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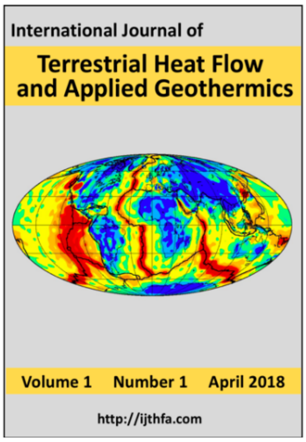

Geothermal Regime and Deep Temperatures of the Siberian Platform

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Abstract

The geothermal regime of the southern segment of the East Siberian platform, where more than 200 heat-flow measurements have been carried out, is well-understood. The present work deals with the study of deep temperatures of the southern Siberian platform, based on results of geothermal measurements in more than 70 boreholes. In addition, measurements of thermal properties have been made mostly on core samples representing the Vendian terrigenous deposits and Riphean magmatic and metamorphic basement rocks. The basement rocks may be subdivided into two groups, with thermal conductivity coefficients varying in the range of 2 and 3 W/m/K. Higher coefficients indicate the presence of carbonate-halogen admixtures. Studies have also been made of the borehole thermograms and temperatures at the bottom and top of the Moti suite, of lower Cambrian age. These boreholes vary in depth from 1300 to 6000 m, and the borehole temperatures attain values as high as 70°C. In this region average heat flow is 38±4 mW/m^2. Higher heat flow values (45±6 mW/m^2) are observed in the anticlinal domes and salt-dome crests, while low heat flow seems to be typical of marginal uplifts. This peculiar geothermal condition is also closely related to hydrodynamic features of the area, where underground seepage flow penetrates to depths of 3-5 km while conductive diffusion of heat prevails in the deeper crust. It is argued that such anomalous conditions exert influence on the dynamics of hydrocarbon accumulation, which in turn is also predetermined by geothermal conditions.

1. Introduction

Geothermics of the Baikal region is of special interest because of the confluence of its major tectonic units of different age and origin. These include a craton (Siberian Platform), two folded areas (Sayan-Baikal and Trans-Baikal), and an evolving rift (Duchkov et al, 1987; Lysak, 1984; Lysak and Dorofeeva, 1997; Dorofeeva et al, 1995). It was hypothesized that the long-term development of the territory is related to the Indo-Eurasian continental collision and variations in mantle heat flow. The focus of the present work is on the southern segment of the Siberian platform (known as the "Irkutsk amphitheater"), which is often considered tectonically stable. It has a two-layer structure, with primarily a lower Paleozoic sedimentary cover overlying Archean-Proterozoic crystalline basement. The results are based on field data collected from about 70 boreholes in the study area. It includes lithological sections, borehole temperature logs of different depths, geothermal gradient determinations. In addition, core samples were selected for further determination of thermal and physical properties of the sediments. Well-known averaging schemes were employed in determining thermal conductivity coefficient for sections of boreholes for which the cores were not available. The actual material sampling sites are shown in figure 1. The record of deep-hole drilling shows predominance of halogen-carbonate sediments in the upper layer of the southern Siberian platform, where terrigenous sediments are less predominant. In the western and northwestern parts of the amphitheater, the sedimentary cover is penetrated by dolerite intrusions that occurred most often in the Permian-Triassic.

The studies of sedimentary cover revealed numerous swell-like and dome-like uplifts and basins (see figure 1) though a considerable part of the sedimentary rocks has monoclinal bedding and dips gradually from the folded mountain range deep into the platform.

The basement of Irkutsk amphitheater occurs at depths between 1.7 and 2.5 km (Nepsky arch) and to depths of 4-5 km (in the zone of Angara dislocations and in the Sayan-Yenisei depression). However, it has been studied only to a depth of about 25 m on the average (from 6 to 80 m).

