PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1989 **328**, 365-375
doi: 10.1098/rsta.1989.0041

Phil. Trans. R. Soc. Lond. A **328**, 365–375 (1989)
Printed in Great Britain

Implications of geomagnetism for mantle structure

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Recent studies of the magnetic field at the core–mantle boundary have revealed fixed sites of either static magnetic features or persistent secular variation. This suggests that part of the magnetic-field behaviour is controlled by the mantle. The most plausible mechanism for core–mantle interaction is thermal coupling, although topography may also be significant. The magnetic sites coincide with anomalies in lower-mantle seismic velocity, as determined from tomography, and density, as determined by flow models of mantle convection constrained by tomography and the geoid. Some magnetic features coincide with subduction zones, particularly those near Indonesia; they may be caused by bumps on the core–mantle boundary beneath trenches. Palaeomagnetic pole positions suggest the magnetic behaviour has persisted for at least 5 Ma, as would be expected if it were controlled from the mantle. These conclusions could be quantified if the frozen-flux hypothesis allowed determination of fluid flow at the core surface, but unfortunately failure of the hypothesis makes all such determinations suspect. Core motions calculated so far suggest the flow is mainly toroidal. Questions about the dynamics of the flow (whether it is steady, stratified, or geostrophic) remain unresolved.

1. Introduction

Secular variation (sv) is the slow change in the Earth's magnetic field that is caused by fluid motion in the liquid core, rather than by external effects. These fluid flows may be an integral part of the dynamo process responsible for generation of the main field, in which case an understanding of sv would lead to a better understanding of the dynamo process, or they may be quite separate (operating on different time scale and in a different part of the liquid core: near the core–mantle boundary, CMB, with the dynamo operating deeper down, for example).

The past five years has seen considerable advances in our understanding of sv. First, a sudden change in 1970 at many observatories in Europe and elsewhere, now called the *jerk*, showed that core fields change on a more rapid timescale than had hitherto been suspected (a review is given in Courtillot & LeMouël 1984). The changes are probably associated with changes in the length of day (Vestine 1952; Le Mouël *et al.* 1981). Secondly, the satellite, MAGSAT (Langel *et al.* 1980) provided the best 'snapshot' of the magnetic field to date and stimulated collaborative research on sv. Thirdly, new studies of old magnetic observations (Gubbins & Bloxham 1985; Bloxham & Gubbins 1985, 1986; Langel *et al.* 1986; Bloxham *et al.* 1989), analysed by new inverse theoretical techniques (Whaler & Gubbins 1980; Shure *et al.* 1982; Parker & Shure 1982; Gubbins 1983; Gubbins & Bloxham 1985), has provided a much better picture of the sv during the past three centuries than had previously been available. There have been several attempts to determine fluid flow in the core from sv, which are described in §3.

The radial component of magnetic field at the CMB for epoch 1980 is shown in figure 1.

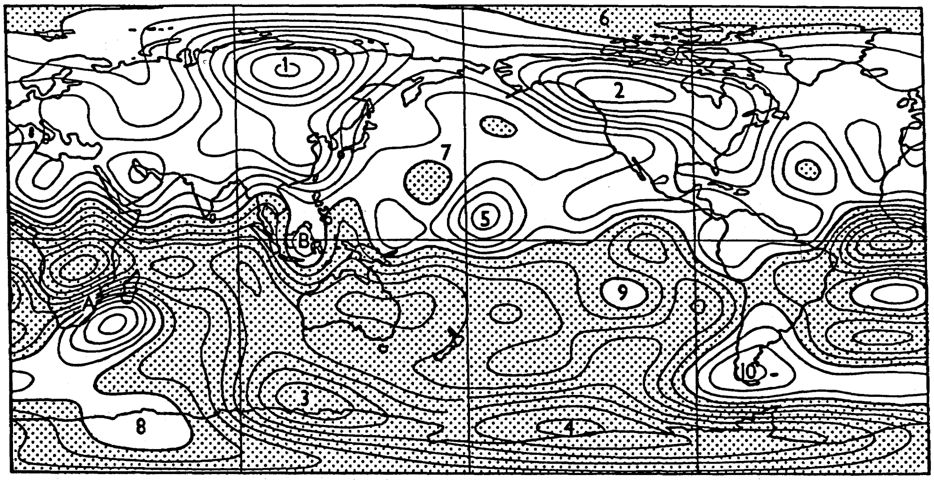

Figure 1. Radial component of magnetic field at the CMB, 1980 (after Gubbins & Bloxham 1985). Contour interval is 100 μT. The thick lines are of zero-radial component: the *null-flux curves*. Features 1–9 have remained nearly stationary throughout the past 300 years. Most of the Earth's dipole moment is contained in features 1–4, called the *main lobes*. Feature 10 and those near A have drifted rapidly westwards. B is the site of rapid *in situ* oscillations.

