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Heat Flow variations in Siberia and neighboring regions: A new look

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Abstract

The present work deals with an updated evaluation of heat flow in Siberia (Asian part of Russia) and neighboring regions. It is based on results of geothermal measurements in more than 1680 boreholes and shallow measurements of bottom sediments in lakes localities in Siberia. Also considered are results of heat flow measurements in about 1500 sites in neighboring areas of China, Mongolia and Kazakhstan. Features of geological structures and development of adjacent regions have been factors considered in the evaluation of thermal regime of Siberia. Most of this territory is occupied by two broad platforms (West-Siberian and East-Siberian), markedly different in their thermal regimes. Heat flow in the West-Siberian plate averages 55–60 mW/m², sometimes rising to 70–80 mW/m². The East-Siberian platform is characterized by a predominance of low heat flow values in the range of 30–40 mW/m². The southern and eastern segments of these platforms are framed by mountain-folded areas (Sayano-Baikal, Transbaikal, Verkhoyano-Kolymskaya areas) with heat flow values (in the range of 70–80 mW/m²). These are formed mainly under the influence of mantle heat sources (asthenosphere upwellings and mantle diapirs). Analysis of temperature distributions shows that thermal conditions in the five-kilometer upper layer of rocks are determined by heat flow values. Nevertheless, the thermal field of the Asian part of Siberia has been insufficiently studied. The work also considers heat flow variations of adjacent regions located south of Siberia: Kazakhstan, Northern China and Mongolia.

1. Introduction

Siberia is a major part of the Asian continent, located on the northern part. It includes two Siberian Platforms, three folded areas (Sayan-Baikal, Trans-Baikal and Verkhoyano-Kolymsk), and an evolving rift (Lysak, 1984; Lysak and Dorofeeva, 1997; Dorofeeva et al, 1995, Golubev, 2007). Geothermics of the Siberian region is of special interest because of the confluence of its major tectonic units of different age and origin. It was hypothesized that the long-term development of the territory is related to the Indo-Eurasian continental collision (Sengor et al., 1993) and variations in mantle heat flow.

The ancient Siberian platform (SP) extends over an area of nearly four million square kilometers, although the western and northern boundaries are not well established. The basement consists of Archean and Proterozoic blocks of various origin (continental terranes, orogenic belts, magmatic

arcs) separated by Proterozoic suture zones (Fig. 1). This region is also referred to as the West Siberian basin (WSB).

It is exposed in the Anabar Shield in the north-central part, in the Olenek High in the northeastern part, in the Yenisey ridge in the west, in the Biryusa block in the south-west of SC and in the Aldan–Stanovoy block in the southeast. The boundaries of the crustal blocks are constrained chiefly by magnetic anomalies and isotope ages (Rosen, 2002) as most of the SP is covered by a thick layer of Riphean–Phanerozoic sediments and by Permo-Triassic flood basalts in the north-west. West Siberian platform (WSP) is often considered tectonically stable.

The young epi-Hercynian West Siberian platform (WSP) is the main oil and gas province of Russia. The WSP heterogeneous basement is composed of blocks of different ages of metamorphic and igneous rocks and is overlain by a thick (on average 4-5 km) sedimentary cover from Mesozoic-Cenozoic sediments. The formation of the sedimentary cover was significantly influenced by Mesozoic rifting and trap

volcanism. For the entire WSP, the main riftogenic structure is the Triassic Urengo-Koltogorsk graben (Aplonov, 1995; Dorofeeva et al., 1995; Surkov and Smirnov, 2003).

