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Evolution of the Dipole Geomagnetic Field. Observations and Models

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Abstract—The works on paleomagnetic observations of the dipole geomagnetic field, its variations, and reversals in the last 3.5 billion years have been reviewed. It was noted that characteristic field variations are related to the evolution of the convection processes in the liquid core due to the effect of magnetic convection and solid core growth. Works on the geochemistry and energy budget of the Earth's core, the effect of the solid core on convection and the generation of the magnetic field, dynamo models are also considered. We consider how core growth affects the magnetic dipole generation and variations, as well as the possibility of magnetic field generation up to the appearance of the solid core. We also pay attention to the fact that not only the magnetic field but also its configuration and time variations, which are caused by the convection evolution in the core on geological timescales, are important factors for the biosphere.

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1. INTRODUCTION

The geomagnetic field is generated in the liquid core by the dynamo mechanism, which is a process by which thermal and gravitational energy is transformed into convection energy and subsequently into magnetic field energy (Roberts and King, 2013). It is important to study the geomagnetic field for a number of reasons. First, the magnetic field is a protective shield that prevents solar wind penetration of the Earth's atmosphere. During geomagnetic field reversals, when the magnetic dipole decreases in amplitude and reversers its polarity, charged particles carried by the wind from the solar atmosphere increase their influence on living organisms on the Earth's surface, as a result of which these organisms can die. Note that the dipole field component plays the main role in protecting the Earth from the solar wind, since the nondipole magnetic field rapidly decreases far from the planet's surface. Therefore, it is of current interest to study the necessary conditions in the Earth's liquid core, resulting in stable dipole configurations of the geomagnetic field.

On the other hand, from the standpoint of geophysics, the geomagnetic field, which penetrates from the depths to the surface, is a unique source of information about the processes proceeding in the liquid core. Since a weakly conducting Earth's mantle does not distort magnetic field variations on timescales longer than ten years, we can reproduce the magnetic field behavior on the liquid core surface with a high degree of accuracy by extrapolating the potential magnetic field. The magnetic field is the only physical field for which it is possible to extrapolate to such a depth without the use of additional information about the mantle structure. With several reservations, the extrapolated magnetic field can be used to reconstruct flows on the liquid core surface (Holme and Schubert, 2007).

According to the paleomagnetic data, the magnetic field existed for at least the last 3.5 billion years (Tarduno et al., 2010), which is close to the Earth's age (4.5 billion years). It is difficult to find rocks for which the primary magnetization can be determined in order to estimate the magnetic field polarity and strength during the early evolution stages. The existence of the magnetic field and the evolution of its morphology during the early Earth evolution stages are closely related to the planet's formation and solid core growth scenarios. The magnetic field age has been intensely studied in two directions: the extension of the paleomagnetic observation base and studying the possible magnetic field evolution scenarios based on the dynamo theory.

The number and quality of paleomagnetic data characterizing the geomagnetic field behavior in the Pre-Cambrian have considerably increased in recent decades (i.e., up to approximately 540 Ma ago). At the same time, the available determinations are still absolutely insufficient for us to speak confidently about the existence of any long-term trends in the geomagnetic field parameter variations during the geological history. We should understand that the developed concepts (e.g., (Gallet et al., 2012)) are purely preliminary.

The advances in the geodynamo theory are also perceptible. Two decades ago, it was unclear whether a large-scale magnetic field could be theoretically self-consistently generated in a sphere by thermal convection (Glatzmaier and Roberts, 1995). At present, geodynamo theory entered an epoch in which the parameters in use are complexly specified and the solution is optimized with respect to a set of criteria such as the field spectral properties and variations (Christensen et al., 2010), the field reversal and excursion fine structure, and the study of the core energetics.

From a mathematical standpoint, the geodynamo model is unusually rigid, since the resolution of extremely small convection scales, which requires considerable computer expenses, should be used to correctly describe the geostrophic balance of forces in the liquid core, resulting in a high flow anisotropy. At the same time, the times and scales interesting for paleomagnetologists exceed the minimal times and scales by many orders of magnitude. The simultaneous resolution of large and small times substantially hinders modeling.

The geomagnetic field evolution on geological timescales is characterized by long-term trends introduced by thermal convection in the Earth's mantle and by solid core growth. If the characteristic times of the processes proceeding in the core and affecting the magnetic field generation are longer than 10 000 years, the convective times in the Earth's mantle are about 10–100 Myr, and the solid core characteristic growth time accounts for several billion years. If the processes that proceed in the mantle and change the thermal flow at the core–mantle boundary affect the geomagnetic field reversal frequency, the energy source physics changes in the Earth's liquid core with increasing solid core. Before the solid core was formed, the energy was caused by thermal cooling due to the temperature gradient at the core–mantle boundary. When the solid core started increasing and the latent crystallization heat was released at the core–mantle boundary and the gravitational energy related to the differentiation of heavy impurity was released, the contribution of thermal convection became less significant. At present, matter differentiation supplies a larger amount of energy than purely thermal convection by a factor of 3 (Nimmo, 2007). According to the estimates, the total power released due to radioactive heating and matter crystallization is 10 ± 4 TW, which is sufficient for magnetic field generation requiring 1–5 TW (Nimmo, 2007). It is not impossible that only thermal convection could not maintain the geomagnetic field. In this case the solid core age would be responsible for the geomagnetic field age. A less categorical standpoint is that the transition from the thermal convection regime to the mixed convection regime was accompanied by the evolution of the geomagnetic field properties.

Although the two models of thermal and compositional convection are mathematically similar, the energy source distribution in these equations, which is responsible for different magnetic field behavior on the Earth's surface, is different. The transition from a regime with purely thermal convection to a mixed regime, when thermal convection and matter differentiation are available, could not avoid observation for the geomagnetic field evolution. An analysis of this phenomenon and the paleomagnetic data pointing to such a possibility are presented in our review.

In addition to purely energetic considerations, the influence of the solid core on the liquid core dynamics is of prime importance. This is related to the fact that convection above and below the solid core cutoff by a Taylor cylinder (TC) has different properties, and the solid core can stabilize the reversal process due to finite conductivity. The thickness of the spherical convective layer decreases with an increasing solid core, which increases multipole magnetic field growth.

Below, we review direct paleomagnetic observations of the magnetic field age, consider the energy estimates for the regimes with purely thermal convection and a mixed regime, and study the influence of the solid core on the hydrodynamics and dipole magnetic field generation in the Earth's core. The latter makes it possible to judge the dipole magnetic field generation in the past.

