Magnetic Field Reversals, Polar Wander, and Core-Mantle Coupling

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True polar wander, the shifting of the entire mantle relative to the earth's spin axis, has been reanalyzed. Over the last 200 million years, true polar wander has been fast (approximately 5 centimeters per year) most of the time, except for a remarkable standstill from 170 to 110 million years ago. This standstill correlates with a decrease in the reversal frequency of the geomagnetic field and episodes of continental breakup. Conversely, true polar wander is high when reversal frequency increases. It is proposed that intermittent convection modulates the thickness of a thermal boundary layer at the base of the mantle and consequently the core-to-mantle heat flux. Emission of hot thermals from the boundary layer leads to increases in mantle convection and true polar wander. In conjunction, cold thermals released from a boundary layer at the top of the liquid core eventually lead to reversals. Changes in the locations of subduction zones may also affect true polar wander. Exceptional volcanism and mass extinctions at the Cretaceous-Tertiary and Permo-Triassic boundaries may be related to thermals released after two unusually long periods with no magnetic reversals. These environmental catastrophes may therefore be a consequence of thermal and chemical couplings in the earth's multilayer heat engine rather than have an extraterrestrial cause.

THE PLATE TECTONIC REVOLUTION HAS PRESENTED A NEW dynamical picture of the earth, in which lithospheric plates are in relative motion with respect to each other, an activity that gives rise to volcanoes and earthquakes. Geoscientists are now extending such concepts of plate mobility to the deeper, less accessible parts of the earth, its silicate mantle and iron core. Considerable interest and debate focus on regions surrounding the core-mantle boundary (CMB) at a depth of about 2900 km (*1, 2*). Seismic tomography, the geophysical counterpart of medical x-ray imaging, reveals a rich three-dimensional picture of the lower mantle. It is found, for instance, that the CMB has a complex topography, with variations possibly as great as 10 km in amplitude (*3*), which was first suggested on a theoretical basis by Hide (*4*). These new observations have exciting consequences for understanding the dynamics of mantle convection (*5*). However, they lack the key dimension of time. This complementary dimension can be provided by the analysis of the past behavior of the earth's magnetic field, both in historical time (the domain of geomagnetism) and in more remote geological time (the domain of paleomagnetism). The spectrum of the geomagnetic field is extensive, from the 1-year time scale of sudden geomagnetic impulses (*6*) to the 10^8-year time scale of changes in the frequency of reversals of the dipole field (*7*). These are believed to reflect changes in the pattern of convecting circulation of the fluid outer part of the core and in the long-term evolution of boundary conditions at the CMB and inner-outer core boundary (ICB). Recently, there have been significant advances in our knowledge of geomagnetism and paleomagnetism, both observational and theoretical, over a large part of the frequency spectrum.

Paleomagnetic data can be derived from diverse sources. These data are available in the form of magnetic anomalies on the ocean floor that tell the relative motions of the wandering plates and in the form of records, frozen in continental rocks, of changes in latitude and orientation of the plates with respect to the earth's magnetic dipole axis, known as apparent polar wander (APW) (*8*). In this way, motions of the lithospheric plates can be traced with respect to the earth's spin axis. Also, Morgan (*9*) has proposed that a number of volcanic chains are the traces of deep-seated mantle plumes that remain more or less stationary with respect to each other and to the mantle. Although the question of whether the plumes are fixed is debated (*10*), plume motions seem to be smaller than most relative plate motions. Other debated topics are the viscosity of the lower mantle and the actual depth at which the plumes originate. However, it still seems to be a reasonable hypothesis that the plumes form a reference frame for the mantle. If so, hot spot traces can be used to infer the relative motions of the plates and mantle. Finally, it is generally accepted that changes in the frequency of field reversals reflect the dynamic evolution of the fluid core (*7, 11*). Therefore, paleomagnetic data provide a means of unraveling the respective evolutions and interactions of the earth's layers, its lithosphere, mantle, and core.

In this article, we first summarize a recent reanalysis (*12, 13*) of the paleomagnetic data from some major continental cratons (stable parts of the crust), which leads to improved estimates of the apparent polar wander paths (APWP) of these cratons. A comparison with hot-spot traces allows us to determine true polar wander (TPW), which is defined as the motion of a mantle reference frame with respect to the rotation axis of the earth. We find what we believe to be a good correlation between TPW and changes in the magnetic reversal rate. Next, we discuss evidence for changes in motions of the lithosphere as a whole. True polar standstill is found to correspond to slower continental velocities, major continental breakup, extensive volcanism, and sea-level changes. We propose that these correlations reflect a fundamental coupling between the core, mantle, and lithosphere, and propose a simple qualitative model in which long-term changes in thickness of the lowermost mantle boundary layer (D″) govern both changes in core convection

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(reflected by changes in reversal frequency) and mantle convection (reflected by TPW, related to the emission of thermal instabilities at the boundary layer). There is, in turn, coupling between upper mantle convection and lithospheric motion expressed both in episodes of continental breakup (*14, 15*) and collision (*12*) or changes in subduction zone geometry (*5, 16*). Finally, we suggest that some biological mass extinctions, particularly at the end of the Permian and of the Cretaceous, which followed long periods with no magnetic reversals and were accompanied by exceptional flood basalt volcanism, may be related to exceptional lower mantle instabilities that are but an extreme manifestation of the general couplings that reflect the earth's history as an episodic heat engine.

