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The Deep Structure of the Lithosphere along the Caucasus–South Caspian Basin–Apsheron Threshold–Middle–Caspian Basin–Turan Plate Seismic Profile

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Abstract—On the basis of reflected wave hodographs interpreted by the method of homogeneous functions, the section of the lithosphere across the Caucasus, Caspian Sea and Turan Plate was obtained without the use of any preliminary section model. In a section of more than 1000 km, mantle and crustal structures and junction patterns between them are seen down to 60 km within the limits of the Kura Basin and the South and Middle Caspian basins and the Turan Plate. The section of the South Caspian Basin is generally consistent with the ideas of E.V. Artyushkov concerning its structure. A sedimentary layer of up to 30 km thick is underlain by a thinned crust about 10 km thick and by high-velocity mantle. The Turan Plate consists of three layers, which are typical for cratons that are about 50 km thick.

Keywords: seismic section, method of homogeneous functions, geological interpretation.
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INTRODUCTION

The study of the deep structure of the lithosphere in the Caspian Sea is of high interest, both in Russia and abroad, with respect to the promise of the discovery of new large hydrocarbon deposits. Despite numerous geological–geophysical studies, many details of the structure and evolution of Caspian Sea basins remain unclear. We attempted to make a geological interpretation of the seismic profiles that were derived in the 20th century by utilizing a new technique that was developed at the Faculty of Geology of Moscow State University. This technique enables one to acquire new data, both about the structure of a sedimentary basin and about the structural peculiarities of the crust and upper mantle in the respective region (Piip, 1991, 2001).

In different years, a huge number of deep seismic sounding (DSS) profiles have been made over the water area of the Caspian Sea and the adjacent territories of the Caucasus and Turkmenistan. We selected only the DSS data that belong to the entire profile that crosses the Caspian region and the adjacent territories of the Caucasus (Kura Basin), South Caspian Basin, Apsheron threshold, Middle Caspian Basin, and the Turan Plate (Aksenovich et al., 1962; Gal’perin and Kosminskaya, 1958; Krasnopevtseva, 1984; Egorkin and Matushkin, 1968). As was noted by G.V. Krasnopevtseva (1984), most of the seismic data of those years are presented in the form of traditional sections of sedimentary, granitic, and basaltic layers with averaged values of boundary and average velocity of elastic waves.

The new interpretations of the seismic data allowed us to derive a detailed seismic section of the Earth’s crust and the upper mantle up to 1100 km long and 60 km in depth, with the identification of the additional characteristics of the deep structural elements in the Caspian region.

BRIEF TECTONIC CHARACTERISTICS

The region of the Caspian Sea crosses the series of latitudinal structural zones of the southeast margin of the ancient Precambrian East European Craton, the young epi-Herzynian Scythian-Turan Plate, and the Alpine-Himalayan orogenic belt in the north-to-south direction (Butaev, 1988; Mezhdunarodnaya ..., 2003; Glumov et al., 2004) (Fig. 1). The northern and southern coastal parts of the Caspian Sea, which are sharply different in terms of age and geodynamics, also influence complex processes in the depths of this region.

E.V. Artyushkov (2007) wrote that the South Caspian Basin formed through a rapid immersion of the ancient continental crust that resulted from gabbro transition into more dense garnet granulites or eclogites under the effect of a mantle diapir within the basaltic layer. This may lead to thinning of the consolidated crust beneath the thick sedimentary layer and to high values of elastic-wave velocity below the Moho discontinuity.

