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21. PALEOMAGNETISM OF THE SERPENTINIZED PERIDOTITE FROM ODP HOLE 670A[1]

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ABSTRACT

Paleomagnetic studies on the serpentinized peridotites recovered from ODP Hole 670A were conducted in three laboratories. High NRM intensities and magnetic susceptibilities were observed in the serpentinized peridotites, which suggest that the remanent and the induced magnetizations of the peridotites cannot be neglected as a source of the magnetic anomalies observed at sea surface. The *in situ* low inclination of the magnetization indicated from the laboratory studies suggests that the peridotite body has been subjected to a large-scale deformation after the acquisition of the magnetization.

INTRODUCTION

During Leg 109 of the Ocean Drilling Program, serpentinized peridotites were drilled down to 92.5 m sub-bottom depth at Hole 670A, situated in the median valley of the Mid-Atlantic Ridge south of the Kane Fracture zone. The rocks around the hole were divided into four lithological units as determined from petrological study. The top unit consists of serpentinized harzburgite with the degree of serpentinization decreasing with depth. The second unit contains 95%–100% serpentinized peridotite. The third unit consist of cpx-bearing harzburgite; the degree of serpentinization in this unit is similar to that in the top unit. The fourth unit is almost completely serpentinized and similar to the second unit.

As reviewed by Bonatti and Hamlyn (1981), oceanic ultramafic rocks have been recovered in relatively young oceanic crust away from large fracture zones, in crustal sections exposed along the large fracture zones, and in sections from trenches at the margins of ocean basins. During the Deep Sea Drilling Project, the *Glomar Challenger* sampled ultramafic rocks at Sites 334 and 895 (Aumento et al., 1977; Melson et al., 1978). The paleomagnetic and rock magnetic studies of these ultramafic rocks (Johnson, 1979; Dunlop and Prevot, 1982) indicated that the magnetization of the oceanic ultramafic rocks are likely contributors to oceanic magnetic anomalies. Because the entire 92.5 m of the drilled section in Hole 670A consists of the serpentinized peridotites, paleomagnetic study on these rocks is important for the discussion of the source layer of the magnetic lineations.

For the shipboard study, 10 minicore samples were taken from the recovered peridotite and paleomagnetic studies were made. The results of the shipboard study is given in Detrick, Honnorez, Brian, Juteau, et al. (1988). The results indicated the high NRM intensity and the high magnetic susceptibility of the serpentinized peridotites. The NRM intensity is comparable to the basalts drilled and dredged in the median valley of the Mid-Atlantic Ridge and is much higher than the average intensity of the basalt samples drilled in most of the DSDP and ODP holes (see, for example, Lowrie, 1977; Harrison, 1981). The susceptibility of the highly serpentinized peridotite is an order of magnitude larger than any oceanic basalts. These magnetic properties of the serpentinized peridotites are important to discuss in terms of the effect on the magnetic lineations observed at sea surface. The low inclination values suggested from the shipboard measurements are also important because they have implications for the rotation or the deformation of the serpentinized peridotite body related to the process of seafloor spreading. It is also to be explained why the peridotite body is observed at the western side of the median valley more than 25 km away from the Kane fracture zone.

Unfortunately, the samples employed in the shipboard study were not sufficient to resolve all of the above mentioned aspects. In the present paper, some shore-based studies on the peridotite samples were added to confirm the results of the shipboard observations.

SAMPLES AND EXPERIMENTS

In Hole 670A, the recovered total length of the core was about 6 m from the 92.5 m drilled section. As evident from the recovery rate, most of the recovered peridotites are in small pieces, and pieces longer than the aperture of the core barrel are very few. Hence, the number of oriented samples is very limited. In the paleomagnetic study, minicore samples were taken from all the oriented rock pieces, and some more samples were taken from unoriented small pieces. From some large pieces, two or more minicore-size samples were taken in order to check the reliability of the remanence properties. Since most of the large oriented pieces are highly serpentinized peridotites, the inclusion of the unoriented samples is important to obtain an unbiased estimate of the magnetic properties of the serpentinized peridotite. The results from the small unoriented pieces are not included for the discussion of the direction of the magnetization.

The procedure for the shore-based paleomagnetic study made in three different laboratories was very similar to the shipboard study. All the samples were progressively demagnetized by the alternating magnetic fields, and the magnetizations were measured by Spinner magnetometers. From the measurements, the NRM intensity, the MDF (Median Destructive Field), and the stable inclination were obtained. The magnetic initial susceptibility was also measured for all the samples.