Apparent Polar Wander

In order to track the bulk motion of the mantle with respect to the earth's spin axis, one must rely on observations made at the surface of the earth. This tracking is therefore a two-step process that uses the lithosphere as an intermediate step, and also requires a number of hypotheses to be made. Paleomagnetism allows one to track the motion of a plate with respect to the spin axis under the hypothesis that the average geomagnetic field is that of a centered dipole whose axis coincides with the rotation axis (*17*). The traces left by hot spots on that same plate are next used to infer the motion of that plate over the mantle (*9*). The two sets of data are combined so that the motion of the mantle reference frame with respect to the (paleomagnetically determined) rotation axis can be traced back in time (*18*).

A global analysis requires that paleomagnetic data and hot-spot traces from all plates be used at the same time, which requires one to relate the data from one plate to those of another by means of relative plate motion models. This can be done only if a pair of plates is separated by a boundary consisting of spreading segments and fracture zones and if corresponding kinematic models are sufficiently accurate. This significantly reduces the number of plates that can actually be related. We have undertaken such an analysis (*12, 13*), restricting ourselves to the Eurasian (EUR), African (AFR), North American (NAM), and Indian (IND) plates, which can be related through accurate models of opening of the North Atlantic (*19*), central Atlantic [(*19*); also see the data of K. Klitgord and H. Schouten, which are discussed in (*20*)] and Indian (*21, 22*) oceans. As a first step, we have reviewed paleomagnetic data from the four plates for the last 200 million years, from the breakup of Gondwanaland onward. A number of such syntheses have been published over the years (*23*), but significant new data regularly become available and selection criteria can be made more stringent. To the generally accepted paleomagnetic reliability criteria (*24*), we have found it necessary to add stringent, though straightforward, geological constraints pertaining to the accuracy of age estimates and the reliability of structural control (*12, 13*). We have more confidence in deductions from a small set of high-quality data than in the cleaning powers of excessive statistical averaging.

Our final compilation (*12, 13*) may seem somewhat meager: the number of poles is 38 for AFR, 36 for EUR, 28 for NAM, and 2 for IND. For each plate, we have first constructed an APWP based on the data from that plate only. Although some scatter and data gaps are obvious, the results are consistent. Figure 1 shows the APWP for Africa as an example. Because of the small number of data (triangles), we have had to average over rather large geological intervals (chosen to be the classical geological intervals, 20 to 30 million years in duration). Paleomagnetic poles from all plates (104 altogether) were then transferred to the African plate, improving both statistical and temporal resolution. Statistical averaging was done every 10 million years, in 20-million-year windows; every other point is therefore independent (Fig. 2). The main features of the APWP, the sharp change in direction at 30 million years and the hairpin at about 130 million years, are preserved and the new synthetic curve statistically agrees everywhere with the curve based on African data only (Fig. 1). The Fisherian statistical confidence intervals are considerably reduced, now approximately 4° at the 95% confidence level and show no signs of increasing systematically with age. Rapid

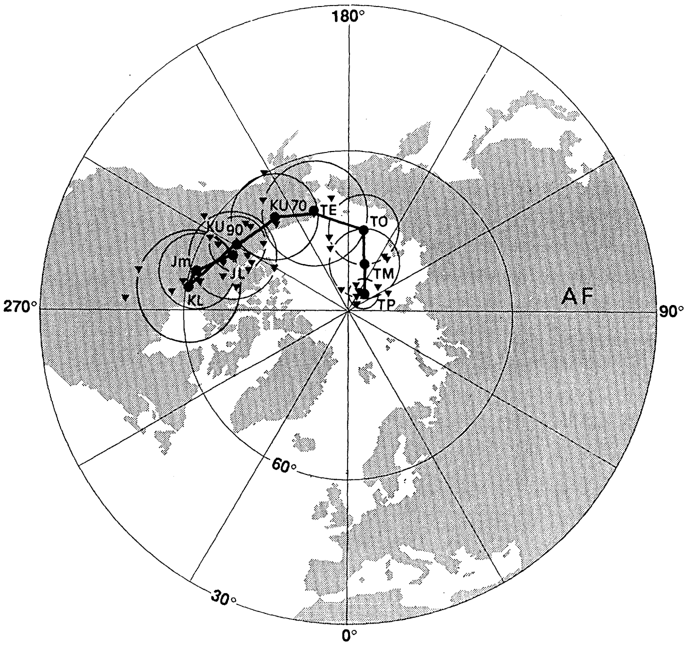

Fig. 1. Apparent polar wander path of Africa (AF) for the last 200 million years, with African data (triangles) only. Filled circles are mean poles (with 95% confidence intervals) for the following geological periods: Pliocene (TP), Miocene (TM), Oligocene (TO), Eocene (TE), upper Cretaceous (KU) (centered on 70 and 90 million years), Lower Cretaceous (KL), middle Jurassic (JM), and lower Jurassic (JL) [after (*12, 13*)].

