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Tectonic Phenomena and Supervising Underlying Geodynamic Processes

V. G. Trifonov[a], * and S. Yu. Sokolov[a]

[a] *Geological Institute of the Russian Academy of Sciences, Moscow, 119017 Russia*

**e-mail: trifonov@ginras.ru*

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Abstract—The study concerns two deep sources of tectonic processes in Late Mesozoic and Cenozoic which influence is transferred and enforced on the spheroid surface – Earth crust. The first source is mantle convection. Its upgoing branches are comprised by mantle superplumes from which the upper mantle flows spreads laterally. Downgoing convection branches are comprised by detached highly metamorphosed fragments of thickened continental lithosphere and partially by subducted slabs, submerged lower than transitional mantle layer (~410–680 km). Major of subduction zones are transformed to subhorizontal lenses at the transitional layer depth participating in upper mantle convection. Coupled with total mantle convection it defines plate tectonic processes and lithosphere density loose, bringing rise amplifying during mountain formation. The second source is outer core flows reflected in magnetic field inversions, which are more frequent during or before of major of tectonic activity phases (phases of compression and transpression deformations strengthen). Inversion frequency rises during neotectonic orogeny. It is supposed, that Earth core flows change its spheroid parameters, which brings to the appearance of volume forces, affecting almost immediately in geological time. Thus core flows contribute to global character of tectonic phases occurrences and synchronicity for superposition of modern mountain formation main phase with plate tectonic processes.

Keywords: mantle and upper mantle convection, orogenic phases and magnetic inversions correlation, global synchronicity of mountain formation periods

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INTRODUCTION

The present paper distinguishes a number of tectonic phenomena characteristic of the Earth's evolution in the Late Mesozoic (beginning from the Late Jurassic) and Cenozoic and also reveals their causes, up to the construction of a global model of geodynamic processes that defines the origination and evolution of the revealed tectonic structures. The concepts of tectonic phenomena and their sequence documented in tectonic structures are formulated on the basis of visual geological observation, or using various instruments, analytical methods, and laboratory modeling. Further research is aimed at finding the cause-and-effect relationships between tectonic phenomena; as a result of this research, the processes that caused the formation and evolution of more general groups of tectonic phenomena can be determined and characterized more or less reliably. Of course, this research faces certain difficulties.

Results of geological observations as a reflection of natural phenomena are always interpretations. Visual observations of geological objects are associated with possible errors due to both objective and subjective factors (the former include, e.g., outcrop conditions; the latter, the theoretical viewpoint of a researcher). When interpreting results of geophysical observations, errors can be related to an extended interpretation of the obtained data: ignoring incorrectness in solutions to inverse geophysical problems, errors in selecting the model of the medium, missing minor anomalies because of strong noise, mistaking noise for a useful signal, and others factors often difficult to take into consideration.

When generalizing and comparing the observation results, errors in interpretation can be made in relation to the convergence of features of different types phenomena, or, vice versa, to the divergence of features of phenomena from the same group. Convergence-related errors can be illustrated by the petrological-geochemical similarity between Late Miocene–Quaternary volcanic rocks from the Armenian Upland and volcanic products of ensialic island arcs, although in the Armenian Upland there are no signs of subduction during the Late Cenozoic. The geochemical similarity of volcanic products reflects the similarity of material in magmatic sources; this is probably because in the Late Cenozoic, relics of Mesotethys slabs remained in the lithosphere as it underwent melting.

The divergence between features of phenomena from the same group can be illustrated by the absence of features of arc volcanism in the back-arc part of the Cyprus island arc, caused by the low subduction rate and oblique movement of the subducted plate (predominance of longitudinal left-lateral strike-slip) in the larger, eastern part of this arc. As a result, sinking material can not be involved in the generation of magmatic sources at the depths necessary. This kind of divergence (i.e., diversity of secondary features) with the stable presence of some main feature (in this case, a mantle seismofocal zone), makes it possible to differentiate a group of similar tectonic phenomena.

Tectonic phenomena reflect the relationships between complex, nonelementary units of a setting. Hence, substantiation of some new phenomenon or identification of some known phenomenon from observation results represents the choice of a version and its characteristics that seem the most probable for a result's consistency with the general structure and sequence of events. Multiple reports about similar observed phenomena can help in elaborating a system of features of general phenomenon (the presence of these features increases the probability of correct interpretation). Identification of some phenomenon from multiple observation results is believed to be quite satisfactory if the respective features have been reported in 80% of studied objects of the same type. With a probabilistic character of these estimates, a generalization based on comparison of tectonic phenomena (i.e., the first derivative of the observation results) will be valid with a 64% probability. A wider generalization based on a number of first derivatives, or a geodynamic model that explains them all, will be valid with a probability of no more than 51%. In this respect, any model constructions based on long series of sequential generalizations will appear doubtful. The present work attempts to maximally reduce the number of relationships in generalization sequences; nevertheless, it should be borne in mind that the resultant models are purely hypothetical.

TECTONIC PHENOMENA UNDER DISCUSSION

Below are the most important tectonic phenomena that have already been established (or evidence for the existence of which has been obtained in recent decades) and are discussed as possibly being caused by geodynamic processes.

(1) Lateral movement of lithospheric plates established from paleogeographic and paleotectonic reconstructions and satellite geodesy data.

(2) Spreading of the oceanic lithosphere revealed from interpretation of striped magnetic anomalies. It was found that spreading zones in many oceanic basins evolve from rift zones formed as the continental lithosphere is pulled apart. The system of geological and petrological–geochemical indicators of spreading zones and oceanic lithosphere generated by them has been developed to identify their paleoanalogs.

(3) Subduction of oceanic or suboceanic lithosphere beneath oceanic or continental lithosphere. The main feature of present-day subduction zones is the presence of a mantle seismofocal zone inclined by some angle relative to subducting slab. The additional features of present-day subduction zones (characteristic longitudinal tectonic zoning and the specific character of magmatism) allow paleoanalogs to be distinguished, although the convergence of features may sometimes result in misinterpretation.

(4) Collision of plates and blocks of the continental lithosphere. This causes syncollisional magmatism and folded-thrust compressional deformations, which in turn lead to thickening of the crust, formation of moderate-height subaerial uplifts, and accumulation of relatively fine-grained erosion products (lower molasse) from these uplifts in basins [21, 22]. The accompanying features make it possible to distinguish paleoanalogs of collisional belts.

(5) Tectonic layering of the lithosphere is a tectonic phenomenon implying that different lithospheric layers are characterized by different degrees of mobility and deformation, up to differences in directions of tectonic movements. This causes detachments at the boundaries of lithospheric layers. Tectonic layering generally manifests itself as autonomous deformation in the upper crust with respect to the lithospheric mantle; note that the lower crust (and sometimes even the middle crust) acts as a mobile layer with a lower viscosity, similar to the role played by the asthenosphere with respect to the entire lithosphere. In particular fold zones, depending on the physical properties of deformed rocks in them, tectonic layering can appear in more complicated and variable forms.