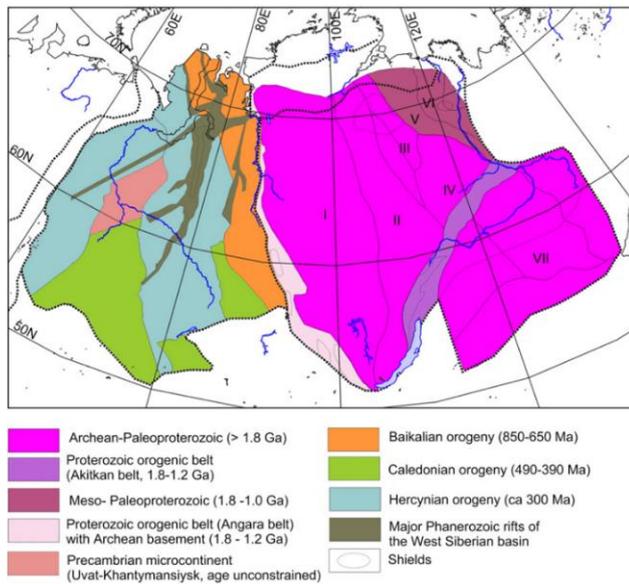


Figure 1 - Tectonic map of Siberian platforms. Bold dotted lines are boundaries of the Siberian platform (SP), West Siberian platform (WSP), and the Urals orogen. I, II, VI, VII – Tungus, Anabar, Olenek and Aldan superterrane; III, IV – Daldyn and Markha terranes of Anabar superterrane; V - Hapschan Paleoproterozoic orogenic belt. (Data sources: Aplonov, 1995; Cherepanova et al., 2013; Rosen, 2003; Sengör et al., 1993; Surkov and Smirnov, 2003).

2. Geothermal Studies

According to the IHFC compilations, 1680 heat flow measurements were carried out in Siberia. According to these data, the average heat flux is 67.9 mW/m² and the standard deviation of the mean heat flux – 57,7 mW/m² (NOAA, 2019). The southwestern part of the Siberian platform (Irkutsk amphitheater) has been studied in most geothermal detail. The locations of heat flow measurements heat flow map of are indicated in the map of Fig. 2.

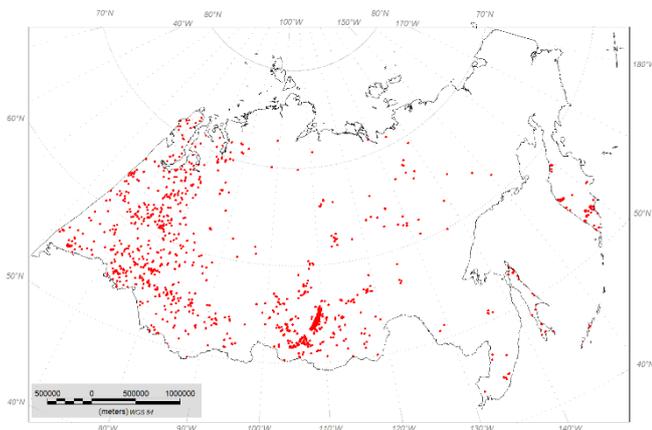


Figure 2 - Locations of heat flow measurements in the Asian parts of Russia that include Siberian Platforms.

Note that most of the measurement sites are located in the western sector. The data collected includes lithological sections, borehole temperature logs of different depths,

geothermal gradient determinations. In addition, core samples were selected for determination of thermal and physical properties of the sediments. The results are based on field data collected from about 700 boreholes in the study area (Kurchikov and Stavitsky, 1987).

The focus of the present work is on geothermal studies of the Siberian platform and adjacent regions. It has a two-layer structure, with primarily a lower Paleozoic sedimentary cover overlying Archean-Proterozoic crystalline basement. Well-known averaging schemes were employed in determining thermal conductivity coefficient for sections of boreholes for which the cores were not available. A summary of thermal conductivity data is presented in Table 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 (Table 1). 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.

Table 1 – Summary of thermal property data for rock types in southern part of Siberia.

Formation	Rock type	Thermal Conductivity (W/m/K)
1	Sandstone	2,7
2	basalt	2.0
3	Silt*	1,8
4	Mudstone	1,9

* Dorofeeva, 1986; Dorofeeva et al., 1995; Dorofeeva and Shapova, 2003).

