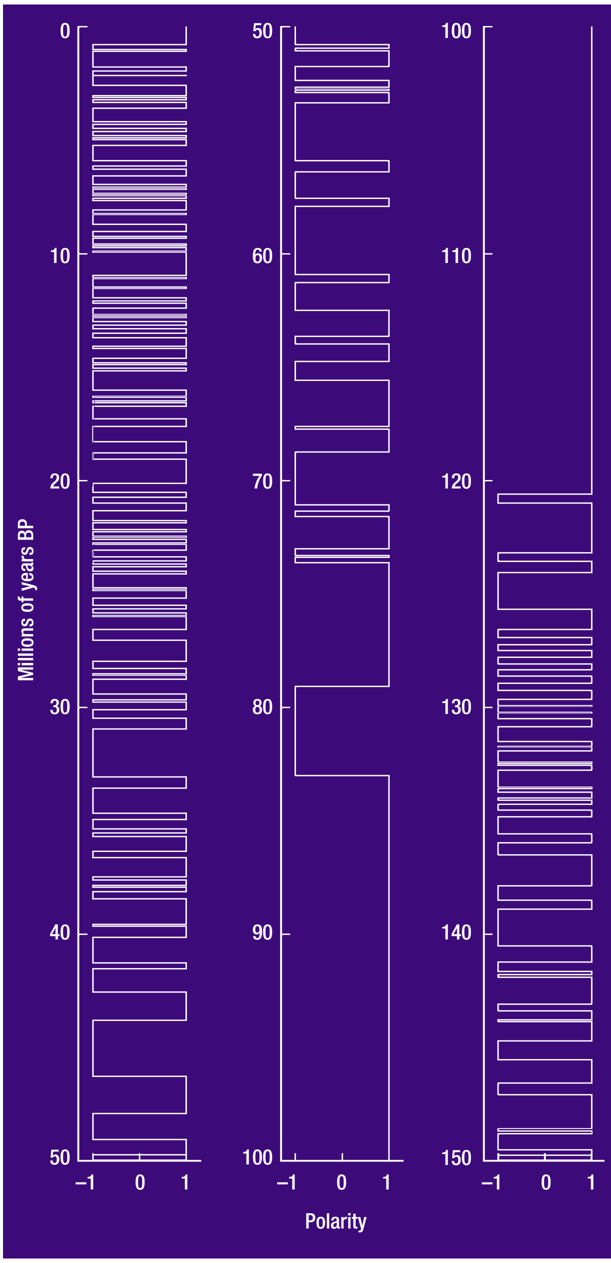
Reversals and excursi

Using palaeomagnetic records, the time-dependence and morphology of the Earth's magnetic field can be studied over geological timescales. In the temporal domain the magnetic field displays a great deal of irregular behaviour, most spectacularly in the form of occasional reversals and excursions. However, in the spatial domain the field displays some persistent asymmetry, not only during stable nontransitional periods but, quite remarkably, during polarity transitions themselves. These observations may indicate that the Earth's liquid iron outer core is coupled to both the solid inner core and the overlying mantle. An understanding of these effects is a prerequisite to solving the magnetohydrodynamic equations describing the geodynamo.