2. PALEOMAGNETIC OBSERVATIONS

The study of geomagnetic field evolution is largely based on the paleomagnetic record that can form in rocks and reflect the direction and value of the magnetic field during the period when these rocks were formed. There are three main mechanisms by which the magnetic field can be recorded in rocks: thermo-remanent, chemical, and orientation (detrital or post-detrital) magnetization. Thermo-remanent magnetization is usually formed when magmatic (effusive and intrusive) rocks cool below the Curie point of magnetic minerals in these rocks. Orientation magnetization is formed in sedimentary rocks when magnetic minerals that fall in sediment during its formation align with the magnetic field. Chemical magnetization originates when magnetic mineral grains are formed in rocks if the grain size exceeds a certain threshold, which usual corresponds to the transition from a supermagnetic state to a one-domain state.

In a first approximation (several conditions should be satisfied), the value of thermo-remanent magnetization is proportional to the strength of the geomagnetic field in which this magnetization was formed. This makes it possible to use this magnetization type to reconstruct the geomagnetic field direction and to determine the field strength. The values of the orienta-

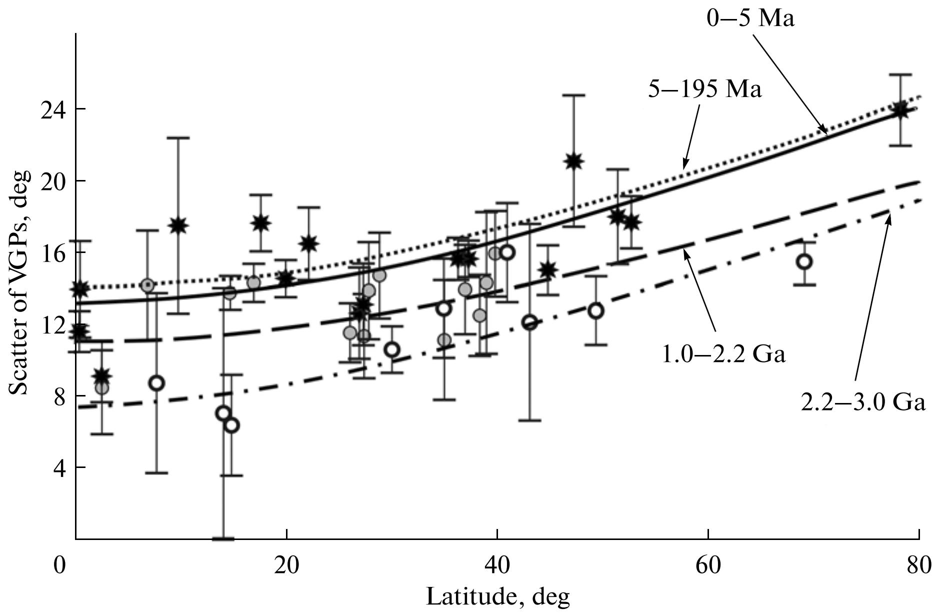

Fig. 1. Latitudinal dependence of paleosecular variations for different time intervals (taken from (Johnson et al., 2008) with changes and simplifications). Explanations are given in the text.

tion and chemical magnetization also naturally depend on the strength of the field that was generated during the magnetization formation. However, these values additionally depend on many other factors, and it is difficult and maybe impossible to estimate the influence of these factors. Therefore, chemical and orientation magnetization are normally used only to determine the direction of the geomagnetic field that was generated during the formation of these magnetizations.

The paleomagnetic method makes it possible to determine the main four geomagnetic field characteristics that can be used to study the field history: the ancient field strength, the geomagnetic reversal frequency, the amplitude of secular variations, and the geometry (i.e., the ratio of the dipole and nondipole field components).

It is important to note that it is more difficult to find objects that retained an ancient paleomagnetic record with increasing studied age. For example, we can find several hundreds and thousands of such objects in order to determine the geomagnetic field strength for the last several million years; however, only a few suitable objects can be found for the Archean and Early Proterozoic.

It is commonly accepted to estimate the amplitude of secular variations by the scatter (S_p) of virtual geomagnetic poles (VGPs), which is calculated using the formula (Cox, 1969):

$$S_p^2 = (N-1)^{-1}\sum_{i=1}^{N}(\Delta_i)^2.$$

Here N is the number of VGPs used in calculations, and Δ_i is the deviation angle of the ith VGP from the rotation axis (the VGP distribution midpoint).

Virtual poles are calculated with paleomagnetic directions obtained based on single volcanic flows, dykes, and other bodies, the magnetization of which was formed rather rapidly (as compared to the secular variation rate).

The secular variation amplitudes for the last 5 Myr (Johnson et al., 2008) are shown by stellas octangula in Fig. 1. The amplitude latitudinal dependence (shown by a solid black l ine) is often approximated by the $S_p^2 = (a\lambda)^2 + b^2$ function, which is usually called the G model (McFadden et al., 1991). Here λ is the latitude where the observation was performed, and a and b are coefficients with a relationship that characterizes the relative contribution of antisymmetric (dipole, octupole, etc.) and symmetric (quadrupole, etc.) geomagnetic field components.

The dotted line in Fig. 1 also shows the same approximation for 5–195 Myr (Tarduno, 2002). A comparison of these two curves makes it possible to conclude that the amplitude of secular variations in the geomagnetic field remained unchanged during the last 200 Myr in a first approximation. However, in a more detailed consideration, several authors (McFadden et al., 1991; Biggin et al., 2008) noted that the amplitudes of secular variations differed during the Cretaceous superchron (118–84 Ma ago) (were smaller) and during a relatively high reversal frequency (were larger).

Figure 1 illustrates data compiled for 1.0–2.2 (gray circles) and 2.2–3.0 (open circles) billion years performed by A.V. Smirnov et al. (2011). These data indicate that the amplitude of secular variations during the Late Archean (2.8–2.5 billion years) and the major part of the Proterozoic (~2.5–0.54 billion years) was pronouncedly smaller than in the last 200 Myr of the geological history. Biggin et al. (2008) arrived at the same conclusion. To explain these differences, the authors propose models in which they assume that the variation value is related to the origination and growth of the inner core and to the development of mantle convection.

However, we should note that the used Precambrian data were obtained for objects of considerably different ages and that all of these objects can indicate only the most general tendencies.

