exhibit quite different dynamical behaviour[11]; accordingly, we expect the behaviour inside the projection of the inner core, along the rotation axis, onto the CMB, which is a circle of 20.4° (Fig. 2), to be different from that outside. The positions of the two main lobes in each hemisphere are consistent with convection rolls parallel to the rotation axis and tangential to the inner core. In Busse's simple model[12] each convection roll has flow along its length induced by the boundary providing the helicity required for dynamo action. Downwelling flow along the rolls will concentrate flux as observed; alternating with these rolls we expect other rolls along which the flow is towards the CMB. Such a roll should be centred on 180° (midway between the concentrations of flux at 120° E and 120° W), where we observe low flux as a result of the upwelling.

The location of the main lobes near 120° W and 120° E suggests a missing third pair of lobes near Greenwich meridian resulting in a three-fold azimuthal symmetry. This would result from a total of six convection rolls, three with flow away from the CMB, and three with flow towards the CMB. The 'missing' third pair of lobes would be in the Atlantic Ocean where the secular variation is strong. We propose that the vigorous fluid motions associated with this stronger secular variation have prevented their formation.

The inner core circle is comparable in size with the zero flux patch observed there (Fig. 2); this may be a result of the different dynamics in this region.

We have presented a highly idealized model of the geodynamo, for a spherical symmetric Earth, with a three-fold azimuthal symmetry and perfect antisymmetry about the equator. In a companion paper we argue that this simple picture is complicated by the effect of lateral heterogeneities in the lower mantle on the flow in the core, which may explain the asymmetrical nature of the secular variation and control the azimuthal orientation of the rolls and other features.

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Thermal core–mantle interactions

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Maps of the magnetic field at the core–mantle boundary for 1715–1980 reveal static features in the field and an absence of westward drift from much of the core–mantle boundary. The static features suggest that flow in the core is coupled to the mantle. We examine different coupling mechanisms and predict lateral inhomogeneity at the core–mantle boundary. Comparison with models of the lower mantle and core–mantle boundary derived seismically and from the geoid is encouraging, though their resolution is currently inadequate for a full comparison to be made with the much better-resolved magnetic field.

In an earlier paper[1] we presented models of the magnetic field at the core-mantle boundary (CMB) at approximately 60 yr intervals from 1715 to 1980. We showed that the secular variation (SV) is confined mainly to the hemisphere 90° E to 90° W, where its character has remained unaltered throughout the 265 yr time-span of the models. Elsewhere we identified static features in the field at the CMB. We suggested that this confinement of SV to one hemisphere and the presence of many static features is the result of coupling of flow in the core to the mantle. Mean zonal flows are expected on theoretical grounds[2,3]: the absence of westward drift of features in the field at the CMB in the Pacific hemisphere suggests that flow in the core may be coupled to the mantle. The flux patches beneath Siberia and Canada, which we have identified with convection rolls[4], should also drift[5]: no drift of these features is observed.

Stationary patches of intense field (static flux bundles) are labelled 1-5 in Fig. 1; they were attributed to flux concentration by downwelling fluid, associated with cold mantle, balancing diffusive decay[1]. Likewise, upwelling may form zero flux patches (labelled 6–9 in Fig. 1) by sweeping field lines away, although we believe the polar patches (6 and 9) to be associated with the dynamical influence of the inner core[4]. In regions where the subsurface toroidal field is strong, upwelling will concentrate intense field beneath the CMB[7,8] leading to the formation of core spots. The core spot pair (10–11) appeared to form under the western Indian Ocean and intensified beneath southern Africa.

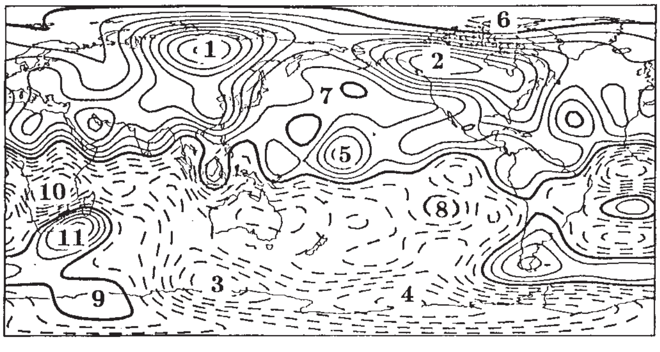

Fig. 1 Map of the radial component of the magnetic field at the core-mantle boundary for 1980 (ref. 6), produced assuming an insulating mantle. Contour interval is 100 μT; solid contours represent flux into the core, broken contours flux out of the core; bold contours represent zero radial field. The following features are indicated: static flux bundles (1-5); static zero flux patches (6-9); core spots (10-11).

