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23. ROCK MAGNETIC PROPERTIES AND OPAQUE MINERALOGY OF SELECTED SAMPLES FROM HOLE 670A[1]

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ABSTRACT

The magnetic properties of 11 samples from Site 670 of Leg 109, 3 harzburgites and 8 highly serpentinized peridotites, have been studied. Reflected light microscopy and Curie temperatures confirm that magnetite is the dominant magnetic mineral in all samples. However, both rock types show different magnetic behavior. Susceptibility, saturation magnetization, and NRM are higher for the serpentinites, because of the higher magnetite content. The hysteresis parameters indicate magnetite particles with pseudosingle domain structure for both rock types. For the remarkable anisotropy of the magnetic susceptibility no definite explanation could be found, because of the complex texture of the samples. In both rock types the presence of maghemite, a product of low temperature oxidation of magnetite, has been indicated by reflected light microscopy and by thermomagnetic analysis. As the maghemite converts to hematite at temperatures above 350°C, the temperature during the serpentinization was below this value assuming that the maghemitization took place at the same time.

INTRODUCTION

Hole 670A was drilled on Leg 109 directly into an outcrop of serpentinized peridotites, several square kilometers in area, which had been discovered by the submersible *Alvin*. The total length of the cored section was 92.5 m with a recovery rate of 7%. The recovered serpentinized peridotites can be separated into two main rock types: dark, bluish serpentinites with more than 75% serpentinization and less altered serpentinized harzburgites, exhibiting primary mantle deformation structures (Shipboard Scientific Party, 1988).

Similar metamorphosed plutonic rocks have been drilled on previous legs (Legs 37, 45, 82). Measurements of the magnetic properties of these rocks (Dunlop and Prévot, 1982; Smith and Banerjee, 1984) show that they make a considerable contribution to the magnetization of the oceanic crust. In this report the magnetic properties of the plutonic rocks of Hole 670A are compared to those of former legs. The relevant paleomagnetic data are reported by Hamano in this volume.

The investigations include the determination of the Curie temperature T_c for the identification of the dominant magnetic minerals and their possible alteration, and the evaluation of the susceptibility anisotropy ellipsoid to check correlations with the texture and fabric of the rocks. The hysteresis parameters such as coercivity H_c, remanent coercivity H_{rc}, saturation magnetization J_s, and saturation remanence J_{rs} were measured to estimate the content, particle size, and magnetic domain structure of the magnetic minerals. Opaque microscopy of polished sections was performed to confirm the results of the rock magnetic measurements.

PETROGRAPHY OF THE SAMPLES, THERMOMAGNETIC ANALYSIS, AND MICROSCOPIC INVESTIGATIONS

The samples of Site 670 which are analyzed in this report come from five stratigraphic units, characterized by two lithologic types: serpentinites in Unit 2 and 4 and serpentinized harzburgites in Units 1, 3, and 6. Samples 5R-1, 11 cm, 5R-2, 134 cm, and 6R-1, 37 cm, from Unit 1 and 3 are less altered harzburgites with preserved primary mineral assemblages. With exception of Sample 9R-1, 107 cm, all other samples were, recovered from Units 2 and 4. These two units consist of serpentinites with 90%–95% serpentine minerals and 5–10 modal% relict primary minerals. Sample 9R-1, 107 cm, from Unit 6, containing both lithologic types, has been taken out of a vein filled with tremolite, carbonite, and antigorite. It shows magnetic behavior which is strongly different to that of the other samples. In Table 1, the samples, their depths, and their stratigraphic and lithologic classification are listed in the first four columns.

The natural remanent magnetization (NRM) shows a strong dependency on the rock type. The less altered harzburgites have NRM values from 107 to 271 × 10^{-6} G. The NRM of the highly serpentinized peridotites is approximately 10 times higher and ranges from 1333 to 8257 × 10^{-6} G.

