57. PALEOMAGNETISM OF BASALTS, LEG 51

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INTRODUCTION

Site 417, occupied during Legs 51 and 52, is located at the southernmost end of the Bermuda Rise (25.11°N, 68.04°W) on magnetic anomaly *M*0, which has been estimated to be 108 × 10^6 years old. Early Aptian sediments recovered immediately at the basalt contact gave paleontological confirmation of this age.

In water about 5500 meters deep, two holes were drilled about 450 meters apart: Hole 417A, a single-bit pilot hole near the top; and Hole 417D, a re-entry hole at the base of a buried hill structure. The 206 meters of basalt penetrated in Hole 417A and the 190 meters penetrated in Hole 417D during Leg 51 consist of fine-grained pillow lava flows separated by hyaloclastic pillow breccias and several coarser grained doleritic units alternatively termed massive flows or intrusions (see Site 417 Report, this volume). Although the basalts are essentially identical in both holes, the rocks of 417A display a high degree of alteration; by contrast, the amount of alteration is only limited in 417D.

A total of 113 and 206 individual basalt samples from Holes 417A and 417D, respectively, have been examined for their paleomagnetic properties. Specimens were drilled and sliced from the working half of the split core in the form of cylinders ("minicores"), 2.45 cm in diameter and 2 to 2.5 cm in length. Absolute orientation is only known with respect to vertical, but fiducial azimuthal markings proved to be useful in considering relative changes in magnetization directions.

Prime objectives of the magnetic measurements were to determine the following:

1) Intensity, direction, and stability of the natural remanent magnetization (NRM).

2) Direction of magnetically stable components of NRM.

3) Estimation of the overall *in situ* magnetization of the basalt sequences penetrated.

EXPERIMENTAL METHODS

Paleomagnetic measurements on a series of 71 (Hole 417A) and 85 (Hole 417D) basalt samples on board the *Glomar Challenger* were supplemented by shore-based work on another 42 (417A) and 131 (417D) samples, including 33 samples from the lower parts of Hole 417D drilled during Leg 52. Much the same equipment and almost identical experimental techniques have been used for both studies.

In both the shipboard and shore-based studies, magnetizations were measured on a DIGICO fluxgate spinner magnetometer. No systematic differences in direction or intensity of magnetically stable test specimens could be observed between the two apparatuses. Progressive alternating field (AF) demagnetization treatments on-board ship were carried out by means of a Schonstedt AC Geophysical Specimen Demagnetizer, model GSD-1, which is a 400 Hz, single-axis, nontumbling device operating in a μm-metal shielded space with an obtainable maximum peak field of 10^3 Oe. Shore-based AF demagnetization was done at 50 Hz using a two-axis tumbler and ambient field cancellation by three mutually orthogonal pairs of Helmholtz coils. As will be discussed more fully later in this report, the results of the shore-based demagnetization were found generally to be somewhat less satisfactory. Here, an acquisition of spurious remanent components was frequently observed, most likely resulting both from a rotational remanent magnetization (Wilson and Lomax, 1972) and/or an anhysteretic magnetization.

Initial susceptibilities were determined with calibrated commercial AC bridges. For computations of the Königsberger ratios (Q = remanent magnetization/induced magnetization), we used an ambient field intensity of 0.46 Oe, as measured at the site.

Prior to AF demagnetization, the viscosity index v (Thellier and Thellier, 1944) was measured for almost all the shore-based samples. This experiment is designed to estimate the amount of secondary viscous remanent magnetization (VRM) relative to the stable primary remanence which for the oceanic basement rocks in general is thought to be a thermo-remanent magnetization (TRM). In a modification of the original Thellier method, the cylindrical axis of the minicores were oriented parallel and antiparallel to the laboratory field (0.48 Oe) for two weeks, respectively. The stable NRM is then calculated as half the sum, the VRM as half the difference of the total remanences measured after each two-week cycle. The viscosity index v is defined as the ratio of the VRM acquired during these two weeks and the stable NRM. As usual values are given in per cent.

RESULTS

Results of the different magnetic measurements performed are summarized in Tables 1 and 2 and presented in detail, with data from Legs 52 and 53 in Levi et al. (this volume). The following parameters are listed: intensity and directions of natural remanent magnetization, stable remanent directions, initial susceptibility, Königsberger ratio and median destructive field (MDF), the alternating field necessary to erase half of the original intensity of magnetization, and a commonplace measure for the relative magnetic stability.

In analyzing and discussing the sets of data obtained, we are concerned with three main aspects:

1) *In situ* magnetic structure as related to the observed magnetic anomaly over the site.

TABLE 1
Summary of Paleomagnetic Results for Hole 417A Basement Rocks

Sample (Interval in cm)	Sub-Bottom Depth (m)	Lithological Unit	Magnetic Unit	I_{stable}	J_{NRM} ($\times 10^{-3}$ emu/cm^3)	SUS ($\times 10^{-3}$ emu/cm^3 $\times$ Oe)	Q	MDF
24-1, 70 to 24-1, 130	218.20–218.80	1	1	-28.0 ±7.8	0.589 ±0.165	0.672 ±0.062	2.0 ±0.7	–
24-2, 90 to 26-1, 75	219.90–237.25	2	2	-20.0 ±3.8	5.95 ±0.89	0.371 ±0.038	35.7 ±5.6	292 ±32
26-1, 95 to 26-2, 75	237.45–238.75	3	3	-19.0 ±3.5	3.11 ±0.77	0.522 ±0.022	12.8 ±2.8	217 ±9
26-3, 90 to 26-4, 25	240.40–241.25	4						
26-5, 85 to 27-2, 35	243.35–247.85	5						
28-2, 45 to 29-7, 45	255.95–274.45	6						
30-3, 0 to 30-4, 70	277.50–279.70	7	? 4	-23.6 ±1.5	5.77 ±0.68	0.645 ±0.040	22.7 ±2.5	196 ±16
30-6, 85 to 31-1, 50	282.85–284.50	8	?					
31-3, 100 to 32-4, 80	288.00–298.80	9						
33-1, 0 to 33-1, 70	303.00–303.70	10	?					
33-3, 5 to 34-5, 100	306.05–319.50	11	5	-19.1 ±1.8	16.4 ±6.6	1.18 ±0.13	29.4 ±11.8	123 ±7
34-6, 25 to 38-5, 60	320.25–353.45	12A	6	-23.5 ±0.9	7.24 ±1.45	0.548 ±0.107	33.9 ±2.4	228 ±17
38-5, 105 to 40-1, 80	353.79–364.21	12B	7	-14.9 ±2.3	3.64 ±0.82	0.400 ±0.060	21.5 ±4.5	240 ±29
40-2, 35 to 42-7, 75	365.15–387.87	12C	8	-22.4 ±1.4	14.9 ±2.7	0.723 ±0.200	31.1 ±2.8	159 ±19
42-7, 75 to 43-1, 130	387.87–389.70	13	(9)	-21.5	6.54	1.23	11.6	160
43-2, 0 to 43-2, 105	389.88–390.85	14	(10)	-24.8	5.38	0.396	29.5	203
43-2, 105 to 44-1, 40	390.85–395.72	15	11A	-22.2 ±1.6	23.9 ±3.7	2.09 ±0.16	28.3 ±6.9	109 ±10
44-2, 0 to 46-1, 0	395.81–407.50		11B	-30.0	3.62 ±0.41	2.72 ±0.14	2.9 ±0.4	65
46-1, 0 to 46-4, 80	407.50–412.80	16	12	-16.1	3.84 ±2.28	1.47 ±0.01	4.0 ±2.6	175 ±25

Note: Mean values listed are arithmetic averages with unit weight given to each sample; errors are standard deviations of the mean. Mean values for magnetic units defined on basis of lithologic units, some combined or subdivided on magnetic evidence. Lithological units are as defined in the Site 417 Report (this volume): I_{stable} = stable inclination in degrees resulting from an AF demagnetization analysis; J_{NRM} = intensity of natural remanent magnetization in emu/cm^3 = Gauss ($\times 10^{-3}$); SUS = initial susceptibility in emu/cm^3 · Oe = Gauss/Oe ($\times 10^{-3}$); Q = Königsberger ratio, based on present ambient field F = 0.46 Oe; and MDF = median destructive field in Oe.