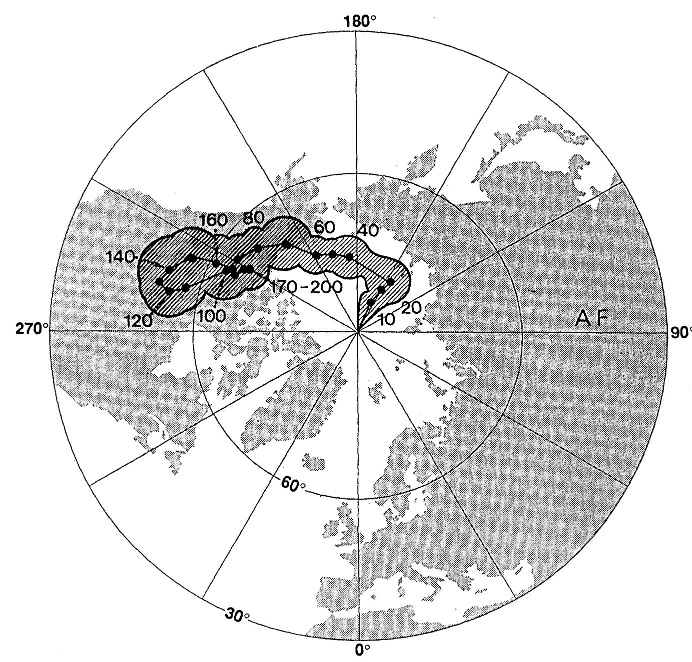

Fig. 2. Synthetic apparent polar wander path of Africa derived from 104 paleomagnetic studies from Africa, Eurasia, North America, and India, transferred to the African plate through the North Atlantic, central Atlantic, and Indian oceans. Averages every 10 million years, with a 20-million-year window (every other point is independent). Ages are labeled in millions of years [after (*12, 13*)].

polar wander takes place on or close to small-circle tracks (*25*) between 200 and 130 million years, between 130 and 30 million years, and from 30 million years to the present. Similar features are found in the EUR and NAM APWPs, despite the distorting effect of relative motions. A bend, or cusp, is found near 30 million years, and a standstill between 70 and 140 million years, the tracks having very different trends before and after the standstill. India displays rather low polar wander between 200 and 80 million years, fast motion from 80 to 30 million years, and little motion since.

The agreement between transferred poles has important consequences. It supports at the same time the paleomagnetic data and the kinematic models. Errors in the kinematic models are unlikely to exceed 1° and are therefore significantly smaller than errors in the paleomagnetic poles (*26*). Moreover, the fundamental hypothesis of a geocentric axial dipole is substantiated, to the accuracy level of the final 95% confidence levels. This casts some doubt on the reliability of previous estimates of long-term nondipole components of the geomagnetic field, whose contributions are unlikely to exceed a few degrees (*13, 27*).

True Polar Wander

The analysis of true polar wander requires the determination of the motions of plates over the hot spots. This has been done by Morgan (*20, 28*), and is shown in Fig. 3, which displays the track followed by an axis of the hot-spot reference frame presently at the north pole, as seen from Africa (triangles). This can be termed a "hot-spot" polar wander path. Comparison of the paleomagnetic and hot-spot APWP (Fig. 3) shows significant differences. Despite an overall resemblance in shape and location, we find that TPW has indeed occurred. The TPW path is determined by first calculating the finite rotation (with axis in the equatorial plane) that brings a paleomagnetic pole of given age to the north pole, and then applying this rotation to the hot-spot pole of corresponding age

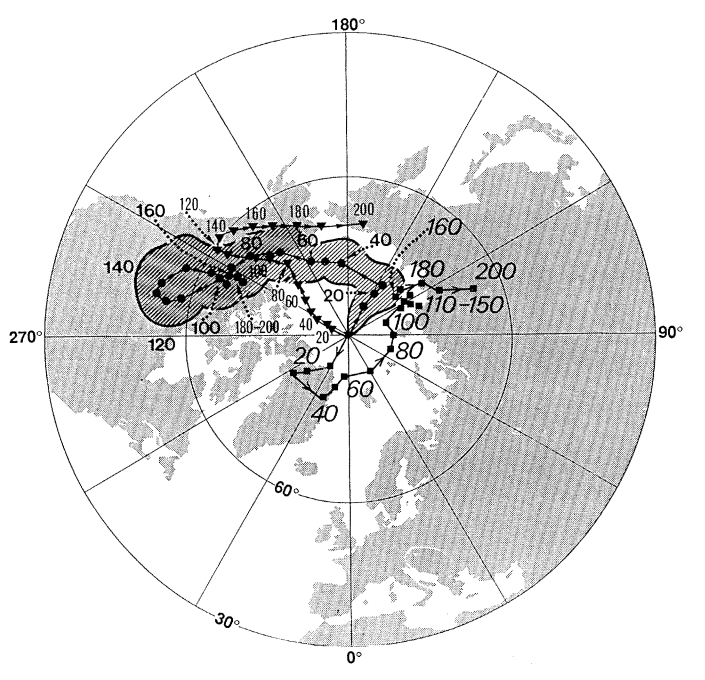

Fig. 3. Comparison of the synthetic paleomagnetic apparent polar wander path of Africa (filled circles) with the synthetic path deduced from a model in which hot spots are fixed [triangles, from (*20, 29*)]. True polar wander (squares) is deduced from the two paths as outlined in the text: it represents global motion of the mantle with respect to the earth's spin axis. 95% confidence intervals, not shown, are on the order of 4°.

(*18*). The resulting curve, which summarizes the motion of the mantle frame of reference with respect to the spin axis, displays some interesting features (squares, Fig. 3). The amplitude of TPW reaches 10° at 30 to 40 million years and 25° at 200 million years, but it does not vary in a uniform way. Fast polar wander occurs from 200 to 170 million years and is followed by a remarkable 60-million-year standstill. A new fast track occurs, with a somewhat different azimuth, from 110 to around 40 to 30 million years, when a sharp cusp (almost a hairpin) occurs with no indication of slowing down. Fast polar wander has continued until the present. Using a simplified model built from small circle tracks separated by cusps (*26*), we find that along-track polar wander velocity has been rather uniform during the fast episodes, between 4 and 5 cm $year^{-1}$. The evolution of TPW velocity is shown as the middle curve in Fig. 4.

