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Heat Flow of Central Asia

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ABSTRACT

Revisions have been made to the geothermal data in Central Asia. These data concern the south Siberian platform (64 boreholes, average flow of 38±4 mW/m^2), the Baikal rift zone (72 boreholes, average flow of 71±21 mW/m^2), the Trans-Baikal area with a moderate rate of mountain formation (57 boreholes, average flow of 51±5 mW/m^2), Mongolia (32 boreholes, heat flow varying from 40 – 64 mW/m^2), and China (about 300 boreholes).

Heat flows in continental East China, which includes four Cenozoic rifts that belong to the western or eastern rift systems, vary from 26 to 106 mW/m^2, with a mean value of 61±2 mW/m^2. The rifts are generally hotter (average flow of 68-70 mW/m^2) than their surroundings (average flow of 49-56 mW/m^2). Especially deep flow over 80-100 mW/m^2 is associated with rift basins and active faults.

Maps of geothermal activity, heat flow, and crustal thickness have been constructed for southeastern Siberia, Mongolia and East China. Correlations have been found between rifting, current geothermal activity, and deep structures of major tectonic units in China.

1. INTRODUCTION

The Baikal region is of special interest for geothermal studies since major tectonic units of different ages and nature meet there, including a craton (Siberian Platform), two folded areas (Sayan-Baikal and Trans-Baikal), and an evolving rift (Duchkov et al. 1987, Lysak 1984, Lysak 1988, Dorofeeva et al. 1994). It was hypothesized that the territory has developed under the effect of Indo-Eurasian continental collision and heat transfer by mantle plumes for a long time. Scanning the depths of the rift revealed and asthenospheric up-warp, with the top presumably reaching the crustal base immediately beneath Baikal. The intricacy of the rifting mechanism and deep structure is reflected in the regional geothermal field as contrasting heat flows within limited areas. However, this may be partly due to shallow effects. Each of the four major tectonic units has its own specific type of geothermal regime in accordance with its geological and thermal history.

Geothermal studies in *Mongolia* began over 35 years ago with an investigation of the temperatures and thicknesses of permafrost by the Institute of Permafrost (Yakutsk). The heat flow of the region was first estimated to be between 34 and 84 mW/m^2 (with a mean of 62±10 mW/m^2) in five 150–170 m deer boreholes in northern (Ardag, Erdenet), central (Harchulun, Ihhayrhan), and southern (Tsagaan-Saburga) Mongolia (Khutorskoi et al. 1986, Khutorskoi and Golubev 1988). From 1980–83, the Soviet-Mongolian Research Expedition run jointly by the Science Academies of the two countries performed studies in Lake Hovsgol (9 heat flow stations) and its surroundings (5 boreholes in two Fields), in central (26 boreholes in 11 fields) and southern (15 boreholes in 5 fields) Mongolia, and at 10 hot springs, which added 28 heat flow data points. Since 1986, geothermal research was included in the activities of the Russian-Mongolian Geophysical Expedition at the Institute of the Earth's Crust in Irkutsk. V.A. Golubev obtained 52 new heat flow data points from the bottom of Lake Hovsgol. R.P. Dorofeeva and A.A. Sintsov, in cooperation with Mongolian technicians, measured temperatures in 55 boreholes in 32 new fields and studied core samples *in situ* and in laboratory. They measured thermal conductivity and geothermal gradients and estimated heat production of rocks having abundances of U, Th, and K abundances (Dorofeeva and Sintsov 1990, Dorofeeva et al. 1994, Dorofeeva et al. 1995).

The thermal conditions of the lithosphere in Mongolia and elsewhere can be described by conductive and convective components associated with groundwater flow that discharges in numerous hot springs along active faults in the Hangayn, Hentiyn, and Hovsgol uplifts (Pissarsky, and Lkhan-Aasuren, 1983). Abundant data on the groundwater chemistry allowed the use of SiO_2, Na, K, and Ca chemical geothermometers for deep temperature modeling and the estimation of convective and conductive heat components in 16 fields (Pissarsky 1982).

The high helium enrichment of thermal waters made it possible to estimate heat flows from $^3He/^4He$ ratios, and these estimates were obtained for 22 hot springs (Pinneker et al. 1995, Lysak and Pissarsky 1999).

Thus, the geothermal field in Mongolia was investigated on the basis of data from 141 heat flow stations, including 55 drilling sites and 26 hot springs.

Continental *China* has a complex tectonic structure with numerous relatively stable Archean and Proterozoic blocks bound by active orogenic zones and basins enclosing cratonic blocks and/or Paleozoic, Mesozoic, and Cenozoic rifts. The territory has experienced effects from a number of large-scale geodynamic events, such as the India/Eurasia collision in southwestern China (Molnar and Tapponnier 1975) and the Late Mesozoic volcanism and attenuation of continental lithosphere (Liu 1987, Ye et al. 1987), accompanied by active faulting in the east. Data of continental rifting in China have recently become available worldwide (Chen 1988, Chen 1994). Cenozoic rifts occur mostly in the eastern part of the country and are well documented in terms of geology, tectonics, deep structure, and evolution (Ma et al. 1984).