The heat flow in the Siberian Platform (SP) area was measured at 80 localities, distributed very unevenly. It varies considerably: from 13 to 63 mW/m² (Balobaev, 1991). The minimum values of heat flow (on average 20-30 mW/m²) are observed in the cratonic region occupying vast parts of the Anabar anticline and in the Botuobinskaya saddle. The low heat flux in these structures generally agrees well with the available data on the material composition and structure of the earth's crust. Measurements in 60 deep (2-3 km) boreholes in the southern Siberian Platform yield heat flow from 21 – 60 mW/m², with a mean of 40±9 mW/m². A higher flux with an average of 45 mW/m² is observed near the surface in faulted anticlines and salt domes. In the uplifts on the platform periphery that border the rift zone, heat flow is less than 30-40 mW/m², but the measurements are fewer in number. The geological and structural features of the platform sediment cover and the related physical anomalies of rocks as well as heat transfer in the Angara-Lena artesian basin chiefly control distributions of heat flow and temperature in the uppermost crust.

Relatively low regional flux and its uniform distribution are evidence of the tectonic stability of the southern Siberian Platform, which can thus be considered a standard of a steady-state geothermal field. Foremost among these are sectors where heat flow is lower than 40 mW/m², coincident with locations of cratonic regions. Such regions are identified in the updated heat flow map of Figure 3.

Within the Altai-Sayan fold area, the heat flow varies from 17 to 80 mW/m², averaging 44 mW/m². It is obvious that the intense tectonic activation, which manifested itself in this region in the Neogene-Quaternary, did not lead to a noticeable increase in the heat flow here. In the Transbaikalian folded

region, the heat flow varies from 30 to 85 mW/m², averaging 52 ± 11 mW/m². About half of this value of the heat flow (20–30 mW/m²) is provided here by radiogenic heat generation in the granite upper layer of the earth's crust. The Verkhoyano-Kolyma fold area has a Late Paleozoic-Mesozoic age and is characterized by a poorly differentiated, but rather high heat flow, varying from 47 to 100 mW/m², with an average value of 66 mW/m². Baikal region have heat flow typical continental rift zone. There appears to be a correlation between heat flow and the composition and age of the basement structures, with high values occurring in the location of Mesozoic grabens.

3. Regional Variations in Heat Flow

The geographic distribution of heat flow, illustrated in the map of Figure 3, reveals presence of several heat flow anomalies. A notable feature is the low heat flow zone located in the region of Siberian craton. It appears to have a southeast extension reaching continental margin and south west extension to the region of Caspian Sea.

Another notable feature is the presence of regions where heat flow is in excess of 60 mW/m². Most prominent is the oval shaped anomaly of relatively high heat flow located to the east of the cratonic region. It apparently extends into the southern parts of the Kamchatka peninsula. Western parts of this anomaly overlie the region of Vitim volcanic activity of Cenozoic age. According to Lysak (1984) residual heat from dike swarms of Udokan and Vitim volcanic fields are related to upper crustal dike swarms that one may expect to occur as part of large igneous provinces, such as the Siberian traps.

Another prominent heat flow anomaly occurs within part of the Baikal Rift Zone (BRZ) and appears to have its origin connected with the rift zone beneath Baikal lake. It has nearly the same shape as the axial zone of Lake Baikal, being narrow and elongated. It probably extends to the south beneath the Caspian Sea and may be responsible for extensive occurrences of mud volcanos in the offshore areas of Kazakhstan.

