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Behavior of oceanic crustal magnetization at high temperatures: Viscous magnetization and the marine magnetic anomaly source layer

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Abstract. Although the source layer for marine magnetic anomalies has been assumed to be the extrusive basalts of uppermost ocean crust, recent studies indicate that lower crustal rocks may also contribute. Because the temperature at which magnetization of crustal rocks achieves long-term stability is crucial to any source layer contribution, we undertook high-temperature VRM (viscous remanent magnetization) experiments on samples of basalt, dike and gabbroic sections. Samples were heated at temperature intervals up to T_c, while a magnetic field was applied for periods between 6 hours and 28 days. Results show that the dike and gabbro samples achieve maximum VRM acquisition near 250°C, well below the T_c of 580°C. The basalt sample shows a peak at 68°C, also well below T_c. Results of this pilot study indicate that the critical isotherm for stable magnetization acquisition is defined by the VRM behavior of the specific crustal section.

Introduction

Identification of the source layer for marine magnetic anomalies has been a subject of intense debate for over 30 years. The anomalies have provided crucial evidence for the history of oceanic plate motion, and their importance in modern tectonic studies cannot be overestimated. In spite of this critical role, the partition between contributions from the extrusive upper crustal rocks and the intrusive lower crustal section has not been determined. Vine and Matthews [1963] recognized early that a major contribution comes from the intensely-magnetized extrusive basalt layer. Recent evidence suggests that dike [Smith, 1990; Pariso and Johnson, 1991; Johnson and Salem, 1994] and gabbroic [Pariso and Johnson, 1993 a and b] sections can also be strongly magnetized.

The thermal history of the crust, Curie temperature (T_c) of the magnetic minerals, acquisition time, and stability of remanent magnetization are critical parameters that define the shape and intensity of the measured anomalies. If the magnetization of the lower crustal rocks is acquired much later than the overlying upper crust, the two contributions will be out of phase and the anomaly will be distorted [Blakely, 1976]. Similarly, if the isochrons that define the polarity boundaries in the lower crust are near-horizontal, their contribution to the anomalies will be small or non-existent. With the recent recognition that dikes and gabbros can be strongly magnetized, it seems appropriate to examine the stability of magnetization of oceanic rocks as a function of temperature.

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Instrumentation and Experimental Design

To carry out these experiments, an instrument was constructed specifically to measure viscous magnetization at high temperature. Figure 1 shows the overall schematic design of the instrument, where the outer shell is a 2-layer μ-metal magnetic shield. The magnetic samples are standard 10 cm^3 paleomagnetic minicores, heated in a sealed and evacuated titanium tube to control oxygen fugacity. The upper part of the sample tube is heated by a non-magnetically wound resistance oven, and heat is transferred to the sample by a massive copper cylinder. Granules of elemental carbon are placed inside the copper cylinder at the beginning of each experiment to provide the necessary C-CO buffer for magnetite.

Magnetometer sensors consist of two single-axis Narod fluxgates with a resolution of 0.03 nT and an accuracy of 0.1 nT. Arithmetic differencing between the lower sample sensor and the upper environmental sensor effectively reduces residual external noise by two orders of magnitude. The applied magnetic field used to induce VRM is 1.5 oe (150,000 nT), but the data shown in Table 1 and Figures 2 and 3 were normalized to a more realistic value of 0.5 oe, assuming VRM acquisition is linear with field strength over the range of 0.5 to 1.5 oe [Nagata, 1961; Dunlop and Özdemir, 1997].

Temperature monitoring and thermal regulation are provided using non-magnetic thermocouples located (1) at the sample position, (2) on the heater coils, and (3) on the coil form for the driving magnetic field to correct for changes in coil form size. Stabilization of the temperature within a variable room temperature required that the sample have a minimum temperature of 40°C. Sample temperatures for each run are accurate to within 1.5°C, and the within-run variability is better than 1°C for approximately 6 hours at 600°C.

To measure the temperature dependence of VRM acquisition, it was important that samples were physically and chemically stable over the course of the entire experiment, and provide reproducible VRM curves over multiple runs. For this reason, each sample was first annealed for approximately 12 hours at 600°C to remove crystal defects and internal strain imparted during the drilling/sampling process [Pariso and Johnson, 1991, 1993]. The annealing process eliminates defect migration or strain relaxation over the course of multiple heating experiments.

