ELSEVIER

Earth and Planetary Science Letters 210 (2003) 191–201

EPSL

www.elsevier.com/locate/epsl

Do superchrons occur without any palaeomagnetic warning?

Gauthier Hulot *, Yves Gallet

Département de Géomagnétisme et Paléomagnétisme, CNRS UMR 7577, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris cedex 05, France

Received 28 November 2002; received in revised form 10 March 2003; accepted 11 March 2003

Abstract

The mainly dipolar geomagnetic field generated by the geodynamo within the Earth's liquid core has reversed its polarity many times in the past. This succession of intervals of alternate polarity defines the geomagnetic polarity time scale (GPTS), usually interpreted as resulting from a Gamma renewal process, the rate of which would be controlled by the boundary conditions imposed by the mantle on the core. In this interpretation, boundary conditions would have occasionally evolved towards being unfavourable to reversals, leading the (reversal) rate of the process to progressively decrease and reach zero at least twice, causing the onset of the so-called Kiaman and Cretaceous very long polarity intervals (superchrons). Here we reconsider this causal link. Analysing the latest and best constrained GPTS (thanks to the continuous record provided by marine magnetic anomalies) describing the past 160 Myr, we found that contrary to earlier claims, no long-term behaviour over the ∼40 Myr preceding the Cretaceous superchron can be seen in the reversal rate that could explain its onset at ∼120 Ma. More generally, it turns out that hardly any special behaviour can be identified in the GPTS, which could have announced this superchron. Only the occurrence of the longest of all pre-superchron intervals (CM1n), ∼3 Myr before the onset of the superchron, could be identified as a precursor. Such a behaviour could possibly be the consequence of medium-term (on the 10 Myr time scale) changes in the boundary conditions imposed by the mantle on the core. But we note that the sole analysis of the GPTS does not allow this to be tested. In fact, it appears that a single stationary process could also explain the entire pre-superchron GPTS, with the only possible exception of CM1n. This suggests that the occurrence of superchrons does not necessarily require changes in boundary conditions and could simply attest for a sudden non-linear transition between a reversing and a non-reversing state of the geodynamo.

Keywords: Geomagnetic Field; reversals; superchrons; statistics

1. Introduction

Although it is well-established that the Earth's magnetic field is more than 3 Gyr old and that reversals already occurred at that time [1], our knowledge of the geomagnetic polarity time scale (GPTS) remains mostly limited to the Phanerozoic (∼550 Myr; e.g., [2]). Throughout that period the geomagnetic field has often changed polarity and at least twice experienced very long intervals of fixed polarity, during the Kiaman reversed superchron (KRS, between ∼310 and ∼260 Ma) and the Cretaceous normal superchron (CNS, be-

* Corresponding author. Tel.: +33-1-44-27-34-06; Fax: +33-1-44-27-33-73.

E-mail address: gh@ipgp.jussieu.fr (G. Hulot).

0012-821X/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0012-821X(03)00130-4

tween ~120 and ~83 Ma). This GPTS is best known since the Upper Jurassic (~160 Myr ago), thanks to the constraints provided by the marine magnetic anomalies not available for older epochs. This period of time includes the CNS. It has therefore been the subject of many studies in the past (see e.g. [2,3] for extensive reviews of earlier work) aiming at elucidating the still open question of why the field exhibited such dramatic changes in its reversing behaviour.

The current dominant view on this topic is the one first worded by McFadden and Merrill [5]. Those authors noted that this best known fraction of the GPTS could be described as resulting from a Gamma renewal process continuously varying in time, except during the CNS when the reversal process remained 'frozen' for over 30 Myr. Their analysis, completed by more recent analysis (e.g., [4,6,7]) led them to conclude that a long-term decrease of the reversal rate could have taken place over the ~40 Myr period preceding the CNS. Such a decrease is indeed suggested by Fig. 1a, which shows an estimate of the reversal rate as a function of time, produced by analysing the GPTS of Kent and Gradstein ([8]; hereafter KG86) with a moving window of width $N=50$ intervals, along the lines suggested by McFadden [9]. This apparent decrease led McFadden and Merrill [5] to suggest that superchrons could have arisen as a result of long-term thermal influence of mantle convection on core dynamics. As mantle convection would have produced slow changes in thermal core–mantle boundary conditions, which would have then become unfavourable to reversals, the reversal rate would have progressively decreased to zero, forcing the geodynamo to switch from a 'reversing' to a 'non-reversing' state at the onset of the CNS [6].

In an earlier paper, however [10], we noted that relying on the same GPTS but plotting the data differently (i.e., the magnetic interval duration as a function of order of occurrence, as proposed by Gallet and Courtillot, [11]) could suggest a different interpretation. Fig. 1b, produced in this way (very similar to our original plot which relied on the slightly different GPTS of Harland et al. [12], hereafter called GTS89), indeed suggests that before the CNS, the reversal process could have in

