Structural evolution of the Earth crust of the East European platform: evidence from the Sarmatian plate. 1. Intra-plate tectonic and stages of the evolution of the Earth’s crust

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Abstract. The problems of intra-plate tectonics and geodynamics of the East European platform are analyzed. It is shown that the current status and tectonic position of regional structures on its territory changed during the Phanerozoic as a result of radical inversion rearrangements of the earth’s crust structure. The sources of forces and deformations and the influence of the anisotropy of the lithosphere on the evolution of the Earth’s crust based on evidence from the Sarmatia plate are considered. It is assumed that collision stress in the crust of the plate during the epochs of platform activation in the Mesozoic and Cenozoic caused the movements of Arabia and Africa and the spreading of the crust in the North Atlantic ridge. The platform is characterized by stable meridional collision compression, except for Sarmatia, where the stress axis is oriented to the north-northwest. This is related to the initial anisotropy of the plate lithosphere and its modern longitudinal structural differentiation. The stress from the boundaries of the platform was transmitted inward and absorbed in the mobile belts, which determined their overall plate mobility. The structure-forming role of collision belts in the evolution of the Earth’s crust has been clarified based on data from the Dniipro-Donetsk Paleorift Belt. A model of the evolution of the belt is proposed, according to which the rift was laid by splitting of the «cold» continental crust with displacement by the Pull-apart basin mechanism. The «built-in» anisotropy of the lithosphere of the Sarmatian plate and the lack of a direct connection between the modern segmentation of the Precambrian consolidated crust and the relief of the sole of the seismic lithosphere are considered. Due to the overall plate collision, the basin underwent inversion uplift and folding. As a result of the change in the mode of deformation along the extension of the belt, two heterogeneously deformed segments were distinguished in its structure. The western segment contains the relics of the rift, but in the eastern segment, the structure of the Graben is destroyed by cover-folding deformations. The modern longitudinal structural and material differentiation of the Sarmatian lithosphere has been established. The general orientation and phasing of the structural rearrangements of the Earth’s crust of the Precambrian Craton have been determined. It was found that the processes of evolution of the structure of the East European platform were caused by changes in geodynamic conditions and tectonic deformation regimes. Initial geotectonic data were obtained, and a rational methodology was chosen for further geodynamic interpretation. The distribution and nature of the inversion rearrangements of the Earth’s crust on the terrain of Sarmatia were clarified by reconstructing the stress field in the Phanerozoic epochs using indirect methods of Geomechanics analysis of discontinuous and folding deformations.

Keywords: Lithosphere, earth’s crust, geodynamic situation, stress field, East European platform, Sarmatia, Pripyat-Dnipro-Donetsk Paleorift Belt.

Структурна еволюція земної кори Східно-Європейської платформи: свідчення із Сарматської плити. 1. Внутрішньо-плитна тектоніка та етапність еволюції

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Анотація. Аналізовано проблеми внутрішньо-плитної тектоніки і геодинаміки Східно-Європейської платформи. Показано, що сучасний статус і тектонічна позиція регіональних структур на її теренах змінився протягом Фанерозою внаслідок докорінних інверсійних перебудов структури земної кори. Розглянуто джерела сил та деформацій і вплив анізотропії літосфери на еволюцію земної кори за свідченням зі Сарматської плити. Передбачено, що колізійний стрес у земній корі плити протягом епох
Introduction

Formulation of the problem. Stress and tension are fundamental parameters of geomechanics that determine geodynamic processes in the Earth’s crust. The tectonic evolution of the lithosphere is characterized by cyclic processes (Wilson, 1966) and occurs during the stages of tectogenesis in an alternating stress field with the advantage of one of the elementary deformation modes — compression, extension, or horizontal displacement (Chebanenko, 1977; Gintov, 2005). The initial factor of the structural and kinematic evolution of the continental crust is its tectonic division along the regular directions of the planetary rift lattice (Chebanenko, 1977; Chikov, 2011). The rhegmatic lattice is the basis of the global deformation framework, the dynamics and kinematics of which are renewed due to changes in the parameters of the tectonic stress field. During the evolution of the Earth’s crust, in various geodynamic situations and tectonic regimes, systems of faults with different azimuth orientations were reactivated, forming frameworks of deformations (Chebanenko, 1977; Gintov, 2005; Bartashchuk, 2019). The reactivation of faults in the Earth’s crust occurred with the adaptation of their genetic type to the character of the current stress field, which changed their structural and dynamic manifestation in the Earth’s crust (Chebanenko, 1977, Timurziev, 2014, Bartashchuk, 2019). Frameworks of tectonites of different directions and kinematics of movements (vergence) controlled different age plans of deformations and formation of folded floors in the inverted structure of the East European Platform (EEP) platform cover (Goryainov, 1999, 2004, 2013, Kopp et al, 2017). During the era of platform activation, movements of blocks and their ensembles and lateral movements of rock massifs within their boundaries took place along the deformation grids (Goryainov et al, 2009, 2017; Timurziev, 2014; Kopp et al, 2017; Orlyuk, Ishchenko, 2019; Bartashchuk, Suyarko, 2018, 2020, 2021). The consequence of the manifestation of lateral movements is the tectonic flow of rock massifs and deformational structure formation, which led to the transformation of the original fracture-block structure of the Earth’s crust into a folded-dislocated one (Chebanenko, 1977; Patalaha, 1979; Chikov, 2011, Kopp et al, 2017; Leonov et al, 2018).