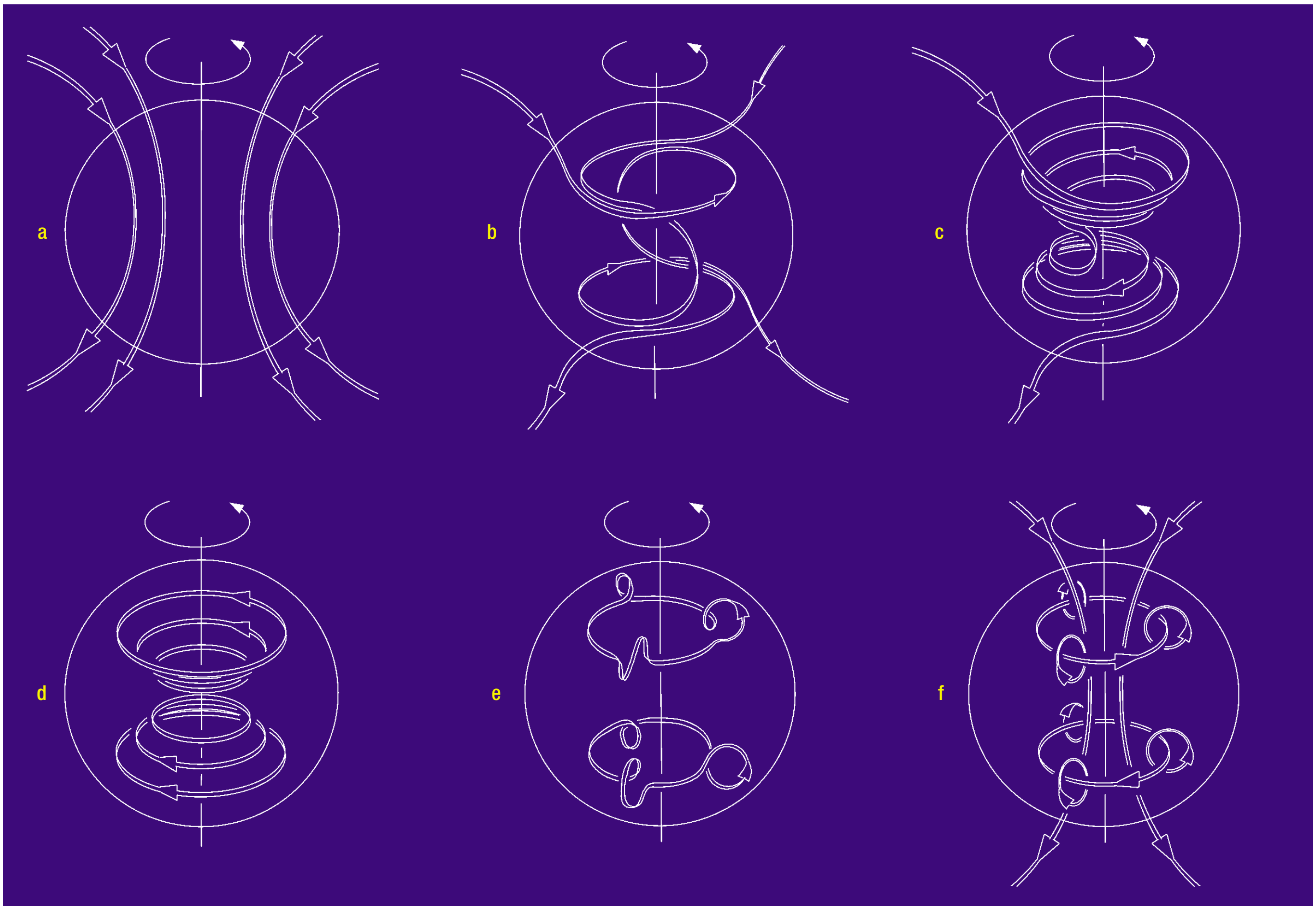
1: The geomagnetic polarity timescale, with "normal" periods (+1) and "reverse" periods (–1). This record, based on the magnetization of oceanic crust (Cande and Kent 1995, Channell *et al.* 1995), shows the great temporal irregularity with which reversals occur; the long interval of normal polarity from 121 Mya to 83 Mya is called the Cretaceous quiet zone.

Transitions of magnetic polarity are irregular in time but regular in space. **Jeffrey Love** reviews these enigmatic phenomena.

Secular variation of the Earth's magnetic field occurs over an astonishingly wide time spectrum, ranging over more than 20 orders of magnitude (Parkinson 1983, Courtillot and LeMouël 1988). The most rapid variations, with sub-millisecond periods, are of external origin, coming from the ionosphere and magnetosphere. Towards the other end of the scale, variations with periods longer than a few decades, and indeed the source of the main part of the geomagnetic field itself, are of internal origin, sustained by fluid motion in the Earth's liquid iron outer core. But of all the secular variation exhibited by the geomagnetic field, it is the occasional reversals of polarity and extreme excursional departures from an axial dipole that are the most dramatic. Polarity transitions are recorded in palaeomagnetic data taken from a wide variety of rocks, but despite having been discovered almost a century ago (Brunhes 1906), a complete understanding of these phenomena remains elusive.

The modern field we observe at the Earth's surface is, obviously, dominantly dipolar. In fact, it is possible to consider the modern field to be an axial dipole aligned with the rotational axis, plus a superimposed multipole perturbation, which gives the field a complex time-dependent morphology and, among other things, makes the total dipole inclined with respect to the rotational axis. Over geological timescales, the field is usually in a so-called stable state, when the axial dipole of the observed magnetic field, be it of one sign or the other, is dominant. When the axial dipole is not so dominant, the field can be described as transitional. If the dipole subsequently returns to dominate, but with the opposite polarity, then the transition is a reversal. Otherwise, if the dipole returns to dominate with a polarity like that before the transition, then the transition is called an excursion. It is theoretically possible to quantify such definitions, but solely on the basis of palaeomagnetic data, which usually come from only a few sites distributed non-uniformly over the Earth's surface, the distinction between a reversal and an excursion is not always very clear. Excursions are sometimes considered to be aborted reversals (Doell and Cox 1972), and non-transitional secular