This model of the main magnetic field is based on MAGSAT satellite data. It was derived by Gubbins & Bloxham (1985), but any model based on a spherical harmonic expansion truncated or tapered near degree 14 will produce a similar map. The analysis assumes the mantle is an electrical insulator. Bloxham *et al.* (1989) have also derived a sequence of field models for epochs 1715, 1777, 1842, 1888, 1905, 1915, 1925, 1935, 1945, 1955, 1966, and 1969, based on nearly 180000 magnetic measurements and using a consistent method of analysis that produces smooth core fields. This 285 year long record gives an excellent picture of recent SV. The time span is long enough to follow movement of certain core-field features across many degrees of longitude, and to observe other features that have remained stationary. The main feature of core-field SV is the westward drift, as it is for surface fields. However, the drift is not global, and is almost completely absent from the Pacific region. One region of low radial flux near Easter Island (feature 9 in figure 1) remains stationary, whereas another patch of flux (near A in figure 1) can be followed from near B in figure 1 in 1777 to its present position near Africa in the same interval of time.

This combination of drifting and fixed features in the field led Bloxham & Gubbins (1987) to suggest the SV was controlled by thermal core–mantle interactions. In this paper, I argue that, as a consequence of core–mantle interactions, published geomagnetic and paleomagnetic data can provide valuable clues to the thermal state and structure of the lower mantle and core. If geomagnetism can provide independent confirmation of proposed models for the lower mantle obtained by seismological and mantle-convection studies, it gives us hope that one day the lower mantle will be mapped and understood in as much detail as the lithosphere. The present situation is similar to that in plate tectonics in 1960. There was then a great deal of circumstantial evidence for contintental drift, some of it dating back several decades. The evidence provided by geomagnetism, through the reversal timescale, converted this circumstantial evidence into a quantitative theory.

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2. Frozen-flux theory and determination of fluid flow at core surface

Roberts & Scott (1965) assumed the core fluid was a perfect conductor and therefore the field lines were frozen to the fluid, by Alfvén's theorem, and could be used as tracers for the flow. Kahle *et al.* (1967) attempted a calculation of fluid flow, but there followed a lull when it was realized that determinations of field at the CMB were poor and determinations of fluid flow from Roberts & Scott's frozen-flux hypothesis were highly non-unique, even with perfect data. Backus (1968) showed that *null-flux curves*, lines where the magnetic field at the core surface is horizontal, are material lines and move with the fluid. It is possible to determine fluid flow normal to these curves but not along them. He also showed the flux through patches of the CMB bounded by null-flux curves remains invariant. Null-flux curves are shown as thick solid lines in figure 1.

Booker (1969) attempted to test the frozen-flux hypothesis by calculating the flux through the northern magnetic hemisphere for several field models. He observed a change associated with the fall in dipole moment, but did not regard it as a violation of the hypothesis because flux could have passed into small-scale features not resolved by his field models. Gubbins & Bloxham (1985) recalculated the flux through the northern magnetic hemisphere using later field models and found in favour of the hypothesis. However, they subsequently studied smaller patches and found a significant change in flux in the south Atlantic region (Bloxham & Gubbins 1986) between epochs 1960, 1970 and 1980, which violated the hypothesis. This small change has now been confirmed as part of a long-term trend dating from the beginning of the century (Bloxham & Gubbins 1985; Bloxham *et al.* 1988). It is not a particularly surprising result, because typical estimates of the electrical conductivity of iron in the core (5×10^5 S m^{-1}) suggest diffusion times of about 100 years for features of the size considered. The frozen-flux hypothesis appears to hold away from the south Atlantic region.

Backus (1968) also derived conditions on the horizontal component of field for the frozen-flux hypothesis to hold. The horizontal components cannot be used to resolve the non-uniqueness in determining fluid flow except on the null-flux curves, although they do provide some information about the shear. In a perfectly conducting core a current sheet may form in the boundary layer at the top of the core, and horizontal components of field may be discontinuous across the CMB. Surface observations of magnetic field only allow determination of the field at the base of the mantle and will not therefore be usable if the jump across the boundary layer is large. Roberts & Scott (1965) analysed the boundary layer and concluded that the jump was negligible; Backus (1968) reanalysed it but came to no firm conclusion; whereas Hide & Stewartson (1972) included Coriolis forces and again concluded the jump was negligible. Barraclough *et al.* (1989) have calculated Backus's conditions and found them to hold for epochs 1960–1980. Thus if we allow use of the radial field to determine core flows, it is consistent to use the horizontal components also.

