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The Earth's magnetic field history for the past 400 Myr

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Abstract

Published and new data on the Earth's past magnetic field have been interpreted in terms of its links with the frequency of magnetic polarity reversals and with tectonic events such as plume-related eruptions and rifting. The paleointensity and reversal frequency variations show an antiphase correlation between 0 and 160 Ma, and the same tendency likely holds for the past 400 Myr. The geomagnetic field intensity averaged over geological ages (stages) appears to evolve in a linearly increasing trend while its variations increase proportionally in amplitude and change in structure. Both paleointensity and reversal frequency patterns correlate with rifting and eruption events. In periods of high rifting activity, the geomagnetic field increases (15 to 30%) and the reversals become about 40% less frequent. Large eruption events between 0 and 150 Ma have been preceded by notable changes in magnetic intensity which decreases and then increases, the lead being most often within a few million years.

Keywords: paleointensity; frequency of reversals; tectonic events

Introduction

There are two basic parameters that represent the behavior of the Earth's past magnetic field: the frequency of reversals F and the paleointensity H (or the virtual dipole moment V). Their general Mesozoic and Paleozoic trends have not been well understood for the shortage of paleomagnetic evidence which diminishes progressively down into the geological history. The views of the Cretaceous evolution of the Earth's field have changed lately: It was assumed to have been much lower than the present field throughout the Cretaceous normal superchron (Bol'shakov and Solodovnikov, 1981; Pecherskii, 2007) until Tarduno et al. (2006), Tauxe and Yamazaki (2007), and Kurazhkovskii et al. (2007) obtained high paleointensity values for the Early Cretaceous. The Early Phanerozoic (Cambrian, Silurian) history of the geomagnetic intensity remains irresolvable with the today's databases.

The frequency of reversals is recorded in magnetic polarity time scales, such as the one recommended in the Stratigraphic Code of Russia (Zhamoida et al., 2000) or the International Time Scale of 2004 (Gradstein et al., 2004) placed at http://www.nhm.uio.no/norges/timescale2.php. The two time scales match quite well over the Cenozoic but differ notably in the Jurassic. Periods older than Triassic bear gaps reaching a few million years and even tens of million years in the Middle and Early Paleozoic (Silurian, Devonian), in all magnetic polarity scales (Gradstein et al., 2004). Thus, the available paleomagnetic data are obviously insufficient to faithfully reconstruct the Earth's field behavior.

On the other hand, correlation of geomagnetic and geotectonic events has implications for the rates of mantle heat transport and for links between processes in the Earth's liquid core and on the surface. The very possibility that geomagnetic and tectonic processes may correlate has been largely discussed in the literature and causes no doubt. Yet, the existing estimates of the rate of heat conduction from the core or for the lags of tectonic events with respect to the geomagnetic events they may be related to are controversial. The heat transport from the core to the surface would take a few million years according to (Dobretsov, 1997; Milanovskii, 1996), 30 Myr as estimated in (Didenko, 1999), and 20–50 Myr in (Pecherskii, 2007). Thus, the issue is far from being explored.

Late Jurassic–Cretaceous paleointensity data collected recently from sedimentary rocks (Guzhikov et al., 2002; Kurazhkovskii et al., 2008), as well as new data on reversals in the Cretaceous (Guzhikov et al., 2007), have bridged gaps in the 170 Myr history of the Earth's magnetic field and provided more clues to the paleointensity-reversals correlation (Kurazhkovskii et al., 2008).

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In this paper we further investigate the links of the past geomagnetic field with some geodynamic processes.

Paleointensity data

The Phanerozoic history of the Earth's magnetic field has been studied using sedimentary rocks and lava flows in which magnetic minerals bear imprints of the primary polarity (coeval with the time of the rock formation) and have remanent magnetization (detrital (DRM) and thermal (TRM) remanence in sediments and lavas, respectively). The paleointensity (*H*) is estimated in different ways from these two magnetization species (Khramov et al., 1982; Tauxe et al., 1995; Yu et al., 2004), but both yield approximately the same accuracy of about 15–20% of the Earth's present field in individual measurements, according to tests with natural sedimentary and igneous rocks formed in a known field (Kurazhkovskii and Kurazhkovskaya, 2001; Valet, 2003).