RESULTS OF THE MEASUREMENTS

In the present paper, results obtained by the shipboard study and the shore-based studies in three laboratories are

[1] Detrick, R., Honnorez, J., Bryan, W. B., Juteau, T., et al., 1990. *Proc. ODP, Sci. Results*, 106/109: College Station, TX (Ocean Drilling Program).

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Table 1. NRM intensity, MDF, Susceptibility, and Q-ratio of the serpentinized peridotites recovered from Hole 670A.

Sample no.	NRM Intensity (10^{-6}emu/cm^3)	MDF (Oe)	Susceptiblity (G/Oe)	Q-ratio
1D-1, 19	4010	484	3548	2.826
2D-1, 45	1992	90	2172	2.293
3W-1, 12	4310	226	2639	4.083
4W-1, 19	231	161	412	1.402
5R-1, 11	107	38	415	0.645
5R-1, 12	110	220	420	0.655
5R-1, 52	2470	25	7925	0.779
5R-1, 55	11080	26	8500	3.259
5R-1, 56	510	110	7500	0.17
5R-1, 111	3703	41	8787	1.054
5R-1, 114	2498	46	8100	0.771
5R-1, 115	590	90	4970	0.297
5R-1, 126	8257	25	8796	2.347
5R-1, 131	3120	70	6650	1.173
5R-1, 134	2015	61	7300	0.69
5R-2, 19	6710	60	8630	1.944
5R-2, 22	3350	23	12137	0.69
5R-2, 52	1333	66	4487	0.743
5R-2, 55	2450	40	9500	0.645
5R-2, 102	455	124	800	1.422
5R-2, 109	330	170	500	1.65
5R-2, 123	350	120	480	1.823
5R-2, 134	271	44	584	1.16
6R-1, 4	145	128	328	1.105
6R-1, 37	188	35	643	0.731
7R-1, 43	7197	34	8521	2.112
7R-1, 73	1400	27	4968	0.705
7R-1, 100	6090	50	6750	2.256
8R/W-1, 31	600	75	1120	1.339
9R-1, 107	44	450	36	3.056

Table 2. NRM inclinations, inclinations of the soft and stable components, and declination differences of the oriented samples.

	Inclinations			$\Delta D1 =$	$\Delta D2 =$
Sample no.	NRM	Soft	Stable	D_{nrm}-D_{stable}	D_{soft}-D_{stable}
4W-1, 19	5.1	15.8	5.1	127.7	64.3
5R-1, 11	−3.1		−3.1		4.5
5R-1, 52	9.6		9.6		6.8
5R-1, 55	−10.5		−10.5		−1.5
5R-1, 56	62.9	53.3	62.9	22.1	59.3
5R-1, 111	29.2	54.6	29.2	−45.3	−9.1
5R-1, 115	−14.3		−14.3		15.2
5R-1, 126	51.9	52.8	51.9	−10.1	−10.3
5R-1, 131	30.5		30.5		−28.4
5R-1, 134	15		15		−2.6
5R-2, 22	−1.7		−1.7		−8.7
5R-2, 52	2.9	36.6	2.9	−53.6	−37.6
5R-2, 55	−1.8		−1.8		−2.4
5R-2, 109	19.6	58.6	19.6	27.9	4.5
6R-1, 4	28.7	50.6	28.7	−137.1	−8.2
7R-1, 100	42.9		42.9		−30.4
8R/W-1, 31	82.1	37.1	82.1	−134.2	−70.8

summarized. In total, 30 peridotite samples were measured. The NRM intensities, the MDFs, the susceptibilities, and the O-ratios are summarized in Table 1, whereas the directional properties of the magnetization for the oriented samples are shown separately in Table 2.

The variation of the NRM intensity is very large. As shown in Figure 1, the intensity varies more than two orders of magnitude from 10^{-4} emu/cm^3 to 10^{-2} emu/cm^3. The lowest intensity was observed in Sample 670A-9R-1, 107 cm. Since this sample was taken from a serpentine-chlorite-tremolite vein, the sample may not represent the property of the serpentinized peridotite. Except for this sample, less serpentinized peridotites tend to have smaller intensity. The recovery rate of this hole was very low, and highly serpentinized

