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Temperature Field and a 3D Geothermal Model of the North Caspian Basin

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Abstract—Specific features of the geothermal field distribution in the North Caspian Basin were derived from 3D and 2D numerical modeling of heat conduction. Temperature was calculated in the upper crust (to a depth of 6 km) and in the entire crust (to a depth of 50 km). It is shown that the background temperature of the basin increases to the southwest. Calculations were made for the distortions in the terrestrial heat flow caused by its redistribution in thermally contrasting rock sequences consisting of high-conductive evaporites and low-conductive terrigenous rocks.

The North Caspian Basin is traditionally recognized within the boundaries of the salt-dome region. Its northwestern limit is traced along the pre-Kungurian tectonic and sedimentary scarp, as high as 1500 m, which extends in the submeridional direction from Kotelnikovo in the south via Volgograd to Saratov in the north and turns abruptly to the east extending at the latitude of Uralsk toward Orenburg. The basin is limited by the Ural Foldbelt in the east, the South Emba Paleozoic tectonic rise in the southeast, and the Donbass-Tuarkyr system of inversion highs in the southwest [3] (Fig. 1). The Caspian Basin had taken its shape within these boundaries as a closed structure only by the end of the Early Permian, when the Ural orogenic belt was formed at its eastern boundary and an inversion-type uplift existed on the spot of the present-day Donbass-Tuarkyr rift system. Before that time various parts of this system were related to different sedimentary basins. The western half of the basin was a part of the sedimentary basin that had been continuously evolving since the Late Riphean, and its eastern part was a fragment of a large orogenic region until the Early Devonian. In the Devonian and Early Carboniferous the entire territory of the basin was a vast area of sedimentation covering the shelf of a deep-water marginal basin, in paleogeographic terms. This basin was localized in front of the subduction zone that separated the East European continent from the Ural paleoocean.

The Kungurian (Permian) evaporites, which occur as domes and stocks because of their tectonic and gravitational instability, are a specific feature of the North Caspian Basin. They mainly consist of rock salt with scarce sulfate segregations and variably thick interbeds of sulfate–terrigenous rocks including mudstone, sandstone, and anhydrite. The dip angles of these rocks vary from a few degrees to 75° because of the ductile flow of salt from the intermediate zones to the cores of the salt massifs. The domes partly or entirely intrude into Upper Permian sedimentary rocks. In some cases, where the domes ceased to grow in the Paleozoic, the overlying Mesozoic rocks lie horizontally; while in other places, where the domes continued to grow further, these rocks are tilted at various angles controlled by the time and rate of the salt rise. In plan the domes are round, elliptical, elongated, or star-shaped. The round domes are characteristic of the central part of the basin while the elongated ones are characteristic of its margins [10].

The rock salt has a high thermal conductivity ranging from 5.5 to 6.5 W/(m · K) and significantly exceeds the heat conductivity of the terrigenous rocks of 1.6–2.0 W/(m · K). This high conductivity contrast and the steep rock contacts are responsible for the marked redistribution of the terrestrial heat flow. Like other potential fields, the heat flow propagates along the paths of least resistance, being concentrated in the salt domes and discharging in the zones between them.

Thus, heat flow refraction is the main cause of the heterogeneous heat flow in the North Caspian Basin. Analyzing the empirical data, one can see that the positive heat flow anomalies above the salt domes are produced mainly by structural and geological heterogeneities as well as by the presence of rock salt layers as heat conductors. However, some other factors controlling the thermal anomalies should be evaluated. They include the heat generated by radioactive decay and exothermal reactions, as well as the heat released by friction and heat-and-mass transfer during halokinesis.

If radiogenic heat generation were the dominant factor, the heat flow would be higher in the zones between the salt domes, where the terrigenous rocks are enriched in isotopes that are longer-living than rock salt. This, however, is not confirmed by the available data. The exothermal reactions in the rock sequences of