After annealing, each VRM acquisition run began by heating the sample above T_c and then cooling it to the VRM acquisition temperature in zero field. A magnetic field was then applied for periods ranging between six hours and 28 days. Six-hour runs were completed on each of the samples for a series of 6 temperatures at intervals between 40°C and T_c. Acquisition times of 7 to 28 days were completed only for a single temperature for each sample. Post-run data process-

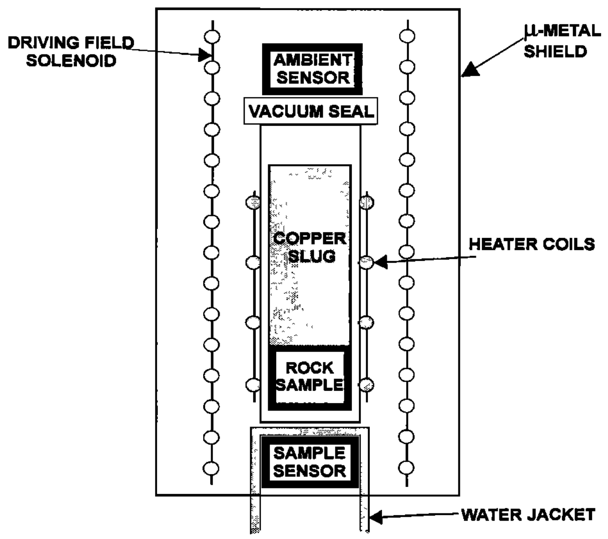

Figure 1. Schematic of experimental instrument (not to scale). Sample chamber is shielded from external fields by a µ-metal shield. The sample is protected from oxidation by a vacuum-sealed chamber and the presence of carbon granules to remove residual oxygen. Field measurements are made by two sensors, and simple arithmetic differencing between the two extracts the sample-induced field.

ing consisted of (1) differencing the sample and environmental fluxgates to remove environmental noise and the effects of external driving field, (2) correction for any time-dependent temperature changes in the oven/sample, and (3) correction for temperature changes in the driving coil. Measurements were made in the applied field and are composed of both induced magnetization (VIM) and remanence (VRM). The induced component at elevated temperature has been subtracted from the data shown in Figures 2 and 3, so that only the remanence is displayed.

Samples Used

Samples from each of the three major rock types that compose oceanic crust were subjected to the high-temperature VRM experiments: an unaltered submarine basalt, two intrusive dike samples, and three gabbros. The magnetic properties of the samples are summarized in Table 1. The basalt was collected by ALVIN from the 1993 CoAxial eruption site, a pillow basalt flow on the central Juan de Fuca Ridge. The magnetic properties of this newly-erupted flow have been intensely studied [Johnson and Tivey, 1995], and the sample used had a T_c near 200°C with a reversible J_s-T curve, indicating the dominant magnetic mineral is unoxidized titanomagnetite with 60% ulvospinel. The two fine-grained diabase dike samples were recovered from DSDP Hole 504b, from the lower part (1700-1800m crustal depth) of the sheeted dike complex, and were discussed in Pariso and Johnson [1991]. Reversible T_c's for both samples are 570°C, indicating a magnetic mineralogy near pure magnetite in composition, and may be the result of secondary alteration [Hall et al., 1999]. The three gabbro samples used were recovered from ODP Site 735b in the Indian Ocean and have widely differing histories and properties. All three gabbros (a late crystallization FeTi-rich gabbro, a normal olivine gabbro, and a strongly mylonitic gabbro) showed a reversible T_c near 580°C, again indicating a magnetic mineralogy near pure magnetite.

Results

Results from the 6-hour experimental runs show that for all the dike and gabbro samples, VRM acquisition increases with increasing temperature to approximately 250°C, but above this temperature VRM acquisition decreases (Fig. 2). The basalt sample displayed similar behavior, with a peak in VRM acquisition between 40°C and 68°C. This behavior displayed by our natural samples is in contrast with some previous VRM observations on synthetic magnetite [Dunlop, 1983; Shimizu, 1960] and Australian granulite samples [Kelso and Banerjee, 1994] that showed systematic increasing VRM acquisition from room temperature to T_c. Our data show a maximum in VRM acquisition at a temperature several hundred degrees below either T_c or blocking temperature, results which are consistent with the small number of previous high-temperature VRM studies on oceanic basalts [Dunlop and Hale, 1977; Prévot and Bina, 1993]. Decay of the VRM in zero field following acquisition was measured and exhibited the same patterns as the VRM acquisition for all samples. However, the net VRM decay at a given temperature was approximately 50% of that acquired over the same time interval.

