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Magnetic study of serpentinized harzburgites from the Islas Orcadas Fracture Zone

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Abstract

Magnetic properties and bulk densities of 27 serpentinized harzburgite samples from the Islas Orcadas Fracture Zone, located in the vicinity of the Bouvet Triple Junction, have been measured and analyzed. Polished sections were examined using reflected light and scanning electron microscopy to characterize the size and geometric arrangement of opaque minerals. The relationship between the saturation magnetization (I_S) and remanent coercive force (H_R) is considered in terms of the amount of ferrimagnetic material and maghemitization. A suite of continental serpentinites from Canada is offered as contrast, to consider the role of weathering and maghemitization. Magnetite in the Islas Orcadas serpentinites is variably maghemitized, whereas continental serpentinites do not appear to contain maghemitized oxides. We verify this with optical microscopy, thermomagnetic analyses and cryogenic temperature cycling of saturation remanence. Maghemitization serves to reduce initial magnetic susceptibility, and introduce error in the use of I_S to evaluate the magnetic mode of magnetite. The presence of maghemite and the existence of a three dimensional vein network for magnetite geometry would suggest that magnetic hysteresis parameters can not reliably indicate grain size. Magnetic hysteresis ratios fall in a restricted range regardless of coercivity. The apparent grain size configured in a three dimensional vein network plus maghemitization might be responsible for this observation. Maghemitization does not affect thermal magnetic stability and enhances the geophysical importance of remanence in serpentinites. Paleomagnetic data suggest that important information about the geologic circumstances for oceanic rock serpentinization is embodied in the paleomagnetic records. This observation may be very important for generation of long wavelength aeromagnetic and possibly even satellite magnetic anomalies.

Introduction

The symmetric location of geomagnetic field anomalies about the axes of mid-oceanic ridges has played a key role in the theory of plate tectonics. While it is clear that rocks in the oceanic crust are the origin of the magnetic anomalies, it is not clear which types of rocks are responsible and exactly how these magnetic rocks are configured.

A large body of experimental evidence suggests that the structure of the magnetic layer is more complex than was suggested earlier (Talwani et al., 1971). The measured magnetization of basalts recovered from layer 2A appears to be insufficient to create marine magnetic anomalies observed at the sea level (Harrison, 1987) and at satellite altitudes (Yanez and LaBrecque, 1997). Oceanic layer 3A gabbros usually have low magnetic stability and remanence (Dunlop and Prevot, 1982) but Pariso and Johnson (1993) reported that 'gabbros can acquire substantial, stable remanent magnetization in a relatively short period of time and are therefore capable of recording reversals of the Earth's magnetic field'. Recent discoveries of serpentinized peridotites in the vicinity of Mid-Atlantic Ridge (MAR) led several authors to conclude that these rocks may constitute a significant part of the oceanic crust (Dick et al., 1984; Bina et al., 1990; Juteau et al.,1990; Casey, 1996). Our attention has been focused on serpentinized rocks because: (1) they are common in fracture zones (F.Z.) and in the rift mountains and (2) when these rocks, with induced or remanent magnetization, are used in magnetic models they can be shown to create the observed magnetic anomalies.

The Bouvet Triple Junction is a major tectonic feature of the southern part of South Atlantic (Figure 1). It marks the site of bifurcation of active plate boundary into the Mid-Atlantic and Southwest Indian Ocean Ridges. In November and December 1976 during cruise 11/76 of the R. V. 'Islas Orcadas' the ridge system and the Islas Orcadas F.Z. in the vicinity of the Bouvet Triple Junction was surveyed. Navigation was performed by combination of satellite and omega positioning (Sclater et al., 1978). The Islas Orcadas F.Z. has about 100 km offset and 3000 m of vertical relief (Sclater et al., 1978). Four dredge sites (sites 56, 58, 59, 60) were made on the southern wall of the Islas Orcadas F.Z. (54°5′ S and 6°4′ E) (Figure 1) and a total of ~440 kg of spinel-harzburgite were recovered. Visual inspection shows that samples from sites 56 and 58 are brown in color and that they can be easily disaggregated. Samples from sites 59 and 60 are mechanically strong and are characterized by dark green color. Dredge sites were spaced at the base, lower middle, upper middle and crest of this F.Z. wall. From the top to the bottom of the wall a systematic decrease in the degree of serpentinization was observed. It is possible that such a large thickness of harzburgite represents an intrusion of the upper mantle along the fracture zone.

Spinel bearing harzburgites and lherzolites constitute about 70% of the abyssal peridotitic rocks which have been recovered at numerous localities in the walls of F.Z's. and in the rift mountains of slow spreading mid-oceanic ridges (Dick and Bullen, 1984). These rocks closely resemble alpine type harzburgites and lherzolites (Bonatti and Hamlyn, 1981) and are believed to be the residues of mantle partial melts depleted in basaltic components, emplaced at the top of the mantle, and finally exposed on the sea floor by faulting of the relatively thin oceanic crust (Dick et al., 1984). Although the chemical and mineralogical changes of ultramafic rocks during serpentinization were investigated by a number of authors (Page, 1967; Moody, 1976; Eckstrand, 1975; Coleman and Keith, 1971; Coleman, 1971; Bonatti and Hamlyn, 1981; Dick and Bullen, 1984; Wicks and Plant, 1979), we are only slowly understanding their magnetic petrology.

Several workers have reported that oceanic serpentinites possess intense and variably stable natural remanent magnetization (NRM), comparable with NRM of oceanic basalts (Bina and Henry, 1990; Krammer, 1990; Nazarova, 1994), and may contribute to the oceanic magnetic anomalies, especially to the long wavelength components (Arkani-Hamed, 1988; Shive et al., 1988; Hamano et al., 1990). The origin of remanence in the oceanic serpentinites is chemical remanent magnetization (CRM) (Dunlop and Prevot, 1982; Krammer, 1990; Nazarova, 1994). CRM forms as magnetite grains grow during the serpentinization of the upper mantle rocks at temperatures, estimated to be $\leq$ 350 °C (Krammer, 1990). The NRM of oceanic serpentinites has a composite character and appears to be the superposition of the original CRM and secondary magnetizations. Specifically these magnetizations are (1) viscous induced magnetization (VIM), which forms at the elevated temperatures in the deep crust, (2) partial thermoremanent magnetization (PTRM), which forms during cooling and emplacement of serpentinites in the upper parts of the oceanic crust, and (3) secondary chemical magnetization which forms during the weathering sometimes coupled with the serpentinization. Weathering leads to the creation of maghemite whose identification is one of the main goals of this paper.