The structure of the contemporary internal stress field EEP is determined by the sum of forces from various sources (Heidbach, et al., 2018). The stress from the boundaries is transmitted inside the platform and is absorbed mostly in the mobile belts, where it causes tearing and folding deformations. In the process of structural evolution of the Earth’s crust, intra-plate linear zones and areas of concentration of collisional deformations were formed on the terrain of Eurasia (Chikov, 2011; Leonov et al., 2018). Within them, regional structures through inversion rearrangements acquired a new tectonic style and structural status and could change their original tectonic position on the platform terrain (Goryainov et al, 2009; Kopp et al, 2017; Bartashchuk, Suyarko, 2020, 2021).

Considering the given data, the actual problem of intra-plate Tectonics and Geodynamics of the EEP is determined, which consists of clarifying the modern structural status and tectonic position of intra-plate regional tectonic structures on its territory. To solve it, the following tasks are set:

1- tectonics-physical identification and geological interpretation of structural manifestations of inversion deformations of the Earth’s crust at time intervals from the epoch to the phase of tectonics evolution during the Phanerozoic;
2. clarification of the tectonic style of deformations of the Earth’s crust in intra-plate areas to clarify the current status and possible changes in the tectonic position of inverted regional structures within them;
3. improvement of the scheme of geotectonic zoning of the EEP, taking into account data on inversion rearrangements of the structure of the continental crust within its boundaries during the Hercynian, Cimmerian and Alpine stages of platform activation.

Choice of research methodology

To find out the mechanism of deformations in the areas of the collision of lithospheric plates, the direction and kinematics of the movements of the blocks that were between the plates are usually restored. The largest structural manifestation in the Planet’s surface has two vertical directions of movement: pulling the edge of the lithosphere into the mantle by a downward convection current due to the subduction of plates or pushing it upward due to the collision of plates with the formation of a mountain-fold structure (Chikov, 2011). Within the continental plates, horizontal movements of blocks with small vertical amplitudes, favorable for platform structure formation, prevail. Structural manifestations of lateral movements and deformations of rock massifs in areas of platforms covered by a sedimentary cover are usually studied by indirect tectonics-physical methods (Rebetsky, 2002). The consequence of the deformations of the lateral movement of rock massifs is coulisse structural paragenesis of horizontal displacement, which is used as a diagnostic indicator of the geodynamic situation of horizontal displacement (Sylvester, 1988; Gintov, 2005; Timurziev, 2014; Leonov et al., 2018).

Indirect tectonics-physical methods of structural-kinematic and paragenetic methods were chosen to solve the problem and consistently solve the tasks of physical analysis of structural patterns of faulting and folding deformations. These methods are effective for reconstructing the parameters of the paleo tension field, restoring tectonic regimes and kinematic mechanisms of inversion deformations, elucidating the patterns of distribution of dislocated rock massifs within regional structures, restoring the direction and kinematics of lateral block movements (vergence).

Discussion

Sources of forces and deformations within the East European Platform. The contemporary stress field of the Planet is the result of the established horizontal location of the geodynamic axis of maximum stress $\sigma_1$ on the continental lithosphere plates (Heidbach et al., 2018). The parameters of the modern tectonic stress field are determined instrumentally on outcrops and mine workings (Gintov, 2005). At the same time, both strong and weak stresses that do not cause residual deformation of the rocks are analyzed. Ancient stresses are studied by indirect tectonics-physical methods and are averaged over a certain episode of geological history. The parameters of the ancient field are restored with the use of Geomechanics parameters of rocks and minerals, therefore stresses exceeding the limit of irreversible deformations are determined. Modern and paleo stress fields characterize different deep layers of deformations of the Earth’s crust. Manifestations of ancient deformations are observed only in the near-surface layers of the earth’s crust, but modern deformations can cover the entire upper consolidated crust with a thickness of 20 – 25 km. The stress field is formed by excessive tension under the action of certain forces, such as the declination ($\sigma_{dev}$) component of the field, in addition to the litho-static (gravitational) load. In the conditions of the upper part of the Earth’s crust, the orientation of the Geodynamic stress axes on the horizontal plane of the tensor of the modern stress field is stable and does not change with depth (Zoback, 1992). At the same time, the magnitude of stresses and deformations increases in stronger rocks, therefore the deviator component of the field is usually manifested in the consolidated foundation and is absent in the sedimentary cover of the platforms. The exception is the tectonics disrupted, intensively folded surfaces of the cover, in which the deviator component increases in comparison with the less stressed state of the platform autochthons overlain by them (Becker A., 1989).

