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Oceanic Basalt Magnetic Properties and the Vine and Matthews Hypothesis*

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Abstract. Königsberger ratios of DSDP basalts were rather low (mean value around 7) but were usually high enough to justify interpreting oceanic anomalies with a remanent magnetization model. Natural remanent magnetizations were considerably lower than in dredged basalts but were strong enough to account for amplitudes of oceanic magnetic anomalies. Both stable and unstable remanent types were encountered. The observed stable inclinations showed a large scatter when compared to expected inclinations, largely due to non-cancellation of secular variation. All the basalts were categorized in deuteric oxidation Class I by opaque petrology observations. Extensive maghemitization, inferred from thermomagnetic analyses, may explain the low NRM intensities. Unstable specimens easily acquired large viscous remanent magnetizations, in some cases as large as the NRM. The basalt magnetic properties were in general accord with the expectations of the Vine and Matthews hypothesis.

Key words: DSDP Basalt — Paleomagnetism — Magnetic Properties — Viscous Remanent Magnetization — Rock Magnetism.

Introduction

The Vine and Matthews hypothesis (1963) requires certain magnetic characteristics of the basalts which form Layer 2 of the oceanic crust. Prior to the formulation of this hypothesis only a relatively limited amount of information about oceanic basalt magnetic properties was available from dredged samples and the Mohole project (Matthews, 1961; Cox and Doell, 1962; Ade-Hall, 1964). Since then information has been obtained from many more unoriented dredge haul samples (Vogt and Ostenso, 1966; Opdyke and Hekinian, 1967; Luyendyk and Melson, 1967; Carmichael, 1970; Park and Irving, 1970; Irving, Robertson and Aumento, 1970; de Boer, Schilling and Krause, 1970; Schaeffer and Schwartz, 1970; Watkins and Paster, 1971; Fox and Opdyke, 1973) and also from a number of Deep Sea Drilling Project (DSDP) samples (Lowrie and Opdyke, 1972; Lowrie and Opdyke, 1973; Lowrie and Hayes in press; Lowrie, Løvlie and Opdyke,

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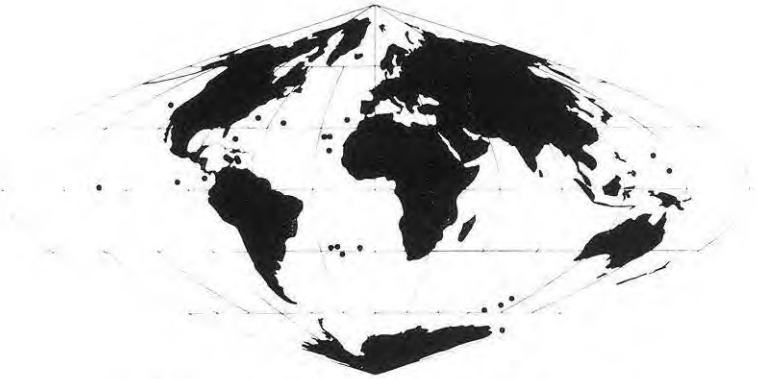

Fig. 1. Locations of the 26 DSDP sites of this study

1973(a), 1973(b)) and other drilled samples (Brooke, Irving and Park, 1970; Ade-Hall, Aumento, Brooke, McKeown, Ryall and Gerstein, 1973). The DSDP basalt collection has certain advantages over the dredged samples; the samples are semi-oriented, in that the vertical direction is known relative to each sample, which permits the inclination of remanent magnetization to be measured. Also, deep sea drilling has been carried out in many deep ocean basins, whereas dredged samples have been obtained only from restricted regions, such as seamounts, fracture zones and ridge crests. The fairly extensive DSDP and dredged collections now allow comparison of the observed magnetic properties with the requirements of the Vine and Matthews hypothesis.

The primary basalt characteristics required for validity of the hypothesis are: (a) the basalt magnetization should be dominated by the remanent component, that is the Königsberger ratio (Q_n) should be much greater than 1.0, (b) the remanent intensity (J_r) should be strong enough to account for the amplitude of the observed anomalies, and (c) the polarity of the remanence should correspond to the sign of the anomaly in which the sample was taken. These in turn require that the remanence should be stable enough to preserve the original magnetization direction over geologic periods of time and through subsequent polarity changes of the geomagnetic field. The magnetic inclinations should also agree with those expected after appropriate plate reconstructions have been made. This leads to the subsidiary but important requirement that significant secondary magnetization components which might alter the original remanent magnetization should not be present.

DSDP basalts from a representatively large number of sites have now been studied. The magnetic properties of basalts from 26 DSDP sites are described here. The site locations (Fig. 1, Table 1) are fairly well distributed

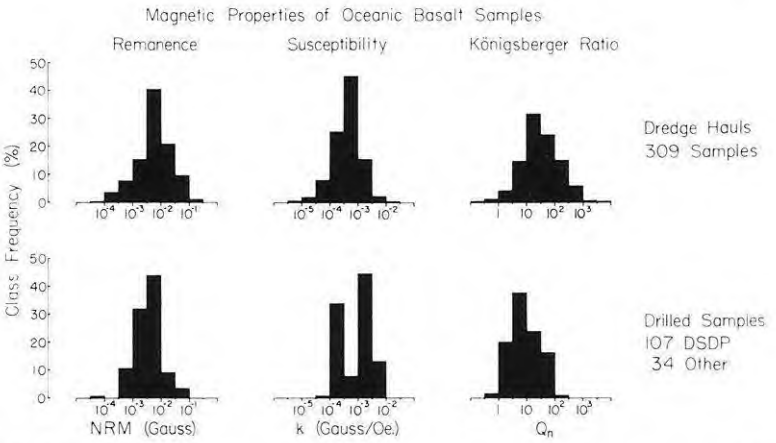

Fig. 2. Histograms of natural remanent magnetization intensity, susceptibility and Königsberger ratio in dredged and drilled oceanic basalt samples

among the world's oceans. There are notable gaps in the Indian Ocean and Central and South Pacific Oceans. However the latitudinal distribution of the 26 sites is good.

The distribution of samples among the sites is not entirely adequate (Table 1). Several samples were obtained from most sites, but some sites are represented by only a single sample. Three or four partially oriented small specimens were obtained and their magnetic properties averaged to give representative values for each sample.

Remanent Magnetic Properties

Histograms of the natural remanent magnetization (NRM), the susceptibility (k) and the Königsberger ratio (Q_n) of 309 dredged samples and 141 drilled samples (107 from DSDP sites) are shown in Fig. 2. For both collections the NRM intensities cover a wide range of almost three orders of magnitude. The (geometric) mean NRM intensity of the dredged basalts is almost double that of the DSDP basalts (Table 2). Although NRM intensity may occasionally vary by an order of magnitude within a given site, most of the variation expressed in the histograms is between-site variation. The mean susceptibility of the dredged basalts is less than half that of the DSDP basalts. Within-site variation is generally not as large as for the NRM intensity. Again, however, there is considerable between-site variation.