2) Spatial distribution of stable magnetization directions bearing on the earth's magnetic field history, the time and sequence of formation of the basaltic oceanic basement, and local and/or areal tectonism.

3) Relationship of rock magnetism to primary differences in magma type, emplacement mode, and the type and degree of alteration in the upper levels of Layer 2 of the oceanic crust.

The third subject is discussed in detail in a separate chapter (Smith and Bleil, this volume) and is only considered here insofar as it is relevant to solve the two other problems.

Natural Remanent Magnetic Properties

Arithmetic and geometric averages for the natural remanent intensities, with unit weight given to either individual samples or magnetic units, are listed in Table 3 together with appropriate data from previous extensive studies on DSDP materials and dredged rock collections. One has to be aware of the fact that NRM intensities and directions measured on ocean floor basalts do not necessarily represent *in situ* properties. Thus, a drilling-induced remanence was identified in Leg 34 and Leg 45 basement rocks (Ade-Hall and Johnson, 1976). In the present case, these spurious magnetizations (probably of viscous, stress, or shock-induced origin) most likely are directed downward, opposing the stable reverse inclinations. Consequently, samples susceptible to acquiring such a component will exhibit trends towards steeper reverse inclinations typically accompanied by an initial increase in intensity upon AF demagnetization. This is actually observed for only a small number of specimens both from pillowed and massive flows in Holes 417A and 417D. If at the same time, large directional changes are displayed upon AF demagnetization, the NRM intensity and MDF are given in brackets (see tables in Levi et al., this volume). The frequent occurrence of a slight intensity increase during the initial demagnetization steps (up to 100 Oe), not correlated with major directional changes, is indicated by an asterisk at the MDF values. In this context, it should be pointed out that the effects described above may as well be attributed to a secondary VRM component acquired in the Brunhes field *in situ*.

Neither a remagnetization during the drilling of the main core nor any *in situ* process affecting the declination direction would directly be detectable in the NRM values measured, as the samples have no azimuthal orientation. The usual stereographic plot of the NRM directions (Figures 1 and 2), therefore, are of relatively little utility for DSDP data sets, aside from testing that the declinations are really more or less randomly distributed. This is true for the Hole 417A samples and the samples from pillowed flows in Hole 417D. Most of the massive flow data from Hole 417D, however, are clearly biased, indicating the presence of a strong spurious magnetization directed along the cylindrical axis of the samples. These components obviously must have been acquired during the drilling of the minicores or the subsequent transport and storage. As all values incorporated in Figures 1 and 2 were measured on board *Glomar Challenger*, we suspect responsibility is properly placed with the shipboard minicore drilling process, because afterwards the samples were never quite in the same position, causing such

TABLE 2
Summary of Paleomagnetic Results for Hole 417D Basement Rocks

Sample (Interval in cm)	Sub-Bottom Depth (m)	Lithological Unit	Magnetic Unit	I_{stable}	J_{NRM} (× 10^{-3} emu/cm^3)	SUS (× 10^{-3} emu/cm^3 × Oe)	Q	MDF
21, CC to 22-2, 115	339.40–346.65		1A	−76.9 ±1.5	21.3 ±3.0	1.79 ±0.29	28.0 ±6.6	174 ±9
22-4, 0 to 26-6, 20	348.50–365.05		1B	−60.1 ±3.0	13.4 ±0.8	1.78 ±0.18	18.3 ±2.9	159 ±14
26-6, 20 to 28-3, 145	365.05–379.75	1	1C	−72.6 ±1.3	11.4 ±1.3	1.09 ±0.21	27.0 ±3.4	229 ±28
28-4, 0 to 28-5, 150	379.80–382.53		1D	−63.2 ±1.3	10.0 ±1.2	0.968 ±0.227	24.8 ±3.7	161 ±24
28-6, 5 to 29-3, 75	382.57–388.21		1E	−68.6 ±1.1	6.87 ±1.35	1.25 ±0.19	14.8 ±2.8	179 ±31
29-3, 75 to 31-3, 150	388.21–407.50		1F	−63.2 ±2.3	8.89 ±1.01	1.18 ±0.19	21.8 ±2.8	240 ±32
31-4, 20 to 32-1, 70	407.70–412.79	2	2	−70.7 ±2.6	6.70 ±1.47	1.06 ±0.23	17.1 ±3.3	198 ±39
32-1, 70 to 34-5, 115	412.79–435.43	3	3	−64.0 ±1.4	4.61 ±1.03	2.33 ±0.06	7.7 ±2.9	130 ±27
34-5, 115 to 37-5, 125	435.43–456.66		4A	−65.9 ±2.1	12.6 ±1.3	0.976 ±0.157	36.8 ±6.9	154 ±14
37-7, 0 to 38-3, 85	458.02–461.26		4B	−71.6 ±1.0	15.6 ±6.0	0.504 ±0.081	67.1 ±28.2	239 ±68
38-5, 95 to 38-6, 75	463.65–464.65		? 4C	−42.9 ±9.0	15.0 ±3.3	1.60 ±0.39	20.6 ±1.2	161 ±12
39-1, 0 to 39-3, 105	464.70–467.86		4D	−72.1 ±1.0	9.41 ±3.39	2.42 ±0.27	12.4 ±5.6	185
39-4, 0 to 40-2, 150	468.21–474.00	4	4E	−65.6 ±1.1	11.3 ±1.6	1.35 ±0.23	19.8 ±4.1	199 ±38
40-3, 0 to 41-6, 25	474.00–482.11		4F	−74.5 ±1.3	9.43 ±1.34	1.56 ±0.33	16.8 ±3.5	165 ±24
41-6, 85 to 41-8, 35	482.61–484.70		4G	−55.0 ±0.3	28.1 ±7.3	1.09 ±0.06	55.7 ±11.9	114
42-1, 0 to 42-2, 150	484.70–487.64		4H	−72.2 ±1.5	3.41 ±1.50	0.982 ±0.195	7.2 ±1.8	165 ±41
42-3, 0 to 42-4, 85	487.64–489.94		4I	−58.9 ±1.4	8.37 ±2.10	2.07 ±0.24	9.0 ±2.2	95 ±6
42-4, 90 to 42-4, 145	489.99–490.53		4K	−72.2 ±3.5	16.9 ±2.7	1.62 ±0.24	22.7 ±0.3	111 ±6
42-5, 35 to 43-1, 140	490.92–495.10	5	5	−30.1 ±2.9	8.08 ±2.81	2.51 ±0.17	8.3 ±3.4	105 ±10
43-2, 0 to 43-5, 125	495.20–500.54	6	6	−21.4 ±4.9	4.03 ±0.63	2.95 ±0.08	2.8 ±0.4	69 ±16
43-6, 125 to 45-2, 145	501.94–514.95	7	7	−29.7 ±3.0	5.24 ±0.81	2.62 ±0.13	4.9 ±1.2	108 ±11

Note: Mean values listed are arithmetic averages with unit weight given to each sample; errors are standard deviations of the mean. Mean values for magnetic units defined on basis of lithologic units, some subdivided on magnetic evidence. Lithological units are as defined in the Site 417 Report (this volume): I_{stable} = stable inclination in degrees resulting from an AF demagnetization analysis; J_{NRM} = intensity of natural remanent magnetization in emu/cm^3 = Gauss (× 10^{-3}); SUS = initial susceptibility in emu/cm^3 · Oe = Gauss/Oe (× 10^{-3}); Q = Königsberger ratio, based on present ambient field F = 0.46 Oe; and MDF = median destructive field in Oe.

