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On the nature of the Earth's magnetic field

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The block of information analyzed in the article includes the currently accepted ideas about the main source of the magnetic field as the axial dipole, the action of which is supplemented by a long series of regional sources. The dipole exists long enough to ignore the influence of the process of its formation, moves in the body of the planet and changes orientation to the opposite one. The duration of the polarity conservation periods varies arbitrarily by two orders of magnitude. There is no physical justification for this strange mechanism; the assumed vehicle is thermal convection in the liquid core of the Earth. It is unknown what energy sustains the heat and mass transfer and how it leads to the listed exotic properties of the magnetic field source. As an alternative, it is proposed to consider convective flows in the global asthenosphere, caused by the influence of active processes in the tectonosphere. Its volume is comparable to the volume of the outer (liquid) core. The global asthenosphere is a layer of partial melting beneath the entire Earth's surface at depths of about 800—1100 km. It was discovered by analyzing the thermal history of the planet. Energy sources can be radioactive decay and polymorphic transformations of matter. Several convective cells can be located within the global asthenosphere; the superposition of their effects presumably forms the main part of the Earth's magnetic field. The preliminary joint solutions of the electromagnetic and hydrodynamic problems available in the literature (for the outer core) indicate, in the author's opinion, that the problem deserves a more substantive study.

Key words: Earth's magnetic field, convection in the core, global asthenosphere.

Introduction. The study of the Earth's magnetic field has acquired specific features with the advent of the plate tectonics hypothesis. Practically out of touch with other areas of this branch of geophysics, a grand block of publications has grown up in which paleomagnetic data were used to explain the movements of continents and terranes, spreading, the movement of young oceanic plates, subduction, etc. The groundlessness of these constructions was quite obvious from the moment they appeared. It was assumed that in the process of improving the hypothesis, the selection of real elements, the accumulation of arguments in their favor, and the exclusion of those contradicting the observed facts of geological history would occur. However, this did not happen. For 60 years of the existence of the hypothesis, it has remained at the same «intuitive» [Dietz, 1961] level. Over time, criticisms multiplied [Gordin, 2007, Storetvedt, 1997, 2010, etc.], without the supporters of the plate tectonics hypothesis to moving on to a substantive justification of the concept. It has turned into a kind of dogma, invulnerable to any negative arguments due to its universal recognition. Therefore, in the author's opinion, the consideration of magnetic field problems should include, as an obligatory element, their application to the origin of magnetic anomalies in the oceans.

Other problems associated with magne-

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tometry are fundamentally different from those mentioned above. It is about the nature of the field source (sources?). And the point is not the lack of desire among specialists to identify the mechanism of its generation, but the complexity of the task.

The magnetic dynamo hypothesis, despite its rather long existence, still lacks a serious physical basis. The comprehensive consideration of the combination of hydrodynamic and electromagnetic processes in the Earth's core remains a matter of uncertain future; there are only estimations for particular cases with fixed parameters for the electromagnetic part of the process [Yanovskiy, 1964; Zharkov, 1983, etc.]. The hydrodynamic component of the hypothesis, which does not even take into account the influence of the electromagnetic one, remains an area of poorly substantiated assumptions. A significant part of them, focusing on thermal convection in the outer liquid core, does not withstand elementary energy control.

Indeed, the dissipation of energy by convective currents, which should ensure the operation of a magnetic dynamo, according to the most optimistic estimates (with a viscosity of molten iron less than 10^8 Pa·s) is about $3 \cdot 10^{11}$ W. The engine of such a mechanism should consume 2 orders of magnitude more energy — $3 \cdot 10^{13}$ W [Zharkov, 1983]. The volume of the outer core (or the entire core, it doesn't matter, these values differ by only 5 %) is $1.66 \cdot 10^{20}$ m^3. Thus, heat generation in the core reaches 0.2 μW/m^3 on average. This is a completely unrealistic value, equal to heat generation in the lower part of the crust. In the lower mantle, heat generation is a maximum of about 0.003 μW/m^3 [Gordienko, 1998], while in the core (judging by the content of radioactive elements in iron meteorites), it is several times less. Heat generation in the core of 0.2 μW/m^3 can provide almost the entire terrestrial heat flow. Considering its significant increase in the past (if this source is radiogenic), we inevitably come to a completely different thermal history of the Earth than known from numerous geological and geophysical findings and a completely different modern state of it; in particular, there can be no question of a solid inner core, etc.

