32. MAGNETIC PROPERTIES OF OCEANIC BASALT SAMPLES[1]

William Lowrie and Dennis E. Hayes, Lamont-Doherty Geological Observatory
of Columbia University, Palisades, New York

ABSTRACT

Stable remanent magnetic properties were measured in oceanic basalts from Sites 265, 266, and 267. Remanent intensities are unusually low at these sites, and at one site the mean remanent inclination is somewhat different from its expected value. Thermomagnetic analysis indicates that the magnetic minerals in the basalts are titanomaghemites, probably formed by low-temperature oxidation of original titanomagnetite. Basalt from Site 274 has a large unstable remanent component and shows a strong tendency to acquire viscous remanence. Measured remanent intensities, inclinations, and polarities of the basalt samples are compared with those values inferred from magnetic lineation model studies. The inclinations inferred from the measured mean remanences at Sites 266, 267, and 274 are consistent with the proposal of a nearly fixed, high-latitude position of the Antarctic plate from 40 m.y.B.P. to the present.

INTRODUCTION

Basalt was recovered at Sites 265, 266, 267 and 274 on Leg 28. The site locations, intensities, and inclinations of the ambient geomagnetic field (1965.0 International Reference Field) at the sites and the computed inclinations of the axial dipole field are given in Table 1.

Hand-size samples, partially oriented so that the upward vertical direction relative to each sample was known, were obtained from each site. Several paleomagnetic specimens in the form of right circular cylinders, ½ in. in diameter and ½ to 1 in. in length, were cut from each sample with a diamond drill. A small chip was reserved from each of several samples for thermomagnetic analysis.

THERMOMAGNETIC ANALYSIS

Thermomagnetic curves were obtained for these specimens using a continuously recording, vertical suspension type of Curie balance based upon a sensitive electrobalance. The thermocouple and electrobalance outputs were applied to the x and y axes, respectively, of an x-y recorder, to give automatic plotting of the thermomagnetic curves. These curves were digitized, recomputed with corrections for thermal hysteresis and thermocouple nonlinearity, and replotted. Magnetization measurements were uncalibrated; temperature calibration was accurate to within 5°C.

Specimens for thermomagnetic analysis were ground to a coarse, millimeter-size powder. This powder was heated in the Curie balance in a field of 3800 oe provided by a 4-in. electromagnet. Fast heating rates were used to bring the specimens to above 600°C in about 12 min. All thermomagnetic analyses were carried out in air.

Each specimen gave a thermomagnetic curve similar to that shown in Figure 1a. This type of curve has been frequently observed in oceanic basalt analysis. It results from the metastable state of the original ferromagnetic mineral, titanomagnetite or titanomaghemite, which is characterized by the initial magnetization, J_i, and a low initial Curie temperature, between 200°C and 400°C. At temperatures above this, the initial mineral separates into a titanium-rich phase and a titanium-poor phase, such as magnetite. On cooling from the maximum

[1]Lamont-Doherty Scientific Contribution No. 2115.

TABLE 1
Site Locations and Values of the 1965.0 International Reference Field and Axial Dipole Field Inclination at the Sites

Site	Latitude	Longitude	1965.0 International Reference Field: Intensity (oe)	1965.0 International Reference Field: Inclination (°)	Axial Dipole Field Inclination (°)
265	53.5°S	109.9°E	0.645	-80.5	-69.7
266	56.4°S	110.1°E	0.660	-81.0	-71.6
267	59.3°S	104.5°E	0.640	-80.5	-73.5
274	69.0°S	173.4°E	0.665	-78.5	-79.1

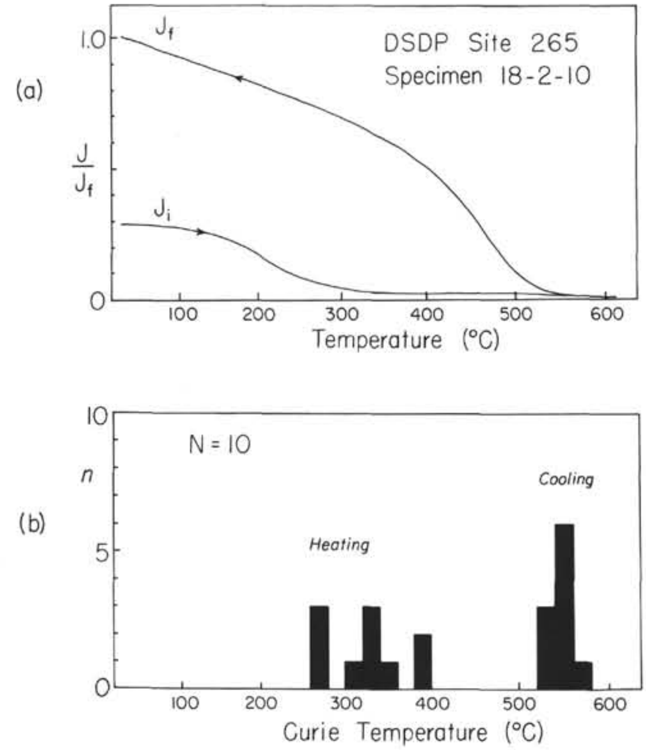

Figure 1. (a) *Typical submarine basalt irreversible thermomagnetic curve. The final magnetization* (J_f) *is greater than the initial magnetization* (J_i), *and the Curie temperature during the heating part of the cycle is lower than during the cooling part.* (b) *Histograms of the Curie temperatures observed during heating and cooling in thermomagnetic analyses of 10 basalt specimens from Leg 28.*

temperature reached, only the magnetite Curie temperature is seen if the phase separation has been carried to completion.

A histogram of the Curie temperatures observed in the heating and cooling halves of the thermomagnetic curves for 10 specimens is shown in Figure 1b. The Curie temperatures are also listed in Table 2, which also shows values for the initial magnetization normalized in terms of the final magnetization, J_f, at the end of the thermomagnetic analysis.