We also note that the data on the Paleozoic (~540–250 Ma ago) are extremely limited. Recent works rather indicate that the amplitude of geomagnetic field secular variations was smaller in that period than in the Mesozoic and Cenozoic (Bazhenov et al., 2014). On the other hand, our data on the boundary between the Paleozoic and Mesozoic (Pavlov et al., 2011) do not make it possible to draw such a conclusion.

Smirnov et al. (2011) justify the possibility of using the G model coefficients in order to estimate the variation in the relative contribution to the general geomagnetic field of the dipole and nondipole components during the geological time. In such a case, a comparison of approximations for 2.2–3.0 billion years (the dot-and-dash line in the figure), 1.0–2.2 billion years (a dashed line), and 0–195 Myr (a dotted line) indicates that in the relative contribution of the nondipole components in the Late Archean was substantially lower than in the Proterozoic and Phanerozoic.

The character of variations in the geomagnetic field strength during the Phanerozoic (from 540 Ma ago to the modern age) and Precambrian (older than 540 Ma) was analyzed in (Shcherbakov et al., 2008; Shcherbakova et al., 2014). The authors of these works emphasized that we can only confidently state that the geomagnetic field has existed for not less than 3.5 billion years, since the data are insufficient and the field strength could change by an order of magnitude over the geological history. The previous assumption that two predominant field strength levels existed during prolonged periods remains unproven. Although the VDM (virtual dipole moment) distributions are often bimodal (Figs. 2a and b), it is not evident that low or high field levels are confined to any geological epoch. For example, rather numerous data indicate that the so-called Mesozoic Dipole Low, i.e., the Mesozoic epoch with a decreased field, exists. However, individual, sufficiently high-quality determinations contradict this conclusion. We emphasize once more that the number of determinations sharply decreases deep in the geological history, such that the number accounts for several dozen determinations for the Paleozoic and Precambrian.

It is very interesting to study the geomagnetic field strength in the Precambrian, since such data can result in the detection of long-term trends in the geomagnetic field evolution. Hale (1987) tried to show that the magnetic field strength considerably increased near the Archean–Proterozoic boundary (~2.5 Ga ago), which may reflect the formation and growth of the inner core at that time. The following determinations did not confirm or disprove this hypothesis completely, since they gave both small and large (as compared to the present-day value, in particular) values for the Late Archean. For example, the most ancient strength determination (Tarduno, 2010) gives a value corresponding to ~50–70% of the present-day level for ~3.4 billion years, and the determination performed by Macouin et al. (2003) shows that the strength value is about 10–15% of the present-day value for 2.15 Ga ago.

Several methods of estimating the geomagnetic field dipole degree in the geological past have been proposed. We should understand that the so-called "paleomagnetic" field is considered in this case, i.e., the field averaged for such a period, which should be taken in order to average secular variations. It is commonly considered that the duration of this period should be not less than 10 ka.

The first, most evident method consists in the construction of a field model that uses spherical expansion and is based on paleomagnetic observations that are sufficiently adequately distributed over the Earth's surface. Such an approach is possible for the 0–5 Myr interval when the data are numerous (several hundred observations and the plate motion can be ignored). Such work was performed in the scope of the TAFI (time-averaged field initiative) project, and its results were published in (Johnson et al., 2008). According to the achieved results, the averaged field was substantially dipole during the Brunhes and Matuyama epochs, with the contribution of the zonal quadrupole component not higher than 2 and 4% in the Brunhes and Matuyama epochs, respectively. The contribution of the octupole (zonal) component is determined less confidently and varies from 1 to 5%.

With increasing age, the amount of data sharply decreases, and additional errors related to the consideration of the plate motion originate. It becomes necessary to use other methods.

For remote geological epochs, researchers use a test consisting of a frequency analysis of inclinations taken from paleomagnetic data distributed over the entire Earth's surface (Evans, 1975). This test proceeds from the fact that the inclination distributions will be different at different combinations of the dipole, quadrupole, and octupole fields. The convenience of this method is that it uses a simple measured geomagnetic field property (inclination) and can be applied to the Precambrian. The method disadvantage is that it requires a sufficiently uniform distribution of

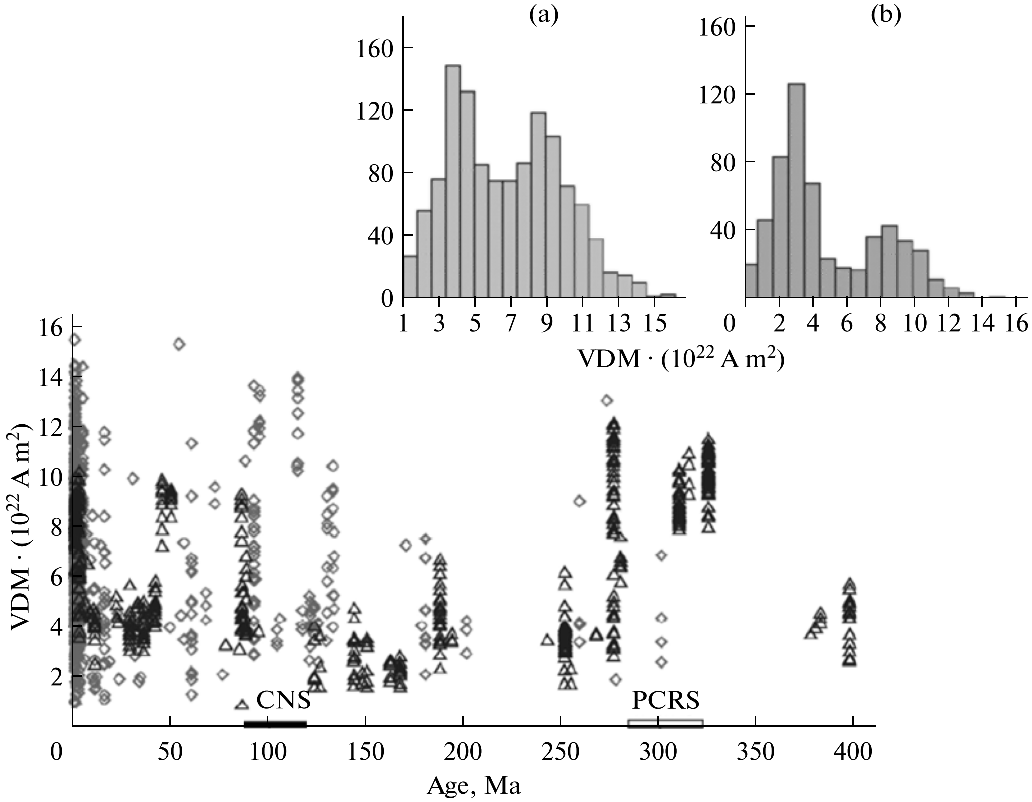

Fig. 2. Geomagnetic field strength determined for the last 400 Myr (Shcherbakov et al., 2008). (CNS) The Cretaceous superchron of normal polarity; (PCRS) the Permian–Carboniferous superchron of reversed polarity.

measured objects over the Earth's surface or a rather considerable time, such that the studied objects (usually located on continents) would sufficiently uniformly "cover" the Earth's surface due to the continental drift (Meert et al., 2003).

