Deep Structure and Geodynamics of the Black Sea−Caspian Region

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Abstract—New data on the crust structure of the Black Sea−Caspian region, including the Scythian and Anatolian plate margins, the Caucasus, Black Sea and Southern Caspian structures are reported. Generalization and analysis of the data of deep seismic studies with an estimate of their reliability were performed and the velocity sections of the crust were constructed. Based on the data of deep drilling data and studies of the crust composition in xenoliths in these sections, three major layers were identified in the crust: granite-gneiss (6.0−6.4 km/s), granulite-gneiss (6.5−6.7 km/s), and basic (6.8−7.2 km/s). According to the thickness of these layers, the major types of the crust were distinguished. Three continental types with all three layers, but different in the total thickness of the crust types were distinguished in the area of the Scythian and Anatolian plates. The oceanic type with thin basic crust and two transitional types, subcontinental and suboceanic, with the different total thickness of the crust and the thickness of the basic layer were distinguished within the deep sea basins. There are anomalous types of the crust in the Caucasus region: the thick crust of the Lesser Caucasus with anomalously low velocities and the thick high-velocity crust of the Reon−Kura Trough. According to the seismological data, the crust of the Black Sea−Caspian region is separated from the platform plates bounding it by the deep faults and crossed by two transform faults; the upper mantle of the Caucasus differs from neighboring regions by reduced velocities. Based on the analysis of the material obtained and CDP data on the basement structure, the new structural and geodynamic schemes of the crust of the entire region were compiled, and it was shown that the formation of depressions with oceanic and suboceanic crust types corresponds to the platform regime characteristic of the depressions of Eastern Europe. A new collisional model with the overthrust of the Anatolian Plate crust onto the crust of the Lesser Caucasus without change of the structure of the upper mantle was proposed to explain the structure of the Caucasus region.

Keywords: Black Sea, Southern Caspian, the Caucasus, the earth's crust, upper mantle, seismic profiles, seismic tomography, types of the Earth's crust, collision model of the Earth's crust, geodynamics, geology

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INTRODUCTION

The Black Sea−Caspian region, which includes the southern margins of the East European Platform (EEP) and Scythian Plate, deep basins of the Black Sea and the South Caspian, and mountain structures of the Greater and Lesser Caucasus, are well studied from the results of detailed investigation of the tectonics of the East European Plate [11, 23, 27, 42]. Extensive studies were carried out in the Black Sea−Caspian region [2, 8, 22, 39, 40, 45, 67, 69]. On tectonic diagrams, this region is described as a wide tectonically active zone between the East European Plate in the north and the Anatolian and Arabian plates in the south. However, the interpretation of these data from the point of the history of the formation of significantly different tectonic structures in the region turned out to be extremely ambiguous; many fundamentally different geodynamic models were proposed: from platform to collisional, which are difficult to reconcile with each other. These models are based on the geological mate-

rial, while the geophysical data on the deep structure of the region were not taken into account. This is due to the difficulty in application of ambiguous data obtained mainly in different years and by different organizations.

The aim of our study was to systematize the seismic data on the structure of the Earth's crust and upper mantle of the Black Sea−Caspian region together with the geological and seismological data obtained, and to provide a new geodynamic model for the evolution of this region. According to this model, the Black Sea−Caspian region is a reworked southern margin of the East European Plate, bounded by deep faults on both sides. As a result of the platform endogenic regime and processing of the Earth's crust due to the intrusion of mantle material into the crust, the deep basins of the Black Sea and South Caspian were formed. The collisional regime in the Caucasus region stimulated thrusting of the Arabian Plate crust over the primary crust of the Scythian Plate without change of the upper mantle structure.
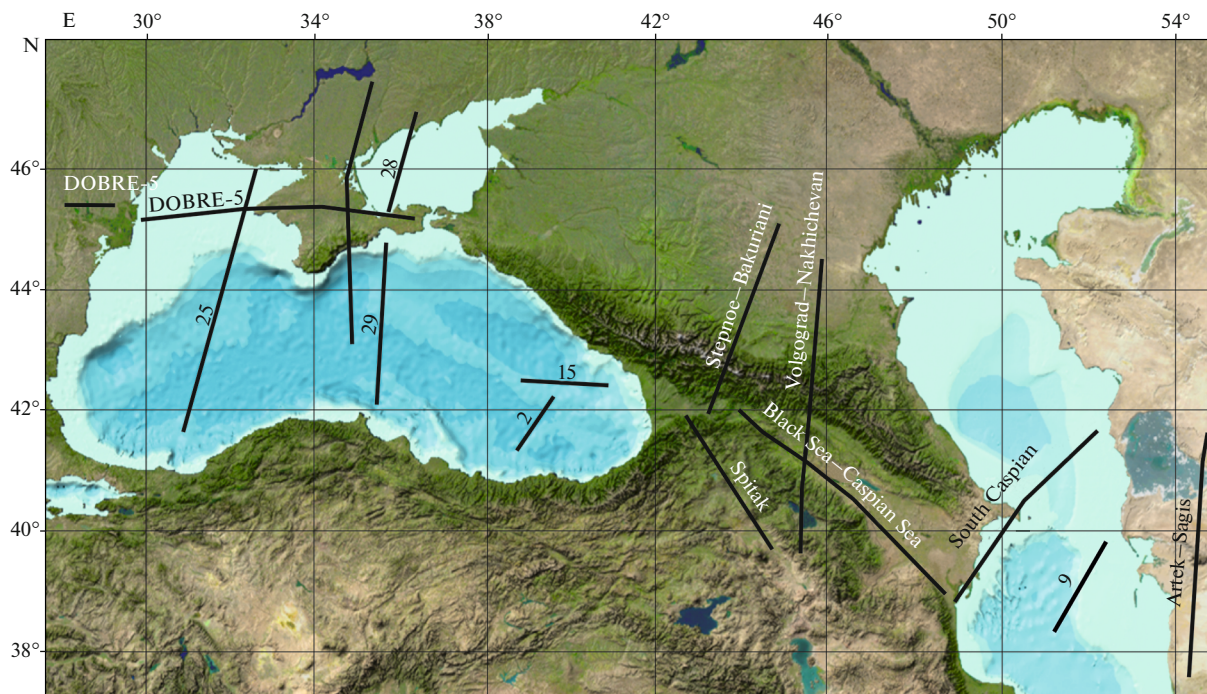
Fig. 1. Scheme of most detailed DSS profiles in Black Sea−Caspian region (after [71], modified).

RESEARCH METHODS

The most detailed data on the structure of the Earth's crust in the Black Sea−Caspian region were obtained by the method of deep seismic sounding (DSS) (Fig. 1) based on the registration of huge explosions along extended profiles. The first DSS studies were carried out by the Institute of Physics of the Earth (USSR Academy of Sciences) in the Tien Shan in 1948−1949 with the registration of explosions in lakes Issyk-Kul and Balkhash [9]. The experimental studies on recording explosions in deep water bodies and in the regions with a thick Earth's crust were carried out just before 1947 in the Black Sea and the Caucasus. The further development of the methodological foundations of the DSS was continued in the Black Sea−Caspian region as well, which was a kind of experimental ground for many geophysical methods for a long time. Thus, the world's first marine studies of DSS with bottom stations and explosions were carried out in the South Caspian [10]. A series of profiles was worked out during these studies, two of them (South Caspian and profile 9) included the most complete observation systems (Fig. 1). At the same time, studies of the structure of the crust in the Black Sea commenced using small hydrophones and seismic vibrators [24, 25, 57]. A dense system of profiles of different lengths was worked out; the most extended and detailed of them were profiles 25, 28, and 29 (Fig. 1).

In the Caucasus, large-scale DSS study was carried out in the 1960s. These were the research of the Ministry of Geology of the USSR together with geophysi-

cal organizations of the Caucasian republics. The profiles Stepnoe−Bakuriani, Volgograd−Nakhichevan, Sukhumi−Masally (Black Sea−Caspian Sea), and Atrek−Sagiz were worked out [11, 18, 19, 38]. In the same period, the Institute of Geophysics of the Academy of Sciences of the Ukrainian SSR (Kyiv, Ukraine) worked out the Black Sea−Ukrainian Shield and the Ukrainian Shield−Carpathian profiles [33, 38, 39]. These studies provided the most detailed version of the DSS based on continuous profiling. Multi-channel reconnaissance stations moved along the profile with a distance between instruments of 100−200 m and simultaneously recorded explosions from 3−4 to 7−8 points. Records were obtained up to offsets of 300−400 km with clear first signals and many waves in the subsequent part of the record. This allowed us to reveal the main structural patterns of the crust in the Black Sea−Caspian region even at that stage, such as an increase in its thickness beneath mountain structures and a reduction beneath deep depressions with a sharp change in the velocity section (Fig. 2).

A significant increase in the detail of the DSS and the study of the Caucasus region by seismic methods were obtained in 1988 after the devastating Spitak Earthquake. At that time, a comprehensive study by the methods of DSS and CWE (converted waves from earthquakes) was carried out along the Lesser Caucasus [30, 43].

A new stage of seismic study in the Black Sea−Caspian region is associated with the recent DSS research
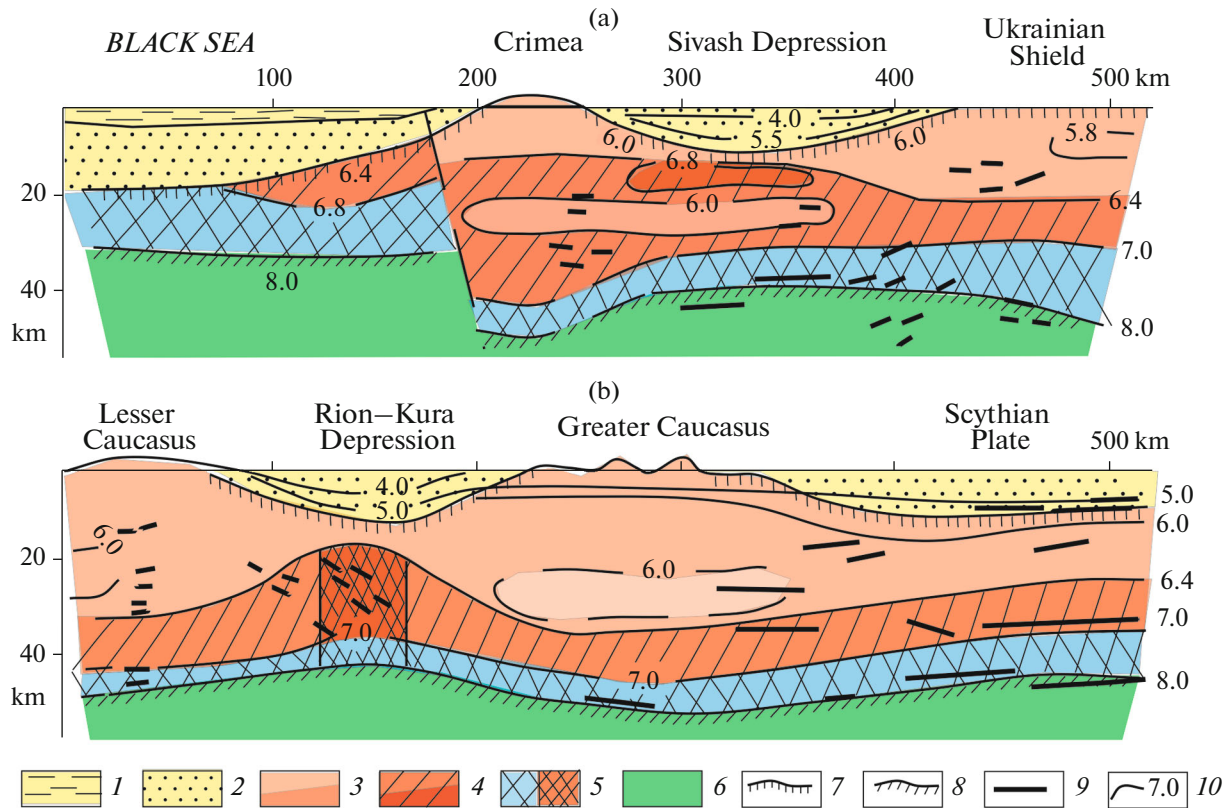
Fig. 2. Seismic sections along DSS profiles. (a) Black Sea−Ukrainian Shield, after [33]; (b) Volgograd−Nakhichevan, after [18]. (*1*) Water layer; (*2*) sedimentary layers; (*3*−*5*) layers of Earth's crust with *P*-wave velocities of 6.0−6.4 km/s (*3*), 6.5−6.7 km/s (*4*), and 6.8−7.2 km/s (*5*); (*6*) upper mantle (8.0 km/s); (*7*) basement surface; (*8*) bottom of Earth's crust, M boundary; (*9*) reflecting boundaries; (*10*) velocity isolines.