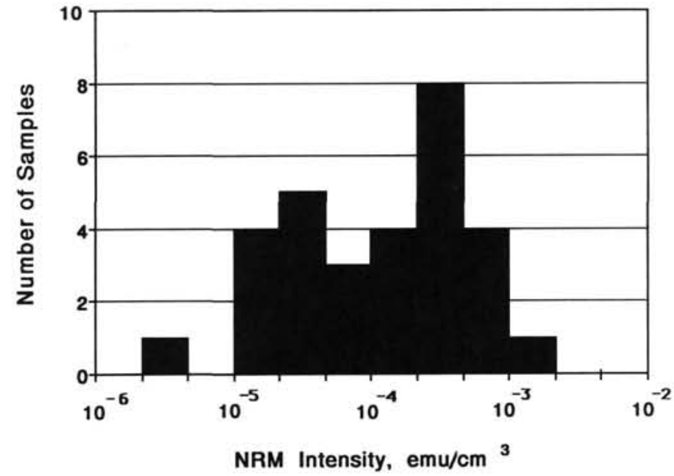

Figure 1. Histogram of the NRM intensity for the serpentinized peridotites recovered from Hole 670A.

samples were preferentially sampled, because the serpentinized samples form larger pieces. The geometric mean of the intensity is 2×10^{-3} emu/cm^3 and the arithmetic mean is 2.5×10^{-3} emu/cm^3. Some examples of the AF (Alternating Field) demagnetization curves are shown in Figure 2. As evident from the figure, most of the samples contain at least two components of the magnetization, although the soft component can not be separated well.

The MDF of the peridotite ranges from 20 Oe to about 500 Oe, where most of the samples have MDF values less than 100 Oe. Figure 3 shows the relation between the MDF and the NRM intensity. The two points at the top right side are for the samples in which the soft and the hard components are about the same order and magnetized in approximately anti-parallel direction. Excluding these two samples, Figure 3 indicates that the higher intensity samples have the lower MDF values.

The susceptibility of the peridotite samples also varies by about two orders of magnitude. The many serpentinized peridotites have the susceptibility values of about 10^{-2} G/Oe. This value is much larger than most of the oceanic basalts. Figure 4 shows the relation between the susceptibility and the NRM intensity for the present peridotite samples and the basalt samples recovered from Hole 648B. The relation indicates that the NRM intensity is mainly controlled by the content of the magnetic minerals in the peridotite samples. The comparison with the basalt data suggests that the maximum NRM intensity of the serpentinized peridotite is comparable to the basalt samples and the susceptibility of the peridotite is about one order of magnitude larger than that of the basalts. Hence, the Q-ratio of the peridotite is much smaller than the basalt. This reflects the relative importance of the induced magnetism in the peridotite samples. The mean and the standard deviation of the Q-ratio in the peridotites are 1.5 and 1.0, respectively.

The shipboard measurement suggested a low inclination for the *in situ* magnetization of the serpentinized peridotite body. To investigate this relationship, we first established the reliability of the magnetization.

Because of the low recovery rate of the peridotite cores and the small pieces of the most of the peridotite samples, oriented samples were very few. Hence, the shipboard interpretation is not conclusive. In order to confirm the low inclination, more samples were taken for the shore-based study. The summary of the directional data for the oriented

