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Magnetic properties of oceanic pillow basalts: evidence from Macquarie Island

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Summary. A combined palaeomagnetic, hysteresis, thermomagnetic, and electron microprobe study has been carried out on pillow basalts from Late Tertiary oceanic crust exposed on Macquarie Island. Oriented cores were collected from four sites in the North Head region where the basalts are unmetamorphosed but have suffered pervasive seafloor weathering and at four sites near Langdon Point where the pillow lavas have experienced metamorphism to the greenschist facies. Field geologic and petrologic evidence suggests that the North Head samples are representative of the weathered zone of Late Tertiary oceanic crust while the specimens from Langdon Point are representative of pillow basalts from >500 m into the oceanic lithosphere. Geometric mean intensities of natural remanence (NRM) were 0.7×10^{-3} G for North Head samples and 0.6×10^{-3} G for specimens from Langdon Point. The geometric mean values of low field susceptibility (χ) and Koenigsberger ratio (Q) for North Head samples (0.1×10^{-3} G Oe^{-1} and 9.8) are similar to those of DSDP basalts. The mean value of χ and Q for Langdon Point samples (2.8×10^{-3} G Oe^{-1} and 0.3) is similar to those observed in metabasalt dredged from oceanic escarpments.

Hysteresis, thermomagnetic and electron microprobe data indicate that the titanomaghemites in the North Head samples have suffered a high degree of low temperature oxidation. Langdon Point samples show reversible thermomagnetic curves with a magnetic Curie temperature (580°C), indicating that metamorphism has altered the magnetic mineralogy. This metamorphism is thought to occur at or near the ridge during the seafloor spreading process. Thus, the NRM of the metamorphosed pillow basalts would still record geomagnetic reversals and contribute to magnetic lineations. The low NRM intensities are ascribed to prolonged seafloor weathering of North Head samples and to metamorphism of the basalts from Langdom Point. Since the 10^{-3} G NRM intensities of pillow basalts are too low to account for the observed amplitude of marine magnetic anomalies, the underlying basaltic and doleritic sheeted dyke complex must also contribute to the anomalies.

1. Introduction

The Vine–Matthews hypothesis (Vine & Matthews 1963) has become one of the cornerstones of theories of global plate tectonics (Morgan 1968; Isacks, Oliver & Sykes 1968). The basic physical mechanism behind the linear magnetic anomalies seems clear, but an accurate model of the source(s) of the magnetic lineations is not yet available. Thorough understanding of the magnetic quiet zones and changes in anomaly amplitudes and frequencies with increasing age of the underlying oceanic crust will only be accomplished by construction of an adequate model of the magnetic properties of oceanic crustal lithologies. Any changes in magnetic properties resulting from seafloor weathering processes should be incorporated in the desired model.

Detailed magnetic and petrologic study of dredged pillow lavas by Carmichael (1970), Irving *et al.* (1970), Marshall & Cox (1971), and Johnson & Atwater (1976) indicates that young pillow basalts are very strongly magnetized. The intensity of natural remanent magnetization (NRM) in some dredged samples has exceeded 10^{-1} G (1 G = 10^3 A m^{-1}). If the NRM intensity does not decrease with depth into the oceanic crust, only a thin (< 1-km thick) layer of such strongly magnetic pillow basalts would be required to account for the entire amplitude of marine magnetic anomalies. Deep-tow magnetometer profiles over oceanic ridge crests also indicate that at least the upper portion of the pillow lava layer of young oceanic crust is very strongly magnetized (Atwater & Mudie 1973; Sclater & Klitgord 1973; Larson *et al.* 1974). Examinations of the effects of seafloor weathering on magnetic properties of dredged basalts have also shown that pillow lavas are very susceptible to low temperature oxidation (Irving 1970; Marshall & Cox 1972). One dominant effect of this oxidation is to decrease the NRM intensity. Since dredge hauls only sample the uppermost pillow lavas of young oceanic crust near active spreading ridges, it is not possible to determine changes of magnetic properties with increasing depth into the oceanic crust.

Recent investigations of Deep-Sea Drilling Project (DSDP) basalts indicate that the upper pillow lavas of ancient oceanic crust have NRM intensities lower than young dredged pillows. Lowrie, Lovlie & Opdyke (1973a, b) reported an average NRM of 1.0×10^{-3} G for DSDP basalts from the Atlantic and an average NRM intensity of 2.0×10^{-3} G for North Pacific DSDP basalts. These lower NRM intensities are probably the result of prolonged seafloor weathering and attendant oxidation of the titanomagnetites. Preliminary results from DSDP deep basement holes suggest that similar processes may be operative at substantial depths into layer 2, even in very young crust (Johnson & Ade-Hall 1975). The results of Leg 37 drilling (JOIDES Staff 1974) near the Mid-Atlantic Ridge south of the Azores indicate that, although strongly magnetized basalts do occur locally, the NRM of the complete 580-m section drilled is not sufficient to produce the observed anomalies.

1.1 OCEANIC CRUST ON MACQUARIE ISLAND

Another approach to the construction of a model of the sources of marine magnetic anomalies is to examine the magnetic properties of oceanic crustal rocks exposed in ophiolite complexes. Moores & Vine (1971, 1972) have undertaken such a study of the petrology and magnetic properties of the Troodos ophiolite complex. Macquarie Island (54° 15′ S, 159° E) also affords an exposure of ancient oceanic crust. Field geologic, petrologic and geochemical studies of Macquarie Island by Varne, Gee & Quilty (1969) and Varne & Rubenach (1972) have revealed lithologies and a stratigraphic sequence similar to those of the Troodos ophiolite complex. In addition, studies of marine magnetic anomalies south-east of Australia have shown east–west trending anomalies as expected from seafloor spreading of the Australia–Antarctic Ridge (Weissel & Hayes 1972). Marine and on-land gravity and magnetic investigations of the region near Macquarie Island by Williamson (1974) have shown magnetic lineations crossing the island and terminating at the Macquarie Trench to the east of Macquarie Island. Palaeontological evidence on Globigerina ooze in interstices between pillows indicates a Pliocene age (Varne *et al.* 1969). The geologic and geophysical data indicate that the oceanic crust now exposed on Macquarie Island was produced during Late Tertiary seafloor spreading of the Australia–Antarctic Ridge, has moved northward with the Indian plate, and has subsequently been uplifted by compression between the Indian and Pacific plates along the Macquarie Ridge Complex. Thus, examination of the magnetic mineralogy of the various lithologies on Macquarie Island offers an exceptional opportunity to determine the magnetic properties of Late Tertiary oceanic crust. The plate tectonic setting of Macquarie Island is illustrated in Varne *et al.* (1969) and Varne & Rubenach (1972).

We have previously published the results of preliminary study of magnetic properties of unoriented hand samples representative of the various lithologies exposed on Macquarie Island (Butler & Banerjee 1973; Banerjee, Butler & Stout 1974). We report here the result of examination of magnetic properties of a much more extensive collection of oriented cores from Macquarie Island pillow lavas.