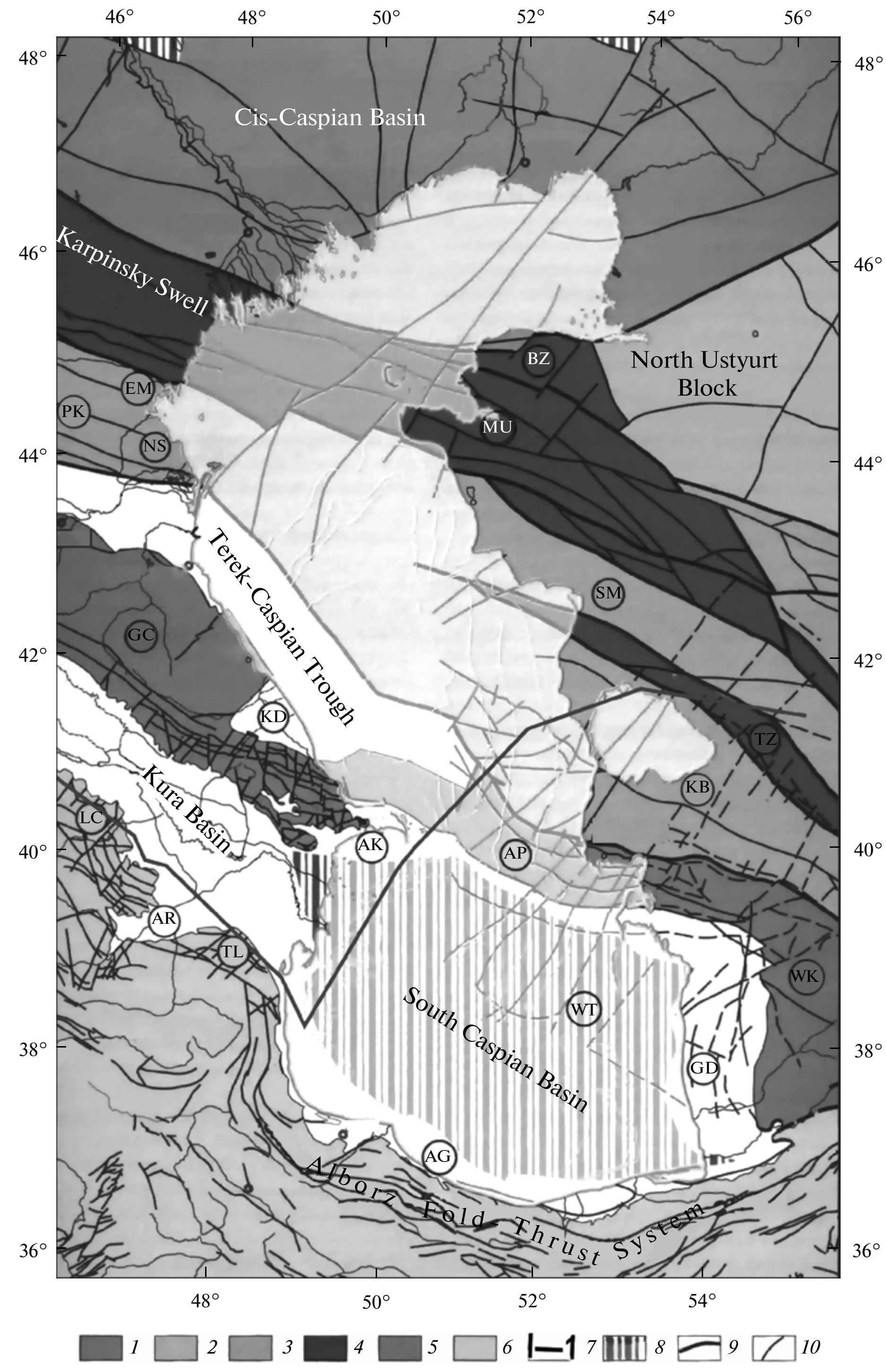

Fig. 1. The tectonic map of the Caspian region from (Mezhdunarodnaya ..., 2003) with the geotraverse line we plotted: *1–4* are basement of cratonic areas: *1*, Early Precambrian, *2*, Baikalian, *3*, Herzynian, *4*, Early Cimmerian; *5*, *6* are Alpine fold systems: *5*, Greater Caucasus and Kopet Dagh, *6*, Lesser Caucasus, Talysh and Alborz; *7*, forearc troughs and basins; *8*, depressions with oceanic crust; *9*, faults corresponding to the boundaries of large structural units; *10*, other significant faults.