To test reproducibility, repeated 6-hour runs were done, and the results differed by 0.5 - 5.5% from the average for the individual samples and temperatures, with only one sample producing results that varied up to 15%. This relatively small variation does not mask the systematic changes in VRM acquisition with increasing temperature for any of the samples. A repeat run at the highest acquisition temperature was done before and after the full temperature series for each sample, and the excellent reproducibility of these before-and-after runs argues against any alteration or physical change in the sample. Results from the longer 7-day runs, which were conducted at or near the temperature of maximum VRM acquisition (250°C for dikes and gabbros and 68°C for basalt), were reproducible to within 2% - 11% of the mean of several runs.

Table 1. Summary of the magnetic properties for samples used in high-temperature experiments. NRM_{eq} is the *in situ* NRM rotated to the equator. Max VRM is the asymptotic value, A, referred to in Equation 1, and is the projected value for the Temperature of Maximum Viscosity (TMV). B and n are the parameters defined in Equation 1.

Sample #	Description	T_c (°C)	TMV (°C)	$NRM_{in\ situ}$ (A/m)	NRM_{eq} (A/m)	Max VRM (A/m)	B	n
ALVC1A	fresh basalt	212	68	18.0	11.2	0.679	4.5×10^{-2}	0.24
140-504b-197R-01-032	lower dike	577	250	3.78	3.78	0.641	3.7×10^{-3}	0.46
140-504b-210R-01-027	lower dike	570	250	5.63	5.63	n/a	n/a	n/a
118-735b-53-3-95	FeTi gabbro	556	250	12.0	8.76	2.38	5.4×10^{-4}	0.52
118-735b-29-1-119	olivine gabbro	553	250	6.54	4.77	1.18	6.2×10^{-4}	0.58
118-735b-16-1-65	mylonitic gabbro	576	250	46.4	33.9	8.22	6.6×10^{-4}	0.52

