14. MAGNETIC PROPERTIES AND OXIDE PETROGRAPHY OF THE SHEETED DIKE COMPLEX IN HOLE 504B¹

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ABSTRACT

Magnetic properties measurements were performed on 47 samples drilled during Leg 111 of the Ocean Drilling Program and oxide petrography was studied in 32 samples taken at depths throughout the sheeted dike complex in Hole 504B. Integration of these data with results from previous DSDP legs shows that while natural remanent magnetization is constant with depth, magnetic susceptibility increases and median demagnetizing field and the Q ratio decrease with depth in the section. These trends appear to be a result of an increase in deuteric oxidation and a decrease in hydrothermal alteration of primary titanomagnetite with depth. A distinct change in stable magnetic inclination occurs between the extrusive basalts and the sheeted dikes and may be a result of tectonic rotation of the upper extrusive basalts.

INTRODUCTION

The study of linear marine magnetic anomalies has been fundamental to current models of plate tectonic processes. Attempts to identify the source layer of these magnetic anomalies have involved many techniques, including the inversion of marine magnetic anomaly field data, magnetic properties measurements of dredge samples and Deep Sea Drilling Project (DSDP) drill cores, and magnetic properties measurements of samples from ophiolites. These studies have resulted in a number of different models of the vertical magnetic structure of oceanic crust which fall into two general categories; those that consider a thin (500-m) extrusive layer to be the primary source of marine magnetic anomalies (Talwani et al., 1971; Atwater and Mudie, 1973; Klitgord et al., 1975; Macdonald, 1977; Johnson, 1979; Swift and Johnson, 1984) and those that include the sheeted dike complex and gabbros as important contributors to marine magnetic anomalies (Fox and Opdyke, 1973; Kent et al., 1978; Harrison, 1981; Banerjee, 1980). The choice between these two classes of models has been difficult to resolve because, until recently, our information regarding the lower crustal layers has been restricted to potentially anomalous samples from ophiolites and dredged from fracture zones.

DSDP Hole 504B, which extends over 1200 m through extrusive basalts into the sheeted dike complex, is the deepest penetration to date into oceanic basement and represents a unique opportunity to study the magnetic structure of the oceanic crust at depths below the extrusive basalts. The present study includes magnetic property measurements and oxide petrography of samples from the drill cores recovered during Ocean Drilling Project (ODP) Leg 111 and specifically addresses (1) the ability of the sheeted dike complex sampled in Hole 504B to contribute to the overlying marine magnetic anomaly and (2) the crustal formation processes that control the magnetization within the sheeted dikes. The magnetic structure of Hole 504B will be discussed in two parts, (1) results from the drill core samples recovered on ODP Leg 111 and (2) the integration of the Leg 111 results with previous DSDP studies of the upper parts of Hole 504B.

RESULTS

The results of magnetic properties measurements from Leg 111 are displayed in Table 1, and plotted against depth in Figure 1. Techniques and experimental methods are described in detail in the *Initial Reports* of the Leg 111 *Proceedings* (Becker, Sakai, et al., 1988) and are discussed in this manuscript only on a minimal level.

Intensity of Remanent Magnetization

As shown in Figure 1A, natural remanent magnetization (J_0) values of Leg 111 samples are somewhat scattered in the upper 10 m, but exhibit a small amount of variation throughout the remainder of the section. While it is possible that our results are biased because of the poor drill core recovery (<15% in the sheeted dikes), an extensive suite of geophysical logs indicates that the recovered samples are similar to the drilled, but unsampled, part of the section. We therefore feel that we are studying a suite of samples that is generally representative of the sheeted dike complex within Hole 504B. The average value of J_0 is 1.9 \times 10⁻³ emu/cm³, roughly twice that of diabase dikes from the Smartville, Troodos, and Bay of Islands ophiolites (Levi and Banerjee, 1977; Swift and Johnson, 1984; Pariso and Johnson, in press).