(6) The diffuse (scattered) character of plate boundaries. This was noted for the first time in [33] to manifest itself in subduction and collisional settings. For example, in Northeast Asia, in the junction zone between the Pacific, Eurasian, and North American plates, the mantle seismofocal zone is the main boundary of the Pacific Plate, but the boundary structures between the Eurasian and North American plates are diffused within a broad deformation belt that includes the Kuril–Kamchatka arc and the back-arc trough in the Sea of Okhotsk [39]. As for the present-day collisional boundary of the Eurasian Plate with the Gondwana plates (African, Arabian, and Indian), it is represented by a deformation belt hundreds of kilometers wide. Within this belt, they mark zones that underwent relatively weaker deformations (microplates, which often appear to be fragments of earlier consolidated crust) and concentrated deformation zones. There may be several such zones marked by maximum relative movement rates, and they do not always match the sutures that remained after closing of

the Tethys. Other mobile belts located at the continental boundaries of lithospheric plates and have evolved in transverse or oblique horizontal compression setting, are organized in a similar manner, independently of whether they appeared at the place of postoceanic sutures of the Alpine tectonic cycle or more ancient ones.

(7) Transition of subduction zones to subhorizontal lenses stretching from the subducting plate at the level of the mantle transition layer. These lenses are also called stagnant slabs [32] and large mantle wedges [36].

(8) Late Cenozoic uplifts that exceed uplifts caused by collisional compression in amplitude and lead to the formation of high mountains and coarse upper molasse.

(9) Mantle superplumes, which are considered flows ascending from the lower mantle to the lithosphere carrying material characterized by low seismic wave velocities, lower viscosity, and, probably, higher temperature.

(10) Folding phases (tectonic phases or orogenies), which are epochs of intensified horizontal shortening and transpressional deformations in the collisional and subduction belts of the Alpine cycle and in older but rejuvenated mobile belts that underwent transverse or oblique compression. The phases are 1–6 Ma long, with peaks of deformations distinguished within longer phases.

(11) Bertrand cycles (Baikalian, Caledonian, Hercynian, and Alpine), long-term (120 to 280 Ma long) global epochs that took place in the Late Proterozoic and Phanerozoic and ended with orogenic epochs characterized by regressions, broad distribution of subaerial uplifts, and intensification of climate zoning with signs of glaciation. Within orogenic epochs, they mark short-term stages (7–10 Ma long) of intensified uplifting, the amplitude of which exceeds that caused by collisional compression [21].

DEEP-SEATED GEODYNAMIC PROCESSES

Geodynamic Interpretations of Tectonic Phenomena

Plate tectonics theory (or simply plate tectonics) combines different phenomena at the level of the lithosphere. These phenomena are, in particular, (1) spreading of the oceanic lithosphere, which implies layering in spreading zones; (2) lateral movement of lithospheric plates; and (3) consumption of the oceanic lithosphere in subduction zones, accompanied by the formation or augmentation of the continental lithosphere and its deformation in the plate layering oceanic lithosphere. When the oceanic lithosphere is consumed during subduction and the continental margins of former ocean approach each other, a large-scale collision evolves to cause deformational thickening of the lithosphere and, in particular, the Earth's crust. According to plate tectonics, the letter point leads to layering. Granite formation that accompanies the collision additionally contributes to crustal thickening and surface uplift.

Further research has shown that certain properties of the geological medium set by the initial plate tectonic model are not ubiquitous. For example, classical plate tectonics ignored rheological lamination of the lithosphere as a factor in tectogenesis. However, it was soon discovered that this factor leads to tectonic stages of the lithosphere, which makes it impossible to calculate the behavior of plates as monolithic objects during their tectonic interaction, at least within the limits of mobile belts. For layering to occur, a subhorizontal force differentiated on depth must exist [12]. Such a tangential component is represented by body forces unrelated to mass and heat transfer [19]. Lithospheric zones with different viscosities and density characteristics are distributed nonuniformly and with time, in a mobile rheological state, transform into a state of horizontal layers with a uniform distribution of these characteristics along them, so it is a state of minimum potential energy. Layering formed in this way therefore has a tectonic nature.

The concept of plate boundaries has also changed: subduction and, moreover, collisional boundaries are diffusive, i.e. deformation belts hundreds of kilometers wide. And, contrary to subduction belts, where the main deformations are concentrated in the seismofocal zone, a collisional belt can have several deformation zones with close deformation rates.

In classical plate tectonics, subduction zones are considered zones where oceanic crust is consumed, to be compensated in spreading zones. Mantle seismofocal zones, which are the main feature of subduction, have been traced down to depths of 600–650 km (i.e., almost to the base of the mantle transition layer). As the seismic tomography methods became available, the continuations of subducted slabs have been revealed in the lower mantle [44]; however, such subduction zones proved to be rare. The majority of studied slabs transform to large mantle wedges at the level of the transition layer, and, additionally, in some cases, high-velocity volumes have been revealed beneath this layer a certain distance from the subduction [40].

The proved tectonic lamination of the lithosphere, diffusivity of plate boundaries, and transition of subduction zones to large mantle wedges have complicated the initial plate tectonic model but have not altered its essence. The main principle that the main tectonic phenomena are caused by the interaction of lithospheric plates has remained unchanged.

Difficulties emerged when researches attempted to explain the peculiarities of recent layering in terms of plate tectonics. There are two layering during the recent orogenic layering [21, 22]. The first was long-term and most likely started in the Late Oligocene (25–24 Ma ago); however, in some orogenic belts, the time of its onset ranged from the late Eocene to the beginning of the Miocene. The second layering that followed began at the end of the Miocene or, in most cases, in the Pliocene (or even in the beginning of the Pleistocene in the Himalayas and Tien Shan), i.e., (7–2 Ma ago). The first stage was marked by the development of deformational thickened zones of the crust and, hence, isostatic uplifts in zones where collisional shortening deformation were concentrated. Since the directions of maximum shortening repeatedly changed during the first stage, subaerial uplifts involved a considerable part of orogenic belts, but their heights usually did not exceed that of intermediate-height mountains (1.0–1.5 km). Thus, the development of orogeny during the first stage was quite consistent with the plate tectonics model.

