versity of physical properties that will allow geologists to map geologic units based not only on their morphology in visible wavelengths, but also on their physical properties. Even fresh crater ejecta show up distinctively with rays of blocky or fine-grained materials; these variations in physical properties may be related to the age of the ejecta.

THEMIS has also collected visible images at a spatial scale of ~20 m/pixel. These images are also well suited to studying the bedrock geology. They show much more morphological detail than the global Viking orbital images at a scale of ~200 m/pixel. These images will help to determine the formation processes of geologic units on Mars. Furthermore, they will likely cover much more of Mars (hopefully global with an extended mission) than the higher resolution (~3 m/pixel) images from the Mars Orbiter Camera on Mars Global Surveyor.

By combining THEMIS thermal and visible images, planetary geologists will be able to map the entire surface with unprecedented insight into the geologic history and evolution of Mars. We can only guess at what startling new discoveries will be uncovered in the coming years as geologists remap Mars with this dramatic new data set.

References

1. P. R. Christensen *et al.*, *Science* **300**, 2056 (2003); published online 5 June 2003 (10.1126/science.1080885).
2. H. H. Kieffer *et al.*, *J. Geophys. Res.* **82**, 4249 (1977).
3. P. R. Christensen, H. J. Moore, in *Mars*, H. H. Kieffer, B. M. Jakosky, C. W. Snyder, M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1992), pp. 686–729.
4. M. P. Golombek *et al.*, *Science* **278**, 1743 (1997).
5. M. T. Mellon *et al.*, *Icarus* **148**, 437 (2000).
6. F. D. Palluconi, H. H. Kieffer, *Icarus*, **45**, 415 (1981).

GEOPHYSICS

Mapping Long-Term Changes in Earth's Magnetic Field

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The existence of a relatively stable geomagnetic field is today pretty much taken for granted, along with associated benefits such as easy navigation and the protection that it provides in shielding Earth from cosmic rays. Yet in the course of Earth history, the field has reversed multiple times, with substantial changes in both its direction and strength between reversals.

These changes can only be studied via the geological record because of the long time scales on which they occur. New paleomagnetic records of both direction and intensity of the field, derived from lava flows and sediments around the world, now allow improved characterization of geomagnetic field behavior.

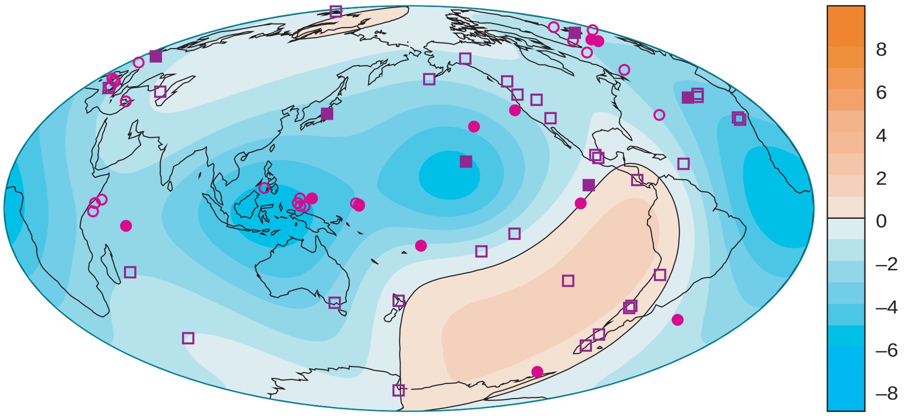
The global distribution, temporal resolution, and quality of data are particularly good for two distinct time periods—from 0 to 3000 years ago (*1*) and from 0 to 5 million years ago (*2*). For these time periods, researchers can use modeling and analysis techniques similar to those used in the study of modern and historical geomagnetic field variations. The resulting maps of average magnetic field geometry (see the figure) and detailed records of intensity variations raise provocative questions about interactions among core and mantle dynamics, Earth's orbit, rotation, and magnetic field environment.

At any instant in time and space, substantial deviations occur from the simplest model for the magnetic field geometry—that of a dipole located at Earth's center. New, very-high-resolution mapping allows investigations of the detailed evolution of the magnetic field on time scales of less than 400 years, as discussed by Finlay and Jackson on page 2084 of this issue (*3*). But there is controversy about whether long-term deviations persist and, if so, what their spatial characteristics are. Better spatial and temporal coverage of paleomagnetic data are needed to map such persistent deviations, motivating extensive new data collection efforts (see the figure).

