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Stationary and nonstationary behaviour within the geomagnetic polarity time scale

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Abstract. We analyse the geomagnetic polarity time scale (GPTS) since the Upper Jurassic by displaying the successive lengths of polarity intervals as a function of their order of occurrence. The sequence consists of three segments. Between the Upper Jurassic and the Lower Cretaceous, segment "A" comprises intervals of short duration, with a mean duration of about 0.29 My, and no clear long-term evolution. Segment "B" begins around 130 Ma, displays a sudden increase of the duration of the magnetic intervals, an interval of maximum duration, the normal Cretaceous superchron, and a long and erratic sequence of intervals with decreasing average duration between 85 Ma and about 25 Ma. From 25 Ma to the present, segment "C" consists of intervals of short duration with a mean value of 0.23 My. This description suggests that the Earth's magnetic field could have experienced a fairly stationary regime until slightly before the onset of the Cretaceous superchron, when the regime has been rapidly and strongly perturbed before progressively returning to another stationary regime about 25 Ma ago. A geophysical explanation for this sequence of events could be that the geodynamo has been perturbed by the arrival of some cold material at the core mantle boundary. As this material would have heated up, the geodynamo would have been brought back to its stationary regime.

1. Introduction

The origin of the numerous polarity changes of the geomagnetic field over the geological time scale is still poorly understood. Marine magnetic anomalies clearly display large changes in reversal frequency since the Upper Jurassic, suggesting a long time constant of about 150 My (McFadden and Merrill, 1984), and magnetostratigraphic results from the Upper Permian to the Middle Jurassic roughly confirm this suggestion since approximately 320 My (Gallet et al., 1992). This type of long-term behaviour reflects either an intrinsic property of the dynamo process itself or a response of the dynamo to some external forcing (e.g. McFadden and Merrill, 1984; 1986; Gubbins, 1987). Recently, Gallet and Courtillot (1995) proposed to complete the commonly used analysis in frequency by displaying the successive lengths of polarity intervals as a function of their order of occurrence in the sequence. In the present study we further consider this representation and point out that it provides new insights on the description of the GPTS since the Upper Jurassic (about 160 Ma).

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2. The GPTS as a function of order of occurence

The GPTS, which displays no statistical difference between the normal and reverse polarity states (McFadden and Merrill, 1984; Merrill and McFadden, 1994), can be described in terms of a Gamma process (i.e. an alteration of a Poisson process, which is a random process with no memory of its past behaviour). One can write the Gamma density probability following the convention of McFadden and Merrill (1986):

$$P(x)=\frac{1}{\Gamma(k)}\lambda^k x^{k-1} e^{-\lambda x} \qquad (1)$$

where Γ(k) is the Gamma function of k and λ is an inherent rate of reversals associated with the unaltered Poisson process. A Gamma process reduces to a Poisson process when k is equal to one. A value for k greater than one can be interpreted either as an artefact linked to some short intervals missing in the GPTS or to some short term memory within the dynamo that would inhibit a second reversal just after a first one has occurred (McFadden and Merrill, 1993). In any case, the Gamma process describing the GPTS is known to be non stationary on time scales of 100 My, essentially because of some variation within the inherent rate λ (k displaying little significant variations except at the time of the Cretaceous superchron; where the reversal process seems to have been completely frozen; e.g., Merrill and McFadden, 1994).

The GPTS can therefore be viewed as the result of a time varying Gamma process, mainly controlled by the mean duration $\mu = k/\lambda$, an estimate of which is given by the average duration $\mu_N(i) = (1/N)\Sigma x_j$ of N intervals of duration x_j about the interval number i. This estimate, which has a variance $Var(\mu_N(i)) \approx (\mu_N(i)^2/kN)$ (McFadden, 1984), can be plotted as a function of i to characterize the evolution of the process creating the GPTS.