ons of the geodynamo



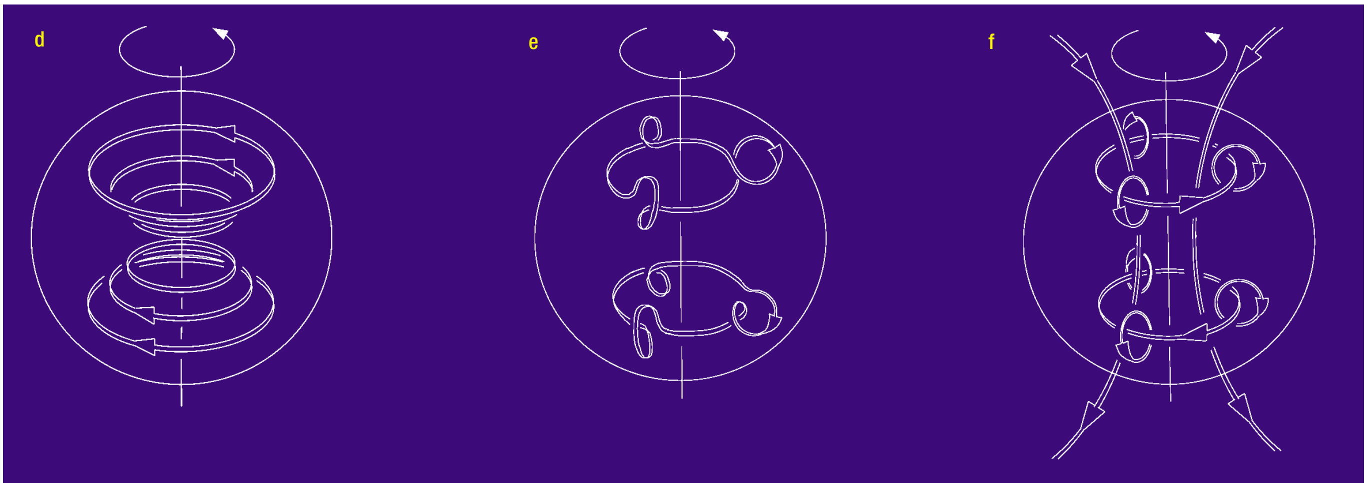
2: The α-ω dynamo mechanism. Conventional geodynamo theory presupposes (a) an initial, primarily dipolar, poloidal magnetic field. The ω-effect consists of differential rotation, (b) and (c), wrapping the magnetic field around the rotational axis, thereby (d) creating a quadrupolar toroidal magnetic field. Symmetry is broken, and dynamo action maintained, by the α-effect, whereby helical upwelling (e) creates loops of magnetic field. These loops coalesce (f) to reinforce the original dipolar field, thus closing the dynamo cycle.

variation can sometimes be confused with excursions. Neat and tidy distinctions between various parts of the continuum of secular variation are difficult if not impossible to make and are always rather arbitrary. Nonetheless, palaeomagnetic data clearly display a certain bimodality: if one plots the magnetic poles of a dipole corresponding to the palaeomagnetic directions at a particular site one finds that the poles tend to reside near one or the other geographic pole; one can conclude that the field is usually dominantly dipolar; see figure 1.

Of course it is fascinating that the magnetic poles try to swap places, and occasionally succeed. The timescales associated with polarity transitions are particularly perplexing. They occur with no apparent temporal regularity. Durations between transitions last from ~5000 years to ~50 million years. And they occur rather quickly: a reversal typically takes from ~5000 to ~20 000 years. But how are these transitions accomplished? Does the field simply disappear and reappear with the opposite polarity? The answer to this question is no. The transitional magnetic field at the Earth's surface does suffer significant diminution, but it does not vanish. Moreover, in contrast to their seeming randomness in time, transitions appear to show geometrical regularity; reversals and excursions tend to resemble each other, an observation which not only has important implications for our understanding of the cause of transitions, but which may also be telling us something important about the nature of the geodynamo.

Dynamo theory

Geomagnetism is an old science. Compasses have been used for millenia and Gilbert (1600) suggested that their north-seeking tendencies arose because the Earth was itself a giant permanent magnet. Soon after, it was discovered that the geomagnetic field varies in a complicated way with time, even over historical timescales. This fact led Halley (1692) to conclude that the interior of the Earth must be moving, although the source of the magnetic field remained a mystery until Larmor (1919) suggested that fluid motion could generate a magnetic field. Now it is generally accepted that convective motion in the Earth's liquid iron outer core, some 2900 km below the surface, provides the requisite motion. Fluid flowing across magnetic field lines induces an electrical current and an associated magnetic field. These inductive effects are described by a combination of Maxwell's equations and Ohm's Law. Depending on the geometrical relationship between the flow and the magnetic field, the induced magnetic field can reinforce the pre-existing magnetic field; such a system is said to be a self-sustaining dynamo. Some maintenance is necessary because the Earth has possessed a



3: How a reversal might be accomplished by a slight modification of α-ω dynamo process. Instead of the last three windows seen in figure 2, we have (d) the same quadrupolar toroidal magnetic field, except that now the net helical upwelling (e) creates loops of magnetic field of the opposite polarity. These loops coalesce (f) to destroy the original dipolar field, and install a field of the opposite polarity.

magnetic field for at least 3.5 billion years (McElhinny and Senanayake 1980), and yet without a dynamo the magnetic field would dissipate in ~10 000 to ~50 000 years because of the core's finite conductivity.