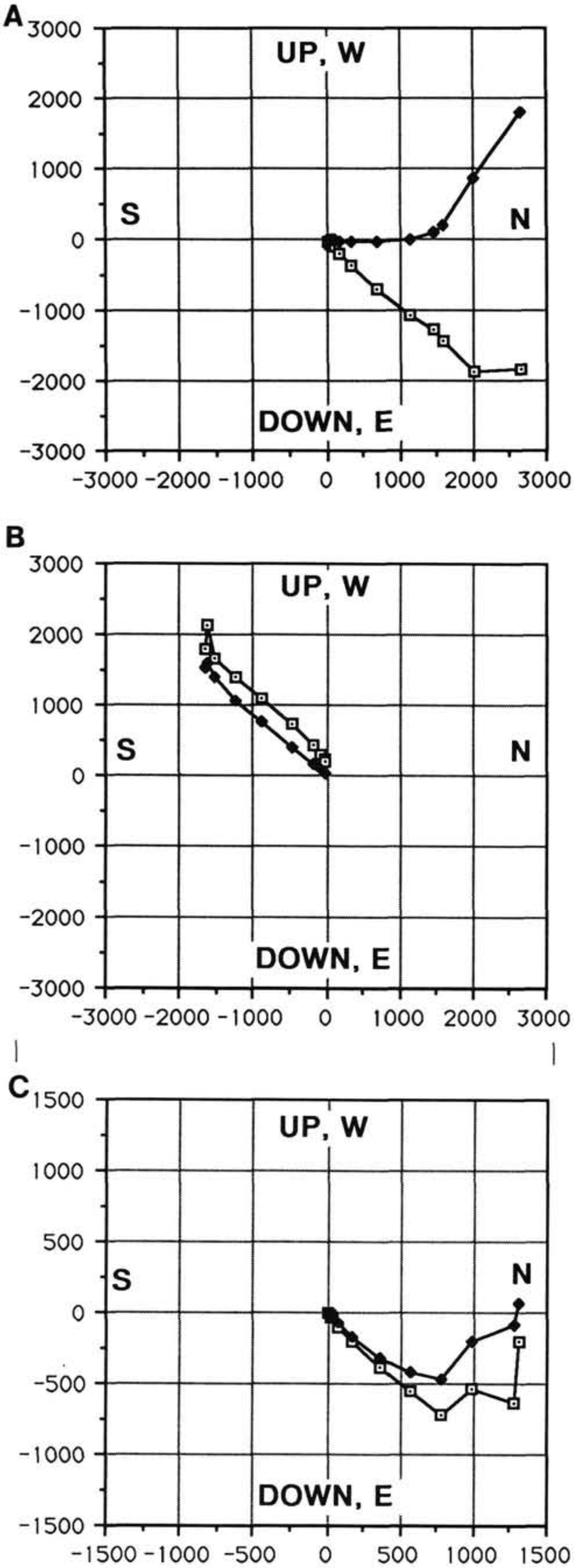

Figure 2. Orthogonal plots of the AF demagnetization curves of the peridotites. **A.** 670A-5R-1, 111 cm. **B.** 670A-5R-1, 131 cm. **C.** 670A-5R-2, 52 cm.

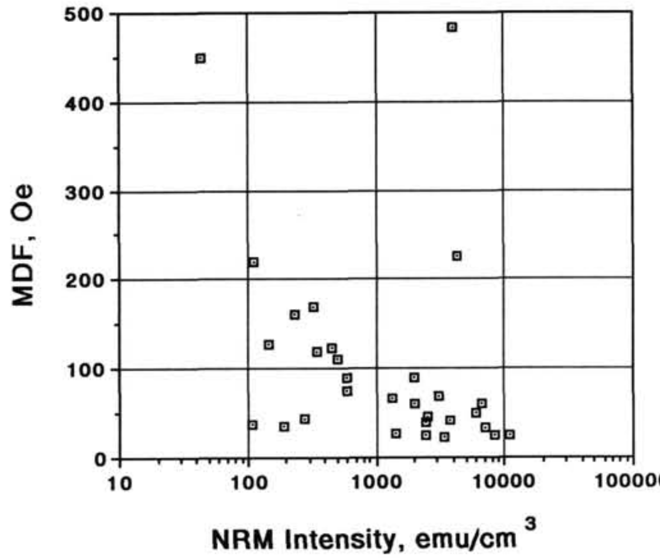

Figure 3. Relation between the MDFs and the NRM intensities of the serpentinized peridotites.

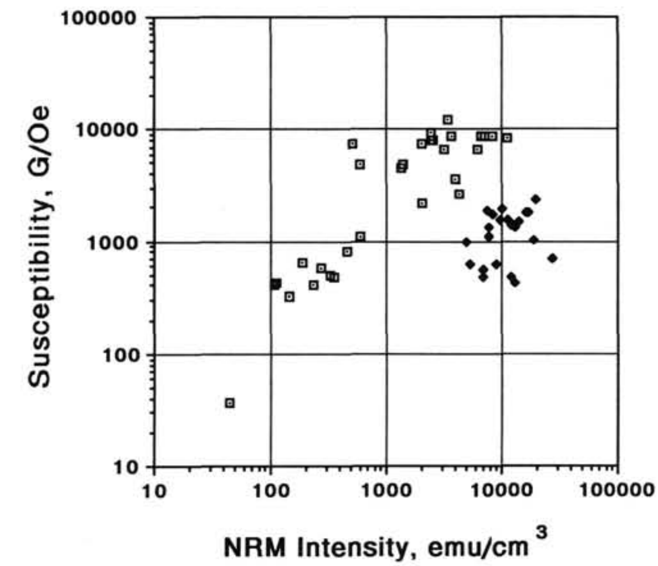

Figure 4. Relation between the NRM intensities and the susceptibilities of the serpentinized peridotites (squares) and basalts (diamonds).

core samples is shown in Table 2. The number of oriented samples is about half of the total number of samples. In Table 2, the NRM inclination, the soft and the hard components of the inclination, and the declination differences are shown. The hard and the soft components were separated on the Zijderveld plot of the AF demagnetization curves of all the samples. The soft component was derived from the least squares fit of a straight line for the range from 50 Oe to 200 Oe, and the hard components were for the range from about 200 Oe to 600 Oe. If the angular difference between the soft and the hard components was less than 20°, the soft components were not adopted since this may suggest that the soft component could not be identified. The definition of the declination differences is shown in the table. The small values of $\Delta D2$ suggest that the effect of the soft component is relatively small.

