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Harold Jeffreys Lecture 1990: Convection in the Earth's Core and Mantle*

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SUMMARY

The Earth's magnetic field is generated by induction of moving electrically conducting fluid in the liquid core. The pattern of magnetic flux on the core surface shows a stationary fourfold symmetry which can arise from large-scale convective motion and time-dependent behaviour that may be caused by near-surface core flows driven, or strongly influenced, by conditions at the core–mantle boundary. Core convection is influenced by earth rotation, and its coupling with lower mantle convection may explain low-order gravity anomalies and the striking tendency for plate motions to be aligned with their poles of relative motion clustered near the geographic axis.

1 THE EARTH'S DYNAMO

The middle half of the Earth is made of liquid iron: the *core*. The innermost 1200 km is thought to be solid iron, the pressure there being high enough to elevate the melting point of iron above the ambient temperature. The core is the only part of the Earth which has high electrical conductivity and is therefore the only possible seat for generation of the Earth's magnetic field. Electric currents associated with the magnetic field decay in about 10^4 years because of electrical resistance. However, we know that the magnetic field has existed for most of Earth's history, over 10^9 years, because virtually every rock we pick up, even the oldest, is magnetized. Some process must sustain the field and the only viable mechanism appears to be a *dynamo* regenerating magnetic field by fluid pushing across field lines. The situation is quite different on the Sun, where the decay rate of electric currents is many times the age of the Universe and no mechanism is required to explain the existence of a magnetic field. However, the Sun's magnetic field reverses every 11 years and we need a mechanism to explain its rapid change. Again, this is thought to be a dynamo process.

An energy source is required to drive any dynamo. The Earth probably requires too much energy for it to be driven by radioactive heating and recent models of the dynamo rely largely on differentiation of the liquid of the outer core into a light constituent and something approximating pure iron, which freezes out to form and accrete the solid inner core. The light material remaining at the base of the outer core drives fluid convection, the

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gravitational energy thus released being available to generate magnetic field (Braginsky 1963; Gubbins 1977; Gubbins, Masters & Jacobs 1979; Stevenson 1983). This energy dissipates eventually as heat which passes out across the core–mantle boundary into the mantle. The dynamo process is thereby an integral part of the Earth's thermal history which the magnetic field can be used to constrain: the cooling rate must be fast enough to supply the required energy to generate a magnetic field, but not so great as to freeze the entire core.

The core's cooling rate is governed by the solid overlying rocky mantle, which undergoes solid state convection and is itself cooling slowly. Simple models of the thermal history which include parameterized convection of the mantle and a simple cooling core model suggest that the present state of the core, in which the central 1000 km is solid and the outer 2500 km is liquid, was reached quite early in the Earth's history and is a long-lived configuration, relatively independent of the Earth's initial state (Mollett 1981; Stevenson, Spohn & Schubert 1983). If the Earth formed hot the mantle would have been mobile and therefore convected vigorously and cooled rapidly. Furthermore, mantle viscosity increases with falling temperature and causes a decrease in both the vigour of convection and the cooling rate. The cooling rate slows still further when the temperature at the centre of the Earth falls below the melting point of iron and the inner core forms, providing latent heat of fusion and an increase in the heat released per unit drop of temperature. This rather satisfying result implies that the Earth's present thermal state is relatively independent of details of its formation. Stevenson, Spohn & Schubert (1983) have speculated that initiation of the inner core was a major event in Earth history.

Neither of our near neighbours, Mars and Venus, have substantial magnetic fields. I believe this is because their cores have frozen solid. This is quite plausible in the case of Mars, which is a small planet and would therefore cool rapidly. Venus presents more of a problem because it is similar to the Earth in size. Possibly convection in Venus's mantle caused it to cool more rapidly and the core to freeze: we already know that the surface manifestations of convection on Venus are quite different from those on the Earth. Alternative views are held by others: Stevenson, Spohn & Schubert (1983) believe the cores of Mars and Venus may be completely molten, with no inner cores, and therefore lack both latent heat of fusion and gravitational energy to power the dynamo, while Busse (1976) essentially attributes the very weak magnetic field of Venus to its slow rotation speed.

The dynamics of the Earth's fluid core present a very difficult problem. Vigorous radial convection, dominated by Coriolis forces associated with the Earth's rotation and strongly influenced by magnetic forces, is required to generate an axial dipolar magnetic field. The problem is an active area of research and we now have quite a good understanding of convection in rotating systems but rather little understanding of the combined effects of magnetic and rotational forces. We can state some general results.

(1) Laboratory experiments, numerical calculations, and theoretical studies indicate quite clearly that rotation tends to align the pattern of convection along the rotation axis. In simple models the convection takes the form of rolls aligned parallel to the axis (Busse & Carrigan 1976). Later work

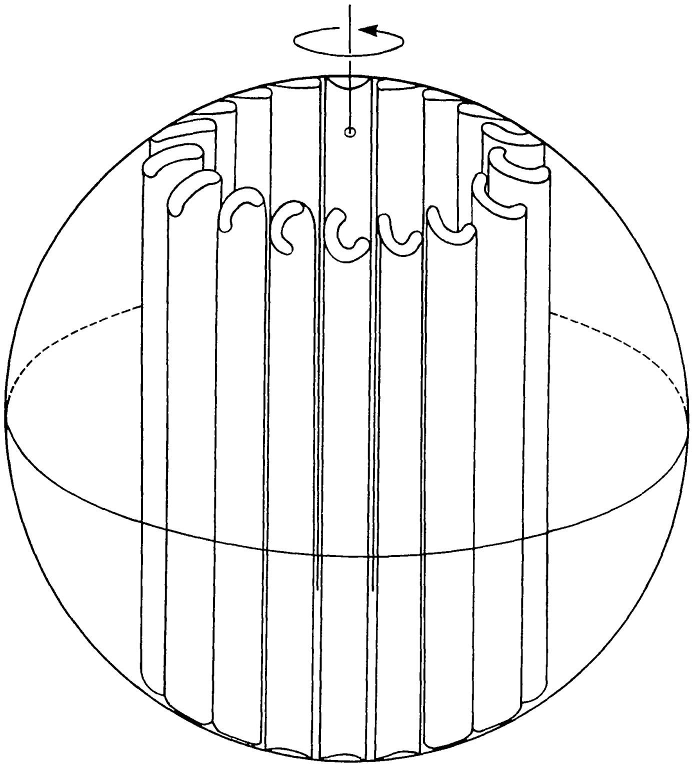

FIG. 1. Schematic convection roll structure in a rotating sphere as seen in experiments and numerical convection at high rotation speeds and low Rayleigh number. Rolls are aligned with the rotation axis because of the Coriolis force, they drift azimuthally, they are most unstable near the axis and therefore touch the inner sphere, and they are curved into spirals, the pitch of the spiral depending on the Prandtl number.