We considered the deep structure along the chosen DSS profile, which crosses the following structural units of the studied region: Caucasian structures (Kura Basin), South Caspian Basin, Apsheron threshold, Middle Caspian Basin, and structures of the Turan Plate (Kara-Bogaz-Gol and Tuarkyr zone). The inter-

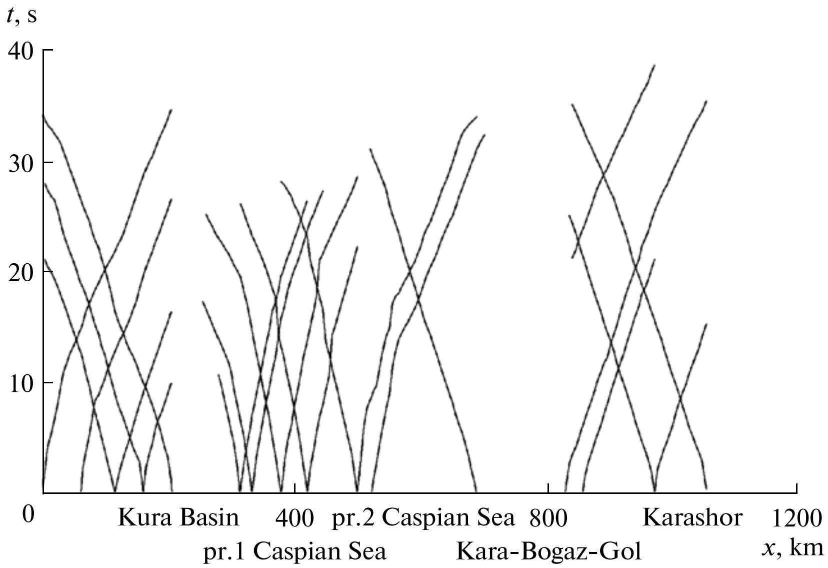

Fig. 2. The observed traveltime curves of first waves along the geotraverse. Names of the profiles used are given.

pretation results based on two central profiles that cross the Caspian Sea were given in (Buvaev and Piip, 2004).

THE METHOD OF SEISMIC DATA INTERPRETATION

Let us present the interpretation results for seismic data along the geotraverse using the *Godograf* software package that was developed at the Faculty of Geology of Moscow State University and the section plotted on the basis of this geotraverse. The program is based on the application of a seismic medium with a homogeneous velocity function. The traveltime curves of seismic waves in the studied geotraverse are presented in Fig. 2.

The traveltime curve were inverted by the homogeneous functions method. This is a method for the automatic computer-based transformation of traveltime curve for first waves into a two-dimensional velocity field in the depth scale; this field contains information about seismic interfaces. Any preliminary information about the structure of the section is not used in this case. The geological interpretation is made in the resulting seismic section. The method is described in detail in (Piip, 1991, 2001). The traveltime curves are depicted in the form of a time section (offset section) in Fig. 3.

The time section indicates that the traveltime curves contain information about the structure of the basin of the Caspian Sea and the adjacent territories. The time section is used for the even linear interpolation of time values with respect to sources, with a step of 25 km. The traveltime curves interpolated with respect to sources are presented in Fig. 4. They were used for the computation of the section.

INTERPRETATION RESULTS

The interpreted DSS section is shown in Fig. 5. Let us consider the deep structure of the units that are crossed by the DSS profile from west to east. The South and Middle Caspian basins are symmetric troughs superimposed upon the adjacent tectonic regions of a sublatitudinal strike (the Turan Plate in the east and Caucasian structures in the west); the trough is limited by deep faults. On the west of the geotraverse, the South Caspian Basin borders the structures of the Kura Basin that belong to the Greater Caucasus.

The **Kura Basin** is situated within the limits of the Greater Caucasus and its more opened part is oriented towards the South Caspian Basin. It is filled with Oligocene–Quaternary molasse underlain by Jurassic–Eocene carbonate-volcanogenic units (Mezhdunarodnaya ..., 2003). The thickness of the sedimentary cover is up to 15 km, according to the DSS data (Fig. 5). It is suggested that the granitic–metamorphic basement, which is exposed in the western and southern margins of the basin and composes the consolidated two-layer crust, is traced in the base of the trough. The value of seismic velocity here is about 7 km/s. The thickness of the crust is no more than 30 km. The consolidated crust forms a fold in the boundary with the South Caspian Basin and the thickness of the sedimentary cover is reduced to 5 km; the rocks that compose the cover are dislocated, probably as a result of compression on the Greater Caucasus side. Judging by the sharp folding, the Kura Basin is most likely divided from the South Caspian Basin by a deep fault (Fig. 5), which formed during the appearance of the meridional structural units of the Caspian Basin.

