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# The Effects of Alteration on the Natural Remanent Magnetization of Three Ophiolite Complexes: Possible Implications for the Oceanic Crust

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Magnetic properties are compared for the pillow basalts and sheeted dike complexes for the following three ophiolite suites: Macquarie Island (~27 million years), Troodos Massif, Cyprus (~middle Cretaceous), and Smartville complex, California (~Jurassic). The magnetic properties of the pillow basalts strongly depend on their degree of alteration. From the least altered, low-temperature-oxidized, upper pillow basalts of Macquarie Island and the pillow basalts of the Troodos Massif (zeolite facies metamorphism) to the most altered pillow basalts of the Smartville complex (greenschist facies metamorphism) the average intensity of the natural remanent magnetization (NRM) decreases from a maximum of $80\times10^{-4}$ to $0.50\times10^{-4}$ gauss; the Koenigsberger ratio ($Q$) decreases from 6 to 0.3; the contribution due to viscous remanent magnetization (VRM) increases, and the NRM stability with respect to alternating fields decreases. For the most altered pillow basalts of the Smartville complex the NRM is probably predominantly a VRM, acquired during the present polarity epoch. Thermomagnetic analyses for the least altered pillow basalts exhibit the characteristic behavior of low-temperature-oxidized cation deficient titanomagnetites, while the more altered pillow basalts have reversible thermomagnetic curves with magnetite-like Curie points, probably caused in situ by thermally induced unmixing of the low-temperature-oxidized titanomagnetites. The sheeted dike complexes have NRM intensities of about $10\times10^{-4}$ gauss and $Q$ values of about 0.8, and most of their magnetic properties do not vary much between the three ophiolite complexes. All the sheeted dike samples have reversible thermomagnetic curves with magnetite-like Curie points. If these ophiolite complexes represent material which was originally formed at spreading centers and if their alteration represents ocean floor metamorphism, then with progressive alteration the pillow basalts lose their magnetic recording qualities and become poorer sources for the marine magnetic anomalies, and the underlying sheeted dike complexes become relatively more important. The most probable site for the occurrence of the sea floor metamorphism is in the relatively high temperature, high heat flow regions near spreading centers.

## 1. Introduction

Understanding the source layer of the marine magnetic anomalies has been the

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focus of a growing number of paleomagnetic and rock magnetic studies. The magnetic properties of unoriented and partly oriented (inclination only) basalts dredged and cored in young oceanic crust near the mid-ocean spreading centers (IRVING *et al.*, 1970; CARMICHAEL, 1970; MARSHALL and COX, 1971a; JOHNSON and ATWATER, 1977) have been interpreted to suggest that only a relatively thin magnetized layer ($<1$ km) is responsible for the observed anomalies. An approximately 500 m thick magnetic layer has also been obtained from the inversion of magnetic anomalies and from the frequent correlation between magnetic and topographic features (TALWANI *et al.*, 1971; SCLATER and KLITGORD, 1973; ATWATER and MUDIE, 1973). However, recent data from the Deep Sea Drilling Project (DSDP), with maximum basement penetration of 583 m, suggest that a magnetic layer several kilometers thick is required to account for the anomalies (SCIENTIFIC PARTY DSDP, LEG 37, 1975; JOHNSON, 1976); this conclusion is inferred because: 1) the NRM intensities are relatively low; 2) apparent reversals are present in the cored columns; 3) a significant fraction of the cored material consists of relatively non-magnetic sediment, rubble, breccia or voids. Thus, DSDP has provided the first hard data suggesting that even in oceanic crust as young as 7 million years (Legs 45 and 46) a 500 m thick basement layer is probably not sufficient to account for the observed anomalies and that the present drilling capabilities of the Glomar Challenger might not be sufficient to sample the entire thickness of the magnetic layer.

The intensity of NRM (natural remanent magnetization) of extrusive oceanic basalts has been shown to decrease dramatically within a few tens of kilometers away from the spreading centers (IRVING *et al.*, 1970; CARMICHAEL, 1970; JOHNSON and ATWATER, 1977) in general agreement with the comparable decrease of the amplitude of the magnetic anomalies. Low temperature oxidation of the remanence-carrying titanomagnetite minerals is now thought to be largely responsible for the observed decrease of NRM intensity (IRVING *et al.*, 1970; CARMICHAEL, 1970; OZIMA and OZIMA, 1971; MARSHALL and COX, 1971b; JOHNSON and MERRILL, 1972). BLAKELY (1976) analyzed magnetic anomaly data and found that the widths of the transition zones between oppositely magnetized oceanic crustal blocks increase with age. BLAKELY (1976) attributes this to thickening with age of the magnetic source layer enhanced by the magnetic degradation of upper extrusives. According to this model, the remanence of the extrusive basalts becomes relatively less important as they become older, and deeper rocks, presumably basaltic or doleritic dikes, become relatively more important as sources for the marine magnetic anomalies.

Ophiolite complexes, which are commonly thought to represent old oceanic crust, are the only presently available source for studying the deeper levels of the oceanic crust in relation to their contributions to the marine magnetic anomalies. In this paper we compare the magnetic properties of three ophiolites, restricting our discussion to the pillow basalts and the underlying dikes, which together probably account for much of the oceanic magnetic signal. The three ophiolites are: 1) the Macquarie Island ophiolite complex (54°S, 159°E), which is about 27 m.y. old (WILLIAMSON, 1974); 2) the Troodes Massif of Cyprus (35°N, 33°E), probably of middle Cretaceous age (MOORES and VINE, 1971); 3) the Smartville ophiolite complex of California (39°N, 121°W), tentatively of Jurassic age (SCHWEICKERT and COWAN, 1975). We find that in each of these ophiolite complexes the dikes contribute a significant and sometimes dominant fraction of the magnetic signal; however, the relative importance of the dike contribution is not related simply to the age of the ophiolite suite, but it depends more on the degree of alteration experienced by the pillow basalts of each complex.

## 2. Some Aspects of Metamorphism and Geochemistry

### *2.1 Macquarie Island*

The doleritic dike swarms have been metamorphosed at different grades within the amphibolite facies (VARNE and RUBENACH, 1972). Some of the pillow basalts have undergone metamorphism at the greenschist facies level (designated as lower pillows); however, some of the pillows (upper pillows) are probably unmetamorphosed, although the presence of clay minerals suggests weathering of these rocks or at most very low grade metamorphism (VARNE and RUBENACH, 1972). CANN (1970) showed that the abundances of Ti, Y, Zr in ocean-floor basalts are affected little, if at all, by secondary weathering and metamorphism. PEARCE and CANN (1971) used these elements to discriminate between different volcanic regimes, and the method has been recently supported by studies of progressive metamorphism within a single basalt flow (SMITH and SMITH, 1976). Ti, Y, Zr analyses of Macquarie Island rocks show that they most closely resemble ocean-floor basalts (VARNE and RUBENACH, 1972). This conclusion has been confirmed more quantitatively by recent Sr isotope studies of WILLIAMS and MURTHY (1977).