In this paper we consider if serpentinized harzburgites recovered in Islas Orcadas fracture zone may be the source of oceanic magnetic anomalies. The significance of serpentinite magnetization in the oceans may be estimated if detailed magnetic studies are coupled with opaque mineral petrology data. Using this approach, we studied serpentinized harzburgites from Islas Orcadas F.Z. in order to (1) assess the size and geometric arrangement of ferrimagnetic minerals, (2) estimate the relationship between the degree of serpentinization and magnetic parameters, (3) identify how weathering affects magnetic hysteresis parameters, and (4) consider the significance of serpentinite magnetization in the oceanic crust and upper mantle.

Experimental procedures

Samples used in this study were slabs obtained from collections at the Woods Hole Oceanographic Institution (WHOI). Measurements of NRM (remanent magnetization), X_0 (initial susceptibility), I_S (saturation magnetization), SIRM (saturation remanent magnetization) and thermal demagnetization experiments were done using 1 cm diameter cores or cubical samples cut from the slabs. Remanence measurements were carried out on a three axis cryogenic magnetometer. Magnetic susceptibility measurements were made using a Bartington MS2 system. Thermomagnetic analysis (Curie point curves) and magnetic hysteresis loops parameters (H_C, H_R SIRM, and I_S) were acquired on the PAR Vibrating Sample Magnetometer. Bulk densities (D) were measured using a Sartorius balance. Based on the magnetic properties measurements, representative samples were chosen for optical microscopy and Scanning Electron Microscope (SEM) studies.

Opaque minerals and thin section analyses

Magnetic mineralogy in serpentinites is mainly magnetite (Fe_3O_4) with very minor awaruite (Ni_3Fe), occasionally Fe and rarely FeCo (see Eckstrand, 1975; Lienert and Wasilewski, 1979). For oceanic and continental serpentinites the Curie points are generally at 575–580 °C which indicate pure magnetite (Smith and Banerjee 1984; Bina and Henry 1990; Lienert and Wasilewski, 1979) and sometimes at 590 °C which suggest Ni_3Fe (see Lienert and Wasilewski, 1979). Chromites can be oxidized along a trend to ferrit chromite then chrome magnetite and, as Shive et al. (1988) describe, metamorphosed peridotites often have Curie points as low as 525 °C (see Wasilewski et al., 1975 for discussion of magnetic properties of the magnetite-chromite solid solutions series).

O'Hanley and Dyar (1993) suggest that magnetite can be a reactant, a product or passive agent during change in serpentinite mineral reactions or texture. O'Hanley and Dyar (1993) studied the relationship between density and magnetic susceptibility (X_0). The solubility of Fe^{3+} in lizardite and the suppression of magnetite formation early in the serpentinization of peridotite accounts for a non linear relationship between density and X_0. X_0 is therefore likely not a reliable indicator of intensity of serpentine crystallization.

This paper considers samples from 4 dredge sites (56, 58, 59 and 60, Figure 1). Polished sections were produced for six samples 60–102, 60–27, 59–72, 59–21, 58–30 and 56–29. These sections were examined under reflected light and scanning electron microscopy to characterize the opaque mineralogy.

Back scattered electron (BSE) images were obtained using a Cambridge scanning electron microscope (SEM) (Figure 2). All of the images were taken at the same magnification so that a comparison of thickness and geometry of the vein like magnetite distributions could be made. The recording conditions were adjusted to emphasize the magnetite, iron sulfide, etc. over the background silicates.

Microscopic observations of polished sections indicate the presence of magnetite in several forms (Figure 2). Fine anhedral to euhedral isolated grains of magnetite are observed (especially for samples from sites 56 and 58). The most typical occurrence of magnetite is veins of various length and width (sites 60 and 59). In some cases veins of magnetite are more or less continuous over several 100 μm, but mostly vein structures are represented by broken segments. The breaks in the vein segments are small, so high magnetic anisotropy is likely. In almost all cases the segments can be characterized (in plane view) as linear rods with shape anisotropy. The brown weathered samples (56–29 and 58–30) have smaller vein thickness and overall grain size. The preferred orientation of the veins may be severe, as for sample 59–21 (Figure 2), suggesting a mimic of the rock fabric. From the examples shown in Figure 2, no clear correlation between vein thickness and magnetic properties can be established (see magnetic data in Table 2). Higher magnification (1000× oil immersion) studies identified a very fine fraction of discrete grains in all samples. We attempted to identify the products of low temperature oxidation for Islas Orcadas harzburgites but there is no obvious indication of maghemite in the SEM micrographs. Also, we did not find any evidence of metals or other exotic minerals.

Thin sections were analyzed by Dick et al. (1984) in order to calculate the primary modal compositions (Table 1). The average abyssal peridotite is a plagioclase free harzburgite with 77% olivine, 19% enstatite, 3% diopside and 0.5% chromian spinel. Data shown in Table 1 indicate that in general the modal composition of Islas Orcadas serpentinites is typical for abyssal peridotites collected in different parts of the mid-ocean ridges (Dick et al., 1984). Petrologically, plagioclase free abyssal peridotites resemble alpine type harzburgites (Bonatti and Hamlyn, 1981) and are considered to be the residues of mantle partial fusion and magma genesis.