1.2 SAMPLING LOCALITIES AND DESCRIPTION

Petrologic data of Varne & Rubenach (1972) indicate that pillow basalts exposed in the North Head region of Macquarie Island are relatively fresh and have not been exposed to metamorphism. Our examination of polished thin sections of eight specimens from this locality confirms this conclusion. Most of the specimens are coarsely porphyritic, consisting of compositionally zoned calcic plagioclase (An_{60-80}) and clinopyroxene phenocrysts in a groundmass of less calcic plagioclase, pyroxene and intergranular patches of devitrified glass. A small percentage of euhedral, reddish Cr-rich spinel is present in all specimens. No olivine is present. Primary gas vesicles in these samples are either empty or partially filled with microcrystalline calcite, clay minerals, hematite and ferriceladonite. The latter has been described by Bence, Papike & Ayuso (1975) in the upper 10 m of DSDP Leg 15 basalts from the Central Caribbean. Late-stage, fine-grained sulphides are ubiquitous.

Pillow lavas collected near Langdon Point have essentially the same silicate mineralogy. The Cr-rich spinel is absent, and the sulphide phases are either rare or absent. The plagioclase phenocrysts are much more altered and vesicles are filled with radial growths of chlorite. Unlike the North Head locality, these rocks have experienced conditions typical of the low grades of metamorphism. Varne & Rubenach (1972) argue that this metamorphism is characteristic of the crustal accretion process at spreading oceanic ridges and is not the result of a metamorphic event associated with the tectonic uplift of Macquarie Island. Although isolated exposures and fault bounded terrain prevent unambiguous assignment to specific levels, the petrologic evidence would suggest that the North Head pillow lavas are representative of the upper (100–200-m ?) portion of the oceanic pillow lava layer while the Langdon Point pillow basalts are from deeper oceanic crust (> ½-km depth ?).

The Fe–Ti oxide phases in both the North Head and Langdon Point localities crystallized from a liquid late in the cooling history. They occur typically as skeletal and dendritic crystals within the fine-grained groundmass. They comprise 2–4 per cent of the total rock by volume, and the dimensions of single grains rarely exceed 10 μm.

In order to investigate the effect of burial metamorphism and seafloor weathering on the magnetic properties of pillow basalts, oriented cores were collected at four sites (#8 to #11) near Langdon Point and at four sites (#12 to #15) on the eastern coast of North Head. The field geologic setting of both sampling localities is illustrated in Varne *et al.* (1969) and Varne & Rubenach (1972). Samples were collected with a portable gasoline powered drill and were oriented by magnetic compass. An average of 10 cores was collected at each site, and an average of two specimens was cut from each oriented core. At each site, sampling covered 6–8 m^2 of outcrop, with samples being taken from four to eight individual pillows at each site. Care was taken to sample both exteriors and interiors of the pillows, which ranged from <½ m to >2 m in linear dimension at both sampling localities.

2. Remanent magnetization

2.1 NATURAL REMANENCE

Because of tectonic disturbance of Macquarie Island, it is impossible to unambiguously determine the original attitude of strata at either the North Head or Langdon Point sampling localities. Thus, directions of natural remanence cannot be used to determine palaeomagnetic pole positions. However, distributions of NRM directions within each sampling site are very useful in determining the precision with which stable remanence is preserved in these rocks.

Stereoplots of NRM directions for site 8 from Langdon Point (metamorphosed) and for site 15 from North Head (unmetamorphosed) are shown in Fig. 1. These sample plots are characteristic of all sampling sites at the two localities. The NRM directions for site 8 show a considerable scatter (α_{95} = 19.6°) about the mean direction of $I = -32.2°$ and $D = 232.8°$. Much of this scatter is toward the present axial dipole field direction at the sampling locality. This observation would indicate that the pillow basalts of the Langdon Point region are susceptible to significant components of viscous magnetization. The NRM directions for site 15 show much less scatter (α_{95} = 8.6°) about their site mean of $I = -31.9°, D = 135.4°$.

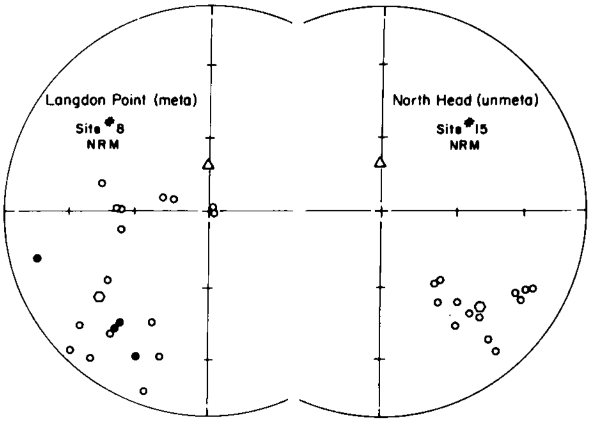

Figure 1. Equal area stereogram of directions of natural remanent magnetization for site 8 from Langdon Point and site 15 from North Head. Open figures indicate directions in the upper hemisphere while solid figures are in the lower hemisphere. The hexagon indicates the site mean NRM direction while the triangle is the present axial dipole field direction at Macquarie Island.

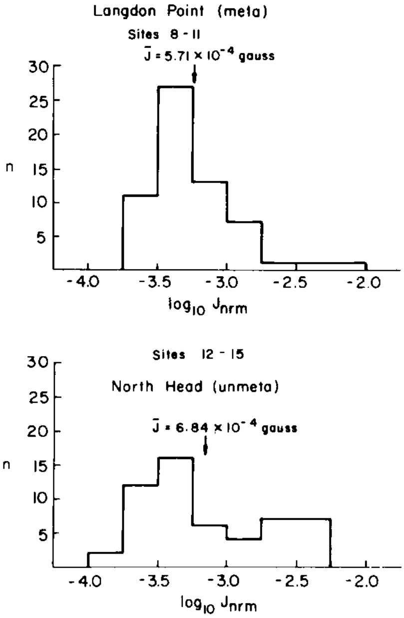

Figure 2. Histograms of intensity of natural remanent magnetism for sites 8–11 from Langdon Point and sites 12–15 from North Head. The geometric mean NRM intensity is 5.71 $\times 10^{-4}$G for sites 8–11 and 6.84 $\times 10^{-4}$G for sites 12–15.

These unmetamorphosed North Head pillow lavas do not appear to be susceptible to large components of viscous magnetization.

Fig. 2 shows a histogram of intensities of natural remanence for all specimens from Langdon Point (sites 8–11) and all specimens from North Head (sites 12–15). Both sampling localities show NRM intensities which are lower than anticipated. The geometric mean intensity of NRM is 0.57 $\times 10^{-3}$ G for sites 8–11 and 0.68 $\times 10^{-3}$ G for sites 12–15. These values are much lower than the 10^{-2} to 10^{-1}-G intensities observed in some dredged pillow basalts, but are similar to the 10^{-3}-G mean intensity observed for Atlantic DSDP basalts (Lowrie *et al.* 1973a). The low intensities of NRM in the Atlantic DSDP samples were thought to be the result of low titanomagnetite content. However, hysteresis measurements of these Macquarie Island samples, described in a later section, show saturation magnetization and saturation remanence values which are similar to those observed for dredged pillow lavas (Irving *et al.* 1970; Marshall & Cox 1972). Thus, it would appear that the low NRM intensities observed for these samples are not due to low titanomagnetite content.

