# Identification of the Carrier of Magnetization in a Basalt Core from Bermuda

M. Powell

DALHOUSIE UNIVERSITY
Department of Geology
Halifax, N.S. Canada B3H 3J5 Telephone (902) 424-2358 Telex: 019-21863

DALHOUSIE UNIVERSITY, DEPARTMENT OF GEOLOGY

B.Sc. HONOURS THESIS

Author: Mike Powell

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Abstract

Peckenham (1981) attempted to use the magnetic properties of a basalt core from Bermuda to help him define the stratigraphy of basalt flows present in the core. The results of his investigation were not helpful. Magnetic data implied that the carrier of magnetization was multidomain magnetite, petrologic evidence revealed that highly substituted spinels were the only potential magnetic phase. The magnetic properties of the basalt were determined in the present study and are similar to Peckenham's (1981) results. Furthur petrologic study and microprobe analysis has revealed multidomain titanomagnetite grains that support the magnetic evidence. It is thought that the titanomagnetite carries the observed remanence.

## Introduction

The purpose of this study is to identify the mineralogical carrier of magnetization in the basalt core recovered by the Bermuda Research Drilling Project 1980. Peckenham (1981) attempted to use the magnetic properties of the core to help define the stratigraphy of the basalt flows. He took eighteen samples from the core in the form of minicores drilled perpendicular to, and oriented with respect to, the main core. The natural remanent magnetization (NRM), and Curie temperature of the samples were measured. The samples were demagnetized using various techniques such as alternating fields, thermal demagnetization and viscous decay methods. The results were not helpful in defining the stratigraphy of the core. Approximately 60 percent of the samples yielded stable inclinatons but these inclinations were not consistently or systematically oriented in the core.

Peckenham (1981) proposed that the lack of consistency might be due to several factors: tectonic rotation of individual pillows or larger blocks that had cooled through their blocking temperatures, shock induced or piezo remanent magnetization (SIRM, PRM) due to the reorientation of large blocks. In addition Peckenham (1981) proposed the presence of a large drilling induced remanent magnetization (DIRM), caused by

rotation of the metallic drill barrel in combination with heating from the drilling action. Peckenham (1981) could not positively identify the mineralogical carrier of magnetization. The Curie temperatures and the characteristics of the NRM data suggested that the source was multidomain magnetite grains, however petrographic observation did not reveal the presence of magnetite in the core. Large spinel grains were the only phase observed in the rock which might be capable of producing the observed magnetization. Work by Richards et al. (1973) and Ozdemir and O'Reilly (1981) indicates that highly substituted titanomagnetites usually show much lower Curie temperatures and intensities than are observed in the core. Peckenham (1981) proposed two possible sources for the magnetization: (1) the spinels in the core, which are highly substituted with Mg and Al, and may be magnetic with high Curie temperatures or (2) small, single to multidomain transition sized, magnetite grains which could not be identified petrographically.

The aim of the present study is to identify the carrier of magnetization in the core. The approach used in this study is similar to that taken by Peckenham (1981). The Curie temperatures and NRM data determined in this study will be compared to Peckenham's (1981) data to verify the magnetic properties of the core. Then a detailed petrographic examination of the core, using electron microprobe analyses, should reveal the most likely source of magnetization.

## Background Theory and Analytical Techniques.

### Natural Remanent Magnetization

When studying the bulk magnetic properties of a rock, it is useful to observe the changes in magnitude and direction of the magnetic field associated with the sample through a process of partial demagnetization. Demagnetization involves the random rotating of the sample in a space where an alternating magnetic field is raised to a certain level and then slowly deceased to zero. The level to which the field is taken is raised in increasing steps. This technique is known as alternating frequency demagnetization. The NRM intensity and inclination are measured after each level of demagnetization. The soft component of the magnetization is easily changed and will be randomized during demagnetization at low magnetic field strengths. The hard component will only be altered by a strong demagnetizing field. A plot of normalized intensity versus demagnetizing field strength will show at what level most of the NRM intensity is lost. This enables one to interpret the nature of the magnetization, which depends mainly on the grain size and chemical composition of the magnetic mineral (O'Reilly, 1984). Often one finds that the direction of the softer component of the sample's magnetic field can be affected by the inducing effect of the earth's present day magnetic field over a period of time,

this is known as viscous remanent magnetization (VRM). If the magnetic field of the sample is viscous then the mineral is multidomain (Dunlop, 1973). As a sample is demagnetized and the softer components are stripped away, the more stable part of the magnetic field is left behind to give stable inclinations. Examples of hard component sources in magnetic minerals are thermal remanent magnetization (TRM) and chemical remanent magnetization (CRM).

The viscosity of magnetization is primarily a function of grain size (O'Reilly, 1984). Domain theory is essential in explaining variations in the magnetic properties of minerals with grain size. A magnetic domain is a region inside a magnetic material where the spontaneous magnetization is of a uniform direction (Banerjee and Moskowitz, 1986). Magnetic minerals can be single-domain (SD), pseudo-single-domain (PSD), or multidomain (MD). A SD grain is uniformly magnetized in one direction. Grains of SD size have stable remanences because it requires a lot of energy to change the direction of spontaneous magnetization to a crystallographically unfavorable direction. The spontaneous magnetization in MD grains form discrete domains that do not have the same directions. In order to minimize their overall magnetic energy, a MD grain can have a spontaneous magnetization of zero if the magnetizations of the domains are such that they cancel each other. Stacey (1963) hypothesized the existence of the PSD grain, in order to explain the SD magnetic

properties observed in grains of theoretical MD size. The idea of PSD grains explains the observation that there is not a sudden change in magnetic properties at the SD-MD boundary (Banerjee and Moskowitz, 1986).

The existence of viscous magnetization is because in a MD grain the domain boundaries can migrate fairly easily to minimize the magnetic energy of the grain. This explains why multidomain grains often do not hold stable remanences.