The structural perturbations in the sedimentary cover reflect the deep-seated dislocations in the crystalline basement of the platform. The rock types employed in thermal property measurements include Vendian terrigenous deposits (argillites, aleurolites and sandstones of the Ushakov suite);

lower Cambrian halogen-carbonate sediments (dolomites, limestones and rock salt primarily of the Moti and Usolye suites); crystalline basement rocks (granites, granosyenites and metamorphic rocks of different composition (Lysak and Dorofeeva, 1997; Dorofeeva, 1982; Dorofeeva and Lysak, 1983). In the basement there is an abundance of magmatic formations of basic (olivine-containing dolerites) and ultrabasic composition and the products of their deep-seated metamorphism (schists containing talc, serpentine and ankerite (Tereschenko and Lobanov, 1981).

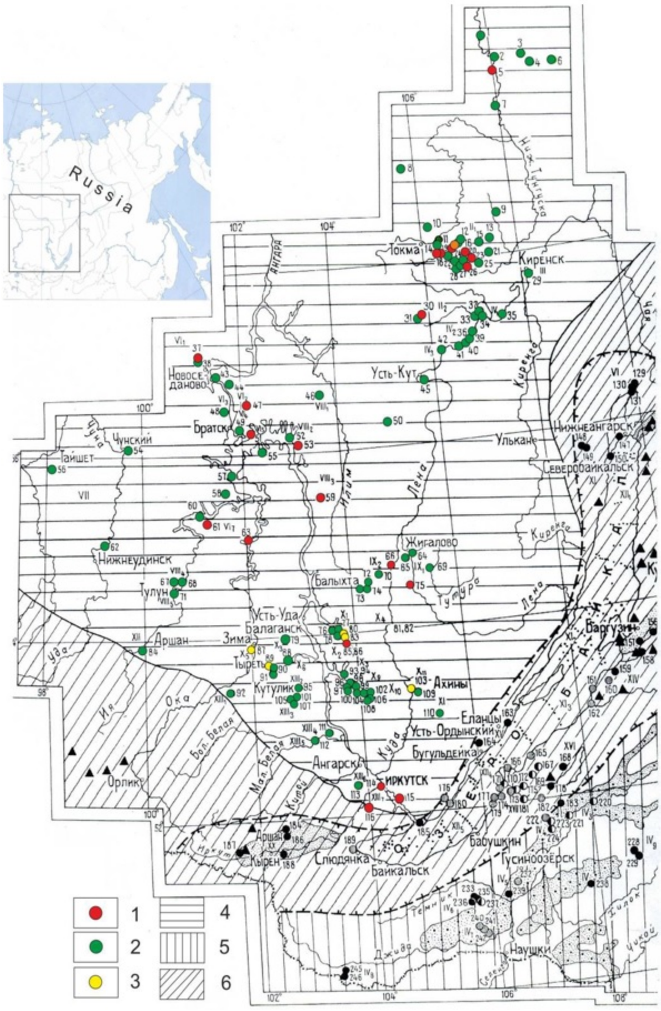

Figure 1 - Points of geothermal investigations and major geologic structures of the southern Siberian platform. The numbers 1-3 indicate localities of heat flow determination.
Locations of samples employed for determinations of thermal properties of the rocks are indicated as: 1 – materials collected by the author of this work, 2 – calculations based on in-hole sections, 3 – data obtained by other organizations (IPhE RAS, IGG RAS). Areas of tectonic activation: 4 – Paleozoic, 5 – Mesozoic, 6 – Cenozoic; 7 – major tectonic structures of the southern Siberian platform: I – Nepsky arch, II – Nepsky dislocations zone, III – Kirensky swell, IV – Markovsky swell, V – Ust-Kutsky arch, VI – Angara dislocations zone, VII – Sayan-Yenisei depression, VIII – Central field of the Irkutsk amphitheater, IX – Zhigalovsky swell, X – Upper Angara dislocations zone, XI – Bozhekhansky swell, XII – Tulunsky protrusion, XIII – Irkutsky protrusion.
The inset map on the top left corner indicates the location of the study area.
Black circles indicate locations of heat flow determination; Black triangle indicate locations of thermal springs.

2. Temperature regime

Basal horizons in the southern Siberian platform are represented by the upper Proterozoic deposits (of Vendian and Riphean ages). These complexes are associated with discovered and predicted oil-and-gas content of this area. The main factor of transformation of organic matter in the interior of the Earth is temperature, i.e. energy potential that is acquired by organic matter (OM) during subsidence of the enclosing deposits. Heat flow from depth is contributes to reconstruction of OM structure (Bazhenova, 2008). This is the main reason for considering the temperature regime in the interior part of the southern Siberian platform. In view of the fact that there are different structural units at the base of the platform sedimentary cover, brief discussions of the following borehole thermograms are pertinent.