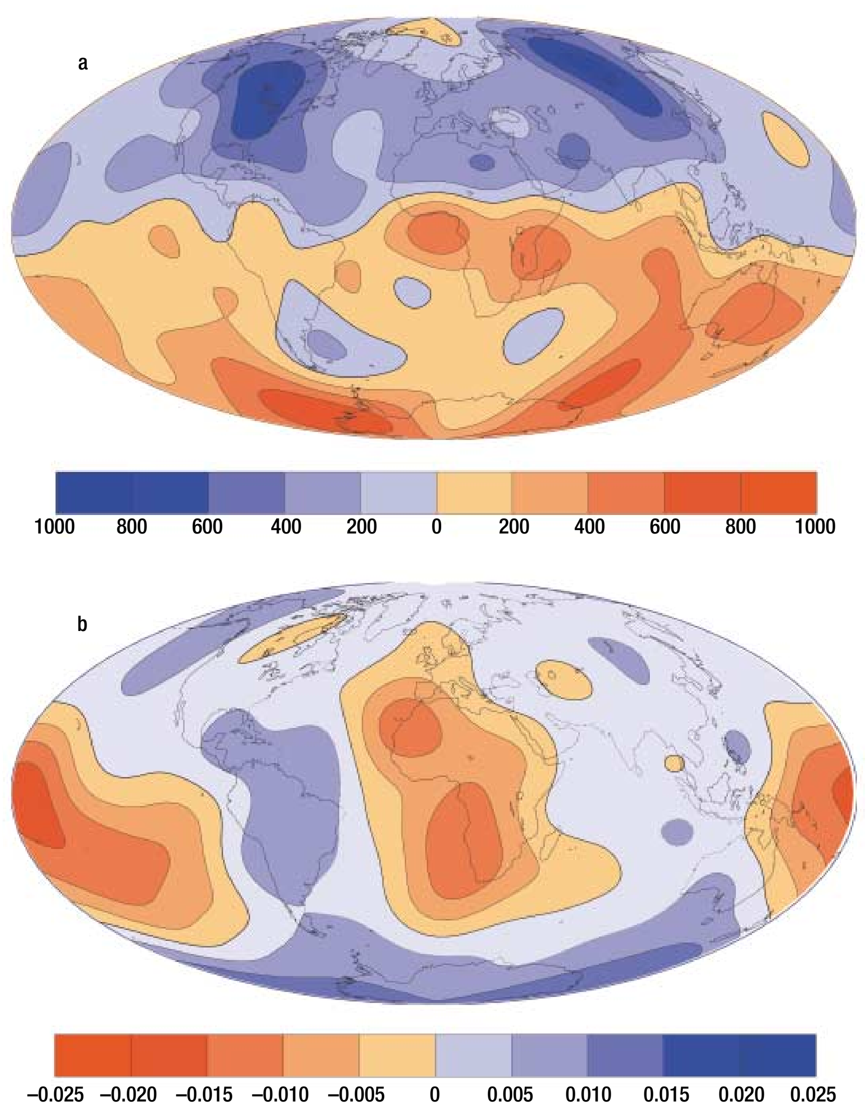
Dynamo theory is difficult, and many issues remain unresolved (Busse 1983, Roberts and Soward 1992, Stevenson 1983). Mechanical dynamos, moving machines consisting of particular arrangements of multiply connected bits of electrical conductors, have been made by engineers since the days of Faraday, but it is not at all obvious that a simply connected conducting fluid body, like that of the Earth's core, could function as a dynamo. Why don't the induced currents simply short-circuit, thereby eliminating field generation? In fact the electrical current in a dynamo, and the magnetic field that it sustains, cannot be too simple; Cowling (1934) showed that no axisymmetric, or even two-dimensional, dynamo field can exist. Although the magnetic north and south poles are (usually) nearly coincident with the geographic poles, which tells us that rotation plays an important role in the dynamics, it is no accident that the compass does not point towards true north everywhere on the Earth's surface. This inherent lack of symmetry means that theoretical progress has been rather slow; few hypothetical fluid velocities sustain numerically tractable magnetic fields (Gubbins 1973), and fewer still sustain fields that bear any resemblance to the observed geomagnetic field (Kumar and Roberts 1975).