Sources of the Earth's magnetic field. Questions arise already when describing the Earth's magnetic field. It is considered necessary to detect, in observation results, a «major» field attributed to some central (preferably, axial, i.e. coinciding with the Earth's rotation axis) dipole (and consider it to have always existed), while viewing all the rest as complications. This approach presumes *a priori* the determining characteristics of the model that should have been found only after the field has been interpreted. The approach, one of the consequences of the Schmidt-Bauer model [Bauer, 1920; Schmidt, 1924], proposes to describe the field by calculating the local magnetic constant (G) and has not been widely used. The G should be the same over the entire surface of the Earth if the field is produced by a single axial central dipole. If the accepted hypothesis is incorrect, G reaches a maximum where the dipole approaches the surface and a symmetric minimum at the place of maximum distance from the surface (if the dipole retains its orientation).The G-map of the Earth shows the location of one extreme 100° away from the other, i.e. the dipole is not simply displaced, but also not continuous or oriented at an angle to the Earth's rotation axis. The same pattern can also be observed in the case of paleofields unless the vector of primary residual magnetization (J_n) is artificially adjusted to the assumption that a geocentric axial dipole really exists (Fig. 1).

The above (and many other) considerations point to the need to use a central regional dipole hypothesis in paleomagnetism: «The magnetic field of the given region, in both present and past, can be described, regardless of its nature, as a central dipole field, whose orientation and magnetic momentum vary in similar ways throughout the region» [Semakov, 1998, p. 100]. While preserving the options for describing the field, this approach makes it possible to avoid risks associated, for example, with the notion of «virtual geomagnetic pole» currently in use. «Virtual geomagnetic pole is the position of the geomagnetic pole as determined in terms of the geomagnetic field elements measured at a certain point (either through direct observations or according to J_n of rocks) on the assumption that the geomagnetic field is the field of the central axial dipole» [Pecherskiy, Didenko, 1995, p. 49]. The initial interpretation of the term rules out the use of paleomagnetic data to determine the region's position relative to the Earth's geographic pole during the period of J_n emergence, and this enables us to avoid numerous tectonic speculations such as plate tectonics.

The point is that, even according to recent observations, estimates of the magnetic pole position are known to deviate from its actual position by as much as 1,500—1,800 km [Kuznetsov, 1990], and the magnetic pole itself is 2,500 km away from the geographic pole. J_n characteristics are much less accurate than those established for the present-day field, especially in primary sedimentary rock structures and intrusions that have undergone stress and folding (including those unnoticeable in the area in which samples were collected and which are part of a large structural form) at which the magnetization becomes anisotropic [Zavoisky, 1999]. Synchrony of the data on J_n in various regions is detected with allowances of hundreds of thousands or millions of years (even more in many cases). The declination and inclination according to historical and archaeomagnetic data experience oscillations with periods of n100—n1000 years with an amplitude of about 100 and differences in determining the position of the pole up to 1—2 thousand km. Thus, the error in determining the continent's former position from paleomagnetic data is comparable to (or exceeds) the size of the continent and the distances to which the continent should allegedly be moved.

