

36. ROCK MAGNETISM OF BASALTS, LEG 34

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INTRODUCTION

This chapter describes rock magnetic properties of 38 basalt samples, 34 from the three Leg 34 Nazca plate sites and 4 from Site 157 of Leg 16, located on the southern flank of the Carnegie Ridge, the only other DSDP Nazca plate site. The value of studying rock magnetic properties lies in increasing our scant knowledge of submarine basalts as magnetic materials and in providing a very sensitive indicator of oxidation to complement the results of geochemical and petrographic studies.

The magnetic properties reported here are the weak magnetic field properties—natural remanence intensity, mean demagnetizing field, initial susceptibility—and the strong field properties—saturation magnetization and Curie point. The combination of Curie point, obtained from the thermal cycling of saturation magnetization and oxide petrography (Ade-Hall et al., *Opaque Petrography of Basalts*, this volume) allows the oxidation state and history of the basalts to be traced.

EXPERIMENTAL METHOD

Natural remanent magnetization intensity (NRM) and mean demagnetizing field (MDF) are usually obtained directly from the alternating field demagnetization of the natural remanent magnetization of basalts. However, the presence of approximately opposed soft and hard components in the NRM of the coarse-grained basalts for the Nazca plate means that, for these rocks, NRM and MDF depend mainly on the difference of two approximately opposed vectors, representing the original magnetizing field and some later field. Correlation with other properties in these conditions would not be expected. For this reason the values of weak field remanence intensity and of mean demagnetizing field in Table 1 are for equivalent single component magnetizations. The estimation of these single component magnetizations is described elsewhere (Ade-Hall and Johnson, *Paleomagnetism of Basalts*, this volume). Since fine-grained basalts have single component natural magnetizations, representing original magnetizing field directions, NRM intensity and MDF can be taken directly from NRM demagnetization results.

Initial susceptibility has been measured using a Soiltest MS 3 bridge. This instrument is intended for the measurement of segments of drill core long enough to extend effectively to infinity from the primary-secondary coil system. In order to work with 1-2 cm long,

2.5-cm diameter minicore wafers and to account for the rapid change of apparent susceptibility with sample length over the range of actual sample lengths used, the bridge has been calibrated using short cylindrical samples of highly paramagnetic salts (FeCl_3 , MnO_2).

Saturation magnetization and Curie point have been measured using a Curie balance consisting of a 7.5-kg electromagnet with Faraday pole pieces, a furnace designed to produce heating rates of up to $100^\circ\text{C}/\text{min}$, a Cahn R-100 electrobalance, and a BBN 800M X-Y recorder. Repeated purging of the furnace with nitrogen before thermal cycling ensured that the effective oxygen fugacity was below that necessary to oxidize the titanomagnetite grains.

The interpretation of the rock magnetism measurements has been considerably enhanced by comparisons with the oxide petrography and oxide grain sizes and contents estimated from measurements made using polished surfaces.

INTERPRETATION OF RESULTS OF THERMAL CYCLING IN STRONG MAGNETIC FIELDS

The main contribution of rock magnetic studies to our knowledge of the geochemical state of the Leg 34 basalts derives from the study of the variation of saturation magnetization with temperature. The results of typical thermal cycles, obtained using the Curie Balance, are shown in Figure 1.

The absence of sharply defined Curie points and lack of reversibility are widespread. In the absence of sharply defined Curie points we follow Grommé et al. (1969) in taking the Curie point as the projection on the temperature axis of the intersection of tangents drawn above and below the smallest radius of curvature segment of the J^{S-T} (saturation moment versus temperature) curve. We note that rare reversibility of a J^{S-T} cycle, within the known thermal hysteresis of the equipment, is only found for the lowest Curie point samples. Since Ozima et al. (1968) have shown that cation-deficient spinels cannot be made to show reversible curves, even at the low oxygen fugacity of our experimental conditions, we take the reversibility of the low Curie point curves as evidence of stoichiometry. Using the relationship between titanomagnetite Curie point and composition given by Readman and O'Reilly (1972), the average values at Sites 319 and 321 of the Curie points for stoichiometric titanomagnetites have been used to obtain a value in the expression $x\text{Fe}_2\text{TiO}_4(1-x)\text{Fe}_3\text{O}_4$. With origin at the calculated values of x , oxidation lines have been drawn on a segment of an $\text{FeO}-\text{Fe}_2\text{O}_3-\text{TiO}_2$ ternary diagram (Figure 2), and the Curie points for cation-deficient titanomag-

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TABLE 1
Rock Magnetic Properties of Leg 34 Basalts

