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INFLUENCE OF MODERN GEODYNAMICS ON THE STRUCTURE AND TECTONICS OF THE BLACK SEA-CASPIAN REGION*

The article considers the monitoring results of long-term geodynamic observations, on the basis of which the concentration areas of elastic stresses and strains in the depositional sequence, displacement of geodetic coordinates of on the Earth's surface, as well as the variations in electric and magnetic fields are studied. The authors analyzed the results of the magnetometric studies to identify the seismomagnetic effect and assessed the stress–strain behavior of seismogenic areas. To observe the changes in the Earth's surface due to geodynamic processes, we used high-precision GPS measurements carried out using the differential method and the so-called GPS base stations. From the comparison of earthquake parameters and based on the geological model of the sedimentary cover with regard to the seismic data of the common depth point (CDP) method, we conclude that the earthquakes recorded in the Black Sea–Caspian region in 2006–2010 occurred on the border between the Mesozoic and Cenozoic levels and within the Cenozoic interval of the geological section. Degassing monitoring based on the geophysical observatories of mud volcanoes indicates that the gas regime and degassing in the region are closely related to the impact of modern geodynamics on the evolution of the surface and deep shells of the Earth, as well as on the accumulation of combustible minerals.

Keywords: *Black Sea–Caspian region, geodynamic processes, mud volcanoes, earthquake, seismicity, deformation, seismology, geodynamics, seismic activity.*
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Introduction

The Black Sea–Caspian region located in the southwest of the Eurasian tectonic plate is an impact area of active modern geodynamics. The critical feature of the structure of the Caspian-Black–Sea region is the stress state of its subsoil, as well as high and varied geodynamic activity. Its striking manifestation is various explosive phenomena, including seismicity, earthquakes, 'sedimentary' volcanism, etc., which governs intensity of geo fluid dynamics in turn [1, 2]. Over the past 20 years, the geodynamic activity in the Africa–Arabian–Eurasian plate system has been measured directly using geodetic observations, primarily GPS [3–5]. Most of the earthquakes that occurred in the study area are associated with the large-scale convergence, divergence and transformation processes in the contact area of the Arabian, Indian, African and Eurasian plates (**Fig. 1**).

The origin and evolution of the Caucasus is mainly explained in terms of plate tectonics. According to [7–9], thrust faults predominate in the modern Caucasus due to continental collision. From the Jurassic to the Paleogene era, subduction of the Tethys Sea bottom occurred along the southern margin of the Turkish and Iranian blocks, resulting in calc-alkaline arc volcanism and in formation of a wide system of back-arc basins. At present, the convergence of continents continues at a rate of up to ~20–30 mm/year [7]) along the strike-slip faults, where most of modern tectonic activity is localized.

Figure 2 shows a close-up of the GPS velocity field around the Greater and Lesser Caucasus, which provides a quantitative basis for estimating the location, velocity and direction of sliding of the main structures under deformation.

As seen in Fig. 2, reduction in the Arabia–Eurasia collision area mainly occurs along the southern border of the Greater Caucasus. The North Caucasian Plate consists of two different-sized elements: the plate itself, having an epigercynian basement, and the Main Ridge block (accretionary prism), located in the frontal part of the plate and having the Paleozoic base. The edge structure of the plate in the Central Caucasus is the uplift of the Front Range. The boundary of these elements is marked by the narrow Pshekish–Tyrnyauz fault area.

Based on the study results, most earthquakes are associated with local geodynamic deformations occurring inside the sedimentary cover (**Fig. 3**). The bulk of the earthquakes recorded in 2006–2010 occurred at the boundary between the Mesozoic and Cenozoic levels and within the Cenozoic interval of the geological section. This conclusion was obtained by comparing the earthquake parameters and a geological model of the sedimentary cover, built according to seismic data by the common depth point (CDP) method.

