Temporal aspects of the last reversal of Earth's magnetic field

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Temporal aspects of the last reversal of Earth's magnetic field

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Spatial palaeomagnetic field data associated with the Matuyama–Brunhes reversal reveal a global pattern of virtual geomagnetic poles (VGPs) so distinct that inferences about the temporal nature, and, possibly, the energetics of the dynamo process, can be drawn. Specifically, what is observed are two pairs of low- and mid-latitude VGP concentrations mirrored about the Equator. Yet, while the path of the virtual pole associated with any given site must pass through the Equator at least once during the polarity transition, remarkably few data record the actual crossing. We propose that early in the reversal process a transitional state was reached within the dynamo and held for a considerable time; only much later was it possible for field changes to take place whereby VGPs crossed the Equator into the Northern Hemisphere. Thus, a barrier to reversal may exist, related, perhaps, to the state of magnetic flux emerging from the solid inner core. Regardless, these palaeomagnetic data suggest that when this apparent barrier was successfully surmounted, field directions at sites about the globe rotated quickly in such a manner that the associated VGPs transited the Equator at minimum rates of speed approaching 1 deg yr^{-1}. The contention that the Matuyama–Brunhes reversal was dominated by quasi-stationary transitional field states of low harmonic order is supported by the data; however, the stage of rapid VGP movement needs to be associated with a predominantly driving dynamo process.

Keywords: Matuyama–Brunhes reversal; geomagnetic field polarity; transition

1. Introduction

Accompanying the first palaeomagnetic investigations that found volcanic rocks to possess a direction of remanent magnetization opposing the ambient field (David 1904; Brunhes 1906) was the newly posed question of geomagnetic field reversal. Yet it took more than half a century before there appeared in the literature an account of directional palaeofield behaviour experienced at a site *during* an actual polarity transition (Van Zijl *et al*. 1962). Soon thereafter it became clear that any attempt to describe global properties of the transitioning field and the associated dynamo process from an individual recording was wrought with uncertainties.

Indeed, although palaeomagnetic records of transitional field behaviour may singularly offer clues about the spatial and time-dependent character of a reversal, each contains at best a partial account of field changes experienced at but one site on Earth's surface. Spatial aspects of the reversing field have largely been the focus

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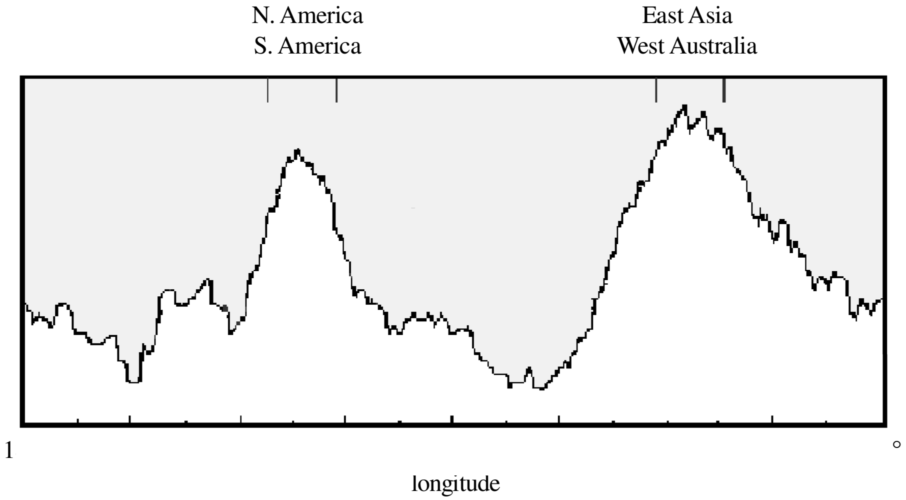

Figure 1. Longitudinal distribution of Matuyama–Brunhes transitional VGPs (after Clement (1991)).

of these investigations, and, over the past few decades, transitional field modelling has steadily evolved from non-dynamical phenomenology and statistical representations (e.g. Cox 1969; Hoffman 1977, 1979; Fuller *et al.* 1979) to models that incorporate observed aspects of the modern day field (e.g. Gubbins 1987, 1994; Merrill & McFadden 1988; Constable 1990; Gubbins & Coe 1993), and, most recently, to three-dimensional computer simulations of the geodynamo that display spontaneous reversal (e.g. Glatzmaier & Roberts 1995). Furthermore, the observation of apparent preferential spatial field behaviour (Clement 1991; Laj *et al.* 1991; Hoffman 1992) has focused attention on the possible role of the lowermost mantle during geomagnetic reversal.