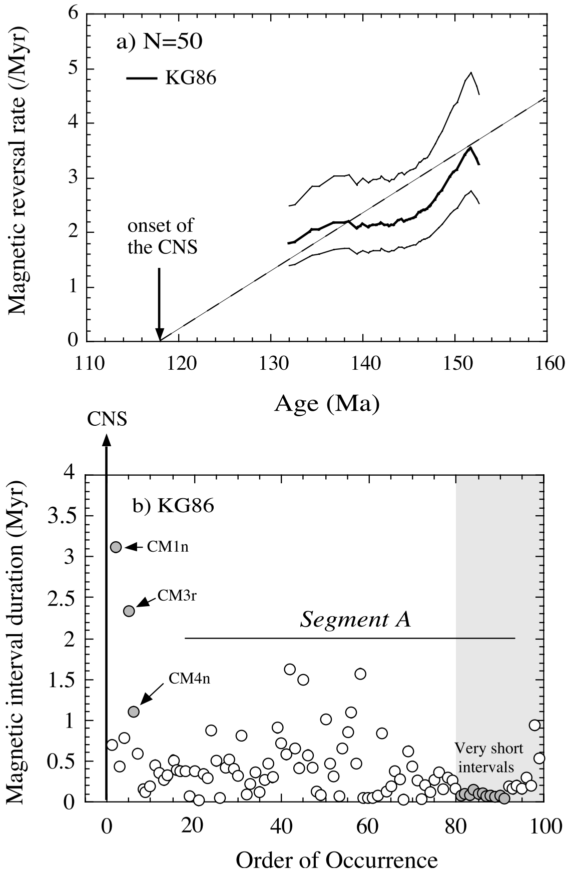

Fig. 1. (a) Estimate of the reversal rate based on KG86 [8] as a function of time between the Upper Jurassic and the onset of the Cretaceous superchron, using moving windows of width $N=50$ intervals, along the lines suggested by McFadden [9]. Also shown, as lighter curves, the 2σ curves between which the true reversal rate is expected to lie, and, as a dashed line, the long-term linear trend towards zero favoured by McFadden and Merrill ([7], see their fig. 1). (b) Length of the magnetic intervals as a function of their order of occurrence in KG86. Also shown are various intervals of interest for the discussion (shaded circles) and the segment A introduced by Gallet and Hulot [10] and discussed by McFadden and Merrill [7]. The grey-shaded area corresponds to the time of the oceanic magnetic anomaly M25 and beyond (corresponding to Middle to Upper Jurassic), within which many short intervals had been tentatively identified in KG86 but are no longer considered in the most recent GPTS (see Fig. 2b).

fact enjoyed a period of fairly stationary regime, ending only maybe ~10 Myr before the CNS, at a time a few substantially longer intervals occurred (CM1n, CM3r and CM4n). As such a change of behaviour would require a much faster change in the boundary conditions than originally proposed by McFadden and Merrill [5], we therefore suggested that this could result from the rapid arrival of some cold mantle material at the core–mantle boundary. Relying on simple simulations, we however acknowledged that both our description and that of McFadden and Merrill [5] seemed to be equally compatible with the data.

More recently, Constable [13] reconsidered the issue under the more general assumption that geomagnetic reversals could be considered as having been generated by a renewal process (be it a Gamma process or else) with an unspecified time varying reversal rate. This study showed that the only robust conclusion one could reach with this respect is that, generally speaking, the reversal rate must have decreased to produce the CNS and subsequently increased again, but that no time constraints (else than trivial) could be put on this global evolution. It was therefore argued that under such general assumptions, the data could not discriminate between a slow long-term decrease in the reversal rate towards zero at the time of the CNS, as proposed by McFadden and Merrill [5], and the much faster decrease our analysis had suggested. But as next pointed out by McFadden and Merrill [7], this conclusion mainly reflected the fact that this study attempted to test too large a family of processes at the same time.

Acknowledging this weakness, McFadden and Merrill [7] indeed decided to design a new statistical test to more specifically test our interpretation. Using this test, they successfully showed that the stationary behaviour we claimed to see in the GPTS up to $\sim$10 Myr before the Cretaceous superchron (segment A in Fig. 1b), was not compatible with the KG86 GPTS. This led them to reject our interpretation in favour of theirs. Unfortunately however, their study lacked completeness with two respects. It did not test the alternate interpretation of McFadden and Merrill [5] that a slow progressive decline of the reversal rate towards zero could be found in the pre-superchron GPTS. It only relied on the old KG86 GPTS which has since then been updated by two independent teams, Gradstein et al. [14] (who produced a GPTS we will refer to as GRAD94) and Channell et al. ([15], hereafter CENT94).

The present study was originally intended to precisely complete the series of tests initiated by McFadden and Merrill [7]. For this purpose, we first generalised their test to also be able to test any assumed long-term trend in the GPTS. We next tested the long-term behaviour of the pre-superchron GPTS as described by GRAD94 and CENT94. This surprisingly leads to a very different answer from that reached by McFadden and Merrill [7]. Both GRAD94 and CENT94 now appear to be incompatible with the scenario of a long-term linear decrease to zero of the reversal rate which could account for the CNS, as favoured by McFadden and Merrill [5,7]. By contrast, the latest data now show that the reversal process could have been stationary not only during segment A, but also over the entire $\sim$40 Myr preceding the sudden onset of the CNS, except possibly for only the last two intervals (amounting to less than 3 Myr). In fact, further scrutinising the medium- and short-term behaviour of the GPTS before the onset of the CNS suggests that independently of the exact behaviour of the GPTS before the CNS, this superchron may have occurred with little, if any, palaeomagnetic warning. This prompts us to reconsider the possible causes of superchrons.