The magnetization of the samples was measured with a Schonsteadt DSM-1 digital spinner magnetometer. The measured total vector of magnetization of the sample was calculated from three mutually perpendicular measured vectors, and then converted into a magnetic moment, an inclination, and a declination via an on-line PDP-12 microprocessor. The samples were demagnetized using alternating fields of peak intensities of 25, 50, 75, 100, 150, 200, 250, 300, 400, and 500 Oersteds (Oe).

The NRM data consists of four parameters: the intensity, the inclination, the median demagnetization field (MDF), and the stable inclination. The NRM intensity is the intensity of the magnetization of the sample before demagnetization. The NRM inclination is the initial inclination of the sample prior to demagnetization. The MDF is the value of the strength of the demagnetizing field when the intensity of magnetization of the

sample is half of its original value. The stable inclination is determined by averaging the inclinations over a range of demagnetization levels if they appear to be reasonably constant. For these basalts a stable inclination was tabulated if the inclinations were all within $\pm 10^{o}$ of the averaged value. This process is somewhat subjective.

## Curie Temperature

The Curie temperature is a function of composition and can often provide some insight into the geochemical nature of the magnetic mineral. Banerjee and Moskowitz (1986) review the fundamental theory explaining the nature of the Curie temperature. In pure magnetite the Curie temperature marks the transition from the ferrimagnetic to the paramagnetic state, with increasing temperature. Below the Curie temperature the ferric and ferrous ions in the octahedral site sublattice are aligned, and cation to cation electron motion is inhibited. The interaction between the oriented octahedral sublattice and the tetrahedral sublattice has the effect of creating a ferrimagnetic state. Above the Curie temperature the electrons are relatively free to move through the octahedral sublattice, due to added thermal energy, giving rise to a paramagnetic state. As the magnetite cationic lattices become increasingly substituted with foreign cations the Curie temperature generally falls. This can result from factors such as decreased alignment in the octahedral

sublattice due to substitution, and dilution of appropriate cations in the sublattices (Richards et al., 1973).

A common method of obtaining the Curie temperature is with the use of a Curie balance. A small piece of sample is suspended, in a bucket, from one arm of a balance in a strong magnetic field gradient. If the weight of the sample plus bucket is known when no magnetic field is present, and is counterbalanced, then the effective weight measured by the balance is due to the force of the magnetic field acting on the sample. The force is proportional to the saturation magnetization and is recorded on the y-axis. If the sample is heated in a vacuum, and the temperature change is recorded, on the x-axis, then a saturation magnetization versus temperature curve can be obtained. The Curie temperature can be deteremined by using the graphical technique of drawing tangents above and below the estimated Curie temperature, and extrapolating the intersection to the temperature axis (Gromme et al., 1969 and Moskowitz, 1981).

There are several sources of error intrinsic in the Curie balance apparatus. At the temperatures measured, approximately 575°C, the error in the platinum / platinum + 13 percent rhodium thermocouple may be as much as 20°C, due to the thermocouple and the sample not being at exactly the same temperature. The balance may sometimes stick causing inaccuracy. Although the

sample is in an oxygen free environment to prevent oxidation, some mass change will occur due to volatiles in the sample being driven off (C. C. Walls, pers. comm., 1987). A reasonable estimate of the error of Curie temperatures is approximately ±25°C.

## Chemical Properties

A JEOL 733 Superprobe electron microprobe was used to determine the chemical compositions of the opaque phases present in the rock. It has scanning electron microscope capability which aided greatly in analysis of the smaller opaque grains. The microprobe has a minimum beam width of approximately three microns and can analyses grains as small as this. Several factors must be taken into consideration when dealing with the analyses. Magnetites and titanomagnetites are often oxidized and therefore non-stoichiometric, due to a deficiency in cations. This leads to low totals of oxides. Calibration with standards is a necessity for calculation of the weight percentagess of oxides. The calibrations are subject to the same experimental error, as the analyses, so error may arise here in oxide totals. The microprobe analyses a volume and this is a source of error if the grain does not extend deep enough into the slide.

## Optical Properties

A Reichert reflected light microscope was used to examine optically the polished thin sections of the samples. The microscope has a maximum magnification of 1350 times. Type A immersion oil for microscopy was used to enhance the colours of the reflected minerals.

## Petrologic Description of the Basalt

Initial examination of the core revealed a distinct bimodal distribution in the rock. Pillowed lavas and intrusive dykes are the two lithologies present that comprise most of the core. Peckenham (1981) describes four basic structural and textural styles observed in the core: (1) intrusives with chilled margins, (2) lavas with pillowed margins, (3) volcanic conglomerates, and (4) volcanic breccia. The latter two are probably due to extrusion of lavas on a steep slope or possibly subaerially. There is also a carbonate biomicrite associated with the extrusives. It contains identifiable foraminifera which date the extrusive flows at no later than middle-late Tertiary (Peckenham, 1981).

The following description of the mineralogy of the basalts is based on the results of Peckenham (1980). The mineralogy of

the major phases is unusual from a compositional point of view. Aside from differences in average grain size, and a small shift in the relative abundances of some phases, the intrusive and extrusive rocks are mineralogically equivalent. The phenocryst fraction of the basalts is composed mostly of clinopyroxene, with a small percentage of spinel grains, and rare altered olivine grains. The groundmass portion of the rock is predominantly composed of clinopyroxene, melilite, and spinel.

The clinopyroxene is referred to as an Mg-augite by Peckenham (1981) according to nomenclature defined by Cameron and Papike (1981). These phenocrysts are on the order of millimeters in size. The melilite in these samples is highly altered to calcite and various unidentifiable phases. However, the diagnostic pegleg structure of melilite is well developed in these rocks. Other phases present as either phenocrysts, groundmass, or replacement minerals are altered sphene, biotite, olivine, apatite, calcite, sulphides (pyrite), analcite, serpentine-talc, hematite, and glass. The olivine in the rock is highly altered to a combination of calcite, talc, chlorite, and quartz. Biotite is titanium rich and compositionally can be considered to be phlogophite-annite. It is dark red to brown in colour and is strongly pleochroic.