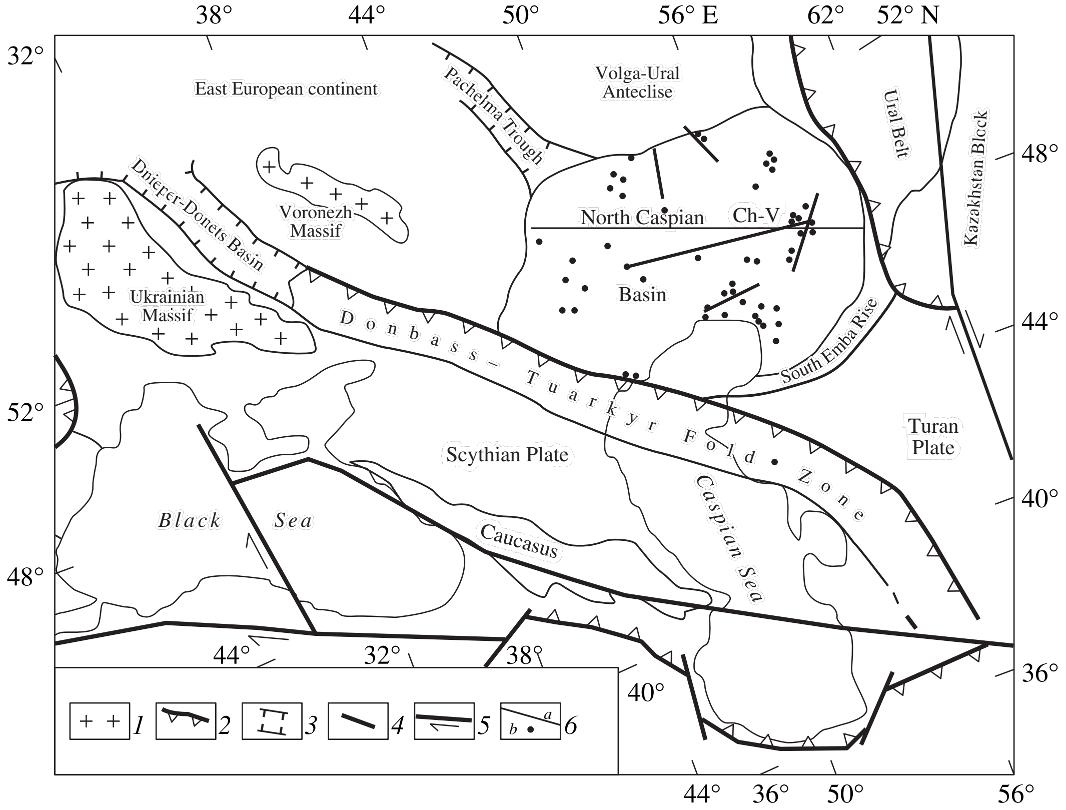

Fig. 1. Tectonic setting of the North Caspian Basin. (*1*) Continental basement rise, (*2*) suture, (*3*) rift system boundary, (*4*) fault, (*5*) transcontinental shear zone, (*6*) profile line: (*a*) Chelkar-Volgograd (Ch–V) DSS profile, (*b*) well bearing temperature data.

this type seem to be highly improbable. Moreover, endothermal processes, in particular halite dissolution, should be expected [11].

A possible role for friction heat and heat-and-mass transfer can be estimated by solving the problem of the cooling of a vertical round cylinder with a diameter and thermal physical properties similar to those of a salt dome. Even assuming that in the course of its intensive rise salt is heated by friction to its melting temperature (800°C), the excess heat flow would be released in 3 Ma, and the salt would cool to the present-day temperature. Yet, it is known that the most intensive growth of salt domes in the North Caspian Basin ended while still in the Triassic. Setting the problem another way, we can find that the stationary temperature distribution will be stabilized in 3 Ma after the salt has risen for 3 km, or, in the absolute value, the additional heat flow would be 0.04 mW/m^2, that is, three orders of magnitude lower than the background value [18].

Because the structural and thermal heterogeneities in the North Caspian Basin produce lateral and vertical variations in the geothermal gradient and heat flow density, an estimation of their background values by simple averaging encounters difficulties and requires the detailed study of temperature distribution practically in each hole.

The mosaic tectonic pattern of the basin, especially of its larger central part, known as the Central North Caspian Depression, should also be taken into account. Here the salt domes are round, and a two-dimensional approximation of the thermal field introduces obvious error. The 2D approximation of the heat flow is possible only in the marginal parts of the basin where the salt swells and ridges are dominant structures [6]. In this connection, we used 3D modeling and representation of the geothermal field for the entire territory of the North Caspian Basin.

The 3D temperature and other geothermal parameter distributions were made on the basis of temperature logging of wells and on some special-purpose measurements.

