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From the Researcher's Notebook

Comparison of Tectonic Phases and Geomagnetic Reversals in the Late Mesozoic and in the Cenozoic

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Abstract—The authors consider the chronological relation of two groups of phenomena in the history of the Earth over the last 150 mln years. One of them is relatively short (a few million years) tectonic phases, or orogenic phases, identified by H.W. Stille in 1924 and characterized by an increase in compressive deformation in mobile belts of the Earth. Deformations that occur during such phases are quite explicable by collisional interactions of lithospheric plates. However, these interactions do not explain the synchronous occurrence of phases in different belts and on different continents. The other group is the frequency of magnetic reversals, i.e., changes such that the positions of magnetic north and magnetic south are interchanged. Tectonic phases are more frequent in epochs of frequent geomagnetic reversals. During the last 24 mln years, when geomagnetic reversals were especially numerous, tectonic phases came one after another in short intervals. An emerging trend for them is the lagging of phase peaks by one to two million years relative to the most frequent magnetic reversals. The chronological relations identified show that tectonic phases are determined not only by geodynamic processes in the lithosphere but also by the action of energy pulses that occur in the Earth's core and at the boundary of the core with the mantle, where the Earth's magnetic field is generated. On the geological time scale, this interaction takes place quickly, which excludes energy pulse convection and prompts the search for other mechanisms of this transfer. It is possible that it takes place because the lithosphere is affected by alternating body forces that occur under a change in currents in the core, which is followed by changes in the mode of the Earth's rotation and the adaptation to it of lithospheric masses.

Keywords: tectonic phases of increase in compressive deformations, geomagnetic reversals over the last 150 mln years.

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More than 90 years have passed since H. Stille [1] identified orogenic phases, which later were called more generally *tectonic phases*. Stille considered a phase as a manifestation of a pulse of shortening, expressed by orogenic deformations and imprinted in a geological section by unconformity, coeval manifestations of such deformations being recorded, even if not globally, in at least several orogenic belts far apart from each other. The list of phases and the principle to identify them were called *Stille's canon* [2]. Insufficient reliability of the dating of tectonic events that underlie phase identification and variations in the age of folding in different zones of even the same orogenic belt were noted.

N.S. Shatskii proposed a fundamentally different interpretation of orogenic phases [3]. By the example of the Ciscaucasia region, he showed that folding developed over a long time and consedimentationally and unconformity at the baseline of the mass lying over the contorted beds reflects the termination of the folding and a change in the mode of the territory's tectonic development. Seemingly, the result obtained refuted the principle that underlies phase identification according to Stille. However, that is not the case. The above and similar examples are a gradual intensification of a certain parameter of a tectonic system, which stops upon reaching an acceptable limit, giving way to another system. In other words, this approach also means that the cessation of the folding formation process is characterized by a maximal deformation, which converges it with Stille's understanding of the orogenic phase as the peak of a tectonic deformation.

Analyzing tectonic events and the nonuniformity of their manifestations in the Mesozoic and Cenozoic, V.E. Khain [4–6] considered, along with orogenic phases as the expression of the intensification of shortening deformations, other tectonic formations and their changes—the development of depressions, sea-

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floor spreading and continental rift zones, and subduction and collision areas and their inherent magmatism. The wide coverage of events, which are some-
1 times unclearly specified spatially and inaccurately dated, dictated transferring to more long-term nonuniformities of the Earth's structural evolution and to manifestations of tectonic activation, which embrace tens of millions of years and called tectonic epochs. However, against the background of such epochs, in collision areas and similar intracontinental and near-ocean pressure and transpressure belts, shorter phases of deformation activation took shape, which correspond to Stille's phases.

For the interval from the Jurassic to the present day, M.G. Lomize [7] analyzed the chronological relation between the following groups of geological data determined by geodynamic processes:

- eustatic fluctuations of the ocean level, associated, in Lomize's opinion, with the volume of mid-ocean ridges;
- changes on the velocities of spreading and horizontal movement of lithospheric plates;
- changes in the velocities of subduction by the intensity of the intrusive magmatism of the North American Cordillera and Japan, as well as on the entire eastern periphery of the Pacific Ocean, and for the Late Cenozoic, by volcanic occurrences of Central America and Oregon;
- the frequency of geomagnetic reversals;
- the chronology of the epochs of orogeny and riftogenesis.