The Curie temperatures for the final mineral correspond to a magnetite containing a small amount of titanium. According to the shape of the solvus curve for the titanomagnetite solid solution series (Nagata, 1962) the exsolution should result in a hemo-ilmenite and a titanomagnetite ($Fe_{3-x}Ti_xO_4$) in which the compositional parameter, x, has a value near 0.05. The mean value of the final mineral Curie temperatures in Figure 1b is 544°C, corresponding to a compositional parameter, x, equal to 0.06.

The range of Curie temperatures for the initial mineral is much wider, ranging from 266°C to 385°C. This indicates quite a large variation in composition for the initial magnetic mineral, due in part to variation in x and also to the fact that both titanomagnetites and titanomaghemites were present.

TABLE 2
Initial and Final Curie Temperatures and Observed and Expected Magnetization Ratios (J_i/J_f) Measured in Thermomagnetic Analyses of Selected Specimens From Each Site

Specimen	Initial Curie Temperature (°C)	Final Curie Temperature (°C)	Observed Ratio $(J_i/J_f)_o$	Expected Ratio $(J_i/J_f)_e$
Site 265				
17-1-25A	266	543	0.252	0.415
17-1-25C	268	545	0.223	0.418
18-2-10	279	521	0.273	0.436
Site 266				
23-1-144	321	538	0.211	0.502
24-1-55A	380	548	0.434	0.595
24-1-55C	385	546	0.461	0.603
Site 267				
7-1-13	352	561	0.175	0.551
Site 274				
44 CC-1	313	546	0.602	0.489
44-2-125	325	556	0.667	0.508
45-2-119	323	532	0.850	0.505

It is possible to distinguish between titanomagnetite and titanomaghemite as the initial magnetic mineral on the basis of thermomagnetic curves determined under vacuum (Ozima and Ozima, 1971). The presence of maghemitization may sometimes also be inferred from curves determined in air using the magnetization ratio, J_i/J_f, together with the Curie temperature (Lowrie et al., 1973). Column 5 of Table 2 shows the magnetization ratios to be expected (Nagata, 1962) for titanomagnetites with initial Curie temperatures such as the ones observed. The observed ratios are much lower than expected for the basalts from Sites 265, 266, and 267 (Table 2), indicating that the titanomagnetites in these specimens are nonstoichiometric (Readman and O'Reilly, 1972). The low-temperature oxidation producing this maghemitization can result from ocean-floor weathering (Marshall and Cox, 1972) or from hydrothermal alteration (Ade-Hall et al., 1971). At Site 274 the observed J_i/J_f ratios are greater than those expected from the Curie temperatures. Factors that may give rise to this are: (a) the initial mineral may be titanomaghemite as at the other sites; or (b) the original titanomagnetite has been oxidized, though this is less likely.

The thermomagnetic analyses indicate that the magnetic mineral in basalts from Sites 265, 266, and 267 is titanomaghemite formed by oxidation of the original titanomagnetite, whereas at Site 274 it may be either titanomagnetite or titanomaghemite.

REMANENT MAGNETIC PROPERTIES

Remanent magnetizations were measured with 105-Hz and 5-Hz spinner magnetometers, and specimen susceptibilities were measured with an a.c. bridge. The intensities of natural remanent magnetization (NRM) and the susceptibilities of all specimens studied are plotted on Figure 2 and listed in Table 3. This table also shows the values of the Königsberger ratio,

$$Q_n = \frac{\text{remanent magnetization}}{\text{induced magnetization}} = \frac{\text{NRM intensity}}{\text{susceptibility} \times \text{field}}$$

The fields used in computing this parameter were the intensities of the 1965.0 International Reference Field at the sites.

The values of NRM intensity, susceptibility, and Königsberger ratios observed in a large number of oceanic basalts from dredge hauls and from DSDP and other ocean bottom drilling have been summarized by Lowrie, in press. The susceptibilities observed in Site 265, 266, and 267 specimens were appreciably lower than average (0.5×10^{-3} Gauss/oe), suggesting a lower than average magnetic mineral content in the basalts from these sites. On the other hand, Site 274 has considerably higher than average susceptibilities, and these are quite uniform with specimen depth.

The NRM intensities show large variability between sites and even within the same site (274). Specimens from Site 265 and Core 44 of Site 274 have average NRM intensities, around 5×10^{-3} Gauss; Site 266 and 267 intensities are very low, while Core 45 of Site 274 has much higher than average intensities.

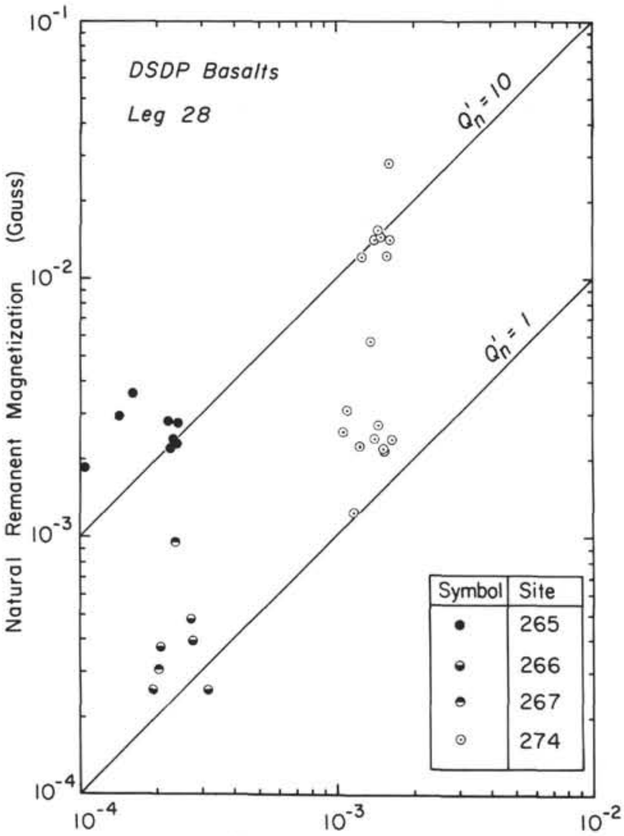

Figure 2. *Natural remanent magnetizations and susceptibilities of all oceanic basalt specimens from Sites 265, 266, 267, and 274. The ratios of these two parameters* (Q_n') *generally lie between 1 and 20.*

The intensity variations are also reflected in the Königsberger ratio, Q_n. For satisfactory interpretation of oceanic magnetic anomalies the remanence should dominate the magnetization; Q_n should be much larger than 1. DSDP basalts have generally given much lower Q_n values (around 3) than dredged basalts (15 on the average). At Site 265 the Q_n values are, therefore, high for DSDP basalts, averaging 23, and are similar to the values observed in dredge hauls. However, at Sites 266 and 267 the Königsberger ratios, although greater than 1, are quite low. At Site 274 the Königsberger ratios from Core 44 are low, while those from Core 45 are satisfactorily high. This difference with sample depth suggests the possibility that the low Königsberger ratios at the other sites may also increase with depth into Layer 2.