(this method was called the wide-angle reflection and refraction (WARR) abroad).

The Institute of Geophysics of the Academy of Sciences of Ukraine (Kyiv) tested the DOBRE-5 profile through the Crimea and the northwestern part of the sea in the framework of the international project DOBRE in the Black Sea area [68] (Fig. 1). In addition, a series of short profiles crossing the Eastern Black Sea depression was worked out [62−64] (Fig. 1, profiles 2 and 15).

In the early 2000s, detailed studies of the crust structure were carried out in the Black Sea area as well, using the method of reflected waves (the common depth point method, CDP), within the international project "Geology Without Limits," in which exploration organizations from Turkey, Romania, and Bulgaria participated [58]. The studies were carried out using pneumatic guns and seismic streamers; a dense network of profiles with a total length of 8890 km was worked out. As a result, the structure of the basement surface and the sedimentary cover over the entire area of the Black Sea deep basins was studied with a high degree of detalization, and in some cases, the structure of the entire crust of the region.

Thus, seismic studies of the Black Sea−Caspian region were carried out by different organizations for almost 70 years with constantly changing monitoring systems and methods for processing of experimental data. The data of the first DSS studies were constantly revised using new methods of interpretation [3−5, 11, 30, 31, 38]. Here we summarized all these materials and assessed its reliability in the basis of mathematical modeling. To do this, the preserved primary records obtained on the most detailed profiles were re-processed using a single technique based on the ray tracing method (Fig. 1). This technique is specified by the application of modeling for construction of the velocity sections, as well as for identification of the type of recorded waves and their intensity.

STRUCTURAL PATTERNS OF THE CRUST OF THE BLACK SEA−CASPIAN REGION

Data of DSS Profiles

The main structural patterns of the Earth's crust in the Black Sea−Caspian region were obtained from the first DSS profiles (Fig. 2). A clear division of the region into crust of different types was shown: platform crust with a thickness of ~40 km, mountain crust
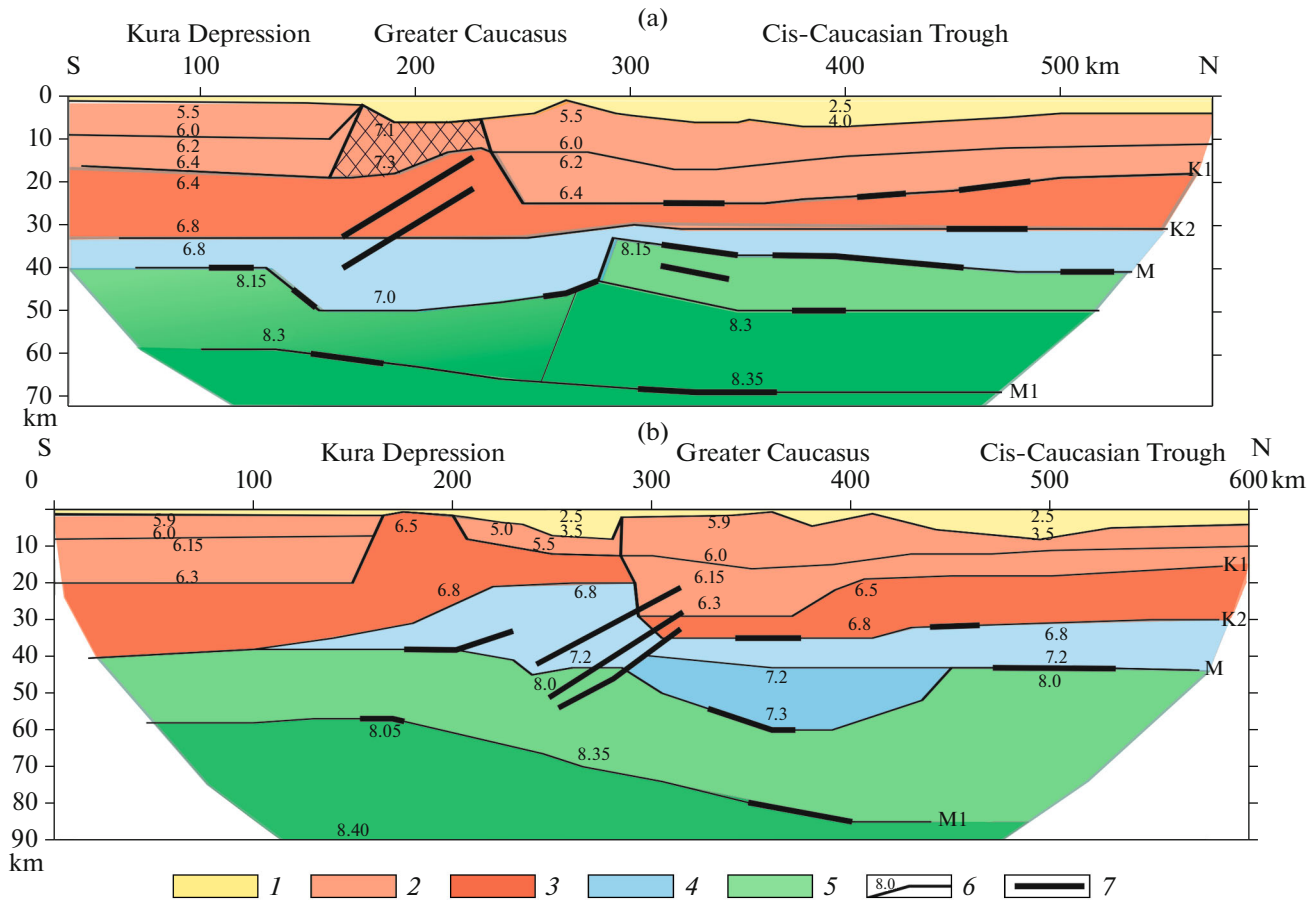
Fig. 3. Seismic sections along profiles crossing Greater Caucasus, modified after [29]. Position of sections is shown in Fig. 1. Profiles: (a) Stepnoe−Bakuriani; (b) Volgograd−Nakhichevan. A layer with anomalously high velocities (>7.3 km/s) is shaded in upper crust. (*1*) Sedimentary layers (≤5.5 km/s); (*2*) granite-gneiss layer (5.8−6.4 km/s); (*3*) granulite-gneiss layer (6.5−6.8 km/s); (*4*) basic layer (6.8−7.2 km/s); (*5*) upper mantle (>8.0 km/s); (*6*) velocity isolines; (*7*) reflecting plains.

with a thickness of >50 km, and deep depression crust of reduced thickness (up to 30 km). At the same time, according to seismic velocities in the consolidated part of the crust, three major layers were distinguished: upper (5.8−6.4 km/s), intermediate (6.5−6.7 km/s), and lower (6.8−7.2 km/s).

According to the data on the Kola Superdeep Borehole and results of studying the physical characteristics of rocks of different compositions, these layers were called granite-gneiss, granulite-gneiss, and mafic layers [31, 50]. They are often referred to simply as upper, middle, and lower crust for brevity. These layers are usually separated by clear seismic boundaries.

Caucasian Region

There are three major structures in the Caucasus region: the mountain structures of the Greater and Lesser Caucasus and the Rion−Kura Depression that separates them. The most detailed and reliable data on the structure of the Greater Caucasus were obtained via the repeated processing of primary materials along the Stepnoe−Bakuriani and Volgograd−Nakhichevan

profiles (Fig. 3). It was shown that the increase in the crust thickness beneath the mountain structure of the Greater Caucasus does not occur smoothly, but along deep faults, which are noted along the Moho (M) boundary and along the internal structure of the Earth's crust. The M boundary, which may be traced by intense reflected waves in the platform part, is destroyed in this zone as a single clear boundary, and is distinguished only by refracted waves. Numerous local dislocations are confined to the fault zone in the form of a series of inclined reflecting boundaries in the southern part of the mountains, and a change in the type of the crust occurs. From the north, the mountain structures of the Greater Caucasus are limited by a deep fault as well, which is clearly expressed in the structure of the M boundary. However, no sharp change in the crust structure is observed along this fault. On the contrary, along the entire extension of the Volgograd−Nakhichevan profile, the crust structure is similar to both the Scythian Plate and to the East European ancient platform. In the region of the Greater Caucasus, the structure of the upper mantle changes sharply: at a depth from 60 to 80 km, inclined
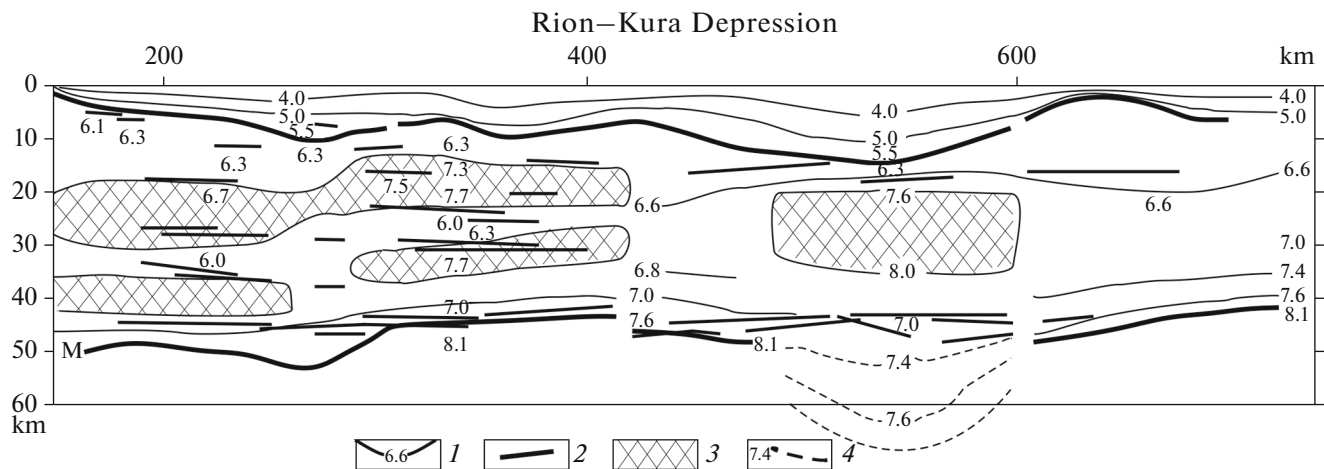
Rion−Kura Depression

Fig. 4. Velocity section for Sukhumi−Masalla profile along Rion−Kura depression from Black Sea to South Caspian, modified after [38]. Position of section is shown in Fig. 1. (*1*) Velocity isolines; (*2*) seismic boundaries; (*3*) areas of increased velocities; (*4*) inferred velocity isolines.

reflecting areas united into the M1 boundary are distinguished (Fig. 3). This boundary plunges from the Kura Depression towards the Cis-Caucasian Trough. A division into the western and eastern parts is clearly marked in the structure of the Earth's crust of the Greater Caucasus and is well expressed in the relief along the Stepnoe−Bakuriani profile (Fig. 1). At the same time, the deep faults are observed in the middle part of the Greater Caucasus, where the structure of the crust changes as well, rather than on the southern margin (Fig. 3a).