Information on temperature in the holes drilled in the North Caspian Basin has increased since the exploration of the South Emba petroliferous province in the prewar years. The first temperature measurements were made in wells drilled to a depth of 2 km at the Dossor, Taskuduk, Makat, Sagiz, and additional oil fields in 1938–1940. The first generalizations of the thermometric data revealed heterogeneity of the geothermal gradients. Their higher values turned out to be related to the anticlines and the lower values, to the synclines [12]. Somewhat later S.S. Kovner [13] developed the theo-

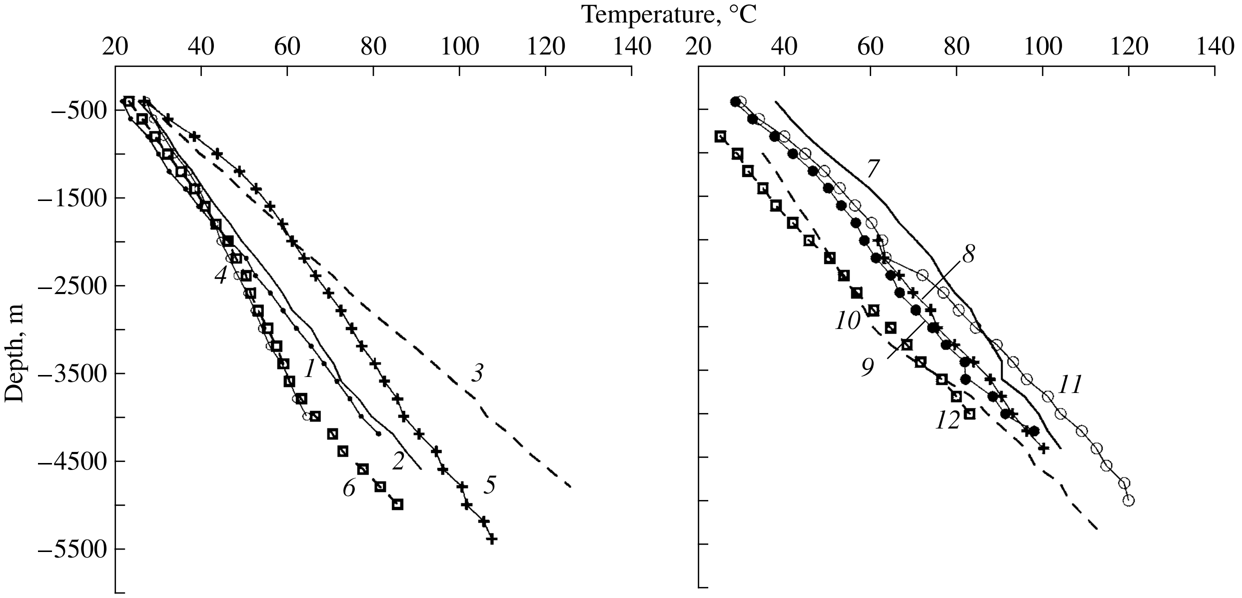

Fig. 2. Thermograms of some deep wells in the North Caspian Basin. Wells: (*1*) Blaksai-89p, (*2*) Karatyube-34, (*3*) Karatyube-35, (*4*) Kumsai-2, (*5*) Biikzhal-SG2, (*6*) Kursai-4, (*7*) Teresken-1p, (*8*) Teplovskaya-1p, (*9*) West Teplovskaya-2p, (*10*) Tashlinskaya-25p, (*11*) Aralsorskaya-SG1, (*12*) Khobdinskaya-1.

retical grounds for using the temperature survey in prospecting for buried dome-shaped structures.

In spite of the extensive thermal logging of the wells drilled in the North Caspian Basin, the generalization of results remained insufficient. The papers published by Sydykov, Dal'yan and co-authors for the eastern part of the basin [5–7], by Zhevago for the central and eastern parts [9], and by Druzhinin for its western part [8] were only exceptions.

The bulk of the regional geothermal data were collected in the course of the compilation of the Geothermal Map of the USSR [4] and stored as temperature logs in archives of the Geothermal Laboratory at the Geological Institute of the Russian Academy of Science. These, as well as more recent data, were used as a basis for our investigations.

We began our study with a tie-in of the wells, the estimation of well standing after drilling operations; a digitizing of the temperature logs; and the compilation of a database with the appropriate graphic materials. As a result of this work we collected information on temperature in 115 wells drilled in the region, including 16 deep wells drilled to a depth of more than 4 km (Fig. 2).

To plot the isotherms in 3D geometry, we used the holes with the most reliable data on the deep temperature distribution; the locations of these holes are shown in Fig. 1.

The 3D temperature and geothermal gradient distribution was plotted using the TECPLOT v.7.0 geoinformation technology (AMTEC Engineering Inc., USA). In addition, we developed some special modules for conversion of thermometric data into the TECPLOT format [20]. This program allowed us to depict the geothermal data in the latitude–longitude–depth coordinates and to perform a 3D interpolation of the observed field. In our case this 3D interpolation was done using an arbitrarily configured network. We used a nonuniform network tied to the hole coordinates (Fig. 3) and to the trends of the seismic profiles, along which the 2D calculations of deep temperatures were made (see Fig. 2). Interpolation parameters were chosen to avoid sharp temperature discrepancies between the holes and profiles, unsupported by the data available.

