Paleomagnetic Study of Antarctic Deep-Sea Cores

Paleomagnetic study of sediments in a revolutionary method of dating events in Earth's history.

N. D. Opdyke, B. Glass, J. D. Hays, J. Foster

That the earth's magnetic field has changed polarity is now accepted as a fact by most geophysicists. Self reversal of certain magnetic minerals have also been shown to be possible, but instances in which self-reversal mechanisms have been proven continue to be rare. Cox *et al.* (*1*) and McDougall and Tarling (*2*), by carrying out simultaneous paleomagnetic and radiometric studies of Pliocene and Pleistocene lava flows, have been able to trace the changes in polarity of the earth's field through the last 4 million years. These they have named in order of increasing age (in millions of years): the Brunhes normal epoch, 0 to 0.7; the Matuyama reversed epoch, 0.7 to 2.4 ± 0.1; the Gauss normal epoch, 2.4 ± 0.1 to 3.35. The Gilbert reversed epoch ended at 3.35 million years and its beginning is not known. Within the Matuyama reversed epoch, two short periods of normal polarity occurred at about 0.9 and 1.9 million years, and these have been termed the Jaramillo and the Olduvai events, respectively. Within the Gauss normal epoch there was a short period of reversed polarity at 3.0 million years, called the Mammoth event. This magnetic stratigraphy is shown schematically in the left-hand column of Fig. 1.

Although most paleomagnetic studies have been of continental rocks, a few have been made of oceanic sediments by McNish and Johnson (*3*), Johnson *et al.* (*4*), Keen (*5*), Harrison and Funnell (*6*), and Fuller *et al.* (*7*). Of these only Harrison and Funnell and Fuller *et al.* found reversals of polarity.

The purpose of this study is to determine whether the direction of remanent magnetism in deep-sea cores can be used for purposes of stratigraphic correlation. Several long cores from high southern latitudes were chosen because at these latitudes the inclination of the magnetic field is sufficiently steep that cores oriented in azimuth are unnecessary; all one needs to know is which end of the core is the top. Also the paleontological stratigraphy based on Radiolaria is known, and this gives no indication of large hiatuses.

All cores used in this study are from the Antarctic region (Fig. 1; Table 1). Three of them were taken in the Bellingshausen Basin (V16-132, -133, and -134), one from near Drake Passage (V18-72), and three from the south Indian Ocean (V16-57, -60, and -66). Three of the cores (V16-133 and -134 and V18-72) were taken in an area of very moderate relief, whereas V16-57, -60, -66, and -132 were taken in areas of rugged relief. V16-60 and -132 were taken from the flanks of hills; V16-57 and -66, near the crests of hills.

Four of these cores (V16-132, -133, -134, and -60) consist of diatomaceous silty lutites in their upper portions and are silty lutites below (Fig. 1). V16-57, on the other hand, is more diatomaceous near the bottom, in fact the lowest 650 centimeters is a diatom ooze. V18-72 is only slightly diatomaceous in its upper part and contains silt and sand laminae, especially near the bottom. One core (V16-66) is a foraminiferal ooze. All the cores contain some ice-rafted material, and all except V16-60 and -66 contain manganese micro-nodules.

Dr. Opdyke is senior research associate, Mr. Glass and Mr. Foster are research assistants, and Dr. Hays is a research associate at Lamont Geological Observatory of Columbia University, Palisades, New York.

Laboratory Procedure

The cores were taken with a piston corer. Since they were cut into 10-foot (3.05-meter) sections aboard ship and the sections are not oriented relative to each other, the variation of the declination is not significant.

The cores were sampled every 10 centimeters, where possible, for a total of about 650 samples. The samples were cut into rough cubes measuring approximately 2 centimeters. If one assumes sedimentation rates between 2 and 10 millimeters per 1000 years, a sample of this size covers a period of from 10,000 to 2000 years. Each was measured on a 5-cycle-per-second spinner magnetometer, an instrument that uses a commercially available two-channel, phase-sensitive, synchronous detector. For each of six spins a measurement is made on two orthogonal components of the projection of the magnetic moment upon a plane normal to the spin axes. The time for a complete six-spin measurement of a 10-cubic-centimeter specimen runs from 2 minutes, for a specimen with a moment of 1×10^{-5} electromagnetic units per cubic centimeter at a 1-second output-meter time constant, to 20 minutes, for a moment of 1×10^{-7} electromagnetic units per cubic centimeter at a 24-second time constant. The 5-cycle-per-second rotation speed is very advantageous when one is working with mechanically weak specimens, which do not disintegrate at such speed.

In order to test for magnetic stability, alternating-field partial demagnetization was carried out in alternating-current fields of increasing strength (*8*). When a normal and a reversed specimen from core V16-133 were subjected to this treatment, the inclination in both specimens became steeper on application of low fields and remained stable even in high fields (Fig. 2).

The shapes of the alternating-field demagnetization curves (Fig. 3) vary widely. In all specimens there was an unstable component that was removed by fields of up to 150 oersteds. The rate of decrease of intensity with fields above this value decreases sharply, indicating that a stable component is present in most specimens. In some specimens having natural remanent magnetism directions that were almost horizontal, the sign of the inclination changed on alternating-field demagnetization. It seems probable that these unstable horizontal components were often acquired when the core was drying in a horizontal position; the direction of magnetization of specimens is known to change on drying, but it seems unlikely that this factor causes specimens that are steeply magnetized to change sign.

Each specimen from cores V16-57 and -134 was partially demagnetized in an alternating field of 150 oersteds; as a result of magnetic cleaning, the dispersion of the inclination in both cores decreased (Fig. 4).

Selected specimens from the other cores also were magnetically cleaned, particularly specimens from near reversals and specimens having shallow inclinations. In several instances these specimens changed sign on alternating-field demagnetization; in some cores this change served to move the boundaries between normal and reversed sections of the core (usually about 10 or 20 centimeters).

Magnetic Stratigraphy

A zone of normally magnetized sediment is present at the top of all cores studied (Fig. 1); we believe this represents the Brunhes normal epoch, which has been defined on the basis of K-A dating by Cox *et al.* (*9*). The K–A based stratigraphy is shown in the left-hand column of Fig. 1. We emphasize that the magnetic stratigraphy obtained from deep-ocean cores is based on the classical methods of stratigraphy—the law of superposition.

We shall hereafter refer to the sediments that we believe represent the Brunhes normal–polarity epoch as the Brunhes normal–polarity series. In all the cores a zone of reversed polarity occurs below the Brunhes normal series; we assume that it represents the Matuyama reversed epoch, and we shall refer to it as the Matuyama reversed

Table 1. Sources of cores. Be, Bellingshausen; Ba, Basin; P, passage; AIR, Atlantic-Indian Ridge; MR, Madagascar Ridge.