Sources of stress and deformation inside the lithosphere plates are considered (Zoback, 1992): planetary forces caused by changes in the parameters of the planet’s rotation in the Earth-Moon system; load forces on the surface of sedimentary rocks, tectonic and volcanic covers, positive geostuctures; local gravitational anomalies caused by variations in rock density; forces that arise due to bending of layers during heating/cooling of the rheological stratified lithosphere; global forces associated with lithosphere plates movements, etc. Planetary and regional forces act together, but the stressed state of the lithosphere is determined by forces of a global scale, the rest are determined by secondary variations. Relatively strong stresses (up to 90 MPa) inside the plates can create loads of mountain structures (Bott, 1991), but the excess static pressure of these geomasking forms regional anomalous fields of relief heights and does not affect the regular stress field of lithosphere plates. The
stress inside the slabs is affected by the movements at the subduction boundaries, but the effects of slab pull and trench suction (Cloetingh, Wortel, 1986) on the upper part of the crust are limited to their area adjacent to the subduction zone. The influence of drag and resistance forces that can act in the sole of lithosphere plates (drag forces mantle drag) is insignificant (Xie et al., 2007).

The intra-plate stress field is most affected by movements in collision belts and mountain-folding systems, on the active edges of lithosphere plates undergoing stresses and deformations (Stampfli, Borel, 2002). Induced collision stress spreads inside the plates at hundreds of km in the terrain of Europe and up to one and a half thousand kilometers in Asia. An influential source of stress is the stress pressure from spreading oceanic ridges. This is evidenced by the intra-plate stress in eastern North America and North-Western Europe due to the displacement of the crust in opposite directions from the Mid-Atlantic Ridge (Zoback, 1992, Heidbach et al., 2018).

Concerning the influence of continental rifting, it was found that against the background of general stretching, episodes of collision compression of the Earth’s crust occur due to the inversion of stresses in the lower layers of the lithosphere (Atmaoui et al., 2006). The tectonic inversion of the rift is accompanied by changes in the composition and thickness of the sedimentary cover of the basin without changing the nature of the movement of the lithosphere plates. Therefore, to model the evolution of rifts, both the dynamic factors of the interaction between the induced forces of the far stress field from the movements in the collision belts, and the static unloading/loading of the structure of the sedimentary basin due to denudation and under the influence of the static pressure of the relief heights considered. During pauses between crustal stresses (up to 30 MPa), basins can undergo uncompensated depth inversion (up to 2 km) due to cessation of clastic sediment supply from upwelling sides. This forms an additional source of forces for the reactivation of ruptures during the tectonics phases against the background of the general displacement of the Earth’s crust.

The structure of the stress field inside the EEP is determined by the sum of forces from various sources and indirectly depends on the anisotropy of the lithosphere, the structure, and the position of the constituent regional structures. Approx the intra-plate stress field is more affected by induction pressure from collisional mountain-fold belts and mid-oceanic spreading ridges. The Platform is characterized by steady meridional collisional compression and sub-latitude and West-Northwest extension (Sim, 2013). The stress axis is oriented along the meridian, except for Sarmatia, where it has a North-Northwest orientation, which is related to the initial anisotropy of the lithosphere (Starostenko et al., 2017). The movement of the Alpine-Himalayan collision belt affects the state of the modern stress field on the adjacent outskirts of Eurasia most of all. The structure of the intra-plate collision field of Sarmatia was determined by stress from the south from the movements of the Arabian and African continental plates, from the north due to crustal spreading in the North Atlantic ridge, and from the southeast from the movements of the alpine terrains of the mountain-folded Caucasus (Stampfli, Borel, 2002, Natal’ in, Senghor, 2005, Meijers et al., 2010).

Intra-plate lineament zones and collision belts are mobile structures capable of both absorption/accumulation of external collision stress and its release through reactivation of movements in fault systems. Movements in mobile belts are usually accompanied by folding and lateral movements of rock blocks and geomasses, which can initiate geotectonic instability of the Craton core of the Platform. The continental palaeorifts of the EEP (Prpyyat-Dnipro-Donetsk, Central Russian, Pachelmskij, and others), which did not occur as oceanic rifts, and at the stage of inversion turned into aulacogen and collision belts, capable of performing the dual role of structural-uniting/tectonic-destructive intra-plate structures. Thus, the structural status and tectonic position of mobile structures on the EEP terrain may change due to a radical restructuring in the new tectonic regime of deformations and contribute to the future division of the crust of the Precambrian Craton into smaller micro-plates (terranes).

