TERRESTRIAL HEAT AND TEMPERATURES IN THE UPPER CRUST IN SOUTH EAST SIBERIA

FLUX THERMIQUE ET TEMPÉRATURES DANS LA CROÛTE SUPÉRIEURE DE LA SIBÉRIE DU SUD-EST

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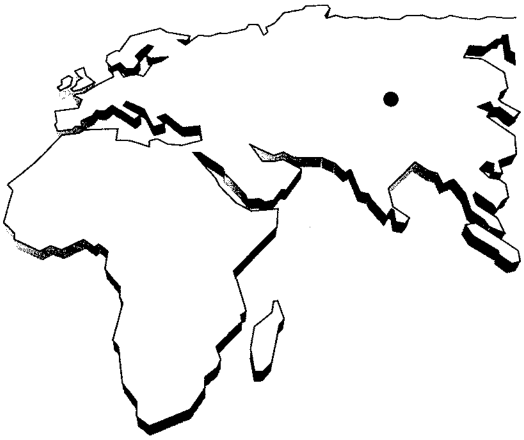

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Des cartes actualisées de distribution de la température et du flux thermique aux profondeurs de 1,3 et 5 km dans la zone de rift du Baïkal et les régions voisines comme la plate-forme sibérienne du sud et la ceinture orogénique de Transbaïkalie démontrent la complexité structurale de la Sibérie du sud-est.

Le champ de flux thermique correspond bien avec la forme structurale des hauts-fonds du socle et des hypocentres associés, et aussi avec les variations de conductivité de la croûte qui témoignent de l'activité tectonique. De toutes les provinces affectées d'un flux thermique moyen, la zone de rift du Baïkal présente les caractéristiques les plus remarquables qui se manifestent par des anomalies de forte amplitude concentrées sur des surfaces étroites. Elles sont associées avec des grabens qui, dans ce cas, montrent un flux thermique plus important que les éperons marginaux, contrairement au cas de la ceinture orogénique de Transbaïkalie où le flux thermique est plus important sur les hauts fonds que dans les grabens.

Les anomalies de flux thermique de la zone de rift du Baïkal sont en grande partie dues à un flux du manteau alimenté par des diapirs de l'asthénosphère qui remontent le long des fissures. Hors des zones de rifting, l'essentiel du flux thermique provient de la croûte. Des anomalies thermiques locales positives sont associées, dans la croûte supérieure, à des phénomènes comme des intrusions liées aux dômes salifères présents dans le craton.

Enfin, les anomalies de flux thermique résultent de la redistribution de la chaleur dans la lithosphère supérieure en fonction des écarts topographiques, des failles, des circulations dans la nappe phréatique et des processus d'érosion et de dépôt.

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Mots-clefs : Température, Gradient géothermique, Conductivité thermique, Flux géothermique, Production chaleur, Croûte terrestre sup., Lena Angara, Baïkal, Transbaïkalie, Rift Baïkal.

ABSTRACT

Updated heat flow and temperature distribution maps of the Baikal rift zone and the neighbouring southernmost Siberian platform and Transbaikalian fold belt, at depths of 1, 3 and 5 km, provide further evidence for the complex structure of South East Siberia. The heat flow field correlates well with the structural form of basement highs and intervening hypocentres, with the variations in electrical conductivity, and particularly well with the tectonic structure. Of the tectonic provinces delineated in the region by their mean heat flow, the Baikal rift zone is the most prominent feature which shows up as a series of relatively narrow high-amplitude regional anomalies. These are associated with rift basins (grabens) which, in this case, display a higher heat flow than the marginal uplifts, unlike the Transbaikalian fold belt where the structural highs show higher heat flow than the intermontane depressions. The regional heat flow anomalies in the Baikal rift zone are mainly due to mantle flux fed by hot asthenospheric diapirs ascending through permeable fracture zones in the lithosphere. Outside the rift zones, the greatest proportion of heat comes from the crust. Local thermal highs are produced by upper crustal sources such as fissure intrusions associated with the rifting or they are associated with salt domes located on the craton. Finally, heat flow anomalies are related to the redistribution of heat in the upper lithosphere due to topographic contrasts, faulting, ground-water circulation and erosional or depositional processes.

Key words : Temperature, Geothermal gradient, Thermal conductivity, Heat flow, Heat production, Upper crust, Angara-Lena Basin, Baikal region, Western Transbaikalia, Baikal rift zone.

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CONTENTS — *TABLE DES MATIÈRES*

INTRODUCTION

The region of South East Siberia (Fig. 1), has lived through a long and turbulent geological history which is imprinted in its structure, composition, morphology and geothermal character. The geothermal field developed under the influence of deep diapirism and was modified by shallow effects such as climate, topography, and ground-water circulation. The knowledge available on the temperature distribution, geothermal gradient and heat conductivity, heat flow and heat production in the upper crust, is mainly derived from a large number of marine and terrestrial geothermal measurements made in Lake Baikal and in boreholes both within and beyond the Baikal rift zone. The results are the basis of the updating of the regional heat flow map and temperature distribution maps at depths of 1, 3 and 5 km, from which heat flow anomalies have been identified.

1. — GEOLOGICAL FRAMEWORK

A comprehensive account of the geological history of the Lake Baikal rift, including its structure and geodynamics, has been given by LOGATCHEV (1993). To avoid repetition, the present review is restricted to some information on the area outside the Baikal rift and to some geophysical observations related to subsequent geothermal interpretation. Relationships between heat flow and geological and geophysical parameters have been calculated by the linear correlation method (LYSAK, 1976; LISAK & ZORIN, 1976).

1.1. TECTONICS AND VOLCANISM

1.1.1. Baikal rift zone

The dominant structural feature of the region is the Baikal rift system of elongated Cenozoic basins with uplifted margins which extends for about 1 800 km from Lake Khubsugul in northern Mongolia to the Tokko basin in Southern Yakutia (Fig. 2). The rift structures are clearly seen in the topography with an amplitude, between the highest ridges (marking the margins) and the sub-Cenozoic basement, of 5-6 km and reaching 8 km in parts of the Lake Baikal rift (LOGATCHEV *et al.*, 1974).

The rift zone developed on a compositionally and structurally heterogeneous Precambrian basement of high-grade metamorphic rocks cut by granitoids. Having stabilized in the Paleozoic after Baikalian (Proterozoic) and Caledonian (Early Paleozoic) folding (BELITCHENKO, 1977), the basement was reworked by Late Mesozoic and Early Cenozoic orogenic movements during which general uplift was accompanied by lithospheric buckling and faulting. The associated slow but sustained erosion smoothed the relief and came to produce the Upper Cretaceous-Paleogene peneplanation surface.

The onset of rifting in the Paleogene was marked by an extension which acted on the axial part of the Sagan-Baikal domal uplift (LOGATCHEV, 1993) and produced graben-like basins with uplifted margins separated by transversal on diagonal mountainous links. The largest basin, 685 km long and up to 60 km wide is, in part, occupied by Lake Baikal. Other rift basins are from 150 to 200 km in length and 30-35 km in width, or narrower (Fig. 2). The basins have accumulated lacustrine, fluvial and glacial sediments which now attain thicknesses of about 2-3 km in the Tunka basin, up to 6-7 km in the central Baikal basin, and almost half as thick in the Barguzin, Chara and other basins (LOGATCHEV, 1993). The major basin-bounding faults clearly acted in the Cenozoic and many are still active. They show both normal and strike-slip offset (SHERMAN, 1992). The inter- and intra-basinal links are cut by smaller scale active faults to which sites of hydrothermal discharge and heat flow anomalies are often attributed (LYSAK, 1988). The latest stage of tectonic activity began in the Pliocene about 3.5 Ma ago and continues today (LOGATCHEV & ZORIN, 1987, 1992; LOGATCHEV, 1993;

FIGURE 1

Location map of South East Siberia.

Sud de la Sibérie orientale.

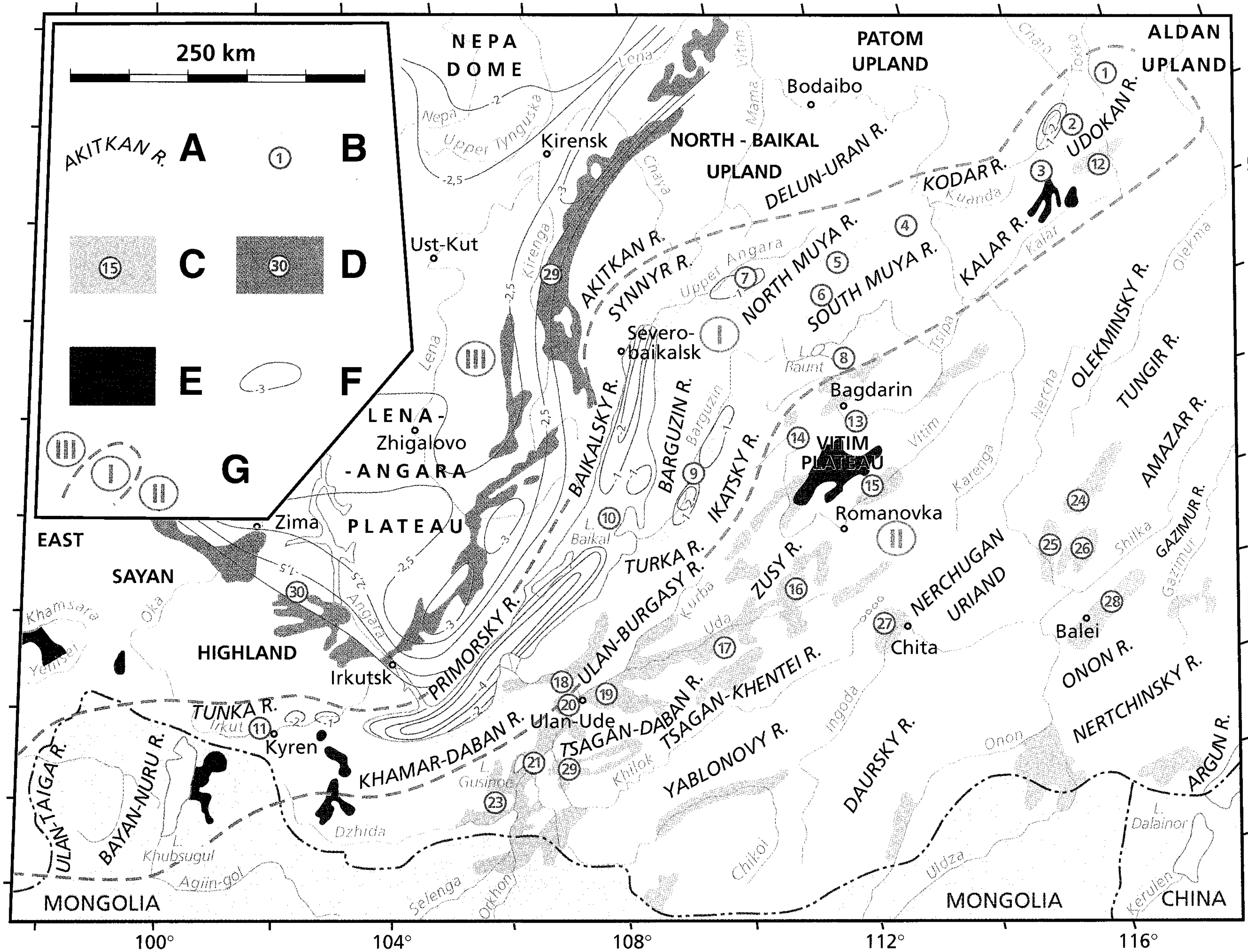
etc...). The relationship between the zones of contemporary tectonic movements and heat flow is proved by the correlation of the latter with the altitude of the Upper Cretaceous-Paleocene peneplain which gives a ratio of −0.64 and for the mean moduli of their gradients r = 0.69. Thus, high heat flow tends to occur in the rift basins as these are at the low points of the old erosional surface and they show the greatest neotectonic movements (LEVI & LYSAC, 1985).

