CONDUCTIVE AND CONVECTIVE HEAT FLOW IN THE BOTTOM OF LAKE BAIKAL AND IN THE SURROUNDING MOUNTAINS

FLUX THERMIQUE CONDUCTIF ET CONVECTIF AU FOND DU LAC BAÏKAL ET DANS LES MONTAGNES ENVIRONNANTES

Vladimir A. GOLUBEV

GOLUBEV, V.A. (1998). — Conductive and convective heat flow in the bottom of Lake Baikal and in the surrounding mountains. [*Flux thermique conductif et convectif au fond du lac Baïkal et dans les montagnes environnantes*]. — *Bull. Centre Rech. Elf Explor. Prod.*, 22, 2, 323-340, 17 fig.; Pau, May 29, (1998) 2000. — ISSN: 1279-8215. CODEN: BCREDP.

Actuellement, le flux thermique au fond du lac Baïkal a été déterminé dans plus de 700 sites. Le flux moyen mesuré est de 73.5 ± 24 mW/m^2 ; après correction topographique et pour la sédimentation, il est de 77.8 ± 24 mW/m^2. La valeur du flux thermique varie largement dans une gamme de 0 à 20.000 mW/m^2. Les valeurs nulles ont été obtenues dans des secteurs à glissements de terrain récents tandis que les maxima sont attribués à des secteurs présentant une activité hydrothermale. Dans le Nord du lac Baïkal, quelques anomalies positives et étroites du flux thermique sont associées à des failles bordières de piedmont voisines de la côte, des deux côtés du lac. Une forte anomalie du flux thermique s'étend sur environ 8 km le long de la côte sud-est de la partie médiane du lac Baïkal. Elle coïncide avec une faille détectée par sismique réflexion multicanaux.

L'anomalie positive la plus importante s'étend sur 30 km dans la partie sud du lac Baïkal. Il a été tenté d'en expliquer l'existence comme la conséquence de l'injection de matériel mantellique dans la croûte supérieure. Des estimations faites en fonction du flux thermique hydrothermal indiquent qu'une telle intrusion, même si elle s'étendait sur 10 à 12 km, ne pourrait maintenir l'anomalie du Sud du lac Baïkal que pendant moins d'un million d'années. Si l'anomalie avait existé plus longtemps, elle devrait avoir été alimentée par des sources renouvelables de chaleur. Les eaux souterraines peuvent constituer une telle source. En pénétrant dans des failles jusqu'à des profondeurs de 3 à 6 km et davantage sous les épaulements du rift, elles se réchauffent dans le champ thermal régional puis circulent vers le bassin du lac Baïkal où elles remontent comme des eaux thermales par le fond faillé du lac. La modélisation montre qu'une telle redistribution de chaleur profonde par déplacement des eaux souterraines est aussi responsable des flux thermiques inférieurs à 40 mW/m^2 observés dans les forages peu profonds réalisés dans les épaulements du rift.

Vladimir GOLUBEV, Institute of the Earth's Crust, Russian Academy of Sciences, Siberian Branch, Lermontova Street, 128, 664033 Irkutsk, Russian Federation (foreign@earth.crust.irk.ru). — June 1995.

Mots-clés : Rift du Baïkal, Flux thermique, Champ géothermal, Activité hydrothermale

ABSTRACT

Up until now heat flow through the bottom of Lake Baikal has been determined in more than 700 sites. Mean measured flux is 73.5 ± 24 mW/m^2; corrected for topography and sedimentation it is 77.8 ± 24 mW/m^2. Heat flow values vary greatly in a range from 0 to 20 000 mW/m^2. The zero values were obtained in localities of recent landslides, while the extreme highs are attributed to sites of hydrothermal discharge. In the northern Baikal, narrow positive heat flow anomalies are associated with near-shore faults extending along bottom foothills on both sides of the basin. An intense heat flow anomaly, about 8 km wide, stretches along the southeastern side of Central Baikal. Its position coincides with a fault detected by seismic multichannel reflection.

The most prominent positive anomaly is the one over 30 km wide, found in South Baikal. An attempt was made earlier to explain this anomaly by injection of mantle material into the upper crust. Estimations performed with regard to hydrothermal outflow of heat show that such an intrusion, even if it were 10 to 12 km wide, would be able to sustain the anomaly in South Baikal for less than 1 My. If the anomaly had existed for a longer time it must have been fed by renewable sources of heat. Ground waters may provide such a source. They penetrate along faults to depths of 3 to 6 km and deeper beneath the rift shoulders where they heat-up in the regional thermal field, then move towards the Baikal basin and ascend through the faulted bottom of Lake Baikal already as thermal waters. Modelling shows that such redistribution of deep heat by moving ground waters is also responsible for low heat flows of less than 40 mW/m^{2}observed in shallow boreholes in the rift shoulders.

Keywords: Baikal Rift, Heat flow, Geothermal field, Hydrothermal activity

1279-8215/00/0022-0323 $ 3.60

CONTENTS — *TABLE DES MATIÈRES*

INTRODUCTION

Data from super-deep boreholes on continents and detailed studies of mid-oceanic spreading zones have shown that the amount of heat transported by convection is often comparable to that transfered conductively, or even a few times higher. The convective component of heat outflow is easier to evaluate in mid-oceanic rifts where the excess heat supplied into the crust by intrusions can be calculated from the known spreading rate. Moreover, its latent portion can be found as a difference between theoretical total heat loss and conductive output measured by routine thermal probing. As far as the continental rifts are concerned, the problem of assessing the amount of mantle material supplied into the crust by rifting and hence, the amount of the associated heat, remains so far unresolved. A high output of convective heat can be expected in continental rifts judging by inherent great variability of conductive flux, high hydrothermal and seismic activity, ongoing extension and faulting. Neglecting the convective component of heat may introduce serious misinterpretation of thermal regime and evolution of continental rifts.

Regional convective heat output can presumably be obtained by summing up its values for separate hot springs, local-scale structures or zones. For the Baikal basin, the mean convective heat is closely balanced by abnormally low heat flow on the rift shoulders. In this respect a question arises as to whether thermal highs in the basins of the Baikal rift may result from redistribution of deep heat by ground waters which move basinwards from below the rift shoulders.

The basin occupied by Lake Baikal is the central segment of the Baikal rift. The lake extends for 636 km with an average width of 40 to 50 km. Its three sub-basins (North, Central and South Baikal) have maximum depths of 920 m, 1637 m and 1416 m respectively, while the bordering ridges have 500 to 2400 m of elevation above the lake level (Fig. 1 and LOGATCHEV, 1993). According to multichannel seismic reflection (Fig. 2), maximum sediment thicknesses are 7, 7.5 and 4.4 km for the South, Central and North sub-basins of Baikal, respectively (HUTCHINSON *et al.*,1992).

