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THERMAL TOMOGRAPHY APPLICATION FOR PROSPECTING IN THE SEDIMENTARY BASINS

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Summary. A thermal tomography technology has been developed, which is recommended to be included in the prospecting and exploration work complex in hydrocarbon fields. The practical value of the thermotomographic technique is to find temperature boundaries that control a particular process of generating or transforming a substance. It has been established that the oil and gas fields localization is controlled by the temperature rise in the sedimentary layer, which are associated with "thermal domes". Heat flow refraction occurs at the boundaries of the domes with country rocks due to the contrast in thermal conductivity of evaporites and terrigenous rocks between the domal zones. This is the main cause of heat flow variation in the lateral and vertical directions in the sedimentary basins. Close correlation between zones of elevated temperature in the sedimentary rocks and petroleum occurrences is confirmed by the results of 2D and 3D geothermal field modeling. 3D temperature models distribution in the Western Arctic area, in the Precaspian, Pripyat and North German depressions are presented. The previously noted relations of oil and gas fields to the deep faults in the studied basins create prerequisites for consideration of the geothermal field as a genetic factor controlling the tectonic features and petroleum resources of the sedimentary and salt-dome basins.

High capital costs at the regional exploration and evaluation stages can be significantly reduced through the use of high-tech geological and geophysical technologies for processing and interpreting existing materials for measuring potential geophysical fields, the results of two- and three-dimensional seismic exploration, the results of basin and thermotomographic modeling, studying the physical and rheological properties of core material.

In this enumeration, a relatively new and unconventional method is "thermotomographic modeling" based on the calculation of deep temperatures and heat flux density in the modern section and in the geological past, including when the catagenesis of organic matter occurred in the Paleozoic basin.

The thermotomographic modeling technology developed at the GIN RAS based on temperatures and heat flow distribution in the modern lithosphere and the sedimentary rocks thermophysical properties as well as on the results of reconstruction of sedimentation. The basis for the project implementation is our own original geothermal data obtained by temperature measurements in deep wells of sedimentary basins, determination of the thermal conductivity of core from well sections, as well as calculations of radiogenic heat generation during spontaneous decay of long-lived isotopes.

The application of theoretical and methodological geothermal aspects in geological exploration practice in oil and gas fields is now becoming ubiquitous. Suffice is to recall that no software product implementing basin modeling technology can do without setting the reduced heat flow as a boundary condition, and thermophysical properties (temperature and thermal conductivity, heat capacity) as model parameters. It follows from this that the accuracy and, consequently, reliability in predicting oil and gas potential using basin modeling depend on the correctness of setting the reduced heat flow as a condition at the lower boundary of the modeling domain.

By reduced heat flow, we mean the heat flow that flows to the sole of the active radiogenic heat generation (RTG) layer. The thickness of this layer depends on the concentration of long-lived isotopes ^{238}U, ^{232}Th, ^{40}K in the Earth's crust, and in platform structures it usually varies from 7 to 20 km. Such a noticeable depth variation makes it necessary to analyze in more detail the share of radiogenic heat in the total heat balance and empirically investigate the reduction, i.e., the decrease in heat flow with depth as the concentration of the listed long-lived isotopes decreases.

Technique of geothermal modeling

The use of three-dimensional geothermal modeling, which we identified as a thermal tomography method (Khutorskoy et al., 2003), is based on volumetric interpolation of the geothermal field. The application of this method opened up opportunities to detect anomalies of temperature and heat flow, which did not appear at all while analyzing the one- or two-dimensional distribution of these parameters.

Especially vividly, the greater informative value of 3D geothermal models compared to 1D and 2D models is manifested in isometric structures, which in most cases are depressions of sedimentary basins.

The practical significance of the thermotomographic technique is to find temperature boundaries that control a particular process of generation or transformation of a substance.

Deep subsurface temperatures along the seismic lines are calculated using the THERMOGRAPHY software (Хуторской, 1996). The calculations are based on the thermal properties of crustal layers in compliance with the established refractor velocities.

Temperature distribution in the sequence is deduced using the finite element method with a quadratic approximation of the temperature function between the junctures of a rectangular grid. The program provides for a grid of 41×41 junctures which solves a two-dimensional problem: what linear dimensions along the *X* and *Z*- axes can be changed by the operator. Lateral flow is assumed to be absent at the lateral boundaries of the modeling domain, that is, $\partial T/\partial x = 0$. We assumed the temperature at the seafloor–water interface known from meteorological data (~1°C) to be the upper end value and heat flow to be the lower end value. Inside the modeling domain, contrasting media configurations and their thermal properties, including thermal diffusivity a (m^2/s), thermal conductivity k ($W/(m\cdot K)$), and normalized thermal source density ($Fi=A/(c.\rho)$) (K/s), were preset. Within the TERM program, which is responsible for calculations, the linear dimensions (Lx and Lz, km) of the modeling domains were preset to determine the linear dimensions of the junctures ($Lx/41$ and $Lz/41$) as well as the solution discretization interval (Ma). The time step of the iteration process was selected automatically by the program and calculated as $\tau = 10^{-7}\cdot(Z^2/4a)$, where Z is the thickness of the modeling domain.

As a result of the digital solution of the thermal conductivity equation, temperate and heat flow distribution $q(z)$ and $q(x)$ for the preset thermal medium at the final moment of the discretization phase were obtained. The file of results renamed as the file of initial temperatures, and calculations in the next phase begin with the final moment of the previous step. Solution discretization is convenient when it is necessary to introduce changes into the thermal medium in response to structural and material changes in geologic sequence, to preset the distribution of new thermal sources and discharge zones, and to revise the estimated paleothermal field parameters. If heat and mass transfer should be included in the model, it can be imitated by presetting end temperature values and/or adiabatic gradients in the depth interval covered by convection.

For each profile, the end temperature value was taken at the upper boundary and heat flow at the lower boundary (q_{bd}) in compliance with the value measured in the nearest well (q_{obs}) minus heat flow generated in the crustal layer above the lower boundary of the modeling domain as a result of the spontaneous decay of long-lived radioactive isotopes (q_{est}), that is, $q_{bd} = q_{obs} - q_{est}$.

The reduced heat flow varied within 30-40 mW/m^2.

A specific feature of three-dimensional modeling is the estimation of temperatures and consequently all other geothermal parameters in the latitude–longitude–depth geometry for the whole region. Using the volumetric interpolation of the TECPLOT program, we obtained a three-dimensional temperature distribution pattern over the whole study interval (down to 35 km) and for the whole region. A similar procedure was applied to obtain a three-dimensional heat flow distribution pattern. The program enables the depth slices of temperature and heat flow values and isothermal surfaces to be plotted for any interval.