### *2.2 Troodos Massif*

The sheeted intrusive complex consists of basaltic dikes metamorphosed at the greenschist facies level (GASS and SMEWING, 1973; VINE and MOORES, 1972). The sheeted dikes grade upwards into the lower pillow lava complex, representing mostly zeolite facies metamorphism (GASS and SMEWING, 1973). Although the zeolite facies—greenschist facies metamorphic boundary is near the bottom of the pillow complex it does not coincide with the lithologic boundary, so that the 'metamorphic contact can occur either within the lower pillow lavas or the sheeted intrusive complex' (GASS and SMEWING, 1973). PEARCE and CANN (1971) analyzed the trace elements of 12 samples from the sheeted intrusive complex and pillow lavas of the Troodos Massif. When plotted on the Ti, Zr, Y triangle, these samples show close affinity to the ocean-floor basalts.

### *2.3 Smartville ophiolite complex*

Preliminary petrological studies show that both in the sheeted dikes and pillow basalts epidote and amphibole are ubiquitous, and sphene and calcite are also frequently present. Thus, assuming a low $P$ high $T$ metamorphic evironment these mineral assemblages suggest metamorphism at greenschist facies grade. The data available thus far are consistent with similar metamorphic grade for both extrusive basalts and sheeted dike complex. In addition, the lack of schistosity and partial preservation of the igneous texture suggest that metamorphism was not accompanied by deformation.

For the ophiolite suites under discussion, the pillow lavas of the Troodos Massif and the upper pillows of Macquarie Island are the least metamorphosed, whereas the lower pillows of Macquarie Island and the pillow basalts from the Smartville complex have been more extensively metamorphosed at the greenschist facies level; at this point it is not possible to distinguish between the metamorphic grades of the lower pillow basalts of Macquarie Island and those of Smartville complex. Of the sheeted dike complexes, the one on Macquarie Island is most severely metamorphosed at the amphibolite facies level, and the dikes of the other two ophiolite suites represent greenschist facies metamorphism.

## 3. Magnetic Properties

### *3.1 Thermomagnetic analyses*

The magnetic phase of fresh extrusive basalts erupting at the mid-ocean ridges is stoichiometric titanomagnetite, whose ulvöspinel content is often near 60 mole percent (JOHNSON and HALL, 1977). At the temperature of the ocean floor these titanomagnetite particles are highly susceptible to low temperature oxidation to cation deficient spinels, titanomaghemites, which are metastable near room temperature, but which, even at temperatures as low as 150°C in some circumstances (JOHNSON and MERRILL, 1973; RYALL and ADE-HALL, 1975), unmix to titanium-poor titanomagnetities and relatively non-magnetic, titanium-rich phases. The various degrees of titanomagnetite alterations have characteristic thermomagnetic signatures (SCHAEFFER and SCHWARZ, 1970; OZIMA and OZIMA, 1971; OZIMA *et al.*,1974).

Figure 1 shows results of thermomagnetic analyses of samples from the three ophiolite complexes; and they are listed in order of increasing inferred age. Thermomagnetic experiments were done using a vibrating sample magnetometer in an external field of 2.5 k Oe and partial pressures of air less than $5\times10^{-6}$ torr. Thermomagnetic analyses of the Macquarie Island and Smartville complexes were done with whole-rock fragments; however, magnetic separates were used in the runs with samples from the Troodos Massif, hence their higher values of saturation magnetization in Fig. 1.

The upper pillows of Macquarie Island exhibit irreversible thermomagnetic curves (BUTLER *et al.*, 1976), consistent with their containing titanomagnetites which had been subjected to low temperature oxidation on the sea floor (SCHAEFFER and SCHWARZ, 1970; OZIMA and OZIMA, 1971). The lower pillows which had been metamorphosed at the greenschist facies grade exhibit reversible thermomagnetic curves, with Curie points very near 580°C: this behavior is consistent with a higher temperature event (prior to the thermomagnetic analysis) which caused unmixing of the

