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GEOLOGY

Formation of the South Caspian Basin As a Result of Phase Transitions in the Lower Continental Crust

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A number of deep troughs with sedimentary sequences no less than 15–20 km thick are known within continents and at their margins. The South Caspian, Near-Caspian, Barents, and Black Sea basins pertain to this category. The thickness of the consolidated crust in their deep parts decreases to 10–20 km, whereas the *P*-wave velocity increases to the values characteristic of basic rocks. Therefore, this crust is often referred to as oceanic [1]. However, according to [2, 3], deep parts of the Barents and Near-Caspian basins are underlain by the continental crust [2, 3]. Its subsidence was caused by phase transitions with compaction of basic rocks in the lower crust.

The large South Caspian petroliferous basin (Fig. 1) is one of the deepest basins on the Earth. The thickness of sediments here reaches 20 km (Fig. 2) or even 25 km [6, 7]. The bottom of the sedimentary cover is separated from the Moho discontinuity by a high-velocity crust 12–18 km thick (Fig. 3) [7, 8]. Most researchers assign this crust to the oceanic type [1, 7]. The Apsheron–Balkhan Threshold at the northern margin of this basin connects fold systems of the Greater Caucasus and Kopetdag. Earthquakes with sources located at a maximum depth of ~70 km occur beneath the threshold and its northern area (Fig. 6 in [8]). Therefore, it is suggested that this zone is a track of subduction of the oceanic lithosphere of the South Caspian beneath the Central Caspian [1, 7, 8].

The oceanic crust formed at the spreading axis subsided for 80 Ma and rapidly waned in time. Sedimentation proceeded in the South Caspian Basin, at least since the Early Cenozoic (most likely, since the Mesozoic) [5]. In general, subsidence of the oceanic crust should have ceased by the Pliocene. However, the subsidence dramatically accelerated in the Pliocene and Pleistocene. Consequently, up to 10 km of sediments were deposited in the basin during this period. Such acceleration of subsidence is impossible for the oceanic crust. Therefore, this phenomenon is explained by an elastic bend of the oceanic lithosphere that was subducted into the mantle in the Apsheron–Balkhan Threshold area north of the South Caspian [1, 7]. In this case, the bend of the lithosphere should increase toward the convergent boundary. However, Fig. 4 shows that uplift rather than subsidence toward the Central Caspian is observed in this area. This trend rules out a substantial contribution of the lithosphere bending to recent subsidence. According to fragmentary evidence, bending of the basement and its subsidence to a depth of 5 km can occur in the northern 25-km-wide part of the basin in one of the near-meridional seismic profiles [7]. In any case, bending of the lithospheric layer rapidly wanes southward and does not contribute much to subsidence of the crust in the main area of the basin.

At the crustal thickness $h_c^0 = 7$ km in oceanic basins, the average depth of water $h_w^0 \approx 5.5$ km. With thickening of the crustal thickness by $\Delta h_c = h_c - h_c^0$ and maintenance of isostatic equilibrium, the water depth decreases by

$$\Delta h_w = [(\rho_m - \rho_c^{oc})/(\rho_m - \rho_w)]\Delta h_c. \qquad (1)$$

Here, $\rho_m = 3330$ kg/m^3 is the mantle density, $\rho_w = 1030$ kg/m^3 is the seawater density, and ρ_c^{oc} is the density of the oceanic crust. In the central part of the basin with crustal thickness $h_c^1 = 12$–18 km (Fig. 3), $\Delta h_c = h_c^1 - h_c^0 = 5$–$11$ km. Substituting this value into (1), we obtain $\Delta h_w = 0.9$–2.1 km. Thus, the initial water depth $h_w^1 = h_w^0 - \Delta h_w = 3.4$–$4.6$ km. The thickness of sediments necessary for filling the oceanic basin with a depth of h_w^1 in the course of isostatic subsidence of the crust under a load of sediments is

