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TECTONIC ZONALITY OF SEDIMENTATION COVER IN THE BLACK SEA–CASPIAN REGION

The article focuses on modeling tectonic zonality of the sedimentation cover in the Black Sea–Caspian Region, and addresses the identification and validation of the Late Paleozoic, Mesozoic, Alpine and recent-time geodynamically active structures. The modeling shows that the significant events, which governed the evolution features of the geodynamically active structures, correlate with the recent time. That is the time when such sedimentation basins as Terek–Caspian, Indol–Kuban, Eastern Kuban and Karkinit have finally set. The first three basins in this list occur in the zones of the reverse geodynamic regime, with dominant extension and downwarping within the limits of cratons, and belong to the Black Sea–Caspian geodynamically active structure. The Karkinit basis belongs to the Scythian geodynamically active structure with generally compressive tectonics, dominant upheaval or relative stabilization. The tectonic features have had the critical influence on both formation of the sedimentation cover of the basins and spatial distribution of minerals.

Keywords: *geodynamically active structure, Black Sea–Caspian Region, sedimentation cover, tectonic regime, three-dimensional model, surface, dynamic activity*
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Introduction

The platform-structured mantle within the limits of the Black Sea–Caspian Region began forming under the Alpine geodynamics. Sedimentation basins reached maturity during the transgressive Cretaceous period including enlargement of the existing basins and origination of new depocenters. The areal patterns of the latter within geodynamically active structures prove that the depressions occur in different systems and under different tectonics.

However, the most significant events that governed evolution of geodynamics and structuring belonged to the recent time. That was the period when such sedimentation basins as Terek–Caspian, Indol–Kuban, Eastern Kuban and Karkinit set. The first three basins occur under conditions of reverse geodynamics, dominated by extension and downwarping within the boundaries of cratons and mobile zones, and belong to the Black Sea–Caspian system of structuring and geodynamics. The Karkinit basin represents the Scythian system of structuring and geodynamics, with the compressional tectonics, dominant upheaval or relative stabilization. The features of the tectonic regime had a critical influence on both the sedimentary cover formation and the spatial occurrence of minerals.

Source information and research procedure

Modeling of the internal tectonic zonality of the Black Sea–Caspian Region basement uses the concept and methods of analysis described by the authors earlier and applied to the smaller scale modeling of the tectonic zonality of the basement in the Russian maritime periphery and adjacent areas [1–5].

The source information for the modeling includes:

- the submarine geological survey data;
- the updated surface structure model of the different-age basement in the Black Sea–Caspian Region;
- the tectonic interpretation data of the basement surface morphology with assistance of current seismic survey, generalized regional gravimetry and magnetometry (maps), as well as using numerous different-age tectonics models of entire Northern Eurasia and the test region specifically [6–19].

Development of the regional structure of the sedimentation cover in the Black Sea–Caspian Region in the late Paleozoic, Mesozoic and Cenozoic ages is described using the non-palinspastic reconstructions of the structural and geodynamic conditions for individual periods of geological history of the mega region, on the analysis of structural models of dividing surfaces between the major sedimentation complexes and on the review of the different-scale geological and geophysical studies of the region. The non-palinspastic, i.e. tied to the modern coordinates of geological objects, reconstructions were made for four geo-chronological epochs fitting with the main stages of distribution, structuring and development of the sedimentation basins in the Black Sea–Caspian Region: late Paleozoic (Permian–early Triassic, ending of Hercynian cycle of tectonogenesis); Mesozoic (medium–late Triassic to late Jurassic–early Cretaceous, Cimmerian tectonic cycle); Alpine (late Jurassic–early Cretaceous to early Eocene inclusive); neotectonics (medium Eocene to Pleistocene inclusive).

The first epoch features consolidation of large crustal masses which form the Hercynian basement of the mobile platforms in the Russian south and the graben–rifting and orogeny zones of different-scale amplitudes and lengths.

The second epoch involves substantial narrowing of the zone of geodynamic activity and its shift from the outer to the inner boundaries of the Paratethys domain, to the Caucasus and near Caucasus zones, with relative stabilization of geodynamics in the north and center of the Scythian Platform.

The third epoch is the stage of the vast expansion of the relatively stabilized geodynamics zone within the limits of the Scythian Platform and localization of the most active rifting, folding and mountain-making mostly in the belt between the northern and southern boundaries of the Black Sea, Middle Caspian and South Caspian basins.

The fourth epoch is the time of modern outlining of the platform, mountain folding and depression systems in the Black Sea–Caspian Region, and shaping of their internal tectonics.

Results

First, we constructed 3D structural models of the dividing surfaces between the major sedimentation complexes (**Fig. 1**). Initial surface gridding included a pitch of 1×1 km. The whole model of the test territory had a cell of 2×2 km with regard to computational capacities. The model of 7 major sedimentation complexes had a size of 2 km to 2 km (**Fig. 2**).