Peckenham (1981) describes the major opaque phase present in the rock as spinel. He notes that the spinel is bimodally

distributed between a millimeter sized phenocryst component and a groundmass component averaging approximately 50 microns in diameter and ranging up to 100 microns in size. The spinel is defined geochemically by a very low chromium content, a fairly high titanium content and abnormally large quantities of magnesium and aluminium. In reflected light, the spinel is characterized by tan coloured centres with blue-gray rims and some inclusions of silicates (Peckenham, 1981).

Since the basalt is silica undersaturated, and thus nepheline normative, and contains melilite as a major phase Peckenham (1981) defined the extrusives as altered glass-bearing to glass-rich melilite-bearing nephelenites to melilites, and the intrusives as melilite-bearing lamprophyres (Streckeisen, 1979).

Results

This section includes an outline of the sampling techniques used, a comparison of the NRM and Curie temperature data of Peckenham (1981) with the eqivalent data of this study. Note that the two data sets are not of the same size, with Peckenham's (1981) data derived from 18 samples and the new data set based on 29 samples. The results of a petrologic study of the spinel and other opaque phases, with corresponding microprobe analyses, are also presented.

## Sample Preparation

Sampling and experimental methods were similar to the techniques used by Peckenham (1981), so that comparisons could be made between the two data sets. Sample locations were chosen with the aid of the detailed core description given by Peckenham (1981). An attempt was made to sample the larger units of extrusives and intrusives, because the core is pervasively veined and interbedded with calcite. This makes drilling of the minicores difficult in the smaller units. The brecciated areas were avoided because inclinations are likely to be rotated, although it is difficult to know whether or not long sections of the core are actually large rotated blocks.

Initially 35 sample locations were marked and drilling of a minicore was attempted at each one. Minicores of some description were obtained at 29 sample locations yielding 24 samples of sufficient size for NRM analysis, 27 polished thin sections. Only 21 Curie temperatures were determined because of limited availiability of the apparatus.

The minicores were trimmed on both ends to produce a small cylinder approximately 2.5 cm in length used for the NRM analysis. A polished thin section was made from one end of each minicore and a small chip was taken off the sample for Curie

temperature determination.

## Natural Remanent Magnetization

The NRM data collected by Peckenham (1981) (Table 1) and the data from this study (Table 2) consist of the NRM intensity, the NRM inclination, the median destructive field, and the stable inclination. The statistics for each property are listed at the bottom of each table.

### Intensities

Peckenham (1981) concluded from the NRM data that the basalts are magnetized with an average remanence of approximately 3 X $10^{-3}$ emu $cm^{-3}$ and standard deviation of 3 X $10^{-3}$ emu $cm^{-3}$ . This value corresponds reasonably well with the average remanence intensity of approximately 2 X$10^{-3}$ emu $cm^{-3}$ and standard deviation of 1 X $10^{-3}$ emu $cm^{-3}$ determined from the new data. If the maximum value of NRM intensity in the original data set (13.36 X $10^{-3}$ emu $cm^{-3}$ from sample BF10-11.25C) is dropped from the statistical calculations, the recalculated average value is about 2 X $10^{-3}$ emu $cm^{-3}$ and the corresponding standard deviation is 1 X $10^{-3}$ emu $cm^{-3}$ . The sample (BF10-11.25C) is a small chip, not a cylinder, and hence is a less reliable sample. This may be the reason that the value is about 3 times that of the next highest value. If the value is left out of the calculation the

| SAMPLE | NRMINT | NRMINC | MDF | STABLE |
|---|---|---|---|---|
| | $X10^{-3}$ (emu $cm^{-3}$) | (°) | (Oe) | (°) |
| BF4-2.4 | 1.210 | 35.3 | 75 | 11.5 |
| BF6-6.8 | 3.600 | 80.0 | 60 | 71.6 |
| BF8-10.30 | 0.157 | 51.9 | 45 | 20.6 |
| BF9-7.4 | 1.440 | 87.0 | 70 | 1.9 |
| BF9-7.8 | 2.210 | 14.2 | 75 | 5.9 |
| BF10-11.25 | 0.019 | 48.9 | 50 | 10.1 |
| BF10-11.25C | 13.360 | 89.0 | 45 | . |
| BF10-11.28 | 2.230 | 53.7 | 55 | 14.3 |
| BF10-19.138 | 3.550 | 41.0 | 20 | 48.6 |
| BF11-5.6 | 4.120 | 62.7 | 50 | 60.9 |
| BF12-12.50 | 2.440 | 8.0 | 20 | . |
| BD4-4.9 | 2.710 | 4.7 | . | 7.6 |
| BD4-7.5 | 0.743 | 38.4 | 45 | 24.1 |
| BD5-6.12 | 3.920 | 50.3 | 40 | . |
| BD5-8.6 | 1.610 | 43.8 | 110 | . |
| BD5-6.18 | 1.400 | 73.4 | 65 | 57.0 |
| BD9-2.63 | 2.480 | 33.9 | 150 | . |
| BD9-2.70 | 2.880 | 39.0 | 140 | . |
| Cases | 18 | 18 | 17 | 12 |
| Minimum | 0.019 | 4.7 | 20 | 1.9 |
| Maximum | 13.360 | 89.0 | 150 | 71.6 |
| Average | 2.782 | 47.5 | 66 | 27.8 |
| St. Dev. | 2.904 | 24.7 | 37 | 24.6 |