Sample (Interval in cm)	NRM ^a J_o	MDF ^a	K^c	J_s^d	T_c^e	$(x,z)^f$	Oxide Phase(s) ^g	Oxide Content ^h		Oxide Average Grain Size (μ)
								(a)	(b)	
Hole 319										
13-1,75-78(1)				NA	344	(0.61,0.82)	Titanomaghemite	0.22	—	4.5
13-1,75-78(2)	1.81	230	2.1	0.52	349	(0.61,0.83)	Titanomaghemite	—	[1.7]	—
13-1,108-111(2)	1.62	240	1.8	0.44	329	(0.61,0.78)	Titanomaghemite	0.30	[1.4]	7.0
Hole 319A										
1-1,14-17(1)	3.78	Indet.	2.1	0.81	355	(0.61,0.85)	Titanomaghemite	1.1	[2.7]	4.4
1-1,39-44(2)	5.10	89	2.0	0.65	288	(0.61,0.67)	Titanomaghemite	2.3	2.0	22
2-1,106-109(1)	NA	NA	NA	0.55	305	(0.61,0.71)	Titanomaghemite	2.5	[1.7]	15
2-1,106-109(2)	12.9	105	1.6	0.63	263	(0.61,0.58)	Titanomaghemite	—	1.9	—
2-1,146-149(2)	23.5	150	7.7	1.4	224	(0.61,0.42)	Titanomaghemite	2.6	3.9	19
3-2,108-111(1)		NA	NA	1.1	291	(0.61,0.67)	Titanomaghemite	2.6	3.4	26
3-2,108-111(2)	18.5	95	2.0	0.47	382	(0.61,0.89)	Titanomaghemite	—	[1.6]	—
3-5,81-84(2)	33.9	40	1.2	1.2	144	(0.61,0.00)	Titanomagnetite	2.6	2.9	20
4-1,133-136(1)		NA	NA	1.3	136	(0.62,0.00)	Titanomagnetite	2.1	3.2	19
4-1,133-136(2)	74.4	25	16.7	1.3	181	(0.61,0.20)	Slightly cation-deficient titanomagnetite	—	3.4	3.3
4-1,141-144(2)	63.4	35	16.3	1.5	172	(0.58,0.00)	Titanomagnetite	2.9	3.6	17
5-1,72-75(2)	77.2	20	21.8	1.4	134	(0.62,0.00)	Titanomagnetite	3.2	3.4	23
5-1,87-90(1)		NA	NA	2.4	144	(0.61,0.00)	Titanomagnetite	2.5	5.8	17
5-1,87-90(2)	76.2	15	23.1	1.6	150	(0.61,0.00)	Titanomagnetite	—	3.9	4.9
6-1,142-145(2)	19.3	410	1.8	0.22	337	(0.61,0.80)	Titanomaghemite	1.7	[1.7]	3.1
7-1,40-43(1)		NA	NA	0.56	334	(0.61,0.79)	Titanomaghemite	2.2	[1.8]	4.8
7-1,40-43(2)	16.8	150	2.9	0.54	338	(0.61,0.80)	Titanomaghemite	—	[1.8]	[1.8]
Hole 320B										
3-1,76-79(1)		NA	0.5	0.21	330		Uncertain	0.73	—	1.6
3-1,76-69(2)	5.06	1040	0.5	0.24	324		Titanomaghemite	—	—	—
4-1,90-93(2)	20.2	320	1.4	0.44	329		Titanomaghemite	1.6	—	3.5
4-1,144-147(2)	22.5	115	3.9	0.68	373		Titanomaghemite	1.1	—	6.1
5-1,108-113(2)	8.06	565	1.3	0.45	322		Titanomaghemite	2.1	—	3.4
5.Bit Sample	7.93	415	0.5	1.0	305		Titanomaghemite	1.4	—	9.1
Site 321										
13-4,91-94(1)		NA	NA	0.61	311	(0.63,0.77)	Titanomaghemite		[2.1]	
13-4,91-94(2)	13.0	265	9.7	1.0	287	(0.63,0.70)	Titanomaghemite	2.3	3.4	[2.8]
13-4,142-145(2)	—	Indet.	11.3	0.33	319	(0.63,0.79)	Titanomaghemite	0.18	[1.2]	12.2
14-1,39-42(1)		65	46.1	2.3	153	(0.63,0.16)	Slightly oxidized titanomagnetite		6.4	6.6
14-1,39-42(2)	179	NA	43.1	2.2	208	(0.63,0.43)	Titanomaghemite	4.0	6.8	25.0
14-1,58-61(2)	—	NA	51.3	1.9	146	(0.63,0.12)	Slightly oxidized titanomagnetite	3.8	5.2	21.4
14-2,12-15(1)	—	NA	43.3	1.9	149	(0.63,0.14)	Slightly oxidized titanomagnetite		5.3	
14-2,12-15(2)	—	NA	49.0	2.0	157	(0.63,0.18)	Slightly oxidized titanomagnetite	3.5	5.6	5.5
14-2,117-120(2)	—	NA	95.3	2.0	120	(0.63,0.0)	Titanomagnetite	1.9	5.3	5.2
14-3,34-37(1)	—	NA	58.9	3.0	176	(0.63,0.28)	Slightly oxidized titanomagnetite		8.7	
14-3,34-37(2)	—	NA	44.1	0.16	157	(0.63,0.18)	Very slightly oxidized titanomagnetite	4.2	0.5	4.6
14-3,44-47(2)	—	NA	65.1	2.2	157	(0.63,0.18)	Very slightly oxidized titanomagnetite	3.7	6.2	24.5
14-4,20-23(2)	—	NA	120.5	6.7	125	(0.63,0.0)	Titanomagnetite	3.9	17.8	21.6
14-4,45-48(2)	223	37	91.5	1.9	125	(0.63,0.0)	Titanomagnetite	4.9	5.1	28.5
Site 157										
49-1,136-138	—	53	62.8	1.7	287		Titanomaghemite			
49-2,1-3	—	42	80.2	2.0	297		Titanomaghemite			
49-2,64-66	—	38	71.2	1.9	282		Titanomaghemite			
49-2,135-137	—	117	92.5	4.0	490		Low titanium titanomagnetite			

^aNatural remanent magnetization (equivalent single component value)($\times 10^{-4}$ emu cm^{-3}).

^bMean demagnetizing field (oe).

^cInitial susceptibility (10^{-4} emu cm^{-3} oe⁻¹).

^dSaturation magnetization (emu g^{-1}).

^eCurie temperature ($^{\circ}\text{C}$).

^fIn $(1-x)\text{Fe}_3\text{O}_4(x)\text{Fe}_2\text{TiO}_4$, z is the fraction of initial Fe^{2+} converted to Fe^{3+} .

^gIdentified from the form of the J_S-T heating cycle; with reversibility indicating titanomagnetite and irreversibility titanomaghemite (cation-deficient titanomagnetite).

^hAs a volume percentage from direct measurement (a) and from saturation moment and Curie point (b).

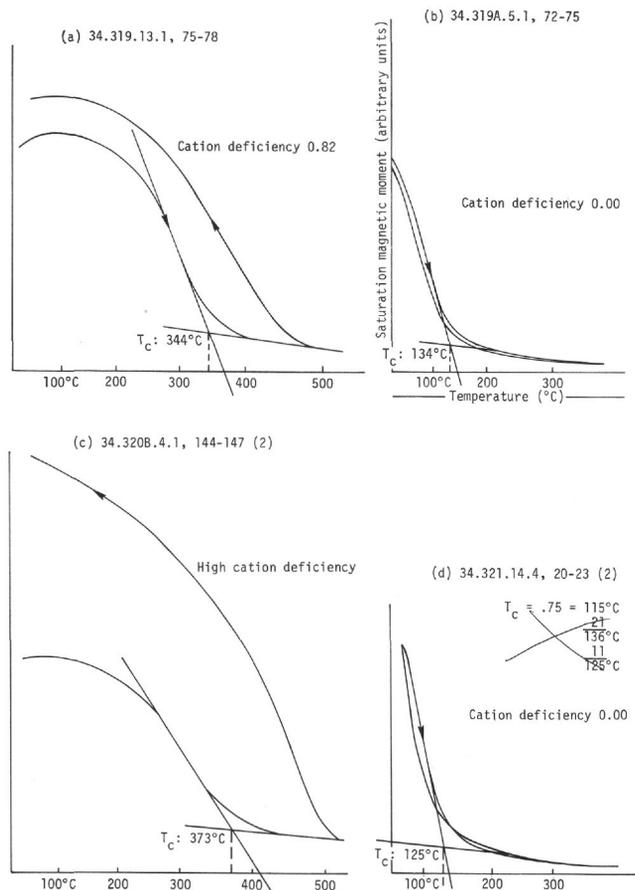


Figure 1. Range of saturation magnetization versus temperature curves showing the effects of stoichiometry and nonstoichiometry of basaltic titanomagnetite.

netites for each sample have been used to find values of z , the fraction of Fe^{2+} in the titanomagnetite molecule now replaced by Fe^{3+} .

RESULTS

Compositions of Stoichiometric Titanomagnetites

At both Sites 319 and 321, a small number of samples showed reversibility of saturation magnetization curves during thermal cycling. This is known to be a feature of stoichiometric titanomagnetite. We use the Curie points of these samples (Table 1) to obtain the ratio of ulvospinel and magnetite molecules in the titanomagnetite (Table 2).