Magnetic results

The room temperature magnetic properties and bulk densities of 27 serpentinized harzburgites from the Islas Orcadas Fracture Zone are shown in Table 2. Mean density for all samples is 2628 ± 86 kg/m^3. Table 2 was constructed by using different pieces of the slab samples obtained from the WHOI collections. The first 5 columns in the Table 2: (I_S)-saturation magnetization, (H_C)-coercive force, (H_R)-remanent coercive force, (R_I=SIRM/Is, (R_H)=H_R/H_C) were derived from the magnetic hysteresis loops, using small specimens, at most 0.6 cm in diameter. The next 4 columns (NRM)-remanent magnetization, (SIRM)- saturation remanent magnetization, (REM) = NRM/SIRM, and (R_K)-ratio of SIRM after liquid nitrogen treatment to the original SIRM were derived from small cubical specimens cut from the same slabs. X_0 and D data

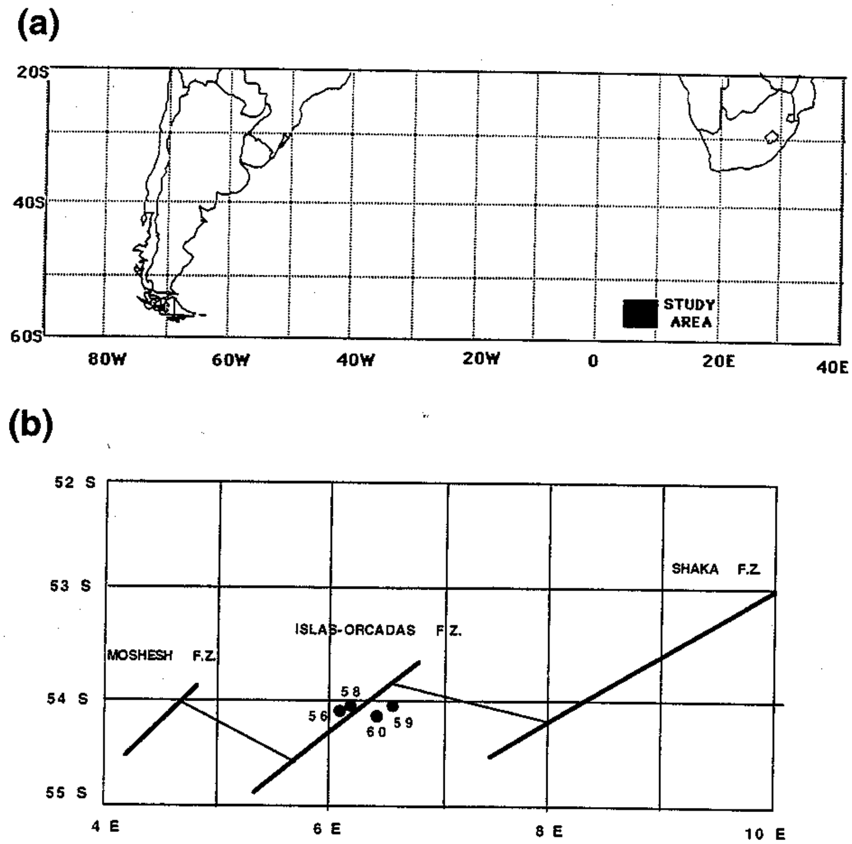

Figure 1. Study area (a) and site location (b) on the Islas Orcadas Fracture Zone where serpentinized harzburgites samples were recovered and measured.

Table I. Modal composition of Islas Orcadas abyssal peridotes (Dick et al., 1984)

NO STATION	LATITUDE	LONGITUDE	NUMBER OF SAMPLES	OLIVINE	ENSTATITE	DIOPSIDE	SPINEL	PLAGIOCLASE
IO11/76-56	54°05′S	06°17′E	6	71.5	22.0	5.51	0.91	0.07
IO11/76-58	54°04′S	06°24′E	6	68.1	25.0	5.93	0.71	0.25
IO11/76-69	54°03′S	06°30′E	6	73.4	21.7	4.15	0.69	0.01
IO11/76-60	54°03′S	06°29′E	13	75.9	19.8	3.6	0.6	0.06

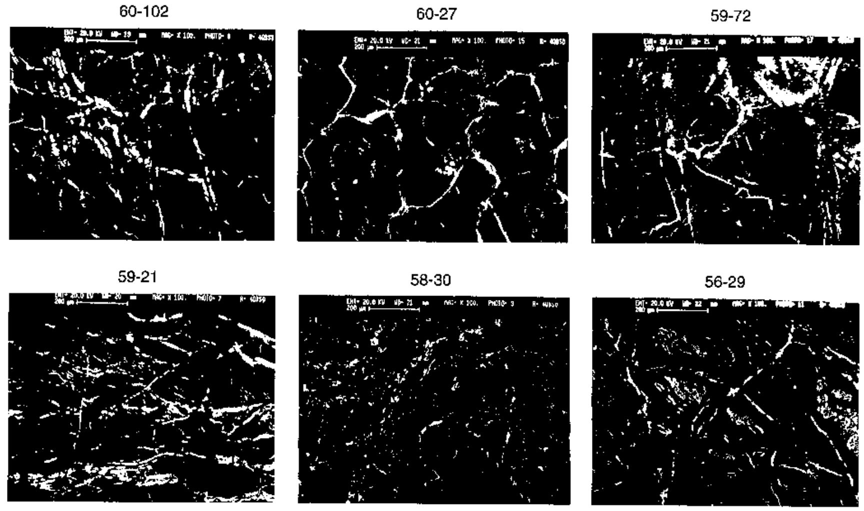

Figure 2. Back scattered electron images for Islas Orcadas serpentinized rocks.

came from 1.2 cm cores which were drilled from the slabs. A set of Canadian continental serpentinites (18 samples) was obtained from F.I. Wicks (Wicks and Plant, 1979) and was included in this study. Magnetic properties of continental Canadian serpentinites are shown in Table 3. All magnetic measurements were performed in the Rock Magnetic Laboratory of Goddard Space Flight Center.

Magnetic hysteresis

Magnetic hysteresis loop data for sites 56, 58, 59, and 60 are presented in Table 2. R_I (ratio of saturation remanence to saturation magnetization) ranges from 0.18–0.37 and R_H (ratio of remanent coercive force to coercive force) ranges from 1.27 to 2.1. Remanent coercive force (H_R) ranges from 14 to 50.5 mT and coercive force (H_C) from 9.3 to 32.5 mT. Using the traditional approach to decipher magnetic hysteresis data one can conclude that much of the remanence is due to ferrimagnetics dominated by small pseudo-single domain (PSD) or single domain (SD) size (Wasilewski, 1987).

