |

## 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.

| Faunal boundary | Depth (cm) | |
|---|---|---|
| | Boundary | Nearest reversal |
| | *Core E14-8* | |
| Ψ-Ω | 230 | No reversal |
| X-Ψ | 530–540 | 530–540 |
| Upper limit of *C. bicornis* | 860–870 | 840–860 |
| Φ-X | 950–970 | 910–920 |
| Υ-Φ | 1085–1095 | 1095–1105 |
| T-Υ | 1550–1570 | 1540–1550 |
| | *Core E13-3* | |
| Ψ-Ω | 50–70 | No reversal |
| X-Ψ | 240–250 | 220–230 |
| Upper limit of *C. bicornis* | 560–570 | 600–610 |
| Φ-X | 650–660 | 650–660 |
| Υ-Φ | 860–870 | 860–870 |

X-Ψ boundary, but the other faunal boundaries down to the Φ-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 *Axoprunum stauraxonium* and *Heliodiscus asteriscus.* In all samples below 2180 centimeters (5.0 million years) are fragments of the diatom species *Ethmodiscus rex*; although it has not been reported south of 30°S (*12*), 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 (Υ-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 (Υ-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′E), in which the vast majority of species are warm-water species, the ranges of *Eucyrtidium 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-unequaled 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 Radiolaria.

Of the multitude of factors that may extinguish 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 *Eucyrtidium 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 postdepositional 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.

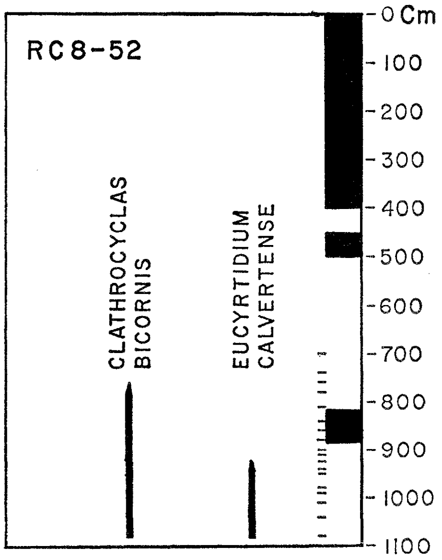


Fig. 10. Stratigraphic ranges of *Clathrocyclas bicornis* and *Eucyrtidium calvertense* compared with magnetic stratigraphy. Graticule at right indicates radiolarian samples.

## 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 Φ-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 Υ-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 several antarctic cores fell somewhat below the Φ-X boundary; this level was dated (*1*) at about 2.5 million years ago. Thus it appears that the major faunal change in antarctic cores during the last 5 million years occured 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 make possible the definition of two new faunal zones. The upper boundary of one of these zones (Υ) 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.

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