2. Generalising the test of McFadden and Merrill (2000)

McFadden and Merrill [7] pointed out that if a stationary process had really produced most of the pre-CNS GPTS, then no long-term trend should be found in it. To test this, they specifically designed a test (hereafter referred to as the M&M2000 test) in which the GPTS is first considered as an ordered sequence of nG interval lengths split into G non-overlapping sets, each of n intervals. Next a statistic ζ for each of the G sets is introduced where ζ is a measure of the length of the intervals in that set. Denote ζ_i the value taken by this statistic for the set number i (i varying from 1 to G). Finally, define the statistic ξ with:

$$\xi = \sum_{i=1}^{G-1} \sum_{j=i+1}^{G} [(\zeta_j/\zeta_i)/(G(G-1)/2)] \tag{1}$$

This statistic will produce values of order 1 if the null assumption ('no-trend') holds. Values significantly larger (respectively smaller) than expected would by contrast lead to reject the null assumption, in favour of the possible existence of a long-term decreasing (respectively increasing) trend. An exact test of the null assumption then requires that we compare the value ξ_{observed} computed for a given portion of GPTS, with the distribution of values $\xi_{\mathrm{simulated}}$ obtained from a large number of synthetic sequences randomly generated by a reference stationary process. In principle, this reference process should be a Gamma process. However, estimates of the Gamma index best fitting the GPTS are always of the order of 1 (e.g., [4]). Thus the Gamma process would only be marginally different from a pure Poisson process. Furthermore, and as discussed in [7], provided ζ_i is not taken to be the shortest interval in the set number i, considering a Poisson process in the present simulations does not appear critical for testing the lack of long-term trends in the GPTS.

In what follows, the test is always being applied as in [7]. The quantity ζ_i being tested is either the length of the longest interval or the average length of all intervals in the set number i (i.e., the test is always run on both quantities). For each test, 10 000 synthetic sequences are being drawn, and a quantity Q is then defined as the number of times the value $\xi_{\mathrm{simulated}}$ for each synthetic sequence exceeds the value ξ_{observed}. This quantity Q is denoted $Q_{\max}$ when testing the length of the longest interval, and Q_{av} when testing the average length of all intervals. The null assumption ('no-trend') is then considered rejected at the 95% confidence level if either $Q_{\max}$ or Q_{av} is less than 500 (in favour of a possible increasing trend in μ) or larger than 9500 (in favour of a possible decreasing trend in μ).

This M&M2000 test efficiently tests the data for the null assumption that there is no long-term trend in the reversal rate. If the data fail this test, the null assumption may safely be rejected. However, it is important to note that rejecting the null (no-trend) assumption does not prove a contrario that a long-term trend is actually compatible with the data. The data may very well turn out to be incompatible with both assumptions.

To also be able to test any alternative null assumptions to the 'no-trend' assumption, we therefore slightly generalised the M&M2000 test. This generalisation will prove useful to also explicitly test the alternative assumption that a long-term decreasing trend leading to a zero value near the onset of the CNS could have existed for the reversal rate $\lambda(t)$. If that assumption is to hold, then we note that introducing a normalised time τ with the help of:

$$\mathrm{d}\tau = \lambda(t)\mathrm{d}t \tag{2}$$

and defining a re-normalised GPTS with:

$$\Theta_i = \int_{\tau_i}^{\tau_{i-1}} \mathrm{d}\tau = \int_{t_i}^{t_{i-1}} \lambda(t)\mathrm{d}t \tag{3}$$

where t_i is the timing of reversal i and Θ_i the re-normalised length of the interval it started, this re-normalised GPTS should no longer display any trend. This can in turn be tested with the previous M&M2000 test. One powerful property of this procedure is that whatever the non-zero value α, changing $\lambda(t)$ into $\alpha\lambda(t)$ does not affect the value of ξ in Eq. 1 for the re-normalised GPTS. Thus, after re-normalisation both $\lambda(t)$ and $\alpha\lambda(t)$ can be tested at the same time by the standard M&M2000 test.

3. Pre-superchron long-term behaviour

McFadden and Merrill [7] have used the pre-superchron GPTS proposed by Kent and Gradstein [8] to reject our suggestion that the reversal process could have been stationary up to ~10 Myr before the Cretaceous superchron (segment A in Fig. 1b). Relying on their test, they indeed showed that the KG86 GPTS was not compatible with such a stationary process. We reproduced their computation and reached the same conclusion.

But other updated GPTS have been published since KG86 [12,14,15]. The first of those (GTS89, [12]) leads to a very similar reversal frequency behaviour, but not the two latest (GRAD94 from [14] as reported in [2], and CENT94 from