In the second stage of orogeny, the rates of vertical movements increased several times, the area involved in uplifts also increased, and the amplitude of uplift of earlier formed mountains increased twofold (even threefold in places). The present-day mountain systems formed, as well as coarse molasse owing to their erosion. In the Alpine–Himalayan mobile belt, as well as in other continental mobile belts, these phenomena involved not only regions of continued fold–thrust and transpressional deformation, but also regions where this deformation had considerably weakened by the Early Pliocene, or even terminated in places in the earlier phases of the Alpine and earlier orogenies. For example, in the Alps, Carpathians, and Greater Caucasus, mountain building intensified on the background of a decrease in collisional shortening. However, even in regions where the contribution of collisional shortening to mountain building increased (e.g., in the Tien Shan–Pamir–Himalayan region), it was from 20 to 50% of that. The rest was contributed by the isostatic response to decompaction of the lower crust and upper mantle. Decompaction of the lithospheric mantle took place due to its partial replacement with asthenospheric material [4]. Decompaction of the lower crust and upper mantle was supplemented by retrograde metamorphism of highly metamorphosed rocks of crustal origin in plastic deformation conditions and under the effect of asthenospheric fluid [5, 22]. Thus, the dominant role of uplifts in the second stage was caused not by the collisional interaction of plates, but by deep transformation of the lithosphere and movements of rocks in the sublithospheric mantle.

Researchers have revealed and substantiated also local mechanisms of structure formation caused by plate interactions, or intensive vertical movements during the second stage of orogeny, or exogenous processes related to climatic factors and their variations. These are such mechanisms as (a) gravitational tectonics, (b) volcanotectonics, (c) granite formation as a source of uplifts, and (d) restoration of isostatic equilibrium disrupted by erosion of uplifts and sedimentation in basins, and changes in glacial load and amount of water in large water layering during transitions between glaciations and interglacials.

Mantle Convection

Soon after the main positions of plate tectonic theory were formulated, it became obvious that the proposed mechanism did not cover effective internal sources of movements and interactions between lithospheric plates. Thus, the mechanism of whole-mantle thermal convection was proposed [31]. However, E.V. Artyushkov [2] and O.G. Sorokhtin [20] argued for a high efficiency of chemical-density convection related to mantle differentiation. It was also supposed that spreading zones corresponded to upwelling convection branches, while subduction and collision zones corresponded to downwelling ones [20].

Further research, especially employing seismic tomography, has convincingly shown that there is no direct correspondence between upwelling and downwelling convection branches, on the one hand, and the mentioned elements of the plate tectonic system, on the other. For spreading zones, the most obvious examples of such a mismatch can be found in oceanic regions around Africa where spreading zones are nearly parallel to each other in some segments. Spreading in these zones augments the African Plate, and since there are no intracontinental zones of lithospheric consumption in Africa to compensate this expansion, the spreading zones on one or both sides of the African Plate are expected to move away from the supposed deep-seated source that feeds them. The discovery that the majority of subducting slabs transform to large mantle wedges shows that subduction zones cannot be fully considered downwelling branches of whole-mantle convection.

V.P. Trubitsyn numerical simulated whole-mantle convection [25, 26, 43]. In his models, the upwelling branch of convection corresponds to mantle superplumes, while the downwelling one corresponds to subduction zones that undergo deformations and alterations at the level of the transition layer but continue to the lower mantle. Convective cells close at the level of the D" layer at the base of the mantle. The D" layer is characterized by lower seismic velocities and thickens up to 250–300 km in sectors of the Earth where mantle superplumes are located. It is supposed that these thickened parts are clusters of hot and heavy material, probably with a relatively high iron content [28, 29].

In calculating mantle convection, a key role is played by the viscosity of the medium. The viscosity of sublithospheric upper mantle rocks, which are assumed to be the upper lateral branch of convection, was calculated from the rates of glacioisostatic uplifts of the Baltic and Canadian shields after the retreat of ice sheets: it was estimated at about 10^{19}–10^{20} Pa [3, 30]. These data were used to construct a hypothetical model of the viscosity distribution in the entire mantle [41]. According

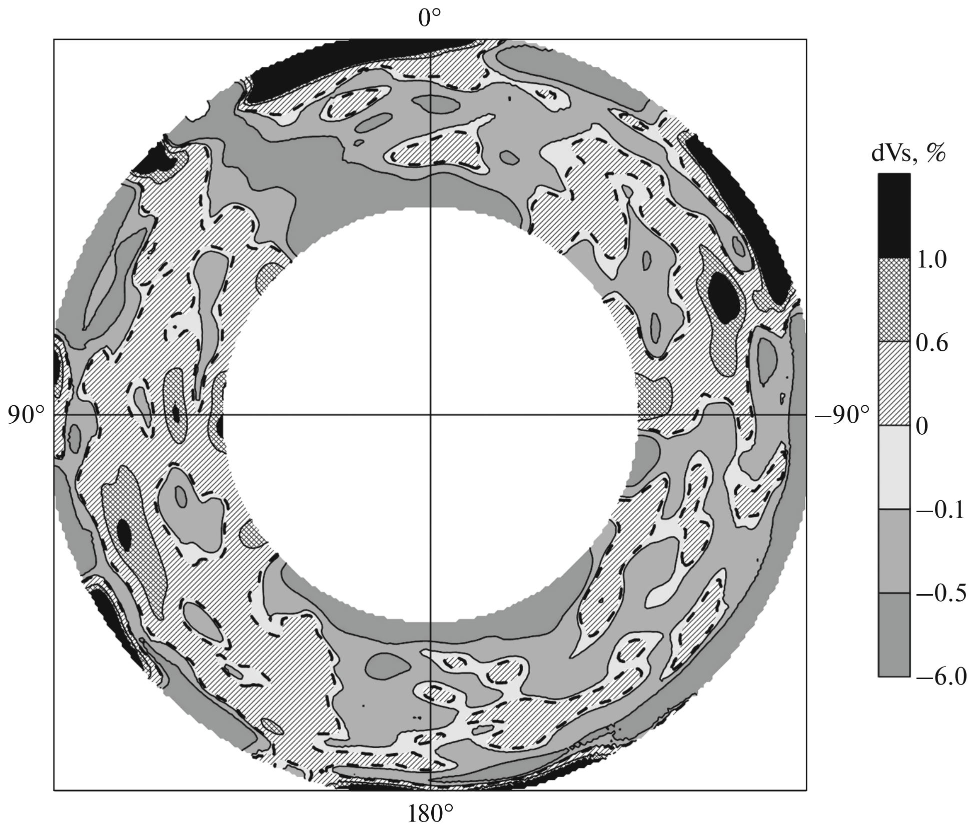

Fig. 1. Equatorial section of modified *S*-wave-based NGRAND seismotomographic mantle model with use of data from [27, 34]. Dashed line denotes zero δV isoline.

to this model, viscosity increases to $\sim 10^{21}$ Pa in the lower part of the transition layer, to $\sim 10^{22}$ Pa in the lower mantle, but it decreases to 10^{19}–10^{20} Pa in thickened parts of the D" layer. Another source for estimating mantle viscosity was laboratory experiments on olivine behavior under high pressures [35]. Application of these experimental results to solving convection equations showed that the viscosity in the lower mantle increases to 10^{24}–10^{25} Pa and convection becomes ineffective at this value. In his numerical simulation of whole-mantle convection, Trubitsyn [25, 26] used both data from the model described in [41] and experimental results on olivine from [35]. In order to ensure the efficiency of whole-mantle convection, he assumed the viscosity of the upper mantle to be $\sim 10^{18}$ Pa, while to calculate the viscosity from experiments with olivine, he decreased one of the coefficients two times (activation volume).