Such an analysis performed for the Cenozoic and Mesozoic (0–250 Myr) shows that the field did not differ from dipole at that time (Kent and Smethurst, 1998). According to the same authors, it is necessary to use the hypothesis, admitting that the contribution of the octupole component could account for up to 25% of the dipole component in order to explain the obtain distribution for the Paleozoic and Precambrian. On the other hand, the observed inclination distributions can also be explained by other causes (e.g., by an insufficiently uniform time and spatial distributions of used paleomagnetic determinations; the latter may specifically be related to the fact that continents were mostly located at low latitudes at that time).

Veikkolainen et al. (2014a, 2014b) analyzed a strongly extended database that included only determinations for magmatic rocks (in order to avoid errors related to the decreased inclination typical of many sedimentary rocks). This analysis indicated that the averaged Precambrian field was substantially dipole with an insignificant contribution of the quadrupole (2%) and octupole (5%) zonal components.

Comparison of the position of coeval paleomagnetic poles, which was obtained for objects that are distant (along latitude) from one another and belong to a unified tectonically coherent continental mass, is one more method for testing the geomagnetic field dipole character in the geological past. To be used in such an analysis, the considered continental mass should extend along a paleomeridian at least over several dozen degrees. Northern Eurasia, which was formed (in the composition of Pangea) by the end of the Permian (~270–280 Ma ago) and occupied both equatorial and polar territories, can be considered such a continental mass. Such an analysis was performed in (Evans et al., 2014). A comparison of the mean paleomagnetic pole in the Upper Permian in southern France (equatorial paleolatitudes) with the so-called true dipole pole obtained for the Upper Permian in the Ural Regions and Kazakhstan (Bazhenov and Shatsillo, 2010) indicated that these poles are statistically identical, which conclusively confirms that the averaged geomagnetic field was dipole in the Late Paleozoic.

The degree of the geomagnetic field dipole can also be estimated based on the paleostrength data. This method is based on the fact that the VDM value is independent of the sampling site paleolatitude for the dipole field. Thus, if an axial dipole hypothesis is true, certain VDM values on the plot of VDM values depending on latitude should group around a horizontal line corresponding to the average value for the considered time interval (Shcherbakov et al., 2008).

Having performed such an analysis, Shcherbakov et al. (2008) carefully concluded that the paleostrength data support a hypothesis of the axial dipole in the last 400 Myr for periods of low paleofield intensity. However, considerable statistical deviations of the VDM value depending on paleolatitude as compared to the value that should have been observed for the time-averaged axial dipole are observed for periods of high intensity. We should note that the applicability of such an approach is substantially restricted, since the number of paleostrength determinations obtained for polar and circumpolar latitudes is extremely small.

Another method of estimating the presence of nondipole components consists of a comparison of the paleomagnetic directions of normal and reversed polarities. A latitudinal dependence of the inclination asymmetry corresponding to normal and reversed polarity should be observed when the contribution of the zonal nondipole components is pronounced. An analysis of the present-day paleomagnetic database for the Precambrian (Veikkolainen et al., 2014a, 2014b) does not show such a dependence, confirming that the dipole component predominates in the averaged Precambrian geomagnetic field.

The asymmetry of the corresponding inclinations should be observed in the presence of azonal components. A.N. Khramov et al. (2012) recently considered this problem carefully. The results achieved by these authors indicate that an inverting equatorial dipole, the value of which can account for 5–8% of the axial dipole value, could exist in the Paleozoic and Early Mesozoic.

The classical method of testing the averaged geomagnetic field dipole in the geological past consists of a comparison of paleolatitudes determined by the paleomagnetic method with independent paleoclimatic indicators, which are usually climate-sensitive lithological varieties, such as evaporates.

One of the last works devoted to this problem (Evans, 2006) shows that almost all evaporate basins were located within an arid band between 15° and 35° latitudes, and the paleolatitudes obtained for these basins by the paleomagnetic method agree well with these values. Such an agreement exists at least for the last 2 billion years, which confirms the hypothesis that the field was substantially dipole during the entire this period.

The magnetic polarity scale (see, e.g., (*Geological* ..., 2012)) is the quintessence of our knowledge of the geomagnetic field polarity variations in the geological past. The character of the geomagnetic field polarity variations is well known from the Late Jurassic (i.e., from approximately 170 Ma agog). Intense magnetostratigraphic studies performed in recent decades promoted further development of the magnetic polarity scale in the Early Mesozoic and Late Paleozoic (from ~350 Ma ago).

While the Middle Paleozoic (Silurian and Devonian, ~440–360 Ma ago) remains almost unstudied from the magnetostratigraphic standpoint, substantial progress has been achieved recently in studying the Early Paleozoic polarity (Pavlov and Gallet, 2005; Pavlov et al., 2012).

The main characteristics of the magnetic polarity scale draft proposed for that time (540–440 Ma ago) are as follows:

(a) the superchron of reversed polarity (the third Phanerozoic superchron “Moiero”) existed for a considerable part of the Early and Middle Ordovician (~480–460 Ma ago);

(b) the frequency of geomagnetic reversals was high (probably maximal in the Phanerozoic) in the Middle Cambrian;

(c) the frequency of geomagnetic reversals decreased in the Late Cambrian and Tremadocian as we approached the superchron;

(d) an anomalous period existed in the geomagnetic field behavior near the boundary between the Phanerozoic and Precambrian;

(e) a dual-polarity superchron was absent in the Ordovician (Algeo, 1996).

The presence of three magnetic polarity superchrons (lasting from ~20 to ~70 Myr) and intervals with an extremely high geomagnetic reversal frequency (the Middle Jurassic, Middle Cambrian) are among the singularities of the first order that are distinguished on the magnetic polarity scale for the entire Phanerozoic. The character of the transition from one state to another state has been intensely discussed, and opposing standpoints have been put forward concerning the assumption whether this transition was gradual or abrupt (Hulot and Gallet, 2003).