STABILITY AND DIRECTION OF MAGNETIZATION

Every specimen was magnetically cleaned in alternating magnetic fields of progressively increasing peak value up to 800 oe to remove unstable components and to isolate the stable remanence. The effects of this treatment on typical specimens from each site are shown in Figure 3. The stable inclinations and the demagnetizing fields at which these inclinations were obtained are given in Table 3. The fields required to randomize 50% of the original remanence, the median destructive field (mdf), were measured from the demagnetization curves and are also shown in Table 3.

Site average values of mdf and observed inclinations are listed in Table 4. The basalts from Site 274 have quite large low-coercivity components with mean mdf of only 80 oe. Detailed demagnetization showed that most of the large initial soft component is little affected by 25-oe fields, but is changed very rapidly between 25 and 100 oe. During AF demagnetization, the direction of remanence was quite consistent.

The basalts from Sites 265, 266, and 267 had very stable remanent magnetizations, with mdf greater than 300 oe and consistent directions.

The polarities observed in all specimens from Site 265 are positive, or indicative of reversed magnetization for Southern Hemisphere samples. Of the two samples from Site 266, one was positive and the other negative. During removal of the soft component from the negatively magnetized sample, there was an initial increase in intensity, while the positively magnetized sample showed a uniform decrease in intensity in this same demagnetization range. This indicates that the soft component was parallel to the stable remanence in the positive sample and antiparallel to it in the negative sample. This soft component must be parallel to a post-sampling field and not an in situ soft component, and implies a sampling error. Because of this uncertainty the true polarity of Site 266 could not be determined. The Site 267 magnetizations were of positive (reversed) polarity.

The Site 274 polarities are all positive. Either these Site 274 polarities indicate reversely magnetized

TABLE 3
Remanent Magnetic Properties of Every Specimen Studied From Leg 28

Specimen	NRM (10^{-3} G)	Suscept-ibility (10^{-3} G/oe)	Königs-berger Ratio	Stable Inclin-ation	Demag-netizing Field (oe)	Median Destruc-tive Field (oe)
Site 265						
17-1-25A	2.97	0.141	32.7	53.5	200	491
17-1-25B	3.61	0.159	35.2	51.7	200	372
17-1-25C	1.88	0.103	28.4	47.3	200	585
18-2-11A	2.78	0.240	18.0	54.7	300	293
18-2-11B	2.82	0.221	19.8	51.8	200	330
18-2-12A	2.30	0.237	15.0	43.2	300	355
18-2-12B	2.41	0.230	16.3	46.9	200	337
18-2-13A	2.26	0.222	15.8	37.2	300	331
Site 266						
23-1-144A	0.26	0.193	2.00	−70.5	200	422
23-1-144B	0.38	0.206	2.77	−72.1	200	690
24-1-55A	0.26	0.315	1.24	69.7	100	197
24-1-55B	0.48	0.270	2.70	75.2	200	171
24-1-55C	0.40	0.274	2.21	71.0	200	212
Site 267						
7-1-14	0.95	0.234	6.38	83.9	200	244
7-1-17	0.31	0.204	2.33	79.8	150	432
Site 274						
44-1, CC-1A	2.74	1.45	2.84	79.2	150	81
44-1, CC-1B	2.41	1.41	2.56	79.9	200	68
44-1, CC-2A	2.37	1.63	2.18	80.9	150	68
44-1, CC-2B	2.23	1.52	2.20	80.5	200	87
44-1, CC-3A	1.26	1.17	1.59	77.3	100	96
44-1, CC-3B	2.22	1.54	2.17	81.5	200	61
44-2-125	5.74	1.36	6.35	82.9	100	44
44-2-126	2.57	1.06	3.64	77.1	100	83
44-2-130A	3.12	1.09	4.32	75.6	100	49
44-2-130B	2.28	1.22	2.80	75.6	100	54
45-1, CC-1	12.3	1.57	11.8	70.9	100	98
45-2-123A	14.5	1.47	14.9	70.7	150	96
45-2-123B	14.4	1.62	13.4	70.6	150	98
45-2-124	12.2	1.27	14.4	68.3	150	115
45-2-125A	18.0	1.62	26.0	71.0	150	86
45-2-125B	15.6	1.44	16.2	67.7	150	100
45-2-126	14.3	1.39	15.5	67.7	150	109

samples, or the basalts have all been remagnetized in the same sense as the present field in the Northern Hemisphere. The latter is an unlikely explanation; if appreciable secondary magnetization were acquired in the laboratory, the inclinations would vary from sample to sample more than the observed inclinations, which are closely grouped (Table 3). However, the low mdf's in Site 274 basalts (Tables 3, 4) indicate the presence of a large soft component of magnetization. Many oceanic basalts with low mdf's have been found to acquire viscous remanent magnetization (VRM) easily (Lowrie, 1973; Lowrie et al., 1973; Pierce et al., 1973).

VISCOUS REMANENT MAGNETIZATION

To examine the relative importance of secondary magnetization components in the Site 274 basalt, a VRM was given to four selected specimens. Each specimen was first demagnetized, its residual remanence was measured, and it was then placed in a known orientation with respect to a 1-oe field. The remanent magnetization was remeasured at approximately logarithmically spaced intervals for a total of almost 3 months. The VRM after time t hours was obtained by finding the vector difference between the observed and initial residual remanence. The acquisition of VRM in each specimen is shown in Figure 4 as a function of log t.