Degassing monitoring based on the geophysical observatories on mud volcanoes indicates that the gas regime and degassing in the region are closely related to the modern geodynamic impact [1–13]. Mapping and assessing the removal scale of carbon-containing gases is one of the critical challenges in modern science. Formation modeling, forecasting and prospecting methods for hydrocarbon (HC) accumulations in complex geological conditions, primarily at great depths, are the important practical tasks.

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Study methods

The studies of the impact exerted by modern geodynamics on the structural and geodynamic systems of the Black Sea–Caspian region used the methods and approaches applied within the framework of the joint research implemented by the Azerbaijan Republican Center of Seismological Service, the Institute of Oil and Gas of the National Academy of Sciences of Azerbaijan and the Russian State Geological Prospecting University named after Sergo Ordzhonikidze.

On the basis of long-term geodynamic monitoring of the Black Sea–Caspian region, we investigated the concentration zones of elastic stresses and strains inside of the depositional sequence; displacement of geodetic coordinates of points located on the Earth's surface; electric and magnetic fields. This study series also included monitoring of geochemical and hydrogeological processes. The seismomagnetic effect (SME) properties were studied in order to analyze the geodynamic mode of the regional structure. We also found the form and behavior of this effect, its physical properties, as well as proved its seismotectonic dependence.

GPS instruments have been used successfully for a number of years to monitor changes of the Earth's surface due to geodynamic processes. High-precision GPS measurements were carried using the differential method and the so-called GPS base stations (this method is also called the relative kinematics method). Each base station in Azerbaijan is equipped with Trimble Net R9 receiver, Zephyr antenna and Choke ring.

As noted above, the impact results of modern geodynamics on the structural and geodynamic systems are mud volcanism and degassing of the Earth. Modern hydrocarbon degassing is accompanied by significant geodynamic phenomena, which are recorded in the form of earthquakes and can be mapped by modern telemetry systems in real time.

Study results and their discussion

The structural and geodynamic systems of the Black Sea–Caspian region are located along the northern part of the collision area of the Arabian and Eurasian plates, and include the most of the Greater and Lesser Caucasus, fore deeps and intermontane areas, as well as the Caspian Sea. The GPS velocity field in the collision area of the Arabian and Eurasian plates is well modeled by a system of blocks and plates (for example, areas with small internal deformations) separated by faults accumulating interblock movements. The current stress state of the lithosphere in the Black Sea–Caspian region is studied based on the World Stress Map (WSM), which includes various global and local databases on focus parameters from various catalogues of the Seismological Service Center of the Republic of Azerbaijan, CMT of Harvard University, USGS DB [14, 15].

By mapping the data obtained, the change in the movement speed of the main structures in the study area was calculated for 1 month. It is found that the velocity varies within 1.5–2.0 mm for the territory of the Greater and Lesser Caucasus in the NNE direction, an within 1.0–1.5 mm for the territory of the Kura–Rion intermountain area in the NE direction. It follows from the analysis of the results that the deformations of the Earth's crust are unevenly distributed in Azerbaijan, although the dominant mode is compression. The study of modern movements and deformations, based on the analysis of the influence exerted by the configuration of the geodetic network elements on the estimates of the Earth's surface deformation, reveals the heterogeneous nature of the deformation field in the region. This is mainly due to the block structure of the region. Based on the GPS data analysis for 2015–2016 the GAMIT program has found that the average velocity is 10 mm per year throughout the region. In the Greater and Lesser Caucasus, the Earth's crust movement in the region occurs in the S–NE direction.

As follows from the work [10], the majority of deformations in the plate collision area occur in three seismically active regions, namely, from the south to the north: Bitlis–Zagros fold and Elbrus–Kopedag thrust belt, the Greater Caucasus mountains and the Caspian Sea central part, which is the Caspian seismic area. The main horizontal constriction area is confined to the west of this northern area, where the Main Caucasian thrust is the dominant structure.

South of the Main Caucasian Thrust, the plate convergence is mainly compensated by lateral displacement of the Earth's crust from the convergence area. Thus, as evidenced by the research results, the deformation in the collision area – the Black Sea–Caspian region – is complex since it includes rotation of the Earth's crust blocks along faults.

