# Serpentinized Peridotites as a Possible Source for Oceanic Magnetic Anomalies

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**Key words:** Ocean Drilling Programme, natural remanent magnetization, krystalline remanent magnetization, degree of serpentinization.

**Abstract.** New data acquired on the slow spreading Mid-Atlantic Ridge during several Legs of the Ocean Drilling Programme (ODP) give evidence that, in many places, serpentinized peridotites constitute the upper oceanic crust in the vicinity of rift valley. This discovery contradicts the classical view on the formation of oceanic crust at the ridge axis, which postulates that only basalts constitute the upper oceanic crust.

The magnetic properties of 57 samples of such serpentinized peridotites, collected at five ODP sites in the Atlantic Ocean, have been analyzed in order to examine the origin and evolution of their natural remanent magnetization (NRM). All samples are characterized by NRM (average value about 3.5 A/M) comparable with NRM of altered oceanic basalts. Average Q-ratio (NRM to induced magnetization ratio) was about 2.

The results reported here give evidence that serpentinization is a complex and irregular process. The local concentration of magnetite is determined by magnetostatic interaction between magnetic grains rather than volume concentration of magnetite. This local concentration, which represents the degree of serpentinization, affects the NRM value. The domain structure of magnetite grains developed during serpentinization is controlled by the degree of serpentinization.

Experimental data show that original remanence of serpentinites exposed in the upper oceanic crust may contribute to the oceanic magnetic anomalies. In particular, serpentinites with magnetite of pseudodomain size represent a very probable source for magnetic anomalies. It is however unlikely that such ODP serpentinites systematically contribute to the oceanic magnetic lineations.

## Introduction

Analysis of the rock type distribution at different transform faults in the Equatorial Atlantic led Bonatti and Honnorez (1976) to conclude that "serpentinized peridotite is a significant part of the normal oceanic crust where it is emplaced by vertical intrusion, mainly into fault zones parallel to the ridge axis". In the last few years this inference has been supported by evidence that serpentinized peridotites are also exposed in the upper oceanic crust far away from the transform faults, in the vicinity of the rift valley of the slow spreading Mid-Atlantic Ridge (Juteau *et al.*, 1990). Serpentinized peridotites were recovered during several ODP Legs in the Atlantic Ocean, at Site 670 (anomaly 1, 0.5 Ma), Site 395 (anomaly 4, 6.5–7.2 Ma), Site 334 (anomaly 5, 9 Ma), Site 560 (anomaly 5D, 12 Ma), Site 558 (anomaly 13, 37 Ma). These observations indicate that serpentinized peridotites constitute a significant part of the normal oceanic crust, at least from 0.5 Ma (Site 670) to 37 Ma (Site 558). See Figure 1.

Several workers reported that oceanic serpentinites possess intense and quite stable natural remanent magnetization (NRM), comparable with NRM of oceanic basalts (Bina and Henry, 1990; Nazarova and Gorodnitsky, 1990), and can possibly contribute to the oceanic magnetic anomalies, especially the long wavelength component (Arkani-Hamed, 1988). Our data show that the average NRM for the studied serpentinized rocks is about 3.5 A/M, with an average Q-ratio (NRM to induced magnetization ratio) of about 2.

The origin of remanence in oceanic serpentinites is krystalline remanent magnetization (KRM), which is considered to be one of the chemical remanent magnetization (CRM) types. KRM forms in magnetite grains during serpentinization of the almost nonmagnetic upper mantle rocks at relatively low temperatures, estimated to be about 350 °C (Krammer, 1990). Magnetic characteristics of KRM formed during serpentinization are not well known and should be the subject of special study. The NRM of oceanic serpentinites has a composite character and is the superposition of low partial

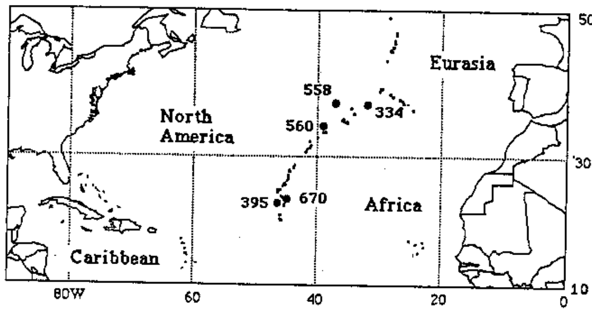


Fig. 1. Location of ODP sites (solid circles) where serpentinite samples were recovered and measured. Small dots are epicenters occurring between 1983 and 1991 defining axis of Mid-Atlantic Ridge, north of 20° N.

