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Avalanches at the core-mantle boundary

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Abstract. The partial collapse of topographic structure at the core-mantle boundary (CMB) in avalanches, slumps or turbidity flows, would cause sudden temperature changes in both the upper core and the lower mantle. Although such collapses are hypothetical, it is interesting to investigate the potential consequences. Downwelling from such events could disrupt core convection cells and trigger geomagnetic excursions and reversals. Buoyant sediment from the freezing of the inner core is hypothesized to rebuild the avalanched structures. Large avalanches could trigger Mantle plumes. Oblique extraterrestrial impacts impart high shear to the CMB, and can trigger one or more simultaneous avalanches, yielding observed coincidences between craters, tektite fields and reversals. A triggered avalanche can explain the coincidence between the formation of the largest known volcanic province (the Ontong-Java Plateau), the start of the 35 Myr Cretaceous geomagnetic quiet period, and reported coincidences between large flood basalts and extinctions.

Introduction

The core-mantle boundary (CMB) was once thought smooth and homogeneous, but recent work shows it to be far more interesting. There are reports of mushy regions (Loper & Roberts, 1981), an uneven ultra-low velocity zone (Garnero, 1998), fuzzy patches (Garnero & Jeanloz, 2000), a core-mantle transition zone, core-rigidity zones (Rost & Revenaugh, 2001; Garnero & Jeanloz, 2000), and large dome-like structures (Helmberger et al., 1998).

Whereas early models had core convection driven by radioactivity or by heat of condensation, recent models suggest it is driven by buoyancy (Lister & Buffett, 1995). According to Buffett (2000), 70% of the density change as the liquid core solidifies is due to the exclusion of light elements. Moffat (1991) proposed that light material accumulates at the inner-core boundary, and breaks away as a blob. Alternatively, the excluded light elements could remain in solution and freeze out as they rise through the 1000 C temperature drop between the inner core and the CMB, and land like snow on the CMB surface. Buffet et al. (2000) estimated that the volume deposition rate of such "sediment" on the CMB would roughly equal the rate of solidification at the inner core. A 0.1 mm/yr inner core growth implies $\approx$ 0.01 mm/yr *average* deposition at the CMB = 10 m/Myr[a], with more in local regions. Criticism of this sediment model was presented by Morse (2001).

Sediment accumulating on sloped surfaces at the CMB might flow immediately into valleys or it might adhere like snow until the surface exceeds the angle of repose and collapses in an avalanche. In this paper I explore the consequences of the assumption that the sediment is redistributed in discrete and abrupt avalanches.

Avalanches

Avalanches at the CMB would entrain core liquid, and be similar in character to turbidity currents on the slopes of the ocean floor. Such flows can occur at relatively shallow slopes, less than a few degrees; thus the structure at the CMB need not be particularly steep prior to collapse. Except for the small angle, the topography of the structures might be similar to that of sand piles or dunes.

The most important effects of CMB avalanches may result from the redistribution of heat in the nearby upper core and lower mantle. For example, consider a 100-m thick avalanche, the amount of material that might accumulate in a few million years above a core upwelling region. The temperature gradient in the lower mantle is believed to be steep; Williams (1998) showed a "broad family of parameters" suggest a gradient of 5-10 C/km, giving 0.5 to 1 C for a 100-m thick Mantle layer. In contrast, the temperature gradient in the liquid core, approximately adiabatic, $\approx$ 0.07 C in 100 m. Thus, as the cool sediment avalanches down the slopes of the CMB (up, actually, since the flow is driven by buoyancy), it mixes with hot liquid iron. The sediment eventually separates from the iron from buoyancy (1-micron particles take a few years) leaving behind a layer of cooled iron, denser by $2\text{x}10^{-5}$ per C. The buoyancy that drives the convection arises from density differences of order[b] 10^{-8}, a factor 10^{3} smaller. Prior to the avalanche, horizontal temperature differences of upwelling vs. downwelling regions were typically[c] 10^{-5}C. Gubbins et al. (1979) estimate the heat flux from the core $\approx$ 0.01 W/m^2. If all this power were to go into warming the chilled layer, it would take several thousand years. So although a 1 C temperature drop is small (as is the 10^{-5} density increase) there is not sufficient upward energy flow to warm the layer before it drops to the core in a downward plume.

