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Electromagnetic core-mantle coupling and paleomagnetic reversal paths

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Abstract. Calculations of electromagnetic torques between the fluid outer core and the heterogeneous lower mantle demonstrate that the geomagnetic field can lock with the mantle during polarity transitions. We show that the Virtual Geomagnetic Pole (VGP) is attracted toward mantle regions with low electrical conductivity and repelled from mantle regions with high conductivity. Using seismically-determined structure of the lower mantle to infer the pattern of conductivity variations at the base of the mantle, we find two preferred reversal routes for the VGP, one beneath the Americas and another beneath Asia. These paths, particularly the one beneath the Americas, lie close to the VGP paths seen in some sedimentary and lava records of polarity reversals, suggesting that the core and mantle are electromagnetically coupled during reversals.

Introduction

Reversals in polarity of the Earth's magnetic field are produced by complex magnetohydrodynamic interactions within the fluid outer core, as calculations of reversing dynamos have recently shown (Glatzmaier and Roberts, 1995). Although the cause of polarity reversals lies within the core, it is likely that the structure of the solid mantle exerts some influence on the reversal process. Evidence for mantle control of the geodynamo on long timescales is the modulation of reversal frequency and the occurrence of polarity superchrons, which are thought to be a consequence of changes in heat loss from the core in response to changes in the vigor of mantle convection (Larson and Olson, 1991).

On shorter timescales, the nature of individual polarity transitions also provides evidence of a mantle influence. Records obtained from deep sea sediments exhibit VGP (virtual geomagnetic pole) rotation through 180° of latitude during polarity change, along paths that are confined in longitude (Clement, 1991; Tric et al., 1991; Laj et al., 1991). The best-delineated path is beneath the Americas; there is another path beneath Asia that is not so clearly defined. Laj et al. [1991] pointed out that the preferred reversal paths coincide with the regions of anomalously high seismic velocity in the lower mantle (see Figure 1), suggesting a connection with the three-dimensional structure of the lower mantle.

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The significance of preferred reversal paths remains controversial. Gubbins and Coe [1993] argue that the VGP should follow one of two equally-probable, antipodal paths. The VGP does not appear to behave in this way, as the Asian path is less well defined than the Americas path. Even more troublesome, the VGPs obtained from volcanic rocks are often inconsistent with the VGPs obtained from deep sea sediments. Some compilations of transitional VGPs from volcanic rocks exhibit no tendency for longitudinal confinement (Prevot and Camps, 1993; Valet et al., 1992; Courtillot and Valet, 1995), while others indicate that transitional VGPs tend to cluster at certain locations close to the paths defined by the sediment data (Hofmann, 1992; Glen et al., 1994; Clement et al., 1995).

Despite the equivocal nature of the paleomagnetic evidence, there are strong physical arguments supporting mantle control of the geomagnetic pole path. Gubbins

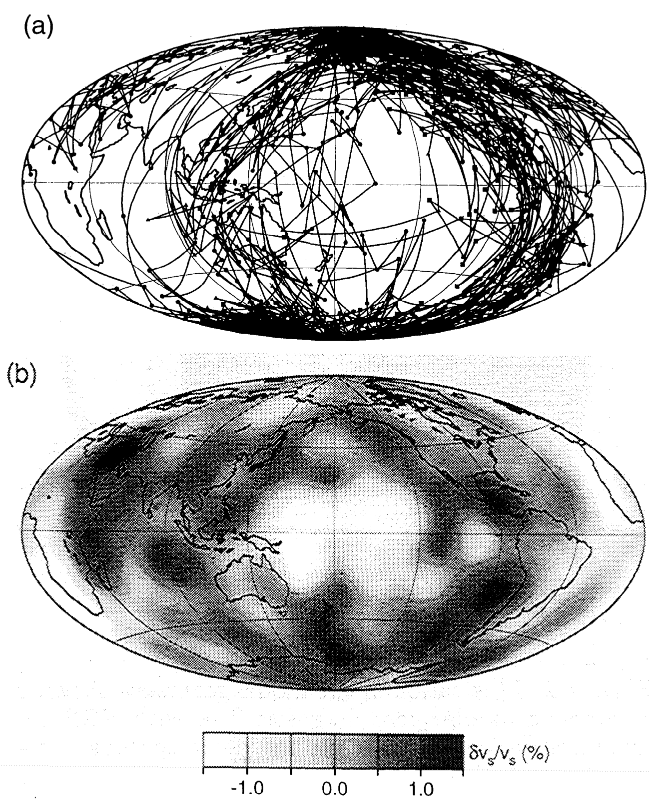

Figure 1. a: Distribution of virtual geomagnetic pole paths during polarity reversals, recorded in sediments from the past 12 Ma, compiled by Laj et al. [1991]; b: Pattern of lower mantle heterogeneity at 2850 km depth from the seismic shear wave velocity model of Su et al. [1994] complete to spherical harmonic degree 12.