Core	Coordinates	Water depth (m)	Region
V16-132	60°44.5'S,107°29'W	4898	BeBa
V16-133	61°56.5'S, 95°03'W	5062	BeBa
V16-134	61°54.0'S, 91°15'W	5138	BeBa
V18- 72	60°29.0'S, 75°57'W	4695	DrakeP
V16- 57	45°14.0'S, 29°29'E	5289	Agulhas Ba
V16- 60	49°59.5'S, 36°45.5'E	4574	AIR, S. flank
V16- 66	42°39.0'S, 45°40'E	3072	S. MR

series. The change in polarity between the two zones is very abrupt in all cores (Fig. 4), with the possible exception of V16-66 in which a zone is very weakly magnetized between 300 and 400 centimeters; unfortunately the change in magnetic polarity takes place within this interval, so that the exact

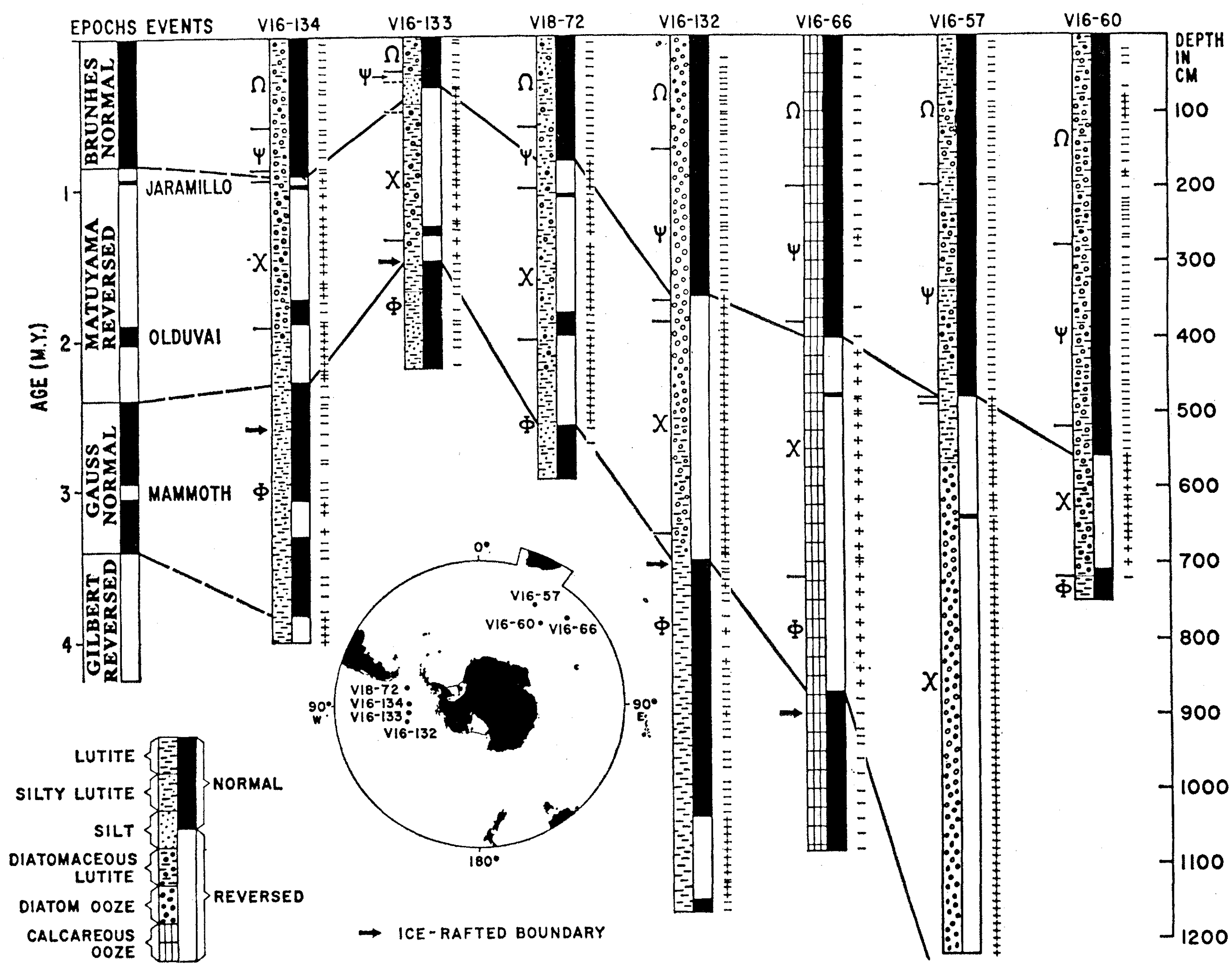


Fig. 1. Correlation of magnetic stratigraphy in seven cores from the Antarctic. Minus signs indicate normally magnetized specimens; plus signs, reversely magnetized. Greek letters denote faunal zones (*17*). Magnetic stratigraphy in left-hand column is from (*1*, *2*). Inset: sources of cores.

position of the change in this core is in some doubt.

Within the Matuyama series, short intervals of normal polarity occur both at the top and toward the bottom of the series. The short normal interval near the top in V16-134, V18-72, V16-66, and V16-57 is presumed to be the Jaramillo event—recently named by Doell and Dalrymple (*10*). The interval of normal polarity toward the bottom of the series in cores V16-134, V16-133, and V18-72 we correlate with the Olduvai event.

None of these zones of normal polarity in the Matuyama series have been found in V16-132. In V16-60 the bottom of the core is normally magnetized, and it is uncertain whether this normal polarity represents the Olduvai event or the beginning of the Gauss normal epoch.

All the cores with the exception of V16-57, and possibly V16-60, have a normal interval below the Matuyama series, which we believe is the Gauss normal series. Within the Gauss normal series in V16-134 there is a short interval of reversed polarity, between 615 and 665 centimeters, which we correlate with the Mammoth event. In V16-132 the zone of reversed polarity between 1035 and 1145 centimeters we also interpret as correlative with the Mammoth event. V16-134 is the only core to pass through the Gauss normal series to an underlying reversed interval that we correlate with the Gilbert reversed epoch.

Two cores, V16-60 and -132, have intervals in which the polarity data are inconsistent. V16-60 has a long, dominantly normal zone from the top to 500 centimeters, but single specimens or groups of specimens have reversed directions at 10, 100, and 180 centimeters. In core V16-132 the directions are consistent down to 700 centimeters; lower, the specimens are weakly magnetized and individual specimens are polarized reversely to those immediately above and below them. Originally the change from the Matuyama to the Gauss series was placed at 800 centimeters.

