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Decay of the virtual dipole moment during polarity transitions and geomagnetic excursions

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Abstract. We have analyzed paleointensity data from five polarity transitions and geomagnetic excursions recorded by lava flows. We find a significant correlation between the logarithm of the virtual dipole moment and the angle between the virtual geomagnetic pole and the Earth's rotation axis. This correlation implies that any physical model for geomagnetic field behavior during transitions and excursions must address the question of how changes in direction are linked to changes in intensity. In addition, large changes in paleointensity may occur even when the virtual geomagnetic pole is still at high latitude so the concept of transitional direction must be redefined.

Introduction

Understanding how and why the geomagnetic field reverses is a major challenge of modern geophysics. Recently there has been considerable debate about the existence and significance of preferred longitudinal bands for virtual geomagnetic poles (VGPs) associated with polarity transitions and geomagnetic excursions [*Clement*, 1991, 1992; *Tric et al.*, 1991; *Laj et al.*, 1991, 1992; *Constable*, 1992; *Hoffman*, 1992; *Valet et al.*, 1992; *McFadden et al.*, 1993]. Most of this discussion has focussed on directional aspects of transitional field behavior, with little attention given to the corresponding changes in intensity. However, earlier studies of Tertiary lava flows on Iceland [*Wilson et al.*, 1972; *Kristjansson and McDougall*, 1982] strongly suggested a relationship between changes in intensity and changes in direction. More recently, *Mary and Courtillot* [1993] have demonstrated the importance of looking at both direction and intensity in their analysis of polarity transition records in terms of a local Cartesian coordinate system. In this paper, we report on a relationship between VGPs and paleointensity, based on an analysis of data from polarity transitions and geomagnetic excursions recorded by lava flows, which are generally regarded as the most reliable recorders of paleointensity.

Background

Many paleomagnetic studies (see *Clement and Constable* [1991]) have shown that during a polarity transition, the intensity of the geomagnetic field appears to decrease to about 10-20% of the pre-transition value and that the decline in intensity often begins well before the major change in field direction. Similarly, the post-transition recovery to full intensity requires more time than the re-establishment of a predominantly axial dipole field configuration. These observations have been subjected to few quantitative analyses because of the difficulties in obtaining reliable paleointensity measurements, particularly from sedimentary records.

We have analyzed published paleointensity data from polarity transitions and geomagnetic excursions recorded by lava flows at five sites: Steens Mountain (Oregon), Tahiti, Kauai (Hawaii), Iceland and Germany. In each case, the paleointensity determinations were based on the Thellier double heating method [*Thellier and Thellier*, 1959]. The Steens Mountain data come from a 15.5 Ma reversed to normal polarity transition whose paleointensity record was reported by *Prévot et al.* [1985]. The dataset contains 157 paleointensity determinations from 73 lava flows. The data from Tahiti [*Chauvin et al.*, 1990] come from four transitions and excursions dated between 1.2 and 0.6 Ma. In this dataset, there are 26 paleointensity determinations from 11 lava flows. Fourteen of the paleointensity determinations are from a single episode, the 1.1 Ma Cobb Mountain subchron. The data from Kauai come from a single reversed to normal transition which is dated between 3.8 to 5.1 Ma [*Bogue and Coe*, 1984]. The dataset contains 13 paleointensity determinations published by *Bogue and Coe* [1984] plus 10 new determinations [*Bogue and Paul*, 1993]. The Icelandic data [*Marshall et al.*, 1988] are from lava flows associated with the Skalamaelifell excursion, which has an estimated age of 12-30 ka. There are 16 paleointensity determinations in this dataset. The dataset from Germany [*Schnepp*, 1992] contains 37 paleointensity determinations from lava flows in the West Eiffel volcanic field. These flows record a geomagnetic excursion dated between 100-600 ka.

Although paleointensity records from lava flows are available from other sites, those records are considerably less complete than the five which we have used. An anomalous record of paleointensity associated with a polarity transition recorded in Iceland [*Shaw*, 1975] is an exception to this statement. Those data indicate that the intensity suddenly became very strong for a brief period midway through the transition. Because similar behavior is not consistently seen in other polarity transitions, the significance of this dataset is uncertain, and it is not included in the present analysis.