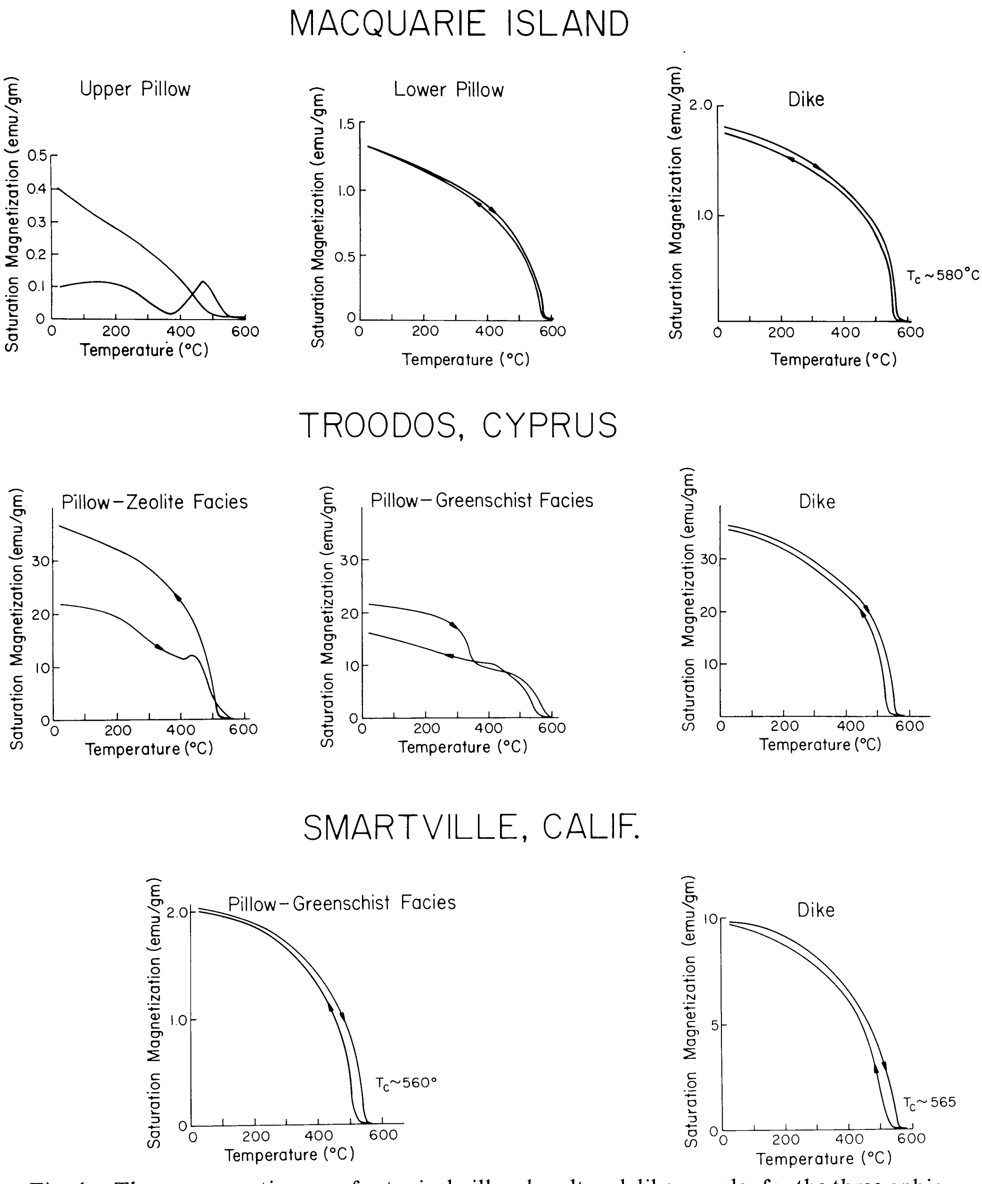


Fig. 1. Thermomagnetic curve for typical pillow basalt and dike samples for the three ophiolite complexes. The experiments were done in vacuum ($<5\times10^{-6}$ torr) and an applied field of $2.5\times10^{3}$ Oe.

titanomaghemite to nearly stoichiometric magnetite and additional non-magnetite phase (BUTLER *et al.*, 1976).

The Troodos Massif pillow basalts, which had undergone zeolite facies metamorphism exhibit irreversible thermomagnetic curves, consistent with the presence of low-temperature-oxidized titanomagnetite. The pillow basalt sample which had been metamorphosed to greenschist facies also has an irreversible thermomagnetic curve

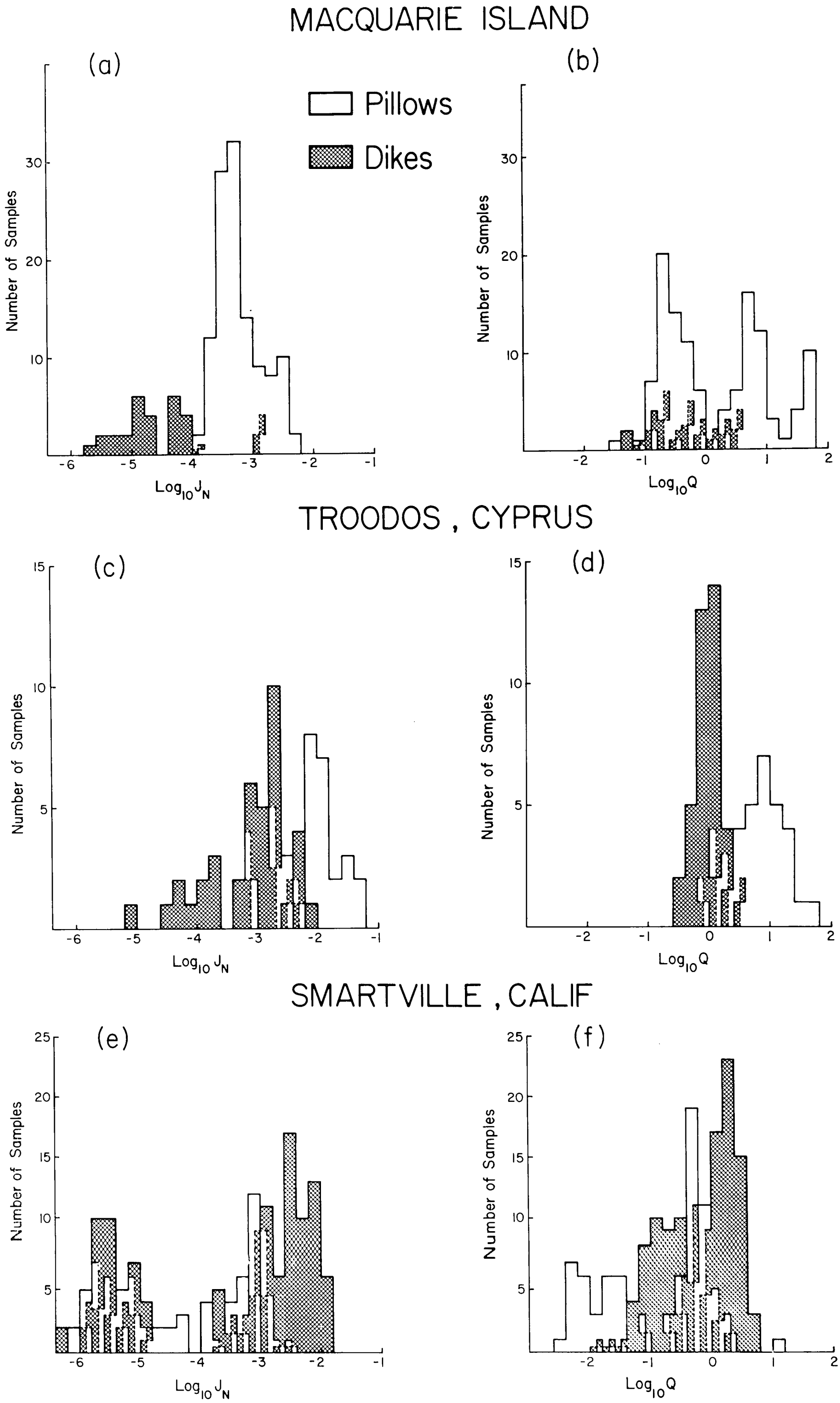
MACQUARIE ISLAND
(a)
(b)
Pillows
Dikes
Number of Samples
Log10 JN
Log10 Q
TROODOS , CYPRUS
(c)
(d)
SMARTVILLE , CALIF
(e)
(f)

Fig. 2

but of a different kind. A substantial drop in $J_S$ (saturation magnetization) occurs near 350°C and the remaining magnetization has a magnetite-like Curie point. $J_S$ after cooling is considerably lower than its value before the thermomagnetic run. This behavior is analogous to that of the lower pillows of Macquarie Island. The metamorphic event presumably caused the unmixing of the low-temperature-oxidized titanomagnetite to highly magnetic, Ti-poor magnetite and relatively non-magnetic, Ti-rich phases. Subsequent to obduction, the magnetite experienced further subaerial low temperature weathering (oxidation) resulting in the production of maghemite, which being unstable to heating, converted to hematite near 350°C during the thermomagnetic run.