thermoremanent magnetization (PTRM), KRM and other secondary magnetizations. In later sections we assume KRM to be the primary magnetization of oceanic serpentinites and consider PTRM as the secondary magnetization. Other secondary magnetizations form at elevated temperatures in the deep crust as well as during subsequent cooling and emplacement of serpentinites in the upper oceanic crust.

The purposes of the present study are (1) to investigate if there exist any correlation between the degree of serpentinization and magnetic characteristics of oceanic serpentinized rocks, (2) to evaluate the relationship between KRM and other secondary magnetizations, (3) to estimate the stability of other secondary magnetizations, and (4) to consider how KRM and other secondary magnetizations may contribute to the oceanic magnetic anomalies.

### The NRM Value and the Degree of Serpentinization

We analyzed the magnetic properties of 57 serpentinized ultramafic rock samples (harzburgites and lherzolites) from five ODP sites (670, 560, 558, 334, 395) and made a correlation analysis between magnetic parameters and degree of serpentinization, by using our laboratory measurements and published data (Dunlop and Prevot, 1982; Smith and Banerjee, 1989; Hamano *et al.*, 1990; Bina and Henry, 1990). Although the lack of petrological data did not allow direct evaluation of the degree of serpentinization, we estimated it by using magnetic measurements. Bina and Henry (1990) assumed that if, during serpentinization, only secondary magnetite is produced, the degree of serpentinization may be estimated by the ratio of iron in magnetite to iron in the whole rock. These authors demonstrated that the degree of serpentinization defined in such way correlates well with magnetic susceptibility (K) and saturation magnetization (Is). Thermomagnetic analysis of our samples showed that magnetite was the only magnetic phase produced during serpentinization. Therefore, we suggest that the degree of serpentinization is proportional to the amount of new magnetite, i.e. K and Is.

No correlation was observed between NRM and Is (Figure 2A) and NRM and K (Figure 3A), while K and Is correlate well (correlation coefficient 0.742, $N = 38$) with each other.

This result confirms previous magnetic studies of serpentinized peridotites, which showed no correlation between NRM and Is (Lienert and Wasilewski, 1979; Nazarova and Gorodnitsky, 1990). On the other hand, the large content of magnetite in our samples (> 1%) (Krammer, 1990) should create intensive magnetostatic interaction between ferromagnetic grains. However, the intensity of magnetostatic interaction is determined by the local rather than the volume concentration of magnetite, the difference being related to uneven distribution of ferromagnetic grains in serpentinized rocks (Scherbakov, 1978). Petrological data indicate that this distribution is very heterogeneous in the ODP serpentinites: in the less serpentinized samples magnetite is poorly dispersed in an olivine matrix, while in more serpentinized samples magnetite