Data Analysis

We denote the virtual dipole moment (VDM) corresponding to a given paleointensity determination by M, and the angular distance between the sampling site and the virtual geomagnetic pole (VGP) by p_o. The VDM is determined from the measured paleointensity, F, by the well-known equation:

$$M = Fr^3/(1 + 3\cos^2 p_o)^{1/2}$$

where r is the radius of the Earth. We denote the angle between

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the dipole axis corresponding to the VDM and the Earth's rotation axis by θ, and the colatitude of the VGP by p_V (Figure 1). In order to obtain a relationship between intensity and direction that is independent of polarity, we always take θ as $\leq 90°$. Thus $\theta = p_V$ for $p_V \leq 90°$, and $\theta = 180° - p_V$ for $p_V > 90°$.

In Figure 2a we plot the logarithm of the VDMs from Steens Mountain against the corresponding value of θ. *Prévot et al.* [1985] plotted the logarithm of the paleointensity against the reversal angle, which is the deviation of the paleomagnetic direction from the axial dipole field direction. No systematic relationship between these parameters is readily seen on their plot. Our analysis yields a linear relationship between ln(M) and θ, with a correlation coefficient of -0.762. This value is significant at the 99% level [*Kennedy and Neville,* 1986].

Despite the high correlation, the dispersion in the data is considerable. This dispersion is probably due to experimental errors inherent in the methods used for paleointensity determination, to variations in rock magnetic properties between samples, and to secular variation. If these are the real sources of the dispersion, they can be mitigated by averaging the data over successive lava flows taken in stratigraphic order. In Figure 2b, we show the Steens Mountain data averaged using a five flow running mean. The dispersion is greatly reduced compared to Figure 2a, and the correlation coefficient increases from -0.762 to -0.923. Also, in Figure 2b, we use different symbols to denote data representing the decline and the recovery of the paleointensity during the polarity transition. There does not appear to be any systematic difference in the patterns of the two symbols.

The data from the other four sites are not as comprehensive as those from Steens Mountain. Nevertheless, they also show a strong linear correlation between ln(M) and θ (Figures 3 and 4). In all cases, the dispersions are comparable to, or smaller than, those of the Steens Mountain data, and the correlation coefficients (Table 1) are all significant at the 99% level.

Discussion

The correlation between ln(M) and θ suggests that during a polarity transition or geomagnetic excursion, the strength of the dipole moment is directly related to the angle θ. To first order, this relationship can be written as:

$$M = M_0 \exp(-\lambda\theta)$$

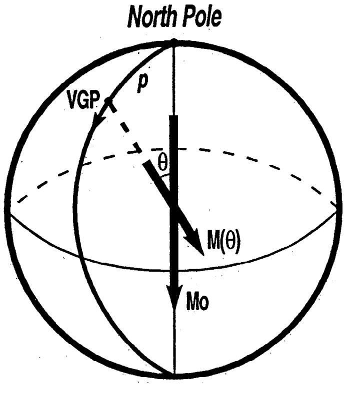

Figure 1. Schematic diagram showing relationship between virtual dipole moment (M), virtual geomagnetic pole (VGP), Earth's rotation axis, angle (θ) between rotation axis and VGP, colatitude (p_V) of the VGP, and angular distance (p_0) between observation site and VGP.

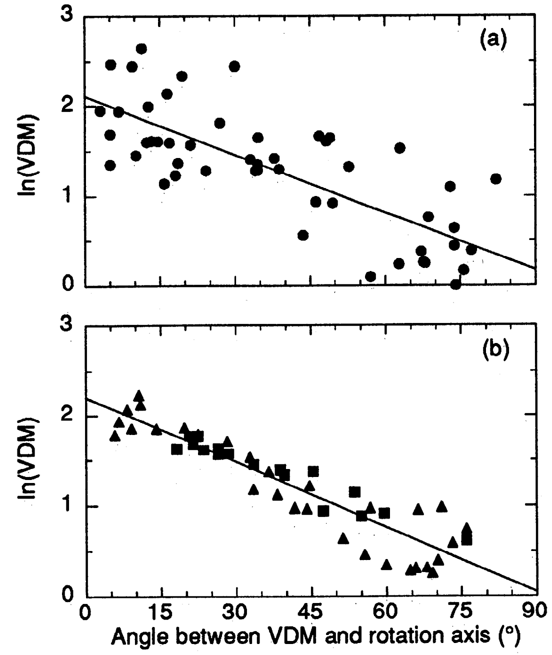

Figure 2. Data from Steens Mountain, Oregon. The graphs show the relationship between the logarithm of the VDM (in 10^{22} Am^2) and the angle between the VGP and the rotation axis. Original data are shown in (a); data based on five point running mean of lava flows in stratigraphic order are shown in (b), where triangles represent the decline in paleointensity and squares represent the recovery of paleointensity.