The pillow basalts of the Smartville complex have all been metamorphosed to greenschist facies, and they all give rise to reversible thermomagnetic curves with single Curie points near 580°C.

The thermomagnetic results for the pillow basalts of the three ophiolite complexes are therefore consistent with petrological data, suggesting that in the order of increasing degree of alteration they are: 1) The low-temperature-oxidized upper pillow basalts of Macquarie Island and the zeolite facies pillow basalts of the Troodos Massif and 2) the lower (greeschist facies) pillow basalts of Macquarie island and the greenschist facies pillows of the Troodos Massif and of the Smartville complex.

The intrusive sheeted dike complexes have all been metamorphosed at or beyond greenschist facies and, without exception, their thermomagnetic curves are reversible with a single magnetite-like Curie point.

### *3.2 Natural remanence and Koenigsberger ratio*

Figure 2 shows histograms of $J_N$ (gauss$=$emu/cm$^3$), the intensity of NRM of the three ophiolite complexes and corresponding histograms for the Koenigsberger ratio, $Q$, ratio of natural remanent to induced magnetization ($Q=J_N/\chi h$, where $\chi$ is the initial susceptibility and $h$ is the inducing magnetic field). The ophiolite suites are listed in order of increasing inferred age. The data for the pillow basalts and sheeted complex of the Troodos Massif is taken directly from VINE and MOORES (1972; their Fig. 2), for which each value plotted represents the average of up to four specimens from each sample. For the Macquarie Island and Smartville complexes each point represents a single specimen. The data for the Macquarie Island pillow basalts is identical to that of BUTLER *et al.* (1976) and differences between Fig. 2 and Butler *et al.*'s Figs. 2 and 7 are due to different plotting-intervals of the logarithms of $J_N$ and $Q$. The plotting-interval of Fig. 2 was determined by that of Fig. 2 of VINE and MOORES (1972). The logarithmic abscissa is used more for compactness than out of philosophical conviction. The average values of Table 1 represent the antilogarithms of the mid-point of the plotting-interval which contains

Fig. 2. Histograms of NRM intensity ($J_N$) and Koenigsberger ratio ($Q$) of the pillow basalts (blank) and dike complexes (cross-hatched) of the three ophiolite complexes. In the determination of $Q$, $h$=0.65, 0.45, 0.50 Oe for the Macquarie Island ophiolite complex, Troodos Massif and Smartville ophiolite complex, respectively.

Table 1. Average values of NRM intensity ($\bar{J}_N$) and Koenigsberger ratio ($\bar{Q}$).

| | $\bar{J}_N$ (gauss) | $\bar{Q}$ | Degree of alteration |
|---|---|---|---|
| | Pillow basalts | | |
| Macquarie Island | $5\times10^{-4}$ | 8 (10) | Upper pillows: low temperature oxidation |
| | | 0.3 (0.4) | Lower pillows: greenschist facies |
| Troodos Massif, Cyprus | $80\times10^{-4}$ | 6.3 (5.7) | Zeolite facies mostly |
| Smartville complex, Calif. | $0.5\times10^{-4}$ | 0.3 (0.3) | Greenschist facies |
| | Sheeted dikes | | |
| Macquarie Island | $0.2\times10^{-4}$ | 0.5 (0.65) | Amphibolite facies |
| Troodos Massif, Cyprus | $13\times10^{-4}$ | 1 (0.9) | Greenschist facies |
| Smartville complex, Calif. | $13\times10^{-4}$ | 0.8 (0.8) | Greenschist facies |

the median value. This procedure was adopted because of the incomplete availability of the Cyprus data. The values obtained in this manner can sometimes deviate from the true median value (e.g., determined for the Macquarie Island and Smartville complexes) by as much as 20 per cent, but these deviations are relatively unimportant for our purposes; we think that maintaining the consistency in the determination is more important in this case. Because of their different geographical locations, the intensity of the magnetic field ($h$) used in determining $Q$ in Fig. 2 is different for the three complexes. $h=0.65$, 0.45, 0.50 Oe for the Macquarie Island ophiolite, Troodos Massif and Smartville complex, respectively, and $\bar{Q}$ corresponding to these fields is listed in Table 1. However, because we are interested in the magnetic properties of these rocks independent of their present location, $\bar{Q}$ was adjusted for $h=$ 0.5 Oe and listed in parentheses in Table 1.

It is evident from Fig. 2 and Table 1 that, relative to the ophiolite complexes that are being compared, the pillow basalts from the Troodos Massif are potentially the best magnetic recorders, both in terms of their high NRM intensity and their high $Q$ value, showing the dominance of the remanent over the induced component. The NRM intensity of the Macquarie Island pillow basalts is on the average about one order of magnitude below the Cyprus pillows and there is, surprisingly, no significant difference in the NRM intensity of the greenschist facies and unmetamorphosed pillows (BUTLER *et al.*, 1976). However, $\bar{Q}$ of the unmetamorphosed pillows is more than 25 times greater than that of the greenschist facies pillow specimens. The average NRM intensity of the pillow basalts from the Smartville complex is about an order of magnitude lower than those from Macquarie Island and their $\bar{Q}$ value is similar to that of the similarly metamorphosed pillows from Macquarie Island. Since many factors affect the intensity of NRM, these values can obviously not be used by themselves to understand the cause for these variations. However, in conjunction with the $\bar{Q}$ values the $J_N$ data suggest that the recording qualities of the pillow basalts deteriorate with increased alteration.

Despite the fact that for the sheeted dikes the NRM intensity is minimum for the most metamorphosed dike complex (Macquarie Island), the differences in the $\bar{Q}$

values for the different sheeted units are small and not significant. The picture that emerges from these data is that with increased alteration (not age) the underlying sheeted dikes become relatively more important as magnetic recorders because of the degradation of the magnetic recording quality of the pillow basalts. For the Smartville complex, in fact, the dikes are the predominant magnetic sources both in terms of $\bar{J}_N$ and $\bar{Q}$.