$$h_s = [(\rho_m - \rho_w)/(\rho_m - \rho_s)]h_w^1. \qquad (2)$$

At $\rho_s = 2500$ kg/m^3 and $h_w^1 = 3.4$–4.6 km,

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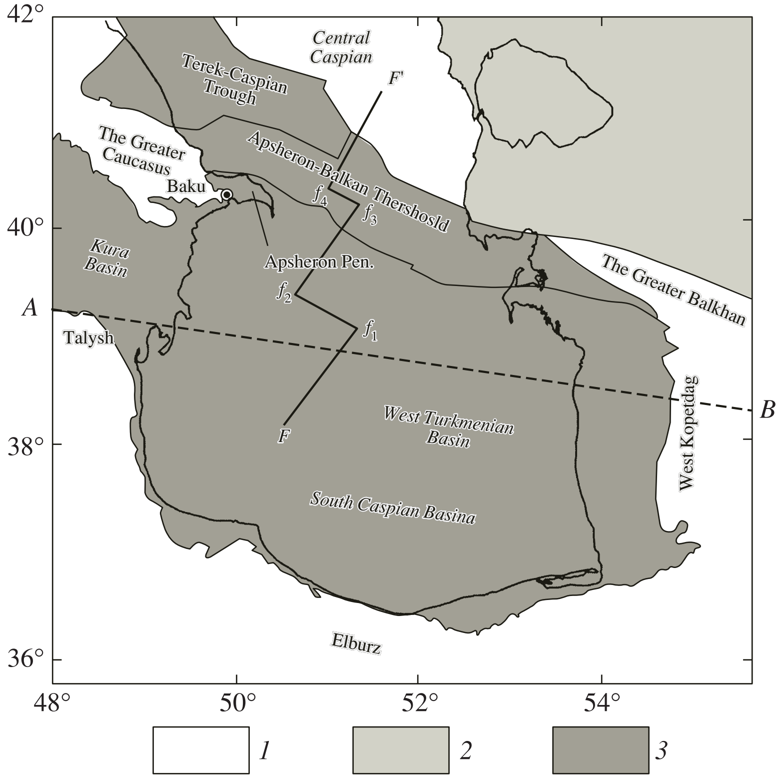

Fig. 1. Main tectonic units of the southern Caspian Sea and adjacent regions, modified after [4]. (*1*) Alpine folded structures; (*2*) sedimentary basins of the Central Caspian and the adjacent Turan Platform; (*3*) deep sedimentary basins of the South Caspian and the adjacent regions. (*AB*, *FF*') Profiles shown in Figs. 3 and 4, respectively.

$$h_s = 9.5\text{–}12.7 \text{ km}. \qquad (3)$$

In some regions with a water depth of ~1 km, the thickness of sediments is, at least, 20 km (Fig. 2). As follows from relationship (2), the replacement of ~1 km of the water column with sediments would result in an additional accumulation of 2.8 km of sediments. Thereby, the thickness of sediments would reach 23 km, which is approximately two times higher than the value in (3).

To maintain the consolidated crust beneath the sediments at a depth of ≥20 km, rocks heavier than the mantle must occur beneath the Moho discontinuity. Large volumes of such rocks can only be represented by eclogites with density $\rho_e = 3500\text{–}3600$ kg/m^3. Gabbro in the basaltic layer of the continental crust is subjected to eclogitization due to the breakdown of plagioclase into dense garnet and sodic clinopyroxene. At the initial gabbro density ρ_{gb}, the formation of the sedimentary basin with a depth of h_s requires the formation of an eclogite layer with a thickness of

$$h_e = (\rho_{gb}/\rho_m)[(\rho_m - \rho_s)/(\rho_e - \rho_{gb})]h_s. \qquad (4)$$

At $\rho_s = 2500$ kg/m^3, $\rho_{gb} = 2930$ kg/m^3, $\rho_e = 3500\text{–}3600$ kg/m^3, and $h_s = 23$ km, the thickness of the eclogitic layer beneath the South Caspian must be $h_e = 25\text{–}29$ km. The formation of the superdeep sedimentary basin in this region was related to the formation of such dense rocks from gabbro in the lower crust.