The research and primary simulation allowed modeling the structure, geodynamics and tectonic zonality in the Black Sea–Caspian Region.

Late Paleozoic Systems (**Fig. 3**). At the age of the Late Paleozoic time in the Black Sea–Caspian Region, up to 11 systems may be distinguished in the structural geodynamics, mostly stretching north to south and containing zones of both compression and tension.

The utmost northern system of the Late Paleozoic geodynamically active structures (GAS) is GAS of the southern margin of the East European Platform. It contains areas generated by general compression, steadily weak upheaval of large massifs of the Ukrainian shield and Voronezh anticlise, and two areas of varied behavior [20].

In one of such areas, the dominant general extension and downwarping are governed by the own sources of geodynamic evolution. The other area (Donbass) is dominated by the compression and upheaval with some local orogeny [21–22]. The compressive stresses are located southward of this area and are associated with the large extension area in the south Azov–northeast Black Sea, with transmission of the extensile and compressive stresses to the north and northeast via the system of the stiff basement of the Azov and Rostov massifs.

The southern boundary of this system joins an echelon of three GAS of the Northern Caucasus, which stretch northwestward and belong to the modern structure of the Scythian Plate and, to a lesser degree, to the Greater Caucasus: Crimean–Caucasus, Northern Scythian and Donets–Astrakhan. Each plate has a zone of tensions (rifting?) at the southwest boundary. The most pronounced zone of this triad, with the highest (major?) thrust potential is connected with the Crimean–Caucasus GAS. It includes at least three long-action nodes of tension, which probably encompass the whole thickness of the crust formed in that period of time.

Origination of the zones of general compression and local orogeny at the northeast and east boundaries of these GAS is probably governed by the lateral thrust generated by these zones, in particular–Tuzlov–Manych zone, Azov–Northern Black Sea–Western Caucasus node of the Crimean–Caucasus GAS and the East Caucasus nodes of the same system [23–29].

The eastward Western Turan GAS unites relatively stable platform massifs of Ustyurt, Middle Caspian–Kara-Bogaz and Amudaryo, and includes the Mangyshlak extension zone situated, unlike the above discussed GAS, not at the margin but in the interior, between the northern and southern block associations.

Specific GAS intrinsic to the abysses of the Black Sea and South Caspian are discussed below.

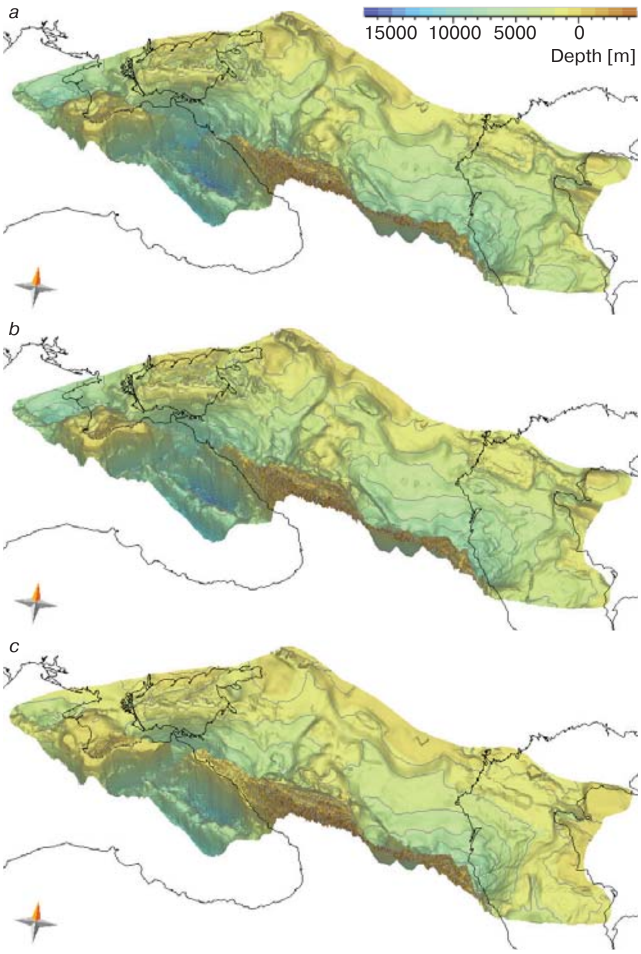

Fig. 1. 3D models:
a—surface of Pre-Jurassic sedimentation; *b*—roof of Jurassic sedimentation; *c*—roof of Cretaceous sedimentation