TABLE 3
Basement Rocks as Magnetic Materials (A); Basement as Source of Magnetic Anomalies (B)

		Mean NRM Intensity (×10^{-3} emu/cm^3)		Mean Susceptibility (×10^{-3} emu/cm^3 · Oe)		Mean Q Ratio		Mean Viscosity Index (%)	
		Arithmetic	Geometric	Arithmetic	Geometric	Arithmetic	Geometric	Arithmetic	Geometric
A.									
Sample means	Hole 417A	9.43 ±9.47	6.53 ±2.38	0.940 ±0.755	0.701 ±2.15	26.8 ±17.3	20.5 ±2.4	4.1 ±8.1	1.0 ±5.9
		(N=112)		(N=106)		(N=105)		(N=41)	
	Hole 417D	9.22 ±6.25	6.93 ±2.46	1.80 ±0.83	1.52 ±1.97	18.2 ±18.5	11.4 ±2.9	10.6 ±15.5	4.5 ±4.1
		(N=159)		(N=205)		(N=158)		(N=120)	
Magnetic unit means	Hole 417A (N=13)	7.76 ±6.60	5.55 ±2.52	0.997 ±0.725	0.809 ±1.92	20.4 ±12.3	14.7 ±2.7	–	–
	Hole 417D (N=21)	11.0 ±6.0	9.59 ±1.71	1.60 ±0.66	1.47 ±1.55	21.1 ±16.0	16.3 ±2.2	–	–
Site means (Lowrie, 1974)	DSDP sites (N=26)	–	2.06	–	0.632	–	7.92	–	–
	Dredge-hauls (N=110)	–	5.76	–	0.318	–	39.9	–	–
Magnetic unit means (Ryall et al., 1977)	Leg 37	3.66 ±2.26	3.05 ±0.19	0.363 ±0.327	0.276 ±0.198	35 ±26	–	–	–
		(N=127)		(N=124)		(N=124)			

B.	Vectorial Mean Inclination (degrees)	Vectorial Mean Intensity[a] (emu/cm^3)	Arithmetic Mean Susceptibility[a] (emu/cm^3 · Oe)	Effective Q Ratio
Hole 417A	−21.6	7.32 × 10^{-3}	0.749 × 10^{-3}	21.2
Hole 417D	−63.8	9.20 × 10^{-3}	1.62 × 10^{-3}	12.3

[a]Reduced to allow for proportions of effectively non-magnetic breccia.

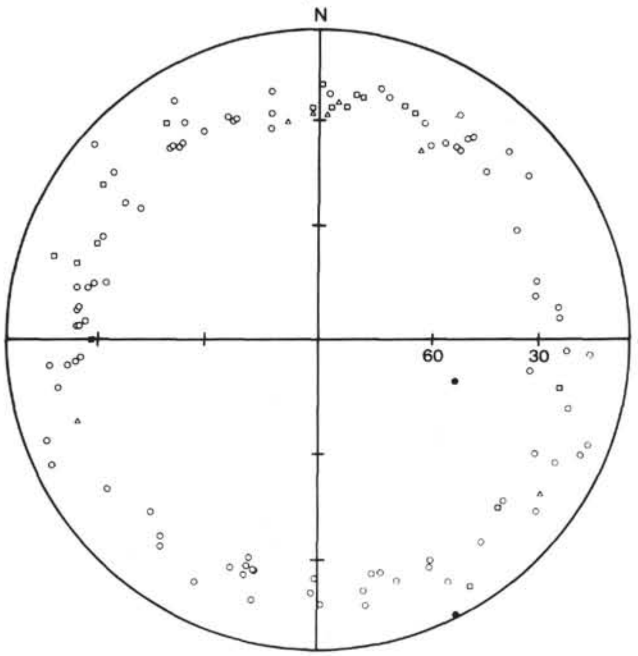

Figure 1. *Stereographic plot of natural remanent magnetization directions of Hole 417A igneous basement rocks. Circles = pillowed basalt; squares = massive flow basalt; triangles = breccia. Open symbols indicate negative, full symbols positive inclination.*

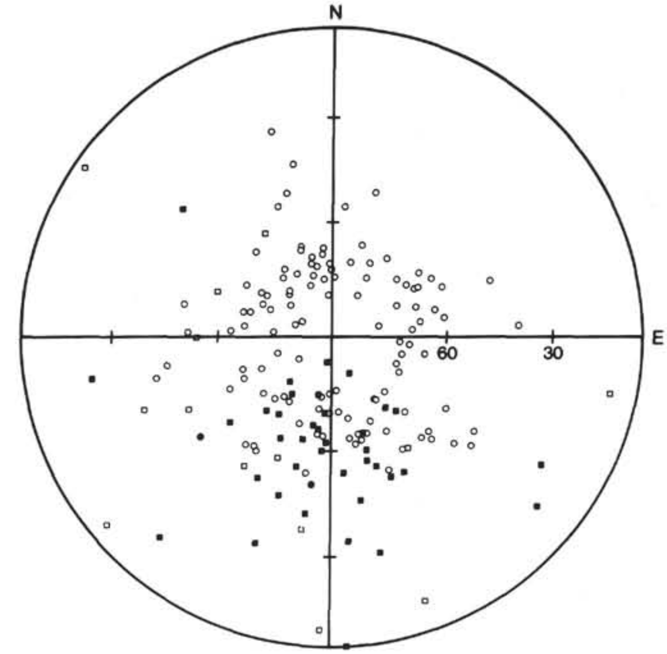

Figure 2. *Stereographic plot of natural remanent magnetization directions of Hole 417D igneous basement rocks. Circles = pillowed basalt; squares = massive flow basalt. Open symbols indicate negative, full symbols positive inclination.*

a uniform magnetic overprinting. For all these samples, NRM intensity and median destructive field are given in brackets when tabulated in Levi et al. (this volume). The bracketed NRM and MDF values are omitted for the mean calculations and diagrams; the same applies to the related Königsberger ratios.

Downhole plots of the various bulk magnetic properties (Figures 3 and 4) elucidate in all cases a remarkably high variability at almost all levels. This variability is observed even on a scale of a few centimeters. High-temperature gradients in the individual basaltic pillows and flows during the original cooling history (causing variations in magnetic oxide abundance and grain size) and, on the other hand, pronounced changes in the degree of alteration (causing low-temperature oxidation of the magnetic oxides) are the two main factors controlling those variations.

For several parameters, Figures 3 and 4 outline certain downhole trends. Obviously, they are not continuous over the whole rock suites encountered and, moreover, there seem to be distinct differences between the two adjacent holes. These features will be discussed in detail on the basis of magnetic unit mean values in a later section.