Until now, heat flow through the bottom of Baikal has been measured in more than 700 sites. The results were partly reported earlier (LUBIMOVA & SHELIAGIN, 1966; DUCHKOV *et al.*,1979; GOLUBEV, 1982a; 1982b; 1987; 1993; GOLUBEV *et al.*,1993; KLERKX *et al.*,1993); newly-obtained data is first revealed in the present paper. A number of papers explain the evolution and state of the regional thermal field of the area (ZORIN & OSOKINA, 1984; GOLUBEV, 1990; 1991; LYSAK, 1978; 1995). Submarine investigations on Baikal with manned submersibles (CRANE *et al.*,1991a, 1991b) have rekindled interest in geothermal studies of the lake.

1. — MEASUREMENT TECHNIQUES AND INSTRUMENTS

Geothermal measurements on Lake Baikal have so far been performed by thermal probes of different types. Heat flow is obtained as a product of gauged temperature gradient in sediments and their thermal conductivity. Until 1976, geothermal gradients were taken by autonomous instruments (LUBIMOVA & SHELIAGIN, 1966; DUCHKOV *et al.*,1979). Nearly 90% of data was obtained by a non-autonomous (cable) multi-sensor thermoprobe described in detail in GOLUBEV (1987) and GOLUBEV *et al.* (1993).

Almost all heat flow stations on Lake Baikal are located on profiles across the lake, 3 to 4 km apart on average; the distance was reduced to 1 or even 0.2 km within anomalies. Measurement sites were positioned from vessel velocity and time spent for covering the respective space between the sites. At 5 to 10 km offshore, uncertainty of positioning was less than 1 km, increasing to 2 km in the axial part of the lake. Since 1990, site locations have been determined by MAGELLAN Global Positioning Satellite Receivers.

Instrumental error inherent in heat flow data amounts to 15%. The error may exceed 25% at stations where the probe could not penetrate deep enough due to high density of sediments.

2. — CORRECTIONS TO MEASURED HEAT FLOWS

Measured heat flow can considerably deviate from its normal values. The deviations may partly be due to conductive redistribution of heat. Among the most important factors in this respect are uneven topography and thermal conductivity contrasts between sediments and crystalline basement.

Deep heat flow undisturbed by topography was determined by introducing a topographic correction to its measured values, separately for each heat flow site by the method of

LACHENBRUCH (1968). The correction was the greatest in the area where the steep northwestern submarine slope of Lake Baikal meets the basin floor: there, it allows for a 10-20% increase in the measured heat flow. On the Academician ridge and Posol'sk Bank (Fig.1) the topographic correction is negative and reaches 5 to 10%.

Mean thermal conductivity of the upper 1 to 3 metres of Lake Baikal sediments measured *in situ* is about 1 W/m°C. It increases with depth but probably does not reach that of the basement even in the lowermost sediment layers (GOLUBEV, 1982a). On its way upwards from great depths, heat flux partly flows around low-conductive sediment bodies that must produce intense marginal heat flow maxima (refraction effect). In Baikal, this effect is expected to be most noticeable near the northwestern side of the basin, where sediments are the thickest (Fig. 2).

The amount of refraction-induced bias of heat flow was estimated by the analytical method (LACHENBRUCH & MARSHALL, 1966). For the purpose of modelling, the geometry of sediment fill of Lake Baikal was assimilated to an elliptical half-cylinder with a 6 km short half-axis and a 15 km long axis. Mean thermal conductivities inside and outside the cylinder were assumed to be 1.5 W/m°C and 2.5 W/m°C, respectively. The results are shown in Figure 3a which indicates that heat flow in sediments makes no more than 0.84% of its undisturbed value. Moreover, because of refraction, heat flow just near the basin edges, where sediments are thin, exceeds the undisturbed flux by a magnitude of 1.4. Hence, the total difference will be 1.4:0.84 = 1.67 times.

Figure 3b shows the pattern of heat flows measured in a 10 km-wide stripe of the bottom near the northwestern side of South and Central Baikal. Contrary to our expectations, the measured heat flow does not change near the shore, where it is 51 ± 8.9 mW/m^2 on average. The only suitable explanation for this steadiness would be the absence of any considerable contrast in mean thermal conductivity between sediments and basement. The low-conductive sediment layer must not be thicker than 1 to 2 km. High thermal conductivity of Lake Baikal sediments at greater depths may be due to excessive contents of diatoms reaching 30 to 60% (see GOLDYREV, 1982). According to TADA (1991), such sediments evolve diagenetically into opal-CT already under temperatures of 50-60 °C and pressures of 200 to 300 bar; at temperatures 10-15 °C higher they may partly grade into quartzite. Thermal conductivity of such siliceous sediments is higher than that of granitic bedrock. Such temperatures and pressures must exist in Baikal sediments already at depths of 1.5 to 2 km. Hence, the upper and the lower sediment units produce opposite marginal effects which almost cancel each other out.