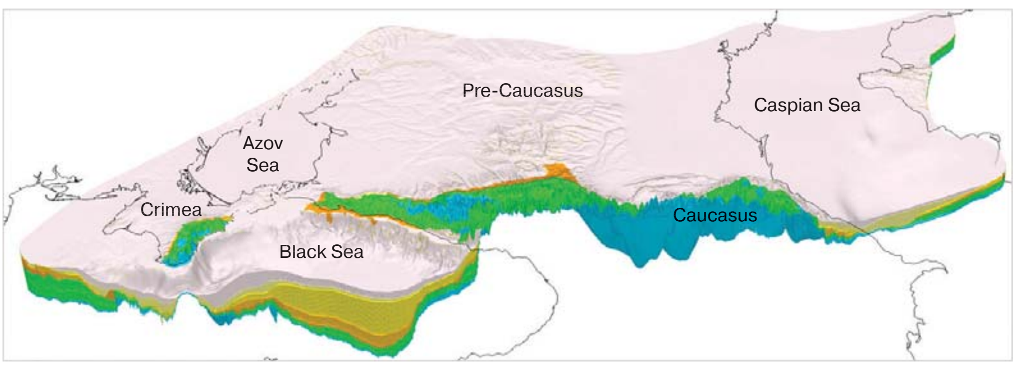

Fig. 2. Model of sedimentation cover in the Black Sea–Caspian Region

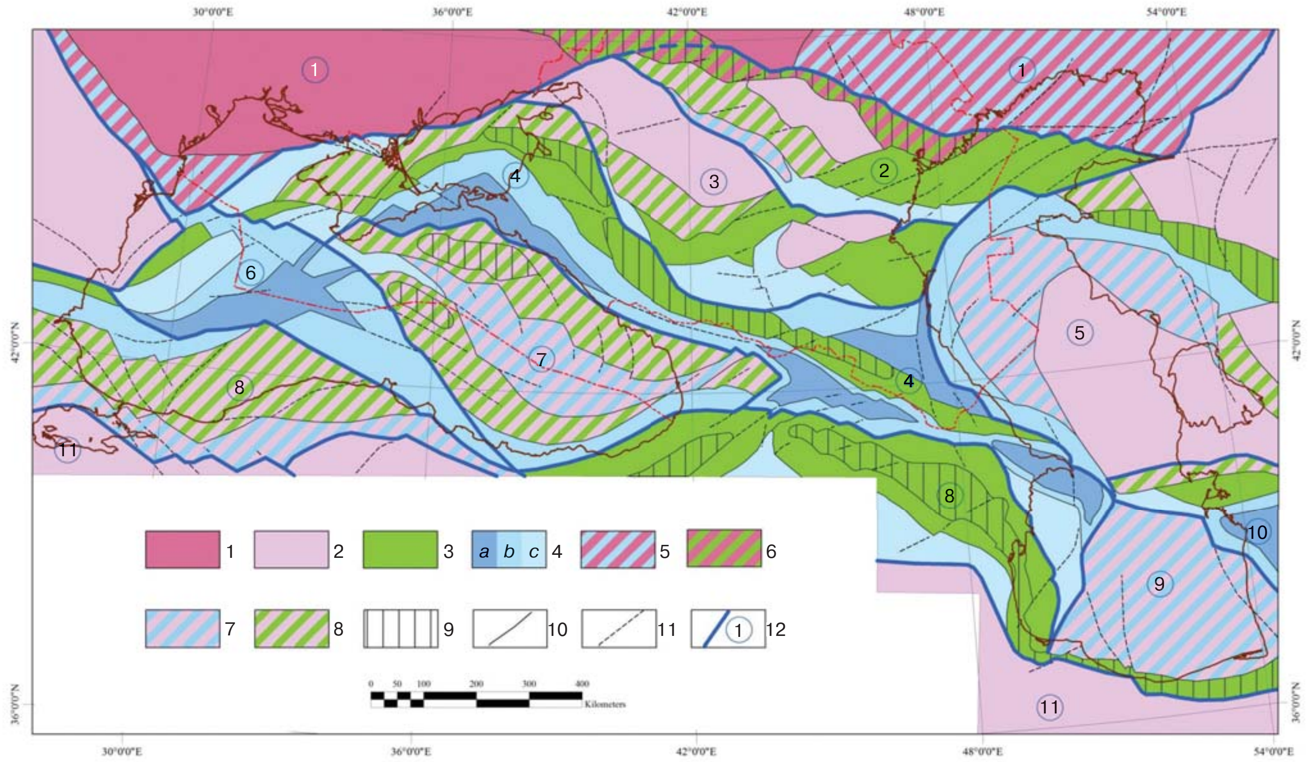

Fig. 3. Late Paleozoic geodynamically active structures of the Black Sea–Caspian Region