Stable Remanent Inclinations

The aim of a demagnetization process consists in defining a reliable original magnetization direction. For igneous oceanic basement rocks, this remanence should be a thermo-remanent magnetization (TRM) acquired during initial cooling. Provided that subsequent tectonic activities can be neglected, a stable inclination will directly be identified as ambient field inclination during eruption. Otherwise, the stable magnetization directions may be used to reconstruct plate motions, or possibly local tectonic events.

Stepwise AF demagnetization processes using peak fields of 25, 50, 100, 150, 200, 300, 400, and 500 Oe were found to be suitable for most of the samples which displayed magnetically less stable overprinted secondary components of magnetization. According to their individual behavior, a number of samples were further demagnetized to a peak field of 1000 Oe or until the remanent intensity was less than 10 per cent of the initial value.

Most of the fine-grained pillow basalts from both holes displayed very minor directional changes upon AF demagnetization, although the range of stable inclination is markedly different from the recent centered axial dipole field direction for the area. In these cases, the stable remanent magnetization directions could simply be defined as mean values of several consecutive demagnetization steps. Standard deviations here typically amount to 1° to 2° for the shipboard measurements and are somewhat higher for the shore-based results. When greater directional changes are observed, i.e., a higher proportion of secondary components is present, vector diagram plots (Zijderfeld, 1966) of the demagnetization data were used to determine the stable directions. When the standard deviation exceeded 5°, the stable inclination and/or declination values given in Levi et al. (this volume) are bracketed; "no" results are given whenever the standard deviation exceeded 10°. Due to the strong spurious magnetization components described above, only a few stable directions could confidently be identified for coarse-grained massive flow units in Hole 417D. Examples for both stable and unstable behavior during AF demagnetization are illustrated in Figures 5a and 5b.

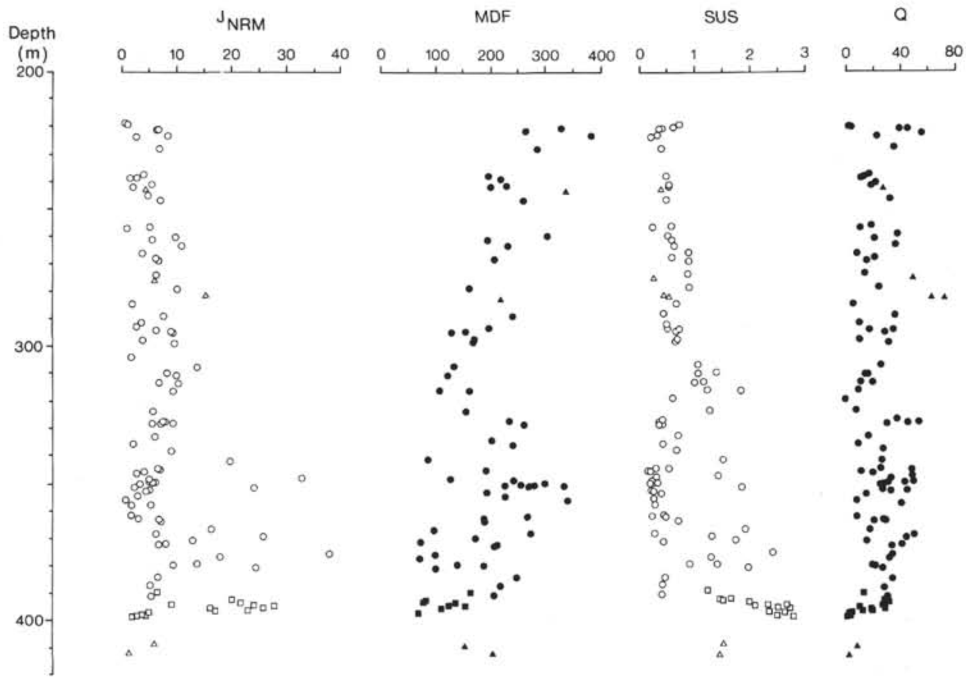

Figure 3. *Downhole variation of the intensity of natural remanent magnetization (J_{NRM} in emu/cm^3 X 10^{-3}), median destructive field (MDF in Oe), initial susceptibility (SUS in emu/cm^3 · Oe X 10^{-3}) and Königsberger ratio Q (based on an ambient field intensity, F, at the drilling site of 0.46 Oe) for Hole 417A basaltic samples. Circles = pillowed basalt; squares = massive flow basalt; triangles = breccia.*

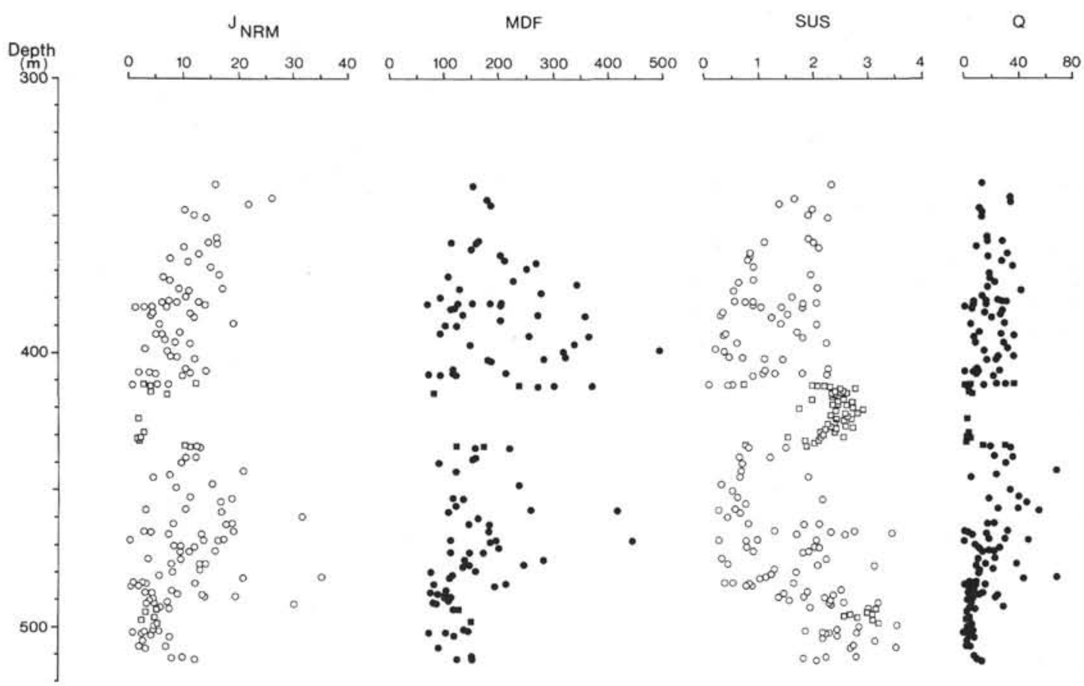

Figure 4. *Downhole variation of the intensity of natural remanent magnetization (J_{NRM} in emu/cm^3 X 10^{-3}), median destructive field (MDF in Oe), initial susceptibility (SUS in emu/cm^3 · Oe X 10^{-3}) and Königsberger ratio Q (ambient field intensity, F, at the drilling site of 0.46 Oe) for Hole 417D basaltic samples. Circles = pillowed basalt; squares = massive flow basalt.*