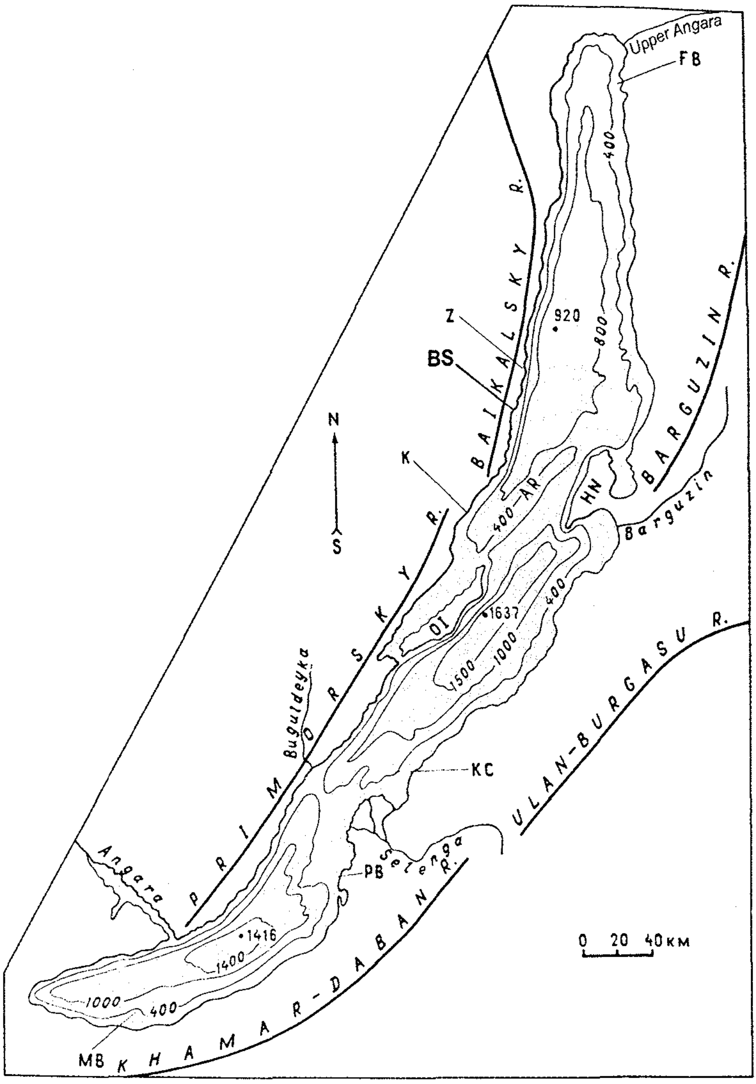


FIGURE 1
Lake Baikal and the surrounding rift shoulders. Bathymetric contour lines in metres. Abbreviations stand for geographical names: FB = Frolikha Bay, Z = Zavarotny cape, BS = Bolshoy Solonzovy cape, K = Kocherikovo, AR = Academician Ridge, HN = Holy Nose peninsula, OI = Olkhon Island, KC = Kukui Canyon, PB = Posolsk Bank, MB = Murin Bank.

Carte du lac Baïkal et des chaînons bordant le rift. Les courbes bathymétriques sont graduées en mètres et les abbréviations correspondent aux entités géographiques (voir ci-dessus).

Another distorting factor is due to the continuous accumulation of sediments whereby some portion of heat is spent heating up newly deposited colder layers. Syn-rift sedimentation in Lake Baikal started some 60 My ago. Throughout this time, the basin has accumulated up to 7.5 km of sediments or perhaps even up to 10 km (HUTCHINSON *et al.*, 1992; SHOLZ *et al.*,1993). The upper 1000 to 2000 m of sediments were deposited throughout the last 3 to 4 My during the "fast rifting" stage while the lower layers formed during the "slow rifting" stage (LOGATCHEV, 1993). As mentioned, getting buried for 1 to 2 km and deeper, sediments apparently enhance considerably in thermal conductivity that lowers the disturbing effect of sedimentation. Taking into consideration such a pattern of sedimentation dynamics and assuming that the thermal conductivity of the Baikal sediments corresponds to that of sandstones, nomograms of HUTCHISON (1985) were used. As a result, the highest

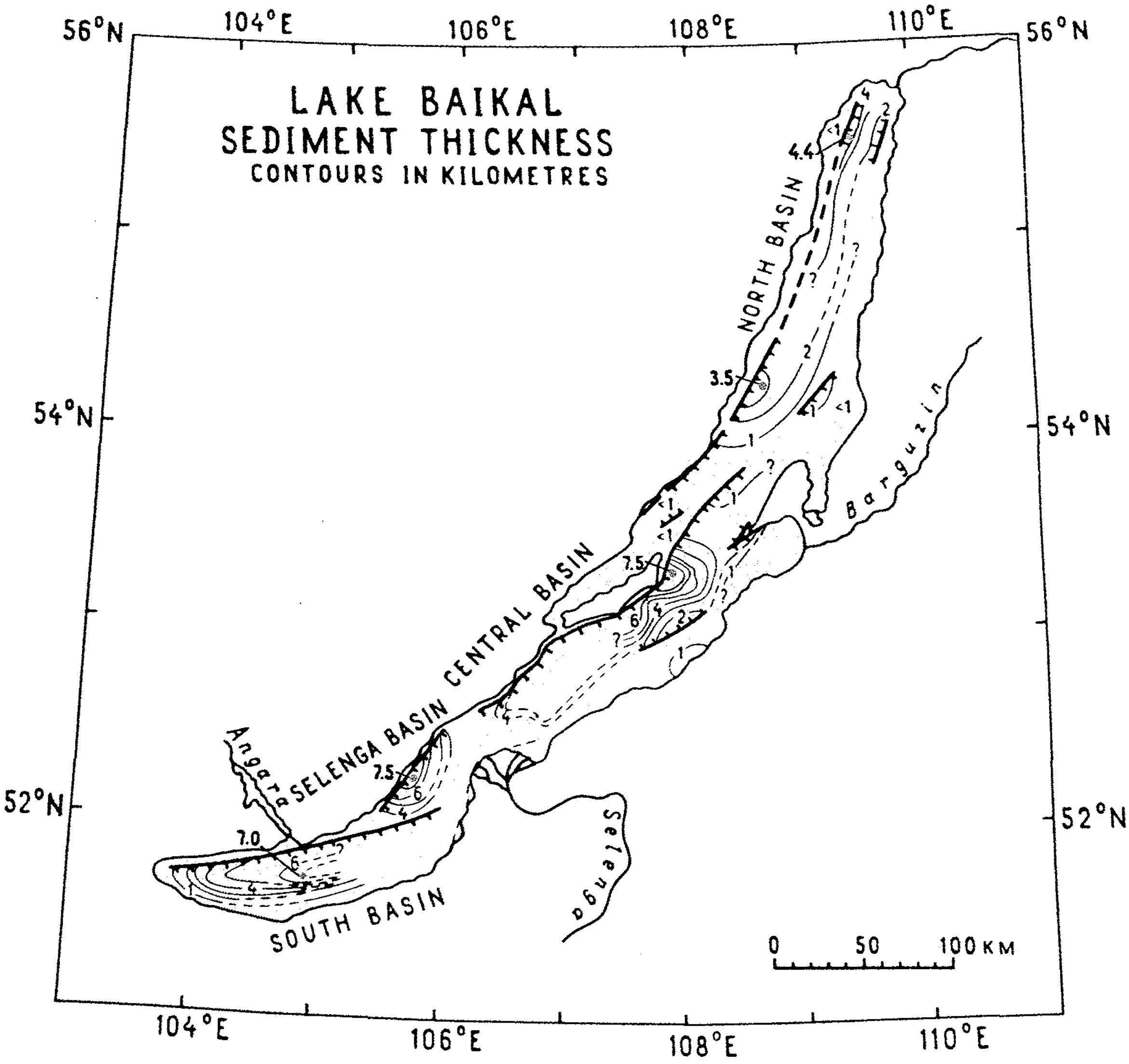


Figure 2

Sediment thickness and major faults on the bottom of Lake Baikal, according to multichannel reflection (sediment thickness according to Hutchinson *et al.*, 1992, fig.4; faults according to Hutchinson *et al.*, 1992, fig.4 and Scholz *et al.*, 1993).
Dashed lines outline estimated sediment thicknesses and dark blue dots maximum thicknesses.