On alternating-field demagnetization the polarity of this zone changed from dominantly positive to dominantly negative, moving the boundary up to 700 centimeters. In general, after alternating-current cleaning, the results were more consistent, but all anomalous determinations were not removed. The meaning of these apparently false reversals is not clear, but they may be caused by one or more of the following factors: (i) magnetic instability (which in the case of V16-132 may be caused by partially decayed manganese micronodules), (ii) physical disturbance by the coring operation or extrusion of the core, (iii) errors in orienting sections of the core or in labeling samples, (iv) slumping or other bottom disturbances, or (v) the presence of previously unrecorded events.

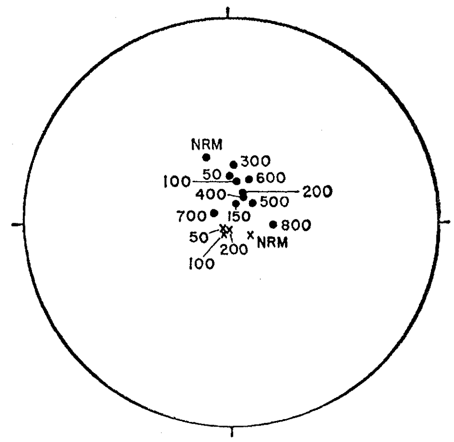


Fig. 2. Stereographic projection of directions of magnetization of two specimens from V16-133. Crosses represent negative inclinations; solid circles, positive. Numbers represent demagnetizing fields in oersteds, *NRM*, natural remanent magnetism.

The magnetic inclination in V16-57 and -134 was examined in some detail, and all specimens from these cores were partially demagnetized in a field of 150 oersteds. The magnetic inclination in V16-57 is very consistent (Fig. 4); the top 480 centimeters is normally magnetized, with no exceptions; at 480 centimeters a sharp reversal of sign occurs, and from there to the bottom of the core the specimens are reversely magnetized, with the exception of one normally magnetized specimen from 640 centimeters. The mean inclination of the top 480 centimeters, which is normally magnetized, is 65 degrees. In the lower part of the core, which is reversely magnetized, the mean inclination is 63 degrees; the ambient field at this location is about 66 degrees. Creer (*11*), averaging the earth's field around lines of latitude, found the mean field at 45 degrees south latitude to be 63 degrees. The inclination of the axial dipole field at this latitude is 63 degrees. Therefore the mean observed inclination in the core has a value that agrees with its present magnetic and geographic latitude.

In V16-134, as in V16-57, the dispersion of the inclination decreased on magnetic cleaning. The mean inclination of all the normally magnetized specimens is 71 degrees, and the same is true of the reversed specimens. The core was taken from 63 degrees south latitude where the ambient field is about 61 degrees. Creer (*11*) averaged the inclination of the ambient field around latitude 60 degrees south and obtained a value of 71.8 degrees, to which the numerical average obtained from both the normal and reversed sections of V16-134 is very close. The mode of the measured inclination is nearly 75 degrees, very close to the inclination of the axial dipole field—73.9 degrees at 60 degrees south. This fact suggests that the dipole field may average to an axial dipole field.

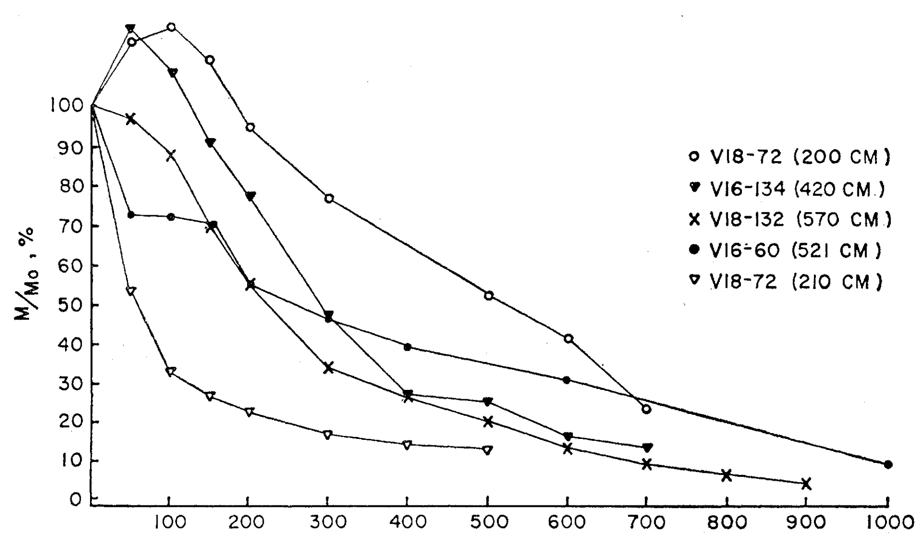


Fig. 3. Alternating-field demagnetization curves of specimens from five cores. *M/Mo* is the ratio of remaining to initial intensity after treatment in the corresponding field.