2.1. Borehole Thermograms of the Nepsky Arch

Vertical distributions of temperatures (designated hereafter as thermograms) of the Danilovsky-145, Verkhne-Chonsky-122, and Dulisminsky-191 boreholes are illustrated in Figure 2. The average thickness of the Moti suite on the Nepsky arch is about 200 m. The average temperature difference between the top and bottom suites is 2–3°C. In this work geothermal gradients (γ) are given in units of °C/km and heat flow (q) in units of mW/m^2. The values measured in Danilovskaya-145, Dulisminskaya-191 and Verkhne-Chonsky-122 boreholes are respectively γ = 0.71, q= 21; γ = 0.94, q= 26; γ = 0.64 (within the depth range 1478 to 1580 m). The temperature in Dulisminsky borehole at 2.5 km is 30°C.

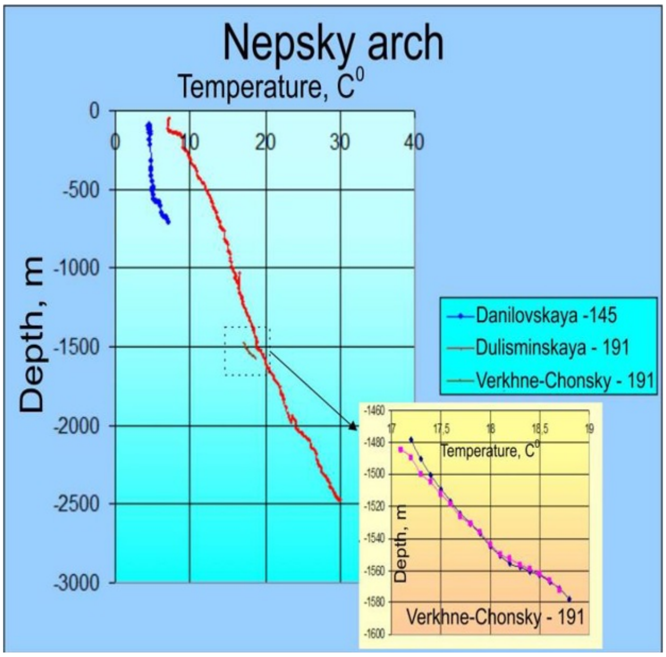

Figure 2 - Borehole thermograms of the Nepsky arch.

2.2. Borehole Thermograms of Angara Dislocations Zone

Thermograms of the Kovinsky-1, Sedanovsky-134, and Kuturminsky-156 boreholes are illustrated in Figure 3. In the Angara dislocations zone, the suite thickness increases to 700 m. The temperature difference between the top and bottom suites is as large as 15–20°C. Geothermal gradients (γ) and heat flow (q) in the Kovinsky-1, Kovinsky-157, Sedanovsky-

134 and Kuturminsky-156 boreholes are respectively $\gamma = 1.34$, $q = 39$; $\gamma = 1.14$, $q = 32$; and $\gamma = 1.6$, $q = 45$. The temperature in Kovinsky-1 borehole at a depth of 4.5 km is greater than 70ºC.

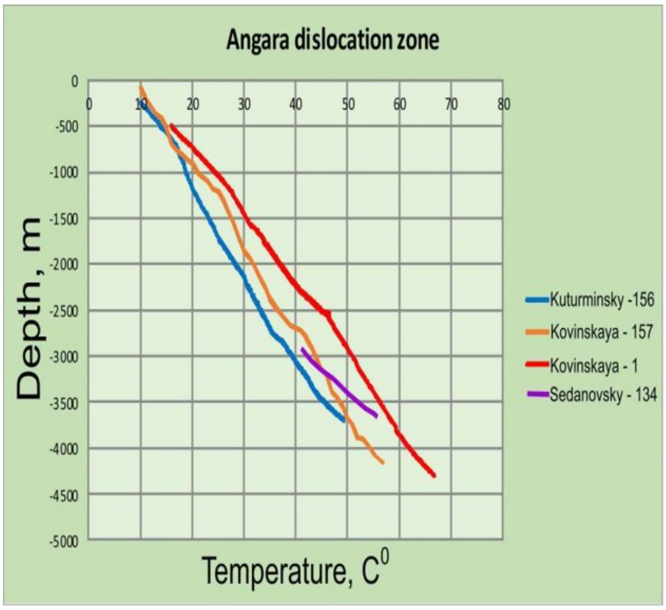

Figure 3 - Borehole thermograms of the Angara dislocations zone.