*3.3 Viscous remanence*

LOWRIE (1973) showed that VRM (viscouse remanent magnetization) contributes substantially to the NRM of some samples from layer 2 of the oceanic lithosphere. VRM acquisition experiments were conducted by us on samples from all three ophiolite complexes. The samples were first demagnetized by alternating fields (AF) to 1,000 Oe, which was taken as the base level for the VRM. VRM was produced in in a 0.45 Oe field and was monitored, typically for about ten weeks ($\sim 10^5$ minutes), and the VRM acquisition versus $\log_{10} t$ (minutes) data for representative samples are shown in Fig. 3. The VRM growth of most of the samples which were studied is usually linear on the semi-logarithmic graph to about $10^3$ minutes; beyond this point, the rate of growth of VRM increases. This behavior is not uncommon in the literature (e.g., review paper on VRM by DUNLOP, 1973). To assess the importance of VRM acquired during the entire Brunhes normal polarity epoch the data obtained in a ten-week experiment is extrapolated to $7 \times 10^5$ years. Such gross extrapolations are always subject to large uncertainties, and this is particularly true in this case where the VRM versus $\log_{10} t$ curves are non-linear. In estimating the VRM produced during the last 700,000 years, we use a linear extraporation through the last two points of the VRM acquisition curves. Because of the increasing rate of change of acquired VRM, our projected Brunhes epoch VRM estimates probably represent a lower limit. The disadvantage of extrapolating VRM experiments done in the laboratory to geological time is that the more stable magnetic grains, having long relaxation times, are not affected during the short laboratory experiments. VRM experiments at progressively higher temperature would 'see' regions of progressively higher relaxation time (NÉEL, 1949) and thus such experiments might be useful for providing better estimates of the importance of VRM in the geologic history of a particular sample.

Although for the Macquarie Island ophiolite we measured the VRM acquisition of only one sample from the upper pillows and one sample from the lower pillows, our data are in very good agreement with the corresponding results of BUTLER *et al.* (1976), who obtained eight VRM acquisition curves for the lower pillows and eight curves for the upper pillow.

Table 2 lists the means of the VRM components, extraporated for the entire Brunhes polarity epoch, relative to the NRM. Because the data are highly scattered (as seen from the standard errors associated with the means) the extraporated VRM was also compared to ARM (anhysteretic remanent magnetization) acquired in an 0.5 Oe direct field superimposed on and parallel to a decreasing AF of an initial value of

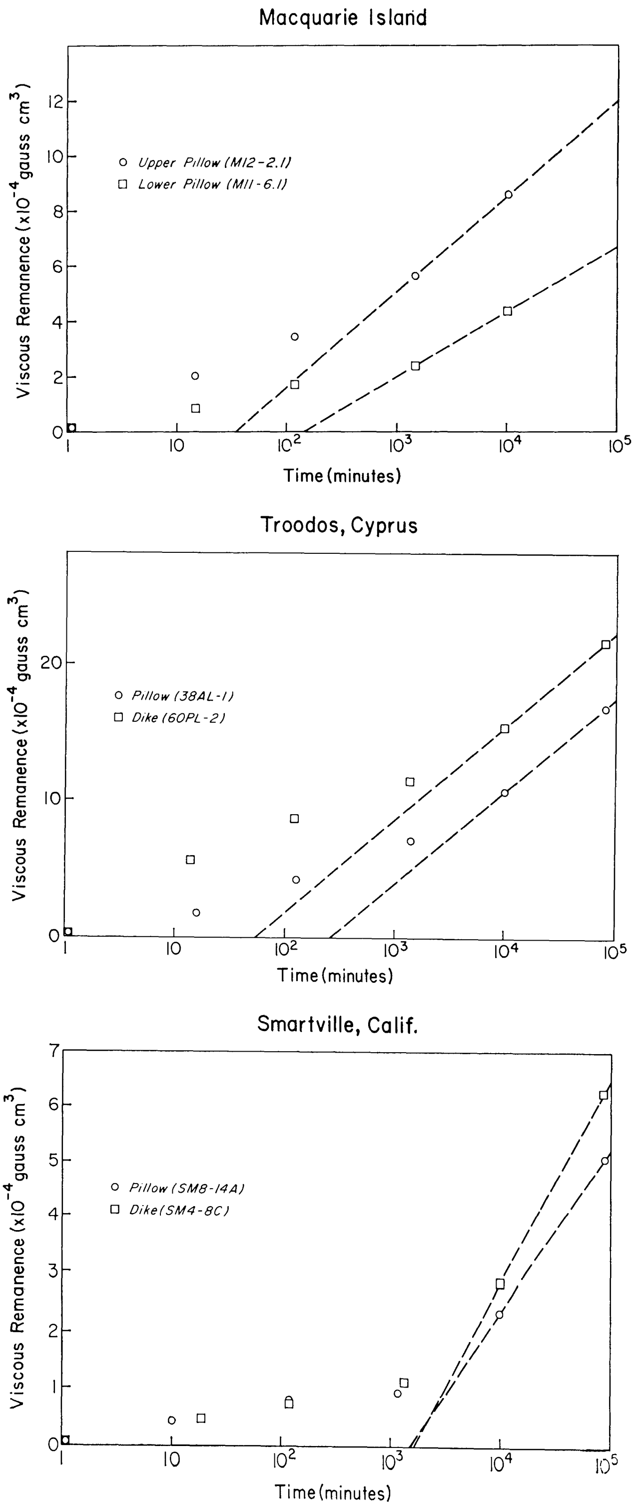


Fig. 3. VRM acquisition in an external field of 0.45 Oe for samples from the three ophiolite complexes. Since the rate of VRM acquisition usually increases with time, the slope of the last two points (dashed lines) was used to estimate the VRM contribution for the entire Brunhes epoch. The zero point for each VRM acquisition experiment is the 1,000 Oe AF demagnetization of the NRM.

Table 2. Relative VRM contribution for the entire Brunhes polarity epoch.

| Locality | Number of samples | | VRM (0.7 my) / NRM $\pm E$* | VRM (0.7 my) / ARM (0.5 Oe) $\pm E$* |
|---|---|---|---|---|
| | | Pillow basalts | | |
| Macquarie Island | 1 | Upper pillow: low temperature oxidation | 0.08 | 0.14 |
| | 1 | Lower pillow: greenschist facies | 0.55 | 0.21 |
| Troodos, Cyprus | 2 | Zeolite facies | 0.11±0.01 | 0.074±0.06 |
| Smartville, Calif. | 4 | Greenschist facies | 0.31±0.13 | 0.30±0.17 |
| | | Sheeted dikes | | |
| Macquarie Island | 2 | Amphibolite facies | 0.08±0.06 | 0.016±0.002 |
| Troodos, Cyprus | 5 | Greenschist facies | 0.31±0.18 | 0.23±0.08 |
| Smartville, Calif. | 7 | Greenschist facies | 0.21±0.08 | 0.25±0.09 |

* $E=\sigma\sqrt{n}$, $\sigma$=standard error.

