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Heat Flow in Salt-Dome Basins of Eurasia: A Comparative Study

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Abstract—The geothermal fields in the Pericaspian, Pripyat, and North German basins are considered. These basins are characterized by widespread Upper Paleozoic evaporite sequences, which underwent halokinesis with the formation of salt domes and plugs owing to tectonic and gravity instability. 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 salt-dome basins. Close correlation between zones of elevated temperature in the sedimentary rocks and petroleum occurrences is confirmed by the results of 2D and 3D modeling of the geothermal field. 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 salt-dome basins.

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INTRODUCTION

Evaporites occupy a considerable volume in many sedimentary basins of the world. These sequences, unique in their genesis and mode of occurrence, were formed from the Cambrian to present time. About half of petroleum provinces are related to evaporite basins. These basins host thermal waters and brines of economic importance; enormous halite and sylvite resources; and sulfur, gypsum, and other mineral deposits. Despite the long exploration history and advances in the study of evaporite basins, they remain priority objects of theoretical investigations and practical development. Geothermal research occupies an important place in these studies.

In this paper, we consider the thermal fields and their links to the geological history and petroleum resource potential in the Pericaspian, Pripyat, and North German basins of northern Eurasia. These basins have been extensively studied by drilling and geophysical methods, including geothermy.

The sedimentary cover of these basins is complicated by salt domes and plugs related to Devonian (Pripyat Basin) and Permian (Pericaspian and North German basins) evaporites and formed as a result of tectonic and gravity instability. The salt domes and plugs are mainly composed of rock salt with inclusions of sulfates and claystone, sandstone, and anhydrite interlayers. The dip angles at the slopes of the salt domes vary from a few degrees to 75°. In some places, salt is completely squeezed out from the interdomal zones and displaced into salt massifs.

As a rule, the salt domes cut through the overlying rocks. When the growth of salt domes ceases, the overlying beds become horizontal. In the places of active growth of salt domes, the suprasalt beds are sloped and the slope depends on the duration and rate of salt emergence. In plan view, the salt domes located in the central part of the basins are round and become elongated in the marginal zones [16].

The thermal conductivity of the rock salt (5.0–5.5 W/(m · K)) is much higher than that of the terrigenous background rocks (1.6–2.0 W/(m · K)). Such a high contrast in thermal conductivity in combination with structural and geological inhomogeneities gives rise to notable redistribution of terrestrial heat flow, which concentrates in the salt domes and runs down in the interdomal zones.

Thus, heat flow refraction is the main cause of heat flow heterogeneity in evaporite basins. As follows from empirical data, the positive heat flow anomalies above salt domes arise largely owing to structural thermophysical inhomogeneities and heat guides related to rock salt bodies. It has been shown that the effects of other factors (heat generation due to radioactive decay and exothermal reactions, heat release of friction during dome growth, and heat and mass transfer accompanying halokinesis) are within the limits of observation errors.

Let us consider the geothermal fields in each of the studied basins in more detail.

THE PERICASPIAN BASIN

The Pericaspian Basin is traditionally outlined within the boundaries of the salt-dome province. Its northwestern boundary coincides with the pre-Kungurian tectonic and sedimentary escarpment up to 1500 m high, which extends in the near-meridional direction from the town of Kotel'nikovo in the south to the city of Saratov in the north. Further, the boundary sharply turns to the east and extends at the latitude of Ural'sk to Orenburg. In the east, the basin is bounded by the Ural folds; in the southeast, by the Paleozoic fault-line South Emba Uplift; and in the southwest, by the Donbass–Tuarkyr system of inversion uplifts [25]. The closed Pericaspian Basin formed within these limits only by the end of Early Permian, when the Ural Foldbelt arose as its eastern boundary and the inversion uplift grew up on the place of the Donbass–Tuarkyr Rift System. Before that, the western part of the basin was a part of the sedimentary basin that continuously developed from the Late Riphean and its eastern portion was a part of the large orogenic region up to the Early Devonian. In the Devonian and Early Carboniferous, the entire basin was a shelf margin of deepwater sea in front of the subduction zone that separated the East European continent from the Ural ocean.

The geothermal measurements in wells started in the Pericaspian Basin as early as before World War II during the geological exploration of the South Emba petroleum province. In 1938–1940, the temperatures in the wells were measured down to a depth of 2 km in the Dossor, Tasquduk, Maqat, Sagyz, and some other petroleum fields. The first data showed nonuniform geothermal gradients, increasing in anticlines and decreasing in synclines [18]. Somewhat later, Kovner [17] developed the theoretical principles of thermal exploration aimed at the search for buried domes in the South Emba province.

Despite the overall thermometry of wells in the Pericaspian Basin, comprehensive reviews of the data obtained are scarce. The publications by Dal'yan et al. [11–13] on the eastern part of basin, Zhevago [15] on the central and eastern parts, and Druzhinin [14] on its western part should be mentioned in this regard.

The main factual data on regional geothermy were collected in the course of preparation of the Geothermal Map of the USSR on a scale of 1 : 5000000 [10] and are kept in the archive of the former geothermal laboratory of the Geological Institute, USSR Academy of Sciences as copies of thermograms. These data and those published subsequently were used in our study.

The ill-conditioned observations were rejected during preliminary processing of the data; the rest of the data were digitized, including the location of wells and the lithology of the penetrated rocks. The database of temperature measurements with related graphic appendix comprises 115 wells, including 16 deep (4 km and deeper) wells (Fig. 1).

The structural and thermophysical inhomogeneities in the Pericaspian Basin create lateral and vertical variations of the geothermal gradient and heat flow density. Therefore, the estimation of the background values requires detailed consideration of the temperature field in practically every well. The mosaic tectonic inhomogeneities should be taken into account, especially within the vast central part of the basin known as the Central Pericaspian Depression. The salt domes are round here and 2D approximation of the thermal field brings about inevitable errors. To a first approximation, 2D approximation of the thermal field parameters is possible only in the marginal parts of the basin, where salt swells and ridges are predominant [12]. Because of this, 3D modeling and representation of the geothermal field were used over the whole territory of the Pericaspian Basin.

The thermometric data in the wells, together with measurements of thermal conductivity of terrigenous rocks, sulfates, and halite penetrated by the wells were the basis for plotting the 3D patterns of temperature and other geothermal parameters.

To plot the isotherms in 3D geometry, the wells with the most reliable (equilibrium) temperature distribution were used; their location is shown in Fig. 2.

