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The distinction between geomagnetic excursions and reversals

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SUMMARY

Two recent studies of the geomagnetic field in the last 1 Myr have found 14 excursions, large changes in direction lasting 5–10 kyr each, six of which are established as global phenomena by correlation between different sites. The older picture of the geomagnetic field enjoying long periods of stable polarity may not therefore be correct; instead, the field appears to suffer many dramatic changes in direction and concomitant reduction in intensity for 10–20 per cent of the time. During excursions the field may reverse in the liquid outer core, which has timescales of 500 yr or less, but not in the solid inner core, where the field must change by diffusion with a timescale of 3 kyr. This timescale is consistent with the remarkably uniform duration of well-dated excursions. The disparity of dynamical timescales between the inner and outer cores, a factor of 10, is consistent with the 10 excursions between full reversals.

Key words: geomagnetic excursions, geomagnetic reversals, inner core, outer core.

1 INTRODUCTION

The geomagnetic record shows complete reversals of polarity at a rate of 2–3 per million years, with a long-term trend in the interval thought to be due to changes in the solid mantle (Jacobs 1994). Intervals of constant polarity are punctuated by polarity excursions, events where the magnetic direction departs greatly from the usual geocentric axial dipole (GAD), sometimes achieving the reverse direction for a short time. Excursions have been discovered in both volcanic and sedimentary records, but it is exceedingly difficult to correlate events at different sites and thus establish them as global.

These observed phenomena have some empirical working definitions. Intervals of constant polarity are called chrons, subchrons, and superchrons, depending on their duration. Excursions take place within these intervals. They have been distinguished from typical secular variation in the historical record, when the field is dominated by a GAD, using the angular departure of the field direction from that of a GAD. For example, Verosub (1977) defined an excursion to be when the virtual geomagnetic pole (VGP) was more than 45° from the geographic pole. Excursions have been distinguished from a pair of reversals by their duration: if the two reversals are not included in the accepted reversal timescale, they constitute an excursion. Cande & Kent (1992) used a limit of 30 kyr in their recent reversal timescale.

Excursions also involve dramatic decreases in intensity. These are well recorded in lava sequences but less well recorded in sediments, which often fail to show any clear reduction in relative intensity at the time of major changes in direction. Intensity changes have not been used in defining an excursion.

To a first approximation, the reversal timescale suggests a random sequence of reversals, consistent with chaotic behaviour of the dynamo. The long-term trend is not random and must be explained by changes in the boundary conditions (Jacobs 1994). There are no such theoretical interpretations for the chron/subchron distinction, which may be artificial. There have been many studies of the statistics of the reversal sequence, some claiming a Poisson process and some not (Merrill & McElhinny 1983). A Poisson process implies no memory of the previous reversal history. The 'memory time' is related to the real distinction between excursions and a pair of reversals, and would be important input to the theory of the geodynamo.

Two recent papers have reported detailed records of recent excursions in the Brunhes. Langereis *et al.* (1997) identified six well-dated, global excursions using an astronomical calibration of sapropel signals to improve the dating significantly. They listed a further five local excursions that are not well correlated globally (Fig. 1). Lund *et al.* (1998) , in a preliminary report on results from ODP leg 172 in the western North Atlantic, found 14 excursions within the Brunhes recorded in sediment drifts with very high rates of accumulation (10–40 cm kyr^{-1}) and therefore a potentially very high resolution of magnetic recording (Fig. 1). Each excursion lasts 2–10 kyr.

The new results paint a quite new picture of geomagnetic behaviour. Excursions appear to be a frequent and intrinsic part of the (palaeomagnetic) secular variation: Lund *et al.*