The differences in these parameters between the two collections are probably real and reflect differences in the sampling distributions. The distribution of dredge haul sites is naturally biassed to regions where basement

Table 1. DSDP site locations, ages, number of samples and specimens, and basalt descriptions from Initial Reports

Site	Location		Age (my)	Number of Samples	Number of Specimens	Flow or Sill	Basalt Description
10	32.6°N	52.3°W	Miocene	6	20	Sill	Fresh, ophitic, vesicular
14	28.3°S	21.0°W	Eocene (39)	3	9	Sill	Weathered, cryptocrystalline to fresh, fine-grained
15	30.9°S	18.0°W	Miocene (21)	1	3	Flow	Fresh, aphanitic
18	28.0°S	8.0°W	Oligocene (25)	2	7	Flow	Weathered, aphanitic
19	28.5°S	23.7°W	Eocene (53)	4	14	Flow	Weathered, aphanitic, vesicular
36	41.0°N	130.1°W	Miocene (8–13)	3	7	Flow	Fresh, glassy
54	15.6°N	140.3°E	Miocene	3	6	Flow	Hydrothermally altered, variolitic
57	8.7°N	143.5°E	Oligocene	7	15	Flow	Fresh, doleritic
77	0.5°N	133.2°W	Oligocene (36)	1	8	Sill	Fresh, fine-grained, vesicular
83	4.0°N	95.7°W	Miocene (11)	1	3	Sill	Fresh, fine-grained
84	5.8°N	82.9°W	Miocene (7–9)	1	9	Sill	Fresh, fine-grained

100	24.7°N	73.8°W	Oxfordian (150)	9	9	Flow	Fresh, fine-grained
105	34.9°N	69.2°W	Oxfordian	14	14	Flow	Altered, fine-grained
136	34.2°N	16.3°W	Aptian (108)	4	6	Flow	Altered, subophitic to intergranular diabase
137	25.9°N	27.1°W	Albian (101)	3	4	Flow	Altered, brecciated with glassy groundmass
138	25.9°N	25.6°W	Cenomanian (105–110)	6	8	Sill	Altered at top, coarse-grained
141	19.4°N	24.0°W	Miocene	5	8	—	Altered (serpentinized)
146	15.1°N	69.4°W	Turonian (87–91)	12	12	Flow	Fresh, doleritic
150	14.5°N	69.4°W	Coniacian (84–87)	3	3	Sill	Fresh, doleritic
151	15.0°N	73.4°W	Santonian (80–84)	2	2	Flow	Fresh, fine-grained, vesicular
152	15.9°N	74.6°W	Campanian (72–80)	3	3	Flow	Weathered, vesicular
153	14.0°N	72.4°W	Turonian (87–91)	3	3	Sill	Fresh, fine-grained, amygdaloidal
265	53.5°S	109.9°E	Miocene (12–15)	2	8	Flow	
266	56.4°S	110.1°E	Oligocene	2	5	Flow	
267	59.3°S	104.5°E	Eocene	1	2	Sill	
274	69.0°S	173.4°E	Eocene	4	17	Flow	

Table 2. Geometric mean values, by samples and by sites, of the natural remanent magnetization (NRM) intensities, susceptibilities (k) and Königsberger ratios (Q_n) in 309 dredged basalt samples and 107 DSDP basalt samples

		Geometric Mean Values		
	Number	Natural Remanent Magnetization (10^{-3} G)	Susceptibility (10^{-3} G/oe)	Königsberger Ratio
Sample Means				
DSDP	107	2.73	1.06	6.06
Dredge-hauls	309	5.37	0.408	29.0
Site Means				
DSDP	26	2.06	0.632	7.92
Dredge-hauls	110	5.76	0.318	39.9

rocks crop out. The DSDP collection does not suffer from this restriction; coverage is more extensive areally over the ocean basins and samples often are obtained at depths from the sediment-basalt interface to several meters below it. The dredge collection probably represents younger and fresher crustal rock, and may also have finer grain sizes than the DSDP collection. This would account for the higher remanence and lower susceptibility of the dredge-hauled material.

The DSDP susceptibility distribution was bimodal. The lower mode resulted principally from unusually low susceptibilities measured in DSDP basalts from the South Atlantic Ocean (Lowrie, Løvlie and Opdyke, 1973(a)) which also had much lower than average NRM intensities.

The Königsberger ratios of the DSDP basalts were much lower than in the dredged samples (Fig. 2); the mean value for dredged basalts was five times larger than for DSDP basalts (Table 2). Nevertheless the DSDP mean value of 6—8 was sufficiently high that in most cases the remanence was the dominant magnetization component, and induced magnetization effects could be neglected However, the existence of a large number of oceanic basalt samples with Q_n close to, or less than, unity indicates the need to consider the perturbing effects of induced magnetizations on anomaly profiles in some regions.

The data show that either the common choice of Layer 2A magnetization of 0.01—0.02 Gauss in anomaly modelling (*e.g.* Herron, 1972) is too high or the magnetic properties of the oceanic basalts dredged and drilled to date represent only the surface skin of Layer 2 and are unrepresentative

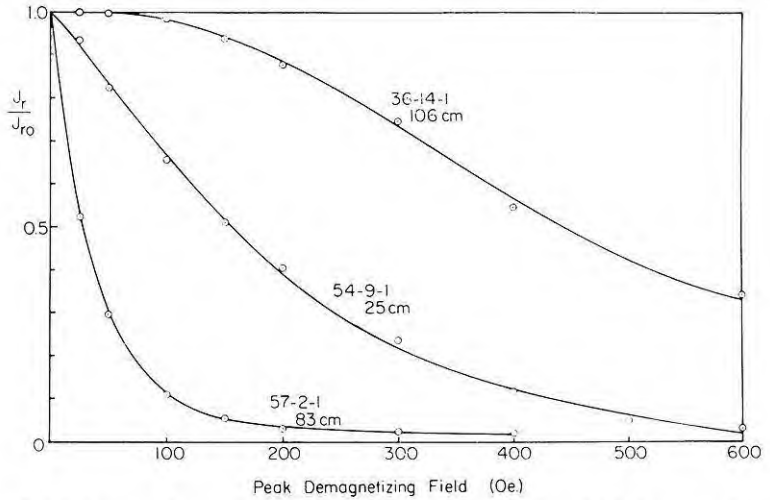

Fig. 3. Variation of remanent intensity during alternating field demagnetization of typical DSDP basalt specimens

of the whole layer. The thickness of the strongly magnetized part of Layer 2 is usually taken to be 500 m (Talwani, Windisch and Langseth, 1971), but if the results of this study are in fact representative, Layer 2A must have at least double this thickness. Resolution of this point must await the analysis of material from the deeper holes planned for future deep sea drilling.

Stability of Magnetization

Storage tests of only a few weeks showed that most, but not all, of the DSDP basalts had stable magnetizations. Detailed alternating field (AF) demagnetization was carried out on every specimen to establish its stable direction of magnetization.