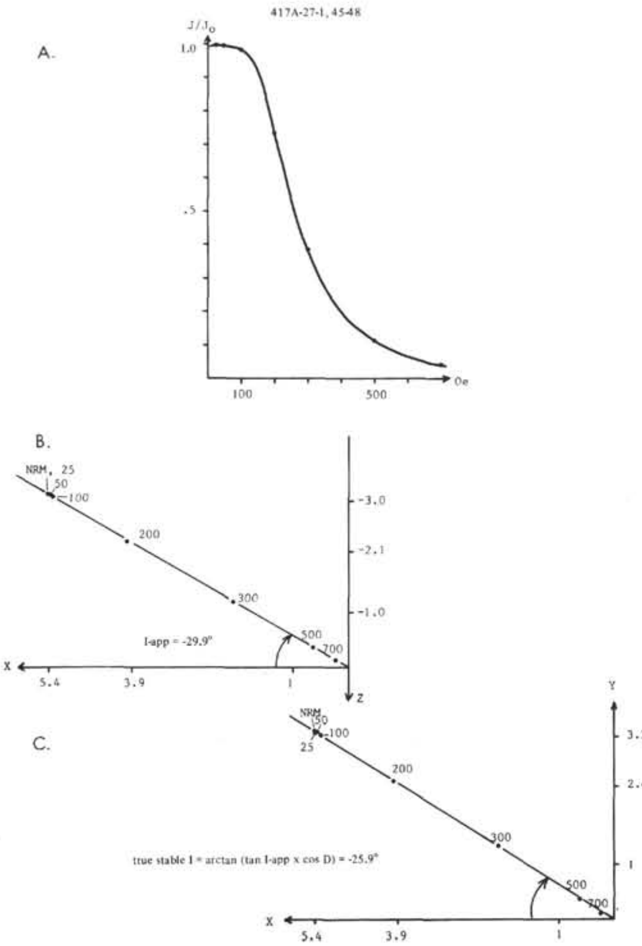

Figure 5a. *Alternating field demagnetization for a typical sample with a single magnetization component. (A) represents J/J_O as a function of the alternating field, where J_O is the initial remanent magnetization. (B) and (C) represent the remanent magnetization vector projected, respectively, on the vertical plane (X,Z) and the horizontal plane (X,Y) (Zijderveld, 1966), for each demagnetizing step (X,Y, and Z X 10^{-3} emu being the three references axes). The stable declination, D, is directly read on the (X,Y) diagram; an apparent stable inclination, I_{app}, is read on the diagram (X,Z). The true stable inclination I is calculated by: I = arc tan (tan I_{app} X cos D).*

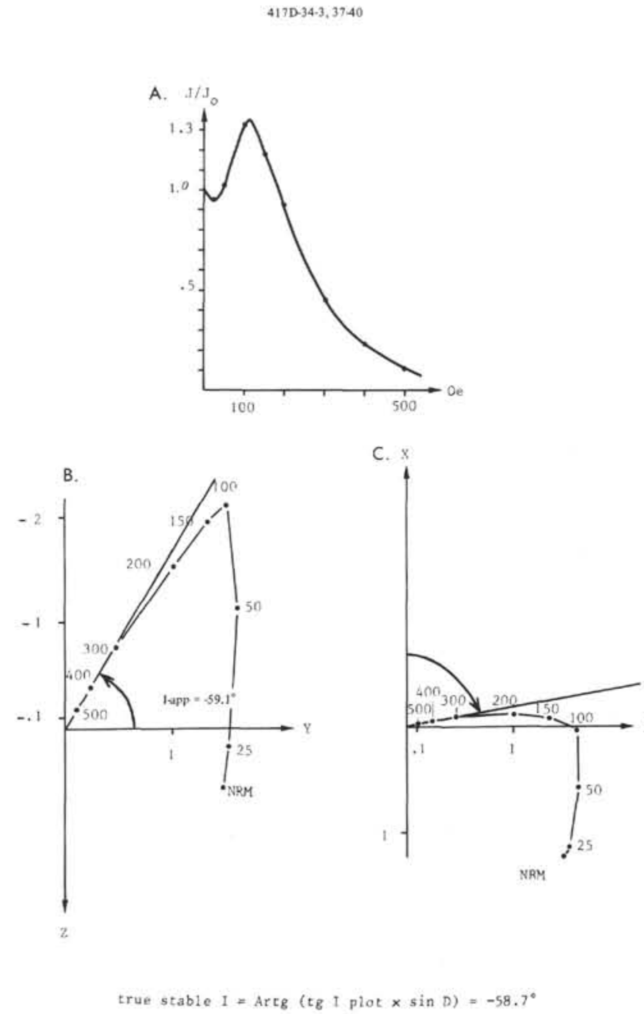

Figure 5b. *Alternating field demagnetization for a typical sample with multicomponent magnetization. Same captions as for Figure 5a, but here the vertical plane (B) is (Y,Z) and the true stable inclination I: I = arc tan (tan I_{app} X sin D), can only be calculated from 300 Oe data after removal of the secondary component(s); X,Y,Z are again in 10^{-3} emu.*

Lithologic and Magnetic Units

The basaltic sequences encountered in each hole have been divided into lithologic units on the basis of petrological, geochemical, and structural criteria. Looking through the tables presented in Levi et al. (this volume), none of the magnetic parameters seems to suggest any appropriate straight forward consistent grouping into magnetic units. Changes in magnetic polarity or major directional variations in inclination repeatedly used for this purpose in former DSDP studies are not observed in the basement section drilled on Leg 51, with the single exception of an inclination change at about 492 meters sub-bottom in Hole 417D.

Assuming a lithologic unit is formed during a single eruptive event, the stable primary inclination should be constant over the entire length of this unit. This is physically justified as the cooling process will be short compared to variations on the geomagnetic time scale, and provided no disturbing subsequent effects such as tectonism are involved.

As discussed above for bulk magnetic properties other than magnetization direction, most of the variations occur on a small scale within single cooling bodies of pillowed basalt or basaltic flows. Nevertheless, differences in magnetic characteristics like NRM intensity, susceptibility, magnetic stability index (MFD), and Königsberger ratio between lithologic units proved to be additional useful information in constructing a magnetic classification scheme for the basement sequences penetrated.

The above-mentioned lack in unequivocal criteria to define magnetic units led us to calculate mean values for the different magnetic parameters simply on the basis of lithological units. These results are shown in Figures 6 and 7.