In addition, the division of the Caucasus crust into two parts with different structures is observed in the Rion−Kura Trough along the Sukhumi−Masally profile (Fig. 4). The velocity model of the crust for the Rion Basin (150−270 km), differs slightly from the model for the Scythian Plate, which is only complicated by a layer with an increased velocity (6.7 km/s) in the middle part. The thicknesses of layers with increased velocities in the Kura depression (270−460 km) increase significantly. The largest high-velocity block covering almost the entire consolidated part of the crust (500−600 km) was identified. However, despite all these changes, which are characteristic of deep depressions, the thickness of the crust remains almost constant and equal to the thickness of the crust of platform areas (>40 km).

The unusual structure of the crust is characteristic of the Lesser Caucasus, which is clearly evident from the Spitak profile (Fig. 5). The crust of these mountains is as thick (50−55 km) as that of the Greater Caucasus, although it can be assumed that low mountains should have "roots" of smaller amplitude along the M boundary. However, the average velocities in the crust of the Lesser Caucasus are significantly lower than those beneath the Greater Caucasus. For example, the velocities in the lower crust in the mafic layer beneath the Lesser Caucasus are lower (6.7−6.8 km/s)

in relation to the velocity in the crust of the Greater Caucasus (6.7−7.2 km/s). The presence of several clear, almost horizontal, reflective boundaries in the crust of the Lesser Caucasus is unusual for a mountain structure. A layer with a reduced velocity is distinguished at a depth of 30−35 km between them, and the M boundary along the entire Spitak profile is traced continuously by intense reflected waves.

In addition, many other structural patterns of the crust of the Lesser Caucasus were identified in the DSS section along the Spitak profile, since the data of the CWE and the observed DSS hodographs of both longitudinal (*P*) and transverse (*S*) waves [30] were applied in processing of the materials along this profile [13, 14]. Large layered intrusions were identified in the upper crust by these waves. A layer with an anomalously high *S*-wave velocity (4.0−4.1 km/s) was identified in the granite-gneiss part of the upper crust, at a depth of 5−15 km in an extended block with an increased (mafic) *P*-wave velocity (>6.6 km/s) (Fig. 5).

Deep Structure of the South Caspian

The data obtained by the DSS method in the deep basin of the South Caspian show that the crust of this deep basin is distinguished by a uniquely thick sedimentary sequence and a thin consolidated part of the crust (Figs. 6a and 6b). It is shown that the deep faults participated in the formation of this deep depression. Thus, in the eastern coastal part of profile 9, the thickness of the crust increases sharply, along a deep fault, from 10 km at the sea margin to 30 km in its deep part. In the north, the South Caspian Basin is limited by a fault identified by the CDP method during exploration studies (Fig. 7). The dimensions of this unique basin are limited by the contours of the Caspian Sea. However, it is evident from the Atrek−Sagiz profile that the South Caspian Trough continues in the coastal part
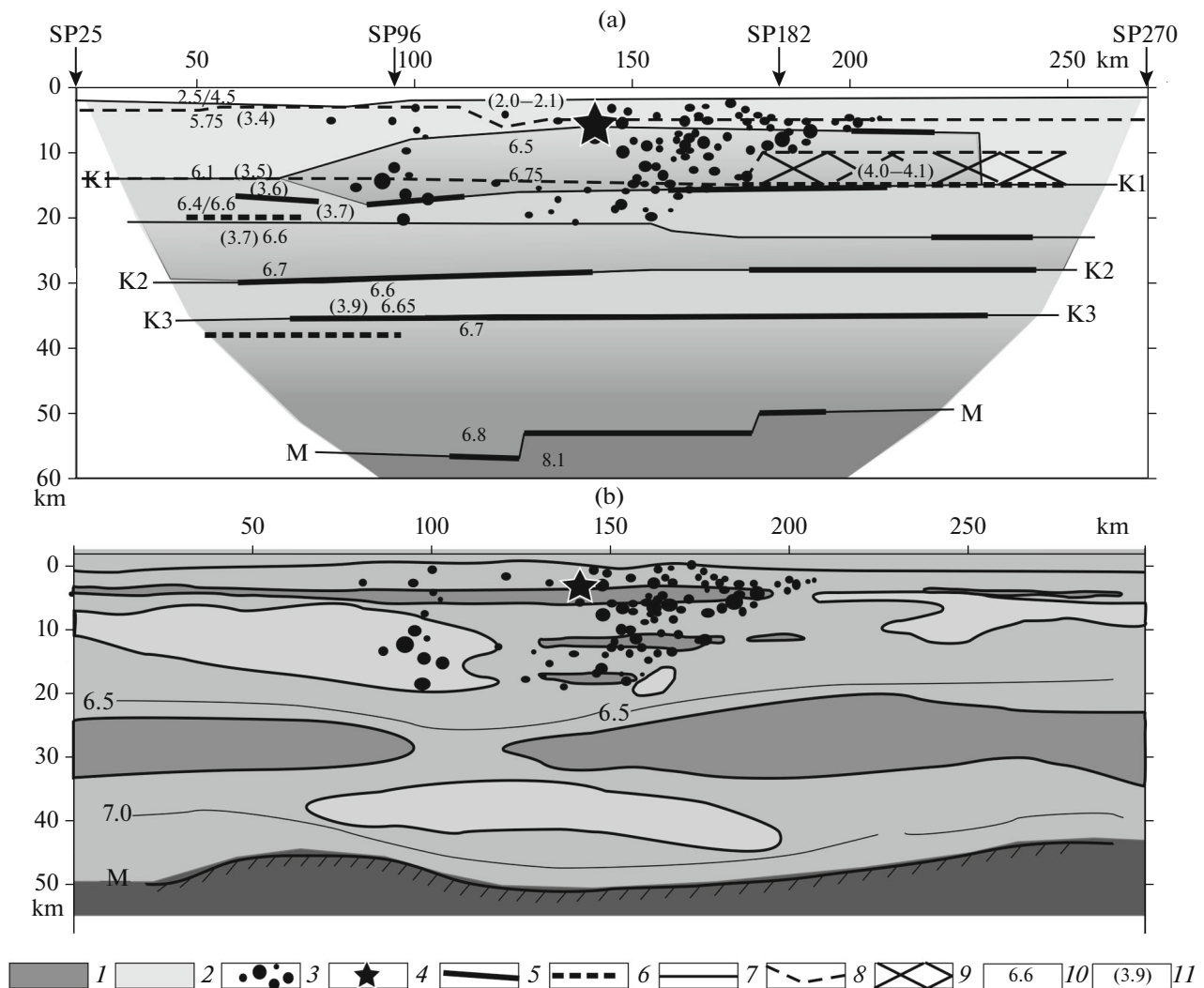
Fig. 5. Seismic sections along Spitak profile. (a) Consolidated seismic section of DSS plotted using data of longitudinal (*P*) and transverse (*S*) waves [30]; (b) velocity section plotted using data of earthquake converted wave method (ECWM), shot point (SP), after [43]. (*1–2*) Velocity ranges: (*1*) low, (*2*) high; (*3*) earthquake epicenters; (*4*) Spitak earthquake; (*5–6*) reflecting plains: (*5*) *P*-waves, (*6*) *S*-waves; (*7–8*) velocity isolines: (*7*) *S*-waves, (*8*) *P*-waves; (*9*) high-velocity block identified by *S*-waves; (*10–11*) velocities (km/s): (*10*) *P*-waves, (*11*) *S*-waves.

along the basement surface, while the crust type changes: with a decrease in the thickness of the sedimentary layer, the thickness of the consolidated crust increases and seismic velocities decrease in it (Fig. 6c). Along the surface of the basement, the South Caspian Depression continues to the west in the form of the Kura Basin. In this basin, the crust type changes as well, but these changes do not correspond to the general laws: the thickness of the crust saturated with high-velocity intrusions remains high (40 km) beneath a sufficiently deep trough (Fig. 4).

Structure of the Crust in the Black Sea Region

The crust structure in the Black Sea region, which includes the Sea of Azov and the Crimea, was studied in more detail than the crust structure of the South Caspian, but uneven in area and depth. According to the DSS data, the deep structure of this region is most fully studied in the western and middle parts of the sea (Fig. 1). Based on these data, the region is clearly divided into two parts: (1) northern part, covering the northwestern shelf of the sea, Crimea and the Sea of Azov with the thick platform-type crust and (2) southern part, with deep depressions and thin suboceanic crust.

The boundary between the northern and southern parts is represented by a deep fault, which is a linear continuation of the Rion–Kura Fault of the Caucasus and the South Caspian. The West Black Sea and East Black Sea deep depressions with the Middle Black Sea uplift separating them are clearly distinguished to the south of this fault, in the deep part of the Black Sea (Fig. 8).
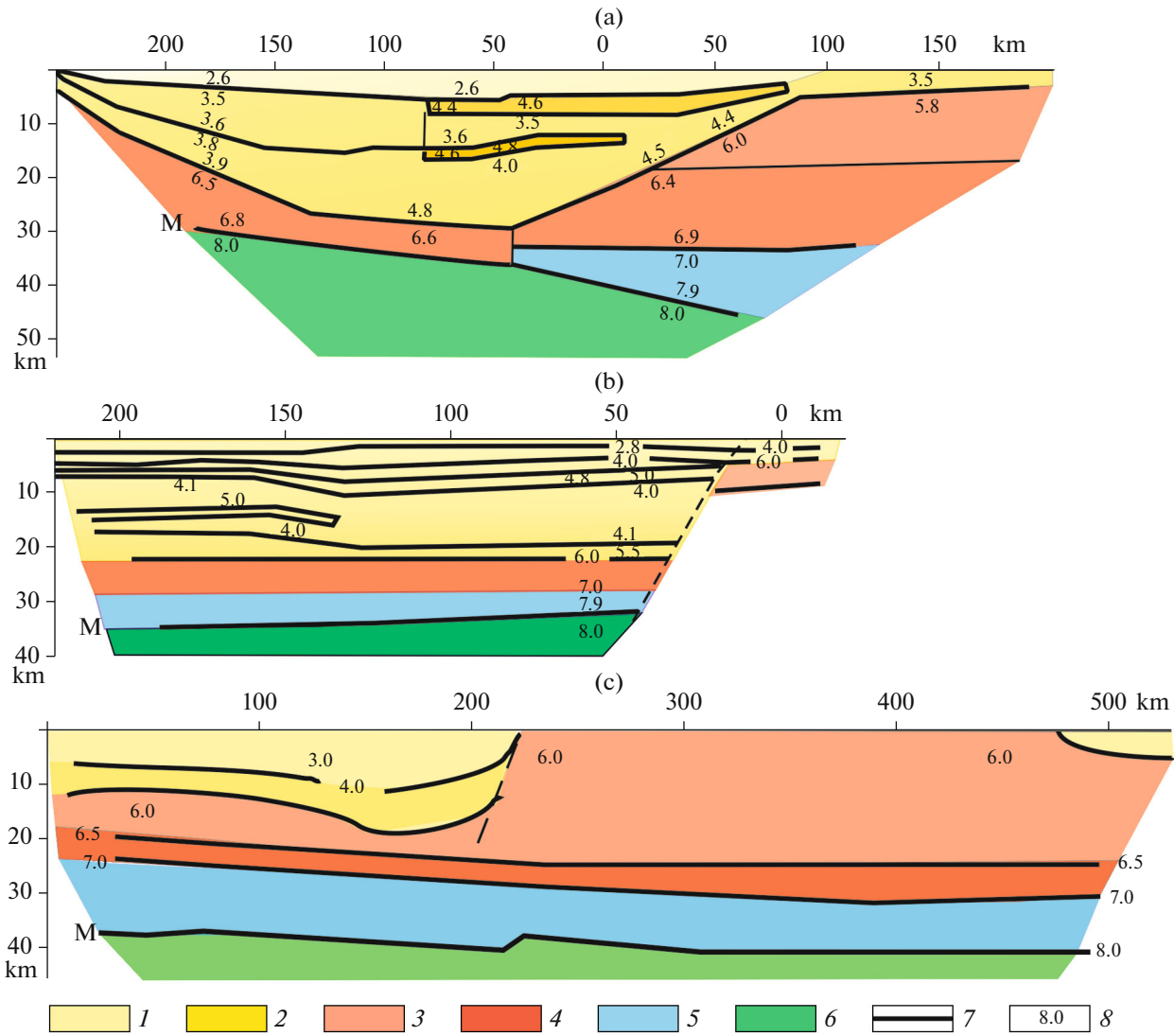
Fig. 6. Seismic sections of Earth's crust in South Caspian. Position of profiles is shown in Fig. 1. (a) South Caspian profile (profiles 1 and 2); (b) profile 9; (c) Artek–Sagiz profile, after [5]. (*1*) Sediments with a velocity of ≤2.8 km/s and a water layer with a thickness up to 1 km; (*2*) sedimentary layers (2.8−5.5 km/s); (*3*) granite-gneiss layer (5.8−6.4 km/s); (*4*) granulite-gneiss layer (6.5−6.8 km/s); (*5*) basic layer (7.0−7.8 km/s); (*6*) upper mantle (>8.0 km/s); (*7*) seismic boundaries; (*8*) *P*-wave velocities.