2.3. Borehole Thermograms of the Bratsk Uplift

Vertical distributions of temperatures for the boreholes Bratsk-1 and Bratsk-3 are illustrated in Figure 4. In this case $\gamma = 1.55$ and $q = 45$. Temperatures as high as 60ºC was encountered in Bratsk-18 borehole, at a depth of 2.5 km.

2.4. Borehole Thermograms of the Central Field of the Irkutsk amphitheater

The temperature in Chorsky-115 borehole at a depth of 2.5 km is 41ºC, with $\gamma = 2.3$, $q = 49$. The thermogram of the Yuzhny-127 borehole has been recorded to a depth of 3.3 km. The bottom hole temperature is 54ºC (Figure 5). There is spike in temperature at 2800m. It is obviously due to a hydrogeological factor – an anomalously high-pressure area, promising in terms of gas.

2.5. Borehole Thermograms of the Kovykta Protrusion

Thermograms of Kovykta-55, 56, 63-A boreholes, illustrated in Figure 6, have $\gamma = 1.55$ and $q = 43$. A thermogram has been recorded up to a depth of 1.6km, for the borehole located in the Tunka valley (Baikal rift). Temperature for the platform was recorded to a depth of 2.5 km.

The Kupsky-143 borehole thermogram is available only for the 2.45-3.05 km depth range. At a depth of 2.8 km, the temperature increases by 5ºC in a very narrow range.

A comparative illustration of borehole thermograms of different tectonic areas in the southern East Siberia (Siberian platform, Baikal rift zone, and Trans-Baikal folded area) is provided in Figure 7.

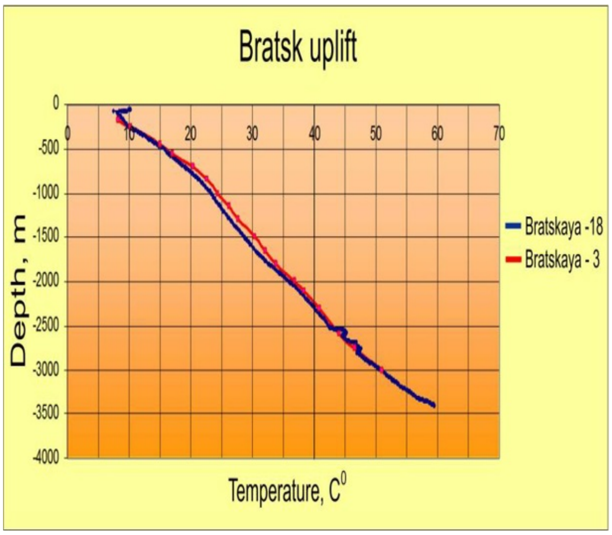

Figure 4 - Borehole thermograms of the Bratsk Uplift.

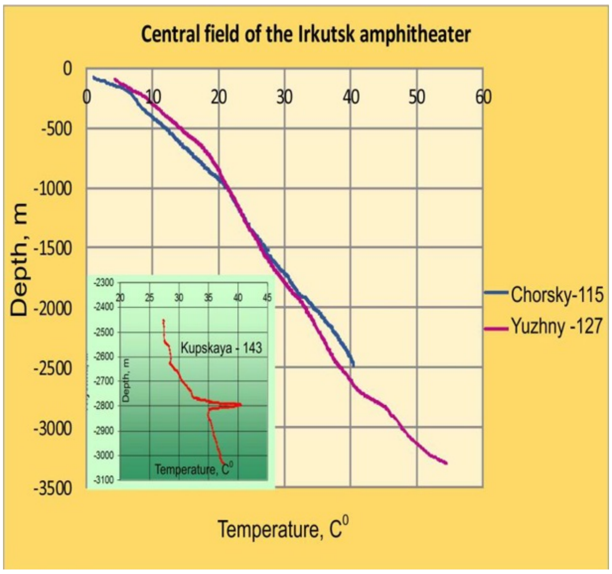

Figure 5 - Borehole thermograms of the Central field of the Irkutsk amphitheater.