The few manifestations of Cenozoic volcanism which are observed, are restricted to the western (Tunka basin) and northeastern (Udokan plateau) flanks of the rift zone. The evidence, though very little, of young volcanicity suggests the presence of dikes in the crust beneath the rift basin that must influence the geothermal field of the area.

1.1.2. Transbaikalian fold area

The Transbaikalian fold area (Transbaikalye) involves relatively low amplitude uplifts and interdomal Mesozoic basins (Fig. 2). These basins range in length from 150 to 180 km and from 15 to 20 km in width (FLORENSOV, 1980). They are filled with Jurassic and Cretaceous volcano-sedimentary sequences up to 2 km thick, the Cenozoic fill being limited in thickness to several dozens of metres.

The crystalline basement of Transbaikalye was consolidated during Early and Late Paleozoic orogenic cycles and activated in the Mesozoic with the formation of numerous basins and the rejuvenation of many faults by Cenozoic movements in the southeastern part of this region.


250 km
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B
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C
30
D
E
-3
F
III
I
II
G
NEPA DOME
PATOM UPLAND
ALDAN UPLAND
Bodaibo
Kirensk
NORTH - BAIKAL UPLAND
DELUN-URAN R.
KODAR R.
UDOKAN R.
Ust-Kut
AKITKAN R.
SYNNYR R.
NORTH MUYA R.
SOUTH MUYA R.
KALAR R.
Severobaikalsk
Bagdarin
LENA-ANGARA PLATEAU
Zhigalovo
BAIKALSKY R.
BARGUZIN R.
IKATSKY R.
VITIM PLATEAU
Romanovka
OLEKMINSKY R.
TUNGIR R.
AMAZAR R.
GAZIMUR R.
Zima
EAST SAYAN HIGHLAND
TURKA R.
ULAN-BURGASY R.
ZUSY R.
NERCHUGAN
URIAND
Chita
Balei
ONON R.
NERTCHINSKY R.
Irkutsk
PRIMORSKY R.
Ulan-Ude
TUNKA R.
Kyren
KHAMAR-DABAN R.
TSAGAN-DABAN R.
TSAGAN-KHENTEI R.
YABLONOVY R.
DAURSKY R.
ARGUN R.
ULAN-TAIGA R.
BAYAN-NURU R.
MONGOLIA
MONGOLIA
CHINA
Lena
Nepa
Upper Tynguska
Kirenga
Chara
Vitim
Mama
Tokko
Kuanda
Kalar
Olekma
Upper Angara
L. Baunt
Barguzin
Tsipa
Nercha
Karenga
Shilka
Gazimur
L. Baikal
Kurba
Uda
Angara
Oka
Khamsara
Yenisei
Irkut
Dzhida
L. Gusinoe
Khilok
Ingoda
Onon
Chikoi
Uldza
Selenga
Orkhon
Agiin-gol
L. Khubsugul
L. Dalainor
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112°
116°
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52°
54°
56°

1.1.3. Southern Siberian platform

The crystalline basement beneath the Southern Siberian platform is composed of Archean blocks separated by Early and Middle Proterozoic fold structures. The basement is covered by 1.5 to 3.0 km thick sediments which are mostly Early Paleozoic carbonates and halogenic series sandwiched between terrigenic rocks. In some places (e.g. near the town of Ust'-kut) the sediment cover is overlain by Permo-Triassic volcanic cover (Silurian Trapps).

The major geomorphological feature of the area is the Lena-Angara plateau. Its eastern and southeastern margins are framed by small younger basins with thin Meso-Cenozoic fluvial and lacustrine fill. The rest of the territory involves domal and swell-like uplifts (Nepa dome, Zhigalovo swell) and structures related to Paleozoic salt domes (Fig. 2).

1.2. HYDROGEOLOGY

Depressions in the Baikal rift zone and Transbaikalye are intermontane artesian basins (Lysak, 1968). The aquifers are attributed to horizons of sand, gravel, and soft sandstone, or to fractured basement groundwater which in these shallow aquifers is cold and fresh, with a salinity as low as 0.1-0.3 g^{-1}. Down to depths of 2-3 km their salinity increases up to 1-3 g^{-1} and temperatures increase from 30 to 90 °C. By their chemistry, the groundwaters are of methane, methane-nitric and sodic-hydrocarbonate type.

The artesian basins are mainly fed by inflow from the bordering ridges. The interstitial water is fresh and of Ca- and Na-rich hydrocarbonate type. The aquifers can be up to several hundred metres in thickness. Where hydrothermal vents occur (mainly in the Barguzin and Tripa-Bount basins to the northeast of Lake Baikal) the groundwater is of nitric, sulphate or sulphate hydrocarbonate sodic type. Salinities are less than 1g/l and temperatures range from 40 to 75 °C. Carbonated springs associated with recent volcanism are colder (20 to 35 °C) and show higher salinities (up to 2.5g/l) than the nitric ones.

The Southeastern Siberian platform, which is part of the Lens-Angara artesian platform, has only fresh groundwater at very shallow depths. Below the erosional base-level, sodic calcium abundances increase substantially, their concentration in brines reaching 300 to 600 g/l^{-1} in the Jurassic carbonate-halogenic evaporite sequences (Pinneker, 1966).

Due to its high mobility and heat capacity, the underground water contributes greatly to the redistribution and evacuation of deep heat and thus controls the regional heat flow and its local anomalies.

1.3. SEISMICITY

The high seismic activity of the Baikal rift zone is represented by frequent earthquakes (4 000-5 000 annually, with magnitudes of up to 5.5 or even greater on the Richter Scale (Solonenko, 1978; Golenetsky, 1990; Solonenko *et al.*, forthcoming). The seismicity shows a mozaic pattern where concentrations of epicentres occur in zones which follow the trend of the rift basins, mostly in the central (Middle Baikal) and northeastern segments (North Maya ridge, etc.) of the Baikal rift zone.

In the highest active zones, where earthquakes can attain magnitudes of 6 and greater, deep heat flow generally exceeds 75-100 mWm^{-2}. Likewise, heat flow anomalies match the distribution of shallow earthquakes (< 10 km).

The high-level seismic activity and the clear delineation of seismic zones indicate that the Baikal rift system is undergoing substantial tectonic stress release resulting in initiation, deepening and broadening of rift valleys, as well as uplifting of the area (Zorin *et al.*, 1977). The stress field is dominated by uneven horizontal extension transversal to the strike of rift structures (Sherman, 1992).

Seismicity is much lower in the Transbaikalian fold area where earthquakes are less frequent and less strong (M < 5). Eastern Transbaikalye is more active due to seismicity which propagates northeastwards from Mongolia. Cenozoic and modern tectonic movements result in doming of the territory.

The studied areas of the Southern Siberian platform are virtually aseismic.

1.4. DEEP ELECTRICAL CONDUCTIVITY

Magnetotelluric soundings in South East Siberia showed the presence of conductors in the crust and upper mantle (Popov, 1990). Two conductors beneath the Baikal rift occur at shallower depths (16 and 20 km) than those in the Trans-

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FIGURE 2

Major structural units and recent topographic features.
A : Mountain ridges and uplands; B : Cenozoic basins; 1, Tokko; 2, Chara; 3, Lower Ingamakit; 4, Muya; 5, North Muya; 6, Muyakan; 7, Upper Angara; 8, Tsipa-Baunt; 9, Barguzin; 10, Baikal; 11, Tunka; C : Mesozoic bassins; 12, Upper Kalar; 13, Malo-Analat; 14, Vitikan; 15, Kholoi; 16, Eravnoe; 17, Khorinsk; 18, Selenga-Itantsa; 19, Ude; 20, Orongoi; 21, Gusinoozersk; 22, Tugnui; 23, Borgoi; 24, Bukachacha; 25, Zulga; 26, Olov; 27, Chita-Ingoda; 28, Udino-Osinsk; D : Mesozoic-Paleozoic basins. 29, Pribaikalskaya; 30; Irkutsko – Cheremkhovskaya; E : Cenozoic basalts; F : Top basement contours (km); G : Limit of Baikal zone (I), Transbaikalian fold belt (II) and Southern Siberian Platform (III).

