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# Plate tectonics may control geomagnetic reversal frequency

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[1] The discovery of the reversals of Earth's magnetic field and the description of plate tectonics are two of the main breakthroughs in geophysics in the 20th century. We claim that these two phenomena are correlated and that plate tectonics controls long-term changes in geomagnetic reversal frequency. More precisely, geological intervals characterized by an asymmetrical distribution of the continents with respect to the equator are followed by intervals of high reversal frequency. We speculate that the distribution and symmetry of mantle structures driving continental motions at the surface influence the equatorial symmetry of the flow within the core and thus change the coupling between the dipolar and quadrupolar modes which controls the occurrence of reversals.

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## 1. Introduction

[2] The geomagnetic reversal frequency is characterized by a stochastic pattern but there is also evidence for a long-term modulation in the rate at which reversals occur. If we refer to the past 80 Myr the average frequency (Figure 1) has increased from zero reversals during the Cretaceous normal superchron (CNS) between 80 Ma and 120 Ma ago to about 4 $\text{Myr}^{-1}$ in the past 5 Myr [*Gallet et al.*, 1992; *Cande and Kent*, 1995; *Kent and Olsen*, 1999]. Prior to the CNS the geomagnetic polarity timescale (GPTS) exhibits a progressive decrease of reversal frequency [*McFadden and Merrill*, 2000; *Lowrie and Kent*, 2004; *Hulot and Gallet*, 2003]. The existence of the Kiaman Reversed Superchron [*Opdyke and Channell*, 1996] at 310–260 Ma and a possible third Phanerozoic superchron around 490–460 Ma [*Pavlov and Gallet*, 2005] suggest that long intervals without reversals may have punctuated a large part of the geomagnetic history yielding the concept of a 200 Myr recurrence in processes associated with the geodynamo.

[3] Such long-term variations are difficult to link to the turbulent flow motions within the Earth's liquid core which have a characteristic time scale of the order of a few centuries. Conversely, they are too short for being accounted by the growth of the inner core which was initiated 1 Ga ago at the latest [*Labrosse and Macouin*, 2003]. Secular changes in Earth's rotation are also possible candidates, but they occur on short time scales (20 to 100 kyr long for Milankovich cyclicities). For these reasons, it is usually assumed that long-term variations in reversal frequency are related to geodynamic processes in the mantle involving changes at the core-mantle boundary (e.g., see *Merrill et al.* [1996] for a review or *Courtillot and Olson* [2007] for a recent study on this matter). Indeed, flow velocity of the mantle does not exceed a few centimeters per year and the characteristic time for mantle convection is therefore of the order of 100 Myr.

## 2. Method and Results

[4] A mechanism has recently been proposed for geomagnetic reversals [*Pétrélis et al.*, 2009] which points out the importance of the coupling between a dipolar and a quadrupolar mode. At linear order, the two modes are decoupled when the core flow is equatorially symmetric but become coupled if the symmetry is broken. This situation yields either a reversal or a field excursion and exhibits specific features (slow decrease and fast recovery, overshoot) that have been documented by paleomagnetic records [*Valet et al.*, 2005]. Note that a similar model [*Pétrélis and Fauve*, 2008] also describes the field reversals observed in an experimental dynamo generated by the counter rotation of two disks in a cylinder filled with liquid sodium [*Berhanu et al.*, 2007]. The same mechanism has been identified in models of astrophysical dynamos [*Gallet and Pétrélis*, 2009] as well as in numerical simulations [*Gissinger*, 2009]. Based on the overall convergence of observations, experiments and models we reasonably infer that the rate of reversals is constrained by breaking of the equatorial symmetry of the flow.