We propose that flow in the core is thermally coupled to the lower mantle, with upwelling beneath hot regions of the lower mantle and downwelling beneath cold regions. Such an argument may be too simplistic: the problem of coupled convection between two fluids of such vastly different properties requires careful analysis. Jones[9] has argued that lateral temperature variations on the CMB will only affect the flow in a thin layer near the CMB. If the upper regions of the core are strongly stably stratified then such effects will be confined to a thin layer, but if we assume the whole core convects then lateral temperature variations in the lowermost mantle may affect a larger region. Free convection in the core, resulting most probably from crystallization at the inner core boundary, drives the dynamo. Free convection is driven in the lower mantle, in large part, by the heat flux from the core. Convection in the lower mantle results in large lateral temperature variations just above

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the CMB: these lateral temperature variations act back on the core to force convection in the core. The forced convection in the core must be relatively weak otherwise the heat flux from beneath hot regions of the mantle to beneath cold regions will be sufficient to remove any lateral temperature variations from the lower mantle on a very short timescale. However, even if the forcing is very weak compared with the free convection it may still be sufficient to affect the pattern of convection in the core, by forcing alignment of convection cells in the core with thermal anomalies in the lowermost mantle.

We can make this argument more quantitative. Lateral temperature variations forcing core flow may be roughly estimated by balancing Coriolis and buoyancy torques:

$$\Omega U \approx \alpha g \Delta T \qquad (1)$$

where $\alpha = 5\times10^{-6}$ is the coefficient of thermal expansion[10], g the acceleration due to gravity, Ω the diurnal rotation rate and T the temperature. Taking 5×10^{-4} m s^{-1} as a typical value of U, then the lateral temperature variations on the CMB $\Delta T \approx 5\times10^{-4}$ K. From the point of view of mantle convection the core fluid acts to make the CMB isothermal: but the heat flux through the CMB will vary laterally.

Consider hot and cold regions a distance L apart. Core fluid flows from hot to cold in time L/U, cooling by ΔT to a depth $(\kappa L/U)^{1/2}$, the thermal diffusion length, where $\kappa = 5\times10^{-6}$ m^2 s^{-1} is the thermal diffusivity[11]. The heat flux, H, carried by this mass of fluid is:

$$H = \rho C_p (\kappa L/U)^{1/2} [\Delta T/(L/U)] \qquad (2)$$

This is the lateral variability in the heat flux necessary to force convection in the core. Taking the density $\rho = 10^4$ kg m^{-3} (ref. 11), the specific heat capacity $C_p = 700$ J kg^{-1} K^{-1} (ref. 13) and $L = 1{,}000$ km, we obtain $H \approx 0.1$ mW m^{-2}, which is very reasonable compared with the total heat flux from the core of the order of 10 mW m^{-2} (ref. 11), implying lateral variability in heat flux of 1%.

We can use this result to calculate the size of the lateral temperature variations which must be maintained in the lower mantle, above the thermal boundary layer at the CMB, to force this flow. Assuming a thickness of 100 km for the thermal boundary layer[12], and a thermal conductivity of 10 W m^{-1} K^{-1} (ref. 12), we find that lateral temperature variations of ~1 K are sufficient. These calculations suggest that forcing of flow in the core by lateral temperature variations in the lower mantle will almost certainly be a significant effect.

We have assumed a molecular value for the thermal diffusivity. The presence of turbulence in the thermal boundary layer would increase the effective diffusivity. The usual expectation is that turbulence acts to increase diffusivities so as to make the Prandtl numbers unity. The molecular magnetic Prandtl number is 0.1 (ref. 11); because the magnetic diffusivity is unlikely to increase greatly, the expected increase in the effective thermal diffusivity is then only a factor of 10 (the increase in viscosity would be very much larger) which is not large enough to vitiate the conclusions of our calculation.