We discuss in detail elsewhere (*13*) the differences between our determination of TPW and previous ones (*29–31*). The path of Andrews (*31*) has an amplitude similar to ours but is much more erratic; that of Livermore *et al.* (*30*) has a similar shape but an amplitude smaller by a factor of 2, from 40 million years ago to the present. We attribute these differences to lack of time resolution, or to the use of some inadequate paleomagnetic data (*32*) or kinematic models.

Comparison of Reversal Frequency and Rate of True Polar Wander

The reversal time scale is now known with good accuracy over the last 165 million years (*33*), although there may well remain unobserved short events. A number of detailed analyses of this record have become available in recent years (*7, 34, 35*). Despite minor differences, these analyses agree in their general conclusions. McFadden and Merrill (*7*) have shown that reversals occur essentially as a Poisson process, with no statistical difference between the normal and the reversed states. The inherent rate of reversals has changed in a rather smooth way since the Jurassic (Fig. 4, top curve); the rate has decreased from about four reversals per million years at 165 million years to zero reversals at 119 million years, when a 36-million-year-long normal period (the so-called Cretaceous Long Normal Superchron or LNS) occurred. The decrease was almost monotonic. From 83 million years onward, a monotonic, almost linear increase brought the rate back to about five reversals per million years. A maximum may have been reached 10 million years ago (*36–38*).

For periods prior to 165 million years, the reversal record is more sketchy. A long reversed superchron (LRS), known as Kiaman, occurred in the Permo-Carboniferous, from about 320 to 250 million years ago (*33, 39*). Reversal frequency is known to have been fairly high in the Jurassic (*33*). Following McFadden and Merrill (*7*), we suggest a regular increase in reversal frequency after the Kiaman LRS (Fig. 4), in the Triassic and Jurassic, by analogy to the recovery period after the Cretaceous LNS. Although it would be hazardous to present the reversal record as having a very long periodicity, with not even two full "periods" represented, the curve shown in Fig. 4 does suggest a ~200- to 150-million-year time constant; this may reflect similar changes in CMB conditions that control reversal-triggering instabilities.

In Fig. 4 we have plotted the changes in reversal frequency and the changes in (along track) velocity of true polar wander for comparison. Although better resolution is required to proceed with certainty, there is a suggestion that times of decaying reversal rate are also periods of slow (or no) true polar wander, whereas periods of growing reversal rate are periods of fast true polar wander. The onset of renewed TPW, at ~110 million years, occurs early within

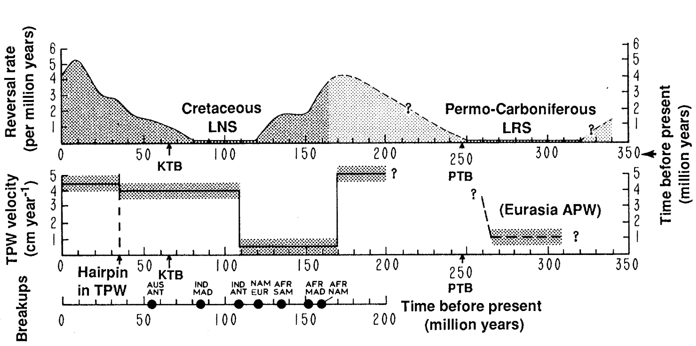

Fig. 4. (**Top**) Changes in frequency of reversals of the geomagnetic field (number per million years) over the last 350 million years, with a dashed line where frequency is less reliable. Abbreviations: LNS, long normal superchron; LRS, long reversed superchron; KTB, Cretaceous-Tertiary boundary; PTB, Permo-Triassic boundary. (**Center**) Along-track true polar wander velocity (in centimeters per year) derived from Fig. 3. The date of the hairpin is shown. Prior to 200 million years, values are suggested by apparent polar wander of Eurasia [see text and (*40*)]. (**Bottom**) Major continental breakups and ocean basin openings. Abbreviations: AFR, Africa; ANT, Antarctica; AUS, Australia; EUR, Eurasia; IND, India; MAD, Madagascar; NAM, North America; SAM, South America.

the Cretaceous LNS; the time resolution of our TPW curve (20-million-year-long independent windows) does not allow for a more precise time correlation. The period of high TPW prior to 170 million years may have coincided with the end of a previous phase of increasing reversal frequency.

There are no available hot-spot motion models prior to 200 million years ago and the TPW curve cannot be extended backwards. However, we find an (admittedly weak) suggestion that TPW may have been very low sometime during the Kiaman LRS, using APW curves as a proxy (*40–43*).

Lithospheric Motions

A correlation between TPW and changes in reversal frequency may indicate a coupling between the mantle and the core. However, the correlation shown in Fig. 4 leaves the remarkable directional change in TPW at 30 to 40 (±10) million years unaccounted for. It is tempting to relate it to the generalized collision of Africa, Arabia, and India against the Eurasian continent. This event climaxed with the encounter of India and Asia starting some 50 million years ago (*22, 43, 44*) and shut off in excess of 5000 km of subduction zones. The pull of cold downgoing slabs is often assumed to be one of the most significant forces applied to lithospheric plates (*45*), and a major collision could alter the torque balance of the lithosphere-asthenosphere system (*18*). Mantle-lithospheric coupling would indeed imply that such an event should be seen in TPW curves. Rona and Richardson (*46*) emphasized the major reorganization of global plate motion that occurred between 35 and 55 million years ago, when collisional plate boundaries increased in total length from 2,500 to 28,500 km (from 5 to 38% of the total length of convergent plate boundaries). Associated with this is the well-known change in trend of the Hawaiian-Emperor seamount chain, also attributed to a redistribution of slab-pull forces acting on the Pacific plate (*47*).