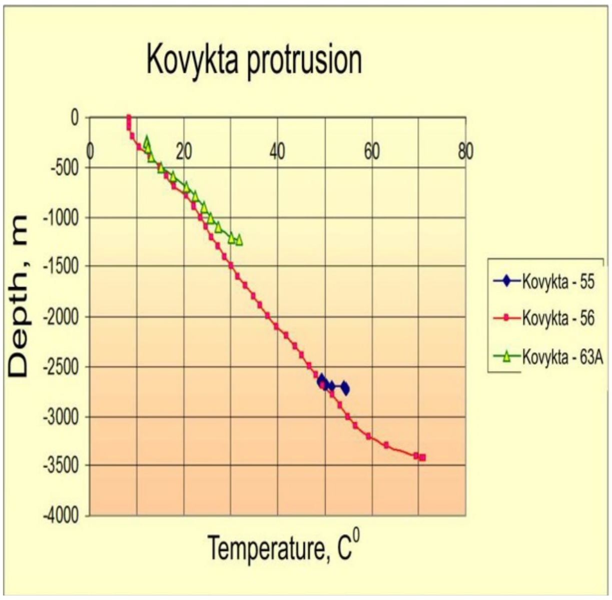

Figure 6 - Borehole thermograms of the Kovykta protrusion.

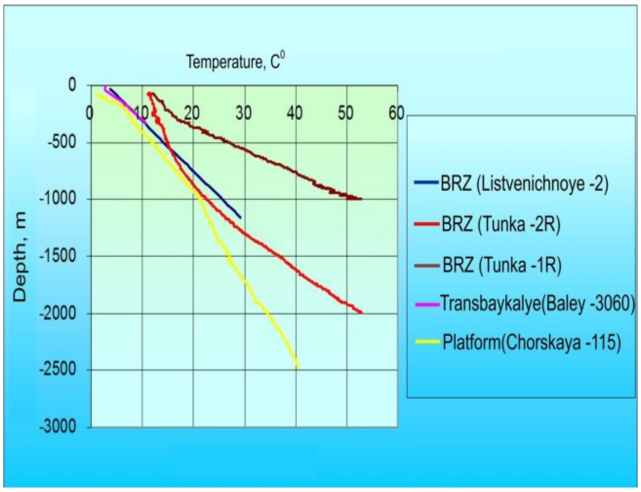

Figure 7 - A comparison of borehole thermograms of Cenozoic, Mesozoic and Paleozoic tectonic regions of East Siberia.

3. Discussion

According to geological studies most of the sedimentary cover was formed in the lower Cambrian. The upper sediments relate to the Lensky stage, and the lower sediments to the Aldanian stage. The upper Aldanian stage is occupied by the Usolye suite (Єus) whose rock salt beds (ranging in thickness from less than 1 m to 50-75 m) alternate with dolomites. The Usolye suite is underlain by the Moti suite (Єmt) whose upper part is also represented by dolomites with interlayered concentric sandstones and clay schists. The detailed study of this suite is usually related to results from oil-and-gas drilling activities.

Temperature conditions in the lower part of the sedimentary cover have been considered and temperature distribution patterns obtained for the top and bottom of the Moti suite, for lower Cambrian and for formations directly overlying the crystalline basement in many places. With regard to the PGA (Production Geological Association) “Irkutsk-geofizika” and “Vost-Sibneftegaz-geologiya” materials were relevant for deep boreholes (Tereschenko and Lobanov, 1981; Fuks and Savintsev, 1981).