BF - Flows
BD - Dykes

Table 1. NRM data from Peckenham (1981) with statistics

| SAMPLE | NRMINT | NRMINC | MDF | STABLE |
|---|---|---|---|---|
| | $X10^{-3}$ (emu $cm^{-3}$) | (°) | (Oe) | (°) |
| 3630(I) | 1.190 | 7.6 | 100 | -2.0 |
| 3820(I) | 2.150 | 14.7 | 130 | 1.6 |
| 4182(E) | 4.070 | . | 75 | 17.8 |
| 4241(I) | 2.690 | 5.1 | 50 | . |
| 4286(I) | 3.060 | 19.0 | 50 | 23.1 |
| 5431(E) | 1.810 | 4.6 | 250 | 10.4 |
| 5514(E) | 2.140 | -37.0 | 280 | -27.9 |
| 6111(E) | 1.560 | 10.5 | 50 | 10.2 |
| 6343(E) | 0.490 | 24.3 | 80 | 16.9 |
| 6475(E) | 1.810 | 0.9 | 30 | 15.8 |
| 6586(E) | 2.090 | 11.2 | 40 | 24.4 |
| 6784(I) | 2.000 | 13.6 | 40 | . |
| 6806(I) | 0.830 | 46.6 | 170 | -1.6 |
| 6845(I) | 1.220 | 26.9 | 200 | 9.0 |
| 7037(E) | 2.020 | 39.8 | 30 | . |
| 7186(E) | 1.880 | 46.6 | 60 | . |
| 7284(E) | 2.610 | 8.2 | 120 | 6.4 |
| 7434(E) | 4.440 | 19.3 | 40 | 14.7 |
| 7675(E) | 2.580 | 3.2 | 60 | 11.5 |
| 7849(E) | 2.800 | 4.9 | 40 | . |
| 7875(E) | 2.100 | 3.5 | 40 | 8.5 |
| 8043(E) | 1.830 | 18.1 | 50 | 17.1 |
| 8205(E) | 2.030 | 3.2 | 60 | 2.2 |
| 8473(E) | 2.050 | 31.8 | 50 | 33.2 |
| Cases | 24 | 22 | 24 | 19 |
| Minimum | 0.490 | -37.0 | 30 | -27.9 |
| Maximum | 4.440 | 46.6 | 280 | 33.2 |
| Average | 2.144 | 12.7 | 87 | 10.1 |
| St. Dev. | 0.884 | 16.6 | 70 | 12.9 |

(E) - Extrusive
(I) - Intrusive

Table 2. NRM data from the present study with statistics.

two data sets correspond very well. Separate calculation of the remanence intensities for the intrusives and extrusives of the present study reveals no significant difference between average values for the two lithologies given the population size and distribution, this result is similar to the result obtained by Peckenham (1981).

## NRM Inclination

The NRM inclinations determined in Peckenham's (1981) data vary from 4.7° to 89.0°, with an average value of approximately 47° and standard deviation of 25°. Corresponding values for the new data set are -37.0° to 46.6°, with an average of approximately 13° and standard deviation of 17°. The minimum value for the new data is possibly the result of a reversed sample, given that it is the only negatively inclined sample out of the entire combined data set. If the reversely magnetized sample is excluded the recalculated average value of inclination is about 15° with a standard deviation of 13° which is not significantly different from the previous average and standard deviation. The statistics of the NRM inclinations suggest the there is a significant difference between the two populations (see Figure 1). The NRM inclinations observed in the new data are significantly lower, and more tightly grouped, than those in the original data. In both Peckenham's (1981) data and the new sets there is no apparent difference between the NRM inclinations