In order to evaluate the remanence direction, we have to first examine the homogeneity of the magnetization in the peridotite samples. For the shore-based study, duplicate minicore samples were obtained from several relatively large oriented core pieces. These minicore samples were demagnetized in different laboratories. The variation of the direction of the magnetization for these samples is shown in Figure 5 on the equal area projection. The samples from the same piece show similar variation of the magnetization during the AF demagnetization. As shown in Figure 5, although the NRM directions were quite different in some samples, the direction becomes similar by the AF demagnetization. This suggests that the hard component of the magnetization is relatively homogeneous within the piece with the size of about several tens of centimeters. The difference of the NRM inclination within each piece is probably due to the difference of the amount of the soft component.

The histograms of the NRM inclination and the inclinations of the hard and the soft components of the magnetizations are shown in Figure 6. The low inclination of the magnetization is apparent even from the NRM inclination. However, the separation of the hard and the soft components indicates that the hard components have a very low inclination with the mean of 0°, whereas the inclination of the soft components is distributed around 50°. The distribution of the NRM inclination suggests the dominance of the hard component in the serpentinized peridotite. Although the number of the samples for the soft inclination is not enough, the distribution of the soft inclination suggests that the origin of the remanence is probably due to *in situ* VRM (Viscous Remanent Magnetization).

DISCUSSION

Previous studies on the serpentinized peridotite have used dredged samples from the seafloor (Irving et al., 1970; CAYTROUGH, 1979), material from ophiolite suites obducted at continental margins (Beske-Diehl and Banerjee, 1980; Banerjee, 1980), and samples recovered from DSDP holes (Dunlop and Prevot, 1982). By compiling these results, Dunlop and Prevot (1982) noted that serpentinites are much more intensely magnetized than other intrusive rocks. They noted the NRM intensity of about 5×10^{-3} emu/cm^3. The observations suggests that the serpentinized peridotites can not be neglected as a source of the magnetic anomaly, if the peridotite body with a considerable mass exists within the oceanic crust.

The important results obtained from the paleomagnetic studies of the serpentinized peridotite drilled from Hole 670A are the large induced and remanent magnetizations of the highly serpentinized peridotites, and the suggested low *in situ* inclination. The former suggests that a linear magnetic anomaly may be caused by the serpentinized peridotite body, and the latter has implications for the formation process of the oceanic crust.

The NRM intensity of the serpentinites is comparable to the dredged and drilled basalt samples from the young oceanic crust, and much larger than the average of the basalts obtained from DSDP and ODP holes. The 500-m thickness of the serpentinites can give the magnetic anomalies comparable to the amplitude to the presently observed magnetic lineations. The susceptibility of the serpentinized peridotite is much larger than the most of the basalt samples. It is very important that the average Q-ratio of the serpentinized peridotites is about 1 by assuming the intensity of the ambient geomagnetic field of 0.4 Oe, and is an order of magnitude smaller than that of the basalt samples. Hence, the remanence and the induced magnetization both affect the magnetic lineations observed at the sea surface.

The peridotite body is observed at the western wall of the median valley. The presently observed correlation between