The comparison of the above characteristics showed that changes in the velocities of spreading, horizontal movement of plates, and subduction, as well as the level of the ocean, directly correlate with each other, which agrees with their singleness in the plate-tectonic system. The frequency of geomagnetic reversals shows, with small deviations, an inverse correlation. The epochs of orogeny and riftogenesis demonstrates a trend to alternation in time, although sometimes they partly coincide. However, neither shows either a direct or indirect correlation with the above parameters.

Studies of the last 20 years have confirmed the existence of Stille's tectonic phases. New data about their age and manifestations on various orogenic belts of the Earth have been obtained. The scale of the values of rocks' remnant magnetization (geomagnetic reversals) of the Late Mesozoic and the Cenozoic has been specified. This has made it possible to turn again to the chronological relation of Cretaceous and Cenozoic tectonic phases and the frequency of the Earth's geomagnetic reversals. For earlier geological epochs, it would be premature to evaluate such a relation due to inaccuracies in determining the age of phases and reversals during some time intervals. The results obtained will be considered below.

TECTONIC PHASES

Below is a brief characteristic of tectonic phases from the Late Jurassic until the present day. It is based on generalizing works [5, 8], supplemented and specified according to published descriptions of tectonic events in individual tectonic zones and areas. Manifestations of shortening and transpressure (a combination of shortening with shearing) deformations,
expressed by folding and offsets by nappe-, thrust-, 2
and slip-strike–type faults, were taken into consideration. Criteria to determine the age of the deformations were unconformities between the dislocated and overlying masses, as well as manifestations of deformation-related metamorphism and, in some places, granite magmatism. The emergence of subaerial uplifts was considered only in cases when it was related to zones where shortening deformations were concentrated. The general intensification of vertical movements, which had begun locally in the Late Miocene and reached its maximum in the Pliocene–Quaternary, was not considered because it had been predetermined by other causes [9].

The Late Cimmerian epoch of tectonic activation embraces the period from the Late Kimmeridgian until the Valanginian, 151–138 Ma. It can be subdivided into three phases, dated approximately to intervals of 151–148, 146–144, and 142–138 Ma. Deformations of this epoch were discovered in Alpine Europe and were also registered in the Far East (the Stanovoy Highlands, Sikhote-Alin', and Japan) and in Northeast Asia. The Yanshan orogeny in China, the Nevadan orogeny in western North America, and the Andean phase in the western part of South America are examples.

The Austrian epoch of tectonic actuation falls on the Mid-Cretaceous, 116–96 Ma. The main deformations of that epoch occurred at the boundary between the Albian and the Cenomanian, about 99–96 Ma. In the Eastern Alps, where the Austrian phase of this epoch was fixed, it is characterized by an unconformable bedding of the Upper Turonian (Gosau facies) on tectonic nappes. In addition, an earlier, Aptian, phase of tectonic activity is outlined, around 116–113 Ma. Most likely, the phases are divided by a long epoch of relative tectonic quiescence. Features of the Austrian orogeny have been recorded in the Carpathians, on the Balkans, in Dobruja, in northern Anatolia, on the Elburz, in the Pamir–Karakoram region, in Central Tibet, in the Khingan (China), in Sikhote-Alin', in Japan, and in Koryakia. Other events close in terms of time to this epoch are the Sevier orogeny in the Cordillera and deformations in southern North America.

The Subhercynian phase falls on the Santonian (~85–82 Ma) and is identified in the foothills of the Harz, as well as in regions of the Eastern Alps and Western Carpathians, on Cyprus (the Mamonia zone), in Anatolia, in the Lesser Caucasus, in the

Zagros thrust zone, in Oman, and in the North American and Mexican Cordilleras.