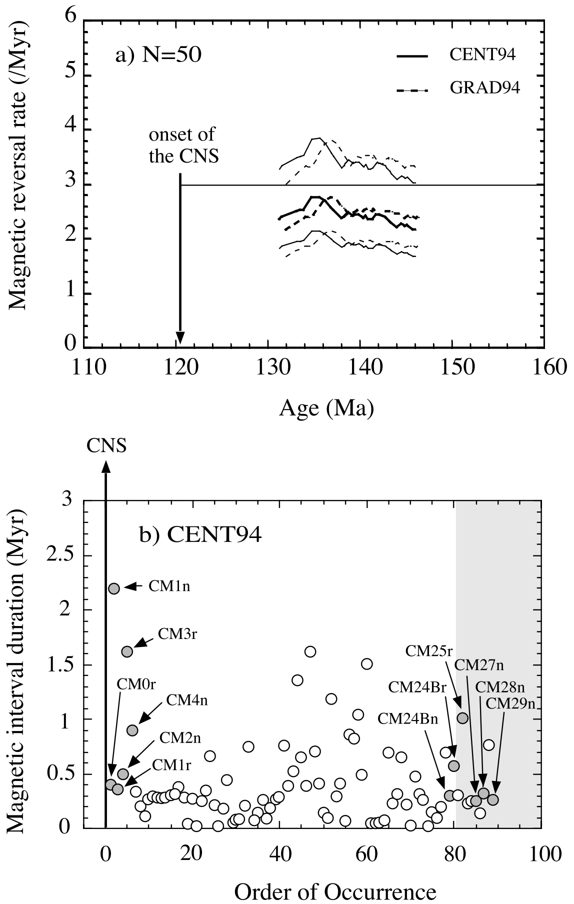

Fig. 2. (a) Same representation as in Fig. 1a but considering GRAD94 (dashed lines) and CENT94 (heavy lines) with $N = 50$. (b) Same representation as in Fig. 1b but for CENT94. Nomenclature as fig. 9 of [15], to which the suffix n (r) has been added to specify the normal (reversed) polarity of the interval. As in Fig. 1b, the grey-shaded area corresponds to the time of the oceanic magnetic anomaly M25 and beyond (corresponding to Middle to Upper Jurassic).

[15]) which rather suggest a lack of long-term trend towards zero (Fig. 2a). Those two results differ for two reasons (compare Figs. 1b and 2b). One is that the few long intervals (CM1n, CM3r and CM4n) which occurred just before the CNS are not lasting as long in the new GPTS as they were thought to last in KG86. The other is that several very short magnetic polarity intervals (with duration of less than 0.1 Myr) counted in the oldest portions of both KG86 and GTS89, are no longer considered in GRAD94 and CENT94. Those intervals had been inferred from the oldest oceanic magnetic anomalies (M25 and beyond, corresponding to Middle to Upper Jurassic), which are difficult to unambiguously interpret in terms of magnetic polarity intervals because of their very weak intensity and are now often attributed to variations in the intensity of the Earth's magnetic field [2,4,16]. Of course, those most recent GPTS could still be the subject of future revisions (allowing for a more precise dating of the magnetic reversals and for the incorporation of some yet undetected short polarity intervals) which could possibly again affect their statistical properties. Nevertheless, they currently are the most suitable to be analysed. In what follows, we will therefore mainly rely on CENT94, the only GPTS involving both a re-analysis of the data and several additional recent oceanic profiles ([15]; see Fig. 2b which also defines the intervals referred to hereafter). But we will also report results obtained from GRAD94 whenever those (slightly but interestingly) differ.

Applied to CENT94, the M&M2000 test first confirms that the 'no-trend' assumption visually suggested by Fig. 2a can no longer be rejected for the GPTS over the entire $\sim$40 Myr preceding the CNS. Considering CENT94 over various time segments, the values we obtain for ξ_{observed} are indeed always well among the 80% most likely values of $\xi_{\text{simulated}}$ (Table 1). Note that this result holds even when the few longer intervals occurring shortly before the CNS (CM4n, CM3r and CM1n) are included in the analysis.

We next applied the re-normalised test to the assumption that the pre-CNS GPTS could have been created by a process with a long-term decreasing reversal rate of the simplest form (as assumed by e.g. McFadden and Merrill, [7]), $\lambda(t) \propto (t - T_0)$, where T_0 is the time $\lambda(t)$ reaches a zero value. As a result of the property mentioned at the end of Section 2, the only parameter we need to vary to test all possibilities is T_0. Fig. 3 shows the results of this test when it is applied to CENT94 between CM24Br and CM4n, i.e., over the shortest and best-known segment successfully tested with M&M2000 against the 'no-trend' assumption (analogous results are obtained when considering segments including the more questionable intervals beyond CM25r). For the test to provide a value $\xi_{observed}$ just at the limit of the 80 and 95% most likely values of $\xi_{simulated}$, T_0 must be less than, respectively, $\sim$10 Ma and $\sim$90 Ma. The chances that a long-term linear trend could have led to a zero value for the reversal rate at T_0 or earlier are thus 10% if $T_0 = 10$ Ma, 2.5% if $T_0 = 90$ Ma. There is virtually no chance that T_0 could have coincided with the onset of the CNS ($T_0 = 120$ Ma). Only a weak trend (with $T_0 < 10$ Ma, corresponding to a relative decrease of $< \sim$24% in the reversal rate between CM25r and the CNS) remains as likely as the 'no-trend' assumption (recall Table 1). However just like the 'no-trend' assumption, such a weak long-term trend assumption would again not explain the sudden lack of reversal after the onset of the CNS. This can readily be tested by now considering the GPTS between CM24Bn and up to (including) the CNS. (In fact, because of the renormalisation procedure, this amounts to include an interval starting at the onset of the CNS and ending at T_0, when $\lambda(t)$ is assumed to have reached its zero value.) Reproducing the previous re-normalised test shows that this extended GPTS cannot be reconciled with values of $T_0 < 10$ Ma (as is also shown in Fig. 3). Thus, no single linear long-term trend towards zero in the reversal rate can account for both the pre-CNS GPTS and the occurrence of the CNS.

Similar tests have been carried out with GRAD94, leading to essentially the same conclusions except for one notable difference. Whereas, just like CENT94, GRAD94 successfully passes the M&M2000 test for the 'no-trend' assumption for all of the tests we carried out, it fails to do so in a marginal way when CM1n (that is, the penultimate interval before the CNS) is included in the analysis (see Table 1). This difference, we note, only arises because the length of CM1n, the longest of all pre-CNS intervals (see Fig. 2b), is assumed to be of 2.69 Myr in GRAD94, instead of 2.19 Myr in CENT94. As we shall see in the next section, this interval may well turn out to be the only 'unusual' event in the pre-CNS GPTS. It could indicate that the stationary assumption implied by the 'no-trend' assumption could have started to fail about 3 Myr before the onset of the CNS.

