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Preferred VGP paths during geomagnetic polarity reversals: Symmetry considerations

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Abstract. The reversing geomagnetic field has been said to have virtual geomagnetic poles (VGPs) confined to a pair of longitudes close to where magnetic flux is concentrated at the core surface today, at approximately 90°W and 110°E. This can be explained if flux remains concentrated on the same longitudes throughout the transition. The VGP path then depends on site position, reversal sense (R→N or N→R), and sense of flux migration (pole- or equator-ward). For transitional fields which remain antisymmetric about the equator, N→R transitions with poleward flux migration give western longitude VGP paths for sites in the NE and SW quadrants and eastern longitude VGP paths for sites in the NW and SE quadrants. Sites on quadrant boundaries record rapid, variable VGP positions. Data from the last (Matuyama-Brunhes) reversal are broadly consistent with poleward flux migration.

1. Introduction

Among the most exciting geophysical measurements currently being made is the detailed recording of the Earth's magnetic field in transition between polarities. Records are now available from both sediments and lavas; the former providing good temporal recording but rather poor magnetic recording and the latter better magnetic recording with only sparse temporal sampling. Transition directions at each site are usually converted to a virtual geomagnetic pole (VGP), and some authors have claimed that VGPs from sediments are confined to one of two longitudes around the Pacific rim (e.g. *Clement* [1991], *Laj et al.* [1991]), while others find similar persistent VGP directions and paths from lavas [*Hoffman*, 1991; *Love*, 1998]. The claim is vigorously contested for both sediments (e.g. *Valet et al.* [1992]) and lavas [*Prévot and Camps*, 1993].

The apparent preferred longitudes are intriguingly close to where most of today's geomagnetic flux is concentrated on the core surface [*Bloxham and Gubbins*, 1985], to the preferred longitudes of paleomagnetic VGPs for the last 5 Myr [*Constable*, 1992], and where lower mantle seismic velocity is high [*Dziewonski and Woodhouse*, 1987]. Some analyses of the time-averaged paleomagnetic field during periods of stable polarity also concentrate flux on these longitudes [*Gubbins and Kelly*, 1993; *Johnson and Constable*, 1995], suggesting that this part of the modern field's morphology is long term. These assertions have been vigorously contested; recent reviews are given by *McElhinny et al.* [1996] and *Gubbins* [1998].

Persistent non-axisymmetric components in either stable or transition fields imply control by the solid mantle. Both transitional and non-transitional preferred VGP longitudes can both can be explained if magnetic flux on the core surface remains concentrated near the two favored longitudes, as demonstrated by *Gubbins and Sarson* [1994]. A number of plausible dynamical mechanisms have been proposed for flux concentration at fixed longitudes; we favor lateral variations in heat flux across the CMB [*Gubbins and Bloxham*, 1987].

In this paper we ask how the VGP observations relate to the whole geomagnetic field. We aim to test physical hypotheses against observations, which we believe is more meaningful than statistical analyses of VGP's.

2. Transitional field symmetries

The basic observation is of two preferred paths, not one, which for a given transition tells us immediately that the transition field is non-dipolar (otherwise only one path would be observed), and that the path is site-dependent. It follows that some sites must record erratic VGP paths or no path at all. In the *Gubbins and Sarson* [1994] model sites at the equator record zero intensity during the transition, when the VGP undergoes an instantaneous transition. This results from the assumed antisymmetry of the field about the equator (E^A). We call this boundary a *nodal line*. A similar boundary in the model exists near meridians ±90° from the flux concentrations, a result of 180° rotational symmetry about the polar axis (P_2). Here, the intensity does not actually vanish but there is a band of low intensity. On either side of this band the VGP falls along different longitudes.