1–3—zones of general compression, dominant upheaval or relative stabilization in the conditions of cratons, mobile platforms, folding and orogeny belts and systems: 1—continental blocks/mega blocks of cratons; 2—continental blocks/mega blocks of mobile platforms; 3—folding and orogeny belts and systems; 4—zones of general extension and downwarping in the regions of predominantly continental or transient-type crust: *a*—axial (rifting?) troughs with local crustal areas of transient or oceanic type; b—heavy crushing and downwarping of continental blocks; *c*—relative compression and weak upheaval in belts and general tension zones; 5–8—zones of varied/pulsed (reverse) geodynamics: 5—dominant extension and downwarping in the limits of cratons; 6—dominant compression and upheaval in the limits of cratons; 7—dominant extension and downwarping in mobile zones; 8—dominant compression and upheaval in mobile zones; 9—localized folding–orogeny and doming–block upheavals/structures; 10—boundaries of structural tectonics elements; 11—fractures, large tectonic lineaments; 12—geodynamically active structures and their indices (1—southern margins of the East European craton; 2—Donets–Astrakhan/Buzachi–Emba; 3—North Scythian (Scythian); 4—Crimean–Caucasus; 5—West Turan; 6—Western Black Sea; 7—Eastern Black Sea; 8—Ponta–Southern Caucasus; 9—Southern Caspian; 10—South Turkmen/Koptedag; 11—Anatolia–Iran; 12—Mysia. Red-color dashes—state border of Russia and some international demarcation lines of water areas

In the west of the Black Sea, the region's largest biaxial extensile Western Black Sea system occurs. Its northwestward axis lies on the axis of the largest Trans-European tectonic lineament—the Teisseyre–Tornquist line. The other, nearly north-southward axis follows the axis of the whole Black Sea depression and pre-Balkan (Lower Kamchian) trough.

A quite detached and independent geodynamically active unit of the time can be the Eastern Black Sea GAS which is tectonically defined as the Euxinus (or East Euxinus) late. As the West Turan GAS, it occurs not in the margin but in the center of the zone dominated by geodynamic tension and downwarping [30–33].

A complex mix of varied geodynamic regimes, with contiguous zones of extension and compression, where the normal graben-rifting tension and the associated orogeny run, characterizes the Ponta–Southern Caucasus geodynamically active structure.

The general compression, relative tectonic stabilization and low-contrast movements are the features of the Mysia and Anatolia–Iran GAS.

Mesozoic GAS (**Fig. 4**). As is mentioned above, the common structural geodynamic feature of this time is narrowing of the zones of active geodynamics and their displacement into interior of the Paratethys area. Against this background, GAS northward of the Ponta–Southern Caucasus geodynamically active structure undergo transformation. Namely, two old systems typical of the Pre-Caucasus, and two new, Northern and Easter Scythian systems transform, and the Black Sea and Southern Caspian GAS join together. At the same time, the West Turan system divides into the Ustyurt and, properly, West Turan systems. It is supposed that the division is governed by actuation of geodynamics and the associated rifting and orogeny in the Karatau–Mangyshlak zone, Middle Caspian and the adjoining areas of the Dagestan coast of the Caspian Sea.

The geodynamically active structure in the south margin of the East European craton, owing to its 'geodynamic rigidity', preserved its exterior configuration. On the other hand, self-development of the body-building stresses in the Pre-Caspian depression could induce redistribution of the dominant upheaval and downwarping sites within its limits.

Relative stabilization was at that time in the system of the Mysia plate, probably, with some expansion in the area owing to inclusion of the Hercynian dislocations of the

