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Geothermal Regime and Deep Temperatures of the Siberian Platform

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ABSTRACT

Based on well-understood geothermal regime of the southern East Siberia (about 200 heat-flow measurement points), the present paper deals with the study of deep temperatures of the southern Siberian platform (more than 70 boreholes, average heat flow 38±4 mW/m2) and thermal properties of core samples mostly representing the Vendian terrigenous deposits and Riphean magmatic and metamorphic basement rocks.

The basement rocks, according to their thermal properties, are subdivided into two groups with thermal conductivity coefficients 3 and 2 W/mK. Higher coefficients indicate the presence of carbonate-halogen admixtures.

Studies have been made of the borehole thermograms and temperatures at the bottom and top of the Moti suite, lower Cambrian (€ mt3). The boreholes vary in depth from 1300 to 6000 m, and the borehole temperature attains a value as high as 70 oC.

Rather intensive heat flow (45±6 mW/m2) is observed in the anticlinal domes and salt-dome crests, and low heat flow rate is typical of marginal uplifts.

Geothermal peculiarity is also closely related to hydrodynamic features of the area where underground water seepage flow penetrates to depths of 3-5 km and diffusion flow prevails in deeper crust. Anomalous formation conditions exert influence on 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 its major tectonic units of different age and origin – a craton (Siberian Platform), two folded areas (Sayan-Baikal and Trans-Baikal), and an evolving rift, e.g. Duchkov et al. (1987), Lysak (1984), Lysak (1988), Dorofeeva et al. (1994). It was hypothesized that the long-term development of the territory is related to the Indo-Eurasian continental collision and mantle heat flow.

The present paper only considers the southern Siberian platform (Irkutsk amphitheater) – a geophysically stable location. It has a two-layer structure: primarily lower Paleozoic sedimentary cover and Archean-Proterozoic crystalline basement. The results are based on the actual geothermal materials (about 70 boreholes in total) – lithological sections, borehole temperature logs of different depths, geothermal gradient determination, core samples selected for further determination of thermal and physical properties of the sediments, and thermal conductivity coefficient averaging using the sections of the boreholes from which the cores were not taken. The actual material sampling sites are shown in Fig. 1.

The record of deep-hole drilling shows predominance of halogen-carbonate sediments in the sedimentary cover of the southern Siberian platform; terrigenous sediments are less predominant there.

In the western and northwestern parts of the amphitheater, the sedimentary cover is penetrated by trappean intrusions that occurred most often in the Permian-Triassic. These rocks are represented by diabases and dolerites.

The studies of sedimentary cover revealed numerous swell-like and dome-like uplifts and basins (see Fig. 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 amphitheater's basement drilled 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) is only studied to a depth of about 25 m on the average (from 6 to 80 m).

The sedimentary cover structures reflect the deep-seated dislocations in the crystalline basement of the platform and largely inherit them.

The studies have been made on thermal characteristics of core samples represented mainly by the 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, e.g. Dorofeeva, (1982), Dorofeeva & Lysak (1983), Lysak & Dorofeeva (1997). 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, e.g. Tereschenko et al., (1981).