That a single central axial dipole predominates in the Earth's magnetic field is

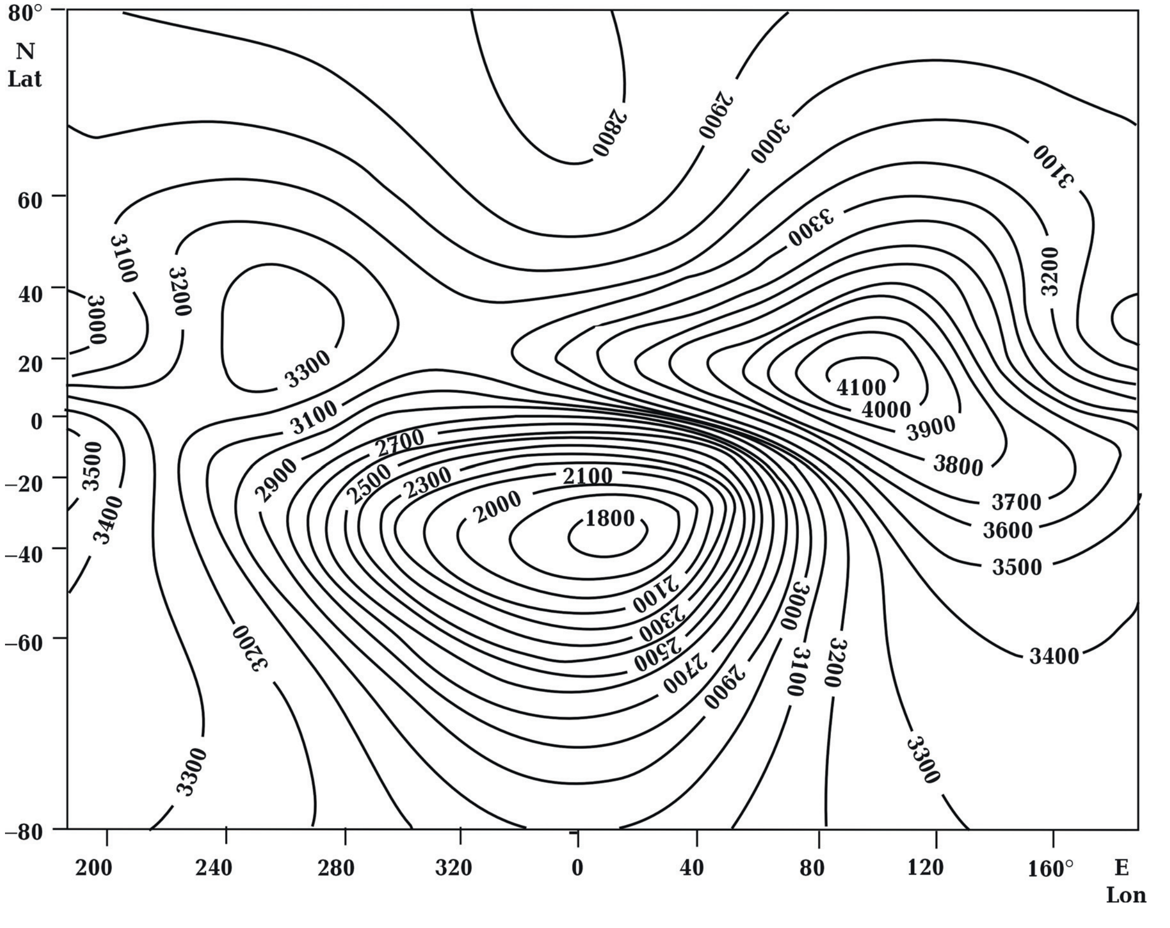

Fig. 1. Map of the Earth's local magnetic constant (isolines in nT) [Semakov, 1996].

disproved by assessing the intensity of the sources responsible for the field, in particular along the 90th meridian: the central dipole — 20 μT, the source of the Brazilian anomaly — 4 μT, Canadian — 6 μT, Siberian — 9 μT, and Antarctic — 4 μT [Kuznetsov, 1998]. In this instance, E.R. Hope's hypothesis [Hope, 1959] on the «agonistic» nature of the drift of the North magnetic pole, i.e., as a point on the line where, at a given moment, the effects of regional sources for which the intensities vary with time, balance out, seems to be perfectly realistic. The same could be said about V.V. Kuznetsov's hypothesis (that a superposition of several sources' effects explains the position of poles and their present motion trajectories of polar drift at polarity reversal and speed of their movement during this procedure [Kuznetsov, 1998]).

Detailed studies of the magnetic field's behavior during inversions and excursions reliably demonstrate the absence of the moment of zero field strength, which is inevitable at remagnetization of the central axial dipole [Sergienko, Shashkanov, 1999].

The field-polarity reversal event analysis prompts a conclusion on its multipolar nature [Gurary, 1988, etc.]. Accordingly, no uniform all-Earth process is involved, and transformation parameters are similar only within separate territories of sizes in the first thousands of km. In the significant tropical part of the oceans (and continents) girdling the Earth, magnetic field anomalies are weakened to the point of being practically indistinguishable. The zone is confined precisely to the contemporary magnetizing field, i.e., it turns out that it plays a very significant role in determining the magnetization of anomaly sources of all ages.

In the past, when magnetic field inversions were considered a relatively rare event (i.e., occurring once every 10 million years), it seemed reasonable to assume that the energy released during the remagnetization of the iron core was insignificant. The density of this energy is quite high: $n10$—$n100$ J/m^3. With the recognition of a higher frequency of inversions, it is necessary to take it into account as well. This consideration significantly increases the «energy requirements» of the process of generating the Earth's magnetic field according to the adopted scheme. During inversions (and, possibly, large excursions, when the pole passes a significant part of the path taken during the inversion) with a periodicity of about 1 million years [Kukal, 1987], the required energy costs increase approximately twice compared to the costs of dissipation alone.