The rocks under study are considered in two groups: the unweathered green colored rocks from

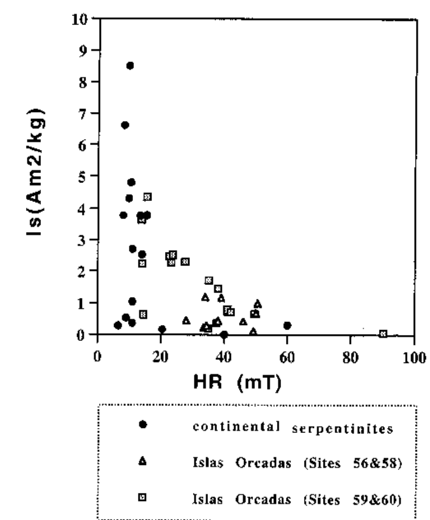

Figure 3. Plot of saturation magnetization (I_S) against remanent coercive force (H_R) for continental (Canadian) and Islas Orcadas serpentinites.

Table 2. Magnetic properties of Islas Orcadas Serpentinites Harzburgites

Sample	Is Am2/Kg	H_C mT	H_R (mT)	R_I	R_H	NRM $10^{-4}Am^2Kg^{-1}$	SIRM $10^{-4}Am^2Kg^{-1}$	REM	R_K	NRM A/M	Xo (SI)	D (Kg/m^3)
56-10	0.68	32.2	50.0	0.367	1.58							2513
56-29	1.18	25.0	34.0	0.353	1.36	7.21	5142.1	0.0014	0.93	1.89	0.011	2650
56.50	0.28	25.6	34.5	0.360	1.35	2.30	2180.6	0.0011	0.84	0.59	0.029	2664
56-54	0.22	20.5	33.5	0.313	1.56	5.34				1.40	0.009	2705
56-57	0.99	32.5	50.5	0.365	1.55							2618
58-12	0.44	25.2	38.0	0.364	1.51	2.44				0.59	0.007	2499
58-18	1.16	26.0	39.0	0.360	1.49							
58-30	0.42	27.8	46.0	0.306	1.66	1.04	3109.2	0.0003	0.95			2674
58-34	0.11	30.6	49.2	0.358	1.60	0.80				0.22	0.003	2829
58-61	0.45	17.5	28.0	0.273	1.60	1.98	3159.5	0.0006	0.97	0.55	0.006	2805
59-12	2.24	9.3	14.0	0.207	1.50	20.66	10863.0	0.0019	0.75	5.42	0.082	2525
59-21	0.63	9.7	14.5	0.175	1.49	79.16	9413.9	0.0084	0.81			
59-49	0.06	65.3	90.0	0.504	1.38	6.42	280.3	0.0229	0.98	1.72	0.035	2688
59-65	3.64	9.7	13.8	0.217	1.42	13.88	6175.8	0.0022	0.89	3.69	0.062	2610
59-72	0.72	25.0	41.0	0.349	1.64	12.64	10837.1	0.0012	0.83	3.29	0.062	2672
59-75	0.66	23.6	49.5	0.237	2.10	0.38	300.9	0.0013	0.80			2523
60-21	0.20	18.1	35.0	0.242	1.94	2.73	2846.8	0.001	0.85	0.69	0.026	2611
60-27	2.31	20.0	27.5	0.301	1.38	7.38	6756.7	0.0011	0.84	2.05	0.023	2732
60-34	0.71	27.5	42.0	0.355	1.53	7.10	4395.4	0.0016	0.94	1.81	0.019	2509
60-41	0.80	25.3	41.0	0.260	1.62	4.13	7794.3	0.0005	0.94	1.06	0.022	2611
60-97	2.49	17.8	22.5	0.329	1.27	8.52	7640.5	0.0011	0.73	2.26	0.035	2635
60-101	1.71	24.7	35.0	0.388	1.42	6.24	6049.6	0.001	0.93			2569
60-102	4.35	10.3	15.5	0.197	1.51	19.29	4598.7	0.0042	0.54	5.12	0.062	2648
60-115	0.36	25.0	37.5	0.335	1.50	9.53				2.47	0.021	2649
60-127	2.53	17.5	23.7	0.282	1.35	14.03				3.65	0.023	2615
60-143	2.28	16.7	23.2	0.273	1.39	25.40				6.77	0.050	2636
60-155	1.45	22.8	38.0	0.304	1.67	1.89	2819.7	0.0007	0.95			2531

Comments: I_S = saturation magnetization, H_C = coercive force, H_R = remanent coercive force, R_I = SIRM/I_S, $R_H = H_R/H_C$, NRM = remanent magnetization, SIRM = saturation remanent magnetization, REM = NRM/SIRM, R_K = ratio of SIRM after liquid nitrogen treatment to the original SIRM, X_O = initial susceptibility, D = bulk density (kg/m^3)

sites 59 and 60, and the weathered brown colored rocks from sites 56 and 58. We analyzed magnetic data for these two groups separately. In Figure 3 saturation magnetization (I_S) is plotted against remanent coercive force (H_R). Two sets of magnetic data are included in this Figure: The Islas Orcadas serpentinites which are the subject of this paper (data for sites 59, 60 and Sites 56, 58 are shown separately), and a set of Canadian continental serpentinites (Table 3).

Our previous magnetic study indicated that oceanic and continental serpentinites exhibit a notable difference (Lienert and Wasilewski, 1979; Nazarova et al., 1995). Optical inspection of the continental serpentinites shows them to contain regularly shaped and optically homogeneous multidomain magnetite grains in contrast to the oceanic serpentinites which contain featherled and mottled veins and small discrete grains of magnetite. Consequently, magnetic hysteresis loops are different for oceanic and continental serpentinites. In general, coercitivities are < 5.5 mT for continental and about 10–30 mT for oceanic serpentinites In accordance with our previous study the continental serpentinites (in contrast with oceanic) appear to be unweathered and not affected by maghemitization (Nazarova et al., 1995). The reason for inclusion of the continental serpentinites in this study is to consider how weathering affects magnetic hysteresis parameters, and to verify the contrast between continental and oceanic serpentinites.