The crust structure of the crust changes regularly to the north of this fault, from the Ukrainian Shield to the Crimean Mountains: the thickness of the crust is maximal in the area of the mountains and ancient shield, but somewhat decreases beneath the Sivash Depression. At the same time, the internal three-layer structure of the crust with a thick granite-gneiss layer typical of the continental crust is preserved. The crust of the shallow Azov Sea and Black Sea in its northwestern part has the same structure (Fig. 9, profile DOBRE-5).

In the northwestern shelf zone, at the transition to the Crimea, there is a series of reflecting areas inclined towards the Crimea, which form a single boundary from the surface at PK120 to a depth of >20 km at PK300, which most likely corresponds to a deep fault.

A more complex structure is observed in the deep part of the Black Sea. The crust structure changes with transition to the deep depressions: the thickness of the crust sharply decreases and the granite-gneiss layer with velocities of 5.8−6.5 km/s disappears. The minimal depth to the M boundary (18 km) and the lowest thickness of the consolidated crust (~5 km) are detected in the deepest part of the basin along profile 25 in the West Black Sea Basin (Fig. 10c).

The deep structure of the eastern part of the Black Sea was studied in less detail, using only a few short profiles [2, 63, 64]. The crust thickness along these profiles is 23 km and the thickness of the consolidated crust is ~10 km (Fig. 10c). The depth to the M boundary in the area of the Middle Black Sea Rise (MBSR) increases
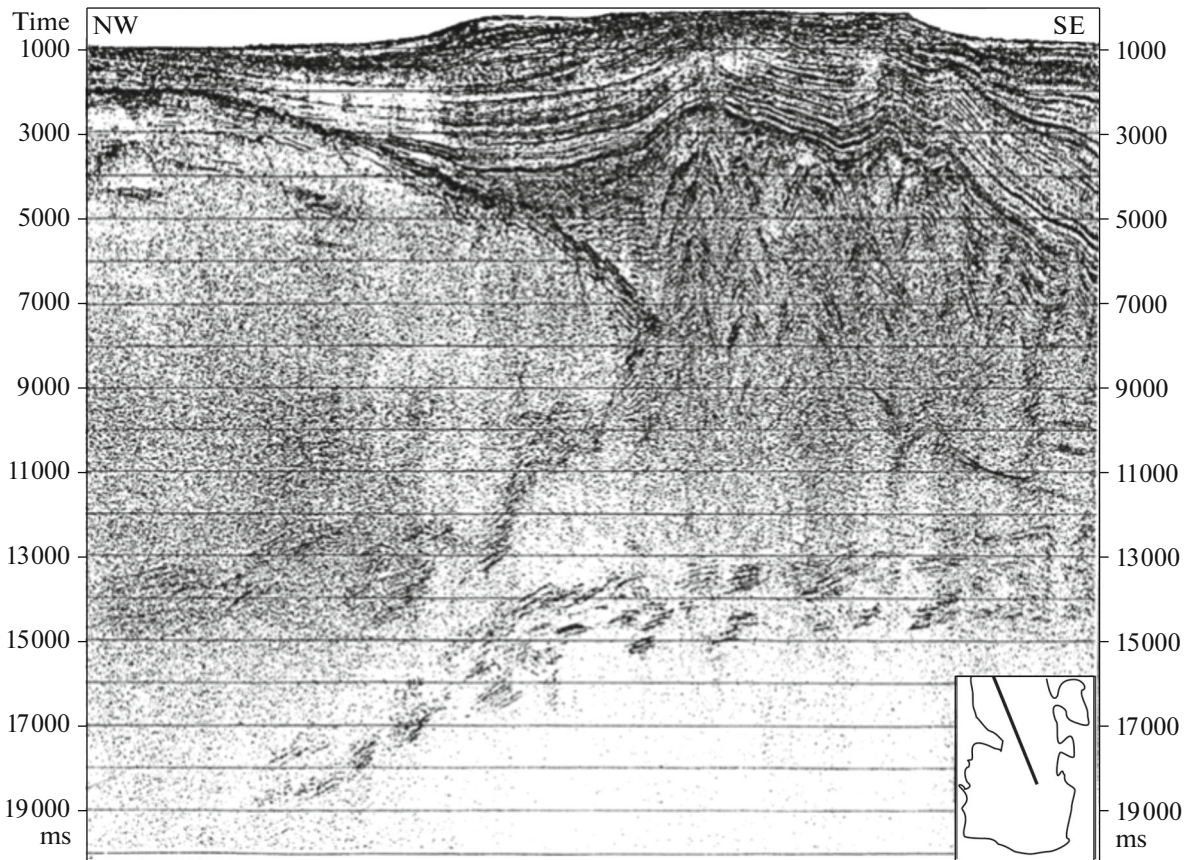
Fig. 7. Seismic time section plotted according to CDP data (after [16]) along a profile crossing a deep fault that bounds Scythian Plate from south.
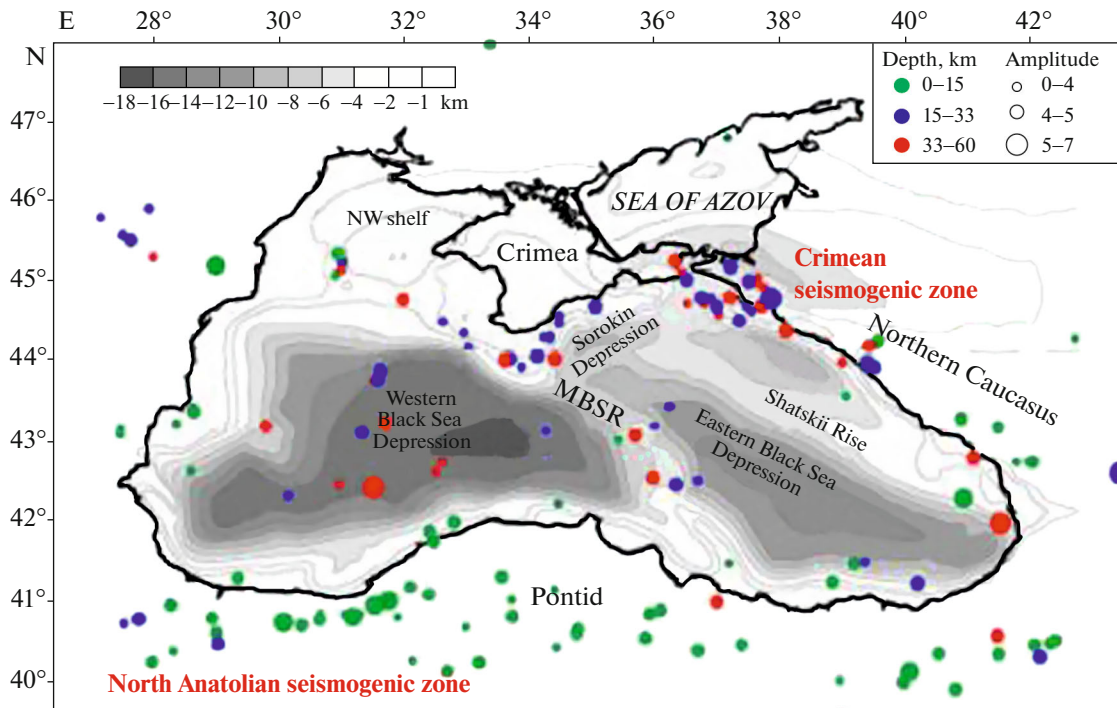

Fig. 8. Scheme of distribution of earthquake epicenters in Black Sea region against background of a depth map to bottom of sedimentary deposits, modified after [46]. MBSR, Middle Black Sea Rise.
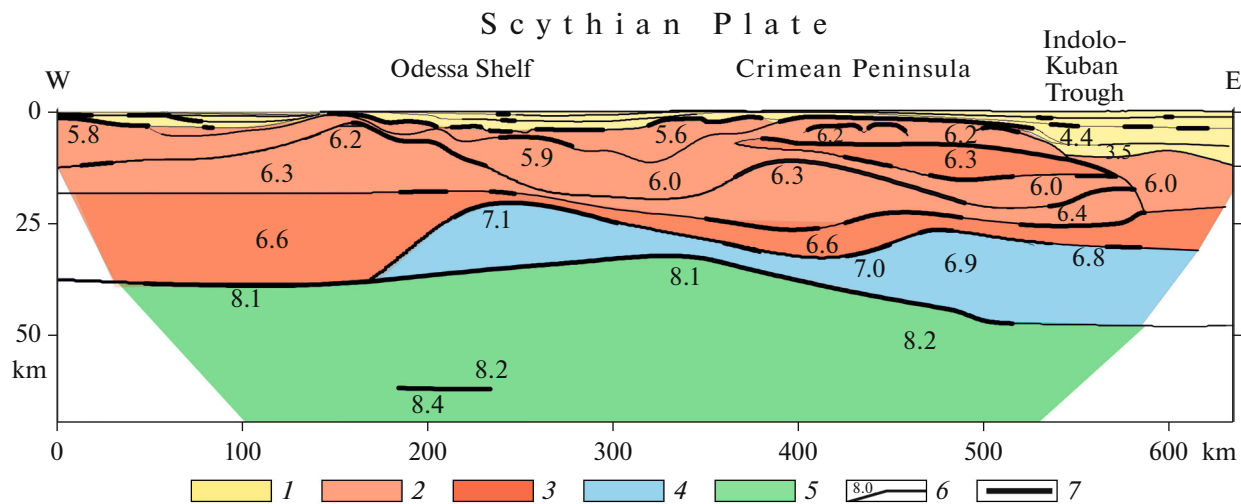
Fig. 9. Seismic section of Earth's crust along DOBRE-5 profile, modified after [68]. (*1*) Sedimentary layers (≤5.5 km/s); (*2*) granite-gneiss layer (5.8−6.4 km/s); (*3*) granulite-gneiss layer (6.5−6.6 km/s); (*4*) basic layer (6.8−7.1 km/s); (*5*) upper mantle (>8.1 km/s); (*6*) velocity isolines; (*7*) seismic boundaries.

to 30 km; the thickness of the granite-gneiss layer increases as well, and the crust becomes similar to that of the Scythian Plate (Fig. 10b). Along profile 29, a complex wave field is registered between the Kerch Strait and the Middle Black Sea Rise, an unambiguous interpretation of which is not given. Waves with a high apparent speed are recorded in the first arrivals there. Considering them as refracted waves, we may assume the presence of a protrusion along the M boundary to a depth of ~20 km in this part of the sea [4]. However, this model is ambiguous: based on the reflected waves recorded in subsequent arrivals, such a wave pattern may be explained by an inclined boundary plunging towards the deep basin. A sharp change in the crust structure is observed upon the transition from the Shatskii Swell to the deep part of the East Black Sea depression as well (Fig. 10c). There is a transition from the thin suboceanic crust to the continental crust over a rather limited interval (~25 km). At the same time, there are changes in all layers of the crust from the sedimentary layer to the Moho boundary, which experiences a sharp subsidence along deep faults from 20 to 30 km, respectively. This zone of change of crust types has a linear character; it is parallel to the coastline of the eastern part of the Black Sea and is associated with the linear magnetic Alushta−Batum anomaly [3].