Determination of fluid flow from magnetic observations requires some regularization to prevent errors in the data from mapping into spurious fluid flows. This regularization also removes the fundamental ambiguity that is present even with perfect data. It is therefore an *ad hoc* means of selecting one particular core flow that fits the data. Several models of fluid flow have been produced in this way, after the pioneering work of Kahle *et al.* (1967), and all suffer from the same fault. More recently, attempts have been made to use the dynamical equations to remove the ambiguity. Three assumptions have been made. I shall discuss each in turn.

First, the flow was assumed stratified and therefore toroidal (Gubbins 1982). The reasons were:

(1) that the heat flow required to sustain the dynamo is rather high and it may not be possible to exceed the adiabatic gradient everywhere in the core; the adiabatic gradient steepens near the CMB, because of the increase in gravitational acceleration across the core, and therefore the most likely site for a sub-adiabatic gradient and stable fluid is near the CMB (Gubbins *et al.* 1982);

(2) low SV occurs near stationary points in the core field, a consequence of stratified flow (Whaler 1980).

Toroidal flows preserve the flux through every patch of the CMB bounded by a contour of radial field (not simply the null-flux curves). They allow determination of fluid flow normal to the contours (but not along them). The ambiguity in determining fluid motion is alleviated but not completely removed by assuming toridal motion. The hypothesis can be tested by calculating the flux integrals that should be conserved, but this has not been done. Several authors have carried out calculations of full fluid velocities and claim the poloidal part is significantly greater than zero, thus contradicting the toroidal hypothesis (Whaler 1986; Gire *et al.* 1986; Voorhies 1986). These statistical arguments are unconvincing, however: they take no account of departures from frozen flux, which are likely to produce spurious poloidal motions.

Secondly, steady flows have been assumed. If the Lorentz forces are weak, the timescale for changes in the fluid velocity might be long compared with that for changes in the magnetic field. In practice, some form of steady flow is always assumed, because SV is estimated by differencing field models at separate epochs. The hypothesis allows unique determination of fluid motion, which is its main attraction. Voorhies & Backus (1985) have proved that any steady flow can be determined uniquely from field models from at least three different epochs. The third epoch allows a second determination of core motion that, provided the field contours are different, allows the non-uniqueness to be resolved. In practice, sufficient time must elapse between the two determinations for the contours to change significantly. Gubbins (1984) studied the 'jerk' interval around 1970 and concluded that the data were inconsistent with steady motion. Nevertheless, there have been several determinations of steady fluid motion (Voorhies 1986; Whaler & Clarke 1988; Bloxham 1988). These authors claim the steady-motion hypothesis is satisfied, in contradiction to Gubbins's result. This may be because they have excluded the jerk or omitted the fine time resolution afforded by observatory annual means around the time of the jerk.

The constraint of steady flow takes the form of a vanishing determinant (Voorhies & Backus 1985). If insufficient time has elapsed between epochs the constraint will be ineffective in restricting the class of fluid flows satisfying the data. It is very likely, therefore, that published 'unique' steady motions are unique because of the regularizing condition used to suppress noise in the determination, and not because of the steady-motion requirement. They are therefore no less *ad hoc* than determinations made without the steady-motion condition. Increasing the time interval, or the accuracy of the field models, is likely to introduce errors due to failure of the frozen-flux hypothesis. The theorem is therefore likely to be of limited use.

Thirdly, LeMouël *et al.* (1985) have assumed tangentially geostrophic flow. This requires the

Lorentz force to be absent from the radial component of the vorticity equation near the CMB. The flow can be determined uniquely within patches of the CMB enclosed by null-flux curves that intersect the geographic equator (see also Backus & LeMouël 1986). Geostrophic motions have been calculated by Gire *et al.* (1986) and Bloxham (1988). The geostrophic constraint takes the form of difference equations that must be satisfied by the spherical harmonic coefficients of the velocity Gire *et al.* (1986). There is a truncation problem: if the velocity series is truncated the geostrophic constraint will not be satisfied by the highest-order harmonics. If the constraint is satisfied perfectly then the high-order harmonices become distorted and it is difficult to fit the observations satisfactorily. Gire *et al.* (1986) applied the geostrophic constraint approximately, in the hope that high harmonics are unimportant, but the truncation problem appears to be very severe. The geostrophic and toroidal motion constraints are $\nabla_h \cdot (\boldsymbol{v} \cos \theta) = 0$ and $\nabla_h \cdot \boldsymbol{v} = 0$ respectively. I have calculated both quantities and found them to be of comparable magnitude for the motions of Gire *et al.* (1986). Bloxham (1988) has calculated both toroidal and fully geostrophic velocities and finds toroidal motions fit the field models better than geostrophic motions. LeMouël (personal communication 1988) has now found satisfactory flows that are fully geostrophic. Thus no calculation demonstrates the core flow satisfies either geostrophic or stratified dynamics.

