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Three Distinct Reversing Modes in the Geodynamo[1]

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Abstract—The data that describe the long-term reversing behavior of the geodynamo show strong and sudden changes in magnetic reversal frequency. This concerns both the onset and the end of superchrons and most probably the occurrence of episodes characterized by extreme geomagnetic reversal frequency (>10–15 rev./Myr). To account for the complexity observed in geomagnetic reversal frequency evolution, we propose a simple scenario in which the geodynamo operates in three distinct reversing modes: i—a "normal" reversing mode generating geomagnetic polarity reversals according to a stationary random process, with on average a reversal rate of ~3 rev./Myr; ii—a non-reversing "superchron" mode characterizing long time intervals without reversal; iii—a hyper-active reversing mode characterized by an extreme geomagnetic reversal frequency. The transitions between the different reversing modes would be sudden, i.e., on the Myr time scale. Following previous studies, we suggest that in the past, the occurrence of these transitions has been modulated by thermal conditions at the core-mantle boundary governed by mantle dynamics. It might also be possible that they were more frequent during the Precambrian, before the nucleation of the inner core, because of a stronger influence on geodynamo activity of the thermal conditions at the core-mantle boundary.

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INTRODUCTION

This study is part of a project initiated several years ago, whose main objective is to determine the evolution in geomagnetic reversal frequency during the Phanerozoic and Proterozoic. It aims at constraining the origin of these variations and especially to develop a better understanding of the interactions between the geodynamo and mantle dynamics. Although these questions are already old, they are still the subject of much debate about the very nature of the process causing long-term changes in geomagnetic reversal frequency (e.g., Merrill et al., 1996; Gallet, 1997; Glatzmaier et al., 1999; Hulot and Gallet, 2003; Lowrie and Kent, 2004; Courtillot and Olson, 2007; Driscoll and Olson, 2011; Aubert et al., 2009, 2011; Biggin et al., 2012; Olson et al., 2013).

Magnetostratigraphic studies carried out in the framework of this project were first focused on the Lower Paleozoic (e.g., Gallet and Pavlov, 1996; Pavlov and Gallet, 1998; 2001; 2005; Gallet et al., 2003a). These enabled us to demonstrate the occurrence during the Ordovician of the third superchron known for the entire Phanerozoic (Gallet and Pavlov, 1996; Pavlov and Gallet, 2005). This superchron, called "Moyero", was preceded during the Cambrian by a time interval characterized by a high geomagnetic reversal frequency of ~7 rev./Myr (Pavlov and Gallet., 2001; Gallet et al., 2003a). More recently, we have conducted several magnetostratigraphic investigations on Precambrian sedimentary sections in Siberia and Urals, dated around 1050 and 850 Ma (Pavlov and Gallet, 2010; Gallet et al., 2000a, 2012). The results define a unique sequence with nearly a hundred geomagnetic polarity reversals, which is currently the most detailed geomagnetic sequence available for the Precambrian. Sharp contrasts are clearly highlighted in the process that generated the geomagnetic polarity reversals, high-frequency periods surrounding long intervals without reversal. One of the latter is a new superchron called "Maya" that occurred about a billion years ago (Pavlov and Gallet, 2010; Gallet et al., 2012).

The objective of this study is to put into perspective the observations above with our knowledge of the variations in geomagnetic reversal frequency over the past 150 Myr, i.e., from the continuous record provided by oceanic magnetic anomalies (for example Cande and Kent, 1992; Channell et al., 1995; Opdyke and Channell, 1996), or during older time intervals of geological history documented by magnetostratigraphic data. This work allows us to envisage a fairly simple scenario, which may account for most of the complexity observed in the long-term geomagnetic reversal evolution.