Principales unités structurales et géographiques.
A : Chaînes de montagnes et hauts plateaux; B : Bassins cénozoïques; 1, Tokko; 2, Chara; 3, Lower Ingamakit; 4, Muya; 5, North Muya; 6, Muyakan; 7, Upper Angara; 8, Tsipa-Baunt; 9, Barguzin; 10, Baikal; 11, Tunka; C : Bassins mésozoïques; 12, Upper Kalar; 13, Malo-Analat; 14, Vitikan; 15, Kholoi; 16, Eravnoe; 17, Khorinsk; 18, Selenga-Itantsa; 19, Ude; 20, Orongoi; 21, Gusinoozersk; 22, Tugnui; 23, Borgoi; 24, Bukachacha; 25, Zulga; 26, Olov; 27, Chita-Ingoda; 28, Udino-Osinsk; D : Bassins mésozoïques-paléozoïques. 29, Pribaikalskaya; 30; Irkutsko – Cheremkhovskaya; E : Basaltes cénozoïques; F : Isobathes du socle; G : Limite de la zone du Baïkal (I), Ceinture plissée de Transbaïkalie (II) et plate-forme sud-sibérienne (III).

baikalian fold area (40 km) and in the craton (100 km). The shallower depths of the electrical conductivity anomalies are related to heat flow (r = – 0.59) (LYSAK, 1976).

The conductors in the Baikal rift zone are probably associated with waveguides resulting from the presence of fluids in the middle crust and basaltic melts in the upper mantle (75-100 km) (POPOV, 1990). This suggestion that the Earth's interior beneath Baikal is more heated than beneath the surrounding areas is supported by geothermal studies.

2. — THE STATUS OF GEOTHERMAL STUDIES IN THE REGION

2.1. HISTORY OF GEOTHERMAL STUDIES

The hot springs on the Baikal shore and the permafrost in the surrounding mountains have been known for more than 250 years. About 40 years of geothermal studies have yielded a fairly rich collection of data broadly reported in the literature. The earliest experiment was temperature logging in deep boreholes located in the Tunka and Barguzin basins, on the Selenga delta into Lake Baikal, as well as on the Siberian platform. These were started in 1952 and continued until 1980. Those early measurements, interpreted and correlated with data on thermal waters in the artesian basin and in fissure hot spring, showed that the upper crust is hotter beneath Lake Baikal than beneath the Southern Siberian.

Later precision measurements were made in relatively shallow exploratory drillholes (0.5 to 1.5 km) in the mountains around Baikal or at hot springs on the shore of Lake Baikal sites of hydrothermal discharge (DUCHKOV & SOKOLOVA, 1974; LUBIMOVA *et al.*, 1975; LYSAK & ZORIN, 1976; BORISENKO & ZAMANA, 1978; etc...). New facts were obtained in the late '70s to early '80s for the Southeastern Siberian platform (DOROFEEVA & LYSAK, 1983), for the northeastern segment of the Baikal rift zone (LYSAK, 1988), and later, the '90s, for the Transbaikalian fold area and North and West Mongolia (DOROFEEVA & SINTSOV, 1990; GOLUBEV, 1992).

Relatively poor offshore coverage is compensated to a great extent by detailed marine investigations in Baikal. The first 11 heat flow measurements in the lake were performed in 1965 (LUBIMOVA & SHELIAGIN, 1966). In the next 20 years the number of heat flow stations had increased to 330 (FOTIADI, 1987) and now, more than 500 stations are run (GOLUBEV *et al.*, 1993). Such amplification of the geothermal research became possible due to innovations introduced by GOLUBEV into the design of instruments and the methodology (GOLUBEV, 1982, 1987; GOLUBEV *et al.*, 1993; GOLUBEV, forthcoming).

2.2. HEAT FLOW STATIONS

Heat flow stations are unevenly distributed over South East Siberia. They are concentrated mostly in the centre of the region, especially in (± 500 underwater measurements by Golubev, forthcoming) and around Lake Baikal (Fig. 3 and 7).

On-land geothermal surveys were conducted in 200 available exploratory drillholes ranging from 0.3 to 3 km in depth (0.3 to 1 km on ridges,1 to 2.5 km in intermontane depressions, and 2.5 to 3 km in the craton) and from 0.5 to 2 km (mostly < 1 km) above sea level in altitude. Measurements were taken between several weeks and several months (occasionally up to five years) after drilling had been completed. Precise measurements were made in 69 boreholes; 19 and 30 holes were used for hydrogeological and cryological studies, respectively, and the remaining 82 were continuously logged for geothermal gradients (27 holes) and temperatures (55 holes).

Marine studies were made at more than 500 sites on transversal profiles across Lake Baikal (only 369 sites are considered by this review) using oceanographic techniques from aboard of a vessel by means of either a thermal gradiometer (LUBIMOVA & SHELIAGIN, 1966; FOTIADI, 1987) or a cable thermistor probe penetrating into bottom sediments (GOLUBEV, 1982, 1988, 1993).

3. — MAIN GEOTHERMAL PARAMETERS : METHODS FOR MEASUREMENTS AND VALUES

3.1. TEMPERATURE

Continuous temperature logging was performed by means of fast-response downhole electric thermometers at a temperature resolution of 0.5 °C in water-filled, but not outblowing holes, which had stabilized for about a month or even a year after drilling. Precision measurements were taken point to point at 10-20 m intervals with a closer spacing where possible at contacts between contrasting lithologies. The thermometer was held for 3-5 minutes or longer at each point thus allowing a high degree of accuracy of 0.1 to 0.01 °C. Bottom water temperatures in Lake Baikal were measured using a cable thermistor probe, while both lowering and raising, to an accuracy of ± 0.002 °C. Temperatures of water in hot springs or in blowing holes were measured mainly by mercury thermometers to an error of ± 0.5 – 0.1 °C.

Measurement depths varied greatly from 1m in Baikal bottom sediments, beneath up to 1 600 m of cold fresh water, to 2.5-3 km deep in intermontane depressions and in the craton. In onshore water wells measurements depth was several 10 s/m and several hundred metres on mountain ridges. The measured temperature of Baikal bottom sediments is about 3 °C. The temperatures at depths of 0.1 to 0.5 km do not exceed 1.5-5 °C (outside permafrost zones). The sediment fill of the rift basins at the same depths is twice as warm (8-12 °C); the fault zones bordering or cross-cutting them are as hot as 30 to 50 °C (LYSAK, 1978). The basement rocks show a variation from 15 °C at a depth of 0.5 km (Khamar-Daban ridge) to 29 °C at a depth of 1.2 km (Primorsky ridge). The temperatures of sediments filling the Tunka basin and Selenga delta, measured at a depth of between 2 and 2.6 km, are above 50-65 °C. The water of fissure springs upflowing from these depths is as hot as 40-75 °C at the well-head or up to 90-95 °C at aquifer depths.

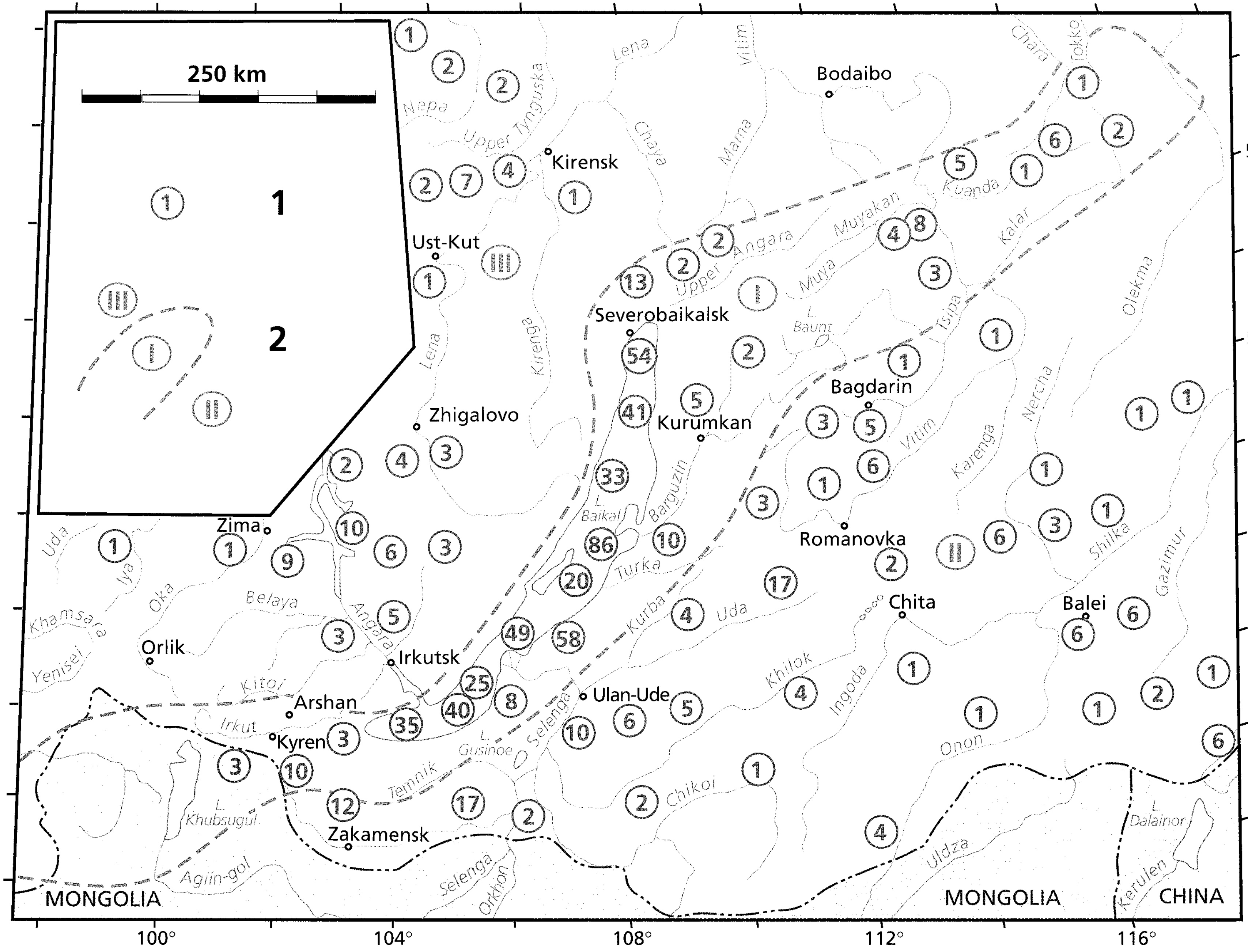

FIGURE 3

1 : Coverage heat flow measurement sites : number in each one-degree grid (1 to 7 on land and 20 to 86 in Lake Baikal); 2 : limit of the Baikal rift zone (I) between the Southern Siberian platform (II) and the Transbaikalian fold belt (III).