According to the actual data available and theoretical calculations, geo-isotherms follow the structural forms of the top or bottom of Moti suite. Rather low temperature ranges (from 14 to 30 °C in the top and from 15 to 35 °C on the bottom) are associated with the Nepsky arch and monoclinal slope in Prisayanye, where the depth of occurrence of basement is no more than 2 km. The average thickness of the Moti suite on the Nepsky arch is about 200m. The difference in temperature between its top and bottom is generally 2-3 °C, increasing to 4-5 °C in the arch-like Yaraktinsky uplift (points No. 16, 21 and 22 in figure 1). The temperature there can get as high as 30 to 40°C in the top and exceed 40°C on the bottom.

The temperatures in the top of the Moti suite vary from 30 to 40°C on most of the southern Siberian platform and are more than 50°C only in the Prisayan-Yenisei syneclise and on the Bratsky swell (Angara dislocations zone). The temperature on the suite bottom typically varies from 40 to 50°C, reaching 60 to 70°C in the northwest of the amphitheater. Local anomalies are characteristic of the Zhigalovsky (points No. 70-74) and Nukutsky (point No. 81) fault zones. The isotherms often contour large anticlinal uplifts: Yaraktinsky (points 16, 19, 23, 27), Markovsky (points 32-35), and Bratsk (points 38, 47, 52, 55 and others). Significant differentiation of the temperature field exists in the southern part of the amphitheater. (figure 8).

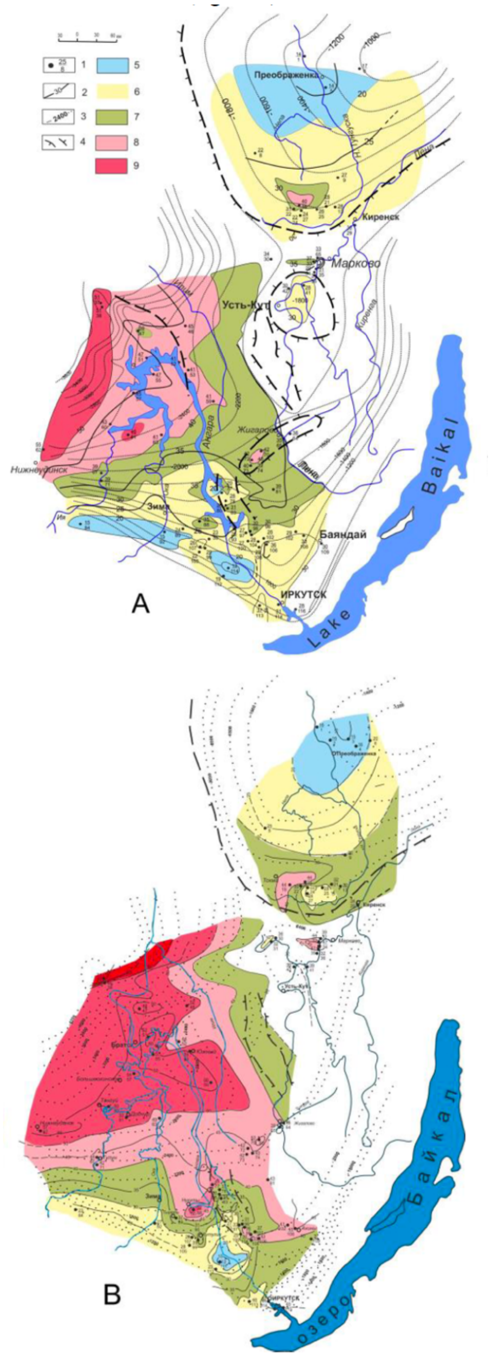

Figure 8 - A pattern of temperatures in the top (a) and bottom (b) of the lower Cambrian Moti suite at the southern Siberian platform. 1 – numerator: temperature, °C; denominator – point number; 2 – temperature isolines, °C; 3 – isohypses of the bottom of the Moti suite, m; 4 – anticlinal structures; heat flow in mW/m²: 5 – less than 20, 6 – 20-30, 7 – 30-40, 8 – 40-50, 9 – more than 50.

Configurations for maximum temperatures in the top and on the bottom of the suite often do not coincide with one another. For example, two maximum values of the temperature recorded in the top of the Moti suite on the Markovsky uplift are 35 and 20 °C whereas only one maximum value (45 °C) is available for the bottom of the suite with an average thickness of about 500 m. The suite thickness increases to 700 m in the

Angara dislocations zone. The temperature difference between the top and bottom of the suite is as large as 15-20°C.