Figure 3 demonstrates the obvious temperature rise, at depth, from NE to SW. For example, in the eastern part of the basin, near the boundary with the Mugodzhary Mountains, the temperatures at the depths of 2 and 3 km are 40–45 and 60–65°C respectively, whereas in the South Emba and Mangyshlak areas the temperatures at the same depth are 55–60 and 70–75°C. At a first approximation, these data are consistent with the heat flow decrease in the eastern part of the North Caspian Basin owing to the nonstationary screening of the terrestrial heat flow in the southern Ural and Mugodzhary Mountains [19].

A similar pattern is observed in the geothermal gradient distribution within a depth interval of 0–2 km (Fig. 4), where its values increase southwestward from 15 to 40–45 mK/m. It appears that at a depth of 3–4 km the gradient is stabilized at 20–35 mK/m level. This phenomenon can be interpreted in different ways. First, it can be explained by the stable thickness and thermal conductivity of the terrigenous rocks in the basins between the domes and in the subsalt rocks. Second, this agrees with the view of some researchers of the

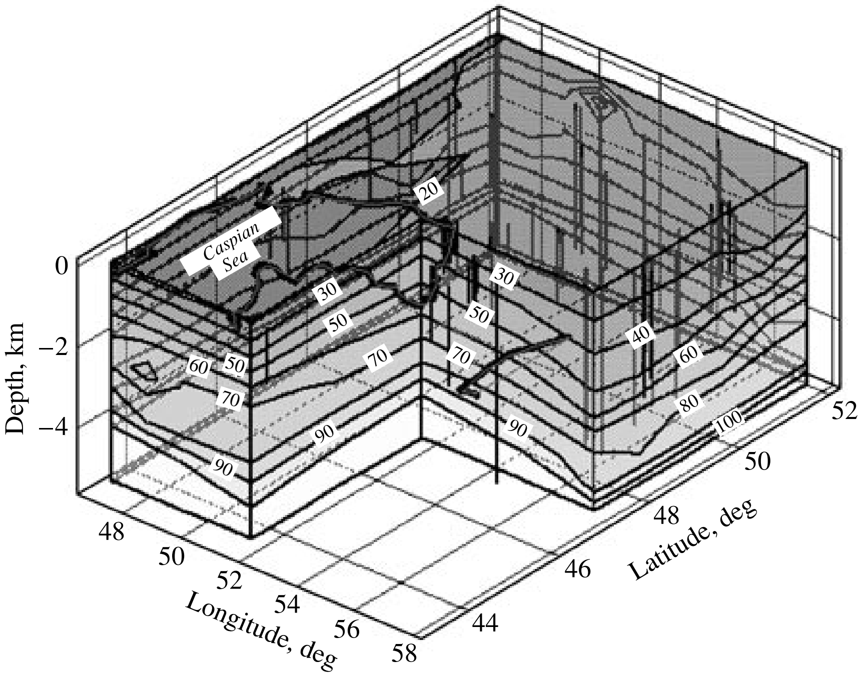

Fig. 3. The 3D plot showing the well location (vertical lines) and the actual temperature (°C) distribution in the North Caspian Basin.