where M_0 is the dipole moment when θ=0, and λ is a (positive) constant. From this relationship, we define the half-moment angle ϕ as the angle at which the VDM falls to half of its value during the transition or excursion. The half-moment angles for the data from Steens Mountain, Iceland, and Germany are all about 30°, but the angles for Tahiti and Kauai are somewhat smaller. The values of the half-moment angles imply that when the VGP moved to latitudes ranging from 60° to 75°, half of the initial dipole moment, M_0, had already been lost. Viewed as a function of θ, the decline in the dipole moment was about twice as precipitous at the two low latitude sites than it was at the other three sites. This observation is consistent with that of *Chauvin et al.* [1990] who found a latitude dependence in remanent intensity for Iceland and Tahiti.

The data in our study come from individual polarity transitions or geomagnetic excursions, except for those from Tahiti where the records are from four transitions and excursions that occurred within 600,000 years. From such a database, we cannot determine whether the value of the half-moment angle is a characteristic of the observation site or of the particular transition or excursion that is being observed. Earlier work on the Icelandic lava flows suggests that the latter might be the case. In the study by *Wilson et al.* [1972], NRM intensities were compiled for 1,400 transitional and non-transitional lava flows spanning the last 12 million years. Using various assumptions as well as paleointensity determinations on 104 samples, *Wilson et al.* [1972] showed that there was a systematic relationship between a quantity which they called the "pseudo-VDM" and the colatitude of the VGP. The relationship between remanent intensity and VGP was confirmed by *Kristjansson and McDougall* (1982) using a database of 2,462 lava flows. Both sets of authors inferred that

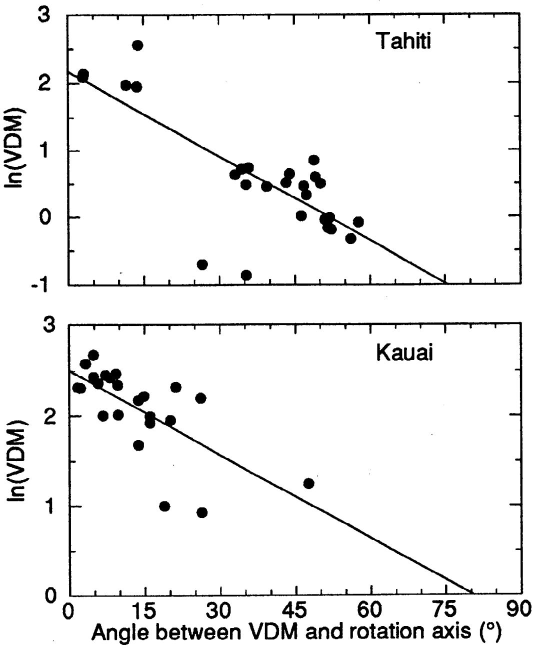

Figure 3. Data from Tahiti and Kauai. Same axes as in Figure 2.

a connection between field intensity and direction had persisted for many millions of years.

In studies that deal only with the directional changes associated with polarity transitions and geomagnetic excursions, VGPs at latitudes greater than 60° are not usually considered transitional. Our work and that of *Mary and Courtillot* [1993] show that VGPs can linger at high latitudes even when the intensity of the field has been reduced by 50%. This implies that the concept of *transitional direction* should be redefined in terms of both direction and intensity, as noted previously [*Prévot et al.*, 1985; *Mary and Courtillot*, 1993].

In our analysis, we have taken θ as the angle between the dipole axis of the VDM and the Earth's rotation axis. In lieu of the rotation axis, we could use the axis that maximizes the value of the correlation coefficient. We call this axis the best-fit dipole axis. The orientations of this axis for the five transitional records are given in Table 1. In four of the five cases, the axis is about 10-15° away from the Earth's rotation axis. We are not sure what, if any, significance to attach to the best-fit dipole axis. Because the present geomagnetic pole is about 12° away from the rotation axis, it is possible that the best-fit dipole axis represents the position of the geomagnetic pole prior to the onset of the transition. This conclusion, however, requires additional examination.