The Laramide epoch embraces the Late Cretaceous and the Early Paleogene (67–61 Ma with the peak of activity at ~65–66 Ma). This activation epoch is clearly expressed in western North America, where it coincides with the main stage of the development of the continental crust. The same activation widely manifested itself in eastern Asia as well, where it is associated with thrusts of Koryakia; strike slips of Sikhote-Alin'; and deformations of the Upper Yana basin, Western Kamchatka, Eastern Sakhalin, Hokkaido, Taiwan, and the Western Philippines. A possible analogue is the Late Yongshang phase in China. In the Alpine–Himalayan orogenic belt, this epoch was not decisive, but it was manifested in the Pamir–Karakoram region, Kohistan, and Baluchistan, as well as in Anatolia, the Balkanides, the Carpathians, the southwestern Alps, and the Pyrenees. At the northwestern and eastern margins of the Arabian Plate (Oman, Zagros, Syria, Cyprus, and Southeastern Anatolia), the main deformations of this phase took place in the Late Maastrichtian.

According to Stille [1], *the Pyrenean orogenic phase* manifested itself at the turn of the Eocene to the Oligocene. Later, it was shown that the main events of this phase had taken place at the end of the Mid-Eocene and in the Late Eocene [2]. Subsequently, however, it was discovered that substantial deformations had occurred later as well, up to the Early Oligocene. Therefore, it is necessary to isolate *the Pyrenean tectonic epoch* (41–33 Ma), which, to all appearances, contained two activation phases, 41–40 and 34–33 Ma, separated by a weaker phase. This epoch was of decisive importance for the development of the continental crust of the Alpine–Himalayan belt and manifested itself in all its segments. In addition to the Pyrenees and Provence, it is recorded in the Alps, Apennines, Tell Atlas, Er Rif, Baetic Cordillera, and other tectonic zones of the western Mediterranean Basin; in the Carpathians, Balkanides, Dinarides–Ellinides, Pontides, and Taurus mountain zones; over the entire Lesser Caucasus (the Trialeti phase); and in El'brus and eastwards, up to the Indo-Burma system and the Indonesian archipelago. Especially significant were deformations in the Himalayas and Karakoram. Manifestations of activation in Sikhote-Alin' are compared with the same epoch.

The Savian phase gravitates to the Late Oligocene–Early Miocene (24–17 Ma, the peak of its activity falling on 20–18 Ma). This phase saw the radical restructuring of the tectonic system of Alpine Europe, associated with the beginning of strike slips along the Azores–Gibraltar fault zone and the resultant rotation of the Corsica–Sardinia block (20.5–19 Ma). This phase was characterized by deformations in the Baetic Cordillera, Er Rif, Tell Atlas, and Apennines; the beginning of the formation of South Vergentic thrusts in the Alps; folding in the Carpathians (the cliff zone); the consumption of the last relics of the Neotethys in Southeastern Anatolia; the formation of the modern Cyprus arc; the beginning of the formation of folds of the bottom of the Tian Shan Mountains; the maxima of deformations in the Greater Himalayas and the Central and Southern Pamirs; and the general reorientation of the deformation field in the Caucasian–Arabian and Pamir–Himalayan segments of the Alpine–Himalayan belt. The beginning strike-slip offsets along the San Andreas Fault in the western part of North America correlate with this phase.

The Styrian (pre-Sarmatian) phase falls to the Mid-Miocene (16–11 Ma) and, most probably, contains two activation peaks, before the Langhian (16–15 Ma) and before the Tortonian (12–11 Ma), with weaker deformations between them. This phase is expressed by the formation of folds and nappes in the external zones of the Baetic Cordillera, Er Rif, Tell Atlas, Apennines, the Northern (the cliff zone) and Southeastern Carpathians, and the Dinarides–Ellinides and the emergence of the Calabro-Sicilian and Cretan–Hellenic arcs. At the end of the phase, another reorientation of the deformation field took place in the Caucasian–Arabian and Pamir–Himalayan segments of the Alpine–Himalayan belt. In the Crimea, Caucasus, and Central Kopet Dag, the phase is characterized by pre-Chokrakian and pre-Sarmatian unconformities, while in the external zone of the Pamirs, it is marked by an unconformity at the base of the Upper Miocene. During this phase, the last relics of the Neotethys closed and folding began in the zone of the Main Zagros Thrust. A possible analogue is the Aleutian deformation phase.