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[a] The volume of the CMB layer known as D" is roughly equal to that of the inner core, suggesting that D" is compacted sediment from the inner core.

[b] If the CMB grows at 10^{-2} mm/yr, and the liquid flows at 0.1 mm/sec = $3\text{x}10^{6}$ mm/yr, then the deposited material comes from the density difference $\approx$ one part in $3\text{x}10^{8}$.

[c] Heat flow from the core < 10^{13} Watts. Assume half the core flows up at 0.1 mm/sec and half down. Take the specific heat of liquid iron = 836 J/kg/C, and density 12.6 gm/cm^3. Then the ΔT up-down is 10^{-5} C to account for the heat flux.

Consequences for the geodynamo

Although the configuration of flow that supports the Earth's dynamo is unknown, substantial progress has been made in numerical models that reproduce the observable characteristics of the measured field (Kuang & Bloxham, 1998). The large dipole component is believed to arise from the α-effect, which tends to align field lines along the axes of the large-scale convective cells; these are, in turn, aligned with the Earth's axis by Coriolis forces. For a recent review, see Buffett (2000).

The cause of geomagnetic reversals is less well understood. It is known from the symmetry of Maxwell's equations that any flow configuration that supports dynamo behavior can support *either* sign of the magnetic field. The prevailing theory for reversal describes the event as a chaotic shift from one sign to another, a phenomena that theoretically occurs in simple dynamos (Cook & Roberts, 1970; Ito, 1980); reversals in full dynamo simulations have been found by Glatzmaier (1995, 1999). A different approach was taken by Muller & Morris (1986), who argued that a reversal was actually a severe disruption of a large convection cell, with a 50% chance that the field would be reestablished in the opposite direction. (Extrapolation of Earth's magnetic field to the CMB suggests that the number of large convection cells is small, with perhaps only two in the northern hemisphere (Bloxham & Gubbins, 1985, Kelly & Gubbins, 1997)). The present model is based on this idea, but it doesn't require the large Earth surface changes in ice volume assumed in the Muller-Morris model.

If sediment accumulates at the upwelling locations, then that is also the site of the major avalanches. If a large cell is disrupted, the scale of the flow pattern is reduced, and this converts the dipole component into higher-order terms. The surface field, dominated by the dipole component, is strongly reduced. Other convective cells could be disrupted by hydrodynamic linking to the first cell. Within a few thousand years, the convective cells reestablish themselves. If the disruption was complete (the magnetic diffusion time of the solid core is a few thousand years), then memory of the previous orientation can be lost. When the field rebuilds, the event is called either an excursion or a reversal.

Mantle plume initiation

The part of the mantle that lost the sediment blanket is exposed to hot iron and is rapidly heated. Using plausible parameters (viscosity $\eta = 10^{21}$ kg/m/s, density $\rho = 3.5\mathrm{x}10^3$ kg/m^3, expansion coef. α = 1.5 x10^{-5} /C, d = 3x10^6 m, thermal diffusivity $\kappa = 10^{-2}$) gives a Rayleigh number $Ra = 10^4$, large enough to suggest that the pulse of heat could play a role in the initiation of a mantle plume. It is possible, however, that mantle plumes would be triggered only by the largest avalanches, with thicknesses >> 100 m.