Extrapolation of the observed magnetic field, down through the Earth's electrically insulating mantle, to the surface of the core shows that the field is complicated there. Although it is still predominantly dipolar, it is between ~5 and ~10 times stronger at the top of the core than it is at the Earth's surface. Unfortunately, the nature of the field inside the core is not known, but a reasonable coherent theory exists. Geophysicists generally believe that the Earth's magnetic field is sustained by the so-called α-ω mechanism (Elsasser 1947, Parker 1955), where core fluid motion, influenced by the Coriolis force, consists of a combination of differential rotation and convective helical motion; see figure 2. Differential rotation generates a strong quadrupolar toroidal field from the dipolar poloidal field, with the interior field strength being ~10 to ~100 times greater in the core interior than it is at the core's surface (Hide and Roberts 1979). The α-ω mechanism has also been shown mathematically to be a consequence of helical turbulence (Braginsky 1964, Steenbeck *et al.* 1966, Moffatt 1970). Upon performing an average over rapidly fluctuating, small lengthscale turbulence, it follows that whilst the geodynamo cannot be persistently axisymmetric, it can, at least theoretically, have an intra-reversal, non-transitional mean which is statistically axisymmetric.

> We need to address the challenge of explaining the source and behaviour of the Earth's magnetic field, and in particular reversals and excursions, simultaneously from both theoretical and observational directions.

The issue of whether or not the mean geomagnetic field is asymmetric is currently a matter of debate. It is an issue of importance because persistent asymmetry in the field's morphology would indicate that the core and mantle are dynamically coupled. Such a possibility was first proposed by Hide (1967) who was inspired by the celebrated Taylor–Proudman theorem of rotating fluid mechanics which demonstrates that small bumps on the boundary of a container of fluid can have a dramatic affect on the fluid's motion, even far from the boundary itself. Since the mantle convects very slowly compared to the core, overturn timescales are ~10^8 and ~10^3 years respectively, the relatively steady nature of the conditions established by the mantle at the core–mantle boundary could affect the pattern of core flow, thereby producing persistent asymmetric features in the magnetic field. Coupling between core and mantle could arise from the presence of topography on the core–mantle boundary, or from thermal or electrical conductivity variations at the base of the mantle.

With an understanding of the boundary conditions applicable to the core, it might be possible to solve correctly the nonlinear magnetohydrodynamic equations that govern the geodynamo. These equations are akin to the equations of oceanography and meteorology, but with the additional complication presented by the magnetic field through the Lorentz force. A great deal of effort is being applied to integrate the dynamic equations on modern supercomputers (Glatzmaier and Roberts 1995, Kuang and Bloxham 1997, Sarson *et al.* 1998); unfortunately rather drastic approximations are necessary to account for the difficult effects of turbulence. Not surprisingly, the dynamo equations describe deterministic chaos, and as we see in the data themselves, the magnetic field can exhibit highly aperiodic variation (Weiss *et al.* 1984). Interestingly, the equations are symmetric under change in sign of the total magnetic field (Merrill *et al.* 1979), and thus there is no reason to expect that the Earth's field should have one polarity or the other (Gubbins and Zhang 1993). Moreover, a reversal may be accomplished by only a slight change in the core's fluid motion; this is illustrated in figure 3. With respect to the "cause" of polarity transitions, mathematical models of



4: (a) Radial component of the core surface magnetic field (μT) averaged over the past 150 years, based on the field model of Bloxham and Jackson (1992). Note the presence of flux patches under Canada and Siberia, along with a corresponding pair in the southern hemisphere. These concentrations of flux are the source of most of the field measured at the Earth's surface. (b) Relative variations in seismic shear velocity, $\delta v_s/v_s$, from Masters *et al.* (1996). Note the longitudinal correlation between the flux patches in (a) and the high shear velocity in (b), as well as the preferred VGP longitudes in figure 6.

hypothetical magneto-mechanical systems can exhibit irregular reversing behaviour (Rikitake 1958). Hence, the invocation of an external random forcing factor, such as ice-ages or meteorite impacts, to account for the irregular occurrence of reversals, represents a solution to a non-problem.

Indeed, the question is not so much why does the Earth's magnetic field reverse, but rather why aren't reversals occurring all the time? The Sun is a familiar dynamo, and it reverses almost regularly every 11 years! This difference may be due to the fact that the Earth has a solid electrically conducting inner core, some 1200 km in radius, where the magnetic field can change only slowly by diffusion. Hollerbach and Jones (1993) have suggested that because the inner core is electromagnetically coupled to the outer core, its presence acts to stabilize the magnetic field; only particularly large fluctuations of the field in the outer core are sufficient to overcome the damping effect of the inner core. Provocative theoretical results such as these provide us with insight, yet much work remains to be done. In particular, theories need to be assessed after quantitative comparison with data.