2.2 ALTERNATING FIELD DEMAGNETIZATION

Complete alternating field (AF) demagnetization curves were obtained for two specimens from each site. Results for sites 8 and 15 are shown in Fig. 3 and are representative of the results for all sites at their respective sampling localities. Site 8 shows an initial rapid decline in NRM intensity followed by a more gradual decrease in intensity for AF > 200 Oe. The initial decline is accompanied by a large directional change in which the NRM direction moves away from the axial dipole direction. These observations would suggest that the NRM of pillow lavas from Langdon Point is composed of a stable remanent component along with a significant viscous component. Specimens from site 15 show a smooth decrease in intensity

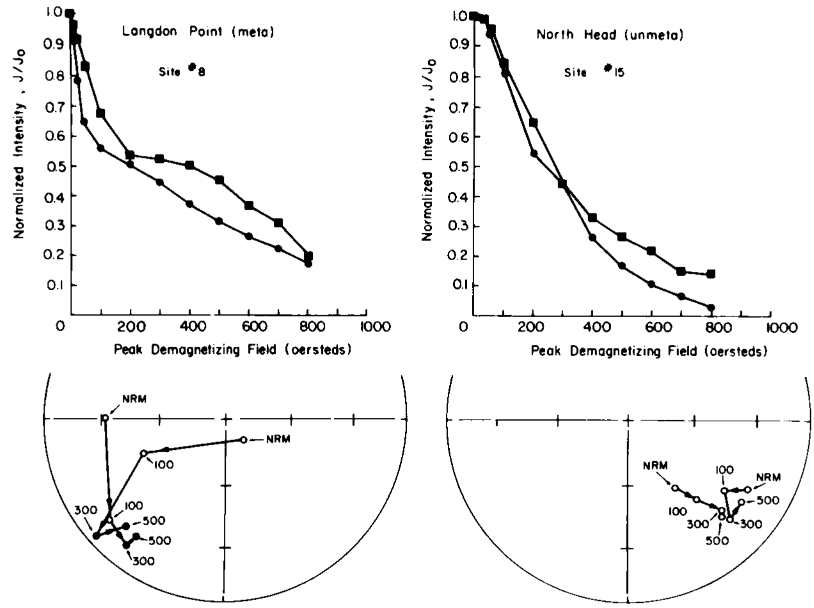

Figure 3. Alternating field demagnetization of sites 8 and 15. Normalized intensity v peak demagnetizing field for two samples from each site are shown above stereograms of attendant NRM directional changes. The numbers adjacent to NRM directions indicate the peak demagnetizing field (Oe).

during AF demagnetization and only a slight movement of NRM direction away from the axial field direction. It would again appear that the North Head pillow basalts contain only a small viscous component in addition to the stable NRM.

Fig. 4 shows the NRM directions of sites 8 and 15 after AF demagnetization at 400 Oe peak field. As expected, demagnetization of site 15 produces only a slight movement of the site mean away from the axial dipole direction (from $I = -31.9°$, $D = 135.4°$ to $I = -21.0$, $D = 136.6°$) and only a small decrease in scatter of NRM (from $\alpha_{95} = 8.6°$ to 4.7°). Thus, only a small viscous component is added to the stable NRM of the samples from North Head. Demagnetization of site 8 has produced a large change in the mean direction (from $I = -32.2°$, $D = 232.8°$ to $I = +18.5°$, $D = 224.9°$) and significantly decreased the scatter in

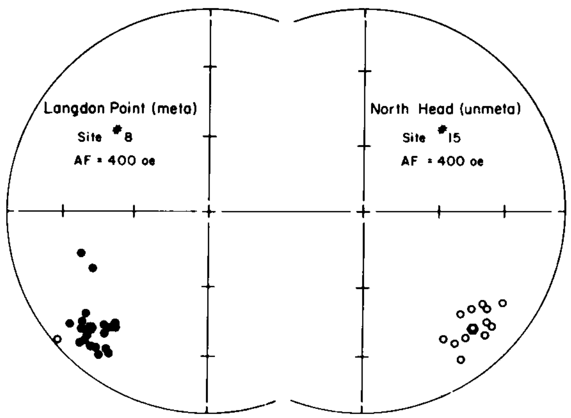

Figure 4. Equal area stereogram of directions of NRM for site 8 and site 15 after demagnetization in a peak alternating field of 400 Oe. The hexagon shows the site mean direction.

directions (from $\alpha_{95} = 19.6^\circ$ to 5.0°). The movement of the mean direction is away from the axial dipole direction. Again, this would indicate that the NRM at the Langdon Point sites contains a large viscous component. By knowing the magnitude and direction of the NRM mean for site 8 along with the direction of the stable component and the direction of the viscous component (assumed parallel to the axial dipole field), the magnitudes of the average stable and viscous components can be calculated. This calculation yields an average stable component of 0.65×10^{-3} G while the average viscous component is 0.55×10^{-3} G.

Histograms of median destructive fields (MDF = AF field required to reduce NRM to 50 per cent of its original intensity) for sites 8–11 and sites 12–15 are shown in Fig. 5. Both localities exhibit a range of AF stabilities with mean MDF between 350 and 450 Oe. These values are similar to those observed for DSDP basalts (Lowrie *et al.* 1973a, b) and indicate good stability of natural remanence.

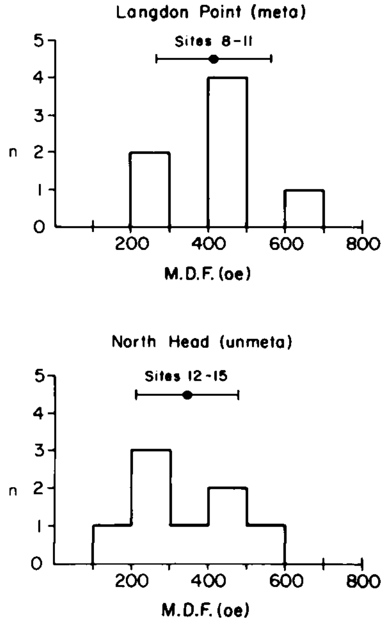

Figure 5. Histograms of median destructive field (MDF) for sites 8–11 and 12–15. Solid circle shows the arithmetic mean and the error bar is two standard deviations.