ISSUES CONCERNING GEOMAGNETIC REVERSAL FREQUENCY SINCE 150 Myr

In a rather paradoxical way, it is still difficult to ascertain the evolution in geomagnetic reversal frequency over the past 150 Myr (e.g., Gallet and Hulot,

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1997; Constable, 2000; McFadden and Merrill, 2000; Hulot and Gallet, 2003; Lowrie and Kent, 2004), even though this time interval is undoubtedly the best documented one. It is generally considered that the frequencies gradually decreased from the Upper Jurassic until the onset of the normal polarity Cretaceous superchron at ca. 121 Ma, and next they increased after the superchron (after ca. 83 Ma; e.g., McFadden and Merrill, 1984; Courtillot and Besse, 1987; Tarduno et al., 2002). Gallet and Hulot (1997) and Hulot and Gallet (2003) were the first to question this slow evolution, thus supporting the idea of a non-stationary process throughout the entire sequence (except during the superchron; see also Gallet and Courtillot, 1995). In particular, Hulot and Gallet (2003) emphasized the rapid blocking of the reversal process at the onset of the Cretaceous superchron. It appears that only the two chrons CM3r and CM1n, whose durations vary according to the chosen geomagnetic polarity timescales, can statistically be considered as precursors of the superchron, i.e., they could prove a short-term (~10 Myr) decreasing trend of the magnetic reversal frequencies before the superchron. The abruptness of the onset of the superchron may indicate that its origin is primarily related to the non-linear nature of the geodynamo (Hulot and Gallet, 2003), or that the response of the geodynamo to external forcing, in particular due to mantle dynamics, is expressed by means of a threshold effect (Courtillot and Olson, 2007).

The variations in magnetic reversal frequency after the end of the Cretaceous superchron also raise many issues, although a trend marked by a gradual increase in frequency until ~25–30 Ma (Courtillot and Gallet, 1995; Gallet and Hulot, 1997; Lowrie and Kent, 2004) remains the preferred option. However, Lowrie and Kent (2004) pointed out that this trend is mainly due to the existence of the two longest chrons, with durations of ~4 and ~5 Myr, that occurred after the superchron. These chrons called C33r and C33n are also interesting because they contain several cryptochrons that were identified by Bouligand et al. (2006) from the analysis of oceanic magnetic anomaly profiles. More recently, a magnetostratigraphic study of Canadian sediments conducted by Lerbekmo and Evans (2012) showed that some of these cryptochrons, in particular six of them within the single chron C33n, could correspond to short chrons with durations of about 50 Kyr. If these results are confirmed, with, as a consequence, the need to incorporate new chrons in the reference Geomagnetic Polarity Time Scale (GPTS), the idea of a gradual change in frequency after the superchron should be abandoned in favor of a relatively rapid recovery of the reversing process, with a frequency of ~2–3 rev./Myr.