A Moho discontinuity in the **South Caspian Basin** is located at a depth of 40 km. It is underlain by very

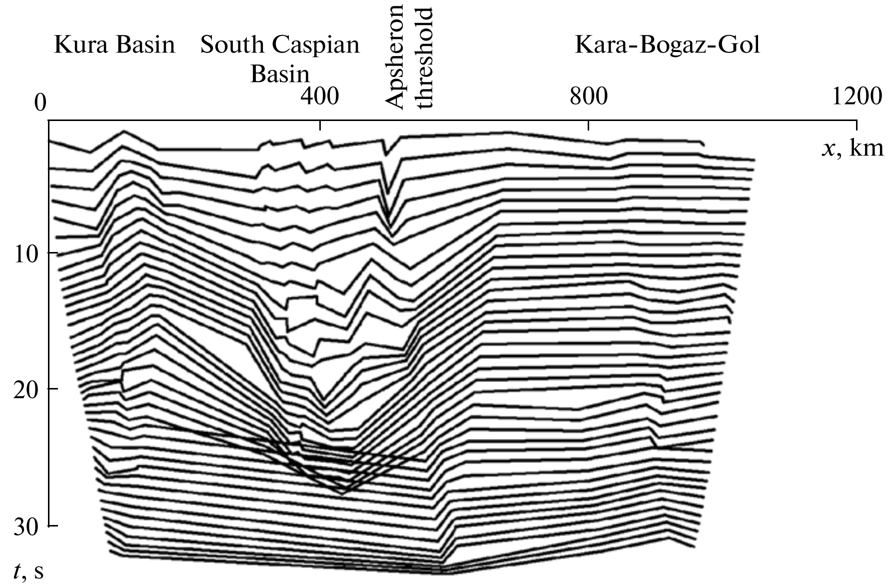

Fig. 3. Time section (offsets cross-section) along the geotraverse.

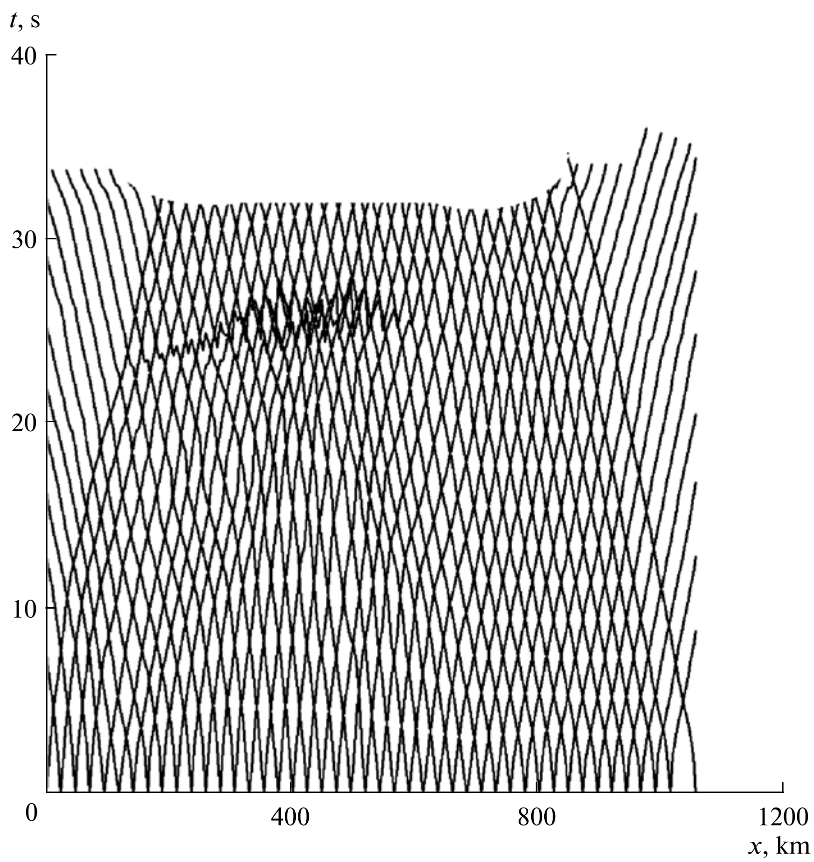

Fig. 4. Interpolated traveltime curves that were used for the computation of the section.