[5] Thus, assuming that heat flow conditions at the core-mantle boundary (CMB) would control reversal frequency and also exert a significant influence on mantle convection, we should expect some link between reversal frequency and plate tectonics. More precisely, we speculate that the long term evolution in reversal rate is caused by changes at the CMB which are linked to the equatorial symmetry of the geographic distribution of the continents. To test this hypothesis we have first calculated the convex envelope of the continents. The convex envelope is a global indicator of the position of the continents and is defined as the smallest convex set containing all segments joining every pair of points on the continents. Thus, it is sensitive to the latitudinal as well as to the longitudinal relative positions of the continents which result from plate tectonics. In order to accomplish this calculation we have used a Mollweide projection and we have either computed or visualized this surface, both methods yielding the same results. In Figure 2 are shown snapshots of the repartition of the continents at different epochs with their convex envelope. The procedure for plate reconstruction relies on oceanic kinematic parameters derived from *Müller et al.* [1993] that have been used at first to place the major continents in their relative positions. The paleomagnetic synthetic Apparent Polar Wander Paths (APWPs) of *Besse and Courtillot* [2002] and *Torsvik et al.* [2008] were then used to fix the paleolatitude grid from

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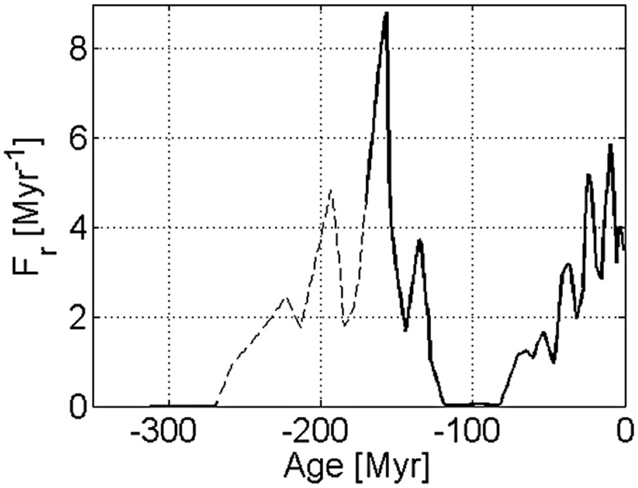

**Figure 1.** Evolution of reversal frequency as a function of time [from *Cande and Kent*, 1995].

0 to 200 Ma and 200 to 320 Ma, respectively. These APWPs were constructed after careful selection of the best paleomagnetic poles available for major continental blocks transferred onto a single reference frame and averaged over 20 Myr long time windows.

[6] The present envelope of the continents is asymmetrical with respect to the equator (Figure 2) with a larger continental surface in the northern hemisphere. A similar situation occurred 200 Myr ago while more continental surface appears to have been present in the southern hemisphere 65 or 260 Myr ago. A quantitative estimate of the asymmetry of continental surface with respect to the equator can be obtained by measuring the first moment of its distance to the equator given by $D = \int z\, dS/St$ where the integral is performed over the convex envelope and St is the Earth area. D has the dimension of a length and its maximum value would be 1600 km if the convex envelop were covering the whole northern hemisphere. Error bars on D have been calculated from the uncertainties on the latitude ($\delta\lambda$) of the continents. We thus constrained the errors by $\delta D = \delta z\, S/St$ (with S being the surface of the convex envelope and $\delta z = 2\,\pi\, R\, \delta\lambda/360$). Here, R is the radius of the Earth and $\delta\lambda$ is measured in degrees. The next step has been to compare the temporal evolution of the D parameter with reversal frequency (Fr) for the past 320 Myr. It is important to note that the geomagnetic polarity time scale is well established from the succession of the oceanic magnetic anomalies for the past 170 Myr, but that the detailed succession of geomagnetic reversals is less defined prior to this age. Consequently, the detailed pattern of reversal frequency is more delicate prior to 170 Myr but the existence of superchrons cannot be questioned. It is striking that the frequency of reversals and the evolution of D plotted in Figure 3a have similar shapes and appear to be correlated with a normalized cross-correlation coefficient of 0.47 for the last 260 Myr. The correlation increases to 0.6 after smoothing Fr by a 40 Ma long time-averaged running window which removes the high frequency variations.