Each VRM acquisition curve can be divided into three regions: (1) $t<10$ hours, (2) $10<t<250$, and (3) >250 hours. In each of these regions the VRM increases approximately logarithmically with time, so that

$$\mathrm{VRM}(t) = S_i \log t$$

where S_i is the magnetic viscosity coefficient. Values of S_i ($i=1, 2, 3$) corresponding to each of the three regions are listed in Table 5.

In regions 1 and 3 the VRM increases slowly at approximately equal rates; S_1 is approximately equal to S_3 which suggests that the acquisition mechanism may be

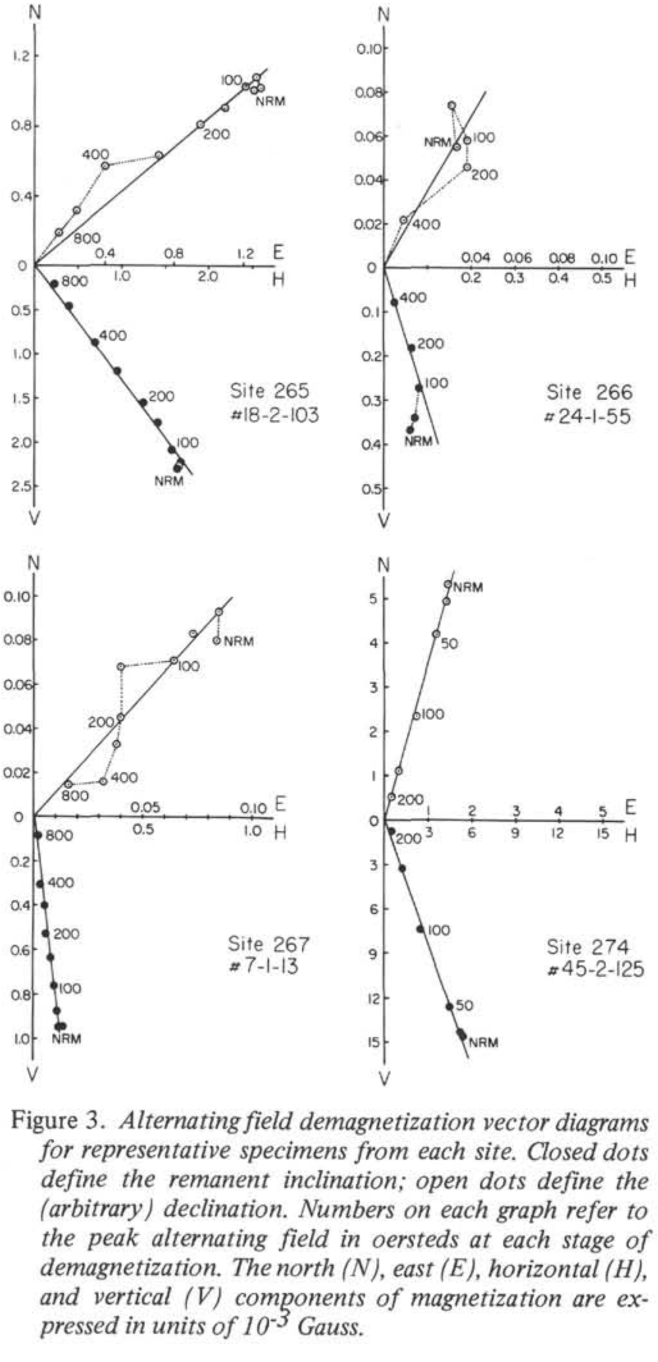

Figure 3. *Alternating field demagnetization vector diagrams for representative specimens from each site. Closed dots define the remanent inclination; open dots define the (arbitrary) declination. Numbers on each graph refer to the peak alternating field in oersteds at each stage of demagnetization. The north (N), east (E), horizontal (H), and vertical (V) components of magnetization are expressed in units of 10^{-3} Gauss.*

the same in these two regions. The rate of VRM acquisition in region 2 is much more rapid than in the other two regions.

These characteristics suggest that two distinct phases contribute to the total VRM in these specimens. The most rapid phase only begins after an initial threshold time has elapsed and is relatively quickly exhausted, but it accounts for the largest portion of the VRM that is acquired. Such acquisition may be due to activation of a discrete magnetic phase. It is known that very fine magnetic grains are present in some oceanic basalts (Evans and Wayman, 1970) and that the grains may be fine enough in some cases for superparamagnetism to be possible (Butler, 1973). Possibly the rapid gain of VRM in region 2 is due to activation of a narrow range of grain sizes, near the superparamagnetic-single domain threshold, which have suitably short relaxation times (of the order of several days) to contribute to VRM. The VRM in regions 1 and 3 may be due to a second, possibly multidomain, phase. Without exact grain size data or other magnetic tests, these possibilities cannot be verified.

The significance of VRM in Site 274 basalts is seen by expressing the magnitude of VRM acquired in the 1-oe field during 1000 hr as a percentage of the original NRM intensity (Table 5). Although in Samples 45-1, CC and 45-2, 126 cm the VRM amounted to only 10% or so of the NRM, in the other two specimens a substantial fraction of the NRM intensity was acquired as VRM even in the short interval of 1000 hr. It is difficult to estimate the magnitude of this effect in a geologic situation, but its serious consequences cannot be ignored.

The low Königsberger ratios at some sites, and the possible presence of significant secondary magnetization components (particularly VRM), could result in enhancement of normally negligible effects, such as that caused by topographic relief of the magnetized layer. Considering the great water depths, though, this effect can still be ignored. A more serious effect could result if the VRM is acquired at the expense of NRM. The original magnetization of the crust would then be altered, leaving greatly reduced magnetization contrasts and associated low amplitude anomalies. This process might be significant in crust underlying the magnetically quiet zones (Lowrie, 1973), but is not likely to be a serious problem in areas of stably magnetized crust.