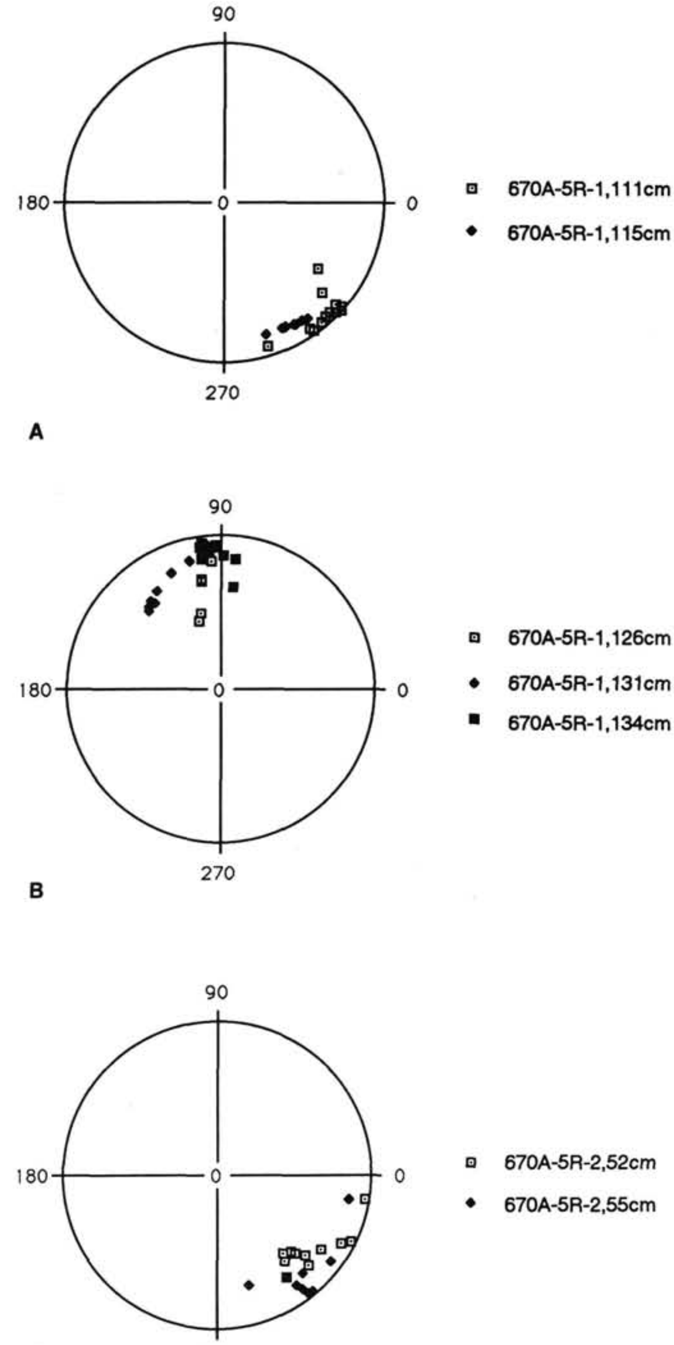

Figure 5. Equal area plot of the variation of the direction of the remanence during the AF demagnetization. **A.** Samples 670A-5R-1, 111 cm and 115 cm from piece 670A-5R-1, #16. **B.** Samples 670A-5R-1, 126 cm, 131 cm, and 134 cm, from piece 670A-5R-1, #17. **C.** Samples 670A-5R-2, 52 cm and 55 cm, from piece 670A-5R-2, #7.

the degree of the serpentinization and the intensity of the magnetization suggests that the remanence carried by the serpentinized peridotite was acquired during the serpentinization of the peridotite. The origin of the remanence is probably CRM (Chemical Remanent Magnetization) caused by the grain growth of the magnetite. At the ridge, the 500°C isotherm is close to the surface. Hence, the age of the magnetization of the serpentinized peridotite might be close to the age of the oceanic crust, and the possible remanence direction is