Anderson (*14*) and Chase and Sprowl (*48*) have shown that the main long wavelength minimum in the geoid (*49*) corresponds to the single great-circle subduction zone that surrounded Pangea (and the proto-Pacific plate) 125 million years ago. Rabinowicz *et al.* (*50*) and Hager (*5, 16*) point out that the return of cold slabs to the lower mantle may be a major way in which this part of the earth is cooled, which would emphasize the importance of subduction zones in controlling to some extent mantle convection.

Coupling between the mantle and lithosphere may be reflected in yet another way. Anderson (*14*) noted that the present-day African geoid high corresponds to the Jurassic configuration of Pangea and contains a large fraction of the world's hot spots. Anderson proposed that the continental aggregation that resulted in Pangea also led to mantle insulation (that is, to hotter than normal mantle). As a result, hot spots and rifts were generated, leading to episodes of continental disruption. We discuss further elsewhere (*27*) the episodic aspect of continental breakup of Gondwana. In Fig. 4 (bottom), we show the major periods of rifting and generation of new oceanic crust along ridge systems in the last 200 million years: formation of some major basins took place at the time when there was no TPW.

Coupling of the lithosphere and mantle could also be evaluated if one could estimate the global motion of a lithospheric reference frame with respect to either a mantle frame or the spin axis (*18, 51*). Gordon and Jurdy (*52*) have recently analyzed Cenozoic global plate motions and have found that there has been small but significant net rotation of the lithosphere relative to the hot spots (*53*). In the common period when we have data for both lithospheric and mantle TPW (65 million years to the present), we find mantle TPW to be significantly larger than the motion of the lithosphere with respect to the mantle. Both are quite nonuniform and the latter reflects the former in an attenuated way: the along-track angular displacement of the mantle with respect to the spin axis (24° in 65 million years) is about four times the angular displacement of the lithosphere over the mantle (6°). Gordon and Jurdy (*52*) found a maximum rate of lithosphere versus hot spot rotation at 40 to 50 million years, which is roughly the time of the hairpin in mantle TPW and of the global plate reorganization.

There is as yet no reliable determination of lithospheric TPW prior to 65 million years. Schult and Gordon (*54*) have determined the root-mean-square velocities of the continents with respect to the hot spots since the early Jurassic, and these velocities appear to correlate rather well with both global root-mean-square velocity and (less well) with lithosphere versus mantle rotation rate (*55*). Schult and Gordon (*54*) found lower root-mean-square continental velocity between 85 and 145 million years. This suggests that there was little motion of the lithosphere with respect to the mantle at the same time (or slightly after, but time resolution may not be sufficient to ascertain this), when there was little motion of the mantle with respect to the spin axis. The drop in continental root-mean-square velocity from 6 to 2 cm year^{-1} shortly after 150 million years ago might therefore mirror the drop in true polar wander from about 5 cm to less than 1 cm year^{-1} about 170 million years (Fig. 4).

Dynamics at the Core-Mantle Boundary

The foregoing discussion provides evidence for long-term variations of several indicators of core, mantle, and lithosphere dynamics, over the last 200 or 300 million years. That these variations appear to have common time constants on the order of 150 to 200 million years and also appear to be correlated, points to some form of coupling between the various shells that comprise the earth on that same time scale. We find that periods when TPW was low correspond to decreasing reversal rate and to low root-mean-square velocities in the lithosphere: a reduced state of convective activity in the mantle appears to be related to a decrease in the rate of production of some form of instability in the fluid core, and also to continental insulation and subsequent continental breakup. Conversely, periods of fast TPW are accompanied by increasing reversal rate, high lithospheric root-mean-square velocities, and continental collisions. Although the time resolution of reversal frequency changes and plate motions is quite good, present limitations come from paleomagnetic APWPs and are at the 10- to 20-million-year level. This precludes at present the accurate determination of lags between the various time series. There is a weak suggestion that changes in mantle TPW somewhat precede core changes.

A number of earlier studies addressed possible coupling between the core and mantle on the very long time scales afforded by the knowledge of the reversal time scale. For instance, with data then available, Vogt (*56*) proposed a correlation between reversal frequency, hot-spot volcanic discharge, and changes in sea level. He concluded that processes in the upper mantle and outer core had to be somehow coupled (*57*). More elaborate models, often based on a fluid-dynamics analysis, were proposed by Jones (*11*), McFadden and Merrill (*7, 58*), and Loper and his colleagues (*59–61*).

Jones (*11*) proposed that changes in reversal frequency could not arise in a dynamo operating under uniform conditions and proposed that they reflected changes in temperature at the CMB. From an analysis of (sometimes very poorly known) physical parameters, Jones (*11*) deduced that the Rayleigh number in the lower mantle could be as high as 10^7; as a result, he proposed that intermittent convection, in the form of rising plumes emitted from a thermal boundary layer at the base of the mantle, should transport heat from the core upward. Two-thirds of the intermittent cycle would be spent in the conductive mode, and the remaining one-third in the active convective mode. According to Jones, CMB temperatures would drop during the convective mode, the Rayleigh number of the core would increase and with it the frequency of reversals (*62*). McFadden and Merrill (*7, 58*) also proposed that changes in reversal frequency were the result of temperature changes at the CMB. They showed that the statistical properties of the reversal record implied a separate source in the core for the stable geomagnetic field and the reversal-triggering mechanism (*63*). They proposed two models, a "hot blob" and a "cold blob." In the hot blob model, hot thermals are emitted at the ICB as a result of freezing of the liquid core and trigger a temporary reorganization of core convection, during which a reversal can occur. In the cold blob model, convection leading to the stable field is primarily due to freezing at the ICB and the instabilities that trigger reversals are cold thermals, generated below the CMB and sinking in the core.