The Curie temperatures (T_c in Table 1) indicate that magnetite with a T_c of 578°C is the dominant magnetic mineral. For six samples (5R-1, 52 cm, 5R-1, 111 cm, 5R-1, 126 cm, 5R-2, 22 cm, 6R-1, 37 cm, and 7R-1, 43 cm) a second magnetic phase with an apparent Curie temperature of 340°–360°C can be seen in the thermomagnetic curves (Fig. 1). Maghemite (γ-Fe_2O_3), which irreversibly converts to hematite (α-Fe_2O_3) at a temperature above 350°C, seems to be the second component visible in the thermomagnetic curves. This statement is supported by a decrease of the saturation magnetization J_s to less than half the initial magnetization.

The content of magnetite has been estimated from the saturation magnetization and is listed in column 6 of Table 1. Less altered harzburgites have much lower magnetite content than the serpentinites. This significant difference suggests that the magnetite content depends on the degree of serpentinization. However, this relationship cannot be generalized as the concentration of magnetite is also dependent on the primary mineralogy, especially the amount of olivine.

Reflected light microscopic investigations of five polished samples, two harzburgites (5R-2, 134 cm, 7R-1, 73 cm) and three serpentinites (5R-1, 52 cm, 5R-2, 22 cm, and 7R-1,73 cm), show different abundances of opaque minerals in the two rock types. The serpentinites contain opaque minerals up to 5%, while the content in the harzburgites is approximately less

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Table 1. Petrography, Curie temperature (T_c), and magnetite concentration (C_{Mt}) of core samples of Hole 670A.

Sample	Sub-bottom depth (m)	Lithologic unit and rock type	NRM (10^{-6} G)	T_c (°C)	C_{Mt} (vol%)
5R-1, 11 cm	45.31	1, serp. harzburgite	107	598	
5R-1, 52 cm	45.72	2, serp. peridotite	2470	577	1.6
5R-1, 111 cm	46.31	2, serp. peridotite	3703	586	1.6
5R-1, 126 cm	46.46	2, serp. peridotite	8257	585	1.6
5R-2, 22 cm	46.92	2, serp. peridotite	3350	579	2.5
5R-2, 52 cm	47.22	2, serp. peridotite	1333	586	0.9
5R-2, 134 cm	48.04	3, harzburgite	271	577	0.1
6R-1, 37 cm	54.97	3, harzburgite	188	580	0.1
7R-1, 43 cm	64.43	4, serpentinite	7197	591	1.7
7R-1, 73 cm	64.73	4, serpentinite	1400	580	1.0
9R-1, 107 cm	84.07	6, vein filled with tremolite, carbonite and antigorite	44		

than 0.5%. The variety of the opaques is larger in the harzburgites: additional to primary and secondary magnetite, pyrite and chromite, sometimes in contact with magnetite, can be found (Fig. 2). There were no indications of hematite in the polished sections.

In the harzburgites magnetite is the most abundant opaque mineral. It occurs as a primary relict mineral and as a secondary component aligned along healed or closed cracks. Magnetite also occurs as a broken seam around nonreflecting grains. The maximum grain size is 10 μm. In some magnetite grains structures typical of low temperature oxidation can be seen (Fig. 2). Covered with magnetic colloid, the maghemized parts are indicated by lighter grey because of lesser attraction of the magnetic colloid (Petersen et al., 1979). There are also indications of cracks in the lighter parts seaming the magnetite grain in Figure 2, probably due to a shrinkage of the crystal lattice which is a typical characteristic of low temperature oxidation.

In the serpentinites nearly all opaque minerals are magnetites with grain sizes up to 100 μm. Only very small grains of pyrite, sometimes within magnetite grains, can be seen. All the magnetite seems to be a product of the secondary mineralization. Magnetite occurs along the dark veins which crosscut the samples in various directions and as a seam along light bands of talc and antigorite as one element of the rings defining the tortoise-shell texture. Perpendicular to the veins small elongate magnetite grains grow radially into the serpen-