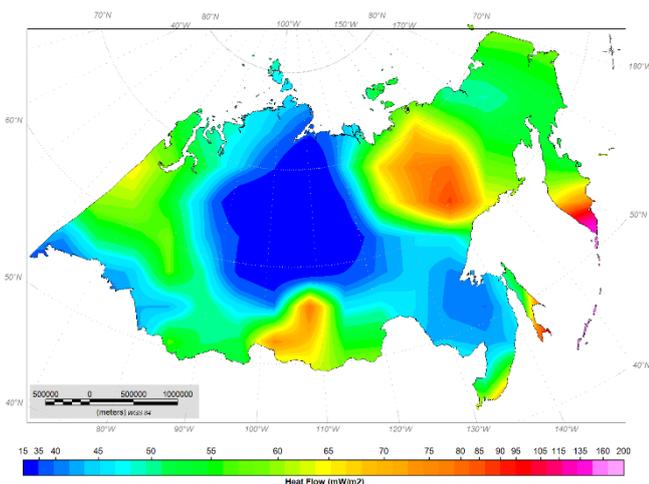


Figure 3 - Updated heat flow map of the provinces of Siberia.

Heat flows and temperatures in the rift ridges that are feeding zones for the latter are lower than in zones of brine discharge in salt domes. From the south and east the platforms are framed by mountain-folded areas with heat flow anomalies (to 70–80 mW/m²) which are formed mainly under the

influence of mantle heat sources (asthenosphere projections or mantle diapirs).

Heat flow through the bottom of *Lake Baikal* exceeds 50 mW/m² nearly everywhere. Anomalous flux above 100–200 mW/m² is found in the center of South Baikal basin and zones of underwater faults most often stretching along the shoreline. Extremely high flows of 250 to 3000 mW/m², locally attaining 6000 to 8000 mW/m², are associated with sources of hydrothermal discharge at the bottom of the lake (Golubev 2007). Heat flow on the remaining onshore areas of the rift zone is lower and averages 59±19 mW/m² (Balobaev et al. 1985; Dorofeeva and Lysak, 2010).

Heat flow is found to be relatively higher (with values greater than 80 mW/m²) within several relatively small pockets along a northeast–southwest trending belt and Baikal Rift Zone. Heat flow is also found to be higher than 80 mW/m² in the southeast corner of the Siberia. In particular, the high heat flow in the Far–East tip appears to be part of the anomalous geothermal region extending from the Japanese island arc.

4. Heat flow Maps in Neighboring regions

The thermal regimes of neighboring regions have been examined as part of attempt to understand the regional extent of heat flow anomalies in Siberia. In this context we examined the nature of data with focus on neighboring areas in Kazakhstan, Mongolia and northeastern China (Manchuria).

4.1. Kazakhstan

The heat flow map of Kazakhstan, illustrated in Fig. 4, reveal the presence of regions of low values in the northern parts, which is adjacent to Siberian Craton. In this region the range of heat flow variations are limited to values of less than 50 mW/m².

In the platform areas, the heat flux does not exceed 40–50 mW/m². There are however two relatively small zones where higher values occur, in the range 50–70 mW/m². The western zone of anomalously high heat flow is located in the Mangyshlak mountains, the eastern one - in the Dzhungar-Balkhash system. Aanalysis of previous results and new data on the geothermal potential of the country indicate the presence potentially exploitable geothermal resources, in particular in the coastal regions western and eastern parts.

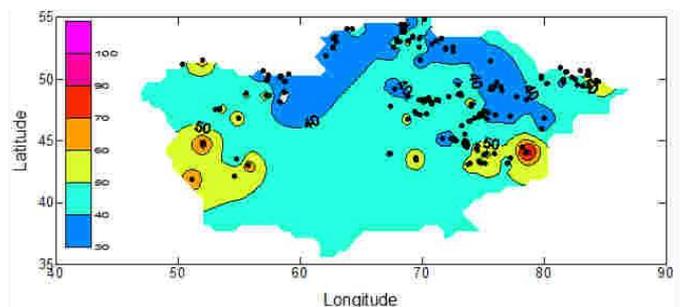


Figure 4 - Heat flow map of Kazakhstan.