Earlier [21, 24], we proposed a model of mantle flow tectonics that reduces to the following principal statements. The upwelling branch of whole-mantle convection is formed by whole-mantle superplumes. Sublithospheric upper mantle flows branch from the superplumes and, because of viscous friction, directly or indirectly cause movement of lithospheric plates. Spreading zones form in regions of plate divergence, while subduction and collision zones originate in plate convergence regions. The downwelling branch of convection is formed by subduction zones, which continue below the mantle transition layer, and detached fragments of dense lithospheric masses beneath cratons and regions of intensive collision (Figs. 1, 2).

The transition of the majority of subducting slabs to large mantle wedges is believed to play a significant role. A number of authors [6, 11] consider them a source of upper mantle convection that plays a considerable, if not determining, role in intraplate magmatism, transformation, and tectonic evolution of the lithosphere of some mobile belts. Upper mantle convection can also explain the peculiarities in the movement of the Pacific Plate [24]. According to seismic tomography, the N–S-trending Central Pacific superplume generates upper mantle flows directed both west and east of it. The eastward flows cause the formation of spreading zones in the East Pacific Rise, where, owing to upper mantle convection, an opposing sublithospheric flow forms that drags the Pacific Plate to the northwest.

The crystallochemical structure of minerals from the mantle transition layer results in the presence of hydroxyl groups (supplied from subducting slabs into

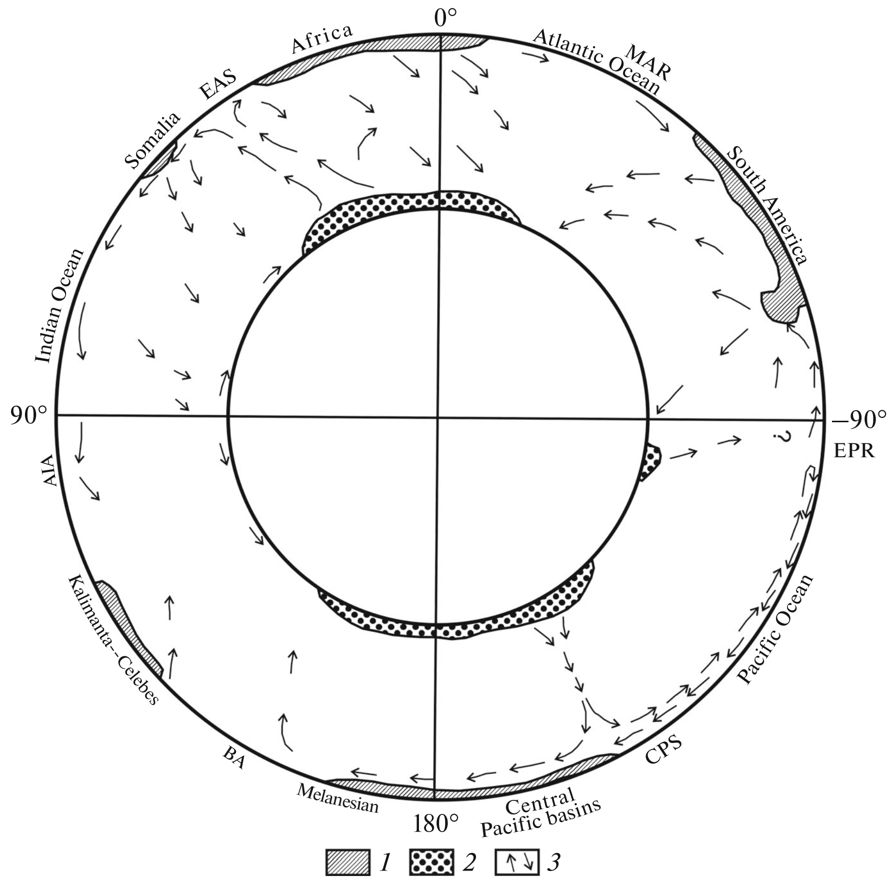

Fig. 2. Mantle profile along equatorial section. Arrows indicate directions of mantle flows. Notation: AIA, Andaman–Indonesian arc; EPR, East Pacific Rise; BA, Bismarck arc; MAR, Mid-Atlantic Ridge; CIR, Central Indian Ridge; CPS, Central Pacific superplume; EAS, Ethiopian–Afar superplume. (*1*) Continental lithosphere; (*2*) D'' layer at base of mantle and clusters of hot and dense material; (*3*) mantle flow directions.

this layer) in them. Along with the possible supply of deep hydrogen into the transition layer, this makes this layer a potential source of water fluids [17, 38, 42]. In epochs of widespread collision, this slows down plate movements and sublithospheric flows propagate beneath regions adjacent to collisional regions. Reworking of the mantle transition layer enriches flows in fluids. The activated mantle partially replaces the mantle part of the lithosphere, and fluids in flows cause metamorphic alterations in the lithosphere and, as a consequence, decompaction. This leads to abrupt intensification of vertical movements in the second, Pliocene–Quaternary stage of the recent mountain building.

The rates of upper mantle lateral flows and downwelling currents in the mantle were estimated in [24]. The rates of upper mantle flows were determined for two regions with different tectonic characteristics: (1) beneath the system of the volcanic Hawaiian Islands and Emperor Ridge, Pacific oceanic plate, and (2) beneath the Arabian continental plate and the Arabian–Caucasian segment of the Alpine–Himalayan orogenic belt. In the former case, the rate was estimated from an analysis of volcanism since the Campanian (~76 Ma ago); in the latter case, since the beginning of the Eocene (~55 Ma ago). In both cases, the rate varied in certain time intervals, but its average value was ~8 cm/yr; remarkably, its value beneath the Hawaii–Emperor Ridge system is close to the rate of plate motion, while beneath the Arabian–Caucasian region, it exceeds the rate of plate motion by several times.

To explain the high rates of flows in the sublithospheric upper mantle, we proposed a model of its structure based on current ideas about the *P–T* parameters of this medium. It has been suggested that the asthenosphere consists of solid fragments varying in size from grains to large blocks, divided by thin films of material characterized by a near-melting state and saturated with fluids in places [24]. The presence of interblock and intergranular matrices with sharply lower viscosity enables the general deformation and high-velocity ductility of solid fragments.

