

## GP53A-04 1425h INVITED

## Magnetization of lower oceanic crust and upper mantle

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The location of the magnetized rocks of the oceanic crust that are responsible for sea-floor spreading magnetic anomalies has been a long-standing problem in geophysics. The recognition of these anomalies was a key stone in the development of the theory of plate tectonics. Our present concept of oceanic crustal magnetization is much more complex than the original, uniformly magnetized model of Vine-Matthews-Morley Hypothesis. Magnetic inversion studies indicated that the upper oceanic extrusive layer (Layer 2A of 0.5km thick) was the only magnetic layer and that it was not necessary to postulate any contribution from deeper parts of oceanic crust. Direct measurements of the magnetic properties of the rocks recovered from the sea floor, however, have shown that the magnetization of Layer 2A, together with the observations that this layer could record geomagnetic field reversals within a vertical section, is insufficient to give the required size of observed magnetic anomalies and that some contribution from lower intrusive rocks is necessary. Magnetization of oceanic intrusive rocks were observed to be reasonably high enough to contribute to sea-floor spreading magnetic anomalies, but were considered somewhat equivocal until late 1980s, in part because studies had been conducted on unoriented dredged and ophiolite samples and on intermittent DSDP/ODP cores. Since ODP Leg 118 that core and recovered continuous 500m of oceanic intrusive layer at Site 735B, Southwest Indian Ridge with an extremely high recovery of 87 percent, there have been several ODP Legs (legs 147, 153, 176, 179 and 209) that were devoted to drilling gabbroic rocks and peridotites. In terms of the magnetization intensities, all of the results obtained from these ODP Legs were supportive of the model that a significant contribution must come from gabbros and peridotites and the source of the lineated magnetic anomalies must reside in most of the oceanic crust as well as crust-mantle boundary. However, it would be wise to note that similar to upper extrusive layer, geomagnetic field reversals were observed for Leg 153 gabbros and that process of magnetization acquisition of mantle peridotites still remains unclear, though we believe mantle peridotites acquire CRM with the formation of magnetite during the process of serpentinization near the ridge axis.

## GP53A-05 1445h INVITED

## Determination of Titanium Content and Degree of Oxidation (Magnetization) of Magnetite in MORB by Electron Microscopy

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Variations in Ti-content of titanomagnetites (x) and variable degrees of oxidation of titanomagnetite to titanomaghemite (z) cause changes in the Curie temperature of MORB samples. Traditionally, however, Curie temperatures have been used as a proxy for one or the other of these parameters. Clearly, without knowing one of these parameters, the other can only be estimated by making assumptions, and this hampers study of the magnetization carriers in fresh and altered MORB. Furthermore, rock magnetic properties of titanomaghemite strongly depend on both x and z. For MORB samples, z values represent a later chemical modification of original titanomagnetite, whereas x values reflect variations in initial Ti content as well as low-temperature alteration in which the Fe/Ti ratio changes. We have developed a method for independently determining x and z by electron microscopy. The data reveal that variations in x and z can occur on temporal and spatial scales that are not always predictable; thus, conclusions drawn from Curie temperatures about correlations between rock magnetic parameters and the composition of the magnetic carriers can be erroneous. In this review, we examine some case histories that illustrate variations in x and z in MORB with ages within the Brunhes Chron as well as back to Mesozoic times.