We have considered a composite GPTS constituted by the Upper Cretaceous to Cenozoic polarity sequence recently proposed by Cande and Kent (1995) and the Upper Jurassic to Lower Cretaceous sequence suggested by Harland et al. (1990). The whole sequence contains 284 intervals, 99 intervals before the Cretaceous superchron and 184 after. We acknowledge that the uncertainties which remain in the precise absolute dates of the Mesozoic GPTS render delicate the detailed analysis of the GPTS, but we believe that they would not notably modify the broad description we intend to do hereafter. The polarity interval durations for both polarities are shown as a function of order of occurrence on Figure 1. The raw data is plotted on Figure 1a, and the corresponding estimates $\mu_N(i)$ for N=25 on Figure 1b (except when they involve the Cretaceous superchron). We have arbitrarily chosen N=25 in order to smooth most of the ambiguous short-term fluctuations. We

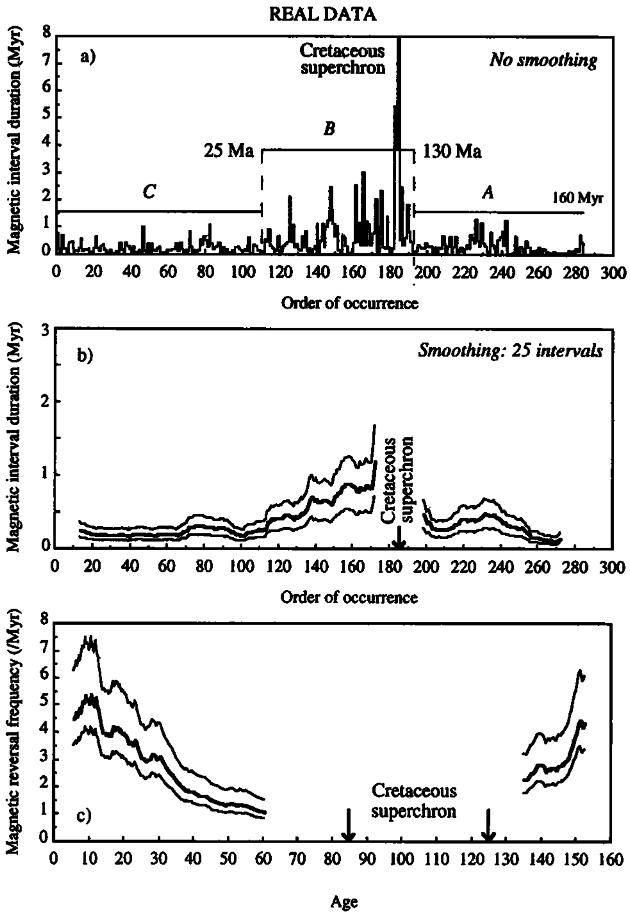

Figure 1. Polarity interval durations as a function of order of occurrence (Fig. 1a,b). The first interval is Brunhes. The raw data is shown on Fig. 1a, and $\mu_N(i)$ for N=25 and k=1 is plotted with its $2\sigma_{N=25}$ errors ($\sigma_N(i)=\mu_N(i)/\sqrt{N}$) on Fig. 1b (except those involving the Cretaceous superchon). Fig. 1c shows λ^*_{50} since approximately 160 Myr. We also plotted the curves $\lambda_+(i)=1/(\mu_{50}(i)+2\sigma_{50}(i))$ and $\lambda_-(i)=1/(\mu_{50}(i)-2\sigma_{50}(i))$ within which λ^*_{50} is expected to fluctuate.

also have considered k=1 to compute the errors associated with μ, although k is usually slightly larger (and thus the uncertainties smaller). Both diagrams support the idea that a difference exists in reversal behaviour before and after the Cretaceous superchron (the Cretaceous superchron #185 is preceeded by only 2 intervals that last longer than 1.5 My, whereas at least 9 such intervals follow it; Fig. 1a). They further suggest that the GPTS can essentially be described by three segments. Between intervals #284 and #193 (segment A: Upper Jurassic-Lower Cretaceous), the magnetic reversals are of short duration with no clear long-term evolution, $\mu_N(i)$ being roughly constant within error bars ($\mu_A=0.29 \pm 0.03$ My). Between intervals #192 and #110 (segment B), the average duration first increases quickly (in less than 10 My), reaches a maximum with the Cretaceous superchron (35 My; Cande and Kent, 1995), and then decreases slowly between intervals #184 and approximately #110 (from about 85 Ma to 25 Ma). A third segment (C) finally characterises intervals #110 to #1. The magnetic intervals are then again of short duration, with $\mu_C=0.23 \pm 0.02$ My. As previously suggested, the observed behaviour resembles flat white noise (Dubois and Pambrun, 1990; Gallet and Courtillot, 1995).