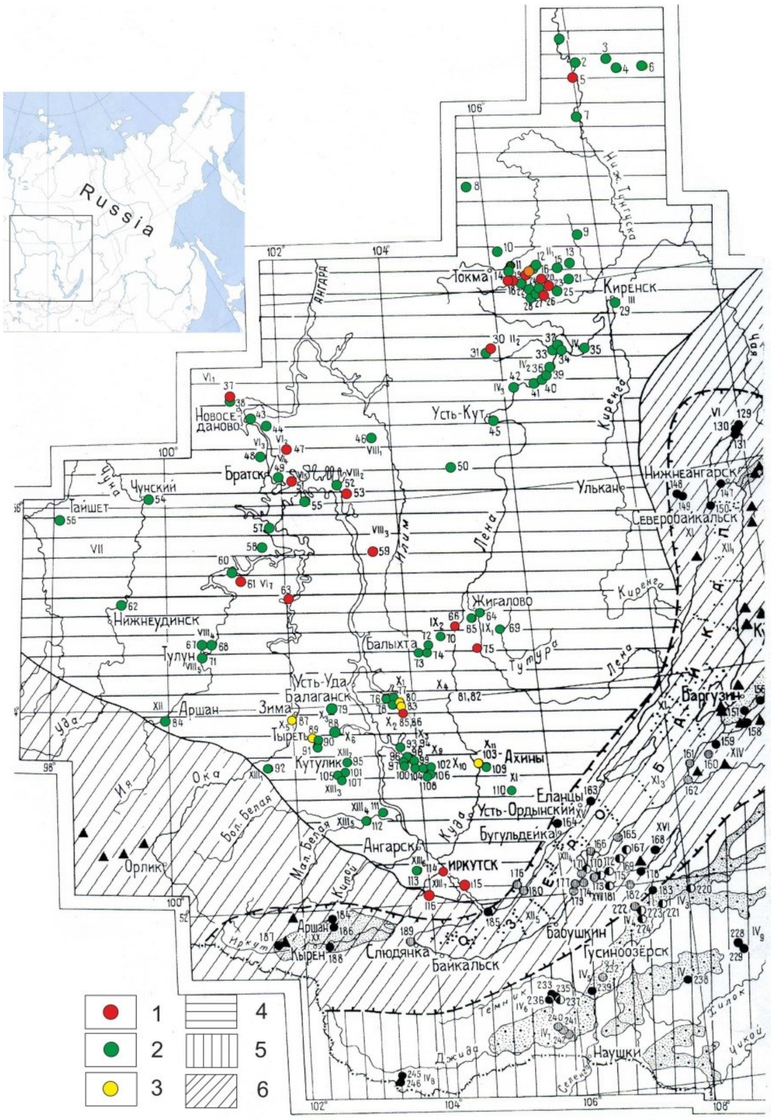

Figure 1: Points of geothermal investigations and major geologic structures of the southern Siberian platform (a); localization of the area (b). 1-3 – points of heat flow determination. The data on thermal properties of the rocks are presented according to: 1 – author's materials, 2 – calculations in hole sections, 3 – data of 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.

2. TEMPERATURE REGIME

Basal horizons in the southern Siberian platform are represented by the upper Proterozoic deposits – Vendian and Riphean. 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 attained by organic matter (OM) during subsidence of the enclosing deposits due to heat flow (HF) from depth and that is spent for the reconstruction of OM structure, e.g. Bazhenova (2008). Therefore, we consider 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, the following borehole thermograms have been recorded for the basic structural elements.

2.1 Borehole thermograms of the Nepsky arch

Presented are the thermograms of the Danilovsky-145, Verkhne-Chonsky-122, and Dulisminsky-191 boreholes.

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. Geothermal gradients measured in Danilovskaya-145, Dulisminskaya-191 and Verkhne-Chonsky-122 boreholes are respectively $\gamma = 0.71$, q= 21; $\gamma = 0.94$, q= 26; $\gamma = 0.64$ (within the depth range 1478 to 1580 m). The Dulisminsky borehole temperature at 2.5 km is 30 Oc (Fig. 2).

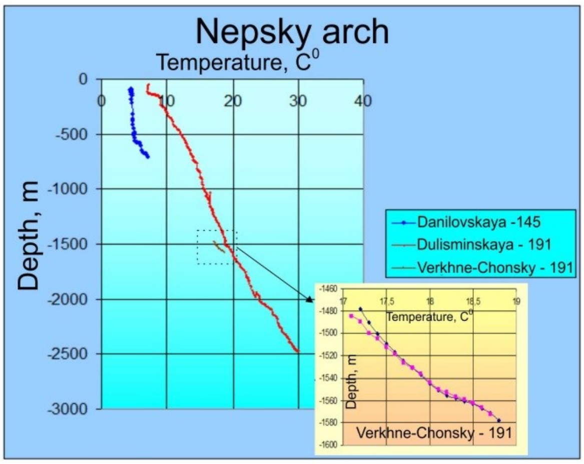

Figure 2: Borehole thermograms of the Nepsky arch.

2.2 Borehole thermograms of the Angara dislocations zone

Presented are the thermograms of the Kovinsky-1, Sedanovsky-134, and Kuturminsky-156.

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 in the Kovinsky-1, 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 Kovinsky-1 borehole temperature at a depth of 4.5 km is higher than 70 °C (Fig. 3).