The 3D pattern of temperature and geothermal gradients was plotted using TECPLOT v. 7.0–10.0 software (AMTEC Engineering Inc., USA). In addition, we worked out special modules to convert the thermometric data into the TECPLOT format [27]. The program allows volumetric interpolation of the observed field using a grid of arbitrary configuration. We used a nonuniform grid tied to the coordinates of the wells and the strikes of the seismic lines along which 2D deep temperature patterns are plotted [23]. The interpolation parameters were set in such a manner as to avoid the jumps of deep temperature between wells and seismic lines unsupported by factual data.

As clearly seen from Fig. 3a, the temperature at deep slices increases from the northeast to southwest. In the eastern part of the basin at the boundary with the Mugodzhary Mountains, the temperatures at depths of 2 and 3 km are 40–45° and 60–65°, respectively, whereas in the South Emba and Manggyshlaq, the temperatures at the same depths are 55–60° and 70–75°. At a first approximation, this pattern supports the assumption of decrease in heat flow in the eastern part of the Pericaspian Basin due to nonstationary screening of the terrestrial heat flow in the South Urals and Mugodzhary [24].

Another 3D model has been calculated for depth interval 0–50 km, which includes the entire crust of

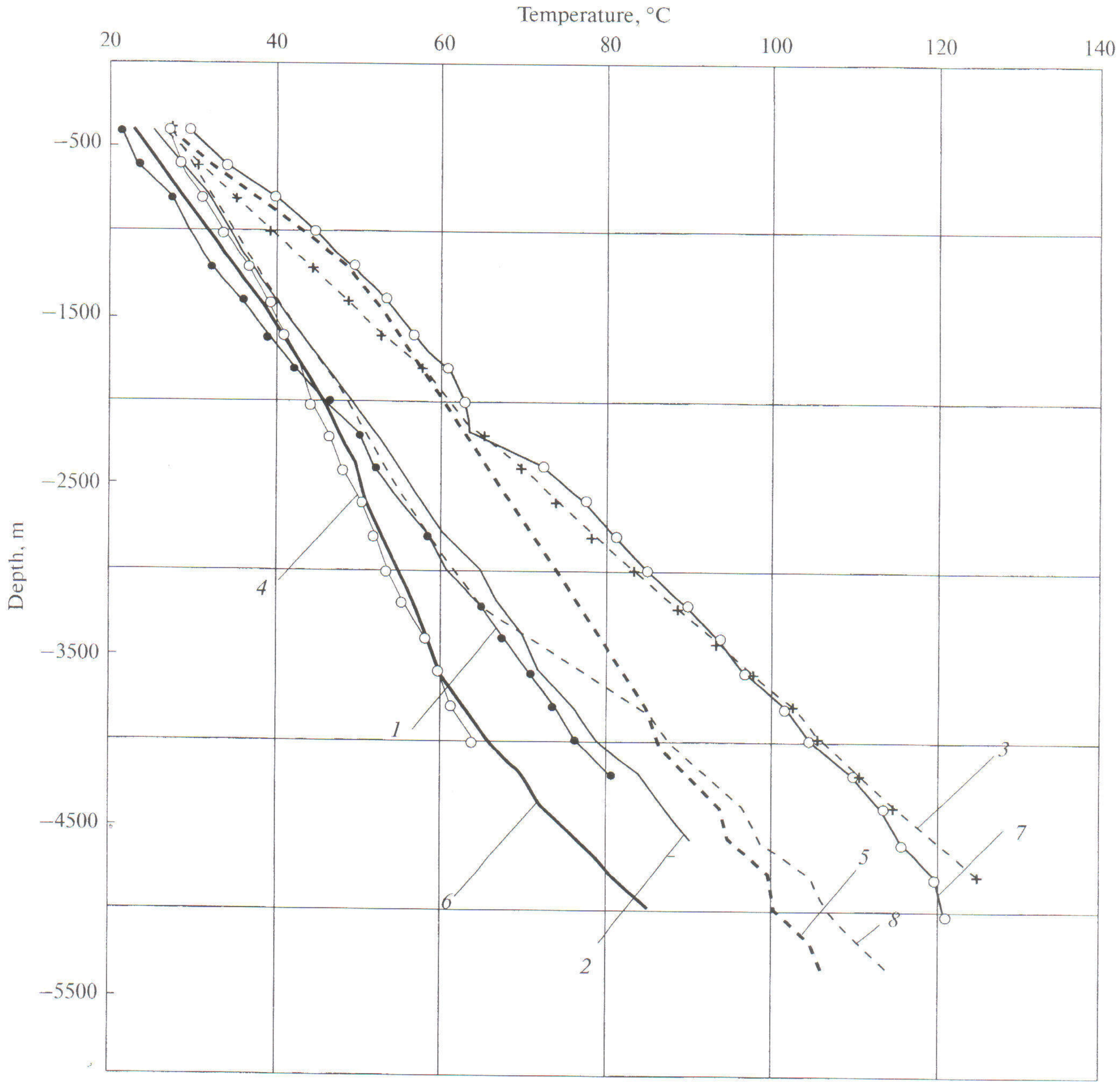

Fig. 1. Thermograms of deep wells in the Pericaspian Basin. Wells (numerals in figure): *1*, Blaksay-89p; *2*, Qaratobe-34; *3*, Qaratobe-35; *4*, Kumsay-2; *5*, Biikzhal-SD2; *6*, Kursay-4; *7*, Aralsor-SD1; *8*, Tashly-25p.

the Pericaspain Basin (Fig. 3b). To plot this model, we used the data on the structure and layer velocity along the seismic lines [4, 20, 21, 23].

The thermophysical parameters of the rocks used in calculation of the deep temperature and heat flow were chosen in accordance with the seismic section (Table 1).

As can be seen from the table, salt and eclogite are the most contrasting rocks. The appearance of eclogite in the lower crust is a distinguishing feature of the Central Pericaspian Depression [6]. Eclogite occurs as a lens of high-velocity rock (7.9–8.1 km/s) up to 10 km in thickness.[1] A second type of boundary conditions at the lower edge of the section were accepted in the modeling; i.e., a constant heat flow was set, and its value corresponded to the measured background value in the deep wells minus radiogenic heat generation

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[1] It should be noted that interpretation of the high-velocity lens as an eclogitic body is equivocal. According to the alternative explanation, a subducted slab of crust pertaining to the Ural paleoocean could have appeared in the lower crust of the basin.