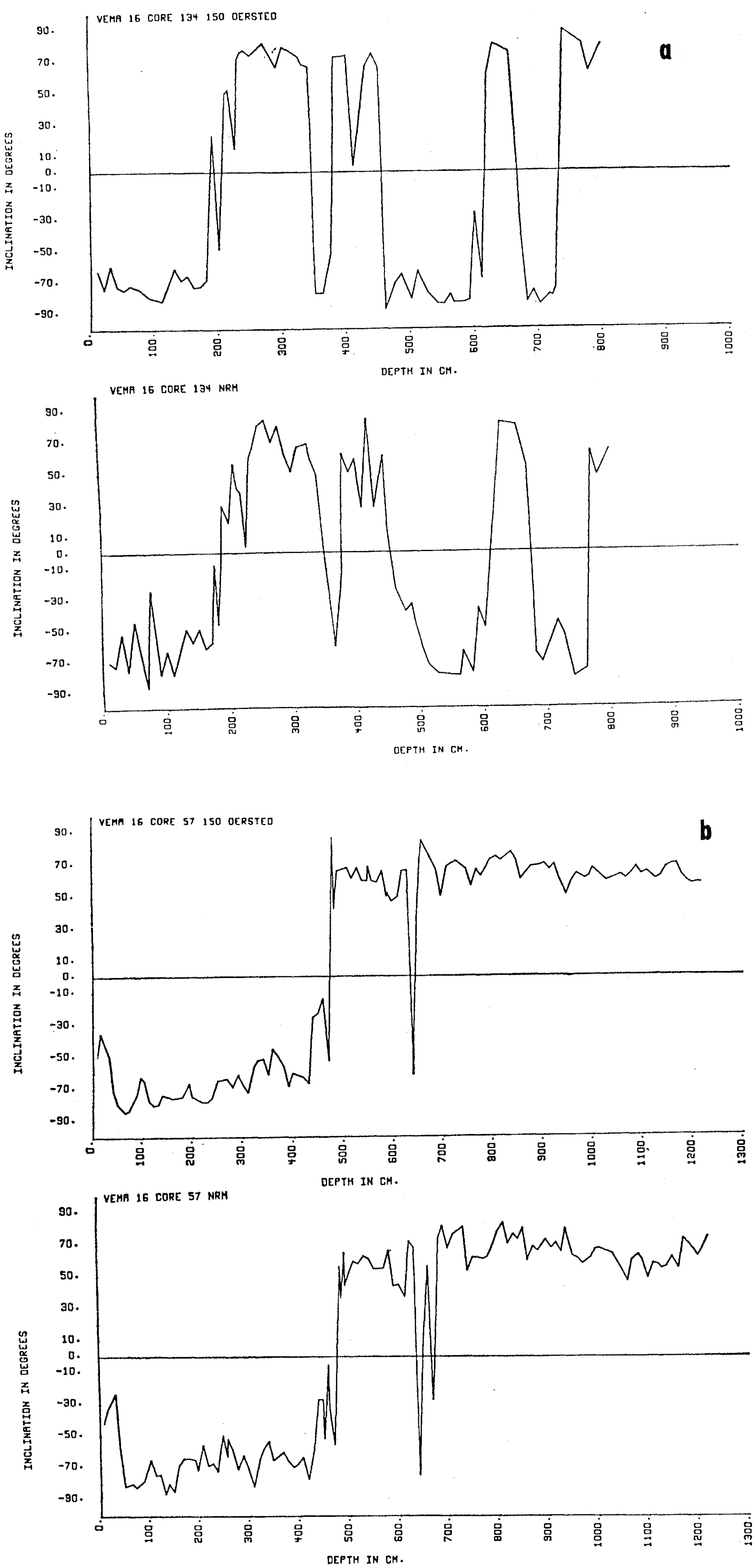


Fig. 4 (left). Plot of inclination versus depth in cores V16-134 (a) and V16-57 (b). *NRM*, natural remnant magnetism.

Earlier workers found that the inclination of the magnetic vector in sediments was consistently less than the inclination of the ambient field (*4*), but their samples were not treated in alternating fields. Our untreated samples also showed a relatively low inclination, but after treatment in alternating fields the inclination was in good agreement with the average field for the latitude of the core site. Keen (*5*), in his study of North Atlantic cores, observed a decrease of inclination with depth, which he attributed to compaction; we found no systematic decrease of inclination with depth in Antarctic cores.

The intensity of magnetization of our cores is usually in the range of 10^{-5} or 10^{-6} electromagnetic units per cubic centimeter. A plot of intensity versus depth, after partial alternating-current demagnetization at 150 oersteds, in cores V16-134 and V16-57 appears in Fig. 5; each specimen was weighed and the intensity is given in electromagnetic units per gram. There is no apparent correlation between small changes in lithology and intensities of magnetization, but there is some indication that the diatomaceous ooze in the bottom of V16-57 has higher intensities than the diatomaceous lutite near the top. Also there is a difference in intensity between cores of very different lithology. The core with the lowest intensities of magnetization is V16-66, a foraminiferal ooze; the other cores are dominantly diatomaceous lutites and have similar intensities.

Positive correlation exists between the reversals and low magnetic intensities. At every reversal in cores V16-57 and -134 there is a drop in intensity (Fig. 5). The lowest intensity measured in V16-57 occurs near the polarity change at 475 centimeters. In core V16-134 also, the lowest measured intensities are near the points of reversal, as one may expect if it is true (as has been postulated by use of the dynamo theory) that when reversal of the field occurs the intensity of the dipole field decreases to zero and builds again with the opposite polarity (*12*).

Keen (*5*) ascribed the magnetization of cores studied by him from the eastern basin of the North Atlantic to the presence of detrital magnetite. Harrison and Peterson (*13*) after study of

Table 2. Sedimentation rates of seven cores.

Interval (10^6 yr)	Rates ($mm/10^3$ yr)						
	V16-134	V16-133	V18-72	V16-132	V16-66	V16-57	V16-60
0.7 to 0.0	2.6	1.1	2.4	5.0	5.8	6.8	8.0
Olduvai to 0.7	1.5	1.6	1.7				
2.4 to 0.7	1.5	1.3	1.9	1.9	2.6	4.2	
Mammoth to 0.7	2.5						
3.5 to 2.4	2.9			3.0			
3.5 to 0.7	2.2			2.5			
Averages							
	2.3	1.2	2.1	3.2	4.1	6.6	8.0

a magnetic mineral found in two cores from the Indian Ocean concluded that it was between magnetite and maghemite in structure, and that the magnetic properties of the sediment suggested formation *in situ*. When magnetic separates made from our cores were examined with an x-ray difractometer, magnetite lines were present in all. Curie-point determinations were made on specimens from several of these cores by Dickson (*14*), and were found to be in the region of about 600°C, close to the curie point of magnetite; however, other magnetic minerals may be present. Some of the magnetite occurs as inclusions in fragments of igneous rocks and therefore appears to be dominantly detrital in character, although the presence of authigenic magnetite cannot be excluded.

Radiolarian Stratigraphy

Four faunal zones have been established for Antarctic deep-sea cores on the basis of Radiolaria (*15*). These zones are designated, from oldest to youngest, Φ, X, Ψ, and Ω and are based primarily on the upward sequential decrease of radiolarian species (Fig. 6, a and b). This sequence has been observed in more than 80 Antarctic deep-sea cores. It has been considered that the upper three zones (X, Ψ, Ω) represent Quaternary sedimentation and that the Φ zone represents the late Tertiary (*15*).

Teh-lung Ku determined the average rate of sedimentation for the Ω zone in an Antarctic core (Eltanin 11-11) by measuring excess Th^{230} (*16*). Thus it was possible to determine the age of the Ψ-Ω boundary as about 400,000 years. Extrapolation through the Ψ and X zones, on the assumption that these zones were similar in rate of sedimentation to the Ω zone, gave estimated ages for the X-Ψ and Φ-X boundaries of 0.9 ± 0.18 and 1.6 ± 0.32 million years, respectively.

In the seven cores studied the magnetic reversals and faunal boundaries are consistently related to each other, an indication that they are both time-dependent phenomena (Fig. 1). By use of the dates of changes in polarity given by Cox *et al.* (*1*), rates of sedimentation can be calculated (Table 2), and from them the age of the Ψ-Ω boundary is calculated as between 0.4 and 0.5 million years. The X-Ψ boundary would have an age of about 0.7 million years; the Φ-X boundary, about 2.0 million years. These ages agree well with the estimates for these boundaries from excess Th^{230}. The fact that two independent methods of dating give similar ages for the faunal zones lends credence to both methods.