high-velocity and high-gradient mantle, where velocity increases from 8 to 9 km/s per 10 km depth. In the center of the South Caspian Basin, a thinned consolidated crust is observed (the velocity is from 6 to 8 km/s) of about 10 km thickness. In the western part of the basin, the thickness of the consolidated crust

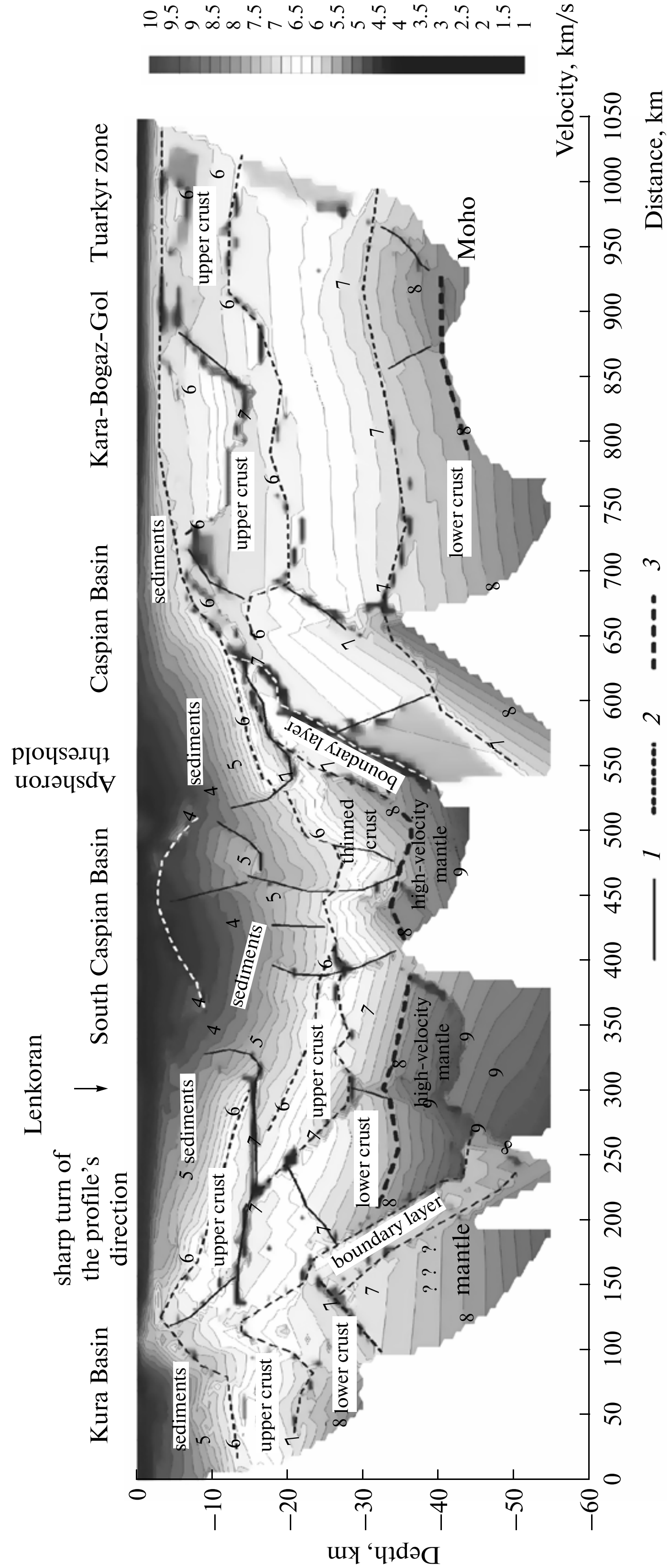

Fig. 5. The seismogeological section along the geotraverse: *1*, faults; *2*, seismic boundaries; *3*, Moho discontinuity. Isolines are drawn with a step of 0.25 km/s.

increases to approximately 20 km and here it is divided into upper and lower parts. In the central part of the basin, the thickness of the sedimentary layer (the velocity is from 1.5 to 6 km/s) reaches 30 km. On the side of the Lenkoran and the Middle Caspian Basin, the lower part of the sedimentary cover is superimposed by the thrusts of the upper crust.