## GP53A-06 1500h

## Insights into the magnetic structure of oceanic crust from near-bottom magnetic field observations.

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The Vine-Matthews-Morley (VMM) hypothesis elegantly explains the basic concept of how Earth's magnetic field is recorded by the seafloor spreading process, but how does it fare at the seafloor? Are reversal boundaries sharply defined on the seafloor or are they simply a gradational zone? How far can we push the resolution of the magnetic signal to estimate timescales? Near-bottom magnetic observations remove the filtering effect of the water depth and allow us to constrain the resolution of the marine magnetic anomaly record, in essence, determine how wide the recording head is in the tape recorder analogy. Since the early 1970's deep-towed magnetic sensors have been used to look at the relationship between magnetic anomalies and the formation of oceanic crust; Project FAMOUS in the Atlantic being a classic early example. A seminal near-bottom magnetic measurement in confirmation of the VMM hypothesis was undertaken at the Brunhes reversal on the East Pacific Rise. In this survey, a deep-tow profile located the "average" position of the reversal boundary, while a submersible-mounted magnetic gradiometer determined the polarity of seafloor outcrops and thus the seafloor polarity boundary. The seafloor boundary was displaced more than a km from the "average boundary" indicating a dipping polarity boundary within the extrusive layer. A similar submersible experiment looked at the vertical cross-section of the Brunhes and Jaramillo chrons exposed at Blanco Fracture Zone. Dipping polarity horizons were mapped in cross section within the extrusive layer showing a dip towards the axis over a lateral distance of more than a kilometer. This implies accretion takes place over a zone several kilometers wide. Detailed studies of how this accretion is achieved are now ongoing and maps of unprecedented resolution show the magnetic character of the seafloor can be resolved on the scale of individual flow units. These studies show that lava can be transported several kilometers from the eruptive trough and deposited off-axis. The width of this accretionary or neovolcanic zone modulates the geomagnetic signal recorded by the lavas and limits the lateral resolution to ~2 km half-width. The amount of time this represents will be dependent on spreading rate. The present day central anomaly magnetic high (CAMH) is a first order estimate of the resolution capability of the spreading center in that it represents a recording of recent intensity of Earth's magnetic field filtered through the crustal accretion process. Even with this resolution limit, it is remarkable how well the VMM hypothesis remains valid even at the seafloor.

## GP54A CC: 519 B Friday 1530h

## Rock Magnetism and the 40th Anniversary of the Vine-Matthews-Morley Hypothesis II (joint with G, T, V)

*Presiding:* D J Dunlop, University of Toronto; J Gee, Scripps Institution of Oceanography

## GP54A-01 1530h

## Near-bottom seafloor spreading anomalies around Hole 801C in Pacific Jurassic crust

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A deep-towed magnetic survey of Jurassic ocean crust was completed in the Pigafetta Basin of the western Pacific in the vicinity of ODP Hole 801C. The objectives of the survey were to extend the marine magnetic anomaly timescale as far back as possible within the remaining marine Jurassic crust extant in the Pacific basin and to tie the Hole 801C results into the lateral magnetic anomaly pattern. Hole 801C reaches 444 meters into Jurassic basement beneath 493 m of sediment cover for a total depth penetration of 937 meters below seafloor (mbsf). Downhole magnetic logging was completed to a depth of 850 mbsf. The magnetic logging data show multiple magnetic anomalies downhole, which implies a high reversal rate if these are all magnetic reversals. The in-phase relationship of the horizontal and vertical magnetic fields imply formation in the southern hemisphere. Apparent inclination calculated from the component data suggest an inclination

of ~40 degrees which implies a latitude of formation ~22S. Monotonic change in inclination downhole is attributed to rotation of the lava sequence during crustal accretion. The computed rotations are approximately equivalent to the dips calculated from the Formation Micro Scanner data, which suggest lava dips up to 40 degrees at depth. The deep-tow survey completed 7 lines, each 35 km long and spaced 1-10 km apart around the Hole. The lines show strong anomalies (200 nT) and good lateral correlation with a strike azimuth of 25 degrees suggesting seafloor spreading magnetic lineations are present at this location. There are ~5 major anomalies over this area implying a reversal rate of ~8 rev/My given a spreading rate of 55 km/My. The hole resides on a small positive anomaly on the southern flank of a larger double-peaked positive magnetic anomaly, which in this hemisphere indicates a reversely magnetized block. This is consistent with the downhole results, which show that the majority of the hole appears to be reverse polarity. Hole 801C thus appears to faithfully record seafloor spreading lineations.