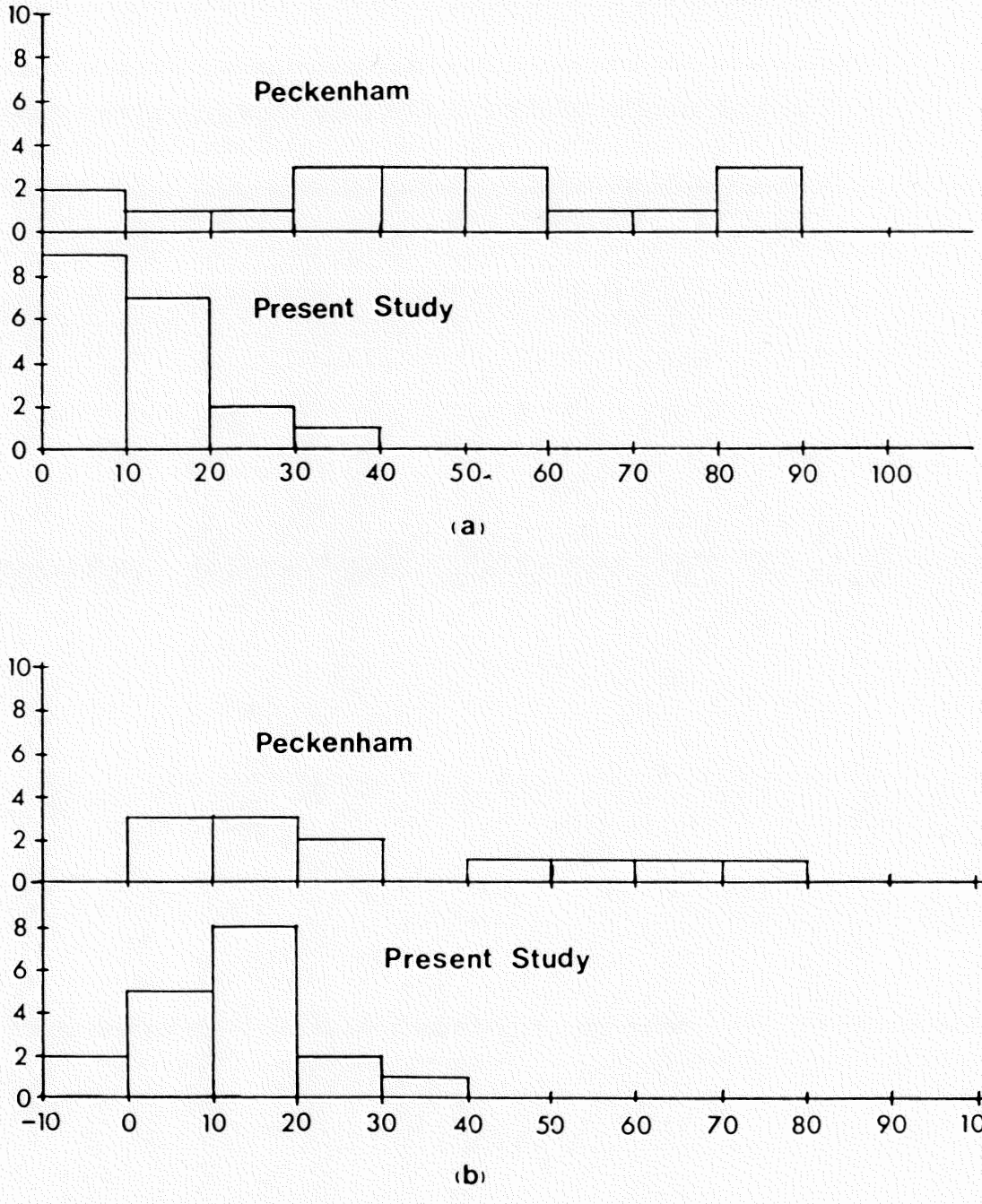


Figure 1. (a) Comparison between the NRM inclinations of Peckenham's (1981) data and data from the present study, (b) comparison between the NRM stable inclinations of the same two data sets.

of the intrusives and the extrusives.

### Median Destructive Field

Peckenham (1981) noted that the characteristic AF demagnetization curves for his samples all showed a rapid decay in normalized magnetic moment with an increasing destructive field. The maximum observed MDF for his data set is 140 Oe. His data show a marked difference in the MDF values for intrusives and extrusives, the extrusives having generally lower values. Figure 2 is a typical demagnetization curve from the present study. The results of Peckenham (1981) are not supported by values of MDF determined in this study. The maximum observed value in the new data set is 280 Oe and not all of the samples show an initial rapid decay as observed by Peckenham (1981). The trend of lower extrusive MDF values is similar but not as obvious in the new data set.

### NRM Stable Inclination

In both of the data sets the stable inclinations that are present are difficult to interpret. They do not define a stable direction of magnetization. A comparison of Peckenham's (1981) data with the new data set shows some difference in the average stable inclinations the new data stable inclinations are lower (see Figure 1(b)). This result is similar to the NRM inclination

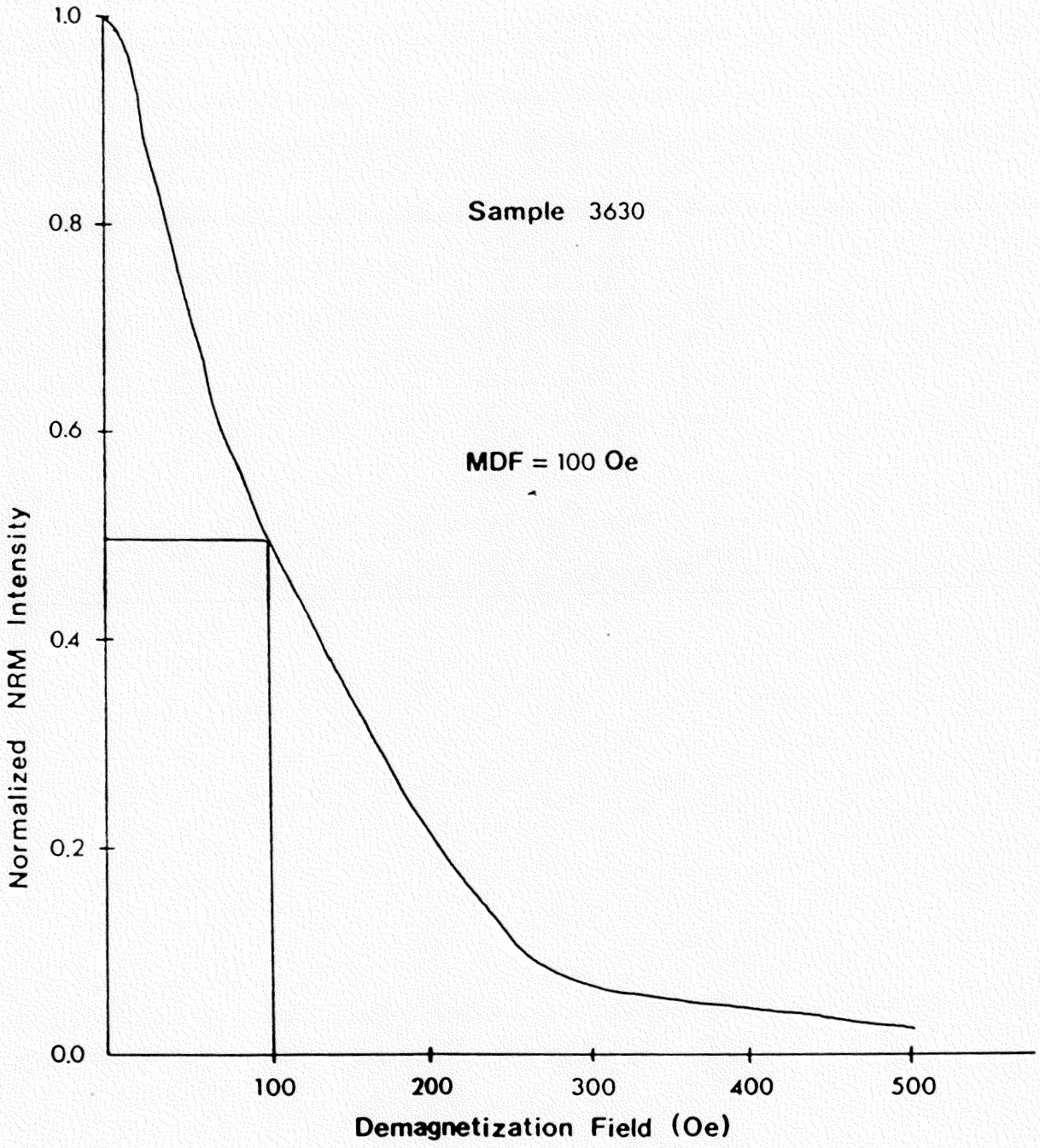


Figure 2. A sample AF demagnetization curve.