Notwithstanding the progress made toward understanding the reversing dynamo, apart from a handful of studies concerning particular recordings (e.g. Coe & Prévot 1989; Coe *et al.* 1995), the temporal nature of the process within a polarity transition has received little attention. Indeed, sophisticated modelling in large part lacks this very important input from observation. For this reason, we now explore time-dependent aspects of the global transitional field, turning not to a single record for direct analysis, but rather to a palaeomagnetic directional database of a particular reversal for indirect analysis.

2. The Matuyama–Brunhes reversal

Specifically, we investigated the palaeomagnetic account of the Matuyama–Brunhes reversal, the polarity transition for which the greatest number of available records exist and which has undergone numerous analyses (e.g. Hillhouse & Cox 1976; Hoffman 1981; Clement 1991; Valet *et al.* 1992; Gubbins & Love 1998). Of particular note is the work of Clement (1991), who analysed all published records of the Matuyama–Brunhes reversal and found a bimodal distribution of VGPs when plotted against longitude (figure 1); this finding helped stimulate the contention that the lower mantle controls the pattern of magnetic flux emerging from the core during field reversal.

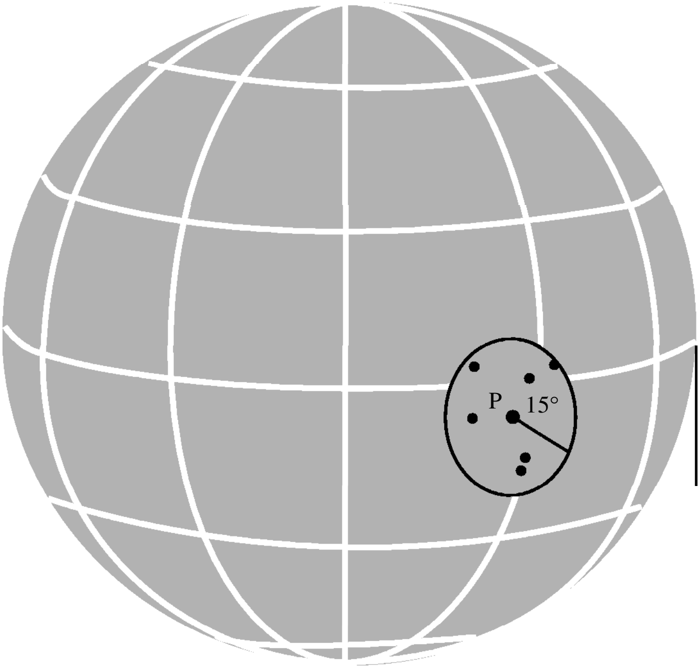

Figure 2. Schematic showing the procedure used for the development of a VGP density plot for the MBD97 Matuyama–Brunhes reversal database: the virtual poles found within a 15° radius about each point between 55° S and 55° N are simply counted.

Here we analyse the recently published MBD97 Matuyama–Brunhes database of Love & Mazaud (1997) since its development involved, for the first time, the application of strict reliability criteria to each published palaeomagnetic record spanning the transition. Of some 62 records found in the literature to span the Matuyama–Brunhes boundary, only 11 satisfied this scrutiny and were admitted to the MBD97 database (Love & Mazaud 1997). Within the database are records derived from deep-sea and exposed sediments, loess deposits, and lavas from sites scattered about the globe. We explore the MBD97 database as it was published, without modification in the interest of objectivity.