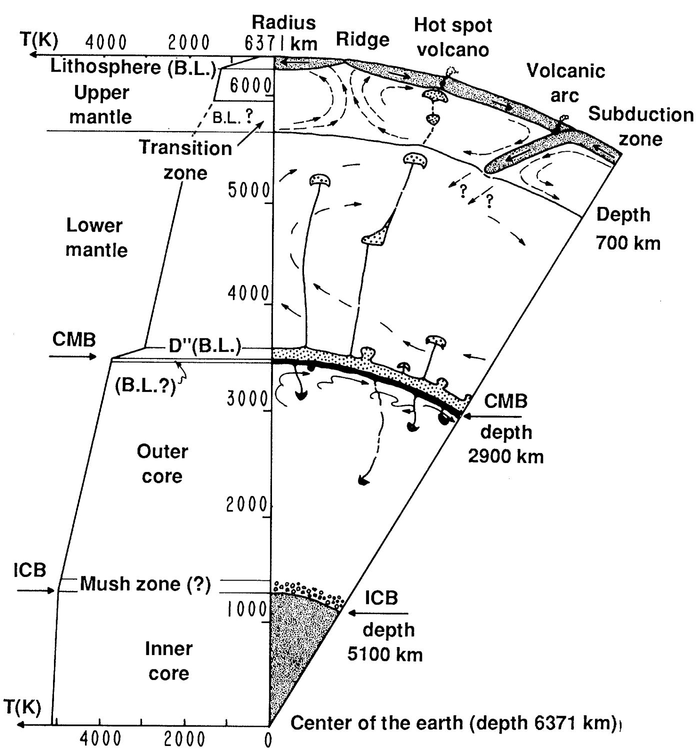

Fig. 5. Schematic diagram of core-mantle coupling. Hot instabilities emitted from D″ in the lowermost mantle rise through the mantle, leading to TPW and lithospheric activity (hot-spot volcanism, faster root-mean-square plate velocities, lithospheric polar wander). Cold instabilities emitted from the top of the core may eventually destabilize the main geomagnetic field and cause reversals. Temperature distribution (in kelvins) is outlined on the left side (*74*). Abbreviations: CMB, core-mantle boundary; ICB, inner-outer core boundary; B.L., boundary layer.

Jones (*11*) proposed to identify the lower mantle thermal boundary layer responsible for intermittent convection with the lowermost part of the mantle known as D″ to seismologists (*64*). Stacey and Loper (*59, 65, 66*) have also interpreted D″ as both a thermal boundary layer and a source of plume instabilities. Although at first they preferred steady over intermittent convection, subsequent studies led Loper and his colleagues to propose marginal stability (*67*) and even unsteady flow (*61*). The flow is thought to oscillate between two states, one in which plume flux is weak, D″ is thin and is growing thicker, and the other in which plume flux is strong and D″ is thick, but growing thinner. Loper and McCartney pointed out that the rate of transfer of heat from the core to the mantle is actually controlled by the temperature gradient across D″. They suggested a gradient of 10 K km^{-1} and a temperature jump of ~800 K, with a thermal boundary layer of 70 km and a kinematic boundary layer of 10 km thickness (*68*). Loper and McCartney (*61*) concluded that changes in reversal frequency reflect changes in the thickness of D″, with infrequent reversals when D″ is thickest and the conductive heat flow across it at its minimum; in that way D″ controls the rate of cooling of the core, hence the energy supply to the dynamo (*69*). In their model, breakup of a thick, unstable D″ layer occurs with the formation of creeping plumes (*70*). The thermal structure of the layer changes on its thermal relaxation time $t = h^2/k$ (where h is the layer thickness and k is thermal diffusivity). Using a thin velocity boundary layer (h = 11 km), Loper and McCartney (*61*) found $t \approx 22$ million years. This is strongly sensitive to h, and also k is not accurately known, so that values of ~200 million years are clearly permitted ($h \approx 20$ to 30 km) (*71*).

Despite some differences, the various models described above have some common features. All rely on establishing a coupling between the core and mantle across the CMB. All are more accurate on the core side because they are constrained by reversal frequency changes, but not on the mantle side. McFadden and Merrill (*58*) noted that if the main features of their model are correct, the variations in reversal frequency should be reflected in plume activity, true polar wander, and surface tectonic processes. We believe that the observations summarized in Fig. 4, which are essentially TPW, but also continental breakups and root-mean-square velocities (*72*), to some extent support these predictions (*73*).

A Simple Model

Despite the difficulty of incorporating so much information over very large space and time ranges in a simple descriptive model, we have attempted to summarize the various dynamical features discussed so far (Fig. 5). A tentative temperature distribution has been suggested on the left side of the figure (*74*), to show the contrast between convective zones with small gradients and conductive boundary layers with larger gradients (*75*).