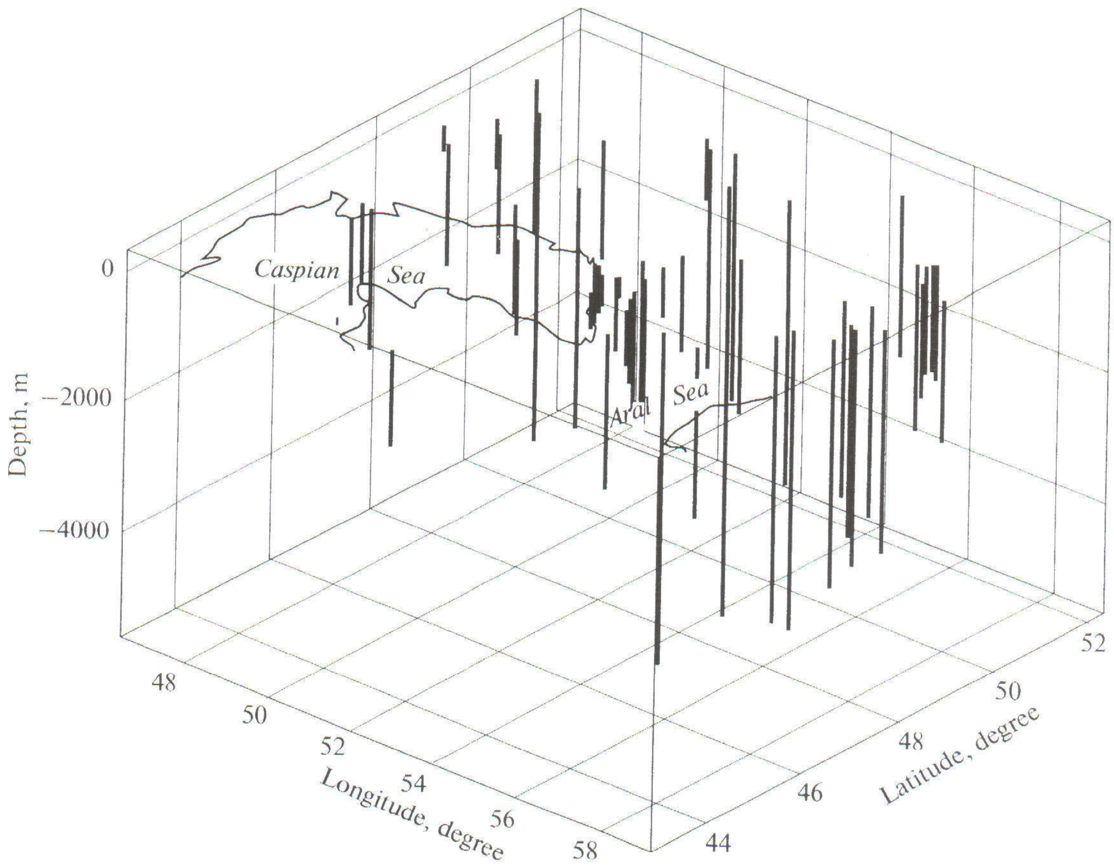

Fig. 2. Location of wells used in 3D modeling.

in the Earth's crust (Table 1). The reduced heat flow is 23 mW/m^2. A constant temperature of the neutral layer, which was set at the upper edge, was calculated from the relationship of the bottom well temperature versus well depth (Fig. 4). The linear fitting of the data allowed us to derive a regression line as a function of temperature T versus well depth Z: $T = (274.86 + Z)/45.80$ [28].

At $Z = 0$, $T = 6°C$. Approximately the same temperature was actually recorded in the neutral layer at a depth of 20–30 m by thermal sounding. The above

Table 1. Thermophysical parameters 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 complex of terrigenous rocks	5.0	2.0	1.5
Rock salt	12.0	5.3	0.4
Subsalt complex of terrigenous rocks	7.0	2.3	1.3
Metamorphic complex ($V_{\text{refr}} = 6.6$ km/s)	8.0	2.5	1.5
Geophysical granitic–metamorphic layer	6.0	2.5	1.8
Geophysical basaltic layer	8.0	2.9	0.3
Eclogite	10.0	3.2	0
Upper mantle	10.0	3.4	0