Systematic geothermal studies have been run in China since the 1970s, and the first report was published in 1979. Measurements at over 900 heat flow stations show variations from 30 to 319 mW/m^2. When the most prominent anomalies in rifts are excluded, this range changes to between 30 and 140 mW/m^2. Heat flows in rifts are known to exceed 70-85 mW/m^2, but no regional account of rifts has been undertaken yet (Pollack and Chapman 1977). To bridge the gap, statistical processing was applied to published Chinese data from main tectonic units, and the results were interpreted in this study. This complements the earlier study on heat flow in continental rifts (Lysak 1988).

2. HEAT FLOW OF DIFFERENT AREAS

2.1. The Baikal Rift Basin

Heat flow through the bottom of *Lake Baikal* exceeds 50 mW/m^2 nearly everywhere. Anomalous flux above 100-200 mW/m^2 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/m^2, locally attaining 6000 to 8000 mW/m^2, are associated with local sources of hydrothermal discharge at the bottom of bottom of the lake (Golubev 1982). Since 1976, underwater vents have been discovered in seven sites on the bottom of northern Lake Baikal and on the submerged basin slope where their discharge is controlled by basin-bounding faults. Calculations showed that convective heat transfer from these sources is 3 times greater than that from conduction. There may be a number of other sources that remain undiscovered. Due to underwater discharge, heat flow is elevated on the periphery of the North Baikal basin and decreases approaching the center. The average flux was calculated to be 71±21 mW/m^2 excluding the extreme values.

Heat flow on the remaining land territory of the rift zone is lower and averages 59±19 mW/m^2. In the Tunka, Barguzin, and Ust'-Selenga rift basins and in zones of the active Tunka and Barguzin faults, the flux locally exceeds 60-80 mW/m^2. However, it is much lower in the rift ridges. It should be noted that only a few tens of measurements have been taken in mountains outside the Baikal and other rift basins of the system, which accounts for over ¾ of the rift zone area in relatively shallow boreholes – 100 to 400 m deep. The measured heat flows vary from 15 – 40 mW/m^2 and only reach 90 mW/m^2 in two boreholes in zones of active faults.

2.2. Siberian Platform and Trans-Baikal Folded Area

Measurements in 60 deep (2-3 km) boreholes in the southern *Siberian Platform* yielded heat flows from 21 – 60 mW/m^2, with a mean of 40±9 mW/m^2. A higher flux (an average of 45 mW/m^2) is observed near the surface in faulted anticlines and salt domes. In the uplifts on the craton periphery that border the rift zone, heat flow is less than 30-40 mW/m^2, but the measurements are few in number. Distributions of heat flow and temperature in the uppermost crust are chiefly controlled by 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. 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. 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 (Dorofeeva et al. 1984, Duchkov et al. 1999).

Measurements in 65 boreholes in the *Trans-Baikal area* southeast of the rift showed heat flow variations from 28 – 95 mW/m^2. High values (above 80 mW/m^2) were observed in the Unda-Gazimur uplift. The average flux there is 52±11 mW/m^2, and that in uplifts is nearly the same or 5-10 mW/m^2 higher than in the rift basins. This difference from the rift zone attests to the absence of any notable heat transfer by groundwater in intermontane artesian basins, possibly because of low elevations and the low permeability of the ridges. The same occurs on the craton, and the geothermal field in the Trans-Baikal area can likewise be considered steady-state, as is also supported by little scatter of heat flow values compared to the rift zone. Heat flow contrasts may occur outside the study territory, in the zone of Cenozoic volcanism (Vitim plateau), and in the strongly fractured upper crust in the south and southeast of the Trans-Baikal area that were also subject to Cenozoic activity (Dorofeeva et al. 1984, Duchkov et al. 1999).

It is noteworthy that approximate mean heat flows were obtained for the Baikal region from helium isotope rations ($^3He/^4He$) in water from hot springs and operating boreholes on the basis of the earlier established empirical relationship between heat flow and isotope rations (Polyak et al. 1992). The resulting mean q was found to be 63±5 mW/m^2 in the rift basins, 57±5 mW/m^2 in the Trans-Baikal area, and 46±3 mW/m^2 in the southern Siberian Platform.

Note only average and abnormal heat flows are considered, as interpretation of the very distribution of heat flux (zoning of the geothermal field, distinguishing its non-homogeneities and gradient zones, etc.) is beyond the scope of the study.

2.3. Thermal Activity of Upper Lithosphere of Mongolia

The distribution of heat flow in *Mongolia* shows regions of high ($q > 60$ mW/m^2), moderate ($q = 50\text{-}60$ mW/m^2), and low ($q < 50$ mW/m^2) thermal activity, as shown in Figure 1. Note that this division is more consistent with the ages of formation and reactivation of continental blocks than with areas of contemporaneous orogenic activity (Polyak et al. 1992, Yanshin 1975).