If robust, the deviations likely reflect the influence of long-lived geographical variations in lowermost mantle properties (such as temperature) on fluid flow and magnetic field generation in the outer core. To improve existing models, data on past field intensities ("paleointensities") are needed to supplement the paleodirection data and compensate for biases in directional averages.

Here we focus on new paleointensity data, which provide insights into magnetic field behavior on a continuum of time scales from millions to perhaps a few thousand years. There are two different kinds of paleointensity observations: absolute measurements of the field strength (from igneous rocks) and relative intensity variations (typically from sediments). The latter can provide a time series of variations relative to some mean or calibrated value. But because of the dearth of long sediment records and of reliable absolute paleointensity data, intensity variations in the geomagnetic field have until recently been poorly defined.

Ten years ago, Valet and Meynadier (*4*) reported the first long sediment record of relative changes in paleointensity, spanning the period from 0 to 4 million years ago. Several reversals of the magnetic field have occurred in this time interval. The dominant feature of this and subsequent records, confirming and extending observations made in the 1960s, are the relatively low paleointensities during field reversals. Furthermore, studies of very-high-sedi-



Changes in Earth's magnetic field. Distribution of relative paleointensity data for 0 to 200,000 years ago (open red circles) and 200,000 to 800,000 years ago (filled red circles) from sediments, new lava flow paleodirectional data (open blue squares), and SBG absolute paleointensity data (filled blue squares). Color map is the time-averaged inclination anomaly in degrees at Earth's surface from a model (LSN1) for the normal polarity field, averaged over 0 to 5 million years ago (*13*). Current time-averaged field models can be tested and improved by incorporating new data sets such as those shown here.

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mentation-rate cores from Ocean Drilling Program (ODP) site 983 (*5*) and a global relative paleointensity average spanning 0 to 800,000 years ago (*6*) show low field intensity during geomagnetic excursions (large deviations of the geomagnetic field direction from that due to an axial dipole).

These observations indicate a general connection between directional and intensity variations, and demonstrate the need for simultaneous records of intensity and direction. Guyodot *et al.* (*7*) have suggested that the relative paleointensity at ODP site 983 varies with periodicities characteristic of Earth's orbital eccentricity, obliquity, and precession. However, the robustness and interpretation of these observations remain controversial. Complexities in analyzing these records include the length and sampling interval of the time series, the spectral techniques, and the proxy used in the relative paleointensity estimate. The choice of proxy is critical in determining whether orbital periodicities in the record reflect geomagnetic intensity changes or climatic variations. Stoner *et al.* (*8*) claim that millennial-scale correlations among relative paleointensity records from geographically distant locations are possible, but the high-frequency spectral coherence of such records is uncertain (*9*).

Absolute paleointensity estimates are possible from lava flows, but the measurements are notoriously difficult because of the risk of sample alteration during the experiment. Submarine basaltic glass (SBG) is less prone to such alteration. For the period from 0 to 5 million years ago, new SBG absolute paleointensity data (see the figure) substantially improve lava flow paleointensity data, which are less extensive than their sedimentary counterparts and discontinuous in time. Tauxe and Love (*10*) have reported more than 50 new reliable estimates of paleointensity from SBG, more than doubling the number of similar-quality measurements available from the existing paleointensity database.

The new data are concentrated in the previously undersampled 0.4 to 4.0 million year period. They have led to the assertion that the oft-quoted average dipole moment for the past 0.78 million years is too high because of the preponderance of young (0 to 0.3 million year) data, and that the average field intensity prior to 0.3 million years ago was lower by a factor of ~2. How many data points are needed to define an average remains an open question, given the large geographic (about 20% standard deviation for the present field) and temporal variability in the dipole moment. Thus, despite the superior quality of the new data, their temporal and spatial distribution remain inadequate, and further data are needed to understand the long-term average field intensity.

Advances in understanding Earth's magnetic field behavior require continuing improvements in data distribution, quality, and accessibility. The use of stringent laboratory procedures is critical for mapping regional differences in field behavior and obtaining temporal resolution of a few thousand years. Continuous long-core relative paleointensity measurements and high-quality absolute paleointensity measurements (*11*) have led to a substantial increase in sediment and lava flow data. A promising avenue for future paleointensity work avoids the heating of samples through use of microwaves (*12*).