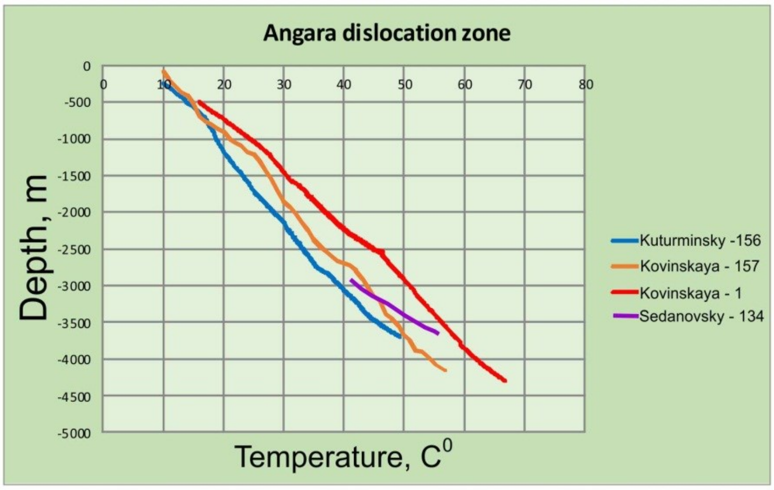

Figure 3: Borehole thermograms of the Angara dislocations zone.

2.3 Borehole thermograms of the Bratsk Uplift

Shown by the example of two boreholes – Bratsk-1 and Bratsk-3 ($\gamma = 1.55$, $q = 45$), the Bratsk-18 borehole temperatures at a depth of 2.5 km are as high as 60 °C (Fig. 4).

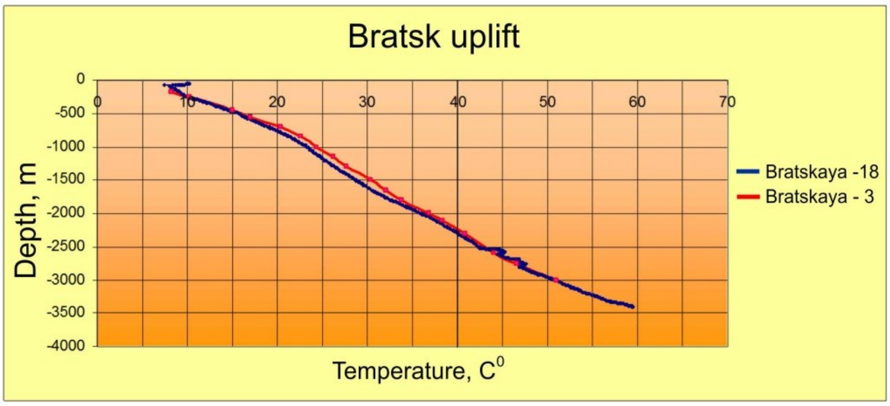

Figure 4: Borehole thermograms of the Bratsk Uplift.

2.4 Borehole thermograms of the Central field of the Irkutsk amphitheater

The Chorsky-115 borehole temperature at a depth of 2.5 km is higher than 41 °C, γ = 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 54 °C. The Kupsky-143 borehole thermogram is available for the 2.45-3.05 km depth range. At a depth of 2.8 km, the temperature increases by 5 °C in a very narrow range. It is obviously due to a hydrogeological factor – an anomalously high-pressure area, promising in terms of gas (Fig. 5).

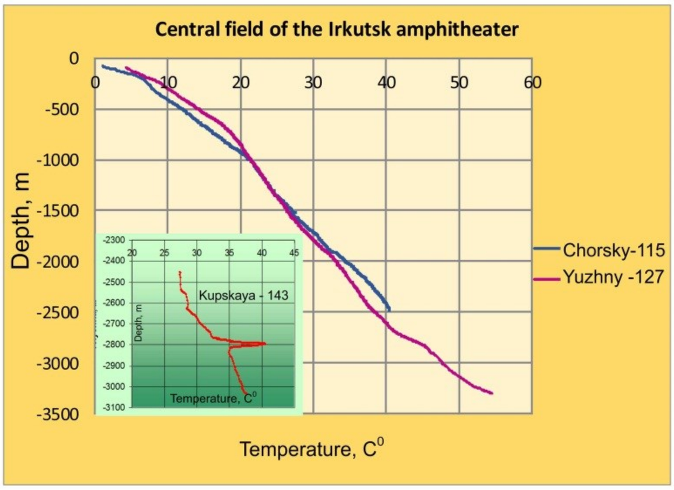

Figure 5: Borehole thermograms of the Central field of the Irkutsk amphitheater.