Maps of toroidal, geostrophic, and steady velocities all account for westward drift of the field pattern in the equatorial Atlantic region and absence of SV in the Pacific. The fluid flow is predominantly westward in the Atlantic hemisphere and absent from the Pacific. The geostrophic and unconstrained flows have upwelling in the Indian Ocean and downwelling off the coast of Peru to allow for this, whereas the toroidal flows return eastwards at high latitudes, avoiding the quiescent Pacific region (for example, see the flows in LeMouël *et al.* 1985). I believe the poloidal part of the flow is rather small and is not adequately determined by any of these calculations; those places where upwelling appears are regions where the frozen-flux hypothesis is suspect because of flux expulsion (Bloxham 1986), and downwelling appears off Peru simply because it must occur somewhere in order to conserve mass.

Core velocity calculations are instructive in providing maps of fluid flow that may aid our intuition, but they are not useful in establishing the dynamical régime in a rigorous statistical manner; in fact, the results may be downright misleading. The flow may appear toroidal (or geostrophic) when in reality it is not. For example, plate movements on the Earth's surface appear horizontal almost everywhere: upwelling and downwelling is confined to ridges and trenches, which occupy very little area. Core convection may be similar, which could explain Whaler's (1980) result. If such is the case, toroidal motions may approximate the flow quite well in most places, but the underlying hypothesis would be quite false.

3. THERMAL CORE–MANTLE INTERACTIONS

Bloxham & Gubbins (1985) suggested several sites of stationary field or of persistent SV activity were tied to the solid mantle. In figure 1, features 6, 7, 8 and 9 are stationary and have low flux; 1–5 are stationary regions of high flux; A is the site of apparent expulsion of toroidal flux; and the undulation in the magnetic equator near B is a site of persistent *in situ* oscillations. Flux concentration could result from fluid downwelling (by Alfvén's theorem the field lines are swept towards the point of downwelling); low flux and toroidal flux expulsion from upwelling. Persistent *in situ* oscillations could be a consequence of a topographic feature on the CMB.

Three mechanisms could explain the mantle's influence of SV. Lateral variation of electrical conductivity in the mantle could preferentially shield SV in, for example, the Pacific region, where it is low. Extreme variations in conductivity are required. The idea is not considered further here. The other two mechanisms are thermal interaction, in which temperature variations in the boundary layer at the base of the mantle drive thermal winds in the core, as proposed by Bloxham & Gubbins (1987), and topography on the CMB, as proposed by Hide (1967) (see also Gubbins & Richards 1986).

Consider thermal interactions first. Lower-mantle convection is likely to be accompanied by lateral variations in temperature of several tens of degrees. There is evidence for lateral variations in seismic velocity in the lower mantle, which could be accounted for by such temperature variations. The core fluid cannot withstand any sizeable lateral variation in temperature, and differences of as much as one degree will drive thermal winds that tend to restore equipotential surfaces to uniform temperature. The mantle will therefore experience a constant temperature, variable heat flux, lower boundary.

There is no doubt that mantle convection will entrain core motions; the only question is whether heat flux variations across the CMB are large enough to drive sufficiently strong core flows to influence the SV: about 0.1–1.0 mm s^{-1}. These flows must carry heat from regions on the CMB where heat transfer into the mantle is low to regions where it is high. The heat carried by the core fluid can be estimated in terms of the fluid velocity, the thermal-diffusion skin depth, and the very small temperature drop experienced by the core fluid in its passage along the CMB (Bloxham & Gubbins 1987). The flow speed can also be related to the small temperature drop by using the thermal wind equation. The resulting heat transfer is of the same order of magnitude as the lateral variation in heat flux into the mantle expected on the basis of mantle convection studies: as much as 100% of the average heat flux (G. A. Houseman, personal communication 1987). Thermal interactions are therefore a plausible agent for sustaining core flows responsible for the SV.

Core fluid must flow from regions of low heat flux, across the CMB, to regions of high heat flux; therefore in the simplest case we expect upwelling beneath the former and downwelling beneath the latter. Regions of high heat flow correspond to low temperatures in the thermal boundary layer at the base of the mantle, and consequently fast seismic velocity (assuming the lower mantle is laterally chemically homogeneous). Bloxham & Gubbins (1987) therefore proposed upwelling of core fluid where the mantle boundary layer was hot, and downwelling where it was cold.