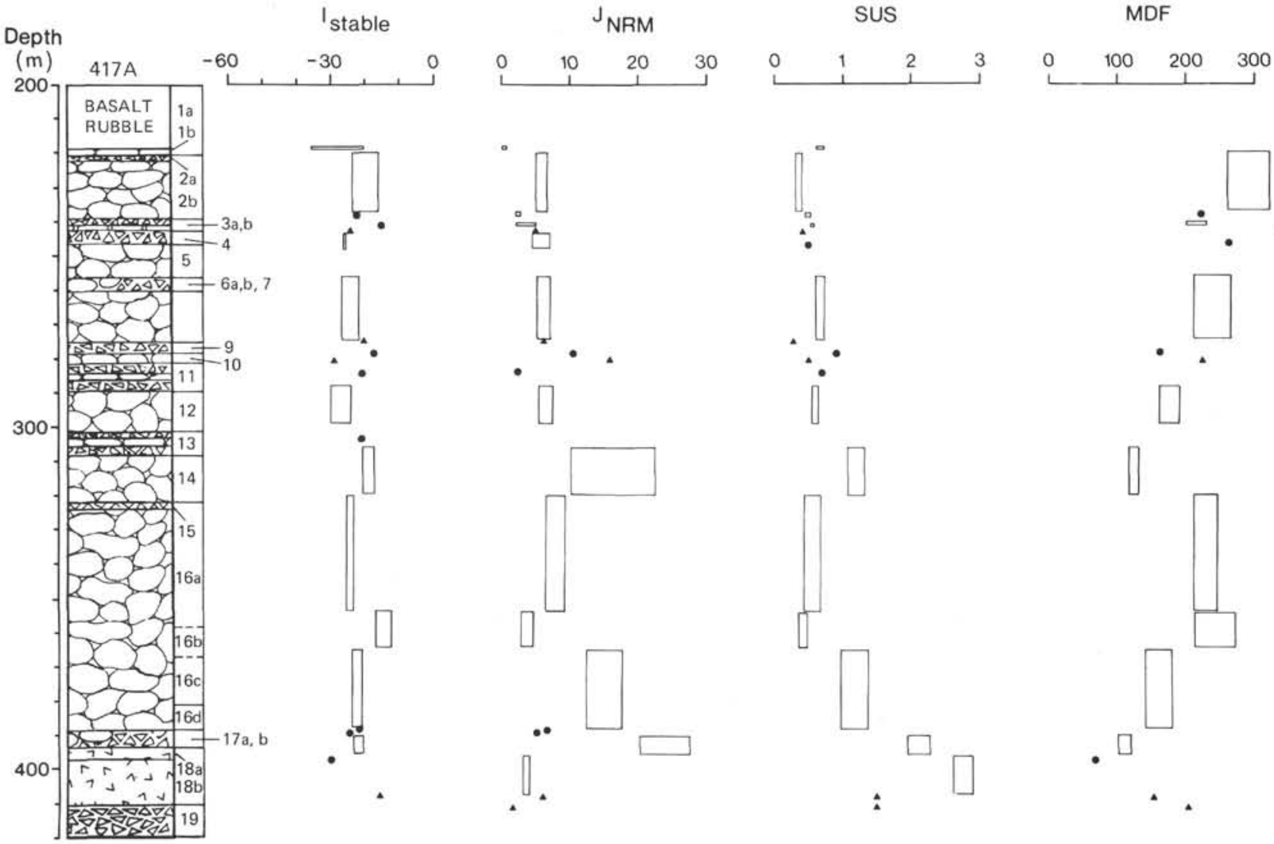

Figure 6. *Magnetic units and individual samples for Hole 417A. The length and width of the bars indicate the thickness of each magnetic unit and the standard deviation of the mean, respectively (see Table 1). For individual samples, circles = pillowed basalt; triangles = breccia. Downhole variation of stable inclination (I_{stable} in degrees), intensity of natural remanent magnetization (J_{NRM} in emu/cm^3 X 10^{-3}), initial susceptibility (SUS in emu/cm^3 · Oe X 10^{-3}), and median destructive field (MDF in Oe).*

Hole 417A

In Hole 417A, only the massive flow unit (lithological Unit 15) has been further subdivided into two magnetic units according to conspicuous differences in both remanent intensity and susceptibility. As illustrated in Figure 6, there is generally very little change in the stable inclination within the entire basement column. The other magnetic properties either remain about constant over several consecutive lithological units (mainly in the upper part of the hole) or reveal some distinct downhole trends of increasing or decreasing average values. Also noteworthy are obvious correlations and breaks at certain levels when comparing different parameters. Those effects are thought to result from primary differences in magma type, emplacement mode, or subsequent alteration history.

Due to very limited range of variation in the stable inclination data, a major difficulty arises in trying to separate effects attributable to earth magnetic field variations from scatter to be assigned to experimental errors. A conservative estimate of $\pm 5°$ total experimental error for an individual sample seems appropriate when combining the inaccuracies resulting from orientation and measurement of the samples and determination of stable inclination values. With this assumption and due to the fact that for many units standard statistical techniques cannot properly be applied on limited data; as matters stand, there is only limited evidence for any conclusion drawn from the stable inclination pattern in Hole 417A.

Notwithstanding these restrictions, at least 5 (perhaps up to 12) separate measurements of the paleomagnetic field inclination were obtained (Figure 6). From analyses of the present-day and Recent earth magnetic field behavior (McDonald and Gunst, 1968; Merrill and McElhinny, 1977), it is evident that the secular variation of the dipole and non-dipole field may comprise a wide range of periods from some 10^3 to some 10^5 years. Individual magnetic units, and adjacent units falling within each other's stable inclination errors, probably were accumulated in less than 100 years. Intervals between eruptions or eruptive sequences are thought to average about 10^4 years (Ryall et al., 1977). With these assumptions, it seems plausible that a time span of 5-10 $\times$ 10^4 years is represented by the igneous sequence in Hole 417A. The formation of the upper levels of Layer 2 of the oceanic crust must be very episodic and, thus, little of the net time is documented in rocks, which in turn limits any possible interpretation in terms of earth magnetic field history.

As the stable inclination remains negative throughout, we may compare the time estimate with the total length of the negative M0 polarity interval of 6.7 $\times$ 10^5 years, calculated