Some anomalous parts therein are Polovininsky (No. 111 in figure 1) and Belsky (No. 112) where the temperature remains constant (15-20°C) throughout the suite with a thickness of about 300 m Such constancy of temperature on these parts may be explained by the prevalence of thick halogen-carbonate units having high thermal conductivity or by heat absorption and transfer of heat by the movement of fluids.

4. Implications for Genesis of Oil Deposits

Local perturbations of geo-temperature field may be caused by long-term accumulation and migration of hydrocarbons because these processes require an input or release of energy, since the observed mosaic structure of geo-temperature field of the sedimentary basin and its abrupt change over short distances are typical of many oil-and-gas-bearing areas (Bazhenova, 2008; Osadchy et al, 1976). In fact, the identified geothermal anomalies are regionally correlated with the distribution pattern of geo-temperatures in the top of the Moti suite on the Angara-Ilim interfluve, Nepsko-Botuobinsky and Angaro-Lensky oil-and-gas-bearing areas, and predicted pattern of distribution of collectors in the southern Siberian platform (Arytyunov et al, 1981). The comparison with this map and predicted pattern allows all geothermal instability parts (high geothermal gradient and heat flow, abrupt anisotropy of thermal properties, highly differentiated geo-temperature field) to be assigned to oil-and-gas promising areas.

The peculiar geothermal environment is also closely related to hydrodynamic characteristics of the area whose inferior part is viewed as the seat of groundwater seepage to depth of 3-5 m under the Angaro-Lensky artesian basin conditions, with deeper crust dominated by diffusion (Pinneker et al, 1980). Thus, abnormally high pore pressure, almost 50 percent higher than hydrostatic pressure, occurs in the southern Nepsky arch in the deposits confined to the carbonate sediments. Such phenomenon occurs in the pore space of sedimentary rocks by penetration of oil-bearing, gas-bearing and water-bearing strata (Avchan et al, 1979). On the contrary, abnormally low values comprising thirty percent of hydrostatic pressure occurs in the northern part of this arch, in the terrigenous sediment deposits (Fuks and Savintsev, 1981). Such abnormal formation conditions certainly influence the dynamics of hydrocarbon accumulations that in turn is also predetermined by the geothermal environment.

The heat flow in the investigated area varies from 21 to 60 mW/m^2 and averages 38±4 mW/m^2. An intensive heat flow (45±6 mW/m^2) is observed in the crests of anticlinal structures and salt domes complicated by tectonic dislocations in the areas of Zhigalovo, Ust-Kut, and others. Low heat flow values are found in the Nepsky arch (28±5 mW/m^2) and marginal uplifts (35±4 mW/m^2) (figure 9a). When the heat flow distribution in the lower Cambrian Moti suite is compared with that in the upper crustal horizons at the southern Siberian platform, it is apparent that the Moti suite related to active Zhigalovsky and Nukutsky fault zones is heated-up to a much greater extent (figure 9b). Partial heat loss or redistribution in the upper sedimentary unit may be due to dynamics of fluid regime.