We next plotted histograms of the duration of the magnetic intervals for the 3 segments (Fig. 2a). Each number of intervals has been divided by the total number of intervals within the respective segment. Whereas segments A and C are indeed very similar, segment B clearly differs eventhough we did not take the onset of B and the Cretaceous superchron into account. Plotting histograms of the relative duration of the magnetic intervals with respect to the time varying estimate of μ gives a different picture (Fig. 2b). The lengths of the magnetic intervals have been divided by their respective mean duration for segments A (μ_A) and C (μ_C), and by a varying value $\mu_B(i)$ defined by a linear trend adjusted to the one observed in Figure 1b (between the value of 1.0 My for interval #184 and 0.23 My for interval #111) for segment B. The three distributions are now very close to one another (Fig. 2b; given the small number of intervals in each segment). This confirms that the GPTS can be interpreted as the result of one process essentially characterized by the parameter μ (except during the onset of B and the Cretaceous superchron).

3. Discussion

Previous analyses have shown that the GPTS is the result of a Gamma process defined by equation (1) and characterized by the two parameters k and λ, or alternately k and $\mu=k/\lambda$. Because k clearly displays little significant variations through the sequence, changes in the GPTS are essentially due to variations either in λ or μ. But neither λ nor μ are readily accessible to

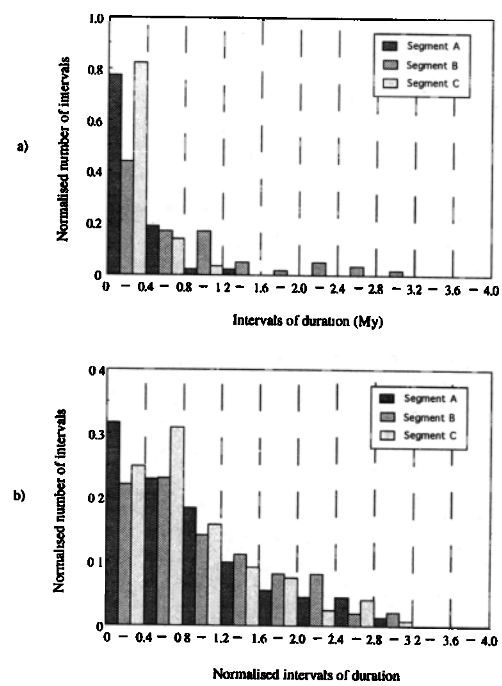

Figure 2. Histograms of duration of the intervals defining the three segments A,B,C. Only the intervals following the Cretaceous superchron have been considered for the segment B. The histograms have been normalized to the total number of intervals within each segment (Fig. 2a). Fig. 2b: same except that the duration of the magnetic intervals has been divided by the time varying estimates of μ displayed on Fig. 1b.

measurement. The only parameter which can be recovered with some good statistical understanding is the estimator $\mu_N(i)$ of μ (McFadden, 1984). Plotting $\mu_N(i)$ as a function of i (order of occurrence) treats each realization of the process with equal weight (Fig. 1b). This representation underlines the different nature of the non-stationarity of the reversal process before and after the Cretaceous superchron. It also shows the close similarity between segments A and C, together with their flat white noise-like behaviour. This latter characteristic suggests that during the corresponding periods of time the geodynamo experienced a fairly stationary regime characterized by the random occurrence of short magnetic polarity intervals (Dubois and Pambrun, 1990; Gallet and Courtillot, 1995). The onset of the Cretaceous superchron at the beginning of segment B, in about 5 My (Harland et al., 1990), shows that the stationary regime defined by segment A rapidly ended slightly before the superchron. In contrast the second part of segment B, between 85 Ma and 25 Ma, indicates a progressive return to another stationary regime (segment C).