Geothermal studies in the Barents Sea

The intense exploration for oil and gas fields in shelf basins that commenced in the 1980s included offshore and deep drilling on islands accompanied by thermal logging. In addition, the first measurements of the heat flow in wells were performed at that time in the southern Kara Sea. In the 1980s-1990s the measurements of heat flow by submersible sounds were performed in the central and southeastern Barents Sea (Verzhbitsky, 2002; Левашкевич, 2005) and the empirical data were subsequently processed with allowance for seasonal bottom-temperature fluctuations (Суетнов, Никульшина, 1988). The processing of thermal measurements made it possible to estimate thermal gradients, while thermophysical studies of drill cores resulted in measurement of the heat conductivity of rocks. These works provided the first conditional values of heat flow in the region under consideration. However, the geothermal measurements in wells were sparse and insufficient for adequate mapping of the temperature and heat flow distribution in such a vast-territory, especially for calculation of deep temperatures in the lithosphere.

Nevertheless, the analysis of available data obtained by measurements in wells and thermal sounding revealed a tendency for an increase in heat flow in the northeastern and northwestern directions. For example, in the zone of conjugation of the Kola microplate and the Baltic Shield, the heat flow averages 54 mW/m^2 and amounts to 70 mW/m^2 in the North Barents Basin and Central Barents Uplift. To a first approximation, such a trend in heat flow variations can be explained by approaching the North Atlantic spreading center, where the thermal activity of the asthenosphere increases. At the same time, our data indicate that the crust of the Barents Plate is subjected to secondary processes, which become younger in the northern direction.

On the basis of interpretation of geothermal data, it was suggested that the secondary thermal processes are related to rifting (Khutorskoy et al., 2003). Modeling of the nonstationary thermal field in order to calculate deep temperatures and heat flows was performed along each of the profiles shown in Fig. 1.

The geotraverses extend via the wells, where the conditional heat flow measurements were conducted. Such measurements made it possible to correctly set the Neumann (second-type) boundary conditions at the lower margin of each profile.

Initial conditions for temperature calculation were set for 60 Ma ago. As follows from paleotectonic reconstructions for the Barents Sea (Верба, Шаров, 1988; Устрицкий, Храмов, 1984), the present-day structure of the crust was already formed by that time. Therefore, the evolution of the thermal field, if it occurred, was related to relaxation of initial thermal heterogeneities rather than to the reorganization of structural and thermophysical elements. Under such boundary and initial conditions, the temperature within the modeling region is rapidly coming to a steady state, which was a priori accepted as a criterion of calculation correctness. The duration of time steps was 10 Ma. Thus, six control stages were taken over the time interval of 60 Ma to verify the stationary state. The modeling has shown that, since the third step, i.e., 30 Ma after the onset of calculation, all the profiles are characterized by a steady-state thermal field.

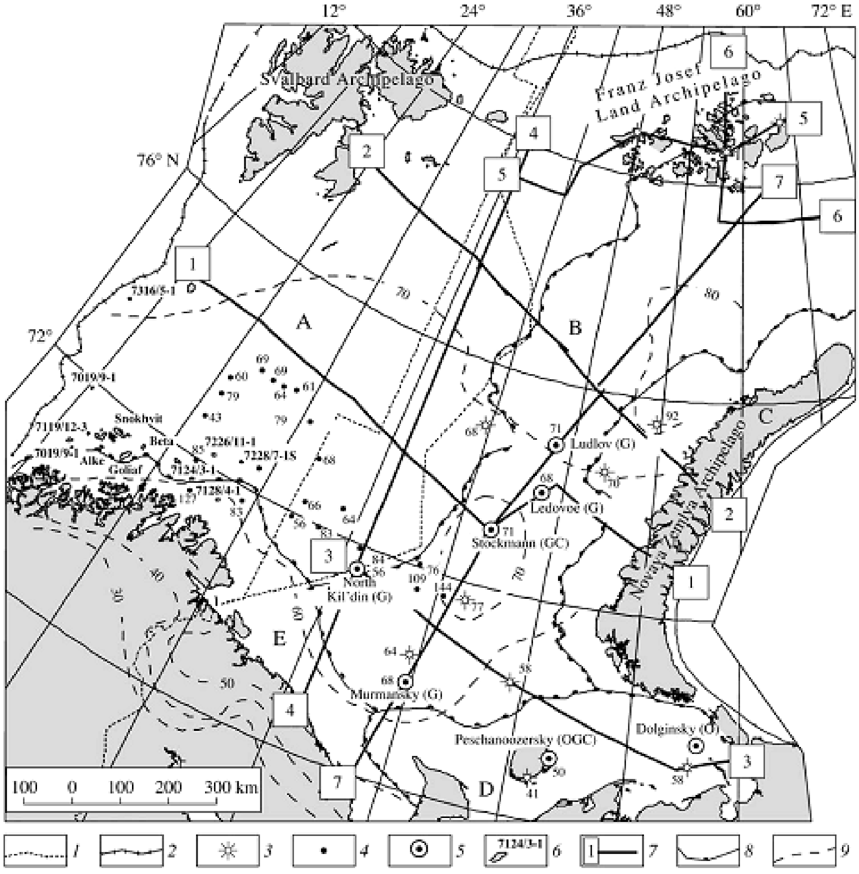


Fig. 1. Map of the heat flow density in the Barents Sea region and adjacent areas. (1) Border of Russia and median line (according to the proposal of Norway of 1970); (2) shelf edge; (3) deep well; (4) station of heat-flow measurements and its value, mW/m^2; (5) petroleum fields in the Russian sector; (6) the same in the Norwegian sector; (7) line of seismic and geological profile and its number; (8) boundaries of regional tectonic elements; (9) contour line of heat flow, mW/m^2. Tectonic elements (letters in figure): (A) Svalbard Plate, (B) East Barents Megatrough, (C) Pai-Khoi–Novaya Zemlya Fold System, (D) Pechora Plate, (E) Kola Homocline. Fluid type: (G) gas, (GC) gas condensate, (OGC) oil–gas condensate, (O) oil

The technique of computing 3D models was described above. Here, we note only that the procedure consists of two stages.

At the first stage, the temperature sections along geotraverses are placed into a three-dimensional plot according to coordinates of their onset, end, and bend points, if there are any. In addition, the modeling accuracy is estimated at this stage by comparison of calculated and measured temperatures at intersections of profiles. The least square method, which was applied to estimate the modeling accuracy, shows that discrepancy between depths of the same isotherms is ~100 m, i.e., 0.7% of the total modeling depth, which equals to 15 km. We consider this uncertainty as admissible.

At the second stage, with the use of 2D temperature ranges as boundary conditions, the 3D volumetric interpolation is carried out. If the distance between profiles is less, the accuracy of the interpolation procedure will be higher. We used as many as 123 geotraverses characterized by CMP and DSS profiling data for the Barents-Kara region in our previous 3D models.

However, the modeling technique used in this work differs from the previous one by the detailed analysis of the geological situation based on drilling results. Therefore, we developed the model using only the seven above-mentioned geotraverses. It is particularly noteworthy to compare models of the first and second generations and to ascertain the factors responsible for their differences, if any exists.

The results obtained at the first stage of 3D modeling – allocation of temperature ranges in the 3D plot – are shown in Fig. 2. A special original computer program that takes into account the depth and position of each profile and transforms initial data of 2D modeling into the TECPLOT format was used to implement this procedure.