The *P*-wave velocity in eclogites is approximately the same as in the mantle [10]. Eclogites are basic rocks confined to the Earth's crust. Therefore, the Moho discontinuity beneath the South Caspian is not the bottom of the crust but a seismic boundary that separates the upper crust and high-grade metamorphic rocks of the lower crust. The upper boundary of the eclogitic layer, which coincides with the Moho discontinuity, is located at a depth of ~30 km (Fig. 3), while the lower boundary is located at a depth of 55–60 km, which is close to the crustal depth of 55 km beneath the adjacent Kura Basin. The total thickness of the consolidated crust beneath the South Caspian, including both its parts situated above and below the Moho discontinuity, is rather great (~40 km). Hence, the lower layer of the continental crust in this region underwent high-grade metamorphism. In this case, the upper part of the continental crust located above the Moho boundary should be composed of sialic rocks. Since these rocks underlie a thick sedimentary layer, they should be strongly heated. According to some estimates [5], the temperature of the upper crust at a depth of 20 km may reach 600–800°C. At ~400°C, the heavy garnet begins to crystallize in sialic rocks [11] and the elastic wave velocity increases [12]. This effect may explain the increase of the *P*-wave

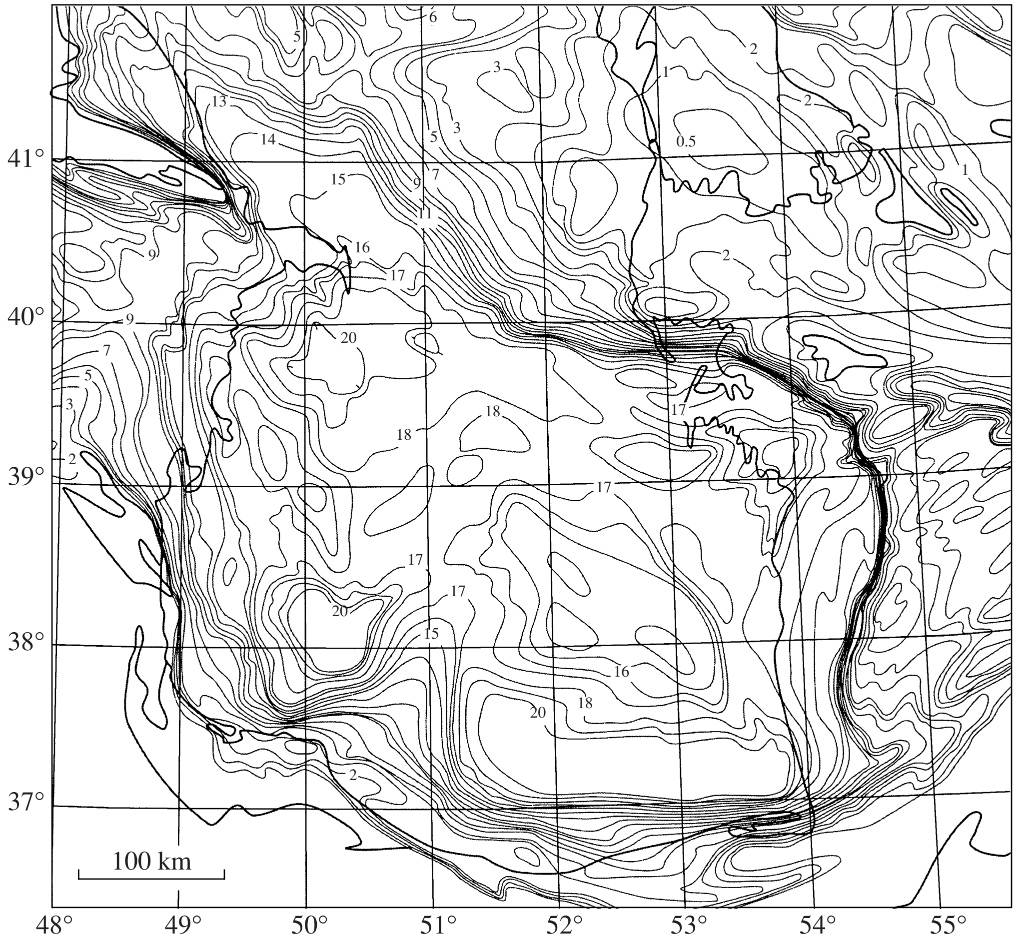

Fig. 2. The depth (km) of the basement in the South Caspian and adjacent regions (modified after [5]).

velocity in the granitic layer to values typical of the basaltic layer (~7 km/s) not only in the South Caspian Basin, but also in other deep troughs (e.g., the East Barents Basin).