The most detailed study of the structure of the basement and sedimentary cover of the Black Sea depressions was recently performed by the CDP in the international project "Geology without Limits" [58]. It was shown that the Middle Black Sea Rise (MBSR) and the Shatskii Swell are the large basement uplifts bounded by deep faults on both sides, and all depressions are bounded by faults as well (Fig. 11a). The West Black Sea Depression, largest in terms of area and depth, is bounded in the south by a fault with amplitude of >10 km. The depth to the basement changes gradually in the northern part of this depression, and a fault of sufficiently large amplitude separates it from the edge of the Scythian Plate only. The Shatskii Swell and Sorokin and Tuapse shallow depressions are distinguished in the eastern part of the Black Sea, to the north of the deep-water East Black Sea Depression (Fig. 8). All these structures are separated by almost vertical faults. Some sharp basement troughs increased in sediment thickness are detected in the Indolo-Kuban Trough as well. The basement surface of all these structures is rather complicated. However, the structure of the sedimentary cover of the depressions is not complex: the boundaries of the layers are almost horizontal and their thickness does not change, i. e. the basement surface smoothly sank between the faults for a long time without change in its shape. At the same time, two stages of such subsidence are noted: first, deep depressions were formed on both sides of the Middle Black Sea Rise; then, the basement subsided within the local parts of the deep depressions. Such a structure is characteristic of platform-type depressions [32]. A large number of local protrusions are observed in the structure of the basement of the Tuapse and Sorokin troughs. This is consistent with the formation of these depressions along the southern edge of the orogens of the Crimean Mountains and North Caucasus.

These are the major patterns of the crust structure in the Black Sea−Caspian region, according to the seismic data. The DSS profiles indicating the deep structure of the Earth's crust in this region are mainly located in the northern part of the region; its southern part was not studied seismically in detail (Fig. 1). Only some seismological data are available for this part.
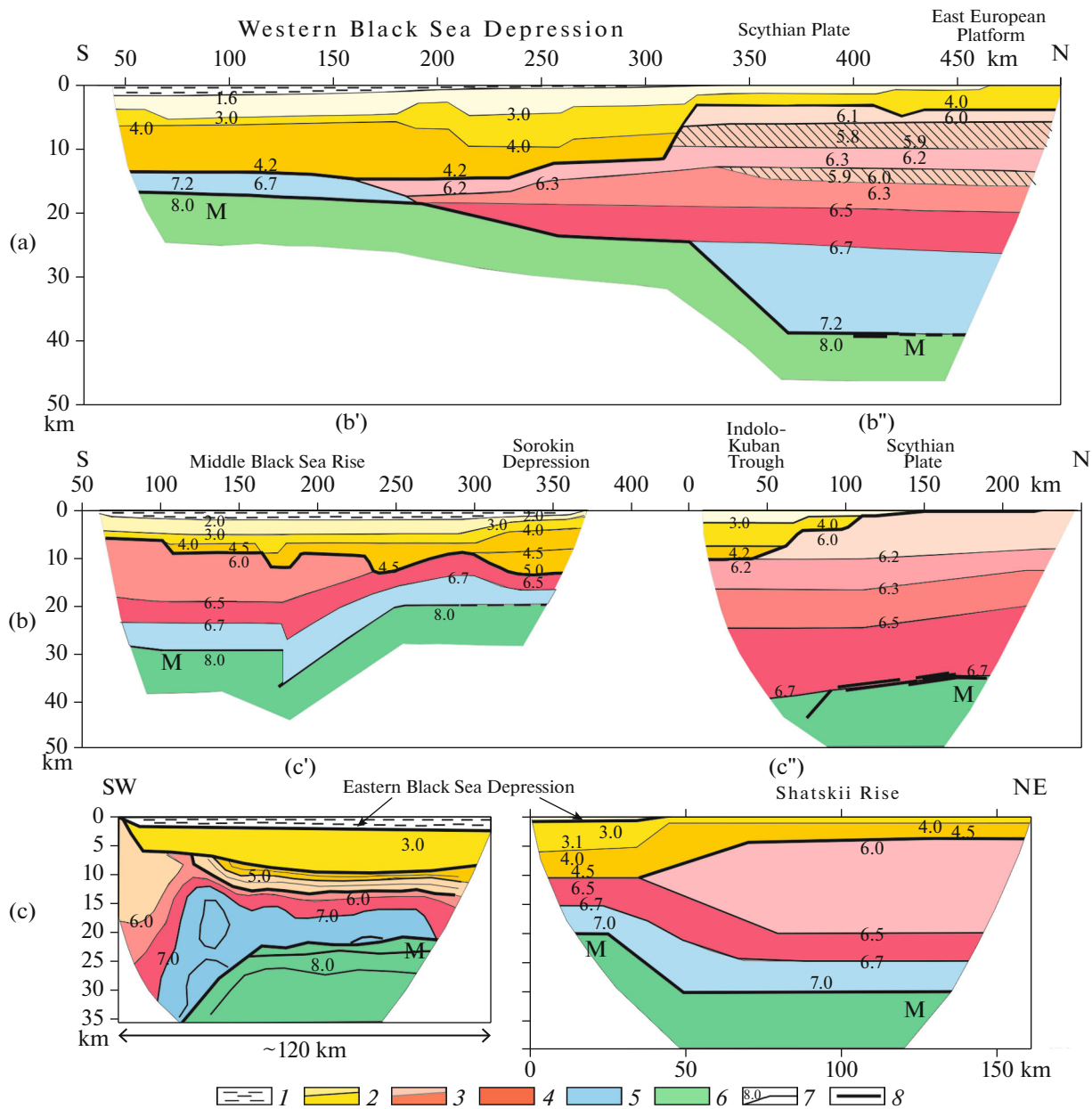
Fig. 10. Seismic sections of Earth's crust along DSS profiles crossing Black Sea Depression. Position of profiles is shown in Fig. 1. (a) Profile 25, after [4]; (b) profiles: (b') 29, after [4], (b'') 28, after [4]); (c) profiles: (c') 2, after [63], (c'') 15, after [3, 64]. (*1*) Sea; (*2*) sedimentary layers (≤5.5 km/s); (*3*) granite-gneiss layer (5.5−6.4 km/s); (*4*) granulite-gneiss layer (6.5−6.8 km/s); (*5*) basic layer (6.8−7.2 km/s); (*6*) upper mantle (>8.0 km/s); (*7*) velocity isolines; (*8*) seismic boundaries.

Seismic Tomography Data

Seismic tomography data are widely applied in the study of the structure of the Earth's crust and upper mantle in the southern part of the Black Sea−Caspian region. In terms of their detail, they are not comparable with the DSS data, but they are distinguished by a high depth and three-dimensional constructions. According to the data of seismic tomography, depth charts were constructed up to the M boundary for the Caucasus and the southern part of the region up to the Arabian Plate [53]. According to these data as well to the DSS data, a thickened crust is observed in the area of the Spitak profile and it has slight changes in the rest of the area. The mountainous regions of the Anatolian Block have the same crust thickness of ~40 km as the Arabian and Scythian platforms, although an increase may be expected in mountainous areas.

Detailed tomographic studies were carried out in the Crimean Mountains and in the adjacent northern part of the Black Sea [12, 52]. The velocity sections of the crust (*P*- and *S*-waves) at depths of 15−25 km
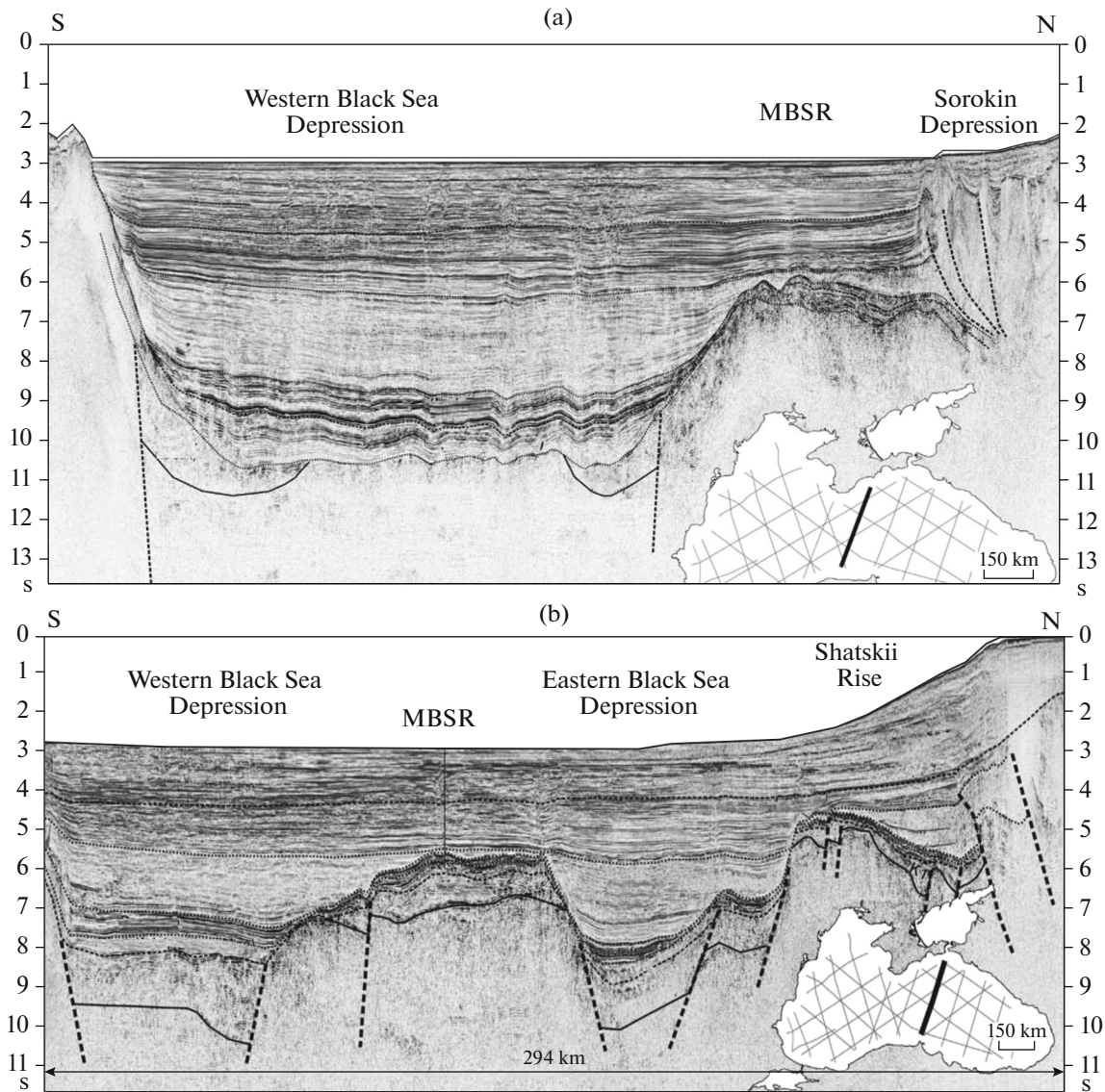
Fig. 11. CDP data for profiles crossing Western Black Sea depression, Middle Black Sea Rise, and Eastern Black Sea Depression, modified after [58]. MBSR, Middle Black Sea Rise.

revealed a clear division of the region into two areas: the western one, which includes the Crimean Mountains, and the eastern Kerch−Taman region with a complex crust structure typical of deep faults.