Volumetric interpolation resulted in obtainment of the model of the temperature field, which makes it possible to determine a temperature in any point of 3D space (Fig. 3). A special blanking in this figure shows temperature domes beneath the South Barents Syneclise and the Pechora–Barents Zone of buried uplifts. The dome extends to the South Kara Basin, where it looks autonomously because of the temperature screen beneath Novaya Zemlya (New Land). In fact, the formation of both domes has the same cause, namely, the occurrence of thick and low-conductivity sediments and the respective increase in the geothermal gradient within this zone. Northward, this effect is enhanced by the local increase in the terrestrial heat flow in the Stockmann–Lunin area and the North Barents Basin. The latter factor determines the appearance of another temperature dome in the western part of the region at the edge of the Norwegian shelf, where the sedimentary cover is relatively thin, but the heat flow is slightly higher in comparison with the background level established for the Barents Plate.

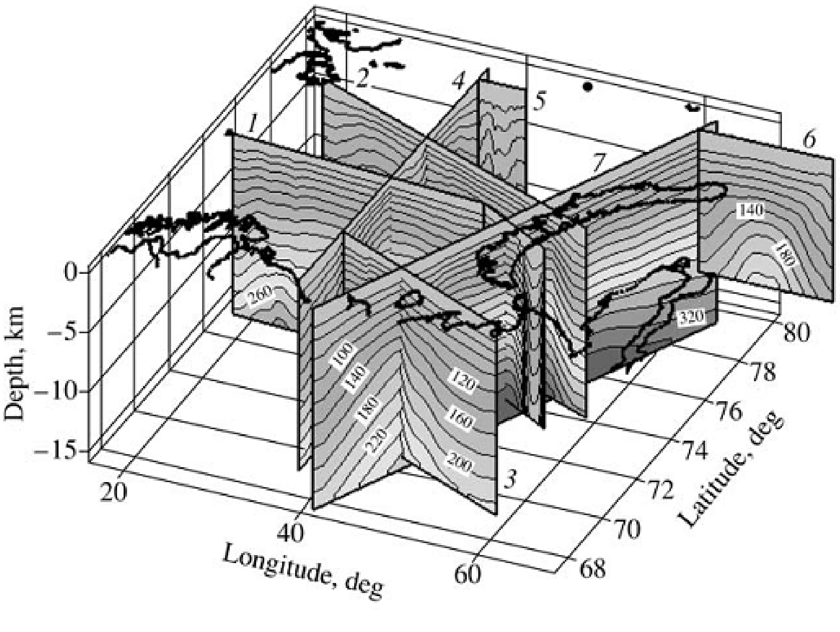


Fig. 2. Temperature sections placed on a 3D plot. See text for explanations. Numerals correspond to numbers of profiles

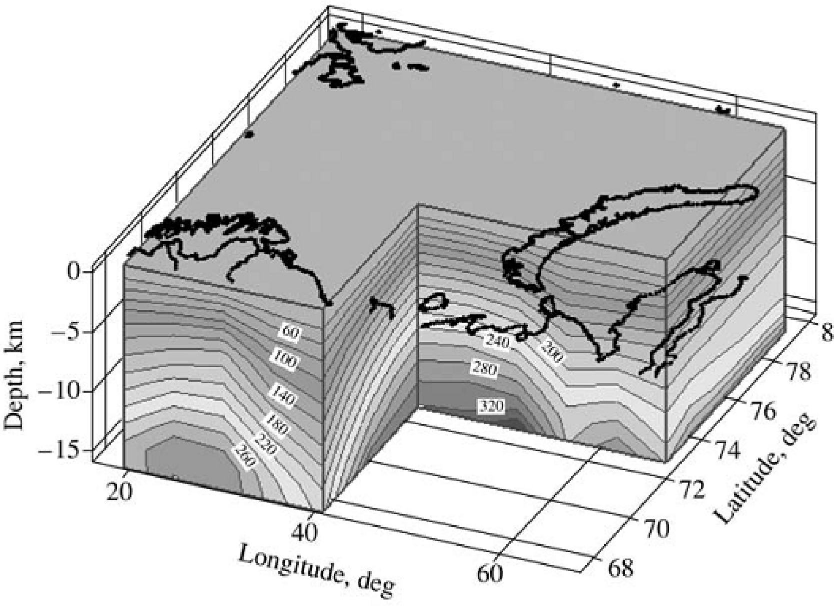


Fig. 3. A 3D model of the temperature field. Isotherms, °C

Gas and gas-condensate fields discovered in the southeastern part of the Barents Sea and South Kara Basin are localized above the temperature dome. Previously, we pointed out that the Stockmann, Ludlov, Ledovy, North Murmansk, Rusanov, and Leningrad fields are confined to the apical part of the temperature dome. This character of localization can probably be used as an additional criterion to forecast the petroleum resource potential.

The North-Caspian Basin

The North Caspian Basin is traditionally recognized within the boundaries of the salt-dome region. Its north-western 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 (Volozh et al., 1998).

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 due to 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.

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, it is possible to 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.

As 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. 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.

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 data on temperature in 115 wells drilled in the region, including 16 deep wells drilled to a depth of more than 4 km (Fig. 4).

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. 5.

Figure 6a 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 depths of 2 and 3 km are 40-45 and 60-65°C respectively, whereas in the South Emba and Mangyshlak areas the temperatures are 55-60 and 70-75°C at the same depth. 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 (Хуторской, 1996).

A similar pattern is observed in the geothermal gradient distribution within a depth interval of 0-5 km (Fig. 6b), where its values increase southwestward from 15 to 40-45 mK/m. It appears that the gradient is stabilized at 20-35 mK/m level at a depth of 3-4 km. In the eastern part of the basin, the temperature is 40-45 and 60-65°C at depths of 2 and 3 km, respectively, whereas in the South Emba district and Mangyshlak Peninsula the temperature is 55-60 and 70-75°C at the same depths. It indicates that heat flow diminishes in the east due to screening of the deep heat flow in the southern Urals and Mugodzhary Mountains in the geological past.

