

- Both k and λ relate flow in a crack to the pore-pressure gradient, but λ has units of cubic instead of square meters and is not strictly a crack permeability.
10. W. F. Brace, J. B. Walsh, W. T. Frangos, *J. Geophys. Res.* **73**, 2225 (1968).
 11. J. T. Fredrich and T.-f. Wong, *ibid.* **91**, 12743 (1986).
 12. H. C. Heard and L. Page, *ibid.* **87**, 9340 (1982).
 13. C. H. Scholz, A. Léger, S. L. Karner, unpublished results.
 14. In the equation, c and r are constants. The units are those of the axes in Fig. 1: k and c are in units of 10^{-21} m^2 , t has units of days, and r has units of $days^{-1}$.
 15. S. F. Cox, M. A. Etheridge, V. J. Wall, *Ore Geol. Rev.* **2**, 65 (1986).
 16. M. S. Paterson and K. Wheatley, *J. Appl. Chem.* **9**, 231 (1959).
 17. G. W. Morey, R. O. Fournier, J. J. Rowe, *Geochim. Cosmochim. Acta* **26**, 1029 (1962); R. S. Beckwith and R. Reeve, *ibid.* **33**, 745 (1969).
 18. R. K. Iler, *The Chemistry of Silica* (Wiley, New York, 1979).
 19. M. L. Blanpied, D. A. Lockner, J. D. Byerlee, *Nature* **358**, 574 (1992).
 20. N. H. Sleep and M. L. Blanpied, *ibid.* **359**, 687 (1992).
 21. S. K. Frape, P. Fritz, R. H. McNutt, *Geochim. Cosmochim. Acta* **48**, 1617 (1984).
 22. R. H. Sibson, F. Robert, K. H. Poulsen, *Geology* **16**, 551 (1988); R. H. Sibson, in *Deformation Mechanisms, Rheology and Tectonics*, R. J. Nye and E. H. Rutter, Eds. (Geological Society, London, 1992), pp. 15–28.
 23. K. Sieh, M. Stuiver, D. Brillinger, *J. Geophys. Res.* **94**, 603 (1989).
 24. We thank R. Fournier and C. Williams for comments on an early draft of the manuscript.

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Grain Size-Dependent Alteration and the Magnetization of Oceanic Basalts

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Unblocking temperatures of natural remanent magnetization were found to extend well above the dominant Curie points in samples of oceanic basalts from the axis of the East Pacific Rise. This phenomenon is attributed to the natural presence in the basalts of three related magnetic phases: an abundant fine-grained and preferentially oxidized titanomagnetite that carries most of the natural remanent magnetism, a few coarser and less oxidized grains of titanomagnetite that account for most of the high-field magnetic properties, and a small contribution to both the natural remanent magnetism and high-field magnetic properties from magnetite that may be due to the disproportionation of the oxidized titanomagnetite under sea-floor conditions. This model is consistent with evidence from the Central Anomaly magnetic high that the original magnetization acquired by oceanic basalts upon cooling is rapidly altered and accounts for the lack of sensitivity of bulk rock magnetic parameters to the degree of alteration of the remanence carrier in oceanic basalts.

The intensely magnetized oceanic extrusive layer, which consists principally of several hundred meters of sheet flows and pillow basalts, is a major source of sea-floor spreading magnetic anomalies (1). As oceanic crust ages, the basalts are altered and their magnetization becomes substantially reduced, even though a record of the geomagnetic field is retained. A hallmark of the alteration process that is most probably responsible for the reduction in magnetization is a progressive increase in Curie temperature as the original titanomagnetite (TM60) carrier of the natural remanent magnetization (NRM) becomes increasingly oxidized to a cation-deficient titanomaghemite (2). A time constant of 500,000 years has long been assumed for this process, on the basis of analysis of dredged basalts and deep-tow magnetics from the slow-spreading Mid-Atlantic Ridge (MAR) (3–5). To explain the Central Anomaly magnetic high over the fast-spreading East Pacific Rise (EPR), the time constant of magnetization decrease must be only ~20,000 years, more than an order of magnitude faster (6). However, the large variation in NRM intensity found in dredged

basalts from near the axis of the EPR (6) or, for that matter, the MAR (3, 4) was not closely accompanied by a systematic variation in the Curie temperatures of the samples.