This interpretation of the GPTS represents an alternative to the one of McFadden and Merrill (1984) which is based on the curve derived from the GPTS by plotting $\lambda^*{}_{50}(i)=1/\mu_{50}(i)$ as a function of the age (and no longer as a function of i). The parameter $\lambda^*{}_{50}$ provides an estimate of λ/k and as k changes little, variations in $\lambda^*{}_{50}$ can be interpreted as changes in the true reversal rate λ (McFadden, 1984). The corresponding curve is shown on Figure 1c together with the bands within which the estimator $\lambda^*{}_{50}$ is expected to fluctuate about λ/k. For the last 100 My, this curve suggests that the reversal rate has gradually increased from the end of the Cretaceous superchron to the present. This interpretation is compatible with the data but is strongly guided by the way the data is presented. The time when the process is clearly non-stationary (our segment B) corresponds to a long period on Figure 1c and invites to extrapolate this behaviour up to the present. Also the choice of N=50 strongly smoothes the curve and short term changes in the trend are impossible to see (only three averages are statistically independent over the last 100 My). On the contrary, our curve (Fig. 1b) closely sticks to the original data (Fig. 1a), involves twice less averaging and provides a better chance of assessing the non-stationarity within the GPTS. It suggests with equal statistical value that changes in behaviour could have indeed occurred about 25 Ma and 130 Ma ago. For further confirmation, we have generated a synthetic magnetic polarity sequence with the help of a Poisson process controlled by a parameter μ equal to μ_A during enough intervals to cover the length of segment A (from 160 to 130 My), stopped during a fictitious superchon, reinitiated with $\mu=\mu_B(i)$ during the time of segment B, and finally made stationary again with $\mu=\mu_C$ during the time of segment C (Fig. 3). Whereas Figure 3c shows the same trends as Figure 1c that led McFadden and Merrill (1984) to their interpretation, Figure 3b properly recovers the three segments we had input and looks very similar to Figure 1b.

Interpreting the reversal behaviour in terms of physical process is notoriously speculative, because little is known about what controls the reversals. Boundary conditions imposed by the core-mantle boundary (CMB) certainly influence the geodynamo and may thus control changes in the GPTS. Here we explicitely assume that changes in μ result from some changes within the CMB boundary conditions. The most

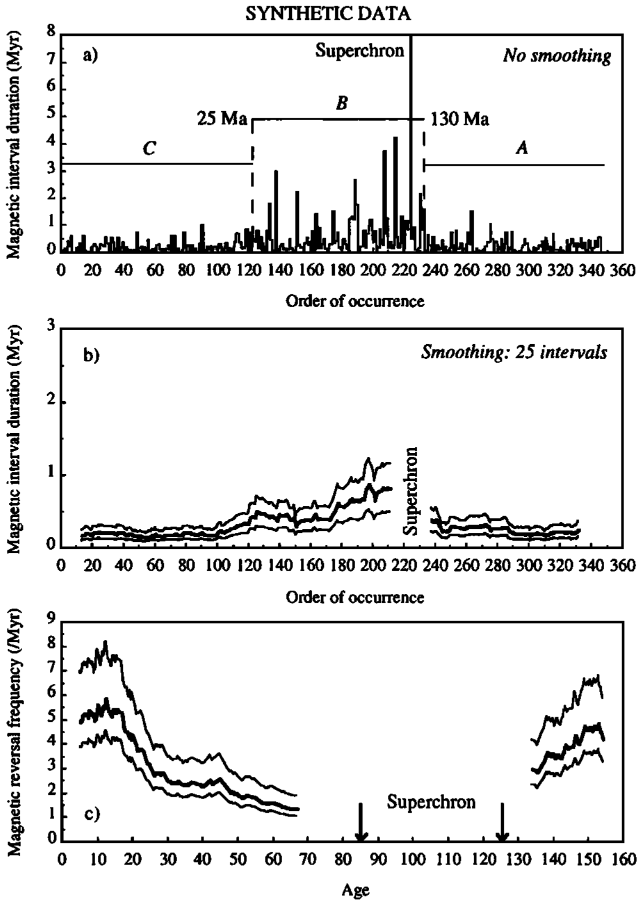

Figure 3. Synthetic magnetic polarity sequence generated as described in the text. Same representations as in Fig. 2.