## GP54A-02 1545h

## Titanium content and degree of oxidation of titanomaghemite in Mesozoic MORB: implications for magnetization intensity

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The magnetization intensity of oceanic crust shows systematic variations with a comparatively low intensity for ages ranging from 10 to 40 Ma, which can be attributed to low-temperature alteration of the natural remanent magnetization carrier titanomagnetite to titanomaghemite. Prior to this low magnetization intensity period, the amplitudes of magnetization are surprisingly higher and stay at a high level between 80 and 160 Ma. Numerous mechanisms have been proposed previously to explain the higher magnetization of older oceanic crust. We present electron microscopy results on Mesozoic mid-ocean ridge basalt (MORB) recovered from 4 ODP/DSDP sites in the southern Indian Ocean, western Pacific Ocean and western Atlantic Ocean. In general, the x values (reflecting titanium content) of titanomagnetite for these 4 sites are less than 0.65 and degrees of oxidation (z) of titanomaghemite are usually less than 0.7. In contrast, x and z of titanomaghemites in MORB with ages between 10 to 40 Ma often reach higher values. Because x and z are two important control factors on rock magnetic properties, the relatively low x and z values for the Mesozoic MORB seem to be, at least in part, responsible for high NRM and saturation magnetization. We will compare and contrast effects of x and z on NRM and rock magnetic properties in Tertiary and Mesozoic MORB samples.

## GP54A-03 1600h INVITED

## Self-reversed magnetizations in oceanic basalts

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Verhoogen (1956) proposed that ionic reordering in titanomaghemite could result in self-reversal of magnetization. This concept was subsequently refined, restricting the composition of titanomaghemite which can undergo self-reversal to higher oxidation states (O'Reilly and Banerjee, 1966) than those originally proposed by Verhoogen (1956). Furthermore, it was thought unlikely that these high oxidation states would be reached under low temperature conditions. For this reason (and others), self-reversal has not been considered in depth, even though many oxidized oceanic basalts contain near antipodal directions. Recently we have reported such directional behavior from oceanic basalts of ODP Site 883 from the northwestern Pacific Ocean (Detroit Seamount). X-ray diffraction and rock magnetic data demonstrate that the high oxidation states that were once thought to be unachievable in low temperature conditions have in fact been reached, probably due to seawater flux. Results from a host of rock magnetic experiments (including pTRM studies, magnetic hysteresis, and high and low thermomagnetic measurements) indicate that self-reversal of remanence has taken place. One of the most important observations is the presence of N-type magnetic behavior, with compensation points distributed above room temperature, for samples showing antipodal natural remanent magnetization (NRM) components. The NRM intensities of such samples are on average 4 times less than

those samples showing single components, suggesting that self-reversal could play some role in controlling marine magnetic anomaly amplitudes.

#### GP54A-04 1620h INVITED

##### On the use of magnetic hysteresis in paleomagnetism for granulometry

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In environmental magnetism and paleomagnetism, measuring magnetic hysteresis has become a routine procedure for characterizing remanence carriers of rocks. In general, values of saturation magnetization ( $M_s$ ), saturation remanence ( $M_r$ ), and coercivity ( $B_c$ ) are determined from hysteresis loops after appropriate non-ferrimagnetic slope correction. In addition, values of remanence coercivity ( $B_{cr}$ ) are generally obtained from separate backfield measurements. The conventional hysteresis measurements have recently been extended to include the very time consuming first order reversal curves (FORCs). In this presentation, we discuss two approaches for determining average grain size accurately and rapidly from hysteresis measurements. (1) Squareness-Coercivity (SC) analysis: Plots of squareness ( $M_r/M_s$ ) versus  $B_c$  characterize not only grain size but also dominant anisotropy, temperature dependence, and volume concentration with better resolution than the traditional Day plot squareness versus ( $M_r/M_s$  versus  $B_{cr}/B_c$ ). SC plots are being calibrated using micromagnetic simulations which agree very well with experimental results. (2) Transient Hysteresis (TH) Transient hysteresis is determined from a partial hysteresis curve in which samples are exposed to a saturation field which is reduced to zero, then increased again to saturation in the same direction. This is a single FORC with the minimum field being zero. The area between the ascending and descending loop is the "transient hysteresis" TH. Micromagnetic modeling and experiments shows TH to be an excellent granulometric indicator. In particular, it clearly distinguishes superparamagnetic (SP) grain from multidomain (MD) since TH results from the action of self-demagnetization that is absent for SP. While many factors such as composition (lithology), field-treatment,

grain shape and size, pre-history, stress, and volume concentration affect hysteresis properties, a combination of SC and TH predict with some confidence the average grain size of remanence carriers with far less effort than, for example, FORC analysis.