DRM- and TRM-derived paleointensities averaged over time intervals of a few million years may be slightly different (Kurazhkovskii et al., 2007). One reason for this discrepancy may lie with the nonuniform rates of sedimentation and volcanism. Volcanic activity increases during periods of eustatic sealevel fall whereas continental deposition is mostly associated with high-stand periods (Seliverstov, 2001). The messages from sediments and lavas are thus different but complementary. The inferred long geomagnetic trends become more reliable if the detrital and thermal remanent magnetization data are processed jointly (Kurazhkovskii et al., 2008; Valet, 2003).

We used the BOROKPINT (http://wwwbrk.adm.yar.ru/palmag/index_e.html) and PINT08 (http://www.geo.uu.nl/~forth/people/Andy/) records of absolute paleointensity, as well as our own published data from sedimentary rocks (Kurazhkovskii et al., 2007, 2008). These databases give almost identical paleointensities averaged over periods of the order of several million years, though they may diverge at a substage scale, mainly because of difference in the data collection process.

Paleointensities in the two databases are derived from thermal remanent magnetization in lava flows. In many cases the paleointensity (*H*) data are complemented with virtual dipole moments (*V*), though the VDM data are scarcer. This is essential in determining average intensities for the remote past (Jurassic–Cretaceous time). In order to avoid information loss, we hereafter analyze the trends of relative paleointensity as normalized to the present Earth's field (H/H_0). When compared, the V/V_0 ($V_0 = 8 \times 10^{22}$ Am^2) and H/H_0 (H_0 = 40 μT) ratios (Fig. 1) give similar absolute intensity patterns.

The gaps of tens of million years in the 160 Ma geological history reconstructed from thermal remanent magnetization (Fig. 1) were filled with DRM data, which reduced the standard deviation of paleointensities averaged over geological ages to $0.1H_0$.

The Phanerozoic history of the Earth's field

The amount of paleointensity data decreases nonuniformly down into the geological past, making it impossible to investigate different time spans to the same resolution. There-