AF Stability of Remanent Intensities

AF demagnetization curves for some representative specimens are shown in Fig. 3. Most specimen demagnetization curves were similar to those of the site 36 or site 54 specimens, but some revealed the presence of large components of low coercivity magnetization as in the case of the site 57 specimen. There was not much variation in magnetic hardness between specimens from the same site. Median destructive fields in the range 200–400 oe. were representative of the largest number of sites (Fig. 4). However, at many sites the median destructive field was much lower, often less than 100 oe.

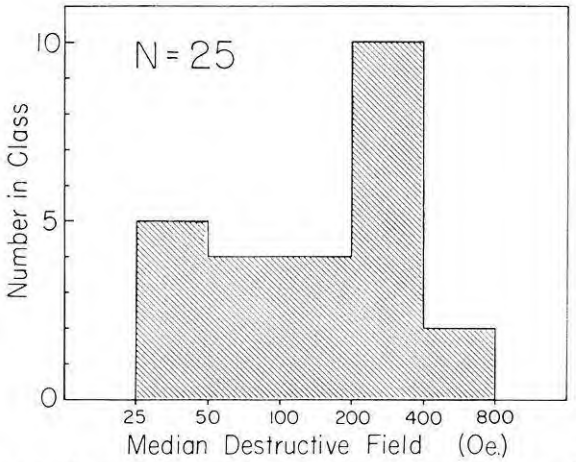

Fig. 4. Geometric mean values of median destructive field at 25 DSDP sites

AF Stability of Remanent Directions

Vector diagrams show the effects of AF demagnetization on the horizontal and vertical components of magnetization in specimens with stable and unstable remanences (Fig. 5). As the peak alternating field is progressively increased there is little variation in either declination or inclination in the specimen from site 77. The stable negative inclination of this site is well defined. The unstable magnetization of the site 57 specimen shows large directional changes as the initial soft component is removed. The stable inclination for this site was only defined for fields between 100 and 250 oe; after treatment in 300 oe. or higher the magnetization became so unstable that it changed even during the time required to make a measurement. It was often not possible to measure quite strongly but unstably magnetized specimens with a 105 Hz spinner magnetometer due to rapid growth or decay of the signals, yet the same unstable magnetizations could be measured satisfactorily with a 5 Hz spinner magnetometer. The large soft component of magnetization apparently could be influenced easily by the stresses involved in spinning them at 105 Hz, which amount to around 444 g at a radius of 1 cm from the rotation axis.

It was possible to define without difficulty a stable direction for specimens whose median destructive fields were greater than 200 oe. For less stable specimens the direction taken was the average of the fairly closely grouped directions in the 100—200 oe. AF demagnetization range. A mean inclination for each site was found by averaging the sample inclinations, which in turn represented the averages of individual specimen inclinations. Each mean was corrected to compensate for the absence of declinations (Briden and Ward, 1966).

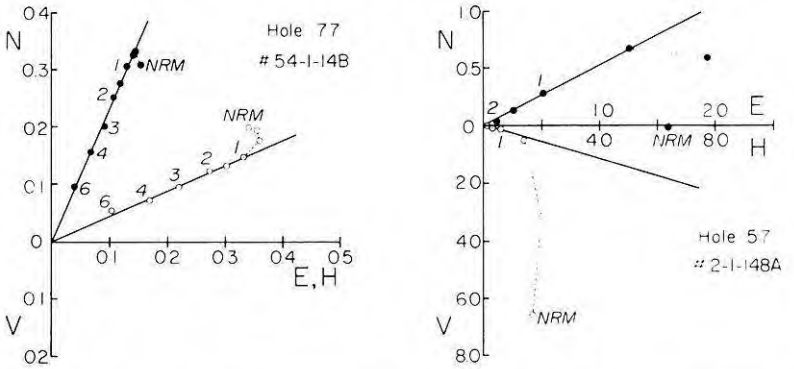

Fig. 5. Vector diagrams representing AF demagnetization of stable and unstable remanences in DSDP basalts

Site Mean Remanent Inclinations

At many sites one or more samples had opposite polarity to the others from the site. This was caused by orientation error resulting from the difficulty of unambiguously orienting the core samples on board ship. It presented a serious problem at sites where only one or two samples were obtained. The polarities observed in the basalts agreed with the anomalies at each site where they were known. For further analysis of the site inclinations, all reversed site mean inclinations were converted to their normal equivalents.

The expected inclinations at the sites were deduced from the following sources. For Legs 2, 3, 11 and 14 in the Atlantic Ocean the global plate reconstructions of Phillips and Forsyth (1972), which incorporate paleomagnetic data from Africa, Europe and North and South America, were used to determine the site paleolatitude at the time of its formation. From this the axial dipole field (ADF) inclination at the site was computed. The ADF inclinations of Leg 15 specimens (Lowrie and Opdyke, 1973) were computed from the Phillips and Forsyth model and also from Cretaceous paleomagnetic data of Creer (1970), Watkins and Cambray (1970), and MacDonald and Opdyke (1972).

Good estimates of the expected inclinations for sites from Legs 5, 6 and 9 in the Pacific Ocean are not possible because of the scarcity of relevant high quality terrestrial paleomagnetic data for the ages involved (Oligocene to Miocene). Tertiary North Pacific pole positions were used for sites 36, 57, and 77; N. American Miocene pole positions for sites 83 and 84, and Taiwan and Ryuku poles for site 54 in the Philippine Sea (McElhinny, 1973).

Paleomagnetic virtual pole positions from the Antarctic continent (McElhinny, 1973) do not differ appreciably from the present pole of

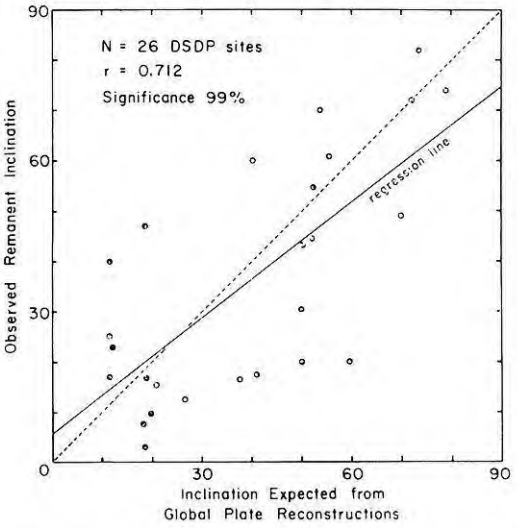

Fig. 6. Comparison of observed site mean remanent inclinations with their expected values

rotation. The formation of the South Indian Ocean is assumed to have taken place by migration of Australia away from a fixed Antarctic plate (Weissel and Hayes, 1972). Expected mean inclinations for Leg 28 sites are therefore assumed to be the ADF inclinations at the sites.

A plot of the site mean remanent inclinations observed in the basalts from the 26 sites of this study against the values expected from the above calculations shows a large amount of scatter (Fig. 6). The correlation (coefficient $r = 0.715$) is moderately strong and is significant. It is also superior to correlations of the observed inclinations with the present ADF site inclinations ($r = 0.625$) and the 1965.0 IRF ($r = 0.525$). In spite of the observed scatter there is statistical agreement between the observed site mean inclinations of DSDP basalts and the inclinations expected from global plate considerations.