Table 1
Results of the test developed by McFadden and Merrill [7] applied to CENT94 [15] and GRAD94 [14] over various time segments

		Time segment (Ma)	N	n	ξ_{av}	Q_{av}	ξ_{max}	Q_{max}
CENT94	CM0r to CM27n	120.60–156.05	85	5	1.3960	2087	1.3447	4187
	CM0r to CM24Br	120.60–154.00	80	5	1.4464	1647	1.4076	3331
	CM1r to CM28n	123.19–156.51	85	5	1.3156	3252	1.4276	3002
	CM1r to CM25r	123.19–155.32	80	5	1.2660	4112	1.2796	5201
	CM4n to CM27n	125.67–156.05	80	5	1.1331	6830	1.0490	8793
	CM4n to CM24Br	125.67–154.00	75	5	1.1634	6100	1.0864	8220
GRAD94	CM0r to CM27n	120.38–156.00	85	5	1.6237	503	1.6083	1311
	CM0r to CM24Br	120.38–154.31	80	5	1.6729	403	1.7075	878
	CM1r to CM28n	123.67–156.29	85	5	1.4563	1464	1.6319	1165
	CM1r to CM25r	123.67–155.51	80	5	1.3103	3377	1.2532	5695
	CM4n to CM27n	126.73–156.00	80	5	1.2555	4377	1.1899	6691
	CM4n to CM24Br	126.73–154.31	75	5	1.2794	3819	1.2534	5573

N is the total number of intervals considered, n the number of intervals in each of the $G = N/n$ non-overlapping sets, ξ_{av} (respectively ξ_{max}) the value computed from Eq. 1 when the average length (respectively the longest interval) in each set is used as a measure, and Q_{av} (respectively Q_{max}), the number of times 10 000 random drawings from a Poisson process lead to a larger than observed value of ξ_{av} (respectively ξ_{max}). Observed values for ξ_{av} and ξ_{max} are always within the 80% most likely values because Q_{av} and Q_{max} always lie between 1000 and 9000. The only noticeable exception is for GRAD94 when CM1n is included in the analysis (in which case Q_{av} takes a value as low as 403, slightly below the 500 (95%) rejection level).

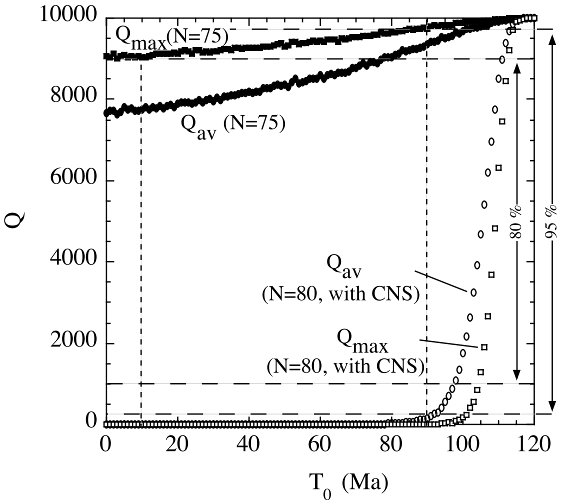

Fig. 3. Results of the M&M2000 test as a function of T_0, after re-normalisation of CENT94 using Eq. 3 and assuming a linear decreasing trend of the form $\lambda(t) \propto (t-T_0)$. Q_{av} (plain circles) and Q_{max} (plain squares) are defined as in Table 1, and refer to the average and maximum length of the re-normalised intervals when $n=5$ and CENT94 is considered between CM24Br and CM4n. Also shown, Q_{av} (empty circles) and Q_{max} (empty squares) are the results from the same computation carried out over CENT94 when considered between CM24Bn and up to an extra interval starting at the onset of the CNS and ending at T_0.

4. Pre-superchron medium- and short-term behaviour

The previous section only dealt with the possibility that a single long-term linear trend towards zero in the reversal rate could have been responsible for the observed GPTS up to and including the CNS. The fact that the data reject this possibility, as implied by our results, and that it is compatible with the 'no-trend' assumption with a sudden occurrence of the CNS, does not however imply that some shorter-term trend of the reversal rate towards zero could not be found. To judge whether this could be the case, we next produced Fig. 4, analogous to Fig. 2a for CENT94, but computed with a moving window of much narrower width $N=10$ intervals. This figure now suggests that the reversal rate could have experienced an oscillating behaviour with a period of ~ 20 Myr before falling to zero near the onset of the CNS. We checked that the data would indeed be compatible with such a behaviour (Fig. 4 shows an example of $\lambda(t)$, compatible with the data with respect to the re-normalised M&M2000 test). Such compatibility is not quite surprising, given the fact that the choice of $\lambda(t)$ is being closely guided by the data itself. In fact a similar oscillating behaviour had already been identified in the early GPTS by previous authors (e.g., [17,18]). But it has also been shown that this kind of pattern could arise when the reversal rate is in fact only the result of a stationary process (e.g., [19,4]). This result is consistent with both those reported in the previous section and the fact that a common constant value of three reversals/Myr can be fitted within the error bars in both Figs. 2a and 4.

At this stage, and if reversals can really be described in terms of a renewal process (as has always implicitly been assumed up to now), it therefore seems that the pre-CNS GPTS does not provide any solid evidence for a trend that could have led to the CNS. Only a medium-term trend could be identified, which is however not statistically requested by the data.