Regions of high thermal activity include Lake Hovsgol, which has a mean heat flow through its bottom as high as 92±7 mW/m^2. Heat flow can reach 120–153 mW/m^2 inside isometric $q > 100$ mW/m^2 anomalies in the central and northern parts of the lake (Polyak et al. 1992, Golubev 1995). Although the sides of the lake are delineated by active faults, the heat flow there is only up to 60 mW/m^2 and reaches 100–143 mW/m^2 only near the northwestern side. Heat flows are higher in regions of subsidence and in active faults bordering them than on bottom uplifts. Land heat flows measured in boreholes on the southwestern lake shore range from 33 – 78 mW/m^2 (a mean of 54±12 mW/m^2). In five hydrothermal vents near the lake, the mean heat flow is 64±9 mW/m^2. The mean deep heat flow on the Hovsgol uplift is 59±10 mW/m^2 in the lake surroundings and reaches 87±7 mW/m^2 if the Hovsgol anomaly is included.

Another region of high thermal activity encompasses the Onon graben, a Mesozoic rift in the Paleozoic Hentiyn uplift and its surroundings (a great part of the Orhon-Tuul depression, the western Kerulen uplift, and the Choybalsan basin reactivated after the Paleozoic). Measurements in boreholes in the Onon graben yielded a mean of 91±7 mW/m^2. Heat flows in hot springs average about 70±15 mW/m^2, and the mean over the graben is 83±17 mW/m^2. This is higher than in the surrounding territory (60 – 70 mW/m^2). The flows estimated in hot springs suggest the presence of active thermal faults in the central Hangayn uplift that are local fields of high thermal activity, as shown in Figure 1 (Lysak et al. 1999).

The average over 94 heat flow stations in the regions of high thermal activity is 83±8 mW/m^2. The mean flow is

85±8 mW/m^2 in the Hovsgol and Onon rift basins and in the Orhon-Tuul depression and is 69±11 mW/m^2 in the bordering mountains (Lysak and Dorofeeva 2003).

Regions of moderate thermal activity in Central and Western Mongolia include the Hangayn uplift (except for its central part), the Altay Mountains, and the greater part of the Hentiyn uplift (excluding the Onon graben) formed in the middle or late Paleozoic. The mean heat flow of 31 data points in these regions is 54±12 mW/m^2.

Central Mongolia is flanked in the south and in the east by **regions of low thermal activity**, where no hot springs are known, as shown in Figure 1. Measurements in 19 boreholes yielded a mean of 41±10 mW/m^2 (Lysak and Dorofeeva 2003).

Heat flow originates mostly in the deep mantle origin in regions of high and moderate thermal activity in which the mean heat production of rocks (A) is below 2.0 μW/m^3 (1.44±0.22 and 1.71±0.52 μW/m^3), and the crustal component predominates in regions of low activity where mean heat production is 2.8±0.6 μW/m^3.

The crustal thickness in Mongolia varies from 36 to 55 km. It is thinner than 43 km beneath the Choybalsan and Dzuunbayan-Tamtsag basins and the Hovsgol and Onon rift basins in the north and northeast, thickens to 45–47 km in broad depressions such as Tes-Selenge, and exceeds 50 km in the Hangayn and Dariganga uplifts. Sediment thickness in rift basins and in depressions varies from tens of meters to 6–7 km. The granitic and basaltic layers are ~20 and >20–35 km, respectively (Zorin et al. 1982).

Heat flow in the shallow crust ranges from 16 – 153 mW/m^2, as shown in Table 1. Thermal conductivity (λ) ranges from 1.0 W/m·K in the bottom sediments of Lake Hovsgol to 2.0–3.0 W/m·K in the bedrock and the mountain borders of depressions. Laboratory estimates of heat production range from 0.56 – 20.4 μW/m^3.

According to the heat flow behavior, the modeled temperatures are expected to be highest in regions of high thermal activity, especially beneath the bottom of Lake Hovsgol and in the Onon graben, and 1.5–2 times lower in regions of moderate and low thermal activity. The validity of this hypothesis was confirmed by calculations.

The thermal state of the shallow lithosphere is reflected in the pattern of predicted temperatures at the crustal base, which varies strongly in depth from 38–45 km in eastern Mongolia to 45–50 km in Central Mongolia and thicker than 45–55 km in the west and northwest (Zorin et al. 1982). The crust is thicker in the Hovsgol, Hangayn, Hentiyn, Altay, and Ihshanhayn uplifts and in the Trans-Altay zone of moderate orogeny and thinner in the Tes-Selenge and Great Lakes Depressions, in the Onon graben, and beneath the Hovsgol basin.