The Φ-X boundary was tentatively correlated by Hays (*15*) with the Pliocene-Pleistocene boundary of Ericson *et al.* (*17*), which is based on several paleontological criteria. Ericson *et al.* (*18*) estimated the age of the Φ-X boundary at about 1.5 million years. Riedel *et al.* (*19*) approximately correlated a faunal boundary in the Pacific, based on the last appearance of the Radiolaria *Pterocanium prismatium* and various nanoplankton, with the boundary of Ericson *et al.* (*17*). The work of Harrison and Funnel (*6*) suggests that the last appearance of *P. prismatium* occurred at or about the time of the polarity change from the Matuyama reversed epoch to the Brunhes normal, about 0.7 million years ago. If this was so, the faunal boundary of Riedel *et al.* (*19*) would correspond in time with the X-Ψ boundary in Antarctic cores—not with Φ-X boundary as suggested by Hays (*15*).

To finally resolve the problem of

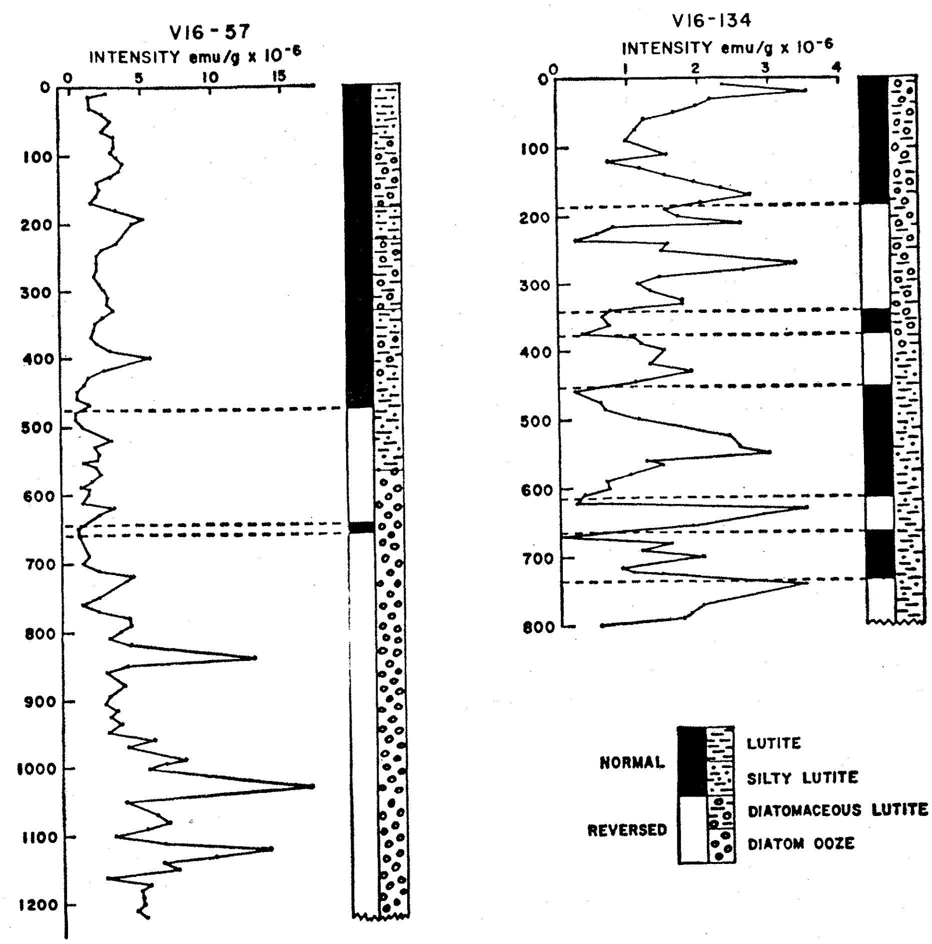


Fig. 5. Plot of intensity versus depth in cores V16-57 and -134 after alternating-current demagnetization at 150 oersteds. *emu*, Electromagnetic units.

the relation of various deep-sea stratigraphic boundaries, the paleomagnetic stratigraphy will have to be worked out for several cores containing the boundaries of Ericson *et al.* (*17*) and of Riedel *et al.* (*19*), which may then be compared with the Antarctic magnetic and faunal sequences.

The lithologic change from tan lutite below to diatomaceous sediments above, which occurs in Antarctic cores at about the same level as the Φ-X boundary, has an age of about 2 million years. This change was interpreted by Hays (*15*) to indicate the time when the vertical circulation of the Antarctic Ocean was stimulated by the initiation of large-scale freezing of sea ice around Antarctica, associated with glaciation of the continent.

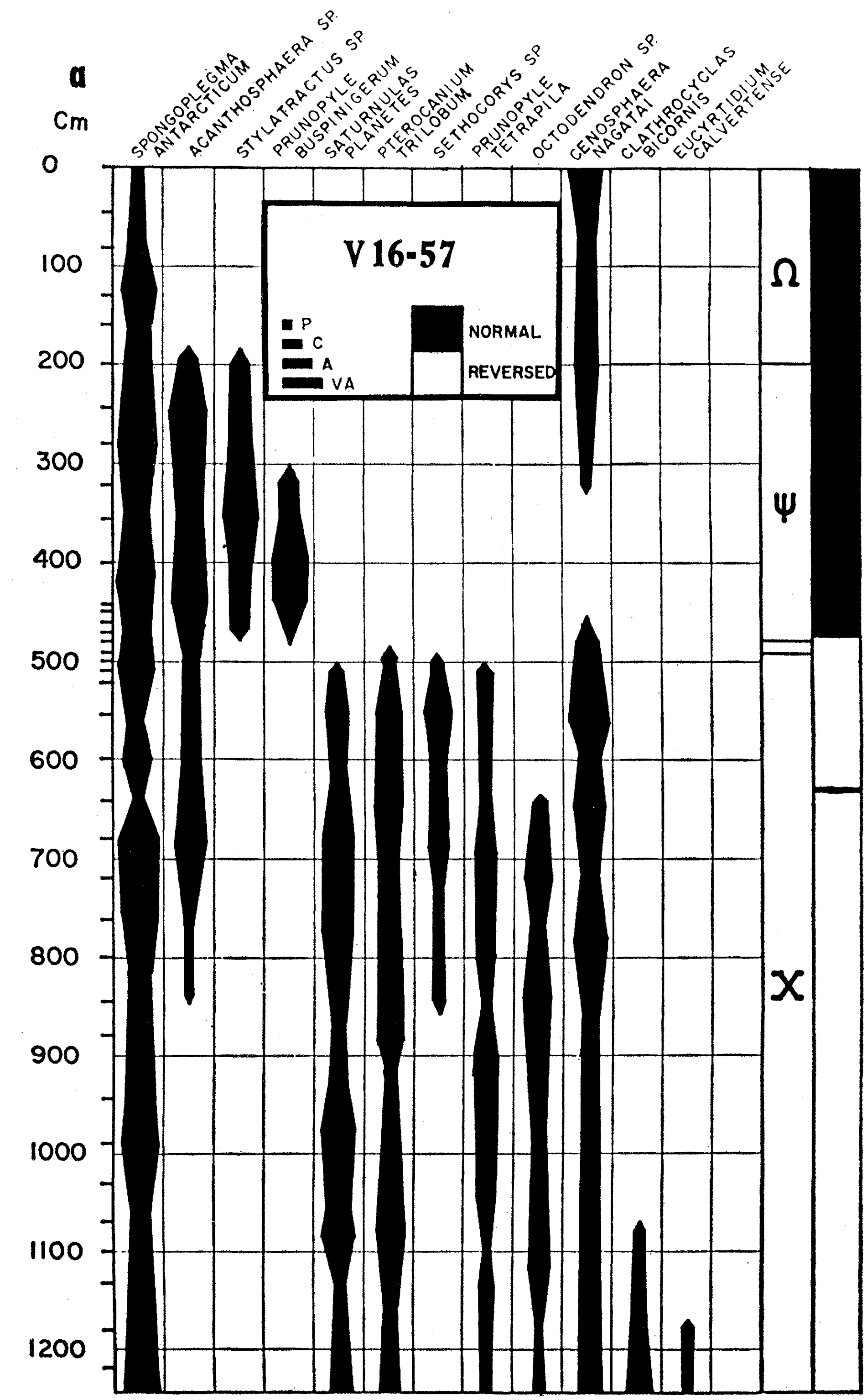
Connolly and Ewing (*20*) found the first occurrence of ice-rafted debris in five Antarctic cores just below the Φ-X boundary, which they interpreted as indicating the earliest Pleistocene glaciation in the southern hemisphere. Ice-rafted detritus, as described by Connolly and Ewing (*20*), occurs in all our cores and a lower limit can be recognized in four (Fig. 1). Two (V16-66 and -132) of the four cores in which a lower limit of ice-rafted detritus can be recognized were studied by Connolly and Ewing (*20*); the lower limit of ice-rafted detritus occurred at 900 and 700 centimeters, respectively. In V16-134 the lower limit of ice-rafted debris is indistinct, but no such debris was observed below 500 centimeters. V16-133 has an abrupt lower limit of ice-rafted material between 300 and 310 centimeters. V16-57 and -60 contain ice-rafted detritus throughout. The sandy nature of core V18-72 prevented positive recognition of ice-rafted particles.