2.5 Borehole thermograms of the Kovykta protrusion

Kovykta-55, 56, 63-A boreholes, γ = 1.55. q = 43 (Fig. 6).

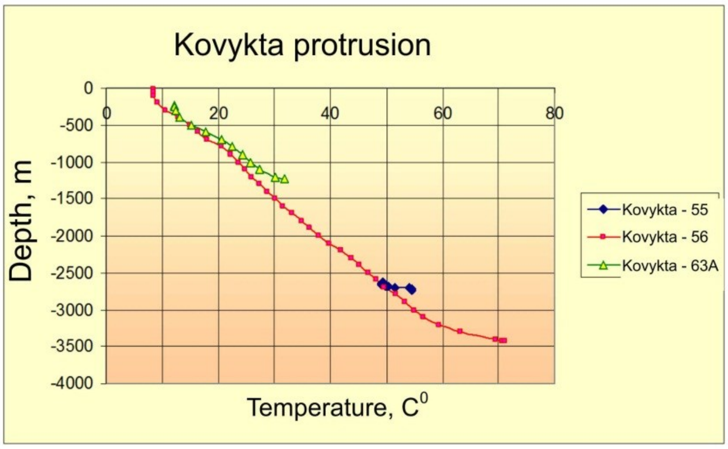

Figure 6: Borehole thermograms of the Kovykta protrusion.

Besides, examples and comparative characteristics are found in borehole thermograms of different tectonic areas in the southern East Siberia: Siberian platform, Baikal rift zone, and Trans-Baikal folded area (Fig. 7). Slice of the temperature graph at 40 oC shows that this temperature for the platform is recorded at a depth of 2.5 km, and for the borehole located in the Tunka valley (Baikal rift) – at a depth of 1.6 km.

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 consentral sandstones and clay schists. The detailed study of this suite was usually related to oil-and-gas drilling activities.

Temperature conditions in the lower part of the sedimentary cover have been considered and temperature distribution patters have been obtained for the top and bottom of the Moti suite, lower Cambrian, directly overlying the crystalline basement in many places (with regard to the PGA (Production Geological Association) "Irkutskgeofizika" and "VostSibneftegazgeologiya" materials on deep boreholes, e,g. Tereschenko et al. (1981), Fuks & Savintsev (1981).

According to the actual data available and theoretical calculations, geoisotherms 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 the basement is no more than 2 km. The average thickness of the Moti suite on the Nepsky arch is about 200 m. 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 Fig. 1). The suite temperature there can get as high as 30-40 °C in the top and exceed 40 °C on the bottom.

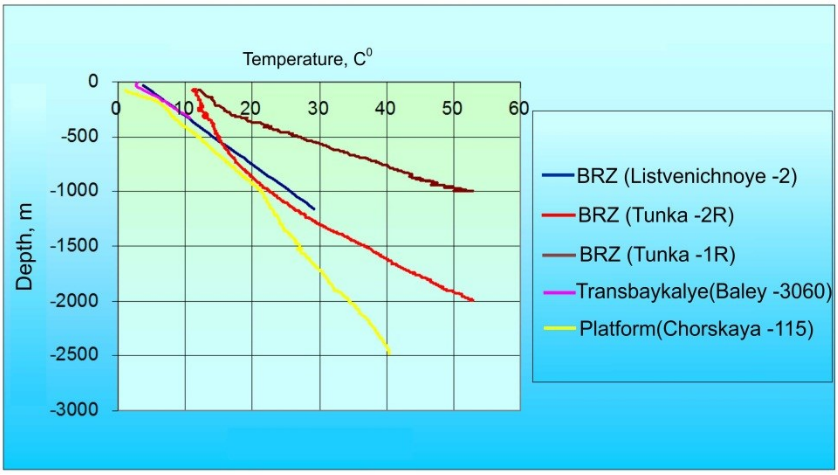

Figure 7: A comparison of borehole thermograms of different Cz, Mz and Pz tectonic regions of East Siberia.