Table III. Magnetic properties of Canadian serpentinites (Wicks and Plant, 1979)

Sample	I_S Am^2/Kg	H_R $^{(mT)}$	R_K
67-15B	2.540	14.0	0.48
67-67B	4.812	10.5	0.59
W70-72	1.037	11.0	
W70-41	0.280	6.5	0.30
FW-SW-2	8.521	9.7	
FW-B-7	3.786	15.5	0.40
67-54B	2.718	11.0	0.45
W70-35	4.316	9.8	0.38
FW-05-4	6.618	8.3	0.52
W70-55	0.533	9.0	0.43
W75-62	0.367	11.0	0.40
67-70A	3.782	8.0	0.33
FW-L-4	0.305	60.0	0.88
67-36A	0.004	40.0	0.80
FW-GV-1	0.169	20.5	0.63
67-54B-2	3.777	13.5	
T179			0.92
FA-MA-3			0.71

Comments: I_S = saturation magnetization, H_R = remanent coercive force, R_K = ratio of SIRM after liquid nitrogen treatment to the original SIRM

The Canadian serpentinites (indicated by shaded circles in Figure 3) show H_R values <20 mT except for two samples with H_R values of 40 mT (sample 67–36A) and 60 mT (sample FWL-4). These two samples have a small amount of very fine grained magnetite. There are also four other continental serpentinites with small amounts of magnetite, but the magnetite present is large grained and multidomain and falls within the main trend. The Canadian serpentinites and Islas Orcadas serpentinites from sites 59 and 60 (all of them contain veins of magnetite) generally show an increase in H_R as I_S decreases. Brownish weathered site 58 and 56 rocks are characterized by relatively small I_S values and a broad range of H_R (see Figure 3).

Bina and Henry (1990) proposed that the degree of serpentinization could be calculated from the ratio of iron in magnetite (I_S = 92 Am^2 kg^{-1} for magnetite) to the whole rock iron content asuming that initial peridotite had no magnetite ($I_S = 0$). Those authors demonstrated that the degree of serpentinization defined in such way correlates well with saturation magnetization (I_s). Bina and Henry (1990) have also noted that a high degree of serpentinization (>80%) is associated with $R_I \leq 0.08$ and that less serpentinized samples exhibit pseudo single domain (PSD) magnetite based on R_I ranging from 0.1 to 0.24. From their data they conclude that in less serpentinized samples, small grains of magnetite occur progressively in an olivine matrix. As serpentinization proceeds magnetite grains develop, occupying cracks and fractures resulting from the increase in rock volume, and hence veins of magnetite are formed.

Thermomagnetic analysis of green unweathered sites 59 and 60 rocks as well as Canadian serpentinites showed that magnetite which was produced during serpentinization.was the main magnetic phase Therefore, we suggest that the degree of serpentinization is proportional to the amount of newly formed magnetite, i.e., I_s. Using the Bina and Henry (1990) assumption to explain the main trend (increase in H_R as I_S decreases) in Figure 3, we can suggest that small grains with high H_R form initially and, as serpentinization proceeds and consequently the magnetite content (I_s) increases, the grains grow in size giving a decrease in H_R. Visual inspection and low Is values for rocks from sites 58 and 56 suggest that they were probably affected by maghemitization.

For the Islas Orcadas rocks the R_I and R_H values are restricted regardless of the broad range in H_C and H_R (Table 2). We feel that networks of magnetite veins like those in Figure 2 (especially for sites 60 and 59) have unknown (at present) magnetic hysteresis and if we assume that maghemitization is important, the story becomes more complicated. The presence of maghemite reduces I_S substantially in artificial samples (up to about 30%) (Ozdemir, 1990) and to an unknown degree in natural samples, this introduces errors in the evaluation of the amount of magnetite.

Thermomagnetic curves and cryogenic temperature cycling of SIRM

Thermomagnetic curves (Curie point curves) (Figure 4) are measured with heating and cooling accomplished in a magnetic field of 1 Tesla, applied continuously. Powdered samples are placed in a Boron Nitride sample holder for the experiments. All Curie temperatures correspond to magnetite and are in the range 550–570 °C (Figure 4). Irreversibility of thermomagnetic curves can be related to the destruction of maghemite during the heating (Ozdemir, 1990). Since all conditions were near the same, it was instructive to compare heating and cooling curves to determine

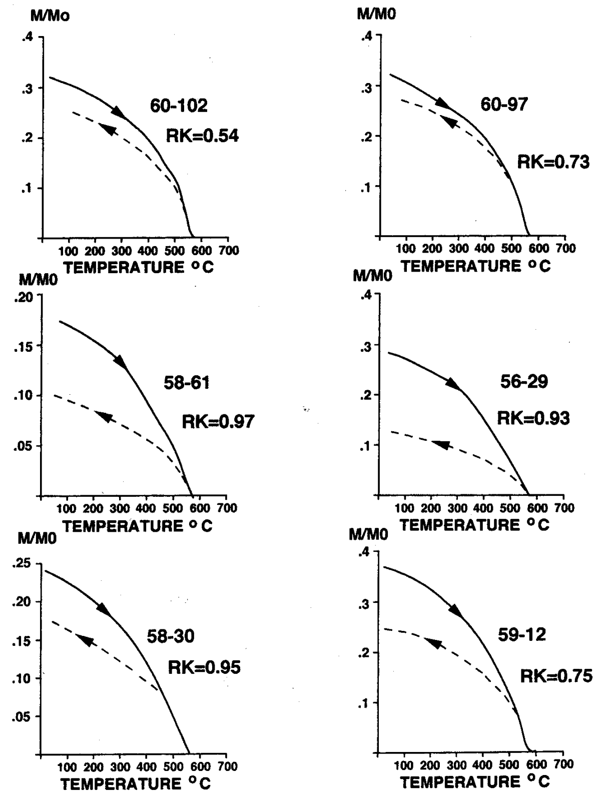

Figure 4. Thermomagnetic curves for Islas Orcadas ultramafic rocks. M/M0 – normalized remanence, Rk – ratio of SIRM after liquid nitrogen treatment (cooling to liquid nitrogen temperature −196 °C and the warming up to room temperature) in zero magnetic field to the original SIRM.

the extent of irreversibility which may relate to the presence of maghemite.