Our knowledge of the geomagnetic reversal frequency in the Precambrian is patchy and fragmentary. A synthesis of the available data (Gallet et al., 2012) makes it possible to propose the reversal evolution model. According to this model (Fig. 3), during the early stages of the geological history corresponding to the Archean and Early Proterozoic (up to 2.0–1.5 Ga ago), the geomagnetic field was characterized by a series of superchrons and extremely rarely reversed its polarity. In the Late Proterozoic (~1.5–0.6 Ga ago), the field was in the intermediate state, when superchrons were sometimes terminated by relatively unstable states with a high reversal frequency. Finally, beginning from the Latest Proterozoic–Early Phanerozoic (~0.6–0.5 Ga ago), the geomagnetic field entered into a reversal regime typical of the last several hundred million years. Such changes could reflect the formation and growth of the inner core of our planet or long-term evolutionary

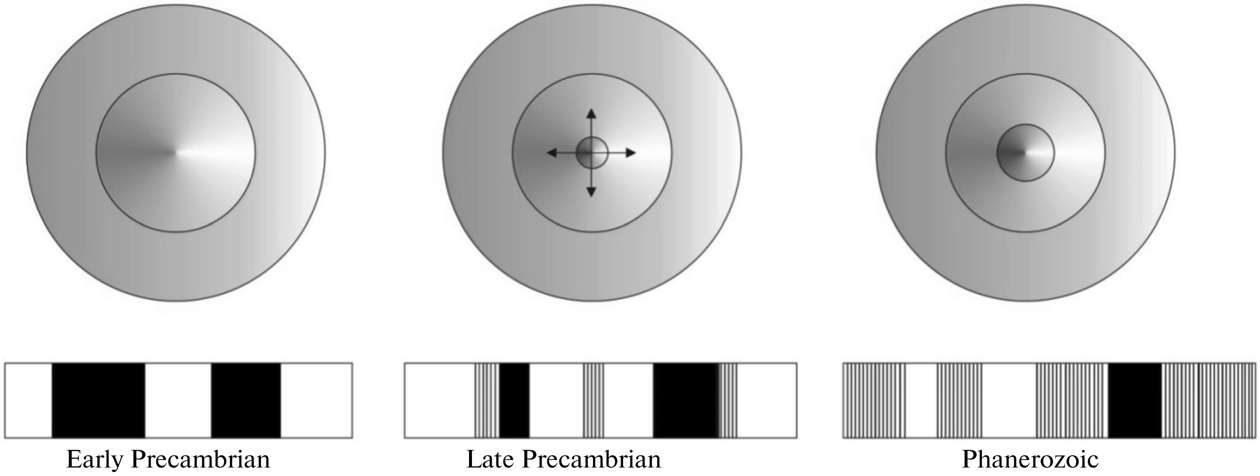

Fig. 3. Evolution of the geomagnetic reversal regime during the geological history according to the model proposed in (Gallet et al., 2012). The Earth's inner core (an inner circle), the Earth's surface (an outer circle), and the boundary between the outer core and mantle (an intermediate circle). The following is schematically shown below from the left to the right: the superchron dynamo operation mode (Early Precambrian); the appearance of the intervals with a high reversal frequency (Late Precambrian); the replacement of the superchron mode by the reversal with a limited number of superchrons and predominant periods with a relatively high reversal frequency (Phanerozoic).

processes at the boundary between the outer core and mantle.

Finishing this review, we should consider the problem of an anomalous geomagnetic field. It is very difficult to coordinate paleomagnetic data in the scope of a central axial dipole hypothesis at least for one of the geological epochs (corresponding to the Late Ediacaran (Vendian)–Early Cambrian, ~580–530 Ma ago). Omitting details, we only note that a hypothesis (Pavlov et al., 2004; Shatsillo et al., 2005) in which the geomagnetic field in the Latest Vendian and Early Cambrian was anomalous and pronouncedly differed from the geomagnetic field in most next epochs was proposed in order to explain the observed paleomagnetic record. In this case this field could be characterized by the presence of two quasi-stable generation modes, which replaced each other in turn. The first mode would correspond to prolonged periods during which an axial mostly monopolar dipole field predominated; the second mode would correspond to relatively short epochs when a reversing circumequatorial or midlatitude dipole predominated.

A similar model was independently proposed in (Abrajevitch and Van der Voo, 2010). The model proposed by us (Pavlov et al., 2004) is aligned with the model of the Early Paleozoic geomagnetic reversals that was developed by A.N. Khramov with collaborators (see, e.g., (Khramov and Iosifidi, 2012). According to this model, the central axial dipole field decreases during reversals, up to complete destruction. In this case the geomagnetic field does not disappear completely but already depends on the superposition of the equatorial dipole and nondipole components, the total value of which can account for 15–20% of the dipole axial field value. Properly speaking, this model could completely describe the observed singularities of the Late Vendian–Early Cambrian paleomagnetic record on the assumption that the duration of the field nonaxial state was relative.

We should assume that an important characteristic of such singular field states would be that certain mostly approximately antipolar magnetic "pole" positions ("superexcursions") were caused by nonaxial dipole reversals when these states were implemented. The possibility of such reversals is confirmed by an analysis that was recently performed in (Khramov and Iosifidi, 2012).

In such a case, the hypothesis of an anomalous geomagnetic field in the Late Vendian–Early Cambrian can be formulated as follows. The geomagnetic field at the boundary between the Precambrian and Cambrian was much less stable than in the Cenozoic, and the normal state of the field corresponding to the dipole was often terminated by geomagnetic excursions that were characterized by the following specific features: (a) the virtual excursion poles were mostly localized in two roughly antipolar regions of the globe located at midlatitudes and low latitudes; (b) the frequency was higher and the duration was longer than in the Cenozoic.