The lower limit of ice-rafted debris in cores that contain it occurs at or just below the lower boundary of the reversed interval that we interpret to represent the Matuyama reversed epoch, indicating an age of about 2.5 million years for the initiation of ice rafting. If Connolly and Ewing's (*20*) interpretation is correct, southern-hemisphere glaciation was initiated about 2.5 million years ago.

From the known dates of reversals, rates of sedimentation have been calculated on the assumption that the core tops are recent, there are no hiatuses, and the dating of the reversals is correct. These assumptions appear to be met in all cores, with the possible exception of V16-60. This point is illustrated by cores V16-134 and V18-72, in which a time-versus-depth plot shows no marked deviations from the average sedimentation rate (Fig. 7). Regardless of the accuracy of the absolute ages of the reversals, it is clear that the average rate of sedimentation in the Indian Ocean cores is relatively higher than in the Bellingshausen Sea cores, whose rates are lower than about 3 millimeters per 1000 years (Table 2).

In cores for which a sedimentation rate during the Matuyama reversed epoch can be calculated, one finds that for all cores except V16-133 this rate is lower than that for the Brunhes normal epoch. In two cores the rate for the Gauss normal can be calculated, and in both it is higher than the rate for the Matuyama reversed epoch (Table 2).

Of the several horizons in Antarctic cores at which radiolarian species disappear, three have been chosen to mark stratigraphic zonal boundaries (*15*). Just above one of these (X-Ψ), several



species appear for the first time. The possibility that abrupt appearances and disappearances of species reflect climatic changes can not be ruled out (*15*). Reversals occur within 30 centimeters of two of the boundaries (Φ-X and X-Ψ), but there is no evidence of a reversal near the Ψ-Ω boundary.

In the seven cores studied, the reversal that marks the boundary between the last reversed epoch (Matuyama) and the present normal epoch (Brunhes) falls within 30 centimeters of the first appearance of *Stylatractus* sp. and other species restricted to the zone (*Larcopyle* sp., Fig. 6a; and *Prunopyle buspinigerum*, Fig. 6b). In four cores the first appearance of these species comes within 10 centimeters of the reversal (V16-133, -134, -132, and -57). In the remaining three cores the reversal is below the appearance of these species in two cores (V16-60 and -66) and above it in one (V18-72, Fig. 1).

Several of the Ω-zone species are morphologically similar to but distinguishable from species that are present in the X zone. Although they are morphologically distinct from their possible ancestors, *P. buspinigerum* and *Stylatractus* sp. may not be different species in a strict biologic sense.

The upper limit of the X zone (in Antarctic cores) is marked by the upper limit in the range of both *Saturnulus planetes* and *Pterocanium trilobum*, but both species now live further north. This limit falls below the last reversal, but within 30 centimeters of it, in all cores but V16-60 and -66; in these two the reversal occurs below the top of the X zone (Fig. 1). In some cores (V16-134, -133, -132, and -57) there is a gap between the last occurrence of X-zone species and the first appearance of species diagnostic of the Ψ zone. The particularly long gap (60 cm) between the X and Ψ zones in V16-133 exists because the paucity of Radiolaria in this interval makes it difficult to draw the boundaries.

The Φ-X boundary is based on the last common occurrence of two species: *Clathrocyclas bicornis* and *Eucyrtidium calvertense* (*15*); the former always ranges higher in the cores than the latter (Fig. 6, a and b). Although the number of species disappearing at this boundary is less than the number that disappear at the X-Ψ boundary, the aspect of the faunal change is more striking because of the great abundance of *E. calvertense* below the Φ-X boundary.

Six of the seven cores studied penetrate the Φ zone; in three of these (V16-134 and -133 and V18-72) the Φ-X boundary occurs within 10 centimeters of the base of the Olduvai event (Fig. 1). In two of the remaining three cores (V16-132, -66) the Olduvai event is not observed and the Φ-X boundary falls some 50 to 100 centimeters above the reversal between the Gauss normal series and the Matuyama reversed series. The magnetic stratigraphy in the lower part of V16-60 is so unclear that one cannot relate the position of the Φ-X boundary to it.