1 : Localisation des points de mesure du flux thermique, 2 : position des limites de la zone de rift du Baïkal (I) entre la plate-forme de Sibérie du Sud (II) et la ceinture plissée de Transbaïkalie (III).

The rift basins are hotter, *i.e.* more heated than the bordering ridges. This holds good, with a similar temperature difference being recorded below on erosional down-cutting (1-2 km), care having been taken to avoid local thermal anomalies. The reverse relationship is observed in the Transbaikalian fold area where the ridges are more heated than the basins. The sediment cover of the Southern Siberian platform only reaches temperatures of 20-30°C below 1.0-1.5 km.

Therefore, the thermal state of the earth's interior beneath the Baikal rift zone differs from that beneath the adjoining areas. Analysis of temperatures *versus* depths and borehole altitudes showed that :

— temperatures increase with depth throughout the study region;

— temperatures increase more rapidly beneath the rift basins in the Baikal rift zone while in Transbaikalye the uplifts are more heated than the depressions.

3.2. **GEOTHERMAL GRADIENT**

The terrestrial gradient (γ, mkm^{-1}) was calculated from temperature logs as a weighted mean of gradients obtained within equally sloped segments of the curves to an error varying from 0.2 to 28 % (Lysak & Zorin, 1978).

The temperature gradient in the Baikal bottom sediments was found as a difference between resistivity increments gained by lower and upper thermistors as the probe was penetrating 1-2 m into sediments. The instrument error in such measurements was ± 10 % (Golubev, 1982).

Very little of the Baikal sediment thickness totalling 4 to 8 km has been so far probed. Within the uppermost strata geothermal gradients vary from 15 to 500 mkm^{-1} and higher (Golubev *et al.*, 1993). Mean gradients for the total sediment thickness in the Baikal basin can be expected to be around 30-40 mkm^{-1} by analogy with the Selenga delta (situated on the southern shore of Lake Baikal and where the temperature gradient has been established in boreholes to a depth of 2 900-3 000 m).

The gradients measured onshore and on the surrounding mountains are about 20 mkm^{-1}, in the zones of fissure springs. Histograms of the temperature gradients of the Baikal rift zone (Fig. 4) are similar in form to those of the Transbaikalian fold belt (Fig. 5a), but those of the rift basin show a greater frequency of high gradients. The mean gradient of 20 mkm^{-1} is the same for the two areas if the extreme values are ignored, however, if they are considered, then the mean gradient is 23 mkm^{-1}. The latter value nearly coincides with the background gradient calculated for the sediments in offshore intermontane basins (24 mkm^{-1}) but is lower than the mean for rift basin fill (27-32 mkm^{-1}). The gradients are considerably lower on the ridges, where they remain within the range 16-18 mkm^{-1}.

Moreover, a more rapid temperature increase is observed in the uplifts of Transkaikalye than in the rift zone (gradients of 19-24 and 16-17 mkm^{-1}, respectively).

Most commonly, the geothermal gradient increases as the borehole altitude decreases. A more complex relationship is observed between the geothermal gradient and depth changes. In the Baikal rift the gradient decreases steadily down to a depth of 500 m and then at greater depths the gradient increases. This occurs beneath both basins and ridges. In Transbaikalye the reverse occurs. This suggests that in the rift zone there is abundant heat influx from the upper mantle whereas in Transbaikalye, especially within uplifted areas, the heat comes from shallow heat sources.

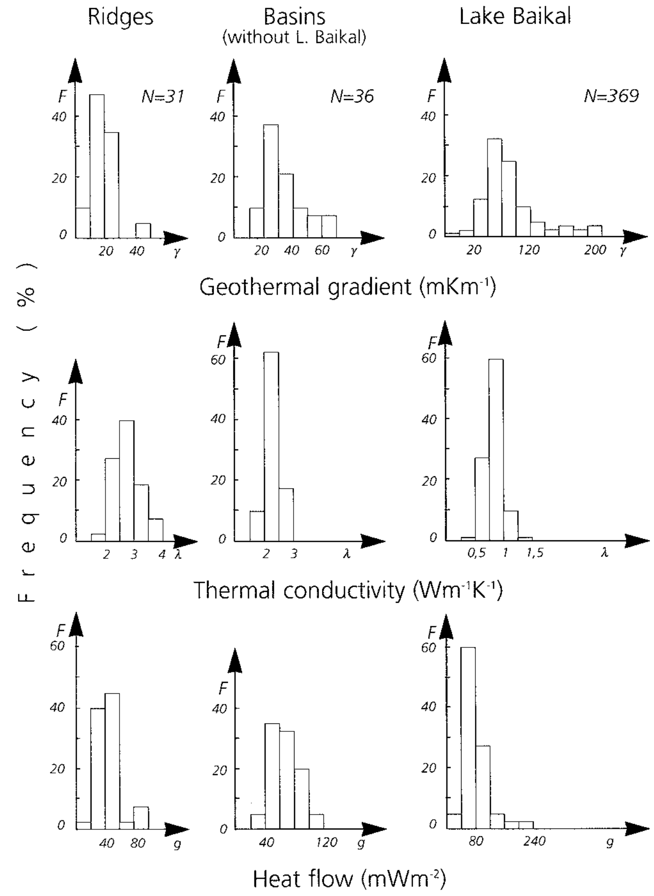

Figure 4

Histograms of geothermal gradient, thermal conductivity and heat flow in the Baikal rift zone.

Histogrammes du gradient géothermique, de la conductivité et du flux thermique dans la zone de rift du Baïkal.

The geothermal gradients in the Southern Siberian platform (Fig. 5) are significantly lower than in the adjacent fold areas. They never exceed 10 mkm^{-1} in the Nepa dome and in the marginal uplifts close to Lake Baikal and the East Sayan mountains, increasing to 15 mkm^{-1} in the centre of this area and in local salt domes. Mean geothermal gradient for the platform cover and uppermost basement is 13 ± 1 mkm^{-1} (Dorofeeva & Lysak, 1983).

3.3. **THERMAL CONDUCTIVITY**

Thermophysical properties of core samples were determined in the laboratory using techniques based on the theory of non-steady-state heat exchange, which are common practice in Russia (Dorofeeva, 1988; Dorofeeva *et al.*, 1994). Thermal conductivity (λ, Wm^{-1}K^{-1}) was found as a weighted

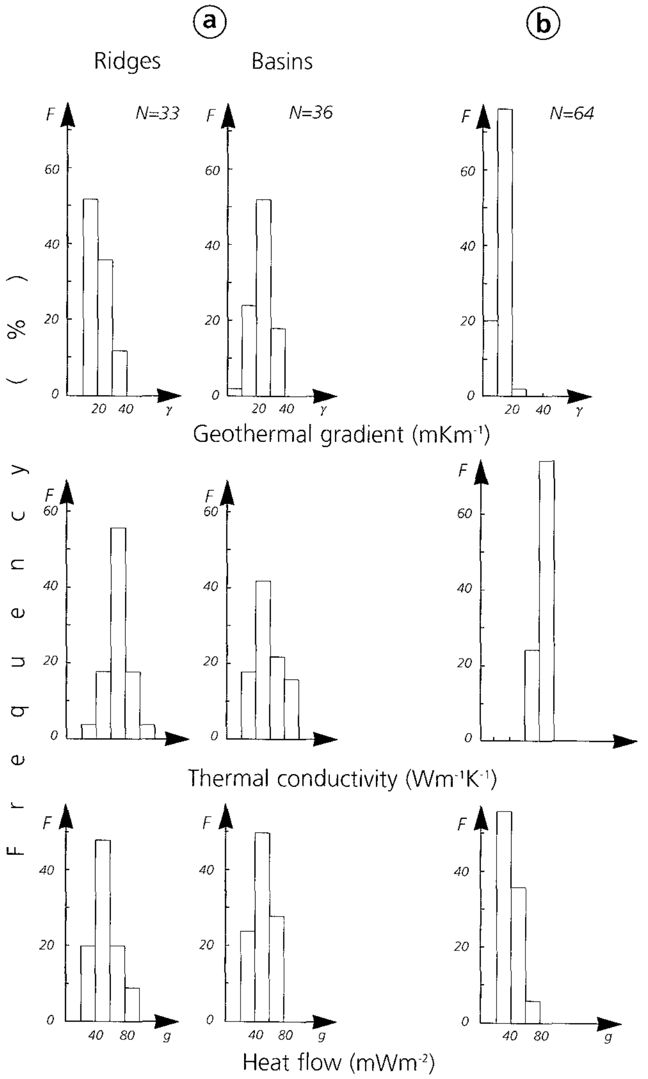

FIGURE 5

Histograms of geothermal gradient, thermal conductivity and heat flow in the Transbaikalian fold belt (a) and in the Southern Siberian platform (b).

Histogrammes du gradient géothermique, de la conductivité et du flux thermique dans la ceinture orogénique de Transbaïkalie (a) et dans la plate-forme de Sibérie du Sud (b).

mean over the section penetrated by borehole, on the basis of thicknesses of similar lithologies as a weigh unit. Thermal conductivity of bottom sediments was determined *in situ* or from their moisture weight percentage (GOLUBEV, 1982).

Mean thermal conductivity of bottom sediments throughout most of Lake Baikal is about 2 $Wm^{-1}K^{-1}$. Lower values of 0.8-0.5 $Wm^{-1}K^{-1}$ are typical of the central North Baikal basin and of the area around the Selenga delta. Those in the Selenga delta are due to high gas content in the bottom sediments. Sites of relatively high thermal conductivity (above 1-1.5 $Wm^{-1}K^{-1}$) are found mainly on the southeastern side of Lake Baikal where the probe penetrated interbedded sand and clay (GOLUBEV, 1982; GOLDYREV, 1982), the higher conductivity being attributed to high gas content in the sediments. Most of the Cenozoic fill of the rift basins has a thermal conductivity of 2 $Wm^{-1}K^{-1}$ which increases up to 2.5 Wm^{-1}-K^{-1} downhole as approaching the basement.

The higher thermal conductivity in the mountains is attributed to the preponderance of Precambrian metamorphic and igneous rocks. FOTIADI (1987) has shown that, in function of composition and fracturing, the thermal conductivity varies considerably (Tab. I).

Cenozoic basalts have much lower conductivities of 1.5-1.7 $Wm^{-1}K^{-1}$ (DOROFEEVA, 1986).