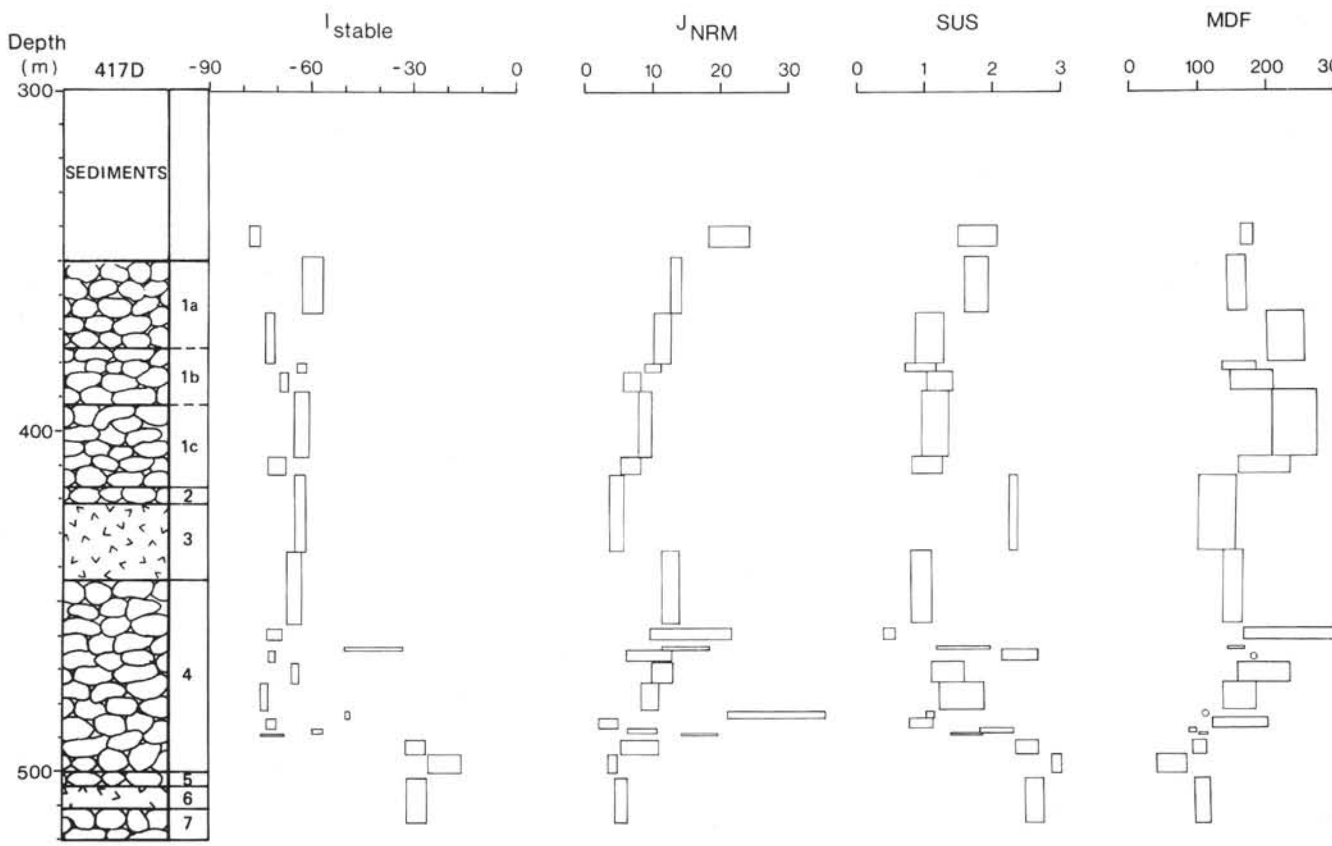

Figure 7. *Magnetic units and individual samples for Hole 417D. The length and width of the bars indicate the thickness of each magnetic unit and the standard deviation of the mean, respectively (see Table 2). For individual samples, circles = pillowed basalt. Downhole variation of stable inclination (I_{stable} in degrees), intensity of natural remanent magnetization (J_{NRM} in emu/cm^3 X 10^{-3}), initial susceptibility (SUS in emu/cm^3 · Oe X 10^{-3}), and median destructive field (MDF in Oe).*

from a 12-km anomaly width (Schouten, 1976) and a spreading rate of 1.8 cm/yr.

Hole 417D

In Hole 417D, basically the same criteria as for Hole 417A have been applied to define magnetic units. It turned out, however, that there was no magnetic justification to adopt the petrological subdivisions of lithologic Unit 1 (see Site 417 Report), which were mainly based on the occurrence of limestones interlayered within the pillowed basalts. Instead, there is reasonable evidence from variations of the stable magnetization direction to establish a number of magnetic subunits. Similarly, lithologic Unit 4 was subdivided into several magnetic units according to directional changes. Unlike one instance in Hole 417A, exclusively changes in stable magnetization direction were used here to define magnetic units (Table 2). As evident from Figure 7, many of the magnetic units are also characterized by distinct ranges in one or several bulk magnetic properties other than stable inclination.

In the downhole trends in NRM intensity, susceptibility, and magnetic stability index (MDF), the massive flow unit (lithologic/magnetic Unit 3) obviously takes a certain key position. In looking at Figure 7, within the uppermost 100 meters of pillowed lavas, the NRM intensity exhibits a gradual decrease along with a less-distinct change of susceptibility in the same sense and no regular change in MDF. As discussed by Smith and Bleil (this volume), none of the intrinsic magnetic and/or mineralogic properties determined at this level allowed an unequivocal interpretation of this rather atypical pattern in NRM intensity. The massive flow unit (Unit 3, about 413 to 435 m sub-bottom) marks a clear break in this trend. Low magnetization intensity and stability (MDF) and, at the same time, high susceptibility values in this unit are compatible with relatively coarse-grained magnetic oxides showing a limited degree of alteration (low-temperature oxidation).

Below Unit 3, the downhole change in the different magnetic parameters is rather uniform, although not continuous at all levels. The observed trends towards decreasing NRM intensity and MDF, and increasing susceptibility with depth are most likely attributable to combined grain-size and alteration effects. There are some indications that with regard to alteration, the massive flow to a certain extent acts as a barrier giving sea water less free access to the underlying rock sequences. Finally, it should be noted that in the lower 100 meters, susceptibility and MDF show very similar patterns in both holes, leading to about the same range of values for these two properties at equal sub-basement depths. This is not true, however, for the NRM intensities.

Regarding the variation of the stable inclination in Hole 417D, about 20 separate measurements of the paleomagnetic field inclination could be identified (Figure 7). Analogous to the above discussion of the Hole 417A results, we conclude that up to 200,000 years may be represented in the igneous sequence drilled during Leg 51 in Hole 417D. The most interesting phenomena here are the consistently steep stable inclinations down to 480 meters sub-bottom, which differ by about 40° both from results deeper in the same hole and from the stable inclination range found nearby in Hole 417A. Anticipating our interpretation in terms of a tectonic event explained in more detail below, it is a crucial point that according to the magnetic evidence, the upper basaltic series encountered in Hole 417D was not accumulated during a single eruption or a short eruptive sequence.

Paleomagnetic Record

In this section, we are concerned with the stable magnetization directions as indicators of the original magnetizing field and the subsequent tectonic history.

In Hole 417A, the analysis of AF demagnetization treatments yielded negative stable inclinations throughout. An arithmetic mean of −22.3° (standard deviation, ±5.7°) is obtained giving unit weight to individual samples, and −21.9 ±4.3°, giving unit weight to magnetic units. Using the basic relationship $\tan \theta = 0.5 \tan I_{stable}$ for a geocentric axial dipole, we find a paleolatitude θ for Site 417 of 11.6 ±3.3° N, indicating that this part of the American plate has moved northward by about 13.5° since the Early Cretaceous. It has to be pointed out that we have to meet at least two requirements for such a simple straightforward calculation to be realistic. First, it must be assumed that the negative inclination observed was acquired during a reverse polarity epoch of the earth magnetic field. As our samples are not oriented with respect to the azimuth, no absolute determination of the declination was possible, this being the only direct and unequivocal test by a paleomagnetic measurement to answer this question. However, our understanding of magnetic anomaly lineations and plate motions of the area strongly suggests that Site 417 was in a position in the Northern Hemisphere when this part of the present ocean crust was formed at the Mid-Atlantic Ridge.

The second point of interest in this context is whether or not a given range of inclination can be quoted as representing a geocentric axial dipole field. Although a time span of several tens of thousands of years may have been necessary to build up the igneous sequence penetrated, due to the episodic character of mid-ocean ridge volcanism, one could argue that a too small proportion of the net time is represented by rocks to adequately trace geomagnetic secular variation. In order to decide on this, we can compare the paleolatitude determined above with that anticipated for Site 417 by Schouten (1976). Table 4 summarizes the paleolatitudes and respective paleo-inclinations calculated on the basis of virtual geomagnetic poles (VGP) for North America, from which it becomes evident that the mean stable inclination of −22.3° obtained in Hole 417A might be in a closer agreement with a Jurassic instead of a Cretaceous age. However, the Jurassic VGP for North America is not very well defined and, taking into account the limits of reliability of the data taken as the basis of this discussion, our result is not significantly different from either. Schouten (1976) proposed a mean of Cretaceous and Jurassic VGP as the most probable reference point. The mean stable inclination value determined for Hole 417A may give some support for this idea. On the other hand, it cannot be completely excluded that this average inclination is still somewhat biased due to an imperfect cancellation of non-axial (or non-dipole) field component since the rock collection did not contain enough separate paleomagnetic directions or represented too short a time interval to randomize those components. Alternatively, minor tectonic tilting (<10°) may have caused a small shift toward a lower inclination range.