The deviation between observed and expected inclinations at any given site varied from 0° at site 266 to as much as 40° at site 36; the mean (absolute) deviation was 14°. Sixteen remanent inclinations were shallower than expected, nine were steeper while one was in exact agreement. The regression line consequently has a lower slope than the line of perfect agreement (Fig. 6). The deviation may result from errors associated with both the expected and observed inclinations. For example, the computations of expected inclination are inexact, involving several stages of approximation. Either the expected inclination is computed directly from the

average of a small quantity of relevant paleomagnetic data, or it results from best-fit paleolatitudes determined by determining average VGP locations and combining these with plate rotations about suitable rotation axes.

There are several possible sources of error in the observed remanent inclinations. Sampling errors in this type of study are greater than in a normal paleomagnetic study largely as a result of inexact determination of the true vertical direction for each sample of core. Other factors which might disturb the observed remanence values are post-magnetization tilting of crustal blocks and the effects of secondary magnetizations, which will be discussed further below.

It is probable, however, that the discrepancies can largely be accounted for by secular variation effects. Due to the rapid cooling undergone by oceanic basalts, many of which have chilled outer crusts, their remanent magnetizations will be acquired in the direction of the ambient geomagnetic field, without averaging to zero the effects of secular variation as might be the case in more slowly cooling igneous bodies. Creer (1962) has shown that within-site dispersions as large as the inclination deviations observed here can result from secular variation of the dipole and non-dipole fields.

Magnetic Mineralogy

Opaque Petrology

Polished sections of several specimens were made for reflected light study using oil immersion lenses giving magnifications up to 1100 diameters.

Opaque minerals were identified by their colors, anisotropy and birefringence. Observations made on Atlantic and Pacific Ocean specimens (Lowrie, Løvlie and Opdyke, 1973(a), 1973(b)) are summarized in Table 3.

The opaque minerals consisted of homogeneous titanomagnetites (or titanomaghemites) with lesser amounts of ilmenite and sulphides (such as pyrrhotite). The titanomagnetite grains were generally finer than 10μ. Some specimens contained coarser grains which on close optical examination showed whitened areas along cracks and on their rims indicative of maghemitization. Most specimen grain sizes were finer than 10μ, and contained a large number of visible grains finer than 1μ in size. It is distinctly likely that an even finer submicroscopic fraction, below the resolution of optical techniques, exists in these specimens. Electron microscope studies have shown large populations of discrete titanomagnetite grains much finer than 0.1μ in diameter in oceanic basalts from the mid-Atlantic ridge (Evans and Wayman, 1972).

Table 3. Opaque petrology descriptions of basalts from Atlantic Ocean and North Pacific Ocean DSDP sites (from Lowrie, Løvlie and Opdyke, 1973(a), 1973(b)).

Site	Description of grains			Volume % Ore Minerals	Degree of Maghemitization
	Titanomagnetites	Ilmenites	Other ore Minerals		
10	Euhedral, 1μ—5μ; skeletal, ($10\mu \times 30\mu$) Large grains non-uniformly magnetized	Euhedral and skeletal, $\sim (3\mu \times 50\mu)$	Some fine sulfides ($<2\mu$) Some chromite	$1^1/_2$—$2^1/_2$%	Moderate (10% by volume)
14	Very fine, 1μ—3μ homogeneous grains	None identified	Some sulfides, some chromite	$2^1/_2$—3%	None observed
15	Skeletal, 2μ—6μ Largest grains non-uniformly magnetized	A few euhedral grains $\sim (3\mu \times 25\mu)$	Sulfides (<5% of total ore minerals)	3%	Slight; on largest grains
18	Some large euhedral grains, most very fine ($<1\mu$)	A few skeletal grains, $\sim (10\mu \times 10\mu)$	A few sulfides	1%	Slight; on largest grains
19	A few large skeletal grains ($\sim 10\mu$), non-uniformly magnetized 60%—95% are $<5\mu$	None identified	None identified	1%	None observed
36	Fine, skeletal, $<5\mu$; uniformly magnetized	Some euhedral grains; rods $\sim (5\mu \times 20\mu)$	Some sulfides, ($<1\mu$)	1—2%	None observed
54	Skeletal, ($<5\mu$) and skeletal, 10μ—60μ	A few rods with hematite rims	Some sulfides	2%	None observed
57	Large, skeletal; 50% are $<10\mu$; 50% are 10μ—200μ	Large rods, often with magnetite	Pyrrhotite, $<1\mu$ to 10μ (10% of total ore)	3—6%	None observed
77	Anhedral, $<5\mu$; some euhedral and anhedral grains, 10μ—40μ	Rods, ($1\mu \times 10\mu$) to ($5\mu \times 40\mu$)	Relics of chromite	3—6%	Slight; on largest grains
83	Anhedral and skeletal $<10\mu$ and 40μ—60μ	Needles, $<5\mu$ thick	Sulfides ($<10\mu$)	2—5%	On largest grains
84	Fine skeletal and anhedral grains, $<5\mu$ Color suggests no alteration	None identified	Sulfides, $<10\mu$ to 20μ (10% of total ore). Chromite relics	1—5%	None observed

The rate at which low-temperature oxidation of the original magnetic mineralogy takes place depends upon the specific surface area and the presence of lattice imperfections (Colombo, Fagherazzi, Gazzarini, Lanzavecchia, and Sironi, 1968). Consequently, the finest grains in an assemblage will be affected by low-temperature oxidation more seriously than coarser grains, and opaque petrological observations made on relatively coarse grains may be inapplicable to finer grains, particularly those below the limit of optical resolution. It is probable that optical techniques are inadequate to describe the degree of maghemitization of fine-grained oceanic basalts. Bulk thermomagnetic analysis provides a suitable alternative technique.

Thermomagnetic Analysis

By rapidly heating basalt specimens in a vacuum to temperatures in excess of 600 °C it has been shown possible to distinguish titanomagnetite from titanomaghemite as the dominant ferrimagnetic mineral (Ozima and Ozima, 1971). When thermomagnetic analysis is carried out in air the same unambiguous interpretation is not possible, but it is possible by using properties of the parent and daughter products of the analysis to identify titanomaghemite (Lowrie, Løvlie and Opdyke, 1973(b)).

The thermomagnetic curve in air of oceanic basalt containing either titanomagnetite or titanomaghemite is irreversible (Ozima and Ozima, 1971). A typical example is shown in Fig. 7(a). The initial magnetization (J_i), produced in a strong field of 3000 oe. or more, decreases on heating rapidly past its initial Curie temperature, which is usually in the range 100—400 °C. When the specimen is heated beyond this stage the original mineral separates into a Ti-rich phase (hemo-ilmenite) and a Ti-poor phase close in composition to magnetite. On cooling from high temperature the stronger magnetization of this magnetite appears at a high Curie temperature, and increases to its room temperature value (J_f). This is greater than the initial value, provided the specimen is not maintained too long at or above 600 °C. This can cause oxidation of the magnetite product, and results in J_f being less than J_i.