showed the rolls to be distorted into a spiral cross section as shown in Fig. 1 (Chamberlain 1979; Chamberlain & Carrigan 1986) and numerical calculations reveal the spiralling to be strongly dependent on the Prandtl number of the fluid, the ratio of kinematic viscosity to thermal diffusivity, and most pronounced at low Prandtl number (Zhang 1991). In an extreme case the convection becomes dominated by zonal axisymmetric motion: such convection may explain the banded appearance of the giant planets.

(2) The Earth's magnetic field has reversed polarity repeatedly, and apparently randomly, in the geological past (Fig. 2). The detailed record shows a gradual change in reversal frequency with a long interval without any polarity change some 80 million years ago (Lowrie 1982). The equations are invariant under change of sign of the magnetic field and therefore polarity reversals should leave the magnetic field unchanged except for sign. This includes any complication we care to impose on either the nature of the convection or the boundary conditions, such as variable heat transfer across the core-mantle boundary.

(3) The equations allow separate solutions with equatorial symmetry ('dipole type') and asymmetry ('octupole type'), as well as mixed symmetries.

(4) The dynamics are influenced significantly by the presence of the inner core. In simple experiments and numerical calculations the most unstable rolls touch the inner core. The imaginary cylinder enclosing the inner core

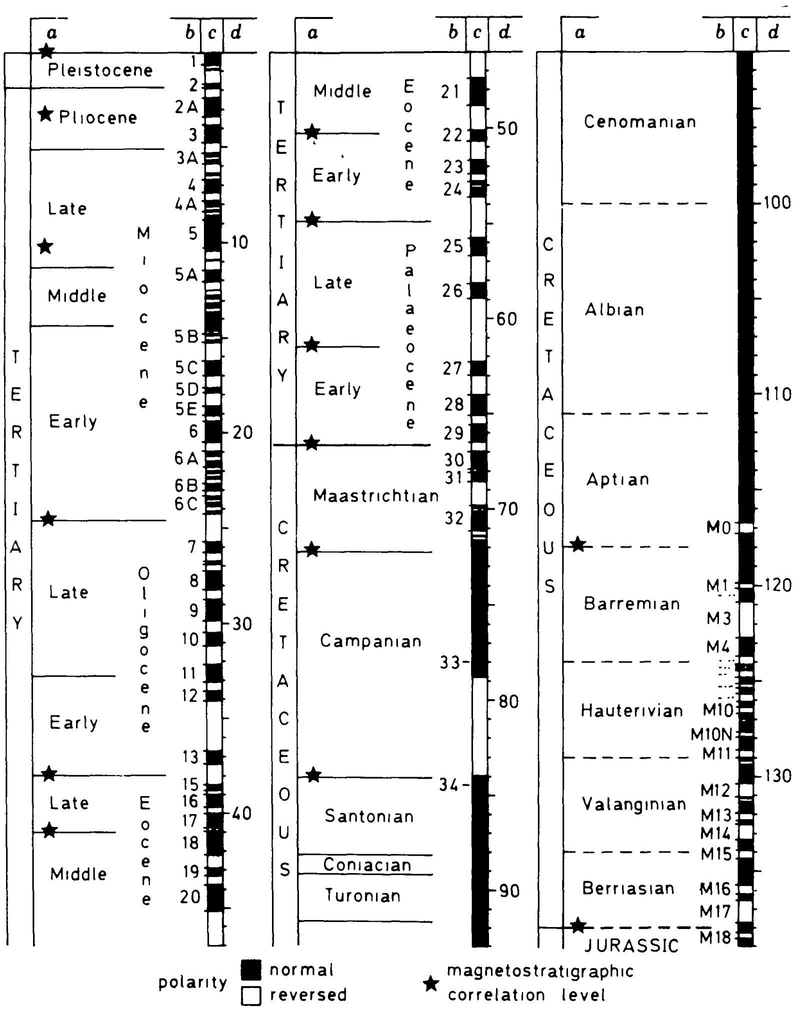

FIG. 2. The time-scale for reversals of polarity of the Earth's magnetic field determined from palaeomagnetism. Reversals occur in an apparently random fashion but the frequency changes on a very long time-scale, presumably because of changes in the boundary conditions imposed by the mantle, and are completely absent from an interval of 30 Myr in the Cretaceous period. From Lowrie (1982).

with its axis parallel to the rotation axis may delineate separate convective regimes.

2 THE OBSERVED GEOMAGNETIC FIELD

We know more about the solar dynamo than the geodynamo. There are three reasons: (i) the dynamics are simpler; (ii) we can observe the surface of the Sun and we can infer magnetic activity upon it because magnetic fields make the surface colder and therefore darker (there are additional, more quantitative, techniques for estimating the surface field on the Sun); and (iii) the solar magnetic field varies rapidly, reversing every 11 years with the Sun-spot cycle, and we can detect quite a wide range of magnetic behaviour in quite a short observing period.