The hypothesis of gravitational (non-thermal) convection in the outer core, occurring when some light elements separate from the inner core during its ongoing crystallization, is not based on any real facts and cannot be verified even at a qualitative level. It is not clear why the additives to iron do not separate from it in the melt, how the constituent part of the substance contained in it at the level of a few percent can lead to a rapid movement of the entire substance, etc.

V.V. Kuznetsov's proposal [Kuznetsov, 1990] to explain the currents causing the magnetic field by the flow of charges when a substance's phase state changes (transition from superdense «gas» of medium-Earth composition to liquid) can only be considered when serious arguments appear in favor of the reality of the used model of the Earth's formation and evolution. The «hot» hypothesis of accretion developed by this author has not yet found serious support.

Estimates of depths (distances from the Earth's center) of magnetic dynamo current systems differ significantly. Although they are made from the same observed field, it seems that they can accommodate equally well currents in a low-power spherical layer with an outer radius of 1300 km [Kuznetsov, 1990] and currents in a ball with a radius of 3500 km [Yanovskiy, 1964; Zharkov, 1983, etc.]. Such «freedom» allows attributing at least some of the field sources to the global asthenosphere [Gordienko, 1998], where both thermal convection and the charge motion during a phase transition are possible, as well as stimulation of gravitational convection, etc.

This layer of partial melting is distributed under all platform and active regions of the Earth under the transition zone from the upper mantle to the lower one (Fig. 2).

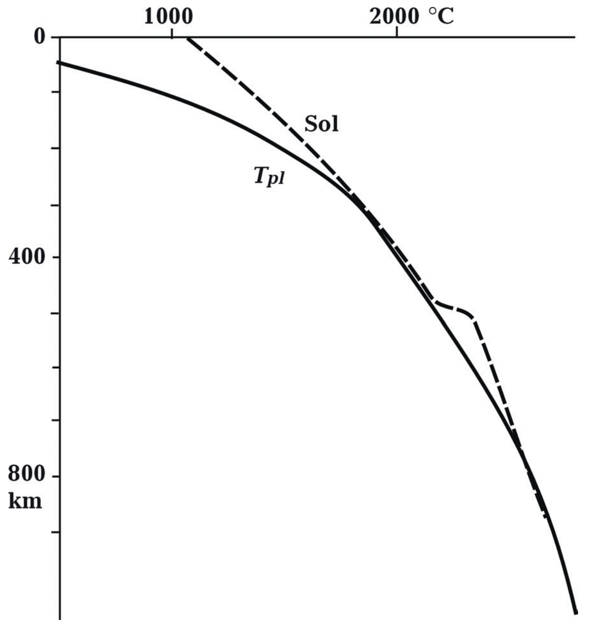

Fig. 2. Thermal model of the Precambrian platform mantle. T_{pl} is the temperature distribution, Sol is the solidus temperature distribution of mantle rocks.

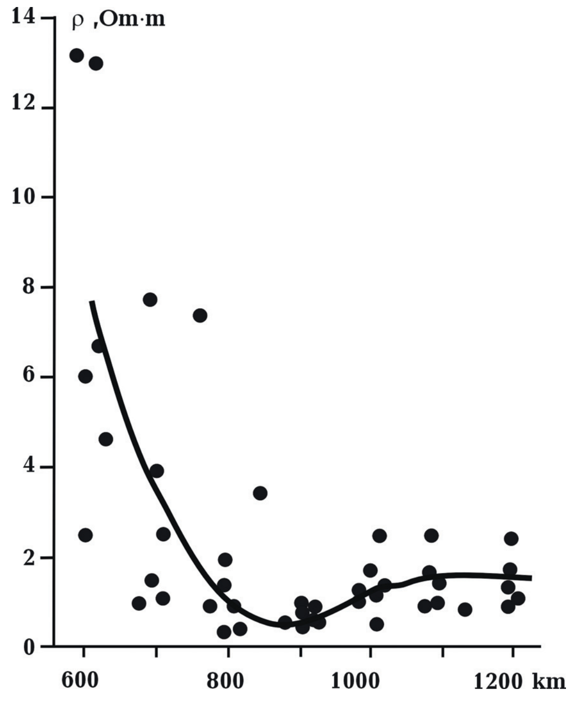

Fig. 3. Distribution of ρ at the depth of the global asthenosphere [Gordienko, 2020].