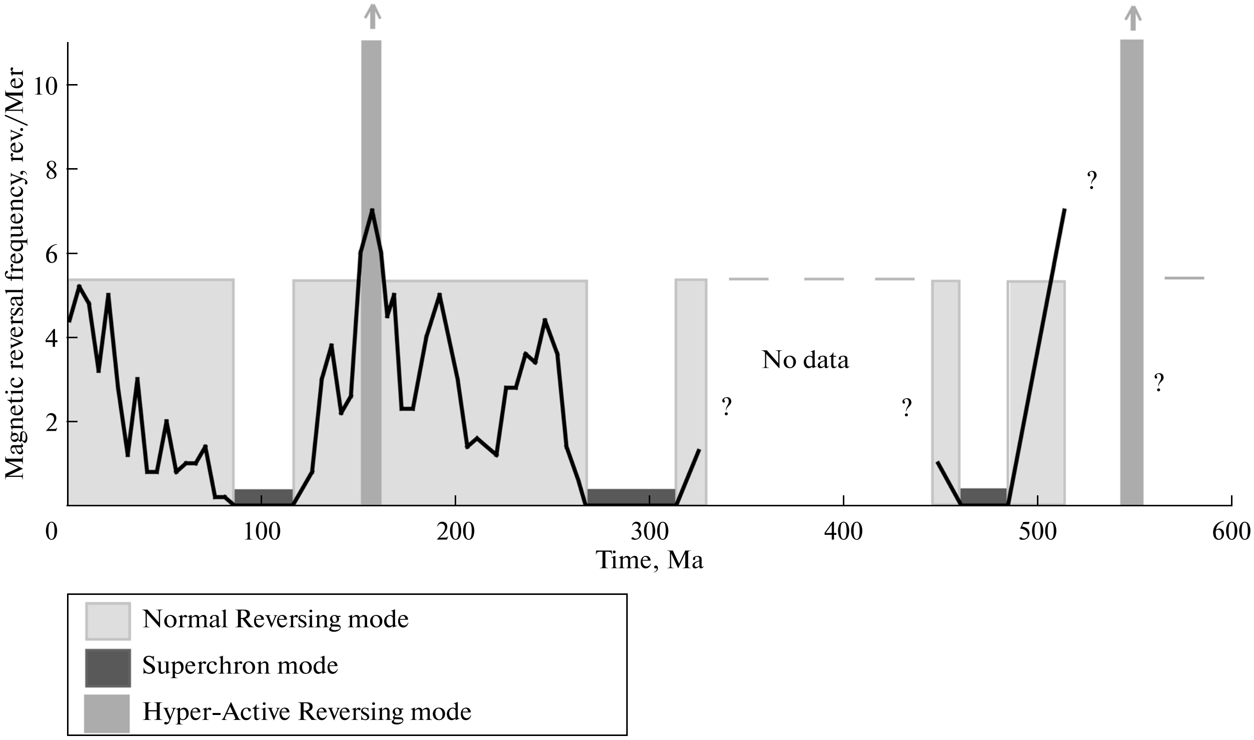
ON EPISODES WITH EXTREME GEOMAGNETIC REVERSAL FREQUENCY

Whereas the existence of superchrons has been known for almost 50 years (e.g., Helsley and Steiner, 1969; see also discussion in Opdyke and Channell, 1996), the occurrence of periods characterized by extreme geomagnetic reversal frequency, i.e., much higher than 10 rev./Myr, is a more recent finding and is still controversial. That such a period could have occurred during the Middle Jurassic (e.g., Handschumacher et al., 1988; Sager et al., 1998; Tivey et al., 2006; Tominaga et al., 2008) is based on the analysis of the oldest oceanic magnetic anomalies found in the Pacific. The amplitude of these magnetic anomalies is weak and their interpretation in terms of geomagnetic polarity reversals therefore remains difficult. However, it seems most probable that during several million years around 160 Ma the reversing process was hyper active, with a frequency (≥12 rev./Myr; e.g., Tivey, 2006) much higher than that having prevailed shortly after, i.e., during the Late Jurassic and the Early Cretaceous until the onset of the Cretaceous superchron, with an average frequency of ~3 rev./Myr (e.g., Hulot and Gallet, 2003; Biggin et al., 2012).

More recently, magnetostratigraphic results obtained from Late Vendian/Ediacaran sedimentary series sampled near the White Sea in northwestern Russia (Popov et al., 2005), in the Urals (Meert et al., 2013; Bazhenov et al., 2016) and in Siberia (Shatsillo et al., 2015) showed the probable occurrence of another episode of reversal hyper-activity around the transition between the Precambrian and Cambrian. The frequency estimates, which directly depend on the sedimentation rates assumed for the azoic studied formations, could again largely exceed 10 rev./Myr. Note that this interpretation would be in agreement with paleomagnetic results obtained by Halls et al. (2015) from Canadian dikes dated at ca. 585 Ma. Let us also recall the magnetostratigraphic results obtained from the Siberian Kulumbe (Pavlov and Gallet, 2001) and Khorbusuonka (Gallet et al., 2003a) sections, which indicate a high magnetic reversal frequency (~7 rev./Myr) during the Middle Cambrian, ~20 Myr after the Precambrian/Cambrian boundary. Given the sampling rate achieved in these studies, it seems possible that the frequency value during the Middle Cambrian was in fact higher.