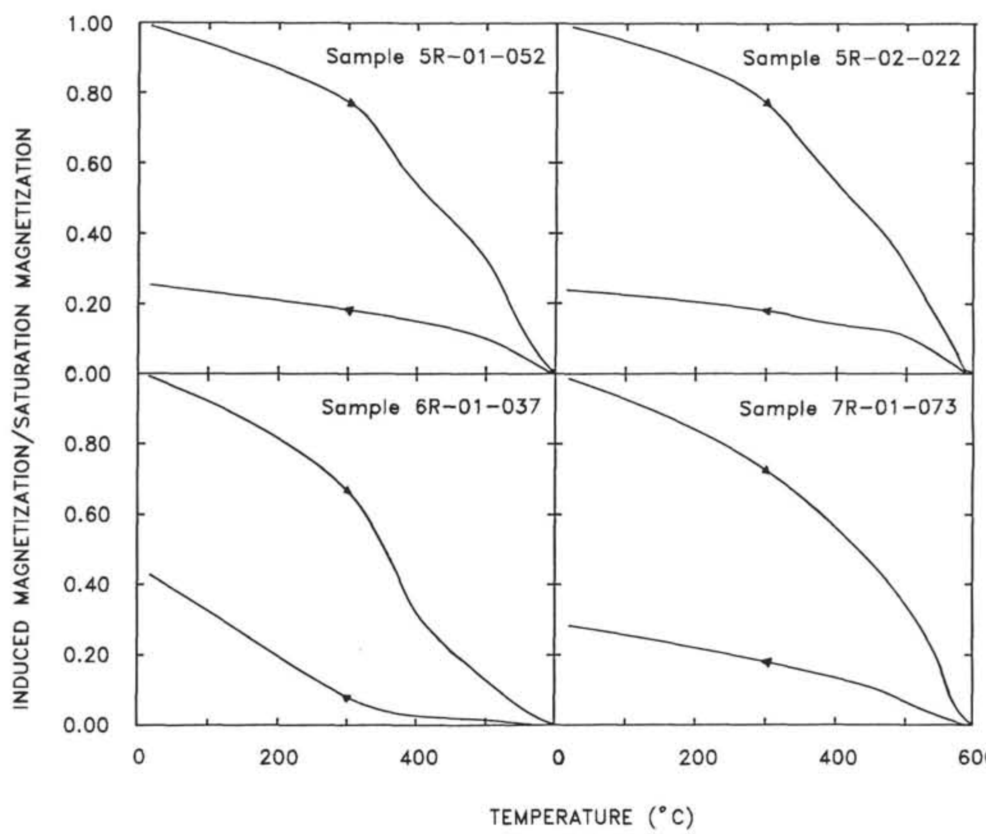

Figure 1. Thermomagnetic curves of four samples of Hole 670 measured in a magnetic field of 5 kOe.

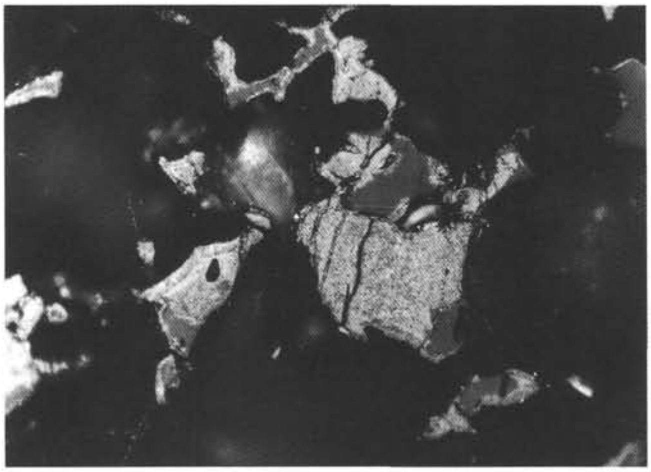

Figure 2. Magnetite grains in contact with chromite covered with magnetic colloid. Maghemized parts are indicated by light grey areas (Sample 6R-1, 37 cm, harzburgite).