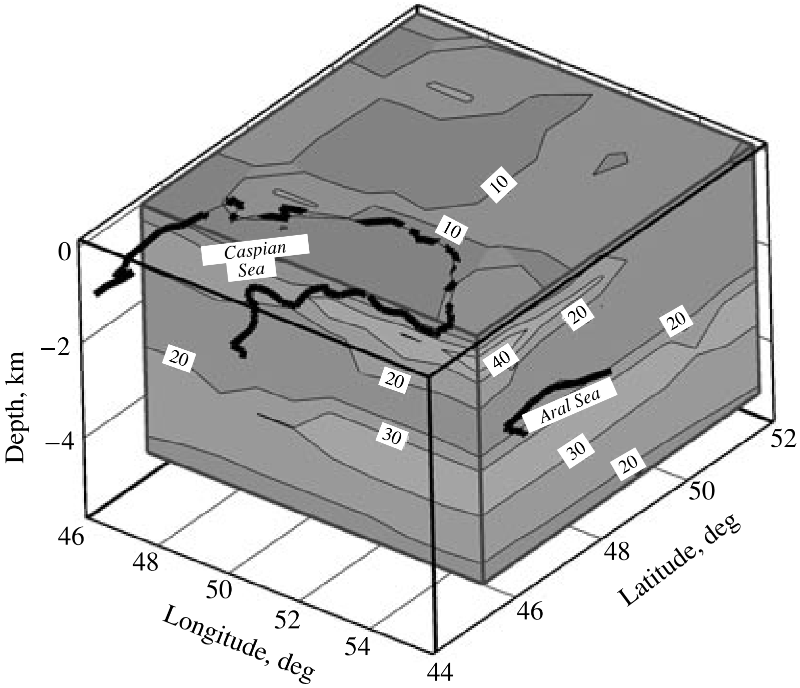

Fig. 4. The 3D plot showing the geothermal gradient (mK/m) distribution in the North Caspian Basin.

Urals [22–24], who suggest that the thermal gradients increase with depth, as follows from the measurements in the Ural SG-4 Superdeep drilled at the western limb of the Tagil Synclinorium. Thus, the geothermal gradient in the zone of the Mugodzhary and the North Caspian Basin conjugation is comparable at a depth of more than 3 km with that in the central part of the basin.

Another 3D model of temperature distribution was calculated for a depth interval of 0–50 km, which comprises the entire crust thickness in the North Caspian

Thermal properties accepted in modeling of geothermal field

Lithotectonic complex	Thermal diffusivity, $n \times 10^{-7}$ (m^2/s)	Thermal conductivity, W/(m · K)	Heat generation, μW/m^3
Suprasalt terrigenous rocks	5.0	2.1	1.5
Rock salt	12.0	5.9	0.4
Subsalt terrigenous rocks	7.0	2.3	1.3
Metamorphic rocks (V_b = 6.6 km/s)	8.0	2.5	1.5
Geophysical granite layer	6.0	2.5	1.8
Geophysical basalt layer	8.0	2.9	0.3
Eclogite (?)	10.0	3.2	0
Upper mantle	10.0	3.4	0

Basin. We deduced this model from the data available for the structure and layer velocities along the profiles shot in the North Caspian Basin [1, 14, 15, 17].

The thermal properties of rocks used in calculations of the crustal temperature and heat flow (table) were chosen in accordance with the seismic section.

As follows from the table, the salt and rocks with eclogite characteristics have the greatest contrast. The occurrence of eclogite-like rocks at the base of the crust is a distinctive feature of the Central Caspian Depression. The eclogite (?) is manifested as a high-velocity (7.9–8.1 km/s) lens, about 10 km in thickness. In our modeling, the boundary conditions of the second type were accepted at the lower contact of the rock sequence, that is, we set the constant heat flow equal to the background value measured in the deep holes drilled in the area minus the radiogenic heat generation within the crust (table). This reduced heat flow was 23 mW/m^2. The constant temperature set at the upper boundary corresponds to the temperature of the “neutral layer”, which was calculated from the variation of the bottom hole temperature with hole depth (Fig. 5). The linear data fitting allowed us to derive a regression formula characterizing the relationship between temperature (T) and the hole depth (Z): $T = (274.86 + Z)/45.80$ [21]. Assuming $Z = 0$, we obtain $T = 6$°C. Approximately the same temperature was measured in the “neutral layer” (at a depth of 20–30 m) with a downhole thermometer.

Using a regression relationship, we also calculated the average geothermal gradient (21.8 mK/m) in the depth interval surveyed. The condition of zero heat outflow at the lateral boundaries was met, that is, $\partial T/\partial x = 0$.

We performed our modeling using the TERMGRAF software package that provides calculating with a finite element method. Temperature and heat flow can be calculated for a given depth under nonstationary conditions for any geometry of structural boundaries and any number of thermal contrasts [19].

The 3D temperature matrix is based on the volumetric interpolation of all numerical data obtained, that is, the measurements in wells and the geothermal data calculated from the seismic profiles (Fig. 6). The correlation of the empirical and calculated data for the holes lying on the profiles and at their intersections showed that the errors in determining the depth of the same isotherms are very low. They reach ±50 m for a depth of less than 5 km or ±150 m for a depth of less than 40 km. Thus, the relative error is no more than 1%.

The Earth’s crust temperature to a depth of 50 km shows the same variation trend with a gradual increase toward the southwest as within the drilled intervals (Fig. 7). In the eastern part of the basin the temperature at the M boundary was estimated as 400°C, a value comparable with those beneath the southern Urals and Mugodzhary [19]. In the Central Caspian Depression, and especially in the South Emba region, the temperature at M level reaches 450–500°C.