Histograms of uppercrustal thermal conductivities in the Baikal rift zone show a complicated pattern (Fig. 4) with lowest λ (below 2-2.5 $Wm^{-1}K^{-1}$) in the rift basins and highest values at the basement beneath them and in the bordering ridges. Variation range is about the same in the Transbaikalian fold area (Fig. 5) with low thermal conductivities of flood basalts in the Vitim plateau and of volcano-sedimentary sequences filling the intermontane depressions, and high conductivities (above 3 $Wm^{-1}K^{-1}$) associated with the Malo-Amalat basin, in the Trans-Baikal region, near Ulan-Ude. Thermal conductivities of rocks in the Southern Siberian platform plot a histogram (Fig. 5) with higher values (above 3 $Wm^{-1}K^{-1}$) for the widespead evaporite and carbonate sections (in the Neya dome, around the towns of Kirensk, Zhigalovo, etc...), and lower conductivities of below 2.5-2.7 $Wm^{-1}K^{-1}$ for the terrigenic sediments and basic intrusions.

Thermal conductivity of the uppermost crystilline basement ranges from 2.2 to 3.0 $Wm^{-1}K^{-1}$ with a mean of 2.45 $Wm^{-1}K^{-1}$ at depths between 1 and 5 km (DOROFEEVA & LYSAK, 1989).

TABLE I

Thermal conductivity of metamorphic and igneous rocks.

Conductivité thermique de roches métamorphiques et plutoniques.

Rock type	**Thermal conductivity $Wm^{-1}K^{-1}$**			
	Minimum	Maximum	Mean	Number of samples
Granite	1.1	3.6	2.4	172
Diabase (Dolerite)	2.5	3.1	2.8	7
Crystalline schists	1.4	5.5	2.7	79
Granite gneiss	1.6	3.8	2.7	38

3.4. HEAT PRODUCTION

Heat production (A, μWm^{-3}) was estimated from the measured uranium, thorium and potassium contents by the method of Rybach & Buntebarth (1982). Abundances of radioactive elements were determined by Dorofeeva (1990) on 100 drill cores and 1 300 *in situ* samples of igneous and metamorphic rocks. This collection was substantially amplified due to studies of other workers (Fotiadi, 1987) and supplemented with reference data published in Dortman (1992).

Heat production at shallow depths was found to vary over a wide range (Fig. 6). In basins, both in the Transbaikalian fold belt and in the Baikal rift zone, heat production is lower than in the surrounding mountains (0.5-1.5 and 1-2 μWm^{-3} respectively). However, in high mountains (higher than 1.5-2 km above sea level) the rocks are essentially lower in radioactive isotopes due to erosion and the heat production decreases down to 1-0.5 μWm^{-3}.

The upper crustal heat production in the craton averages 1.3 μWm^{-3} (Dorofeeva & Lysak, 1989).

3.5. HEAT FLOW

The heat flow values (q, mWm^{-2}) were computed as the product of weighted mean thermal conductivity and temperature gradient applied to the logged section of drillholes (on land) or to the probed thickness of bottom sediments (in the lake).

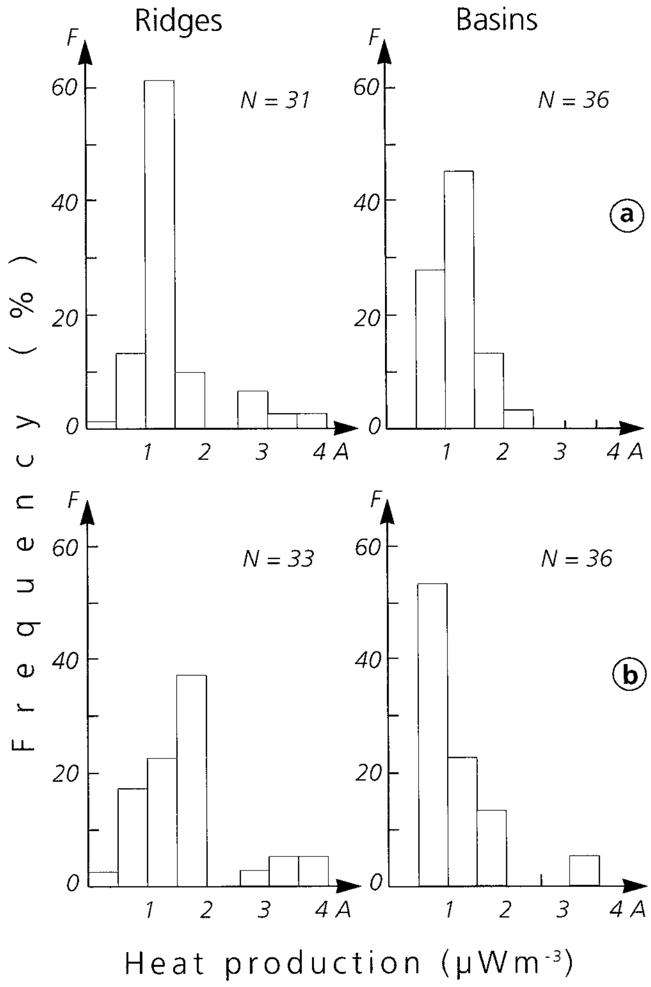

Figure 6

Histograms of heat production in the Baikal rift zone (a) and in the Transbaikalian fold belt (b).

Histogrammes de production de chaleur dans la zone de rift du Baïkal (a) et la ceinture orogénique de Transbaïkalie (b).

Corrections have been applied to the gradient to account for the effect of topography, sedimentation and ambient water (to marine gradients) (Golubev, 1982) and to the thermal conductivity of soft sediments to allow for their water content (Duchkov & Sokolova, 1974; Dorofeeva, 1988). Topographic effects are generally cancelled by sedimentary lenses, that reduced the total correction of the heat flow to within 10-20 % in shallow and to 5-10 % in deep boreholes. The total correction applied to the bottom sediment heat flow amounted to 15-20 %. The heat flow of the Baikal basin is described in detail in Golubev (forthcoming). So here we restrict the review to a summary that the Baikal heat flow is highly uneven and varies from several dozens to several hundred or even thousand mW/m^2 (Fig. 5). Against the background flux of around 50 mWm^{-2}, extremely high values of above 1 000 or 8 000 mW^{-2} stand out which are associated with hydrothermal events. The thermal highs (in excess of 100-200 mWm^{-2}) occur in narrow elongated zones most commonly parallel to the shore. Mean heat flow averaged over about 600 determinations, extreme values being omitted from consideration, is 71 ± 21 mWm^{-2} (Golubev *et al.*, 1993). However, recent geothermal measurements made during the obtaining of two 100 m cores recovered in March 1993 from a deep underwater drilling site near the Bugul-deika delta (western coast of Lake Baikal) raise a number of problems which may result in a revision of previous heat flow estimation (Dorofeeva, pers. commun.).

The regional flux of the rift zone other than below the lake is between 18 and 134 mWm^{-2}, as determined from 67 boreholes, with a mean of 56 mWm^{-2}.

Deep heat flow is the highest (above 60-70 mWm^{-2}) in the Selenga delta and the Barguzin and Tunka rift basins, locally exceeding 80-100 mWm^{-2} in the bordering fault zones. It drops down to 50-80 mWm^{-2} in the northeastern

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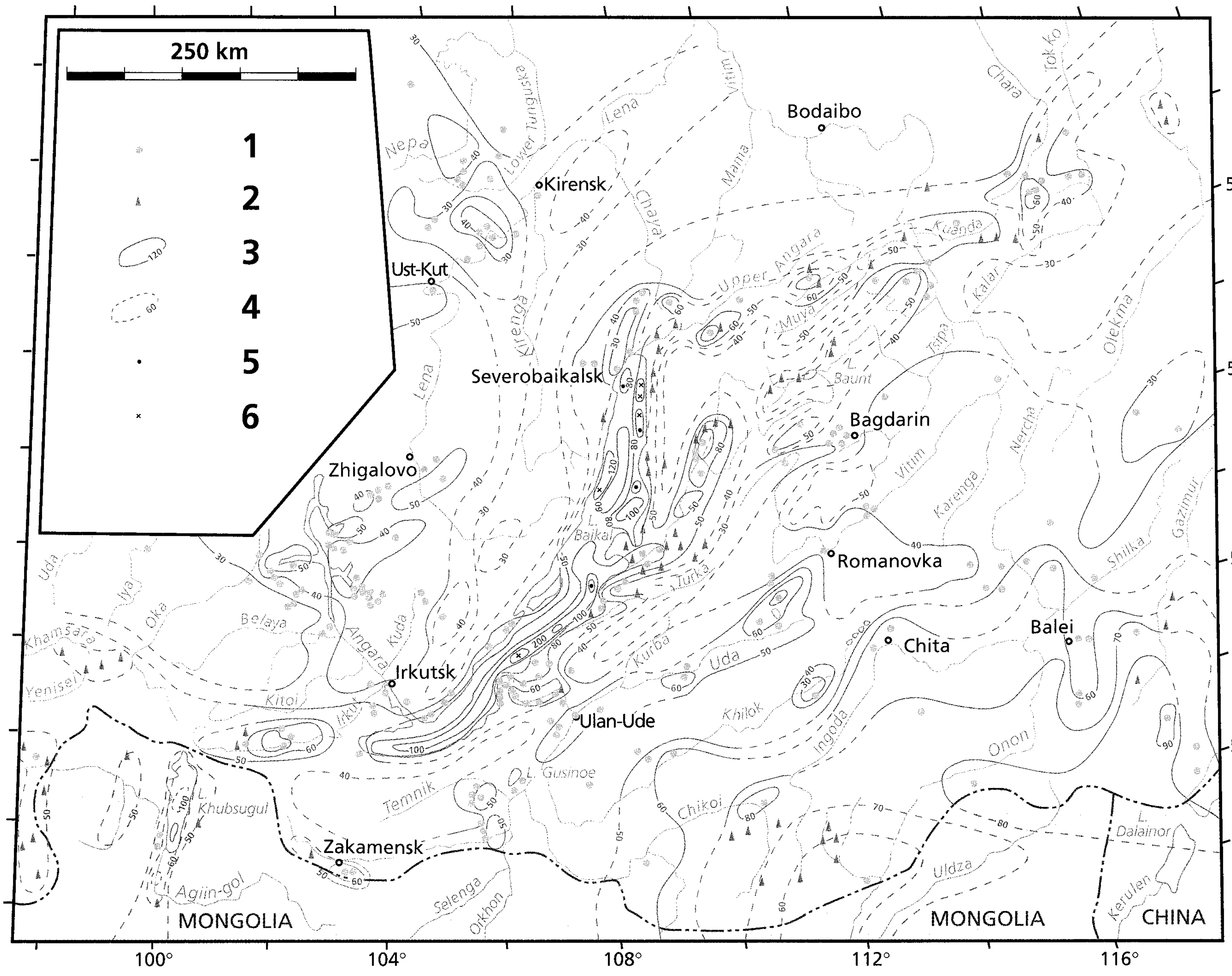
Figure 7

Heat flow in South East Siberia.
1 : heat flow measurement sites on land; 2 : hot springs; 3 et 4 : isotherms of certain (3) and hypothetical (4) heat flow values in mWm^{-2}; 5 et 6 : zones of high heat flow in Lake Baikal.