Topography of an isothermal CMB will also affect convection because isotherms no longer coincide with equipotentials. Tilting the boundary is analogous to tilting g in plane-layer convection, which is known to set up large convection cells[13]. The sense is downward for a depression into the fluid, the same as for a cold region. The flow is determined by the aspect ratio of the bump and the vertical superadiabatic temperature gradient in the core. With a high superadiabatic temperature gradient of 1 K km^{-1} in the thermal boundary layer at the top of the core the equivalent ΔT is 10^{-3} K, for a bump of height 1 km and width 1,000 km, which is large enough to influence convection, but such a bump would be warmed by the core flow in a few hundred years, so that the thermal effect of a bump appears slight. In any case this thermal effect of a bump, as distinct from the topographic, or mechanical, effect that we consider below,

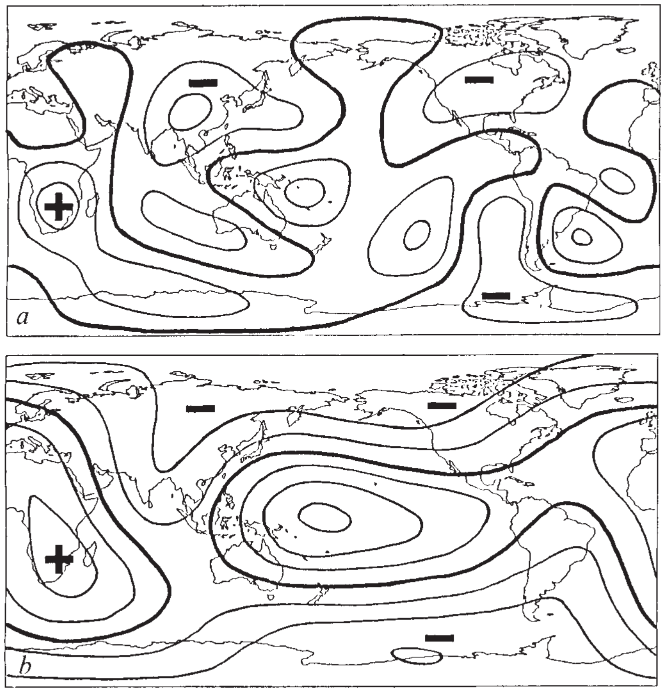

Fig. 2 *a*, Map of lateral variations in seismic *P*-wave velocity at the CMB after Dziewonski[14]. The contour interval is 0.5%. Maximum spherical harmonic degree, six. *b*, Map of the CMB after Hager *et al.*[15]. The contour interval is 500 m. Maximum spherical harmonic degree, three. In each map the + sign represents a region of anomalously hot mantle (elevated CMB) corresponding to the core spots beneath southern Africa (upwelling flow), and the − signs represent regions of anomalously cold mantle corresponding to static flux bundles (downwelling flow). Although there is certainly an encouraging indication that regions of upwelling in the core are associated with regions of hot mantle, and downwelling with cold mantle, the resolution is insufficient for a full comparison to be made.

is of the same sign as the effect of thermal anomalies in the lower mantle, because depressions of the CMB into the core are believed to correspond to regions of anomalously cold mantle.

Mantle temperature inhomogeneities can be mapped from variations in seismic velocity, geoid anomalies and laws relating them to ρ and T (refs 14 and 15). Cold mantle will have high seismic velocity and correspond to depressed CMB; hot mantle the reverse. In Fig. 2 we compare these magnetically inferred lateral homogeneities at the CMB with a map of lateral variations in seismic *P*-wave velocity in the lowermost mantle[14], and with a map of topography of the CMB[15]. Although the correlation is certainly encouraging, and lends support to our hypothesis of thermal coupling, the resolution of these maps is insufficient for a full comparison to be made with the magnetic field map in Fig. 1 that contains information out to spherical harmonic degree 12.

We should consider other mechanisms besides thermal effects that may result in a coupling of flow in the core to the mantle and explain the correlation with lower mantle inhomogeneities: we consider the mechanical effect of bumps, mentioned above, and electromagnetic coupling. The terms topographic core-mantle coupling and electromagnetic core–mantle coupling are normally applied to the exchange of angular momentum between the core and the mantle in studies of decade changes in the length of day[16]. Our concern here is rather different: we seek mechanisms by which the pattern of convection in the core may be fixed by inhomogeneities in the lower mantle.