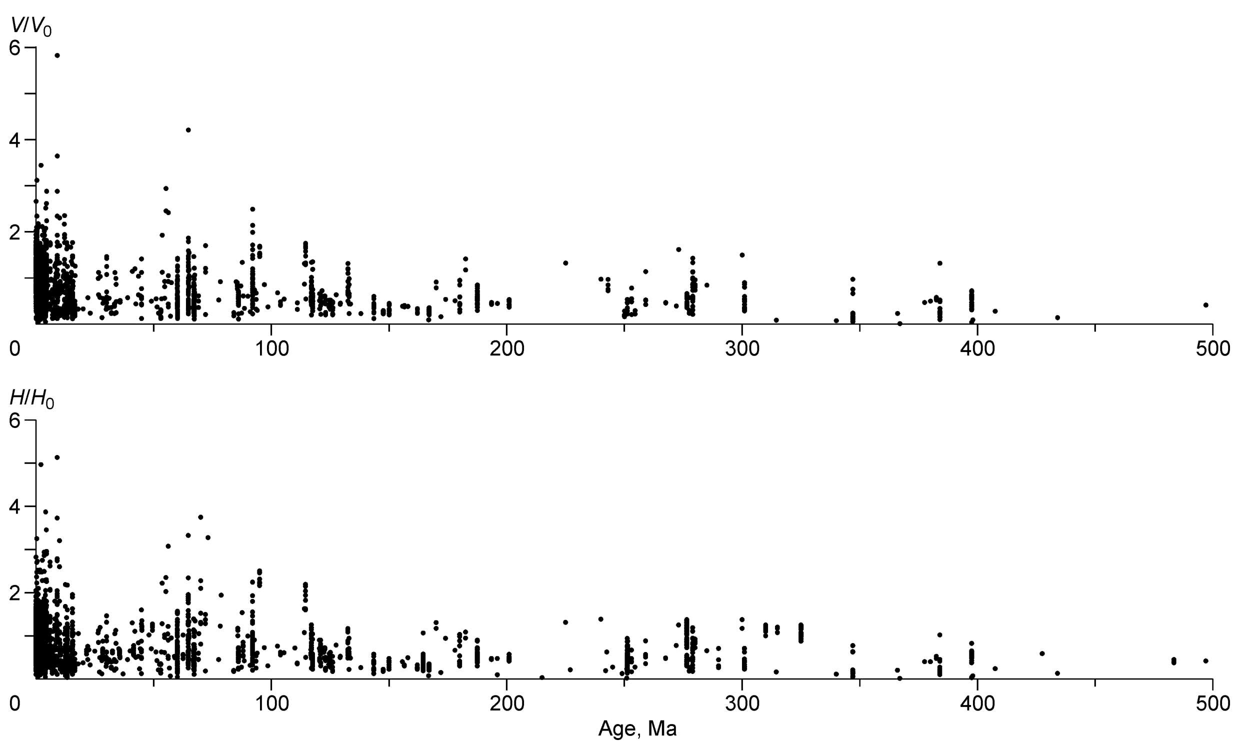

Fig. 1. Paleointensity (H/H_0) and virtual dipole geomagnetic moment (V/V_0), derived from TRM data, BOROKPINT database.

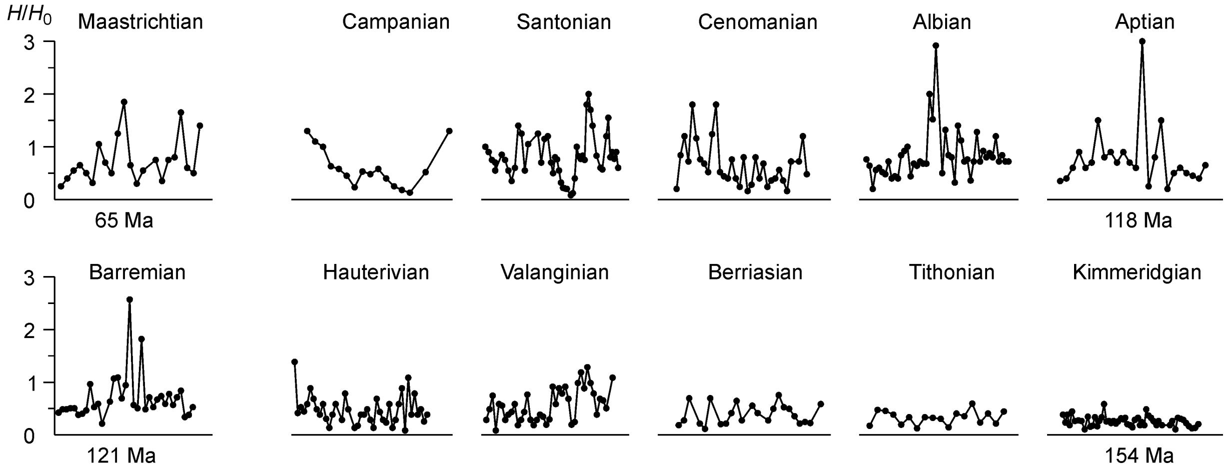

Fig. 2. Fragments of DRM-derived Jurassic–Cretaceous geomagnetic intensity patterns (Kurazhkovskii et al., 2008).

fore, we divided the geomagnetic field history into three unequal intervals of (0–65), (65–170), and (170 to ~450) Ma.

Cenozoic. Latest Cenozoic (0 to 4.5 Ma) geomagnetic intensities have been quite well studied from both DRM and TRM data. Sedimentary records were used (Valet and Meynadier, 1993) to obtain continuous paleointensity trends and to estimate the periodicity and amplitudes of variations. The revealed periodicity was from tens to hundreds of kyr (Guyodo and Valet, 1999; Valet and Meynadier, 1993), and the variation amplitudes were mostly small. However, the geomagnetic field in the Brunhes chron (past 780 kyr) was slightly higher than during the previous shorter polarity cycles (Valet and Meynadier, 1993). Note that there is some difference in the DRM- and TRM-derived paleointensities for this interval: $0.7H_0$ (Guyodo and Valet, 1999; Kurazhkovskii et al., 2005) and $1H_0$ (Solodovnikov, 1999b), respectively.