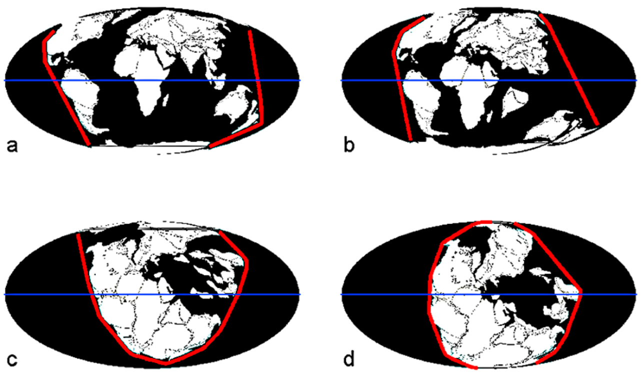

**Figure 2.** Position of the continents with their convex envelope (red line) at various periods of time: (a) present time, (b) 65 Myr ago, (c) 200 Myr ago, (d) 260 Myr ago.

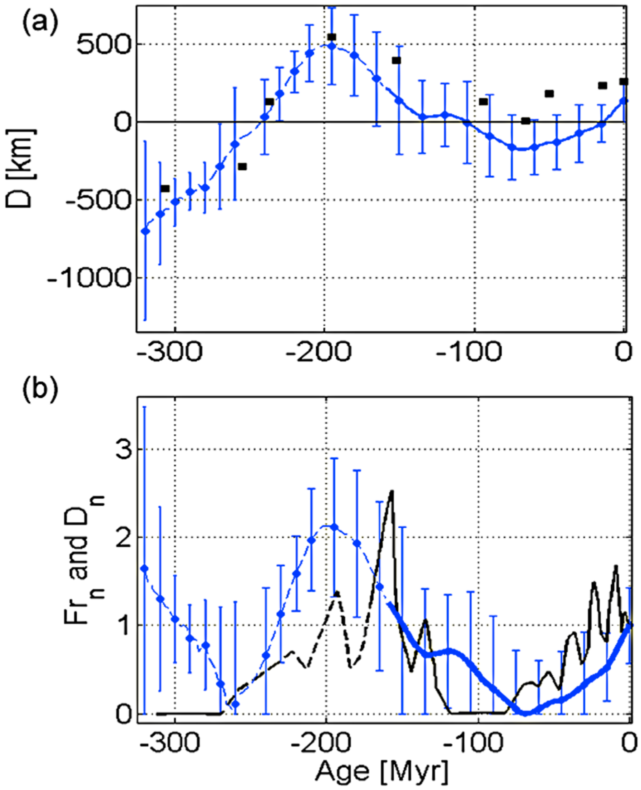

**Figure 3.** (a) Temporal evolution of the D parameter which characterizes the asymmetrical distribution of the continents about the paleomagnetically defined paleo-equator. Data derived from magnetic oceanic anomalies are shown by a continuous line. Blue dots correspond to the reconstructions used in this study. For comparison black squares represent the reconstructions obtained by Scotese. (b) Comparison between changes in reversal frequency (black line) and the D parameter obtained after $Dn = |D - D[-65\ Myr]|$ (blue line). The bold line corresponds to the past 170 Ma documented by magnetic oceanic anomalies. Error bars represent uncertainties in continental reconstructions. Both curves have been normalized to their present value.

[7] The correlation appears clearly in Figure 3b where D has been shifted by a constant value so that its absolute value can then be directly compared with the reversal frequency. The evolution of both parameters shows the same structure which reveals that the intervals of large reversal frequencies

were associated with significant breaking of the equatorial symmetry. The decrease of Fr between −200 and −120 Ma is accompanied by a southward motion of the continents while the increase of Fr over the past 80 Myr is coherent with a northward motion. This is particularly clear, for instance, for Oceania and India. Unfortunately, the existing data base does not allow us to investigate with sufficient accuracy whether similar correlations have been present during older intervals. It could be argued that uncertainties in the calculation of D are large enough to induce incorrect trends. In order to investigate this possibility we have generated values of D every 15 Myr from random independent Gaussian drawings with mean and standard deviation as displayed in Figure 3a. We have determined the best linear fit for the intervals −260 to −195, −180 to −90 and −60 to 0 Ma. The slope of the fit is a random number and we can calculate the probability that its sign is different from the one observed in the variations of Fr (for instance that D is actually decreasing between −260 and −195 Myr while Fr is increasing). Since the probabilities of such events are 4.4%, 6.5% and 7.4%, respectively, we infer that the similar patterns of Fr and D unlikely result from errors in the determination of D.