Figure 3. Secondary magnetite along a dark vein with elongate magnetite grains grown in radially oriented cracks (Sample 5R-1, 52 cm, serpentinite).

tine minerals (Fig. 3). A further occurrence of the magnetite could be interpreted in two ways, either as a seam surrounding an olivine neoblast or as a fracture filling which has undergone deformation resulting in a meander texture (Fig. 4). Also clusters of fine granular magnetites without any particular shape or orientation are visible.

THE MAGNETIC SUSCEPTIBILITY AND ANISOTROPY OF THE SUSCEPTIBILITY

The magnetic susceptibility varies from 0.42×10^{-3} G/Oe to 12.1×10^{-3} G/Oe with exception of Sample 9R-1, 7 cm, (36×10^{-6} G/Oe). The serpentinites have a mean susceptibility of 7.82×10^{-3} G/Oe and the harzburgites 0.56×10^{-3} G/Oe. This significant difference is easily explained by the dependence of the susceptibility on the magnetite content for pseudo-single domain (PSD) and multidomain (MD) particles. In addition nearly all samples seem to have a small amount of superparamagnetic particles, indicated by the ratio k/J_s which is larger than 0.8. Similar values for this ratio are also described by Dunlop and Prévot (1982) for the serpentinized peridotites of Leg 45.

The anisotropy of the magnetic susceptibility defined by the P-factor (ratio of maximum susceptibility to minimum susceptibility k_1/k_3) varies from 1.068 to 1.261 with a mean value of 1.13 ± 0.06 (Table 2). P-factors of 1.2 and more are very common for metamorphic rocks (Janak, 1973). The inclinations of the maximum susceptibility of the samples with poor or good orientation (five samples) are between 6° and 40°. Although this is consistent with the inclination of the foliation of approximately 20°, defined by elongate orthopyroxene (Units 2 and 3), the result should not be overrated. The presence of a tortoise-shell texture and crosscutting of serpentine veins suggests that there should be no uniform direction of maximum susceptibility. The three normalized orthogonal susceptibilities k_1, k_2, and k_3, which define the rotational anisotropy ellipsoid, give no indications for a particular shape. Disc shaped (oblate) ellipsoids, characterized by a E-factor $((k_2)^2/k_1/k_3)$ larger than 1 can be found as well as elongate (prolate) ellipsoids with E-factors smaller than 1 in both lithologic rock types.

Based on the microscopic investigations, the anisotropy is related to two causes. In the serpentinites with a high amount of magnetite, the magnetic grains are concentrated in the dark veins of serpentine minerals intersecting the samples in different directions. Assuming nearly parallel layering of the veins, the anisotropy ellipsoid would have an oblate shape with minimum susceptibility perpendicular to the plane of the veins. This is related to the large self-demagnetization factor in this direction. In some samples with E-factors larger than 1, an approximately parallel layering of the dark veins can be seen (5R-1, 26 cm, 5R-2, 22 cm, and 6R-1, 137 cm). However, the direction of the minimum susceptibility does not always coincide with the obvious direction of the normal vector to the plane defined by the dark veins. A second source for the anisotropy probably could be the elongate magnetite grains standing nearly perpendicular on the veins as can be seen in Figure 3.

HYSTERESIS PARAMETERS

As indicated in Table 3 the saturation magnetization J_s is strongly dependent on the lithologic type. The mean value for the less altered harzburgites is 0.75 G while the serpentinites