The temperatures in the top of the Moti suite vary from 30 to 40 °C on the 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 60-70 °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 No. 16, 19, 23, 27), Markovsky (points No. 32-35), and Bratsk (points No. 38, 47, 52, 55 and others).

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.

Significant differentiation of the temperature field exists in the southern part of the amphitheater. Some anomalous parts therein are Polovininsky (No. 111 in Fig. 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 (Fig. 8).

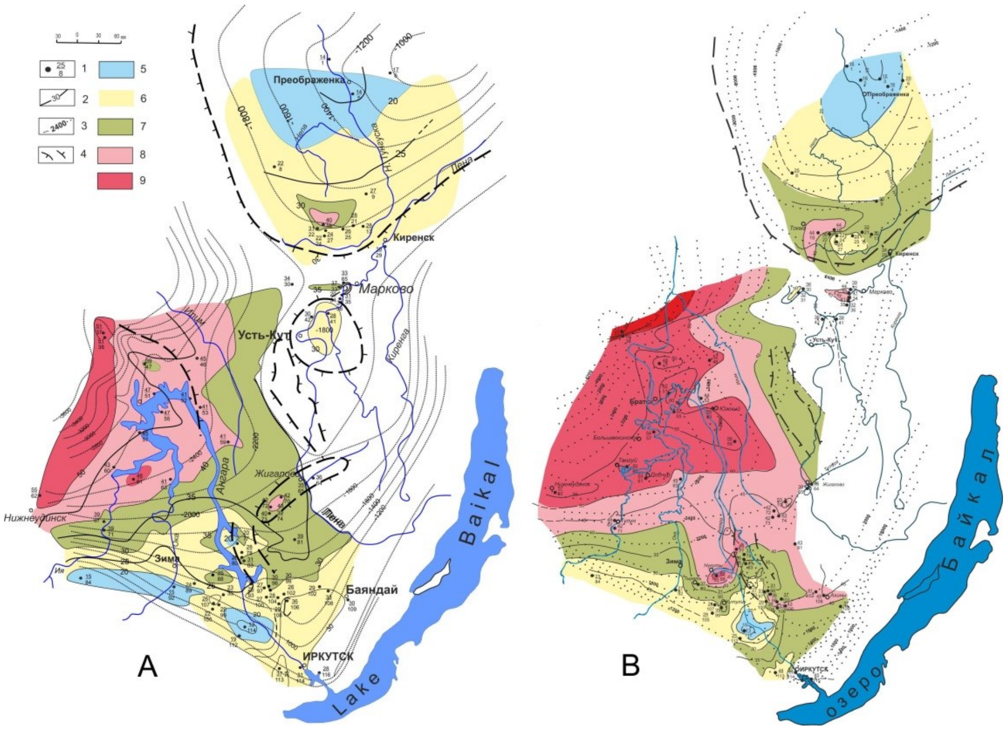

Figure 8: A pattern of temperature distribution in the top (a) and bottom (b) of the lower Cambrian Moti suite at the southern Siberial platform. 1 – numerator: temperature, °C; denominator – point number; 2 – temperature isolines, °C; 3 – isohypses of the bottom of the Moti suite, m; 4 – anticlinal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

Local perturbations of geotemperature field may be caused by the formation, long-term accumulation and migration of hydrocarbons because these processes require an input or release of energy, since the observed mosaic structure of geotemperature field of the sedimentary basin and its abrupt change over short distances are typical of many oil-and-gas-bearing areas, e.g. Bazhenova (2008), Osadchy et al. (1976). In fact, the identified geothermal anomalies are regionally correlated with the distribution pattern of geotemperatures 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, e.g. Map… (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 geotemperature 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, e.g. 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, e.g. Avchyan (1979). On the contrary, abnormally low pore pressure comprising 30 percent of hydrostatic pressure occurs in the northern part of this arch, in the terrigenous sediment deposits, e.g. Fuks & Savintsev (1981). Such abnormal formation conditions certainly influence the dynamics of hydrocarbon accumulations that in turn is also predetermined by the geothermal environment.