The South Caspian Basin is filled with a thick sedimentary stratum of up to 30 km in the center. The thickness of Pliocene–Quaternary deposits is 10 km. Below, we consider the Miocene and Oligocene clayey deposits that occur with the associated roots of mud volcanoes (Mezhdunarodnaya ..., 2003; Khain, 2005). The thickness of the consolidated crust is less here and is 10 to 20 km. The velocities of seismic waves are from 6.0 to 8.0 km/s, which is typical for the oceanic layer. The velocities of the seismic waves below the Moho discontinuity increase from 8.0 to 9.0 km/s (Fig. 5).

Based on the geological data, intensive immersion of the South Caspian Basin began in the Oligocene and was associated with the accumulation of sandy–clayey deposits more than 10 km thick. In the late Miocene, with respect to the Messinian salinity crisis (the Mediterranean Sea had lost its connection with the ocean), the water level in the Caspian basin abruptly dropped. The Mediterranean Basin was reclaimed in the Pliocene, when Atlantic water penetrated through the zone of the modern-day Strait of Gibraltar; downwarping sharply intensified and, resulting from it, an additional stratum of more than 10 km of sedimentary deposits accumulated in particular areas of the sea for five million years (Grachev, 2000). Some researchers (Jackson et al., 2002; Allen et al., 2002; Rodkin, 2003) came to the conclusion that the oceanic lithosphere of the South Caspian Basin was subducted beneath the framing mountains of Alborz.

The manifestation of Late Miocene–Quaternary volcanism was noted in (Jackson et al., 2002; Allen et al., 2002). The structural studies in the northern part of Alborz indicate that the faults that are located at its boundary with the South Caspian Basin are compression faults and, as researchers believe, are associated with the subduction of the crust of the South Caspian Basin beneath Alborz. Data on the focal mechanisms of earthquakes mainly imply a northeastern orientation of compression axes (Ulomov, 2003).

The Moho discontinuity beneath the basin occurs at a depth of about 35–40 km, while this occurs at 40–45 km in the basin margins. The basin is distinguished by the presence of a significant isostasy distortion: negative anomalies exceed –100 mGal (they resemble anomalies that are observed in the deep-water trenches of Pacific island arcs). Magnetotelluric sounding indicated that a domain of low specific resistance occurs in the upper mantle beneath the crust (Grachev, 2000). The upper mantle beneath the basin also corresponds to the zone of surface wave attenuation (Priestley and Cipar, 1993). The surface of the asthenosphere forms a salient beneath the South Caspian Basin at a depth of 40–60 km and is sunken to 100–120 km in the peripherals (Geofizicheskie ..., 1996). These data, as well as a slightly increased thermal flux (70–100 mW/m^2), may indicate the presence of a fluid-saturated asthenospheric diapir beneath the basin.

The formation of the South Caspian Basin occurred as a result of two deep processes, viz., by the rapid immersion and simultaneous transformation of gabbros and other igneous rocks into denser garnet granulites or eclogite (Artyushkov, 2007). This author believes that sharply accelerated immersion of the basin in the Pliocene and Pleistocene was caused by the penetration of active asthenospheric fluid into the crust and this was a catalyst for the shape transition of gabbro into eclogite. The effect of deep fluid fluxes has been found in many sedimentary basins (Rodkin, 2003). The South Caspian Basin is likely a surface expression of the mantle flux, a kind of hot spot where rocks of the new sialic crust were transformed under the effects of asthenospheric fluids into highly metamorphic simatic rocks that formed under conditions of high pressure and temperature (Artyushkov, 2007; Rodnikov, 2007).

Apsheron threshold. The South Caspian Basin on its north is divided from the Middle Caspian Basin with the Apsheron threshold, which joins the fold structures of the Greater Caucasus and Kopet Dagh. The folded Mesozoic–Eocene rocks found in the western part of the Apsheron threshold are most likely a continuation of the Greater Caucasus. As they go eastwards, they gradually turn into the nondeformed coeval layers of the West Turkmenian Lowland's folded cover (Garagash, Khortov, and Shlezinger, 1999).

