Taking the Pulse of the Geodynamo

Paleomagnetic Research at UW-Madison

by Brad Singer and Ken Hoffman

Iron-rich, electrically-conducting fluid swirling within the outer core generates Earth's magnetic field via a dynamo process. Both the geometry and strength of the field that we experience at Earth's surface, 3000 km above the outer core, vary greatly on time scales ranging from seconds to millions of years. Geologists are well aware of these changes—the difference in direction between "north" found by a Brunton compass and the north pole of Earth's rotation axis may change by several degrees per year—this is secular variation. Students also learn that Earth's magnetic field has completely reversed its polarity dozens of times during the Cenozoic—half of the time that Brunton compass would have been pointing south—and that dating of these polarity reversals using the K-Ar radio-isotopic clock was crucial to establishing the theory of seafloor spreading, hence plate tectonics. Yet, the underlying causes of dynamo behavior, particularly polarity reversal, remain among the most enigmatic in all of geophysics, much less basic physics.

Input toward attaining a more complete understanding of the source of the geomagnetic field and its various behaviors comes today from a variety of sources—magnetic observatory data, computer-assisted modeling, fabricated laboratory dynamos, and paleomagnetic studies. However, only through paleomagnetic investigation of the record "fossilized" in rocks at the time of their formation do we gain actual input as to what had been experienced on Earth's surface in the geologic past. For more than a decade, Professor Brad Singer and UW-Madison Senior Research Scientist Kenneth Hoffman have been collaborating to generate ever more precise and complete paleomagnetic observations associated with both polarity reversals and unsuccessful, or aborted, attempts by the dynamo to reverse polarity known as field excursions. Recently our findings led to a new model of the dynamo that was published, along with a "News of the Week" commentary by Dick Kerr, in the September 28, 2008 issue of *Science*.

Our data come from rare sequences of lava flows that happen to have erupted at ocean island or arc volcanoes *during* the very brief periods when the field was reversing, or attempting to reverse, polarity. Upon cooling, these lava flows record successive "snapshots" of changes in the geometry and intensity of the magnetic field experienced at a specific location on Earth's surface. Acquiring oriented samples from each lava flow with a gasoline-powered drill requires field campaigns that have taken Singer and Hoffman to volcanoes in, among other places, Tahiti, the Canary Islands, Chile, Cape Verde, Iceland, France, Guatemala (on the cover), New Zealand, and Australia (Figure 1).

The causes of dynamo behavior, including polarity reversal, are the focus of collaborative research by Professor Brad Singer and Senior Research Scientist Kenneth Hoffman. The two recently published in *Science* a new hypothesis, suggesting a separation between deep and shallow sources of Earth's magnetic field.

Figure 1. **Ken Hoffman drilling to collect oriented core samples from a lava flow sequence on La Palma, Canary Islands, in January 2000. These particular lava flows have been ^{40}Ar/^{39}Ar-dated at 579,000 years before the present and were found to record the Big Lost excursion shown Figure 2.** *(Brad Singer)*

Once the ancient magnetic direction recorded by the microscopic iron-titanium oxide grains in these lavas are measured in Hoffman's paleomagnetism laboratory at California Polytechnic State University, San Luis Obispo, where he is a professor emeritus, a representative "Virtual Geomagnetic Pole" or VGP for short, can be plotted on a globe. These VGPs make possible a polar path of the event that then can be analyzed and compared with other available, sometimes synchronous VGP paths obtained from other locations. How we know which reversal or excursion has been sampled comes from the crucial role played by Singer who determines precise ages using the ^{40}Ar/^{39}Ar variant of K-Ar dating in the geochronology lab he established at UW-Madison in 2000 (http://www.geology.wisc.edu/~raregas/).

Indeed, ^{40}Ar/^{39}Ar geochronology represents a quantum leap relative to K-Ar dating, such that ages may now be determined from Quaternary lava flows with a precision of about 1 to 2%. This resolving power has led to a remarkable discovery: the dynamo has been far more unstable than previously thought. We have found evidence in lava flows that the field has not only weakened considerably and then reversed polarity six times during the last 2.6 million years, but also that at least 23 field excursions took place (Figure 2). This finding has been corroborated by magnetic measurements of sediments collected at several sites by the Ocean Drilling Program during the past decade. Clearly, field excursions are a globally important component of dynamo behavior and our findings have led to the development of a Geomagnetic Instability Time Scale (GITS) aimed at the next generation of supercomputer-assisted modeling of the dynamo.