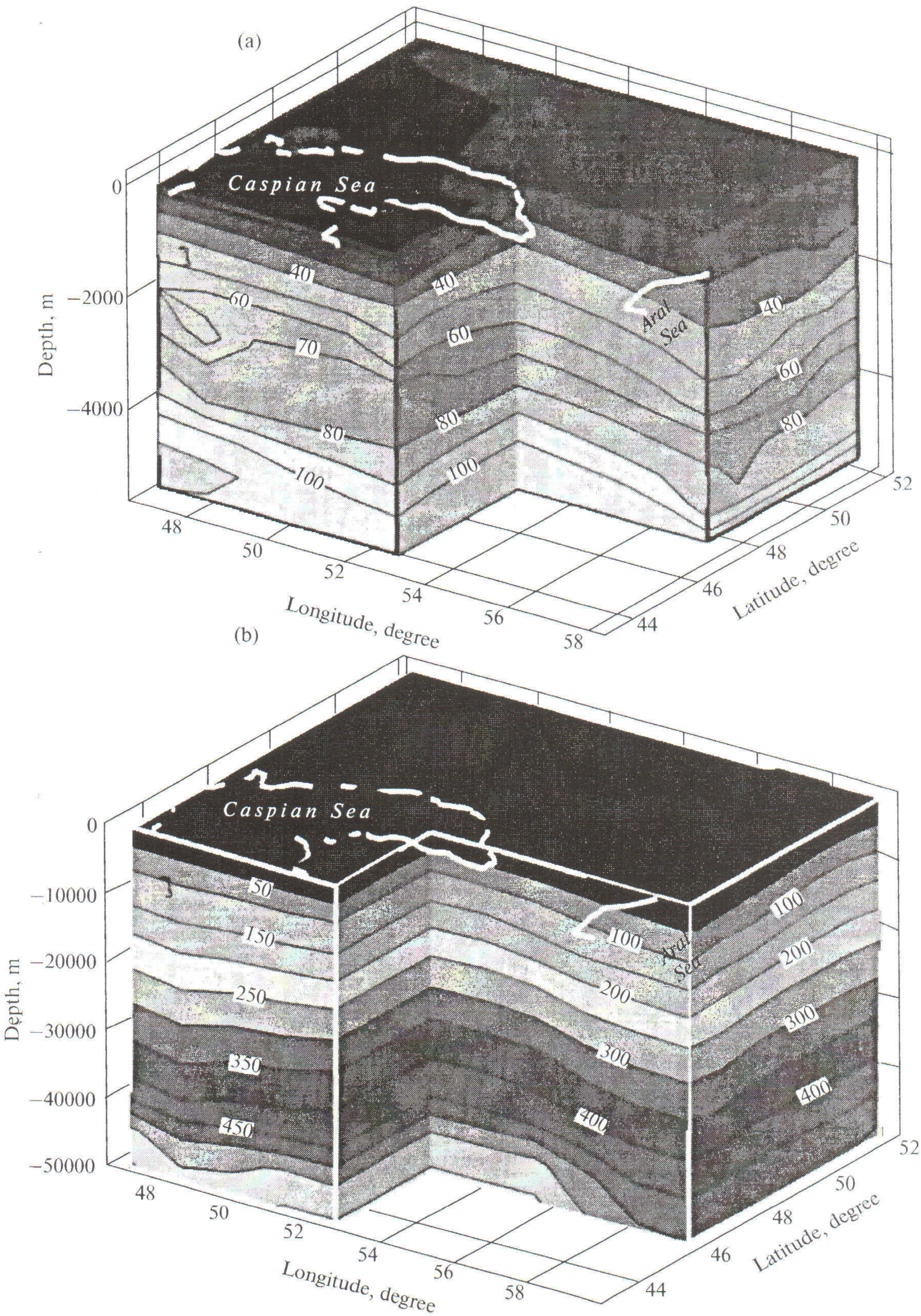

Fig. 3. 3D models of deep temperature in the Pericaspian Basin: (a) interval of drilling (0–5 km) and (b) the whole Earth's crust (0–50 km).

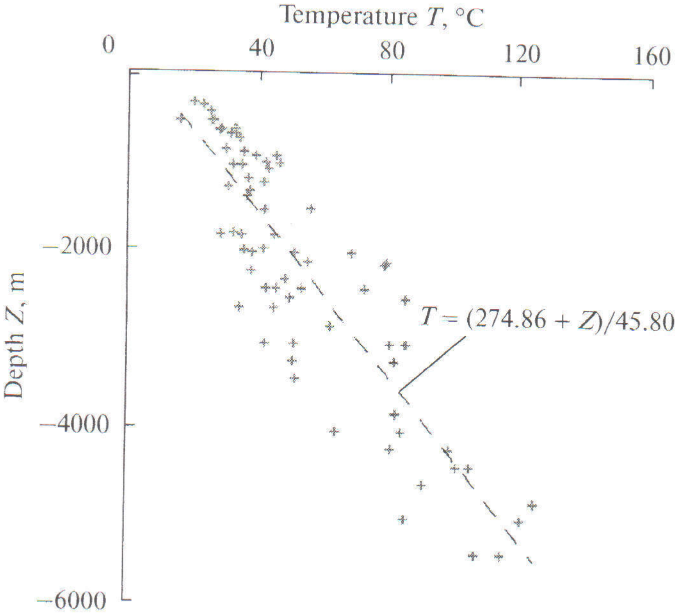

Fig. 4. Relationship between temperature at the well bottom and the well depth. See text for explanation.

regression was also used for calculation of the mean geothermal gradient in the interval of well measurements (21.8 mK/m). The condition of zero lateral outflow of heat, i.e., $\partial T/\partial x = 0$, was observed on the lateral boundaries of the modeling region.

The modeling was carried out using TERMGRAF software, which makes it possible to calculate deep temperatures and heat flows at any geometry of the structural boundaries and any number of thermophysical contrasts using the method of finite elements [24].

The plotting of the 3D temperature matrix is based on volumetric interpolation of all numerical data obtained from measurements in the wells and calculated geothermal data along the seismic lines. Comparison of empirical and calculated data for the wells in the seismic lines and the intersections of lines has shown that the discrepancy in the depths of the isotherms is insignificant: ±50 m at a depth above 5 km and ±150 m at a depth of 5–40 km. Thus, the uncertainty of model approximation of the factual data is below 1%.

The temperatures in the Earth's crust down to a depth of 50 km reveal the same tendency as in the interval of drilling; i.e., they gradually increase southwestward (Fig. 3b). At the Moho discontinuity in the eastern part of the basin, the temperature is 400°C, which is equal to the temperature beneath fold systems of the South Urals and Mugodzhary [24], whereas in the Central Pericaspian Depression, especially in the South Emba area, the temperature at the M surface reaches 450–500°C.

Isotherms, rising from the meridian of Mugodzhary westward, form several cupolas with their apexes located in the areas of South Emba, the Dead Kultuk salt flat, and northern Manggyshlaq, as well as the Astrakhan and Buzuluk swells (Fig. 5). Note that the aforementioned spatial correlation between the temperature cupolas and economic petroleum fields established in the Pechora Basin of the Barents Sea and the South Kara Basin [26] is also evident here; the above-mentioned areas of Russia and Kazakhstan are centers of intense output of oil and gas.

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 [2]. 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. [1].

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 [1], 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 [9].

Thus, the geological history and structure combined with fault tectonics allow us to suggest that not only were products of erosion supplied to the marine