Statistical analysis of earthquake parameters and interpretation of CDP seismic data

The statistical analysis results on earthquake parameters show that the hypocenters of the vast majority of earthquakes, including the strongest quakes, are located on the contact surface of the Mesozoic and Cenozoic levels of the geological section. According to statistics, 2405 earthquake hypocenters out of 3642 are located at a depth of less than 22 km. The number of earthquakes with an epicenter in the interval of 8–22 km is 1986, which is 55% of the total.

The epicenter analysis shows that their gravity center is shifting from the northeast to the southeast. Moreover, it coincides with the axial line of surface deepening of the Mesozoic complex of deposits in this direction. Thus, with growing thickness of the depositional sequence, the magnitudes of the earthquake hypocenters within the specified period (2006–2011) increase. At the same time, the number of earthquakes occurred at depths of $8<h<22$ km sharply increases and their distribution area expands throughout the entire territory of the South Caspian basin. There is also a significant shift in the epicenter coordinates towards the Caspian Sea, where there were more earthquakes at depths less than 22 km in general. The analysis of the diagrams of the earthquake hypocenter distribution in depth shows that the sources of earthquakes, the epicenters of which are within the interval of $0.5<h<8.0$ km, are associated with the geodynamic processes in the plastic Paleogene–Miocene sediments. The number of earthquakes with epicenters at $8<h<22$ km is 1986 from 2006 to 2010. As shown by the seismic sections in **Fig. 4** (A–A, B–B, C–C lines), the sources of these earthquakes are located at the contact of the Mesozoic and Cenozoic depositional sequences and in the inner parts of the Cenozoic. The first group of the sources is associated with the geological section movements at the contact surface of the Mesozoic and Cenozoic intervals at the depths of 8–22 km, having a general slope in the northwest–southeast direction.

The second group of hypocenters is associated with the internal dislocations in the Cenozoic age layers with molasse composition. In other words, these earthquakes took place at

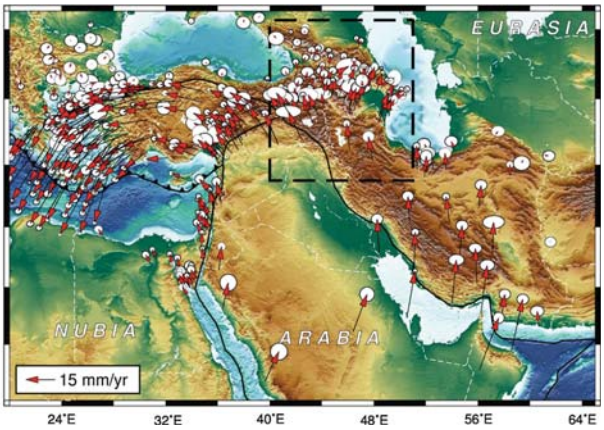

Fig. 1. GPS speeds and 95% confidence ellipses relative to Eurasia (according to [6]) in the Eastern Mediterranean by [7], with updated speeds in the Caucasus

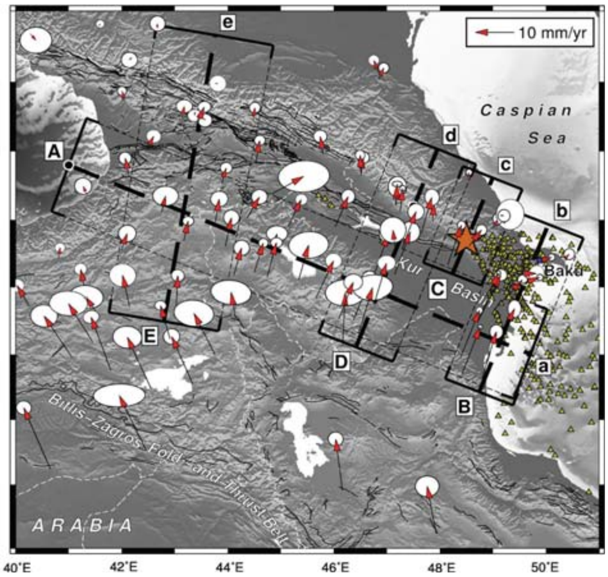

Fig. 2. Map of plate movement velocities in the Caucasus relative to Eurasia. GPS velocities and 95% confidence ellipses relative to Eurasia for the eastern collision area. Lateral (AA′) and parallel (BB′-EE′) velocity profiles across the Caucasus system, which roughly coincide with the GCFTB surface expression:

1 – GPS-based velocities of plates, mm/yr [10]; *2* – 95% confidence ellipses relative to Eurasia for the eastern collision area; *3* – 1902 Shamakhi earthquake epicenter

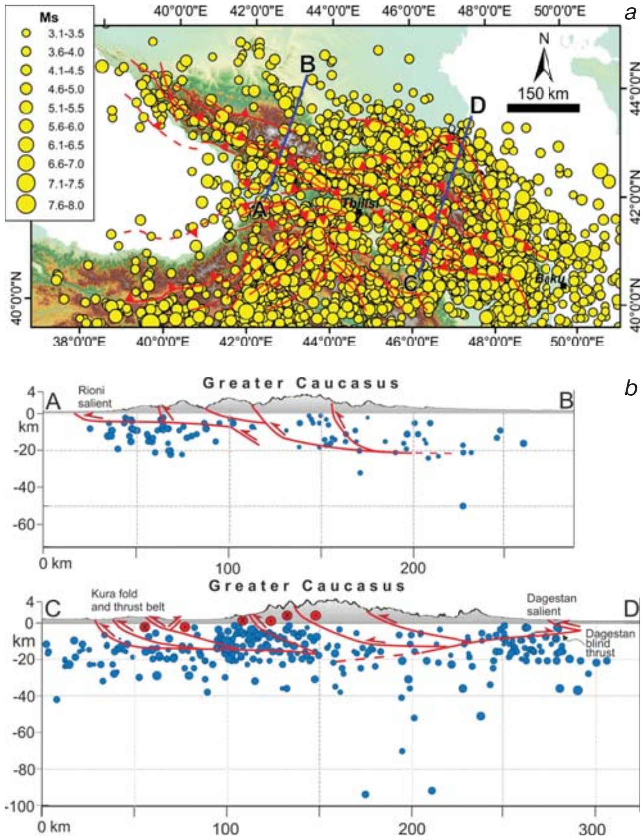

Fig. 3. (*a*) Map of independent earthquake epicenters in the Black Sea–Caspian region (yellow) and the main active faults (red); (*b*) section of the western (A–B) and eastern (C–D) parts of the Greater Caucasus with the points of seismic events with MS>3.5 (blue) and the main active faults (red)

the inner points of the thick depositional sequence and in the contact area of the Mesozoic and Cenozoic deposits.

It is seen in the time section shown in Fig. 4 (E–E line) that the seismic section corresponds to a geological section composed of plastic rocks at depths of up to 7.5 km (dh = 5×3|2 = 7.5 km, an average velocity of 3.0 km/s). The section shows that the geological section is strongly dislocated under the influence of tangential forces induced by the horizontal reduction in the size of the South Caspian Basin as a whole. At the same time, the Cenozoic interval of the section is involved in the strong shearing processes, which initiated shear faults, while the Mesozoic interval composed of more competent rocks is made concave into a syncline. The time sections in Fig. 4 along the C–C and F–F lines are the convincing evidence of the ongoing narrowing of the mentioned basin.

The earthquakes of the next group, as we see it, also occurred in the inner layers of the Cenozoic depositional sequence and in the Meso–Cenozoic contact surface. The mechanism of these earthquakes is associated mainly with mud volcanic processes.

At the same time, we believe that the dominant role belongs to fluid-dynamic processes and to tangential compression of the entire sedimentation basin [16–18]. This is confirmed by comparing the seismic sections shown in Fig. 4 (C–C and D–D lines) with the map of earthquake epicenters in Fig. 3. The earthquakes at the depths greater than 22 km occurred as a result of compression of the entire South Caspian basin under the influence of global plate tectonic processes.