It is not easy to provide a theoretical explanation for the relationship that we have found. One reason for this difficulty is that in computing the VDM, we are using a dipole model to describe a field that may have significant non-dipole components. The same problem arises when the VGP is used to determine if there are preferred longitudinal bands for transitional VGPs, but this has not prevented the discussion from being lively and fruitful. Some participants in the debate about VGP paths [e.g. *Laj et al.*, 1991; *Constable*, 1992] believe that the preferred longitudinal bands are caused by a standing equatorial dipole which becomes evident only when the main (axial) dipole disappears. This view has been challenged by *Prévot and Camp* [1993] and *Quidelleur and Valet* [1993], but the issue has not yet been fully resolved. If the standing equatorial dipole does exist, our work provides information about the way in which the decline of the main dipole leads to the emergence of the equatorial dipole.

An alternate view, not dependent on the existence of preferred longitudinal bands, is that during transitions and excursions, the non-dipole components become much more important relative to the dipole component [*Courtillot et al.*, 1992]. At any given site, this results in large deviations of the net directional field (VGP) from the axial dipole configuration and in reduced values of the net field intensity (VDM). In this context, we have found that, not surprisingly, these two parameters are related and that the relationship is an exponential or some similar function.

Any model based on dipole and non-dipole components must ultimately be converted into the more realistic realm of flux distributions at the core/mantle boundary and convection cells in the core itself. If our result stands up to further scrutiny, based on the analysis of records of other transitions and excursions, then it provides a strong constraint for any model of geomagnetic field behavior.

Conclusions

Our most important result is the indication of a quantitative relationship between paleointensity and the corresponding paleodirections during polarity transitions and geomagnetic excursions. Although more work is needed before we can fully understand the meaning of this relationship, it is clear that any new physical models for geomagnetic field behavior during transitions and excursions must address the question of how changes in direction are linked to changes in intensity. It is also important that paleomagnetic studies of transitions and excursions provide paleointensity data against which these models can be tested. Because most of the available paleomagnetic records come from sedimentary sequences, it is also imperative to obtain high-quality relative paleointensity data from sedimentary transition records.

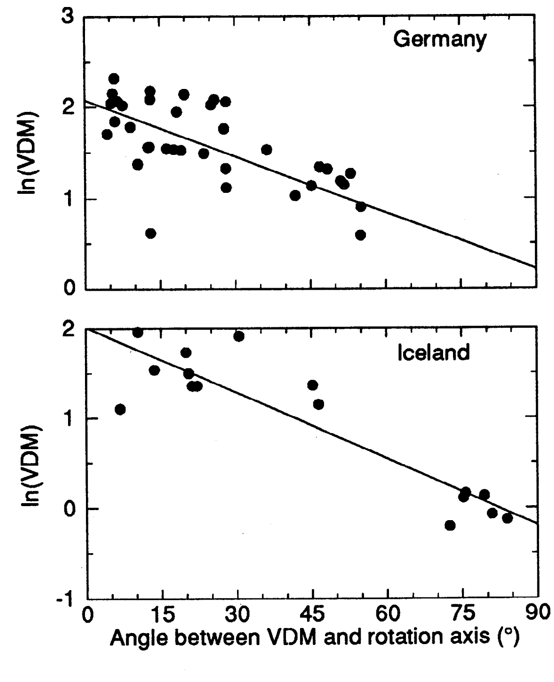

Figure 4. Data from Germany and Iceland. Same axes as in Figure 2.

Table 1. Correlation coefficients and coordinates of best-fit axes

Location (Age)	Best-fit axis	r_p	r_b	ϕ
Steens Mtn (15.5 Ma)	80°S, 187°	-0.762	-0.794	32°
Kauai (3.8 - 5.1 Ma)	82°S, 42°	-0.687	-0.721	22°
Tahiti (0.6-1.2 Ma)	74°N, 235°	-0.772	-0.836	16°
W. Eiffel (0.1-0.6 Ma)	89°S, 175°	-0.688	-0.688	34°
Iceland (12 - 30 ka)	72°N, 133°	-0.908	-0.946	28°

r_p is the correlation coefficient of ln(M) and θ relative to the Earth's rotation axis; r_b is the correlation coefficient relative to the best-fit axis; ϕ is the half-moment angle defined in the text.

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