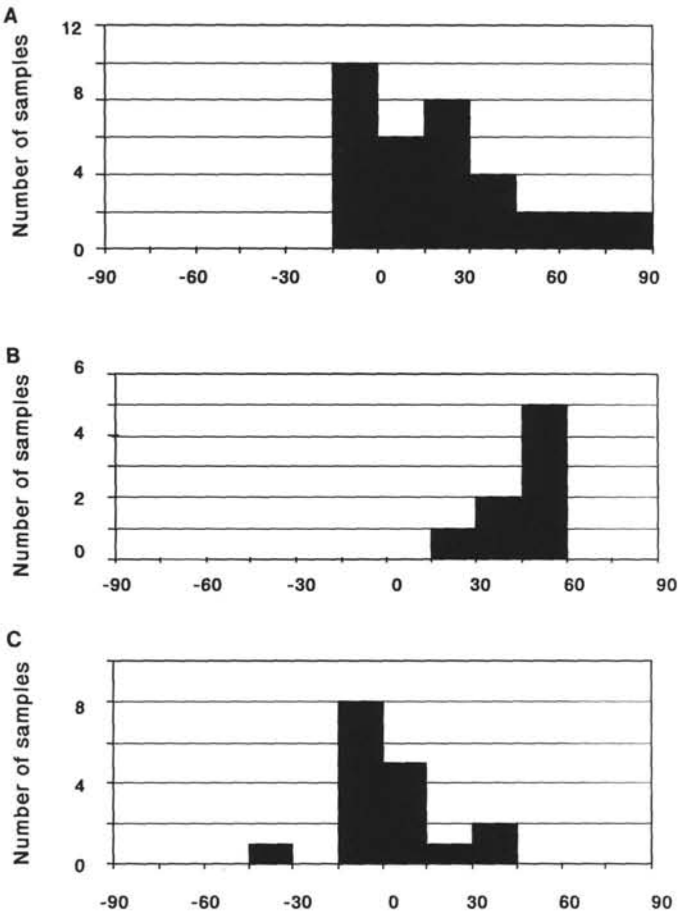

Figure 6. Histograms of observed inclinations. **A.** NRM inclination. **B.** Inclination of the soft components. **C.** Inclination of the stable components.

assumed to be parallel to that of the surrounding oceanic crust. Therefore, the existence of the peridotite patches in the shallow oceanic crust, will not severely affect the surface pattern of the magnetic anomalies. On the other hand, the effect of the induced magnetization is different. Since the induced magnetization is always parallel to the ambient magnetic field, the magnetization may cause the change of the pattern of the magnetic anomalies. Because of the large induced magnetization, the large peridotite body with the thickness of more than several hundred meters may severely affect the pattern. This might be the cause of the offset of anomaly 1 at the north of Site 670 (Schulz et al., 1986).

The effect of the possible deep-seated serpentinized peridotite layer on the magnetic anomaly is different from the surface exposures of the peridotite. In the normal oceanic crust, the 500°C isotherm is more than 10 km. Hence, the thick serpentinized peridotite can possibly exist if enough water for the serpentinization is supplied. The serpentinization and the acquisition of the remanence occur when the peridotite crosses the 500°C isotherm. Because the magnetized body is aligned parallel to the ridge axis where lateral thermal gradients are expected to be steep, the acquired CRM should be developed over a short period of time. Therefore, it is not impossible that the serpentinized peridotite layer can be the magnetic source layer for prominent lineations. If the magnetization of the serpentinized peridotite is 10^{-2} emu/cm^3 and the top of the serpentinized layer coincides with the Moho discontinuity, 6–7 km thickness of the serpentinized layer would produce an anomaly at the sea surface comparable to the observed amplitude of the magnetic lineations. Contrary to the former case, the induced magnetization does not affect the anomaly pattern if the susceptibility is constant over the oceanic crust.

The low inclination of the serpentinized peridotite is important for the discussion of the formation history of the oceanic crust. The present experiment indicates that the *in situ* inclination of the magnetization of the peridotite body is close to the horizontal direction. It is not reasonable to assume that the geomagnetic field when the remanence was acquired had a horizontal direction. One possible interpretation of the low inclination is that it may be due to the magnetic anisotropy of the peridotites. However, this requires very large anisotropy (even when the anisotropy ratio is 1.5, the maximum deflection is only 11.6°; see McElhinny, 1967) to cause the horizontal magnetization when the inclination of the ambient geomagnetic field has the inclination of about 40°, and the observed susceptibility anisotropy in the present serpentinized peridotite is at most several percent. Alternatively, the rotation or the deformation of the peridotite body after the acquisition of the remanence is a more appealing explanation for the low inclination. Thus, the low inclination may contain information on the rotation or deformation history of the peridotite body. This analysis could be made more easily and reliably if we could observe the declination of the magnetization, which has been made in other paleomagnetic studies. Unfortunately, the drilled core samples are not oriented in the horizontal direction. One possibility is that the VRM component can be used for the orientation of the drilled samples. The direction of the VRM can be safely assumed to be in north direction. For the present samples, the soft component of the remanence seems to be of VRM origin. However, among the present samples this component cannot be clearly separated from the stable component because of the low-VRM component. In Table 2, the declination difference between the hard and the soft components is given for a few samples in which the soft component has been separated. The results give a large scatter. In the following section, some possibilities based on this large scatter are discussed.

The simplest explanation for the low inclination is a rigid body rotation. Verosub and Moores (1981) proposed a tectonic rotation model in order to explain the shallow inclinations observed at many DSDP sites. The rotation around the vertical axis does not alter the inclination. Hence, the rotation around the horizontal axis should be employed to explain the low inclination. Assuming that the original remanence direction was in the north direction with an inclination of about 40°, the smallest rotation is the 40° rotation along an axis oriented in an east-west direction. In this case, the rotation does not change the declination of the magnetization. Considering the formation process of the oceanic crust, the rotation around an axis oriented in a north-south direction is more plausible. In this case, the rotational amount of about 90° is required. In any of the above rigid rotation cases, coherency of the declination is expected. On the other hand, the scatter of the declinations indicated from Table 2 is not compatible with this simple model.