The large petroliferous basins are characterized by high rates of subsidence of the crust during certain epochs [2, 3] that mark abrupt acceleration of the process of eclogitization owing to the infiltration of the asthenospheric surface-active fluid into the lithosphere [13]. In the South Caspian, this effect was responsible for rapid subsidence of the crust in the Pliocene–Quaternary. The deep depression formed in this process was mainly filled with sediments eroded from uplifts in the adjacent mountain ranges and the East European Platform. Judging from deposition of deepwater sediments in the Oligocene and Miocene, the region also underwent fast subsidence at the Eocene–Oligocene boundary. The presence of fragments of the Paleocene deepwater sediments in mud volcanoes indicates that the region also underwent fast subsidence in the Early Cenozoic or Late Mesozoic. Manifestation of such subsidence in the South Caspian petroliferous basin (potential fuel resource 8–10 Gt) corroborates the association of such basins with zones of rapid subsidence of the continental crust.

In the stable regions, the effective thickness of the elastic part of the lithosphere T_e varies from a few tens to hundreds of kilometers. Thereby, width L of the region with the lithospheric layer subjected to elastic bending is 100–300 km. The supply of the asthenospheric surface-active fluid into the lithosphere during periods of fast subsidence results in a drastic softening of the lithosphere [13]. This is evident from the formation of steep flexures in many sedimentary basins involved in rapid subsidence. As follows from Fig. 2, the basement of the South Caspian Basin is surrounded by flexures with a maximal width of 10*n* km and height varying from *n* to 10–12 km. In the right-hand part of Fig. 4, one can see a flexure 50 km wide and 11 km high in the north of the basin.

The effective thickness T_e of the elastic part of the lithosphere shows the following relationship with the characteristic width of the bent layer [13]: $(T_e)_{\text{km}} \sim 5.3 \cdot 10^{-2}[(L)_{\text{km}}]^{4/3}$. At L = 20–50 km, T_e is ~3–10 km. Such small T_e values indicate the softening of the lithosphere

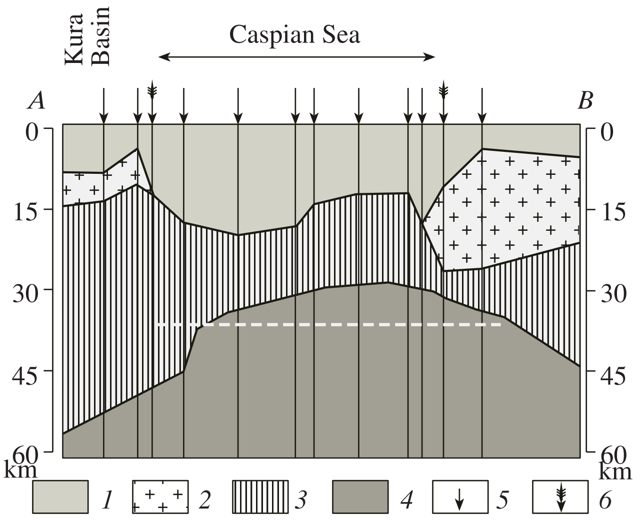

Fig. 3. The crustal structure of the western Kura Basin, South Caspian Basin, and the region adjoining this basin in the west based on DDS data and observations of converted waves at the sites of geophones (modified after [8]). The profile is shown in Fig. 1. (*1*) Sediments; (*2*) "granitic" layer (V_p = 5.8–6.5 km/s); (*3*) "basaltic" layer (V_p = 6.5–7.8 km/s); (*4*) upper mantle; (*5*) line of seismic reflection recording; (*6*) site of geophones.

in the South Caspian Basin during its subsidence in the Pliocene and Pleistocene.