Magnetic Susceptibility

Magnetic susceptibility (χ_0) is plotted vs. depth in Figure 1B. Like the J₀ values, there is substantial scatter in the upper 10 m of the section, but the average χ_0 values increase from 1×10^{-3} to 2.5 $\times 10^{-3}$ cgs. Susceptibility is a function of both the grain size and concentration of magnetic minerals, and the data thus suggest that one or both of these is gradually increasing with depth.

Koenigsberger Ratio

The Koenigsberger, or Q, ratio was calculated using the formula $J_0/(\chi_0 \times H)$, where H is a magnetic field value of 0.5 Oe. This parameter is commonly used to determine whether the insitu magnetization of a given section is dominated by a remanent magnetic component (Q > 1) or an induced magnetic component (Q < 1). All values of Q plotted vs. depth in Figure 1C are greater than 1.0, which indicates that the in-situ magnetization is dominated by the remanent magnetization. The decrease of the average value of Q from 3.0 at the top of the section to slightly greater than 1.0 at the bottom of the section suggests that an induced magnetic component parallel to the field at Hole 504B becomes more important with depth. In contrast with the Q values of the Hole 504B samples, Q values from ophiolite complexes (with the exception of Samail) are always almost always less than 1.0 (Levi and Banerjee, 1977; Luyendyk et al., 1982; Swift and Johnson, 1984).

¹ Becker, K., Sakai, H., et al., 1989. Proc. ODP, Sci. Results, 111: College Station, TX (Ocean Drilling Program).

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Table 1. Magnetic property measurements of Leg	g 111	samples from	Hole 504B.
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Core, section, interval (cm)	Depth (mbsf)	Circular standard deviation (degrees)	Stable inclination (degrees)	(× 10 ^{-3^J0} emu/cm ³)	$(\times 10^{-3} \text{ cgs})$	Median demagnetizing field (Oe)	Q
42R-1, 6-8	1352.86	2.0	- 37	6.00	3.06	97	3.9
42R-1, 129-131	1354.09	6.7	8	0.03	0.05	575	1.3
42R-2, 35-37	1354.65	3.7		2.60	1.66	575	3.1
42R-2, 57-59	1354.87	1.6	- 25	3.42	1.92	75	3.6
43R-1, 6-8	1359.36	4.1	17	4.03	1.98	186	4.1
43R-1, 99-101	1360.29	2.6	-23	0.21	0.19	182	2.1
43R-1, 105-107	1360.35	5.8	-17	0.26	0.47	222	1.1
43R-2, 60-62	1361.40	2.9	-20	0.90	0.08	138	23.5
44R-1, 32-34	1369.02	3.0		1.58	1.51	147	2.1
44R-1, 89-91	1369.59	2.0	-15	1.34	1.64	149	1.6
45R-1, 2-4	1378.32	2.6	- 28	1.93	1.10	161	3.5
45R-1, 95-97	1379.25	2.7	- 22	2.35	1.63	139	2.9
45R-2, 54-56	1380.34	5.0	2.2	0.73	0.49	530	3.0
45R-2, 123-125	1381.03	2.5	- 23	2.08	1.15	121	3.6
45R-3, 44-46	1381.74	3.9	- 22	1.94	1.59	143	2.4
45R-3, 129-131	1382.59	3.1	12	2.23	1.22	141	3.7
47R-1, 39-41	1397.79	1.2	8	2.18	1.61	132	2.7
47R-1, 63-65	1398.03	1.7	14	2.81	1.82	118	3.1
47R-2, 44-46	1398.94	2.1	7	2.14	1.85	131	2.3
47R-2, 76-78	1399.26	2.0	20	2.19	2.00	89	2.2
48R-1, 61-63	1407.41	1.3	7	2.19	1.77	152	2.5
48R-1, 68-70	1407.48	3.9	2	1.74	1.87	161	1.9
48R-2, 52-54	1408.82	1.0	5	3.09	1.89	130	3.3
49R-1, 34-36	1417.24	1.7	5	1.58	1.59	172	2.0
49R-1, 82-84	1417.72	3.4	5	1.65	1.69	171	2.0
49R-2, 19-21	1418.54	1.9	-7	1.26	1.54	187	1.6
50R-1, 27-29	1426.67	1.3	10	1.42	1.33	153	2.1
50R-1, 113-115	1427.53	2.9	5	1.52	1.35	104	2.2
50R-1, 135-137	1427.75	1.6	24	2.46	1.77	106	2.8
52R-1, 123-125	1437.13	3.2	8	1.78	1.89	75	1.9
53R-1, 64-66	1445.94	2.0	-6	2.00	1.87	72	2.1
53R-2, 9-11	1446.89			2100	1.55	12.00	
54R-1, 14-16	1454.44	2.0	10	1.38	1.26	173	2.2
54R-1, 64-66	1454.94	2.0	15	1.50	1.57	115	
54R-1, 76-78	1455.06	3.1	16	1 99	1.75	143	2.3
55R-1, 43-45	1459.43	1.1	-1	1.50	2.71	161	1.1
58R-1, 12-14	1482.62	0.9	- 19	1.08	2.12	138	1.0
61R-1 4-6	1504.14	1.6	8	1.73	2.11	102	1.6
61R-1 57-59	1504 67	2.1	8	1.65	2.51	105	1.3
63R-1, 43-45	1512.03	3.1	8	1.83	3.56	140	1.0
63R-1 99-101	1512.59	14	-2	4 61	2.53	77	3.6
63R-2 6-8	1513 16	3.8	_3	1.36	2 52	148	11
63R-2, 17-19	1513.27	2.0	2	2 44	3.12	160	1.6
64R-1, 7-9	1515.17	1.5	21	4 48	2.93	90	3.1
65R-1 29-31	1529.79	3.8	12	1.36	1.90	148	1.4
69R-1 66-68	1548.26	4.8	4	1.54	2.26	106	1.4
69R-1 80-82	1548 40	12.4	8	2.08	2 54	127	1.6