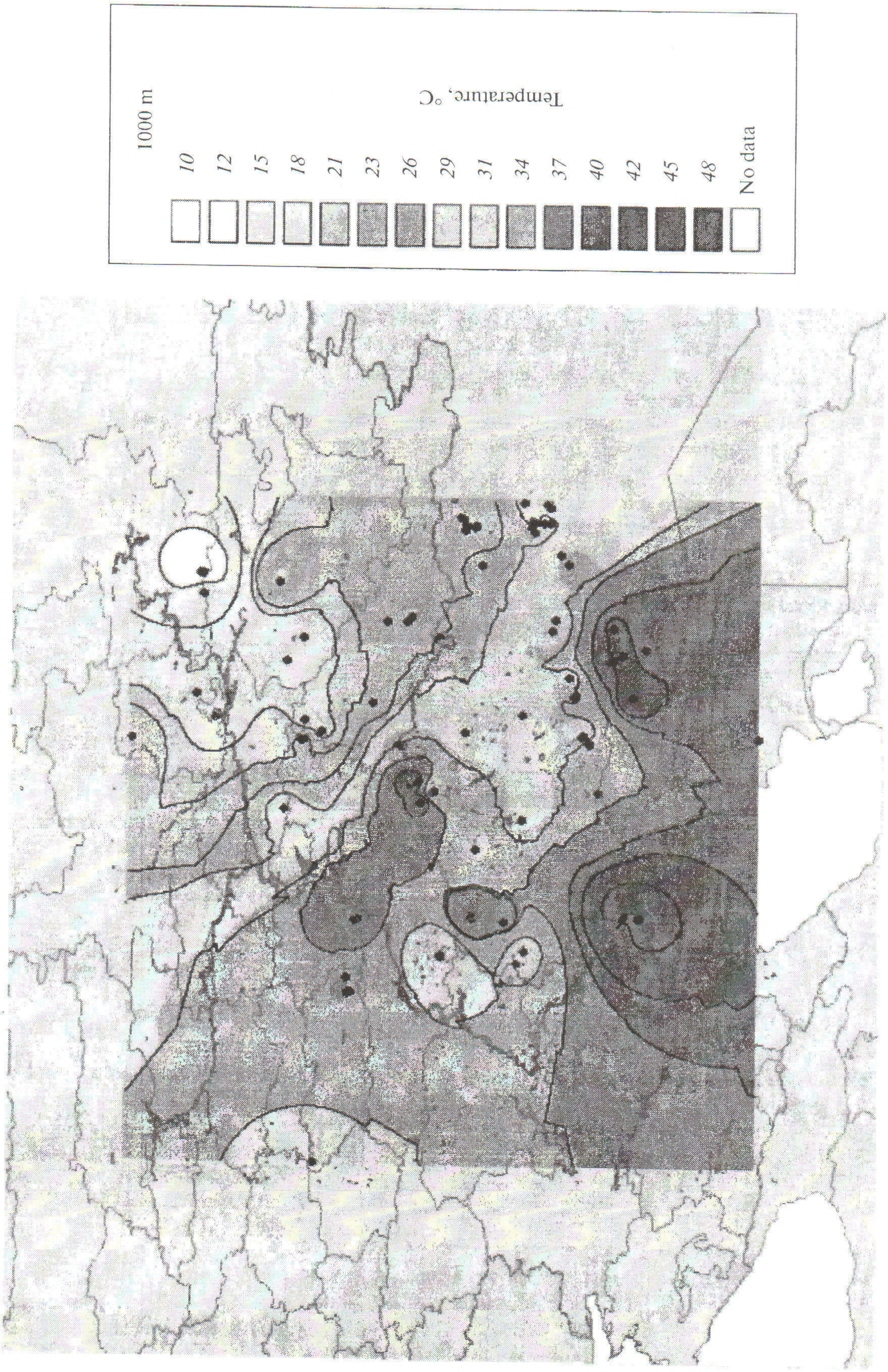

Fig. 5. Temperature at a depth of 1000 m in the Volga–Ural province from thermometry of wells.

basin from the adjacent land but deep matter was also transported therein along permeable faults, especially during the deposition of salt-bearing sequences. Some faults have retained their activity to present and are reflected in the thermal field.

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 [22, 29]. The thermograms measured in the northern, central, and southern zone are shown in Fig. 6. The configuration of the thermograms in the northern zone (Vishany, Chkalovo, Ozarichi wells) differs from those in the 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 zone and 60–75 mW/m^2 in the northern zone.

The causes of the different background heat flow values in the northern and southern parts of the trough were discussed in [29]. 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 thermal 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. Judging from geophysical data, these deep faults drain the mantle.

The relation of emerging salt bodies to the faults in the subsalt bed is clearly seen in the Pripyat Trough [1]. The overwhelming majority of the Upper Frasnian and the Upper Famennian salt domes are fault-line and localized in the uplifted walls of the faults.

To date, 69 oil fields are known in the Pripyat Basin. The oil pools are confined mainly to subsalt (largely carbonate) and intersalt sequences. Most of the oil fields are related to structural steps in the northern zone, where a system of four mantle-rooted faults dips to the south. The Prokhorovka, Sydovitsy, Berezino, and Otrubok oil fields are localized along the marginal Northern Fault. In close proximity to this fault, the Ozemlinsky, South Ozemlinsky, Pervomaisky, West Aleksandrovo, and South Aleksandrovo oil fields extend along the deep, mantle-rooted Ozemlinsky–Pervomaisky Fault. Farther to the south, the East Drozdy, Borisovo, Vishany, Davydovo, Sosnovka, Ostashkovichi, Tishkovo, and Rechitsa oil fields are controlled by the deep, mantle-rooted Rechitsa–Vishany Fault. Seven oil fields have been discovered in the subsided wall of this fault. The Oktyabr'sky, North Domanovichi, Kazansky, Zolotukhino, Malodushinsky, and Barsukovo oil fields, and a number of smaller fields, are known in the regional, mantle-rooted Chervonoslobodsky Fault Zone.

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 [8]. It was pointed out that the temperature in the Northern Fault Zone is higher than in the marginal Southern Fault Zone. As follows from temperature measurements in the wells, the difference is 20–25°C at similar levels. In the Northern Fault Zone itself, the temperature increases from the west eastward.

Quantitative estimation of the temperature field in the Pripyat Basin was carried out on the basis of its 3D modeling using the technology described above. The initial data were information on the temperature in the wells and on the thermal conductivity of the rocks in the section [3, 26, 29]. 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 [7, 35].

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. 7 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. When extrapolat-