DISCUSSION

The general idea that the reversing state of the geodynamo varied in a continuous way during the Phanerozoic, over time scales of a few tens of million years, still prevails. In the 80s, it was embedded in descriptions of the geomagnetic reversal sequence over the past 150 Myr. This was largely based on the (apparent) gradual recovery of the reversing process after the end of the Cretaceous superchron (e.g., McFadden and Merrill, 1984). However, as noted above, this gradual



Schematic long-term evolution of the reversing regime of the geodynamo during the Phanerozoic. The dark curve, redrawn from Gallet et al. (2012), exhibits the changes in magnetic reversal frequency as recovered from the marine magnetic anomalies over the past 150 Myr (using sliding windows of 5 Myr) and from available magnetostratigraphic data beyond (the frequency estimates were then computed over time intervals determined by the duration of the corresponding geological stages). The alternation between the three existing geodynamo reversing modes proposed in our study is shown using a grey color code: in light grey the normal reversing mode, in dark grey the superchron mode, and in medium grey the hyper-active reversing mode.

evolution is primarily constrained by the two chrons immediately following the superchron (Lowrie and Kent, 2004), whose integrity can be questioned (Lerbekmo and Evans, 2012). Gallet et al. (2012) highlight the fact that the available magnetostratigraphic data allowing us to constrain the Late Permian—Early Triassic GPTS argue for an average reversal frequency of ~3 rev./Myr only a few million years after the end of the Permo-Carboniferous Kiaman superchron (e.g., Gallet et al., 2000b; Hounslaw and Muttoni, 2010). Note that a similar fast recovery of the reversing process was also suggested by Elston et al. (2012) after a superchron found around 1.4 Ga. Likewise, the sudden stop of the reversing process at the onset of superchrons is supported by several studies, including those of Hulot and Gallet (2003) for the Cretaceous superchron and of Pavlov et Gallet (2010) for the ~1.05 Gyr-old "Maya" superchron discovered in eastern Siberia.

The data that have a bearing on the long-term evolution in geomagnetic reversal frequency strongly suggest sharp and sudden changes in that evolution. This concerns both the onset and the end of superchrons and, apparently, the occurrence of episodes characterized by extreme geomagnetic reversal frequency. This extreme frequency (>10–15 rev./Myr) does not appear comparable to the values currently referred to as "high frequency", for instance during the Miocene, the Upper Jurassic and the Upper Triassic (with frequency values of 3 to 5 rev./Myr; e.g., Channell and Opdyke, 1996; Gallet et al., 1992; 2003b), and probably during the Middle Cambrian and the lower Jurassic, two periods characterized by slightly higher frequency values (Gallet et al., 2003a; Biggin et al., 2012).

In order to constrain possible connections between the activity of the geodynamo and mantle dynamics, one requires a consistent description of long-term variations in reversal frequency. Despite considerable improvements over the past decades, our reversal frequency database is still rather incomplete. The observations we make above lead us to propose a rather radical but simple option, that can hopefully be tested with more data in the near future. We propose that the geodynamo operates in three distinct reversing modes with "sudden" transitions, i.e., on the Myr time scale, between modes (figure):

i—A reversing mode (referred to as the "normal reversing" mode, or NR mode), that would generate geomagnetic polarity reversals according to a stationary random process, with on average a frequency of ~3 rev./Myr, in agreement with the non-linear nature of the magneto-hydrodynamic processes acting in the core (e.g., Hulot and Gallet, 2003). For instance, this mode would concern the reversal sequence determined from the end of the Kiaman superchron (during the Late Permian) until the Middle Jurassic episode of reversal hyper activity, as well as the entire sequence observed since the end of the Cretaceous superchron, or after chron C33n (see below). Here we note that for the latter sequence, we do not make a distinction between two stationary segments (or reversing regimes) as in Lowrie and Kent (2004).

ii—A non-reversing mode (referred to as the "superchron" mode, or "S" mode) characterized by the occurrence of long intervals without reversal, as for instance during the Cretaceous, the Permo-Carboniferous and the Ordovician. Following Lowrie and Kent (2004), we include in this mode all chrons having a duration longer than ~4–5 Myr. At the end of the Mesozoic, this may concern C33n and C33r depending on the origin of the cryptochrons detected within these two chrons.

iii—A mode characterized by an extreme geomagnetic reversal frequency (referred to as "hyper-active reversing" mode, or HAR mode), with frequency values >10–15 rev./Myr. At least two such episodes would have occurred since the Uppermost Precambrian, one around the Precambrian/Cambrian boundary (Popov et al., 2005; Meert et al., 2013; Shatsillo et al., 2015), the second during the Middle Jurassic (e.g., Tivey et al., 2006).