Épaisseur des sédiments et failles majeures du lac Baïkal, d'après la sismique réflexion (épaisseur des sédiments d'après Hutchinson et al., *1992, fig.4 ; failles d'après Hutchinson* et al., *1992 et Scholz* et al., 1993) .
Les courbes en tireté indiquent l'épaisseur estimée des sédiments et les points bleu foncé les épaisseurs maxima.

sedimentation correction even in the vicinity of Selenga delta turned out to be within 20 and 25%.

The two major corrections (for topography and sedimentation) partly cancel each other out, both being comparable in amount and opposite in sign. The resulting correction to the regional heat flow adds only 6% to its mean empirical value.

At the same time, sedimentation effect is complicated by occasional episodes of redeposition due to submarine landslides, mudflows, etc. As a result, the fairly thick layer of evenly cold sediments is deposited at once at the base of submarine slopes. Heat flow measured in such sediments immediately after deposition will be about zero, and will grow gradually to approach its original value. Figure 4b shows that after deposition of layers 1, 5, 10, 20, and 100 metres thick, heat flow measured there at a depth of 1 metre would gain 80% of the original value in 1, 25, 100, 400 and 10 000 years respectively (Von Herzen & Uyeda, 1963).

Upslope, where the sediments came from, a layer becomes exposed, which used to be at a certain depth and hence was hotter than the ambient lake floor. After the sediments have moved away, heat flow there will long retain its value, exceeding the background one (Fig. 4a). The respective curves in Figure 4a and 4b are symmetrical, so in areas where such offsetting events took place, existence of two matching anomalies

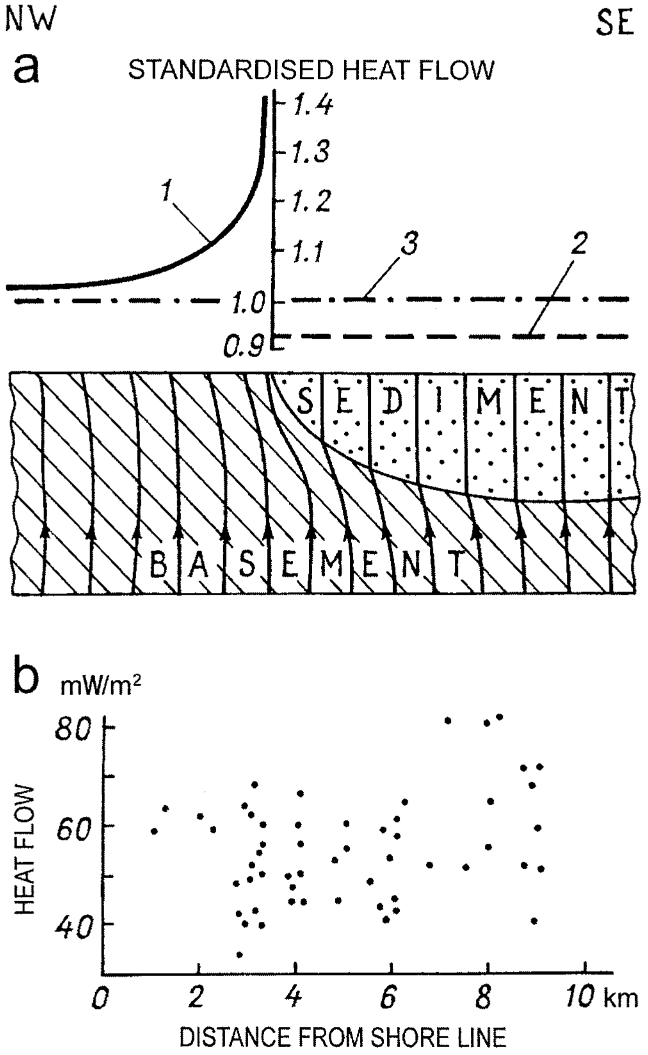


FIGURE 3

Heat flow near the northwestern shore of South and Central Baikal.

(a) results of modelling of the refraction effect for the case when thermal conductivity of sediments is 1.50 W/m °C and that of the basement is 2.5 W/m °C.

Standardised heat flow: 1 = through the basement near the basin edge; 2 = through the sediments; 3 = undisturbed heat flow .

(b) measured heat flows corrected for topography; arithmetic mean: q_1 = 51.9 mW/m².

Flux thermique près de la côte NW du lac Baïkal Sud et Central.

(a) résultats de la modélisation de l'effet réfraction dans le cas où la conductivité thermique des sédiments est de 1.50 W/m °C et celle du socle de 2.5 W/m °C. Flux thermique normalisé : 1 = au travers du socle près de la bordure du bassin ; 2 = au travers des sédiments ; 3 = flux thermique non perturbé.

(b) valeurs du flux thermique après correction topographique ; moyenne arithmétique : q_1 = 51.9 mW/m².

should be expected, equal in magnitude and opposite in sign. Detailed geothermal studies show that such anomalies exist in Lake Baikal (GOLUBEV, 1982a).

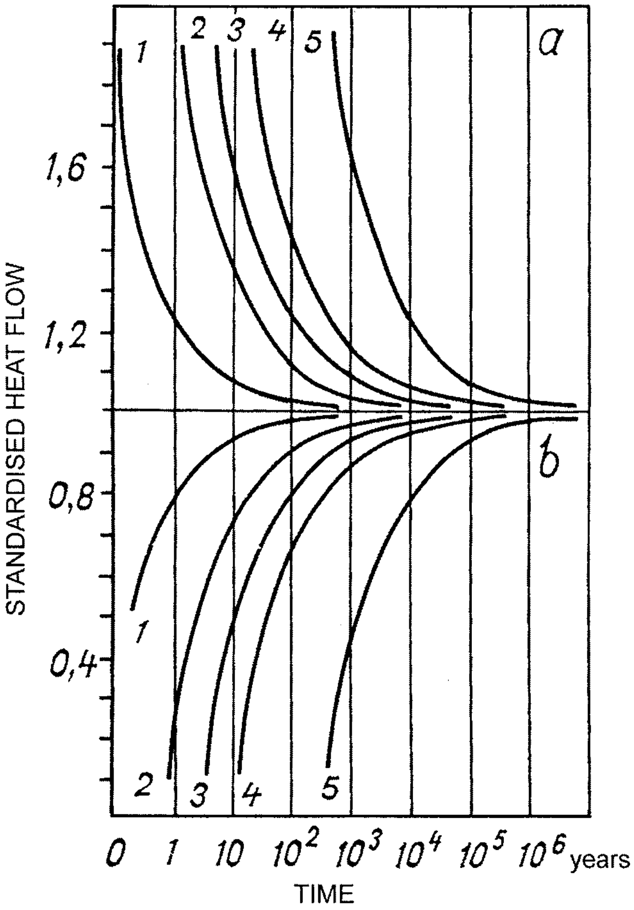


FIGURE 4

Variations of heat flow at a depth of 1 m (standardised versus undisturbed deep flux) as a function of time after: removal (a), or redeposition (b) of a sediment layer of 1, 5, 10, 20 and 100 metres thick (numbered successively). Thermal diffusivity of sediments is taken to be 3 x 10^{-7} m²/s (after VON HERZEN & UYEDA, 1963).