and Sarson [1994] have shown that preferred VGP paths can be produced by persistent asymmetry in the geodynamo, as might result from thermal coupling between the core and the mantle through laterally heterogeneous heat flow at the core-mantle boundary. Runcorn [1992] proposed a much simpler mechanism, based on electromagnetic coupling. Runcorn suggested that electromagnetic torques rotate the core into preferred positions relative to the heterogeneous lower mantle during magnetic polarity reversals. The electromagnetic torques envisioned by Runcorn, due to currents in the mantle induced by temporal changes in the transition field, are far too small to be dynamically significant. However, we demonstrate here that there are additional electromagnetic torques due to mantle heterogeneity that were overlooked by Runcorn, which are far larger and which yield pole paths that lie close to the observed ones.

Electromagnetic Torques from a Reversing Dipole

Figure 2 illustrates the essential parts of the model. For simplicity we assume the transition field is dipolar, with its instantaneous orientation determined by VGP coordinates (θ_1, ϕ_1). This assumption is made in order to illustrate the principle; the mechanism works equally well for quadrupolar or octupolar transition fields. We ignore the effects of (unknown) core toroidal fields. In addition we assume that the electrical conductivity in the D″ region is much higher than the rest of the mantle, and because of thickness variations, the total conductance of D″ is laterally variable, as shown schematically in Figure 2.

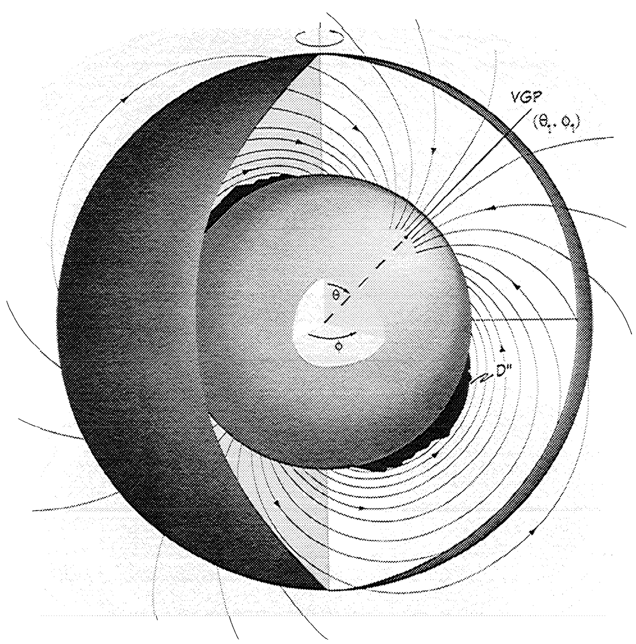

Figure 2. Illustration of the model geometry, showing a reversing dipolar core magnetic field with VGP coordinates (θ_1, ϕ_1) permeating the heterogeneous, electrically conducting D″ layer at the base of the mantle. Electric currents maintaining the dipole field leak from the core into the D″ layer. Electromagnetic torques derived from the interaction of the D″ electric currents with the magnetic field rotate the VGP and the core with respect to the mantle during the magnetic field reversal.

Under these conditions, the electric currents supporting the dipolar field leak from the core into the D″ region. Interaction between these leakage currents and the dipole field results in electromagnetic torques on the mantle and equal, opposing torques on the core. The component of torque acting on the mantle in the direction parallel to the rotation axis is known to be (Rochester, 1962; Love and Bloxham, 1994)

$$\Gamma = -\int J_\theta B_r r sin\theta dV \quad (1)$$

where J_θ and B_r are the co-latitude component of the leakage current and the radial component of the magnetic field, respectively, and the integration extends over the volume of the D″ region. The effect of this couple is to rotate the core (and the magnetic field) with respect to the mantle during the reversal. Corotation of the core and the magnetic field is implicit in the frozen flux approximation, and a similar calculation has shown that the same effect also results when, in place of the frozen flux approximation, the core flow is assumed to be geostrophic. Depending on the pattern of thickness variations in D″, there may exist special VGP positions at which the torque is zero and to which the pole is attracted. Furthermore, if there exists continuous curves defined by the locus of these points connecting the north and south geographic poles, such curves represent preferred reversal paths for the VGP.