By contrast, the Earth's magnetic field is observed at the Earth's surface, 3000 km above the conducting core. Maps of surface field are useless for interpretation; we require them at the conducting surface, the core–mantle boundary, for interpretation. The mantle is an electrical insulator and it is possible, in principle, to determine the magnetic field at the core–mantle boundary by solving Laplace's equation using measurements made at the Earth's surface as boundary conditions. This calculation of the core field is unstable, but modern methods of inverse theory provide self-consistent solutions which show good agreement between widely differing datasets.

In 1980 I began a project to collect magnetic data and form maps of the magnetic field at the core–mantle boundary. The Earth's magnetic field changes on a time-scale of centuries, rather than decades as on the Sun, and we had to examine the historical archives of magnetic measurements. For the twentieth century there is a large volume of satellite and survey data in machine-readable form. Permanent magnetic observatories have been operated in many parts of the world and provide the most accurate measurements possible with existing instrumentation. It has been possible, using this very large data set, to construct core–mantle boundary magnetic field maps for every decade of the twentieth century up to 1980. The latest models provide very good control on the quality of these maps: certain small features in the older maps are considered spurious if they do not appear in the recent maps, which are based on better data. Likewise, long-lasting features appearing in all the maps are likely to be true features (Bloxham, Gubbins & Jackson 1989).

Measurements in the nineteenth century were also numerous but they had not been archived and collected properly. A great many measurements were made during sea voyages. Data from the early part of the nineteenth century had already been archived by General Sir Edward Sabine, but measurements from later in the century had not been archived at all. We were able to find well over ten thousand magnetic observations from the nineteenth century with a reasonable global distribution. We have used them to construct magnetic field maps centred on two epochs, one in 1845 (Bloxham 1985, 1986), at about the time of the Royal Navy survey of the Southern Ocean, and another in 1877.5 (Jackson 1989, Bloxham, Gubbins & Jackson 1989), at about the time of the *Challenger* Expedition, the first iron ship built for scientific exploration and discovery.

In the eighteenth century the data suffer from a lack of measurement of magnetic intensity. The first absolute intensity determination was made by Gauss in the early nineteenth century. Captain Cook's voyages provided very good data for the latter part of the eighteenth century, and the exploits of Halley and the French Astronomer Royal, Feuillée, provide us with very good data from its early years (although the navigation was rather poor and considerable effort was made in correcting and assessing longitude, Bloxham 1985). The data gave maps centred on epochs 1715 and 1777 (Bloxham 1986).

The seventeenth century provided about three thousand observations, almost all of which are of declination, that is the angle between the compass direction and true north. Nevertheless, we have been able to construct a map centred on epoch 1615 for the seventeenth century (Hutcheson 1990; Hutcheson & Gubbins 1990). More recently, the data have been used to construct time-dependent models of the magnetic field (Hutcheson 1990).

This research project has been more successful than I expected. The reason

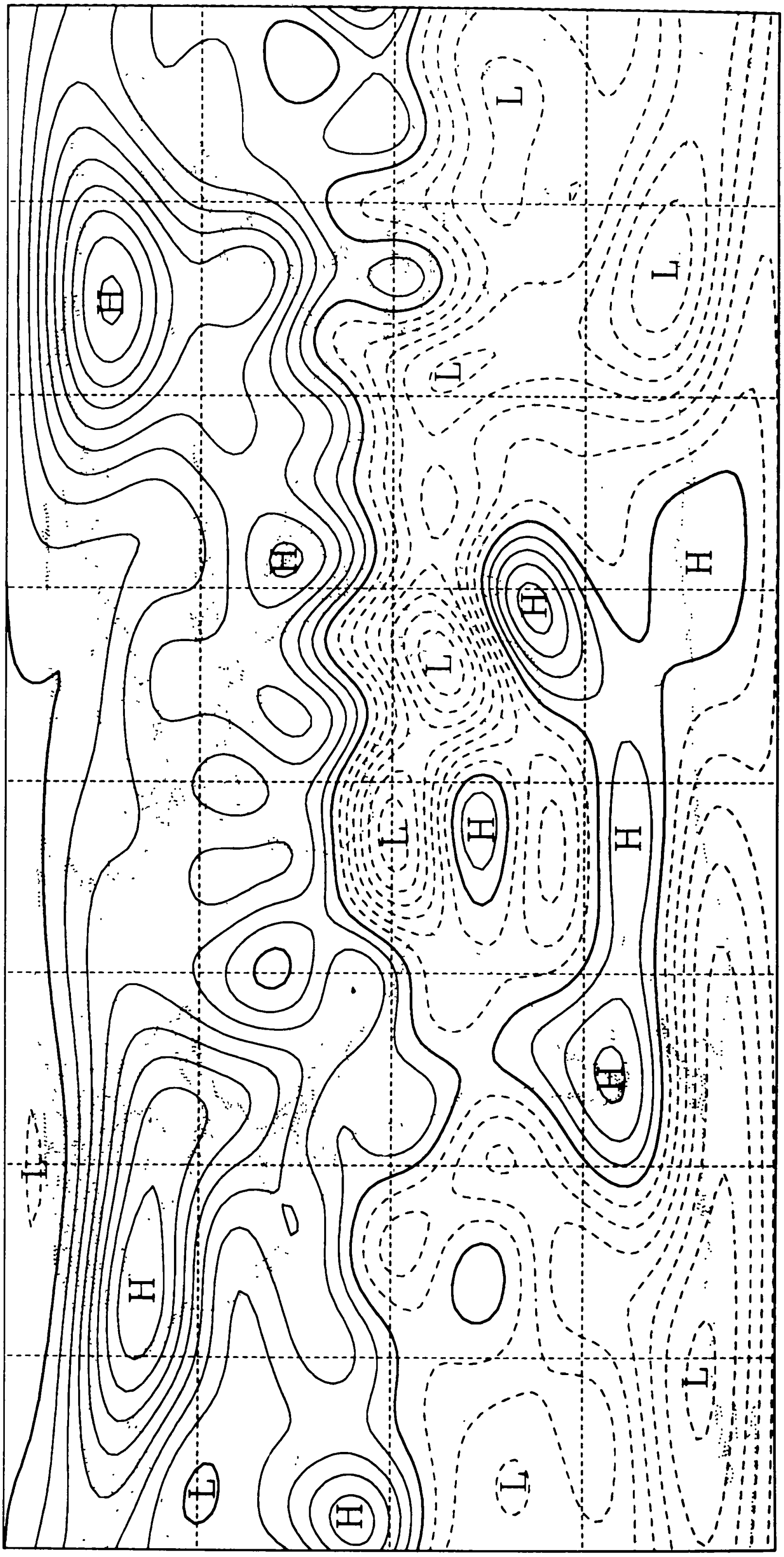

FIG. 3. The vertical component of magnetic field at the core–mantle boundary in 1980.