## 3. Discussion and Conclusion

[8] The D parameter has been defined to quantify the equatorial symmetry inherent to the continental masses. The link with reversal frequency indicates that mantle dynamics has a profound influence on dynamo processes, and thus implies a direct relation between the lower mantle and the upper core. As observed numerically by *Phillips and Bunge* [2005] supercontinents promote temperature anomalies on the largest scales. In a first scenario breaking of equatorial symmetry in the repartition of the continents is linked to the distribution of zones with descending and ascending material which drives thermal heterogeneities in the lower mantle. According to *Buffett* [2007] this would imply an offset of 40–50 Myr between changes at the CMB and plate motions at the surface. Unfortunately, the size of the error bars precludes us to discern the exact time relationship between D and Fr in Figure 3. The second possibility is to assume that the coupling exists via a global motion of the mantle which can also be described by true polar wander [see, e.g., *Besse and Courtillot*, 2002]. Under this assumption the evolution of mantle heterogeneities closely follows the motion of continents. This scenario would imply similar patterns between D and the north-south component of the true polar wander. Work in progress indicates that this is indeed the case.

[9] Several numerical dynamos [*Olson and Christensen*, 2002; *Willis et al.*, 2007; *Aubert et al.*, 2008] and laboratory experiments have pointed out the role of long wavelength heat flux heterogeneity at the CMB on the structure of the field. The role of heterogeneous heat flux at the CMB on reversal frequency has also been explored [*Glatzmaier et al.*, 1999; *Coe and Glatzmaier*, 2006; *Olson et al.*, 2010]. *Kutzner and Christensen* [2004] have investigated numerical dynamos with heterogeneous heat flux and found higher reversal frequencies in dynamos with positive axisymmetrical equatorial heat flux and lower reversal frequencies in presence of negative axisymmetrical equatorial heat flux anomalies. These results emphasize the importance of equatorial symmetry on reversal frequency, which finds a natural explanation in the framework of the model for geomagnetic reversals involving a coupling between a dipolar and a quadrupolar mode [*Pétrélis et al.*, 2009]. The existence of a link between motions at the earth's surface and within the core implies that when the heat flux at the CMB breaks the equatorial symmetry, so does the flow in the outer core. This situation favours the coupling of the dipolar and quadrupolar modes which generates reversals and thus increases their frequency. Having this mechanism in mind, we stress that the D parameter is a global quantity which is mostly sensitive to the largest scales of the plate pattern and increases with the distance between two continental masses located at the same latitude. Since distant continents generate large scale modifications in the mantle and the core, it is reasonable to consider that such large scale structures have a strong effect on the geodynamo.

[10] By subtracting the value of D at −65 Myr, we are able to almost superimpose Fr and Dn without affecting the cross-correlation. We note that the value D (−65 Myr) lies within the uncertainties. This shift is for instance not observable in the time series of D extracted from the data of C. R. Scotese (Plate tectonic maps and continental drift animations, PALEOMAP project, www.scotese.com), indicated here by black squares in Figure 3a. We can thus reasonably infer that it is not significant. We also expect that more sophisticated estimates could increase the correlation or capture shorter time scale variations of Fr. One could for instance introduce a dependence on the position of the ridges or of the subduction zones or ponderate the effects by the surface thermal flux or by the position with respect to the inner core tangent cylinder. In any case, D is obviously an indirect quantification of the effects of plate tectonics on the boundary conditions at the CMB and it is thus quite satisfactory that this simple quantity appears to be correlated with reversal frequency.

[11] *Eide and Torsvik* [1996] have argued that the last two superchrons were different because the detailed positions of the continents were not the same. We point out that the present approach accounts for the entire spectrum of reversal frequency, from superchrons to tiny polarity intervals.

[12] The present results suggest that plate tectonics has exerted a significant control on the geomagnetic reversal frequency (for at least the past 300 Myr), and thus bring additional evidence assessing the importance of mantle dynamics in the mechanisms driving long-term dynamo processes. The next step is to constrain further the link between plate motions and the upper mantle and ultimately with the physical properties at the core-mantle boundary.

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