**Tectonics and Geodynamics of the East European Platform and Sarmatia.** The ancient crustal core of the EEP consists of three continental plates: Fennoscandia, Sarmatia, and Volgouralia (Bogdanova et al., 1996) (Fig. 1). The foundation of the Platform is not covered by the Phanerozoic sedimentary cover in the Northwest (Fennoscandian Shield) and in the south, within the Ukrainian Shield (USH), where Proterozoic and Archaean crystalline rocks come to the surface. Sarmatia separated from Volgo-Uralia about 2.0 billion years ago with the formation of a terrain of oceanic crust that separated them. At the same time, subduction began on the northern edge of Sarmatia, which led to its collision with Fennoscandia and its unification as part of the Craton core of the EEP (1.75 billion years ago). The Fennoscandian craton stabilized 1.2 billion years ago when a dome
structure formed in the Archean crust of Volgouralia (Bogdanova et al., 1996). The Sarmatian plate in the core of the crust stabilized during the late archaean – early Paleoproterozoic due to the combination of several terranes aged 3.8-2.8 billion years.

The Teixeira-Tornquist Trans-European Suture Zone (TESZ) is the Western boundary of the EEP with the young West European Plate, composed of several Phanerozoic microplates and terranes (Kruglov, Cypko, 1988) (Fig. 1, inset). The TESZ was formed by the collision of continental microplates, which lasted until the Varissian tectonics phase (Bogdanova et al., 2006). The Ural Mountains as the eastern border of the EEP tectonically separate Europe from Asia. Due to the closure of the Ural paleo-ocean in the Carboniferous (0.35-0.25 billion years ago), the East European Craton joined the Siberian Craton. The Eastern flank consists of an ensemble of accreted terranes and subducted oceanic plates (Brown et al., 1996).

The formation of the EEP cratonic core through the unification of Fenno-Scandia, Sarmatia, and Volgo-Uralia took place 1.25–0.8 billion years ago. Simultaneously with this event, during several episodes of rifting, the Central Russian paleorift belt of submeridional extension was formed (Bogdanova et al., 1996). Several peripheral rift structures accompany a series of echeloned grabens that make up the belt. This is the Volyn-Orshan Late Riphean depression, which separates Fenno-Scandia from Asia. Due to the closure of the Ural paleo-ocean in the Carboniferous (0.35-0.25 billion years ago), the East European Craton joined the Siberian Craton. The Eastern flank consists of an ensemble of accreted terranes and subducted oceanic plates (Brown et al., 1996).

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Fig. 1. Position of the Dnipro-Donetsk Paleorift on the Sarmatia Plate and the Eastern European Platform (inset), (Bogdanova et al., 1996) with additions, (Bartashchuk, Suyarko, 2018, 2020).

Sarmatia and the Pachelm and Prypyat-Dnipro-Dontsk Paleorift (PDDP), which are located to the north and south-west of the Central Russian Paleorift Belt. It is assumed that during the late Riphean rifting, Volgo-Uralia acted as a tectonic wedge between Fennoscandia and Sarmatia, and subsequently the three plates merged into the core of the modern craton (Bogdanova et al., 2006).

The sub-latitudinal structure of the PDDP is part of the long transregional Sarmatian-Turanian mobile belt of Eurasia, which extends from the Pripyat Paleo-Through to the Tien-Shan mountain-fold structure (Kopp et al., 2017). The Western part of the belt obliquely crosses the Sarmatia, separating the Archean-Proterozoic crystalline massifs of the Ush and Voronezh Anteclise (VA) (Kruglov, Cypko, 1988; Zartskij et al., 1992) (Fig. 2). The Ingulec’-Kryvyi Rih-Krupec’ Seam divides the VA into the Bryansk (Western) and Kursk (Eastern) microplates, as well as the USh into the Western (Volyn, Podil, Bug, Rosyn) and Eastern (Middle Dnieper, Azov) ensembles of Archean-Proterozoic Geoblocks, which make up the previously independent, respectively, Western and Eastern microplates of the Sarmatian craton core (Bogdanova et al., 1996). The Seam branches in a fan-like fashion into constituent deformation zones of cleavage extending from the USh across the rift-like structure of the PDDP in the Northern direction to the VA slopes (Krylov, Cypko, 1988) (Fig. 1).