The coincidence or near coincidence of faunal changes with reversals in these cores suggests a causal relation. It has been suggested (*12*) that at the time of a reversal the intensity of the earth's dipole field must have decreased to zero; as a result, the earth's surface would have been subjected to a higher incidence of cosmic radiation than normal, which may have caused a higher mutation rate that strongly affected the evolutionary process (Uffen, *21*). Simpson (*22*) has recently presented paleomagnetic and paleontological evidence from the Cambrian to the Recent that, he believes, supports the thesis that reversals have in fact profoundly affected evolution. Both Uffen's and Simpson's views on accelerated mutation ignore the consensus among geneticists that there is no recognizable relation between evolutionary rate and mutation rate (*23*).

Our data are still insufficient to lend much support to Uffen's hypothesis, but more-detailed work now in progress at Lamont (on these and other cores) ultimately may serve to test it. We wish only to draw attention to the fact that our study showed two reversals and two faunal changes closely associated

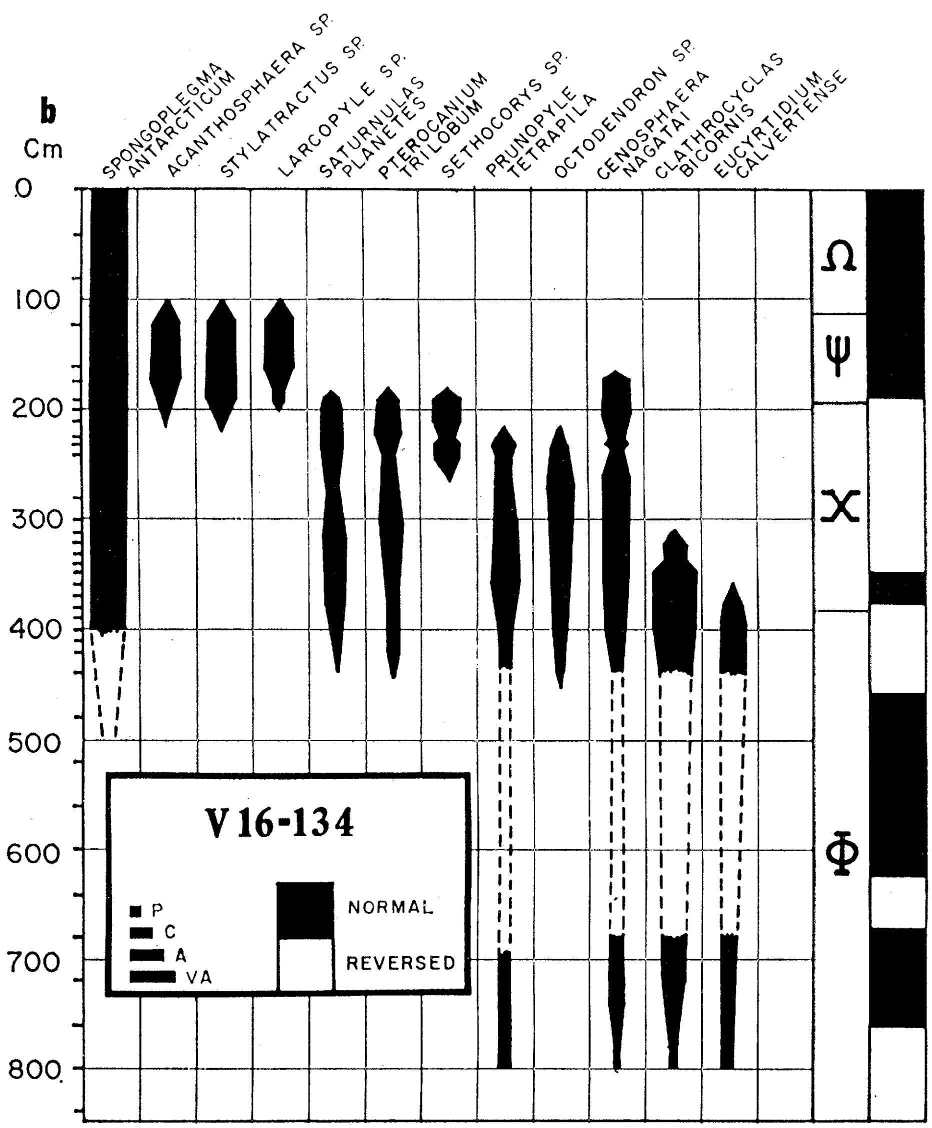


Fig. 6 (a and b). Ranges of indicator species in two cores. Graticule lines at left indicate sample locations in cores. *P*, present, *C*, common, *A*, abundant, *VA*, very abundant. Magnetic stratigraphies shown in right-hand column.

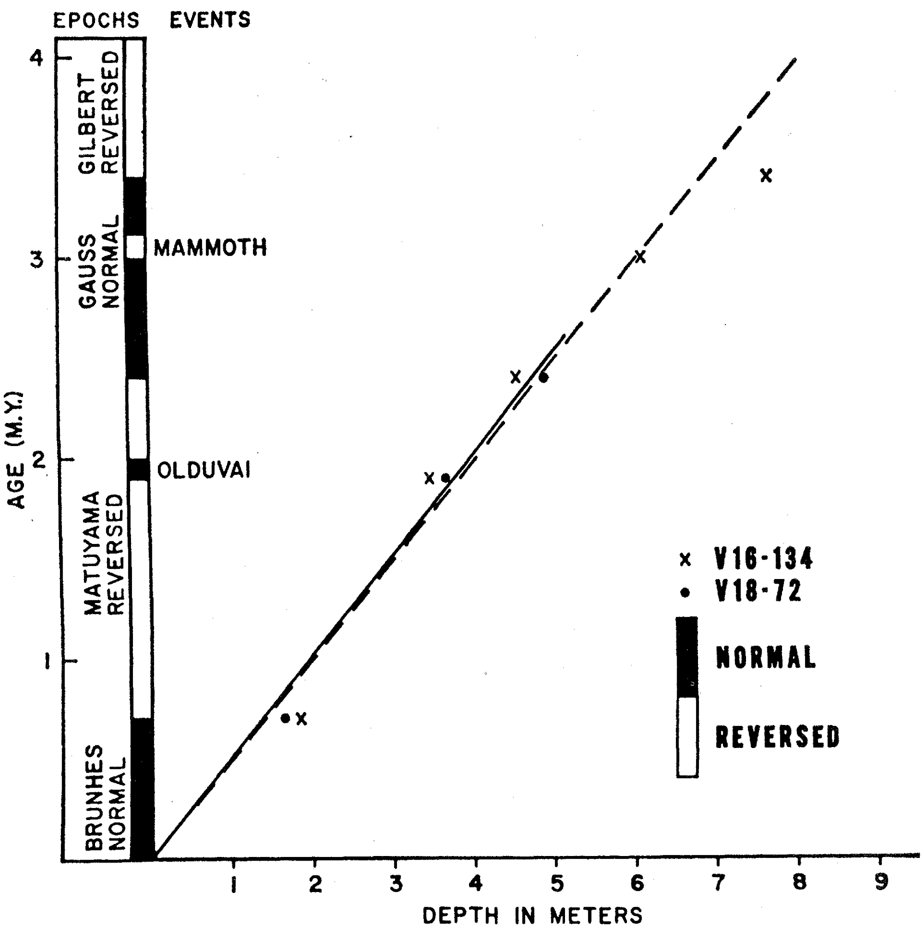


Fig. 7. Time-versus-depth plots for cores V16-134 and V18-72.

in several Antarctic cores; we hope other workers may have something to contribute to this problem. Harrison and Funnel's (*7*) finding that a reversal and extinction of the radiolarian species *Pterocanium prismatium* occur at about the same level in equatorial Pacific cores supports a possible causal relation.