The proposed model agrees with the computer simulation data (Glatzmaier and Olson, 2005). This work indicated that a field that can be described by an inclined dipole in a first approximation can exist during reversals. The predominant position of magnetic "poles" during reversals was proposed by several researchers and was explained by the existence of some inhomogeneities at the core–mantle boundary (Clement, 1991; Tric et al., 1991; Laj et al., 1991; Prevot and Camp, 1993; Hofmann, 1991, 1992; Quidelleur and Valet, 1994). It was shown (Ishihara and Kida, 2002; Aubert and Wicht, 2004; Gassinger et al., 2012) that the dynamo generating mostly the equatorial dipole field can theoretically exist or the equatorial dipole can coexist (alternate) with the axial dipole. Both configurations can be implemented in a certain space of parameters dependent on the combination of the electric conductivity and conducting fluid viscosity with conducting-layer thickness. Abrajevitch and Van der Voo (2010) noted that it is still unclear whether such a combination of parameters was sometime formed in the Earth history. These parameters substantially depend on the heat flow in the core and at the core–mantle boundary: the inner core composition, size, and age; and the mantle thermal properties, i.e., the parameters that still insufficiently adequately correspond to the Earth geological history. Our data make it possible to answer this question rather positively.

3. ENERGY BUDGET AND CORE GEOCHEMISTRY

The geomagnetic field dating is closely related to the energy that is required for the magnetic field generation and is estimated based on magnetic field Joule dissipation. Since the magnetic field distribution in the Earth's core changes from model to model (Roberts et al., 2003), the scatter of parameters is also considerable.

The heat flow on the Earth's surface is 44 TW. The heat flow that comes from the core–mantle boundary varies from 3 TW (Sleep, 1990) to 15 TW (Roberts et al., 2003). The remaining part of the heat flow observed on the surface is maintained by the Earth's mantle. The scatter of the values depends on the processes proceeding in the core and on the convection intensity in the mantle. In the absence of radioactive heating in the liquid core when the heat flow at the core–mantle boundary is 6–14 TW, the age of the solid core is 0.37–1.90 billion years (for more detail, see (Nimmo, 2007)), which is substantially smaller than the Earth age. Since it is difficult to obtain agreement between paleomagnetic data (Labrosse and Macouin, 2003), according to which the magnetic field is older, and the inner core size, the idea reappeared that the core contains a significant radioactive heat source, most probably ^{40}K (Buffett, 2002), which has a half-life period of 1.5 billion years. The concentration of the ^{40}K isotope reaches 0.012% of the entire available potassium. The hypothesis was stimulated by the observed deficit of ^{40}K in the Earth's mantle, which is related to the increase in the isotope concentration in the liquid core due to its redistribution. Consideration of ^{40}K makes it possible to increase the heat flow value due to radioactive heating, since the probability of magnetic field generation before the appearance of a solid core increases. According to these works, compositional convection related to the formation of the inner core supplies more energy to the geodynamo than thermal convection (Gubbins, 1977; Lister, 2003). It is important to estimate the core cooling rate. It was independently estimated (Davies, 1988; Sleep, 1990) that the heat flow is about 2–3 TW. It was assumed that plumes move from the core (Stacey and Loper, 1984). The maximal values for the plume frontal zones are about 3.5 TW (Hill et al., 1992). It is considered (Davies, 2007) that the existent liquid core cooling rate can maintain the magnetic field with the present-day strength. According to these estimates, the present-day cooling rate means that the inner core grew relatively rapidly, and the core age is less than 2 billion years (Labrosse et al., 2001). This in turn means that only thermal convection existed before the formation of the inner core, and this requires a substantially larger heat flow for the magnetic field generation (Gubbins et al., 2003). The assumption that the core was substantially hotter than the present-day core seems improbable (Buffett, 2002; Nimmo et al., 2004).

The assumption that the potassium concentration in the core is high was discussed for some time from the standpoint of its geochemical correspondence (Oversby and Ringwood, 1972; Goettel, 1974). However, strong arguments were made (O'Neill and Palme, 1998; McDonough, 2003) that the potassium concentration is low. Davies (2007) concluded that the existing uncertainties in the mantle convection modes do not make it possible to distinctly determine the potassium concentration in the liquid core.

The anomalies in the ^{186}Os–^{187}Os isotopes found in lavas (Brandon et al., 2003; Puchtel et al., 2005) are also related to the core geochemistry, according to which the age of the solid core is not more than 3.5 billion years. The appearance of these anomalies is related to a growth of the solid core. However, the existent of such anomalies is also explained differently (Lassiter, 2006; Hauri and Hart, 1993; Baker and Jensen, 2004).

4. THE EFFECT OF THE SOLID CORE

The solid core radius is 1200 km, which accounts for 30% of the lunar radius, and the core volume accounts for 0.043 of the entire Earth's core volume. The core was formed due to the crystallization of iron compounds at high pressures. On the one hand, such a small body should not substantially affect the processes proceeding on the Earth. However, this is not the case (see below). In particular, since the rotation is fast, the solid core volume and the variation in convection properties below and above the solid core (within a Taylor cylinder) and outside the core become important factors. On the other hand, since the solid core volume is small, we can consider that the processes proceeding in the Earth's mantle are recorded in this core (Sumita and Bergman, 2007).

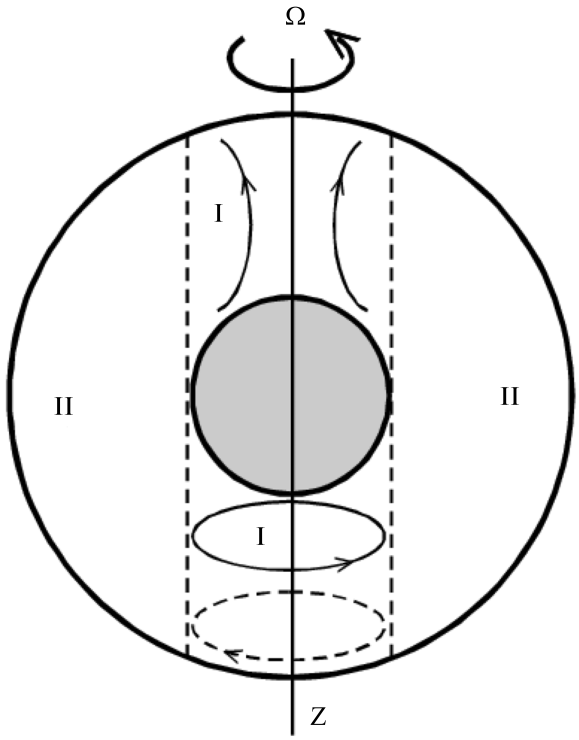

Fig. 4. TC divides the liquid core into regions I and II. The directions of large-scale flows are shown by arrows. Many cyclones and anticyclones, which create nonzero mean hydrodynamic helicity, extend along the rotation axis (Z) near the TC boundary in region II. The helicity signs are negative and positive in the Northern and Southern Hemispheres, respectively. The existence of mean hydrodynamic helicity is the necessary condition for the generation of a large-scale magnetic field.