DISCUSSION

The magnetic properties of the oceanic basalts recovered during Leg 28 of the Deep Sea Drilling Project between Australia and Antarctica are extremely important in evaluating several problems associated with the spreading process, the absolute sense of plate motions, and the fidelity of sea-floor spreading in recording and preserving the original geomagnetic field directions. Weissel and Hayes (1972) have studied the magnetic lineation pattern throughout the area and have noted several important inconsistencies with regard to the inferred NRM properties of the underlying layer 2.

Sites 265, 266, and 267 all lie within the western zone (zone C) described by Weissel and Hayes. They noted that for anomalies of the same age, but on opposite flanks of the ridge and associated with crust older than about 15 m.y., there is a systematic difference in the inferred intensities of magnetization. Assuming a simple Vine and Matthews model, with magnetized crust 0.5 km thick, whose upper surface corresponds to the top of layer 2, the best estimate of NRM intensity is 5×10^{-3} emu/cc for the southern flank and about twice that value for the northern flank, although the analysis is imprecise. Weissel and Hayes further noted that the best-fit inclinations deduced by matching the observed anomaly shapes suggest that the remanent inclinations of crustal blocks now on the Australian plate were about 15°-20°

TABLE 4
Site Geometric Mean Values of Remanent Magnetic Properties and Site Mean Inclinations and Polarities, Compared to Expected (Axial Dipole Field) Inclinations

Site	Number of Samples	Number of Specimens	Geometric Mean Values: Natural Remanent Magnetization ($\times 10^{-3}$ G)	Susceptibility ($\times 10^{-3}$ G/oe)	Königsberger Ratio	Median Destructive Field (oe)	Axial Dipole Field Inclination (I_d)	Mean Remanence Inclination (I_o)	Standard Error of Remanent Inclinations	Inclination Shallowing $dI = \|I_d\| - \|I_o\|$
265	2	8	2.6	0.17	23	395	−69.7	+48.3	2.1	+21
266	2	5	0.34	0.24	2.2	323	−71.6	±71.7	1.1	0
267	1	2	0.54	0.22	3.9	325	−73.5	+81.9	2.0	−8
274	4	17	6.1	1.4	6.5	80	−79.1	+75.1	1.2	+4

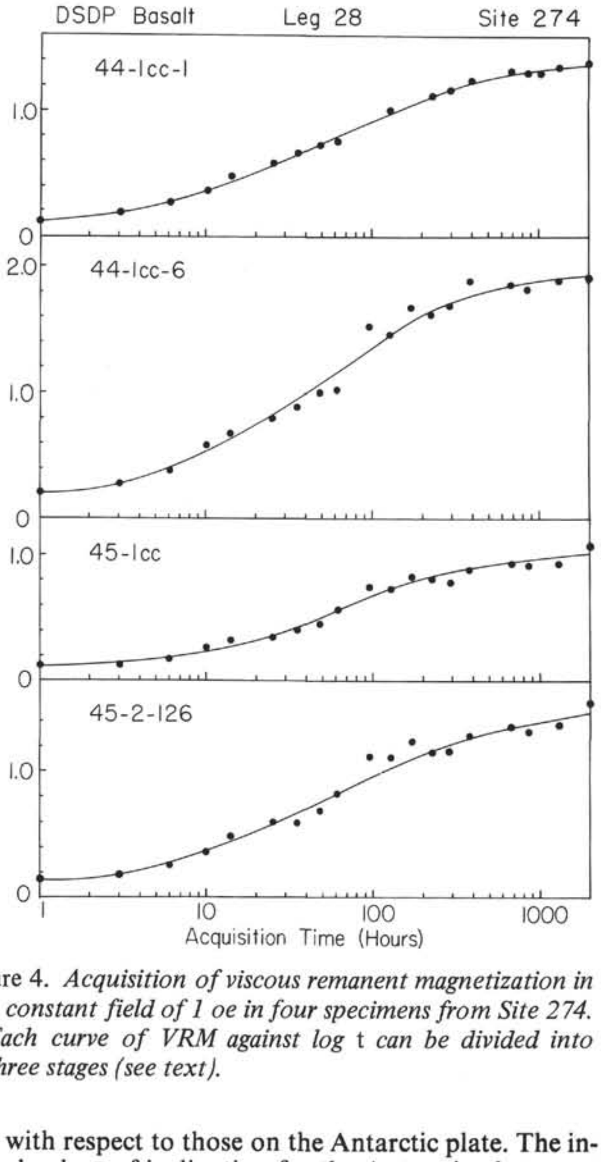

Figure 4. *Acquisition of viscous remanent magnetization in a constant field of 1 oe in four specimens from Site 274. Each curve of VRM against log* t *can be divided into three stages (see text).*

low with respect to those on the Antarctic plate. The inferred values of inclination for the Antarctic plate were approximately correct if one assumed that Antarctica had remained fixed in a near-polar position throughout the Cenozoic. It follows then that the inclinations on the northern plate have been systematically reduced by about 20°. Although there are many ways to destroy a portion of the NRM, it is not at all obvious how a stable component of remanent magnetization can be increased systematically over many millions of years. Hence the inference of altered inclinations and typical intensity values on the north flank seems paradoxical when compared with the reasonable inclinations and relatively low intensities on the southern flank.

The NRM intensities measured in samples from Sites 265 and 274 are in reasonable agreement with the inferred values of bulk magnetization from the model calculations of sea-floor spreading lineations. However, the NRM intensities at Sites 266 and 267 are low by about an order of magnitude with regard to expected values, even though the stability of the samples is extremely high.