For purposes of calculation we represent the D″ region as a thin conducting layer with variable thickness $\delta D(\theta, \phi)$ and we use only the fundamental mode of an inclined dipole field to represent the magnetic field and its associated electric current density within the core. Then the component of torque along the mantle rotation axis (1) reduces to

$$\Gamma(\theta_1, \phi_1) = -\frac{\pi^2}{4\mu_0}\frac{\sigma_m}{\sigma_c}\int \delta D(\theta, \phi) B_r \frac{\partial B_r}{\partial \phi} dS \quad (2)$$

where σ_m and σ_c are the electrical conductivity of the D″ region and the core, respectively, B_r is the radial magnetic field on the core-mantle boundary, μ_0 is permeability, and the integration is over the core-mantle boundary surface.

Pole Paths from Mantle Seismic Structure

In order to find preferred pole paths using (2), we need an estimate of the conductivity in D″ plus a global model of its lateral thickness variations $\delta D(\theta, \phi)$. Although the structure of D″ appears quite complex (Nataf and Houard, 1993; Loper and Lay, 1995), there is evidence for a chemically distinct, laterally heterogeneous layer just above the core-mantle boundary that could be a good electrical conductor. Garnero and Helmberger [1996] have identified a mantle-side boundary layer characterized by up to 10% reduction in seismic P-velocity and thickness up to 40 km beneath the Pacific. This layer is detected beneath the central Pacific low velocity structure in the lower mantle imaged by seismic tomography shown in Figure 1b. In addition, it appears to be missing from beneath the circum-Pacific high velocity structure in the lower mantle (Garnero and Helmberger, 1996).

Based on this association, we use the pattern of shear wave velocity variations in the lower mantle obtained from seismic tomography as a global indicator of $\delta D(\theta, \phi)$. We set

$$\delta D = -K \frac{\delta v}{v} \tag{3}$$

where $\delta v / v$ is a tomographic model of shear wave velocity heterogeneity in the lower mantle and K is a scale factor adjusted to give $\delta D = 40$ km beneath the central Pacific, as determined by Garnero and Helmberger [1996].

Figure 3 shows the variation of torque Γ as a function of VGP position computed from (2) and (3), using the mantle S-wave velocity model of Su et al. [1994] evaluated at 2850 km depth. There are four zero-torque curves in Figure 3, but only two represent preferred pole paths. The two curves labeled U in Figure 3 are the locus of dynamically unstable points for the VGP. The electromagnetic torque tends to repel the dipole (and the core) away from these curves. Both unstable, zero-torque curves pass through the regions with slow seismic velocity in the mantle, which we have modeled as the thickest regions of the conducting D″ layer. The two zero-torque curves labeled S in Figure 3 represent stable paths for the VGP. The electromagnetic torque tends to attract the VGP toward these curves. Both of the stable paths pass through regions with fast seismic velocity in the mantle, which correspond to regions where D″ is thin in our calculation. The trajectories of the stable VGP paths are particularly sensitive to the lower mantle seismic velocity structure at spherical harmonic degree 2 and orders 1 and 2. There are two preferred paths because the spectrum of lower mantle heterogeneity peaks at spherical harmonic degree 2. The paths have antipodal symmetry because of the dipolar field assumption and they nearly coincide with lines of longitude because of the predominance of mantle heterogeneity at spherical harmonic degree and order 2.

Comparison of Figures 1 and 3 shows that the preferred reversal paths calculated from the Su et al. [1994] mantle tomography model are close to the bands of VGP data assembled by Laj et al. [1991]. The calculated path beneath the Americas lies within the data band in the northern hemisphere and is displaced by about 20° in longitude from the center of the data band in the southern hemisphere. The calculated path beneath Asia lies midway between the two clusters of VGPs in that hemisphere. Note that the integral in (2) used to calculate the pole paths contains no adjustable parameters, other than the seismic velocity model. While the fits between the calculated and observed pole paths are not exact, their proximity offers strong support for the concept that electromagnetic torques affect polarity reversals paths.