Strong-field thermomagnetic curves were measured in air with three sets of Curie balance; a horizontal motion type (University of Bergen), and automatically recording, vertical motion types corrected for specimen weight loss (University of Pittsburgh, and Lamont-Doherty Geological Observatory). Magnetizations were uncalibrated; temperature measurement accuracy was 5 °C.

For titanomagnetites ($xFe_2TiO_4 \cdot (1-x)Fe_3O_4$) the composition parameter, x, which defines the ulvospinel proportion in the titanomagnetite, determines the initial Curie temperature. After phase separation the mag-

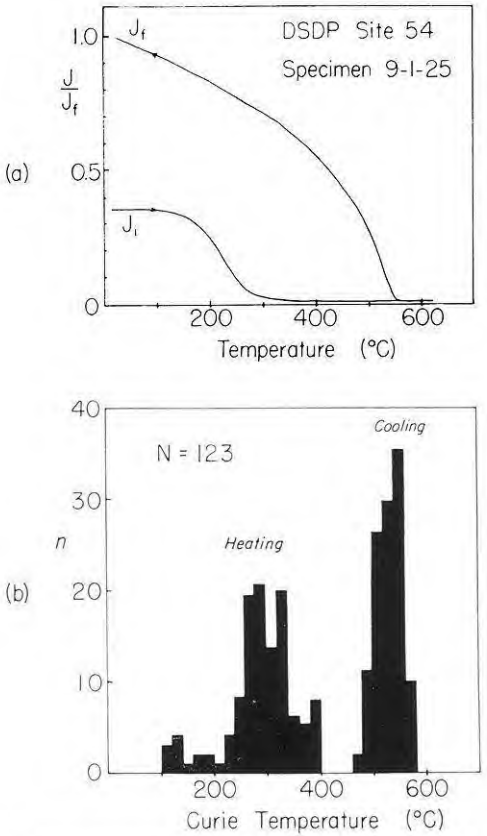

Fig. 7 a. Typical thermomagnetic curve in a DSDP basalt. b Curie temperatures of the initial and final magnetic minerals from thermomagnetic analyses of 123 DSDP basalt specimens

netite end-member should have an x-value of around 0.05 (Kawai, Kume and Sasajima: in Nagata, 1962). The mean of the higher Curie temperatures measured in 123 thermomagnetic analyses of DSDP basalts (Fig. 7(b)) was 530 °C, corresponding to a mean $x = 0.085$ (Nagata, 1962). The initial Curie temperatures of these specimens were mainly between 220 °C and 400 °C, with a small group lower than 200 °C corresponding to specimens from site 57.

The room-temperature strong field magnetization, J_f, of the near-magnetite product mineral may be computed according to its known dependence on x (Nagata, 1962). The magnetization of the initial titanomagnetite, J_i, may then be expressed in terms of the final mineral by using the measured ratio (J_i/J_f) from the thermomagnetic curves. The titano-

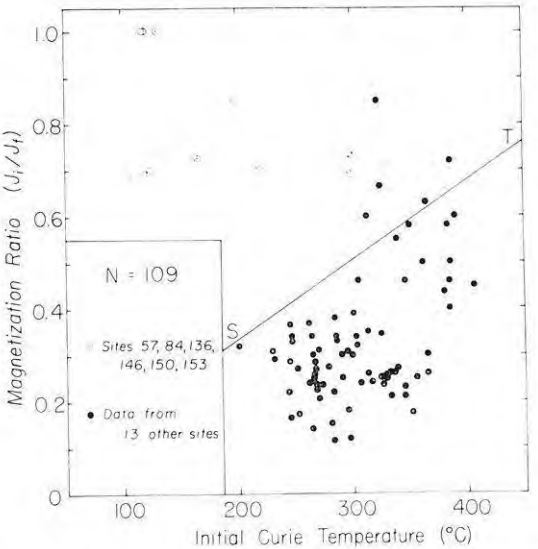

Fig. 8. Ratios of initial to final magnetizations and the initial Curie temperatures in thermomagnetic analyses of 109 DSDP basalt specimens

magnetite magnetization J_i and its initial Curie temperature are related by the compositional parameter x. It is therefore possible to determine the exact relationship between (J_i/J_f) and initial Curie temperature for a stoichiometric titanomagnetite. For the range of x observed in oceanic basalts this is the straight line S—T in Fig. 8. The magnetization ratios, J_i/J_f, observed in 109 DSDP specimens (50 samples; 19 sites) are plotted against the initial Curie temperature of the specimen. Thermomagnetic analyses in which the magnetite product was apparently oxidized have been excluded from these considerations.

There are several reasons why the points in Fig. 8 do not lie on the line S—T. Firstly, the volume of the product magnetite is likely to be less than that of the initial titanomagnetite, as a Ti-rich phase also exsolves. Because of this volume change the observed magnetization ratio should be greater than the ratio of the spontaneous magnetizations; stoichiometric titanomagnetites should be represented by points above the line S—T. Secondly, partial high temperature oxidation of the magnetite formed will reduce J_f, and will give a point above the line. This will also happen if incomplete phase separation takes place. Each of these effects displaces a point above the line S—T in Fig. 8.

If the initial titanomagnetite is non-stoichiometric, the point will fall below the line. Maghemitization causes elevation of the Curie temperature and reduction of the spontaneous magnetization (Ade-Hall, Palmer and

Hubbard, 1971; Readman and O'Reilly, 1972). Each of these displaces a point below the line S—T. However, if the magnetite product is oxidized at high temperature, J_i/J_f will be increased and the point may fall in the upper field. It is, therefore, not possible to discuss without ambiguity the original condition of the titanomagnetites from sites 57, 84, 136, 146, 150 and 153 (Fig. 8) all of which are represented by points in the upper field.

It is quite apparent from these data, however, that oceanic basalts from a large majority of the 19 DSDP sites studied are maghemitized. Points from 13 sites fall almost entirely in the lower field, with only a small number near or above the separating line. If volumetric change could be taken into account, the position of line S—T would be even higher on the figure.

It may be concluded from these thermomagnetic studies that maghemitization, whether resulting from ocean-floor weathering (Marshall and Cox, 1972) or regional hydrothermal alteration (Ade-Hall, Palmer and Hubbard, 1971), may have altered considerably the original magnetic properties of the basalts. It is unlikely, even if chemical remanent magnetization (CRM) is associated with the oxidation, that the original directions will have been appreciably altered (Marshall and Cox, 1972), although this may possibly contribute to the observed discrepancies between observed and expected inclinations (Fig. 6). The reduction in remanent intensity which accompanies the maghemitization (Johnson and Merrill, 1973) has been proposed as an explanation for the observed decrease of magnetic anomaly amplitude with distance from the axis of a mid-ocean ridge (Irving, 1970). The proposal is supported by the results of this study.