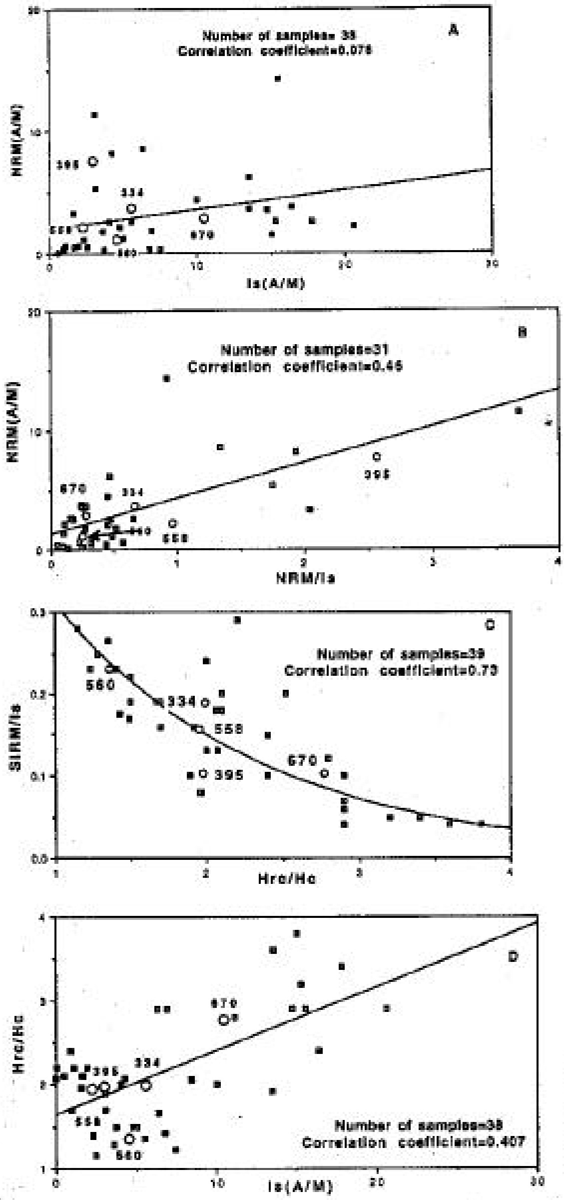


Fig. 2. (A) Correlation between NRM and Is for ODP serpentinites; (B) Correlation between NRM and NRM/Is for ODP serpentinites; (C) Correlation between SIRM/Is and Hrc/Hc for ODP serpentinites; (D) Correlation between Hrc/Hc and Is for ODP serpentinites. Squares are laboratory measurements of specimens, open circles are averages for ODP sites.

560) grains. This trend suggests that in the ODP serpentinites the domain structure of magnetite grains is determined by the degree of serpentinization.

### KRM and Secondary Magnetizations

Several types of secondary magnetizations can be superimposed on the original KRM. At high temperatures, in the deep crust, serpentinized peridotites acquire viscous remanent magnetization (VRM) as a function of time (Smith, 1984). At low temperatures the process of magnetite single-phase oxidation, sometimes coupled to serpentinization, results in the creation of maghemite and the acquisition of chemical remanent magnetization (CRM). However, maghemite was not observed in most of the ODP serpentinites. Thermomagnetic data show occurrence of maghemite for only several samples from Site 670 (Krammer, 1990). Partial thermoremanent magnetization (PTRM) may also form during cooling and emplacement of serpentinites in the upper oceanic crust. Simple thermal magnetic cleaning, i.e. heating samples above the assumed serpentinization temperature (350 °C) and cooling in a zero magnetic field, will cause secondary VRM, PTRM and CRM to disappear. We assume that the remaining magnetization is KRM. This assumption is supported by the excellent correlation observed between the degree of the serpentinization (K) and the remaining magnetization, presumably the KRM (Figure 3B). This result shows that the poor correlation between the NRM value and the degree of serpentinization (Figures 2A, 3A) is at least partially related to the formation of secondary magnetizations.

Specimens from Site 670 (sample 670A-5R-1, 137–139 cm), Site 558 (sample 558-43-1W, 129–133 cm) and Site 560 (sample 560-3-1, 9–13 cm) were heated to 400 °C and cooled in a zero magnetic field. The similarity of coercivity spectra of anhysteretic remanent magnetization (ARM) and remaining component after magnetic cleaning as well as average value of their ratio (about 2) strongly support the suggestion that the remaining remanent magnetization is KRM (Nguen and Pechersky, 1987). Figure 4 displays typical Zijderveld plots of the AF demagnetization before and after treatment for samples from Sites 670 and 560. Before heating, samples from Site 670 (coarse PSD grains) showed multicomponent behaviour. Secondary as well as primary components are somewhat soft. Samples are completely demagnetized at about 35 mT (Figure 4A). After treatment and removal of secondary components, demagnetization curves became mainly univectorial (Figure 4B). The KRM/NRM ratio is about 1. It is worth noting that median destructive fields (m.d.f.) for NRM and KRM are close and low (about 15 mT). However, a.f. demagnetization curves for samples from Site 560 (PSD grains) showed univectorial stable behaviour before and after treatment. We did not observe secondary magnetizations on Zijderveld diagrams although the KRM/NRM ratio is about 0.73; m.d.f. values are slightly different, i.e. about 38 mT for NRM and 30 mT for KRM (Figure 4C, D).