We consider below how the solid core affects the liquid core hydrodynamics and the magnetic field generation.

4.1. Hydrodynamics

The solid core divides the liquid core into two regions (see Fig. 4) with different convection properties. A cylinder, which is drawn along the rotation axis (Z) and describes the solid core, is called a Taylor cylinder (TC). The first indications that convection behaves differently in regions I and II were obtained in the Stewartson problem, where a sphere rotated rapidly and the differential rotation of the inner and outer boundaries about the rotation axis was insignificant. It turned out that region I corotates rigidly, and the angular velocity gradient exists in region II. Moreover, a Stewartson boundary layer, which has a complex structure with multilevel asymptotics with respect to Ekman numbers, exists along TC (Kleeorin et al., 1997).

Differences between regions I and II also remain in the presence of Archimedean forces. When the critical Rayleigh value is reached, convection originates in region II because a liquid moves along the outer boundary at a smaller angle with respect to the rotation axis in region II than in region I. Therefore, the effect of the Coriolis force, which curls the flow in planes perpendicular to the rotation axis, appears to be lower. Correspondingly, the loss by dissipation in region II is smaller than in region I, and convection originates earlier.

An increase in the Rayleigh number (Reshetnyak, 2010) results in the development of convection in region I, which gradually penetrates into region I, where it remains larger-scale. A large-scale rotation in opposite directions appears near the boundary with the solid core and mantle within the TC, resulting in angular momentum from a liquid onto the solid core. Therefore, the solid core rotates about the mantle (Aurnou et al., 2003), which is observed by seismologists (Song and Richards, 1996).

Solid core growth is accompanied by a decrease in the convection shell thickness. For the Earth, the convection shell thickness is 0.65 in terms of the liquid core outer radius. Without rotation, this would result in a decrease in the convection cell horizontal dimension. Thus, for a plane layer, the cell horizontal scale is larger than the vertical scale by a factor of 1.4. The shape of convection cells in a spherical layer, which are observed in convection problems in the mantle (Schubert et al., 2001), also indicates that the vertical and horizontal scales are close to each other. For planets, the situation is different, since a geostrophic balance related to fast rotation is observed in the core. In this state the cell vertical scale is much larger than the horizontal scale such that the scale ratio can be several orders of magnitude. However, in this case cell thinning due to an increase in the solid core results in a decrease in the geostrophic effect; i.e., the role of rotation decreases because the cell boundaries approach each other and start responding to each other, introducing additional field gradients along the vertical. We subsequently indicate that a decrease in the role of rotation results in a suppression of the dipole magnetic field.

The solid core appears due to the differentiation of a heavier liquid core component and to the corresponding release of latent heat at the solid core boundary during crystallization. The distribution of thermal sources in models of thermal and compositional convection is fundamentally different. In the first case, thermal sources are uniformly distributed in the entire liquid core volume. In the second case, these sources concentrate near the boundary with the solid core, and the temperature gradient has a step in this region. The existence of a large-scale temperature gradient (over the entire liquid core thickness) is optimal for the creation of large-scale flows. Radioactive heating, which is uniformly distributed in the volume, results in less effective convection than thermal sources at the boundary with the solid core, since the liquid core upper layers excessively overheat and the temperature gradient decreases. It interesting that the effect of thermal boundary conditions at the outer boundary decreases in the case of mixed convection (Hori et al., 2012). In other words, the current influence of thermal inhomogeneities at the core–mantle boundary is less significant than during the period when the inner core was absent.

4.2. The Generation of the Magnetic Field

The influence of the inner core on the dynamo process has been intensely discussed, since the physical effects responsible for the magnetic field behavior are extremely numerous. The early works based on paleomagnetic and thermal models of development assumed that this influence is significant (Stevenson et al., 1983; Hale, 1987). At the same time, a recent 3D numerical simulation of the dynamo indicates that the effect would be rather insignificant (Aubert et al., 2009). Therefore, it is interesting whether dynamo models can restrict the inner core age. We try to represent different approaches and (which can be more interesting for a reader) and to inform about different physical effects that make it possible to judge the influence of a solid core growth on the magnetic field behavior and, correspondingly, the possible geomagnetic field dating proposed by a theory.

The conductivity of the solid core is close to that of the liquid core. Since the characteristic diffusion time in the solid core is about 1000 years, which is larger than the characteristics convection times in the liquid core, the solid core decelerates sharp variation in the magnetic field including the field reversal. This fact was referred to for the first time in (Hollerbach and Jones, 1993), where the effect of a decrease in the number of reversals was obtained for the axisymmetric alpha–omega dynamo model. Wicht (2002) challenged this result, since the reversal statistics varied only insignificantly when the solid core dimension and conductivity were realistically estimated in a 3D dynamo model. This discrepancy was caused by a difference in the magnetic field configuration in the models. In the mean field model (Hollerbach and Jones, 1993), the generated large-scale magnetic field penetrated the solid core, and the characteristic diffusion time was considerable. Small-scale magnetic fields related to a turbulent boundary layer are observed for 3D models at the boundary with the solid core. The scale of their penetration into the solid core is restricted by the skin effect; i.e., the degree of the magnetic field and solid core entanglement becomes lower than in the mean field model. In 3D dynamo models, the generated large-scale magnetic field far from always has the Z configuration observed in mean field models, where the magnetic field looks like a column along the rotation axis (Z) and penetrates the solid core (Braginsky, 1978). This in turn means that the degree of the magnetic field synchronization in different hemispheres becomes lower in 3D models.

The generation of a large-scale magnetic field by turbulent flows in the Earth's liquid core is caused by a breakdown of the mirror symmetry related to the daily rotation. The mean hydrodynamic helicity, which is closely related to the alpha effect, is observed in addition to large-scale differential rotation. The helicity is concentrated along TC boundaries. Considerable angular velocity gradients concentrate outside TC and within TC when the Rayleigh numbers are already moderate. Based on the general considerations of symmetry, we can anticipate that the magnetic dipole axis will be parallel to the planet rotation axis when the rotation is high-speed and the convection intensity is sufficient for field generation. In other words, the dipole is in the vicinity of the geographic pole and does not leave TC. This regime corresponds to small Rossby numbers and is observed in 3D dynamo models (Christensen and Aubert, 2006). An increase in the ratio of intensity of the buoyancy forces to the rotation forces gives an inverse effect: the role of rotation decreases, and the dipole deviations from the rotation axis become considerable; therefore, magnetic field reversals are possible. TC crosses the core–mantle boundary at an angle of 20.5° with respect to the rotation axis. If the magnetic field has the Z configuration (Braginsky, 1978), i.e., looking like a vertical column coincident with TC, a similar angle with the axis at the Earth's surface level will be 14°, which is within the present-day magnetic dipole variations between reversals. Based on these concepts, we could anticipate a smaller amplitude of variations in the magnetic field inclination during the early stages of solid core development, when the core was smaller. It is clear that this effect is similar to the influence of the difference in the thermal source concentration between the thermal and compositional convection referred to in the previous section.