Median Demagnetizing Field

All of the Leg 111 samples were subjected to alternating field demagnetization in order to determine stable magnetic inclinations. The value of the alternating field that results in removal of one-half of the natural remanent magnetization is referred to as the median demagnetizing field (MDF). This parameter is often used to characterize the stability, or hardness, of the remanent magnetization and is, among other things, a function of magnetic grain size. The MDF values for the Leg 111 samples displayed in Figure 1D show a slight decrease (from a running average of 160 to 100 Oe) with depth. This suggests that the remanent magnetization becomes softer with depth in the section. Together with the susceptibility values, this is consistent with a magnetic grain size that increases as a function of depth.

Stable Inclination

Values of stable inclination are plotted vs. depth in Figure 2 for the entire section sampled at Hole 504B, including data compiled from previous investigations at Hole 504B by Smith and Banerjee (1986). Stable inclination values have a large vari-

ation throughout the section, with a change in mean inclination from -24° in the pillow basalts to -1° in the sheeted dikes. This change in stable inclination is also dramatically apparent in the downhole magnetic logging records acquired at this site (see Kinoshita et al., this volume). The expected dipole inclination is 0°, and although the inclination in the sheeted dike complex agrees well with the expected value, the inclination in the extrusives differs significantly.

The magnetic polarity of the drill cores is usually determined using the magnetic inclination because the recovered core is not azimuthally oriented. This complicates the polarity determination for equatorial or low-latitude sites, where the bulk of the magnetization is contained in the horizontal component instead of the vertical component. At Hole 504B, the overlying marine magnetic anomaly is of reversed polarity. The extrusive basalts, which are the major contributor to the magnetic anomaly, would also be reversed magnetized, consistent with their inclination. Because the average inclination of the dikes is essentially 0°, it is not possible to determine from the discrete sample data whether the dike complex has the same polarity as the extrusives or a different polarity. Although we subsequently argue that the sheeted

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Figure 1. Magnetic properties measurements plotted vs. depth for Leg 111 samples from Hole 504B. A. Natural remanent magnetization. B. Magnetic susceptibility. C. Koenigsberger ratio. D. Median demagnetizing field.

dike complex is capable of making a contribution to the magnetic anomaly, it certainly is substantially less than that of the extrusive basalts, and thus, the polarity of the overlying magnetic anomaly is not a strong argument for the polarity of magnetization in the dikes. From this data we cannot rule out the possibility that the dikes could be magnetized in the opposite direction of the overlying basalts. Fortunately, independent analyses of the downhole magnetic log (Kinoshita et al., this volume) indicate that the sheeted complex is indeed reversed magnetized, and thus there is only a discrepancy in inclination between the two units.