2.3 VISCOUS MAGNETIZATION

Acquisition of viscous magnetization was examined for two specimens from each site. All specimens had previously been AF demagnetized in a 1000-Oe peak field. Specimens were then placed in a solenoid and exposed to a 1-Oe field. The intensity of viscous remanence (VRM) was measured periodically during the course of the experiment. Results of VRM acquisition for one specimen from site 8 and one specimen from site 14 are shown in Fig. 6. As expected from examination of NRM directions and AF demagnetization behaviour, specimens from sites 8–11 showed more rapid VRM acquisition than specimens from sites 12–15. The slope of the VRM *v* log *T* plots yields the viscosity coefficient, *S*. The geometric mean of viscosity coefficients is 2.3×10^{-5} G Oe^{-1} for sites 8–11 and 6.0×10^{-6} G Oe^{-1} for sites 12–15. These viscous acquisition experiments confirm that the pillow basalts from

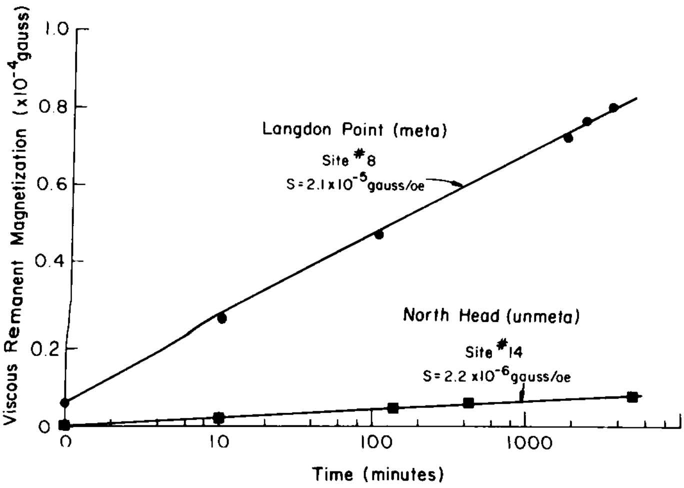

Figure 6. Acquisition of viscous remanence in 1 Oe field. Results for one sample from site 8 and one sample from site 14 are shown. Magnetic viscosity coefficient, S, is indicated for each sample.

Langdon Point are much more susceptible to viscous magnetization than are the pillow lavas from the North Head region. This observation is the first indication of a difference in magnetic mineralogy between these two collections of oceanic pillow basalts.

2.4 SUSCEPTIBILITY AND KOENIGSBERGER RATIO

Low field susceptibilities, χ, of all specimens were measured on a commercial AC susceptibility bridge. Koenigsberger ratios, Q, were then calculated by dividing the intensity of natural remanence by the induced intensity = χH. The present field intensity (0.65 Oe) at Macquarie Island was used for H. Results of the susceptibility measurements and calculated Koenigsberger ratios are shown in Fig. 7. The North Head specimens (sites 12–15) show χ and Q values which are similar to those observed for Atlantic and Pacific DSDP basalts (Lowrie *et al.* 1973a,b). However, the Langdon Point specimens (sites 8–11) show a very high susceptibility and resulting low Koenigsberger ratio. The geometric mean susceptibility of $2.8 \times 10^{-3}\,\mathrm{G\,Oe^{-1}}$ is much higher than observed for almost all DSDP and dredged basalts. Similarly, the geometric mean Koenigsberger ratio of 0.31 is much lower than observed in most oceanic pillow lavas. This high χ and low Q in the Langdon Point samples is another indication of a difference in magnetic mineralogy between the two suites of pillow basalts. The important mean parameters of the natural remanence observed at both Macquarie Island sampling localities are summarized in Table 1.

3 Magnetic mineralogy

3.1 HYSTERESIS PROPERTIES

A vibrating sample magnetometer and an electromagnet capable of 20 kOe magnetizing fields were used to obtain hysteresis loops on two samples from each site. Hysteresis experiments were performed on each sample both before and after thermomagnetic analysis. Paramagnetic susceptibility, χ_p, was determined for each sample, using the high field portion of the hysteresis loops, while bulk coercive force, H_c, and saturation remanence, J_r, were read

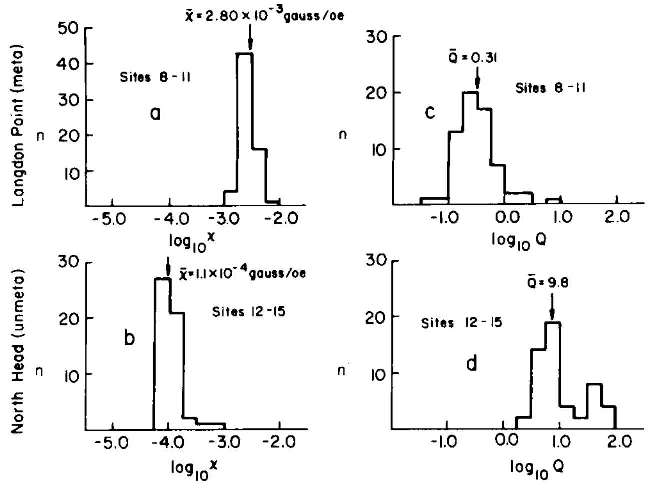

Figure 7. Histograms of susceptibilities (χ) and Koenigsberger ratios (Q). Susceptibilities for sites 8–11 and sites 12–15 are shown in (a) and (b) respectively, while Koenigsberger ratios are shown in (c) and (d) for sites 8–11 and sites 12–15, respectively. Geometric mean values are shown by the arrows and numerical values in each histogram.

Table 1. Average parameters of remanent magnetism.

Locality	Natural remanence (10^{-3} G)	Susceptibility (10^{-3} G Oe^{-1})	Koenigsberger ratio (Q)	MDF	Viscosity coefficient (10^{-5} G Oe^{-1})†
Langdon Point (sites 8–11)	0.57*	2.80	0.31	415	2.3
North Head (sites 12–15)	0.68	0.11	9.8	340	0.6

Notes:

* Intensity of NRM in direction of stable remanence = 0.65×10^{-3} G, see text.

† Time measured in minutes.

directly from each hysteresis loop. Saturation magnetization, J_s, produced by the ferromagnetic minerals, was determined by subtracting the paramagnetic contribution from the high field portion of the hysteresis loops. Remanence to saturation ratio, J_r/J_s, was then calculated for each sample.

Hysteresis parameters obtained before thermomagnetic analysis are listed in Table 2. The difference in magnetic mineralogy suspected from the studies of remanent magnetic properties is dramatically evident in the hysteresis data. The only hysteresis parameter which is similar between the two sampling localities is the paramagnetic susceptibility. Saturation magnetization and saturation remanence are much higher for Langdon Point samples (sites 8–11) than for the samples from North Head (sites 12–15). This could indicate either a higher ferromagnetic content or a higher spontaneous magnetization in the Langdon Point samples. The J_r/J_s ratio and H_c values are much higher for North Head samples. In most North Head samples the remanence to saturation ratio is very close to the 0.5 value, indicative of an assemblage of single-domain (SD) particles with shape anisotropy (Stoner & Wohlfarth 1949). This observation indicates that the unmetamorphosed pillow basalts of North Head contain a distribution of magnetic grains which is predominantly within the SD

Table 2. Hysteresis properties.

Site	J_s (emu g^{-1})	J_r (emu g^{-1})	J_r/J_s	H_c (Oe)	χ_p (emu g^{-1} Oe^{-1})
Langdon Point					
8	1.23	0.28	0.23	67	8.75×10^{-6}
	1.57	0.11	0.07	65	12.0
9	1.39	0.10	0.07	66	8.00
	0.49	0.11	0.23	180	10.0
10	1.32	0.12	0.09	60	8.00
	1.37	0.14	0.10	72	8.00
11	1.18	0.18	0.15	125	8.00
	1.18	0.18	0.15	127	10.0
North Head					
12	0.130	0.050	0.38	260	9.80×10^{-6}
	0.146	0.070	0.48	240	9.80
13	0.274	0.060	0.23	115	8.00
14	0.090	0.040	0.44	205	6.80
	0.066	0.038	0.57	280	9.20
15	0.078	0.040	0.51	240	6.00
	0.078	0.036	0.46	245	6.20

range. By contrast, the low J_r/J_s ratios and low H_c values for the Langdon Point pillow lavas indicate a substantial multidomain (MD) content. This higher MD content would also explain the higher magnetic viscosity coefficients observed in specimens from Langdon Point.