The interpretation results of the time and depth seismic sections obtained from CDP seismic data on the onshore territory of the South Caspian depression (A–A, B–B, C–C and E–E lines) and in the Caspian Sea (D–D and F–F lines) indicate that they have completely different features of the seismogeological structure. The seismic section along the A–A line approximates depths up to 8 km. The time sections

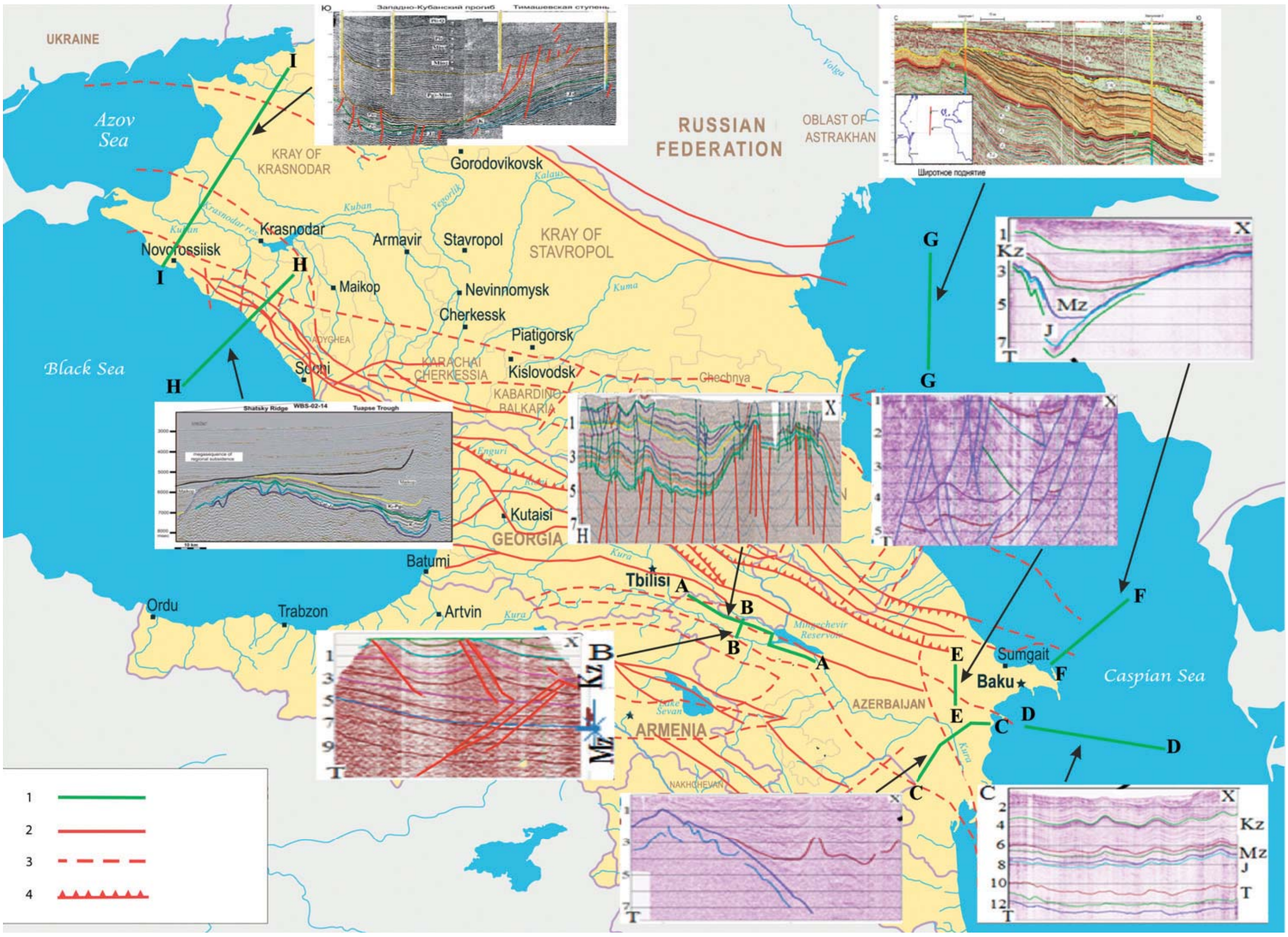

Fig. 4. Seismic profiles characterizing tectonic structure of areas along the lines: A–A, B–B, C–C, D–D, E–E и F–F, G-G, H-H, I-I:
1 – lines of seismic sections, 2 – largest faults, 3 – supposed faults, 4 – largest thrusts and overthrusts

make it possible to assess the tectonic structure of areas along the line of seismic observations down to depths as follows (at an average velocity of seismic wave in the geological environment of $\approx$ 3 km/s): B–B<12 km, C–C<10 km, D–D<20 km, E–E<7 km and F–F<10 km. The analysis of the wave field dynamics and kinematics along the sections specified shows that the geological section is most strongly dislocated along the lines: A–A, B–B and E–E to the depths of 5 km. This section interval corresponds to the Cenozoic depositional sequence. It can be seen along the A–A and B–B lines that the Mesozoic level of the geological section is also divided into tectonic blocks. From the comparison, the tectonic blocks along the Mesozoic and Cenozoic levels are formed at different times and there is no direct connection between them. In other words, their formation mechanism is somewhat different. At the Cenozoic level, we observe that the ruptures were formed in parallel with the folding process that took place during the horizontal compression of the entire sedimentary basin, and they are younger in age than the tectonic blocks in the Mesozoic section interval.

The same applies to the time section along the E–E line (Shemakha–Kobystan area). The time sections along the D–D, F–F and C–C lines characterize geological sections with completely different parameters, but they are similar to each other at the same time. Based on the results obtained, we map schematically the orientation of compression and tension axes of the studied earthquakes at the depths of 0–10 km, 11–25 km and 25–45 km for 2003–2018.