The 24° difference between the expected and observed inclinations in the pillow basalts appears to be too large to attribute solely to secular variation of the geomagnetic field during crustal



Figure 2. Stable magnetic inclination (I_s , in degrees) plotted vs. depth for samples from Hole 504B. Although there is a large amount of scatter throughout the section, the change in the mean stable inclination value between the upper extrusives and sheeted dikes is apparent.

formation. It is suggested that the observed inclination change is due to tectonic rotation of the upper part of the crustal section. Rotation may have occurred along a listric normal fault, such as those previously observed in ophiolites. Faults that dip inward and strike parallel to the paleoaxis of spread are observed in the Troodos Ophiolite (Hurst et al., 1987). It is interesting to note, as did Smith and Banerjee (1986), that contrary to most models of crustal formation (e.g., Hall and Robinson, 1979), the magnetic data are consistent with crustal rotation at this site *toward*, rather than away from, the axis of spreading. The proposed listric fault, in this example, must have dipped outward, away from the spreading center.

Oxide Mineralogy

Oxide minerals were examined in reflected light, both in air and oil, at magnifications of $400 \times$ and $1250 \times$ using a Zeiss photomicroscope. Polished thin sections were generously provided from the upper part of the sheeted complex by Guy Smith, and the oxide petrography study thus includes 32 samples taken throughout the entire sheeted dike complex sampled at Hole 504B. A summary of the results of oxide petrography provided in Table 2 includes a brief overall description and semiquantitative estimates of the degree of high-temperature (>600°C) deuteric oxidation and the amount of hydrothermal alteration.

The deuteric oxidation classification was slightly modified from that proposed by Ade-Hall et al. (1968) to describe the oxidation levels in the samples from Hole 504B as follows: C1 titanomagnetite grains are homogeneous, C2 titanomagnetite grains have a small number of ilmenite lamellae oriented parallel to the octahedral planes of the titanomagnetite host, C3 titanomagnetite grains consist of 50% or more ilmenite lamellae, and C4 titanomagnetite grains consist of 50% or more ilmenite bodies in irregular, or podlike, shapes within the titanomagnetite host. Higher levels of oxidation (C5 and C6 of the Ade-Hall classification system), such as alteration of magnetite to hematite, were not observed.

The hydrothermal alteration of titanomagnetite is described in detail by Ade-Hall et al. (1971). The hydrothermal alteration classification system used in this paper is based on Hall et al. (in press) as follows: H1 titanomagnetites have not been visibly altered by a hydrothermal fluid, H2 titanomagnetites are characterized by the presence of fine anatase granules or by incipient replacement of ilmenite lamellae by sphene, H3 titanomagnetites are completely granulated to anatase or show complete replacement of ilmenite lamellae by sphene, H4 titanomagnetites are similar to H3 grains but also have areas of iron loss, H5 titanomagnetites are at least 50% replaced by anatase or rutile, and H6 grains are completely replaced by anatase or rutile.

The primary oxide phases are similar throughout the entire sheeted dike section. This is expected because the geochemistry of the recovered basalts is consistently an olivine tholeiite that has been hydrothermally altered to greenschist facies. Both titanomagnetite and ilmenite are present as discrete, primary phases and are textually interstitial with respect to the silicate phases. Grains are subhedral to anhedral in shape and vary greatly in size, with most between 20 and 100 μ m in cross section.