4.2. Mongolia

The heat flow map of Mongolia, illustrated in Fig. 5, reveal large areas of low to moderate values, in the range of 20 to 60 mW/m², covering the entire country. In regions of moderate geothermal activity in central Mongolia, heat flow is in the range of 50–60 mW/m². Regions of southern Mongolia,

of low seismic-activity, are characterized by values as low as 40–50 mW/m². The thermal evolution of the lithosphere in Mongolia seems to have controlled its structural and compositional changes, especially at shallow depths (Lysak and Dorofeeva, 2003).

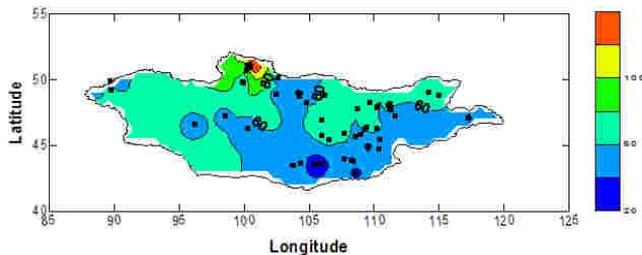


Figure 4 - Heat Flow map of Mongolia.

4.3. Northeastern China (Manchuria)

Manchuria (in northeastern China) has long border with the southern part of Siberia. The updated heat flow map (Fig. 5) of northern China is found to exhibit features compatible with those observed in the southern part of Siberia. The heat flow trends observed in southern and central parts are characterized by moderate values, in the range of 60 to 80 mW/m², the average being 61±2 mW/m² (Jiang et al, 2019). The major high heat flow anomaly in the southern parts in the Himalayan region of Cenozoic uplift has characteristics similar to those observed in the large igneous province (LIP) of the Siberian traps.

Moderately high heat flow (in the range of 80–100 mW/m²) are found in areas of rift basins and active faults. Considerable tectonic and seismic activity occur in the Cenozoic rifts of East China, but these are much lower than those found in other continental rifts with similar deep structure and evolution, such as Baikal rift (Lysak and Dorofeeva, 2005).

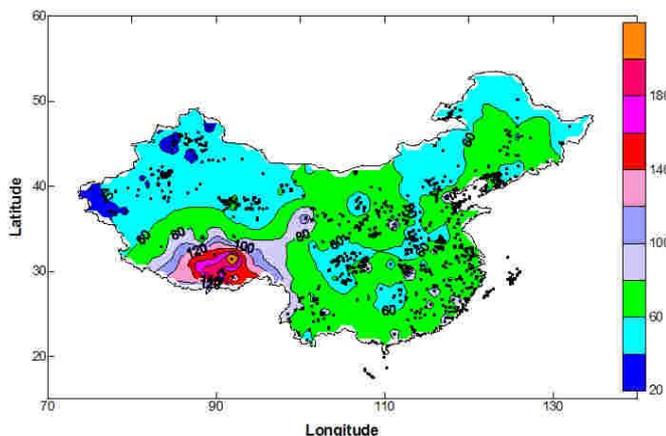


Figure 5 - The updated heat flow map of continental China.

5. Conclusions

Data collected in more than 1680 boreholes were used for updated assessment of heat flow in Siberia. This include about 800 measurements in the Baikal region and 700 in the Baikal basin (mostly shallow measurements using immersion thermographs). Additional estimates were derived from results of measurements in three underwater boreholes in Lake Baikal (“Baikal Drilling Project”) and from seismic reflection data indicating the lower boundary of the gas hydrate layer (300–400 m) in the lake bottom sediments (Duchkov et al., 1999).

According to these measurements, the mean heat flow in the Baikal basin is 71±21 mW/m². A number of extremely high values (250 – 3000 and even 6000 – 8000 mW/m²) are attributed to sites of hydrothermal vents at the bottom of the lake (Golubev, 2007). Flux through the marginal belts of rift ridges is much lower, ranging from 15 – 40 mW/m². This is probably due to thermal refraction effects at the contact zones.

In the Siberian Platform, the mean heat flow is found to be 40±9 mW/m². The mean value for the corresponding Trans-Baikal area is 52±11 mW/m².

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