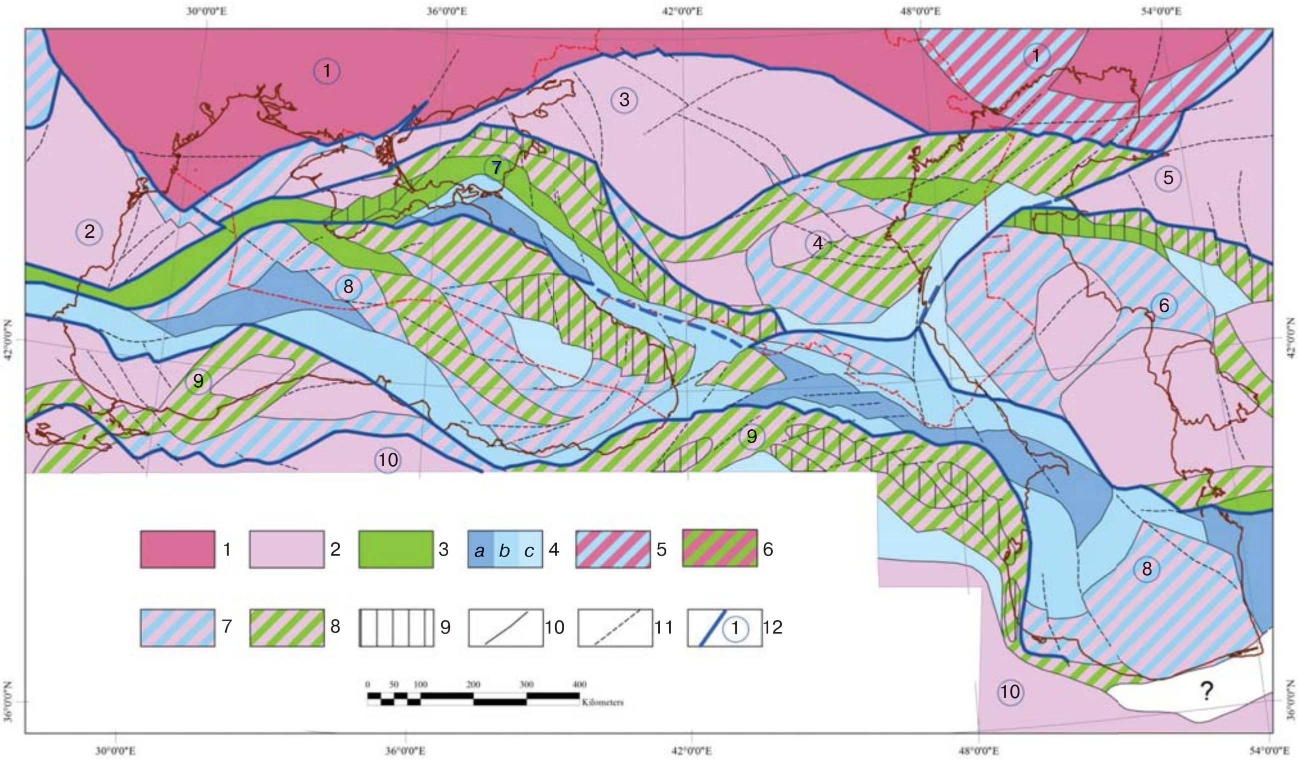

Fig. 4. Mesozoic geodynamically active structures in the Black Sea–Caspian Region (legend is in Fig. 3):
Geodynamically active structures (circled indices): 1—southern margin of the East European craton; 2—Mysia; 3—Donets–Astrakhan/North Scythian; 4—East Scythian; 5—Ustyurt; 6—West Turan; 7—Northern Black Sea–Caucasus; 8—Black Sea–Southern Caspian; 9—Ponta–Southern Caucasus; 10–Anatolia–Iran.
Red-color dashes—state border of Russia and some international demarcation lines of water areas

Nanevska–Krapets (by [34]) zone of the current Western Black Sea shelf.

The same situation is a feature of the neo North Scythian, or Donets–Astrakhan GAS, formed at the location of the earlier geodynamically active structures, and including also the narrow Northern Crimea–Northern Azov Sea zone.

The varied geodynamics with the noticeable domination of upheavals and relatively small sites of stabilization, which agree with the stiff basement blocks, is intrinsic to the East Scythian GAS.

The relative stabilization regime is a feature of the Ustyurt GAS. The southward West Turan GAS, probably, under appreciable geodynamic impact exerted from the south by the Southern Caspian segment of the Black Sea–Caspian system, and having a small—Central Mangyshlak—zone of extensile stresses, is characterized mostly by varied regimes, with the prevailing compression and tension, and with the relatively stable core bodies in the areas of the Peschany Mys–Rakushechny Mys and Kara Bogaz block masses of the Middle Caspian and the east-adjacent territories.

Highly active geodynamics combining faulting, folding and orogeny keeps on within the limits of the Northern Black Sea–Caucasus GAS. This system contacts in the south the equally active Black Sea–Southern Caspian system which can, later on (optionally), split into two independent geodynamic units; their in-between boundary can follow a tectonic line conformable with the northwester marine limitation of the East Ponta, probably generated by shearing.

A feature of this system, as follows from the model, is actuation of extensile processes in the internal area of the Euxinus block mass (plate) in the east of the Black Sea, which represents a new phase of destruction of this, once joint, relict structure of the Earth's crust.

Active tension lasts in the west of the Black Sea depression, where a series of depressions of the Eastern Caucasus, Southern Caucasus, northwestern and near-Apsheron zones of the Southern Caspian join together into a single wide and long extensile structure [35–41].

The southern Ponta–Southern Caucasus limit of the Black Sea–Caspian Region experiences the set, mostly varied geodynamics which embraces the areas and zones of tension and dominant downwarping, compression and local orogeny, as well as the relatively stable sites.

Alpine systems (**Fig. 5**). During this tectonic and geodynamic cycle, the territories of relatively stable regime, with southward displacement of active tension, compression and associated structuring, continue expanding.

The southern margin of the East European craton keeps relatively stable. Similar regimes set almost in the whole territory of the Scythian plate, except for its Caspian side [42–48], where the zone of varied regimes with the dominant extension and downwarping forms, and the southern margin, with inceptive submontane troughs.