3.2 THERMOMAGNETIC ANALYSIS

Strong field (2.5 kOe) thermomagnetic ($J_s - T$) curves were obtained using a vibrating sample magnetometer equipped with a furnace and vacuum capability. Thermocouples were calibrated by measuring Curie temperatures (θ) of pure nickel ($\theta = 358°$C) and pure magnetite ($\theta = 580°$C). All thermal cycles were done in strong vacuum (pressure never exceeding 2×10^{-6} torr). A complete heating and cooling cycle normally required 2 hr.

A typical thermomagnetic curve for sites 8–11 is shown in Fig. 8(a), while Fig. 8(b) illustrates a representative thermomagnetic curve for sites 12–15. All samples from the Langdon Point locality showed Curie temperatures very near 580°C, indicating that the magnetic mineral in these metamorphosed pillow lavas is magnetite with little or no Ti content. All thermomagnetic cycles for samples from sites 8–11 were very nearly reversible. To our knowledge, reversible thermomagnetic curves showing 580°C Curie points have not been previously observed in analyses of dredged pillow basalts or DSDP basalts. This 'unusual' behaviour is almost certainly the result of the metamorphism experienced by the Langdon Point basalts. We will return to this point in the discussion.

Fig. 8(b) shows an example of the irreversible thermomagnetic curves observed for all samples from North Head. An initial Curie temperature, θ_i, between 300 and 400°C is followed by an increase in magnetization and a subsequent final Curie point, θ_f, between 500 and 580°C. Saturation magnetization after thermal cycling, J_f, was always greater than the initial saturation magnetization, J_i. This type of irreversible thermomagnetic behaviour has been observed in both dredged pillow lavas (Marshall & Cox 1972; Ozima & Larson 1970;

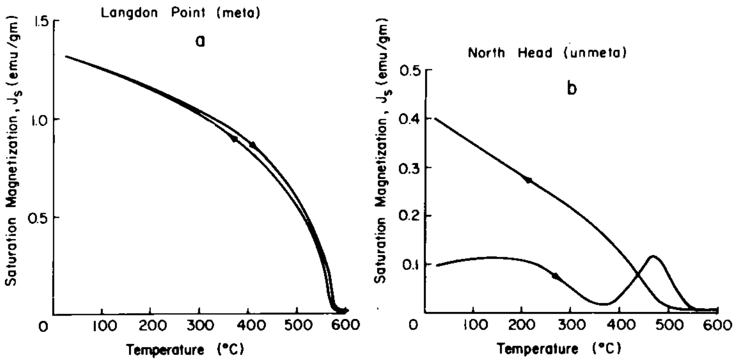

Figure 8. Thermomagnetic curves. A typical thermomagnetic curve for Langdon Point pillow basalts (sites 8–11) is shown in (a) while (b) shows typical thermomagnetic behaviour for North Head samples (sites 12–15). Both curves were done in strong vacuum (2×10^{-6} torr) and a magnetizing field of 2.5 kOe.

Ozima & Ozima 1971) and in DSDP basalts (Lowrie *et al.* 1973a). Observation of irreversible $J_s - T$ behaviour for samples heated in the high vacuum used in these experiments suggests that the magnetic mineral present in these North Head pillow basalts is a non-stoichiometric cation deficient titanomaghemite.

A summary of the initial and final Curie points (θ_i and θ_f) observed in the thermomagnetic analyses are listed in Table 3 along with the ratio of initial to final saturation magnetization, J_i/J_f. These ratios of saturation magnetization were determined from the hysteresis loops measured before and after thermomagnetic analyses. The reversibility of the $J_s - T$ curves for the Langdon Point samples is indicated by J_i/J_f ratios very near unity. In contrast, the irreversible nature of the thermomagnetic curves for samples from North Head is illustrated by the very low J_i/J_f ratios and large differences between θ_i and θ_f. The thermomagnetic parameters for the North Head samples are also illustrated in Fig. 9.

Table 3. Thermomagnetic properties.

Site	θ_i	θ_f	J_i/J_f
Langdon Point			
8	580		1.09
	575		1.05
9	580		1.00
	580		0.93
10	580		0.98
	570		1.00
11	570		1.05
	580		1.00
North Head			
12	305	550	0.35
	320	560	0.20
13	340	530	0.45
14	360	550	0.20
	370	560	0.13
14	380	560	0.16
	380	560	0.18

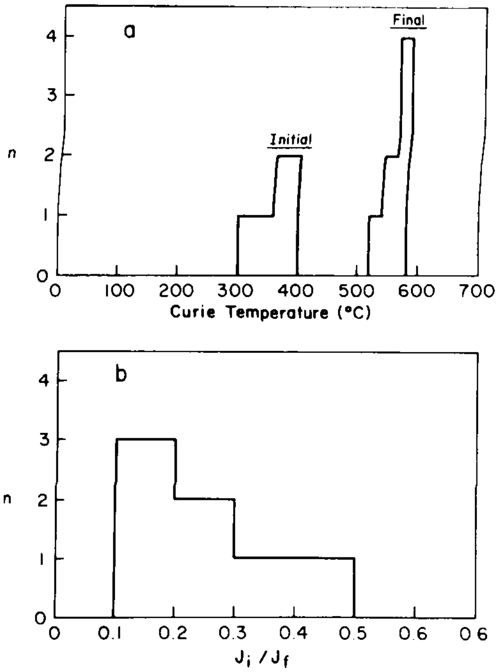

Figure 9. Thermomagnetic parameters of North Head samples (sites 12–15). Histogram of initial and final Curie temperatures observed in thermomagnetic curves is shown in (a). Histogram of ratio of initial saturation magnetization, J_i, to final saturation magnetization, J_f, for North Head samples is shown in (b).

As with the other magnetic properties of the North Head pillow lavas, these $J_s - T$ parameters are very similar to those observed by Lowrie *et al.* (1973a, b) for Atlantic and Pacific DSDP basalts.

In an attempt to confirm the cation-deficient nature of the magnetic mineral in the samples from North Head, determination of FeO : Fe$_2$O$_3$ ratio by wet chemical analysis was undertaken. However, inability to obtain sufficiently pure magnetic separates led to ambiguous results. In another effort to confirm that the important magnetic mineral of these samples is a nonstoichiometric titanomaghemite, a technique of thermomagnetic data analysis developed by Lowrie *et al.* (1973b) was employed. For stoichiometric titanomagnetites, $Fe_{3-x}Ti_xO_4$, the compositional parameter x is related to both the Curie temperature and the spontaneous magnetization. Thus, by assuming that the titanomagnetites are stoichiometric, the initial Curie points, θ_i, can be used to derive a compositional parameter, x_θ. Similarly, a compositional parameter, x_j, can be derived from the J_i/J_f ratio by assuming that magnetite results from the phase splitting observed during thermomagnetic analysis. In Fig. 10, values of x_j based on saturation magnetization data are plotted against the x_θ values derived from the observed initial Curie points. As pointed out by Lowrie *et al.* (1973b), data points falling on or above the $x_j = x_\theta$ line on such a diagram are strong evidence that the magnetic mineral involved is a cation-deficient titanomaghemite. The thermomagnetic data for North Head samples shown in Fig. 10 confirm that the magnetic mineral is definitely a cation-deficient titanomaghemite. Marshall & Cox (1972) have shown that the oxidation of stoichiometric titanomagnetites to titanomaghemites is the natural consequence of seafloor weathering of oceanic pillow basalts. Thus, the thermomagnetic data provide strong evidence that the low NRM intensities observed for pillow basalts from North Head of Macquarie Island are the result of prolonged seafloor weathering.