As seen in Figure 5, Sites 265 and 266 were located over a portion of the magnetic reversal sequence containing short duration events. It has recently been suggested on statistical grounds by Blakeley (1974) that there are probably additional small duration magnetic events present in the time interval from 15 to 22 m.y.B.P. that are not represented within the Heirtzler et al. (1968) time scale. For these reasons it is difficult to confidently predict the polarity of recovered basalts from an analysis of sea-floor lineations. The fact that the lineations were formed at high latitudes (i.e., high NRM inclinations) and have presumably not moved geographically eliminates some uncertainties and makes it relatively easy to identify by inspection the position of major polarity block boundaries with respect to magnetic anomaly peaks. An examination of the observed sequence at Sites 265 and 266 strongly suggests that the rocks should be reversely and normally polarized, respectively. The measured polarity at Site 265 agrees with this interpretation; the measured Site 266 polarity could not be unambiguously interpreted, as one of the two samples must have been accidentally inverted. Sites 267 and 274 are even more difficult to evaluate in this

TABLE 5
Viscous Remanent Magnetization (VRM) Characteristics of Site 274 Specimens in a 1-oe Field

Specimen	NRM ($\times10^{-3}$ G)	S_1 ($\times10^{-3}$ G)	S_2 ($\times10^{-3}$ G)	S_3 ($\times10^{-3}$ G)	VRM_{1000} ($\times10^{-3}$ G)	$[\frac{VRM_{1000}}{NRM}]$ (%)
44-1, CC-1A	2.74	0.21	0.56	0.18	1.32	48.2
44-1, CC-3B	2.22	0.28	0.86	0.18	1.87	84.2
45-1, CC	12.33	0.11	0.44	0.14	0.94	7.6
45-2-126	12.19	0.21	0.63	0.26	1.37	11.2

Note: S_1, S_2, and S_3 are the magnetic viscosity coefficients in stages 1, 2, and 3, respectively; VRM_{1000} is the VRM acquired in 1000 hours.

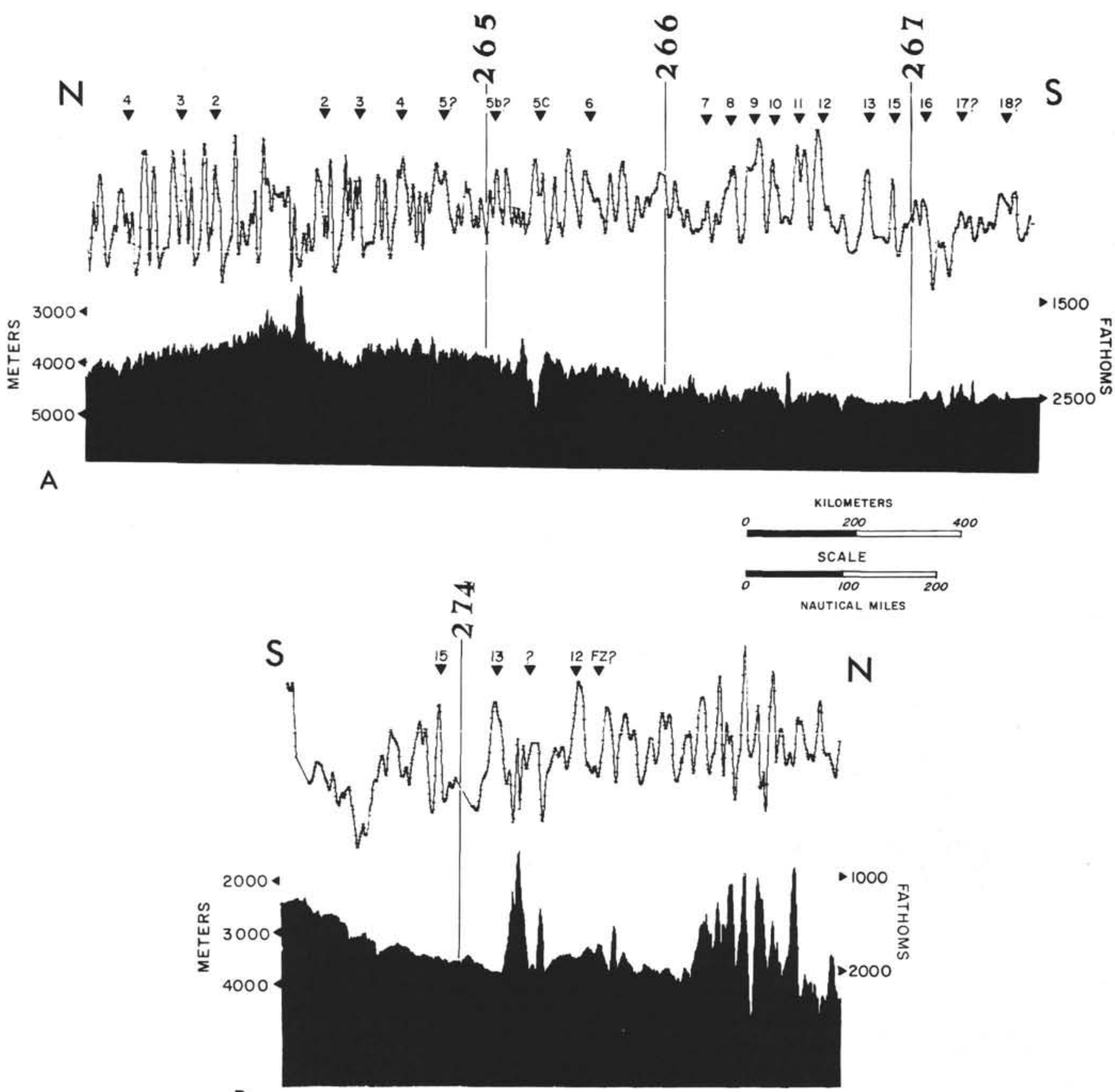

Figure 5. *Magnetic profile along the track of* Glomar Challenger *showing locations of Leg 28 sites with respect to the local magnetic anomalies.*

manner. Our best estimate is that the Site 267 polarity should be normal (although it could be reversed) and that Site 274 polarity should be reversed (although it could possibly be normal). The Site 274 data agree with this interpreted reversed polarity. Although only a very small sample was obtained from Site 267, two specimens gave the same reversed polarity, in contradiction with our best estimate.

It is perhaps unreasonable at the scale of an isolated drill site (core) always to expect to find agreement between the observed NRM polarities and those predicted from the lineation pattern. Discrepancies could arise as a consequence of mixing or coalescing of basalts of various ages. This is not altogether an unlikely possibility considering that only the upper few meters of layer 2, the portion most susceptible to contamination by later flows, have been sampled.