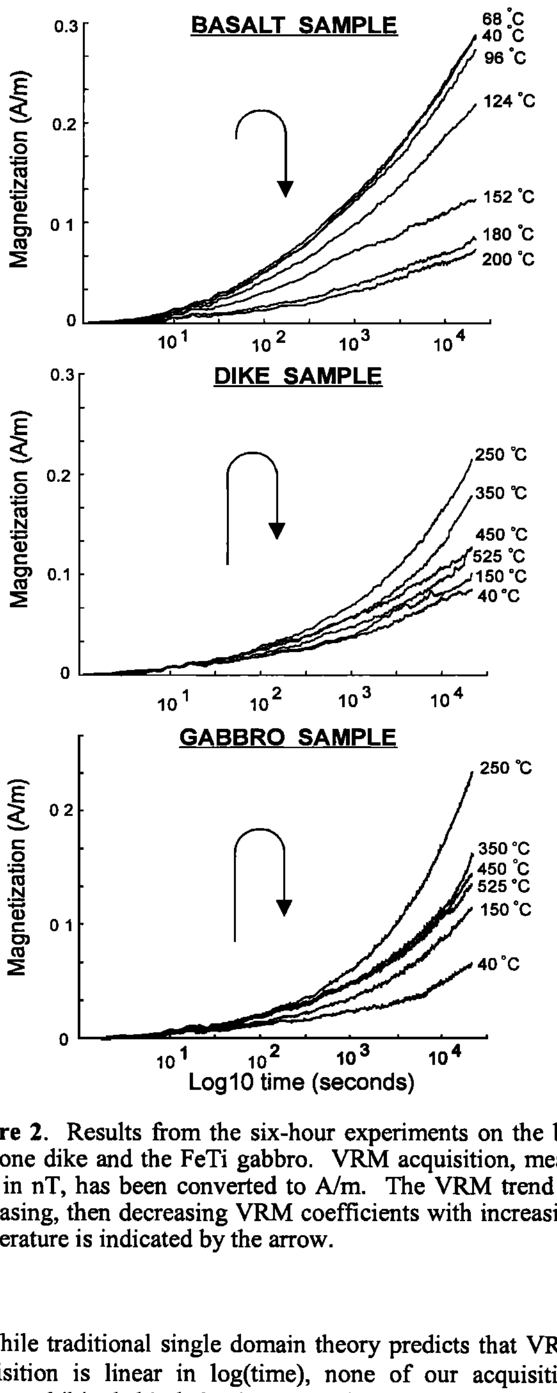

Figure 2. Results from the six-hour experiments on the basalt, one dike and the FeTi gabbro. VRM acquisition, measured in nT, has been converted to A/m. The VRM trend of increasing, then decreasing VRM coefficients with increasing temperature is indicated by the arrow.

While traditional single domain theory predicts that VRM acquisition is linear in log(time), none of our acquisition curves exhibited this behavior (Fig. 2). Other studies have also observed this non-linearity in log(time) [Dunlop, 1983; Lowrie and Kent, 1978; Prévot and Bina, 1993; Smith, 1984; Dunlop and Özdemir, 1997], and several variations on the log(time) dependence have been used to describe VRM acquisition. However, none of these expressions fit our experimental data, so we chose to use an empirical equation in order to extrapolate results obtained from the initial six hours of data to the longer seven day runs. When this was successful, we felt confident in extending our extrapolations to more meaningful geological times. We chose the best-fit hyperbolic tangent in linear time to describe the acquisition:

$$\mathrm{VRM} = A * \tanh(Bt^{n}) \qquad (1)$$

where VRM is in A/m, t is linear time in seconds, A is the asymptotic VRM value (see Fig. 3), and B and n are factors related to the acquisition rate. Parameters B and n are assumed to differ between samples, but are assumed constant for a given sample at all temperatures. This function adequately describes the general pattern of VRM acquisition, including zero VRM at zero time, and an asymptotic rise to a finite value at infinite time.

The asymptotic value, A, provides an indication of the role VRM acquisition plays in long-term stability of crustal magnetization. If the value of A is a significant fraction of the sample's NRM, we can then expect that VRM will contribute to the crustal magnetization. To estimate this asymptotic VRM value, we fit Equation 1 to the data from the 7-day runs, obtaining values for A, B and n (Table 1). Using these values for B and n, we then fit Equation 1 to the 6-hour runs at all temperatures, determining A. The resulting values for A, plotted in Fig. 4, represent a significant fraction of the samples' NRM values, in some cases exceeding 25% of the NRM.

Discussion and Conclusions

Our new experimental data, while representing only a small number of samples and with experimental runs that are many orders of magnitude shorter than geological time, indicate that some of our present assumptions about the source layer of marine magnetic anomalies may require reexamination. First, the important temperature for the acquisition of stable magnetization does not appear to be the T_c or blocking temperature, but is instead the Temperature of Maximum Viscosity (TMV), which for our lower crustal samples was near 250°C. For crustal rocks to faithfully record the direction of the geomagnetic field over geological intervals, it appears to be necessary for the ambient temperature to drop below the unstable TMV interval where it can acquire substantial viscous magnetization in relatively short times.

For our unaltered submarine basalt sample, the TMV appears to fall between 40-68°C. Bina and Prevot [1994] also show a TMV at 60°C and 80°C for two submarine basalt samples aged 3 and 30 Ma respectively. Dunlop and Hale [1976] report a TMV in VRM decay in basalts and diabases aged 3.5 – 16.5 Ma. While Smith [1984] observes more "classical" VRM behavior on several doleritic basalts, the highest temperature of measurement was 105°C, and the unannealed samples were AF demagnetized.