#### GP54A-05 1640h

##### Testing for Magnetostrictive Control of Coercivity in Titanomaghemite-Bearing Oceanic Basalt.

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We study the source of high coercivity in four oceanic basalts (from ODP sites 238, 572D, 470A and 556) containing highly oxidized titanomaghemite (titanium content parameter  $x \approx 0.55$  and oxidation parameter  $z \approx 0.9$  on average). Most of the titanomaghemite is likely in single-domain grains with uniaxial anisotropy, since the ratio of saturation remanence  $J_{RS}$  to saturation magnetization  $J_S$  approaches 0.50 ( $J_{RS}/J_S = 0.46$  on average). We show that the uniaxial anisotropy is very likely magnetostrictively controlled through internal stresses in the titanomaghemite grains. This allows us to estimate the saturation magnetostriction  $\lambda_S$  and the internal stress magnitude  $\sigma_i$  of the titanomaghemite in each basalt by measuring the coercive force  $H_C$  of the basalt, and by measuring the reversible change in  $J_{RS}$  of the basalt due to a small compression applied parallel to  $J_{RS}$ . This yields four  $\lambda_S$  estimates (with  $\sim 50\%$  expected error) ranging from  $3 \times 10^{-6}$  to  $10 \times 10^{-6}$  and averaging  $6 \times 10^{-6}$ . It also yields four  $\sigma_i$  estimates averaging  $2 \times 10^8$  Pa, which is similar to the internal stress magnitude thought to be responsible for the high coercivity of ball-milled single-domain titanomagnetite ( $x \approx 0.6$ ) and natural single-domain hematite. We also show that cooling to  $120^\circ\text{C}$  causes  $H_C J_S$  for each oceanic basalt to vary in approximate proportion to  $(1 - \frac{T}{T_C})^n$  with  $n$  between 1.9 and

2.0 (where  $T$  is temperature and  $T_C$  is Curie point, both in  $^\circ\text{C}$ ). This implies that  $\lambda_S$  of titanomaghemite with  $x \approx 0.55$  and  $z \approx 0.9$  also varies in this way on cooling to  $120^\circ\text{C}$  (assuming that  $\sigma_i$  remains constant on cooling). Our results support the hypothesis that coercivity is often magnetostrictively controlled by internal stresses in the highly oxidized titanomaghemites typical of oceanic basalts older than  $\sim 10$  Ma. We suggest that this hypothesis can be further tested by more extensive observation of whether cooling to  $120^\circ\text{C}$  often causes  $H_C J_S$  of such basalts to vary in approximate proportion to  $(1 - \frac{T}{T_C})^n$  with  $n$  near 1.9 or 2.0.

#### GP54A-06 1655h

##### First-order reversal curve (FORC) diagrams of magnetic mixtures: micromagnetic models and measurements

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Natural samples, such as MORBs, often contain mixtures of magnetic minerals in various domain states. An accurate identification of the magnetic minerals and domain states is usually needed for paleodirection/paleointensity studies. However, mixtures greatly complicate magnetic signals. First-order reversal curve (FORC) diagrams are a new and powerful tool for investigating the distribution of microcoercive force in a rock sample. In order to test whether FORC diagrams could be used to unravel magnetic mixtures in natural samples, we calculated FORC diagrams for mixtures of single-domain (SD) magnetite with a bimodal coercivity distribution, using a 3D unconstrained micromagnetic model. We find that FORC diagrams are linearly additive, regardless of the interaction state of the system. Measurements of FORC diagrams using synthetic SD and pseudo-single-domain magnetite samples also show linear additivity of FORCs. Therefore FORC diagrams could be used to predict the proportion of end-members in a sample having a bimodal size or coercivity distribution, provided that the end-members are known.

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