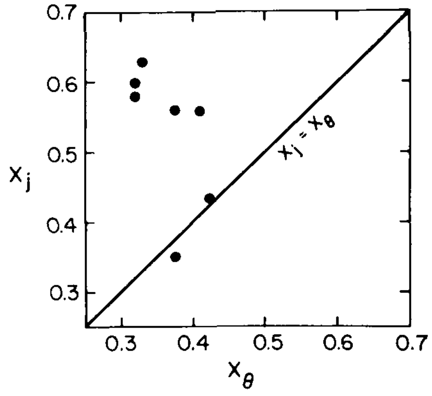

Figure 10. Comparison of titanomagnetite compositional parameter x_j determined from saturation magnetization data and compositional parameter x_θ determined from initial Curie point. Only data for North Head samples (sites 12–15) were used.

3.3 ELECTRON MICROPROBE STUDIES

The dramatic differences in hysteresis parameters, and the results of our thermomagnetic data between the two sampling localities on Macquarie Island, are a result of the different chemical composition of the ferromagnetic minerals. In order to better characterize the Fe–Ti oxide phases, and in particular the cation deficient titanomaghemites in the North Head samples, we attempted to analyse individual grains in polished thin sections prepared from the same cores used for the magnetic studies. Although the maximum dimension of single grains is several microns, their skeletal form makes it virtually impossible to isolate a focused electron beam entirely on the phase of interest. We, therefore, selected grains that were completely embedded in plagioclase feldspar and then simultaneously analysed the mixture for total atomic Fe and Ti. A third detector simultaneously monitored either Ca or Al in order to evaluate the proportion of plagioclase to oxide. As the beam traversed the region of interest and the proportion of plagioclase to oxide phase decreased, the X-ray intensities for Fe(K_α) and Ti(K_α) approached those expected for the pure oxide phase. *The X-ray intensities were calibrated against well-characterized gravimetric standards,* recalculated in terms of cations per four oxygen atoms. Various mixtures of oxide and plagioclase give the same ratio Fe/Ti (atomic) characteristic of the oxide phase alone, providing there is no substantial contribution of Fe and Ti from the plagioclase. This was confirmed by separate analysis of the larger feldspar grains. The elements Mg, Mn, Zn, Cr and S were routinely checked to insure correct identity of a phase. In each case, the observed X-ray intensity could not be distinguished from background values.

In this manner, Fe and Ti concentrations were ratioed for an average of 20–25 grains per polished section and plotted in Fig. 11. This diagram is a portion of the Fe–Ti–O plane in which compositions are plotted in terms of atom fraction of the components FeO, Fe_2O_3 and TiO_2. Lines of constant Fe/Ti are horizontal lines of progressive oxidation and are therefore radial to oxygen. As this ratio provides one independent variable in the Fe–Ti–O plane, the oxidation state of these small grains remains undefined by electron microprobe techniques alone. A second independent parameter, however, is provided by the Curie temperatures of each sample. In the case of the North Head samples, the electron microprobe data indicate that the chemistry of the initially unoxidized titanomagnetites centre around $Fe_{2.3}Ti_{0.7}O_4$. Unfortunately, the relationship between Curie temperature and oxidation parameter z is poorly known for large values of x ($Fe_{3-x}Ti_xO_4$). The data of O'Reilly &

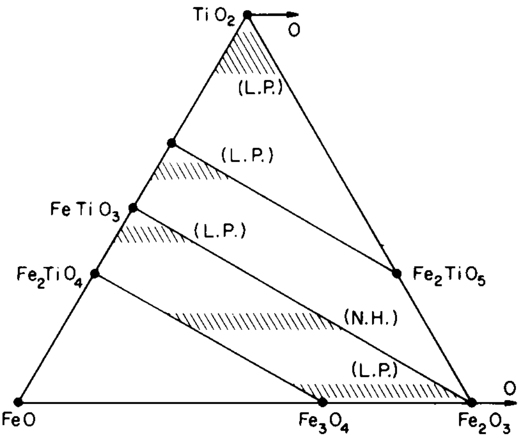

Figure 11. Fe/Ti values by electron microprobe for opaque oxide phases. Symbol (L.P.) denotes Langdon Point samples M-8–M-11. Symbol (N.H.) denotes North Head samples M-12–M-15. Compositions of other phases plotted in terms of cation proportions of the components FeO, Fe_2O_3 and TiO_2. Oxidation lines are horizontal in this diagram. Shaded regions are radial to oxygen. Widths of regions give approximate range of Fe/Ti for all specimens.

Readman (1971) and Ozima & Sakamoto (1971) are shown in Fig. 12 for θ_i in North Head sample M-14. These data suggest that the oxidation parameter z of a typical North Head sample after seafloor weathering has a minimum value of 0.4, which corresponds to a maximum Fe^{2+}/Fe^{3+} of approximately 0.8.

In contrast, Fig. 11 shows that cation-deficient titanomaghemites are absent in samples collected from the Langdon Point locality. Instead, a pure magnetite and a variety of high Ti phases are present. Because of their fine grain size and apparently intergrown habit, the latter are extremely difficult to identify optically. Rutile, Ti-rich hemoilmenite and possibly an orthorhombic phase are apparently present on the basis of Fe/Ti electron microprobe determinations. The latter two, however, could also represent exsolved mixtures of yet even finer-grained phases. The Fe/Ti values for magnetite indicate significant Ti. This must certainly represent various submicroscopic mixtures of magnetite and a more Ti-rich phase.

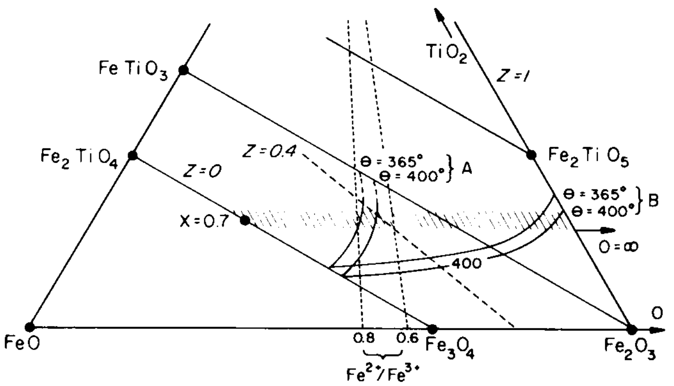

Figure 12. Fe/Ti values and θ_i for North Head sample M-14. Curved solid lines give Curie temperatures according to (A) Ozima & Sakamoto (1971) and (B) O'Reilly & Readman (1971). Dotted lines are radial to TiO_2 and give range of Fe^{2+}/Fe^{3+} consistent with the lower range of T_θ above. The minimum oxidation parameter z on this basis is 0.4. Compositions plotted in cation proportions of the components FeO, Fe_2O_3 and TiO_2.