A more paradoxical result of some early paleomagnetic studies of dredged basalts from the MAR was that the maximum unblocking temperatures of NRM invariably extended 50° to 100°C above the dominant Curie temperature. The systematic elevation of NRM unblocking temperatures was regarded by Irving (3) as a laboratory artifact and was attributed to the formation during thermal demagnetization of a new higher unblocking temperature phase that inherited its magnetization direction from the parent material. This interpretation was very influential in subsequent rock magnetic studies of oceanic basalts, and thermal demagnetization, a key technique in characterizing remanence in most other rocks, has seldom been used since. In this report, we test the importance of the Irving hypothesis by heating and cooling samples of oceanic basalts under a variety of conditions in the laboratory.

The young basalt samples from the EPR that we studied show a similar systematic discrepancy between unblocking temperature spectrum of NRM and Curie temperature. For example, even after

thermal demagnetization of a sample at 200°C, well above the estimated Curie temperature of 150°C, about 50% of the initial NRM remained (Fig. 1A). The NRM nevertheless had a similar direction over the entire unblocking temperature range (Fig. 1B). The NRM of the EPR ridge axis basalts is thus characterized by significant unblocking of NRM occurring even above 300°C, consistent with an oxidized TM60 as the carrier. Yet, the high-field temperature experiments would suggest that a relatively unoxidized TM60 is the principal magnetic mineral, even though there is little unblocking of NRM by the dominant Curie point.

We initially tried to reproduce the Irving effect in a series of prolonged heating experiments at temperatures of 100° to 300°C in zero field (Fig. 2). The remanence after even 100 hours of heating was not appreciably different from the remanence after the 1 hour of heating typically used in thermal demagnetization. Even when the susceptibility markedly increased over prolonged heating at 300°C, which may have resulted from the inversion of some oxidized TM60 in the sample, the remanence direction and unblocking temperature distribution above 300°C were still essentially unaffected.

We next gave the samples a thermoremanent magnetization (TRM) at a high angle to the NRM direction by cooling them in a 0.03-mT field from 200°C; this temperature is above the dominant Curie point of 150°C but below the unblocking temperatures of ~50% of the NRM. The resulting magnetization was then progressively demagnetized in 25°C steps from 50°C to 600°C (Fig. 3). If the Irving effect were operative, the entire remanence including any unblocking temperature components above the Curie point should have been aligned along the laboratory-induced thermoremanence direction. Instead, the laboratory-induced thermoremanence was effectively demagnetized by 200° to 225°C, and with further thermal demagnetization we recovered the appropriate fraction of the original NRM vector.

The fine-grained EPR basalts showed little evidence of oxidation during these

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or other experiments (7). We therefore conclude that the NRM that has unblocking temperatures above the dominant Curie point is original and not an artifact of laboratory treatment. Thus, the bulk rock magnetic properties deduced from the high-field temperature experiments do not reflect the principal carrier of the NRM, and unoxidized TM60, corresponding to the dominant Curie temperature phase, evidently contributes little to the NRM of these young basalts.

This paradoxical result can be accounted for by a model of grain size-dependent alteration, similar to that suggested by Bina and Prévot (8), in which abundant fine-grained and oxidized TM60 carries most of the NRM whereas a few coarser and less oxidized grains of TM60 account for most of the high-field magnetic properties (Fig. 4A). Most of the grains would have sizes appropriate for stable single-domain (SD) behavior for TM60, but the distribution would also include some larger multidomain (MD) grains [greater than about $0.5 \mu\text{m}$ (9)]. The NRM will be carried predominantly by SD grains. Because of their large specific surface areas, the SD grains will be-

come oxidized faster and more thoroughly than the larger MD grains (10); their magnetization will decrease, and their unblocking temperatures as a sensitive proxy for their Curie point will increase. The relatively unoxidized MD grains will hardly contribute to the NRM but, because of their large relative volume, will tend to dominate the magnetization in high-field experiments.

The EPR basalts typically show high ratios of saturation remanent magnetization to saturation magnetization (M_r/M_s) from 0.35 to 0.65. Because titanomagnetite grains are commonly assumed to have uniaxial magnetic anisotropy [theoretical limit of $M_r/M_s = 0.5$ for SD grains (11)], such high ratios would effectively exclude the presence of MD grains, which are

characterized by low M_r/M_s ratios. Yet, petrographic observations indicate the presence of skeletal TM60 grains greater than a few micrometers in size. Moreover, the highest M_r/M_s values point to multiaxial anisotropy, which we take to be equivalent to a cubic case [theoretical limit of $M_r/M_s = 0.87$ (12)], as the important control on the magnetization in the basalts (13). The relative contributions of partially oxidized SD and unoxidized MD grain size fractions can thus be balanced to account for the observed Curie temperature, hysteresis, and NRM properties of the basalts (Fig. 4B).