The most striking feature of the oxide minerals is the variation in the degree of both deuteric oxidation and hydrothermal alteration. Between 1055 and 1152 m below seafloor (mbsf), there is no optical evidence of ilmenite formed during high-temperature oxidation of primary titanomagnetite. The first occurrence of very fine $(1-\mu m)$ ilmenite lamellae is at 1152 mbsf. With increasing depth, the density of the lamellae within the host titanomagnetite also increases (from C1 to C3 of the modified Ade-Hall classification). At 1378 mbsf, ilmenite grains were first observed (and commonly seen deeper in the section) in irregular and podlike shapes that in many cases coalesce on the perimeter of the host titanomagnetite (Pl. 1, Fig. 1).

Although the irregular, or podlike, ilmenite morphology is not mentioned in either the Ade-Hall et al. (1968) or Wilson and Haggerty (1966) high-temperature oxidation models, it is described in Buddington and Lindsley (1964) and has been suggested to be indicative of very high temperatures or a very slow cooling history. Germane to the Hole 504B sheeted dikes samples, a change in the abundance and morphology of ilmenite within the section would simply require a cooling rate that decreases as a function of depth. An alternative explanation for the observed changes in oxide mineralogy with depth is that they are of a hydrothermal origin. However, Ramdohr (1980) describes the formation of ilmenite as taking place only at temperatures above 500°C. The greenschist facies alteration observed in the Hole 504B samples is thought to take place at temperatures less than 400°C (Alt et al., 1986); thus, we think it unlikely that the observed ilmenite formed as a result of oxidation by hydrothermal fluids. In summary, although there is substantial variation between adjacent samples and even within grains, the overall trend is one of an increasing degree of high-temperature oxidation with depth.

All of the observed primary titanomagnetite grains have been moderately to heavily altered by hydrothermal fluid. As described by Ade-Hall et al. (1971), the nature of this alteration is strongly dependent upon the degree of high-temperature oxidation that took place prior to interaction with a hydrothermal fluid. Titanomagnetite grains that have experienced little or no previous oxidation to ilmenite/magnetite networks are characterized by granulation (i.e., the formation of very fine granules of anatase within the titanomagnetite grains) (Pl. 1, Fig. 2). As the degree of hydrothermal alteration increases, secondary minTable 2. Summary of oxide petrography descriptions of samples from the sheeted dike complex, Hole 504B.

Depth (mbsf)	Oxidation class ^a	Hydrothermal alteration class ^b	Additional comments
960.00	C1	H4	Titanomagnetite nearly completely granulated to sphene and anatase
1068.00	C1	H2	Titanomagnetite is variably granulated and has low-temperature cracks
1100.00	Cl	H4	Titanomagnetite nearly completely granulated to sphene and anatase
1150.00	C1	H2	Magnetite is pervasively, but lightly, granulated; discrete ilmenite grains are unaltered
1152.00	C1	H3	Titanomagnetite is granulated to variable degrees, has low temperature cracks, and rare, very fine ilmenite lamellae
1190.00	C3	H2	Titanomagnetite pervasively, but lightly, granu-
1261.00	C3	H2-H3	Titanomagnetite granulated to varying degrees;
1295.00	C1-C2	H3-H4	Titanomagnetite heavily altered to sphene and anatase granules; discrete ilmenite grains unaltered
1327.00	C1	4	Titanomagnetite is heavily altered to sphene and anatase; discrete ilmenite grains are unal- tered
1354.65	C1	H2	Nondeuterically altered titanomagnetites have variable degrees of hydrothermal granula- tion
1359.36	C2	H2	Ilmenite lamellae generally unaltered; remaining titanomagnetite is granulated
1360.29	?	H6	Titanomagnetite is completely altered to massive anatase ghosts
1361.40 1369.02	C2-C3 C1	H3-H4 H2	Titanomagnetite is quite variably granulated Titanomagnetite pervasively, but lightly, granu-
1378.32	C3	H4	Magnetite part of magnetite/ilmenite network is nearly completely altered to sphene; il-
1380.34	C2-C3	H5	Magnetite nearly completely altered to anatase;
1382.59	C2-C3	H5	Magnetite nearly completely altered to anatase;
1398.03	C2	H2	Ilmenite lamellar or podlike, with some altered
1399.26	C2-C3	H2	Ilmenite lamellar or podlike, with some altered to sphene: magnetite is lightly granulated
1408.82	C2-C3	H2	Very fine ilmenite lamellae; light granulation of magnetite
1417.24	C2	H3	Lamellar and irregular ilmenite are rarely hydrothermally altered; magnetite is granu- lated
1418.54	C2	H3	Lamellar and irregular ilmenite are rarely hydrothermally altered; magnetite is granu- lated
1426.67	C2	H3	Ilmenite is both lamellar and podlike and variably altered to sphene; magnetite bears anatase granules
1427.75	C2-C3	H2-H3	Ilmenite is always lamellar and commonly altered to sphene on grain peripheries; magnetite is anatase bearing and has lost iron
1445.94	C2	H5	Ilmenite lamellae are altered to sphene; large iron losses in magnetite
1454.44	C2	H2	Thin and irregular ilmenite are rarely altered to sphene: magnetite bears anatase granules
1455.06	C1-C2	H2	Ilmenite commonly altered to sphene; magnetite bears anatase granules
1504.67	C3	H1-H2	Lamellar and podlike ilmenite is unaltered; magnetite is lightly altered to anatase
1512.59	C3-C4	H3	Magnetite is generally unaltered; ilmenite lamellae and pods altered to sphene
1513.16	C3-C4	Н3	Magnetite is generally unaltered; ilmenite lamellae and pods altered to sphene
1529.79	C3-C4	H1-H2	Ilmenite is podlike; magnetite bears small number of secondary anatase granules
1548.40	C3-C4	H1-H2	Abundant ilmenite is irregular in form; small crystals of anatase are the only alteration product of magnetite