In a last attempt to possibly identify 'precursors' of the CNS in the GPTS one can finally turn back to the raw data shown in Fig. 2b. There we see that what caused the final medium-term decrease in the reversal rate of Fig. 4 is only the occurrence of the three long intervals, CM4n,

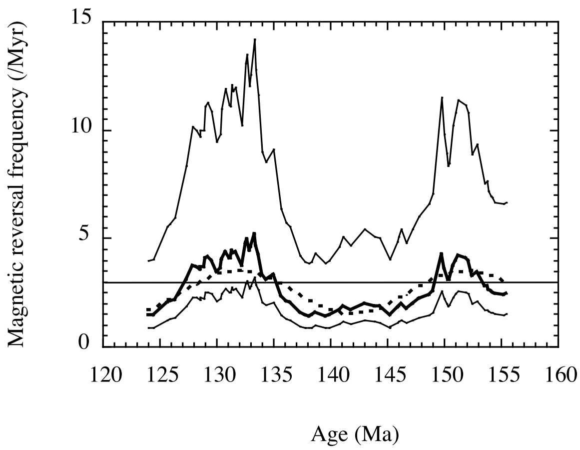

Fig. 4. Estimate of the reversal rates based on CENT94 with $N=10$ (continuous line). The dashed lines indicate a sinusoidal behaviour with a 20-Myr long period fitted to the data.

CM3r and CM1n, just before the CNS. Those are the intervals signalling the end of segment A in [10]. Based on KG86, they were estimated to have occurred over a period of $\sim$10 Myr. But in the new GPTS, this time is now reduced to $\sim$6 Myr. In addition, both CM4n and CM3r now appear to be of sizes comparable to that of earlier intervals in the GPTS, leaving CM1n, the longest of all pre-CNS intervals, as the only apparently unusual event. The probability that in one drawing an interval longer than CM1n (I(CM1n) = 2.19 Myr) could have occurred as a result of a Poisson process with a reversal rate of λ = three reversals/Myr (the constant value fitting both Figs. 2a and 4), is indeed small ($P(\mathrm{CM1n}) = \exp(-\lambda I(\mathrm{CM1n})) = 0.14\%$). But the probability is much larger (of $P'(\mathrm{CM1n}) = 1-(1-P(\mathrm{CM1n}))^{89} = 12\%$) that at least one such interval can be observed within the entire GPTS, which counts 89 intervals between CM29n and the CNS. Thus, what seems to make CM1n remarkable is not so much its length but its occurrence just two intervals before the CNS.

We should however recognise that the previous calculations are quite sensitive to the exact value of I(CM1n). Using GRAD94 (for which I(CM1n) = 2.69 Myr) in place of CENT94 illustrates this point usefully. This then leads to $P(\mathrm{CM1n}) = 0.03\%$ and $P'(\mathrm{CM1n}) = 2.7\%$, and indicates that if CM1n indeed turns out to be as large as claimed in GRAD94, its length also should then be considered as unusual. This result is in fact entirely consistent with the results of Section 3, which showed that GRAD94 marginally failed the M&M2000 test for the 'no-trend' assumption when CM1n is included, because of the slightly larger value of I(CM1n) in GRAD94 than in CENT94.

In summary, if reversals can be described in terms of a renewal process, it appears that the data may not have been produced by a process with a long-term linear decreasing to zero reversal rate also accounting for the CNS. But it may have been produced by a process with an oscillatory reversal rate up to the CNS, or by a stationary process up to CM1n, which then appears to be the only remarkable pre-CNS interval, $\sim$3 Myr before the onset of the CNS.

5. Discussion

As already stated in Section 1, the current dominant theory for the origin of superchrons is that they occur as a consequence of mantle-induced changes in core–mantle boundary conditions. Some support for this type of explanation has recently come from numerical simulations of dynamos which indeed suggest that the nature of the boundary conditions imposed on such dynamos would affect the field produced, and possibly the likelihood of reversals [20]. Many mantle dynamic processes could thus be, and have in fact been, invoked to explain changes in the reversal rate and the occurrence of superchrons: long-term mantle convection [5], crypto-continents drafting at the base of the mantle [21], changes in the form of the outer core linked to major plate reorganisations [22], instabilities in the D″ layer leading to plume eruptions [23–25], or the arrival of cold material within D″ [10,26,27]. However all those mantle processes seem to only involve medium to long time scales (from 10 to hundreds of Myr). They could therefore only account for medium- and long-term changes in the boundary conditions. To what extent could they then indeed be held responsible for the occurrence of the CNS?

From our results, we can first conclude that the slowest of those processes can hardly be invoked. They would produce a long-term change in the reversal rate leading to the CNS in a way, which is incompatible with the data. By contrast, processes producing changes in the boundary conditions on the 10–20 Myr time scale could more easily be invoked, as they could then possibly produce changes in the reversal rate of the kind seen in Fig. 4. This possibility however raises a paradoxical situation. Indeed, if we are to stick to the assumption that reversals can be described in terms of a renewal process, then we know that the oscillatory behaviour seen in Fig. 4 could have been equally produced either by a process with an oscillatory reversal rate, or by an entirely stationary process, except possibly for CM1n (the only possibly unusual interval we could identify before the CNS). Thus, the behaviour of the GPTS would unlikely reflect the true effect of medium-term changes in the boundary conditions.

As a consequence, no signal in the GPTS could possibly be interpreted as a warning of an incoming superchron, except possibly again, CM1n.