1,000 Oe. This was done to try to relate the VRM intensity to the specific remanence carrying ability of the sample. Despite the large scatter of both NRM and ARM-normalized data, the trend of their mean values is the same. For the upper pillows of the Macquarie Island ophiolite complex and for the pillows of the Troodos Massif the VRM contribution is seen to be least significant. However, for the metamorphosed pillows of Macquarie Island and the Smartville complex the VRM represents a substantial fraction of the samples' NRM. For the sheeted dike complexes of the Troodos Massif and Smartville, both having been altered to the greenschist facies, the VRM contributions are comparable and represent a substantial fraction of the NRM; however, the dikes of Macquarie Island, which exhibit metamorphism to the amphibolite facies, are least affected by VRM.

Thus the increased contribution of VRM to the NRM of the more highly altered pillow basalts is consistent with the results of the previous section, showing progressive degradation of the magnetic recording qualities of the pillow basalts with increased alteration. For dikes, the capability of VRM acquisition is not obviously related to their metamorphic grade.

### 3.4 *Alternating field demagnetization*

Alternating field (AF) demagnetization of NRM was done for samples from the three ophiolite complexes to assess their intensity and directional stability. Figure 4 shows representative AF demagnetization results for one pillow basalts specimen and one dike specimen from each ophiolite complex. Both the normalized intensity and the equal area stereographic projection of the NRM directions are reproduced for each specimen as function of increasing alternating fields.

The samples for the Macquarie Island ophiolite have median destructive fields (MDF) typically between 300 and 500 Oe for both pillow and dike specimens, and there is no significant difference between the MDF values of upper the lower pillows

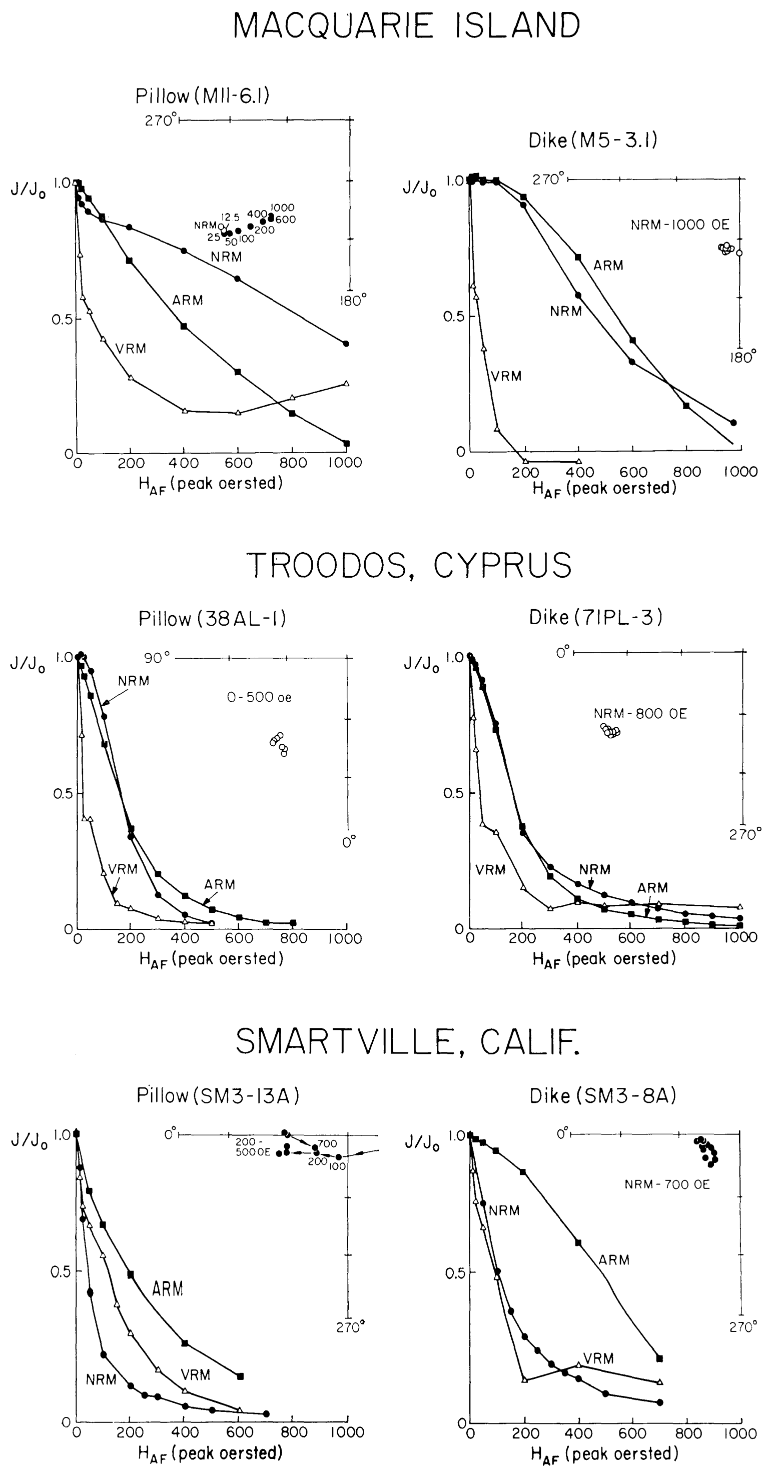
MACQUARIE ISLAND
Pillow (MII-6.1)
Dike (M5-3.1)
J/J0
1.0
0.5
0
270°
180°
NRM
ARM
VRM
NRM-1000 OE
200 400 600 800 1000
HAF (peak oersted)
TROODOS, CYPRUS
Pillow (38AL-1)
Dike (71PL-3)
90°
0°
0-500 oe
NRM-800 OE
270°
SMARTVILLE, CALIF.
Pillow (SM3-13A)
Dike (SM3-8A)
200-500OE
700
200
100
NRM-700 OE

Fig. 4

(BUTLER *et al.*, 1976). The samples' stable directions are distinct from the present direction of the geocentric axial dipole at the sampling locality, and samples from a single site exhibit only small scatter in their directions. The NRM directions of samples from the upper pillow basalts and dikes are often also the stable directions but the lower pillow basalts usually contain a significant VRM component parallel to the present field (BUTLER *et al.*, 1976) which can usually be removed by AF demagnetization between 100 and 200 Oe. Because Macquarie Island is highly faulted, no meaningful between-site comparisons of the magnetization-directions could be made.

The MDFs of samples from the Troodos Massif are usually between 100 and 200 Oe for both pillow basalts and sheeted dike specimens, and the stable direction is often indistinguishable from the NRM direction. In addition, the NRM directions are distinct from the present field direction on Cyprus (VINE and MOORES, 1972). Unfortunately, all the samples which were studied by us were unoriented.