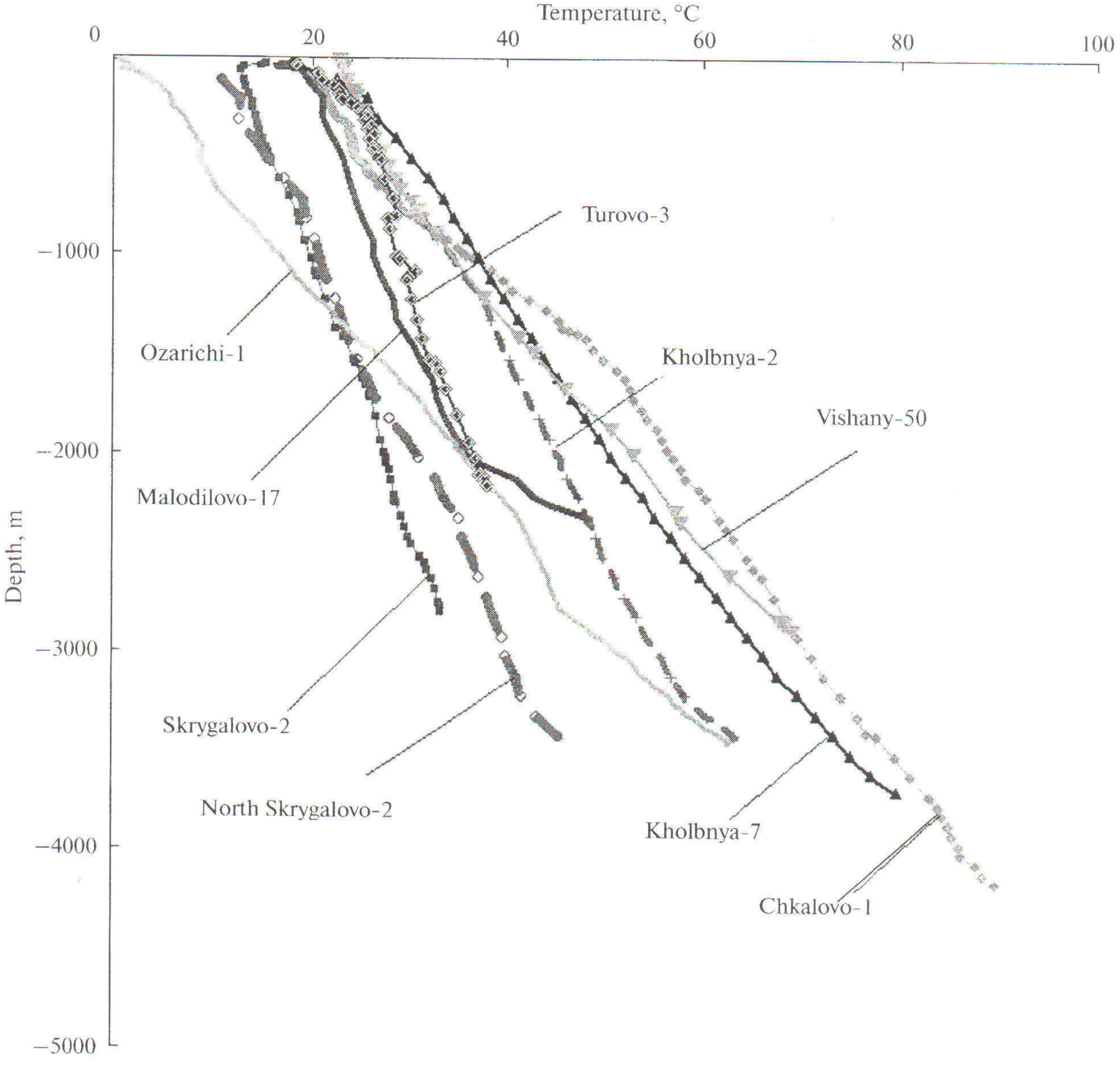

Fig. 6. Thermograms of deep wells in the Pripyat Basin.

ing the temperature to a depth, 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.

Thus, we reveal the same tendency of temperature distribution in the Earth's crust as 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. 7). In the Pripyat Basin, the temperature cupola is related to the deep faults that provide additional mass and heat transfer [9]. This 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

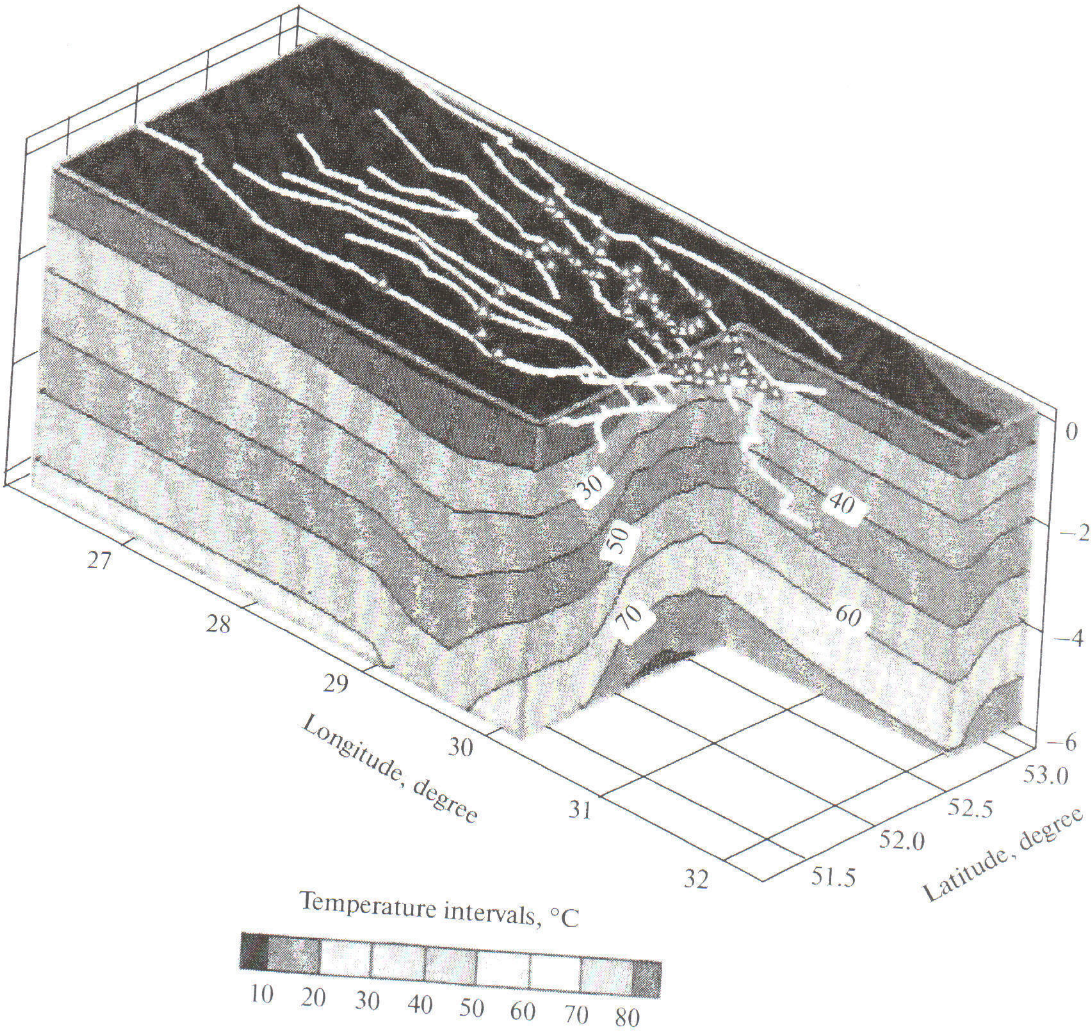

Fig. 7. 3D temperature model of the Earth's crust in the Pripyat Basin. The white lines are deep faults; the white triangles are oil fields.

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 [6].

The CEPP comprises the following large structural units: (1) the North Sea Syneclise that covers the North Sea and the adjacent territories of eastern England, northwestern Germany, the Netherlands, and Denmark; (2) the North German Basin; (3) the Danish–Polish Trough; and (4) the Baltic Syneclise [30].

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 [30].