The rates of downwelling flows in the mantle were approximately estimated for the African and South American margins of the Atlantic. Analysis of the seismic tomography data on both sides of the South and Central Atlantic revealed mantle volumes with higher seismic velocities. These domains were traced down to 2000–2200 km, where they lost their isolated character and were interpreted as detached and sinking fragments of the continental lithosphere (note that beneath South America they may also include the slab of oceanic lithosphere subducting from the west). These clusters of high-velocity domains on both sides of the Atlantic are tilted toward each other and join at depths of 2000–2200 km (Fig. 3). If we add up the lateral distances between the most and least submerged fragments on both sides of the Atlantic, the obtained sum will be close to the width of the deep-water part of the ocean. This gives us grounds to consider that detached fragments of the continental lithosphere began to submerge simultaneously with the beginning of opening of the Atlantic, and the distance between fragments that later detached gradually increased as the sides of the ocean were pulled apart. Since the spreading in this region of the Atlantic began in the earliest Jurassic (~200 Ma ago) and the fragments that then detached from the base of the continental lithosphere reached a depth of 1800–2100 km, we obtain an average rate of sinking of ~0.9–1.0 cm/yr.

The obtained rates of downwelling flows in the mantle are less than the rates of lateral upper mantle flows (and rates of upwelling flows in mantle superplumes, which are probably about the same) by almost an order of magnitude. This suggests that downwelling flows should occupy a volume much larger than that occupied by upwelling ones, otherwise downwelling flows could not compensate upwelling flows. These results, however, have not supported the existence of descending mantle flows at a depth greater than 2200 km. If we assume the existence of such flows and that they complete the turnover of whole-mantle convection, then it is possible to conclude from the data presented above that the time necessary to close the convection turnover cycle is comparable to the duration of the Alpine tectonic cycle.

The mantle flow tectonics model explains, in terms of whole-mantle convection and its derivatives, both tectonic phenomena unified by plate tectonics and certain phenomena that plate tectonics can not explain, first of all, intensification of vertical movements in the second stage of the recent orogenic epoch. Still, this model does not attempt to explain all tectonic phenomena in their entirety. For example, significant phenomena could not be explained by the proposed interpretations, such as (1) the formation of large basins on the continental crust, the subsidence of which was not caused by extension nor completely formed by it, and (2) origination of large igneous provinces overlapping plates independently of age and composition. Artyushkov [4] attributed the former to the metamorphogenic densification of lithospheric rocks, while the latter is considered in [16] as manifestation of plume tectonics. It is not clear yet whether these large igneous provinces should be considered as derivatives of superplumes like the Ethiopian–Afar or Central Pacific superplumes, because the tectonotypes of these objects are relatively old and not reflected in seismotomographic data.

Tectonic Reflection of Geodynamic Events in the Earth's Core

We have compared folding phases that manifested synchronously in different mobile belts since the Late Jurassic until the present and the frequency of geomagnetic reversals [23]. During this time interval, tectonic phases took place in epochs of both stable unidirectional magnetic polarity and frequent geomagnetic reversals; however, they usually either coincided with epochs of frequent geomagnetic reversals or immediately followed them (Fig. 4). The synchronicity of the majority of tectonic phases and epochs of frequent geomagnetic reversals is discussed below in this context. Beginning from the Late Oligocene (i.e., during the neotectonic orogenic epoch, when reversals occurred especially frequently), tectonic phases followed each other separated by 1–1.5 Ma intervals (up to ~3 Ma between the Styrian and Attic phases), which was absolutely incomparable to the long-term intervals between earlier phases. Note that the peaks of deformational activity within the neotectonic phases followed intervals with the maximum frequency of reversals, after every 1–2 Ma (Fig. 5).

It is important to substantiate the synchronicity of most tectonic phases within the Alpine cycle and time intervals of frequent geomagnetic reversals because, according to modern ideas, processes in the Earth's core and their interaction with the mantle play a key role in the origination and functioning of the geomagnetic field [7]. It is believed that currents in the core, combined with the rotation of the spheroid and the high conductivity of material, form the structure of the regular geomagnetic field; in a first approximation, this field can be described as the field of a dipole oriented along the axis of rotation passing through the center of masses [8].

The geodynamic implication of these processes on the lithosphere—through convection or other forms of heat and mass transfer in the mantle—cannot cause tectonic phases. At a rate of upwelling branches of mantle convective heat and mass transfer of 8–10 cm/yr, the time for a convective disturbance to pass the 2800 km interval from the core to the base of lithosphere would be 35–28 Ma, whereas tectonic phases are linked to epochs of frequent changes in magnetic polarity: during the last 24 Ma, the phases were manifested 1–2 Ma after their peaks (Figs. 4, 5). Thus, there is another, nonconvective, quasi-instant (on the geological time scale) way that energy is transferred from processes in the Earth's core to the lithosphere.