As can be seen in Figure 4, the amount of magnetization lost on cooling is variable, but considerable, especially for samples from sites 56 and 58. There may also be a minor amount of oxidation that contributes to the loss of magnetization. The dark green samples from sites 60 and 59 show less irreversibility compared to sites 58 and 56 (Figure 4). The numbers in parentheses are the R_K values, where R_K is the ratio of SIRM measured after cooling to liquid nitrogen temperature (−196 °C) and then warming to room temperature in zero field to the original SIRM (at room temperature). The cooling and heating took place inside a three stage mu metal shield. We use this ratio because the appearance of maghemite can cause an increase in the R_K ratio (Hartstra, 1982b) and thus is a qualitative check on the presence of this mineral. Figure 4 shows that the R_K ratio increases with increasing the irreversibility between heating and cooling curves. This suggests that the difference between the heating

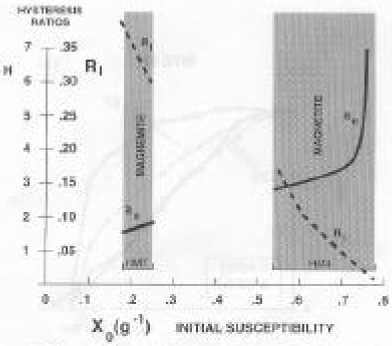

Figure 5. Magnetic hysteresis loop ratios the R_I (SIRM/Is) and R_H (H_R/H_C) are plotted against X_0 (initial susceptibility) for two different microstructures HM4 (magnetite) and HM7 (maghemite). Bracketed range above Xo axis indicates range in Xo for 250 μm to <5 μm size separates for each microstructure. Data from Hartstra (1982a, b).

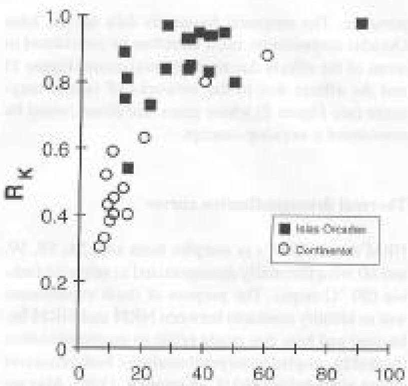

Figure 6. Relationship between R_K and H_R for Continental and Islas Orcadas serpentinites.

and cooling curves during thermomagnetic analysis is caused by maghemitization.

In order to illustrate the contrast between maghemite and magnetite we used the data from Hartstra (1982a) to construct Figure 5. In Figure 5, magnetic hysteresis loop ratios R_I and R_H are plotted against initial magnetic susceptibility (X_0) for maghemite HM7 and magnetite HM4. The dashed and solid lines represent the range in R_I and R_H respectively for the entire size sequence (<5 μm to 250 μm) studied by Hartstra (1982a). There is no overlap, the magnetite and maghemite data are discrete. Further, one sees the difference in initial magnetic susceptibility appropriate to the contrast in magnetic hardness. Bracketed HM7 and HM4 at the bottom of Figure 5 indicate the range in all parameters for the size range (<5 μm to 250 μm) for maghemite and magnetite, respectively.

Hartstra showed that R_K ranged from 0.21 for magnetite grain size of 150–100 μm to 0.5 for magnetite with grain size <5 μm and for maghemite R_K ranged from 0.92 for the 150–100 μm to 0.98 for <5 μm grain size (Hartstra, 1982b). At the same time Parry (1982) showed that single domain (SD) magnetite had an R_K of 0.96. Therefore, very fine (SD) magnetite and maghemite has lost very little of the SIRM during the liquid nitrogen cycling. Parry (1982) also studied bimodal mixtures of 200 μm and 100 μm magnetite with SD magnetite where the volume fraction of coarse to SD magnetite was 0.97. With the 100 μm coarse fraction the R_K value was 0.55 and with the 200 μm course fraction the R_K value was 0.80. This mixture experiment demonstrates the dominance of the single domain fraction even when present in small amounts.

The experimental results discussed above can be summarized as follows: (1) for single domain magnetite and for maghemite $R_K > 0.9$, for magnetite with grain sizes < 5 μm $R_K < 0.5$; (2) R_K with lowest values (0.21) is associated with the coarsest grain size (100–150 μm); (3) $R_H > 3$ for coarse magnetite and $R_H < 2$ for maghemite; (4) $R_I < 0.2$ for coarse magnetite and $R_I > 0.3$ for maghemite.

In Figure 6 the R_K value is plotted against H_R for the Islas Orcadas oceanic serpentinites and the same continental suite used in Figure 3 (see Table 2 and Table 3). Except for sample 60–102, all Islas Orcadas serpentinites have $R_K > 0.7$. All continental serpentinites have $R_K < 0.6$ except for two samples with small amounts of very fine grained magnetite having large H_R relative to the other samples. Clearly there are anomalies such as the continental serpentinites with large R_K, but this can be demonstrated to be associated with SD – like magnetite by the large H_R values.

Reference to Table 2 indicates that all Islas Orcadas serpentinites have a restricted range of R_I and R_H which certainly is suggestive of maghemite importance. The magnetic hysteresis data for the Islas Orcadas serpentinites must therefore be considered in terms of the effects due to maghemitization (Figure 5) and the effects due to the networks of veined magnetite (see Figure 2) where grain size alone cannot be considered a working concept.

Thermal demagnetization curves

NRM's and SIRM's in samples from sites 56, 58, 59, and 60 were thermally demagnetized in stepwise fashion (50 °C steps). The purpose of these experiments was to identify contrasts between NRM and SIRM behaviour and how this might relate to maghemitization (probably coupled to serpentinization); both processes taking place below 350 °C (Krammer, 1990). Also we attempted to decipher any episodic serpentinization using the paleomagnetic data. We discuss the thermal demagnetization of NRM's and SIRM's in samples from sites 60, 59, and 56 and 58 with consideration of the REM values (ratio of natural remanence to saturation remanence, NRM/SIRM) and the R_K values, as these parameters are important in addressing maghemitization and assessing the efficiency of acquiring remanence associated with serpentinization. Examples of typical NRM and SIRM thermal demagnetization curves are plotted in Figures 7(a) (site 60), 7(b) (site 59), and 7(c) (sites 56 and 58).