The specific electrical resistivity (SER) mantle at a depth of about 1000 km (without the asthenosphere) is about 10^{-1} Ohm·m [Zharkov, 1983, Semenov, 1990, etc.]. The real asthenosphere in the upper mantle by its appearance leads to an order of magnitude decrease in the SER of rocks. Thus, resistance values of 10^{-2} Ohm·m can be expected here. In general, these values are not contradicted by the still rather uncertain information on the conductivity of such depths obtained with global MVSs [Rotanova et al., 1994]. Although somewhat larger values are obtained (but still at the level of tenths of Ohm·m), their specific values can be attributed largely to the usual influence of a one-dimensional model (Fig. 3).

The SER of the molten iron core is 10^{-5} Ohm·m [Zharkov, 1983], 10^{-3}—10^{-5} Ohm·m [Kuznetsov, 1990] or $0.3{\cdot}10^{-3}$ Ohm·m [Yanovskiy, 1964].

The magnetic field components for the current in the spherical layer can be tentatively estimated as the sum of the effects of circular currents [Tamm, 1966]. The effect of the current in the asthenosphere (at equal intensity) turns out to be approximately an order of magnitude greater than the effect of the current in the core and almost two orders of magnitude greater than the current's effect at the boundary of the outer and inner cores. The volumes of the global asthenosphere (at its thickness of about 300 km) and the outer core are almost the same. Having attributed the sources of at least the continental anomalies to the asthenosphere at a depth of 800—1100 km, it is easier to explain their confinement to the continents, since according to the results of the global magnetovariational sounding (using field observation data from the MAGSAT satellite), there is a noticeable difference in the conductivity of the global asthenosphere in the «continental» and «oceanic» hemispheres [Rotanova et al., 1994].

Accepting the new concept of the origin of the Earth's magnetic field may cast doubt on many options for its use in paleomagnetic studies, and, consequently, in tectonic reconstructions. Therefore, it makes sense to give at least a preliminary assessment of the possibility of the formation of its sources in the global asthenosphere. Naturally, we are talking about a combination of the effects of many convective cells.

One of the examples can be considered based on of the data of deep processes that

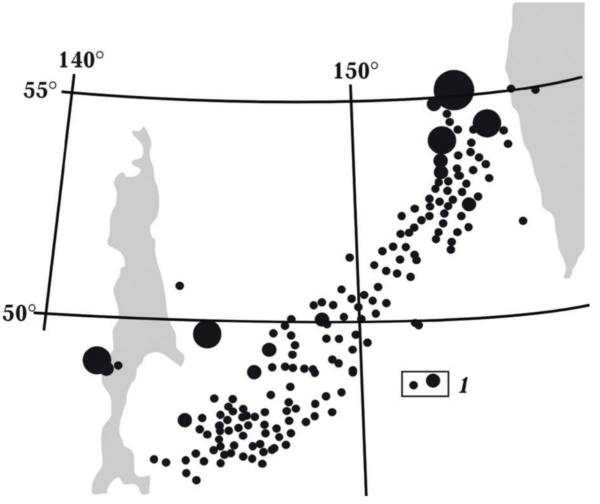

Fig. 4. Epicenters of earthquakes with different magnitudes (*1*) at depths of 400—700 km.

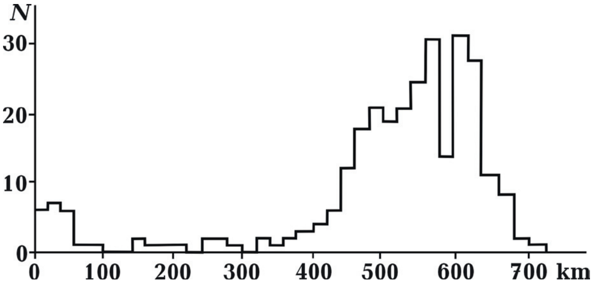

Fig. 5. Concentration of earthquakes in the oceanization area of the Okhotsk Sea in the depth interval of the polymorphic transitions zone.

led to the Okhotsk earthquake in May 2013 with a hypocenter depth of about 640 km (Fig. 4, 5). For this event, the aftershock area 200×300 km in size was studied for the first time, the entire seismogenic zone at this depth of 1300×300 km.