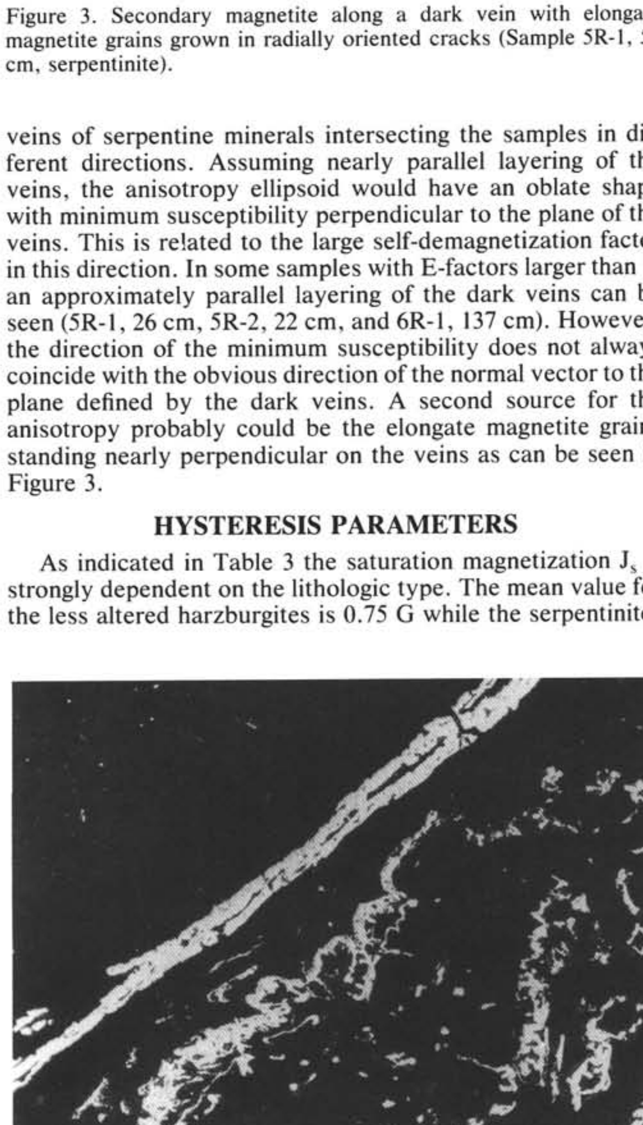

Figure 4. Typical occurrence of secondary magnetite: long undeformed elongate grains next to magnetite with meander texture caused probably by deformation (Sample 7R-1, 73 cm, serpentinite).

Table 2. Susceptibility (k) and anisotropy (P) of the susceptibility of core samples of Hole 670A.

Sample	Unit	k (10^{-6} G/Oe)	k/J_s (10^{-3}/Oe)	k_1	k_2	k_3	P k_1/k_3	E $\frac{(k_2)^2}{k_1/k_3}$
5R-1, 11 cm	1	415		1.03	1.00	0.97	1.07	1.00
5R-1, 52 cm	2	7925	0.99	1.12	0.99	0.89	1.26	0.98
5R-1, 111 cm	2	8787	1.11	1.04	1.00	0.96	1.08	1.00
5R-1, 126 cm	2	8796	1.13	1.07	1.03	0.90	1.19	1.10
5R-2, 22 cm	2	12137	1.00	1.07	1.05	0.89	1.20	1.16
5R-2, 52 cm	2	4487	1.04	1.07	0.99	0.94	1.13	0.98
5R-2, 134 cm	3	584	0.83	1.06	0.99	0.96	1.10	0.97
6R-1, 37 cm	3	643	0.82	1.03	1.02	0.95	1.08	1.07
7R-1, 43 cm	4	8521	1.01	1.07	0.99	0.94	1.13	0.99
7R-1, 73 cm	4	4968	0.97	1.05	1.02	0.93	1.12	1.07
9R-1, 107 cm	6	36		1.03	1.03	0.94	1.10	1.09

have a 10 times higher average saturation magnetization of 7.68 G. As can be easily seen by reflected light microscopy, the magnetite content is the reason for the differences. The volume concentration of magnetite deduced from the saturation magnetization lies between 1% and 2.5% for the serpentinites and is approximately 0.1% for the harzburgites.

The ratio R_J of saturation remanence J_{rs} to saturation magnetization J_s (J_{rs}/J_s) contains information about the grain size and the domain structure of the magnetite particles (Day et al., 1977). As expected this ratio is different for the two lithologic types. The magnetites in serpentinites with R_J ratios between 0.06 and 0.13 show a tendency to the PSD-MD border at $R_J = 0.05$ while those of the harzburgites with a mean value of $R_J = 0.2$ are well within the PSD range (Day et al., 1977). In general the grain sizes of the magnetites for both types correspond to PSD particles with diameters between 1 and 15 μm. The largest diameters found by reflected light microscopy are approximately 50 μm.