Flux thermique dans le sud de la Sibérie orientale.
1 : points de mesure du flux thermique à terre; 2 : sources chaudes; 3 et 4 : isothermes des valeurs du flux thermique (en mWm^{-2}) confirmées (3) et hypothétiques (4); 5 et 6 : zones de fort flux thermique dans le lac Baïkal (5 : 200-250 mWm^{-2}, et 6 : 1 000-2 000 mWm^{-2}).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Severobaikalsk
Bagdarin
Zhigalovo
Romanovka
Irkutsk
Chita
Balei
Ulan-Ude
Zakamensk
MONGOLIA
MONGOLIA
CHINA
Nepa
Lower Tunguska
Lena
Vitim
Mama
Chara
Tokko
Kirenga
Upper Angara
Muya
Kuanda
Kalar
Olekma
Tsipa
L. Baunt
Vitim
Karenga
Nercha
Shilka
Gazimur
L. Baikal
Turka
Kurba
Uda
Khilok
Ingoda
Onon
Chikoi
Uldza
Kerulen
L. Dalainor
Uda
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Oka
Belaya
Angara
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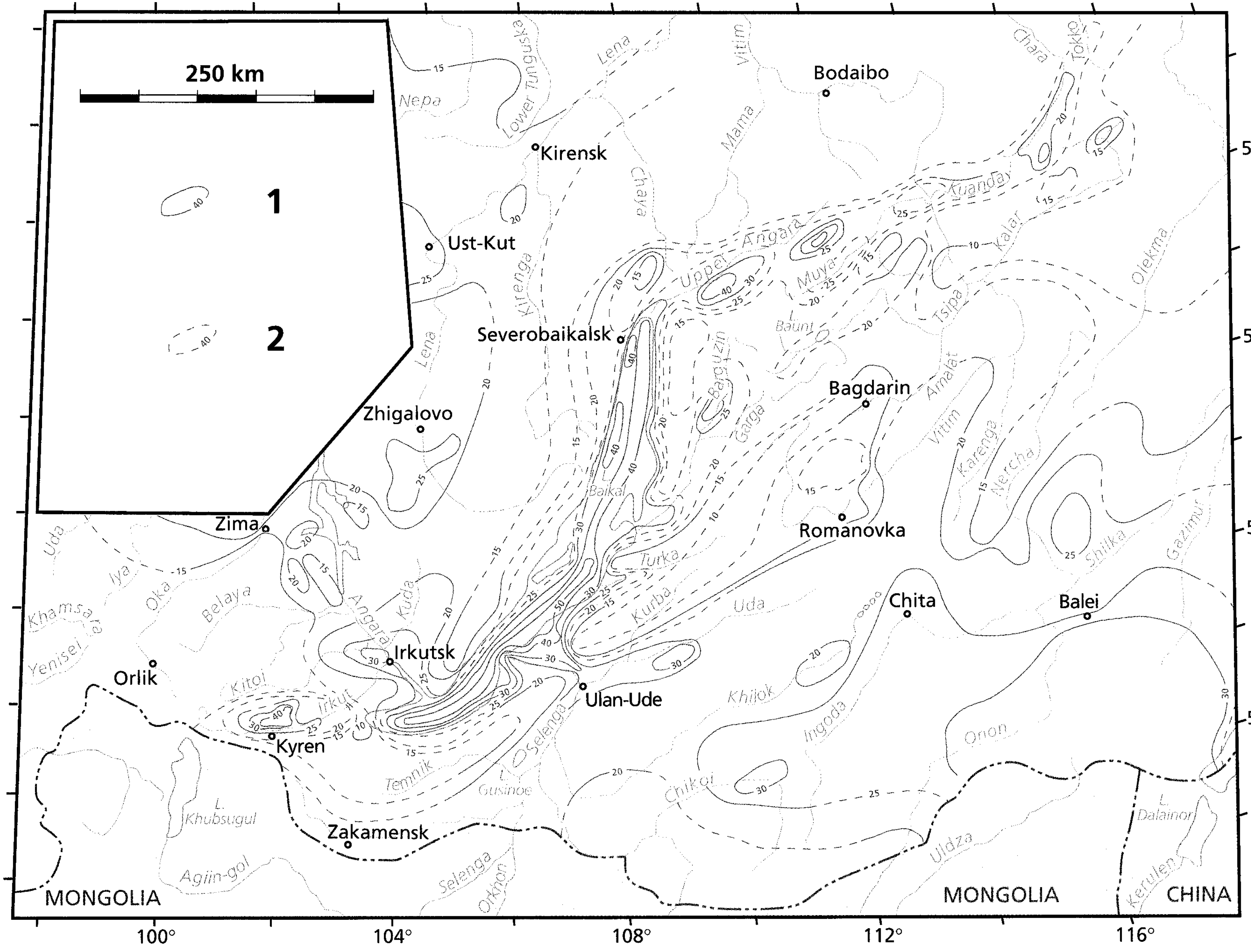
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Upper Angara
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Tsipa
Olekma
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Barguzin
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Nercha
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Gazimur
Baikal
Turka
Kurba
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Iya
Oka
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Khamsara
Yenisei
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flank of the rift zone amounting to 70-80 mWm^{-2} only in some localities (in the Upper Angara and Ingamakit basins, and in the North Muya ridge) (Fig. 7). Owing to the lack of boreholes, some rift basins (Tsipa-Baunt, Muya) remain uncovered by geothermal surveys. The heat flow there can be inferred to exceed 50 mWm-2 by analogy with other basins and based on their geological, geophysical and hydrological settings (Lysak, 1984, 1992).

Excess heat is brought by thermal water in the intermontane artesian basins which are prominent on the thermal field as regional anomalies involving local highs associated with faults.

The heat flow in the basin-bounding ridges is considerably lower and averages 40 mWm^{-2}, from 29 borehole determinations; two boreholes drilled in fault zones yielded a flux above 90 mWm^{-2}. At high altitudes the flux could be below 40-30 mWm^{-2}, though this is based on only a few measurements and theoretical considerations (Fig. 8).

The vertical distribution of heat flow in the Baikal rift zone reflects the same pattern as the geothermal gradient : a steady decrease down to a depth of 0.5 km from a mean of 61 to 52 mWm^{-2}, followed by an increase to 88 mWm^{-2} at a depth of 2 km. This is indicative of an excess heat supply from a deep source beneath the rift basins, and of a non-steady-state thermal regime in the rift zone.

In the Transbaikalian fold area the heat flow was found to range between 28 to 75 mWm^{-2} in 66 holes. Abnormally high flows, up to 80 mWm^{-2} were observed in three places (Fig. 7). Mean heat flow over Transbaikalye is 51 ± 6 mWm^{-2} (Fotiadi, 1987). Unlike the rift zone, the uplifts in the fold area are on average 5-10 mWm^{-2} hotter that in the intermontane depressions. The thermal field is generally steady-state over the area, excluding some localities affected by Cenozoic volcanism and fracture zones subjected to Mesozoic-Cenozoic activity.

The heat flow on the craton varies from 21 to 60 mWm^{-2}, averaging around 38 ± 4 mWm^{-2}. Relatively high flux of 45 ± 8 mWm^{-2} occurs in zones of discharge above faulted salt domes (e.g. in the vicinity of Zhigalovo); low flux is observed on the Nepa dome (28 ± 5 mWm^{-2}) and on the marginal uplifts (35 ± mWm^{-2}). Therefore, heat flow pattern is controlled by geological and structural features of the sediment cover and the associated thermophysical heterogeneity, as well as by transport of heat by underground water.

4. — LATERAL TEMPERATURE DISTRIBUTION AT DEPTHS OF 1, 3 AND 5 KM

4.1. METHOD OF CALCULATION

The available geothermal measurements render temperature distribution mostly restricted to depths of 1-2 km. Temperatures below these depths down to 5 km, have been inferred from measured or surmised geothermal parameters using the formula of Pollack (1965) for steady heat conduction. The formula was modified by Dorofeeva (Fotiadi, 1987) to the following relationship :

$$T_n = T_{n-1} + \frac{1}{\lambda_n}\left\{(Z_n - Z_{n-1})\left[q_0 - \sum_{i=0}^{n-1} A_1 (Z_i - Z_{i-1})\right] - \frac{A_n}{2}(Z_n - Z_{n-1})^2\right\}$$

where T_n is temperature at the required depth; T_{n-1} is that at maximum measured depth (both in °C) : λ_n ($Wm^{-1}K^{-1}$) is thermal conductivity; $(Z_n - Z_{n-1})$ and $(Z_i - Z_{i-1})$ (m) are thicknesses of the n-th and i-th layers (measurement depth subtracted from required depth); q_0 (mWm^{-2}) is surface heat flow; A_n and A_1 (μWm^{-3}) is heat production of the n-th and i-th layers.

Calculations were performed on the basis of the following initial assumptions for the input parameters :

— the thermal field is at steady state;

— thermal conductivities (in Wm^{-1}), at a given depth, are constant for the major units (Tab. II); the depth variant approximates to a step function (Dorofeeva & Lysak, 1989);

— heat production (in μWm^{-3}) for the major units (Tab. III); all these values decrease steadily with depth by 30-50 % as approximated by a step model (Dorofeeva, 1990);

— heat flows as obtained from heat-flow stations with all the corrections applied (see above).

Since the solution is for the steady-state conditions, the results are not applicable to tectonically active areas.