Triggered avalanches

The CMB sediment's angle of repose depends not only on the properties of the sediment, but also on shear stress from motion of the liquid past the surface. The convective velocity is estimated from the changes in the non-dipole component of the geomagnetic field to be about 0.1 mm/sec. The shear would be changed suddenly, and over most of the surface of the CMB, if there is an abrupt change in the angular velocity of the mantle. This would occur with the oblique impact of an asteroid or comet. Consider, for example, a comet with velocity 25 km/sec, density 2000 kg/m^3, radius 5 km, mass $m = 10^{15}$ kg, impacting the edge of the Earth. The angular velocity of the mantle changes by $\Delta\Omega = mvR/I = 2\mathrm{x}10^{-12}$/sec. ($R$ is Earth's radius; I = mantle's moment of inertia = 7x10^{37} kg m^2.) At the CMB, this imparts a velocity v = 0.01 mm/sec . However, because the initial gradient is steep, the shear stress $F/A = \eta\ \partial v/\partial z$ is greater than that from preexisting flows. The new velocity diffuses into the liquid core with a characteristic distance $\delta(t) = (2\eta\ t/\rho)^{1/2}$. Taking viscosity η = 0.015 Pa s, ρ = 12x10^3 kg/m^3, $\partial v/\partial z \approx v/\delta$, gives δ = 1.5 x10^{-3} $t^{1/2}$ with t in seconds. After a day, $\delta \approx 0.5$ m, and the shear stress is > 10^2 times larger than in the preexisting flow (e.g. v = 0.1 mm/sec, with δ > 1 km.

Additional coupling mechanisms could be important. If the magnetic field of the core is coupled to entrained iron in the sediment, the sudden acceleration of the mantle could break a deep layer of sediment, triggering a slab avalanche. If the avalanche is long range, or if separate avalanches are coupled (e.g. by an impact), then the result could be separate but simultaneous plumes. Larson et al. (1999) drew attention to nearly simultaneous mantle plumes at widely separate locations at 61-62 Ma.

Mass extinctions, impacts, and flood basalts

Flood basalts were associated with mass extinctions by Rampino & Stothers (1988). In a recent review, Wignall (2001) found four basalt/extinction pairs particularly strong. He states, "Curiously, the onset of eruptions slightly post-dates the main phase of extinctions." Although this lag should be verified, note that it is a *prediction* of the impact avalanche model, since the extinctions are caused by the impact and are immediate, but the flood basalt follows with the plume.

In most simulations, mantle plumes take tens of millions of years to reach the surface; such delay could destroy correlation between basalts and impact extinctions. However, the possibility of ultra-fast plumes, reaching the surface in less than a million years, is discussed by Larson et al. (1999) and Thompson & Tackley (1998). Comet showers, spreading the extinctions over 1 Myr or more (Muller, 1985; Hut, 1987) also allow for correlations between impact extinctions and delayed plumes.

Geomagnetic reversals & impacts

There is intriguing evidence linking reversals directly to impacts. The 24-km Ries impact crater in Germany (age 14.8 ± 1 Ma) has reversed polarity in the fall-back breccias but normal polarity in the first crater sediments; thus a reversal took place immediately following the impact (Pohl, 1978). Lee & Wei (2000) report that the

Australasian microtektites preceded the Brunhes-Matuyama reversal by only 6 to 16.5 kyr. (See also Burns, 1989; deMenocal,1990; Schneider, 1992). The avalanche theory predicts that the decay of the surface field should begin within a few hundred to a few thousand years after the impact (the characteristic time for core convection). The measured date, however, does not reflect this initial decay; but rather the *reversal* which takes place during an extended low-field period. Thus the 6-16 kyr delay between the tektites and the "reversal" is compatible with the avalanche model.

Despite the large Chicxulub crater, no reversal occurs at the Cretaceous-Tertiary boundary. However, the unusually high abundance of iridium at this event suggests this impact was vertical, since simulations of oblique impacts show that much of the impactor retains its horizontal component of velocity, and the iridium would be ejected back out into space (Pierazzo & Melosh, 2000). This conclusion disagrees with that of Schultz and D'Hondt (1996), who argued the impact is oblique. A vertical impact should not trigger an avalanche.

Geomagnetic quiet periods

The period from 120 to 85 Ma, which has no geomagnetic reversals, was linked to mantle plume activity by Larson and Olson (1991) who speculated that the quiet period was associated with a core heat flux event that also created the Ontong-Java plateau, the largest volcanic province on Earth, which formed at 120 Ma. Glatzmaier et al. (1999) showed in simulations that mantle thermal structure could modulate the reversal frequency. The avalanche model offers a different explanation for the cooincidence: a large oblique impact caused simultaneous avalanches over much of CMB, and trigger the Ontong-Java plume. With the extensive collapse, no additional avalanches could occur until substantial new sediment was deposited. After 35 million years, slopes reached their angle of repose, and avalanches again triggered reversals. The gradual increase of the rate of reversals from 85 Ma to the present is consistent with this picture; see Figure 1.