The structure of the Central, Dnipro-Dontsk Segment of the PDDP consists of a narrow early Riphean trough in the basement, a wider Devonian Dnipro Graben and superimposed extensive structures of the Upper Paleozoic suprarift basin and Mesozoic-Cenozoic platform syneclise. Together, they are known as the Dnipro-Dontsk Depression (DDD) (Arsirij et al., 1984, Krylov, Cypko, 1988). Marginal rift-cored mantle faults form the shoulders of the Dnipro Graben and control the Early Riphean and Late Devonian rift and later syncline complexes of the paleo-basin. The Northern and Southern flanks of the Graben cover the southern slope of the VA and the northern slopes of the USh. The axis of the Graben is arcuately concave with the convex side to the South and dips in the South-East direction, where the depth of the surface of the Archean-Proterozoic folded basement increases from 5 to 20-22 km (Fig. 1). The Graben is almost orthogonally superimposed on pre-rift sub-meridional tectonic seams and suture zones (Kherson–Smolensk, Ingulets-Kryvyi Rih, Donetsk–Bryansk) and deep faults (Odesa-Talnivsk, Ingulec’-Bryansk, Verhovci-Lgov, Odesa, Central-Azov-Slov’yanohirsk) (Krylov, Cypko, 1988). This transverse tectonic framework divides the Paleorift structure from West to East into the Chernihiv, Lokhvycya, and Izyum Segments and the Donetsk Foldbelt (DF) (Arsirij et al., 1984) (Fig. 1).

The central lineament of the Ingulec-Kryvyi Rih-Krupec’ Seam in the Dnipro Graben is the Verhovci-Lgov crustal-mantle fault, which bisects the DDD transversely almost in half (Fig. 1). Along this fault, a neotectonic axis of kinematic symmetry was formed, which divides the Archean-Proterozoic craton core of Sarmatia into Western and Eastern relatively independent geodynamically microplates, with different structures, thicknesses and composition of lithosphere layers and currently opposite kinematics of the movements of blocks and massifs of rocks within their boundaries (Bartashchuk, Suyarko, 2018).

Anisotropy of the Lithosphere and structural differentiation of the Sarmatia crust were considered in this study. The Lithosphere of Sarmatia below the PDDP thins to the South-East from 35-42 km in the Chernihiv segment to 15-25 km in the Lokhvycya and Izyum segments and thickens to 25-30 km at the DF border (Starostenko et al., 2017) (Fig. 3). Crustal density at the Moho section increase to the South-East from 3.12 g/cm3 in Chernihiv to 3.18 g/cm3 in the Lokhvycya segments and from 3.18-3.20 g/cm3 in the Izyum segment to 3.36 g/cm3 in the DF. Under the Chernihiv segment lies the thickest lithosphere up to 280 km, but under Lokhvycya there is a dome-structure relic of the rift at the base of the Lithosphere at a depth of 120 km (Fig. 4). The base of the Lithosphere rises to the South-East up to 80 km, which is due to the opening of the Devonian rift basin in that direction into the Tethys paleo-ocean (Stampfli, Borel, 2002, Natal’in, Sengor, 2005, Meijers et al., 2010).

As a result of structural and material differentiation in the mantle at depths of 50-250 km, zones of anomalous velocities of longitudinal seismic waves formed (Starostenko et al., 2017) (Fig. 4). In the zone of reduced velocities below Lokhvycya and the Eastern part of the Chernihiv segment, a section of «overlapping» of velocity anomalies is localized. In the Lithosphere below it, at depths of 70-130 km, a layer of abnormally high velocity was formed, possibly due to the intrusion of mantle material from under the massif of the USh. The subduction of the mantle slab was facilitated by the gentle slope of the plane of the northern marginal fault, the type of which changes with depth from steep shear-thrust to gentle subduction (Sydorenko et al., 2017) (Fig. 2). In the western part of the Chernihiv segment, the consolidated crust consists of a «diorete layer», the Asthenosphere has increased velocities of longitudinal seismic waves (Fig. 5). Its Eastern part is composed of a «granite-free» rift
crust, and magnetic bodies are localized in compacted «diorite» and «basalt layers» Moho relief consistent with the relief of the sole of the lithosphere.

In the Lokhvycya segment, the «granite-free» crust, the «basalt layer» also decreases in thickness due to the thickening of the «crust-mantle mixture» layer (Starostenko et al., 2017). In the roofs of the «basalt layer», the «crust-mantle mixture», the soles of the consolidated crust and seismic lithosphere formed a domed uplift, which is considered a relic of the Early Riphean rift (Arsirij et al., 1984).

The Western part of the Izyum segment has a «granite-free» crust with a thinned «diorite layer», a «crust-mantle mixture» is developed everywhere (Fig. 5). Here, a lenticular body with a density of 3.50 g/cm³ was formed in the subcrustal mantle due to the rise of the Moho interface and the Lithosphere sole (Figs. 4, 5). In the Eastern part of the Izyum segment, the crust contains a thin «diorite layer», and uplift has formed in the roof of the «basalt layer». The «crust-mantle mixture» here forms a lens of anomalously high density (3.20 g/cm³) 12 km thick at the Moho section. Below the Moho section at depths of 60–80 km, the upper mantle is compacted to 3.50 g/cm³. In the Donetsk segment, the thinning of the «diorite layer» under the axial part of the Graben is associated with the maximum roof rise of the roof of the «basalt2 layer with the formation of a domed uplift in the Moho section. Thanks to this, on the Western slopes of the DF at the base of the Dnipro Graben, the sedimentary cover rests on the «basalt window», and the «crust-mantle mixture» reaches a maximum thickness of 16 km in the Graben (Figs. 4, 5).