It is interesting at this stage of the discussion, to nevertheless consider the possibility that the reversal process could be more deterministic than implied by a pure renewal process. The oscillating behaviour seen in Fig. 4 could then turn out to be more significant than implied by the tests reported above (as argued by e.g., Mazaud and Laj, [28]). One could then argue that, as a consequence of changes in boundary conditions, the reversal rate effectively decreased within 12 Myr and reached a threshold, which started a sequence of events eventually leading to the CNS. The existence of a very similar decrease which started at ~150 Ma yielded a minimum reversal rate similar to the one reached at ~124 Ma (the latest value we may compute from the GPTS with $N=10$) and yet did not lead to any superchron, would then provide an interesting constraint on this threshold. Its value would be of at most 1.5 reversals/Myr and would be reached between ~124 Ma and the onset of the CNS at ~120 Ma. Again, if we turn back to the raw data of Fig. 2b, we see that the only way we could know this threshold has in fact been reached is because of the occurrence of CM1n.

It however seems to us that another explanation should now be reconsidered with greater care: that the CNS (and more generally superchrons) be a consequence of the non-linear nature of the geodynamo. We indeed recall that simplified numerical 'disk-dynamos' have been studied in the past, which were able to produce reversals with a chaotic behaviour, spontaneously alternating periods with frequent reversals with long periods without any reversal (e.g., [29,30]; for a recent review see also Jacobs [3]). Although Hide [31] recently noted that those simulations could only be considered as extremely simplified models of the real Earth and fail to contain some important physical ingredients (such as mechanical dissipation of energy), they do suggest that the non-linear physics of the geodynamo could lead to a similar behaviour and spontaneously lead to superchrons with hardly any warning. Given the limits noted by Hide [31], however, drawing more conclusions from such comparisons would probably be unwise.

A much better step would then be to turn to the 3D fluid dynamo codes successfully developed in the past 10 yr ([32,33]; see also [34] for a recent extensive review), and study the statistics of the reversals they produce when boundary conditions are kept fixed. Those codes have their own drawbacks: they all run with non-dimensional parameters (notably, the Ekman number) which are very remote from the values thought to characterise the real Earth, and are much more CPU costly than disk-dynamos. But they can be run to simulate real, albeit not Earth-scaled, 3D fluid dynamos. Such runs have already been carried out under various types of boundary conditions. Unfortunately, none have yet been run for long enough under fixed boundary conditions to allow the statistical behaviour of reversals to be studied. Given the current progress in computational capacities, this could however soon be done. This would first make it possible to check whether the reversal process may indeed be considered as a renewal process, or should be considered as more deterministic. This would also make it possible to test the conjecture that the non-linear effects inherent to the fluid dynamo equations could lead to superchrons in a way analogous we suggest could explain the data.

From an observational point of view, there are several ways the predictable or unpredictable nature of the CNS could otherwise further be probed. One could first double-check the details of the GPTS just before the CNS and confirm that no reversals are to be found inside what is presently considered the CNS (a possibility currently dismissed but that some have already considered [35,36]). One could also analyse the temporal behaviour of complementary palaeomagnetic properties, such as the palaeosecular variation or the field intensity, especially before the onset and ending of the CNS. Those properties have already been used to try and establish some correlations between their behaviour and that of the GPTS over the past 200 Myr (e.g., [37–40]). But the data are still scarce and no convincing results have yet been obtained. With this respect, no doubt that gathering a larger PSV and intensity data set for the periods of interest would be of particular interest.

Acknowledgements

We thank V. Courtillot, A. Mazaud and anonymous reviewers for helpful comments on various versions of this manuscript. IPGP Contribution no. 1900 and INSU-CNRS IT Contribution no. 338.*[AC]*