The fact that other elevated temperature VRM studies have observed similar behavior in a wide variety of basalts leads us

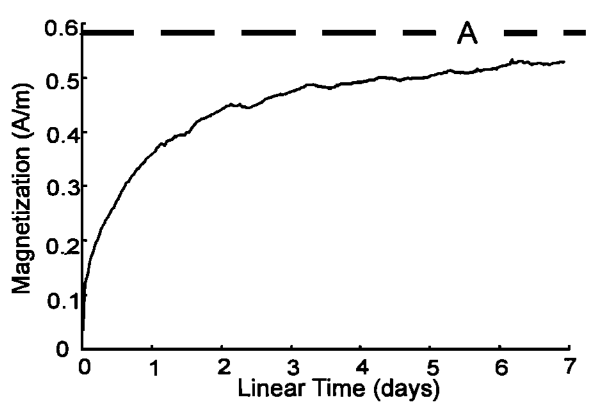

Figure 3. An example VRM acquisition over a 7-day data run for one of the 504b dike samples at 250°C. Note that magnetization approaches the VRM asymptotic value, A.

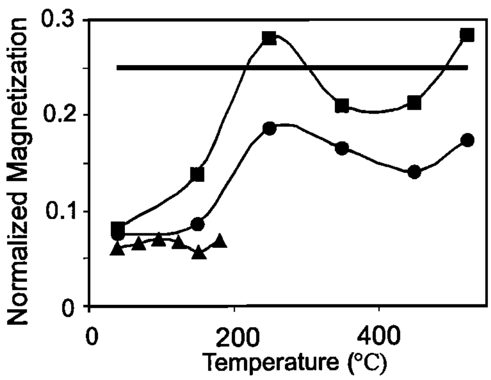

Figure 4. Projected values of asymptotic VRM, A, as a function of temperature for the basalt (triangles), one dike (circles) and the FeTi gabbro (squares). The VRM values are shown as a fraction of the samples' NRM values, normalized to $J_s(T)$ and rotated to equatorial latitude. The solid line represents 25% NRM at the elevated temperatures.

to believe that TMV behavior may be a general property of submarine basalts. This interpretation has implications for areas such as the east flank of the Juan de Fuca Ridge which is subjected to re-heating of the oceanic crust by rapid sedimentation near the axis [Davis et al, 1997]. This re-heating will not destroy the extrusive basalt component of the anomaly source layer (at least by VRM acquisition) until temperatures are very near T_c. This is one explanation to the presence of well-defined magnetic anomalies on the heavily-sedimented Juan de Fuca plate, even in those areas where the upper crustal temperatures approach or exceed 100°C.

Experimental data from the 504b dikes and 735b gabbros showed TMV values near 250°C. All samples had relatively pure magnetite (T_c = 580°) as the relevant magnetic mineral, but the lower crustal samples had a wide range of magnetic mineral grain sizes and shapes, initial magnetic properties, and thermal histories. While fewer previous VRM studies have been performed on lower crustal rocks, Pozzi and Dubuisson [1992] performed high-temperature VRM experiments on serpentinized peridotites which, in some cases, produced a TMV at 250-350°C. At this relatively low temperature of 250°C in laboratory time scales, our gabbro samples can acquire a VRM component that is 25% of NRM, while the dike sample achieved a VRM component that was nearly 20% of NRM (Table 1). If these results can be generalized, the implication is that lower crustal rocks could initially acquire a quasi-stable magnetization in the temperature interval between the T_c and TMV, but this magnetization can subsequently be modified by viscous magnetization as the crustal temperatures decrease through the TMV.

If substantiated by further VRM experiments to be a general result for oceanic rocks, the implications of a much lower (<250°C) TMV for the acquisition of stable magnetization for the lower crustal layers are profound. The shape of the polarity boundaries within any magnetic anomaly source layer are strongly temperature dependent, and if the temperature of acquisition of stable magnetization is low (<200°C), these isochrons will be near-horizontal, and any possible contribution from this layer will be reduced. Additionally, the delay in magnetization of these lower crustal rocks produced by a 250°C TMV means that stable acquisition will occur considerably later than the magnetization of the overlying upper crustal rocks, and there will be necessarily a substantial, and perhaps destructive, phase lag between the contributions of the two stratigraphic layers. Therefore, any substantial lowering of the temperature for the final acquisition of stable magnetization for magnetite-bearing rocks will reduce possible contribution from the lower crust. In light of increasing evidence that lower crustal rocks are strongly magnetized and do, in some cases, contribute substantially to the marine magnetic anomaly source layer, this apparent paradox requires further examination.

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