Variations du flux thermique en fonction du temps, à une profondeur de 1 m et normalisé par rapport au flux profond non perturbé, après : enlèvement, (a), ou redéposition (b), d'une couche de sédiments de 1, 5, 10, 20 et 100 mètres d'épaisseur (couches numérotées de 1 à 5 respectivement). Le pouvoir de diffusion thermale des sédiments est choisi à 3 x 10^{-7} m²/s (d'après VON HERZEN & UYEDA, 1963).

Theoretical data shows that seasonal temperature variations on the lake bottom may considerably disturb the corresponding heat flow. The deviations should have opposite signs for summer and winter. However, heat flow measurements held in the same sites in summer and in winter (from ice) did not reveal any significant difference (GOLUBEV, 1982a). Taking this fact into consideration and keeping in mind that nearly all geothermal studies on Baikal were held at depths greater than 250 m, climatic variations are neglected in the present study.

3. — DISTRIBUTION OF CONDUCTIVE AND CONVECTIVE HEAT FLOWS

3.1. REGIONAL-SCALE PATTERN

Distribution of measured heat flows for 45 profiles and for separate stations within and around the lake is shown in Figure 5. The pattern of mean heat flow is shown by contour lines in Figure 6. Near the north-western edge of South and Central Baikal the flux is relatively low and varies between 50 and 70 mW/m^2; it increases to 100 or locally 200 mW/m^2 approaching the lake axis and towards its southeastern side. A narrow (8 to 10 km wide) zone of abnormal flux extending for over 100 km was discovered in the lower segment of the southeastern slope of Central Baikal. Average heat flow in the Academician ridge varies from below 70 mW/m^2 near Olkhon Island to above 80 to 90 mW/m^2 northeast of it. In North Baikal, low and stable flux in the lake axis sharply increases, especially to the eastern side of the lake where a few kilometres wide anomaly stretches for several dozen kilometres.

To obtain relevant regional-scale geothermal parameters, mean heat flows were calculated separately for 10' (WE) by 6' (NS) rectangles of the lake bottom. The resultant mean over the 196 rectangles is 73.5 ± 24 mW/m^2 before correction for topography and sedimentation, and 77.8 ± 24 mW/m^2 after correction.

3.2. NORTH BAIKAL SUB-BASIN

The particularity of the northern part of the Baikal basin is the presence of a large number of onshore hot springs. Not surprisingly, the available geothermal, hydrophysical and hydrochemical data implicitly or explicitly indicates hydrothermal discharge under the water (Golubev, 1982a, 1993; Golubev *et al.*,1993; Klerkx *et al.*,1993).

Fairly even heat flow of 50 to 70 mW/m^2 over 60% of the bottom of North Baikal becomes highly variable shorewards averaging 80 to 100 mW/m^2 in lower and median parts of the eastern underwater slopes. Data on individual profiles and stations (Fig. 5) shows abnormal flows of 300 to 1000 mW/m^2 and sometimes several watts per square metre, restricted to small areas on the bottom of the lake near both sides of the sub-basin, throughout all its 220 km length up to the Holy Nose peninsula (Fig. 1). Mean flux outside the anomaly is 72 mW/m^2.

The extremely high heat flows, dozens of times in excess of the mean value, can be produced by hydrothermal vents. Direct evidence in Frolikha Bay revealed that the temperature in the lowest 20 metres of water increases by 0.1 to 0.15 °C (Golubev, 1982a, 1993). This growth is accompanied by an increase in electric conductivity of water (Klerkx *et al.*,1993). The highest heat flow measured by Golubev from aboard a vessel is 20 W/m^2, while measurements from "Pisces" submersibles gave a value as high as 37 W/m^2 (Crane *et al.*,1991a). Non-linear downward growth of sediment temperature suggests that thermal water should ascend to the lake bottom at a velocity of 35 m/year (Golubev *et al.*,1993). At the same time no bottom water temperature rise associated with heat flow maxima was found elsewhere (Fig. 7), suggesting that most of hydrothermal discharge through the North Baikal bottom occurs diffusely. Like in oceans, the thick sediment layer precludes the existence of sustained permeable channels for hydrothermal vents while the ascending thermal waters may give almost all their original heat to sediments by diffuse discharge. It means that, as the first approximation, the measured conductive heat flows in the North Baikal bottom can be assumed to total both conductive and convective heat.

Let us estimate convective heat output through the bottom of North Baikal as a difference between empirical conductive flux and the heat flow which would presumably exist without hydrothermal discharge. In the axial part of North Baikal contoured by the 60 mW/m^2, isotherm mean heat flow is 58 mW/m^2 (Fig. 6). This value looks the least disturbed by hydrothermalism and can be taken as a reference for the remaining part of the sub-basin. At the same time, the empirical mean outside the 60 mW/m^2 contour line is 81 mW/m^2 over an area of 7 x 10^3 km^2 (7 x 10^9 m^2). The convective output of heat through the bottom of North Baikal (**Q**) should be (Golubev, 1993):

$$Q = (81-58) \times 1\ \mathrm{mW/m^2} \times 7 \times 10^9\ \mathrm{m^2} = 161 \times 10^6\ \mathrm{W} = 161\ \mathrm{MW}$$

Calculations with the use of solute geothermometers showed that the water in hot springs of the Baikal rift is on average as hot as 99 °C (t_1) at their depths of origin (Golubev, 1982b). As assumed above, on its way upwards, the thermal water gives nearly all its original heat to the surrounding Baikal sediments. Hence, their output temperature (t_2) should equal that of the bottom surface (about 3 °C). From these assumptions and taking the volumetric heat capacity of water (**c**) to be 4.18 x 10^6 J/°C m^3, total flow rate of subaqueous hydrothermal discharge (**m**) can be calculated by the formula:

$$m = \frac{Q}{c(t_1 - t_2)} \qquad 1$$

Substituting the above assumed values into the formula, we obtain a total flow rate of thermal fluid through the bottom of North Baikal amounting to 0.4 m^3/s (Golubev, 1993).