During the early 1990's a controversial suggestion was made, based on the observation of apparently systematic VGP paths, that the lower mantle has a significant role in the reversal process. Perhaps the strongest evidence in support of long-term mantle control over the geodynamo—at least on a hundred year time scale—comes from direct analysis of the so-called non-axial dipole NAD-field. The NAD is the complex, weak field that remains given removal of the otherwise dominant axial dipole—the term that must vanish before a change in polarity can take place. Specifically, features seen in plots at Earth's surface both for the present day and when averaged over the past 400 years appear extremely similar (Figure 3). Indeed, if there were no hold of magnetic flux at the core surface over this amount of time, such a result would be highly improbable at best.

To our surprise we found a pattern of dynamo behavior recorded by lava flows erupted several hundred thousand years ago that mimics that of the NAD field in modern times. More specifically, lava flows that record the earliest portion of the last reversal of Earth's magnetic field 780,000 years ago, as well as five excursions that took place during the following 250,000 years, show that Earth's magnetic field weakened several times as if it were about to switch its north and south poles, only to return to full strength without reversing. During each excursion, the magnetic field that was initially pointing toward the north pole shifted around so that in Germany the VGPs scattered broadly over Eurasia. At the same time, in Tahiti, the field pointed to the southwest associated with a more tightly focused grouping of VGPs near western Australia. This contrasting behavior is consistent with the modern NAD field which features a prominent concentration of magnetic flux arising from beneath Australasia and which has a very strong pull on the field direction over a significant portion of the globe—from the Indian Ocean to half-way into the Pacific (including Tahiti). Not so for Germany, where this flux feature has a limited influence simply because it is so far away (Figure 3).

We hypothesize in our *Science* paper that the reason for the persistent re-emergence of similar field directions on occasions when the axial dipole weakened during the past million years or more is actually tied to plate tectonic processes at Earth's surface. During the Cenozoic, subducted cold oceanic plates have sunk through the mantle all the way to the top of the core beneath Australasia. Strong evidence of this comes from seismic tomographic studies of the lower mantle near the core. The abundance of relatively cold material in this "slab graveyard" would cool the underlying core fluid and cause it to sink. The magnetic flux held in this downwelling fluid would thereby strengthen. We argue that these particular conditions have persisted for well over a million years. Moreover, we propose that this regional source of magnetic field seen at Earth's surface is spatially separated from the source responsible for the usually strong and dominating axial dipole. Magnetic observation and models of the dynamo suggest that the axial dipole field is generated by a deeper source within the outer core, the field spiraling around north-south cylinders of fluid convection adjacent to the solid inner core. Yet, the remaining NAD field is generated at shallow depth in regions where the core fluid is most strongly influenced by the overlying mantle (see figure on the cover).

Currently, Earth's largely axial dipole magnetic field is weakening at a rate such that within the next two millenia its intensity would vanish, causing a full polarity reversal like that not seen since the last polarity reversal about 780,000 years ago (Figure 2). If this occurs, our model predicts that the shallow core sources responsible for the remaining NAD field will again dominate and produce a now-familiar configuration over Earth's surface. For the next several years we will be acquiring new paleo-