The Attic phase falls to the end of the Miocene (8–5.5 Ma). It was identified in the Ellinides and recorded in the Greater Caucasus, the Kopet Dag, El'brus, the Higher Zagros, Makran, Baluchistan, the Himalayas, and southeast Asia. The first regional unconformity in the Afghan-Tajik Depression and deformations in Yunnan province (Southeast China) coincide with this phase. Fold-formation movements on Kamchatka, Sakhalin, and Hokkaido and the acceleration of the strike slip by several times along the San Andreas Fault (8 Ma) correlate with the phase.

The Rhone (pre-Akchagilian) phase is dated to 4.5–3.5 Ma. In addition to the foothills of the Alps, it was characteristic of the restructuring of the Dead Sea Transform strike-slip system (~3.7 Ma), the fold-formation motions in the Crimea, Caucasus, Kopet Dag, and Lower Zagros, and northeastern Asia and the western part of North America. The acceleration of the strike slip along the San Andreas Fault (4.5–4 Ma) coincides with this phase.

The Valahian–Pasadenian phase embraces the last 2 mln years and contains three episodes of tectonic activation: 2–1.8 and 1–0.8 Ma and the last 0.5 mln years. The Valahian phase was identified in the south-

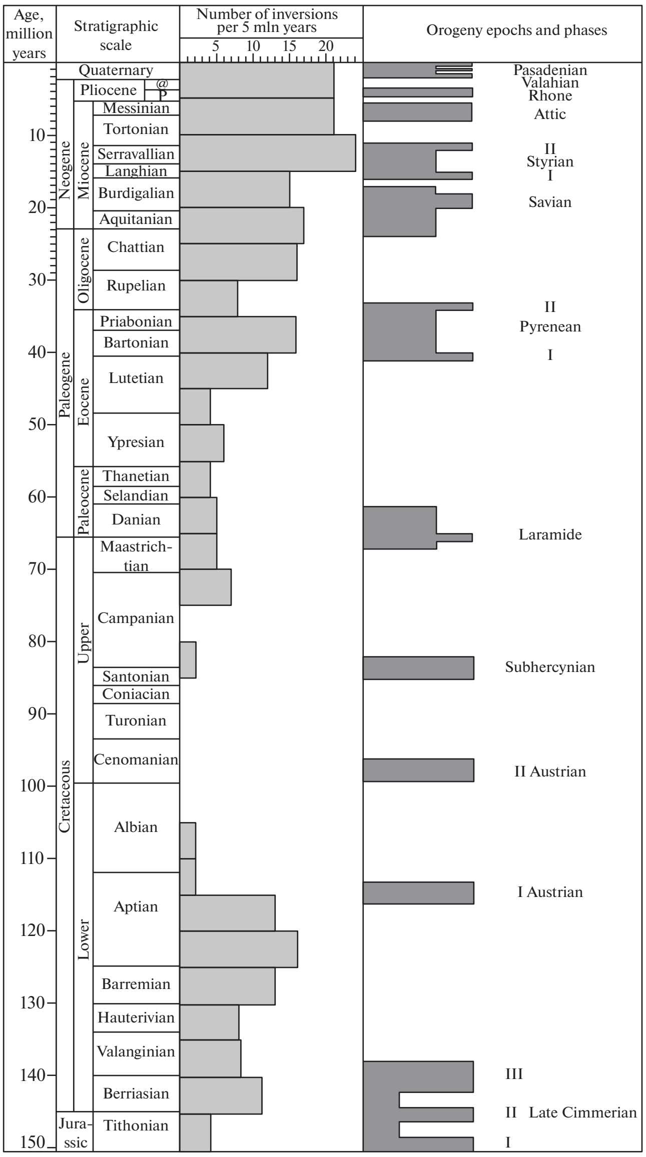

Fig. 1. Comparison of the phases and epochs of the activation of compression and transpressure deformations from the Late Jurassic up to the present day and the frequency of magnetic polarity inversions. The number of geomagnetic reversals by intervals of 5 mln years is presented.