The geomagnetic field intensities for the (4.5–65) Ma interval are based mainly on TRM determinations in lavas (Fig. 1). The field was lower in the Early–Middle Paleogene than in the Neogene: $(0.6–0.7)H_0$ against $1H_0$ (Heller et al., 2003; Macouin et al., 2004; Solodovnikov, 1999a). The amplitude of paleointensity variations reached $2H_0$ in the beginning of the Paleogene, reduced to $0.5H_0$ in the latest Paleogene–Eocene, and then increased again in the Neogene.

Late Mesozoic. The (65–170) Ma paleointensity patterns have been inferred from both DRM and TRM data. The Mesozoic (especially Cretaceous) geomagnetic field was previously assumed (Bol'shakov and Solodovnikov, 1981) to have been as low as $\sim 0.5H_0$, but more recent estimates (Kurazhkovskii et al., 2007; Tarduno et al., 2006; Tauxe and Yamazaki, 2007) gave values as high as $1H_0$ or even higher during the Cretaceous normal polarity superchron. According to DRM data (Kurazhkovskii et al., 2008), the Earth's field was high in the Early Cretaceous between the Berriasian and the Barremian, and then its average remained close to the present value (Fig. 2). Furthermore, the very patterns of variations changed at the Hauterivian–Barremian boundary: minor oscillations about the average gave way to bursts ($3H_0$ the highest) alternated with quiescent spells. The average paleointensity in the Cretaceous was rather high ($\sim 0.7H_0$) and its bursts likewise reached $3H_0$. The DRM- and TRM-derived average Cretaceous intensities agree to a good accuracy.

Early Mesozoic. The average values and variations of geomagnetic intensity through the Jurassic–Triassic period (Bol'shakov and Solodovnikov, 1981; Heller et al., 2003; Macouin et al., 2004) were lower than in Cretaceous–Paleogene time (Fig. 1). Fragments of Late Jurassic intensity patterns (Fig. 2) from detrital remanent magnetization of sedimentary rocks likewise indicated low average field values and minor variations. Nevertheless, the TRM-based paleointensity records we used and the evidence from (Heller et al., 2003; Macouin et al., 2004) show an unstable field increasing to $0.7H_0$ in the Late Triassic–Early Jurassic.

Paleozoic. The views of the Permian–Carboniferous geomagnetic field history have not changed much through time (Bol'shakov and Solodovnikov, 1981; Heller et al., 2003). Average paleointensity estimates for this time span differ slightly in different publications: $1H_0$ in (Bol'shakov and Solodovnikov, 1981; Heller et al., 2003) and $0.7H_0$ in (Macouin et al., 2004), possibly, for the data scarcity and high variability of the Permian–Carboniferous field. The paleointensity databases and synthesis of results from (Heller et al., 2003; Macouin et al., 2004) indicate quite a high field about $1H_o$.

The earlier history of the Earth's field is poorly known. The BOROKPINT and PINT08 databases indicate a much lower average paleointensity in the Silurian–Devonian than in the Carboniferous–Permian. The rather high values for the latter period were inferred from Paleozoic sedimentary rocks (Khramov et al., 1982) and then confirmed by TRM data. The DRM-derived paleointensity evidence for Ordovician–Silurian time (Khramov et al., 1982) remains unique and predicts the Silurian field to have been much lower than in the Ordovician.

Thus, the paleofield intensity has had a complicated Phanerozoic history. In a rough approximation, its average values and variations were rather low in the (10–40) and (130–260) Ma intervals and high during the spells of (40–122) and (260–330) Ma. These general patterns were hypothesized already in (Bol'shakov and Solodovnikov, 1981) and then further updated, mostly for the Cretaceous and Cenozoic periods. For Early Mesozoic–Paleozoic time, there has not been much revision through the three recent decades.