for the success is twofold. First, there were far more magnetic observations than we realized. During the seventeenth, eighteenth and early nineteenth centuries magnetic measurements were important for navigation, and navigation was the most important scientific issue. In the latter part of the nineteenth century and the early half of the twentieth century, magnetic surveying was found useful in prospecting for minerals, which promoted continued activity in magnetic surveying. Secondly, the errors of our measurements are set not by the instruments themselves but rather by the effects of magnetized rocks. This signal, which comes from the Earth's crust and not the core, is of no direct interest to core studies, although it is important for geology, and we regard it as noise. It has a magnitude of several hundred nT compared with modern instrument error of a few nT; even the very old measurements provide greater accuracy than the limits set by the crustal noise. A modern survey measurement is of little more value in mapping the core field than a land measurement made in 1715 or a sea measurement made by Captain Cook. At permanent observatories it is possible to remove the crustal signal, which is constant, and monitor time changes of the core field directly.

The resulting map of the vertical component of magnetic field or the core surface is shown in Fig. 3; maps of magnetic components at the Earth's surface for these models are in Gubbins (1989) and further maps of core fields are in Bloxham, Gubbins & Jackson (1989) and Hutcheson & Gubbins (1990). There are a number of interesting features in the core field. First note that the main part of the magnetic field is concentrated in four main lobes at around 60° N and S and about 120° E and W, respectively. The regions over the North Pole and the South Pole have very low flux. These features are stationary and occur in all our maps. The region in the Pacific, where there is very low flux encircling a central high south-west of Hawaii, has remained stationary throughout the historical period: about 400 years. The pattern in the Atlantic region drifts west very rapidly, and in the Indian Ocean off South Africa a patch of reverse flux, i.e. a region where the magnetic field points inwards in the Southern Hemisphere rather than outwards, has blown up during the twentieth century and still grows today. This behaviour is similar to that of sunspots, where magnetic flux is pushed through the solar surface.

3 INTERPRETATION OF RECENT GEOMAGNETIC CHANGE

The principal stationary part of the magnetic field is the four main lobes. Their symmetry about the equator is remarkable, and they have remained quite stationary throughout the period of historical measurement. In very early times the two southern hemisphere lobes merge into one, but Bloxham (1985) has shown this to be caused by lack of adequate data in Antarctica in early periods. The symmetry can be explained if this is a dynamo-generated field and the dynamo is producing a field with the equatorial symmetry described in § 1. Hutcheson (1990) has calculated solutions to the kinematic dynamo problem and plotted the resulting surface magnetic field. These solutions correspond to fixed fluid flows, chosen arbitrarily but with some consideration of typical fluid motions driven by rotating convection, and stationary magnetic fields. The fluid motions are based on earlier calculations reported by Lilley (1970) and Kumar & Roberts (1975). A typical surface field is shown in Fig. 4; the symmetry is chosen to simplify the calculations but the solution shows clearly the fourfold pattern in the flux; the flux concentrations lie above regions of downwelling fluid because the convergent flow tends to concentrate magnetic field lines.

In the Earth the patches of low flux over the poles coincide quite well with the size of the inner core, suggesting the main lobes are generated by some kind of convective flow which is strongly influenced by the inner core, another result expected from the theory of convection in a rotating spherical shell described in §1. It is therefore possible that the principal stationary pattern in the Earth's magnetic field arises from dynamo action due to a simple large-scale convective flow.

The Earth's dipole moment is gradually decreasing. The magnetic field in Roman times is known from measurements on magnetized artefacts to have been stronger than it is anywhere on the Earth's surface today. This decay is rather rapid and is still continuing and, if it continues for a further thousand years, will lead to the elimination of the entire magnetic field. Note that the dipole moment is decreasing not because of a general weakening of the magnetic field at the core surface, but rather because of increasing complexity of the pattern there. The net moment and field strength at the Earth's surface is decreased because of the higher attenuation with distance from the source of small-scale fields.

The dipole moment is a weighted average of the vertical field at the core surface. To obtain the moment, the vertical field is multiplied by the sine of the latitude and the result integrated over the surface. If we plot the *dipole function* – the vertical component times the sine of the latitude – on the core surface in equal area projection we can determine which parts of the magnetic field contribute to the moment and cause its diminution. It is immediately obvious from maps of the dipole function and its rate of change with time that growth of the 'core spots' in the Southern Hemisphere causes the fall in dipole moment (Fig. 5). These regions of reverse flux not only grow in strength but they also migrate south into regions where the sine of the latitude is greater, thereby having a bigger effect on the dipole moment. If another such core spot were to form and drift south-west with the speed of the existing two, the moment would be reduced to zero in about another thousand years (Gubbins 1987). Understanding the mechanism causing these spots may indicate how the Earth's magnetic field undergoes polarity reversal. Core spots can form by upwelling of flux which initially resides inside the core and is predominantly horizontal. The flux is pushed through the surface forming a pair of spots, both of which intensify, one reversed and one in the same sense as most of the flux in the southern hemisphere. This mechanism is similar to the one operating on the Sun producing Sunspots.