ern part of the pre-Carpathian depression and corresponds to the first episode. The manifestations of the first two episodes have been fixed on the shores of the Black and Caspian seas, on the northern edges of the Middle and Lower Kura depressions, in the South Caspian Depression, in the foothills of the Taurus Mountains, in the Zagros piedmont zone (~0.9 Ma), on Makran, in the Afghan-Tajik Depression, and in Northeast Asia. The Pasadenian phase has been identified in California and is expressed by an unconformity between the lower parts of the Mid-Pleistocene and the Late Pleistocene. Its analogues have been discovered in all mobile belts as manifestations of active tectonics. Local unconformities, described in the Afghan-Tajik Depression, on the northeastern coast of the Persian Gulf, and along the shores of the Black and Caspian seas, testify to a differently ranked non-uniformity of movements during the Pasadenian phase. At the same time, it has become obvious that it must not be broken away from earlier episodes of Quaternary activity, with which it forms a single tectonic phase.

Tectonic phases, starting from the Savian, closely follow each other. Intervals between them usually do not exceed 1–1.5 mln years; only the interval between the Styrian and Attic phases reaches ~3 mln years, which is incommensurable with the intervals between earlier phases. Most likely, the Savian and subsequent tectonic phases should be united into the neotectonic stage of deformation activation.

RESULTS OF THE COMPARISON OF TECTONIC PHASES AND THE FREQUENCY OF GEOMAGNETIC REVERSALS

Considering the existing uncertainties in the dating of tectonic events, the obtained assessments of the age of tectonic phases are approximate. Nonetheless, they reflect a general tendency. From the end of the Jurassic through the present day, the frequency of the occurrence of these phases has been different (Fig. 1). They quickly followed each other during the Late Cimmerian tectonic epoch. Then a long (95 mln years) interval took place, during which only the relatively short Early Austrian, Main Austrian, and Subhercynian phases and the somewhat longer (~6 mln years) Laramide tectonic epoch with a short activation phase occurred. Then the Pyrenean activation epoch (~8 mln years) with two peaks of activity took place, followed by a new relatively quiescent stage of ~9 mln years. After it, over the last 24 mln years, tectonic phases with activation peaks and intervals of relatively low activity followed each other, being divided by short intervals of relative quiescence.

The tectonic phases identified were compared to the scale of remanent magnetization in rocks [10, 11], which is a sequence of states of direct and reversed magnetic polarity at a certain time. The state of the first type is characterized by the same features as the modern magnetic field, when the north magnetic pole is at northern latitudes, while the state of the second type is characterized by the opposite position of the magnetic poles. These states changed during the geological history with varying frequencies, forming both more or less long epochs of consistent uniform polarity and short episodes when it changed. For comparison with tectonic phases, the criterion of the number of reversals has been chosen, i.e., transfers from one polarity to the other over 5 mln years. For the neotectonic stage (from the Late Oligocene to the present day), when phases were especially frequent and the age of phases and reversals is established more accurately, phases have also been compared with the number of reversals over 1 mln years (Fig. 2).

The comparison has shown the following. The Late Cimmerian tectonic epoch was characterized by moderately frequent and frequent polarity inversion, which continued up to the Austrian phase. Then came a long period of normal polarity, i.e., the full or almost full absence of reversals, to which the Main Austrian and Subhercynian tectonic phases fall. The Laramide tectonic epoch was characterized by a moderate number of reversals, after which their number decreased. It increased during the Pyrenean tectonic epoch. Then, after a decrease in the number of reversals in the Early Oligocene, their number increased during the Savian phase, reached maximal values in the Mid-Miocene (the Styrian phase), and remained high up to the Quaternary (the Attic, Rhone, and Valahian–Pasadenian phases).