These results give evidence that samples from Site 670 (coarse PSD grains) probably acquired secondary magnetization in a field of opposite polarity, during a relatively long period of serpentinization. On the other hand, Zijderveld diagrams for samples from Site 560 (PSD grains) may not be able to resolve the secondary components because initial KRM and secondary magnetizations were acquired in a field of the same polarity, during a shorter period of time.

### Magnetic Stability of Secondary Magnetizations

The magnetic stability of secondary magnetizations is of great importance for their possible contribution to the oceanic magnetic anomalies.

To address this question, we conducted laboratory experiments to create PTRM and viscous PTRM (sum of VRM and PTRM) in samples from Sites 670 and 560 in the laboratory. Experiments were performed on duplicate samples of serpentinites, after removing natural secondary magnetizations (heating) and the remaining KRM (a.f. demagnetization), i.e. from zero magnetic state. All measurements were carried out at room temperature. PTRM was created at temperatures from 350 °C to 20 °C during cooling of the samples in the Earth's magnetic field. Viscous PTRM was created in the same temperature interval after holding samples at $T = 350$ °C for 3 hours: this time is sufficient for VRM to reach saturation according to Bina and Henry (1990).

The PTRM/KRM ratio varies from 0.29 (samples from Site 560) to 0.72 (samples from Site 670). When PTRM is much less than KRM, their m.d.f. values, especially for MD magnetite grains (samples from Site 670) are much larger (m.d.f. = 25

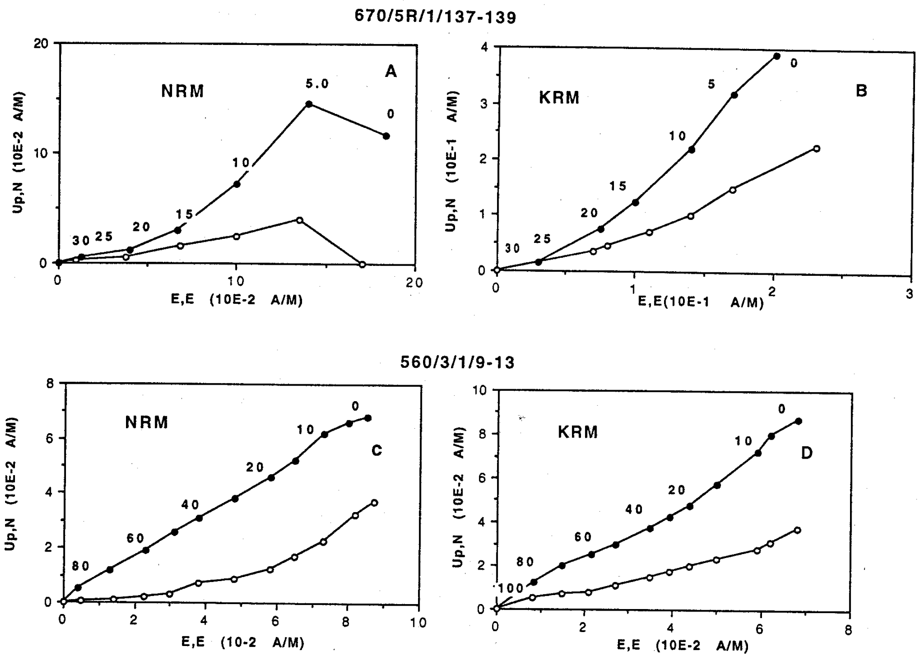


Fig. 4. Zijderveld plots of the a.f. demagnetization curves for samples from Site 670 (A) NRM; (B) KRM and for samples from Site 560; (C) NRM; (D) KRM. Solid circles represent the horizontal component, open circles represent the vertical component. Demagnetizing fields near circles are in mT.

mT). Such a high PTRM (350 °C–20 °C) stability is also observed for serpentinites dredged from different transform faults in the Atlantic Ocean (Kane FZ, 15–20 FZ, Doldrums FZ). In almost all cases, more than 30% of the magnetization remains, even after a.f. demagnetization at 100 mT. Secondary components of high magnetic stability were not observed during NRM a.f. demagnetization of ODP serpentinites, and were not revealed on Zijderveld diagrams (Figure 4). This gives evidence that initial remanence and laboratory PTRM were created in grains of different sizes and most blocking temperatures are above the assumed temperature of serpentinization (350 °C). The high magnetic stability of PTRM (350–20 °C), created on serpentinites after KRM a.f. demagnetization, can be characteristic of KRM.