The best known feature of geomagnetic secular variation is the westward drift. Drift occurs mainly in the Atlantic region and, rather surprisingly, it is absent from the core–mantle boundary beneath the Pacific hemisphere. It cannot therefore be explained by a solid-body rotation of the core relative to the mantle: the motion of core fluid relative to the mantle is more complex. If electrical diffusion can be ignored, the magnetic field can be treated as if

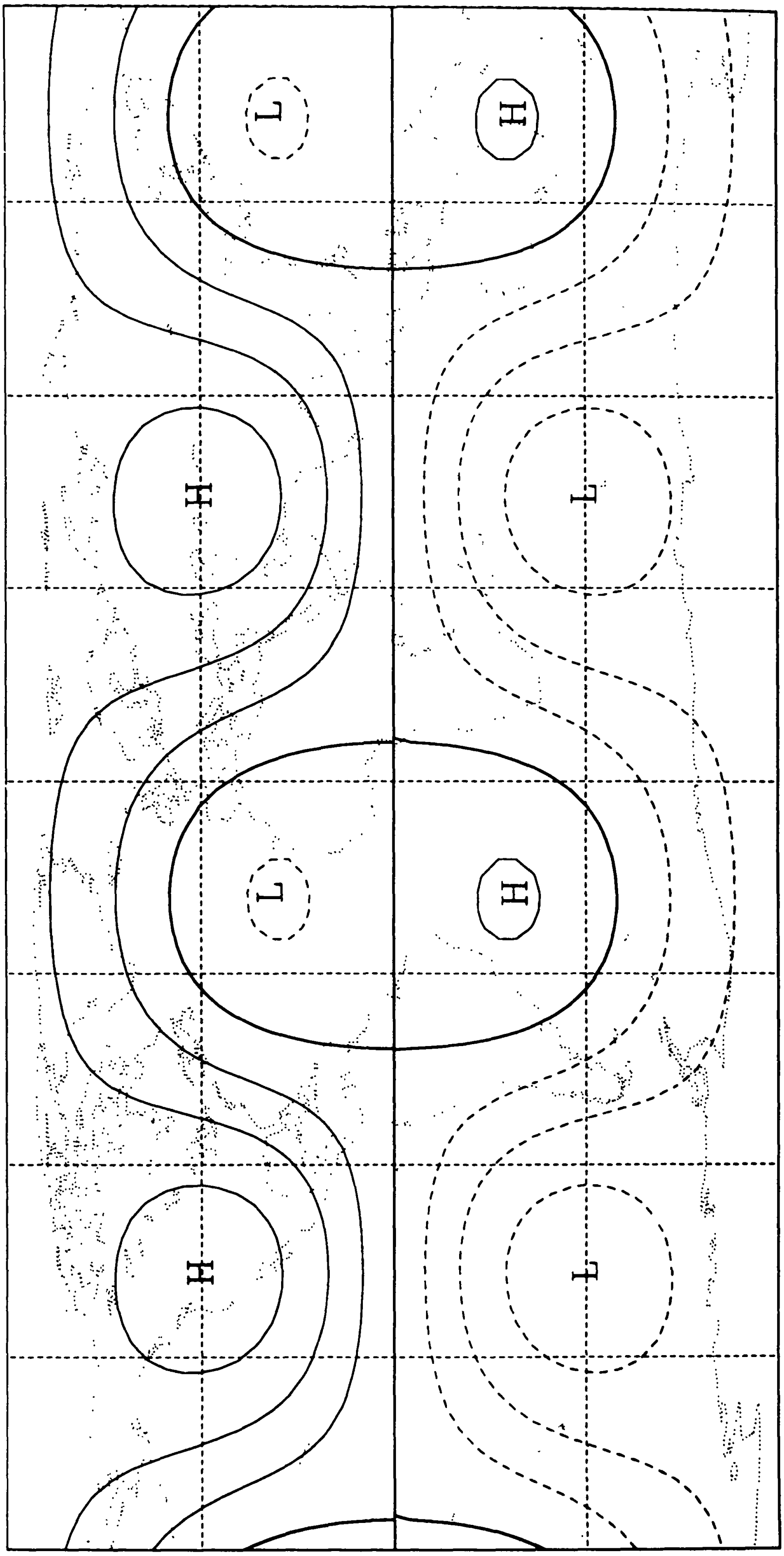

FIG. 4. The vertical component of magnetic field calculated from the solution to the kinematic dynamo problem with a simple, large-scale convective flow pattern and differential rotation. The high symmetry reflects the simplicity of the solution. Note the four regions of intense magnetic field which occur above downwelling fluid, the flow towards the downwelling serves to concentrate the flux. These concentrations are to be compared with the four stationary lobes in the Earth's field in Fig. 3. Redrawn after Hutcheson (1990).