Clearly the compositions of the stoichiometric titanomagnetites of the basalts at these two sites are closely confined within each site, and between-site average values are not significantly different. The average values of x of 0.61 and 0.63 for the two sites lie within the rather small range of values implied by the Curie point distribution for historic or older but unburied subaerial basalts containing homogeneous titanomagnetite (Creer and Ibbetson, 1970; Ade-Hall et al., 1971) and for very young submarine lavas from the Median Valley of the Mid-Atlantic Ridge (Shaeffer and Schwarz, 1970). The significance of the small range of x values for basaltic

TABLE 2
Leg 34 Basalt Samples Containing Stoichiometric Titanomagnetite

Sample (Interval in cm)	Curie Point (°C)	x in $x\text{Fe}_2\text{TiO}_4(1-x)\text{Fe}_3\text{O}_4$	Average and Range for Site
Hole 319A			
3-5, 81-84 (2)	144	0.61	0.61, +0.01 -0.03
4-1, 133-136 (2)	136	0.62	
4-1, 141-144 (2)	172	0.58	
5-1, 72-75 (2)	134	0.62	
5-1, 87-90 (1)	144	0.61	
5-1, 87-90 (2)	150	147	
Site 321			
14-2, 117-120 (2)	120	0.63	0.63, ±0.00
14-2, 20-23 (2)	125	0.63	
14-4, 45-48 (2)	125	0.63	

titanomagnetites is of considerable interest. Explanation may lie in the restricted magmatic composition, oxygen fugacity, and temperature ranges during the initial cooling of basalts (Carmichael and Nicholls, 1967).

Ulvospinel content in titanomagnetite can also be obtained through electron microprobe analysis. Rice (personal communication) has attempted to analyze the stoichiometric titanomagnetite of Samples 321-14-2, 117-120 cm (2) and 321-14-4, 45-48 cm (2). In both samples titanomagnetites of skeletal form predominate although occasional anhedral grains also occur. Even for these relatively coarse-grained massive basalt samples, it was impossible to find titanomagnetites of sufficiently large size to analyze without the microprobe beam spreading into the adjacent silicates. The best results were obtained for the coarsest grained sample, 321-14-4, 117-120 cm (2), where the average minimum dimension of analyzed grains is 24μ . Here seven spot analyses for Fe, Ti, Mg, Cr, and Mn, distributed between three grains, fall within a range of equivalent oxide weights from 86% to 90%. On the assumption of pure iron-titanium oxides the x (ulvospinel) values are closely confined between 0.50 and 0.51. This is significantly less than the value of 0.6 obtained from the thermomagnetic tests. In contrast, Bunch and Lalonde (this volume) and Mazzullo et al. (this volume) give microprobe analyses of titanomagnetite from Leg 34 basalts which can be interpreted as yielding x values identical with the values obtained from the magnetic measurements. In order to obtain this agreement, it is necessary to neglect small contents of Al_2O_3 , MgO , and MnO to assume that the fact that the oxides determined only sum to 90%-95% introduces insignificant error in x and to average the slightly but significantly different sets of values obtained by the two groups. This variation in microprobe analyzer compositions for titanomagnetites probably arises from different degrees of spreading of the electron beam into silicates adjacent to the grains under examination. Beam spreading may also account for the apparent presence of Al_2O_3 and MgO in the titanomagnetites. We conclude that the thermomagnetic tests probably give the most reliable result for the ulvospinel content in titanomagnetite and that the electron

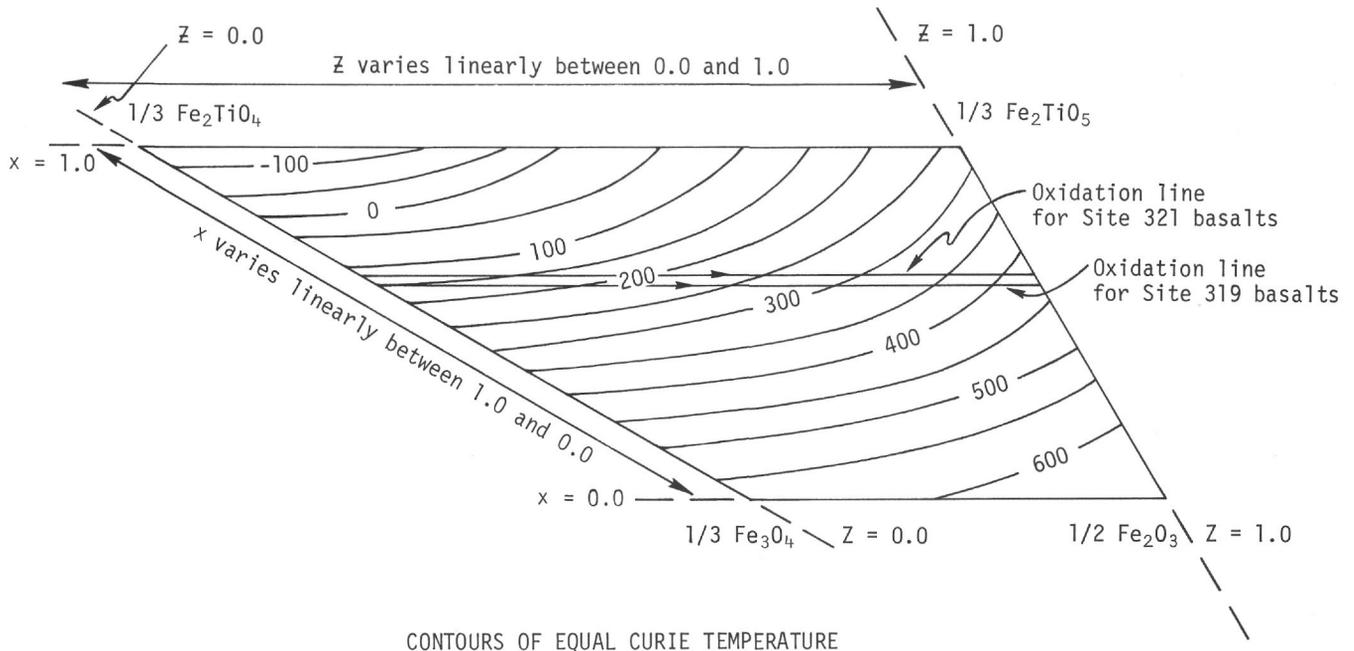


Figure 2. Variation of Curie point with degree of cation deficiency in titanomagnetite (after Readman and O'Reilly, 1972).

probe microanalyzer results confirm that we are dealing with high titanium titanomagnetites.

Titanomaghemites—Cation-Deficient Titanomagnetites

Most Leg 34 basalt samples show marked irreversibility during the thermal cycling of saturation magnetization. This feature, together with the presence of Curie points higher than for the stoichiometric titanomagnetites, indicate that titanomaghemites, or cation-deficient titanomagnetites, are the ferrimagnetic minerals present. From the information given above it is reasonable to assume that these titanomaghemites are derived, through a low temperature oxidation process, from stoichiometric titanomagnetites of the compositions found at each site (Table 2). With this assumption, we can find the degree of cation deficiency of each sample from its position on the oxidation lines of Figure 2. The degree of cation deficiency, expressed in terms of the fraction of Fe^{2+} oxidized to Fe^{3+} (z), is given in Table 1. Values range from 0 for stoichiometric titanomagnetite rather continuously to 0.91, representing the almost complete replacement of Fe^{2+} by Fe^{3+} . We note that a majority of samples (74%) from Sites 319 and 321 contain cation-deficient titanomagnetite. With one exception, the Site 157 and 320 samples also contain cation-deficient titanomagnetite. In the absence of stoichiometric titanomagnetite from these sites, no estimates of degree of cation deficiency can be given. However, the small range of reported x values suggests that similar ranges of cation deficiency obtained at all the Nazca plate sites. The single exception, Sample 157-49-2, 135-137 cm, has a fairly reversible high Curie point saturation magnetization cycle. This is readily explained in terms of oxide petrographic observations. In contrast with the other samples, which contain only homogeneous oxide grains, the latter sample contains titanomagnetite with exsolved ilmenite lamellae (see Ade-Hall

et al., Opaque Petrography of Basalts, this volume). The reversible, high Curie point saturation magnetization cycle represents titanium-poor stoichiometric titanomagnetite remaining after the partial removal of titanium to form ilmenite lamellae.