It is located inside the transition zone (TZ) from the upper to the lower mantle, where the minerals of the rocks are transformed into a denser modification (olivine—wadsleyite—ringwoodite). The course of deep processes in the region has been restored. This is the initial phase of oceanization of the Epicimmerian plate. It includes, in particular, the subsidence of relatively cold subcrustal matter to the upper boundary of the transition zone (about 450 km), creating a negative thermal anomaly and compaction in the TZ. Compaction is accompanied by heat release. As a result, an alternation of zones with different signs of temperature gradients is formed (Fig. 6),

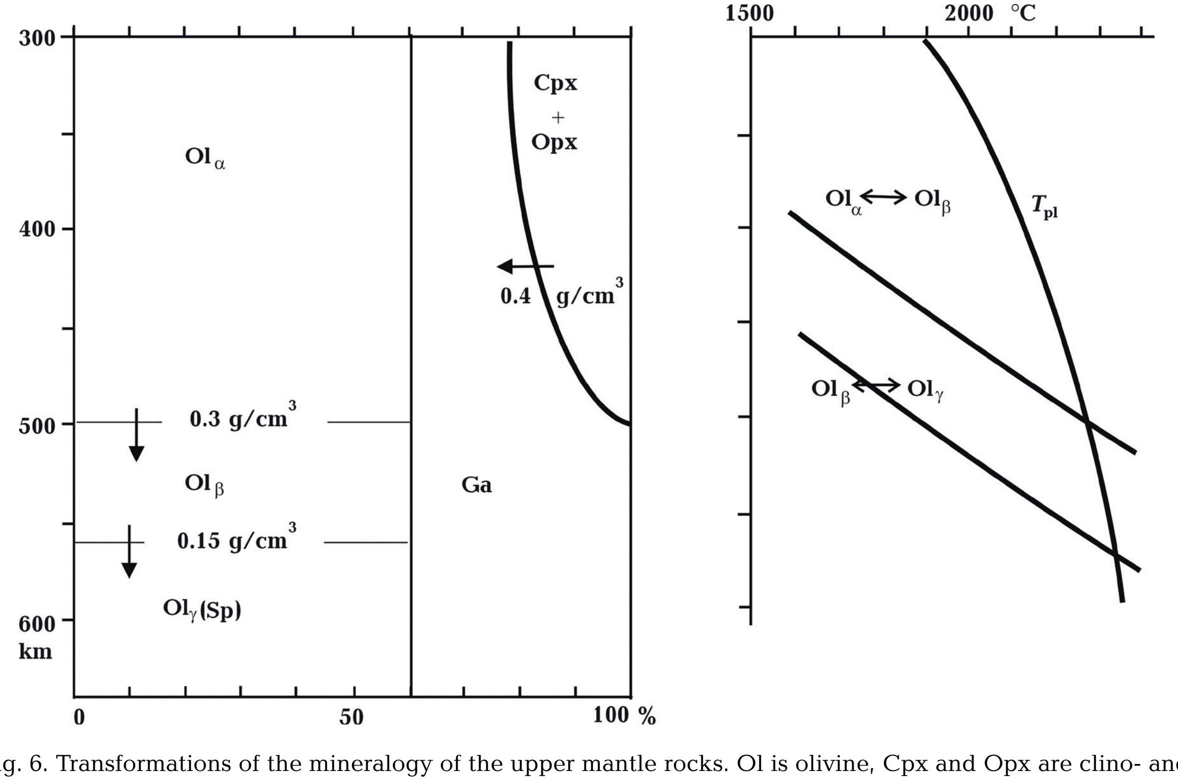

Fig. 6. Transformations of the mineralogy of the upper mantle rocks. Ol is olivine, Cpx and Opx are clino- and orthopyroxenes, Gr is garnet, and Sp is spinel. Arrows show the direction of density growth. T_{pl} is the temperature distribution before the beginning of the considered deep process.

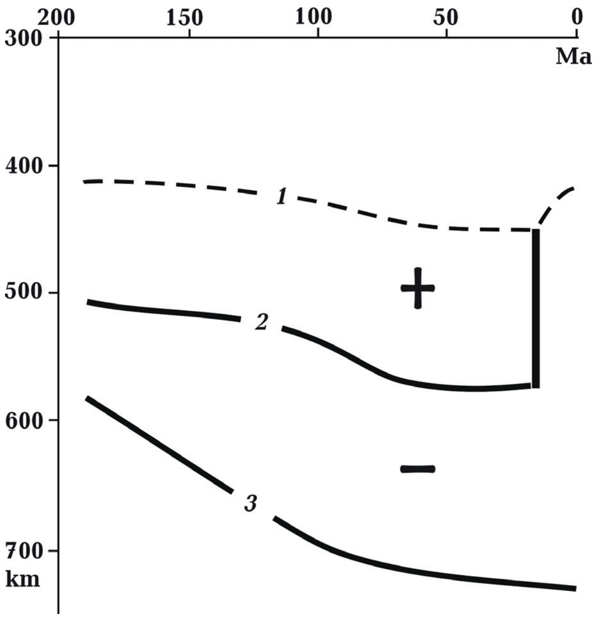

Fig. 7. Zones of rock volume changes under the influence of polymorphic transitions in the considered region: *1* — depth of the start of the Olα↔Olβ transition, *2* — the boundary of the change in the sign of the temperature change with time, *3* — the boundary of zero temperature changes or the surface of the global asthenosphere; + and – are zones of expansion and compression of rocks.

the depth of which varies with time (Fig. 7).