The specimens from the Smartville ophiolite, both pillow basalts and dikes, exhibit highly unstable NRM; often the MDF is not a meaningful measure of the samples' stability; whenever it is, the MDFs are usually less than 100 Oe and frequently less than 50 Oe. Although the NRM direction could sometimes be chosen as the stable direction, the stable direction is often very similar to the present direction of the geocentric axial dipole at the sampling site.

Many factors influence the stability of the remanence as measured by AF demagnetization; for example, the type of remanence, size and shape distributions of the magnetic particles, as well as their chemistry, mineralogy and oxidation states all influence the stability of the remanence. Because one or more of these parameters is usually unknown, we induced artificial remanences in samples from each site and from each lithology of the three ophiolite complexs in an attempt to determine the type of remanence represented by the NRM. The artificial remanences which were used are: VRM in a 0.45 Oe direct field applied for duration of up to $10^5$ minutes; ARM produced by a 0.5 Oe direct field superimposed on and parallel to an alternating field decreasing to zero from an amplitude of 1,000 Oe; saturation IRM (isothermal remanent magnetization) produced in a direct field of $15 \times 10^3$ Oe. Typically, the ARM is more stable than the IRM, which, in turn, is more stable than the VRM.

LEVI and MERRILL (1976) have shown, for a broad range of magnetite-bearing samples that ARM and TRM (thermal remanent magnetization) produced in weak biasing fields have similar stabilities with respect to AF demagnetization. CRM (chemical remanent magnetization) can be either less stable or more stable than TRM or ARM depending on the nature of the chemical change (e.g., grain growth, oxidation or reduction), the size and shape of the particle and its chemical composition (see,

Fig. 4. AF demagnetization of NRM, ARM and VRM for representative samples from the three ophiolites. ARM was produced by a 0.5 Oe biasing field superimposed on and parallel to a decreasing alternating field whose maximum amplitude is 1,000 Oe. VRM was produced in a 0.45 Oe field applied for between $10^4$ and $10^5$ minutes. Normalized intensities are plotted versus peak AF demagnetizing field. Also shown are the equal area projections of the NRM directions upon progressive AF demagnetization. Note that the appropriate quadrant of the stereogram has sometimes been rotated for snug fit.

for example, review paper by MERRILL, 1975). In Fig. 4, AF demagnetization curves of NRM, ARM and VRM are shown for representative samples from the three ophiolite complexes. For the Macquarie Island ophiolite complex and for the Troodos Massif, the AF demagnetization curves of the NRM are usually much more similar to those of the ARM, the VRM demagnetization curves being distinctly less stable. This pattern is maintained for both pillow basalts and dike samples. On the other hand, for the Smartville complex , where both pillow basalts and dike samples have much 'softer' NRM, the NRM AF demagnetization curves usually more closely resemble those of the VRM than of the ARM. The strongest statement that is supported by these data is that the NRM of the Smartville pillow basalts and dikes is probably a VRM acquired during the present polarity epoch. In contrast, the NRM of the Macquarie Island samples and those from the Troodos Massif is probably not a VRM. The NRM of the zeolite facies pillow basalts of the Troodos Massif and the upper pillows of the Macquarie Island complex might represent the original TRM, subsequently modified by low temperature oxidation. The NRM of the lower pillow basalts and sheeted dikes of Macquarie Island and the greenschist pillow basalts and sheeted dikes of the Troodos Massif might be either a TRM or a CRM.

## 4. Discussion

Two important assumptions are implicit whenever the magnetic properties of an ophiolite complex are used directly to construct magnetic models for the oceanic crust: 1) the ophiolite complex represents typical ocean crust originally formed at a spreading center; and 2) obduction onto land had no significant effect on the magnetic properties.

The presence of pillow basalts and overlying deep sea cherts at the three ophiolite complexes of this study are strong evidence for their marine origin. In addition, for the Troodos Massif and the Macquarie Island ophiolite the affinities of the trace elements Ti, Zr, Y to those of ocean-floor basalts seem convincing. In addition to its tectonic setting, probably the most compelling evidence for a spreading center origin of the Macquarie Island ophiolite complex is found in the Sr isopope data (WILLIAMS and MURTHY, 1977). However, even for the most thoroughly examined ophiolite complex (the Troodos Massif) controversy exists as to the environment of its origin, spreading center versus island arc (e.g., MIYASHIRO, 1975; MOORES, 1975). At present, it appears that there are no clear-cut means for resolving this controversy.

The second assumption is probably more difficult to test. However, the apparent lack of deformation of the ophiolite complexes might be taken to support the assumption of 'gentle' obduction, leading one to the conclusion that the observed greenschist or amphibolite facies metamorphism took place prior to obduction. On the other hand, DSDP basalts drilled thus far are *not* metamorphosed (beyond hydrothermal alteration and low temperature weathering) although, again, it is possible that DSDP drilling has not yet tapped deep enough levels of the oceanic crust. It might be that ophiolite complexes do not represent 'typical', relatively passive oceanic crust, but rather that they might represent regions which were tectonically more active such as areas adjacent to transform faults or adjacent to boundaries between oceanic plates and continents and thus susceptible to more extensive metamorphism.

The metamorphic grade of both the Macquarie Island complex and of the Troodos Massif increases with depth. This supports the position that metamorphism occurred on the sea floor rather than during obduction, because such alteration stratigraphy fits readily into the framework of present models of the ocean crust, which show steep temperature gradients, particularly near spreading centers (e.g., SLEEP, 1975; KUSZNIR and BOTT, 1976). However, in the Smartville complex the metamorphic grade does not appear to increase with depth, which might be used to argue that in this case additional metamorphism occurred during or after obduction.

Recognizing the serious uncertainties about the assumptions listed at the head of this section, we return for the remainder of the discussion to the framework established by these assumptions.

The pillow basalts of the three ophiolite complexes reflect progressive metamorphism increasing from the low-temperature-oxidized and the zeolitized pillows of the Macquarie Island ophiolite and the Troodos Massif to the greenschift facies pillows of Macquarie Island, Troodos Massif and the Smartville complex. In addition, recent documentation of the available data shows that the ulvöspinel content of unaltered basalts from different oceans is restricted to rather rarrow range between $0.55<x<0.68$, where $x$ is the mole fraction of ulvöspinel (OZIMA *et al.*, 1974; JOHNSON and HALL, 1977). Therefore, if it is assumed that TRM is the original NRM of the pillow basalts of these three ophiolite complexes and that their magnetic mineralogy was initially similar, then the magnetic properties of the three suites of pillow basalts might reflect their magnetic evolution with increased alteration.