Spatial Distribution of Titanomagnetite and Titanomaghemites

Figure 3 shows the distribution with depth at each site of Curie point and therefore, by implication, of titanomagnetite and titanomaghemite composition. Two features of the short basement profiles are notable. The first is that only at Site 321 is a decrease in Curie point with depth evident. Rise in Curie point, indicating cation deficiency in titanomaghemite, is a measure of the degree of low temperature chemical alteration that takes place on contact between lava and seawater (Irving et al., 1970). This alteration process is often known by the somewhat obscure term, halmyrolysis. The Curie point profiles indicate that the low temperature alteration of basement basalts at these sites does not generally decrease to zero with depth over a few tens of meters from a surface maximum, as has been observed at some DSDP sites in older oceanic basement (Hyndman, 1974). In fact, the decrease in alteration with depth at Site 321 can be explained by another mechanism, which provides a general explanation for the Nazca plate data. In this preferred explanation alteration is most strongly related to the structure of the basalts. Pillowed sequences at all sites are uniformly highly altered as is the upper part of the massive basalt sequence at Site 319. Only the lowest 10 meters of massive basalt at Site 319, at 25 to 35 meters subbasement, and the massive basalt below 2 meters subbasement at Site 321 have avoided significant alteration. In this context it is significant that the coarse-grained doleritic basalt of Oligocene age from DSDP Site 57 (Melson, 1971) is the only other DSDP

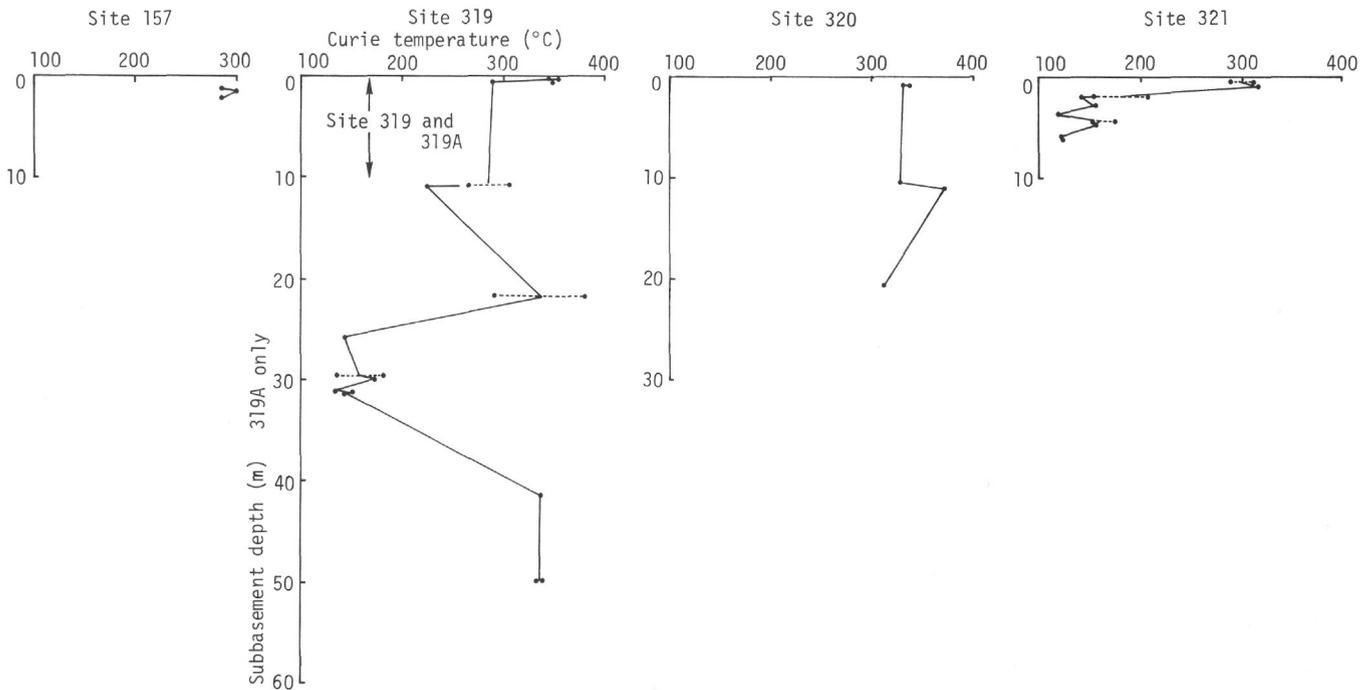


Figure 3. Distributions of Curie point with depth at the four Nazca plate DSDP sites.

Pacific basaltic material reported as showing 100°-200°C Curie points. Pillow basalts from 11 other sites all have Curie points in the 225°-325°C range (Lowrie et al., 1973). The simplest interpretation of the magnetic results is that the access of circulating seawater to the basement basalts is restricted in the more massive material. However, this explanation is apparently contradicted by the CO_2 and in particular, the H_2O contents of the basalts (Hart, this volume). At Site 319, where both pillow and massive material are well represented, the massive basalts of Core 2, 3, 4, and 5 have the highest water contents. Bass (personal communication) has suggested that water content and low temperature oxidation of titanomagnetite might not be expected to relate in massive basalts. It is observed (Bass, this volume) that *nonoxidative* alteration of the Nazca plate massive basalts, characterized by the formation of blue-green smectites, is ubiquitous. It is the formation of the blue-green smectites and other nonoxidative secondary minerals that accounts for most of the water uptake. *Oxidative* alteration, identified by low temperature oxidation of both smectites and titanomagnetites, progresses more slowly in the massive basalt and is accompanied by little further addition of water. In contrast, the high surface area to volume ratios for pillows ensures that both nonoxidative and oxidative alteration fronts completely pervade all but the very youngest pillows, giving rise to the relationship between water content and titanomagnetite low temperature oxidations described by Irving et al. (1970).

Regardless of the explanation for the relationship between water content and the low temperature oxidation of titanomagnetite, it is clear that any overall reduction in halmyrolysis with depth must take place over an interval that is considerably in excess of the deepest basement penetration of 60 meters at Site 319.

Controls on Magnetic Properties

This section is concerned with the origin of the wide ranges in values of the important magnetic properties, natural remanent magnetization intensity (J_o), mean demagnetizing field (MDF), initial susceptibility (k), and saturation magnetization (J_s). For a full examination of this problem both magnetic and petrographic information will be used, and where necessary, reference should be made to Table 1 (Ade-Hall et al., *Opaque Petrography of Basalts*, this volume).