This result may be underestimated. Some of the ascending water apparently has its output temperature warmer than the ambient near-bottom Baikal water. This is shown both by the bottomward increase of water temperature in Frolikha Bay and by its less intense regional growth, observed in the deepest part of North Baikal (Golubev, 1982a; Golubev *et al.*,1993). The latter growth involves a water layer of 3.5 x 10^3 km^2 in area and 20 metres in thickness (Fig. 7). At some stations, the temperature increment within this layer reaches 0.02 °C (Golubev, 1982a), the mean excess temperature in it being 0.01 to 0°C. It is easy to calculate that the volume of the layer is 70 km^3 (70 x 10^9 m^3) and the excess heat amounts to:

$$70 \times 10^9\ \mathrm{m^3} \times 4.18 \times 10^6\ \mathrm{J/^\circ C\ m^3} \times 0.01\ ^\circ\mathrm{C} = 2.93 \times 10^{15}\ \mathrm{J}$$

Complete renewal of bottom water in Lake Baikal occurs on average once in 8 years (Weiss *et al.*,1991). Hence, in one year (3.15 x 10^7 s), 1/8 of the anomalous warm layer gets replaced with colder water from above. Using the data mentioned above, the amount of convective heat input in the very bottom water of North Baikal can be calculated as:

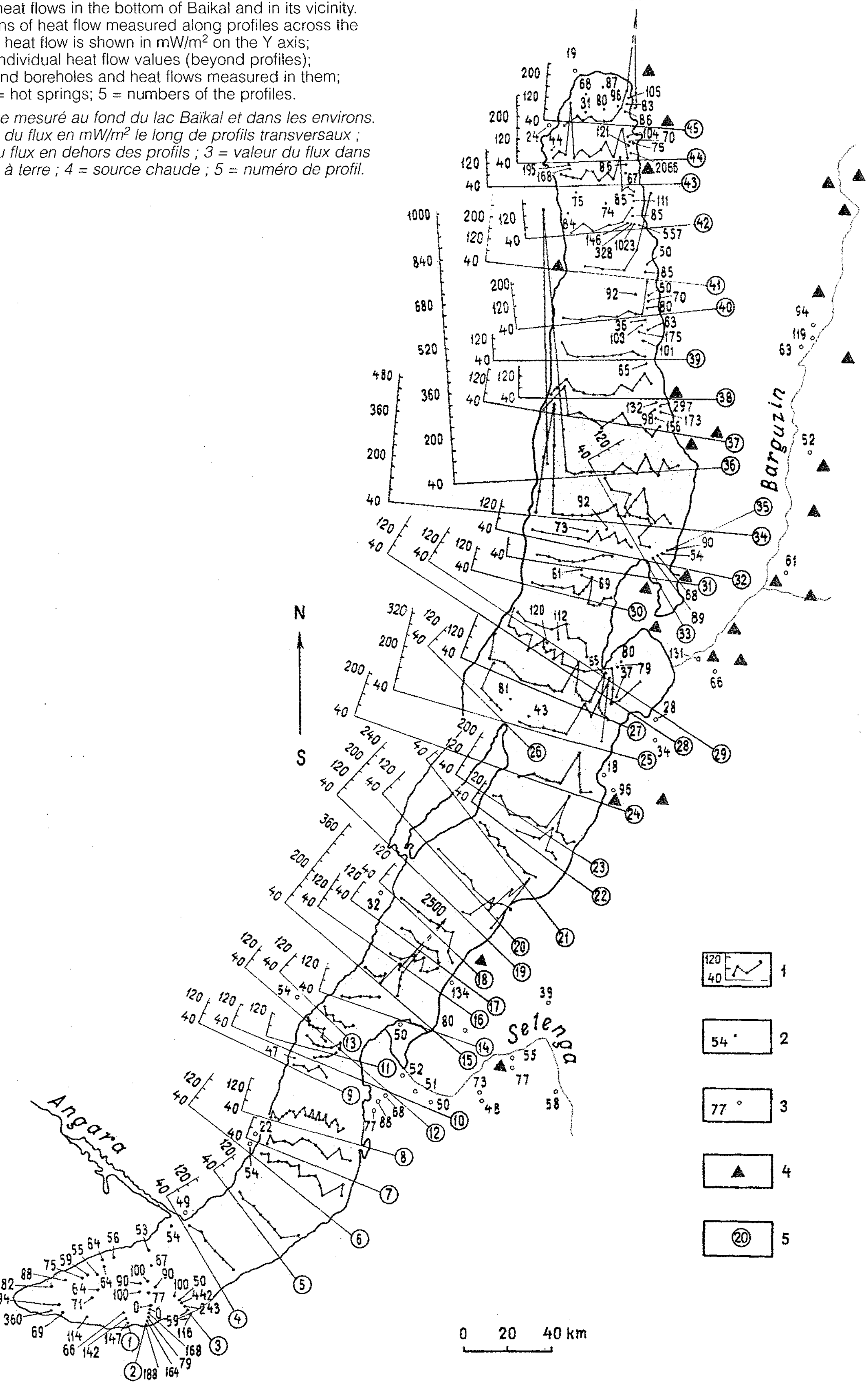
$$2.93 \times 10^{15}\ \mathrm{J} / (8 \times 3.15 \times 10^7\ \mathrm{s}) = 11.7 \times 10^6\ \mathrm{W} = 11.7\ \mathrm{MW}$$

Calculations of static stability of the Baikal water based upon *in situ* measurements of its electric conductivity and temperature are indicative that submarine thermal waters in Lake Baikal have higher salinity and consequently higher density

FIGURE 5

Measured heat flows in the bottom of Baikal and in its vicinity.
1 = variations of heat flow measured along profiles across the lake; heat flow is shown in mW/m^2 on the Y axis;
2 = individual heat flow values (beyond profiles);
3 = on-land boreholes and heat flows measured in them;
4 = hot springs; 5 = numbers of the profiles.

Flux thermique mesuré au fond du lac Baïkal et dans les environs.
1 = valeurs du flux en mW/m^2 le long de profils transversaux ;
2 = valeur du flux en dehors des profils ; 3 = valeur du flux dans des forages à terre ; 4 = source chaude ; 5 = numéro de profil.