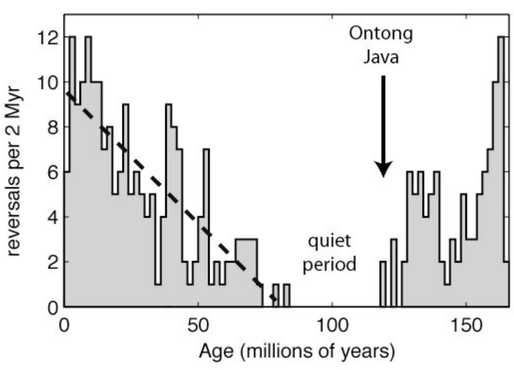

Figure 1. Rate of geomagnetic reversals for the past 160 Myr. The 35 Myr quiet period began at the time of the formation of the Ontong-Java plateau, the largest volcanic province on Earth. The dotted line is the best linear fit to the increase in reversal rate after the quiet period.

A crater at 110-120 Ma had a high chance of being subducted. Even so, there are two candidates: Carswell in Saskatchewan (115 ± 10 Ma, diam 39 km), and Tookoonooka in Australia (128 ± 5 Ma, diam 55 km).[d] It would be useful to obtain better ages, or remote evidence (e.g. shocked quartz) that allows for the relative dating with respect to the formation of the Ontong-Java plateau.

Compilation of the mass extinction of fossil genera by Sepkoski (1989, 1990) shows a significant extinction peak at 120 Ma, particularly in fossil corals, foraminifera, marine arthropods, and echinoderms. These could be the consequence of an impact event that triggered both the volcanic event and the geomagnetic quiet period.

Decadal variations

Theories that attribute the decadal variations of Earth's spin to core-mantle coupling assume the coupling is constant but that the flow varies. It is possible, however, that the flow is constant but the coupling changed by avalanches. Small avalanches should be much more frequent than large ones. Study of sand avalanches (Held, 1990) and turbidite deposits (Rothman, 1994) found the size followed an integral power law distribution with exponent ≈ -1.4. If geomagnetic reversals with 1 Myr intervals are due to avalanches 100-m thick, then in a decade we expect avalanches smaller by a factor of $10^{5/1.4}$, i.e. 3 cm thick. If core-mantle coupling were due to structures 1 km in size, then a 3 cm avalanche would change the coupling by $3x10^{-5}$. Such topographic changes could contribute to decadal variations and possibly to the excitation of the Chandler wobble.

Predictions

If CMB avalanches are responsible for geomagnetic reversals, the model predicts that the morphology of the reversal is different from that seen in the simulations of Glatzmaier et al. (1999). In the avalanche model, the dipole field first drops in intensity, remains low for several core convection periods (several hundred to a few thousand years), and then rapidly rebuilds with the opposite sign, in contrast to the immediate flips seen in the spontaneous reversal simulations. Impacts (and proxies, e.g. microtektites) should *precede* the reversals.

Extended avalanches 1-m thick could have measurable effects on the gravitational multipole moments of the Earth; the changes reported by Cox and Chao (2002) could have a component from CMB avalanches.

The CMB is predicted to have sedimentary deposits with material capable of maintaining shear prior to collapse. The structure of the CMB should be organized into the geometry that one gets when avalanche limits the shapes: relatively sharp ridges, surface sloped near the angle of repose, long valleys, and evidence of frequent small avalanches. The theory requires that the large mantle plumes associated with geomagnetic quiet periods

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[d] A list of craters and their properties is maintained at http://gdcinfo.agg.nrcan.gc.ca/crater/world_craters_e.html

originate at the CMB. Since the turbulent structure in the liquid core is not decreased during geomagnetic quiet periods, but is broken into smaller structures, higher order geomagnetic moments should increase, rather than disappear (as might be expected from other models).

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