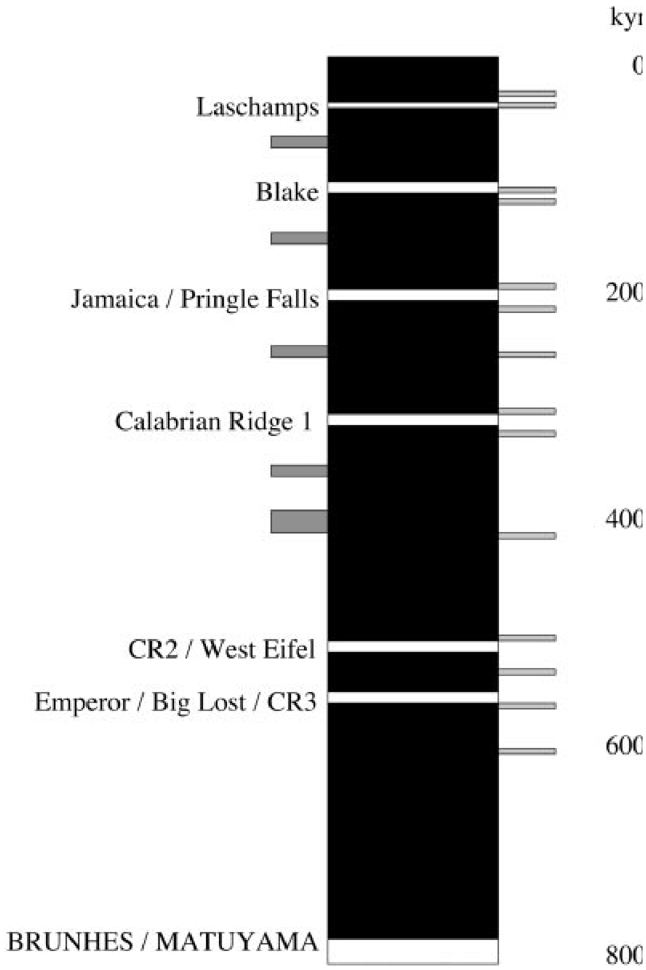

Figure 1. Excursions reported by Langereis *et al.* (1997) (left side) and by Lund *et al.* (1998) from ODP leg 172 in the western North Atlantic (right side). Full white bands are global events correlated at several sites; their width approximates their duration. Events on the right side are preliminary, and have been identified in four marine cores. Ages are approximate and no attempt is made to indicate their duration.

(1998) estimated the field to be in an 'excursional' state for 20 per cent of the Brunhes. Moreover, the dating of Langereis *et al.* (1997) provides a remarkably consistent estimate of the duration of each excursion (5–10 kyr). The behaviour is not chaotic but representative of a dynamical system with a characteristic timescale. In this paper I make the case for this to be the time required by the magnetic field to change in the inner core, probably the longest intrinsic timescale of the geodynamo.

2 DEFINITION OF AN EXCURSION

We should be clear about what we mean by an excursion, which entails distinguishing it from both (a) a large secular variation event and (b) a pair of full reversals. An empirical definition for (a) is a large, local movement of the VGP from the geographic pole, and for (b) a short duration of the altered polarity.

Now that some excursions are identified at several sites worldwide, it is worth extending condition (a) to a global field. The obvious condition is when the GAD becomes comparable to the non-dipole field. The surface field energy is given by Lowes' formula,

$$E=\sum_{l,m}(l+1)(g_l^{m2}+h_l^{m2}),$$

where g_l^m and h_l^m are the usual geomagnetic coefficients. The contribution from g_1^0 gives the GAD. For epoch 1980 this was 91 per cent of the whole; equality with the non-dipole contribution would require g_1^0 to fall to slightly less than a third of its present value, keeping the remaining coefficients the same. This would also reduce the intensity to about 10 per cent of its present value; larger intensities would be achieved with the same angular dispersion by increasing both the GAD and the non-dipole field, keeping them in the same ratio.

Condition (b) implies a timescale for the geodynamo, the geodynamo's 'memory' of the previous reversed state, which needs a precise definition. I propose defining it as minus the normal state. An excursion that achieves 180° change in direction at many sites can then be distinguished from a pair of reversals by a failure to establish the negative, fully reversed state. This definition demands sufficient time to establish a time average either side of the excursion. The measured duration of an excursion is therefore indicative of the time taken to establish the $-\boldsymbol{B}$ state plus that to establish a time average.