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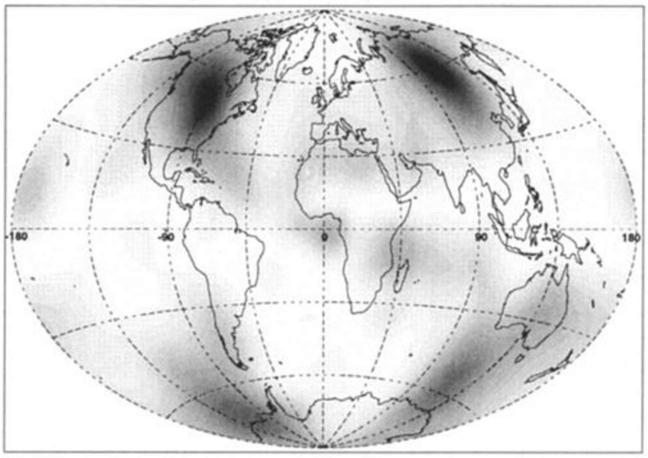

Figure 1. The square of the radial component of magnetic field (B_r^2) at the core surface averaged over time from 1690 to 1990 using the time dependent models of *Bloxham and Jackson* [1992]. Note the main concentrations of flux near longitudes 110°E and W, latitudes about 60°N and S. Contour interval 0.02 $(\mathrm{mT})^2$, Aitoff projection.

The behavior of the Gubbins & Sarson dynamo may be summarized in a simple way which shows it to be typical of any pole- or equator-ward oscillation that keeps flux concentrated on two longitudes. Zero and low intensity lines are where contributions from the four main flux concentrations cancel. The VGP is drawn towards the nearest flux concentration, onto one of the dominant longitudes. As flux migrates towards the pole the VGP remains close to one of the two longitudes, with the VGP path depending on site quadrant and sense of flux migration.

$E^A P_2$ symmetry is certainly a possible solution of the full dynamical equations [*Gubbins and Zhang*, 1993], but is it representative of the actual geomagnetic field? We do not know the details of the transition field because the data are so few, but the modern field shows a high degree of equatorial antisymmetry in the non-dipole field. Furthermore, most of the flux on the CMB is concentrated near longitudes ±90°, approximating the P_2 symmetry. Figure 1 shows the square of the radial component averaged over the 300-year historical record 1690–1990.

To estimate the preferred longitudes more precisely we average the square of the radial component over latitude to produce the function of longitude shown in Figure 2. The four curves are for the 1980 field model of *Gubbins and Bloxham* [1985], the historical averages AD1690-1840, AD1840-1990 [*Bloxham and Jackson*, 1992], and the 5 Myr-paleomagnetic time average of *Kelly and Gubbins* [1997]. Flux is slightly more confined for the historical averages than for the 1980 model, the opposite of what one would expect if secular variation caused these parts of the field to drift in longitude. The peaks are broader for the paleomagnetic time average, possibly because of the poorer quality of the dataset.

An important symmetry of the equations of magnetohydrodynamics is invariance under sign reversal of the magnetic field. Provided the reversal is complete, for a given site R→N and N→R transitions give VGP positions differing by 180° [*Gubbins and Coe*, 1993]. This does not hold for incomplete reversals, where some memory remains of the previous polarity state (during an excursion, for example, the flux may migrate one way then return along the same path). If P_2 symmetry holds then a pair of preferred longitudes 180° apart can result from data from different sites even for reversals of one polarity sense. We take the preferred VGP longitudes for the Earth to be ±90°, and fix the longitude in the dynamo model to bring the flux onto these longitudes.

For transitions of the type we describe, with $E^A P_2$ symmetry and flux concentration on two longitudes, path selection is determined by (1) sense of polarity (R→N or N→R), (2) direction of flux migration, and (3) site quadrant. For a N→R transition, poleward flux migration gives western VGP paths for sites in the NE and SW quadrants and eastern paths for the NW and SE quadrants.