comparison. If the apparently reversed sample 5514(E) is dropped, the resultant recalculated values are similar to the previously calculated values, and do not change the observations significantly. There is no significant difference between stable inclinations seen in the extrusives and intrusives in the new data set.

## Curie Temperature

The results for the Curie temperature determinations of Peckenham's (1981) data are given in Table 3, and the results from the present study are given in Table 4. A sample graph used to calculate the Curie temperature is shown in Figure 3. The statistical results of the Curie temperature determinations for Peckenham's (1981) data give an average value of 573°C with a standard deviation of 26°C. This is indistinguishable from the average of 569°C with a standard deviation of 26°C determined for the present study data. The two data sets show strikingly similar results for Curie temperature determinations. The saturation magnetization has also been determined from the Curie temperature data of the present study. The average value of the saturation magnetization is approximately 2.9 emu $g^{-1}$ with a standard deviation of 1.4 emu $g^{-1}$. Since the saturization magnetization of magnetite is 92 emu $g^{-1}$ (O'Reilly, 1984) the observed magnetization would be produced by less than three percent, by volume, magnetite in the rock.

| SAMPLE | CURIE TEMPERATURE (°C) |
|---|---|
| BF4-2.4 | 597 |
| BF8-10.30 | 597 |
| BF9-7.4 | 575 |
| BF10-11.25 | 597 |
| BF10-19.138 | 579 |
| BF11-5.6 | 539 |
| BF12-12.50 | 553 |
| BD4-4.9 | 579 |
| BD5-6.12 | 606 |
| BD5-8.6 | 539 |
| BD9-2.70 | 539 |
| Cases | 11 |
| Minimum | 539 |
| Maximum | 606 |
| Average | 573 |
| St. Dev. | 26 |

Table 3. Curie temperature data from Peckenham (1981) with statistics.

| SAMPLE | CURIE TEMPERATURE | JSAT |
|---|---|---|
| | (°C) | (emu $g^{-1}$) |
| 3467(E) | 577 | 3.33 |
| 3630(I) | 548 | 0.55 |
| 3820(I) | 544 | 2.00 |
| 4182(E) | 575 | 4.14 |
| 4241(I) | 593 | 4.80 |
| 4286(I) | 579 | 4.66 |
| 4362(E) | 557 | 2.54 |
| 5183(E) | 566 | 1.67 |
| 5431(E) | . | 0.75 |
| 5514(E) | 575 | 4.19 |
| 6111(E) | 575 | 0.74 |
| 6586(E) | 593 | 3.38 |
| 6784(I) | 588 | 1.76 |
| 6806(I) | 557 | 2.02 |
| 6845(I) | 526 | 2.61 |
| 7037(E) | 566 | 1.94 |
| 7186(E) | 588 | 1.72 |
| 7675(E) | 597 | 4.66 |
| 8043(E) | 584 | 4.27 |
| 8205(E) | 593 | 3.28 |
| 8473(E) | 577 | 3.55 |
| 8691(E) | 489 | 4.28 |
| Cases | 21 | 22 |
| Minimum | 489 | 0.55 |
| Maximum | 597 | 4.80 |
| Average | 569 | 2.86 |
| St. Dev. | 26 | 1.37 |