I see no way to define an excursion without defining the reversed state, and sign reversal is the only workable definition. Field reversal is a fundamental symmetry of the dynamo equations: if $\boldsymbol{B}$ is a solution then so is $-\boldsymbol{B}$. There are good theoretical reasons for believing the Earth's N and R states follow this symmetry (Gubbins 1998), and little or no palaeomagnetic evidence to contradict it (Merrill & McElhinny 1983). This definition is surprisingly useful because the field reversal symmetry has some unexpected consequences. For example, a preferred VGP path for a transition $N\rightarrow R$ requires the antipodal path for a subsequent $R\rightarrow N$ transition (Gubbins & Coe 1993), and the antipodal states of Langereis *et al.* (1992) cannot exist. This rule does not apply to excursions because the field may retain memory of the initial state. Studies of VGP paths using mixed data from reversals and transitions should take this into account.

3 ROLE OF THE INNER CORE

The natural timescale for the geodynamo is that of diffusion, normally taken to be the time for a dipolar field to decay by a factor of e (about 25 kyr for core conductivity $\sigma=5\times10^5$). Timescales associated with the fluid flow are shorter, a reflection of the size of the magnetic Reynolds number required for dynamo action ($R_{\mathrm{m}}\approx100$). The convective overturn time, based on westward drift rates and the outer core shell thickness, is about 500 yr. Periods of hydromagnetic waves will be smaller still, about 100 yr, with torsional oscillations having even shorter periods of 10 yr. Changes of the magnetic field in the outer core are achieved by fluid flow, with diffusion playing a secondary role, and will therefore be fast compared with the diffusion time.

Hollerbach & Jones (1993) made the important observation that the magnetic field in the solid inner core can only change by diffusion, which would take longer. The diffusion time for the inner core, based on the same criterion as above, is 3 kyr. The inner core stabilizes the magnetic field by imposing a magnetic inertia. Moreover, Hollerbach & Jones (1995) found in dynamo calculations that the inner core divided the outer core into two distinct dynamical regions separated by the tangent cylinder with axis parallel to the rotation axis. Inside the tangent cylinder the fluid was relatively quiescent, enhancing the inertia. By contrast, fluid outside the tangent cylinder changed on the more rapid timescales of the liquid core. The longest timescale in the whole system is therefore likely to be set by the electrical diffusion time of the inner core, or possibly its tangent cylinder: 3–5 kyr based on current estimates of core conductivity.

This prompts me to propose that excursions are events in which the geomagnetic field reverses in the liquid outer core but not in the solid inner core. The magnetic inertia imposed by the inner core delays full reversal for several thousand years, during which time the original polarity may establish itself in the outer core. The duration of excursions established by Langereis *et al.* (1997) is 5–10 kyr, similar to that expected from the estimated diffusion time of the inner core if we allow for the time to re-establish stable polarity. 10 or more excursions in the Brunhes suggests tenfold more rapid changes in the outer core than in the inner core, again consistent with an overturn time of 500 yr.

4 CONCLUSIONS

New measurements suggest that 'stable' polarity intervals are punctuated by many excursions lasting 5–10 kyr, in which the field direction changes substantially and the intensity drops. The timing of these events may appear random but refined dating has shown their duration to be remarkably uniform at 5–10 kyr. This is evidence for a distinct timescale in the dynamo, rather than chaotic behaviour, associated with the time for the magnetic field to change in the inner core.

Excursions involve a rapid collapse of the field, which would be very difficult to model if they are associated with small-scale internal fields. The new generation of 3-D numerical models might simulate this sort of behaviour yet not be typical of the real Earth because they use hyperdiffusivity and do not approach the low-viscosity limit in some important ways, notably in the formation of small-scale flows when the magnetic field is weak. 2.5-D models are capable of reaching the low-viscosity limit but often fail to generate magnetic fields (Walker *et al.* 1998). Morrison & Fearn (1999) gave an example where increasing the Rayleigh number of a 2.5-D dynamo killed the dynamo action completely until the Rayleigh number was substantially increased. This type of behaviour might explain the frequent collapses in field strength associated with excursions within the Brunhes.

An excursion may involve field reversal in the outer core but not the inner core, with its longer characteristic time. The *e*-folding time is 3 kyr but the field needs to reverse and then re-establish stable polarity, which will take somewhat longer, consistent with the measured duration. A full reversal only follows if the reversed outer core field persists for this length of time, a rather unlikely occurrence because of the shorter timescale, about 500 yr, of dynamics in the fluid core. 10 or more excursions between full reversals suggests a factor 10 difference in the timescales of the two cores. Without a solid inner core, reversals would be 10 times more frequent.

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