In general, the anisotropy of the Lithosphere in the central part of the Precambrian core of Sarmatia is manifested in variations in the composition and thicknesses of the layers of the consolidated crust, the relief of the Moho surfaces, the Lithosphere sole, and the Earth’s crust (Starostenko et al., 2017) (Figs. 3-5). This is clearly reflected along the extension of the Paleorift belt in the fundamental differences in the deep structure of its Western (Chernihiv and Lokhvycya segments) and Eastern (Izyum and DF segments) parts. In the same way, a longitudinal structural and material differentiation of the lithosphere is established within the boundaries of the lithosphere, which determines the division of the shield into heterogeneous and different-age cratonic geoblocks, which are considered as part of the Western (Volyn, Podil, Buh, Rosyn) and Eastern (Central Dnipro, Azov) mi-
croplates of the Precambrian core Sarmatia (Krylov, Tsypko, 1988, Zaritskij et al., 1992, Gintov, 2005). In addition, changes in the orientation of the transverse seismic wave splitting vector have been established in the lithosphere under the Paleorift (Sydorenko et al., 2017). This heterogeneity is considered evidence of structural and material features due to the ancient embedded («frozen») anisotropy of the Lithosphere of the Sarmatia plate (Wüstefeld et al., 2009).

Thus, considering the original, «built-in» anisotropy of the Sarmatia lithosphere and the fact that the modern segmentation of the Precambrian consolidated crust of the Craton has no direct connection with the topography of the sole of the seismic lithosphere, the following conclusion is made. The present in the sublatitudinal direction structured material differentiation of the Sarmatia lithosphere and the longitudinal structural heterogeneity of the manifestation of inversion deformations of the Earth’s crust along the extension of the crystalline massifs of the USh, VA and the rift-like structure of the PDDP can be explained only by significant inversion rearrangements of the Earth’s crust during the long Phanerozoic history of the development of Sarmatia (Krylov, Sypko, 1988). Below we consider the general features of the most significant stages of the formation and structural evolution of the Sarmatia crust, caused by fundamental changes in geodynamic conditions and inversion of tectonic deformation regimes on the EEP terrain.

**Geodynamic conditions and stages of crustal evolution of Sarmatia plate.** Sarmatia emerged as a stable Archean craton in the Late Archean-Early Proterozoic (3.8 to 2.8 Ga) due to the fusion of three continental microplates of different ages (Bogdanova et al., 1996). Neoarchean-Proterozoic crustal-mantle breaks, tectonic seams, and sutures cross the Sarmatia lithosphere with a thickness of 180-260 km and plunge into the mantle by 100-200 km (Arsirij et al., 1984, Krylov, Sypko, 1988, Zaritskij et al., 1992) (Fig. 1-4). Submeridional zones of deep faults in the consolidated crust, thanks to their repeated reactivation in the alternating stress field, form a tectonic framework that controls the processes of structural evolution. On the terrains of the USh, PDDP, and VA, horizontal displacements along this framework reach amplitudes of tens to the first hundreds of km (Chebanenko, 1977, Goryainov, 2004, 2013, Kopp et al, 2017, Orlyuk, Ishchenko, 2019, Bartashchuk, Su-
Fig. 5. The deep structure of the Earth’s crust on sections across the Dnipro-Donetsk Paleorift (Starostenko et al., 2017). Symbols: 1 – the Moho boundary; 2-6 – layers of the Earth’s crust: 2 – sedimentary, 3 – granite, 4 – diorite, 5 – basalt, 6 – crust-mantle mixture; 7 – edge faults of the Graben; 8 – axis of the Graben.

In the Precambrian, the West and East parts of both crystalline massifs developed as separate Western and Eastern microplates (terrains) at a great distance from each other (Gorbatschev and Bogdanova, 1993; Bogdanova et al., 1996).

According to the Plate-plume tectonic model (Gintov, 2014), the Precambrian evolution of Sarmatia includes stages of collision with subduction of the continental crust and spreading of the oceanic crust. At the same time, there were repeated divergences and mergers of several Geoblocks of the USh as part of the Western and Eastern parts (microplates) of the cratonic core of the Plate. The processes of convergence/divergence of the crust determined the initial («frozen») anisotropy of the Sarmatia lithosphere and the formation of mobile submeridional seam and suture zones. During the Phanerozoic, the North Pole of the Planet moved from equatorial latitudes to its present position, while the EEP underwent a clockwise rotation of up to 90°, then all geoblocks and microplates were welded together as part of the Sarmatia craton.