4 Discussion

The magnetic properties of the samples from North Head on Macquarie Island show dramatic similarity to DSDP basalts. Lowrie *et al.* (1973a) attributed the low NRM intensity (10^{-3} G) of the Atlantic DSDP basalts to low titanomagnetite content. However, the saturation magnetization and saturation remanence observed in hysteresis experiments indicate that the titanomagnetite content of the North Head samples is comparable to that of dredged pillow lavas. The low intensity of natural remanence (0.7×10^{-3} G) observed in these Late Tertiary basalts from Macquarie Island must be reflecting the effects of prolonged seafloor weathering and associated low temperature oxidation of the titanomagnetites. Indeed, thermomagnetic analysis has confirmed that these pillow lava samples contain highly oxidized cation deficient titanomaghemites. Several mechanisms for decrease in intensity of NRM during low temperature oxidation of titanomagnetites have been proposed (Marshall & Cox 1972; Banerjee 1971; Butler 1973), and probably all play some role in decreasing the natural remanent intensity.

In constructing a model of the magnetic properties of the oceanic crust, it is essential to know the depth into the oceanic crust which is represented by the sample collection under study. For most dredged basalts or the early DSDP samples, this is usually a trivial problem since one is almost always sampling the upper few metres of the oceanic crust. However, this can be a difficult problem when examining oceanic crustal materials exposed in ophiolite complexes or dredged from oceanic escarpments. It is not possible to determine the depth of the North Head sampling locality from direct field evidence. However, seismic velocity data on Pacific DSDP basalts and analysis of seismic refraction profiles provide some indirect evidence. Christensen & Salisbury (1973) have measured seismic velocities of Pacific DSDP basalts and have found decreasing velocity with increasing degree of submarine weathering. This decrease of velocity by weathering can be observed in seismic refraction profiles when the depth of weathering exceeds 'several hundred metres'. Although a wide distribution exists in the reported layer 2 refraction velocities, Christensen & Salisbury (1973) have shown that the depth of weathering in oceanic crust older than 80 My has penetrated at least several hundred metres into the oceanic lithosphere. Although no quantitative knowledge of the depth of weathering as a function of age of the oceanic crust is yet available, the depth of the downward advancing weathering front would probably not exceed 200 m in Late Tertiary oceanic crust. Since the pillow basalts from North Head of Macquarie Island have definitely suffered extensive seafloor weathering, they are probably representative of the upper 100–200 m of the pillow lava layer of Late Tertiary oceanic crust.

Although the NRM intensities of the basalts from Langdon Point on Macquarie Island are similar to those observed for samples from North Head and DSDP basalts, almost all other magnetic properties are very different from oceanic basalts previously examined. There is some similarity of NRM intensity, susceptibility, and Koenigsberger ratio between the Langdon Point samples and the metabasalts dredged from escarpments in the Atlantic and Caribbean by Fox & Opdyke (1973). However, lack of hysteresis and thermomagnetic data for the dredged metabasalts make more thorough comparison impossible. The petrologic evidence of Varne & Rubenach (1972) indicates that the basalts from Langdon Point have experienced significant metamorphism, perhaps into the greenschist facies. This metamorphism is thought to have occurred at the time of crustal accretion at the spreading centre and is not associated with the tectonic uplift of Macquarie Island.

The fine-grained titanomagnetites observed in young dredged pillow basalts are known to be very susceptible to chemical change when heated (Marshall & Cox 1972). Any thermal event experienced by these rapidly-quenched extrusive basalts would almost certainly yield chemical changes in the magnetic mineralogy. These chemical changes will likely result in the production of magnetite and Ti-rich hemoilmenite at the expense of the original titanomagnetite. Pillow basalts at any significant depth into the oceanic crust will be exposed to heating by intrusion of feeder dikes leading to overlying pillow lavas, emplacement of underlying sheeted dike and plutonic complexes, or even exothermic hydration reactions within the metamorphosed pillow lavas themselves (Varne & Rubenach 1972). Thus, the metamorphosed pillow lavas from Langdon Point are probably the natural consequence of metamorphism experienced by basalts at significant depth into the oceanic crust.

Incorporation of the data on Langdon Point samples into a model of magnetic properties of the oceanic crust requires an estimate of the depth into the oceanic crust which is being sampled. Again, we must resort to indirect evidence. Gass & Smewing (1973) have found that the zeolite to greenschist facies transition takes place at a depth of 1000 m in the ophiolite complex of the Troodos massif. Although the applicability of the Troodos data to Macquarie Island is uncertain, the greenschist facies metamorphism of the Langdon Point basalts would suggest that this sample collection is representative of depths > 500 m into the oceanic crust. In the Troodos ophiolite complex, the base of the pillow lava series occurs at 1-km depth, and the outcrop becomes 60 per cent basaltic dikes at this level. In the Langdon Point sampling locality, the outcrop is essentially 100 per cent pillow basalts. This observation would suggest that the pillow lavas collected at Langdon Point were derived from < 1-km depth. Therefore, the field geologic and petrologic evidence indicates that the samples from the Langdon Point locality on Macquarie Island are representative of pillow basalts at 500–1000-m depth into the oceanic pillow lava layer.

Since the metamorphism of these deeper pillow lavas is thought to take place during the seafloor spreading process, the NRM of these metamorphosed basalts would still be able to record geomagnetic reversals and contribute to marine magnetic anomalies. Although the Koenigsberger ratio is much lower than in dredged pillow basalts, the examination of natural remanence in the Langdon Point samples indicates that these metamorphosed pillow lavas contain a stable remanence of 0.7×10^{-3} G. The effect of the high susceptibility and low Koenigsberger ratio in a layer of these metamorphosed basalts is impossible to assess without knowledge of the nature of transition in magnetic properties between these basalts and the overlying unmetamorphosed (but weathered) pillow lavas. However, any significant topography in such a high susceptibility layer would yield magnetic anomalies unrelated to geomagnetic reversals. The effect of the large viscous magnetization components observed in the Langdon Point samples is also difficult to evaluate. However, if the layer of metamorphosed basalts is laterally uniform in viscosity coefficient, S, the acquisition of viscous remanence would be uniform and no magnetic anomaly would result. The above mentioned effects of a layer of metamorphosed pillow lavas are admittedly speculative and are in need of confirmation by study of magnetic properties of other ophiolite complexes and samples from deep DSDP drill holes.

It is noteworthy that the NRM intensities observed by Vine & Moores (1972) for pillow basalts from the Troodos massif are significantly higher than those observed at either sampling locality on Macquarie Island. The reasons for this difference are unknown at present. Absence of hysteresis and thermomagnetic data for the Troodos samples makes a detailed comparison difficult.