Interestingly, the description above could find an echo in the millennial-scale behavior of the solar dynamo, although the processes and their time constants are totally different. Usoskin et al. (2014) demonstrated the existence over the past three thousand years of three distinct operational modes in solar activity: a "normal" mode (the most common), a mode associated with Grand minima and a rare third mode associated with Grand maxima. Following this analogy, the superchrons and the HAR episodes, as well as the solar Grand minima and Grand maxima, would not be the tails of a highly variable behavior, but rather the result of a small number of different operational modes with abrupt transitions between them (see also McFadden and Merrill, 1995).

Our scenario further integrates the possibility of a modulation of the long-term reversing evolution by mantle dynamics. In this respect, another analogy with the behavior of the solar dynamo may be instructive. Usoskin et al. (2016) recently showed that during the Holocene, the frequency of solar Grand minima and Grand maxima has varied according to a multimillennial cycle, called Hallstatt, with a period of ~2400 years (see also Steinhilber et al., 2012). It appears that the Hallstatt cycle modulated the probability of occurrence of instantaneous transitions between the different operational modes, with more Grand minima (resp. Grand maxima) during the lows (resp. highs) of the Hallstatt cycle.

The assumption here is that mantle convection associated with the Wilson cycle could play the same role as the solar Hallstatt cycle. By governing the thermal conditions at the core-mantle boundary, mantle dynamics could have controlled the sudden transitions between the different reversing modes.

In this sense, this hypothesis converges with numerous studies (e.g., McFadden and Merrill, 1984; Courtillot and Besse, 1987; Glatzmaier et al., 1999; Tarduno et al., 2002; Courtillot and Olson, 2007; Driscoll and Olson, 2011; Pétrélis et al., 2011; Aubert et al., 2009; 2011; Biggin et al., 2012, Olson et al., 2013). For instance, using a numerical dynamo, Driscoll and Olson (2011) suggested a correlation between core heat flow minima (resp. maxima) and periods of superchron (resp. with frequent reversals). Lhuillier et al. (2013) also showed that numerical dynamos running under homogeneous thermal conditions at the core-mantle boundary do not seem to generate spontaneous transitions between the reversing and superchron regimes. Following Pétrélis et al. (2011), the effect on reversal process could be more related to the flow patterns within the core that would be driven by plate tectonics and by the associated structures in the mantle.

Furthermore, assuming a late nucleation of the inner core (i.e., younger than 1 Gyr; Labrosse et al., 2003; Aubert et al., 2009), it might also be possible that the transitions between the different reversing modes were more frequent during the Precambrian because of a stronger influence of the thermal conditions at the core-mantle boundary on geodynamo activity before inner-core nucleation (Wicht et al., 2011; Gallet et al., 2012).

Although speculative, the scenario described in this study accounts for the complexity observed in the long-term evolution in geomagnetic reversal frequency. This complexity would come from the imbrication of two processes characterized by very different time scales: the geodynamo with sudden Myr-scale transitions between its different reversing modes and the 100 Myr-scale mantle convection processes. We recognize that testing our scenario will be a very difficult exercise. A positive sign could probably arise from the discovery of several superchrons within a relatively short time interval (i.e., ~50–60 Myr). Hence, our study emphasizes the importance of pursuing investigations on both superchrons (S mode) and episodes of reversal hyper activity (HAR mode) that are still poorly constrained. From this point of view, the entire period between the Late Ordovician and the Carboniferous, i.e., between the end of the Moyero superchron and the onset of the Kiaman superchron, is of particular interest, as this time interval is practically devoid of magnetostratigraphic data.

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