The analysis of the seismic process sequence shows that the considered sources have a certain connection. The analysis results of the distributions of strong earthquake sources make it possible to conclude that all strong earthquakes (M≥5.0) are confined to the crystalline basement surface area in the territory of the study region [19]. The Zagatala and Balaken earthquakes also prove this conclusion. An exception is the Ismayilli earthquake at the depth H=41 km, while the crystalline basement surface is at the depth of 10–12 km here. It should be noted that this is not the only earthquake in this area with such a source depth. A number of weak and medium-strength earthquakes with a source depth of about 40 km were noted here before. We believe that such an anomalous seismotectonic phenomenon for this area is associated with the complex regional fault tectonics and requires additional research [28].

Study results of mud volcanism

One of the most striking phenomena of modern geodynamics is its explosive variety – mud volcanism [20, 21]. Seismic monitoring using advanced seismic technology to image the underwater mud volcanoes was used to map the spatial position of the stimulation sources. Based on the interpretation of superdeep seismic data, we established unambiguous connections of the eruptive channel with the oil and gas generating intervals of the geological section, formation depth of their HW sources, geometric shapes and parameters of their eruptive channels.

The modeling results allowed creating a “sedimentation model” of mud volcano formation, indicating that their force generated under the influence of sedimentation load is evenly distributed over the entire surface relative to the liquid mass, as a result of which a tension area and a fracture system are created on the convex formation surface. These fractures are the first channels for the liquefied clay mass to squeeze towards the surface. Erosion and destruction of the near-fault surface constantly occur at the initial mud volcano formation stage, as a result of which an eruptive channel of the mud volcano is created [20, 22]. With an increase in the volume of rocks transported into the sedimentation basin, the geostatic pressure on the lower environment (mud mass in this case) increases. As a result of this process, a mud mass with the non-Newtonian liquid properties is squeezed out into the upper half-space and a volcano crater is created (second phase). At the end, the mud mass contains no rock fragments from the upper medium. The mud mass volume is preserved at all stages, which leads to the general subsidence of the sedimentation surface. That is, the initial phase of the source and eruptive channel of the mud volcano are formed according to the Rayleigh – Taylor theory of instability, and the subsequent phases take place due to the geostatic pressure.