Temperatures were estimated using 2D finite-difference modeling of non-steady-state thermal fields assuming lithospheric heating by mantle diapirs associated with tectonic activity and rifting in the Baikal rift. A diapir in Mongolia rising from a depth of 120 km was hypothesized to reach the crustal base (40 km) in a 33.3 million year period and to heat the lower crust to 600^{o}C and the Moho up to 1100–1200^{o}C. Constant temperature within broad asthenospheric up-warps was accounted for by small-scale convection. The results of this modeling show that the heated lithosphere gradually cools down, the temperature field reaches steady state in 70 million years, the lithosphere thickens to 90–100 km, and the temperature at the crustal base decreases to between 600 and 800^{o}C. These results are supported by models of the contemporaneous thermal state of the lithosphere in Mongolia (Zorin and Osokina 1981, Zorin et al. 1982).

It was estimated that temperatures on the Moho (at an average depth of 40–50 km) range between 400–500 ^{o}C in regions of low thermal activity and 600–750 ^{o}C in regions of moderate activity, and they exceed 1000–1200 ^{o}C in most active areas. Abrupt temperature changes within short distances indicate a strongly heterogeneous thermal field, but thinner crust does not necessarily mean higher temperature, as in the neighboring Baikal rift and Transbalkalia (Duchkov et al. 1999).

The estimated deep temperatures show that major structures in active thermal regions undergo a stage of heating in areas of both intense (Hovsgol basin and eastern Hentiyn uplift) and weak (Kerulen uplift and Choybalsan basin) orogeny. The Choybalsan basin may be a zone of latent shallow magmatism. Regions of moderate thermal activity with lower temperatures may belong to areas of intense orogeny. The Orhon-Tuul depression and the Altay uplift are apparently stable, but the Hangayn uplift is locally heated in zones of active thermal faults marked by numerous vents of thermal water. Regions of low thermal activity experience cooling, even when located in areas of intense orogeny (Tes-Selenge, Trans-Altay, etc).

Thus, the lithosphere in Mongolia is hotter in its northern and northeastern parts than in central, western, and southern regions.

2.4. Heat Flow of China

Heat flow and other geothermal parameters were measured at 255 stations in East China (130 stations within rifts), in boreholes at 0 – 5 km depths, as shown in Table 1.

No temperature measurements are available at heat flow stations. Published temperature profiles for depths of 1–3 km show higher temperatures in rifts (45–50 ^{o}C) and lower temperatures in the surrounding orogens and stable blocks (40 and 30 ^{o}C, respectively) (Wang et al. 1995).

The geothermal gradient (γ) is 29±1.6 mK/m on average, being higher in rifts (37.9±2.8 mK/m), especially in the East China system (44.3±2.9 mK/m) with the Liaohe and Bo Hai rifts (48.4±2.7 mK/m), and 1.5–2 times lower in orogens and stable blocks (See Table 1).

Thermal conductivity was measured in laboratory in cores and the weighted mean was estimated within the intervals of temperature measurements (Wang, J.Y. and Wang, J.A. 1988). The mean thermal conductivity of terrigenous sediments in rift basins is 1.85±0.14 W/(m·K) and that of marine sediments from Bo Hai is 1.41–1.21 W/(m·K). Sediments locally alternated with crystalline rocks in the southwestern East China rift system including the Bozhong, Huanghua, Jizhong, and Jiyang rifts (separated by uplifts) show a conductivity of 2.27±0.29 W/(m·K). Samples from other rifts show similar values, as shown in Table 1). Similar conductivities were obtained for the greater part of orogens and stable blocks, with the exceptions of lower values in the Kunlun-Qinlin zone (1.79±0.09 W/(m·K)) and higher values in the Northeastern zone (an average of 4.85±1.12 W/(m·K) from 33 stations, and up to 7.79±1.31 W/(m·K) from 12 stations in the southern part of the zone within ore fields).

Heat flow stations are located mostly in rifts within the Ordos and South China blocks, especially in the East China system and the Tongcheng-Lujiang folded area, and fewer stations are located in other tectonic units. Each unit is represented by a mean regional heat flow consisting of local values (including anomalies in faults) and background values. (See Table 1.) Heat flow in the continental rifts range from 16 – 106 mW/m^2, with a mean heat flow of 61±2 mW/m^2 (Pollack and Chapman 1977). Mean heat flow is 67±2 mW/m^2 in Cenozoic rifts and reaches 68–70 mW/m^2 in the East China and Shanxi systems. It is lower (64-56 mW/m^2) in the Hehuai and Yinchuan-Hetao rifts. Mean heat flow exceeds 60 mW/m^2 in the Tongcheng-Lujiang zone and the southern East China folded area and is below 60 mW/m^2 in other zones and blocks. Heat flows are generally 1.4–1.5 times higher in active faults than in their surroundings over the whole territory of China and 1.6–1.8 times higher within each separate tectonic unit .