Conclusion

It is instructive to examine what implications the results of this study have for constructing a model of the magnetic properties of the oceanic crust and sources of marine magnetic anomalies. There is adequate evidence from deep-tow magnetometer profiles and examination of pillow lavas dredged from active spreading ridges to indicate a high intensity of natural remanence ($>10^{-2}$ G) for at least the upper 100 m of young oceanic crust. However, a growing body of evidence from DSDP basalts and the present data on the pillow lavas from North Head on Macquarie Island indicate that progressive submarine weathering of the oceanic crust decreases the NRM intensity of the upper portion of ancient oceanic crust to $\sim 10^{-3}$ G. Lowrie *et al.* (1973a) have suggested that the 10^{-3} G NRM intensities of DSDP basalts are perhaps only representative of the strongly-weathered zone at the top of the pillow lava layer and that unweathered pillow lavas below the weathered zone may be more strongly magnetized. However, if the pillow lavas from Langdon Point on Macquarie Island are representative of pillow basalts in the 500–1000-m depth interval, the NRM intensity of these deeper extrusives would also be in the 10^{-3} G range. Since a 1-km thick layer of pillow basalts magnetized at 10^{-3} G is not sufficient to yield the observed amplitude of marine magnetic anomalies, it is necessary to conclude that the underlying basaltic and doleritic sheeted dike complexes also play a role in the production of magnetic anomalies. Thus, the rock–magnetic data seem to suggest a model in which the contribution to magnetic anomalies by the pillow layer decreases with increasing age of the oceanic crust. The underlying basaltic and doleritic dikes may not be susceptible to alteration and resultant decrease in NRM intensity (Banerjee *et al.* 1974). Therefore, the contribution to magnetic anomalies by the basaltic and doleritic dikes may remain constant while the contribution from the pillow lava layer is decreasing with age. Analyses of magnetic anomaly profiles by Cox, Blakely & Phillips (1972) and Blakely (1976) have also suggested a two-layer model for the sources of marine magnetic anomalies.

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References

Atwater, T. & Mudie, J. D., 1973. Detailed near-bottom geophysical study of the Gorda Rise, *J. geophys. Res.*, 78, 8665–8686.

Banerjee, S. K., 1971. Decay of marine anomalies by ferrous ion diffusion, *Nature Phys. Sci.*, 229, 181.

Banerjee, S. K., Butler, R. F. & Stout, J. H., 1974. Magnetic properties and mineralogy of exposed oceanic crust on Macquarie Island, *Z. Geophys.*, 40, 537–548.

Bence, A. E., Papike, J. J. & Ayuso, R. A., 1975. Petrology of submarine basalts from the Central Caribbean: DSDP Leg 15, *J. geophys. Res.*, 80, 4775–4804.

Blakely, R. J., 1976. Increase in thickness of the magnetic layer as a function of age, *International Woollard Symposium*, Honolulu, December 8–10, 1974, in press.

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

Butler, R. F. & Banerjee, S. K., 1973. Magnetic properties of exposed oceanic crust on Macquarie Island, *Nature Phys. Sci.*, 244, 115–118.

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

Christensen, N. I. & Salisbury, M. H., 1973. Velocities, elastic moduli, and weathering-age relations for Pacific layer 2 basalts, *Earth Planet. Sci. Lett.*, **19**, 461–470.

Cox, A., Blakely, R. J. & Phillips, J. D., 1972. A two-layer model for marine magnetic anomalies, *EOS, Trans. AGU*, **53**, 974.

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

Gass, I. G. & Smewing, J. D., 1973. Intrusion, extrusion, and metamorphism at constructive margins: Evidence from the Troodos Massif, Cyprus, *Nature*, **242**, 26–29.

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

Irving, E., Park, J. K., Haggerty, S. E., Aumento, F. & Loncarevic, B., 1970. Magnetism and opaque mineralogy of basalts from the mid-Atlantic Ridge at 45° N, *Nature*, **228**, 974–976.

Isacks, B., Oliver, J. & Sykes, L. R., 1968. Seismology and the new global tectonics, *J. geophys. Res.*, **73**, 5855–5899.

Johnson, H. P. & Ade-Hall, J. M., 1975. Magnetic results from basalts and sediments from the Nazca Plate, *Nature*, **257**, 471–473.

Johnson, H. P. & Atwater, T., 1976. A magnetic study of the basalts from the mid-Atlantic Ridge at 37° N, *Geol. Soc. Am. Bull.*, in press.

JOIDES Scientific Staff, 1974. Leg 37 – the volcanic layer, *Geotimes*, **19** (12), 16–18.

Larson, R. L., Larson, P. A., Mudie, J. D. & Spiess, F. N., 1974. Models of near-bottom magnetic anomalies on the East Pacific Rise crest at 21° N, *J. geophys. Res.*, **79**, 2686–2689.

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

Lowrie, W., Lovlie, R. & Opdyke, N. D., 1973b. Magnetic properties of Deep Sea Drilling Project basalts from the North Pacific Ocean, *J. geophys. Res.*, **78**, 7647–7660.

Marshall, M. & Cox, A., 1971. Magnetism of pillow basalts and their petrology, *Geol. Soc. Am. Bull.*, **82**, 537–552.

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

Moores, E. M. & Vine, F. J., 1971. The Troodos Massif, Cyprus, and other ophiolites as oceanic crust, evaluation and implications, *Phil. Trans. R. Soc. Lond. A*, **268**, 443–466.

Morgan, W. J., 1968. Rises, trenches, great faults, and crustal blocks, *J. geophys. Res.*, **73**, 1959–1982.

O'Reilly, W. & Readman, P. W., 1971. The preparation and unmixing of cation-deficient magnetites, *Z. Geophys.*, **37**, 321–327.

Ozima, M. & Larson, E. E., 1970. Low- and high-temperature oxidation of titanomagnetite in relation to changes in the magnetic properties of submarine basalts, *J. geophys. Res.*, **75**, 1003–1017.

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

Ozima, M. & Sakamoto, N, 1971. Magnetic properties of synthesized titanomaghemite, *J. geophys. Res.*, **76**, 7035–7046.

Sclater, J. G. & Klitgord, K. D., 1973. A detailed heat flow, topographic, and magnetic survey across the Galapagos spreading center at 86° W, *J. geophys. Res.*, **78**, 6951–6975.

Stoner, E. C. & Wohlfarth, E. P., 1949. A mechanism of magnetic hysteresis in heterogeneous alloys, *Phil. Trans. R. Soc. Lond. A*, **240**, 599–642.

Varne, R., Gee, R. D. & Quilty, P. G. J., 1969. Macquarie Island and the cause of oceanic linear magnetic anomalies, *Science*, **166**, 230–232.

Varne, R. & Rubenach, M. J., 1972. Geology of Macquarie Island and its relationship to oceanic crust, *Ant. Res. Ser.*, **19**, 251–266.

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

Vine, F. J. & Moores, E. M., 1972. A model for the gross structure, petrology, and magnetic properties of oceanic crust, *Geol. Soc. Am. Mem.*, No. 132, 195–205.

Weissel, J. K. & Hayes, D. E., 1972. Magnetic anomalies in the Southeast Indian Ocean, *Ant. Res. Ser.*, **19**, 165–196.

Williamson, P., 1974. Recent studies of Macquarie Island and the Macquarie Ridge complex, *Bull. Aust. Soc. Explor. Geophys.*, **5**, 19–22.