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

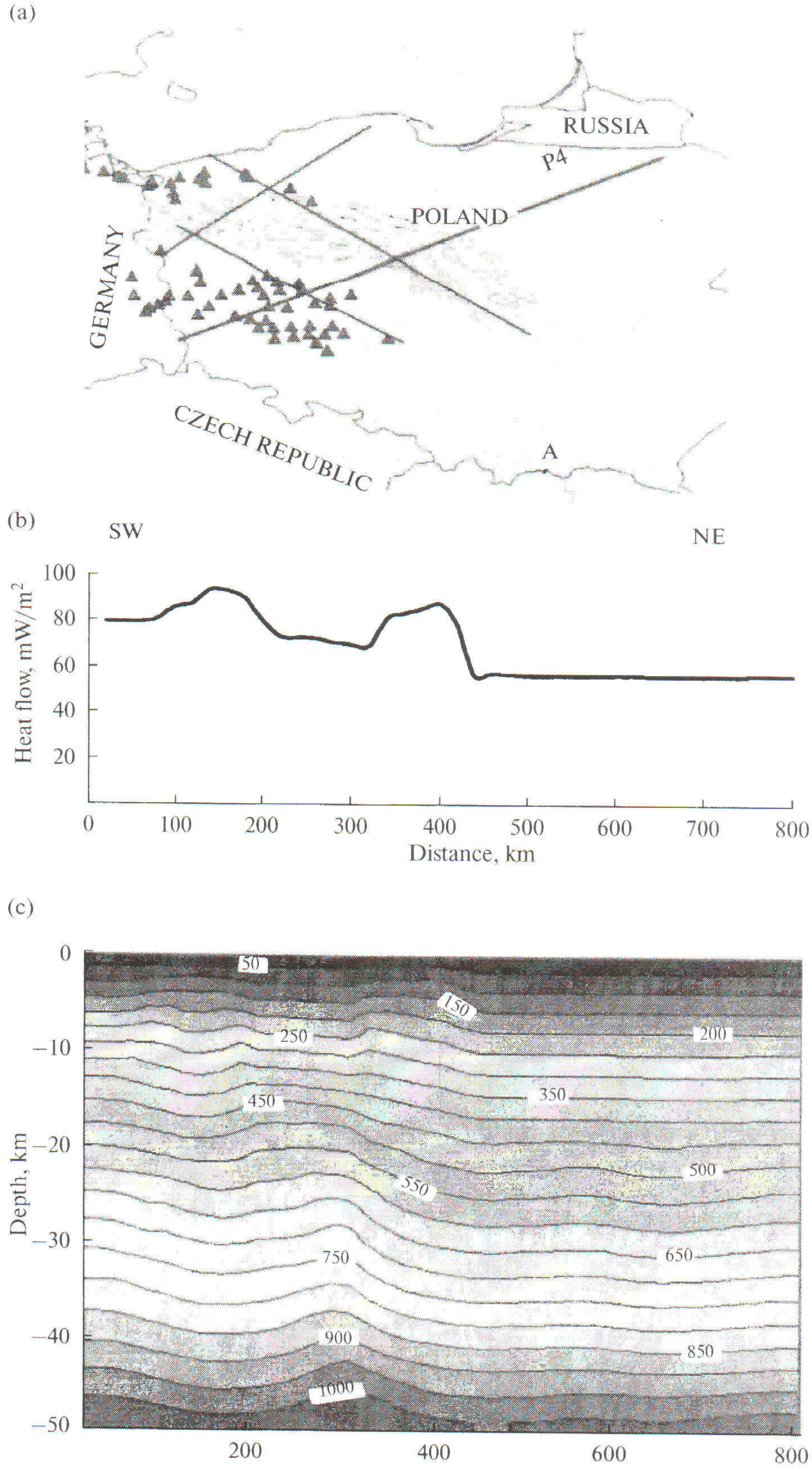

Fig. 8. 2D geothermal model of the North German Basin along profile P4: (a) location of profile P4, (b) distribution of heat flow along profile P4, (c) temperature section along profile P4.