This mechanism for thermal core–mantle interaction can be made quantitative. Assume the frozen-flux conditions hold and the jump in horizontal component of magnetic field across the CMB is negligible. Assume also that the flow is geostrophic, and that the Lorentz force is absent from all three components of the vorticity equation. This set of assumptions goes beyond those made by LeMouël *et al.* (1985), who used only the radial components of the vorticity and induction equations. The vorticity equation is

$$(\boldsymbol{\Omega}\cdot\nabla)\boldsymbol{v} = -\alpha\nabla T\times\boldsymbol{g}, \qquad (1)$$

where α is the thermal expansion coefficient and T is the (nearly uniform) temperature at the CMB. This equation, plus the full magnetic induction equation, allows determination of T everywhere, provided the magnetic field satisfies a certain point condition on the CMB.

All published velocity models show predominantly westward flow in the Atlantic hemisphere.

Equation (1) leads to westward flow if the temperature gradient is in a north–south direction. The ϕ component of (1) gives

$$\frac{\partial v_\phi}{\partial z} = \frac{\alpha g}{\Omega r}\frac{\partial T}{\partial \theta}, \tag{2}$$

which gives a maximum shear at the Equator for a dipolar temperature distribution. This dipolar form can dominate the temperature distribution when a formal inversion is carried out (work in progress). This is a very unsatisfactory result, because the westward drift is attributed to a specific CMB temperature distribution: *one for which there is no independent corroborative evidence.* The westward drift is more likely the consequence of magnetohydrodynamic instabilities, which tend to migrate westward (see, for example, Acheson & Hide 1973). Rather than accept such an implausible explanation for westward drift, we must abandon one of the hypotheses that leads to the determination of temperature. The frozen-flux hypothesis is known to fail in certain regions, but the westward drift is unlikely to be driven by diffusion. The more likely candidate is presence of a Lorentz force in equation (1). The Lorentz force contains derivatives of magnetic field that are not continuous across the CMB, and therefore it cannot be estimated from surface data. Further formal inversion is not possible, and an *a priori* model of Lorentz force is needed. This is an illustration as to how formal inversion can be misleading: the temperature profiles fit the data quite well, and all magnetic field maps satisfy the consistency conditions tolerably well, but the results are physically implausible.

Hide (1967) proposed that topography could influence core flows strongly. There are sound arguments for believing that topographic torquing of the mantle is responsible for observed changes in the length of day (Hide, this Symposium). This coupling is rather different from the longer-term interactions under discussion here. Hide & Malin (1970) proposed a correlation between the non-dipole field, rotated eastwards by about 140°, and the low spherical–harmonic degree terms in the geoid, to support the idea. In terms of the new CMB fields, such as those in figure 1, Hide & Malin's correlation (see also Malin & Hide 1982) appears to be mainly between the rapidly westward-drifting features, such as A in the Atlantic region, and a geoid anomaly almost coincident with the Pacific Basin. There seems no reason to select these two features for correlation, and it is very hard to understand how a topographic feature on the CMB can shed an image of itself in the core field, which subsequently drifts to the west. A bump is likely to produce standing oscillations and generate propagating instabilities or waves, as appears to happen near B of figure 1.

A bump also has a thermal effect. If we cause a bump to form on the CMB, so that mantle protrudes into the core, it will entrain convection in the core in exactly the same way as if we had made that part of the mantle cold. The bump introduces a cold temperature at depth within the core. It is therefore difficult to separate topographic and thermal anomalies in a convecting mantle. Cold, descending mantle material will cause both a bump and a cold patch on the CMB, so both effects are inextricably linked. It is possible, in principle, to determine CMB topography independently from the seismic velocity of the lower mantle, and thereby separate the two effects. If the mantle is chemically inhomogenous the effects of bumps and temperature will be difficult.

4. CONFIRMING EVIDENCE

The theory of core–mantle interactions outlined in the previous section is predictive, and can therefore be confirmed or disproved by using different observations. If the sv is controlled by the mantle, then we should expect the same field morphology and pattern of sv to apply throughout the recent geological past. The historical record may be too short to provide a 'typical' example of field behaviour, but there is hope that palaeomagnetism can provide evidence of long-term geomagnetic changes. Palaeomagnetic pole determinations have been used to reconstruct past plate motions. In the past 5 Ma the plates have not moved significantly and the collection of pole positions allow study of the non-dipole field. One well-known feature of these pole positions is 'far-sidedness' (Wilson 1970), in which a palaeomagnetic pole always appears further away than the geographical pole. The effect persists throughout many reversals. I have suggested this is an effect of geographical distribution of the data (Gubbins 1988). The four main lobes of the field (1–4 in figure 1) cause far-sidedness in the extreme north Atlantic, as observed, but *near*-sidedness in the corresponding latitudes in the Pacific hemisphere; the reverse flux features (such as 10 in figure 1) cause *near*-sidedness in the south Atlantic. Significant *near*-sidedness is found in the south Atlantic and north Pacific regions when the palaeomagnetic pole data are grouped according to geographical location. Unfortunately there are rather few pole determinations from these areas. The model also predicts near-sidedness in the southeast Pacific, which is not observed. No other satisfactory explanation has been offered for the far-sided bias to the pole positions.