Above the CMB, a thermal boundary layer (tentatively identified with D″) releases thermals to a viscous colder lower mantle. The rate of production of these instabilities depends on the boundary layer thickness, being larger when it is thicker. These instabilities may affect both the sluggish convection in the lower mantle (velocities ~1 mm $year^{-1}$ outside thermals) and TPW. These thermals in turn trigger thermals in the less viscous, faster convecting upper mantle (velocities ~1 to 10^2 cm $year^{-1}$ or 10^{-10} to 10^{-8} m sec^{-1}), which are expressed as mantle hot spots, which in turn feed hot-spot volcanics. The plume route may also be affected by mantle convection (*70*); it has been suggested that the large-scale convection is driven by subducting slabs, which cool the mantle from the top (*5, 50, 60*), and which would introduce further feedback and coupling into the system. Then, modulated activity of the upper mantle is translated into modulated activity of the lithosphere, possibly with a time lag: this is expressed in hot-spot related volcanism on one hand and relative plate motions on the other hand (root-mean-square velocities and lithospheric TPW).

Below the CMB, a thin boundary layer of core material emits cold thermals. These thermals are emitted at different rates and this modulates the rate of the (infrequent) reversals that some of them may trigger. The thicker the core boundary layer, the faster the production of thermals and the reversal rate. Thermals can suffer complex deformation as they are sheared by the convecting outer core layers. Flow in these layers, which is responsible for geomagnetic secular variation, can be complex and quite fast (~10 km $year^{-1}$ or 0.5 mm sec^{-1}). Recent progress in the analysis and modeling of secular variation supports the existence of thermals (jets) in the outer core and of sudden changes in their dynamics, and also the idea that the sources of secular variation of the main (dipole) and nondipole fields could be separate. Le Mouël (*76*) has proposed that the Coriolis force dominates the force budget at the top of the core. Under the approximation that time constants are short enough and the electrical conductivity of the core high enough for diffusion to be neglected [the so-called "frozen-flux" approximation (*77*)], Le Mouël (*76*) then showed that the existing dipolar field is not involved in the process by which the whole field (dipole and nondipole) changes in time. This provides a theoretical basis for the long known fact that secular variation of the dipole and nondipole parts of the field appear to be decoupled; it also supports the suggestion that sources of the nondipole field are close to the CMB, whereas the source of the main field would be deeper. This is similar to the conclusion of McFadden and Merrill (*58*), that sources of the main field and of the process that triggers reversals (which we would like to associate with nondipole secular variation) are topologically separate. Under the same geostrophic approximation, fluid flow at the surface of the core is found to be rather simple, with an ascending jet below the Indian Ocean and descending flow below Peru (*78*). Although both the frozen-flux and geostrophic approximations are the sources of ongoing debate (*79*), all studies strongly suggest that flow in the core is coupled to the mantle (*80, 81*).

Long Superchrons and Mass Extinctions

Over the last 350 million years, the earth's magnetic field has failed to reverse during two exceptionally long periods, the Cretaceous LNS (35 million years) and the Permo-Carboniferous LRS (70 million years, Fig. 4). According to the model described above, such periods of minimum production of reversal-triggering instabilities would correspond to a maximum in the heat flow conducted through the core boundary layer to the CMB and subsequently to a maximum in the thickness of the lower mantle thermal boundary layer. This layer would reach an unusual thickness, and would then break up with the emission of unusually large or numerous instabilities (thermals or creeping plumes). The lower mantle boundary layer would then deflate, heat flow conducted through it would increase, and reversal-triggering cold blobs could be produced again in the core. The unusual thermals would ascend through the lower mantle and would either continue through the upper mantle or generate new thermals if the upper mantle forms a separate convective layer. This could finally generate exceptional volcanism at the earth's surface and might result in climatic disruption, possibly leading to major extinction events.

We note, as others have before, that the two largest extinction events, the Permo-Triassic and the Cretaceous-Tertiary (*82*), occur shortly after the end of the two long superchrons (KTB and PTB on Fig. 4), and that major volcanism accompanies them (*83*). We have recently argued (*84*) that the Deccan traps in India, one of the largest volcanic deposits on the earth, erupted at the Cretaceous-Tertiary boundary in less than 0.5 million years, ranking as the largest volcanic catastrophe in the last 200 million years. We further proposed that the Deccan traps marked the onset at the earth's surface of the hot-spot trace whose active end is now at Réunion Island. We suggest that this exceptional event is related to an unusually large instability that developed from the lower mantle thermal boundary layer toward the end of the Cretaceous LNS (83 million years), as outlined in the above scenario. Other volcanic events, possibly related to other plumes, occurred at about the same time in the North Atlantic Tertiary volcanic province (*85*) and the Walvis ridge in the South Atlantic (*86*). The 15- to 20-million-year lag between plume emission at D″ and the first traces of volcanic activity at the surface is not incompatible with proposed plume ascent velocities through the mantle (*66*), considering the time that could be spent at the upper-lower mantle and asthenosphere-lithosphere transition zones. Although typical ascent velocities are often suggested to be ~1 m $year^{-1}$ (*9, 66*), the viscosity and other parameters of the lower mantle are rather uncertain and rising material that must establish a new plume after a long period of quiescence may rise at least an order of magnitude more slowly than subsequent pulses (*61*). A velocity of 30 cm $year^{-1}$ (2900 km in 10 million years) is therefore reasonable (*57, 87*). The case of the Permo-Triassic boundary has not been studied to the same extent as the Cretaceous-Tertiary boundary, although the large Siberian traps are known to have erupted at about the right time (*88*).