Coesite, diamond, and other minerals crystallized at a depth of 100–150 km are found in foldbelts within blocks of metasedimentary and crystalline rocks of the crust [14, 15]. This is usually attributed to subduction of the continental crust into the mantle. The continental lithosphere is commonly lighter than the asthenosphere. Therefore, it is suggested that the heavy subducted plate of the oceanic lithosphere draws the continental lithosphere into the asthenosphere or the continental lithosphere is pushed into the asthenosphere by a great compressive force.

Compaction of rocks in the lower crust due to phase transitions beneath deep sedimentary basins increases the average density of the continental lithosphere. In the case of strong compression of the crust, the main body of sediments is commonly detached from the basement and preserved in the foldbelt in the form of nappes and steep folds. If the consolidated lithosphere has a high density, it can be subducted into the asthenosphere together with a small amount of sediments. Let us consider the conditions when the given layer turns out to be heavier than the asthenosphere.

The oceanic lithosphere commonly undergoes subduction in the regions where its average density ρ_{oc} is equal to or higher than the density of the asthenosphere ρ_a (~3200 kg/m^3) [9]. The thickness of the oceanic lithosphere and its density ρ_{oc} diminish with decreasing age t of the lithosphere. At $t \approx 10$ Ma, ρ_{oc} and ρ_a become equal; the younger oceanic lithosphere turns out to be lighter than the asthenosphere and is not involved in subduction [9]. The average depth of the water that covers the 10-Ma-old lithosphere is $h_w^1 = 3.5$ km. Based on comparison of the isostatic equilibrium position of the oceanic lithosphere (with $t = 10$ Ma) and the consolidated part of the continental lithosphere beneath a sedimentary basin (with a depth of h_s), it can be shown that the continental lithospheric layer becomes heavier than the asthenosphere at

$$h_s > [(\rho_a - \rho_w)/(\rho_a - \rho_s)]h_w^1. \qquad (5)$$

It is important that the thickness and density of the layers that make up the consolidated lithosphere are not included in this relationship. Among the parameters that correspond to specific sedimentary basins, only h_s and the average density of the sedimentary cover ρ_s are included in Eq. (5). These parameters are usually known rather definitely. For example, according to Eq. (5), at ρ_s = 2550–2600 kg/m^3, h_s > 12–13 km. This value is much less than the thickness of sediments in the Barents Sea, Near-Caspian Basin, Vilyui Syneclise, and many other basins. For the South Caspian, condition (5) at ρ_s = 2500 kg/m^3 is realized at h_s > 11 km, which is approximately twice as small as the thickness of sediments in this region. Irrespective of the continental or oceanic nature of the crust, a very great thickness of sediments is required to fill deepwater basins, such as the Black Sea, Gulf of Mexico, or basins of the eastern Mediterranean. Hence, the consolidated part of the lithosphere beneath these basins is heavier than the asthenosphere.

In many sedimentary basins of continents and their margins, the thickness of sediments exceeds 12–13 km. Nevertheless, subduction is not generally recorded in them. Hence, in addition to great compressive stress, a drastic softening of the lithospheric layer is needed for initiating subduction. In the South Caspian, the consolidated lithosphere overlain by ~20 km of sediments should be heavier than the asthenosphere. The trough is situated in the Alpine–Himalayan Foldbelt dominated by compressive stresses. The lithosphere of this trough experienced drastic softening in the Recent epoch. Under such conditions, subduction of the heavy continental lithosphere into the mantle should be expected.