Bumps on the CMB may also have a mechanical effect on the flow in the core, but it seems improbable that undulations a few kilometres in height but several thousand kilometres in wavelength will have a very great effect on core motions, a view supported by Anufriyev and Braginsky[17]. Certainly regions of pronounced upwelling and downwelling are unlikely to result; entrainement of Taylor columns by bumps is a possibility, but this cannot explain upwelling beneath regions of elevated CMB. Hide and Malin[18] correlated the long-wavelength geoid with the rotated non-dipole field, which is quite different from the correlation we are proposing. It is very hard to explain why the field pattern should rotate while retaining a signature of the CMB; in fact, the significance of Hide and Malin's correlation itself is in some doubt[19].

Flow in the highly electrically conducting core is electromagnetically coupled to the very much poorer conducting lower mantle: the movement of magnetic field lines in the mantle, as a result of advection due to fluid motions in the core, induces an electromotive force in the lower mantle. Although this probably has an important effect on the relative rotation of the core and mantle[16], and the effect is likely to vary laterally due to the temperature dependence of mantle conductivity, it is difficult to see why upwelling flow would be concentrated beneath regions of hot mantle and downwelling beneath cold regions as a result of variations in electromagnetic coupling.

Chemical inhomogeneity in the lower mantle may produce seismic velocity and density variations unrelated to the mantle temperature and destroy the concurrence of cold regions with fast, dense mantle, although chemical and thermal variations may be related. The favourable comparison with the magnetic field suggests a predominantly thermal origin for the large scale variations in seismic velocity observed in the lower mantle.

Determination of lateral variations in seismic velocity in the lower mantle is difficult; determination of CMB topography from the geoid and mantle density variations is also very uncertain as it involves a host of untested assumptions and unknown parameters (such as the viscosity profile of the mantle). Now, such models do not approach the accuracy with which we know the magnetic field at the CMB, for which terms up to at least spherical harmonic degree ten are well determined throughout the twentieth century, and terms up to degree eight back to the early eighteenth century. New initiatives aimed at the collection of higher quality global seismic data should improve the resolution of lateral variations in the lower mantle: it will be interesting to see if such improvements reveal some of the smaller thermal anomalies (such as that associated with the feature beneath the central Pacific labelled 5 in Fig. 1) which we believe to exist.

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Crustal thinning on the Aquitaine shelf, Bay of Biscay, from deep seismic data

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In recent years an increasing amount of new scientific data on the structure and nature of the whole continental crust has been acquired from deep seismic profiling. The Bay of Biscay profile was recorded in 1984 at sea along the Aquitaine platform for the French ECORS group in association with Hispanoil. It collected a unique set of two-ship multi-channel seismic data with constant offset and expanded spread profiles in a complex geological area. The data are of very good quality and contain clear Moho and lower crust reflections as seen under most parts of Western Europe where similar experiments have been conducted[1-4]. This profile provided for the first time the most convincing evidence for an anomalously thin crust below a rifted basin, the Parentis Basin, which is directly connected to the oceanic area of the Bay of Biscay. It gives new constraints for understanding the formation of extensional sedimentary basins.

The experiment was carried out along a 300-km-long line oriented north-south from the Armorican Shelf to the Cantabria margin (Fig. 1). A normal incidence seismic profile was shot and recorded up to 15 s by the *GECO Gamma* vessel using an 8,536 in^3 air gun source at 2,000 psi and a 3-km-long streamer. At the same time shots were recorded up to 16 s by the IFP vessel *Résolution* steaming behind with a 7.5-km constant offset and towing a 2.4-km-long streamer to simulate a long-array spread. Processing was done by Elf-Aquitaine, providing a 30-fold CDP (common depth-point) stacked section for the near offset profile which was then migrated, and a 24-fold CDP stacked section for the large offset profile which was muted from 0 to 7.5 s to avoid refraction arrivals. A spectacular increase in energy from the deep reflectors as well as a remarkable improvement in the definition of the lower crust and of the Moho were obtained with the wide-aperture data which also helped in cancelling the diffractions (Fig. 2). At intervals along this profile, six expanding-spread profiles were also acquired. This latter survey showed that the main changes in acoustic facies or in the pattern of reflections observed on the vertical reflection data are associated with velocity discontinuities. Beneath the sediments which correspond to velocities of less than 5.7 km s^{-1}, the upper crust is characterized by velocities ranging from 5.9 to 6.2 km s^{-1}, while they range from 6.5 to 7.1 km s^{-1} in the lower crust[5]. The two-way time corresponding to the location of the Moho is marked by a strong wide-angle reflection on each expanded spread profile (ESP) and an abrupt disappearance of the deepest high amplitude reflectors on the vertical seismic data. The major results are given in Fig. 3. They include