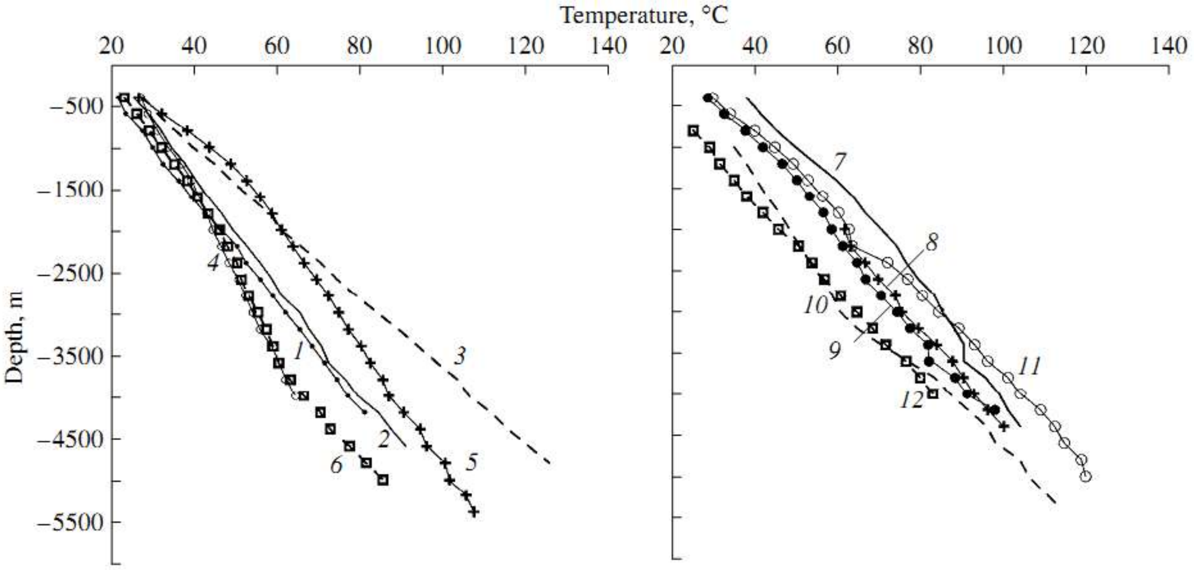


Fig. 4. Thermograms of some deep wells in the North Caspian Basin.
Wells: (1) Blaksai-89p, (2) Karatyube-34, (3) Karatyube-35, (4) Kumsai-2, (5) Biikzhal-SG2, (6) Kursai-4, (7) Teresken-1p, (8) Teplovskaya-1p, (9) West Teplovskaya-2p, (10) Tashlinskaya-25p, (11) Aralsorskaya-SG1, (12) Khobdinskaya-1

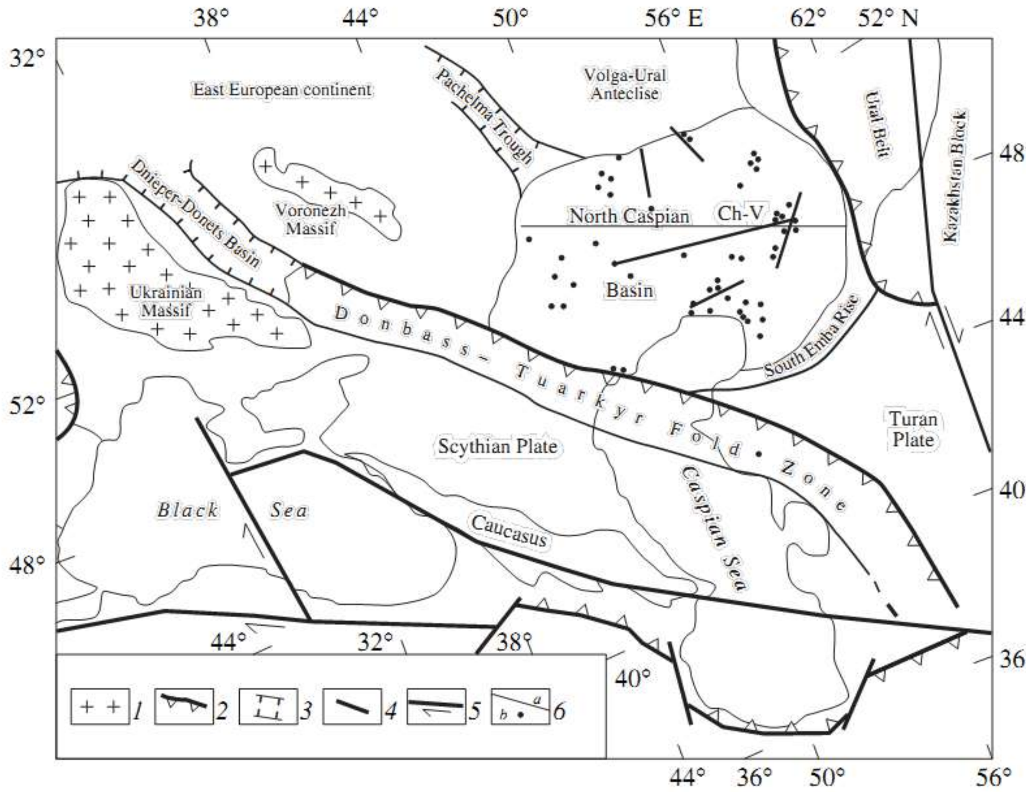


Fig. 5. Tectonic setting of the North Caspian Basin. (1) Continental basement rise, (2) suture, (3) rift system boundary, (4) fault, (5) transcontinental shear zone, (6) profile line: (a) Chelkar-Volgograd (Ch–V) DSS profile, (b) well bearing temperature data

Ascending westward from the longitude of the Mugodzhary Mountains, the isotherms form several domes, the apices of which are localized in the areas of South Emba, Mertvy Kultuk Sor, the North Mangyshlak Peninsula, as well as in the Astrakhan and Buzuluk arches (Khutorskoy et al., 2010). Thus, the spatial association of thermal domes and zones with economic petroleum resources occurs in the Pericaspian region as elsewhere.

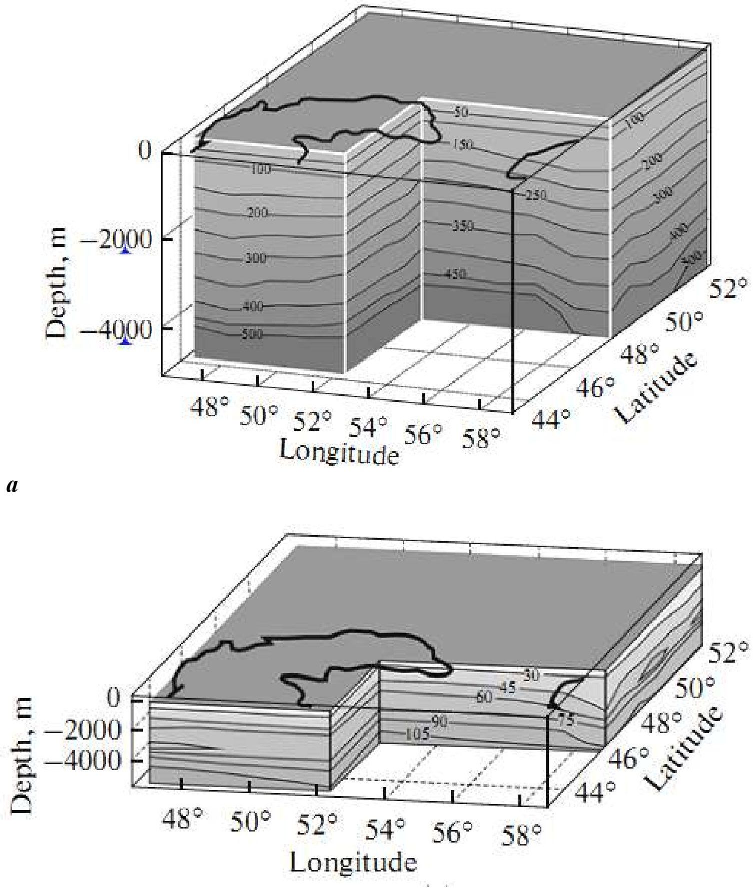
The Pripyat basin

The Pripyat Basin is localized in the trough bearing the same name and situated between the Belarussian and Voronezh anteclises and the Zhlobin Saddle in the north and the Ukrainian Shield in the south, which divide them. The basin extends for 280 km in the W–E direction and reaches 150 km in width, being an element of the planetary fault belt called the Sarmatian-Turan Lineament that strikes in the northwestern direction from the spurs of the Hissar Range in the east, extends south of the Pericaspian Basin to the Podlyassy-Brest Trough in the west. This lineament effectively connects the East and West European evaporite provinces.