Some discrepancies exist between the observed and expected stable remanent inclinations at these four Leg 28 sites (Table 4). Large discrepancies between observed and expected inclinations are common in DSDP oceanic basalts and may arise from a combination of many sources (Lowrie et al., 1973; Lowrie, in press). A principal source for these errors is thought to be chilling of the basalt on extrusion, which results in rapid freezing-in of the thermoremanence. In this rapid type of acquisition there is no time for secular variation effects to be averaged out, hence the ambient geomagnetic field direction is preserved which includes nonaxial dipole contributions. The discrepancies that result may account in large measure for the observed inclinations at Sites 265, 266, and 267. In spite of these discrepancies, and the consequent errors inherent in calculating virtual geomagnetic pole (VGP) positions, it is worthwhile to perform a calculation for these data because of the paucity of other Tertiary paleomagnetic data from Antarctica. The measured NRM inclinations in the Leg 28 DSDP basalts provide the only paleomagnetic information pertinent to the position of Antarctica and the Antarctic plate from the early Tertiary to the present.

It is generally assumed, primarily on the basis of the scanty paleomagnetic studies from Antarctica and Australia and of the relative motion of the two plates, that the Antarctic plate has been fixed in a high latitude position at least throughout the Cenozoic. A close examination of the published data shows that there is only one paleomagnetic sample location for East Antarctica for the upper Tertiary and none for West Antarctica in the Tertiary although results from three Upper Cretaceous sites indicate a high latitude ($\sim 85°$S) position of West Antarctica for that time (McElhinny, 1973; Dalziel et al., 1973). Kellogg and Reynolds (1974) reported a Middle Cretaceous VGP position for West Antarctica that virtually coincides with the present spin axis. The question of the absolute latitudinal position with respect to the spin axis is particularly important in the case of Antarctica in terms of understanding the long-term paleoclimatic and glacial history of the continent. If Antarctica has truly been in a high latitude position throughout the Cenozoic, it is clear that, although a near-polar position is a necessary condition to generate and sustain glaciation, it is not a sufficient condition. There is strong evidence from pollen and spore studies on the continent that in the early Tertiary, Antarctica was in a temperate climate. From the results reported in this volume, the inception of major continental glaciation appears to have been about 20-25 m.y. ago in the late Oligocene or earliest Miocene.

Table 6 shows the present latitude, the paleolatitude inferred from the mean remanent inclination, and the assumption of an axial dipole field, and the deduced latitudinal change in the position of the site since acquisition of the NRM for Sites 265, 266, 267, and 274. An approximate age in millions of years has been inferred for each site from an analysis of sea-floor spreading lineations using the time scale of Heirtzler et al. (1968). The observed lineations along the track of *Glomar Challenger* are shown in Figure 5. Sites 265, 266, and 267 are located on progressively older portions of the south flank of the Southeast Indian Ridge, in part to confirm the earlier deductions with regard to the spreading history in this region. The only unusual aspect of this combination of three sites is that at Site 265 an anomalously thick sequence of sediment overlies the basaltic layer 2. The anomalous sediment is almost entirely attributed to a very rapid sedimentation rate of about 100 m/m.y. during the last 1 to 2 m.y., whereas the rest of the sedimentary section is normal.

Site 274 also lies on the Antarctic plate, much further to the east but not far from the plate boundary separating the Indian and Pacific plates. The area is dissected by numerous small fracture zones; however, an examination of *Glomar Challenger* data and *Eltanin* tracks leads us to a reasonably confident conclusion that Site 274 is located on crust about 38-39 m.y. old, comparable in age to that at Site 267.

Paleomagnetic results from Australia show that since the Oligocene the apparent polar wander path of Australia has been essentially north-south through about 20° of latitude, a result entirely consistent with the inferred northward motion of Australia with respect to Antarctica of about 30° since the Eocene. It may be noted from Tables 4 and 6 that the inclinations inferred from the mean measured remanences at Sites 266, 267, and 274 are consistent with a fixed position of the Antarctic plate within about 10° of latitude of its present position from 40 m.y.B.P. to the present. Paleomagnetic results from the Miocene for Australia are not compatible with 20° of southward motion of the Antarctic plate in the last 15 m.y. implied from Site 265 inclinations.

The colatitude deduced from the paleomagnetic inclination at a site defines a circle centered on the site. This circle is the locus of possible VGP positions that would give the measured inclinations at the site. When such data are available for a second site of similar age on the same rigid plate, the possible VGP positions are restricted to the two intersection points of the two circles. The locus of VGP positions for a third site of the same age would define optimum VGP on position at the common point of intersection. If the three circles do not intersect at a point, the optimum VGP position may be taken to be the "center" of spherical triangle defined by the three closest points of intersection.

TABLE 6
Comparison of Latitudes and Paleolatitudes Deduced From the Remanent Inclinations and the Assumption of a Dipole Field

Site	Age from Sea-Floor Spreading Lineations (m.y.)	Anomaly (See Figure 5)	Present Latitude	"Axial Dipole" Paleolatitude	ΔL of Antarctic Plate[a]
265	12-14	5-5b	53.54°S	29.3°S	24.2°S
266	23-24	6-7	56.4°S	56.6°S	0.2°N
267	41	15-16	59.3°S	74.1°S	14.8°N
274	38-39	14	69.00°S	61.9°S	7.1°S

[a]ΔL represents apparent latitudinal change.

In the present case Sites 267 and 274 are approximately the same age (38-40 m.y.). Their paleo-colatitudes, deduced from the remanent inclinations, are 15.9° and 28.1°, respectively. The two points of intersection of the VGP loci are at 72°S, 80°E and 51°S, 128°E (Figure 6). The former of these locations is preferable, as it is consistent with other data that imply a relatively fixed position for Antarctica. We caution that this "VGP" is an "instantaneous pole," formed by combining magnetization data from two sources that may contain appreciable components of secular variation.