The 3D calculations indicate (Hori et al., 2014) that the effect of the solid core is reduced to an increase in the magnetic field dipole, since the generation region shifts toward the solid core boundary. The relation between the magnetic field and the solid core, which is observed as a decrease in the number of magnetic field reversals, becomes closer in this case. On the other hand, the weakening of high harmonics relative to the dipole increases with increasing distance of the generation zone from an observer. Since paleomagnetic data do not show a considerable decrease in the reversal frequency (Tarduno et al., 2010, 2011; Aubert et al., 2010; Smirnov et al., 2011), we can assume that the solid core generation age is more than 1 Ga ago.

According to the paleomagnetic observations, the geodynamo mostly maintained the dipole magnetic field, the strength of which was comparable with the present-day strength at least 3.4 Ga ago (Tarduno et al., 2007, 2010; Aubert et al., 2010). On the other hand, thermal models indicate that the solid core age is 1–2 billion years (Labrosse and Poirier, 2001; Labrosse, 2003; Nimmo, 2007). According to more recent estimates of the thermal conductivity in the Earth's core, the solid core is even younger (Pozzo et al., 2012). It is interesting to use the dynamo without an inner core, which acts due to cooling of the liquid core, to model early stages of the Earth evolution, when the core was absent (Lister and Buffett, 1995).

In contrast to the geochemical studies, according to which the age of the inner core and, correspondingly, the magnetic field is more than 3.5 billion years (Brandon et al., 2003), models with specified heat flows (Labrosse et al., 2001; Buffett, 2002), Earth evolution models (Nimmo et al., 2004), and numerical convection models for the core (Butter et al., 2005) indicate that the inner core age is about 1.5 billion years.

The experimental work (Aurnou et al., 2003) and the numerical model (Aubert, 2005) also indicated that rapid growth of the inner core is consistent with the buoyancy flow at the core–mantle boundary, which is required for modeling vortices in the polar regions observed at present (Olson and Aurnou, 1999). It was indicated (Labrosse et al., 2001; Nimmo et al., 2004; Butler et al., 2005) that the inner core age changes insignificantly if core radioactivity is taken into account. It is interesting that the solid core age decreases if the inner core growth rate decreases when thermal sources are taken into account (Butler et al., 2005). As was mentioned above, radioactive heating of the liquid core upper layers can result in a decrease in the convection intensity and, correspondingly, in less intense magnetic field generation. This effect is actually reproduced in 3D dynamo models. Costin and Butler (2006) found that heating of the liquid core upper layers due to radioactivity can result in less intense magnetic field generation and even in a complete stoppage of dynamo processes.

According to the model presented in (Heimpel and Evans, 2013), in which the solid core age is about 1 Ga (Labrosse et al., 2001), the magnetic dipole inclination can be anomalous if the core is absent, which correlates with observations (Kent and Smethurst, 1998). The heat flow distribution at the core–mantle boundary near poles weakly affects the inclination behavior.

Dunlop (2011) noted that three models of magnetic field strength variations during the geological time exist and should be tested. According to the first model, the dynamo was weak during the Archean and Proterozoic and considerably increased in the Phanerozoic. According to the second model, the dynamo of the present-day type started operating near the Archean–Proterozoic boundary. According to the third model, a powerful dynamo existed as long ago as the Early Archean and was the same during the considerable part of the geological history.

Dipole field stability on long timescales, which includes such stability with respect to reversals, is an important factor for environmental evolution. If the process of reversal proceeds for several thousand years, this process, together with the previous and the following magnetic field weakening, lasts about 50 kyr (Valet et al., 2005). Such prolonged field weakening can substantially affect the evolution of the biosphere.

As was mentioned above, mantle convection can affect the reversal frequency. The 3D modeling indicates (Christensen et al., 1999) that intensification of the heat flow (by about 50%) near geographic poles results in a decrease in the number of reversals and in an increase in the dipole degree. Takahashi et al. (2008) indicated that a symmetric distribution of the heat flow about the equator increases the magnetic field strength. These authors related anomalous magnetic field strengthening during the Cretaceous superchron to these phenomena. We note that these results are directly related to the concepts of the role of rotation and related cylindrical symmetry. For more detail, see (Reshetnyak and Heida, 2013), in which the distributions of geomagnetic field reversals similar to the 3D calculations were obtained in the Domino models as functions of the heat flow spatial distribution.

Variations in thermal boundary conditions, which are related to a change in the thermal regime in the mantle, are registered in the dipole magnetic field behavior. Driscoll and Olson (2009) considered the geodynamo model with many reversals, growing solid core, and variable planet rotation velocity (under the action of tides) and heat flow. The obtained scatter of the magnetic field polarity durations and the magnetic field variation spectrum are close to the observed situation. Olson et al. (2013) showed that only heat flow variations result in a change in the duration of the zones in which the magnetic field polarity is constant and deviation of the magnetic field from the axial symmetry. The authors relate the considered variations in the boundary conditions to the formation of the Pangea supercontinent.

5. CONCLUSIONS

If 20–30 years ago the geomagnetic field dating was episodic and only related to paleomagnetic observations, this problem has been transformed by now into a research trend, including paleomagnetic observations and studies of the core geochemistry, the evolution of the planet and its shells (the liquid core and mantle), and solid core growth. A theory of convection and dynamo in the Earth's core was also developed. The works on modeling the liquid core and dynamo evolution are various; they try to take into account the main physical effects and use geophysical parameters. Nevertheless, we can distinguish two trends corresponding to paleomagnetic observations and models.

The observations indicate that the geomagnetic field existed 3.5 Ga ago. According to the dynamo models, three thirds of the energy that triggers convection in the Earth's core is released during growth of the solid core, which is about 1–2 Ga old. Numerous data allow us to assume that the field strength and variation properties depend on the solid core evolution; however, observations that confirm these assumptions have only started to appear.

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