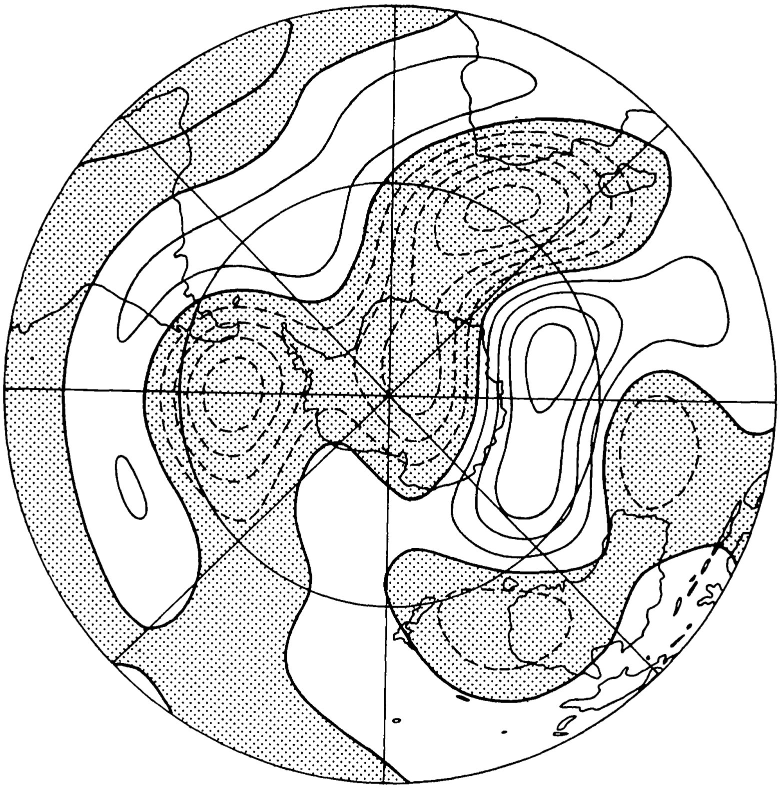

FIG. 5. The rate of change of the *dipole function* in the Southern Hemisphere in equal area projection for the mid-twentieth century. The function is $Z \cos\theta$, where Z is the vertical component of magnetic field and θ the colatitude. The Earth's dipole moment is the integral of the dipole function, so this map illustrates those core field features responsible for its present decay. The Northern Hemisphere map is relatively featureless, showing that almost all of the drop in moment is caused by motion and growth of the reverse flux patches beneath the South Atlantic region. From Gubbins (1987).

frozen to the fluid and it becomes possible to determine fluid velocity at the core surface from observations of the secular variation (Roberts & Scott 1965; and a recent review is Bloxham & Jackson 1991). A relatively simple flow found by Lloyd & Gubbins (1990), consisting of two gyres, one in the North Atlantic and one in the South Atlantic, as shown in Fig. 6, can explain over 95% of the observed change in the field at the present day.

Why should some features of the magnetic field drift and others not? Why should the Pacific region remain static? One possible explanation is that the solid boundary influences the core flow and pattern of magnetic behaviour. Calculations of fluid flow at the core–mantle boundary from secular variation also allow the calculation of its vertical gradient, the shear (Lloyd & Gubbins 1990). The sign of the shear indicates that the flow decreases in intensity with depth in the core, suggesting perhaps that the flow is driven from the boundary rather than from below.

The morphology of the geomagnetic field suggests that a stationary pattern (the four lobes) is generated deep down by rather slow fluid flow operating a dynamo mechanism, which is disrupted by vigorous motions forced by the boundary. There are further reasons, which I shall discuss in

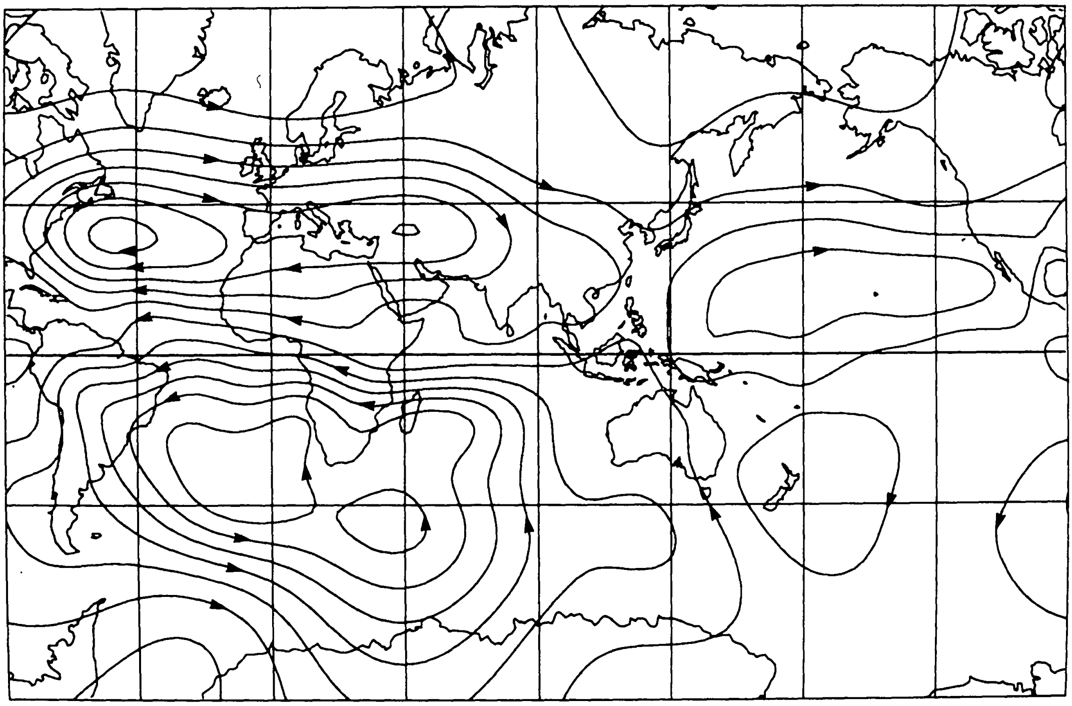

FIG. 6. Fluid motions at the core surface calculated from recent secular change in the magnetic field. The flow is assumed to be toroidal and accounts for more than 95 per cent of the observed magnetic change. From Lloyd & Gubbins (1990).

the next section, to suppose that both the deep and surface flows are influenced by the boundary.

4 CORE–MANTLE INTERACTIONS

The solid mantle can influence core flow through topography (bumps on the boundary influence the flow; Hide 1967); temperature anomalies (variations in heat flux across the core–mantle boundary drive flow; Bloxham & Gubbins 1987); variations in electrical conductivity (regions of very high electrical conductivity may exist in the mantle and could screen out magnetic variations in certain places; Li & Jeanloz 1987); or possibly chemical variations in the mantle. All these ideas have been suggested but only the second, temperature, has been developed into a quantitative theory and its predictions tested against observation. Gubbins (1991) shows that most of the toroidal flow in Fig. 6 can be driven by reasonable lateral temperature gradients, and Bloxham & Jackson (1991) show that temperature gradients can explain other flows equally well.

Convection in the core and in the mantle must be coupled. The mantle, although solid, convects on a very long time-scale by solid state creep and is often treated as a fluid in simple modelling studies. Two layers of fluid with an interface may be coupled together by viscous forces; in this case flow at the top of the lower region drives flow in the same direction in the fluid above it. A convective cell in the lower region drives penetrative convection in a cell rotating in the opposite direction in the upper layer.