 ^a Describes the average degree of high-temperature, deuteric oxidation of primary oxides observed in the samples, as explained in the text.
^b Describes the average degree of hydrothermal alteration of oxides in the sample, as explained in the text.

erals such as anatase or sphene are formed and iron is mobilized and migrates out of the grain (Pl. 1, Fig. 3). On the other hand, titanomagnetite grains that experienced high-temperature oxidation substantial enough to form magnetite and ilmenite networks interact with hydrothermal fluid in two different fashions. First, ilmenite lamellae alter to form sphene, and a relict lamellae texture remains within the titanomagnetite (Pl. 1, Fig. 4). Less commonly, the iron in the magnetite part of the ilmenite-magnetite network is mobilized and migrates out of the grain, leaving behind the remaining, unaltered ilmenite lamellae and ghostlike anatase masses in place of the magnetite in the original titanomagnetite grains.

All of the preceding described textures occur within the Hole 504B dikes. As with high-temperature oxidation, there is a great deal of variation in the amount of hydrothermal alteration within one sample and between adjacent samples. The following overall trends are discerned in the sheeted dike complex from the opaque mineralogy:

1. The amount of magnetite that has experienced iron migration decreases with depth in the section.

2. Volumetrically, hydrothermal alteration products of titanomagnetite become less abundant with depth.

3. Concurrent with the increasing degree of high-temperature oxidation, the textural expression of hydrothermal alteration changes with depth, from granulation to replacement of lamellae structures.

DISCUSSION

To place the crustal section drilled during Leg 111 within the context of Hole 504B as a whole, we have compiled magnetic data from previous DSDP paleomagnetic studies, including those of Furuta and Levi (1983), Pechersky et al. (1983), Facey et al. (1985), Kinoshita et al. (1985), and Smith and Banerjee (1985). These data are plotted vs. depth in Figure 3. Because our main purpose in this paper is to examine the magnetic structure of the

sheeted dike complex, we therefore present only a brief summary of the magnetic structure of the upper two lithologic units and refer readers to Smith and Banerjee's (1986) complete study of the upper part of Hole 504B.