A number of physical features of titanomagnetite are known to affect magnetic properties. Some are obvious, such as abundance, while others are less obviously related such as grain size and degree of cation deficiency. Each of these physical properties varies widely in the Nazca plate basalts, with abundance and grain size varying by more than an order of magnitude and cation deficiency from stoichiometry to close to the complete absence of Fe^{2+} . The problem here is to separate the effects of these different variables. We proceed by considering the influence of these parameters on each magnetic property.

Natural Remanent Magnetization, J_o

For the small titanomagnetite concentration of the Leg 34 basalts of 0.18% to 4.9% by volume, J_o may safely be assumed to be directly proportional to titanomagnetite volume. However, when allowance is made for differences in titanomagnetite volume from sample to sample, large differences in J_o values remain. For basalts from Sites 319 and 321 the range in J_o , after allowance for titanomagnetite volume, is still an order of magnitude. The problem is to decide whether one or both of grain size or cation deficiency provides the additional control of J_o . The difficulty in deciding which factor is dominant lies in the lack of a reliable model for the

behavior of J_0 with either factor, Prediction of behavior of J_0 with grain size could be made if the proportion of single domain (SD), pseudosingle domain (PSD), and multidomain (MD) titanomagnetite grains in each sample were known. However, although distributions of average grain sizes are known (Table 1), they cannot be assigned to the SD, PSD, and MD categories in the absence of agreement on where the boundaries between these categories lie for titanomagnetite (e.g., Evans, 1972). Again, while the dependence of J_0 on cation deficiency can be predicted theoretically from the dependence of J_0 on cation deficiency, the observed order of magnitude ranges in J_0 may be too large to be accounted for simply in this way.

We proceed by assuming no particular form for the dependence of J_0 on grain size or cation deficiency and examine our own data for evidence that one or other factor is dominant. The Site 319 basalts provide such evidence. We find that a plot of J_0 and titanomagnetite grain size (Figure 4) may be divided realistically into three regions: near the origin there is a field containing points for pillow fragments, for which both J_0 and grain size are low. Cation deficiency is uniformly high for the titanomagnetites of these pillow samples. Points for the massive basalts fall within a field defined by a range in J_0 of 5 to $80 \times 10^{-4} \text{ emu cm}^{-3}$ and grain size of 15μ to 26μ . Magnetite content is rather uniform for these samples (Table 1). A much greater range in J_0 than grain size characterizes this field. A clear division between strongly magnetized samples with stoichiometric (or nearly so) titanomagnetite and weakly magnetized moderately or highly oxidized samples is a feature of the massive basalt field. No dependence on grain size, within the limited range of values, is evident. It can be argued that differences in intensity of the original magnetizing field may have resulted in the division of the massive basalt

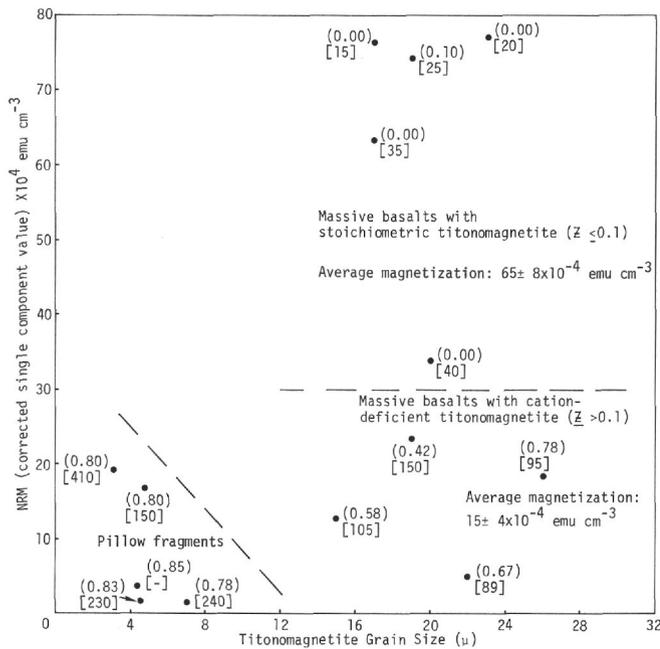


Figure 4. Site 319 basalts. Equivalent single component NRM intensity plotted with titanomagnetite grain size.

field on the plot of Figure 4. However, the uniform occurrence of an unexpectedly steep cleaned NRM direction through the whole of the Site 319 basement section suggests magnetization over a short period of time, with little variation in magnetizing field intensity. Thus, it seems safe to assume that the division of the massive basalt field implies that titanomagnetite cation deficiency is the main control on the magnitude of J_0 . Presumably the high magnetization of the Site 321 massive basalts is also related to their low degree of titanomagnetite cation deficiency. Figure 5 shows J_0 for the massive basalts plotted with titanomagnetite cation deficiency; a factor of five decrease in J_0 between $z = 0$ and $z = 0.8$ is seen to occur. Ryall (in preparation) finds, for samples of equal grain size, an effect in the same sense but of larger magnitude in pillow basalts dredged from the vicinity of the Median Valley of the Mid-Atlantic Ridge, while Johnson and Merrill (1973) have found a similar effect in the laboratory low temperature oxidation of submarine basalt.

There are several likely physical mechanisms for the observed strong dependence of J_0 on z . One is the sharp decrease in J_0 for z at high values and Readman and

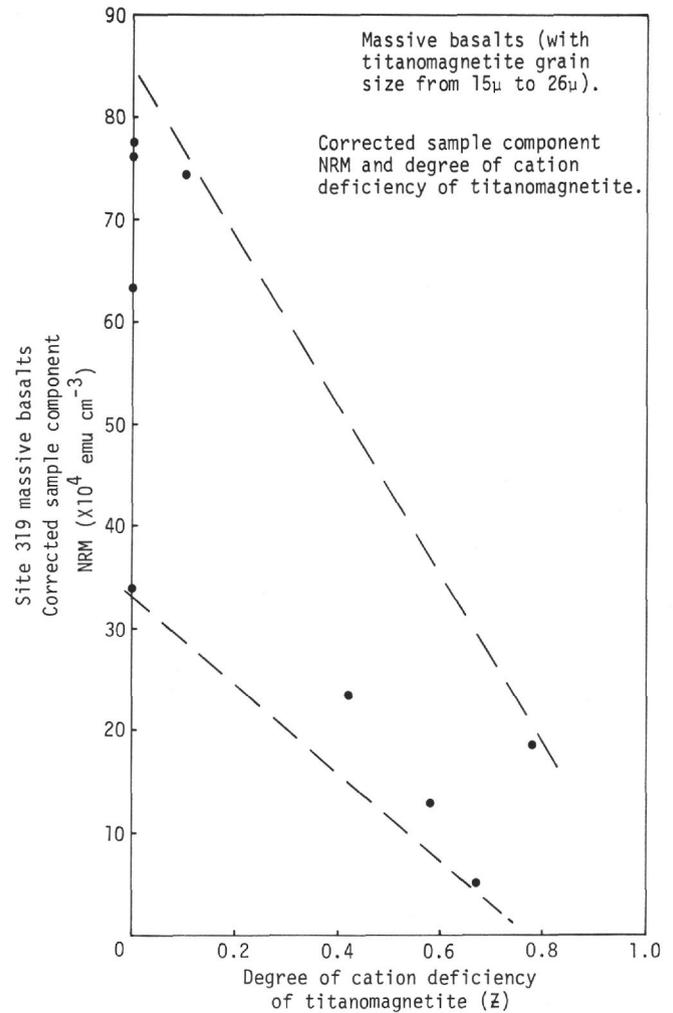


Figure 5. Massive basalts from Site 319. Equivalent single component NRM intensity plotted with titanomagnetite cation deficiency.