At the Early Riphean stage, several troughs were formed in the context of stretching of the Earth’s crust, which was accompanied by basalt magmatism of the Sambetskiy Complex, gold-silver, and copper mineralization. After the early Paleozoic stabilization, continental rifting began in the Middle Devonian with the formation of a graben in their place. The manifestation of magmatism of the rift stage is titanopyroxenites of the Azov Complex and differentiated volcanics (from diamond-bearing alkaline picrites to rhyolites). During the platform stage in the Carboniferous, the sedimentary basin sank with the accumulation of carbonaceous-terrigenous-carbonate formation. It is complicated by the Anastasia Igeous Complex, composed of gabbrous dikes and volcanic rock, from trachy-basals to alkaline rhyolites. The overall plate collision was accompanied by folding and strike-slip deformations in the geodynamic setting of the Andean-type active margin. During the Permian-Early Triassic platform activation, an inversion uplift of the basin took place, which was accompanied by intrusions of granites and diorites of the South Donbas Magmatic Complex. From the late Triassic, the Cimmerian stage of folding began due to the movements of the Caucasian terrains. Associated with it are intrusions of the Nesvitaevsyki Andesite-trachyandesite and
Mius-Kerchyk Lamprophyre Complexes. The stage of tectonic stabilization occurred with the transition to the platform regime at the Cretaceous-Paleogene boundary before neotectonic activation. The fading Cimmerian movements were accompanied by dyke diorite-dacite magmatic rock, low-temperature hydro-thermalites, and folded deformations of Lower Cretaceous rocks.

The kinematic model of rifting (Bartashchuk, 2018, 2019) predicts the establishment of a rift-like structure in the body of the Sarmatia plate by the mechanism of «unthermal» rifting due to elastic rupture of the «cold» continental Earth’s crust. During the late Proterozoic, at the pre-rift stage, an «embryonic» linear deformation megazone of cleavage was laid along the azimuth directions of the North-West diagonal system of the planetary fault lattice (291°–312°, 315°–339°). During the Early Riphean epoch of rifting, as a result of because of movements along the main lineament zone, several echeloned trough valleys were formed according to the «Pill-apart basin» kinematic mechanism. During the Devonian synplatform rifting, in the context of plate-wide crustal stretching, the crustal blocks were displaced within the trough basins by a system of «listric» faults with the formation of a graben echelon. Rifting of the active «thermal» type began due to the intrusion of the mantle plume, the influence of which initiated deformations of simple stretching and domed uplift of the Earth’s crust in a field with a horizontal orientation of the axes of intermediate (average) and minimum compressive stresses σ2, σ3 at the vertical axis of the maximum stress σ1. The axis of intermediate stress (σ2) was located parallel to the extension of the rift belt, and the axis of maximum tension (σ3) was located orthogonally. Under such conditions, vertical separation cracks open to ascending mantle fluids were formed in the rocks in re-activated rupture-discharge systems. The kinematics of the rifting process and the longitudinal structural differentiation of the belt structure were controlled by transform shifts along the azimuthal directions of the northeastern diagonal fault system (24°–30°, 39°–45°, 54°–63°), «Tectonic rails» of rifting is controlled by deformation lattices of faults of different ages.

The platform paleo-basins known as the «Dniipro-Donetsk Depression» (DDD) and «Donbas» existed during the Middle Devonian to Early Permian. Evidence for this is the relict rift framework, Devonian alkali-basalt volcanism, and the Paleozoic platform cover structured into folded floors during stages of tectonic inversion. The DDD ceased to exist at the end of the Hercynian due to fold deformations of the cover during the Zaalian and Palatinate phases (more than 250 million years ago). In the Cimmerian (Donets phase) and Alpine (Laramian and Attic phases) epochs, the Eastern segment of the Paleorift belt underwent uplift, the structure of the Donbas depression turned into a folded belt (DF) because of tectonic disruptions in the basement and cover-folding deformations of the sedimentary cover. Due to this, the Mesozoic complex is almost completely eroded, and three structural floors (Hercynian, Laramian, Attic) were formed in the cover, the structure of which is controlled by deformation lattices of faults of different ages.

In the Alpine folded floors of the Eastern segment of the PDDP, folded thrust covers were formed behind the cross-thrust framework, expressed in the daytime relief of the Donetsk Kryazh (Kruglov, Cypko, 1988). Lateral movements of blocks and massifs of rocks on the Southern slope of the Dniipro Graben led to the overlapping of rift and platform complexes of the cover at several stratigraphic levels by thrust blocks and plates of crystalline rocks of the Precambrian basement. As a result, the South-Donbas Mélange Zone was formed on the Northern slope of the Azov Geoblock of the USh, manifested in the relief of the Azov Upland (Goryainov et al, 2009).