In contrast to the rigid rotation model, a deformation model may give more scatter in the direction of the magnetization. A combination of vertical compression and horizontal extension is the simplest possible deformation scheme in this tectonic setting. This strain system is sometimes called pure shear, where no bulk rotation is included. In this deformation, shallowing of the inclination is expected if magnetic grains are not equidimensional. But, the efficiency of a pure shear strain is not sufficient to explain the observed low inclination. This type of deformation also does not alter the declination direction. On the other hand, a simple shear deformation is more efficient, since the deformation contains a rigid rotation component as well as a pure shear. Horizontal and vertical shear both can give the inferred rotation of the inclination. However, a simple shear causes some variation between the inclination and the declination depending on the sense of shear. However, the observed inclinations are consistently low, and no apparent correlation is observed between the inclination and the declination. This observation can be explained by 90° of rotation around a horizontal axis in north-south direction plus a rotation around the vertical axis due to a subordinate horizontal shear deformation. Evidently more information is required to fully define the rotation history of the serpentinized body.

CONCLUSION

Our conclusions are the following:

1. The NRM intensities of the serpentinites recovered from Hole 670A are very large and comparable with the dredged and drilled basalt samples in the young oceanic crust.
2. The susceptibilities of the serpentinites are much larger than most of the oceanic basalts, and the Q-ratio is an order of magnitude smaller than that of the basalts.
3. The existence of the serpentinites in the oceanic crust can disturb the oceanic magnetic anomalies.
4. The stable inclination of the serpentinized body is nearly horizontal, which suggests some rotations and/or deformations of the serpentinized body after the acquisition of the remanence.

REFERENCES

Aumento, F., Melson, W. G., et al., 1977. *Init. Repts. DSDP,* 37: Washington (U. S. Govt. Printing Office).

Banerjee, S. K., 1980. Magnetism of the oceanic crust: evidence from ophiolite complexes. *J. Geophys. Res.,* 85:3557–3566.

Beske-Diehl, S., and Banerjee, S. K., 1980. Metamorphism in the Troodos ophiolite: implications for marine magnetic anomalies. *Nature,* 285:563–564.

Bonatti, E., and Hamlyn, P. R., 1981. Oceanic ultramafic rocks. *In* (Eds.), *The Sea*, vol. 7: 241–283.

CAYTROUGH, 1979. Geological and geophysical investigation of the Mid Cayman Rise spreading center: initial results and observations, *In* Talwani, M., Harrison, C.G.A., and Hayes, D. E. (Eds.), *Deep Drilling Results in the Atlantic Ocean: Ocean Crust.* Washington (Am. Geophys. Union), 66–94.

Detrick, R., Honnorez, J., Bryan, W. B., Juteau, T., et al., 1988. *Proc. ODP, Init. Repts.,* 106/109. College Station, TX (Ocean Drilling Program).

Dunlop, D. J., and Prevot, M., 1982. Magnetic properties and opaque mineralogy of drilled submarine intrusive rocks. *Geophys. J. R. Astron. Soc.,* 69:763–802.

Harrison, C.G.A., 1981. Magnetism of the oceanic crust. *In* (Eds.), *The Sea*, vol. 7: 219–239.

Irving, E., Robertson, W. A., and Aumento, F., 1970. The Mid-Atlantic Ridge near 45 N, VI. Remanent intensity, susceptibility and iron content of dredged samples. *Can. J. Earth Sci.,* 7:226–238.

Johnson, H. P., 1979. Magnetization of the oceanic crust. *Rev. Geophys. Space Phys.,* 17:215–226.

Lowrie, W., 1977. Intensity and direction of magnetization in oceanic basalts. *J. Geol. Soc. (London),* 133:61–82.

Melson, W. G., Rabinowitz, P. D., et al., 1978. *Init. Repts. DSDP,* 45, Washington (U. S. Govt. Printing Office).

Schultz, N. J., Detrick, R. S., and Miller, S. P., 1986. Three-dimensional inversion of magnetic anomalies in the Mid-Atlantic Ridge rift valley south of the Kane Fracture Zone. *EOS,* 67:1213.

Verosub, K. L., and Moores, E. M., 1981. Tectonic rotations in extensional regimes and their paleomagnetic consequences for oceanic basalts. *J. Geophys. Res.,* 86:6335–6349.

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