The seismic tomography data of key importance were obtained from the structure of the upper mantle of the Caucasus [55, 70]. According to these data, the region of the Lesser and Greater Caucasus differs from neighboring plates in lower velocities to the depth of the entire lithosphere (up to 350 km) (Fig. 12). Previously, only local channels of low velocities under the volcanoes of the Lesser and Greater Caucasus were clearly distinguished in this region. There is a coincidence of the boundaries of this mantle zone of low velocities with the boundaries of the Caucasus. This fact allows us to assume that the upper mantle of the

Caucasus is an independent lithospheric block with its own rheological and geodynamic features.

Important seismological data on the crust structure of the Black Sea−Caspian region crust were obtained from the distribution of epicenters of deep earthquakes. The results of earthquake registration by the system of Russian seismic stations for the entire monitoring period until the 1990s are given in [44] (Fig. 13). According to these data, two bands of the most intense seismicity are distinguished in the region, which trace almost parallel deep disturbances that limit the Caucasus and the depressions of the Black and Caspian Seas on both sides. The southern fault is most clearly identified in its western part to the south from the Black Sea. It is well studied from the seismological data; this is the North Anatolian seismic zone
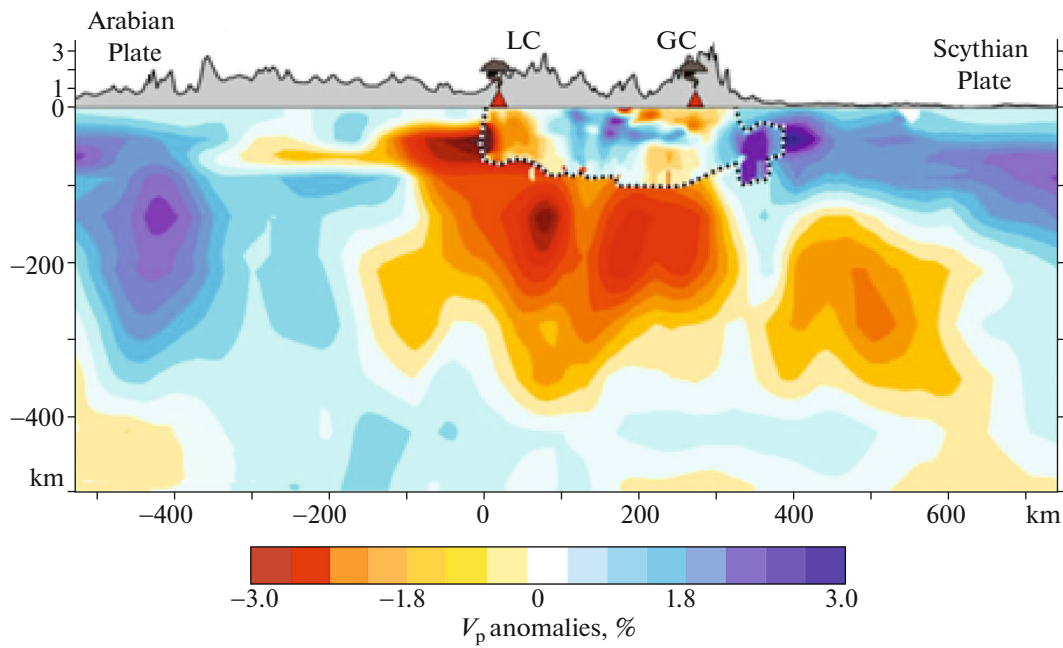
Fig. 12. Velocity model of upper mantle of Caucasus based on seismic tomography data, modified after [55]. LC, Lesser Caucasus; GC, Greater Caucasus. area, for which a more detailed model was constructed using nearby earthquakes (after [70]), is shown by dotted line; volcanoes are indicated by red triangles.
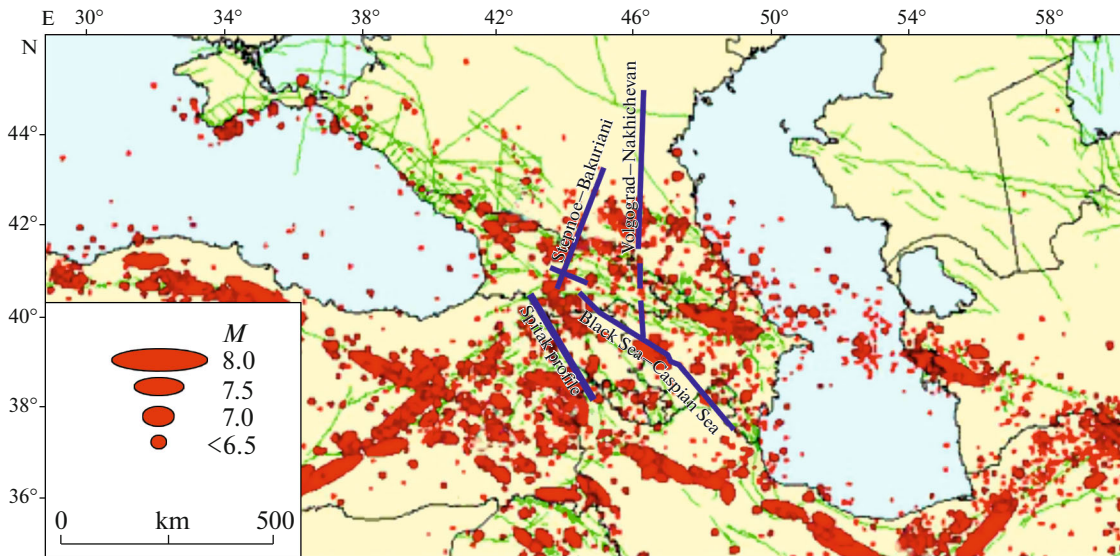

Fig. 13. Epicenters of earthquakes on territory of Black Sea—Caspian region, after [44]. Caucasian DSS profiles are shown by blue lines. Position of profiles is shown in Fig. 1.

(Fig. 8). Further to the east, it continues to the southern borders of the South Caspian, then sharply bends in the Kapetdag area. The seismic focal zone, which limits the studied region from the north, is characterized by the highest seismicity in the region of the Greater Caucasus and South Caspian; in the Black Sea, it stands out along southern Crimea. This dislo-cation is well detected in the structural patterns of the Earth's crust in the Greater Caucasus, as well as in the South Caspian region (Figs. 3b and 7).

In addition to the two main latitudinal faults, the transform faults are clearly distinguished in this region. A transform fault in the Black Sea is traced along the Middle Black Sea Rise (Fig. 8).
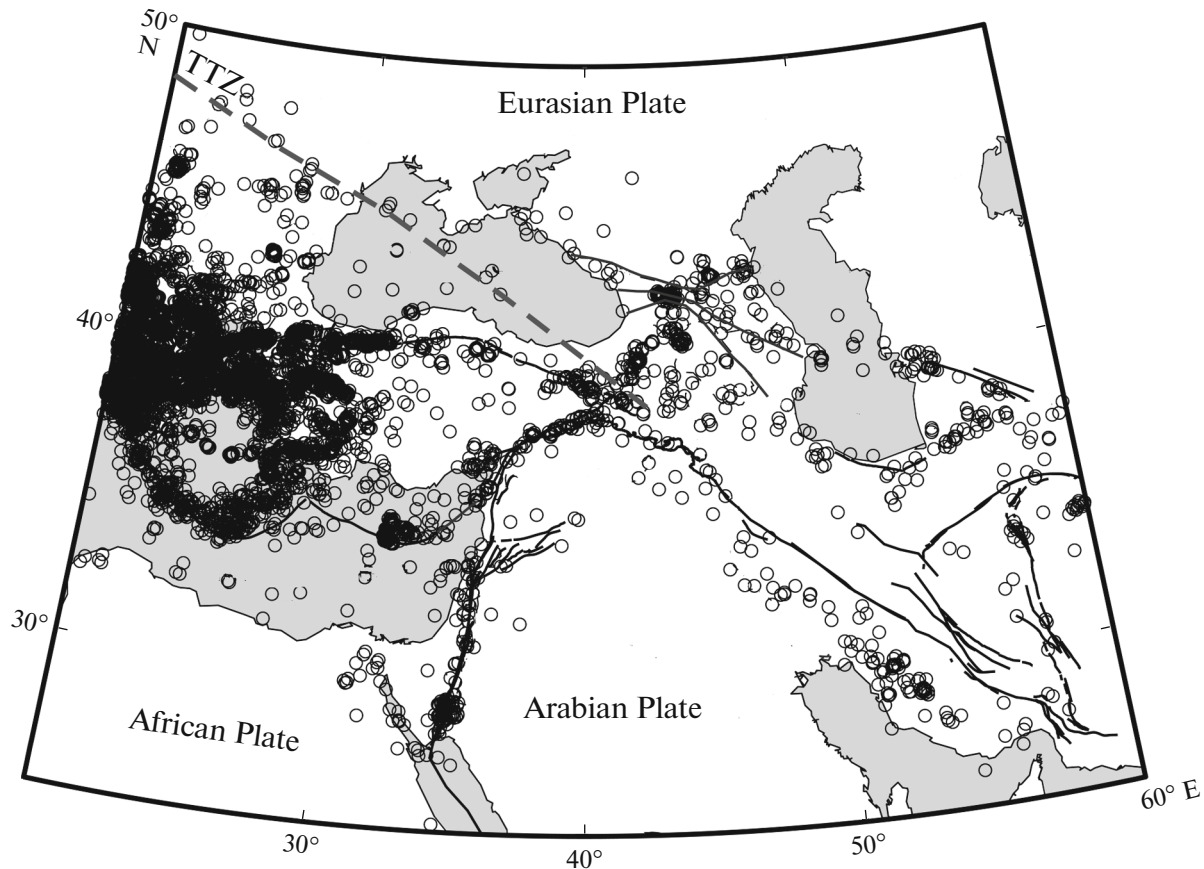
Fig. 14. Epicenters of earthquakes of Black Sea—Caspian region and of Arabian Plate, modified after [47]. The Tornquist—Teiseir fault zone (TTZ) and the fault along the Central Black Sea uplift are indicated (dotted line). The position of this zone is shown in Fig. 8.

Earthquakes along this uplift are of great depth and magnitude, typical of deep faults. The reliability of these constructions is supported by the data on deep earthquakes in this region, the results of which are generalized for the western and southern environs of the Black Sea—Caspian region in [47] (Fig. 14). According to these data, the transform fault that crosses the Black Sea may be identified by change in the nature of seismicity. An even clearer transform fault stands out in the Caucasus region. It is shown that this fault is a continuation of the fault that bounds the Arabian Plate from the northwest.

The reported seismological data supplement the DSS data on the structure of the Earth's crust and upper mantle in the Black Sea—Caspian region significantly. This allows us to compile a structural diagram of the Earth's crust for the entire area.

DISCUSSION

Generalized Structural Scheme of the Earth's Crust for the Black Sea—Caspian Region

Based on the analysis and generalization of seismotectonic and seismological data, we constructed a new structural scheme of the Earth's crust for the Black Sea—Caspian region, on which the major types of crust and deep faults were identified (Fig. 15). To determine the type of crust, the classification proposed in [7] and the data on the composition of the continental crust obtained from the Kola Superdeep Borehole [31] and in the study of xenoliths [50] were applied.

In addition to the thickness, the data on three major crust layers of the different composition were used in the form of the major parameters of the crust in this classification (Fig. 15a): granite-gneiss with longitudinal wave velocities of 5.8—6.4 km/s; granulite-gneiss (6.4—6.7 km/s); and granulite-mafic layer (6.6—7.2 km/s).

On this basis, six major types of the crust were distinguished: three continental types differing mainly in the thickness of the crust, two transitional (subcontinental and suboceanic), and one oceanic (Fig. 15).