New data on Jurassic–Cretaceous paleointensity history (Kurazhkovskii et al., 2008) show changes both in amplitude and structure of variations. Namely, the average geomagnetic field was generally low (Fig. 2), and the variations had an approximately stable amplitude in the Oxfordian–Berriasian. In the Hauterivian, the paleointensity increased slightly, and the variations were stronger correspondingly. The average Barremian–Maastrichtian field was high, and its bursts alternated with periods of minor variations (Fig. 2).

Geomagnetic field intensity and magnetic reversals

The Phanerozoic magnetic polarity scales of Zhamoida et al. (2000) and Gradstein et al. (2004) give approximately similar records of the frequency of magnetic reversals, with quite long spans of rare or no reversals in the latest Early–earliest Late Cretaceous, in the Carboniferous–Permian, and in the Late Cambrian–Ordovician, and rather frequent reversals in the Late Paleogene–Neogene, Jurassic–Triassic, and Silurian–Devonian periods.

However, more detailed reversal patterns remain controversial: reversals in the (83–118) Ma interval appear to be absent in (Gradstein et al., 2004) but existing, though few, in (Guzhikov et al., 2003; Molostovskii et al., 2007; Zhamoida et al., 2000). The reversal frequencies within some stages of the Jurassic are times different in the scales of Zhamoida et al. (2000) and Gradstein et al. (2004). Thus, the inferred frequency of magnetic reversals for the least explored intervals will depend largely on the polarity scale choice.

Comparison of paleointensity and polarity data is not easy because of different periodicities. Paleointensity is specific to each point of the geological time scale while the duration of polarity chrons (intervals between two next reversals) may reach tens of kyr to millions of years. Therefore, variations in the reversal frequency are to be considered over long time spans from 1 Myr (in case of frequent reversals) to tens of Myr (in case of rare reversals).

The paleomagnetic data being unevenly distributed over the time scale, we explore the paleointensity-reversal frequency correlation separately for two periods of 0–160 Ma (Fig. 3) and 0–400 Ma (Fig. 4). The reversal frequency data points in the curve of Fig. 3 (Jurassic and Cenozoic time) are averages over geological ages (stages) from (Zhamoida et al., 2000) (for the Cretaceous) and from (Guzhikov et al., 2007), and the paleointensities are according to the BOROKPINT database and (Kurazhkovskii et al., 2008). The right-hand y axis shows the frequency of reversals (Late Jurassic) calculated with reference to (Gradstein et al., 2004). The stage boundaries are according to (Zhamoida et al., 2000). The Coniacian stage being as short as ~1 Myr, we give joint Coniacian–Santonian means of geomagnetic intensities. 95% confidence intervals are provided as a check of paleointensity accuracy.

The two correlated parameters are in antiphase (Fig. 3): the intervals of highest paleointensity most often correspond to periods of least frequent reversals. It is impossible to continue this correlation on into the past for the controversy about the frequency of reversals in the Jurassic (Fig. 3) and for the scarcity of paleointensity data (Fig. 1). The standard error of the stage-averaged intensity is generally within $0.1H_0$ for the