Taking into account these data, several significant stages can be distinguished in the structural evolution of the Sarmatia crust, following the geodynamic conditions and tectonic regimes of deformations that gradually changed on the terrain of the EEP:

1 – the Paleoproterozoic collision of Fenno-Scandia and Sarmatia due to the subduction of the oceanic Earth’s crust on the Northern edge of Sarmatia with the unification of the crystalline massifs of the USh and VA;

2 – the Early Riphean episode of the «unthermal», passive type of rifting with the splitting of the «cold» continental Earth’s crust of the cratonic core of the platform in the mode of whole-plate collision due to
the displacement of blocks along the linear germ zone of cleavage with the formation of several echeloned trough basins according to the Pull-apart basin kinematic mechanism;

3 – the Devonian sin-continental rifting of the «thermal» type in the geodynamic setting of plate-wide crustal displacement on dome structures under the thermal influence of the mantle plume with the formation of several echeloned grabens united in the composition of rift belts;

4 – Hercynian – Early Cimmerian platform activation in a collision stress environment against the background of plate-wide deflection of platform sedimentary basins with the formation of linear folded zones, including with the participation of salt tectonics;

5 – Cimmerian-Alpine platform tectonic activity in the context of the interference of the whole-plate sub-meridional collision and the regional horizontal shear field with the uplift of the territory, the drainage of sedimentation basins and the formation of intensively inverted areas in the structure of the platform, such as the cover-fold region of Donbas in the Eastern segment of the Paleorift belt.

Conclusions

1. The unification of continental micro-plates with the help of deep tectonic seams in the stable craton core of the EEP, which were previously at a distance from each other, is an important consequence of the structural evolution of the Earth’s crust. However, subduction/rift belts can perform, in addition to structure-forming, the role of destructive intra-plate structures. During episodes of rifting, mobile zones, and belts initiate geodynamic instability of the Platform and contribute to the future division of the Earth’s crust into constituent micro-plates and the latter into terrains. As a result of the movements along the boundary faults that control them, intra-plate belts appear as mobile structures capable of absorbing/accumulating external collision stress. The release of stress in paleorift belts that have not turned into oceanic rifts is accompanied by tectonic disruptions, folding, and lateral movements of dislocated rock masses. Due to the inversion of tectonic regimes, the rift-like structures of the Platform depressions later turn into collision belts. Thus, the structural status and tectonic position of regional structures on the platform may change during the structural evolution of the Earth’s crust.

2. The structure of the stress field inside the EEP is determined by the established meridional collision compression and latitudinal stretching of the Earth’s crust, except for Sarmatia. The Sarmatia field of North-North-West orientation is determined by stress from the South from the movements of the Arabian and African continental plates, from the north due to the spreading of the oceanic crust in the North Atlantic Ridge, and from the South-East from the movements of the Alpine terrains of the mountain-folding system of the Caucasus.

3. Considering the Precambrian, «embedded», sub-latitude structural-material anisotropy of the Lithosphere of the Sarmatia plate and the lack of a direct structural connection between the relief of the sole of the seismic lithosphere and the modern tectonic division of the consolidated Earth’s crust, an important theoretical conclusion is made. The modern longitudinal structural differentiation of the Earth’s crust of Sarmatia along the extension of the crystalline masses of the USh, VA, and the PDDP paleorift-like structure is caused by repeated inversion deformations and rearrangements of the structure of the Earth’s crust at the Phanerozoic.

4. In the process of structural evolution of the EEP Earth’s crust, defining stages are distinguished, the geodynamic conditions and tectonic regimes of deformations on its terrain:

1 – the Proterozoic collision of Fenno-Scandia and Sarmatia due to subduction of the oceanic crust on the Northern edge of Sarmatia with the unification of the crystalline masses of the USh and VA;

2 – Early Riphean «athermal» rifting with the splitting of the «cold» continental crust in the geodynamic setting of a general plate collision and displacement by the Pull-apart basin kinematic mechanism with the formation of a series of echeloned troughs;

3 – Devonian sin-continental «thermal» rifting in a setting of plate-wide crustal displacement under the influence of a mantle plume with the formation of several grabens into rift belts;

4 – Hercynian-Early Cimmerian platform tectonic activation in a collisional stress environment against the background of plate-wide deflection of superimposed platform basins with the formation of linear folded zones;

5 – Cimmerian-Alpine platform tectonic activation in the setting of general-plate, sub-meridional, collision interference stress and regional, mostly sub-latitude, horizontal shear field with uplift of the territory, draining of sedimentation basins and the formation of areas of intensely inverted structure of the Earth’s crust.
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