Our model indicates that the original NRM acquired by TM60 upon emplacement and cooling of the basalts is lost rapidly, as the fine-grained, remanence-carrying SD fraction is preferentially ox-

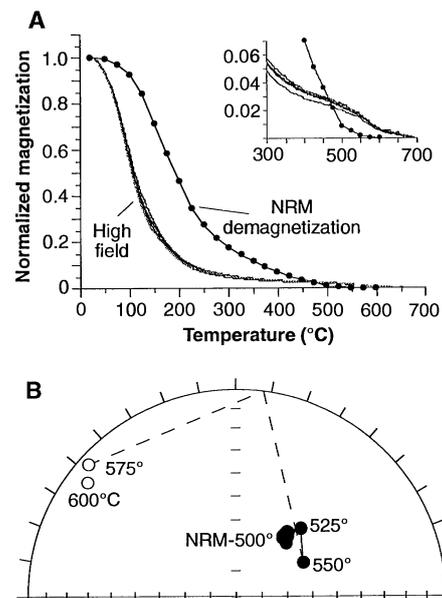


Fig. 1. Comparison between the temperature variation of NRM and high-field magnetization of a representative basalt sample (CH114-10) from the EPR. (A) NRM (filled circles) shows little unblocking at or below the dominant Curie temperature ($\sim 150^\circ\text{C}$) as observed in multiple high-field temperature curves from five adjacent basalt specimens. (Inset) An expanded plot showing the presence of a phase with high NRM unblocking (525° to 550°C) and Curie temperature ($\sim 580^\circ\text{C}$) compatible with the presence of a small fraction of magnetite. (B) Stereonet showing the relatively constant direction of NRM over the entire range of unblocking from room temperature to $\sim 550^\circ\text{C}$.

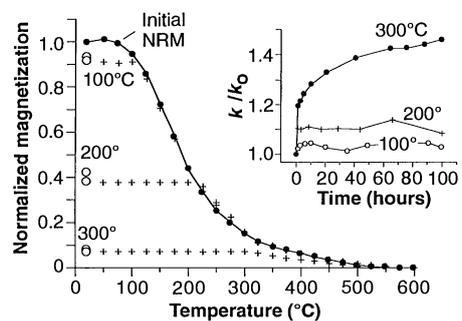


Fig. 2. Demagnetization results of a basalt sample (CH114-10) from the EPR subjected to prolonged heating in zero field at various temperatures. Open circles indicate remanence remaining after 1 hour and 100 hours of heating in zero field at the indicated temperatures. The remanence after 100-hour heating as well as the subsequent demagnetization of these specimens (+) is not significantly different from that of the previously unheated specimen (filled circles). (Inset) Variation of room-temperature susceptibility, normalized to the initial value, k/k_0 , of specimens over prolonged heating experiments.

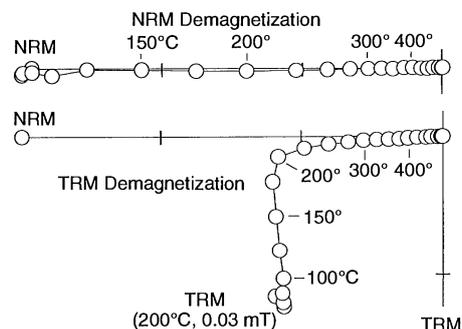


Fig. 3. Orthogonal vector end-point diagrams of thermal demagnetization in 25°C steps of NRM (top) compared to that of a TRM imparted at high angle to the original NRM direction (bottom) in specimens of basalt sample CH114-10 from the EPR. The TRM is essentially removed by 200°C to 225°C , after which the original NRM direction is recovered.