The crust types differ mainly in the thickness of the granite-gneiss layer. It makes up most of the crust in continental types, while its thickness is reduced in the subcontinental crust, and it is absent in the suboceanic and oceanic crust.
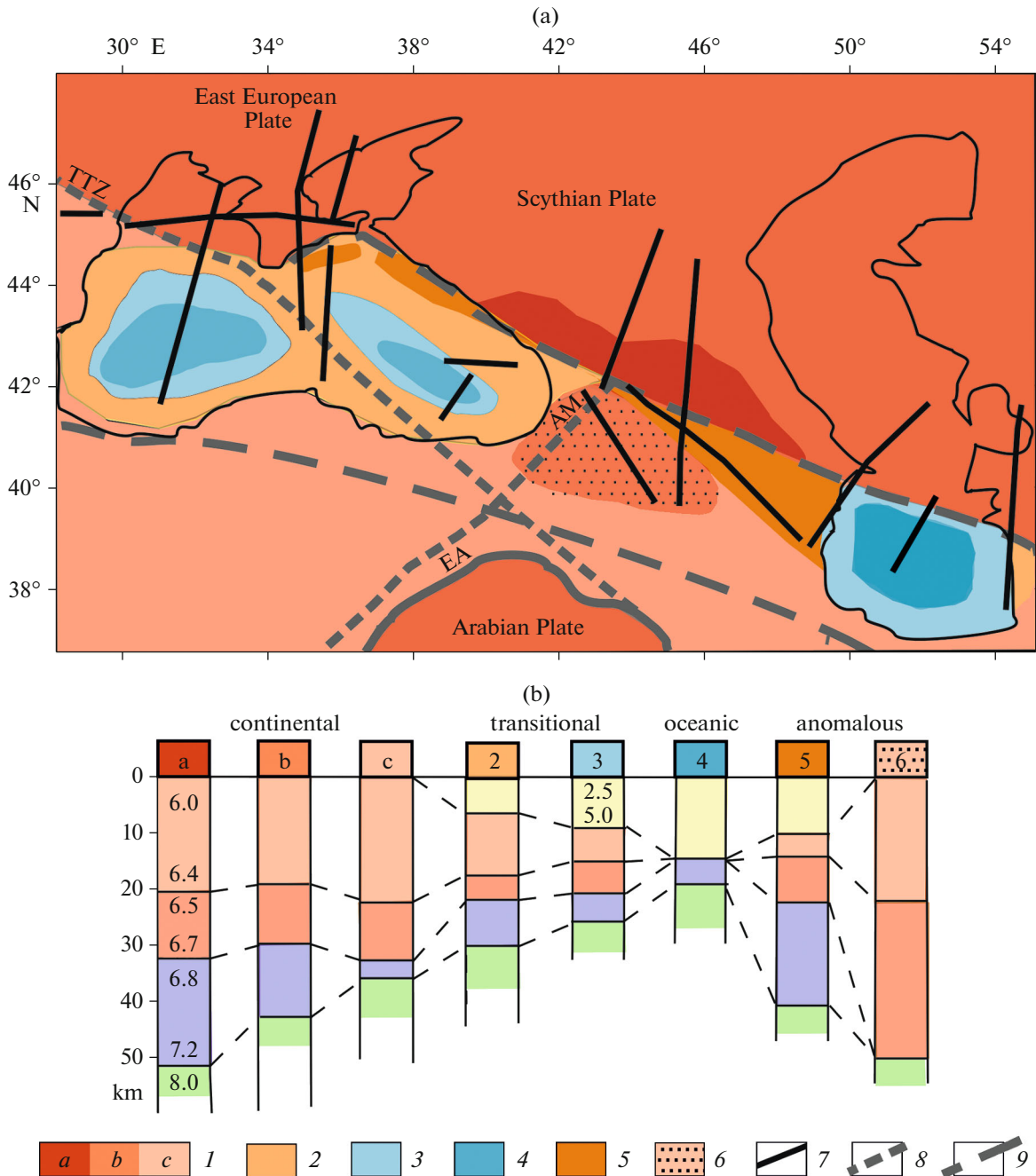
Fig. 15. Results of a comprehensive interpretation of geophysical data on structure of Earth's crust in Black Sea–Caspian region. (a) Structural scheme of crust with major types of crust and deep faults; (b) velocity models for major crust types. faults limiting Black Sea–Caspian region are indicated: EA, East Anatolian; AM, Allahani–Makhachkala. TTZ, Tornquist–Teisseyre fault zone. (*1–4*) Crust types: (*1*) continental, with three layers: granite-gneiss, granulite-gneiss, and mafic with different thickness: (*a*) >50 km, (*b*) ~40 km, (*c*) ~30 km, (*2*) subcontinental, (*3*) suboceanic, (*4*) oceanic (mafic crust, ~10 km); (*5*) crust of Lesser Caucasus; (*6*) crust of Reon–Kura Depression; (*7*) DSS profiles; (*8–9*) faults: (*8*) transform, (*9*) deep.

The continental type of the crust of great thickness and with high average velocities in the consolidated part is identified within the Greater Caucasus (Figs. 3, 15b, type 1). A crust type with an average thickness of ~40 km and the same high average velocities covers the area of the East European Platform and the Scythian Plate (Figs. 2a, 3). The continental crust with a thickness from 30 to 40 km and with reduced average velocities is characteristic of the western and southern margins of the Black Sea–Caspian region. A regular change in crust types occurs in the West Black Sea Depression with an increase in the thickness of the sedimentary cover (Fig. 10). The change in the crust type is sharp in the deep East Black Sea Depression bounded on

both sides by deep faults. The crust type changes immediately from the continental to suboceanic in the South Caspian, as the depth to the basement increases (Fig. 6b). However, all this does not violate the general patterns that are characteristic of many other depressions identified within platforms of different ages as well [32].

In addition to the major crust types given above, two anomalous types were identified in the Caucasus region. This is a thick continental-type crust, but with very low velocities. Such crust is detected in the western part of the Lesser Caucasus along the Spitak profile (Fig. 5). The thickness of the crust is more than 50 km there, similarly to the Greater Caucasus, but the velocities in the crust are lower, which is characteristic of the third type of the crust. Another anomalous type of crust is identified in the Rion−Kura Depression (Fig. 4). As in the other basins, the seismic velocities in the crust are very high here, but the thickness of the crust does not decrease and remains >40 km, as on the platforms.

The data on large faults is an essential compliment to the maps of crustal types. The presented structural scheme shows the system of major faults identified from the seismic data and from data on the distribution of epicenters of deep earthquakes (Figs. 13 and 14). There is a general pattern: as a rule, these faults coincide with areas of a sharp change in the crust type. A fault that limits the Greater Caucasus in the south and separates the South Caspian Basin from the Scythian Plate is the clearest in the DSS sections. This fault is clearly distinguished by sharp changes in depth to the M boundary and along the inclined reflecting areas bordering the Greater Caucasus from both sides in the sections that cross the Greater Caucasus (Fig. 3). In the area of the South Caspian, it may be identified according to the CDP data and along the Atrek−Sagiz profile (Figs. 6 and 7). The continuation of this fault in the western direction is indicated by a small number of earthquakes along the northeastern margin of the Black Sea up to the seismogenic zone in the region of the Indolo−Kuban Trough. It changes its shape abruptly and eventually breaks off in the area of this trough (Fig. 8). This seismically active fault zone coincides with the southern margin of the Scythian Plate throughout its length from the Caspian Sea to the Crimean Mountains. A fault is distinguished in the northwestern part of the Black Sea as well, on profile 25, where the crust type changes from the continental to the transitional type, but based on the epicenters of deep earthquakes, it is detected along the Middle Black Sea Rise rather than along the margin of the Scythian Plate (Fig. 10a). According to the tectonic schemes of the European continent, it is clearly seen that this fault is most likely a continuation of the Teisseyre−Tornquist fault zone (TTZ), which separates the ancient East European Platform and the young plates of Western Europe. The deep structure of this zone was studied in detail by a series of DSS pro-

files [38, 54]. The change in the crust types from the thick 40−50-km high-velocity crust of the ancient platform to the low-velocity crust of the young West European plates with a thickness of 25−35 km is a characteristic feature of this zone in all profiles. It is noted that according to the system of deep earthquakes, the TTZ is detected southward along the Middle Black Sea Rise to the northeastern boundary of the Arabian Plate. A transform fault is identified in the Caucasus region, which is a continuation of the northwestern boundary of the Arabian Plate (Fig. 14). These are the Alakhani−Makhachkala and East Anatolian faults, well studied by the geological data, which are clearly traced by deep earthquakes. These faults divide the mountain structure of the Greater Caucasus into western and eastern parts (Fig. 1).

Thus, the constructed structural scheme showed a complex and heterogeneous structure of the crust in the Black Sea−Caspian region with a combination of different crust types. At the same time, there are clearly expressed general patterns. The entire region is bounded on both sides by two practically parallel seismically active zones of deep faults. The upper mantle between them is characterized by low seismic velocities and forms an extended suture zone between the East European and Arabian lithospheric plates. A relationship between the crust type and the geological history of large tectonic formations was registered, which opens up the possibilities of the seismic method in the study of the processes of the evolution and formation of the Earth's crust in this region. The formation of large crustal blocks with layers of the same composition consistent over the area is associated with the long-term deep endogenic modes, which allows us to use these data for the study of the geodynamics of this region.

Basic Geodynamic Models of the Region

The first most fully developed geodynamic model of the Black Sea−Caspian region was proposed by V.V. Belousov, according to which this region was considered as a tectonotype of the completed geosynclinal evolution, reworked by various endogenic regimes, but in general, of a platform character [6, 15]. The reported CDP data on the structure of the Black Sea and South Caspian crust provide unambiguous evidence for the platform nature of their formation, which is characteristic of most of deep basins of the East European Platform and the Eurasian shelf of the Atlantic [32, 37] (Fig. 10). The nature of such depressions is well explained by the processes of crust basification, i.e. saturation of the upper part of the crust with mantle intrusions and products of metamorphism of the granite-gneiss layer, as well as eclogitization of the of the lower crust, increasing their seismic velocity up to the mantle values [1, 41]. These processes result in gradual transformation of the conti-

nental crust into subcontinental and then into suboceanic crust.

However, the platform model of the evolution of the Black Sea−Caspian region cannot explain the complex structure of the Caucasus crust and its anomalous types. At present, most of geodynamic models for this region are based on the collisional nature of its formation. It is assumed the evolution of the Neotethys Ocean in the Cretaceous and northward movement of the large block of the Arabian Plate resulted in the subduction of the oceanic crust beneath the southern margin of the continental Eurasian Plate [65, 66]. N.B. Kuznetsov et al. [20] developed a new global collisional model of the Black Sea−Caspian region based on the studied age of lithospheric plates from dated detrital zircons. It was assumed that the band of Peri-Gondwana terranes known in the northern Appalachians, Western and Central Europe, Middle East, North Africa, and Arabia extends into the northern Black Sea region, Ciscaucasia, and Caspian Sea region, composing the basement of the Scythian and Turanian epi-Paleozoic platforms, and may be traced further to the east, to the southern Trans-Urals, taking part in the structure of the Paleozoids of the southern part of the Urals [20, 28, 56]. At the same time, of great importance is the different age of the East European Platform and the Scythian Plate [20]. However, the data on the age of this slab is still insufficient. The boundary between the East European Platform and the Scythian Plate is distinguished on the tectonic map of Europe, mainly by the change in the age of the sedimentary cover [23]. According to the seismic data, this boundary is not distinguished, while at the same time, all other boundaries of the East European Platform are the deep faults and suture zones, on which the type of the crust changes dramatically. All these facts do not contradict to the idea of the Scythian Plate as the margin of the East European Platform reworked by rifting processes in the Late Paleozoic−Early Mesozoic [60].