Support for this pole location is obtained by comparing with the paleomagnetic results of Leg 29 samples from Sites 280A and 282, of the same age (38 m.y.), on the Australian plate (Lowrie and Israfil, in press). Reconstructed motion of the Australian plate away from an assumed fixed Antarctic plate (Weissel and Hayes, 1972) implies that Sites 280A and 282 were magnetized at 66.6°S, 159.1°E and 60.8°S, 149.3°E, respectively. Their remanent inclinations gave paleo-colatitudes of 30.2° and 43.0°, respectively. The VGP loci for these two sites intersect at 71°S, 23°E and 41°S, 146°E. The first of these two locations is only 18° from the favored VGP position for our Leg 28 data.

This appears to be the first instance where DSDP basalt inclinations could be used to determine a possible VGP position. It is also the only Tertiary paleomagnetic pole position for East Antarctica. The relatively small discrepancy of 18° from the rotation axis can easily be attributed to unaveraged secular variation effects (the present north and south magnetic poles are 17° and 22°, respectively, from the rotation axis). In this case the Leg 28 paleomagnetic data may be interpreted as supporting the idea that the Antarctic plate has occupied nearly the same high latitude position since the early Tertiary.

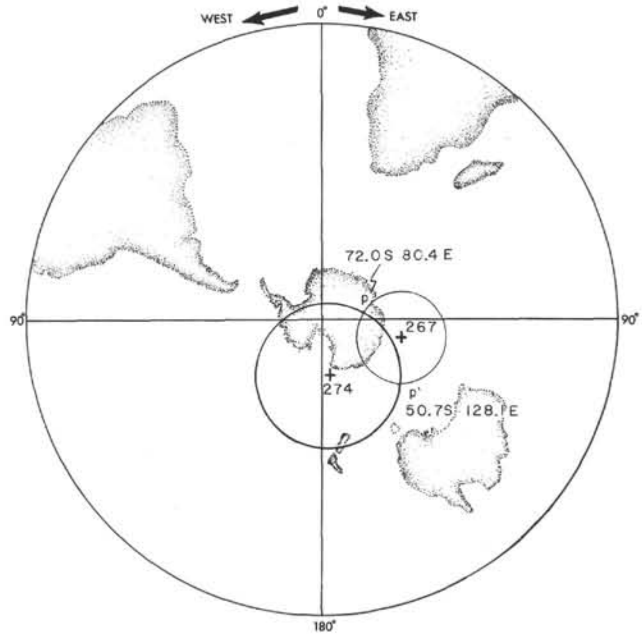

Figure 6. *Locations of two VGP positions from the paleo-colatitudes from Sites 267 and 274. The preferred location is at P.*

ACKNOWLEDGMENTS

This research was supported in part by the Office of Naval Research, through Grant N00014-67-A-0108-0004. We are grateful to Dr. N.D. Opdyke and Dr. R. Larson for reading the manuscript and offering constructive criticisms.

REFERENCES

Ade-Hall, J.M., Palmer, H.C., and Hubbard, T.P., 1971. The magnetic and opaque petrologic response of basalts to regional hydrothermal alteration: Geophys. J. Roy. Astrom. Soc., v. 24, p. 137-174.

Blakely, R.J., 1974. Geomagnetic reversals and crustal spreading rates during the Miocene: J. Geophys. Res., v. 79, p. 2979-2985.

Butler, R.F., 1973. Stable single-domain to superparamagnetic transition during low-temperature oxidation of oceanic basalts: J. Geophys. Res., v. 78, p. 6868-6876.

Dalziel, I.W.D., Kligfield, R., Lowrie, W., Opdyke, N.D., 1973. Paleomagnetic data from the Southernmost Andes and the Antarctandes. *In* Tarling, D.H. and Runcorn, S.K. (Eds.), Implications of continental drift to the earth sciences, vol. 1: London (Academic Press).

Evans, M.E. and Wayman, M.L., 1970. An investigation of small magnetic particles by means of electron microscopy: Earth Planet. Sci. Lett., v. 9, p. 365-370.

Kellogg, K.S. and Reynolds, R.L., 1974. Paleomagnetic study of igneous rocks of the northern Lassiter coast: Antarctic J., p. 38-40.

Lowrie, W., 1973. Viscous remanent magnetization in oceanic basalts: Nature, v. 243, p. 27-29.

———, in press. Oceanic basalt magnetic properties and the Vine and matthews hypothesis: ZGeophysik.

Lowrie, W. and Israfil, in press. Paleomagnetism of basalt samples from Leg 29; *In*.

Lowrie, W., Lovlie, R., and Opdyke, N.D., 1973. Magnetic properties of Deep Sea Drilling Project basalts from the North Pacific Ocean: J. Geophys. Res., v. 78, p. 7647-7660.

Marshall, M. and Cox, A., 1972. Magnetic changes in pillow basalt due to sea floor weathering: J. Geophys. Res., v. 77, p. 6459-6469.

McElhinny, M.W., 1973. Paleomagnetism and plate tectonics: Cambridge (Cambridge Univ. Press).

Nagata, T., 1962. Magnetic properties of ferromagnetic minerals of Fe-Ti-O system. *In* Benedum Earth Magnetism Symposium Proc., University of Pittsburgh Press, p. 69-86.

Ozima, M. and Ozima, M., 1971. Characteristic thermomagnetic curve in submarine basalts: J. Geophys. Res., v. 76, p. 2051-2056.

Pierce, J.W., Denham, C.R., and Luyendyk, B.P., Paleomagnetic results from basalt samples, DSDP Leg 26: EOS Trans. AGU, v. 54, p. 1027.

Readman, P.W., and O'Reilly, W., 1972. Magnetic properties of oxidized (caton-deficient) titanomagnetites $(Fe, Ti, \square)_3 O_4$: J. Geomagnet. Geoelec., v. 24, p. 69-90.

Weissel, J.K., and Hayes, D.E., 1972. Magnetic anomalies in the southeast Indian Ocean. *In* Hayes, D.E. (Ed.), Antarctic oceanology II, The Australian-New Zealand sector, Antarctic Res. Ser., v. 19, Washington (American Geophysical Union), p. 165-196.