From measurements on samples with varying degree of serpentinization by Lienert and Wasilewsky (1979), an inverse correlation of the serpentinization with the R_J ratio was deduced. Based on the results of Lienert and Wasilewsky (1979), the evaluated content of serpentine for the Hole 670A serpentinites is 82%–97% and for the harzburgites of approximately 60%, which is in good agreement with the petrographic description of the two rock types. This supports the conclusion that the grain sizes of the magnetites could be a better parameter to estimate the degree of serpentinization than the amount of magnetite.

The ratio R_H of remanent coercive force H_{rc} to coercive force H_c (H_{rc}/H_c) relates to similar domain structures as described for the R_J ratio. The R_H values of the serpentinites of 2–3 are characteristic for grain sizes in the PSD range. The harzburgites have values of 1.5–2 indicating small PSD grains with diameters between 0.5 and 1 μm (Dunlop and Prévot, 1982, Day et al., 1977).

Table 3. Hysteresis parameters and the ratios R_H and R_J of core samples of Hole 670A (H_c coercivity, H_{rc} remanent coercivity, J_s saturation magnetization, and J_{rs} saturation remanence).

Sample	Unit	H_c (Oe)	H_{rc} (Oe)	J_s (mG)	J_{rs} (mG)	R_J (J_{rs}/J_s)	R_H (H_{rc}/H_c)
5R-1, 11 cm	1	170	302		70		1.78
5R-1, 52 cm	2	55	140	7976	544	0.068	2.55
5R-1, 111 cm	2	50	144	7929	457	0.057	2.88
5R-1, 126 cm	2	55	148	7789	529	0.068	2.69
5R-2, 22 cm	2	53	155	12199	704	0.057	2.92
5R-2, 52 cm	2	60	142	4316	329	0.076	2.37
5R-2, 134 cm	3	142	257	703	147	0.209	1.81
6R-1, 37 cm	3	138	255	783	150	0.191	1.85
7R-1, 43 cm	4	61	185	8445	511	0.060	3.03
7R-1, 73 cm	4	102	208	5113	680	0.133	2.04
9R-1, 107 cm	6	250	600		8.7		2.40

DISCUSSION

Because of the relatively small number of samples the valuation of the results of the rock magnetic investigations is difficult. The two rock types have consistent and homogeneous magnetic properties. The results are also in good agreement with measurements made on similar plutonic rocks from the ocean floor (Smith and Banerjee, 1984; Dunlop and Prévot, 1982). In particular the serpentinized peridotites of Leg 37 (Site 334) and Leg 45 (Site 395) show similar magnetic behavior (NRM, susceptibility, and hysteresis parameters) to the serpentinites of Unit 2 and 4. However, the degree of serpentinization seems to be higher for our samples as indicated by smaller R_J ratios (Fig. 5). The harzburgites of Unit 1 and 3 have more similarities with the peridotites of Leg 82 (Smith and Banerjee, 1984).

A remarkable difference to the ultramafic samples from Legs 37, 45, and 82 is the occurrence of maghemite, proved by thermomagnetic curves and microscopic analysis of the opaque mineralogy. The maghemite is a product of low temperature oxidation (150°–250°C) of magnetites, which has been studied extensively on titanomagnetites of ocean floor basalts. For ultramafic rocks of the fracture zones near the ridge axis (Legs 37, 45, 82) no indications of low temperature oxidation of titanium-free magnetites have been described before. The reason for the absence of maghemite is probably the history of metamorphism, especially temperature and pressure conditions during serpentinization. As the metastable maghemite converts irreversibly to the stable hematite phase at temperatures above 350°C, the temperatures must have been below this transition point since the oxidation. If the maghemitization is coupled to the serpentinization and took place at the same time, the temperature of metamorphism was below 350°C, taking into account a decrease of the transition temperature with pressure (Kushiro, 1960). This is in good agreement with the maximum temperature of 325°C given by Elthon (1981) for the chrysotile-lizardite serpentinites.