References

[1] P. Layer, A. Kröner, M. McWilliams, An archean geomagnetic reversal in the Kaap Valley pluton, South Africa, Science 273 (1996) 943–946.
[2] N. Opdyke, J. Channell, Magnetic Stratigraphy, Academic Press, San Diego, CA, 1996.
[3] J. Jacobs, Reversals of the Earth's Magnetic Field, Cambridge University Press, Cambridge, 1994.
[4] R. Merrill, M. McElhinny, P. McFadden, The Magnetic Field of the Earth, Paleomagnetism, the Core and the Deep Mantle, Academic Press, San Diego, CA, 1996.
[5] P. McFadden, R. Merrill, Lower mantle convection and geomagnetism, J. Geophys. Res. 89 (1984) 3354–3362.
[6] P. McFadden, R. Merrill, Fundamental transitions in the geodynamo as suggested by paleomagnetic data, Phys. Earth Planet. Inter. 91 (1995) 253–260.
[7] P. McFadden, R. Merrill, Evolution of the geomagnetic reversal rate since 160 Ma: Is the process continuous?, J. Geophys. Res. 105 (2000) 28455–28460.
[8] D. Kent, F. Gradstein, The Geology of North America, in: P. Vogt, B. Tucholke (Eds.), The Western North Atlantic Region, vol. M, Geological Society of America, Boulder, CO, 1986, pp. 45–50.
[9] P. McFadden, Statistical tools for the analysis of geomagnetic reversal sequences, J. Geophys. Res. 89 (1984) 3363–3372.
[10] Y. Gallet, G. Hulot, Stationary and non-stationary behaviour within the geomagnetic polarity time scale, Geophys. Res. Lett. 24 (1997) 1875–1878.
[11] Y. Gallet, V. Courtillot, Geomagnetic reversal behaviour since 100 Ma, Phys. Earth Planet. Inter. 92 (1995) 235–244.
[12] W. Harland, R. Armstrong, A. Cox, L. Craig, A. Smith, D. Smith, A Geologic Time Scale, Cambridge University Press, Cambridge, 1990.
[13] C. Constable, On rates of occurrence of geomagnetic reversals, Phys. Earth Planet. Inter. 118 (2000) 181–193.
[14] F. Gradstein, F. Agterberg, J. Ogg, J. Hardenbol, P. van Veen, J. Thierry, Z. Huang, A Mesozoic time scale, J. Geophys. Res. 99 (1994) 24051–24074.
[15] J. Channell, E. Erba, M. Nakanishi, K. Tamaki, Geochronology, Time Scales and Stratigraphic Correlation, in: W. Berggren, D. Kent, M. Aubry, J. Hardenbol (Eds.), SEPM Spec. Publ. 54 (1995) 51–64.
[16] M. McElhinny, P. McFadden, Paleomagnetism, Continents and Oceans, Academic Press, San Diego, CA, 2000.
[17] A. Mazaud, C. Laj, L. de Sèze, K. Verosub, 15 m.y. periodicity in the frequency of geomagnetic reversals, Nature 304 (1983) 328–330.
[18] D. Raup, Magnetic reversals and mass extinctions, Nature 314 (1985) 341–343.
[19] T. Lutz, The magnetic reversal record is not periodic, Nature 317 (1985) 404–407.
[20] G. Glatzmaier, R. Coe, L. Hongre, P. Roberts, The role of the Earth's mantle in controlling the frequency of geomagnetic reversals, Nature 401 (1999) 885–890.
[21] F. Stacey, Effect on the core structure within D′, Geophys. Astrophys. Fluid Dynam. 60 (1991) 157–163.
[22] L.-E. Ricou, D. Gibert, The magnetic reversal sequence studied using wavelet analysis: a record of the Earth's tectonic history at the core–mantle boundary, C. R. Acad. Sci. Paris 325 (1997) 753–759.
[23] D. Loper, K. McCartney, Mantle plumes and the periodicity of magnetic field reversals, Geophys. Res. Lett. 13 (1986) 1525–1528.
[24] V. Courtillot, J. Besse, Magnetic field reversals, polar wander, and Core–Mantle coupling, Science 237 (1987) 1140–1147.
[25] R. Larson, P. Olson, Mantle plumes control magnetic reversal frequency, Earth Planet. Sci. Lett. 107 (1991) 437–447.
[26] E. Eide, T. Torsvik, Paleozoic supercontinental assembly, mantle flushing, and genesis of the Kiaman superchron, Earth Planet. Sci. Lett. 144 (1996) 389–402.
[27] D. Brunet, P. Machetel, Large-scale tectonic features induced by mantle avalanches with phase, temperature, and pressure lateral variations of viscosity, J. Geophys. Res. 103 (1998) 4929–4945.
[28] A. Mazaud, C. Laj, The 15-m.y. geomagnetic reversal periodicity: a quantitative test, Earth Planet. Sci. Lett. 107 (1991) 689–696.
[29] K. Ito, Chaos in the Rikitake two-disc dynamo system, Earth Planet. Sci. Lett. 51 (1980) 451–456.
[30] D. Crossley, O. Jensen, J. Jacobs, The stochastic excitation of reversals in simple dynamos, Phys. Earth Planet. Inter. 42 (1986) 143–153.
[31] R. Hide, Structural instability of the Rikitake disk dynamo, Geophys. Res. Lett. 22 (1995) 1057–1059.
[32] G. Glatzmaier, P. Roberts, A three-dimensional convective dynamo solution with rotating and finitely conducting inner core and mantle, Phys. Earth Planet. Inter. 91 (1995) 63–75.
[33] W. Kuang, J. Bloxham, An Earth-like numerical dynamo model, Nature 389 (1997) 371–374.
[34] E. Dormy, J.-P. Valet, V. Courtillot, Numerical models of the geodynamo and observational constraints, Geochem. Geophys. Geosyst. 1 (2000) 2000GC000062.

[35] J. Tarduno, Brief reversed polarity interval during the Cretaceous normal polarity superchron, Geology 18 (1990) 683–686.
[36] S. Gilder, Y. Chen, J.-P. Cogné, X. Tan, V. Courtillot, D. Sun, Y. Li, Paleomagnetism of Upper Jurassic to Lower Cretaceous volcanic and sedimentary rocks from the western Tarim Basin and implications for inclination shallowing and absolute dating of the M0 (ISEA?) chron, Earth Planet. Sci. Lett. 206 (2003) 587–600.
[37] P. McFadden, R. Merrill, W. McElhinny, S. Lee, Reversals of the Earth's magnetic field and temporal variations of the dynamo families, J. Geophys. Res. 96 (1991) 3923–3933.
[38] M. Prévot, M. El-Messaoud Derder, M. McWilliams, J. Thompson, Intensity of the Earth's magnetic field: evidence for a Mesozoic dipole low, Earth Planet. Sci. Lett. 97 (1990) 129–139.
[39] M. Cronin, L. Tauxe, C. Constable, P. Selkin, T. Pick, Noise in the quiet zone, Earth Planet. Sci. Lett. 190 (2001) 13–30.
[40] R. Heller, R. Merrill, P. McFadden, The variation of intensity of earth's magnetic field with time, Phys. Earth Planet. Inter. 131 (2002) 237–249.