Active faults that bound or cross the rifts, especially on their flanks, are marked by hot springs. Spring water in the northern and southern terminations of the Shanxi and Liaohe rifts can reach 60–80 ^oC. Springs are especially abundant in active orogens around the rifts. Temperatures reach 40–70^{o}C (and occasionally 80–90^{o}C) in the Tongcheng-Lujiang and North China zones and 40–60 ^{o}C in the Yangshan and Kunlun-Qinlin zones. No hot springs were found within stable blocks, except for in the South China block (Shandong Peninsula).

The distribution of heat flows and hot springs generally fits the regional tectonic framework and the pattern of neotectonic activity in the main tectonic units in East China, especially in rifts. The reported data suggest that the crust is additionally heated from crustal magma sources beneath regions with high heat flows (>80–100 mW/m^2) and high temperature (80–100 ^{o}C) subsurface fluids venting on the surface. These sources are apparently absent in regions where hot springs are cooler than 40–60^{o}C and heat flows are below 60 mW/m^2.

2.4.1. Geothermal Activity and Rifting.

Geothermal activity refers to the range of laterally variable regional heat flows in main tectonic units. East China includes several geothermal zones in Cenozoic rifts and the surrounding orogens and stable blocks, with low (<40 mW/m^2), moderate (from 40 – 60 mW/m^2), high (from 60 to 80 mW/m^2), and very high (over 80–100 mW/m^2) activity.

Very high geothermal activity is restricted to certain areas in the East China rift system (mostly to the northwestern parts of the Liaohe, Bo Hai, Bozhong, and Huanghua basins) and to a few active areas in the Shanxi rift (southwestern parts of the Weihe, Jiuyongcheng, and Feihe rift basins). The remainder of territory of these rifts exhibit high activity, including the Hehuai system. High activity was also observed in the Tongcheng-Lujiang folded area, in the eastern Ordos block, and possibly in fields of Cenozoic magmatism in the north and south of the region. The Yinchuan-Hetao rift system and its surroundings show moderate activity, except for the highly active southeastern Yangchang basin. The other orogens (especially, Yuanshan) and stable blocks show moderate and weak geothermal activity.

In zones of high activity, the crust is as thin as 32–37 km, and the conductor depths (plume top) are 67–82 km (i.e. the closest to the crustal base). Therefore, heat flow in those areas has a high mantle component. It was estimated that the contribution of the mantle component to the surface flow (69 mW/m^2) in the East China rift system (Liaohe rift) reached 75 % during active rifting in the Eocene-Oligocene (Wang J. and Wang J.A. 1988). During the post-rift stage since the Miocene, heat flow declined to 65 mW/m^2, but the ratio of the mantle-to-surface flow became only 12% lower. Heat flow is mainly of crustal origin and is related to radiogenic heat production in zones of moderate and weak geothermal activity where the crustal thickness is 40 km or thicker and the conductor depth exceeds 100 km. The contribution of radiogenic heat exceeds 50–60 % (Lysak and Dorofeeva 2005).

Zones of abnormal heat flow trace the depths of the so-called **geothermal asthenosphere** associated with partial melting at 1100–1200^{o}C or locally 800^{o}C (Tuezov 1990). The geothermal asthenosphere in the East China rift system is located at depths between 25 and 50 km. In the Bo Hai basin, its top locally warps up to <25 km, and heat flow over these places exceeds 80–90 mW/m^2. The up-warps of the geothermal asthenosphere are separated by dips exceeding 25–50 km with 60–70 mW/m^2 surface heat flow over them. A similar pattern of partial melting can be inferred for the southern and northern Shanxi rift, surrounded by areas where the geothermal asthenosphere is as deep as 75–100 km. Heat flow anomalies associated with mantle heat sources are produced by convective rather than conductive transport. However, during the rapid rise of magma melts through faulted crust, convective transport gives way to conduction once magma has intruded.

The up-warps of the geothermal asthenosphere coincide with the seismic belt of East China, where seismic activity induced by the regional system of faults and faulted rocks has provided pathways for magma since the Cenozoic.

Cenozoic rifting in East China is commonly attributed to two main causes (Tian et al. 1992, Wang, J.Y. and Wang, J.A. 1988): (i) thermal attenuation of the continental lithosphere as a result of mantle diapirism associated with the subduction of the Pacific plate beneath the western continental margin (East China rift system) and (ii) extension and strike-slip faulting associated with the rotation of the Ordos block under the effect of stresses from the India-Eurasia collision (Circum-Ordos rift system). The top of the geothermal asthenosphere in the eastern system of rifts is closest to the crustal base or is locally even above the latter in Bo Hai and in the Hebei Plain. The moderate geothermal activity of the almost amagmatic Yinchuan-Hetao rift in the western system indicates that no hot plumes exist beneath the relatively thick crust (43 km on average), but they can be expected to appear in the future, judging from the shallow depth (50 km) of the geothermal asthenosphere and a history of high seismicity (Tuezov 1990). The existence of plumes beneath the Shanxi rift, with its high geothermal activity, thin crust (37 km), and Cenozoic magmatism, is quite probable in some localities, though the geothermal asthenosphere is rather deep (>50–70 km).