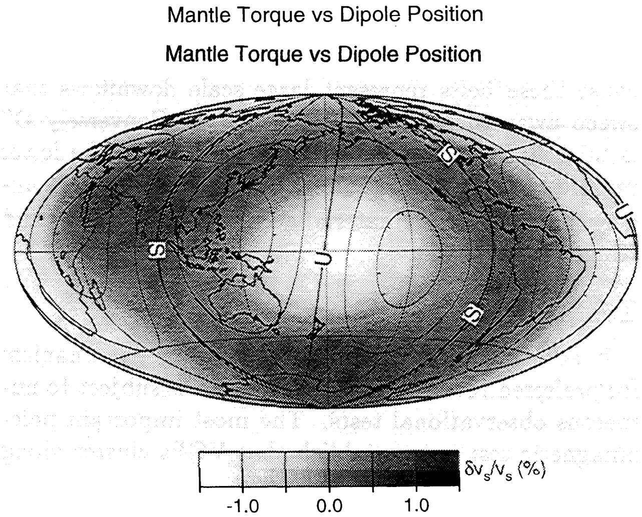

Figure 3. Electromagnetic torque exerted on the mantle as a function of VGP position, computed using lower mantle seismic structure to model electrical conductivity in the D″ layer. Variations in the component of torque about the rotation axis are shown in line contours; the shaded contours show the Su et al. [1994] seismic structure of the lower mantle at 2850 km depth truncated at spherical harmonic degree 4. The two zero-torque contours labeled U define the locus of dynamically unstable pole positions; the two zero-torque contours labeled S define the locus of dynamically stable pole positions and represent the preferred paths for the VGP during reversals. Note the close correspondence between the two computed reversal paths and the observed VGP bands in Figure 1.

The probability that the VGP will follow either of the two paths depends on the magnitude of the torque variations over the core-mantle boundary. In order to rotate the core into alignment with the mantle along one of these curves during a typical reversal lasting a few thousand years, torque variations of order $\pm 10^{17}$ N-m are required. This is about one order of magnitude less than the torques required to explain the decade-scale length-of-day variations (Jault et al., 1988; Jackson et al., 1993). According to (2), the torque variations are proportional to σ_m / σ_c, the ratio of D″ layer and core conductivities, the amplitude of D″ thickness undulations, and the radial magnetic field on the core-mantle boundary during the polarity change. Using the present-day field strength, torques of the required magnitude occur provided $\sigma_m / \sigma_c \simeq 0.01$. If during polarity reversal the magnetic field remains dipolar, as assumed, but drops to $\sim$ 10% of the present day intensity, the electrical conductivity in D″ must be comparable to the core conductivity to achieve the necessary torque.

Connection with Mantle Convection

Our model offers the following explanation for why the geomagnetic pole reverses along paths that correlate with lower mantle seismic structure. The VGP is electromagnetically attracted to regions where the conducting D″ layer is thin and repelled from regions where it is thick. Thin regions of D″ lie beneath the belts of high seismic velocity in the lower mantle because these belts represent large scale downflows that sweep away the dense material in D″. Conversely D″ is thick beneath regions with low velocity in the lower mantle because these represent large scale upflows under which the dense material accumulates (Kellogg and King, 1993).

Tests of the Model

In addition to providing a straightforward mechanism for preferred reversal paths, this model is subject to numerous observational tests. The most important paleomagnetic test is to establish that VGPs cluster along zero-torque paths *when the transition field is dipolar.* The fit of the calculated and observed pole paths to the mantle seismic tomography presumes a negative correlation between D″ thickness variations and lower mantle seismic velocity variations, on a global scale. The basal layer detected by Garnero and Helmberger [1996] has this property in the few regions on the core-mantle boundary that have been studied, but it is unknown if this relationship holds elsewhere. Finally, the D″ layer must be highly conducting, in order for the electromagnetic torques to be strong enough to lock the core into preferred positions relative to the mantle as the field reverses. The decade-scale length-of-day fluctuations have long been used to argue for electromagnetic coupling and high conductivity in D″ (Stewart, et al., 1995). The 10% reduction in P-wave velocity in D″ reported by Garnero and Helmberger [1996] could be produced by substantial ($\simeq$ 20%) metallic iron infiltrated from the core. Calculations by Jeanloz [1993] indicate this is more than enough iron to provide the high electrical conductivity required for strong electromagnetic coupling.

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