Similar conditions set in the Mysia and Ustyurt GAS, and in the vast areas of the West Turan system. The relative stabilization within the limits of these systems may allow some vibrations which govern distribution of positive and negative platform structures. The variable regimes are intrinsic to the

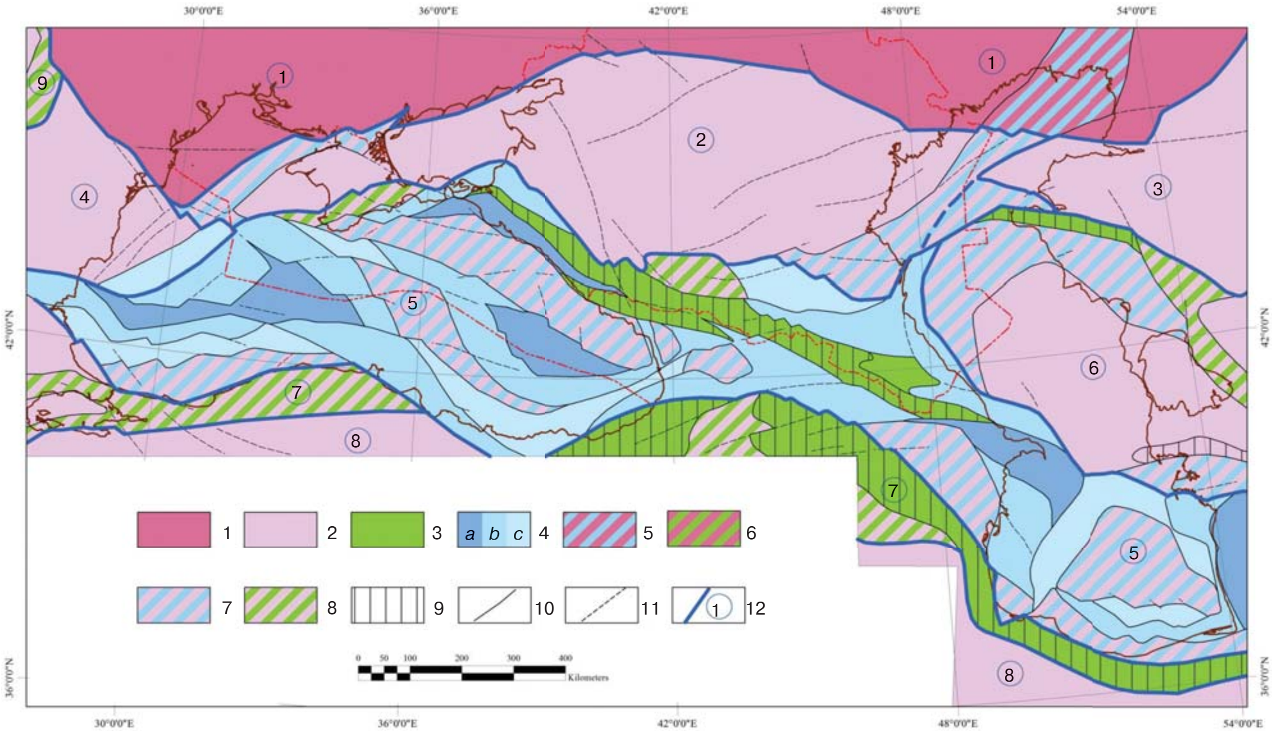

Fig. 5. Alpine geodynamically active structures of the Black Sea–Caspian Region (legend is in Fig. 3.):
Geodynamically active structures (circled indices): 1—southern margin of East European craton; 2—Scythian; 3—Ustyurt; 4—Mysia; 5—Black Sea–Caucasus–Southern Caspian/West Turkmen; 6—West Turan; 7—Ponta–Southern Caucasus; 8—Anatolia–Iran.
Red-color dashes—state border of Russia and some international demarcation lines of water areas