Viscous Remanent Magnetization

Acquisition of VRM

Although most DSDP basalt specimens were found to be quite stable, specimens from several sites showed significant changes in direction during storage tests in the geomagnetic field, and had median destructive fields lower than 100 oe. The large soft components in these specimens made them very susceptible to the acquisition of viscous remanent magnetization (VRM).

VRM was given to many specimens with median destructive fields lower than 150 oe. The specimens were first demagnetized, their remanences were measured, and they were placed in a uniform constant field for up to 3 months. At repeated intervals the remanent magnetization was measured with a spinner magnetometer, each observation time (less than 5 minutes) being much shorter than the time of acquisition, t. The increase in magnetization over the $t=0$ value represented the acquired VRM. Typical VRM acquisition curves are shown in Fig. 9.

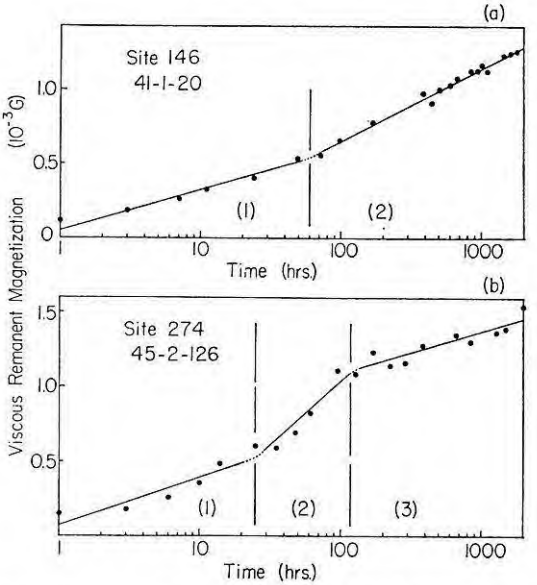

Fig. 9. a Two-stage and b three-stage acquisition of viscous remanent magnetization

The acquired VRM at time t can be expressed

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

where $S(t)$ is the magnetic viscosity coefficient.

Two general types of acquisition curve have been observed in DSDP basalts (Fig. 9). The first, and most commonly observed, consists of two stages in each of which the magnetic viscosity coefficient is a constant. The second type shows three-stage development of VRM. The magnetic viscosity coefficients in the first and third stages (S_1 and S_3, respectively) are considerably smaller than in the second stage (S_2; Table 4). It is possible that the two-stage type might develop into a three-stage type if the observations were continued beyond the three month duration of each of these experiments.

Origin of the VRM

Logarithmic development of VRM may result from either a multidomain process or one involving fine particles whose size places them close to the boundary between superparamagnetic and single domain behavior at room temperature. This fine-grain VRM would necessarily involve a narrow range of particle sizes with appropriate magnetic relaxation times.

Table 4. Acquisition of viscous remanent magnetization in DSDP basalts. Site 57 specimens acquired VRM in 0.53 oe. field; all other acquisitions were in 1.0 oe. field. VRM_{1000} is the VRM acquired in 1000 hours; S_1, S_2 and S_3 are the measured magnetic viscosity coefficients in three stages of the acquisition (see text). NRM intensity, susceptibility and median destructive field (m.d.f.) represent the initial remanent properties of the specimens

Site	Specimen	Natural Remanent Magnetization (10^{-3} G)	Susceptibility (10^{-3} G/oe)	Median Destructive Field (oe)	S_1 (10^{-3} G)	S_2 (10^{-3} G)	S_3 (10^{-3} G)	VRM_{1000} (10^{-3} G)	$\frac{VRM_{1000}}{NRM}$ (%)
57	2–1– 83	4.20	1.93	28	0.19	0.32	—	0.83	20
	2–1–113	2.43	2.35	47	0.14	0.39	—	0.92	38
	2–1–148A	6.85	2.05	29	0.15	0.32	—	0.79	12
	2–1–148C	3.15	1.96	102	0.19	0.28	—	0.75	24
	2–2– 48	6.85	1.58	35	0.13	0.30	—	0.73	11
	2–2– 60	3.32	1.42	49	0.09	0.35	—	0.79	24
	2–2–149	2.81	2.25	29	0.15	0.39	—	0.93	33
	3–1– 12	2.57	1.71	34	0.17	0.35	—	0.87	34
100	11–1– 20	16.04	3.76	74	0.43	0.72	0.50	1.83	11
	11–1–100	23.69	3.16	94	—	0.51	—	1.51	6
	11–1–125	6.18	3.59	61	0.54	0.95	0.62	2.49	40
105	42–2– 5	3.53	1.46	156	0.16	0.51	0.11	0.68	19
	42–2– 38	1.07	2.84	84	0.36	0.66	0.19	1.34	124
	42–2– 71	3.09	2.40	120	0.25	0.63	0.23	1.18	38
	42–2–105	3.21	2.17	129	0.21	0.71	0.24	0.98	31
	42–2–121	1.43	2.59	79	0.39	1.13	0.36	1.55	108
	42–2–147	3.27	1.87	144	0.26	0.59	0.16	0.91	28
136	9–1– 4	15.20	3.47	15	0.16	0.44	—	1.07	7
	9–1– 14	8.06	2.86	48	0.14	0.49	—	0.99	123
	9–1– 34	8.86	3.53	41	0.20	0.84	—	1.84	21

137	17–1– 65	2.43	0.81	89	0.04	0.05	—	0.14	6
138	7–1– 68	3.60	3.07	92	0.08	0.13	—	0.38	11
	7–1– 79	3.17	2.71	105	0.04	0.12	—	0.26	8
	7–1–120	0.49	0.68	66	0.02	0.04	—	0.10	21
	7–1–145	2.14	2.69	34	0.12	0.22	—	0.56	26
141	10–1– 97	4.14	0.92	141	0.02	0.06	—	0.15	4
	10–1– 99	3.17	1.02	139	0.04	0.08	—	0.18	6
	10–1–110	1.63	1.09	113	0.05	0.10	—	0.20	12
146	41–1– 20	2.65	2.35	41	0.28	0.49	—	1.13	43
	41–2– 2	1.21	2.91	36	0.27	0.37	—	1.13	93
	42–2– 70	2.81	2.38	56	0.42	0.71	—	1.75	62
	42–3–148	2.78	2.48	35	0.42	0.76	—	1.72	62
	43–2–123	5.93	2.37	34	0.27	0.54	—	1.39	23
	43–3– 73	3.79	2.53	42	0.47	0.71	—	1.75	46
	43–4–130	4.98	2.47	39	0.49	0.67	—	1.76	35
150	11–2– 65	3.92	1.83	50	0.23	0.66	—	1.39	36
	12–1–132	6.64	1.98	65	0.32	0.66	—	1.40	21
	12–2–125	4.69	2.06	64	0.37	0.66	—	1.46	31
151	14–1–118	5.84	1.59	110	0.08	0.14	—	0.56	10
	15–1–148	1.96	1.36	117	0.08	0.15	—	0.39	20
152	23–1–112	2.38	3.54	102	0.17	0.34	—	0.75	31
	24–1– 68	1.68	3.33	127	0.13	0.33	—	0.58	35
	24–2– 75	8.32	3.46	96	0.12	0.29	—	0.57	7
153	19–1–118	8.81	3.45	41	0.33	0.76	—	1.53	17
	20–1–147	5.88	3.28	52	0.27	0.70	—	1.39	24
	20–2– 82	3.52	3.02	40	0.33	0.72	—	1.55	44
274	44–1– cc	2.74	1.45	81	0.21	0.56	0.18	1.32	48
	44–3– cc	2.22	1.54	61	0.23	0.86	0.18	1.78	84
	45–1– cc	12.33	1.57	98	0.07	0.44	0.08	0.94	8
	45–2– 2	12.19	1.27	115	0.21	0.63	0.26	1.37	11

Because of the relatively large magnetic moments associated with the grains, fine particle VRM should be stronger than multidomain VRM acquired under equivalent conditions (Dunlop, 1973).