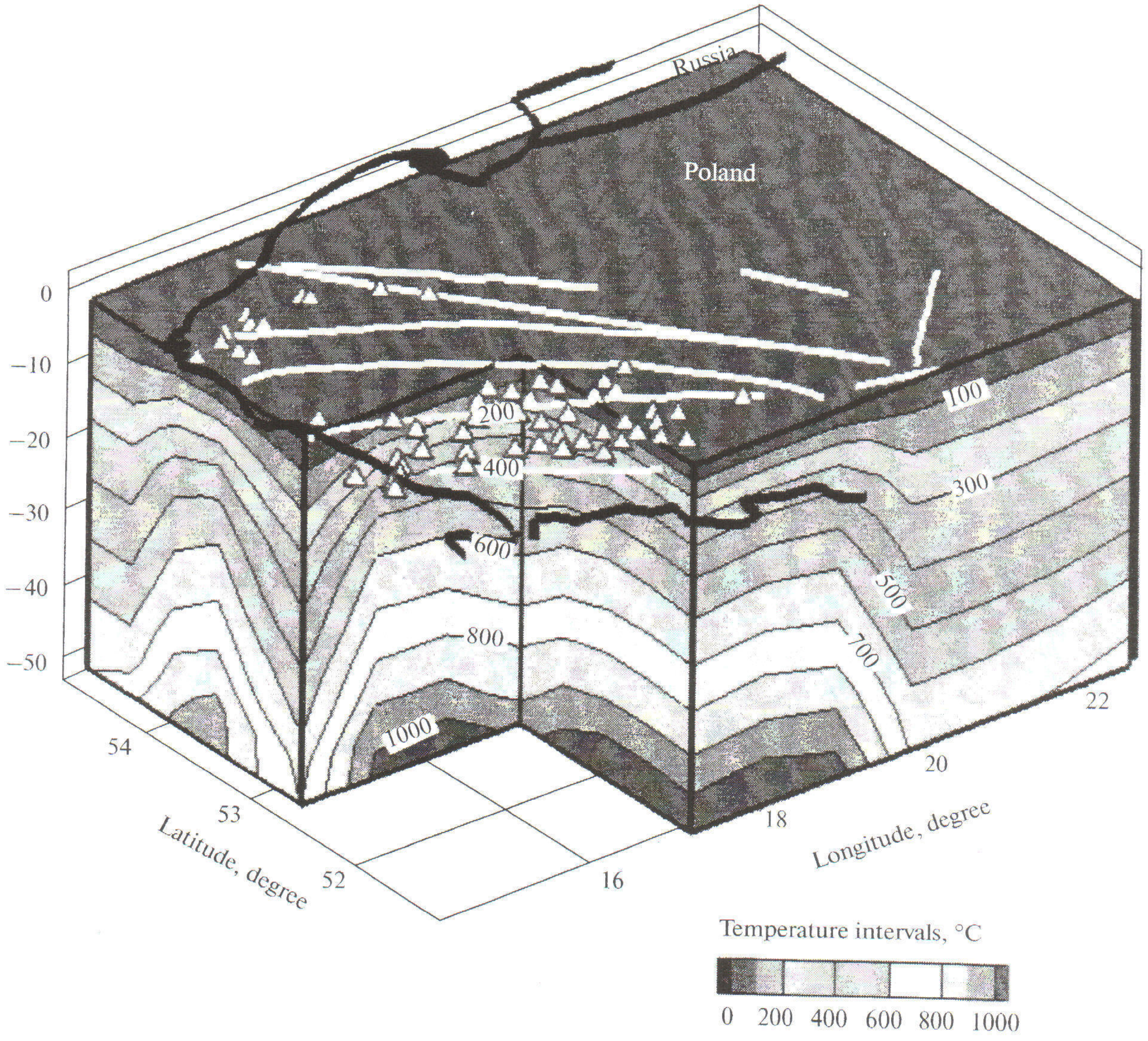

Fig. 9. 3D temperature model of the eastern part of the North German Basin (Polish Basin). White lines are deep faults; white triangles are oil fields.

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 [31].

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 part (Gubben, Lüben, Staakow), and in the southwestern part (Fallstein); the gas fields are concentrated in the southeastern part of the basin [5].

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 [34].

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.

Table 2. 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.

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 southeast. 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-described 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 [33], the background heat flow here is 80–85 mW/m^2, 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. This model is based on the temperatures in wells and the thermal conductivity of the rocks in section, as well as on the data concerning the structural and geological setting along the DDS lines [32, 33, 37].

The model heat flow and temperature along the line P4 that extends in Poland in the northeastern direction along the Foresudetian Homocline (Figs. 8a, 8b) 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 (Polish) 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 mark of 450 km (Figs. 8a, 8b), where salt domes disappear. In the opinion of [30], this is precisely the place where the crystallinicum of the East European Platform borders on the eastern margin of the CEPP. The high values of heat flow at the onset of the profile are related to deep faults (Fig. 9).

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 2). 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. 9) demonstrates a pronounced temperature cupola related to faults and salt domes, i.e., to the area of oil fields.

In the western part of the North German Basin, a temperature cupola in the 3D temperature model (Fig. 10) is spatially correlated with oil fields.

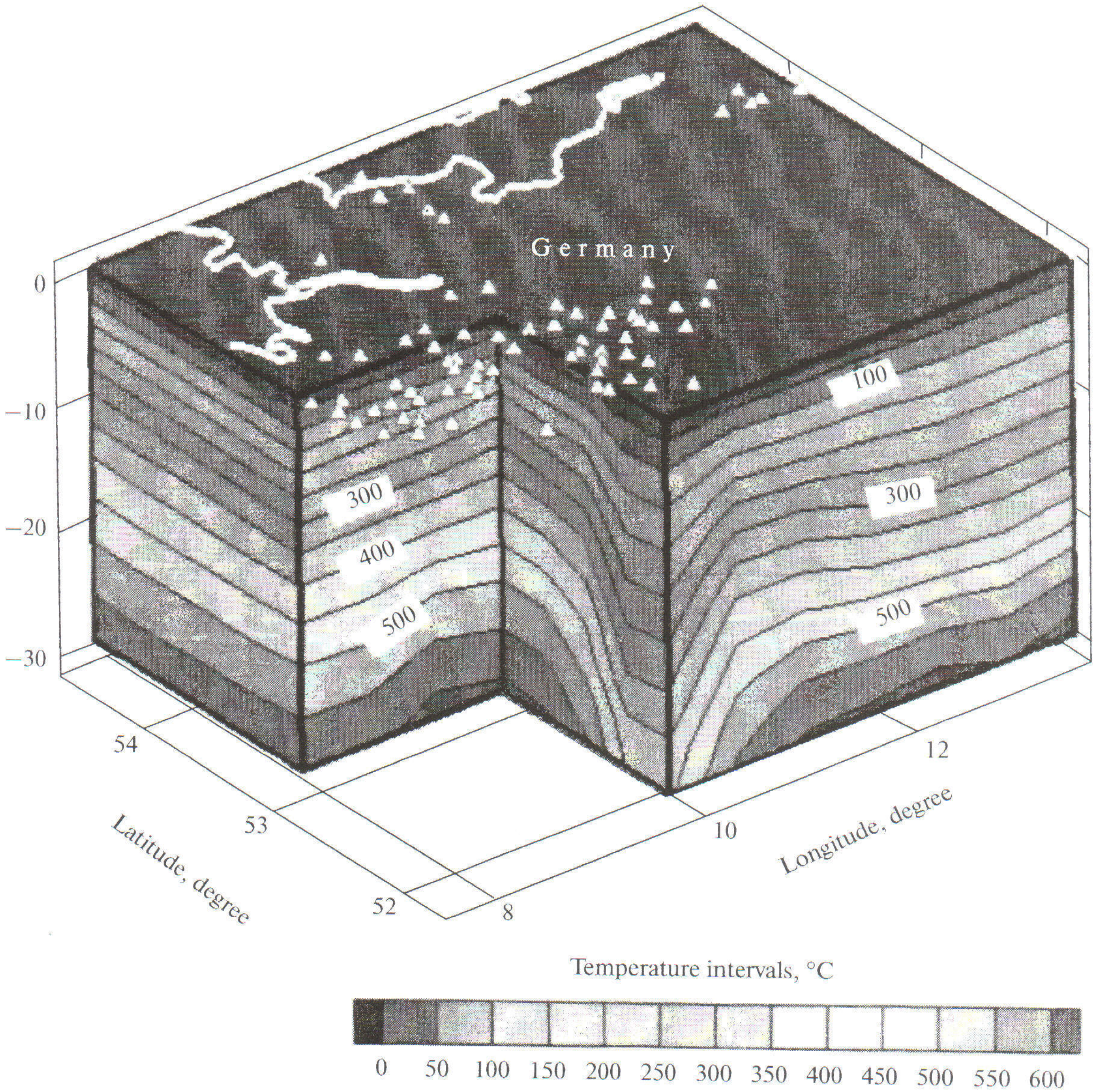

Fig. 10. 3D temperature model of the western part of the North German Basin (Polish Basin). White triangles are oil fields.

CONCLUSIONS

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 [25].

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* [26] 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. In all of the studied shelf or evaporite basins, thermal cupolas reveal close spatial relationships to the above-localized hydrocarbon fields. 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 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 the depths where the catagenetic temperature is suitable for transformation of organic matter yields 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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