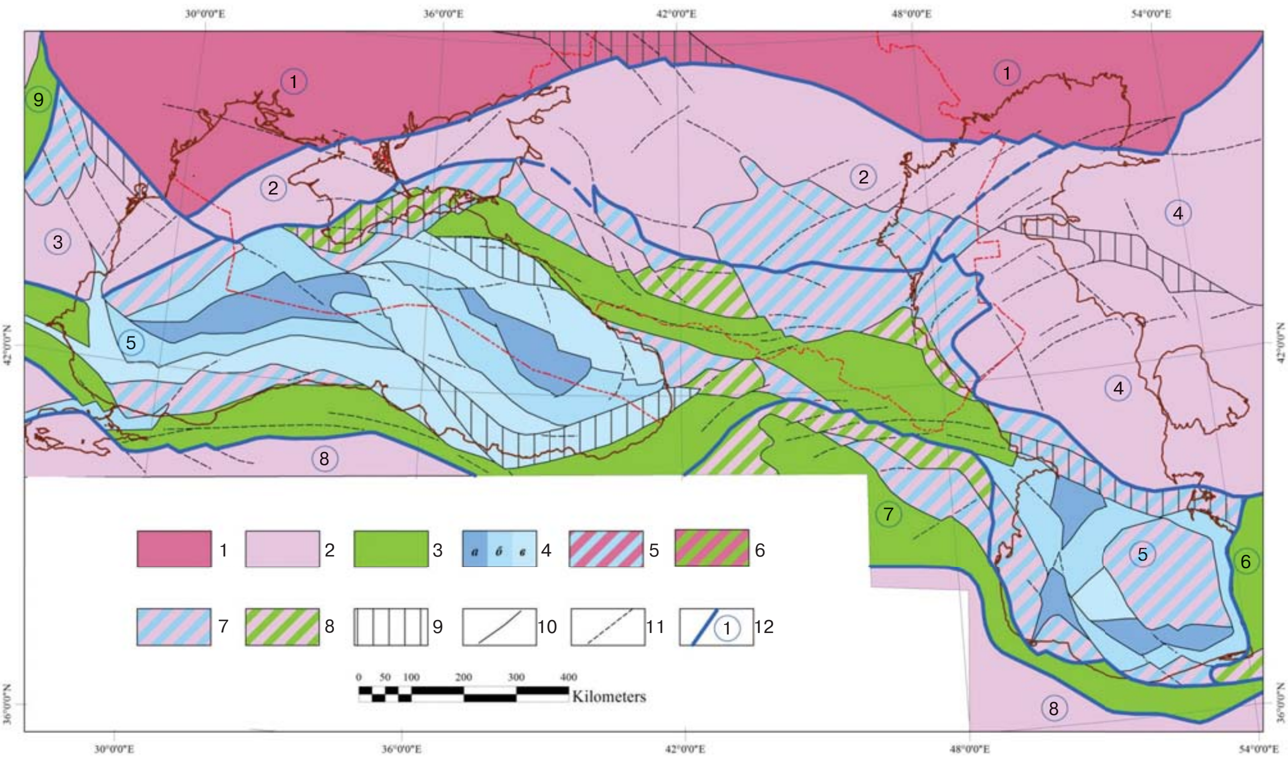

Fig. 6. Recent geodynamically active structures in the Black Sea–Caspian Region (legend is in Fig. 3.):
Geodynamically active structures (circled indices): 1—southern margin of East European craton; 2–Scythian; 3—Mysia 4—Ustyurt–West Turan; 5—Black Sea–Caspian; 6—Trans-Caspian–Turkmen; 7—Smaller Caucasus–Binalud; 8—Anatolia–Iran.
Red-color dashes—state border of Russia and some international demarcation lines of water areas

margins of some systems facing zones of interactions between block masses.

The geodynamically active structures, which integrate compression and tension zones in the regions of the Black Sea, Caucasus and Southern Caspian [49], join into the single Black Sea–Caucasus–Southern Caspian system. At the same time, the local Paleozoic–Mesozoic (or even more ancient?) Euxinus block mass loses its integrity and independence, and decomposes into zones and areas having their own geodynamic trends concordant with the general regime of development of the Black Sea depression [50].

The Ponta–Southern Caucasus and Anatolia–Iran GAS mainly preserve the set geodynamic regime, at some intensification of compression and orogeny.

Recent geodynamically active structures (**Fig. 6**). The recent geodynamically active structures of the Black Sea–Caspian Region feature the southern localization of the most active tension, compression and the associated structuring, while the north is an area of platform stabilization with prevailing vibrations. Only the southern margin of this area, adjoining the active movement belt, gets 'captured' by these movements and, thereby, adjoins this belt.

The Southern Eurasia Belt of mobile platforms is concordant with the geodynamically active structures which feature dominant stabilization at the current stage of tectonics and geodynamics, namely, the Mysia, Scythian and Ustyurt–West Turkmen GAS.

The most pronounced extension and downwarping and the associated compression and orogeny are connected with the Black Sea–Caspian geodynamically active structure. The regional extension situations take place mostly in the depressions of the Black Sea and Southern Caspian. The situations of compression supportive to orogeny are mainly typical of the southern periphery of deep sea depressions and, locally, to the northern periphery of the Black Sea depression in its contact zone with the Scythian plate and the southern periphery of the Scythian GAS.

The outline of the Black Sea–Caspian GAS involves also the zone of varied geodynamics in the southern margin of the Scythian plate.

The alternate activity geodynamics of the previous ages is preserved in the Smaller Caucasus–Binalud system, which may be associated with its occurrence in the 'arrow' (vector) of pressure from the side of the Arabia block mass, oriented from the southwest to the southeast, in line of the Eastern Caucasus–Northern Caspian, and with periodic compression–tension pulses from the side of this block mass.

Conclusions

Based on the reconstruction and analysis of development and evolution of the geodynamically active structures in the Black Sea–Caspian Region, and in the framework of the constructed models, the authors have drawn some conclusions as follows.