Viscous coupling is only important if the viscosities of the two fluids are comparable, which is manifestly not the case for the mantle and core. The core has a viscosity roughly similar to that of water whereas the mantle is harder than any solid container we are likely to construct in the laboratory for a convection experiment; the core must therefore see the mantle as a rigid envelope and the coupling is thermal. Consider again a convective overturn in the lower fluid. Over the rising plume, the upper fluid is heated and therefore becomes buoyant, and fluid in the upper layer rises above the rising plume in the lower layer. Likewise, the sinking plume in the lower layer cools and the fluid in the upper layer immediately above it also becomes cold and sinks, thereby setting up a convective cell in the upper layer which rotates in the same direction as in the lower layer, creating flows in opposition across the interface. This is in contrast to viscous coupling, in which shear stresses across the interface drive flows in the same direction in both layers. In a real situation the connection between the two layers may be more complicated, or even time dependent (Zhang & Gubbins 1991).

Core flows are measured in kilometres per year; very much faster than mantle convection flows which, like the motions of the plates, are measured in centimetres per year. The core fluid will act relatively rapidly to eliminate any temperature variations that are created by mantle convection: in fact, the temperature variations are unlikely to exceed a small fraction of one degree and the core–mantle interface will appear to the mantle as very close to isothermal. Any convecting fluid subjected to a constant temperature boundary must allow variations in heat flux: it is impossible to fix both temperature and heat flux. Numerical models of mantle convection suggest the variation may be as much as 100 per cent (G.Houseman, personal communication 1986). The induced core flow acts to carry heat from where the heat flux is low to regions where it is high. Again, numerical values suggest that core flows of the magnitude suggested by the magnetic variations can be driven by quite modest variations in heat flux (Bloxham & Gubbins 1987).

There is another thermal boundary layer at the base of the mantle; the bottom boundary is isothermal and therefore regions with high heat flux will have a large temperature drop across the boundary layer and the top of the boundary layer will be cold. Likewise, regions of low heat flux will be hot at the top of the boundary layer. Seismic waves sample the temperature of the mantle indirectly through the effect of temperature on the rigidity. Lateral variations in seismic wave speed suggest that the temperature variation could be several hundred degrees, ample to drive typical core flows of a few km yr^{-1}. Gubbins & Richards (1986) show a map corresponding to the temperature at the base of the mantle which exhibits some interesting correlations with some of the features of the magnetic field (Fig. 7). In particular, the four main lobes coincide with cold regions, the Pacific hemisphere is hot, as is the region beneath Africa where upwelling may force flux expulsion. This correlation is rather different from the one proposed much earlier by Hide & Malin (1970), in which only the non-dipole part of the magnetic field was correlated with the low-order gravity field after rotation to account for the westward drift.