Differentiation of rocks with respect to 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 provides geothermal closedness 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 are equal respectively to λ = 3 and 2 W/mK. Higher coefficients are associated with the presence of carbonate admixtures.

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 geotemperature field.

The heat flow in the investigated area varies from 21 to 60 mW/m2 and averages 38±4 mW/m2. An intensive heat flow (45±6 mW/m2) 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/m2) and marginal uplifts (35±4 mW/m2) (Fig. 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 (Fig. 9b).

Partial heat loss or redistribution in the upper sedimentary unit may be due to dynamics of fluid regime.

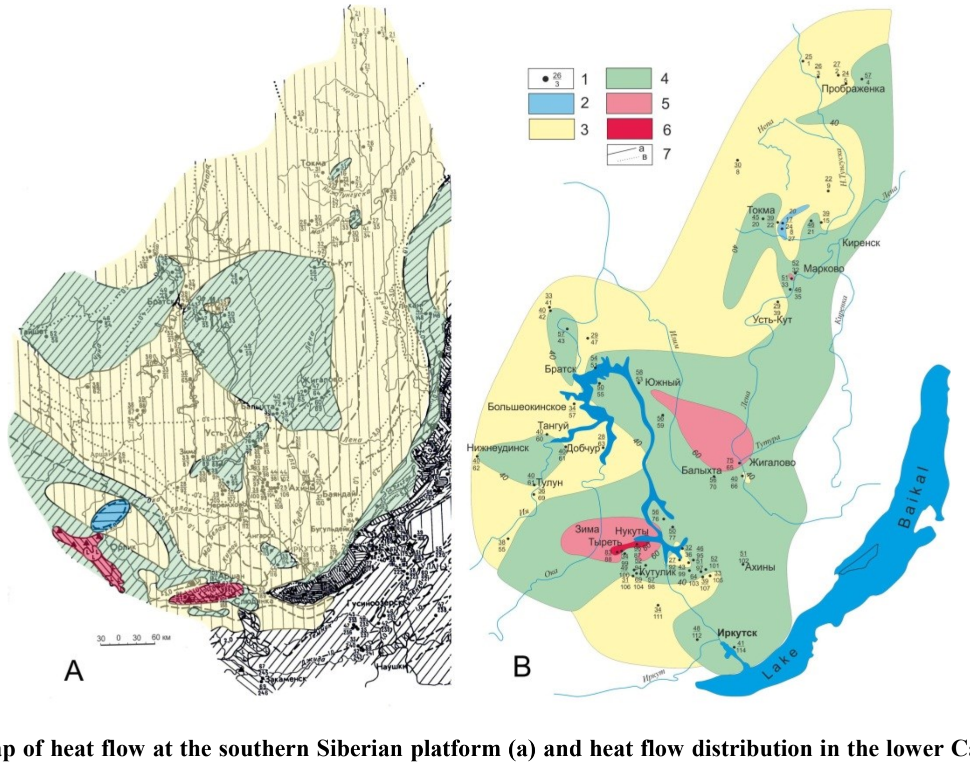

Figure 9: A map of heat flow at the southern Siberian platform (a) and heat flow distribution in the lower Cambrian Moti suite (b). 1 - see Fig. 8. Heat flow, mW/m2: 2- less than 20, 3- 20-40, 4- 40-60, 5- 60-80, 6-more than 80, 7 - depths to crystalline basement: a - actual, b - inferred.

3. CONCLUSION

The Siberian platform is characterized by a prevalence of low heat flow values between 35 and 40 mW/m2. The heat flow values as high as 50-60 mW/m2 occur in the depressed section of the platform and in the southern parts (Irkutsk amphitheater). The values lower than the background heat flow, 20 mW/m2 on the average, are observed on the Nepsky arch (Yakutsk diamond-bearing province) that 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 determination of temperature conditions in the lower sedimentary cover involved making patterns of temperature distribution in the top and bottom of the Moti suite that in many places overlies directly the crystalline basement and is geothermally well-known 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 geotemperature field.

NOMENCLATURE

Temperature, ^{o}C

Heat flow (q), mW/m^2

Thermal conductivity (λ), W/m·K

Geothermal gradient (γ), mK/m

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