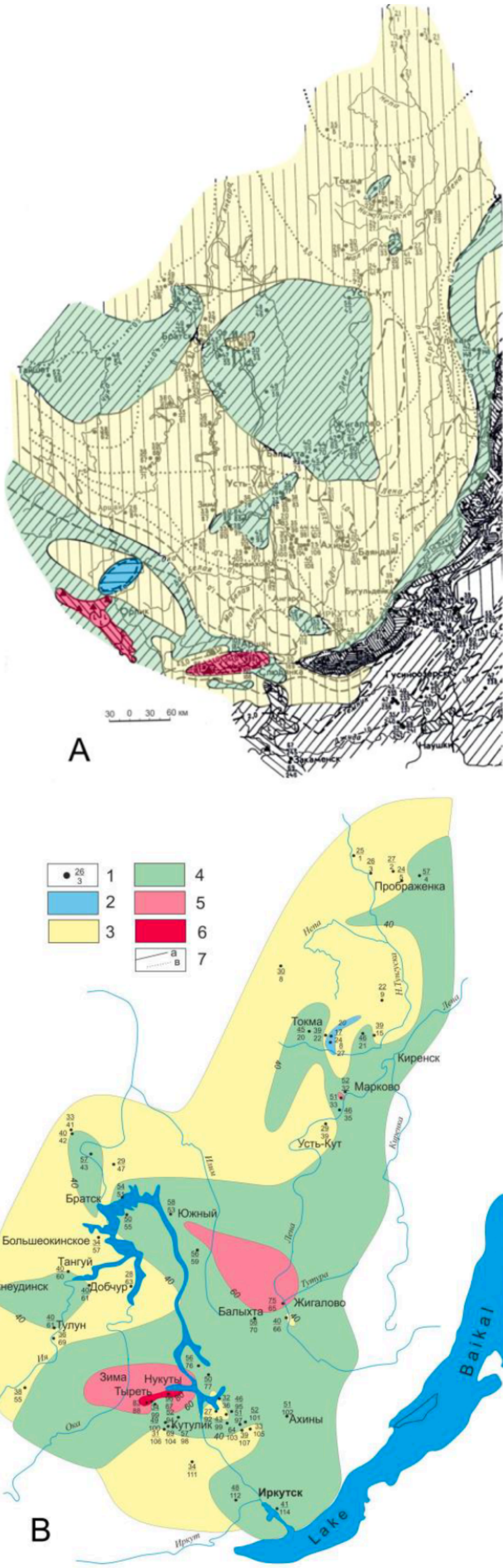

Figure 9 - A map of heat flow at the southern Siberian platform (a) and heat flow distribution in the lower Cambrian Moti suite (b). 1 - see figure 8. Heat flow, mW/m2: 2- less than 20, 3- 20-40, 4- 40-60, 5- 60-80, 6-more than 80, 7 - depths to crystalline basement: a - actual, b - inferred.

There is a certain relationship between the structural elements of the crystalline basement of the amphitheater and its geothermal parameters. It implies that fracture zones in the crystalline basement (as well as fault zones in the sedimentary unit) are characterized by an abrupt change (usually increase) in geothermal gradient, a decrease in thermal conductivity, higher values of local heat flow, and increasing inhomogeneity of the geo-temperature field.

Differences in thermal conductivity made it possible to identify thermally conductive (carbonate-halogen rocks) and thermally insulating (terrigenous rocks) groups of strata in the section. The presence of strata with low thermal conductivity in the section provide geothermal conditions that may be favorable for oil accumulations. This may play a certain role in the formation of the oil-and-gas-saturated Parfenovsky horizon of the Moti suite, primarily composed of sandstones.

The basement rocks can be divided into two groups according to their thermal properties. These groups comprise rocks whose thermal conductivities (λ) are respectively 3 and 2 W/m/K. Higher coefficients are associated with the presence of carbonate admixtures.

5. Conclusions

The results of the present work indicate that Siberian platform is characterized by a prevalence of low heat flow values between 35 and 40 mW/m^2. The heat flow values as high as 50-60 mW/m^2 occur in the depressed section of the platform and in the southern parts (Irkutsk amphitheater). Values lower than the background heat flow, 20mW/m^2 on the average, are observed on the Nepsky arch (Yakutsk diamond-bearing province). This is the most ancient and most uplifted part of the Siberian platform at an average lithospheric thickness of 200 km. Such lithospheric thickening should have acted as an anchor preventing the Asian lithospheric plate motion in the Phanerozoic. However, heat flow anomaly in the Yakutsk diamond-bearing province suggests a non-stationary temperature field therein.

The assessment of temperature conditions in the lower sedimentary cover have been carried out based on patterns of temperature distribution in the top and bottom of the Moti suite. This suite overlies directly the crystalline basement and is a well-known geothermal area.

There is a certain relationship between the structural elements of the crystalline basement and its geothermal parameters. It implies that fracture zones in the crystalline basement (as well as fault zones in the sedimentary unit) are characterized by an abrupt change (usually increase) in geothermal gradient, a decrease in thermal conductivity, higher values of local heat flow, and increasing inhomogeneity of the geo-temperature field.

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