Palaeomagnetism and field morphology

A history of the Earth's magnetic field is preserved in piles of frozen lava flows, in wind-blown loess deposited in arid environments, in mud laying on the bottoms of lakes and oceans, and in archaeological artefacts such as fired bricks and pottery. When an igneous rock cools it is magnetized in a direction roughly aligned with the local magnetic field of the Earth at the time and place of deposition (Néel 1949, Dunlop and Özdemir 1997). Similarly, during the accumulation of sediment, magnetized particles tend to align themselves with the local field; magnetization is affected when compaction locks the particles into place (Johnson *et al.* 1948, Verosub 1977). The different types of palaeomagnetic data are complementary; individual field directions are generally recorded most reliably by lavas and archaeological artefacts, and they offer the only means of obtaining absolute palaeointensities, but because sediments accumulate fairly constantly, their records are more temporally continuous. Palaeomagnetic measurements are notoriously tricky to make since rocks are subject to alteration and remagnetization after their initial emplacement (Butler 1992, Tauxe 1998), and thus the history of the Earth's magnetic field cannot be said to be set in stone. Consistent results from different rock types, of course, can help to verify particular palaeomagnetic results. This is especially true for studies of reversals and excursions, when, because the field is of relatively low intensity, the palaeomagnetic signature within the rock is weak. Fortunately, our understanding of how rock becomes magnetized is improving and measurement methods are being refined. Consequently, reliable palaeomagnetic data, especially those rare transitional data, are rapidly increasing in number.

Because of its importance to dynamo theory, the morphology of the magnetic field and whether or not it actually displays statistical asymmetry is a subject of current and concentrated research. Historical measurements made over the past few hundred years indicate that the field at the core–mantle boundary has important persistent non-axisymmetric features (Bloxham and Gubbins 1985), see figure 4. Unfortunately, time-averages of palaeomagnetic data recording intrareversal periods over the past few million years are more equivocal; some investigators claim significant non-axisymmetry (Gubbins and Kelly 1993, Johnson and Constable 1995) whilst others disagree (McElhinny *et al.* 1996, Carlut and Courtillot 1998), contending that the palaeomagnetic data can support only axisymmetric dipolar and quadrupolar field ingredients.

What is not widely appreciated within the geophysical community is that a persistent axial dipole–quadrupole field is in itself evidence of core–mantle coupling, because it gives a field that is asymmetrical across the equatorial plane. There is no dynamical reason to expect the magnetic field in the northern and southern hemispheres to be persistently different in the case of a homogeneous core–mantle boundary. To address these issues it is useful to inspect palaeomagnetic data recording the field during transitions, when the axial dipole is less dominant. For a full reversal of the field, the axial dipole must at some time disappear, and therefore a statistical assessment of transitional data may be more likely to reveal possibly persistent features in the Earth's magnetic field.

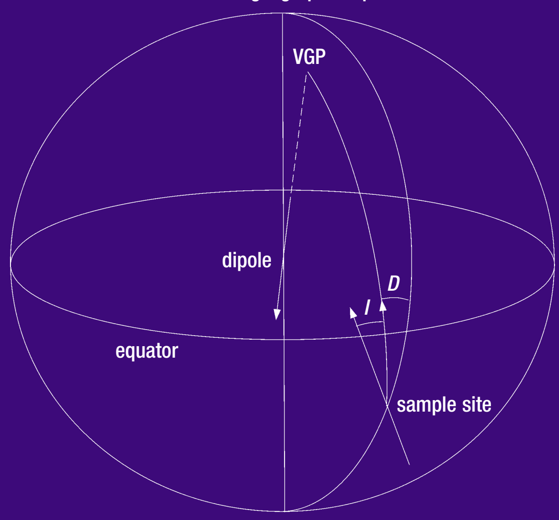
The nature of transitional fields

Recently, a compilation of sedimentary palaeomagnetic data from several different sites appeared to show that reversals and excursions exhibit geometric regularity (Laj *et al.* 1991), in that transitions tend to resemble each other by apparently exhibiting similar field patterns. This assertion was made on the basis of maps of virtual geomagnetic poles (VGPs), the magnetic pole of a dipole corresponding to field directions from each palaeomagnetic site; see figure 5. Laj *et al.* found that VGPs from multiple transitions tend to fall along either American or Asian–Australian longitudes.