Thus, there is no consistent direct or reversed correlation of tectonic phases with the number of geomagnetic reversals. However, a trend has been identified according to which the frequency of phases increases as the number of geomagnetic reversals grows (see Fig. 1). A more detailed comparison for the period from the Late Oligocene through the present day, i.e., during the neotectonic stage, has made it possible to identify another peculiarity (see Fig. 2): against the background of many reversals, short minima outstrip equally short phases and peaks of tectonic activation by 1–2 mln years.

Tectonic phases as maxima of manifestations of compression or transpressure deformations are polygenic. The appearance of phases is determined by a wide spread of collisional and similar tectonic frameworks of compression and shear under the structure of the continental crust suitable for their manifestation. The conditions of the appearance of tectonic phases, according to plate tectonic theory, are determined by the behavior of rock masses under the interaction of lithospheric plates. However, this theory does not explain the synchronicity of tectonic activation phases in different mobile belts and even different continents. It holds that the emergence of synchronous global phases is rather a combination of exceptional circumstances than a rule. This synchronicity can be determined by the geodynamic action of processes manifesting themselves in geomagnetic reversals on the lithosphere.

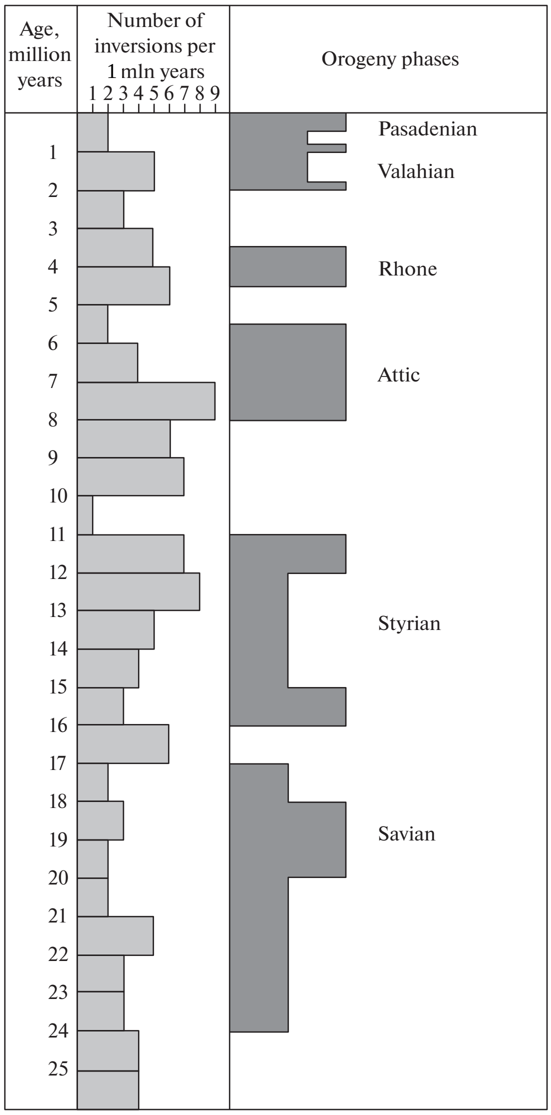

Fig. 2. Comparison of the phases and episodes of the activation of compression and transpressure deformations from the Late Oligocene up to the present day and the frequency of magnetic polarity inversions. The number of geomagnetic reversals by intervals of 1 mln years is presented.

POSSIBLE CAUSES OF THE CORRELATION BETWEEN TECTONIC PHASES AND THE FREQUENCY OF GEOMAGNETIC REVERSALS

According to modern ideas, of decisive importance for the creation and functioning of the Earth's magnetic field are processes in the Earth's core and their interaction with the mantle [12]. The geodynamic action of these processes on the lithosphere by means of convection or other forms of heat and mass transfer in the mantle cannot be a source of tectonic phases. The velocities of the ascending branches of mantle convective heat and mass transfer are commensurable with those of upper mantle flows, which represent the lateral branch of convection and move lithospheric plates [13]. The velocity of the flows is around 8 cm per year on average. At this velocity, it would have taken a convective disturbance ~35 mln years to cover a distance of 2800 km from the core to the base of the lithosphere; however, tectonic phases are close in terms of time to epochs of frequent magnetic polarity inversions and, over the last 24 mln years, have probably been manifested following their maxima every 1–2 mln years. Hence, there exists another quasi-immediate (on geological time scale) way, other than convective, to transfer to the lithosphere the energy from deep processes that determine both superficial orogeny and variations of the Earth's magnetic field. Since the spatiotemporal structure of the normal magnetic field is determined by the character of flows in the external core, a change in the parameters of these flows can lead to the emergence of alternating body forces in the mantle, which quickly act on the lithosphere.