Viscous PTRM, created in the laboratory at room temperature, shows multicomponent behaviour. We believe that the soft component observed for the range 0–5 mT has a viscous origin, identical to the soft secondary magnetization observed on Zijderveld plots for samples from Site 670. The hard component was found between 7.5 and 100 mT, and has PTRM origin.

## Discussion and Conclusions

Recent seismic data (Purdy and Detrick, 1986) reveal that the basaltic crust of the Mid-Atlantic Ridge is much thinner than was previously thought. Such a thin basaltic layer creates favourable conditions for exposition of upper mantle rocks in the upper oceanic crust, either by listric normal faulting (Karson and Dick, 1984) or by serpentinite diapirism (Bonatti and Honnorez, 1976).

The (infrequent) discovery of serpentinized peridotites in the vicinity of the Mid-Atlantic rift valley led several authors to consider these rocks as an important part of the oceanic crust for slow spreading ridges (Juteau *et al.*, 1990). In order to have a significant contribution to the source of the oceanic magnetic anomalies, serpentinized peridotites must form a continuous layer either in the deep or upper crust (Nazarova, 1991). In both cases, the mechanism of original remanence (KRM) acquisition by almost the nonmagnetic upper mantle rocks is of crucial importance and generally differs from the one which derives TRM acquisition by oceanic basalts. The acquisition of secondary magnetizations is also important for their possible contribution to the oceanic magnetic anomalies.

Our results give evidence that serpentinization is a complex and irregular process. The NRM value is determined by the local concentration rather than by the volume concentration of magnetite, i.e. the degree of serpentinization. On the other hand, the NRM value and the degree of serpentinization show no systematic relationship because the concentration of magnetite is dependent on the primary mineralogy, in particular on the amount of initial olivine which can be different for different samples. In addition, the degree of serpentinization controls the domain structure of magnetite formed during serpentinization.

Our results confirm Shive's observation that "qualitatively PSD behaviour of magnetite grains is characterized by SD-like stability with MD-like behaviour" (Shive, 1989). Fine PSD grains of magnetite are characterized by weak, stable and, in most cases, univectorial magnetization (Site 560). As the serpentinization proceeds and serpentinites intrude to the upper parts of the oceanic crust, the magnetite size becomes larger, magnetization increases and becomes multicomponent (MD grains, Site 670). Experimental data show that original remanence of serpentinites in the upper oceanic crust is strong enough to contribute to the oceanic magnetic anomalies. In particular, serpentinites with magnetite of PSD size is a very likely source of magnetic anomalies. Nevertheless we do not believe that ODP serpentinites can create linear magnetic anomalies.

Laboratory studies of samples from Site 670 reveal components of magnetization with different orientations, suggesting that serpentinization of these samples was long, spanning several magnetic field reversals. Samples from Sites 560 and 558 did not show different orientations, KRM and secondary magnetizations being likely created during one polarity interval.

Experiments dedicated to the creation of PTRM and viscous PTRM from zero magnetic state showed that the nature of the soft component, observed for samples from Site 670, is viscous remanent magnetization (VRM). This viscous component is not a significant part of NRM and can be easily removed by heating above 350 °C and cooling in zero magnetic field. PTRM created in the laboratory belongs to magnetite grains whose blocking temperatures are higher than the assumed temperature of serpentinization (above 350 °C). This is essential to explain why we did not find PTRM on Zijderveld diagrams. Ultramafic rocks can acquire very stable viscous PTRM as the temperature decreases during the emplacement of serpentinites in the upper oceanic crust. This intense and magnetically stable magnetization can contribute to the long wavelength component, as suggested by Arkani-Hamed (1988).

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