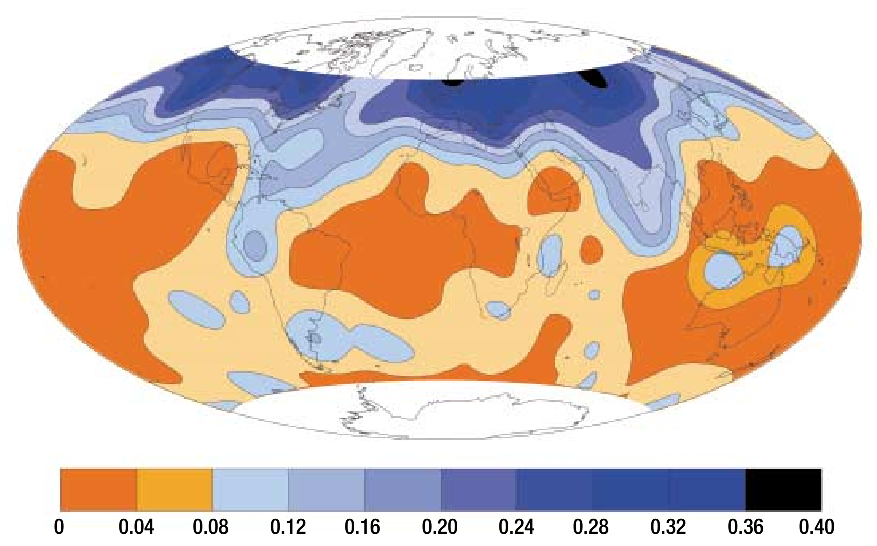
The geodynamic importance of such an observation can hardly be overstated. Since the duration between transitions is longer than both the core's convective overturn timescale and its magnetic diffusive timescale, the only plausible mechanism by which the core could retain a memory of previous transitions, particularly a non-axisymmetric feature such as preferred longitudes, is through some form of core–mantle coupling. To reinforce this possibility, Laj *et al.* and Constable (1992) have drawn attention to the apparent correlation between the preferred longitudes, quasi-stationary features in the modern field, and lower mantle seismic velocity variations (arising perhaps from thermal or compositional heterogeneities); see figure 4. These provocative results have been greeted with scepticism and doubt about the adequacy of the geographic distribution of palaeomagnetic sites (Valet *et al.* 1992) and the reliability of the sedimentary records (Langereis *et al.* 1992). Moreover, arguments about the statistical significance of the sedimentary results have been inconclusive (Laj *et al.* 1992, McFadden *et al.* 1993).

Of course, one way of addressing a controversy is to analyse an independent dataset, and in this sense palaeomagnetic lava data are particularly attractive. An initial analysis of palaeomagnetic data from lavas deposited when volcanoes happened to erupt during transitions appeared to indicate that reversals and excursions are statistically axisymmetric (Prévot and Camps 1993). However, a subsequent inspection of the lava data by Love (1998, 2000a) proved to be more encouraging. Much of the difficulty with analysing lava data stems from the extreme irregularity with which volcanoes erupt; amongst the available lava data some transitions are recorded in great detail because of prolific local volcanic activity, whilst other transitions are recorded more sparsely because of relative quiescence in local volcanic activity. For a statistical analysis of multiple transitions, so that they are counted more uniformly, it is necessary to account for differences in recording density. After normalization the volcanic data do in fact show a tendency for VGPs to fall along American and Asian–Australian longitudes, a result consistent with the sedimentary data (figure 6).

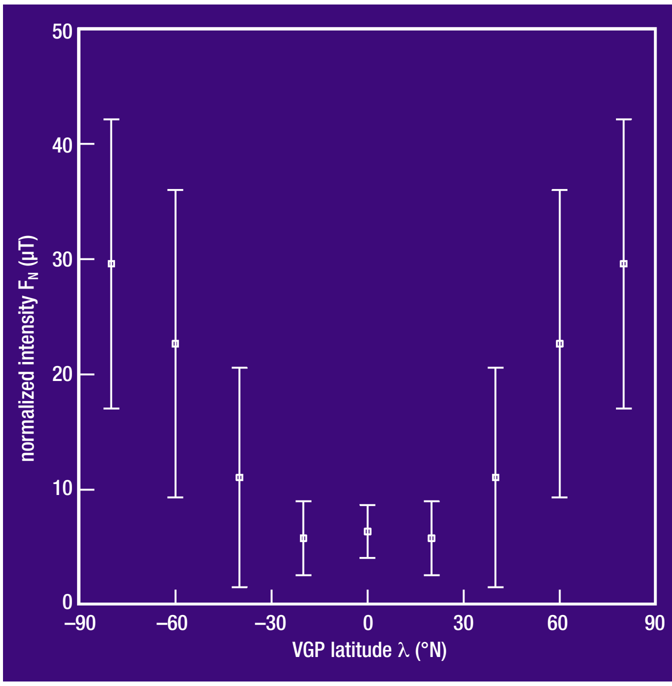
Palaeomagnetic directions are, of course, only part of the story. Lavas provide an absolute measure of the Earth's field intensity over geological timescales (Thellier and Thellier 1959), and the data show that the intensity can vary dramatically in time. The variation is usually within a factor of three of its present value (Kono and Tanaka 1995), and periods of high (or low) intensity can persist for tens of millions of years. Such a timescale is longer than the convective and magnetic diffusive timescales of the core, and might be further evidence of some form of core–mantle cou-