3. Our analysis of the MBD97 database

We have determined the density distribution of MBD97 transitional VGPs about the globe within the latitude band between 55° S and 55° N by way of a procedure in which all virtual poles within a 15° radius encircling a given point are simply counted (see figure 2). The resulting global density, which incorporates the 311 VGPs contained within the database lying between latitudes 70° S and 70° N, is shown in figure 3. Two general observations can immediately be drawn from these results. First, the VGP distribution shows considerable structure. Indeed, there exist two distinct sets of grouped VGPs remarkably mirrored about the Equator: a dominant pair near Western Australia and within Siberia, and a less significant pair in the southwestern Atlantic near the Falkland Islands and Northeastern Canada. Since

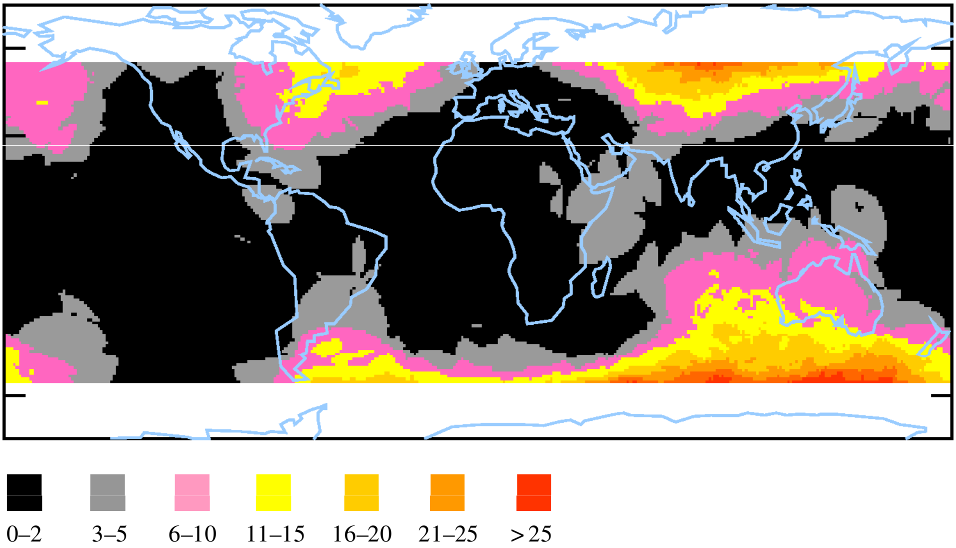

Figure 3. VGP density plot for the Matuyama–Brunhes reversal determined from the MBD97 database.

the recording sites represented in the MBD97 database span the globe (see Love & Mazaud 1997), this rather simple structure may signify the dominance of lasting transitional field configurations with low-order symmetry, as claimed by Hoffman (1992, 1996).

This suggestion of quasi-stationary transitional field states during the Matuyama–Brunhes reversal needs to be considered alongside the second observation, namely, that there exists a meandering band of variable latitudinal extent (shown in black) encircling the globe delineating all points surrounded by no more than two VGPs within a radius of 15°. In particular, when one isolates the latitudinal band between the Equator and 30° N, a region representing 29% of Earth's surface area for which VGPs may be considered clearly intermediate (from, say, 60° N to 60° S), one finds only 17 out of 208 intermediate VGPs in the MBD97 database, or just 8%. Figure 4 displays the latitudinal dependence of Northern Hemisphere VGPs observed through a 5° sliding window. Clearly visible in the figure is an abrupt change in the nature of the distribution, one which separates the few low-latitude VGPs from the rest of the population.

4. Spatial-temporal aspects

When attempting to evaluate the significance of this low-latitude paucity in virtual poles, it is important to recognize first that the VGP distribution contained in the MBD97 database does *not* suggest a simple diminution in VGP density with latitude toward the Equator, as might be expected from an accelerating reversal process. Indeed, the spare number of VGPs found almost uniformly within the 0–30° N latitudinal band is not equally observed within the 0–30° S band, within which there exists a high-density cluster of virtual poles in the east Indian Ocean near Australia (figure 5). As indicated in the figure, this low-latitude concentration is composed of clustered sequences of VGPs associated with five sites which span the globe. Pro-