important conditions are believed to be the thermal ones at the CMB which control the heat flux extracted from the core. Gubbins (1987) pointed out the possible influence of mantle thermal lateral variations on the behaviour of the magnetic field. Stacey (1991) further suggested that there might be crypto-continents drafting and inducing additional lateral thermal variations at the CMB. But changes produced in this way are slow and can hardly account for the rapid freezing of the reversal process in less then 10 My. Several other authors underlined the fact that the heat flux is controlled by the thickness of the D" layer (assumed to be a thermal boundary layer) at the base of the mantle and that this thickness is likely to change every time a plume erupts as a result of some instabilities within D" (e.g., Loper and McCartney, 1986; Courtillot and Besse, 1987; Larson and Olson, 1991). But Loper (1992) showed that partially emptying D" only leads to slow changes within the heat flux (on time scales of a billion years). A plume leaving D" would therefore not better account for the A, B, C sequence.

In contrast, if some cold material could be brought quickly in direct contact with the core, the heat flux would be promptly and drastically altered. Such a thermal anomaly could possibly explain the sudden onset of segment B. For a slab-like structure with a thermal diffusivity $k=10^{-6}m^2s^{-1}$ that arrives in contact with the core, the flux below this structure is proportional at any subsequent time t to the temperature gradient $\Delta T/(k\pi t)^{1/2}$, where ΔT is the initial temperature contrast between the core and the cold anomaly (e.g., Turcotte and Schubert, 1982). This temperature gradient goes back to a value comparable to the one the thermal boundary layer enjoyed before the arrival of the cold material (∇T), after a relaxation time of the order of $b^2/k\pi$, where $b=\Delta T/\nabla T$ is the distance from the CMB within the thermal boundary corresponding to a temperature drop of ΔT. This can be assumed to be of the order of the thickness of the thermal boundary layer itself (say 100 km). A relaxation time of about 100 My is found, which is the order of magnitude of the duration of our segment B. A possible interpretation of the A,B,C sequence is then that the thermal boundary conditions could have remained stable during A, have been perturbed at the onset of B by the arrival of some cold material at the CMB, and have settled back as the cold material was heated back to some thermal equilibrium. The mechanism that could push cold material at the CMB remains uncertain. An efficient candidate could be a mantle avalanche. Indeed, 3-D numerical models of mantle convection incorporating an endothermic phase transformation at the 660 km discontinuity all display hybrid convection. This type of convection is mainly two-layered but occasionnally may experience flushing events during which cold material suddenly sinks from the upper mantle into the lower mantle (e.g., Machetel and Weber, 1991). As an alternative, a subducted slab could have penetrated into the lower mantle and landed at the CMB (e.g., Christensen, 1996; Eide and Torsvik, 1996). Such events seem to be rare enough to account for the fact that just one is being seen in the 160 My long GPTS, and quick enough for the material to remain significantly cold when it reaches the CMB.

This interpretation of the GPTS assumes that reversals of the geomagnetic field are strongly inhibited by the local increase in the heat flux associated with the arrival of cold material at the CMB. We note that such local changes would modify the boundary conditions. Altering the boundary conditions in rotating convective systems clearly impose strong and global constraints on the nature of the solution chosen by the system (e.g., Zhang and Gubbins, 1993). We therefore suggest that these changes could prevent the system from going through intermediate states that would normally lead to a reversal. At the onset of B, the perturbation would have been particularly strong and the system would have remained stuck in one polarity. As the cold material would have progressively heated up, the perturbation would have been weaker, only proportionnally impeding the reversals. This further suggests that the size of the cold anomaly arriving at the CMB could provoke and determine the duration of the subsequent superchron. This could explain the longer duration of the Kiaman superchron occurring during the Late Paleozoic (Harland et al., 1990). This scenario does not preclude some correlations with plume eruptions possibly triggered by the arrival of the cold material within D".

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