O'Reilly (personal communication) indicate at rapid decrease at $z > 0.6$ to $J_o = 0$ at $z = 1$. Another possible mechanism is the replacement of some of the titanomagnetite with sphene and other nonmagnetic phases, thereby reducing the total amount of material contributing to J_o . Yet another possibility is that the subdivision of the titanomagnetite grains by cracks (see Ade-Hall and Johnson, "Opaque Petrography of Basalts, this volume) gives rise to grains in the paramagnetic size range which do not contribute to J_o .

Mean Demagnetizing Field (MDF)

This is defined as the peak demagnetizing field required to reduce the remanence to half of its undemagnetized value. Elsewhere it is found to be a function of titanomagnetite grain size for the size range found in the Nazca plate basalts (Ade-Hall et al., 1973). The Nazca plate basalts, with nearly two orders of magnitude variation in MDF from 15 oe to 1040 oe, also show an inverse dependence of MDF on measured grain size (Figure 6). Note that the MDF values of Table 1 and Figure 6 are estimated for equivalent single component values of J_o , which differ from the observed J_o values for the massive basalts.

In accounting for the observed dependence of MDF on grain size, the problem of separation of variables again arises, since both grain size variation (Johnson et al., in press) and degree of titanomagnetite cation deficiency (Ryall, in preparation; Johnson and Merrill, 1973) are known to affect MDF. As in the case of J_o , the relative importance of the dependence of MDF on grain size or cation deficiency can be tested by analysis of the data for the Site 319 massive basalts (Figures 4 and 7).

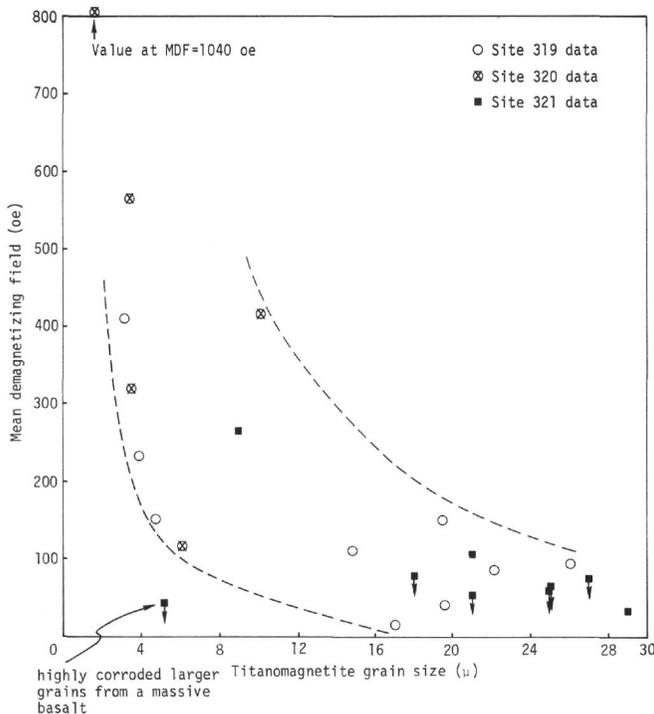


Figure 6. Variation of mean demagnetizing field with titanomagnetite grain size for basalts from Sites 319, 320, and 321.

MDF and cation deficiency vary here with the type of basalt in the following manner:

		Average Grain Size (μ)	z	
Pillow fragments				
MDF:	258 \pm 55oe	4.9 \pm 0.8	0.80 \pm 0.01	(4 samples)
Oxidized massive basalts:	110 \pm 14oe	21 \pm 2	0.61 \pm 0.08	(4 samples)
Unoxidized massive basalts:	25 \pm 5oe	19 \pm 1	0.02 \pm 0.02	(5 samples)

Clearly, for the Site 319 basalts at least, the degree of titanomagnetite cation deficiency has a stronger control, proportionally, on MDF than does grain size. Thus, the ratio of the average MDF of the pillows to the oxidized massive basalts, is only 2.35, while the ratio of the average MDF of the oxidized and unoxidized massive basalts is 4.07. The MDF values for the two Site 321

Variation of mean demagnetizing field with degree of titanomagnetite cation deficiency.

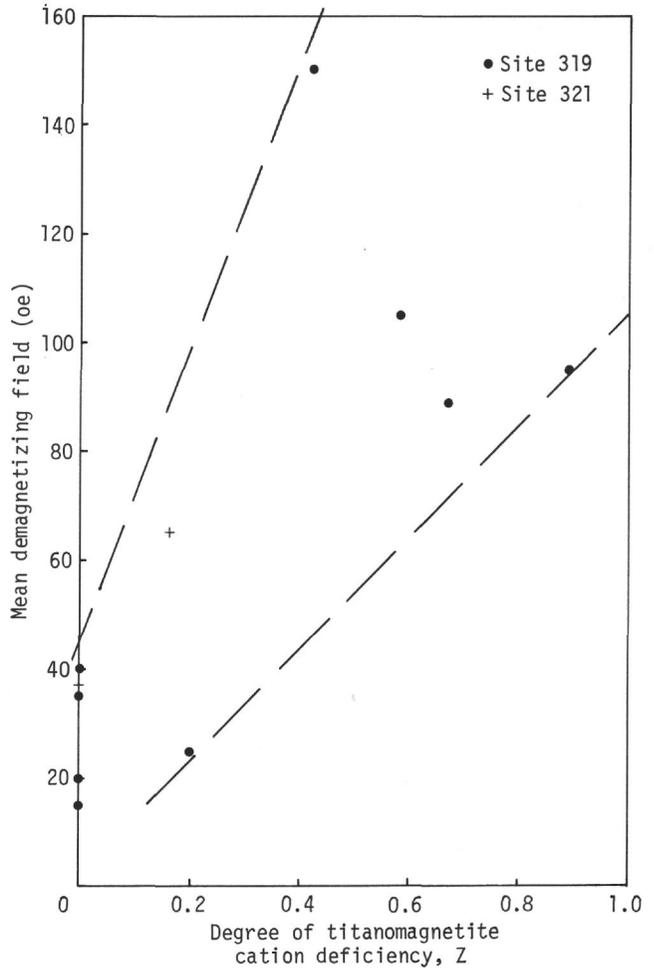


Figure 7. Massive basalts from Site 319. Variation of mean demagnetizing field with titanomagnetite cation deficiency.

massive basalts for which the equivalent single component NRM intensity is available follow well the distribution of MDF and titanomagnetite cation deficiency for the Site 319 massive basalts (Figure 7). Several physical mechanisms for these relationships can be suggested. The sharp increase in MDF in the oxidized massive basalts may, in fact, be a grain size effect, following from the subdivision of titanomagnetite grains by volume change cracks during the oxidation process (see Ade-Hall et al., *Opaque Petrography of Basalts*, this volume, for illustrations of this effect). Stress during oxidation, before or after cracking occurs, is also likely to increase MDF (Shive, 1969). Again, the high MDFs of oxidized samples may in part be the result of CRM generation during oxidation, the CRM providing the hardest NRM component (Johnson and Merrill, 1973).