The close similarity between the magnetic coefficients S_1 and S_3 suggests that they represent the same process. Stage 1 VRM (and stage 3, when present) may represent multidomain behavior. However, true multidomain behavior in pure magnetite only exists in particles larger than 17 μ in size (Parry, 1965). In titanomagnetites or titanomaghemites the critical grain size is even larger. Most titanomagnetite grains observed in polished sections of these basalts (Table 3) are much finer than this so true multidomain behavior is unlikely. Possibly the VRM is associated with pseudo-single domain particles (Stacey, 1962) which should be common in the range of opaque mineral grain sizes observed in oceanic basalts.

Superposed on this pseudo-single domain or multidomain VRM is the stage 2 process, which is not activated until after a threshold interval of 10—50 hours. This may be associated with fine particles between single domain and superparamagnetic sizes. The superparamagnetic (relaxation time $< 10^2$ sec) to single domain threshold grain size is 0.052 μm in titanomagnetite ($x = 0.4$) and 0.108 μm if it is non-stoichiometric (Readman and O'Reilly, 1972). Development of a superparamagnetic fraction (defined by relaxation times shorter than the unusually large but geologically reasonable limit of 1000 years) has been shown to be possible in oceanic basalts as a result of maghemitization (Butler, 1973) Because of the known fine grain size determined optically for many of these DSDP basalts and the reported presence of discrete submicroscopic titanomagnetites in oceanic basalts (Evans and Wayman, 1972) it seems likely that the stage 2 VRM acquisition is associated with a narrow range of very fine grain sizes close to the room-temperature superparamagnetic-single domain transition threshold, possessing relaxation times of the order of a few days.

Implications of VRM

The seriousness of VRM in the DSDP basalt specimens studied may be seen by comparing the intensity of VRM acquired in 1,000 hours (VRM_{1000}) in a 1 oe. field with the intensity of NRM in the same specimen (Table 4). In a few specimens this VRM_{1000} exceeded the original NRM intensities and in half of the specimens it amounted to over 30 % of the NRM; in 18 % of the specimens the VRM_{1000} was less than 10 % of the NRM intensity. Considerable variation of the fraction (VRM_{1000}/NRM) occurred among specimens from the same site.

These data were obtained only for specimens with median destructive fields below 150 oe. As yet no data have been obtained for specimens from sites with more stable remanent characteristics. However, because of their

higher median destructive fields and the general absence of significant changes during preliminary storage tests, it is unlikely that VRM could amount to more than a few percent of the NRM in such specimens. Also, most of the VRM were acquired from the demagnetized state. It is not expected that the ability to acquire VRM depends upon the state of remanence in such fine grained basalts. However, the acquisition of VRM in different remanent states, and in high m.d.f. specimens, is currently being investigated.

It may be concluded from these studies that, although VRM is probably not a significant component of the NRM of stably magnetized specimens, in low m.d.f. specimens it may amount to a large percentage of the original NRM.

The low m.d.f. sites are located primarily in regions where linear magnetic anomaly patterns are absent or poorly developed (e.g. Carribbean Sea, E. and W. Atlantic margins, Southeast Indian Ocean margin). Remagnetization of the oceanic crust by VRM acquisition would cause deterioration of any original anomaly pattern. This characteristic has been offered as an explanation of magnetic quiet zones (Lowrie, 1973). The mineralogical or textural properties that give rise to this viscous magnetic behavior are thought to result from unusual conditions during initial continental rifting (Irving, 1970).

Conclusions

The natural remanent magnetizations of most DSDP basalts from regions with well developed linear magnetic anomaly patterns were in good accord with the expectations of the Vine and Matthews hypothesis (1963). The remanence was much greater than the magnetization that could be induced in the basalts by the ambient geomagnetic field, although the Königsberger ratios were considerably lower than those measured in dredged basalts. The NRM intensities were large enough to give observed magnetic anomaly amplitudes, but the magnetic anomalies must be attributed to a thicker magnetized layer than the 500 m usually assumed in model studies.

The remanent polarities agreed with the signs of local magnetic anomalies at all sites where such survey information was available. The stable remanent inclination at individual sites commonly was appreciably different from the value expected at the site. However, in spite of the large scatter there was good statistical agreement between observed and expected inclinations when compensation was made for global plate motions. The discrepancies were attributed largely to non-cancellation of secular variation effects.

Optical petrology and thermomagnetic analyses indicated that all of the DSDP basalts studied belonged to class I of the deuteric oxidation scheme of

Wilson and Watkins (1967). Extensive maghemitization appeared to be present in basalts from a majority of the sites investigated. Although the chemical remanent magnetization associated with the maghemitization probably could not account for the inclination discrepancies, it may be the principal reason for the rather low remanences found in the DSDP samples.

Although most samples had good stability against alternating field demagnetization and in storage tests, a significant proportion had large soft components. These acquired viscous remanent magnetization so readily that large fractions of the NRM could be developed in only a few weeks in the laboratory.

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References

Ade-Hall, J.M.: The magnetic properties of some submarine oceanic lavas. Geophys. J. *9*, 85–92, 1964

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

Ade-Hall, J.M., Aumento, F., Brooke, J., McKeown, D.L., Ryall, P.J.C., Gerstein, R.: The mid-Atlantic ridge near 45°N: XII. Magnetic results from basalt drill cores from the median valley. Can. J. Earth Sci. *10*, 679–696, 1973

Briden, J.C., Ward, M.A.: Analysis of magnetic inclination in borecores. Pure Appl. Geophys. *63*, 133–152, 1966

Brooke, J., Irving, E., Park, J.K.: The mid-Atlantic ridge at 45°N: XIII. Magnetic properties of basalt bore core. Can. J. Earth Sci. *7*, 1515–1527, 1970

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

Carmichael, C.M.: The mid-Atlantic ridge near 45°N: VII. Magnetic properties and opaque mineralogy of dredged samples. Can. J. Earth Sci. *7*, 239–256, 1970

Colombo, U., Fagherazzi, G., Gazzarini, F., Lanzavecchia, G., Sironi, G.: Mechanism of low-temperature oxidation of magnetites. Nature *219*, 1036–1037, 1968