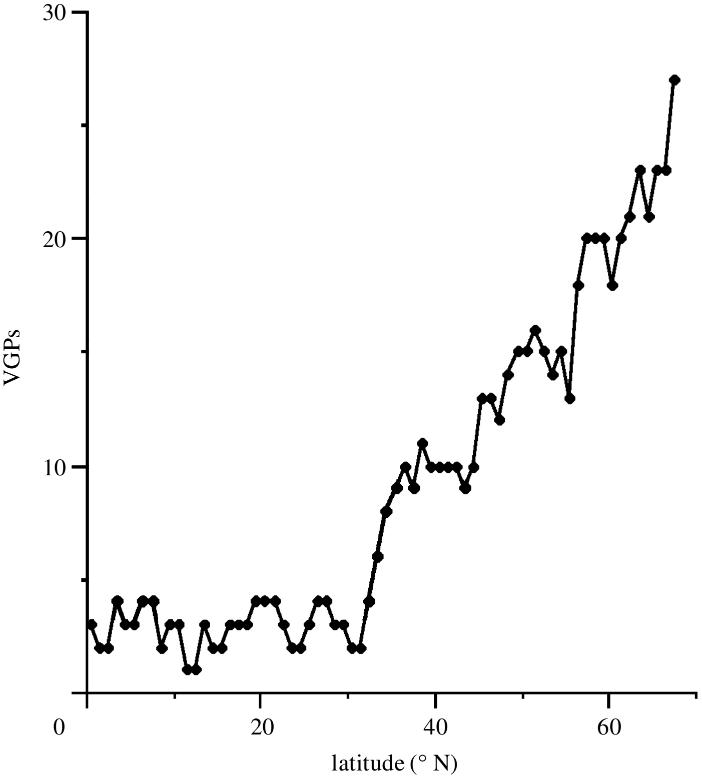

Figure 4. The number of Northern Hemisphere Matuyama–Brunhes VGPs as a function of latitude as determined through a 5° sliding window. Note the abrupt change between the low-latitude and higher-latitude distributions.

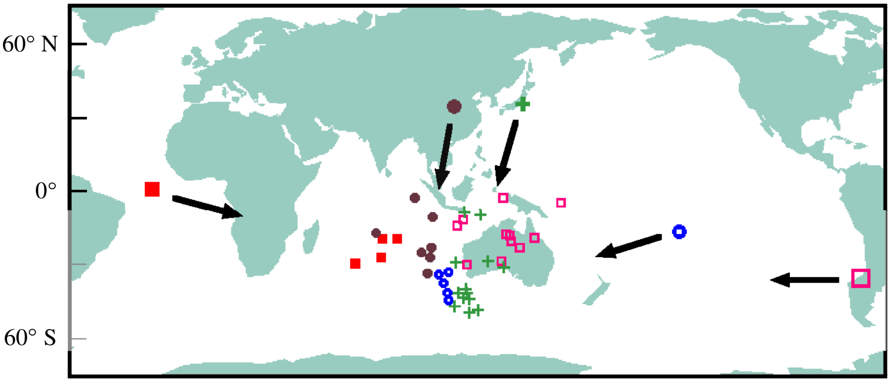

Figure 5. Five sequences of low-latitude VGPs (smaller symbols) that comprise the cluster patch near Western Australia. Data obtained from exposed sediments (crosses), deep-sea sediments (solid squares), loess deposits (solid circles), and lavas (open squares, open circles) are represented. The associated recording sites (larger symbols) are also indicated.

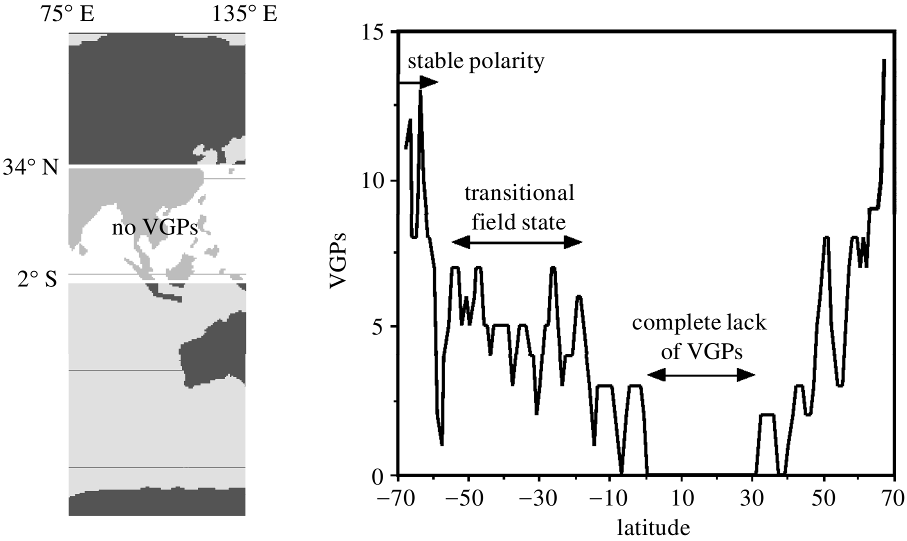

Figure 6. Map of the meridional band between 75 and 135° E which possesses nearly one-third of the MBD97 Matuyama–Brunhes VGPs between 70° S and 70° N, and the latitudinal distribution of VGPs lying within this band determined through a 5° sliding window.

vided these recordings are indeed contemporaneous, a long-lived and largely dipolar transitional field state is suggested for this stage of the reversal process.