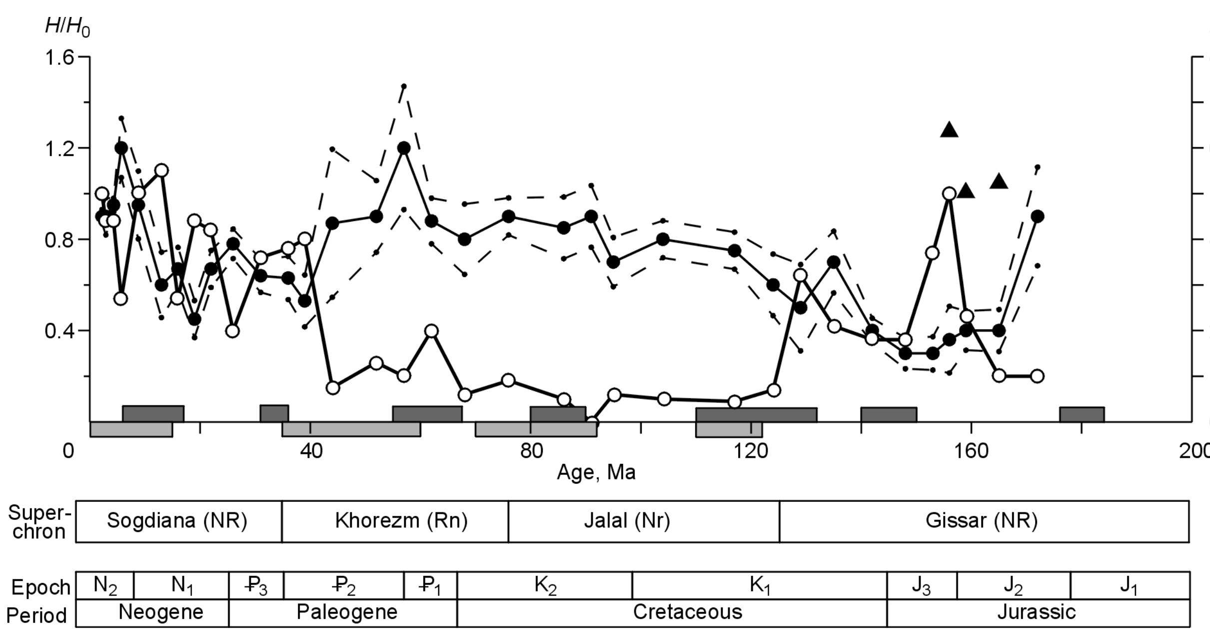

Fig. 3. Stage-averaged paleointensity (H/H_0, dark circles) according to BOROKPINT database and (Kurazhkovskii et al., 2008) and frequency of reversals (F) (light circles) (Zhomoida et al., 2000) for the past 170 Myr. Triangles show frequency of reversals in Bathonian–Oxfordian according to geologic time scale of Gradstein et al. (2004). Dark rectangles are time spans of plume-related eruptions (Dobretsov, 1997; Grachev, 2000). Light rectangles show rifting events (Khain and Lomize, 2005). Dashed line is 95% confidence intervals.

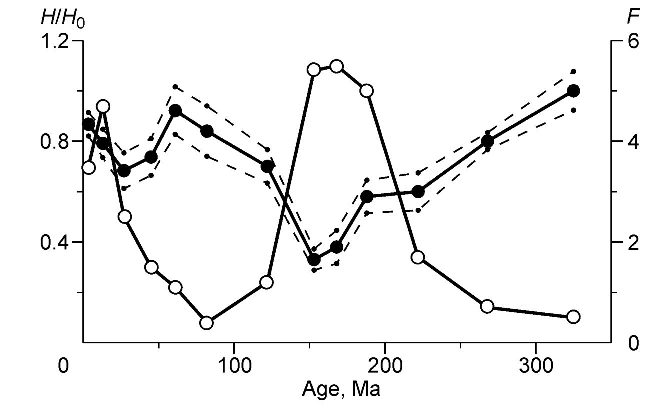

Fig. 4. Variations of stage-averaged paleointensity (dark circles) according to PINT08 database and (Kurazhkovskii et al., 2008) and frequency of reversals (light circles) according to (Gradstein et al., 2004) for past 400 Myr. Dashed line is 95% confidence intervals.

past 160 Myr but grows with geological time. The behavior patterns of the two characteristics likewise change with time. For instance, roughly similar reversal frequencies in the Late Jurassic and in the Neogene correspond to different geomagnetic intensities. They show a common trend, and the general correlation between the two curves is as low as ~–0.3. The average reversal frequency and paleointensity values generally increase from the past to the present (Borisova, 1986; Mazaud et al., 1983). With regard to the time trend, their correlation is ~–0.7.

The increasing trend of the Earth's field from the beginning to the end of the Phanerozoic (Fig. 1) may be due either to specific features of field generation (which is, in our view, unlikely) or to progressive decrease in the primary thermal remanent magnetization. The problem of this decrease for rocks older than 10 Ma was discussed in (Borisova, 1986).