The Apsheron threshold corresponds to a narrow zone of recorded earthquake focuses (Ulomov, Polyakova, and Medvedeva, 1999). Based on the DSS data (Baranova, Kosminskaya, and Pavlenkova, 1990), a high-difference step is identified in the surface of the crystalline basement: from 2–3 to 20 km southwards. Seemingly, this is the zone of the most intensively expressed fault tectonics. The Apsheron threshold is likely a zone of deep faults that appeared in the Late Miocene according to V.E. Khain (Khain, Popkov, and Yudin, 2010). The thickness of the crust is about 40 km and it is underlain with high-velocity (9 km/s) rocks of the mantle.

The **Middle Caspian Basin** is seen in the section as an asymmetric basin with a steep western side, where the thickness of sedimentary rocks is up to 20 km. The thickness of the crust is about 40 km. In the section, the Middle Caspian Basin is seen as a scarp or a thrust fault in the upper part of the general section across the South and Middle Caspian basins, rather than an independent structure. Generally, the section of the basin is symmetric from the sides of the Lenkoran and Middle Caspian Basin; the thickness of the sedimentary layer is nearly equal here (up to 15 km). In the uppermost part of the South Caspian Basin, the layer is identified with a velocity of more than 4 km/s in its foot and with an inversion structure (its convex side is directed upwards). The head-on thrusts in the upper crust and the convex structure in the upper part of the sedimentary cover probably indicate that immersion in the basin was simultaneous accompanied by compression.

On the west and east, the South and Middle Caspian basins are limited by symmetrical sloped (about 15°) layers with velocities that are lower than in the embedding rocks (7 to 8 km/s) and a thickness of 5 km. These layers are referred to as boundary layers in the section. They may be suture zones, because the Middle and South Caspian basins were likely formed later than the adjacent structures.

The basement is broken by a series of faults. It has been suggested (Ismagilov et al., 2003) that the Precambrian crystalline basement of the Turan Plate continues beneath the Middle Caspian Basin and is covered by Paleozoic metamorphic rocks. The basin is filled with Jurassic–Quaternary deposits, whose thickness is up to 20 km according to the data of the new interpreted seismic profiles.

On its east, the Caspian Sea Basin borders the Turan Plate. In the section, the plate has an ordinary structure, viz., three layers of consolidated crust; the Moho discontinuity (8 km/s) is at a depth of about 50 km; the thickness of sedimentary deposits is 2–3 km. The upper crust is very low-velocity (5.7–6.2 km/s) and low-gradient, but is of significant thickness (15–20 km). Below, the middle crust is distinguished; its velocity changes along the vertical from 6 to 7.2 km/s at the thickness of about 20 km. The gradient is constant and low.

The lower crust of the Turan Plate is less thick (10–12 km) and has a higher gradient of velocity. As it approaches the Caspian Sea Basin, the upper crust of the Turan Plate wedges out, while the middle and lower crusts are immersed beneath the structures of the Caspian Sea Basin at an angle of about 15°; additionally, the latter two layers are transformed in such a way that the middle crust becomes homogeneous with a velocity of about 7 km/s, while the thickness of the lower one decreases. These transformations might occur during the accumulation of sediments in the Caspian Sea Basin.

CONCLUSIONS

Based on the newly interpretated seismic data, a deep section of the lithosphere was made. It crossed the following structural units of the Caspian region: the Caucasus (Kura Basin), South Caspian Basin, Apsheron threshold, Middle Caspian Basin, and the structures of the Turan Plate (Kara-Bogaz-Gol and Tuarkyr zone).

It has been found that the South and Middle Caspian basins along the profile are symmetrical troughs that are overlain upon the adjacent tectonic units of sublatitudinal strike (the Turan Plate in the east and the Caucasus in the west, which are divided from the adjacent structural units by deep faults).

Additional data on the deep structure of sedimentary basins were acquired. In particular, the thickness of sediments is 40 km in the South Caspian Basin and 20 km in the Middle Caspian Basin.

The South Caspian Basin likely resulted from mantle flux; it is a kind of hot spot where rocks of the new sialic crust were transformed under the effect of asthenospheric fluids into highly metamorphic simatic rocks that formed under the conditions of high pressure and temperature. This suggestion is verified by the high values of velocities in the mantle beneath the Moho discontinuity.

The resulting section generally verifies the ideas of E.V. Artyushkov about the structure and evolution of the South Caspian Basin.

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