For all samples REM values are quite low and range from 0.0003 to 0.004 (Table 2), indicating inefficient remanent acquisition during serpentinization. For example thermoremanence in magnetite gives REM values of ~0.01–0.02 and Lienert and Wasilewski (1979) recorded REM values ranging from 0.001 to 0.003 for continental serpentinites, which clearly acquire chemical magnetization during production of magnetite at temperatures <500 °C. Similar REM values (0.001–0.004) were recorded for samples 60–27, 60–97 and 60–102 which have reversible thermomagnetic curves (Figure 4) and the smallest R_K's (Table 2). These particular samples exhibit the highest level of NRM thermal stability and have >50% of their NRM unblocked beyond 500 °C. Samples with larger R_K's and lower REM (ranging from 0.0005 to 0.001) (samples 60–34, 60–41, 60–101, 60–155) are less stable and have 50% of their NRM unblocked by 350–500 °C. For all site 60 samples 50% of the SIRM is unblocked by 350–500 °C (Table 2, Figure 7(a)).

For Site 59 harzburgites the REM values range between 0.001 and 0.002 for most of the samples and

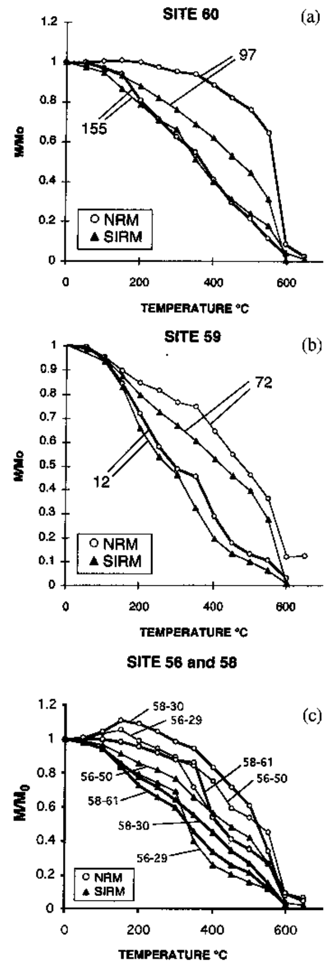

Figure 7. Typical thermal demagnetization curves of Islas Orcadas ultramafic rocks: M/M0 – normalized remances (a) NRM and SIRM thermal demagnetization for samples 60–97 and 60–155; (b) NRM and SIRM thermal demagnetization for samples 59–72 and 59–12; (c) NRM and SIRM thermal demagnetization for sites 58 and 56.

the relationship between R_K and thermal unblocking is exactly opposite to that from site 60 (Figure 7 (b)).

The lowest REM values (0.0003–0.0006) are related to weathered rocks from site 58. All R_K values for sites 56 and 58 are >0.9 except for 56–50 (Table 2); 50% of NRM is unblocked by 350–450 °C, whereas 50% of SIRM is unblocked by 450–600 °C (Figure 7(c)).

Distinction in the unblocking temperatures for NRM and SIRM is not surprising since, in contrast with NRM, all magnetic minerals contribute to the SIRM regardless of grain size or composition This established relationship between R_K, REM and 50% NRM unblocking temperatures indicates inefficient remanent acquisition during serpentinization and higher magnetic thermal stability of serpentinites with lower R_K and higher REM values.

For all samples that were thermally demagnetized (Figure 7) we acquired paleomagnetic data. Though the dredged samples were not oriented, an arbitrary orientation was preserved throughout the thermal demagnetization and therefore the behavior of the remanence could be evaluated. Surprisingly, we found no excursions of significant noise in the data suggesting that once serpentinization began it proceeded relatively rapidly and that the orientation of the geomagnetic field with respect to the serpentinite block was fixed during the serpentinization process. This fixed relationship also applies to weathered samples from sites 56 and 58 implying that the weathering progressed while the blocks were fixed. The serpentinization likely took place rapidly after emplacement in the upper crust and certainly not during any kind of episodic emplacement that would require dislocation of the blocks with respect to the orientation of the geomagnetic field.

Discussion

Previous investigations showed that remanence of serpentinites in the upper oceanic crust is intense (average about 3 A/m) and stable enough to contribute to the magnetic anomalies (Dunlop and Prevot, 1982; Bina and Henry, 1990; Krammer, 1990; Nazarova, 1994). In order to have a significant regular contribution to the linear magnetic anomalies serpentinized peridotites must form a continuous layer in the crust. Currently geophysical evidence of a continuous serpentinite layer in the oceanic lithosphere is lacking, which indicates that oceanic serpentinites may not play a significant role in the creation of linear magnetic anomalies.

However, data acquired during several Legs of Ocean Drilling Program (ODP) (Sites 670, 395, 334, 560, 558, 920B, 920D) give evidence that serpentinized rocks constitute a significant part of the normal oceanic crust at least from 0.5 Ma (Site 670) to 37 Ma (Site 558) in the vicinity of the rift valley of the slow spreading Mid-Atlantic Ridge (Juteau et al., 1990). Their remanence (average value about 3.5 A/m) is strong enough to contribute to the oceanic magnetic anomalies. In particular, ODP serpentinites with magnetite of PSD size is a very likely source of magnetic anomalies (Bina and Henry, 1990; Krammer, 1990; Nazarova, 1994).

Islas Orcadas fracture zone serpentinized harzburgites represent typical abyssal peridotitic rocks recovered at numerous localities in the oceanic crust. The mean remanence (3.1 A/m) of unweathered green rocks from sites 59 and 60 is in accordance with previous studies, whereas the mean NRM of weathered rocks from sites 56 and 58 is about 0.9 A/m (Table 2). Experiments on thermal demagnetization indicate that NRM of all these rocks is quite stable. Half of the initial remanence is lost by about 500 °C for samples from site 60 which have reversible thermomagnetic curves and the smallest R_K's. All other samples (except 59–21) have 50% of the NRM unblocked beyond 350 °C, i.e., above the estimated temperature of serpentinization in the oceanic crust. (Krammer, 1990). Paleomagnetic study did not reveal any directions variability in magnetization which suggests that serpentinization was proceeding rapidly.