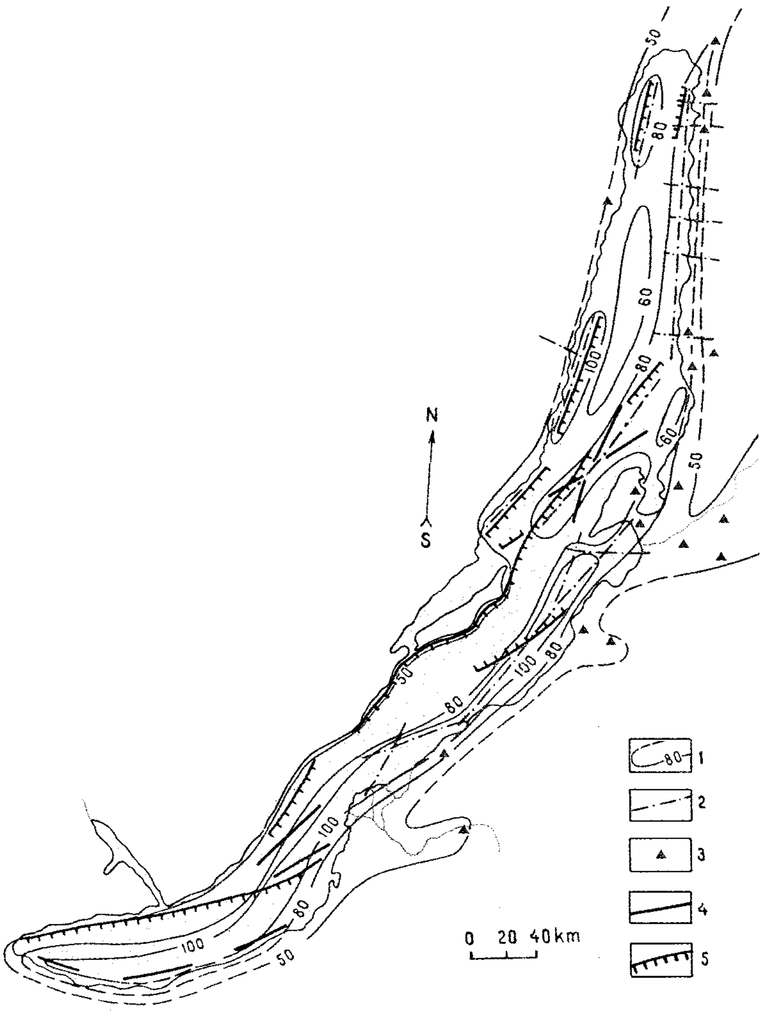


FIGURE 6

Heat flow field and faults on the bottom of Lake Baikal.
1 = contour lines of measured heat flow (in mW/m^2);
2 = axes of heat flow anomalies; 3 = faults associated with hydrothermal discharge and zones of abrupt changes in heat flow values;
4 = faults detected by multichannel reflection (after HUTCHINSON *et al.*, 1992 and SCHOLZ *et al.*, 1993); 5 = on-land hot springs.

Carte du flux thermique et des failles au fond du lac Baïkal.
1 = lignes isoflux en mW/m^2 ; 2 = axe d'anomalie de flux ; 3 = failles associées à des décharges hydrothermales et zones de changement brusque de flux ;
4 = failles détectées par sismique réflexion (d'après HUTCHINSON et al., *1992 et* SCHOLZ et al., 1993*) ; 5 = source chaude terrestre.*

with respect to the ambient water (GOLUBEV, 1982a; GOLUBEV *et al.*,1993; KLERKX *et al.*,1993). Almost all thermal highs shown in Figure 7 are restricted to median parts of underwater basin slopes. Thus, after they discharge, the thermal waters should flow downslope to greater depth. On their way, they lose their excess density by dilution while ambient lake water and only the most mineralised of them can reach the near-bottom "warm" layer and feed it (Fig. 7). Others just get dispersed in the lake water. It means that the above-calculated amount of heat transported by the thermal water is also underestimated.

The calculations should also involve data on 10 onshore springs (Fig. 7). Their proper heat output together with the amount of heat lost on water/rock contacts in conduits make in total 30.3 MW. Total hydrothermal output of heat obtained by summation of its components (161 MW + 11.7 MW + 30.3 MW) is 203 MW over the 220 km long segment of the North Baikal sub-basin, or 0.92 MW/km (GOLUBEV, 1993).

Infiltration of meteoric water is supposed to be responsible for low near-surface heat flow in rift shoulders (see below, section 4). Each kilometre of the North Baikal length receives drainage waters from about 45 km^2 of seaward slopes of the Barguzin and Baikalsky ridges (Fig. 1). Having divided the amount of heat loss per unit length (0.92 MW/km) by this area, we find that due to infiltration, the near-surface heat flow in the ridges around North Baikal must be 21 mW/m^2 lower than the deep flux (GOLUBEV, 1993). The measured heat flows in these ridges are low and range between 20 and 40 mW/m^2 (LYSAK, 1995).

3.3. KOCHERIKOVO-ZAVAROTNY HEAT FLOW ANOMALIES

A few zones of high heat flow were found near the western edge of North Baikal, near capes Kocherikovo and Zavarotny (Fig. 1). The southernmost zone (Kocherikovo, profiles 26 to 28, Fig. 5 and 8) extends for 30 km along the submarine foothill. Another anomaly roughly 50 km long is located 40 km to the north. Its southern half (Bolshoy Solonzovy cape, profile 34) is attributed to the upper and median parts of the underwater slope; the anomaly shifts down to the slope foot and somewhat departs from it by its northern segment (Zavarotny cape, profile 36, Fig. 5 and 8). In the western termination of profiles 26 to 28, the flux is 2 to 3 times as high as that eastwards. Heat flows obtained on profiles 34 and 36 reach 480 and 1000 mW/m^2, which is 10 to 20 times in excess of the background. The anomalies are no wider than 2 km, which testifies to the shallow depths of their sources. They may result from heat exchange between the walls of fault conduits and thermal waters up-flowing from depths of about 2 km. Total rate of discharge over the two anomalous zones is 60 to 80 l/s (GOLUBEV, 1982a).