Comparing the magnetic properties of both rock types, serpentinites and harzburgites, the differences can be explained by variations in grain size and magnetite content. The serpentinites have a magnetite content of up to 5% while the harzburgites have less than 0.5%. Hysteresis parameters such as H_c and J_{rs} indicate PSD grains for both rock types with diameters from 0.5 to 15 μm (Day et al., 1977). The serpentinites tend to have magnetite grains near the MD transition, while the grains of the harzburgites are smaller and nearer to the border with SD grains (Fig. 5). The magnetic anisotropy of

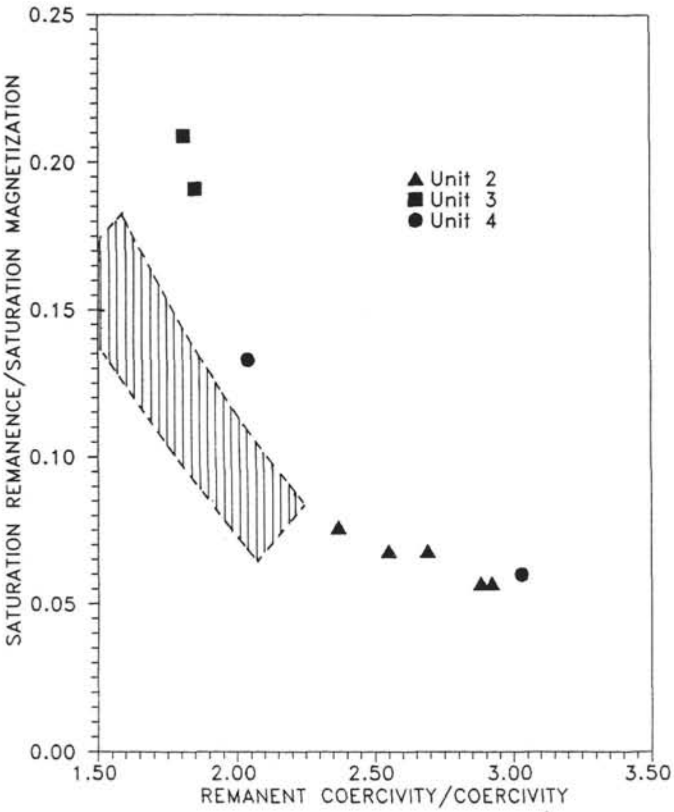

Figure 5. R_H and R_J ratios of Hole 670 samples compared with the results of Dunlop and Prévot (1982) for the serpentinized peridotites of Leg 37 and Leg 45 (vertically hatched area).

the harzburgites seems to be of lower degree and with a tendency to more triaxial or prolate shape.

The measurement of the magnetic anisotropy and the shape and orientation of the anisotropy ellipsoid did not elucidate the complex tortoise-shell texture. Samples with large rings forming this texture and with veins of serpentinites approximately parallel layered have foliation factors (F-factor) greater than 1. However, the directions of the principal axes defining the anisotropy ellipsoid are not in general consistent with macroscopic visible orientations of the serpentine veins and a dominant direction of the foliation is not deducible from the F-factor. If the ring structures are small compared to the samples, the foliation factor becomes equal or smaller than 1 due to a triaxial or prolate shape of the anisotropy ellipsoid.

The reason for the relatively high but not unusual magnetic anisotropy is probably the orientation of the elongate magnetite grains in the fabric of the rocks. The structure is complicated by the fact that the magnetites do not only seam the dark veins but also appear to grow perpendicular to the veins into the serpentine melange along small cracks or microfractures. Also the magnetites building up a rim around the olivine pseudomorphs bring a certain contribution to the anisotropy. These different orientations of the grains result in an anisotropy ellipsoid which is difficult to correlate with the macroscopic and microscopic textures.

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