Seismic tomography gives an estimate of seismic velocity in the lower mantle that may be interpreted as temperature if the mantle is chemically homogeneous. A map of velocity anomalies derived by Dziewonski (1984) is shown in figure 2. The fast regions (marked +) coincide with flux lobes 1 (contour +125 in figure 2) and 2 (contour +75 in figure 2), and the

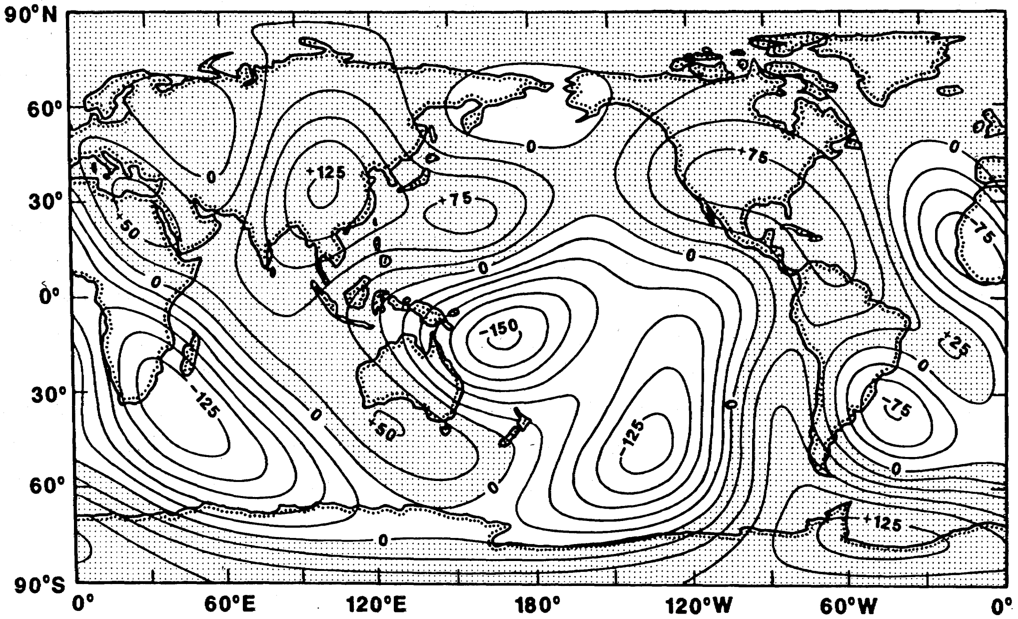

FIGURE 2. Lateral variations in P-wave velocity in the lowermost mantle, after Dziewonski (1984). Contour interval is 25 m s^{-1}.

slow region (contour −125 in figure 2) with the region of flux expulsion (A in figure 1). The agreement is rather qualitative, but is encouraging support for thermal interactions. The main core features are likely to be generated with antisymmetry about the equator (Gubbins & Bloxham 1987) and therefore if lobes 1 and 2 are tied, then 3 and 4 would be fixed. In fact we should not expect perfect coincidence of features. Gubbins & Bloxham (1987) argue that the flux lobes must lie close to the inner core circle if they are part of the main dynamo field and therefore a manifestation of deep-core convection; they may therefore be concentrated some way away from the temperature anomaly (such as appears to be the case with lobe 1).

A better and more surprising correlation is shown by a calculation of 'dynamical CMB topography' using the method of Hager *et al.* (1985). A model of mantle convection is based on the geoid and seismic tomography data assuming chemical homogeneity and a simple relation between density and seismic velocity. The CMB topography results from temperature variations throughout the lower mantle, and is therefore a good guide to the overall temperature anomaly in the lowermost mantle. Figure 3 illustrates the results of one such calculation; the expected temperature anomalies are all present, including hot regions near magnetic features 6, 7, 8 and 9, and a small cold spot near 5. It is not possible to do full justice to the comparison of the various geomagnetic and tomographic maps in this short review. A more complete discussion and a full set of figures is given in Bloxham *et al.* (1989).