The most salient feature of Figure 3 is the abrupt change in magnetic properties at the boundaries between the three major crustal units: the extrusive basalts, the transition zone composed of both extrusives and dikes, and the sheeted dike complex. The upper extrusive sequence sampled in Hole 504B is magnetically similar to other marine basalts, with a mean J₀ of 5.5×10^{-3} emu/cm³, Q values greater than 1, and relatively stable magnetic directions. The magnetic carrier in these extrusive units is a titanomagnetite that underwent only low-temperature oxidation. The transition zone is made up of both extrusives and dikes that were extensively hydrothermally altered and have a greatly reduced J_0 (0.63 \times 10⁻³ emu/cm³ mean value), Q values greater than 1, and high MDF values. The change in magnetic properties between the extrusive section and the transition zone is caused by a dramatic grain-size reduction that, as the magnetic properties and opaque mineralogy indicate, is due to leaching of large amounts iron from the primary titanomagnetites and replacement by sphene. Similar effects are seen in areas of intense hydrothermal alteration in the lower extrusive sequence of the Troodos, Cyprus, and Bay of Islands ophiolites (Swift and Johnson, 1984; Johnson and Pariso, 1987).

Compared with the extrusives, the sheeted complex at Hole 504B has a somewhat lower mean J_0 , and a lower mean χ_0 . The J_0 variation is not surprising, given the expected increase in overall grain size of magnetite between basalt and diabase. However, examination of the sheeted complex as a whole shows that magnetic susceptibility steadily increases, and the values of the MDF and Q steadily decrease as a function of depth. The values of J_0 , on the other hand, remain relatively constant (although scatter does increase downhole). Based upon these parameters, and the results of the opaque petrography, it appears that the changes observed in the magnetic properties within the sheeted



Figure 3. Combined magnetic data compiled from previous DSDP results and from Leg 111 data plotted vs. depth. Natural remanent magnetization in emu/cm³, magnetic susceptibility in cgs units, and median demagnetizing field in Oe.

complex are the result of different degrees of deuteric and hydrothermal alteration. In the upper part of the sheeted complex deuteric oxidation is uncommon; hydrothermal alteration is dominant and results in pervasive granulation and loss of iron from primary titanomagnetite grains. This results in a small effective magnetic grain size and a decrease in the amount of magnetite present. However, with increasing depth in the section, deuteric oxidation increases, hydrothermal alteration commonly results in alteration of ilmenite lamellae to sphene, and the amount of iron leached from the host titanomagnetite grains decreases. This combination of processes results in more magnetite remaining in the rock and a systematic increase in grain size with depth.

The difference in magnetic properties between the extrusives and the sheeted dikes and the trends observed within the respective lithologic units in Hole 504B are similar to those studied by Hall and Fisher (1987) within the Troodos Ophiolite. Although they observed an abrupt change in mean values of J_0 , χ_0 , and MDF between the extrusives and the sheeted dikes, the Troodos section sampled in their study did not contain a transition zone as intensely hydrothermally altered as the transition zone observed at Hole 504B. In the Hall and Fisher model (1987), the extrusives and dikes have a post-emplacement alteration history that includes both high-temperature oxidation and subsequent hydrothermal alteration. In contrast to our observations of the Hole 504B samples, they did not see a gradient in the degree of these two processes with depth. Instead, they included a third step in which the altered magnetite grains are subsequently annealed and made effectively larger by reheating related to the dike injection process. Their model requires a dike abundance of at least 30% and attributes the gradient in magnetic properties to an increase in dike abundance and formation of secondary magnetite with depth. The identifying characteristics of this type of secondary magnetite as carefully described by the authors were not obvious in our observations of the Hole 504B oxides.

Implications for Crustal Formation Processes

The increase in degree of deuteric oxidation with depth suggests, reasonably, that the lower part of the dike complex cooled at a slower rate than the upper part of the complex. The observed decrease in hydrothermal alteration of magnetite with depth in the section could be a result of (1) a change in the chemical stability of magnetite resulting from an increase in temperature within the section or, more likely, (2) a decrease in the amount of available fluid interacting with the surrounding rock. Because an increase in the amount of secondary actinolite with depth was also observed, a slight increase in metamorphic grade may very well have also occurred (Alt et al., this volume).