It has become generally accepted that major extinction events correspond to impacts of large extraterrestrial bodies on the earth (*89, 90*). However, one can argue that the case for a volcanic cause cannot be ignored (*85, 86*). It would be particularly appropriate, in the light of the data and model proposed here, to further test the idea that catastrophic extinctions are related to catastrophic volcanism with primary internal sources. It would seem attractive to us to envision a model in which "neo-catastrophism" and "neo-uniformitarianism" (*89*) are blended, as imposed by observations. The earth is a heat engine, which continuously cools through its surface; heat must flow through its layers of vastly different physical properties, by way of conduction or convection, with significant between-layer (core-mantle-lithosphere-atmosphere) thermal or chemical couplings (*75*), and delays. Heat flow through the core-mantle boundary appears to fluctuate on a ~200-million-year time scale, and possibly on shorter time scales of 30 million years and less. We suggest that this is reflected in long-term changes in the core (through the dynamo), mantle (through plumes and TPW), lithosphere (through tectonic and volcanic activity, and plate motions), and eventually biosphere (through climatic variations at the surface and biological consequences).

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64. The D″ layer is a region in which it has been proposed that seismic velocity gradients decrease significantly and may even be negative. The picture is still far from clear, with recent suggestions of anisotropy and increasing evidence for large-scale lateral heterogeneities together with CMB topography [see (*3, 5*); D. J. Doornbos, *J. Geophys. Res.* **88**, 3498 (1983); S. Spiliopoulos, F. D. Stacey, *Phys. Earth Planet. Inter.* **41**, 225 (1986); K. C. Creager and T. H. Jordan, *Geophys. Res. Lett.* **13**, 1497 (1986].
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91. This article is dedicated to Allan Cox who introduced one of us (V.C.) and many others to the fascinating world of paleomagnetism and plate tectonics. The paper was written while V.C. enjoyed the friendly and stimulating atmosphere of the Department of Geological Sciences, University of California at Santa Barbara, which is thanked for partial support. Support for this research was also provided by Ministère de l'Education Nationale, Institut de Physique du Globe and Institut National des Sciences de l'Univers (Centre National de la Recherche Scientifique). Discussion with and comments from D. Anderson, M. Fuller, C. Jaupart, J. L. Le Mouël, R. Merrill, J. Morgan, J. P. Poirier, and F. Spera, who read a first version of this paper, are gratefully acknowledged. Also acknowledged is help in typing from P. Mori and E. Dzuro, and in drafting from D. Crouch and G. Dupin. The following contributed comments, reprints, or preprints at various stages: D. Anderson, T. Atwater, R. Clayton, A. Fabre, B. Hager, D. Jurdy, D. Loper, C. B. Officer, P. Patriat, J. P. Poirier, J. Ségoufin, and N. Sleep. This is Institut de Physique du Globe contribution NS 965.

Picosecond Holographic-Grating Spectroscopy

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Interfering light waves produce an optical interference pattern in any medium that interacts with light. This modulation of some physical parameter of the system acts as a classical holographic grating for optical radiation. When such a grating is produced through interaction of pulsed light waves with an optical transition, a transient grating is formed whose decay is a measure of the relaxation time of the excited state. Transient gratings can be formed in real space or in frequency space depending on the time ordering of the interfering light waves. The two gratings are related by a space-time transformation and contain complementary information on the optical dynamics of a system. The status of a grating can be probed by a delayed third pulse, which diffracts off this grating in a direction determined by the wave vector difference of the interfering light beams. This generalized concept of a transient grating can be used to interpret many picosecond-pulse optical experiments on condensed-phase systems. Examples of some low-temperature experiments will be presented. In principle, many of these experiments could also be performed by using stochastic broad-band excitation. In these nonlinear photon-interference experiments the time resolution is determined by the correlation time of the light source rather than its pulse width.

With recent advances in dye-laser technology, interest in the field of optical spectroscopy has shifted from spectral analysis to optical dynamics. Whereas Galileo Galilei used his heartbeat to time-resolve dynamics (*1*), physical processes can now be measured optically on a time scale where light travels only tens of micrometers. Optical pulses with a duration of a picosecond or less that can be tuned from the near ultraviolet to the near infrared are now readily available; visible pulses of only a few optical cycles have already been reported (*2*).

Fleming has recently reviewed the applications of picosecond spectroscopy in chemistry (*3*). In this article we highlight only a certain class of pulsed optical experiments; we concentrate on three-pulse optical pump-probe experiments in which the sample is excited with two interfering light pulses that produce a real-time hologram or transient grating. The decay of this transient grating is monitored by the use of a third time-delayed probe pulse that diffracts off this grating in a well-defined direction.

The type of transient grating formed depends on the time coincidence of the excitation pulses. In the case of time-coincident pulses a transient spatial grating is formed, which resembles a classical ruled or holographic grating. When the pulses are not coincident, a nonclassical holographic population grating in the frequency domain is generated. The fringe spacing in this "frequency" grating is $1/t_{12}$, where t_{12} is the time interval between the excitation pulses. Diffraction off this grating yields signals that are delayed by the same time interval t_{12}. These signals are called photon echoes.

The buildup of any grating is sensitive to the phase difference of the interfering light beams; the phase difference must be kept constant during the preparation period. Burland and co-workers (*4*) showed that the temporal buildup of a permanent spatial grating, formed by a photochemical reaction, contains information about the order, quantum yield, and spectroscopy of the intermediates of this reaction. Dynamical information about the optical pumping cycle of an optical transition is also contained in the buildup of the accumulated frequency-domain grating (*5*), but no experiments have as yet exploited this possibility.

The decay of a transient spatial grating is generally caused by population-relaxation and spatial-diffusion processes. These processes are known as T_1-type processes in optical dynamics. They often proceed at room temperature on a picosecond or even nanosecond time scale so that experiments with transient spatial gratings are feasible over a large temperature range. This field has been reviewed by Eichler (*6*) and more recently by Fayer (*7*). Scattering experi-

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