The amount of energy released during a polymorphic transition can be determined by the well-known formula of A. Ringwood [Ringwood, 1981]: $HG = -2RT\ln(u_1/u_2)$ where *HG* is the heat generation, *R* is the gas constant, *T* is the temperature in degrees Kelvin, and *u* is the crystallization energy.

The *HG* value is large being $5 \cdot 10^7$ J/m^3 (for u_1/u_2 of about 2000 °C it is approximately 0.9), but the heat release is very slow. Waves approaching the global asthenosphere are also slow, and the intensity of thermal anomalies is low (tens of degrees), but it is still possible to assume convection stimulation in a significant area. Many similar sources of magnetic field will create a kind of one dipole, polarity reversal will be possible. However, it will no longer be possible to represent the views adopted today by the manifestation of the «main dipole». The absence of earthquakes deeper than 700 km may indicate reduced viscosity of the substance above the accepted roof of the global asthenosphere, and the interval of 700—800 km is included in the convective motion.

Activation of the global asthenosphere by the rise of heated asthenolith from below, from the surface of the core, cannot be ruled out. The temperature difference between the core and the sole of the global asthenosphere is 1050 °C. It is larger than adiabatic. The asthenolith will heat the sole of the global asthenosphere by 100—150 °C (given the area of the surfaces) and stimulate convection. However, data on heat generation in the lower mantle are lacking for a confident estimate.

In principle, the basis for estimating heat generation in the lower mantle can be derived from the total number of radiogenic energy sources in the shell created from chondrite material (Fig. 8). A «magma ocean» was formed from it during melting, which accompanied the separation of the core, convection, and the transfer of the most fusible

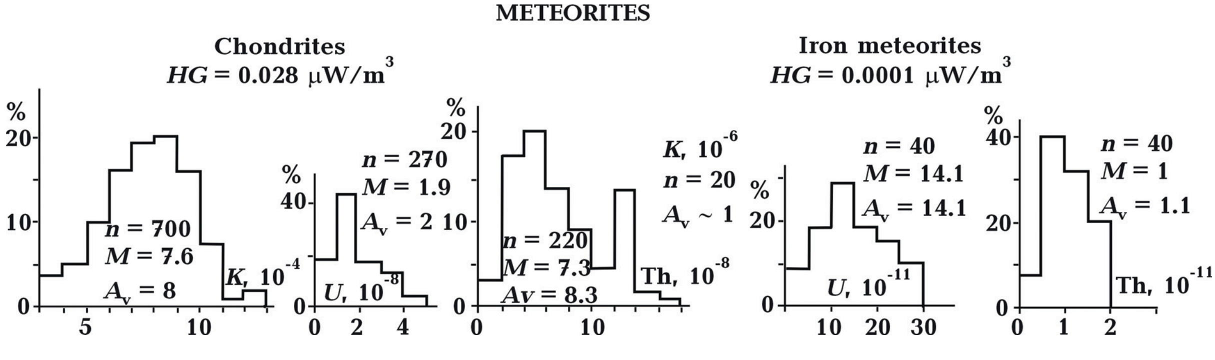

Fig. 8. Histograms of K, U, and Th content distributions in meteorites [Clark, 1969, etc.]; *n* is the number of analyses used, *M* is the median value, and A_v is the mean.

Distribution of radiogenic energy sources in the Earth's shell

Layer	Deep, km	Volume, 10^{12} km^3	*HG*, W/km^3	*E*, 10^{12} W
Crust	0—42	0.021	500	10,5
Upper mantle	42—470	0.201	50	10,0
Transition zone	470—800	0.130	19	2.5
Global asthenosphere	800—1100	0.116	19	2,2

and radioactive elements-enriched part of the substance to the upper shell. It cooled to the solidus temperature, highlighting the upper mantle and crust in its composition.