The region with earthquake sources located at a depth of 50–70 km beneath the Apsheron–Balkhan Threshold and its northern area is ~100 km wide [8]. If these earthquakes occur in the subducted plate, the latter must be underthrust northward, at least over the same distance. In this case, the sediments detached from the subducted plate should be compressed for ~100 km. The sedimentary cover in foldbelts is subjected to strong compression owing to the formation of large nappes and steep folds. In the South Caspian, compression has been developing during the last 3.4 Ma since the late Pliocene. Thereby, sediments of the productive lower Pliocene sequence were detached from

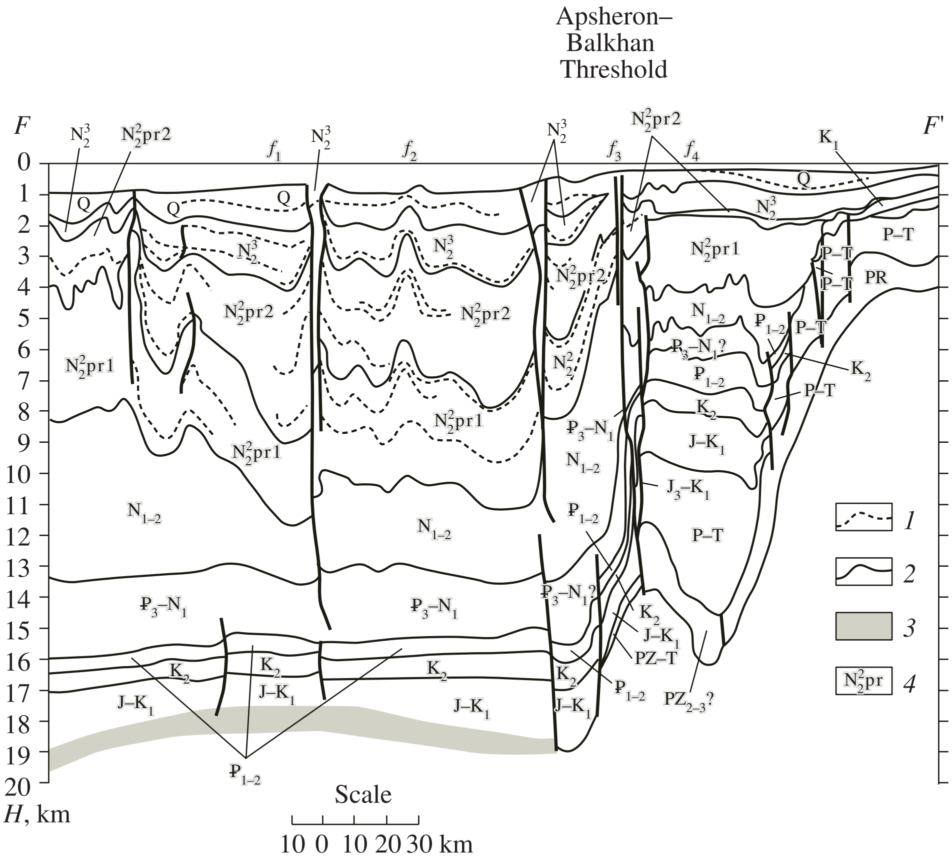

Fig. 4. The section of the upper sedimentary cover of the South Caspian compiled from seismic profiling data on reflected waves along line FF' shown in Fig. 1 (modified after [5]). (*1*) Age boundaries; (*2*) reflectors; (*3*) crystalline basement; (*4*) productive sequence.

the underlying rocks that are mainly composed of plastic clays. As follows from Fig. 4, large nappes did not appear in the region under consideration. Only numerous folds were formed here (see also Figs. 61, 64 in [5]). In the section shown in Fig. 4, the vertical scale is tenfold exaggerated in comparison with the horizontal scale. Actually, the slopes of faults are not great and mostly do not exceed a few degrees. Under these conditions, the total compression of the folded sedimentary beds is not greater than 10 km, which is much less than the suggested northward underthrusting of the South Caspian lithosphere. Thus, although the consolidated lithosphere in the study region is heavier than the asthenosphere, subduction did not occur here in the Recent epoch.

Most earthquake sources beneath the Apsheron–Balkan Threshold and its northern area are located at a depth of 30–50 km. This depth corresponds to the lower continental crust overlapped by a thick sedimentary cover. The sources do not make up an inclined seismofocal zone, which is typical of subduction zones at active margins. The predominance of tensile stress in the former region indicates the development of normal faulting. This may be related to the ongoing compaction of rocks in the lower crust owing to spatially irregular phase transitions.

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