Currently, the Europrobe model worked out in the fundamental international project by a large team of leading European researchers [51] is one of the most developed collisional models of the Black Sea−Caspian region (Fig. 16). This model generalizes a large amount of geological and geophysical data, and, in this respect, is the most reasonable. In addition, this model agrees well with our structural scheme of this region, especially for its western part, and describes in detail the fault system in the Black Sea region and in the Caucasus (Figs. 15, 16). However, the data on the fault tectonics of the South Caspian in the Europrobe model are limited, and the extension of the southern Black Sea−Caspian Fault to the Caspian Sea is not shown in this model. The participation of the Arabian Plate in the formation of the structure of the Caucasus region is well reflected in the Europrobe model. It is shown that the transform fault that crosses the Caucasus is a continuation of the fault that bounds the Arabian Plate from the west. The transform fault identi-fied along the Middle Black Sea Rise is traced in the model by change of the structural patterns of the Black Sea crust and further along the eastern margin of the Arabian Plate as well. However, comparison of the Europrobe model with the data on the deep structure of the region showed that some structural patterns of the crust and upper mantle of the region are not explained by this model. For example, according to tomographic data, a zone of low velocities is distinguished in the upper mantle of the Caucasus, but no block of a rigid plate that intruded this zone was identified (Fig. 12).

A description of the geodynamic evolution of individual structural patterns of the Black Sea−Caspian region within the collisional model is given in [16, 21, 22, 26, 48, 49, 59, 61, 65]. This region is considered as a system of concentrated dislocations confined to the southern edge of the Eurasian lithospheric plate, while the folded systems of the Crimea, Caucasus, and Kopetdag represent a single system of dislocations associated with a lithospheric shear penetrating the sedimentary cover, consolidated crust, and subcrustal layers of the mantle [34]. In addition, it is shown that this shear occurred along two main sublatitudinal faults that bound the Black Sea−Caspian region. Such model provides good explanation for the pronounced linearity of these faults, which was difficult to associate with the collision of the East European and Arabian plates. More local shears were identified from the geological data in the Caucasus region in [17, 36]. However, the transform faults identified from the seismological data and traced as linearly elongated from the East European Platform to the Arabian Plate showed that all these shears could not change the structure of the region in the regional plan significantly (Fig. 14).

Thus, the following two main groups of models were proposed for explanation of the geodynamic processes in the Black Sea−Caspian region on the basis of the platform and collisional history of the formation of the major tectonic structures:

(1) Models in which this region is considered as a reworked edge of the East European lithospheric plate;

(2) Models in which the region is considered as a part of the global Alpine−Himalayan collisional zone.

These models are primarily based on the geological data. The geophysical studies on the structure of the Earth's crust and upper mantle carried out in this region allow us to supplement these data on the likely geodynamic processes of the formation of the region significantly and suggest the ways to harmonize different geodynamic models in the form of a single integrated model.
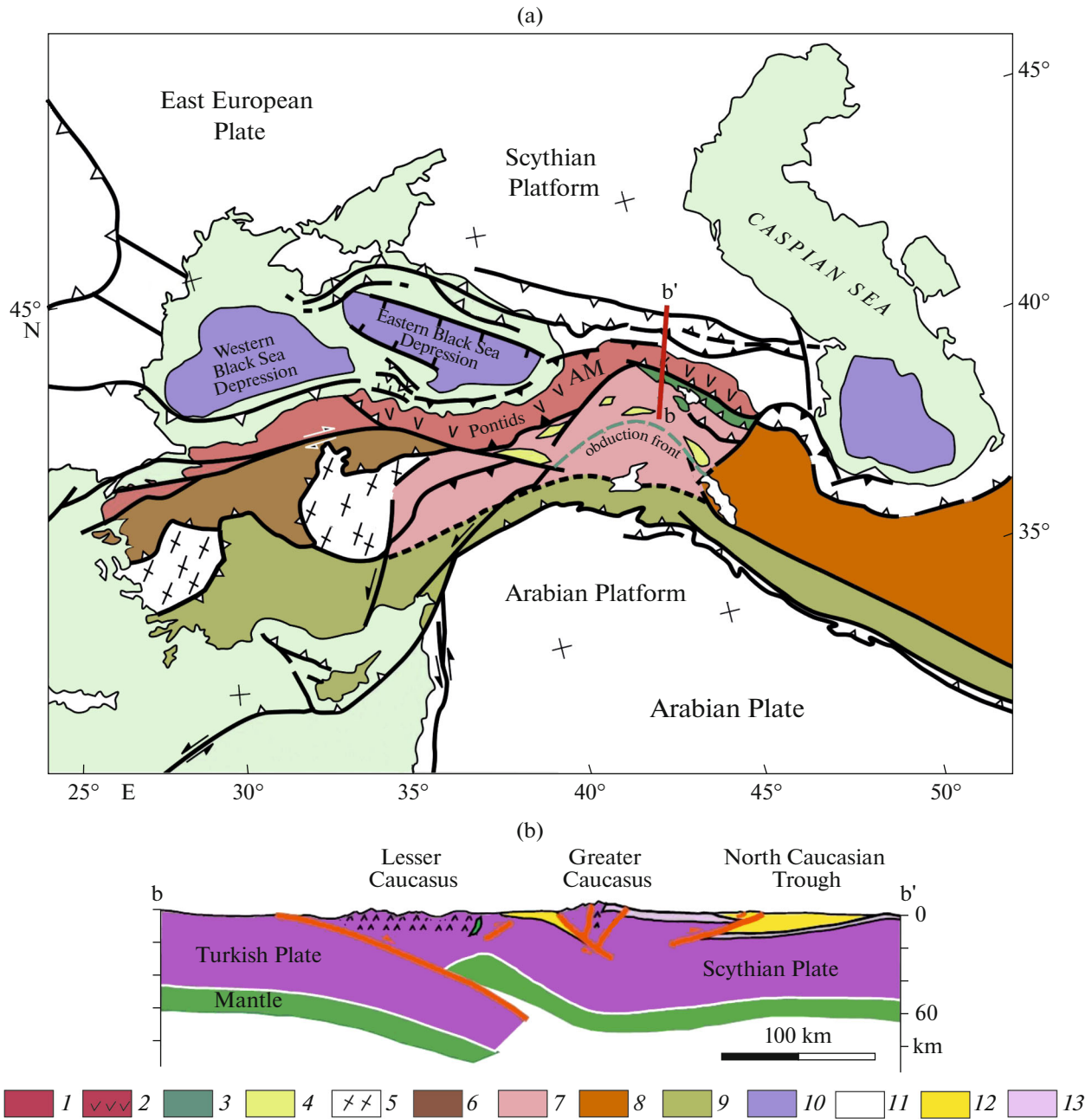
Fig. 16. Geodynamic model of lithosphere in Black Sea–Caspian region, according to data of Europrobe International Project, modified after [51, 65]. (a) Structural scheme of Earth's crust with identified Caucasian collision block; (b) section of Caucasus lithosphere assumed by collisional model, after [65, 66]. AM, Allahani–Makhachkala Fault. (*1–2*) European margin: (*1*) Pontids, (*2*) including magmatic arcs: Pontids, Somkheto–Karabakh; (*3*) Lesser Caucasus, including ophiolites; (*4*) ophiolites of Anatolian Peninsula; (*5*) metamorphic massifs; (*6–8*) terranes: (*6*) accreted Sakarya, (*7*) accreted South Armenian (Anatolids–Taurids), (*8*) Iranian, accreted during ancient Cimmerian orogeny; (*9*) Anatolids–Taurids with obducted ophiolites and Peri-Arabian blocks (Lycian nappes), including ophiolites; (*10*) inferred oceanic crust; (*11*) platforms; (*12–13*) depressions: (*12*) Cenozoic, (*13*) Mesozoic.

Complex Geodynamic Model
of the Black Sea–Caspian Region

According to our new integrated geodynamic model, the Black Sea–Caspian region may be considered as a complex wide suture zone between the East European and Arabian lithospheric plates, which was formed via two major geodynamic processes (platform and collisional). The platform regime resulted in the reworking of the lithosphere of the southern margin of the East European Platform with the formation of linearly elongated zones of deep faults along the platform boundary and deep depressions of the Black Sea and

the South Caspian. The mechanisms of the evolution of platform structures were well studied on different continents and it was shown that they are mainly associated with physicochemical transformations of the matter of the Earth's upper spheres. An important role in such transformations is assigned to energy-saturated mantle fluids. This is supported by the data of the study of the nature of the elevated temperature mode in the Black Sea–Caspian region [35]. The collisional processes are characterized by the formation of folded structures and complex mutual movements of individual lithospheric blocks. These processes explain the structure of the Earth's crust in the Caucasus region, caused by the northward movement of the block of the Arabian Plate and the wide abundance of thrust tectonics in the region. However, the geophysical data showed that these processes covered the Earth's crust of the Caucasus only, while the upper mantle of the ancient East European Plate withstood pressure from the Alpine–Himalayan collision zone and retained the linear shape of its southern boundary (Fig. 14). The characteristics of the Earth's crust of the Lesser Caucasus obtained from the seismic data allowed us to refine the details of this collision model. We showed that two layers separated by a zone of reduced velocity and two reflecting boundaries are clearly distinguished in the anomalously thick crust of the Lesser Caucasus (Fig. 5). Such crust could have formed via overthrusting of the crust of the Arabian Plate onto the crust of the Caucasus region. This overthrust occurred at the level of the multilayered Moho boundary without affecting the upper mantle. The structure of the thick (>40 km) high-velocity crust of the Rion–Kura Depression may be explained by a complex combination of crustal reworking by mantle intrusions with deformation processes of crust compression under the action of the Lesser Caucasus block advancing on it.

CONCLUSIONS

Generalization and analysis of the geophysical data on the structure of the Black Sea–Caspian region, which includes such different tectonic structures as the depressions of the Black Sea and the South Caspian, mountain structures of the Caucasus and the edges of the Scythian and Anatolian plates, provided the following well-founded structural patterns of the Earth's crust and upper mantle of this region:

(1) The crust of the Scythian Plate, including the Greater Caucasus, belongs to the continental type with a thickness of >40 km with three major layers: granite-gneiss with longitudinal wave velocities of 5.8–6.4 km/s; granulite-gneiss (6.4–6.7 km/s); and granulite-mafic (6.6–7.2 km/s).

(2) The crust of the deep basins of the Black Sea and South Caspian is characterized by an anomalously thick sedimentary sequence (>20 km) and a thin (5–10 km) basic crust. This is an oceanic-type crust, which is separated from the continental crust by transitional types: subcontinental and suboceanic.

(3) The crust of the Lesser Caucasus is as thick as the crust of the Greater Caucasus, but the velocities are anomalously low in it and the mafic layer is almost absent, which is an anomalous type of the crust. In addition, this anomalous type is characteristic of the intermountain Rion–Kura Basin, since the velocities are high in it, similarly to the deep suboceanic basins, but the thickness is higher than ~40 km.

(4) The upper mantle of the Caucasus region is characterized by the low velocities (≤8.0 km/s), which is associated with the high-temperature regime in the region. Abnormally low velocities are registered in the area of the Lesser Caucasus.

(5) Deep faults play an important role in the formation of the structures with different types of the crust and upper mantle. Two extended submeridial faults limit the region, separating it from the East European and Arabian lithospheric plates. Two transform faults that cross the Black Sea and the Caucasus are a continuation of deep faults bordering the northeastern and southwestern margins of the thick block of the Arabian Plate. A series of local faults divides the crust of the depressions into separate blocks with different thicknesses of the sedimentary cover.

(6) The obtained structural patterns of the Earth's crust in the Black Sea–Caspian region are applied for construction of a new generalized scheme of the crust, which shows the types of the crust and deep faults that separate them.

(7) The obtained structural scheme of the Earth's crust allows us to suggest a new integrated geodynamic model for the evolution of the region, the including platform and collisional endogenic modes, based on the generalization and analysis of all geological and geophysical material. The platform mode resulted in the formation of deep depressions in the Black and Caspian Seas and linearly elongated zones of deep faults along the southern boundary of the East European Plate. The collisional processes explain the structure of the Lesser Caucasus, which was formed as a result of overthrusting of the crust of the Arabian Plate onto the crust of the Caucasus region. This overthrusting occurred at the level of the multilayered Moho boundary, without affecting the upper mantle. The structure of the thick high-velocity crust in the area of the Rion–Kura Depression is explained by the reworking of the crust by mantle intrusions and compression of the crust under the influence of the Lesser Caucasus block moving on the depression.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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