High tectonic activity of East China and Cenozoic rifting in its territory apparently have been driven by active heat transport from a hot mantle plume rising through rifted and faulted lithosphere.

3. CONCLUSION

About 800 heat flow measurements have been performed in the Baikal region, including over 700 in the Baikal basin (mostly shallow measurements using immersion thermographs). According to these measurements, the mean heat flow in the Baikal basin is 71±21 mW/m^2. A number of extremely high values (250 – 3000 and even 6000 – 8000 mW/m^2) are attributed to sites of hydrothermal vents at the bottom of the lake. Flux through the rift ridges is much lower, ranging from 15 – 40 mW/m^2. In the southern Siberian Platform, the mean heat flow is 40±9 mW/m^2, and in the neighboring Trans-Baikal area, it is 52±11 mW/m^2.

The observed contrasts may be due to heat transfer by groundwater in intermontane artesian basins. Groundwater discharge leads to an apparent decrease (20 mW/m^2 lower) in surficial flux in the rift ridges and an increase in rift basins (areas of discharge).

More heat flow estimates were obtained from measurements in two underwater boreholes at Lake Baikal and from seismic reflection data indicating the lower boundary of the gas hydrate layer (300–400 m) in the lake bottom sediments. About 500 heat flow values based on seismic data in the South and Central Baikal basins yielded an average of 76±10 mW/m^2. The new results validated the earlier determinations based on shallow (1–5 m) geothermal measurements. It has been concluded that heat flow in the Baikal bottom sediments does not show any notable variations until depths of 300–400 m are reached.

The heat flow data were used to predict temperatures in the crust at depths of 1, 3, 10, 20, 30, 40, and 50 km. In the lower crust at depths of 40–50 km beneath the Baikal and other rift basins, temperatures vary from 700 – 1000^{o}C. Temperatures of 400–500 ^{o}C are expected beneath the rift ridges and in the surrounding areas of the Siberian Platform and Trans-Baikal region. The quality of geothermal prediction depends mainly on the accuracy of determination and knowledge of the nature of heat flow (deep or surficial flux). The latter to a great extent depends on steadiness of the thermal field. Heat flows approach steady-state values in the Siberian Platform, in the Trans-Baikal area, and possibly in the sediment fill of the rift basins (as a result of hydrothermal discharge). On the contrary, heat flow through the rift ridges is considerably underestimated, and thus, no reliable geothermal modeling is possible for these regions.

The modeled deep geothermal temperatures were correlated with the estimates obtained independently using thermobarometry in deep mantle xenoliths in Cenozoic alkaline basalts sampled in the Baikal region. The latter estimates (850–950 ^{o}C at depths of 40–50 km) confirm the predictions, but only in the Baikal and other rift basins. The temperatures are also this high beneath the rift ridges (300–500^{o}C higher than those obtained from geothermal extrapolations). Synthetic analysis of the results of conventional geothermometry and thermobarometry of mineral assemblages in crustal and mantle xenoliths offers new opportunities for studying the nature of heat flow anomalies and assessment of reliability of geothermal modeling (Lysak and Dorofeeva 2003).

The thermal state of the lithosphere in Mongolia was investigated on the basis of measured geothermal parameters and predicted temperatures at depths of 40–50 km (average crustal thickness over the greatest part of the territory). The heat flow distribution in Mongolia is controlled by tectonomagmatic activity associated with Mesozoic and Cenozoic rifting and active thermal faulting of the old continental crust. The interior is hottest beneath rifts (Cenozoic rift of the Hovsgol basin and Mesozoic rift of the Onon graben, with heat flows above 70–90 mW/m^2 and Moho temperatures of 1000–1200^{o}C) and coldest in southern Mongolia (heat flow under 50–40 mW/m^2 and predicted Moho temperatures below 500^{o}C in the South-Mongolian Hercynian orogenic belt). Over the rest of the territory, the heat flow and temperature ranges are 50–60 mW/m^2 and 600–700^{o}C, respectively.

The territory of Mongolia is comprised of regions of different thermal activity. Regions of high thermal activity (q >60 mW/m^2) involve narrow linear heat flow anomalies in rifts (Lake Hovsgol and Onon graben) and zones of hypothetical subsurface magmatism (Kerulen uplift and Choybalsan basin), which are possibly associated with mantle diapirism. In regions of moderate thermal activity (q from 50 – 60 mW/m^2), heat flows regularly decrease with rock age and crustal cooling. Regions of low thermal activity (q < 50–40 mW/m^2) in Western and Southern Mongolia are in the middle Carboniferous zone of subduction, where the Paleotethys oceanic crust subducted beneath Northern Eurasia (Molnar and Tapponnier 1975). Lithospheric cooling in these regions is confirmed by anomalously low flows, as shown in Table 1. The predicted deep temperatures indicate that the lithosphere in Northern and Northeastern Mongolia is in a quasi-steady thermal state and is much hotter than in the Western and Southern regions. Heat flow is higher in depressions within high-activity thermal regions and in uplifts within regions of moderate and low thermal activity, where higher temperatures beneath uplifted areas are associated with ongoing crustal uplift.