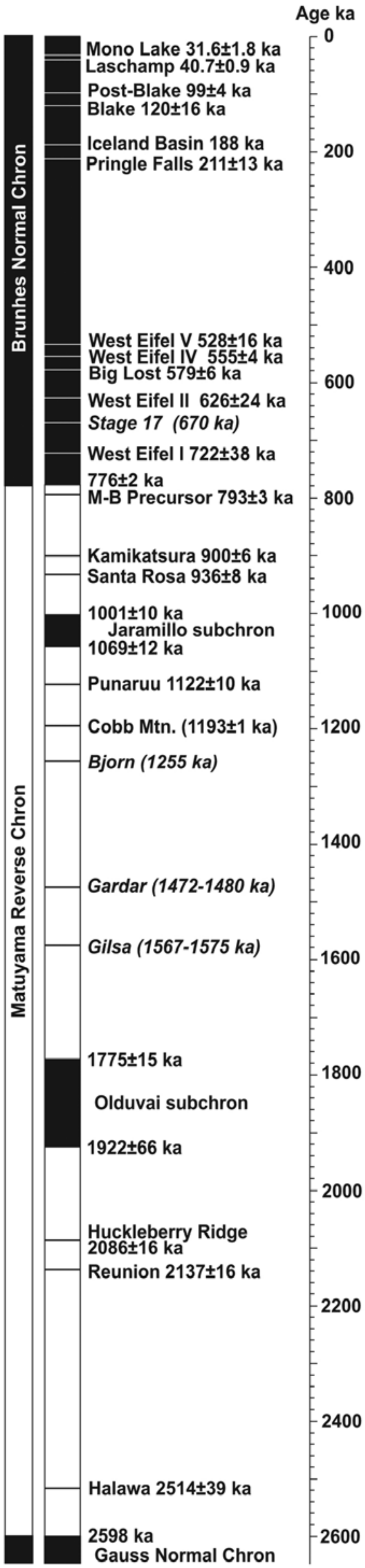

Figure 2. **A Geomagnetic Instability Time Scale (GITS) based mainly on ^{40}Ar/^{39}Ar-dated volcanic rocks that record five polarity reversals and eighteen field excursions during the past 2.6 million years. Black represents normal polarity, white is reversed. Excursions are named after the location in which they have been initially discovered.**

magnetic data from early Cenozoic lavas that record a polarity reversal in Australia—located directly over the most prominent non-axial dipole field source. With these data we hope to better understand how the shallow core field may influence the process of polarity reversal as viewed from Earth's surface. ●

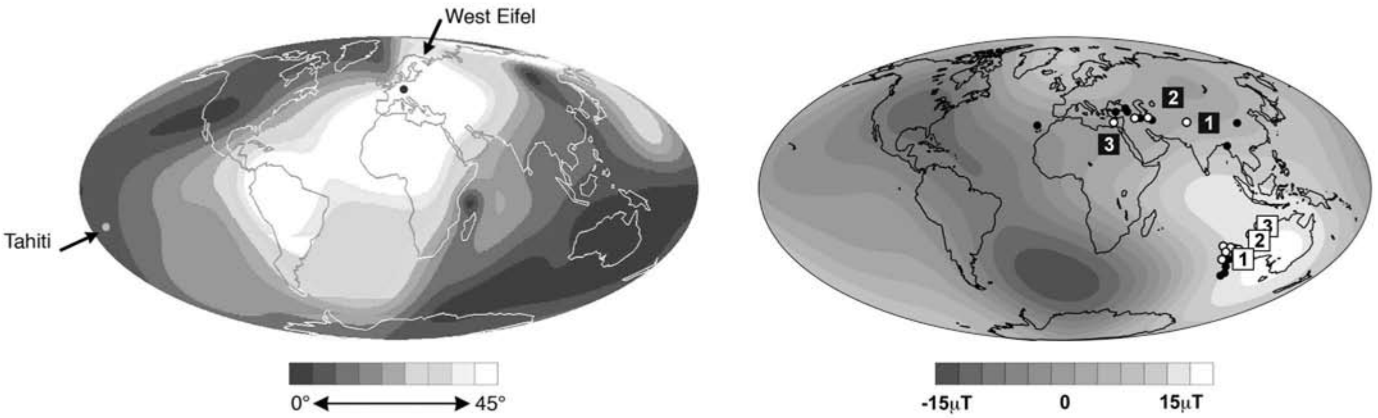

Figure 3. **(Left) Contoured angular change from 1900 to 2000 of the NAD field Virtual Geomagnetic Poles (VGPs) about the globe. (Right) (i) Transitional north VGPs recorded in lavas on Tahiti (clustered near west Australia) and West Eifel (falling over much of Eurasia), each case spanning ~200,000 years (Big Lost excursion VGPs, which were recorded at both sites 580,000 years ago have open symbols), and (ii) concurrent south VGPs for the years 1900, 1950, and 2000 (indicated on the map by 1, 2, and 3, respectively) NAD field at Tahiti (white squares) and West Eifel (black squares) plotted on the time-averaged surface NAD field** *(after Hoffman and Singer, 2008;* Science*)*.

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