4.2. TEMPERATURE DISTRIBUTION AT A DEPTH OF 1 KM

Temperatures at a depth of 1 km were measured in 65 boreholes. They show a lateral variation which ranges from 7 to 26 °C in mountain ridges and on the craton and from 34 to 53 °C in the rift basins (Tab. IV). Mean theoretical and empirical values virtually coincide : they are 27 and 28 °C respectively, for the Baikal rift zone, 22 °C for the Transbaikalian fold area, and 18 °C for the Southern Siberian platform. The rift basins are contoured by the 20 °C isothermal line (Fig. 8). Inside, the contour temperature rises locally from 37 to 56 °C in the Tunka basin, from 33 to 55 °C in the Selenga delta, and from 26 to 66 °C in the Barguzin basin. Beneath Baikal, the temperature may attain 40-50 °C (Golubev, pers. commun.) but must remain within 25-30 °C under the basins on the northeastern flank of the rift zone.

Against the regional means of below 25 °C in Transbaikalye and about 18 °C in the Southern Siberian platform, few highs of 30 °C and more occur locally (Fig. 8 and Tab. IV).

Figure 8

Temperature (°C) distribution at a depth of 1 km, compiled from measurements and also calculated by Dorofeeva & Lysak (1989) (on land) and Golubev (1982) (beneath Lake Baikal).
Isotherms (contour interval : 5 °C) measured or calculated (1), hypothetical (2).

Répartition des températures à 1 km de profondeur établie à partir des mesures et des calculs de Dorofeeva & Lysak (1989) à terre, et de Golubev (1982) sous le lac Baïkal.
Isothermes (intervalle : 5 °C) mesurés ou calculés (1), ou hypothétiques (2).

TABLE II
Thermal conductivities for the major structural units.
Conductivités thermiques des unités structurales majeures.

Zone	Unit	Thermal Conductivity (Wm^{-1})	
		Superficial	Depth variant from 0.5-5 km
Baikal rift	Basin fill	2.1	increasing by 0.2-0.3
	Crystalline basement	2.4	increasing by 0.2-0.3 or almost constant beneath the basin
	Bordering ridges	2.4	decreasing by 0.2-0.5
Southern Siberian platform	Sedimentary cover	3	no data
	Basement	2.45	no data
Transbaikalian fold area	Uplifts	no data	decreasing by 0.2-0.7
	Depressions	no data	increasing by 0.4-0.7

TABLE III
Heat production for the major units.
Production de chaleur des unités structurales majeures.

Zone	Unit	Heat production (μWm^{-3})
Baikal rift	Basin fill	0.6-0.9
	Crystalline basement	1.03-1.29
	Bordering ridges	1.03-1.29
Southern Siberian platform	Sedimentary cover	1.3
	Basement	0.78
Transbaikalian fold area	Crystalline rocks of uplifts	1.2-1.7
	Depressions	0.6-0.9

4.3. TEMPERATURE DISTRIBUTION AT A DEPTH OF 3 KM

Due to the lack of direct measurements in the study region, all the temperatures at this depth are theoretically inferred (Tab. IV). The Baikal rift zone falls within the 40 °C contour line including local highs of 60-80 °C and more within the rift basins (Fig. 9). In Southeastern Transbaikalye the temperatures exceed 80 °C over most of the territory. At this depth, the Southern Siberian platform is about 25 °C colder.

Mean background temperatures are almost the same for the Baikal rift zone as for the Transbaikalian fold area (51 and 50 °C, respectively). However, the rift zone has more thermal highs (above 100 °C) than the Transbaikalian fold belt-sixteen sites as opposed to two (Fig. 9). While the mean temperatures are comparable, the extremes are quite different with the Transbaikalian ridges being only 10 °C hotter, and the interior of the rift basins 30 °C hotter than the mean. This difference becomes twice or three times as great under Lake Baikal where the Upper Crust must be as hot as 100-130 °C (Golubev, pers. commun.).

4.4. TEMPERATURE DISTRIBUTION AT A DEPTH OF 5 KM

The theoretical background temperatures at a depth of 5 km are more or less uniform throughout the study region remaining at below 100 °C. However, local highs, especially under rift basins, yield means of 115 °C for the Baikal rift zone, 99 °C for Transbaikalye and 70 °C for the Southern Siberian platform (Tab. IV).

The rift zone is enclosed within the 80 °C isothermal line, and the rift basins are contoured by the isotherms of

TABLE IV

Temperature distribution at depths of 1, 3 and 5 km.

Répartition des températures aux profondeurs de 1, 3 et 5 km.

Measured or calculated temperatures, °C	Baikal rift zone			Transbaikalian fold area			Baikal rift zone and Transbaikalian fold area together	Southern Siberian platform
	Ridges	Basins	Zone as a whole	Ridges	Basins	Zone as a whole		
	Depth 1 km							
Measured temperatures :	26	18-53	18-53	12	33	12-33	12-53	14-29
mean	26 (1)*	28 (7)	28 (8)	12 (1)	33 (1)	22 (2)	27 (10)	18 (55)
Calculated temperatures :								
background (below 35°C)	7-26	13-28	7-28	10-33	10-35	10-35	7-33	16-33
mean	16 (29)	24 (22)	20 (51)	20 (33)	23 (36)	22(69)	21(120)	18(61)
abnormal (above 35°C)	45-47	36-97	45-97	-	-	-	-	-
mean	46 (2)	51 (14)	51 (16)	-	-	-	51 (16)	-
total	18 (31)	35 (36)	27 (67)	20 (33)	23 (36)	22 (69)	24 (136)	18 (61)
	Depth 3 km							
Calculated temperatures :								
background (below 80°C)	20-76	43-74	20-76	33-79	31-78	33-79	20-79	26-70
mean	46 (29)	61 (15)	51 (44)	54 (27)	57 (29)	55 (56)	54 (100)	43 (64)
abnormal (above 80°C)	128-131	86-174	86-174	82-104	82-92	82-104	82-174	-
mean	130 (2)	112 (21)	114 (23)	94 (6)	86 (7)	90 (13)	105 (36)	-
total	83 (31)	91 (36)	73 (67)	61 (33)	62 (36)	62 (69)	67 (136)	43 (64)
	Depth 5 km							
Calculated temperatures :								
background (below 100°C)	28-98	56-98	28-98	54-97	52-98	52-98	28-98	40-90
mean	65 (23)	77 (6)	67 (29)	80 (20)	74 (16)	77 (36)	73 (65)	67 (59)
abnormal (above 100°C)	100-205	102-280	100-280	101-179	101-144	101-179	100-280	101-118
mean	136 (8)	156 (30)	151 (38)	131 (13)	116 (20)	122 (33)	138 (71)	106 (5)
total	83 (31)	142 (36)	115 (67)	100 (33)	97 (36)	99 (69)	107 (136)	70 (64)

* Bracketed are numbers of logged boreholes

80 and 100 °C (Fig. 10). Inside the 100 °C isotherm temperatures may rise up to 120-150 °C in the Tunka and Barguzin basins, and up to 150-200 °C beneath Baikal (Golubev, pers. commun.). Highs of above 100 °C are anticipated in Southeastern Transbaikalye and in the Borgoi, Uda and Eravnoye basins.

The intervening areas are at about 80 °C. The temperature difference between the craton and the fold areas averages 35 °C.

5. — THE NATURE OF GEOTHERMAL ANOMALIES

Regional and local geothermal anomalies occur throughout the study region, as shown by heat flow measurements and the temperature distribution at depths of 0.5 to 5 km. They are mainly associated with rift basins in the central and Western Baikal rift zone and with areas involved in Cenozoic activity in Southeastern Transbaikalye; anomalies were even found in some localities of the Southern Siberian platform. The magnitude of the anomalies is controlled by the structure and topography of the area, by the presence and thickness of permafrost, by vertical lithological and structural heterogeneity of the crust and the related variations in thermal conductivity, by underground (especially hydrothermal) water circulation, and by variations in the contributions of heat from crustal and mantle radioactivity to the heat flow.

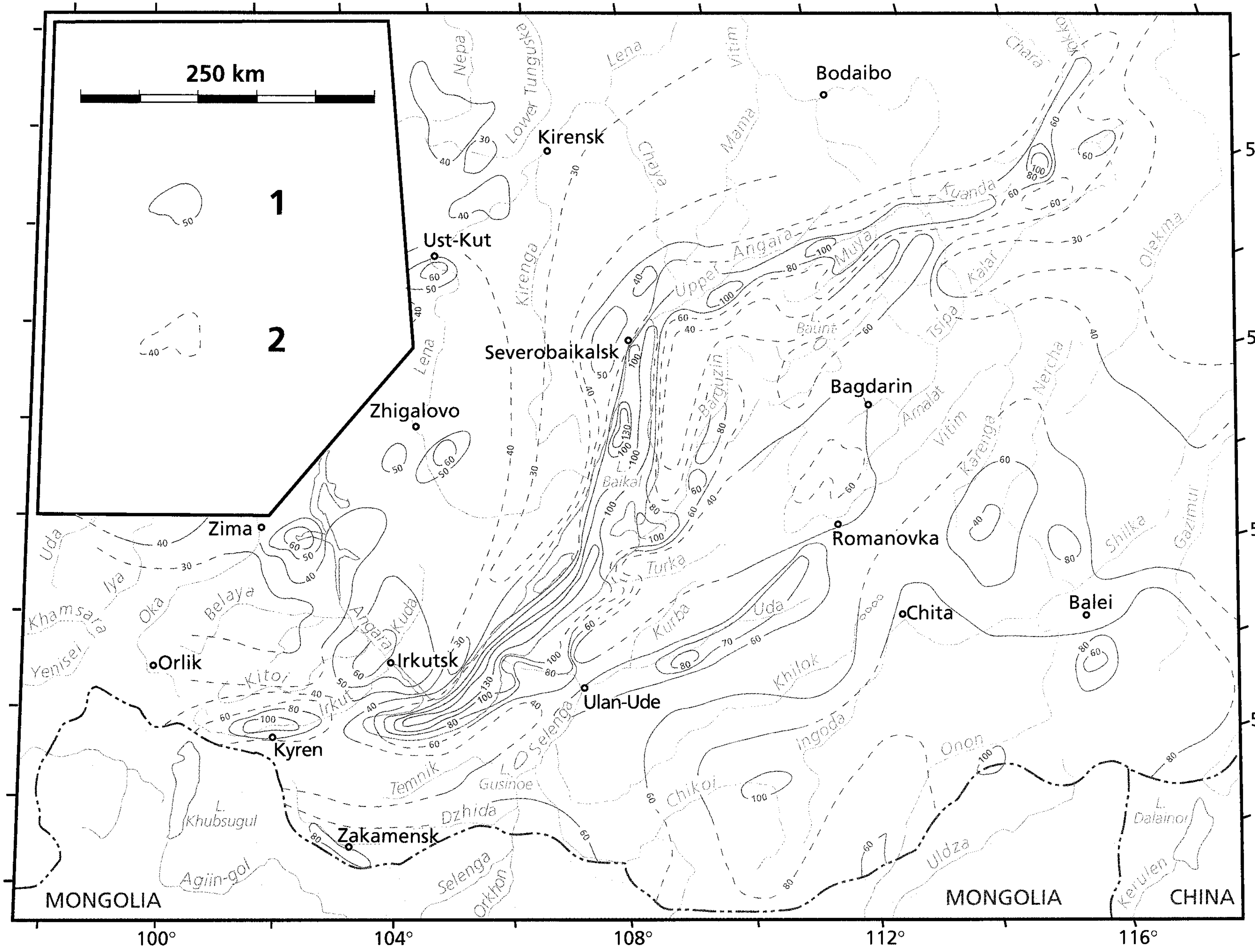
The regional heat flow in the mountains around the rift basins and interbasinal links of the Baikal rift zone, as well as in the adjacent areas of Transbaikalye and Southern Siberian platform, is dominated by conductive heat transfer. The radioactive heat contributes the greatest to the regional flux in Transbaikalye (60-70 %) and the least (less than 30 %) in the Baikal rift zone (Fotiadi, 1987; Dorofeeva *et al.*, 1994). The rest of the heat flow is provided by the mantle which in stable areas, contributes approximately one third of the total heat flux.