The territory of continental East China includes four Cenozoic rifts that belong to the western (Yinchuan-Hetao and Shanxi rifts) and eastern (East China and Hehuai rifts) systems, in which heat flows are notably higher than in their surroundings (an average of 68–70 mW/m^2 versus 56–49 mW/m^2). Particularly high deep flow exceeding 80–100 mW/m^2 is associated with rift basins and active faults. Heat flows in the region depend weakly on the age of the consolidated basement, but they have stronger correlation with recent tectonomagmatic activity.

Heat flow variations reflect the lower intensity of rifting in incipient rifts (56 mW/m^2 in the Yinchuan-Hetao rift and 60 mW/m^2 in active faults) and higher intensity in active rifts (68–70 mW/m^2 regional mean in the East China rift system and over 77–80 mW/m^2 in active faults). Geothermal data show strong correlation with geological and geophysical evidence of rift evolution and deep structure, especially with crustal thickness, conductor depth, and seismicity.

Regional heat flow anomalies and Cenozoic rifting are apparently induced by heating from a mantle plume rising through a rifted and faulted lithosphere. Activity is associated with the subduction of the Pacific plate beneath eastern Eurasia in the eastern system and with horizontal strain and extension caused by the rotation of the Ordos block under India and Eurasia in the western system, where thermal control has been minor.

Despite high tectonic and seismic activity, heat flow in the Cenozoic rifts of East China is much lower than in other continental rifts with similar deep structure and evolution, such as Baikal (74±7 mW/m^2) and Rheingraben (83±3 mW/m^2), and Rio Crande (92±4 mW/m^2) (Lysak 1988, Reiter 1986). A great portion of deep heat in the active rifts of East China (Shanxi and Yinchuan-Hetao) is spent on seismicity. Conversely, in passive rifts, the heat released in earthquakes additionally increases deep heat flow within active faults (e.g. Liaohe, Bo Hai, and Hehuai rifts).

Table 1: Geothermal Parameters in Upper Lithosphere of Mongolia and China

Station and structure	n	Geothermal gradient, mK/m	Thermal conductivity, W/m·K	Heat flow, mW/m^2
		Range $\gamma \pm 2\sigma/\sqrt{n}$	Range $\lambda \pm 2\sigma/\sqrt{n}$	Range $q \pm 2\sigma/\sqrt{n}$
Mongolia				
Lake Hovsgol (Hovsgol basin)	61	34 – 168 89 ± 7	0.70 – 1.40 1.04 ± 0.04	44 – 153 92 ± 7
Hot springs in mountains around Lake Hovsgol	5	–	–	32 – 86 64 ± 9
Boreholes in mountains around Lake Hovsgol	5	13 – 21 19 ± 4	2.30 – 2.90 2.6 ± 0.24	33 – 78 54 ± 12
Boreholes in Onon graben	3	25 – 43 32 ± 10	2.20 – 3.13 2.73 ± 0.56	84– 94 91 ± 7
Hot springs	2	–	–	61 – 79 70 ± 15
Boreholes in Kerulen uplift	3	25 – 35 31 ± 6	1.80 – 3.23 2.29 ± 0.94	55 – 71 64 ± 8
Hot springs	1	–	–	55
Boreholes in Choybalsan basin	3	21 – 25 24 ± 3	2.50 – 2.70 2.60 ± 0.12	53 – 66 61 ± 8
Boreholes in Orhon-Tuul depression	12	12 – 32 22 ± 4	2.14 – 3.60 2.73 ± 0.20	30 – 84 59 ± 10
Boreholes in Hangayn uplift	5	18 – 24 21 ± 3	2.60 – 2.69 2.14 ± 0.69	22 – 73 54 ± 12
Hot springs in Hangayn uplift	18	–	–	22 – 73 56 ± 11
Mines in Altay uplift	2	13 – 20 16 ± 7	3.30 – 3.40 3.35 ± 0.10	41 – 66 54 ± 26
Boreholes in Hentiyn uplift	6	18 – 50 27 ± 10	1.20 – 2.59 2.19 ± 0.42	31 – 62 49 ± 10
Boreholes in Tes-Selenge depression an Great Lakes Depression	4	13 – 25 18 ± 3	1.90 – 3.70 2.73 ± 0.64	46 – 58 48 ± 5
Boreholes in Trans-Altay orogenic area	3	16 – 33 24 ± 10	1.64 – 2.27 1.90 ± 0.38	35 – 54 43 ± 12
Boreholes in Dzuunbayan-Tamtsag basin	6	14 – 25	0.60 – 2.70	25 – 49