Figure 6 shows the latitudinal dependence of the VGPs found in a 60°-wide longitudinal band (between 75 and 135° E) containing the Indian Ocean/Australian cluster observed through a 5° sliding window for all virtual poles residing between 70° S and 70° N: a sector containing nearly one-third of the MBD97 virtual poles (109 of 331) analysed in figure 3. We claim that distinct stages of the geomagnetic reversal process may be observable in figure 6: first, there exists an abrupt decrease in the number of VGPs—falling from a maximum of 13 to a minimum of 1—in the range between mid-window latitudes at 63.5° S and 57.5° S; this feature may delineate the boundary between full reverse polarity and transitional fields. The number of VGPs then recovers, averaging five in number for mid-window points spanning some 41°, poles that for the most part lie west of Australia (see figure 5). The number of VGPs is then seen to vanish continuously for the next 36° of latitude (corresponding to mid-window latitude points from 0.5° N to 31.5° N).

In contrast, the Matuyama–Brunhes VGP distribution also contains a 60°-wide longitudinal band within the east Pacific (between 210 and 270° E) uniformly dilute in virtual poles (see figure 3) through the entire latitudinal range under study (i.e. from 70° S to 70° N). Given the global distribution of recording sites represented in the MBD97 database, the sparse number of virtual poles within this sector (only 9 of 331) suggests that preferential, non-random behaviour of the VGP takes place not only during the Matuyama–Brunhes transition, but also during the time before and after the reversal when virtual poles lie in closer proximity to the geographical poles.

The Matuyama–Brunhes global VGP distribution (figure 3) possesses remarkable structure and symmetry with respect to the Equator, a pattern that is unlikely to have been produced by smoothed, or otherwise artefactual, data. How then may the distribution—especially the complete lack of VGPs observed at low latitude in the densely populated 75–135° E longitudinal band—be explained? The clearly observed preference for the transitional VGPs to reside in particular low- and mid-latitude locations (figure 3) attests to a kinetic process that is largely stop-and-go (e.g. Prévot *et al.* 1985; Hoffman 1986; Laj *et al.* 1987). Further, we propose that early in the transition process a metastable field state was produced in which VGPs grouped in the Southern Hemisphere.

This quasi-static situation, we argue, persisted until the geodynamo was able to surmount an apparent barrier to reversal that separates transitional field states associated with Southern Hemisphere and Northern Hemisphere VGPs. In this regard, Gubbins (1999) has recently proposed that magnetic flux emerging from the solid inner core is more likely than not to block a movement by the dynamo toward reversal, producing no more than a geomagnetic excursion. If so, then, perhaps magnetic flux emanating from the inner core was capable of halting the process near the start of the Matuyama–Brunhes transition, while subsequent diffusion of flux out of the inner core ultimately allowed a continuation of the reversal process and, thus, VGP transit across the Equator.

5. Rapidity of VGP movement

When transitional virtual poles cluster during a time of apparent quasi-equilibrium, field decay due to flux diffusion in the outer core is essentially balanced by field growth through frozen-in flux generation. Yet, the lack of low-latitude Northern Hemisphere VGPs (see figures 4 and 6) strongly suggests that when the virtual poles were finally able to cross the Equator they did so rapidly. Such an abrupt field change further suggests that at that time the balance between flux diffusion and frozen-in flux had broken down and that the latter process largely dominated.