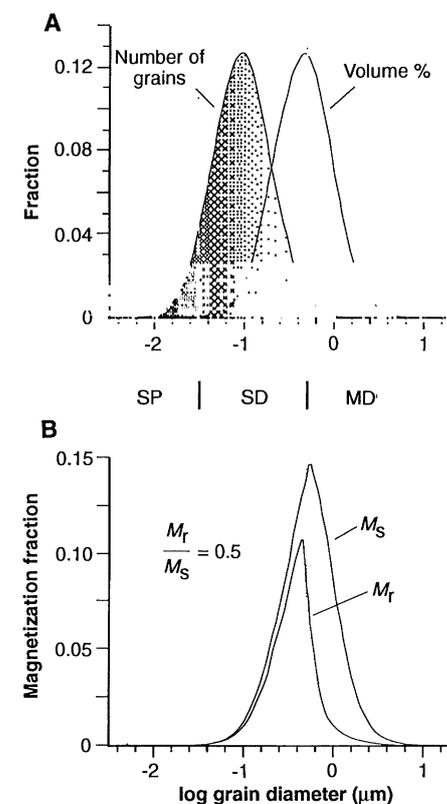


Fig. 4. (A) Model lognormal grain size distribution and corresponding volumetric contribution for spherical grains of TM60. The SD size range for TM60 extends from the superparamagnetic (SP) threshold at about $0.03 \mu\text{m}$ (25) to the MD threshold at about $0.5 \mu\text{m}$ (9). Grain size-dependent, low-temperature oxidation [with accompanying $\sim 50\%$ total reduction in saturation magnetization (14)] is illustrated by shading (darker for greater oxidation). (B) Relative contribution of M_r and M_s for SP ($M_r/M_s < 0.01$), SD ($M_r/M_s = 0.87$), and MD ($M_r/M_s = 0.1$) fractions, with a gradation across the SD-MD boundary where the balance is particularly sensitive to the assumed magnetic properties. Integrated areas for M_r and M_s curves give an overall $M_r/M_s = 0.5$.

idized. Indeed, most of the basalt samples we studied were taken within just a few kilometers of the axis of the fast-spreading EPR (6), yet all showed NRM unblocking temperatures that extended well beyond the dominant Curie points. The remanence resulting from the single-phase oxidation will be reduced in magnitude by a combination of related mechanisms (14, 15), producing the short-wavelength magnetization contrast required to account for the Central Anomaly magnetic high as the locus of young volcanism. Even if the remanence forms along the ambient external field rather than inheriting the original NRM direction (16), the apparent rapidity of magnetic alteration of the oceanic extrusive source layer as a whole (6, 17) will still result in a high-fidelity recording of the geomagnetic field, as is evident in magnetic anomalies (18).

Although most of the NRM is unblocked by about 300°C in the EPR basalts, some of the remanence typically persists until 525° to 550°C (Fig. 1A, inset). Our experimental results strongly suggest that this remanence is carried by magnetite as a naturally occurring phase (19). Disproportionation of cation-deficient titanomaghemite under sea-floor alteration conditions is a possible and likely explanation for the origin of the magnetite (20), which may result in acquisition of a secondary magnetization [for example, (21)]. An alternative interpretation is that the magnetite represents an original, minor constituent in oceanic basalts (22). The very long-term variations in oceanic basalt magnetization documented in the Deep Sea Drilling Program and Oceanic Drilling Project samples and in amplitudes of marine magnetic anomalies (23) may result from the integrated response of a growing fraction of magnetite to the reversing geomagnetic field, as suggested by the model of Raymond and LaBrecque (24).