Within permeable crust, for example, in fracture zones beneath the rift basins, the contribution from the mantle increases by a factor of 1.5 to 2. This is due to excess deep heat transmitted by convection from fissure intrusions or deeply-rooted hydrothermal venting sites. Thus, local high anomalies which are superimposed on the regional picture (Fig. 7 to 10) are due to tectonothermal activity and convective transfer of heat from highly permeable and active zones of the uppermost crust.

6. — CONCLUSION

Terrestrial heat flow is a fundamental geophysical indicator of the energy status of the Earth's interior and how it acts in different geodynamic processes, for example in rifting.

Refined and updated maps of the heat flow and temperature distribution at 1, 3 and 5 km depths in the Baikal rift zone and the adjacent southernmost Siberian platform and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Tsipa
Severobaikalsk
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Karenga
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Transbaikalye provide further evidence of the complex structure of the region. The geothermal field of the region correlates with altitudes of erosional surface and topographic contrasts, with hypocentres depth, with hydrothermal activity, seismicity, and electrical conductivity. The best correlation is with tectonic activity. Areas delineated by their mean heat flow correspond roughly with tectonic provinces. Among them, the Baikal rift zone is the most prominent feature which appears on the heat flow map as a series of relatively narrow regional anomalies and unevenly distributed local thermal highs, all of which are associated with the rift basins.

The presence of regional heat flow anomalies, as is the onset of rifting, is related to the ascent of hot asthenospheric diapirs in zones of lithospheric structural heterogeneity. Local thermal anomalies are produced by upper-crustal sources such as fissure-mantle injections or venting. Their distribution is controlled by topographic, erosional (or depositional) and hydrogeological conditions. The local highs are often associated with zones of active faulting which provide channels for heat and mass transport.

The contrasting and laterally variable heat flow of the Baikal rift zone, together with lithospheric thinning and intense contemporary tectonism (made evident by the high seismicity), indicates that the rifting is in full development.

In the Transbaikalian fold area (especially in its south-eastern part), the mountain ridges are more heated than intermontane depressions. The geothermal field of the Southern Siberian platform is fairly smooth which testifies to its tectonic stability. Zones of abnormally high flux of above 75-100 mWm^{-2} in the Baikal rift zone and Transbaikalye, especially those out by numerous faults and abundant hydrothermal vents, are considered to be prospective for the extraction of geothermal energy. Geothermal conditions of the Southern Siberian platform are favourable for the accumulation of hydrocarbons beneath the evaporitic series and in reservoirs at the base of the sedimentary cover, and are thus productive for oil and gas.

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Figure 9

Temperature (°C) distribution at a depth of 3 km, compiled from measurements and also calculated by Dorofeeva and Lysak (1989) (on land) and Golubev (1982) (beneath Lake Baikal).
Isotherms (contour interval : 10 °C) measured or calculated (1), hypothetical (2).

Répartition des températures à 3 km de profondeur établie à partir des mesures et des calculs de Dorofeeva & Lysak (1989) à terre, et de Golubev (1982) sous le lac Baïkal.
Isothermes (intervalle : 10 °C) mesurés ou calculés (1), ou hypothétiques (2).

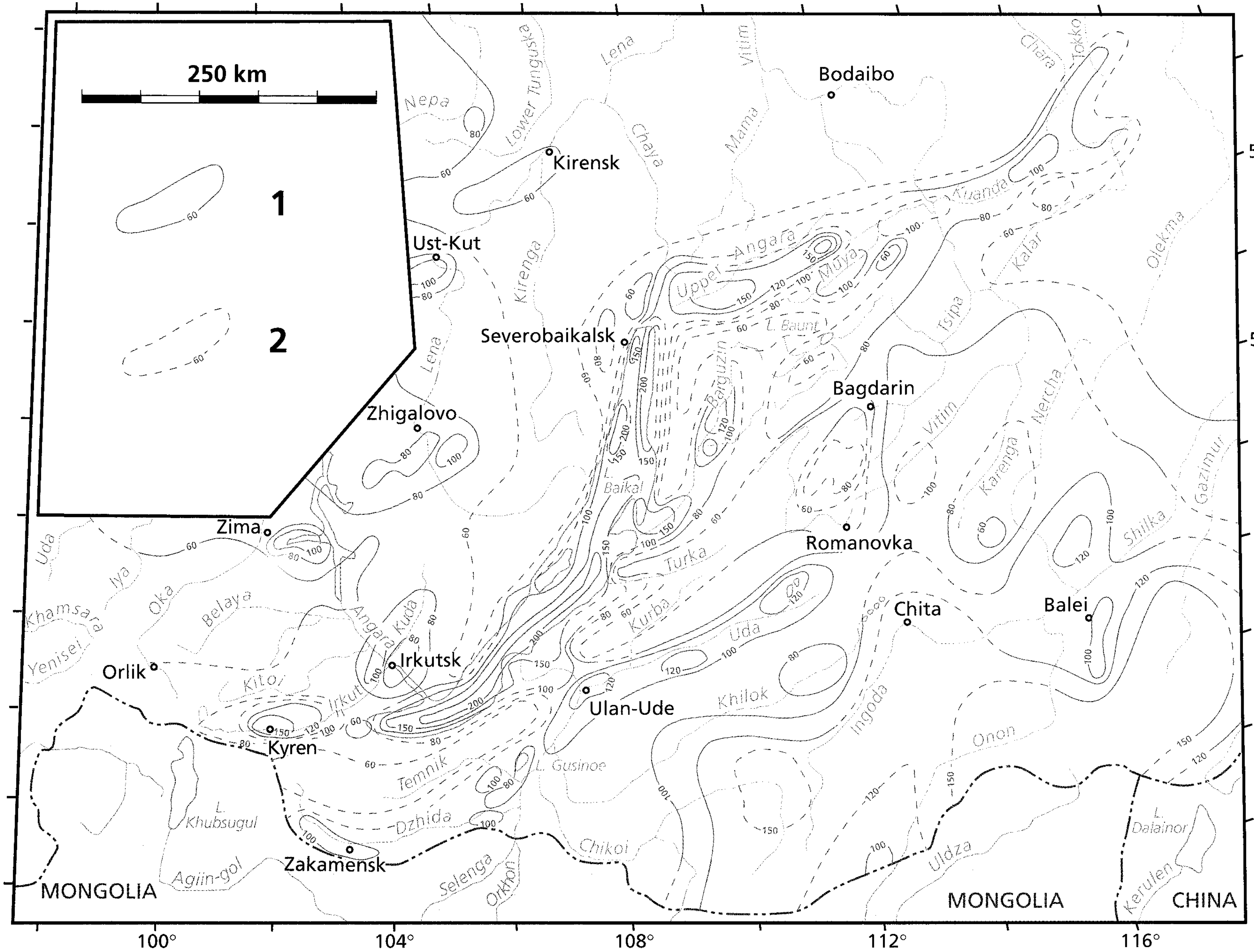
250 km
1
2
60
Bodaibo
Kirensk
Ust-Kut
Severobaikalsk
Bagdarin
Zhigalovo
Zima
Romanovka
Chita
Balei
Irkutsk
Orlik
Ulan-Ude
Kyren
Zakamensk
MONGOLIA
MONGOLIA
CHINA
Nepa
Lower Tunguska
Lena
Vitim
Chaya
Mama
Chara
Tokko
Nyanda
Kalar
Olekma
Upper Angara
Muya
L. Baunt
Tsipa
Kirenga
Barguzin
Baikal
Nercha
Karenga
Gazimur
Shilka
Turka
Kurba
Uda
Khilok
Ingoda
Onon
Uldza
Kerulen
L. Dalainor
Iya
Oka
Belaya
Khamsara
Yenisei
Kitoi
Irkut
Angara
Kuda
Temnik
Dzhida
L. Gusinoe
Chikoi
Selenga
Orkhon
L. Khubsugul
Agiin-gol
56°
54°
52°
50°
100°
104°
108°
112°
116°
60
80
100
120
150
200

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Figure 10

Temperature (°C) distribution at a depth of 5 km, compiled from measurements and also calculated by Dorofeeva & Lysak (1989) (on land) and Golubev (1982) (beneath Lake Baikal).
Isotherms (contour interval : 20 °C) measured or calculated (1), hypothetical (2).

Répartition des températures à 5 km de profondeur établie à partir de mesures et aussi des calculs de Dorofeeva & Lysak (1989) à terre, et de Golubev (1982) sous le lac Baïkal.
Isothermes (intervalle : 20 °C) mesurés ou calculés (1), ou hypothétiques (2).