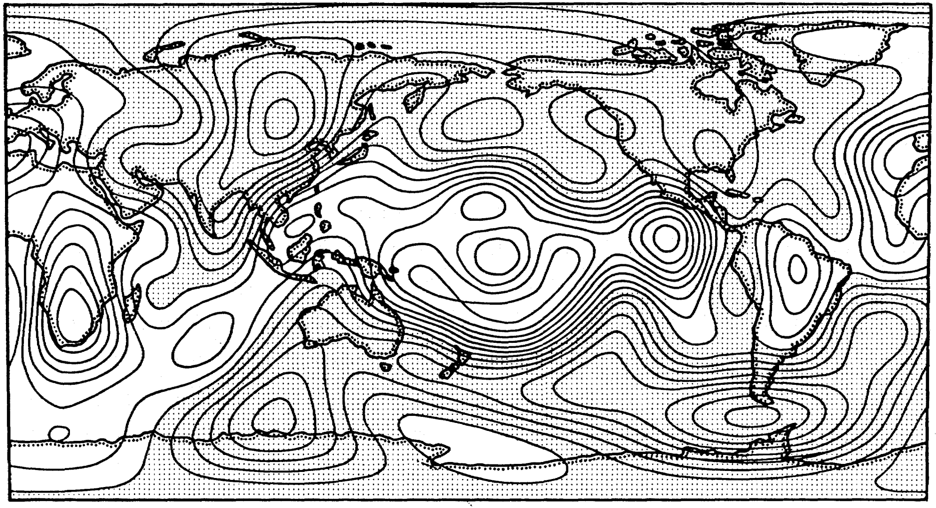

FIGURE 3. 'Dynamic CMB topography' as calculated by the method of Hager *et al.* (1985) from Gubbins & Richards (1986). Assumed viscosity models and relations between seismic velocity and density are constrained by the geoid and seismic tomography to produce density and temperature anomalies throughout the convecting mantle. Deformations to the interfaces are also produced, as shown here for the CMB. The contour interval is 400 m. These deformations are directly related to an average of the temperature variations in the overlying mantle.

Morelli & Dziewonski (1987) have determined a model of the CMB directly from observations of PcP and PKP waves. Surprisingly, they find significant topography beneath the subduction zones. It would be easy to dismiss this result as perhaps an earthquake source effect, but the geomagnetism lends some support to it. The region of very low SV in the Pacific is delineated well by the ring-of-fire around the Pacific: perhaps there is a connection via bumps on the CMB. The topography on the CMB is beneath the trenches and not at the base of subducted lithosphere; it must therefore be associated with a mass anomaly at the trench rather than some effect of the whole slab. This observation must remain questionable until the seismological result is confirmed and some satisfactory mechanism is found for topographic interaction between the core and mantle.

5. Conclusions

I have reviewed a number of new ideas for driving SV. The main conclusion is that formal inversions for fluid velocity at the core surface are likely to yield maps that will aid our intuition, but they cannot be used in a quantitative way to confirm or deny hypotheses for the underlying dynamics. Future advances are more likely to come from developing specific models (for westward-drifting instabilities, for example), and making qualitative comparisons with observations, than from inversion.

The qualitative ideas presented in this paper can be classified as reliable, plausible, or speculative (depending more on the nature of the theory than the statistical fit to the observations). Reliable results include the field morphology at the CMB, the general pattern of SV (such as westward drift in the Atlantic hemisphere and low SV in the Pacific region, oscillations and drift of persistent features in the field, even some quite small ones, and predominantly westward fluid motion in the Atlantic hemisphere region, a feature shared by all velocity determinations). It is also quite clear that flux diffusion occurs on parts of the CMB.

If the temperature anomalies inferred from tomographic studies of the lower mantle exist, they will drive fluid flow in the core of the right magnitude to cause SV. The theory of thermal interactions is at this stage plausible, and needs better confirmation from independent data and a more quantitative theory to be made reliable. It is also likely that Lorentz forces play an important role in the SV.

Topographic interaction between the core and mantle is speculative. The tomographic results of Morelli & Dziewonski (1987) must be confirmed, and a theory found that can explain how a small bump on the CMB can produce a drastic effect on the magnetic field. There is a good analogy with meteorology: it is well known that mountains can affect the weather, but a mountain chain like the Andes does not stop all atmospheric circulation to the east of it. Something equally drastic must happen to the west of a bump on the CMB beneath the west coast of South America to explain the absence of SV in the Pacific hemisphere.