Westward from the Mugodzhary meridian, the isotherms rise making up a dome with its apex situated in

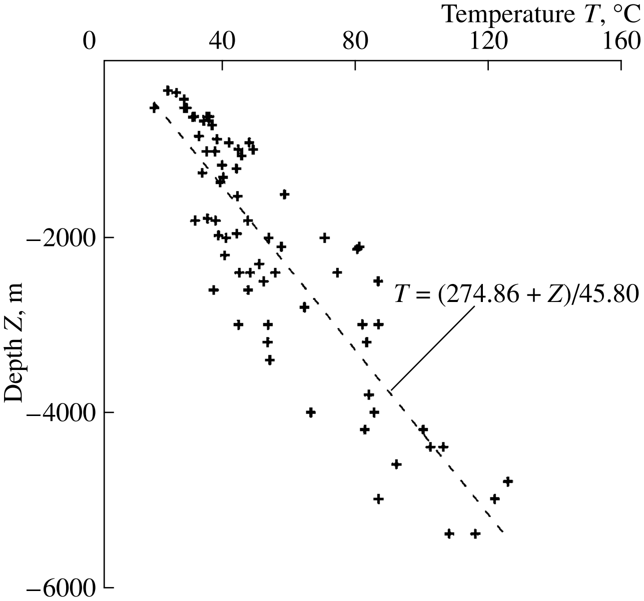

Fig. 5. The bottom-hole temperature vs. hole depth in the central and eastern North Caspian Basin.

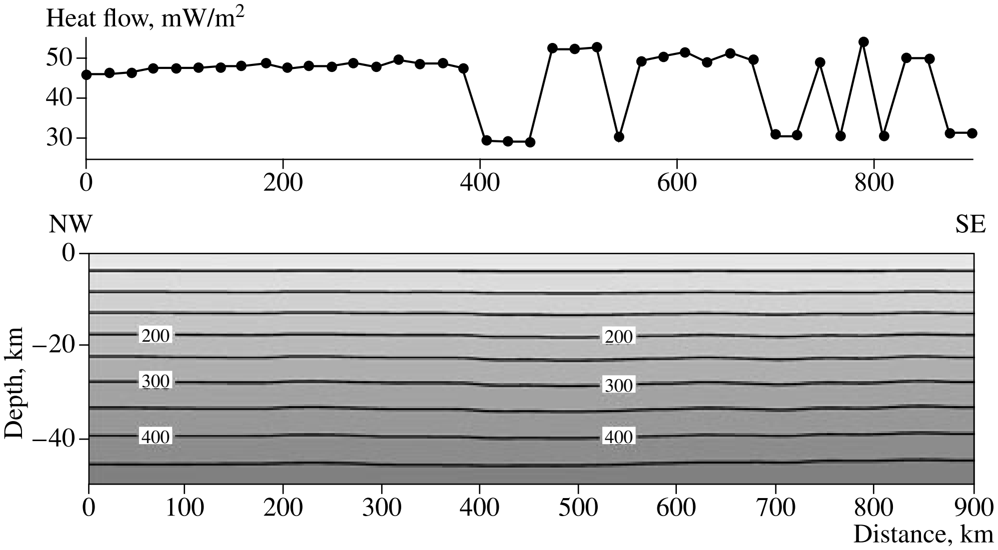

Fig. 6. The temperature (bottom) and heat flow (top) distribution along the Chelgar-Volgograd DSS profile. See Fig. 1 for the profile location.