Until now, limited data sets have led to a somewhat artificial separation of studies of paleodirection and paleointensity. The availability of colocated, contemporaneous records of intensity and direction with better temporal information promote a different approach: that of analyzing the full vector evolution of the geomagnetic field.

Perhaps the most exciting implications of the improved data sets and models are the suggestion of lower mantle influence on the dynamics of the outer core, and the claimed detection of orbital periodicities in geomagnetic records. The arguments in favor of such interactions may be qualitatively appealing but are not yet supported by strong theoretical arguments. Addressing these questions will require improved understanding of geomagnetic field variations and close integration with research in paleoclimate, orbital dynamics, and geophysical studies of deep Earth.

References

1. C. G. Constable, C. L. Johnson, S. P. Lund, *Philos. Trans. R. Soc. London* **358**, 991 (2000).
2. D. Gubbins, P. Kelly, *Nature* **365**, 829 (1993).
3. C. C. Finlay, A. Jackson, *Science* **300**, 2084 (2003).
4. J. P. Valet, L. Meynadier, *Nature* **366**, 234 (1993).
5. J. E. T. Channell, *J. Geophys. Res.* **104**, 22937 (1999).
6. Y. Guyodo, J. P. Valet, *Nature* **399**, 249 (1999).
7. Y. Guyodo, P. Gaillot, J. E. T. Channell, *Earth Planet. Sci. Lett.* **184**, 109 (2000).
8. J. S. Stoner, C. Laj, J. E. T. Channel, C. Kissel, *Quat. Sci. Rev.* **21**, 1141 (2002).
9. D. G. McMillan, C. G. Constable, R. L. Parker, *Earth Planet. Sci. Lett.* **201**, 509 (2002).
10. L. Tauxe, J. J. Love, *Geol., Geochem. Geosyst.* **4**, 10.1029/2001GC000276 (2003).
11. E. Thellier, O. Thellier, *Ann. Geophys.* **15**, 285 (1959).
12. M. J. Hill, M. N. Gratton, J. Shaw, *Geophys. J. Int.* **151**, 157 (2002).
13. C. L. Johnson, C. G. Constable, *Geophys. J. Int.* **131**, 643 (1997).

BIOPHYSICS

Myosin Motors Walk the Walk

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Like its better-known cousin the myosin II of muscle, myosin V is a molecular motor that moves along actin filaments powered by the hydrolysis of ATP. However, unlike muscle myosin, which depends on teamwork for movement, myosin V works alone to move intracellular vesicles around cells. A hotly debated question is whether the two heads of the myosin V motor move along an actin filament in a hand-over-hand manner (akin to human walking), or whether they shuffle along one behind the other like "inchworms." On page 2061 of this issue, Yildiz *et al*. (*1*) report data that are consistent with the "hand-over-hand" model. They used total internal reflection fluorescence light microscopy to track a single fluorophore attached to one of the myosin heads as it moved along an actin filament. They found that the myosin head "swings" through 74 nm for each molecule of ATP hydrolyzed, each time advancing the myosin V by about 37 nm. This discovery provides compelling evidence in favor of the hand-over-hand model.

Myosins are a diverse protein family comprising 18 different classes (*2*), of which muscle myosin II is the best characterized. Myosin II works by converting small structural rearrangements at the catalytic site within the motor domain into a large swing or power-stroke of the light-chain binding domain. This serves as a flexible lever arm, transferring force to the object that is being moved. In this model, the presence of nucleotide (ATP or ADP and inorganic phosphate) at the catalytic site is tightly coupled both to the affinity of myosin for actin and to the lever-arm position. The "power-stroke" must occur when myosin is firmly attached to actin, and a "recovery-stroke" when it is detached. If the two heads of a double-headed myosin molecule cycle asynchronously, then they could move along the actin filament processively (that is, in a series of steps) (*3*, *4*). However, for this system to work, at least one of the two myosin heads must be bound to actin at all times. Thus, either the two heads must work in a coordinated fashion or each myosin head must spend most of its cycle time attached to actin (having a high "duty-cycle" ratio).

Biochemical studies have shown that myosin V is a motor with a high duty-cycle ratio (*5*). Furthermore, the light-chain binding domains of myosin V (each carrying six

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