From a practical viewpoint of obtaining original cooling TRM inclinations, it is realistic to divide the distribution of Figure 6 into three areas.

(a) For grain sizes of greater than 12μ MDF is always low, ranging from 15 oe to 150 oe. Very careful alternating field remanence cleaning is needed to separate original cooling TRM inclinations from the NRM of samples with MDF values in the lower half of this range. Large soft components are characteristically included in the NRMs of these samples regardless of low temperature oxidation state. An original cooling TRM direction, on which a plate motion estimate may be based, is likely to be represented clearly only in the last remaining 1% or so of the NRM.

(b) For grain sizes of 4μ to 12μ , MDF ranges widely from 115 oe to 415 oe, giving rise to NRMs usually consisting of a small soft component and a large hard component.

(c) For grain sizes of less than 4μ MDF ranges between 230 oe and 1040 oe. Soft components are absent from NRMs in this area.

Initial Susceptibility, k

This must be a function of magnetite abundance at small concentration levels and, for pure magnetite at least, is known from experimentation to be inversely related to the grain size with a range and variation of 30% over the range of sizes found in the Nazca plate basalts (Parry, 1965). In the Nazca plate basalts titanomagnetite abundance varies by a factor of two, leading to an anticipated maximum range of a factor of three in susceptibility. However, as the data of Table 1 indicate, susceptibility varies by at least a factor of 20 for the basalts at both Sites 319 and 321. It seems that either the grain size dependence must be greater for titanomagnetite than for magnetite or that the influence of cation deficiency must be taken into account. Again we appeal to the data for the Site 319 massive basalts for guidance. With grain size and abundance essentially constant, we find that the average value of k for the unoxidized samples is a factor of 6.5 greater than the average value for the oxidized samples (Figure 8). On this model the high susceptibilities of the Site 321 massive basalts are consistent with the high titanomagnetite abundance and low cation deficiency. Thus, degree of cation deficiency is found to be the major influence on initial susceptibility. A possible

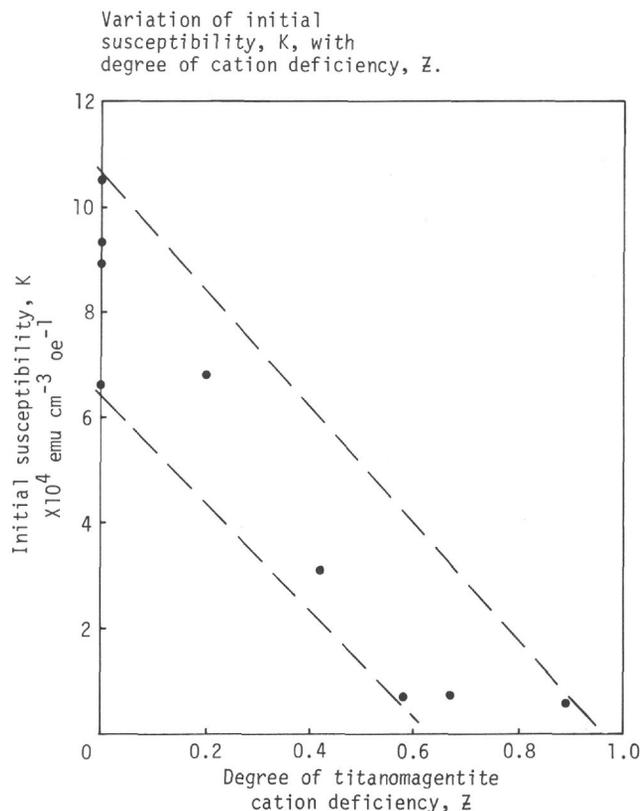


Figure 8. Massive basalts from Site 319. Variation of initial susceptibility with titanomagnetite cation deficiency.

mechanism for this strong dependence is the replacement of titanomagnetite by nonmagnetic phases such as sphene.

Saturation Magnetization, J_s

This must depend on titanomagnetite abundance and also on composition, decreasing rapidly with increasing x and more slowly with increasing z , to $z \approx 0.6$, and then more rapidly (Readman and O'Reilly, 1972 and personal communication). The only anticipated grain size effect is a decrease at the transition from single domain to superparamagnetic states. The J_s values for the Site 319 and 321 basalts match the predictions of small change for $0 \leq z \leq 0.4$ reasonably, but generally show very much diminished values for $z > 0.6$ (Figure 9). That this conclusion is not the result of the weighting of the data by many fine-grained pillow samples, with the implication of an undetected grain size dependence, is shown by a generally similar pattern of J_s dependence on z for the Site 319 massive basalts, for which grain size and abundance are essentially constant (Figure 10). The dependence of J_s on z with the rapid decrease in J_s for $z > 0.6$ is the same as that described by Readman and O'Reilly (1972). The replacement of titanomagnetite by nonmagnetic silicates at high z values is likely to be an additional factor in reducing the saturation magnetization.

SUMMARY AND CONCLUSIONS

The main results of this investigation of the rock magnetic properties of the Nazca plate basalts are the