References

Acheson, D. J. & Hide, R. 1973 *Rep. Prog. Phys.* **36**, 159–221.
Backus, G. E. 1968 *Phil. Trans. R. Soc. Lond.* A **262**, 239–266.
Backus, G. E. & LeMouël, J.-L. 1986 *Geophys. Jl R. astr. Soc.* **85**, 617–628.
Barraclough, D. R., Gubbins, D. & Kerridge, D. 1989 *Geophys. Jl R. astr. Soc.* (Submitted.)
Bloxham, J. 1986 *Geophys. Jl R. astr. Soc.* **87**, 669–678.
Bloxham, J. 1988 *Geophys. Res. Lett.* **15**, 585–588.
Bloxham, J. & Gubbins, D. 1985 *Nature, Lond.* **317**, 777–781.
Bloxham, J. & Gubbins, D. 1986 *Geophys. Jl R. astr. Soc.* **84**, 139–152.
Bloxham, J. & Gubbins, D. 1987 *Nature, Lond.* **325**, 511–513.
Bloxham, J., Gubbins, D. & Jackson, A. 1989 *Phil. Trans. R. Soc. Lond.* (Submitted.)
Booker, J. R. 1969 *Proc. R. Soc. Lond.* A **309**, 27–40.
Courtillot, V. & LeMouël, J.-L. 1984 *Nature, Lond.* **311**, 709–716.
Dziewonski, A. M. 1984 *J. geophys. Res.* **89**, 5929–5952.
Gire, C., LeMouël, J.-L. & Madden, T. 1986 *Geophys. Jl R. astr. Soc.* **84**, 1–29.
Gubbins, D. 1982 *Phil. Trans. R. Soc. Lond.* A **306**, 247–254.

Gubbins, D. 1983 *Geophys. Jl R. astr. Soc.* **73**, 641–652.

Gubbins, D. 1984 *Geophys. Jl R. astr. Soc.* **77**, 753–766.

Gubbins, D. 1988 *J. geophys. Res.* **93**, 3413–3420.

Gubbins, D. & Bloxham, J. 1985 *Geophys. Jl R. astr. Soc.* **80**, 696–713.

Gubbins, D. & Bloxham, J. 1987 *Nature, Lond.* **325**, 509–511.

Gubbins, D. & Richards, M. 1986 *Geophys. Res. Lett.* **13**, 1521–1524.

Gubbins, D., Thomson, C. J. & Whaler, K. A. 1982 *Geophys. Jl R. astr. Soc.* **68**, 241–251.

Hager, B. H., Clayton, R. W., Richard, M. A., Comer, R. P. & Dziewonski, A. M. 1985 *Nature, Lond.* **313**, 541–545.

Hide, R. 1967 *Science, Wash.* **157**, 55–57.

Hide, R. & Malin, S. R. C. 1970 *Nature, Lond*, **225**, 605–609.

Hide, R. & Stewartson, K. 1972 *Rev. Geophys. Space Phys.* **10**, 579–598.

Kahle, A. B., Vestine, E. H. & Ball, R. H. 1967 *J. geophys. Res.* **72**, 1095–1108.

Langel, R. L., Estes, R. H., Mead, G. D., Fabiano, E. B. & Lancaster, E. R. 1980 *Geophys. Res. Lett.* **7**, 793–796.

Langel, R. L., Kerridge, D. J., Barraclough, D. R. & Malin, S. R. C. 1986 *J. Geomagn. Geoelect, Kyoto.* **38**, 573–597.

LeMouël, J.-L., Gire, C. & Madden, T. 1985 *Physics Earth planet. Inter.* **39**, 270–287.

LeMouël, J.-L., Madden, T. R., Ducruix, J. & Courtillot, V. 1981 *Nature, Lond.* **290**, 763–765.

Malin, S. R. C. & Hide, R. 1982 *Phil. Trans. R. Soc. Lond.* A**306**, 281–289.

Morelli, A. & Dziewonski, A. M. 1987 *Nature, Lond.* **325**, 678–683.

Parker, R. L. & Shure, L. 1982 *Geophys. Res. Lett.* **9**, 812–815.

Roberts, P. H. & Scott, S. 1965 *J. Geomagn. Geoelect, Kyoto* **17**, 137–151.

Shure, L., Parker, R. L. & Backus, G. E. 1982 *Physics Earth planet. Inter.* **28**, 215–229.

Vestine, E. H. 1952 *Proc. natn. Acad. Sci. USA.* **38**, 1030–1038.

Voorhies, C. V. 1986 *J. geophys. Res.* **91**, 12444–12466.

Voorhies, C. V. & Backus, G. E. 1985 *Geophys. Astrophys. Fluid Dyn.* **32**, 163–173.

Whaler, K. A. 1980 *Nature, Lond.* **287**, 528–530.

Whaler, K. A. 1986 *Geophys. Jl R. astr. Soc.* **86**, 563–588.

Whaler, K. A. & Clarke, S. O. 1988 *Geophys. Jl R. astr. Soc.* **94**, 143–155.

Whaler, K. A. & Gubbins, D. 1980 *Geophys. Jl R. astr. Soc.* **65**, 645–693.

Wilson, R. L. 1970 *Geophys. Jl R. astr. Soc.* **19**, 417–437.