		20 ± 3	2.10 ± 0.38	43 ± 13
Boreholes in Central Gobi depression	2	14 – 28 21 ± 14	1.40 – 1.74 1.57 ± 0.34	28 – 40 34 ± 11
Boreholes in Ihshanhayn uplift	4	10 – 20 16 ± 5	1.60 – 2.76 2.18 ± 0.61	16 – 44 32 ± 12
China				
Rifts (Yinchuan-Hetao, Shanxi, East China system, Liaohe and Bo Hai, Bozhong, Huanghua, Jizhong, Jiyang)	(83) **Depth, m** 500-5000 2243±250	(64) 21.3-59.9 37.9±2.8	(64) 1.21-3.55 1.85±0.14	(130) 40-106 67±2
Orogens (Yangshan, Southern North-East zone, Tongcheng-Lujiang, Runlun-Qinlin)	(23) 250-3900 1032±936	(42) 8.9-64.6 23.8-10.2	(42) 1,67-10.4 3.98-±0.84	(54) 26-105 56±4
Ordos	(52) 200-4630 2120-±284	(58) 18.7-35.9 26.8-4.0	(58) 1.25-3.32 2.15±0.44	(58) 37-81 57±11

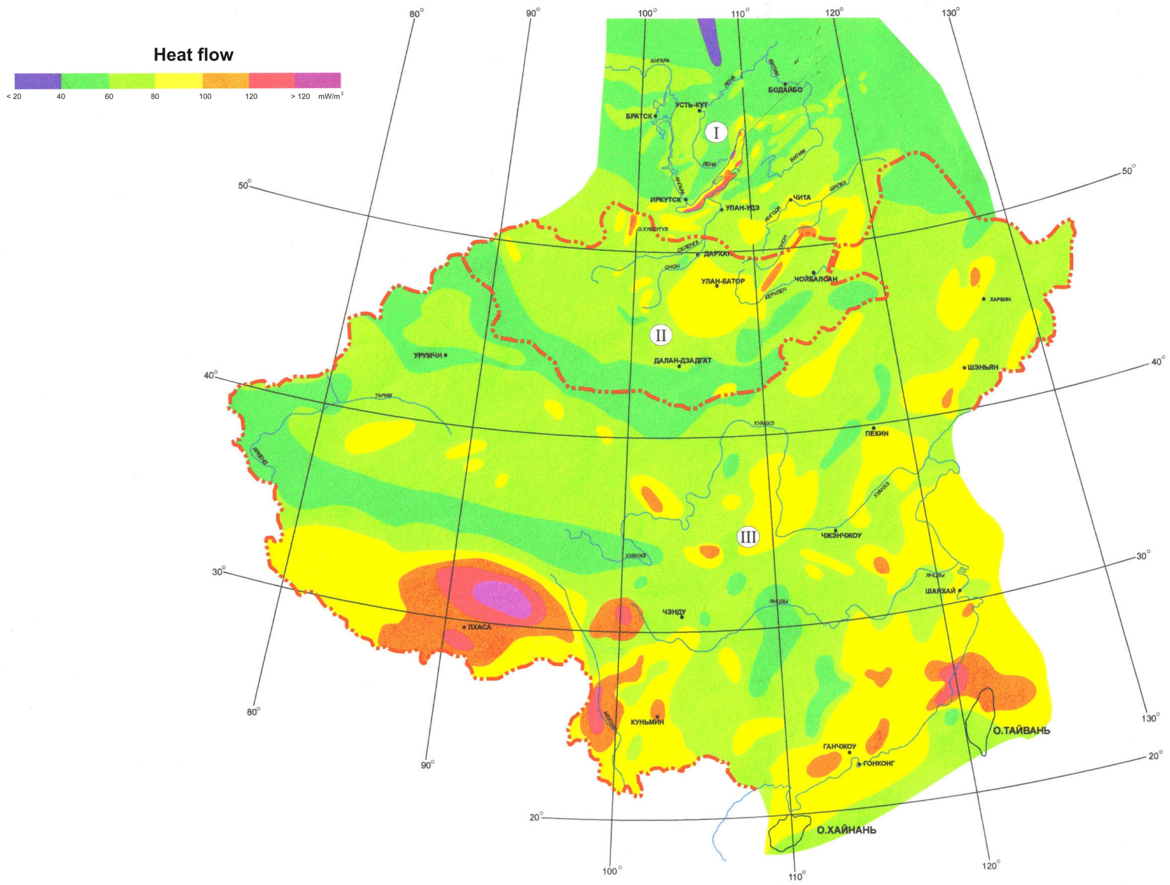

Figure 1: Heat flow map of Central Asia: I - South-Eastern Siberia, II – Mongolia, III – China

NOMENCLATURE

Heat flow (q), mW/m^2

Heat production (A), $\mu W/m^3$

Thermal conductivity (λ), W/m·K

Geothermal gradient (γ), mK/m

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