Cox, A., Doell, R.R.: Magnetic properties of the basalt in hole EM7, Mohole Project. J. Geophys. Res. *67*, 3997–4004, 1962

Creer, K.M.: The dispersion of the geomagnetic field due to secular variation and its determination for remote times from paleomagnetic data. J. Geophys. Res. *67*, 3461–3476, 1962

Creer, K.M.: A paleomagnetic survey of South American rock formations. Phil. Trans. Roy Soc. London *A267*, 457–558, 1970

de Boer, J., Schilling, J.G. and Krause, D.C.: Reykjanes ridge: implications of magnetic properties of dredged rock. Earth Planet. Sci. Lett. *9*, 55–60, 1970

Dunlop, D.J.: Theory of the magnetic viscosity of lunar rocks. Rev. Geophys. Space Phys. *11*, 855–901, 1973

Evans, M.E., Wayman, M.L.: The mid-Atlantic ridge near 45°N: XIX. An electron microscope investigation of the magnetic minerals in basalt samples Can. J. Earth Sci. *9*, 671–678, 1972

Fox, P.J., Opdyke, N.D.: Geology of the oceanic crust: Magnetic properties of oceanic rocks. J. Geophys. Res. *78*, 5139–5154, 1973

Herron, E.M.: Sea-floor spreading and the Cenozoic history of the East Central Pacific. Geol. Soc. Am. Bull. *83*, 1671–1692, 1972

Irving, E.: The mid-Atlantic ridge at 45°N: XIV. Oxidation and magnetic properties of basalt; review and discussion. Can. J. Earth Sci. *7*, 1528–1538, 1970

Irving, E., Robertson, W.A., Aumento, F.: The mid-Atlantic ridge near 45°N: VI. Remanent intensity, susceptibility and iron content. Can. J. Earth Sci. *7*, 226–238, 1970

Johnson, H.P., Merrill, R.T.: Low-temperature oxidation of a titanomagnetite and the implications for paleomagnetism. J. Geophys. Res. *78*, 4938–4949, 1973

Lowrie, W.: Viscous remanent magnetization in oceanic basalts, Nature *243*, 27–29, 1973

Lowrie, W., Hayes, D. E.: Magnetic properties of oceanic basalt samples. Initial Reports of the Deep Sea Drilling Project, vol. *28*, U.S. Government Printing Office, Wash-ington, D. C., in press

Lowrie, W., Opdyke, N.D.: Paleomagnetism of igneous samples. Initial Reports of the Deep Sea Drilling Project, vol. *14*, pp. 777–784, U.S. Government Printing Office, Washington, D.C., 1972

Lowrie, W., Opdyke, N.D.: Paleomagnetism of igneous and sedimentary samples, Initial Reports of the Deep Sea Drilling Project. vol. *15*, pp. 1017–1022 U.S. Government Printing Office, Washington, D.C., 1973

Lowrie, W., Løvlie, R., Opdyke, N.D.: The magnetic properties of Deep Sea Drilling Project basalts from the Atlantic Ocean. Earth Planet. Sci. Lett. *17*, 338–349, 1973(a)

Lowrie, W., Løvlie, R., Opdyke, N.D.: Magnetic properties of Deep Sea Drilling Project basalts from the North Pacific Ocean. J. Geophys. Res. *78*, 7647–7660, 1973(b)

Luyendyk, B.P., Melson, W.G.: Magnetic properties and petrology of rocks near the crest of the mid-Atlantic ridge. Nature *215*, 147–149, 1967

MacDonald, W.D., Opdyke, N.D.: Tectonic rotations suggested by paleomagnetic results from Northern Colombia, South America. J. Geophys. Res. *77*, 5720–5730, 1972

McElhinny, M.W.: Paleomagnetism and Plate Tectonics. 358 pp. Cambridge University Press, 1973

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

Matthews, D.H.: Lavas from an abyssal hill on the floor of the N. Atlantic ocean. Nature *190*, 158–159, 1961

Nagata. T.: Magnetic properties of ferrimagnetic minerals of Fe-Ti-O system, Proc. Benedum Symposium, pp. 69–86, Univ. Pittsburgh Press, 1962

Opdyke, N.D., Hekinian, R.: Magnetic properties of some igneous rocks from the mid-Atlantic ridge. J. Geophys. Res. *72*, 2257–2260, 1967

Ozima, M., Ozima, M.: Characteristic thermomagnetic curve in submarine basalts. J. Geophys. Res. *76*, 2051–2056, 1971

Park, J.K., Irving, E.: The mid-Atlantic ridge near 45°N: XII. Coercivity, secondary magnetization, polarity, and thermal stability of dredged samples. Can. J. Earth Sci. *7*, 1499–1514, 1970

Parry, L.G.: Magnetic properties of dispersed magnetite powders. Phil. Mag. *11*, 303–312, 1965

Phillips, J.D., Forsyth, D.: Plate tectonics, paleomagnetism and the opening of the Atlantic. Geol. Soc. Am. Bull. *83*, 1579–1600, 1972

Readman, P.W., O'Reilly, W.: Magnetic properties of oxidized (cation-deficient) titanomagnetites (Fe, Ti, □)$_3$ O$_4$. J. Geomagn. Geoelectr. *24*, 69–90, 1972

Schaeffer, R.M., Schwarz, E.J.: The mid-Atlantic ridge near 45°N: IX. Thermomagnetics of dredged samples of igneous rocks. Can. J. Earth Sci. *7*, 268–273, 1970

Stacey, F.D.: A generalized theory of thermoremanence, covering the transition from single domain to multi-domain magnetic grains. Phil. Mag. *7*, 1887–1900, 1962

Talwani, M., Windisch, C., Langseth, M.G., Jr: Reykjanes ridge crest: A detailed geophysical study. J. Geophys. Res. *76*, 473–517, 1971

Vine, F.J., Matthews, D.H.: Magnetic anomalies over oceanic ridges. Nature *199*, 947–949, 1963

Vogt, P.R., Ostenso, N.A.: Magnetic survey over the mid-Atlantic ridge between 42°N and 46°N. J. Geophys. Res. *71*, 4389–4411, 1966

Watkins, N.D., Cambray, F.W.: Paleomagnetism of Cretaceous dikes from Jamaica. Geophys. J. *212*, 163–179, 1970

Watkins, N.D., Paster, T.P.: The magnetic properties of igneous rocks from the ocean floor. Phil. Trans. Roy. Soc. London *A 268*, 507–550, 1971

Weissel, J.K., Hayes, D.E.: Magnetic anomalies in the southeast Indian Ocean, Antarctic Oceanology II, The Australian-New Zealand Sector, Antarctic Res. Ser. Vol. *19*, (editor D.E. Hayes), pp. 165–196, AGU Washington, D.C., 1972

Wilson, R.L., Watkins, N.D.: Correlation of petrology and natural magnetic polarity in Columbia plateau basalts. Geophys. J. *12*, 405–424, 1967

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