In our opinion, the source of changes in the flows on the core is the redistribution of masses in the system of the external liquid and the internal solid core, which leads to a change in the regime of the Earth's rotation. It is assumed [10] that flows in the core in combination with the rotation of the spheroid and the high conductivity of material form the structure of the Earth's normal magnetic field, which in the first approximation can be approximated by the field of a dipole oriented to the rotation axis, running through the center of mass. However, studies on variations of the normal field over the past 50 years have shown that the dipole's parameters demonstrate a spatial shift of its center in time northwards from the equator relative to the center of mass [14]. This testifies to a change in the magnetic field–forming structure of the flows of the liquid core material, the average density of which is higher than the density of the mantle's bottom by nearly 50%. Changes in the position of these masses dominating in the Earth's body, which favor a change in the characteristics of the moment of inertia relative to the current axis of rotation, should lead to a change in the Earth's rotation mode. In addition, there are calculations [15] that testify to a shift of the solid core inside the liquid one. If the solid core with an average density that is 15% higher than that of the external core is subject to a shift, this also must lead to a change in the Earth's rotation mode, which is, in particular, a change in the position of the axis of rotation inside the body of the spheroid. This is confirmed by data of the International Earth Rotation and Reference Systems Service [16] for the last 100 years, the analysis of which shows that the pole of rotation is shifting southwards along 70° W with a velocity of about 10 cm per year. The above values are of the same order as the geodynamic velocities obtained by geological data and the data of the analysis of the anomalous magnetic field of spreading areas of the ocean. This confirms the assumption concerning the coherence of the velocities of the behavior of geodynamic processes of the same scale in the Earth's body.

Let us consider the possible consequences of a change in the position of the axis of rotation. Assume that the rotation body is not solid but laminated with a block structure and the ability to shift some layers and blocks relative to others. In this case, mobile masses (blocks and layers) situated on the surface of a spheroid (the lithosphere) and having a less viscous layer (the asthenosphere) at the base will gravitate to a position in which the mobile masses become adapted to the new mode of rotation. The goal of the adaptation is a diagonal form of the tensor of inertia [17]. In other words, mobile masses on the earth's surface should concentrate close to the equator and be more or less uniformly distributed along its circle. Note that the paths of mass transfer on the surface in accordance with the new position of the axis of rotation, determined by the larger masses of the core, can be different. This assumption is confirmed by the simultaneous collapse of the sublatitudinal paleoocean Tethys and the opening of the northern segment of the Atlantic in the Late Triassic and the Early Jurassic. The dislocations of plates testify to the tendency to shifting lithospheric masses towards the equator with the simultaneous trend to their more uniform distribution along its perimeter, which is proved by the formation of a submeridional ocean.

The conditions of the adaptation of mobile masses to the new mode of rotation make it possible to calculate theoretically the direction of their displacement. This calculation was performed in [18]. We observe the fundamental coincidence of the logic of the calculated movement of lithospheric masses with GPS data for North and South America, Eastern and Northeastern Eurasia, and a part of Oceania. Difference are present, but the coincidence of the main components of the movement is satisfactory. Strong differences between the calculation results and GPS data are observable in the area that coincides with the outline of the African superplume over the mantle base.

Therefore, the connection between magnetic reversals and tectonic activation phases is indirect. Both phenomena can be consequences of the alternating spatial structure of flows of material with a high density and conductivity in the external liquid core, which leads, on the one hand, to a geomagnetic reversal and, on the other, to a change in the mode of rotation under the redistribution of large internal masses and the adaptation of the lithosphere to it.

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