Table 4. Curie temperatures and Jsat data from the present study with statistics

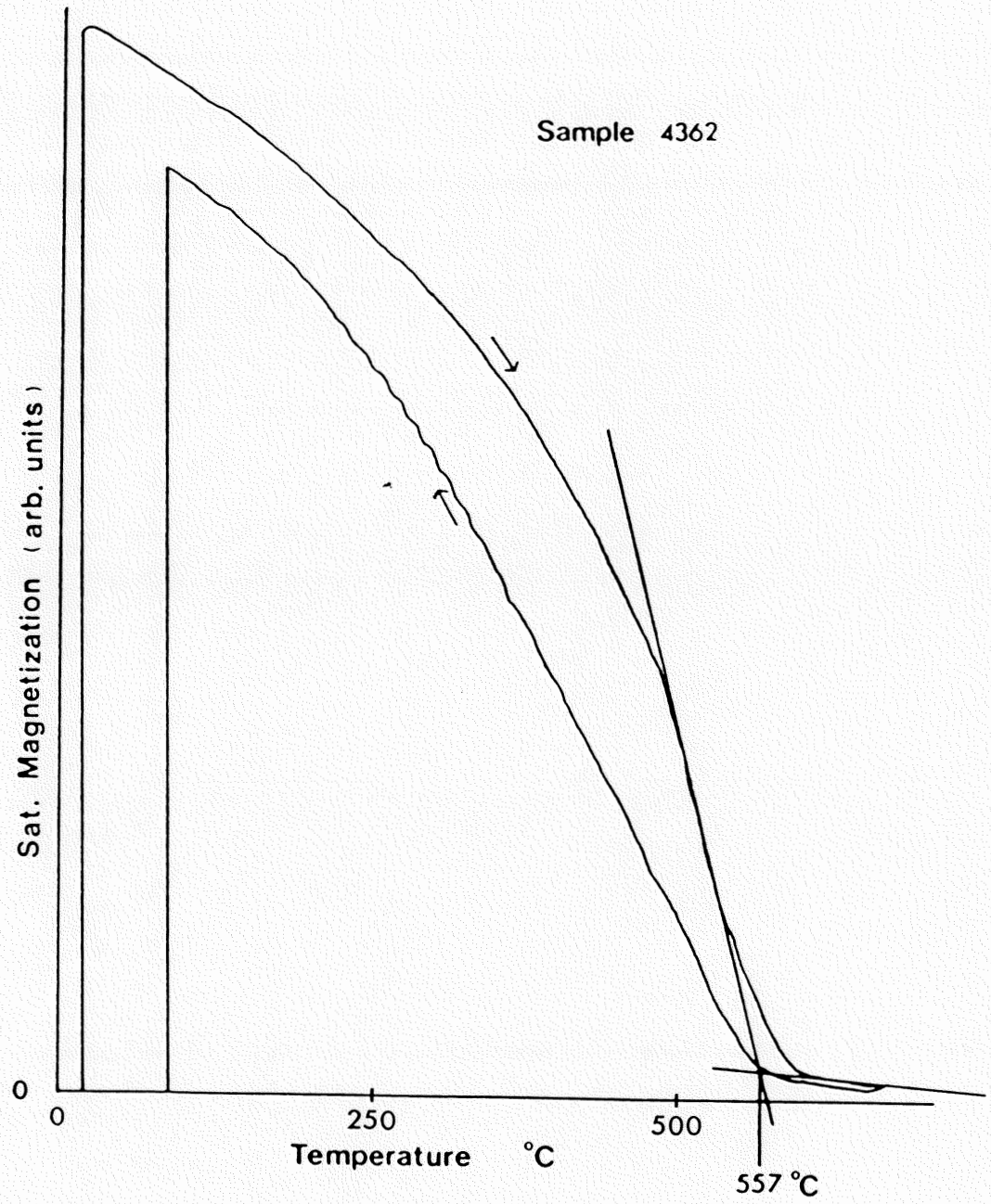


Figure 3. A sample Curie temperature curve.

## Petrologic and Microprobe Results

Petrologically the spinel grains in these basalts are as Peckenham (1981) described. Phenocrysts of 1-2 mm and groundmass spinels averaging 50 microns in size. Some of the spinels show exsolution patterns in which the exsolved material appears to be a transparent phase, although spinel is known to exsolve magnetite (Ramdohr, 1980). Recent microprobe analyses of these spinels are consistent with those analyses shown by Peckenham (1981). Two additional phases have been identified in these rocks: (1) phenocryst and groundmass-sized titanomagnetites with titanium contents generally equivalent to $x \leq 0.1$, in $(x)Fe_2TiO_4$-$(x-1)Fe_3O_4$, either blue-gray or tan coloured, (2) very chromium rich spinels, averaging 10 weight percent chrome, of phenocryst and groundmass size, dark brown in colour occupying the cores of some larger spinel or titanomagnetite grains. Table 5 contains typical microprobe analyses of these various phases, and these data represent approximately 50 opaque mineral analyses carried out on the basalt. These data suggests two prospective sources for the observed magnetization: (1) large MD highly substituted spinel, and (2) large, low titanium, MD titanomagnetites. Peckenham (1981) determined that the modal percentage of spinel in the rock is about 15%, this would include the newly identified titanomagnetite. It is very difficult to distinguish the spinel and titanomagnetite in reflected light. Appparently the spinel

| Oxide | 7875GR3C | 7875GR2 | 7675GR3C | 7037GR1R | 6806GR1R |
|---|---|---|---|---|---|
| $SiO_2$ | 4.46 | 3.66 | 5.25 | 5.36 | 6.13 |
| $TiO_2$ | 1.10 | 1.02 | 2.68 | 1.50 | 1.82 |
| $Al_2O_3$ | 0.53 | 0.51 | 0.55 | 0.85 | 0.59 |
| $Cr_2O_3$ | 0.15 | 0.15 | 0.14 | 0.11 | 0.25 |
| FeO | 77.88 | 78.20 | 76.91 | 75.94 | 72.04 |
| MnO | 0.21 | 0.20 | 0.04 | 0.15 | 0.09 |
| MgO | 0.04 | 0.01 | 0.14 | 0.15 | 0.00 |
| CaO | 0.81 | 0.61 | 0.84 | 0.80 | 0.84 |
| Total | 85.19 | 84.34 | 86.55 | 84.84 | 82.77 |
| MDF | 40 | 40 | 60 | 30 | 170 |

(a)

| Oxide | 6806GR1C | 6806GR2 | 6845GR1C | 6784GR2R | 7875GR1C |
|---|---|---|---|---|---|
| $SiO_2$ | 0.07 | 0.06 | 0.00 | 0.00 | 0.14 |
| $TiO_2$ | 12.32 | 8.93 | 15.25 | 17.63 | 15.40 |
| $Al_2O_3$ | 6.96 | 10.75 | 7.45 | 6.96 | 5.52 |
| $Cr_2O_3$ | 10.92 | 14.87 | 0.27 | 0.26 | 0.18 |
| FeO | 56.53 | 50.24 | 62.06 | 58.21 | 65.88 |
| MnO | 0.44 | 0.42 | 0.51 | 0.53 | 0.61 |
| MgO | 9.61 | 11.02 | 9.34 | 11.32 | 8.98 |
| CaO | 0.09 | 0.40 | 0.00 | 0.13 | 0.10 |
| Total | 96.94 | 96.68 | 94.88 | 95.04 | 96.80 |
| MDF | 170 | 170 | 200 | 40 | 40 |

(b)

Table 5. Sample microprobe analyses, (a) analyses of titanomagnetites, (b) analyses of spinels, note that the first two analyses are chromium-rich.

and titanomagnetite phases can occur as both the tan and blue-gray in colour. This property makes it very difficult to determine the relative modal percents of the various phases without extensive microprobe analyses.