The Pripyat Trough is bounded in the north and south by mantle rooted faults. A number of W–E trending faults are traced within the trough, and some of them are of mantle origin, as well. (Айзберг и др., 2007).

The trough is filled with sedimentary rocks in the stratigraphic range from the Middle Devonian to the Middle Triassic and was formed in the Late Paleozoic. The maximum thickness of the platform cover is 5.5-6.0 km. The upper and lower Upper Devonian salt-bearing sequences are separated by a carbonate-clayey intrasalt sequence. The upper salt-bearing sequence is predominant. Its maximum thickness of 3 km is established near the northern wall of the trough (Айзберг и др., 2007), whereas in the central and southern parts the thickness is 0.6-2.5 km and 0.7-2.0 km respectively.

The thickness of the lower salt-bearing sequence is several times less than that of the upper one. In contrast to the lower sequence, the upper sequence is characterized by more pronounced salt tectonics with well-developed salt domes, plugs and swells. The evaporite sequences were deposited in a transgressing deepwater marine basin. The sedimentation was accompanied by active faulting and volcanic activity in the northeastern part of the trough and the adjacent territory. Sedimentary-volcanic sequences and alkali basalts are coeval with evaporite sequences (Геология Беларуси, 2001).



a

b

Fig. 6. 3D models of deep temperature distribution in Pericaspian Basin:
(a) temperature distribution within interval of drilling (0-50 km); (b) the same in Earth's crust (0-5 km)

The geothermal characterization of the trough is based on temperature measurements in more than 200 wells. Most wells are located in the northern zone of the trough. Its southern part is less studied. The heat flow has been calculated in most wells (Пархомов, 1985; Tsybulya, Levashkevich, 1990). The thermograms measured in the northern, central, and southern zone are shown in Fig. 7.

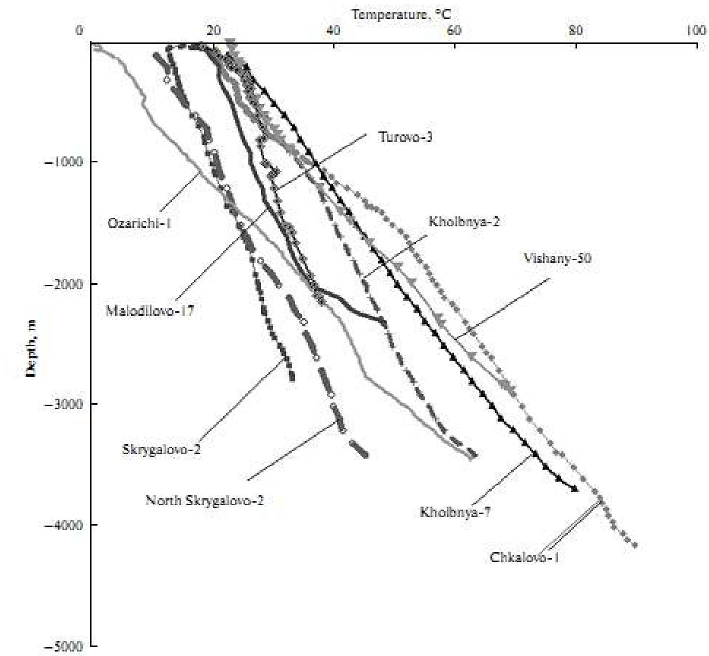


Fig. 7. Thermograms of deep wells in the Pripyat Basin

The configuration of the thermograms in the northern zone (Vishany, Chkalovo, Ozarichi wells) differs from those in other two zones indicating a special geothermal setting. This difference is reflected in the heat flow density, which is 45-50 mW/m^2 in the marginal southern and 60-75 mW/m^2 in the northern zones.

The causes of different background heat flow values in the northern and southern parts of the trough were discussed in (Tsybulya, Levashkevich, 1990). The authors of this publication attach great importance to the refraction of the heat flow related to structural and thermophysical inhomogeneities and consider this factor to be crucial for interpretation of the lateral variation within the same zone. For example, above the apical parts and margins of the Rechitsa and Pervomaisky salt domes, the heat flow attains 124 and 106 mW/m^2, respectively, whereas the background heat flow in the zone as a whole is 75 mW/m^2. At the same time, a different contribution of radiogenic heat generation and variable permeability of deep faults for the fluids provides an additional influx of heat in the zones under comparison. The calculated contribution of radiogenic heat in the northern part of the trough is 29 mW/m^2 compared to 13 mW/m^2 in the southern zone. The appreciable difference in the radiogenic component of the heat flow is explained firstly by different values of specific heat generation (0.5-1.0 μW/m^3) in the southern zone and 1.5-2.0 μW/m^3 in the northern zone) and secondly by thickening of the granitic-metamorphic crustal layer, which provides the main contribution to radiogenic heat generation in the northern zone. The remainder of the background heat flow is generated by its supply from the mantle and the lower crust along permeable deep faults, which are more numerous in the northern zone than in the southern one. According to geophysical data, these deep faults drain the mantle.

It is noteworthy that the oil fields are confined to the W–E-trending deep faults and are concentrated mainly in the positive anomalies of heat flow in the northern zone. Attention to the relationship between the petroleum resource potential of the sedimentary cover and temperature was first paid in (Garetsky et al., 1990). It was pointed out that the temperature in the Northern Fault Zone is higher than in the marginal Southern Fault Zone. As it follows from temperature measurements in wells, the difference is 20-25°C at similar levels. The temperature increases from the west eastward in the Northernmost Fault Zone.

Quantitative estimation of the temperature field in the Pripyat Basin was carried out on the basis of its 3D-modeling using the above mentioned technology. The initial data were data on the temperature in wells and on the thermal conductivity of the rocks in the section. The thermophysical structure was set on the basis of seismic CDP profiling and deep seismic sounding (DSS) along a series of N–S-trending lines (Thibo et al., 2003).

Detailed knowledge of the heat flow and its radiogenic component made it possible to specify the reduced heat flow at the lower edge of the modeling region (a depth of 6 km) in particular lithotectonic zones and the distribution of radiogenic heat sources within this region. At the upper edge coinciding with the neutral layer, the mean annual temperature (8°C) is established from measurements in wells.

The 3D temperature model of the upper crust in the Pripyat Basin is shown in Fig. 8 together with the location of deep faults and oil fields. A northward increase in temperature is clearly seen. At a depth of 4 km, the temperature in the southern part of the trough is 45-50°C and increases to 65-70°C in its northern part. At a depth of 6 km, the corresponding values are 65-70°C and 85-90°C. It can be shown that the temperature conditions of catagenesis of oil (T =120°C) is attained in the northern part of the basin at a depth of 8.5-9.0 km while extrapolating the temperature to a depth.