REFERENCES AND NOTES

- M. Talwani, C. C. Windisch, M. G. Langseth Jr., *J. Geophys. Res.* **76**, 473 (1971); T. Atwater and J. D. Mudie, *ibid.* **78**, 8665 (1973).
- W. O'Reilly, *Rock and Mineral Magnetism* (Chapman & Hall, New York, 1984).
- E. Irving, *Can. J. Earth Sci.* **7**, 1528 (1970).
- H. P. Johnson and T. Atwater, *Geol. Soc. Am. Bull.* **88**, 637 (1977).
- K. C. Macdonald, *ibid.*, p. 541.
- J. Gee and D. V. Kent, *Geophys. Res. Lett.* **21**, 297 (1994).
- Detailed rock magnetic experiments were conducted on 10 of the 21 samples described in (6). These include 65 prolonged heating and 15 TRM experiments. Magnetic hysteresis and high-field temperature data were obtained for the entire sample set.
- M. M. Bina and M. Prévot, *Phys. Earth Planet. Inter.* **54**, 169 (1989).
- H. C. Soffel and E. Appel, *ibid.* **30**, 348 (1982); B. M. Moskowitz and S. L. Haldegahl, *J. Geophys. Res.* **92**, 10667 (1987).
- K. J. Gallagher, W. Feitnecht, U. Mannweiler, *Nature* **217**, 1118 (1968).
- E. C. Stoner and E. P. Wohlfarth, *Philos. Trans. R. Soc. London* **240**, 599 (1948).
- E. P. Wohlfarth and D. G. Tonge, *Philos. Mag.* **2**, 1333 (1957); I. Joffe and R. Heuberger, *ibid.* **29**, 1051 (1974).
- J. Gee and D. V. Kent, in preparation.
- T. Nishitani and M. Kono, *J. Geomagn. Geoelectr.* **41**, 19 (1989).
- Ö. Özdemir and W. O'Reilly, *Earth Planet. Sci. Lett.* **57**, 437 (1982); J. Housden and W. O'Reilly, *Phys. Earth Planet. Inter.* **64**, 261 (1990).
- Ö. Özdemir and D. J. Dunlop, *J. Geophys. Res.* **90**, 11513 (1985).
- J. M. Hall, *J. Geomagn. Geoelectr.* **29**, 411 (1977); H. P. Johnson *et al.*, *Eos* **74**, 620 (1993).
- S. C. Cande and D. V. Kent, *J. Geophys. Res.* **97**, 15075 (1992).
- Comparison of zero-field heating and TRM acquisition at 300°C indicates that the generation of new magnetite, as evidenced by large susceptibility increases in the basalt samples, is reflected in the remanent magnetization only if formed or cooled in the presence of an external magnetic field.
- W. O'Reilly, *Phys. Earth Planet. Inter.* **31**, 65 (1983); J. Housden, A. de Sa, W. O'Reilly, *J. Geomagn. Geoelectr.* **40**, 63 (1988).
- D. J. Dunlop, *Rep. Prog. Phys.* **53**, 707 (1990).
- T. Pick and L. Tauxe, *J. Geophys. Res.* **98**, 17949 (1993); *Nature* **366**, 238 (1993).
- U. Bleil and N. Petersen, *Nature* **301**, 384 (1983); H. P. Johnson and J. E. Pariso, *J. Geophys. Res.* **98**, 435 (1993); T. Furuta, *Geophys. J. Int.* **113**, 95 (1993).
- C. A. Raymond and J. L. LaBrecque, *J. Geophys. Res.* **92**, 8077 (1987).
- R. F. Butler and S. K. Banerjee, *ibid.* **80**, 4049 (1975); Ö. Özdemir and W. O'Reilly, *Phys. Earth Planet. Inter.* **25**, 406 (1981).
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Rapid Emplacement of Young Oceanic Lithosphere: Argon Geochronology of the Oman Ophiolite

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$^{40}\text{Ar}/^{39}\text{Ar}$ dates of emplacement-related metamorphic rocks beneath the Samail ophiolite in Oman show that cooling to $<525^\circ\text{C}$ occurred within ~ 1 million years of igneous crystallization of the ophiolite. This unexpectedly short time span and rapid cooling means that old, cold continental or oceanic lithosphere must have been adjacent to the ophiolite during spreading and then been thrust beneath the ophiolite almost immediately afterward.

Key to understanding how ophiolites—large (up to 50,000 km²) but thin (<20 km) and dense (3000 to 3300 kg m⁻³) sheets of oceanic rock—are emplaced onto continental margins (1) is knowing the age of the ophiolite at the time the emplacement process began. Typically, this is achieved by determining when igneous rocks in the ophiolite crystallized at a spreading center and by determining the age of metamorphic rocks associated with the emplacement process. Estimates of such time intervals range from less than 5 million years (My) for the Samail ophiolite, Oman (2, 3), to nearly 20 My for the Bay of Islands, Newfoundland (4), and Brooks Range, Alaska, ophiolites (5). The longer estimates are based on the cooling ages of high-grade metamorphic rocks, which are found beneath most well-preserved ophiolites (6). A short time span means that the ophiolite was young at the time intraoceanic thrusting began and then cooled rapidly. In contrast, a long time span implies that the ophiolite

cooled more slowly than normal oceanic lithosphere, retaining heat by some mechanism such as intraoceanic magmatism. It is shown here that the Samail ophiolite was ~ 1 My old at the time intraoceanic thrusting began.

The Samail ophiolite of Oman and the United Arab Emirates is the best exposed, largest (100 km by 500 km), least deformed, and perhaps most studied ophiolite in the world (7–11). Most of the ophiolite bears the geochemical signature of formation at a mid-ocean-ridge-type spreading center. Younger, volumetrically less substantial volcanic and plutonic rocks may have been derived from subduction zone or within-plate sources (12). Though now distended by normal faulting, the Samail ophiolite is inferred to have been 15 to 20 km thick before its emplacement onto the Arabian craton in Late Cretaceous time (9, 13) (Fig. 1). In all, 7 km of crustal gabbros, sheeted dikes, and volcanic rocks overlie 10 km of tectonized upper mantle peridotite. This entire oceanic lithosphere section was thrust over adjacent oceanic lithosphere and then onto the Arabian craton along a several-hundred-meter-thick shear zone

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