Any attempt to assess limits on the speed of the VGPs through low latitudes from spatial palaeomagnetic data such as these assumes, first, an understanding of the total reversal time. Estimated durations for directional movement during the Matuyama–Brunhes reversal range broadly from 2300 (see Love & Mazaud 1997) to 12 kyr (Singer & Pringle 1996). Given the paucity of Northern Hemisphere low-latitude VGPs (figure 4), these duration values suggest that the virtual pole moved through the 0–30° N band somwhere within 184 to 960 yr. This calculation, however, assumes that the VGPs made no more than a single Equatorial crossing and that the VGP paths remained meridional (Laj *et al.* 1991; Clement 1991). Yet there is strong evidence from sites in both hemispheres that virtual pole behaviour was far more complicated during the Matuyama–Brunhes reversal.

Some five Equatorial passes by the VGP are observed in three highly detailed parallel records obtained from North Atlantic deep-sea sediment cores (Channell & Lehman 1997). We show (in figure 7) VGP behaviour representative of these data (from Hole 984C), noting that they are from continuous measurements of the core using a U-channel technique. As can be seen, this complex VGP path contains a back-and-forth Equatorial transit between Siberia and the South Atlantic and, therefore, a considerable azimuthal component to the motion. Further, the detailed Matuyama–Brunhes VGP path obtained from a sequence of Tahitian lavas, and currently under investigation by this author (see Hoffman & Soukup 1996), displays at least five back-and-forth Equatorial crossings within the 60°-wide longitudinal band shown in figure 6.

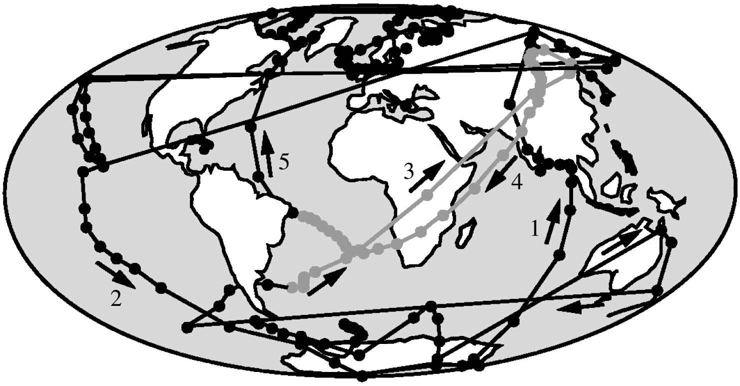

Figure 7. Matuyama–Brunhes recording obtained from high-deposition-rate North Atlantic sediments from Hole 984C. The detailed VGP path seen in this record, as well as in two other parallel records from the site, contains five equatorial crossings (indicated by number). Back-and-forth motion between clustered positions in Siberia and the South Atlantic is also a common feature of these records. (Note that unlike the records contained in the MBD97 database, these data were obtained through quasi-continuous measurement of the deep-sea core using a U-channel technique; after Channell & Lehman (1997).)

Thus, let us assume a degree of complexity for the *average* Matuyama–Brunhes VGP path compatible with these recent palaeomagnetic studies. Specifically, assume the reversing virtual poles (1) cross the Equator five times before completion of the reversal, and (2) run along oblique pathways with, say, equal amounts of azimuthal and meridional movement. Such an average VGP path through the 0–30° N latitudinal band would then possess a minimum estimated speed approaching 1 deg yr^{-1}, some seven times more rapid than the single-pass meridional path case.

6. Conclusion

Investigation of the select MBD97 database for the Matuyama–Brunhes reversal strongly supports the earlier contention that this polarity transition was dominated by quasi-stationary, long-lived transitional field states, during which time VGPs associated with sites about the globe clustered in one of four low- and mid-latitude localities. The clear paucity of low-latitude VGPs contained in the database, especially between 0 and 30° N, suggests, next, that the dynamo process of reversal can be halted early on by some form of barrier. The cause of such a barrier is unknown; however, it may be associated with the temporal state of flux emanating from the inner core. Regardless, rapid directional field changes did take place, perhaps after this apparent barrier was successfully surmounted, and only then were the VGPs able to cross the Equator.

With recently acquired Matuyama–Brunhes data indicating at least five equatorial passes by the VGP at sites in both hemispheres, the minimum rate of speed for VGP movement at low latitudes (albeit site-dependent) approaches 1 deg yr^{-1}. Although quantitatively uncertain, this clear rapidity of directional behaviour implied by the MBD97 database points to driving dynamo action during this stage of the reversal process. Thus, it may well be that only at this point, well within the polarity change, is vector field behaviour substantially restricted by limitations imposed by the process of frozen-in flux.

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