Thus, we reveal the same tendency of temperature distribution in the Earth's crust as it has been described in the Pericaspian Basin. The oil fields are confined to the temperature cupola, or the zone of rising isotherms in the sedimentary cover (Fig. 8). In the Pripyat Basin, the temperature cupola is related to the deep faults that provide additional mass and heat transfer. It implies that a possible cause of the thermal anomalies is the supply of deep, hydrocarbon- bearing fluids along the permeable fault zones. Such a process ensures a higher background heat flow in the northern part of the Pripyat Basin in comparison with the Pericaspian Basin, where no indications of advective heat and mass transfer are established to date.

The North German basin

The North German Basin occupies the middle part of the Central European petroleum province (CEPP) and is filled with Phanerozoic sedimentary rocks up to 12-14 km in total thickness. The Devonian terrigenous and carbonate rocks occur at the base of the section, upsection, they give way to Lower Carboniferous carbonate rocks. The Upper Carboniferous and Lower Permian (Rotliegende) rocks are composed of terrigenous coarse–clastic rocks; often these are red beds. The Upper Permian rocks (Zechstein) consist of terrigenous and carbonate rocks in the lower part of the section, which are replaced upward with anhydrite and dolomite and further with rock salt and anhydrite. Rock salt is the most abundant in the Strassfurt Formation (van Wees et al., 2000).

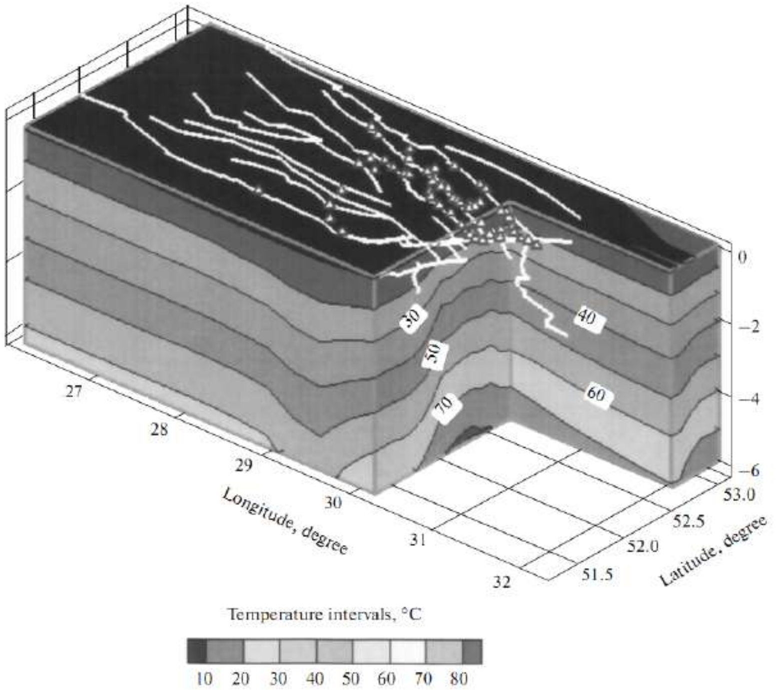


Fig. 8. 3D temperature model of the Earth's crust in the Pripyat Basin. The white lines are deep faults; the white triangles are oil fields

The North German Basin adjoins the North Sea Syneclise. Before the Cenozoic, the basin consisted of a number of troughs expressed in the Mesozoic sedimentary cover. The large Lower Saxonian Trough, extending in the latitudinal direction occupies the western part of the basin; the small Hannover and Gifhorn troughs striking in the meridional and southwestern directions are situated eastward. The SW-trending West and East Holstein troughs are outlined in the northwest of the North German Basin.

The basin as a whole is characterized by the development of salt tectonics that involves the Upper Permian (Zechstein) salt. Extended and exposed linear salt ridges are typical (Bayer et al., 1999).

The North German Basin is distinguished by a complex structure dominated by the intersection of the Rhenish and Hercynian dislocations different in age and orientation, which are accompanied by variations in the thickness of the Cretaceous, Jurassic, and Triassic sequences and sharp unconformities. The basin is asymmetric in cross section. The thickness of the Paleozoic rocks attains 5 km and the Mesozoic rocks are as thick as 8 km. The Triassic sequence contains members of rock salt up to 100 m thick (Clausen, Pedersen, 1999).

Hydrocarbon occurrences are noted within a wide stratigraphic interval. Hydrocarbons have been found in the Paleogene, Cretaceous, Jurassic, Triassic, Permian, and Carboniferous rocks. The gas reservoirs are hosted mainly in the Permian, Triassic, and to a lesser extent, Carboniferous sedimentary rocks, determining the spatial zoning in the localization of oil and gas pools.

Within the state borders of Germany, a few tens of mainly small oil and gas fields are known. The oil fields are located in the northern part of the North German Basin (Reikenhagen, Grimmen, Lüttow), in its northeastern (Gubben, Lüben, Staakow), and in the southwestern parts (Fallstein); the gas fields are concentrated in the southeastern part of the basin (Буштар, Львов, 1979).

The largest buried Lower Saxonian Trough is situated in the south of the North German Basin. The trough is expressed in the stratigraphic range from the Upper Triassic to the Lower Cretaceous and especially pronounced in the Upper Jurassic rocks. In the west, the Lower Saxonian Trough is closed at the northeastern plunging of the Central Netherland Rise (Emsland Slope), where the thickness of the Jurassic and Cretaceous rocks is markedly reduced (Mazur, Scheck-Wenderoth, 2005).

The lowland portion of the North German Basin is located in eastern Germany, in the middle part of the CEPP. Carboniferous, Devonian, and Ordovician rocks are penetrated in this part of the basin.

The structure of the Polish part of the basin is controlled by conjugation of the Precambrian platform (Baltic Syneclise) in the northeast with the epi-Hercynian platform (North German Basin) in the south-east. The junction zone is expressed in a buried foredeep that adjoins the Baltic Syneclise in the northeast and the Mid-Polish Swell exposed in the

Swiétokrzyskie Mountains. This part of the basin is filled largely with Mesozoic (up to 8 km) and Paleozoic (more than 12 km) sequences. The Paleozoic section is characterized by a thick (2500 m) Permian salt-bearing sequence. Most of the hydrocarbon fields are localized in the Foresudeten Homocline, where 25 gas fields (Otyn, Senkowice, Cheklin, etc.) and six oil and oil-gas fields (Rybaki, Polenzko, Nova-Söl, etc.) were discovered after 1960.

As in the above mentioned basins, the hydrocarbon fields are attracted to thermal anomalies. At the same time, the heat flow in the CEPP is higher than in the Pripyat and Pericaspian basins. According to (Majorowicz et al., 2003), the background heat flow is 80-85 mW/m^2 here, i.e., corresponding to the anomalous values in other basins.