The preceding results could be explained by a model in which fluid permeability decreases as a function of depth, thus changing the cooling rate. This model is supported by borehole measurements of electrical resistivity that indicate that fracture porosity decreases with depth (Pezard and Anderson, this volume). In addition, the magnetic and opaque mineralogy results suggest that the present measured fracture porosity is, in this particular case, a good indicator of the initial formation fracture density when the crustal temperatures were much higher.

Implications for the Magnetic Anomaly Source Layer

The average of value of J_0 (1.6 × 10⁻³ emu/cm³) observed in the sheeted dike complex sampled at Hole 504B is somewhat lower than that of the overlying pillows (5.5 × 10⁻³ emu/cm³). This value of J_0 coupled with Q values greater than 1.0 meet the basic criteria suggested by Swift and Johnson (1984) for a magnetic anomaly source layer. Given the lower mean J_0 and greater depth of the sheeted dike complex, we thus conclude that the dikes sampled in Hole 504B can indeed make a contribution to the overlying magnetic anomalies, but do so to a lesser extent than the extrusive basalts. The opaque mineralogy studies indicate that the magnetic properties of the dikes are strongly influenced by both the rate of crustal cooling and the degree of hydrothermal alteration. It thus appears that for a given oceanic crustal section, the ability of the various lithologic units to contribute to marine magnetic anomalies is dependent, in a fairly complicated manner, on these cooling and alteration processes. In the Hole 504B crustal section, an increase in the high-temperature oxidation of primary titanomagnetite with depth, which we interpret as evidence of a slower cooling rate, appears to result in a gradual decrease in the ability of diabase to function as a source layer for marine magnetic anomalies. In contrast, the upper part of the sheeted complex appears to have cooled more quickly and experienced more extensive hydrothermal alteration, a process that has, in effect, decreased the amount of magnetite, but increased its stability as a carrier of remanence. As observed in the ophiolite studies, however, very extensive hydrothermal alteration can also result in a dramatic decrease in the ability of the sheeted dikes to act as a source layer (Johnson and Pariso, 1987; Swift and Johnson, 1984). Thus, it is difficult to generalize the potential contribution of the sheeted dike section to marine magnetic anomalies because the magnetic properties of a given crustal section are heavily dependent upon crustal formation processes that, as yet, are not well defined for the lower crustal layers.

CONCLUSIONS

The observed change in stable magnetic inclination between the extrusive basalts and the sheeted dikes suggests that the upper part of the crustal section at Hole 504B was tectonically rotated. Such a rotation may have occurred along a listric fault that dipped away from the spreading center and thus tipped the extrusive basalts toward the axis of spreading. The slower cooling rate indicated by opaque mineralogy for the lower part of the sheeted dike complex in comparison with the upper section might have resulted from decreasing fluid permeability with depth. The magnetic properties of the dike complex vary with the degree of deuteric and hydrothermal alteration, but, in general, indicate that the sheeted dike complex sampled at Hole 504B may contribute to the overlying magnetic anomaly.

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Plate 1. Photomicrographs of Leg 111 samples from Hole 504B. The long dimension of the photomicrographs is 75 μ m. 1. Titanomagnetite grain that was oxidized at high temperatures to form ilmenite, photographed in oil in reflected light. Ilmenite bodies are irregular and podlike and commonly are coalesced in cracks or on the periphery of the grain. Some of the ilmenite bodies are elongate parallel to the octahedral plane of the host titanomagnetite and were probably initially continuous lamellae. 2. Titanomagnetite that experienced light, hydrothermal granulation to form small anatase granules within the titanomagnetite, photographed in oil in reflected light. 3. Titanomagnetite that experienced extensive hydrothermal granulation. Much of the iron has been leached away, leaving small anatase granules behind. 4. Titanomagnetite that was oxidized at high temperatures to form ilmenite lamellae. The ilmenite lamellae have subsequently been altered to sphene during interaction with a hydrothermal fluid.