Examination of a subset some of Islas Orcadas samples with reflected light microscopy indicates that veins of magnetite are present in all samples, with vein thickness being the obvious variant and a very fine fraction of discrete grains in all samples. Krammer (1990) analyzed reflected light microscopic data for serpentinized harzburgites recovered at Site 670A and came to the conclusion that in some magnetite grains structures, typical of low temperature oxidation, can be seen. He observed that 'covered with magnetic colloid, the maghemitized parts are indicated by lighter grey because of lesser attraction of the magnetite colloid. There are also indications of cracks in the lighter parts seaming the magnetite grains probably due to a shrinkage of the crystal lattice, which is a typical characteristic of low temperature oxidation'. In this study microscopic observations did not reveal any of these maghemite structures. Also in the optical studies and in the Curie point curves we find no evidence of metals or other exotic minerals.

However, an interesting inverse relationship between the saturation magnetization (I_S) and the remanent coercive force (H_R) (Figure 3) must be considered in terms of amount of ferrimagnetic material and the degree of weathering. The general trend shows that the I_S increase as H_R decreases, for continental serpentinites and harzburgites from sites 59 and 60. This may be explained in terms of progressive serpentinization (Bina and Henry, 1990). At the same time the relatively low I_S in brownish sample sites (56 and 58) may be interpreted in terms of weathering after a certain level of serpentinization has been reached. The growth patterns in the vein – like network (as suggested by Bina and Henry, 1990) may simply be a consequence of structural readjustment in the rock undergoing serpentinization, which by itself could promote further serpentinization by allowing rapid access to hydrothermal fluid. This would suggest mobile iron, otherwise the veins would not be the likely pattern for the distribution of magnetite. Looking at the mode of magnetite distribution with depth into a body undergoing serpentinization would certainly be instructive.

The obvious color contrasts between green site 59 and 60 rocks, and brown site 56 and 58 rocks, suggest weathering contrasts, and the likely influence of the hydrothermal deep sea environment suggests that oxidation of the magnetite in the oceanic serpentinites is likely. Therefore, a number of experiments were done to address the issue of maghemitization. The Curie Point curves all show some degree of irreversibility between heating and cooling curves with the most extensive irreversibility associated with rocks from sites 56 and 58. Embodied in the magnetic hysteresis loop data is further insight into the role of maghemite. The Harstra (1983) data were considered by Warner and Wasilewski (1990) to indicate that microstructure was more important than grain size in determining magnetic hysteresis and in influencing initial magnetic susceptibility. They plotted Harstra's hysteresis ratios (R_I and R_H) against initial magnetic susceptibility. In Figure 5 we removed the exsolution category, thereby allowing a contrast between magnetite and maghemite. Figure 5 partially explains why the Islas Orcadas serpentinites have a restricted range in R_I and R_H (see Table 2) regardless of size of the veins of magnetite which may actually be maghemitized to varying degrees. The reduction in magnetic susceptibility (i.e., induced magnetization) with maghemitization, enhances the geophysical importance of remanence in serpentinites.

Conclusions

1. The Islas Orcadas serpentinized harzburgites contain veins of magnetite of varying thickness together with very fine magnetite as observed optically by high magnification (1000x). There are no metals (i.e. Fe or Ni_3Fe) in the serpentinites based on our microscopic and magnetic analyses.
2. A plot of saturation magnetization (I_S) versus remanent coercive force (H_R) shows two trends: (a) I_S decreasing as H_R increases and (b) a broad range of H_R value with relatively small I_S value. This interesting relationship can be explained partially in terms of progressive serpentinization and weathering. However, the full relationship between I_S and H_R for unweathered samples is not clear.
3. Heating and cooling Curie point curves indicate irreversibility usually attendant with destruction of maghemite during heating. R_K is > 0.7 for the Islas Orcadas serpentinites and <0.6 for continental serpentinites, which have little or no irreversibility in Curie point analysis. These data suggest that in contrast to continental serpentinites Islas Orcadas harzburgites are strongly affected by maghemitization.
4. Literature (Hartstra, 1982b; Hartstra, 1983; Parry 1982) results show maghemite and single domain (SD) magnetite have R_K values >0.9. The magnetic hysteresis loop data (R_I and R_H) which is restricted for the Islas Orcadas serpentinites, regardless of the H_R (remanent coercive force) value, is in accord with data presented by Hartstra (1982a) for maghemite. This interesting contrast between magnetite and maghemite represents a reconsideration of the Hartstra (1982a) data which was first done by Warner and Wasilewski (1990). Recognizing the presence of maghemite in serpentinized rocks is important since the I_S value may be 20–30% less for maghemite thereby introducing an error in using I_S to estimate the amount of magnetite. Also, the initial magnetic susceptibility would be substantially reduced thereby over emphasizing magnetic remanence. If maghemite or any other microstructure is present, the use of R_I and R_H for determination of grain size must be seriously questioned Another important con-

sideration for interpretation of magnetic hysteresis data is the presence of a three dimensional network of veins of magnetic oxide. We do not know, at present, how this affects magnetite hysteresis data.

5. Paleomagnetic results from the serpentinites both weathered and unweathered suggest that serpentinization and weathering proceeded rapidly and that there was no significant dislocation of the blocks with respect to the direction of the geomagnetic field during the alterations. This is at variance with other studies (Smith and Banerjee, 1984; Bina and Henry, 1990) and suggests that important information about the geologic circumstances for oceanic rock serpentinization is embodied in the paleomagnetic records. This observation may be very important for generation of long wave aeromagnetic and possibly even satellite magnetic anomalies (Dyment et al., 1997)
6. The mean bulk density value measured for 25 samples is 2628 ± 86 kg/m^3. This agrees quite well with the commonly accepted value of 2700 kg/m^3 for oceanic crustal density as used in gravity anomaly calculations (Prince and Forsyth, 1988; Tolstoy et al., 1993).

In conclusion the data presented in this paper suggest that unweathered serpentinized harzburgites, which are common in the oceanic crust, (like site 59 and 60 rocks) are capable of acquiring quite intense and stable magnetization and may be considered as a viable source of oceanic magnetic anomalies. Maghemitization does not affect thermal magnetic stability and enhances the geophysical importance of remanence in serpentinites.

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