For the paleointensity-reversal frequency correlation through the past 400 Myr (Fig. 4), we used the PINT08 database and the time scale by Gradstein et al. (2004). The PINT08 database does not differ much from BOROKPINT, and the time scale of (Gradstein et al., 2004) is advantageous over that of (Zhamoida et al., 2000) in a better resolution of the Jurassic and Triassic polarity chrons. Paleointensities are averaged over geological epochs before the Triassic and over geological periods for the Triassic through Carboniferous (more detailed correlation being impossible for the lack of data). The H and F curves in Fig. 4 correlate at –0.7. The antiphase correlation between the geomagnetic field intensity and the frequency of magnetic reversals generally holds from 400 Ma to Present irrespective of chosen averaging intervals or databases (Figs. 3 and 4), but breaks down in the two recent epochs (past 10–15 Myr).

Geomagnetic field intensity and tectonic processes

It has been currently assumed that there are three basic prerequisites of the Earth's field generation: a conducting liquid core, radiating fluxes of liquid (heat convection), and planet's spin (Sokolov, 2004). The parameters of the geomagnetic field should depend on the rate of heat convection in the core and on the Earth's rotation velocity. The relative contributions of these agents are hard to investigate as their variations are interdependent. Periodic changes in the rotation velocity at about 200 Myr are caused by tidal friction variations in the system 'Earth–Moon–Sun' (Avsyuk, 1991). However, for relatively short (1 to 30 Myr) spells, one may assume that the Earth's spin is uniform and that the processes with these characteristic times have deep-seated controls (Dobretsov, 1997). Changes in heat conduction across the core–mantle boundary do not show up explicitly but implicit evidence may come from variability of tectonic events. More rapid heat transport to the Earth's surface should precede (or accompany) the peaks of rifting activity and large eruption events. Thus, rifting and basalt volcanism may be presumably correlated with the behavior of the Earth's magnetic field.

Most of major flood-basalt events, which are attributed to plumes (Dobretsov, 1997; Grachev, 2000), correlate with paleointensity changes (Fig. 3). Prior to surface manifestations of sublithospheric processes, the paleointensity changes its behavior (first decreases and then increases, for 0.3 to $0.4H_0$ on average, in the course of a few following million years), and the reversals become more frequent. The characteristic times of these cycles are 10–20 Myr, and the leads relative to volcanism are 2–5 Myr. In the case of frequent eruptions (e.g., Dobretsov (1997) and Grachev (2000) report several such events between 110 and 137 Ma), the short-term periodicity becomes filtered out in averaging over geological ages. This does not mean, however, that the geomagnetic cyclicity disappears. See, for instance, the intervals of relatively high and low paleointensities in the Valanginian, Hauterivian, Barremian, Aptian, Albian, and Cenomanian (Fig. 2). Unfortunately, more exact correlation of these patterns with basaltic volcanism is limited for data shortage.

A better resolution is possible for the Cenozoic (Fig. 5), when the onset of large eruptions (Dobretsov, 1997; Grachev, 2000) corresponded to lower frequency of reversals (Mazaud et al., 1983).

The existence of paleointensity cycles of the order of 100 Myr was discovered by Bol'shakov and Solodovnikov (1981) and validated by more recent data (Figs. 3 and 4). The activity of flood-basalt volcanism changed slightly in accord with these changes. Namely, eruptions were rather frequent (every 15 Myr) during periods of increasing and high geomagnetic field in the Cretaceous–Paleogene, but less frequent (every ~30 Myr) in Jurassic and Eocene time when paleointensity was low.

There is no enough data to analyze the paleointensity behavior prior to the Early Triassic flood-basalt event in Siberia (Siberian traps) but the frequency of reversals, like in the Cretaceous–Cenozoic, increased before the event (265 Ma) and decreased after it (245 Ma), according to (Zhamoida et al., 2000; Gradstein et al., 2004).