5: A virtual geomagnetic pole (VGP) corresponds to the magnetic pole of a dipole for field directions, inclinations and declinations (*I,D*) at a particular palaeomagnetic site. To make such a transformation, it is not necessary that the field actually be dipolar or even close to dipolar, the VGP is truly "virtual". Of course, if the field is actually a dipole, then data from different sites will give coincident VGPs, otherwise nondipolar ingredients in the field will give a scatter of VGPs. In the study of reversals and excursions, plotting data as VGPs is simply a convenient way of displaying data on a map. In this discussion we adopt the (geomagnetic) polarity convention of plotting transitional VGPs lying initially near the north geographic pole (regardless of magnetic sign). Under this convention, excursions are defined as periods of time when the directional data give VGPs which migrate from the north geographic pole to some mid-latitude position, only to return subsequently to the vicinity of the north pole; a reversal consists of VGPs migrating from the vicinity of the north pole to the south pole.



6: Map of the probability distribution of transitional VGPs from 141 separate records of reversals and excursions which occurred over the past 20 Myr and taken from a number of different volcanic sites. Each VGP has been normalized, to emphasize mid-latitude values and to account for the extreme variability with which volcanoes erupt (Love 1998). The geomagnetic polarity convention (Prévot and Camps 1993) has been used: magnetic poles lying initially near the north geographic pole are plotted regardless of magnetic sign. Statistical significance has been verified by χ^2, Kuiper, and bootstrap analyses (Love 1998, Love 2000a). Units are probability/steradian. Note the tendency for VGPs to fall along American and Asian longitudes.



7: Following Dagley and Wilson (1971) among others, binned intensities F_N, normalized for site latitude, versus VGP latitude λ, are shown. The average intensity is for a 20° latitude bin and the standard deviation is shown with error bars. For a given VGP latitude the intensity can vary quite a bit, but transitional (non-transitional) directions correspond, on average, to low (high) intensities.

pling; as the mantle slowly convects, and the conditions at the core–mantle boundary change, the efficiency of the dynamo might change as well (Prévot and Perrin 1992), which, in turn, could affect the frequency with which reversals and excursions occur (Merrill and McFadden 1990). With respect to transitional periods themselves, they correspond to periods of rapid and dramatic intensity variation. In figure 7, showing the field intensity as a function of VGP latitude, note that the intensity dropping to ~10% to ~20% of the pre- and post-transitional state. More recently, Love (2000b) has attempted to quantify the link between field intensity and the rate at which the field changes in time.

Implications

Although both palaeomagnetism and dynamo theory are the subject of continuing work, certain generalities about polarity transitions can now be drawn, and suitable speculations made. If, for a given transition, VGPs from different geographical sites were found to follow a single path from one geographic pole to the next, then we could conclude that transitional fields are essentially dipolar. Statistically, this is not the case. In fact, the bilongitudinal distribution of transitional VGPs seen in figure 6 indicates that reversals and excursions have important non-dipolar ingredients.

The existence of core–mantle coupling is demonstrated by the fact that the non-transitional field is predominantly a dipole plus a quadrupole, that preferred VGP longitudes are temporally stationary, that the main part of the modern field at the core–mantle boundary consists of flux patches on those same longitudes, and that the preferred longitudes are correlated with lateral seismic velocity variations at the base of the mantle. Finally, periods of high (or low) field intensity persisting for several millions years are additional evidence for core–mantle coupling, because only the mantle evolves over such timescales. An unresolved issue concerns the nature of the coupling mechanism. Progress on this point is necessary since understanding the conditions at the core–mantle boundary is a prerequisite to solving the partial differential equations governing the dynamics of the geodynamo.

Today, the subject of geomagnetism is at a critical juncture. Computational advances are being made, yet dynamo simulations only represent rough approximations of the processes occurring in the core, and results are often so complicated that they are difficult to understand. Although high-quality palaeomagnetic data are coming from lavas, sediments and archaeological artefacts, significantly more data are needed. Perhaps most importantly, the gulf that exists between the observationalist and the theorist needs to be bridged. We need theories that, whilst encompassing the physically important effects, are simple enough to be usefully compared with palaeomagnetic data. We need statistical methods that, whilst accounting for the errors in the data, are robust enough to reveal interesting and previously undetected patterns in the data which can usefully constrain theories. In short, we need to address the challenge of explaining the source and behaviour of the Earth's magnetic field, in particular reversals and excursions, simultaneously from both theoretical and observational directions. ●

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