It is found that earthquakes also play an important role in the mud volcanic process – earthquake magnitudes, source depth, energy class, and distance between the epicenter and the volcano [23]. The energy and power of fluid-generating processes in the source will characterize the strength of shallow earthquakes and mud volcanoes [11, 24–30].

Summary

The modern geodynamic feature in the territory of the Black Sea–Caspian region is its explosive variety – seismicity, earthquakes and ‘sedimentary’ volcanism, which govern intensity of geo fluid dynamics in turn.

The sources of most earthquakes are associated with local geodynamic deformations inside the sedimentary cover in the Black See – Caspian region located in the southwest of the Eurasian tectonic plate. Most of the earthquakes occurred at the boundary between the Mesozoic and Cenozoic levels and within the Cenozoic interval of the geological section. The rest (smaller) part of the earthquakes occurs inside the Mesozoic part of the Earth’s crust. Based on the analysis of the section geological structure features, we have proposed a seismic-geodynamic model of the studied area. The earthquake mechanisms in the Black Sea – Caspian region are associated with the impact of modern geodynamic processes on structural and geodynamic systems. The concept of the earthquake confinement to the areas of the known tectonic faults is not supported by the CDP seismic data. However, they have a high correlation coefficient with faults formed during modern geodynamic and fluid-dynamic processes. These processes are accompanied by the global plate tectonic movements that initiate regional tangential compression of sedimentary basins and mud volcanic activity in the inner layers of the Cenozoic depositional sequence. The earthquakes that occurred in the inner layers of the sedimentary strata are the mechanism of relaxation of stresses accumulated under tangential compression of the entire basin and due to fluid-dynamic processes.

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GEOLOGY AND GOLD CONTENT OF CARBONACEOUS SHALE IN BAIKAL MINERALIZATION SITE, SOUTHERN URAL

The authors analyze gold mineralization in Baikal site inside Kumak ore field, adjoined to Bredin black shale sediments (C1bd). It is found that the gold mineralization within the site adjoins mostly bands of quart–micaceous–tourmaline metasomatically altered carbonaceous shale. Float sampling of all local rock varieties shows commercial content of gold (to 6.5 g/t) and stable high content of silver (to 7.6 g/t). Gold is mostly finely dispersed, and is connected with two basic mineral associations: gold–bismuth–telluride and native gold intergrown with tourmaline. The analysis of compositions of gold particles reveals their high carat type. Chemically, tourmaline belongs to dravite and foitite, and is similar to tourmaline from the deposits of orogenic gold and gold-bearing sulfide ores. Tight accretion of fine needle-like tourmaline and gold implies their synchronous formation, and allows assessing Baikal site as the quartz–tourmaline gold ore formation.

Keywords: *Southern Ural, Kumak ore field, Baikal ore site, carbonaceous shale, black shale, noble metals, gold, silver, telluride, tourmaline.*
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Introduction

Black shale sediments are widely spread worldwide. They represent a very favorable geochemical environment for the primary chemical adsorption of noble and rare metals and are the source of such metals during metamorphic alteration [1–6]. Black shale sediments are associated with gold deposits in the world and in the Southern Ural [7–10]. In the Orenburg Region of the Southern Ural, gold-bearing ore occurs in carbon deposits of Kumak ore field adjoining the Anikhovsky Graben of the East Ural Uplift. Here, a score or two gold ore deposits were discovered (East Tykasha, Kommercheskoe, Zabaikal, Baikal, Tsentralnoe, Kumak, Kumak South, etc.). Numerous exploration and geological studies accomplished in this area within nearly a century enabled adjustment of the ore field geology, as well as the metallogeny imaging and reconstruction of deposition of sediments [7, 11–14].

The key objectives of this study are examination of carbon deposits in Baikal mineralization site, assessment of their gold content, and specification of features of noble-metal