The shell volume is $0.9{\cdot}10^{12}$ km^3, i.e. the total number of radiogenic energy sources is $25.2{\cdot}10^{12}$ W. Assuming the *HG* of the crust and upper mantle to be known [Gordienko, 2017, etc.], we determine their share in this heat release. For continents and oceans, the total number of sources in the crust and upper mantle is practically the same. The Table presents continental (average for geosynclines and platforms) data. This is natural, since according to the theory, at the beginning of oceanization, the conditions were the same as on modern continents. Afterwards, the sources from the crust were mainly transferred to the upper mantle (which corresponds to the experimental data).

It can be assumed that in the entire lower mantle and transition zone there is a certain amount of radiogenic energy sources in a vanishingly low concentration. Nevertheless, their preservation in higher concentrations in the lower part of the former magmatic ocean seems more logical. This option is presented in Table, and most of the mantle and core are devoid of radiogenic heat sources. From the above data, the definition of the Earth's tectonosphere is clear — it is the depth interval where there is energy to support deep processes. This is definitely the crust and upper mantle and, possibly, the underlying layer to the bottom of the global asthenosphere.

The small heat generation within the global asthenosphere still ensures the accumulation of energy (before its consumption during the movement of matter) necessary for the inversion (see above) over 100—1000 years.

In recent years, there have been quite a few publications in the literature describing calculations of convection in a spherical layer (outer core), probably suitable for inducing a magnetic field. Let us mention [Soloviev, 2015] as an example. The author notes that, due to great difficulties, the hydromagnetic dynamo is studied using kinematic models, in which the fluid velocity is assumed to be constant. In his work, «the following equations are considered together: energy, taking into account internal heat sources and Joule dissipation; movement taking into account magnetic, inertial, viscous and lifting forces; magnetic induction, continuity for velocity and magnetic induction» [Soloviev, 2015, p. 106]. For the boundary conditions used, two convective cells are obtained, in which the temperatures, current functions, and magnetic field components change significantly with time, quantitatively and qualitatively. The local Nusselt numbers reach 2—12, which, with a negligible initial geothermal gradient in the global asthenosphere (about two adiabatic gradients — see above), makes it possible to fairly highly estimate the suitability of currents for generating a magnetic field.

Naturally, the described results, obtained at the level of dimensionless similarity criteria, can only be considered as indications of the prospects of such calculations for solving the problem. But their concretization is clearly of interest.

Conclusion. The collected material on the nature of the Earth's magnetic field supports the unsuitability of the central dipole model for the adequate use of magnetometric data in the study of reversals. The applicability of currently common ideas about the migration of magnetic poles and displacements of blocks of the tectonosphere is questionable. The author has already expressed assumptions about the connection between the sources of the field and the processes in the global asthenosphere before. The article outlines a variant of a specific mechanism for their implementation. Testing the mechanism's viability requires a lot of complex work.

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Про природу магнітного поля Землі

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Аналізований у статті блок інформації включає прийняті в даний час уявлення про головне джерело магнітного поля — осьовий диполь, дія якого доповнюється довгим рядом регіональних джерел. Диполь існує завжди (досить довго, щоб можна було ігнорувати вплив процесу його утворення), хоча переміщується в тілі планети та змінює орієнтацію на протилежну. Тривалість періодів збереження полярності довільно змінюється на два порядки. Фізичне обґрунтування цього дивного механізму відсутнє. Передбачається, що йдеться про теплову конвекцію в рідкому ядрі Землі. За рахунок якої енергії відбувається тепломасоперенесення і як із факту його існування випливають перелічені екзотичні властивості джерела магнітного поля — невідомо. Як альтернатива пропонується розглянути конвективні перетікання у глобальній астеносфері, що спричинені впливом активних процесів у тектоносфері. Її обсяг можна порівняти з обсягом зовнішнього (рідкого) ядра. Глобальна астеносфера являє собою шар часткового плавлення під усією поверхнею Землі на глибинах близько 800—1100 км. Він виявлений під час аналізу теплової історії планети. Джерелами енергії можуть бути радіоактивний розпад і поліморфні перетворення речовини. У межах глобальної астеносфери може розміщуватися кілька конвективних осередків, суперпозиція їхніх ефектів, ймовірно, формує головну частину магнітного поля Землі. Наявні в літературі попередні спільні розв'язання електромагнітних і гідродинамічних задач (отримані для зовнішнього ядра) свідчать, на думку автора, про те, що проблема заслуговує на більш предметне вивчення.

Ключові слова: магнітне поле Землі, конвекція у ядрі, глобальна астеносфера.