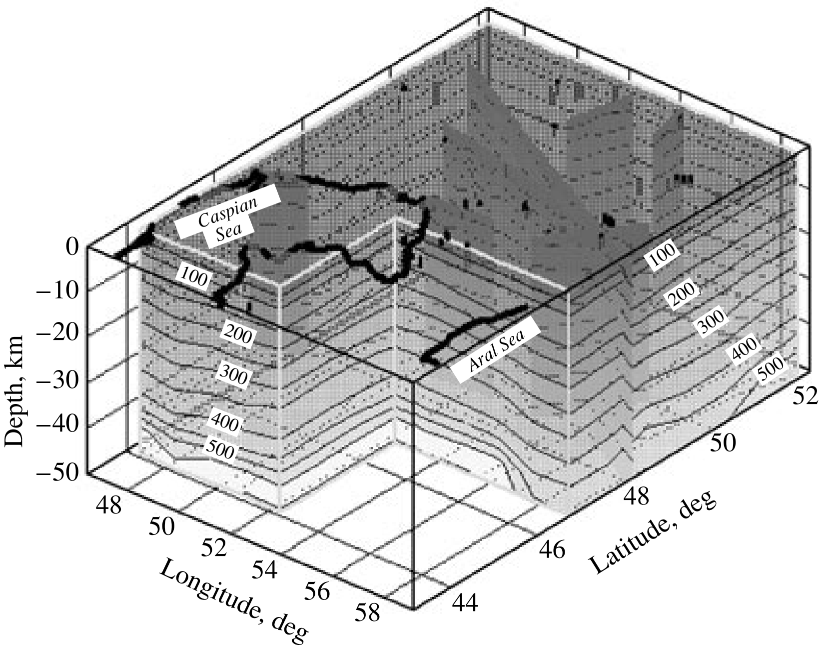

Fig. 7. The 3D plot showing the temperature distribution within the crust of the North Caspian Basin. Vertical lines denote wells. The temperature variation along the DSS profiles is also shown.

the areas of South Emba, the Mertvyi Kultuk salt flat, and North Mangyshlak. The spatial correlation of temperature domes and oil production zones previously established in the Pechora Basin of the Barentz Sea region and in the South Kara Basin [16] remains valid here too, because the areas of the Kazakhstan Republic, mentioned above, are the sites of intensive hydrocarbon production.

The temperature dome formation is related to the presence of a high-velocity layer at the crust–mantle boundary that coincides with a high-conductive eclogite lens (?). Thus, the temperature dome should be regarded as a result of a heat flow perturbation induced by structural and thermal heterogeneities, rather than by lateral mantle heat flow variations, which are thought to be unlikely because the basement has the same pre-Riphean or Early Riphean age in different parts of the basin [2].

Having analyzed the geothermal field of the North Caspian Basin as a whole, we could state that all varia-