Since reversals are almost instantaneous (geologically speaking), and because the polarity of the field is a global phenomenon, paleomagnetic stratigraphy is a powerful tool for correlating and dating deep-sea cores. Studies of North Pacific cores at Lamont show that reversals occurring in them can be correlated with those in Antarctic cores.

Deep-sea cores also provide a powerful tool for studying paleomagnetic stratigraphy. This study shows that some deep-sea cores contain a complete or nearly complete record of the history of the earth's magnetic field back to about 3.5 million years. There is striking agreement between the continuous record of deep-sea cores and the earlier discontinuous land record (*1*). Future work on cores with high sedimentation rates will provide detailed geomagnetic histories of short intervals of time, while work on long cores with low sedimentation rates will extend the continuous record beyond 4 million years.

Summary

The magnetic inclinations and intensities of about 650 samples from seven deep-sea cores taken in the Antarctic were measured on a spinner magnetometer. This series of measurements provided a magnetic stratigraphy, based on zones of normally or reversally polarized specimens for each core, which was then correlated with the magnetic stratigraphy of Cox *et al.* (*1*). One core (V16-134) gave a continuous record of the paleomagnetic field back to about 3.5 million years.

When selected samples were subjected to alternating-field demagnetization, most were found to have an unstable component that was removed by fields of 150 oersteds; all samples from two cores were partially demagnetized in a field of 150 oersteds. The average inclination in these two cores was then in good agreement with the average inclination of the ambient field for the latitude of the core site. It was also found that the intensities of the samples decreased at the points of reversal; this finding is to be expected if, as has been postulated by the dynamo theory, the intensity of the dipole field decreases to zero and builds again with opposite polarity. We believe that the magnetization of the cores results from the presence of detrital magnetite, although other magnetic minerals also may be present.

Four faunal zones (Φ, X, Ψ, and Ω) have been recognized in these Antarctic cores on the basis of upward sequential disappearance of Radiolaria. The faunal boundaries and reversals consistently have the same relations to one another, indicating that they are both time-dependent phenomena.

Using previously determined times of reversal, one may date the following events in the cores:

1) Radiolarian faunal boundaries: Φ-X, 2 million years; X-Ψ, 0.7 million years; Ψ-Ω, 0.4 to 0.5 million years. These dates are in good agreement with ages previously extrapolated from radiometric dates.

2) Initiation of Antarctic diatom-ooze deposition, approximately 2.0 million years ago.

3) First occurrence of ice-rafted detritus, approximately 2.5 million years ago.

One can also calculate rates of sedimentation, which vary in the cores studied from 1.1 to about 8.0 millimeters per 1000 years. Sedimentation rates for the Indian Ocean cores are higher than for the Bellingshausen Sea cores. The near-coincidence of faunal changes and reversals in the cores suggests but does not prove a causal relation.

We conclude from this study that paleomagnetic stratigraphy is a unique method for correlating and dating deep-sea cores, and that future work with such cores may provide a complete or nearly complete record of the history of the earth's magnetic field beyond 4 million years.

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What Are Mathematicians Doing?

Their search for abstractions leads to applications.

Bernard Friedman

The past 20 years have seen a great increase in the number of mathematicians and a noticeable flourishing in all branches of mathematics. Many new techniques have been devised, and many important unsolved problems have been settled. Mathematical techniques and ideas have permeated not only the natural sciences but also the social sciences, and even the management of large business organizations. Because of the belief that mathematics is vitally important for our technology and for the development of our society, the government has supported an increase in mathematics research and has sponsored attempts to improve mathematics education.

The past few years, however, have seen a growing disillusion, not so much with mathematics as with mathematicians. The signs are small but significant. A few years ago the employment ads in the New York Sunday *Times* contained many requests for mathematicians. Today they ask for programmers or for systems analysts instead of mathematicians. At many universities the science and engineering departments insist that their students are not being taught the mathematics they need, and they claim that the solution is to have separate mathematics departments in the engineering colleges. Similar criticism comes from my colleagues in physics, who tell me that when they have a differential equation to solve, or a contour integral to evaluate, they know it is useless to go to the mathematics department for help. R. W. Hamming says in *Science* (*1*) "much of modern mathematics is not related to science but rather appears to be more closely related to the famous scholastic arguing of the Middle Ages."

The continual complaint of these people reduces to this: "where is mathematics going and what are mathematicians doing?" This query comes not only from mathematically unsophisticated laymen but also from mathematically sophisticated and technically trained people. I recall a question once asked me by a well-known physicist. In the course of a discussion about mathematics he expostulated, "I have studied and used mathematics all my life. I have known some of the greatest mathematicians, such as John von Neumann and Hermann Weyl. Yet when I try to understand, just in a general way, not in detail, what some of your young colleagues are doing, I find myself baffled. I'm not a mathematical ignoramus. Can you explain to me what they are doing and, more important, how relevant it is to my work in physics?" I had to confess that to explain what my colleagues were doing would take at least a week of preparatory lecturing, that their work is not directed toward physics, and that it probably has in fact no application other than in mathematics itself. To this he said with disgust, "Well if mathematics is now just another discipline like Sanskrit, then why should the university and the nation support mathematics on the scale they have been doing?"

The question is a serious one, and it has disturbed me for a long time. I believe that both the university and the nation are right in supporting and expanding mathematics research and training, but it is not easy to give objective evidence to support my beliefs. Instead, I shall discuss a slightly simpler question: What are mathematicians doing and where are they going?

Struggle for Generality

What are mathematicians doing? They are doing mathematics, and at an ever-increasing rate. Where are they going? They are going in the direction of a more elegant, a more unified, and, necessarily, a more abstract approach to the study of mathematical structures. The important idea here is the emphasis on mathematical structures. We—and by "we" I mean most people in the mathematics profession—are no longer interested in particular problems and their detailed solutions. Instead, we are interested in the method by which the solution was obtained. Thus, a proof of Goldbach's conjecture that every even integer is the sum of two prime numbers would

The author is professor of mathematics, University of California, Berkeley. This article is adapted from his vice-presidential address to Section A of the AAAS, presented 27 December 1965 at the Berkeley meeting.