A 3D temperature model was plotted for the quantitative characterization of the deep temperature regime in the North German Basin (Fig.9). This model is based on temperature in wells and the thermal conductivity of rocks in section, as well as on the data concerning the structural and geological setting along the DDS lines (Majorowicz et al., 2003; Thibo et al., 2003).

Comparison of deep temperatures in the Pericaspian, Pripyat, and North German basins

Depth, km	Temperature, °C			
	Pericaspian	Pripyat	North German (eastern part)	North German (western part)
0–5	$\frac{42}{8-104}$	$\frac{37}{8-74}$	$\frac{87}{9-242}$	$\frac{86}{9-165}$
5–10	$\frac{105}{46-159}$	–	$\frac{215}{106-397}$	$\frac{214}{93-306}$
10–20	$\frac{192}{95-274}$	–	$\frac{366}{194-612}$	$\frac{343}{168-477}$

Note: numerator is the average temperature; denominator is the temperature range.

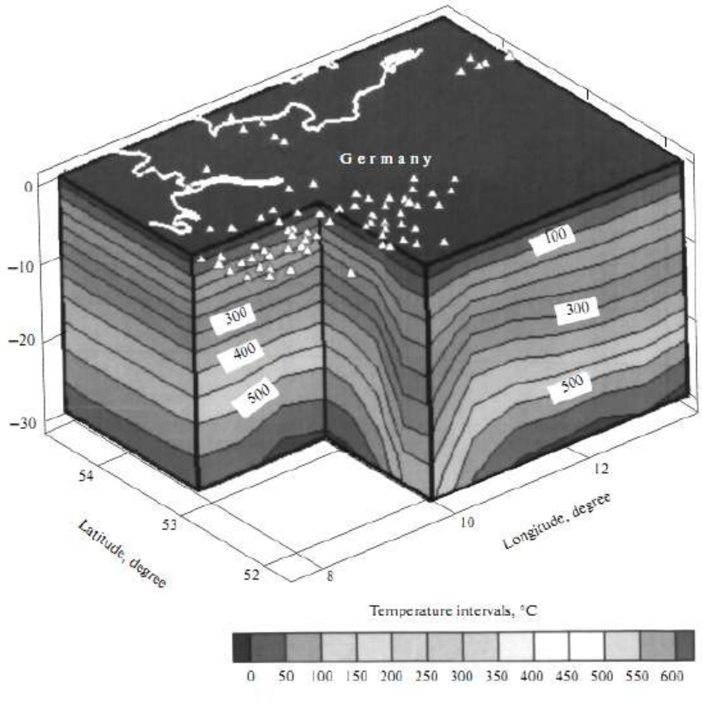


Fig. 9. 3D temperature model of the western part of the North German Basin (Saxsonian sector). White triangles are oil fields

The model heat flow and temperature that extends in Poland show a notable increase in heat flow (up to 100 mW/m^2 against the background value of 65 mW/m^2) and the appearance of thermal cupolas in the temperature section. These anomalies are confined to the eastern (Silesian) part of the North German Basin enriched in salt domes and related hydrocarbon fields. A decrease in heat flow down to background level is noted at the longitude 20°E (Fig. 10), where salt domes disappear. According to (Bayer et al., 1999), this is precisely the place where the crystallinicum of the East European Platform borders on the eastern margin of the CEPP.

The catagenetic temperature interval of organic matter transformation, which is favorable to the formation of hydrocarbon concentrations occurs in the zone of the section at a depth of 3.0-4.5 km (Table).

We cannot rule out the occurrence of hydrocarbons in the northeastern segment of the section beyond the salt dome zone, but the catagenetic interval is located here at a depth of 6.0-6.5 km. The 3D model of deep temperature in the eastern part of the North German Basin (Fig. 10) shows a pronounced temperature cupola related to faults and salt domes, i.e., to the area of oil fields. A temperature cupola in the 3D temperature model (Fig. 9) is spatially correlated with oil fields in the western part of the North German Basin.

Conclusions

(1) The geothermal field of such isometric regions as the Barents Sea Basin can be reliably depicted only in 3D geometry. This technique offers an opportunity to estimate both lateral and vertical variations of the thermal field. (2) Temperature and heat-flow anomalies are formed as a result of nonstationary distribution of heat sources and structural and thermophysical heterogeneities determined by lithological and tectonic factors. (3) The thermotomographic analysis of petroliferous basins has shown that economic accumulations of hydrocarbons are localized above zones of rising isotherms or thermal domes that were outlined for the first time by 3D modeling of the geothermal field in the eastern Barents Sea and the southern Kara Sea.

Of three considered salt dome basins in northern Eurasia, the Pericaspian and North German basins may be referred to the exogonal type, whereas the Pripyat Basin – to the intracontinental type. All of the basins underwent deep and persistent sagging in the Late Paleozoic with accumulation of evaporites (rock salt and anhydrite) intercalated by terrigenous rocks.

Under the effect of gravity and tangential compression, the salt-bearing sequences were transformed into salt domes, plugs, and swells, which cut through or deform the overlying rocks. Halogenic rocks have anomalously high thermal conductivity in comparison with terrigenous rocks. The contrast in thermal conductivity and the sharp structural boundaries between the salt domes and sedimentary rocks of the interdomal zones create conditions for perturbation of the terrestrial heat flow, which is concentrated in the salt bodies and brings about distinct anomalies of heat flow above the apexes of the salt domes and their marginal parts. These anomalies exceed the background values by 50-60% and should be considered one of the main features of the geothermal field in the salt dome basins.

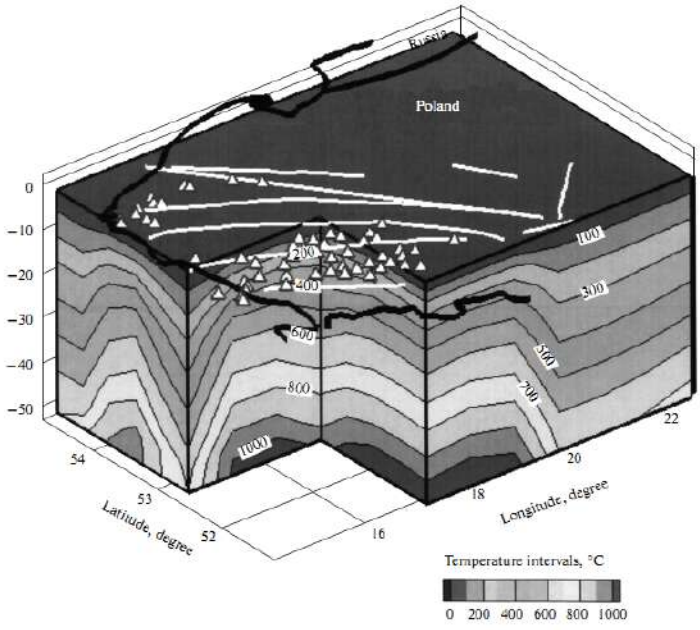


Fig. 10. 3D temperature model of the eastern part of the North German Basin (Silesian sector). White lines are deep faults; white triangles are oil fields

The spatial distribution of the salt domes and variation of their shapes show their close relations to faults. As a rule, the salt domes are localized along the fault zones and elongated along their strikes. The salt domes with isometric or star-shaped contours in plan view are confined to the central, most subsided parts of the Pericaspian and North German basins.