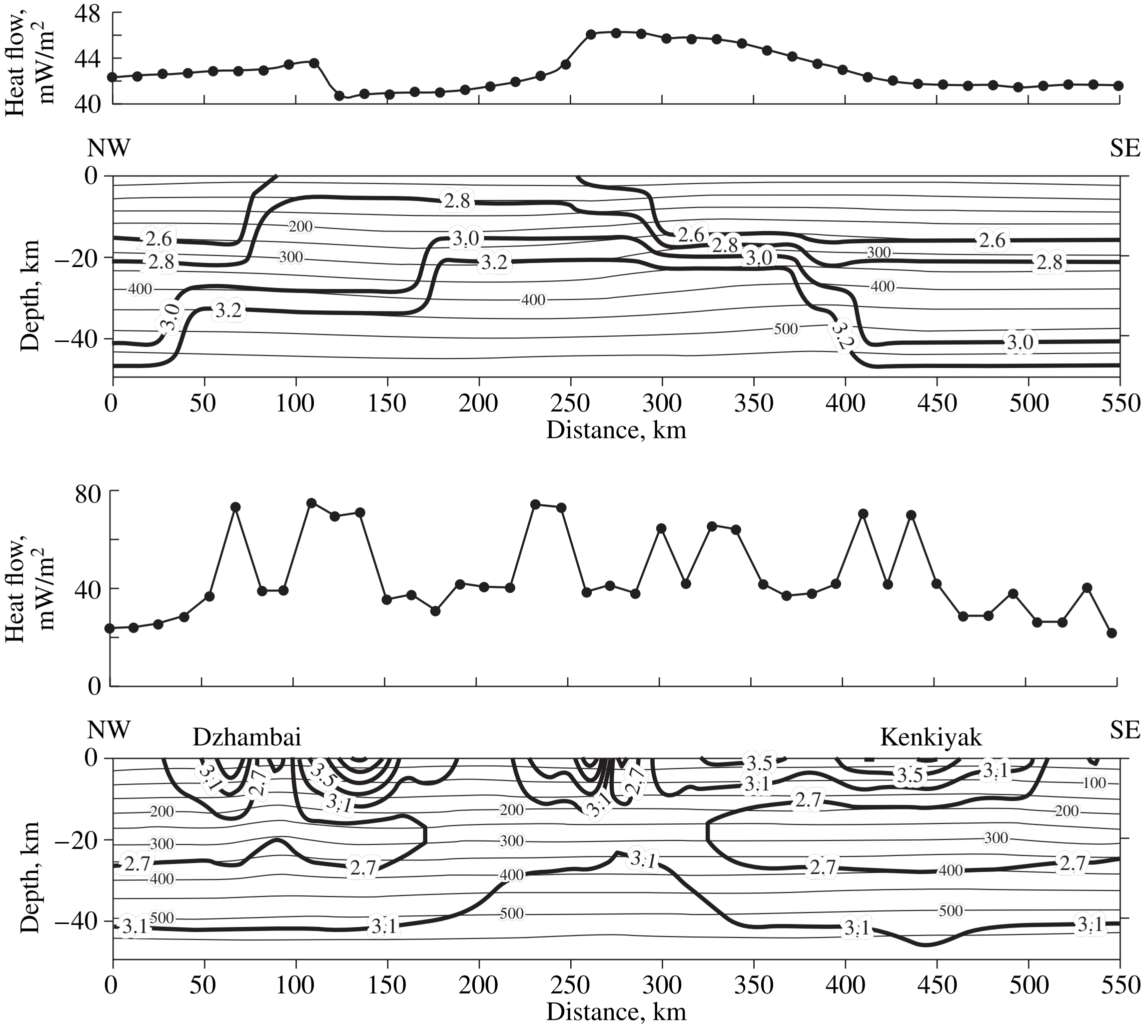

Fig. 8. The temperature distribution in the lithosphere and heat flow distribution along the Dzhambai-Kenkiyak profile before the salt dome formation for the time of 260 Ma (top) and at the present time (bottom). The solid lines show the thermal conductivity (W/(m · K) distribution.

tions of temperature, geothermal gradients, and heat flow density in the region are explained merely by the redistribution of heat flow under conditions of contrasting thermal conductivity. The most drastic heat-flow distortions arise at the contacts between salt and host terrigenous rocks and at the contacts of eclogite (?) with the adjacent lower crustal rocks. The only exception is the conjugation zone between the eastern North Caspian Basin and the Mugodzhary Mountains, where the deep-seated thrust sheets of the foldbelt make up the zones of low heat flow extending over the adjacent areas of the sedimentary basin.

As can be seen from Fig. 5, all holes, 1.0–1.5 km deep, drilled in the suprasalt rocks or in the zones between the salt domes reveal elevated temperature gradients because of the low thermal conductivity of the terrigenous rocks. The deeper holes penetrating evaporites demonstrate a notably lower average temperature gradient. This is a qualitative statement based on the experimental data. However, using numerical modeling with TERMGRAF software, we are able to estimate the effects of structural and thermal heterogeneities both in the geological past and at the present time.

This is illustrated by a latitudinal heat flow profile extending from the Dzhambai Dome to the Kenkiyak Dome (Fig. 8). The profile includes the central North Caspian Depression in the west and the Aktyubinsk–North Caspian zone of uplifts in the east [Yu.A. Volozh, private communication, 1997].

The boundary between these zones is supposed to be controlled by a gently dipping deep-seated fault in the basement, traced by seismic reflection measurements. The eastern segment of the profile is characterized by thinning of the terrigenous–evaporite rock complex and by the rise of the 6.2 km/s velocity boundary to a depth of 9–12 km, in contrast to the western segment of the profile where this boundary was recorded in a depth range of 18–22 km. A high-velocity layer, presumably an eclogite (?) lens, was outlined in the lower crust of the Central Caspian Depression. The thermal properties of the rocks used to calculate the crustal temperature and heat flow (table) have been chosen in compliance with seismic data. The model calculation of crustal temperature and heat flow before the formation of salt domes (260 Ma ago) did not show any local high-frequency distortions of the thermal field.

The high-conductive salt domes serve as the main factor deforming the thermal field and distorting the background heat flow by 70–80%. The effect of the eclogite (?) lens manifests itself as a lateral temperature gradient zone in the lower crust (a depth interval of 250–400 km in Fig. 8). This thermal field configuration is responsible for the temperature dome mentioned above.

CONCLUSIONS

(1) The geothermal field of the North Caspian Basin can be displayed correctly only in 3D geometry.

(2) The temperature of the deep-seated rocks increases westward, that is, the temperature in the central North Caspian Basin is generally higher than that in the eastern marginal zone.

(3) Geothermal gradient variations are most notable in the upper layer, at a depth of less than 3 km, with the absolute values growing in the same western direction; below a depth of 3 km the gradient is stabilized almost everywhere.

(4) The lateral heat flow variations are caused by heat flow perturbations related to the structural and thermal heterogeneities. The contact between evaporites and terrigenous rocks is the most contrasting boundary. Distortions arise both in the temperature and heat-flow field, largely at the dome margins.

(5) The temperature dome in the lower part of the Earth's crust is attributed to the refraction of the heat flow by a high-conductive eclogite lens (?). The large oil fields in the South Emba, northern Turan Plate, and Mangyshlak are spatially related to this dome.

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