3. Application to Matuyama-Brunhes

We are now ready to test the hypothesis against data. Real geomagnetic transitions are very unlikely to remain as simple and symmetrical as dynamo models: nodal lines will at best be diffuse bands, and different reversals are likely to give different transition fields; excursions may also be different. We therefore concentrate on a single full reversal. The Matuyama-Brunhes (M-B) is recorded best by the paleomagnetic data.

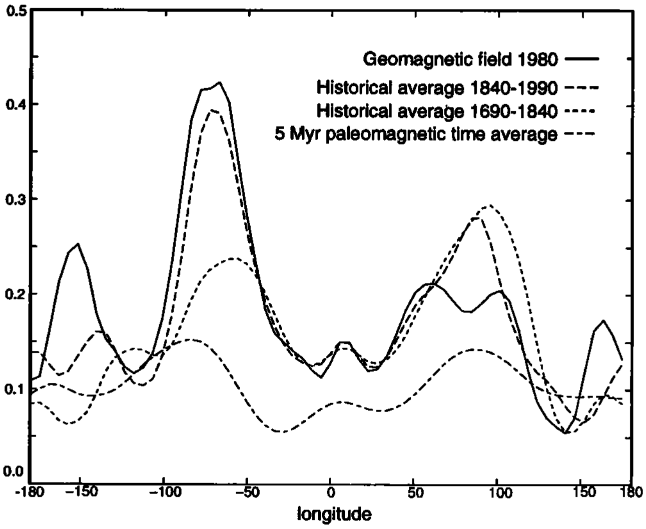

Figure 2. B_r^2 averaged in latitude for a 1980 main field [*Gubbins and Bloxham*, 1985] (full line), time-average 1840–1980 (long dashed), 1840–1990 (short dashed) and the paleomagnetic time-average of *Kelly and Gubbins* [1997] (dot-dash). Note the peaks near longitudes ±90°.

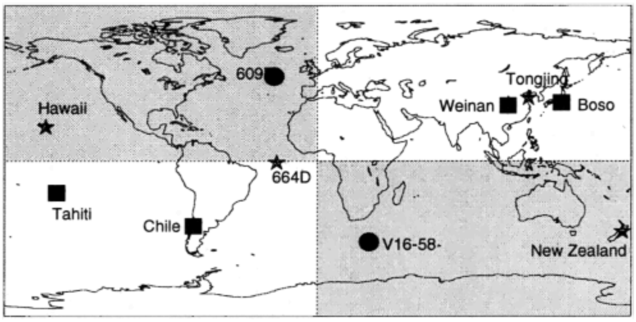

Figure 3. Sites recording the M-B transition field reliably. Squares give eastern VGP paths, circles western, and stars a null result. Quadrants are for a transition field with symmetry about the equator and Greenwich meridian, approximately the case for the stable field.

Love and Mazaud [1997] give 11 sites with good recordings of the transition field for M-B. The VGP paths (see Figure 4 of *Love and Mazaud* [1997]) were assigned east, west, or null. The sites are plotted in Figure 3 together with nodal lines appropriate for flux concentration near ±90°. The procedure is similar to doing a fault plane solution in seismology. The NW and SE quadrants have western paths and the NE and SW quadrants eastern paths. The null sites at New Zealand and the core 664D in the Atlantic lie close to nodal lines. Tongjing in China and Hawaii are exceptions, but they have only a single "intermediate" VGP each.

Adding 180° to the longitude of VGP paths from sites in the NW and SE quadrants and omitting nodal sites gives just one dominant longitude (Figure 4). M-B was an R→N transition and sites in the NW quadrant record western VGP paths. The flux must migrate polewards to be consistent with a transition field with $E^A P_2$ symmetry.