## Discussion

### NRM

It appears that there is a significant difference between the NRM inclination populations of the two data sets (Figure 1). The lower NRM inclinations in the new data set could be due to the core being stored on its side in the Earth's near vertical field in Halifax for the last five years. Inducing a horizontal magnetization. In the meantime the DIRM, suggested by Peckenham (1981) as the cause for the steep NRM inclinations found in the original data set, has perhaps decayed away. The MDF values obtained for samples from both data sets imply that a large component of the observed field is of a soft nature. These two facts suggest a large viscous component in the observed magnetization of the core. If the magnetization of the core behaves in a viscous manner, a logical assumption is that the carrier is multidomain.

Some stable inclinations are seen in the core. However, their significance is not obvious given the inconsistent

directions they show. If the stable inclinations were real remanent inclinations, the values should be similar to the inclination of the earth's magnetic field in Bermuda during late Tertiary time. The inclination then would have been approximately 40° (Habicht, 1979) at that time. The stable NRM inclinations do not show this. Events such as small scale rotation of the core may be responsible for the scatter. There seems to be a decrease in the value for the means of the stable inclinations between the two data sets, similar to the trend observed in the NRM inclinations. This could be a statistical manifestation of the small number of determinations or it could be caused by viscous decay of the magnetization of the basalts.

If the carrier is multidomain, as the evidence from natural remanent magnetization implies, it is feasible to put some limitations on the grain size of potential carriers of magnetization. For titanomagnetites, the most common magnetic carrier in basaltic rocks the transition from single to multidomain takes place over a range of values depending on composition, grain shape, and magnetic history (O'Reilly, 1984). These values are equal to or greater than those for pure magnetite, the transition size from pseudosingle to multidomain is approximately 15 to 20 microns (Parry, 1965; Bailey, 1975; Day et al., 1977). It should be noted that the composition of the phase plays a very important role in determining the transition size.

In conclusion it would seem that evidence gained from a comparison of the natural remanent magnetization data from the original and new data sets has revealed a viscous magnetization in the rock, which implies a MD carrier, suggesting a grain size lower limit of about 15 to 20 microns for the prospective carrier of magnetization.

## Curie Temperature

Curie temperature results suggest that nearly pure magnetite is the carrier of magnetization in these rocks. Readman and O'Reilly (1971) calculated the Curie temperature of pure magnetite as 575°C. However, the Curie temperature of pure magnetite is known to vary up to 581°C (Lindsley, 1976). These values are indistinguishable given the accuracy of the Curie temperature determinations. It is known that the substitution of titanium and other cations, such as magnesium and aliminium, into the magnetite structure has the effect of reducing the Curie temperature (O'Donovan and O'Reilly, 1977; Blasse, 1964; Ozdemir and O'Reilly, 1978; and Richards et al., 1973). It should be noted that the spinels in these rocks are, generally, more substituted than any of the synthetic compounds prepared in other studies, except for that of Blasse (1964) with magnesium cations. Ozedemir and O'Reilly (1978) showed that for a titanomagnetite with a titanium content of 0.6 and an aluminium content of 0.25, the Curie temperature is approximately 0°C. Curie temperatures

determined in the present study are in the range of 575 C and the spinels are generally richer in aluminium so it is unlikely that the spinels are magnetic at room temperature.

Peckenham (1981) correctly points out several problems with the application of Curie temperature information from other studies. None of the above mentioned studies deal with large multidomain grains. There is some debate as to whether these synthetic spinels accurately reproduce the magnetic properties of real spinels. Direct application of these studies is difficult because of the compositional gap between the synthetic and real spinels. Peckenham (1981) had proposed that the spinel grains present in the rock may account for its observed magnetic character. This should be kept in mind as a possibility, given the rather odd composition of the spinels and the fact that synthetic analogues of that particular composition have not been studied magnetically in detail.

It is more likely that titanomagnetites could be the source of the observed Curie temperatures. O'Reilly (1984) gives a simple linear relationship between Curie temerature and X, the amount of titanium substituted standardized to 4 oxygens. The Curie temperatures for titanomagnetites of these compositions ($X \leq 0.1$) would be near the Curie temperature for pure magnetite but still some tens of degrees to low. Oxidation most likely plays a role in increasing the Curie temperature to very nearly that of

pure magnetite. Evidence for some oxidation of the spinels is that the microprobe analyses for the titanomagnetites are often low (see Table 5), possibly implying a small degree of non-stoichiometry. The Curie temperature curves do not support this idea, being nearly reversible.

### Petrologic Evidence

Optical identification of the titanomagnetite is very difficult because the differences between the it and the spinels are subtle. The results of the petrologic study and microprobe data suggest two possible sources of magnetization: (1) large, low titanium, MD titanomagnetite, and (2) large, highly substituted, MD spinel.

## Conclusions

The NRM inclination and MDF data provide a basis for the conclusion that the carrier has a VRM, and therefore is MD, implying grain size restrictions. The titanomagnetite and spinel easily comply with this limitation.

The Curie temperature data suggest titanomagnetite with a slight degree of oxidation is the carrier. Considering that all studies of substituted spinels have shown low Curie temperatures, it is not probable that the spinels would generate the observed

Curie temperatures.

Microprobe data has shown that some of the grains previously identified by Peckenham (1981) as spinels are actually titanomagnetite. Titanomagnetite grains of this size range (groundmass to phenocryst) would be MD which is consistent with the observed NRM behaviour. It is therefore not necessary to invoke the presence of sub-microscopic magnetite as the carrier of magnetization, proposed by Peckenham (1981).

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