The pillow basalts of the Troodos Massif and the upper pillows of Macquarie Island, which exhibit cation deficient titanomagnetites are typical of rocks dredged and drilled in the world's oceans in terms of their magnetic mineralogy as well as the characteristics of their remanence properties. In addition, rock magnetic studies of the uppermost extrusives of oceanic crust have shown that the low-temperature oxidation of the titanomagnetites occurs within only a few kilometers of the spreading centers (CARMICHAEL, 1970; IRVING *et al.*, 1970; OZIMA *et al.*, 1974; JOHNSON and ATWATER, 1977), and studies of DSDP rocks have shown that the cation deficient spinel phase is preserved as a metastable phase in oceanic crust as old as $100\times10^6$ years to depths in excess of 500 meters. It is thus likely that magnetic properties of the low-temperature-oxidized pillow basalts of the Troodos Massif and of Macquarie Island were frozen in them since shortly after they were extruded at their respective spreading centers.

The more interesting extrusives, which are present at some of the ophiolite complexes have been metamorphosed to greenschist facies and exhibit reversible thermomagnetic curves with Curie points near that of magnetite; such thermomagnetic behavior has essentially no equivalents among DSDP rocks. Whenever metamorphosed and low-temperature-oxidized extrusives are found in the same ophiolite complex (Macquarie Island and Troodos Massif), the metamorphosed pillow basalts appear to be stratigraphically lower. Heating due to burial or to contact with hot rocks or hot aqueous solution could be the cause for metamorphism. Such heating, in turn, would cause unmixing of the low-temperature-oxidized titanomagnetite to a more Fe-rich magnetic spinel, approaching magnetite, and Ti-rich, relatively non-magnetic, phases. VARNE and RUBENACH (1972; attributed by them to Turner, 1968), suggest that exothermic hydration reactions within the pillow basalts might be an additional heat source to effect metamorphism and consequently the unmixing of the cation-deficient titanomagnetites. The occurrence of such a thermal event is consistent with the magnetite-like Curie points of the lower pillow basalts from Macquarie Island and the greenschist facies pillows from the Troodos Massif and Smartville complex. From our present knowledge and inferences about the thermal structure of the oceanic lithosphere it seems that the most likely place for the pillow basalts to be subjected to such a thermal metamorphic event is near the spreading centers. Of course, it is possible that not all extrusive sections experience the higher temperatures required to unmix the titanomaghemites, so that in some sections of the oceanic crust irreversible thermomagnetic curves might be preserved throughout the entire extrusive column.

Although the greenshist facies metamorphosed pillow basalts are inferior magnetic recorders as compared with the zeolitized and unmetamorphosed pillow basalts, there is considerable variation between the magnetic properties of greenschist facies metamorphosed pillow basalts of the Smartville complex and the lower (greenschist facies) pillows from Macquarie Island. This is not surprising, as greenschist facies metamorphism can occur over a relatively broad pressure-temperature range. Thus differences in the magnetic properties of the metamorphosed pillow basalts could be due to differences in the pressure-temperature conditions which prevailed during metamorphism, differences in the initial bulk chemistry of the basalts, or differences in the fluids present during metamorphism. For example, the titanomagnetite grains of the lower pillow lavas of Macquarie Island are only a few microns in size, have skeletal shapes suggestive of quenched textures, and are too small for exsolution lamellae to be resolved. In contrast, the titanomagnetite grains of some of the pillows from the Smartville complex are often larger than 20 $\mu$m, their shapes are anhedral to subhedral, and no exsolution lamellae were seen. The apparent homogeneity of the grains and the apparent absence of pseudobrookite in the metamorphosed pillow basalts suggest that unmixing of the titanomaghemites must have occurred below 600°C (CARMICHAEL and NICHOLLS, 1967).

The magnetic properties of the sheeted dikes cannot be readily correlated with metamorphic grade. Although the dikes have been significantly metamorphosed, their magnetic properties show relatively little variation (Tables 1 and 2). Part of the reason for this might be a result of the slower cooling history of the dikes, facilitating high temperature oxidation, so that magnetite might have been the predominant magnetic mineral when the original TRM was produced. This supposition is strongly supported by theoretical models for thermal structure at spreading centers (SLEEP, 1975; KUSZNIR and BOTT, 1976). In particular, KUSZNIR and BOTT (1976) have provided models for the isotherms in layer 3 (where the dikes occur), taking into account the release of latent heat of solidification. Their Figure 5 shows that for a spreading rate of 3 cm/y magnetite would probably be produced by high temperature oxidation and that it will acquire a pure TRM within about 330,000 years from the time of intrusion, i.e., most likely the TRM will reflect the ambient magnetic field intensity and direction of the dike intrusion epoch. However, the precise direction and intensity of the remanence will depend on the reversal frequency of the magnetic field, the spreading rate, and on the degree to which the isotherms are modified by hydrothermal circulation.

KRISTJÁNSSON (1972) obtained magnetite-like Curie points for four basalt samples recovered between 900 m and 1,932 m depth in Iceland with accompanying microscopic evidence of high temperature oxidation and KRISTJÁNSSON and WATKINS (1977) draw attention to the possible importance of such high-temperature-oxidation magnetite as a source of magnetic anomalies.

An interesting result is that the NRM intensity of the dikes from Macquarie Island is nearly two orders of magnitude lower than the NRM intensity of the other two sheeted dike complexes. In contrast to the sheeted dikes of the Smartville complex, which have abundant titanomagnetite particles, the only opaque oxide phase in the seeted dikes of Macquarie Island consists of minute ($<1$ $\mu$m wide) elongated magnetite grains within the plagioclase crystals, which were not affected by the metamorphism (BANERJEE *et al.*, 1974). It is possible that during metamorphism to the amphibolite facies, the original titanomagnetite grains (except those in the plagioclase) participated in the reaction(s) that produced the metamorphic amphiboles (J. Stout, personal communications, 1977).

If the marine magnetic anomalies originate predominantly from a two layer oceanic crust, where pillow basalts overlie intrusive sheeted dike complexes, then our data from three ophiolite complexes suggest that progressive alteration adversely affects the magnetic-recording qualities of the pillow basalts, rendering them progressively poorer as a source for the marine magnetic anomalies. At the same time, progressive alteration of the sheeted dikes from the same ophiolite complexes leaves their magnetic properties relatively less affected. Thus with increasing alteration of the pillow basalts the dikes become relatively more important as sources for the marine magnetic anomalies. Although from our data it is not possible to determine where in time and space the alteration actually takes place, present thermal models of the oceanic crust suggest that the most likely place for the occurrence of such depth dependent metamorphism is near the spreading center origin of the particular ocean crust.

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