Development of the Black Sea–Caspian Region in the period from the Late Paleozoic age to the Pleistocene had a trend of gradually decaying geodynamic activity, directed from the northern external boundary of the Paratethys towards its interior, and extrinsically resembled freezing of a long ice-hole between large ice fields in an ice aquatic area.

In the northern belt of this region, because of the gradual decrease in the geodynamic activity and owing to the stabilization of large block masses in the basement, a belt of mobile platforms overlaid sometimes with a rather thick cover was formed. Higher mobility of these platforms is preserved mostly at the tectonic boundaries between the block masses and their associations. Thus, at these boundaries, dislocation of both the basement and sedimentation cover increases, and the spatial 'density' and geometrical 'volumes' of potential hydrocarbon traps grow.

In the Central Black Sea–Caucasus–Southern Caspian belt, the geodynamics is most active and longer, and is preserved up to the present moment. The geodynamic activity shows itself in the formation of high-amplitude orogenic structures, deep depressions with preserved relict structures of the ancient basement, in the gigantic total amplitude of the surface structures of the basement—from the tops of mountains to the bottom of the sedimentation cover in depressions (up to 25–30 km), which suggests the huge potential energy reserves for the self-development of the regional tectonics, and, finally, in the extremely high level of the recent seismicity.

In the southern outskirts of the Black Sea–Caspian Region, the Anatolia–Iran system of mobile block masses is formed on the mainly high basement with relatively thin sedimentation cover and with widely spread magmatic events of various geological age. This system represents a unique 'buffer' between the Black Sea–Caspian Region and the Arabia block mass (which is assumed as one of the critical geodynamic factor of structuring in this region), which redistributes its own geodynamic impulses.

The geophysical study of large interaction zones between the block masses at the level of the basement of mobile platforms, which initiates deformation of the overlying cover and influences sedimentation conditions, is of practical interest in exploration and localization of mineral deposits, including oil and gas promising bodies, at the level of deep horizons of the plate cover.

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MODERN STRUCTURAL AND TECTONIC MODEL OF THE CASPIAN REGION

The article analyzes the development and evolution of the structural and geodynamic systems of the sedimentary complex in the Caspian region, and the results of structural and tectonic modeling of individual tectonic zones in the region. Based on the modeling results, an important feature of the morphology and structure of the basement surface and sedimentary complex in the Caspian Sea is the tracked sea extension of many elements detected on land. The main features of the morphology and structure of the basement surface and sedimentary complex in the Caspian region are the presence of superdeep depressions of the earth's crust, with the basement depth up to 16 km or more in the North Caspian and up to 20–24 km in the South Caspian, as well as the distinct longitudinal (sublatitudinal) tectonic zonality of the region. Constructed as a result of the implemented reconstructions, the generalized geological and tectonic model of the uneven-aged basement surface comprises the sea and continental parts of the region under study.

Keywords: *Caspian region, structural and geodynamic systems, modeling, morphology, basement, sedimentary complex, geological and tectonic model*

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Introduction

The aim of this work is to analyze the development and evolution of the structural and geodynamic systems of the sedimentary complex in the Caspian region. The main feature of the morphology and structure of the basement surface in the Caspian region is the presence of superdeep depressions of the earth's crust with the basement depth up to 16 km or more in the North Caspian and up to 20–24 km in the South Caspian. Each of these depressions, in the deepest part, includes the graniteless areas of the earth crust; each of them is associated with the discovery of oil and gas, including large and unique hydrocarbon resources. Geologically, we understand the basement surface in sea regions as the partition of the plate complexes of an undisturbed or very weakly disturbed sedimentary cover and, to a different extent, disturbed and uneven-aged basement complexes, which may include layers of deformed primary platform section. The combination of superdeep depressions and high-stand areas of the eroded surface in the folded basement within the mountainous areas of the region, primarily in the Greater Caucasus, governs a gigantic vertical range of the generalized relief of the basement surface in the region, amounting to at least 25–30 km.

Research technique

The main research methods include: paleotectonic and paleogeographic reconstructions, construction of general structural maps, numerical spatial and temporal basin modeling. During the research of the Caspian region and adjacent territories, we used classical methods of reconstructing sedimentation conditions in the geological past, such as the analyses of thicknesses and facies, formation composition of sediments, breaks and disconformities, using a large amount of published and archived materials.

Modeling of tectonic development is the process of reconstructing history of changes in the tectonic processes of downwarding and rise in time and space, as well as reconstructing stages of initiation and kinematic activity of faults and their systems in the region. To make up such reconstructions of basin evolution and the evolution of discontinuous systems in the area under consideration, we collected and systematized all currently available regional and geological, geophysical, lithological and petrological, lithological and stratigraphic, geochemical and other data on their structure.