The deep-seated core convection may also couple to variations in

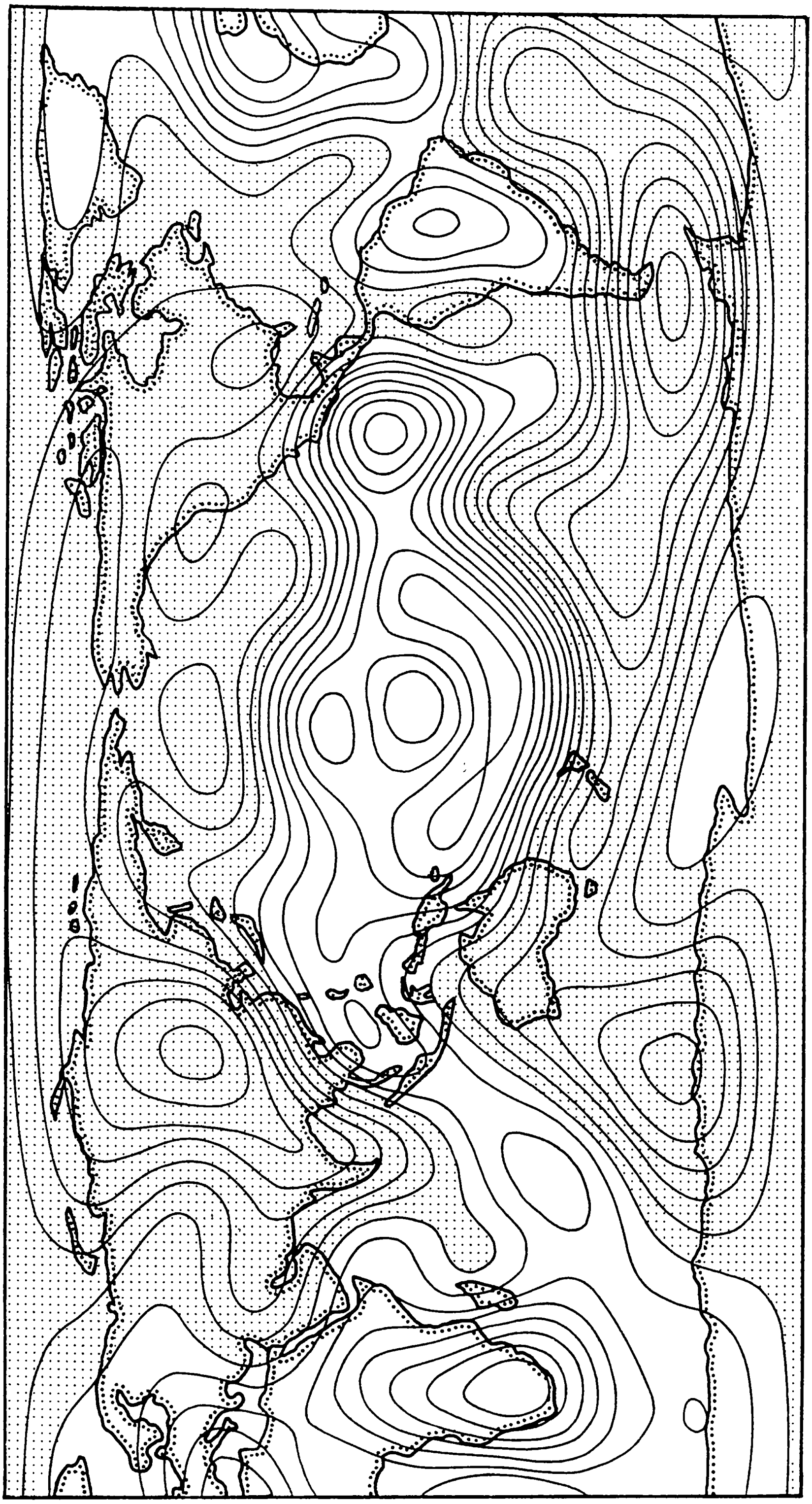

FIG. 7. An estimate of the temperature of the lowermost mantle inferred from gravity and seismic velocities. The stippled region is cold. Note the correlation between cold patches and the four main lobes in the field in Fig. 3, the hot region beneath southern Africa where flux expulsion occurs, and the generally hot region beneath the Pacific basin.

temperature across the core–mantle boundary. Normally fluid flows in rotating convection drift in longitude, but a forced variation in boundary heat flux may favour a stationary pattern locked to the imposed boundary temperature, explaining the four main stationary flux patches. Time-dependent core convection, in the form of drifting rolls for example, may lock to the imposed boundary condition for an extended period of time, then perhaps suddenly change and reform relatively quickly to lock once again. Such phenomena have been observed in baroclinic experiments (e.g. Hide 1966).

Is the mantle influenced by core convection? The time-scale of mantle convection is so long that one might think it unlikely. However, core convection is strongly influenced by the Earth's rotation and the inner core. Possibly the anomalies we observed at the base of the mantle, particularly those coincident with the main lobes in the field, have developed in response to the predominant time-averaged fluid flow in the core. Once these anomalies form, and the core locks to it, it is likely to remain in that state for a relatively long period of time. Rotating convection has a characteristic latitude dependence in the heat flux, with highest heat flowing across mid-latitudes (Gilman 1977; Zhang & Busse 1988), and mantle convection may adjust so that maximum heat is transported in mid-latitudes.

There is a further complication: the Earth tends to spin with its principal axis of inertia along the rotation axis, thus making the largest departure from hydrostatic shape coincide with the equator. Mantle convection can lead to changes in the principal axis of inertia which will cause the mantle to roll over and present the principal inertia axis along the spin axis once again. This is an example of 'true polar wander'; it is seen by the core as a movement of the features on the core–mantle boundary. Plate motions are represented as rotations on a sphere by *poles of rotation*: a pole of rotation is a point on the Earth's surface that is stationary when viewed from two separate plates; the relative motion of the two rigid plates is described completely by rotation about an axis through the pole. There are many poles of rotation, one corresponding to every pair of plates and these poles show a remarkable concentration in high latitudes (e.g. Minster & Jordan 1978). Clustering of the poles of rotation arises naturally from three requirements imposed by the system. First, it is a stable configuration of moving plates, and is therefore favoured. Secondly, as Busse (1983) has pointed out, the dominant large-scale pattern of mantle convection determines the principal axis of inertia and is therefore fixed relative to the geographic axis and, provided the plate motions are associated with the dominant mode of large-scale convection, the poles of rotation can be expected to cluster in high latitudes. A third suggestion, presented here, is that core motions tend to lock to mantle convection with high heat flux in equatorial or mid-latitudes and low heat flux over the poles. This long-term influence on mantle convection will favour plate motions which maximize the heat flux in equatorial latitudes: those with poles of rotation at high latitudes.

5 SUMMARY

I have tried to describe some of the major advances of the last two decades in our understanding of the processes operating in the core and deep mantle that generate the magnetic field. Simple energy considerations have shown the very existence of the magnetic field to be an inseparable part of the Earth's thermal history. The energy budget is rather tight and the models must not allow too much heat to pass across the core–mantle boundary. This is quite a serious restriction on the range of possible mechanisms available for powering the field and a useful constraint on the range of parameters governing convection: the Rayleigh number cannot be too large. Models of the Earth's thermal history must satisfy two severe constraints: the mantle must convect sufficiently vigorously to allow sufficient heat to escape from the core to drive the dynamo, but not so much as to freeze the liquid core. Our neighbouring planets lack strong magnetic fields like the Earth's and perhaps they have failed to satisfy one of these two conditions: their cores are either stable because of insufficient heat loss, or solidified because of excessive heat loss.

Slow changes in the magnetic field have been observed over the past few centuries, since magnetic surveying began, and even larger changes are inferred from studies of magnetized rocks and archaeological remains. These changes have been mapped into fluid flow on the core surface and there is now substantial agreement between different calculations. Furthermore, the morphology of the stationary part of the magnetic field at the core–mantle boundary has a characteristic fourfold symmetry which could arise from dynamo action of a simple, large-scale convective flow operating deep within the core.

Flow near the core surface could be forced by lateral variations in temperature of heat flux across the core–mantle boundary. Preliminary calculations without magnetic fields show convection driven in this way penetrates deep within the core. Comparison of maps of the geoid, seismic velocity of the lower mantle, and magnetic field suggests correlations that could be explained by thermal forcing of core flow. Furthermore, deep core convection could be locked to thermal anomalies in the lowermost mantle causing stationary flows. This steady pattern can be disrupted by surface flow, also driven by the influence of the overlying solid mantle.

Finally, coupling of the convection systems in both core, where the dynamics is governed by rotation and magnetic fields, and the mantle, which has a much longer overturn time and therefore imposes long-term conditions on core convection, may explain the curious clustering of poles of rotation of the plates in high latitudes: rotation imposes a latitudinal variation of heat flux from the core which requires more heat to be transferred through the mantle in equatorial than polar regions. This condition is satisfied most easily by arranging the spreading ridges to lie north–south, with the corresponding poles of rotation in high latitudes.

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