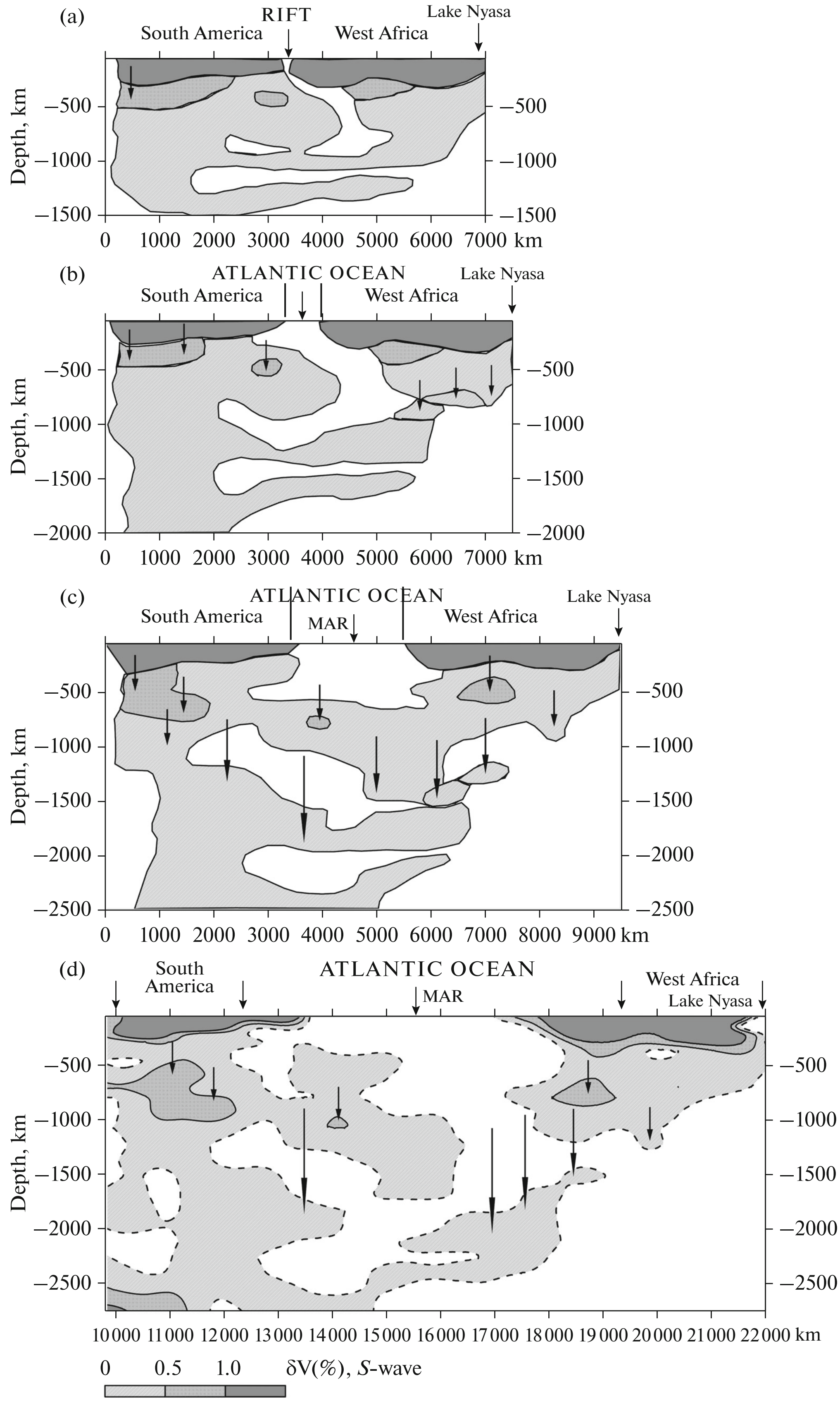

Fig. 3. Stages of sinking for detached fragments of thickened continental lithosphere in South American and African margins of Atlantic, after [24, 27] with modifications and additions: (a) beginning of Jurassic, (b) Cretaceous, (c) Paleogene, (d) present day. Arrows show directions of sinking of heavy mantle blocks, with length of arrow reflecting value. Dashed line denotes zero δV isoline.

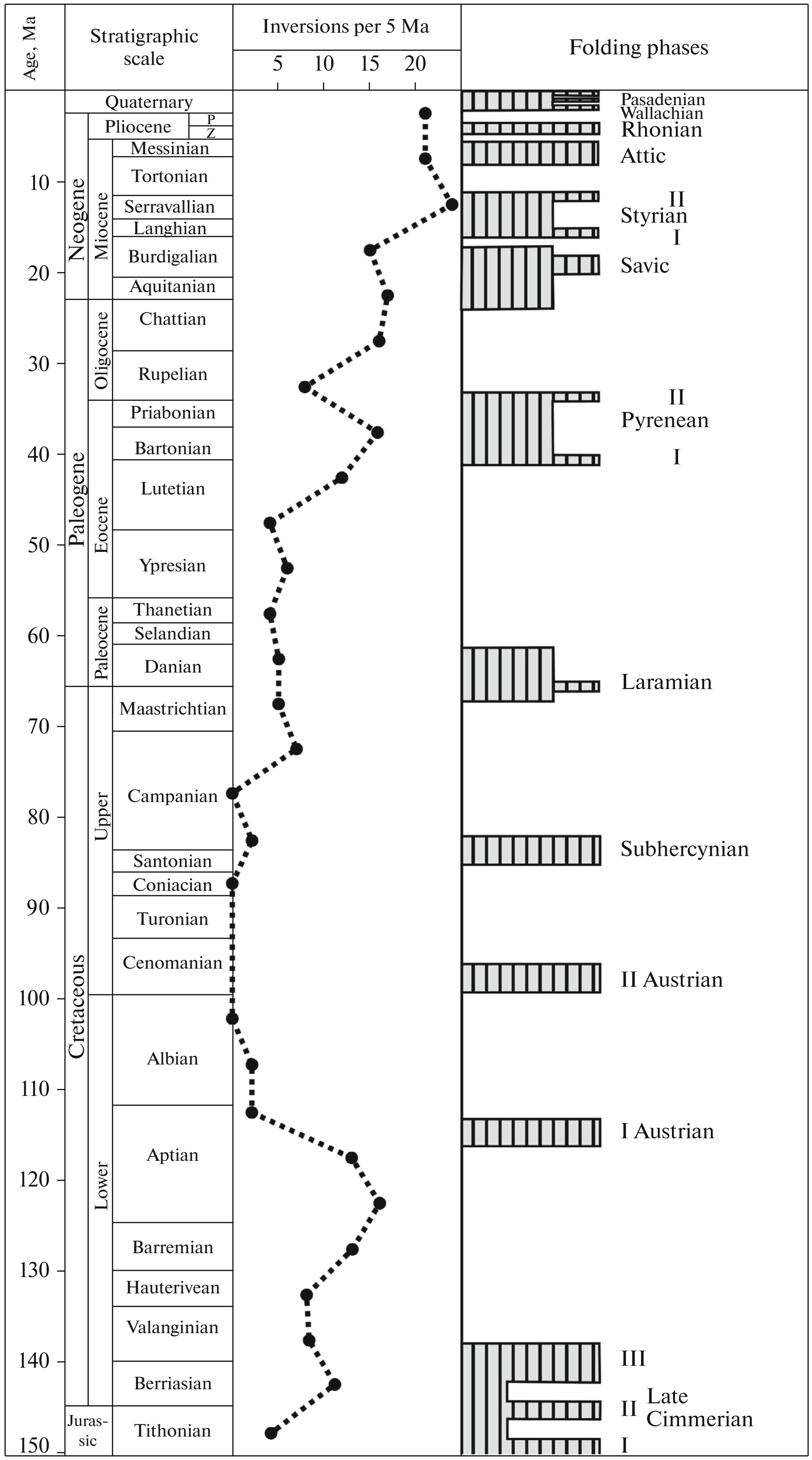

Fig. 4. Comparison of phases and epochs when compressional and transpressional deformations were activated from late Jurassic until present, as well as frequency of geomagnetic reversals, using data of [23] with modifications and additions. Number of geomagnetic reversals within time intervals of 5 Ma long is shown.

The dipole parameters revealed from the study of variations in the regular magnetic field for the last 50 years demonstrate a spatial shift of its center with time: to the north of the equator, relative to the center of masses [9]. This indicates a change in currents within the liquid core (note that it is their pattern that forms geomagnetic field), with the average density of the core exceeding that of the lower mantle by almost 50%. Changes in the positions of these masses dominating in the Earth's interior cause changes in the characteristics of the moment of intertia with respect to the current axis of rotation, and then have to lead to changes in the regime of Earth's rotation. Some calculations show that the solid core shifts within the liquid one [1]. If we take into account that the mean density of the solid core is higher than that of the outer liquid core by ~15%, such a shift may also lead to a change in the Earth's rotation, in particular, to a change in the position of the axis of rotation within the spheroid. This idea is supported by data from the International Earth Rotation and Reference Systems Service [37] for the last 100 years: analysis of these data suggests that the pole of rotation shifts to the south along 70° W by ~10 cm/yr.