Note that although the data on paleointensity and frequency of magnetic reversals were obtained with different methods and objects, both parameters of the Earth's field show changes

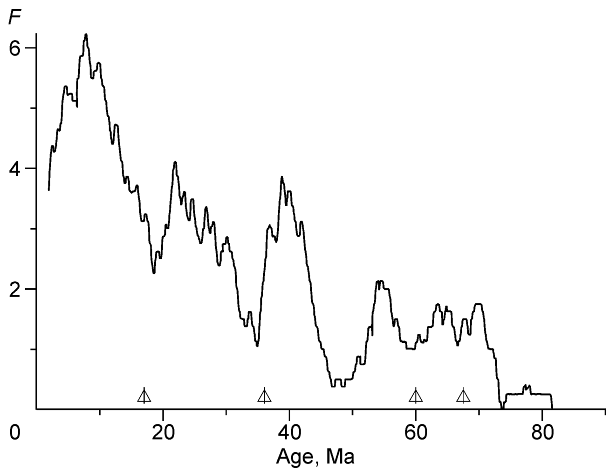

Fig. 5. Frequency of reversals (Mazaud et al., 1983) correlated to flood-basalt events (triangles) (Dobretsov, 1997; Grachev, 2000).

before large eruption events. Thus, two independent sets of paleomagnetic data indicate linkage between geomagnetic and geotectonic processes.

Another point that hampers direct comparison of paleointensity and tectonic data is the lack of unanimity about the age limits and even the very existence of geotectonic cycles. Khain and Lomize (2005) suggested a division of the past 200 Myr geological history according to rifting activity. We (Kurazhkovskii et al., 2007) used this division to correlate paleointensity data with rifting phases and showed that geomagnetic field increased during rifting events, and the average intensity changes reached 15–30% as a function of rifting phases. The frequency of reversals, on the contrary, decreased (40% on average), as calculated using the scale of (Zhamoida et al., 2000).

Milanovskii (1996) divided the geological history into shorter cycles (less than 10 Myr) of dominant crustal strain (extension or compression). With the BOROKPINT database, we calculated average geomagnetic intensities over extension and compression intervals of the past 170 Myr (20 intervals) and found out that it was ~20% higher during the periods of extension (rifting).

Discussion

Thus, there is a correlation among the patterns of paleointensity, reversal frequency, and flood-basalt events. Possibly, they all are governed by a common process associated with heat transport from the Earth's core. The theoretical justification of this mechanism being beyond the scope of our paper, we only state the very existence of the linkage.

Data on paleointensity variations for the past 80–250 Myr allow a tentative inference that volcanism may be related to geomagnetic processes. More detailed data on the frequency of reversals in the Cenozoic support this inference and show reversals to become less frequent in the beginning of eruption events.

The geomagnetic-geotectonic relationship can be explained in terms of two known models implying uneven core cooling. As heat is conducted more slowly across the core–mantle boundary, the outer core overheats and the geodynamo becomes less stable, i.e., the frequency of reversals increases (Dobretsov, 1997). When the heat loss is more rapid, on the contrary, the geodynamo is more efficient and the reversals become less frequent (Didenko, 1999; Larson and Olson, 1991). Overheating of the core–mantle boundary (greater reversal frequency) accelerates the upward heat conduction, which, in turn, is attendant with a decrease in the reversal frequency and plume volcanism. We make no predictions of when the plume forms and come off the outer core. Nevertheless, the whole process from presumable core overheating to eruptions takes no more than a few million years. Correspondingly, the heat transport through the mantle should be no slower than 1 m/yr, which is proximal to the estimates in (Dobretsov et al., 1993; Milanovskii, 1996).

Joint interpretation of data reported in (Khain and Lomize, 2005) and (Dobretsov, 1997; Grachev, 2000) (Fig. 3) indicates that the onset of rifting most often coincides with activity of superplumes showing up on the surface. Thus, the paleointensity increase that postdates major eruptions correlates with phases of rifting activity.

Conclusions

The behavior of Earth's past magnetic field, as understood from published and new data, shows a correlation with the frequency of magnetic reversals and with the geotectonic processes of volcanism and rifting. The paleointensity values averaged over geological stages are in antiphase with the frequency of reversals between 0 an 160 Ma, and the same tendency appears to hold since 400 Ma. The averaged paleointensity evolves in a linearly increasing trend, and its variations increase proportionally in amplitude and change in structure.

In periods of high rifting activity, the geomagnetic field increases for 15 to 30%, and the reversals become about 40% less frequent. Plume-related large eruption events between 0 and 150 Ma are preceded by notable changes in magnetic intensity which decreases and then increases, the leads being most often within a few million years.

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