4. Discussion

We believe that the apparent preference for transitional VGPs to fall along longitudes where magnetic flux is concentrated during stable periods deserves further investigation. Previous studies of VGP preferred longitudes have ignored the underlying physical processes. Statistical tests have, thus far, only been used to examine simple hypotheses, such as randomness of the mean VGP longitude. Such hypotheses are, in some respects, too restrictive (they ignore the possibility of nodal sites) while in others they are not restrictive enough (they do not consider, for example, systematic path selection for sites in the same quadrant or from single sites). We contend that it is better to use the transitional data to explore (and perhaps eliminate) physical models rather than perform purely statistical tests, because inappropriate combinations of datasets will often appear random.

We have deliberately chosen to test a very specific model. It would be astonishing if the Earth were really as simple and symmetric as this model, and with improved data it will probably be necessary to modify or reject it. There are four underlying assumptions, which we now list and discuss critically:

1. *R-N symmetry.* This is a basic property of the equations of magnetohydrodynamics, but the field may carry some memory of an earlier polarity, in which case the transition can be considered incomplete. A core overturn time of 1,000 years suggests that a reversal would be complete in a few tens of thousands of years. Thus, excursions may not obey this symmetry, but M-B should.

2. E^A *symmetry* is seen in the stable field, mainly in the dominant equatorial dipole, and is naturally selected as the most unstable mode in most dynamo calculations. However, reversals may well be associated with disturbances of the opposite symmetry [*Constable*, 1992; *Gubbins*, 1987].

3. P_2 *symmetry.* Lateral variations in the boundary conditions are needed to stop the field drifting and impose on it a large scale structure. The Pacific rim anomaly may concentrate flux at approximately, but not exactly, ±90°. The present flux concentrations are not quite antipodal (110°E and 90°W), which would spread the VGP paths if both R→N or N→R transitions are plotted together.

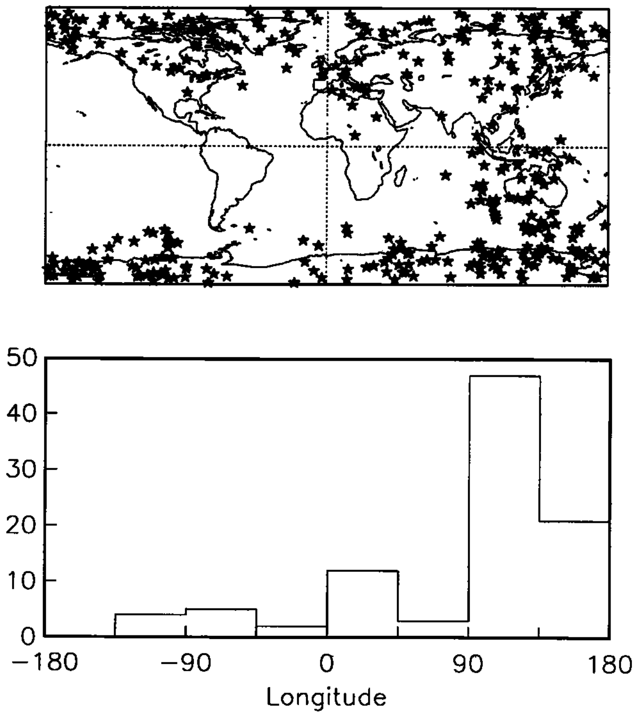

Figure 4. VGPs (with $\alpha_{95} < 30°$) of non-nodal sites, with 180° added to the longitudes of data from NW and SE geographic quadrants. Histogram gives the number of transitional VGPs (latitudes between ±55°) lying in each 45° longitude band.

4. *Sense of flux migration.* Both the dynamo model and M-B are consistent with migration of flux from equator to pole. This is probably a coincidence: the sense depends on details of the fluid flow and other dynamo wave solutions are known to travel in the opposite direction.

Like our comparison of the M-B data with a dynamo model, we wish to promote the use of paleomagnetic data to explore physical models. Such comparisons, together with the continued collection of data and the development of theory, should further our understanding of the physics of geomagnetic reversals. We do not claim to "prove" longitude confinement of VGPs, only to propose a physically meaningful hypothesis for testing.

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