The changes in liquid core flows responsible for the formation of the normal geomagnetic field reflect, in our opinion, redistribution of masses in the system incorporating the outer liquid and solid inner core, which results in a change in Earth's rotation. This could generate variable body forces in the mantle. These forces manifest themselves the most intensively in the lithosphere and Earth's crust, which are the most inhomogeneous and laminated, characterized by a block structure, and have a contact with the free surface (that coincides with the surface of the solid Earth) and a contact with the less viscous layer at the base. Under the effect of subhorizontal body force, this difference causes vertical differentiation and intensifies lamination. Thus, the relationship between geomagnetic reversals and phases of tectonic activation is indirect. Both of the mentioned phenomena may be consequences of the variable spatial structure of high-density material flows, on the one hand, and high conductivity in the outer liquid core, on the other; in aggregate, these factors lead to both geomagnetic reversals and changes in the Earth's rotation with corresponding adaptations of positions and movement rates of lithospheric fragments to new conditions.

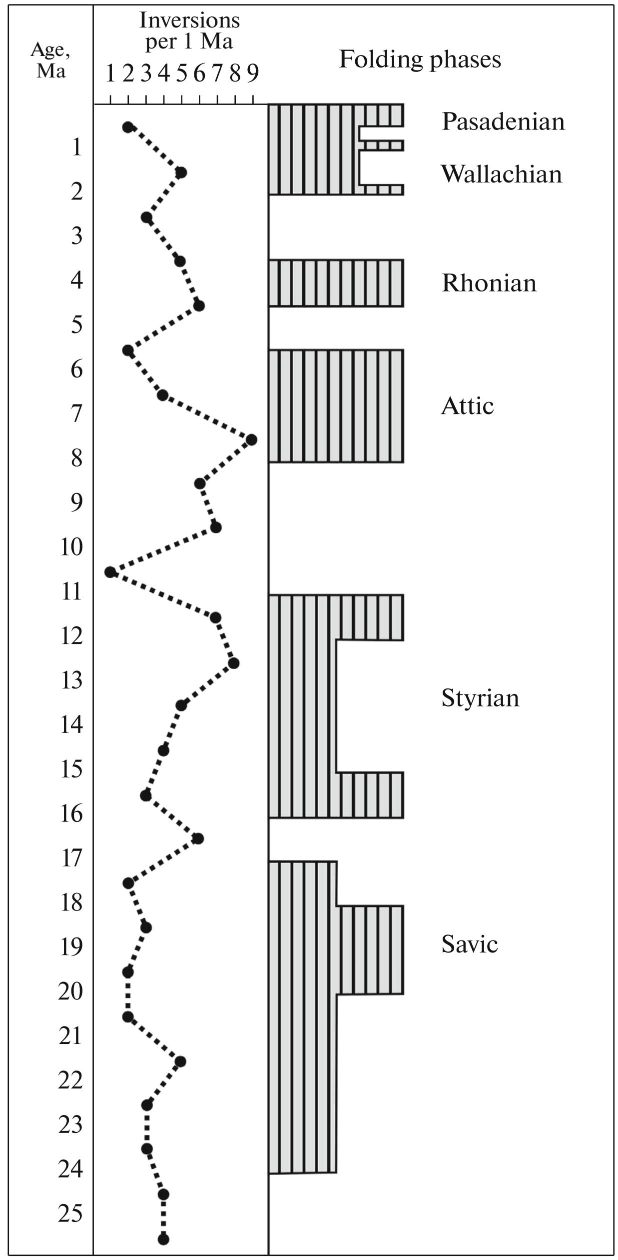

Fig. 5. Comparison of phases and epochs when compressional and transpressional deformations were activated from late Oligocene until present, as well as frequency of geomagnetic reversals, using data of [23] with modifications and additions. Number of geomagnetic reversals on within time intervals of 1 Ma long is shown.

HIERARCHY OF TECTONIC SYSTEMS

Statistical physics and thermodynamics consider any physical bodies as systems whose states are defined by a set of parameters (temperature, pressure, density, chemical potential, energy saturation, etc.). These parameters are interrelated in such a way that a change in one initiates certain processes that lead to changes in the other parameters to restore balance in the entire system. Tectonic systems are sets of natural processes interrelated within certain geological volumes and directly or indirectly lead to motion of the lithosphere and origination of structural forms in it [14, 15].

There is the notion of structural stresses in technical sciences: these stresses are equated within a certain volume of a medium, in the absence of external loads at the boundary surfaces. Structural stresses serve as a measure of disruption of the equilibrium state of matter. In a geological setting, stresses can occur under the effect of both outer (relative to the considered volume) loads and inner sources, but we can isolate volumes of the medium where acting stresses are equalized. At the same time, tectonic systems are systems of stresses that appear at different organizational levels of a geological setting when an equilibrium state of any parameter characterizing this medium as a thermodynamic system is disrupted [14]. The size of a domain where structural relationships between the elements of a system close can be a measure of the rank of a tectonic system. In this sense, we can speak about systems of global and local rank, and as well as systems covering different layers of the Earth.

Most deformations and displacements available for direct observation emerge under the effect of local tectonic systems. For example, although complex structure of deformation and displacement zones at plate boundaries (major plates and microplates, especially collisional ones) reflects deep interactions, it is largely caused by geomechanical peculiarities of free-surface media, in this case, by surface of the solid Earth. In the systems responsible for these structures, the structure-forming source acts as the main factor accompanied by secondary ones, and interaction between these factors causes the complexity of tectonic manifestations that are usually spatially confined by the uppermost crust.

The systems responsible for manifestations of gravitational tectonics are usually also located within the uppermost crust. Isostatic compensation of vertical movements that occur due to the erosion of rises and accumulation of the corresponding erosion products in basins takes place in the middle and lower crust [18]. Manifestations of volcanotectonics are caused by the system of processes limited by the depth at which magmatic chambers can be located (the Earth's crust and the mantle lithosphere). This does not exclude, however, the fact that chambers can be occasionally filled with material from sublithospheric upper mantle flows or from mantle superplumes, but these types of supply are not directly related to manifestations of volcanotectonics.

Isostatic compensation of present-day and retreated ice sheets and the corresponding changes in water volume in the World Ocean takes place, as is believed, at the asthenosphere level, but glacioisostasy beneath ancient shields can be partially implemented by movement of rock masses within crustal waveguides.