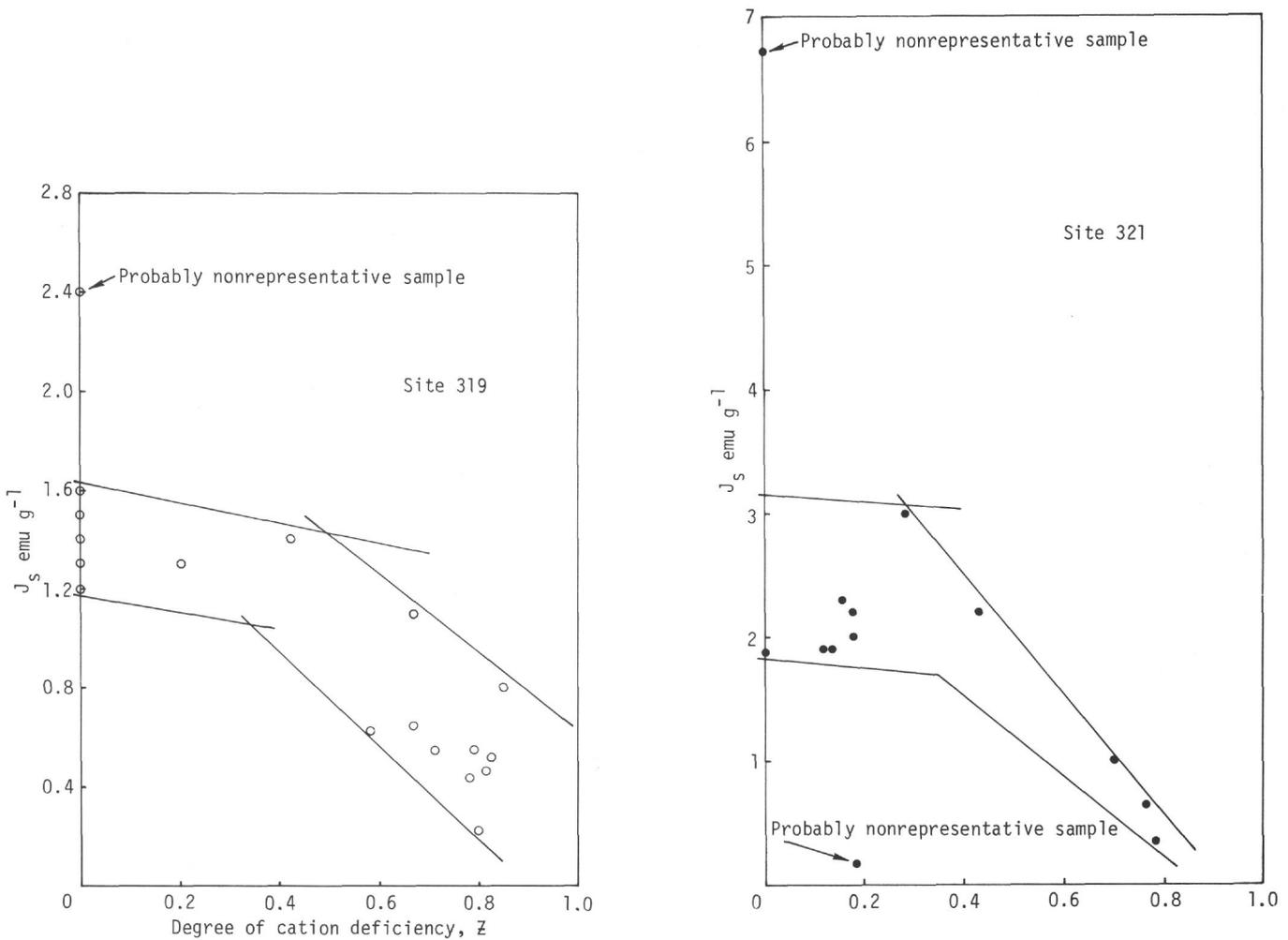


Figure 9. Variation of saturation magnetization with titanomagnetite cation deficiency for the basalts from Sites 319 and 321.

widespread presence of very low temperature oxidation of titanomagnetite, presumably associated with the halmyrolitic alteration of the basalts as a whole, and the dominant influence this type of alteration has on the magnetic properties of the basalts.

Low temperature oxidation of titanomagnetite varies irregularly in the different basement sections. Continuous decrease in degree of alteration with depth, as recorded elsewhere, is not generally seen. Instead, alteration is strongly related to the type of basalt encountered, with all pillow and some massive basalt extensively altered. The only unaltered titanomagnetite encountered occurs in massive basalts at Sites 319 and 321.

An apparent contradiction, is to be found in the different implications suggested by the magnetic and geochemical results, respectively, regarding basalt alteration. While the magnetic results indicate that unaltered titanomagnetites exist only in some of the massive basalts, the values of water content suggest that the massive basalts are more altered than the pillow basalts. Explanation for this situation is likely to lie in the association of water with nonoxidative alteration of the massive basalt.

Starting with titanomagnetite compositions of close to $0.6\text{Fe}_2\text{Tio}_4 \cdot 0.4\text{Fe}_3\text{O}_4$, at least for the Sites 319 and 321

basalts, low temperature oxidation has produced a range of cation-deficient phases with maximum values in excess of 0.9. Proof of the nature of the very low temperature alteration process lies in the fact that such high cation deficiency states are only stable at close to ambient temperature (Ryall, in preparation; Johnson and Merrill, 1973). Seyfried et al. (this volume) provide independent evidence of the low temperature nature of this process: The isotope composition of secondary minerals in the massive basalts of Site 321 indicates very low temperature formation, for example, 7°C for calcite. Since the low temperature oxidation of titanomagnetite appears to belong to the period of seawater alteration and secondary mineral formation, a similar temperature for the formation of the cation-deficient phases can be assumed.

Three variables control the magnetic properties, J_o , MDF, k , and J_s of the Nazca plate basalts. These are abundance, grain size, and degree of cation deficiency of the titanomagnetite. For all four properties the degree of cation deficiency, z , provides the dominant influence, with J_o , k , and J_s decreasing and MDF increasing with increasing z .

The physical mechanism or mechanisms for the dependence of magnetic properties on z are not known with certainty. However, probable mechanism in-

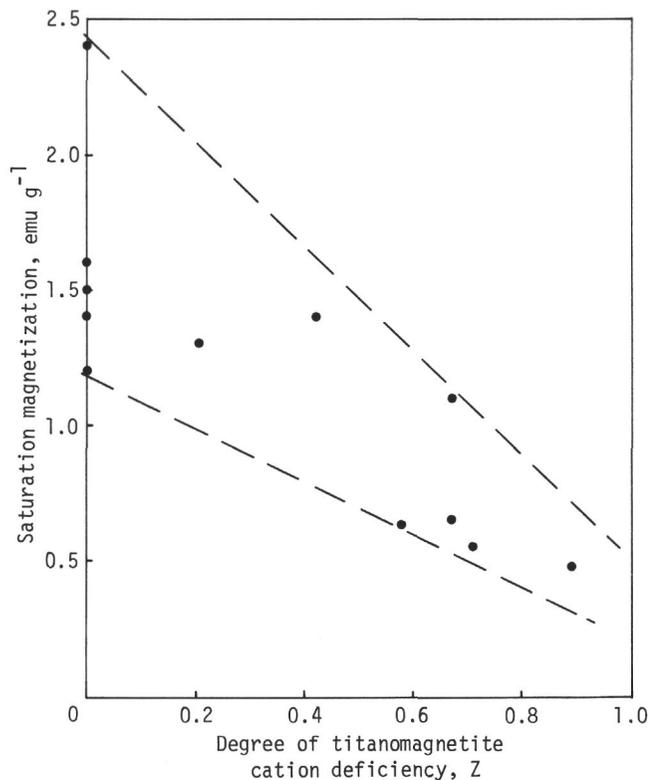


Figure 10. Massive basalts from Site 319. Variation of saturation magnetization with titanomagnetite cation deficiency.

clude: (a) Decrease in effective grain size, in contrast with observed grain size, when grains are subdivided by volume change cracks, with the possible production of superparamagnetic grains in high z conditions. (b) Loss of magnetic oxide material by replacement by non-magnetic phases such as sphene and iron hydroxides. (c) A sharp decrease in J_s on which J_0 and k depend, for $z > 0.6$.

Noting the strong influence of titanomagnetite cation deficiency on J_0 , it might be expected that extensive directional remagnetization would occur during the alteration process. However, as already suggested by Marshall and Cox (1971), Johnson and Merrill (1974), and Ryall (in preparation), this does not seem to be the case since samples with both highly oxidized and stoichiometric titanomagnetite yield on cleaning very similar paleomagnetic directions (Ade-Hall and Johnson, *Paleomagnetism of Basalts*, this volume). Thus it seems that plate motion and original magnetizing field information can safely be identified in at least most paleomagnetic directions from halmyrolyzed submarine basalts.

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