TABLE 4
Virtual Geomagnetic Poles (VGP) for North America at its Present Latitude; Apparent Paleolatitudes and Respective Inclinations for Site 417 Due to Geocentric Axial Dipole

VGP for North America	
Cretaceous	69° N, 172° W; α_{95} = 4°
Jurassic	64° N, 174° W, α_{95} = 33°

	Latitude	Inclination
Present	25.1° N	±43.1°
Cretaceous	18.4° N	±33.6°
Jurassic	11.1° N	±21.4°

In Hole 417D only, in the lowermost igneous sequence encountered on Leg 51 (below Core 42, Section 4), a similar range of stable inclinations was found as in Hole 417A. A sample mean value of −27.4 ±9.2° (unit mean −27.1 ±4.9°) obtained there is almost the same as that determined for the deeper portion of the hole drilled during Leg 52 (Levi et al., this volume). In clear contrast, the upper 150 meters of the section yielded a sample mean of I_{stable} = −66.1 ±8.3° (unit mean −66.1 ±8.3°); of course, the problem arises of explaining this large difference.

The anomalously steep inclinations definitely exceed any normal geomagnetic secular variation, and it is almost certain that they do not represent an original paleomagnetic direction close to a geocentric axial dipole field. Any plausible interpretation in terms of plate tectonics, therefore, can immediately be ruled out. As with several previous DSDP legs, we must decide between the possible causes of either a tectonic rotation or a recording of an atypical earth magnetic field configuration. Unlike the results obtained for other sites however, we may hope that the high recovery achieved will help to answer this question.

A recording of an atypical earth magnetic field configuration, i.e., a geomagnetic polarity transition or a time interval when the earth field was far away from the ideal axial dipole state ("an excursion"), does not seem to be the appropriate solution here for a number of reasons. According to our present knowledge, an anomalous earth field behavior usually takes place over short periods of time (up to several thousands of years). Within the steep stable inclination data, there are no obvious directional changes, even near the break toward normal inclination values at about 490 meters sub-bottom. This would imply a more or less instantaneous emplacement of the whole lava pile which is hardly compatible with petrological evidences like geochemical variations and interlayered limestones. Instead, the changes seen in the stable inclinations most likely contain the recording of normal secular variation over a relatively long time (Figure 7). There are absolutely no indications for a reduced magnetization intensity resulting from a low field intensity, a typical feature during anomalous field configurations. Hall and Ryall (1977) have pointed out that the recording of geomagnetic transitions or excursions by an episodic volcanism is statistically very improbable. Analyses of a great number of Icelandic lava flows showed that only about 5 per cent had recorded a transitional field state. In comparison, extended sequences of unusually steep or shallow inclinations were found in most of the deeper DSDP holes drilled in recent years, indicating that massive block faulting is a common phenomenon in mid-ocean tectonics.

Assuming the tectonic explanation is correct, the difference between the actual steep inclination and the axial dipole values requires a rotation of at least about 40°, assuming a dip to the south about a subhorizontal axis of rotation directed about east-west. This is a minimum condition: any dipping or otherwise-directed axis must be paired with an even greater angle of rotation to attain the same change in inclination. Again, the lack in azimuthal orientation of the samples does not allow to give more specification of this point.

It should be mentioned that some confirmation for the rotation was found in the orientation of presumed horizontal-reference features like bedding of interlayered limestones and chilled margins of pillowed basalts and vertical-referenced features such as joint patterns in massive flows. Comparing results for the upper part of Hole 417D with the lower sections of this hole and the adjacent Hole 417A, these measurements consistently showed angular differences of 30° to 40°. In the vicinity where the stable inclination values abruptly change from steep to normal in Hole 417D, the basalts showed abundant healed fractures, microfaults with slicken sides, and evidence of brecciation suggesting the proximity of a fault or perhaps the fault zone itself.

The most attractive movement resulting in the observed rotation would be a gravitational slumping, probably initiated by normal faulting. The sub-horizontal bedding of the sediments immediately above the basalts indicates that this tectonic event must have occurred shortly after eruption of the basalts. Finally, it is notable that from direct observations in the median valley of the Mid-Atlantic Ridge (e.g., McDonald et al., 1975), no such steep dipping blocks have been reported to date.

The Basaltic Basement as Source of the Geomagnetic Anomaly Lineation

This final section is concerned with the relation between magnetic anomalies and the net *in situ* magnetization of the oceanic basement. Attempts to find the vertical extent and magnetic characteristics of the source layer for the linear pattern of magnetic anomalies in ocean basins are made both through magnetic measurements on materials dredged and drilled from the ocean floor, and through modeling and inversion of the magnetic anomalies. Although considerable effort has been devoted to this problem in recent years, results of the two approaches remained significantly different.

Anomaly modeling and inversion techniques (Talwani et al., 1971; Atwater and Mudie, 1973; Sclater and Klitgord, 1973) suggest magnetization intensities of 7.5 to 12.5 × 10^{-3} emu/cm³ and a uniformly magnetized layer about 500 meters thick, assuming dipolar directions. In contrast, analyses of recovered samples (Lowrie, 1974; Ryall et al., 1977) indicate magnetization intensities of about 4 × 10^{-3} emu/cm³ which, in turn, would require a 1- to 2-km thick magnetized layer. Former DSDP studies have shown that at least in places, the effective net magnetization may be reduced considerably due to a number of factors such as the occurrence of polarity reversals, extended sections of anomalously shallow inclinations, and interbedded effectively non-magnetic sediments, rubble, or breccia zones.

To determine the net remanent magnetization intensity of the basement section encountered, we applied a similar procedure as proposed by Ryall et al. (1977). Mean vectorial inclinations, I_u, and intensities, J_u, are first calculated for each magnetic unit using the following formulas:

$$\bar{I}_u = \tan^{-1}\frac{(\Sigma J_{NRM}\ \sin I_{NRM})}{(\Sigma J_{NRM}\ \cos I_{NRM})}$$

and

$$\bar{J}_u = \frac{[(\Sigma J_{NRM}\cos I_{NRM})^2 + (\Sigma J_{NRM}\sin I_{NRM})^2]^{1/2}}{N}$$

where N is the number of samples included in the mean.

The azimuth is assumed to be oriented uniformly to the south. For the analogous calculation of an overall vectorial mean on the basis of magnetic units, the $\bar{J}_u$ values are weighted for proportions of effectively nonmagnetic materials. This average further allows for the relative thickness of the different units. The results are listed in Table 3.

A further point of interest would be to consider the *in situ* induced magnetization which the rocks have acquired since the beginning of the Brunhes normal polarity epoch. With an average weighted initial susceptibility and an ambient field intensity of 0.46 Oe, we can calculate a mean instantaneous induced magnetization of 0.345 × 10^{-3} emu/cm³ in Hole 417A and of 0.745 × 10^{-3} emu/cm³ in Hole 417D. However, as shown by Plessard and Prévot (1977) on submarine basalts, this induced magnetization increases considerably with time (magnetic aftereffect), so that the extrapolated *in situ* viscous induced magnetization, VIM, acquired during the Brunhes normal polarity epoch would be several times higher than the instantaneous induced magnetization. But, because the effect of the VIM would only be to shift the zero line of the magnetic profiles toward more positive values without appreciable changing their contours, taking into account the contribution of the *in situ* VIM to the magnetic anomaly pattern is not necessarily required. Since the averages of the NRM intensities (7.32 × 10^{-3} emu/cm³ in Hole 417A and 9.20 × 10^{-3} emu/cm³ in Hole 417D) are similar to those predicted by modeling and inversion techniques, the source of the magnetic anomaly at Site 417 appears to lie in the upper 1000 meters of Layer 2.

It should be noted, however, that these values are definitely higher than any previous DSDP results. With regard to the magnetic anomaly lineation in ocean basins, the relatively old Cretaceous crust investigated here yielded rather excellent agreement with the general concept developed by anomaly modeling and inversion techniques, which up to now could never be achieved by basement drilling in younger Tertiary areas in the Atlantic.

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