The considered salt dome basins are distinguished by high petroleum resource potential. Oil pools are penetrated at different depth levels and in various structural relationships with the evaporites. The general tendency links the oil fields to fault zones and zones of elevated temperature in the sedimentary cover.

The term thermal cupola (Khutorskoy et al., 2003) is introduced into the geological and geophysical terminology to denote the zones of elevated isotherms clearly expressed in the temperature sections of 2D and 3D models and spatially coinciding with hydrocarbon fields. Thermal cupolas reveal close spatial relationships to the above localized hydrocarbon fields in all of the studied shelf or evaporite basins. It is evident that in the areas of thermal cupolas the temperature interval of catagenesis of organic matter is located nearer to the Earth's surface. The three salt dome basins considered here are not exceptions in this respect. These basins demonstrate spatial combinations of fault zones, oil fields, areas of higher heat flow, and thermal cupolas in the field of deep temperature.

According to 3D modeling, the temperature range at a depth of 1000-2000 m is 30-36°C in the Barents Basin, 28-46°C in the Pericaspian Basin, 28-40°C in the Pripyat Basin, and 38-88°C in the North German Basin, so that the North-German Basin is the most heated.

Calculation of depths where the catagenetic temperature is suitable for transformation of organic matter yields 6-7 km for Barents Basin, 7.0-8.5 km for the Pericaspian Basin, 8.5-9.5 km for the Pripyat Basin, and 3-7 km for the North German Basin.

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ПРИМЕНЕНИЕ ТЕРМИЧЕСКОЙ ТОМОГРАФИИ ДЛЯ РАЗВЕДКИ В ОСАДОЧНЫХ БАССЕЙНАХ

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Резюме. Разработана технология термической томографии, которую рекомендуется включить в комплекс поисково-разведочных работ на месторождениях углеводородов. Практическое значение термотомографической методики заключается в нахождении температурных границ, контролирующих тот или иной процесс генерации или трансформации вещества, расчете глубины гидротермальных изменений рудного вещества, глубины зон фаций метаморфизма, положения изотермы Кюри. Для прогнозирования нефтегазоносности оценивается глубина температурного интервала, в котором происходят катагенетические изменения органического вещества. Численный расчет глубинных температур производился на основе решения двухмерного уравнения теплопроводности с неограниченным числом контрастных комплексов и с учетом радиогенной теплогенерации в масштабах модельной области. На нижней границе области моделирования задавался тепловой поток при условии отсутствия радиогенной теплогенерации (редуцированный тепловой поток). Установлено, что локализация месторождений нефти и газа определяется повышением температуры в осадочном слое, которое связано с «термическими куполами». Рефракция теплового потока происходит на границах куполов с вмещающими породами из-за контраста теплопроводности эвапоритов и терригенных пород между купольными зонами. Это является основной причиной изменения теплового потока в латеральном и вертикальном направлениях в осадочных бассейнах. Тесная корреляция между зонами повышенных температур в осадочных породах и нефтегазопроявлениями подтверждается результатами 2D и 3D моделирования геотермического поля. Представлены результаты измерения теплового потока и трехмерные модели распределения температуры в Западной Арктике, в Прикаспийской, Припятской и Северо-Германской впадинах. Рассчитана глубина расположения температурных условий катагенеза органического вещества, что в первом приближении позволяет прогнозировать глубину нефтематеринского комплекса. Отмеченная ранее связь месторождений нефти и газа с глубинными разломами в изученных бассейнах создает предпосылки для рассмотрения теплового поля как генетического фактора, контролирующего тектонические особенности и нефтегазовые ресурсы осадочных и солянокупольных бассейнов.

Ключевые слова: *температура, тепловой поток, осадочный бассейн, соляной купол, моделирование*

ÇÖKMƏ HÖVZƏLƏRİN KƏŞFİYYATINDA TERMİK TOMOQRAFİYANIN TƏTBİQİ

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Xülasə. Karbohidrogen yataqlarında axtarış-kəşfiyyat işləri kompleksinə daxil edilməsi tövsiyə olunan termiki tomoqrafiyanın texnologiyası işlənilmişdir. Termotomoqrafik metodikanın tətbiqi əhəmiyyəti, maddənin bu və ya digər generasiya və yaxud transformasiya prosesini nəzarətləndirən, temperatur sərhədlərinin tapılmasından ibarətdir. Neft-qazlılığın proqnozlaşdırılması üçün üzvi maddənin katagenenik dəyişməsinin baş verdiyi temperatur intervalının dərinliyi qiymətləndirilir. Həmin metodika vasitəsilə hidrotermal dəyişmənin, metamorfizmin fasiya zonalarının dərinliyi, Küri izotermlərinin mövqeyi hesablanır. Dərinlik temperaturlarının ədədi qiyməti kontrast komplekslərin məhdudsuz sayına malik, istilikkeçirmənin iki ölçülü tənliyinin həlli əsasında və model sahəsi miqyasında radiogen istilik generasiyası nəzərə alınmaqla yerinə yetirilirdi. Modelləşdirmə sahənin alt sərhədində radiogen istilik generasiyasının (reduksiya olunmuş istilik axını) olmadığı şəraitdə istilik axını verilirdi. Təyin edilmişdir ki, neft və qaz yataqlarının lokallaşması "termik gümbəz"lərlə əlaqədar olan çökmə qatda temperaturun yüksəlməsi ilə müəyyən edilir. İstilik axının refraksiyası, evaporitlərin istilikkeçiriciliyinin və terrigen süxurların gümbəz zonaları arasında kontrastlığı səbəbindən, gümbəzlərin yerləşdirici süxurlarla sərhədində baş verir. Bu, çökmə hövzələrdə lateral və şaquli istiqamətlərdə istilik axınının dəyişməsinin əsas səbəbidir. Çökmə süxurlarda yüksəlmiş temperatur zonaları və neft-qaz təzahürləri arasındakı sıx korrelyasiya geotermik sahənin 2D və 3D modelləşdirmə nəticələri ilə təsdiq olunur. Qərbi Arktikada, Xəzəryanı, Pripyat və Şimalı Almaniya əyilmələrində istilik axınları ölçmələrinin nəticələri təqdim edilmişdir. Üzvi maddənin katagenetik temperatur şəraitinin yerləşmə dərinlikləri hesablanmışdır ki, o ilk yanaşmadan neft mənbəyi kompleksinin dərinliyini proqnozlaşdırmağa imkan verir. Öyrənilmiş hövzələrdə, əvvəl qeyd edilmiş neft və qaz yataqlarının dərinlik qırılmaları ilə əlaqəsi, çökmə və duz gümbəzli hövzələrin tektonik xüsusiyyətlərini və neft-qaz ehtiyatlarını nəzarətləndirən istilik sahəsini genetik amil kimi qəbul etməyə zəmin yaradır.

Açar sözlər: *temperatur, istilik axını, çökmə hövzə, duz gümbəzi, modelləşdirmə*