The system of processes unified by the mantle flow tectonics model and, in particular, plate tectonics, involves the Earth's entire mantle, since it is eventually caused by whole-mantle convection. This does not exclude the possibility that individual elements of this system (subsystems) are limited to the upper mantle and transition layer. These are such phenomena as spreading; lateral movement of plates by upper mantle sublithospheric flows; upper mantle convection; deep transformations and movements leading to decompaction of the upper mantle and lower crust and intensification of vertical movements in the second stage of mountain building; and, to a large degree, subduction if the subducting slabs completely or partially turn into large mantle wedges.

The relationships between the plate tectonics elements of the discussed system and the processes of mountain building appear to be complicated. The term tectonic cycle was proposed when the geosyncline paradigm dominated: based on the limited amount of geological observations, the idea appeared to imply that geosynclines underwent a directed evolution during a cycle that to ended with folding and mountain building. As the observations from different tectonic regions accumulated, it became evident that similar processes interpreted as the origination and evolution of geosynclines within one tectonic cycle were not simultaneous in different regions, and not every phase or epoch of folding led to orogeny in vast areas. That was how the idea about the early and late Alpides, Hercynides of different ages, etc., appeared. In terms of plate tectonics, this means that different basins with oceanic or suboceanic crust originated and opened in different time periods. However, orogenic epochs and, above of all, the peak, second stage of mountain building manifested themselves synchronously over vast areas. Epochs 7–10-Ma long, similar to the second stage of the recent mountain building, were distinguished in the late Hercynian (Artinskian age) and late Caledonian (Eifelian age) cycles. Manifestations of mountain building pertaining to the Artinskian were documented in Paleozoic fold belts of the Urals and central Asia [13], and those of the Eifelian were revealed in different Caledonian systems [10]. Both in the Early Permian and Middle Devonian, there are examples of how mountain building either immediately followed the epoch of thrust-and-fold deformation or was separated from it by a significant time interval. In both cases, the second stage coincided with partial reconstruction of (1) the plate tectonics system (arrangement of basins with oceanic crust, subduction zones, etc.) and, probably, (2) the system of mantle flows that determine plate movements [21].

The broad distribution of the collision determined the occurrence of deformational rises expressed in the relief and was also not simultaneous in different mountain-folded belts. A high degree of proximity of continents, which is attributed by many researchers to an extensive collision, does not fit timewise with mountain building epochs. For example, the maximum "clustering" of continents, which is defined as the Pangean epoch, took place in the Carboniferous, while the second stage of the Hercynian orogenic epoch was in the Early Permian. The recent orogenic epoch and its second stage are characterized by a smaller degree of proximity of continents compared to the Pangean epoch.

Thus, we arrive at the conclusion that the plate tectonic "conveyor," which is represented on the Earth's surface by the opening and closing of basins with oceanic crust and is expressed in the corresponding deposits, deformation, magmatic and metamorphic manifestations, operated asynchronously in different regions; however, global orogenic epochs were superimposed on these manifestations of different ages, and a second stage of mountain building was synchronously manifested everywhere.

Under particular geological settings, folding phases reflect compressional and transpressional deformation in regions of the collisional and subductional interaction of plates; therefore, in this sense, they are one of the links in the plate tectonics model, while in a more general sense, they are components of the mantle flow tectonics model. However, neither model can explain the simultaneity of manifestations of folding phases (tectonic phases) in different mobile belts and segments of large belts. The revealed synchronicity for most tectonic phases and frequent geomagnetic reversals in the Late Mesozoic–Cenozoic indicates that such synchronicity is determined by material flows in the Earth's core. These flows generate the normal magnetic field and are believed to cause changes in the parameters of Earth's rotation through the origination of body forces and deformation in the mantle, which allow the mantle to adapt to the altered geodynamic settings. This deformation is manifested especially clearly in the lithosphere and, to the highest degree, in the Earth's crust, the structure of which is the most heterogeneous and is located at the outer boundary of the solid Earth.

Thus, the synchronicity for most tectonic phases and frequent geomagnetic reversals is a manifestation of the global tectonic system that includes both the Earth's core and all other terrestrial envelopes. Being manifested only in tectonic phases, this system seemingly had a limited effect on the evolution of the outer envelopes of the Earth in terms of mantle flow tectonics. However, the role played by core flows may be more significant.

During the neotectonic orogenic epoch (from the late Oligocene until the present, i.e. in the last 25–24 Ma), the geodynamics effects of processes in the Earth's core, reflected in the synchronicity of geomagnetic reversals and tectonic phases, was manifested so frequently and caused such significant fluctuations in the entire system of processes unified by the mantle flow tectonics model that they may have resulted in the destruction and reconstruction of this system. The second stage of the orogenic epoch could be the apogee of this evolution: upper mantle flows determining plate interactions became turbulent and led to decompaction of the upper mantle and lower crust, and this abruptly intensified orogenic vertical motions.

The role played by processes in the Earth's core in the evolution of Paleozoic orogenic epochs remains unclear, because no frequent geomagnetic reversals were revealed during the Early Permian stage of mountain building.

In terms of both the plate tectonics model and of mantle flow tectonics model, the spatial positions of branches of whole-mantle convection and structural units determined by them do not demonstrate any relationship with the parameters of Earth's rotation. A probable exception is two main superplumes, the Ethiopian–Afar and Central Pacific: in present-day coordinates, they are N–S direction aligned and located in opposite segments of the Earth, at about 30°–35° E and 160°–155° W, respectively. In contrast to both considered models, the global system of tectonic processes determined by flows in the Earth's core is related to the rotation parameter, because the forces determining its tectonic manifestations occur owing to variations in these parameters.

CONCLUSIONS

The tectonic phenomena and generated structures of the Late Mesozoic–Cenozoic appear to be the result of interference between systems of geodynamic processes involving different volumes and depths of the Earth. For example, various local deformation appearing during plate interactions and vertical motions, which are caused in turn by deep-seated transformations, are usually limited to the lithosphere. The processes expressed by tectonic phenomena described in terms of the mantle flow tectonics model cover the Earth's entire mantle, although the rest of the elements of this system (spreading, lateral plate motions, a significant part of subduction zones, material transformations leading to intensified vertical movement) take place only in the upper mantle, including the transition layer.

Geodynamic processes expressed in the synchronicity of frequent geomagnetic reversals and most tectonic phases are probably triggered by redistribution of material in the Earth's core and thus involve all geospheres. It has been suggested that this system facilitated the onset of the recent orogenic epoch. In contrast to geodynamic processes unified by the mantle flow tectonics model, in terms of which mantle flows show no significant relationship with the parameters of the Earth's rotation, synchronicity processes are coupled with flows in the Earth's core, so they can change rotation parameters. These changes cause tectonic manifestations of the mentioned system of processes, and this system in turn becomes a significant factor in tectogenesis.

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