The existence of these elongated zones of hydrothermal discharge is evidently related to high hydraulic permeability: the western edge of the North sub-basin in this area involves depressions apparently formed by listric faults (Fig. 8). Block rotation caused additional uplift of the footwall and subsidence of the hanging wall. This produced longitudinal grabens 3 to 5 km wide, with their bottoms subsided for 300 to 400 m with respect to the eastern margin of the tilted blocks. The rotation could have induced formation of a fracture zone widening downwards. With such a geometry the zone is highly permeable to ascending water. The common origin of the subaerial and submarine grabens is also evidenced by the fact that the upper layers of their sediment fill are made-up of red

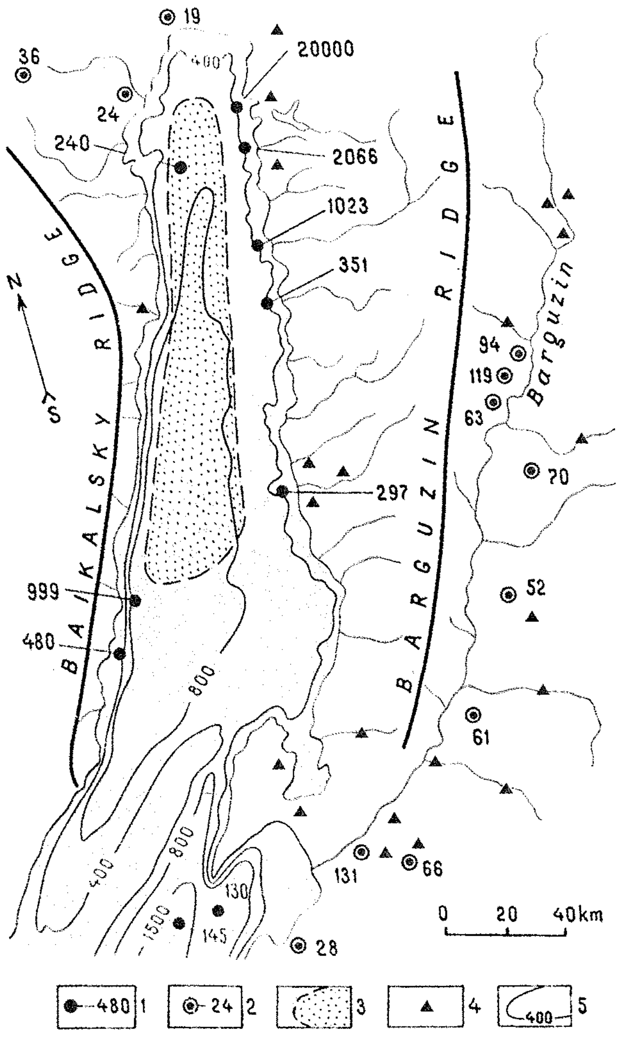


FIGURE 7

Locations of heat flow highs and evidence of hydrothermal discharge on-shore and on the bottom of North Baikal. 1 = extremely high flows on the bottom; 2 = heat flow as measured in on-land boreholes (mW/m²); 3 = area where regional-scale downward increase in bottom water temperatures was found (see text); 4 = hot springs; 5 = bathymetry (in m).

Localisation des valeurs élevées du flux thermique et des manifestations de décharges hydrothermales, à terre et au fond du lac Baïkal Nord. 1 = flux très élevé au fond du lac ; 2 = flux thermique dans des forages à terre (mW/m²) ; 3 = zone à accroissement vers le bas, à l'échelle régionale, des températures d'eau du fond du lac (voir texte) ; 4 = sources chaudes ; 5 = bathymétrie (m).

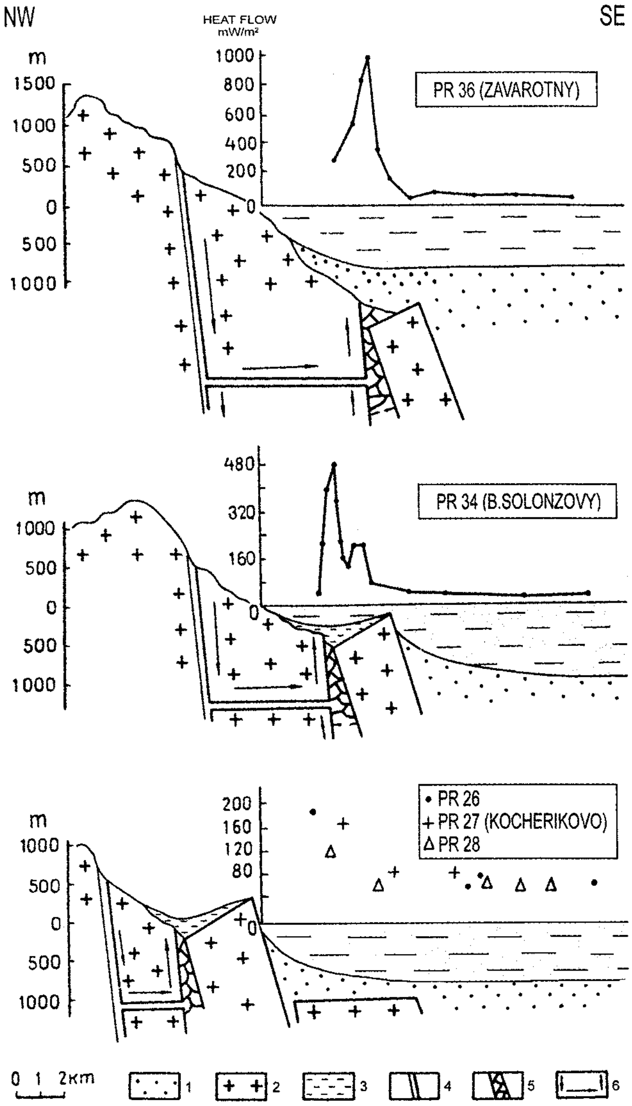


FIGURE 8

Heat flows in and around grabens on the western slope of North Baikal. 1 = recent soft bottom sediments; 2 = basement blocks; 3 = dense clays; 4 = faults, 5 = fracture zones; 6 = direction of ground water movement.

Flux thermique dans le graben du lac Baïkal Nord et son versant occidental. 1 = sédiments meubles récents ; 2 = panneaux de socle ; 3 = argile compacte ; 4 = faille ; 5 = zone broyée ; 6 = direction d'écoulement des eaux souterraines.

dense clays unusual for Baikal (Fig. 8). Note that as the grabens disappear in the area of profiles 29 to 32, so do the edge-related anomalies. Such anomalies are absent from the whole 400 km length of the northwestern side of Central and South Baikal where the grabens are also absent (Fig. 5).

3.4. ACADEMICIAN RIDGE

The Academician ridge is about 140 km long with a sediment cover less than 1 km thick (Fig. 2) and a maximum heat flow of 120 to 150 mW/m² (profiles 26 to 34 and 36, Fig. 5 and 9). In the southwestern part of the ridge, the heat flow is 70 mW/m² on average and amounts to 80 to 100 mW/m² in the northeast, 20 to 40 mW/m² higher than outside the ridge. The anomaly is about 15 km wide. It changes in width along strike, together with a narrowing of the ridge, both being twice as narrow in their central parts than at their extremities. On some of the seven profiles shown in Figure 9, the anomaly is marked by two well-defined peaks. The major high corresponds to the ridge axis; the other one, seen in different profiles, may mark faults on which Central and North Baikal basins subsided on each side of the ridge. The magnitude of the anomaly was esti-

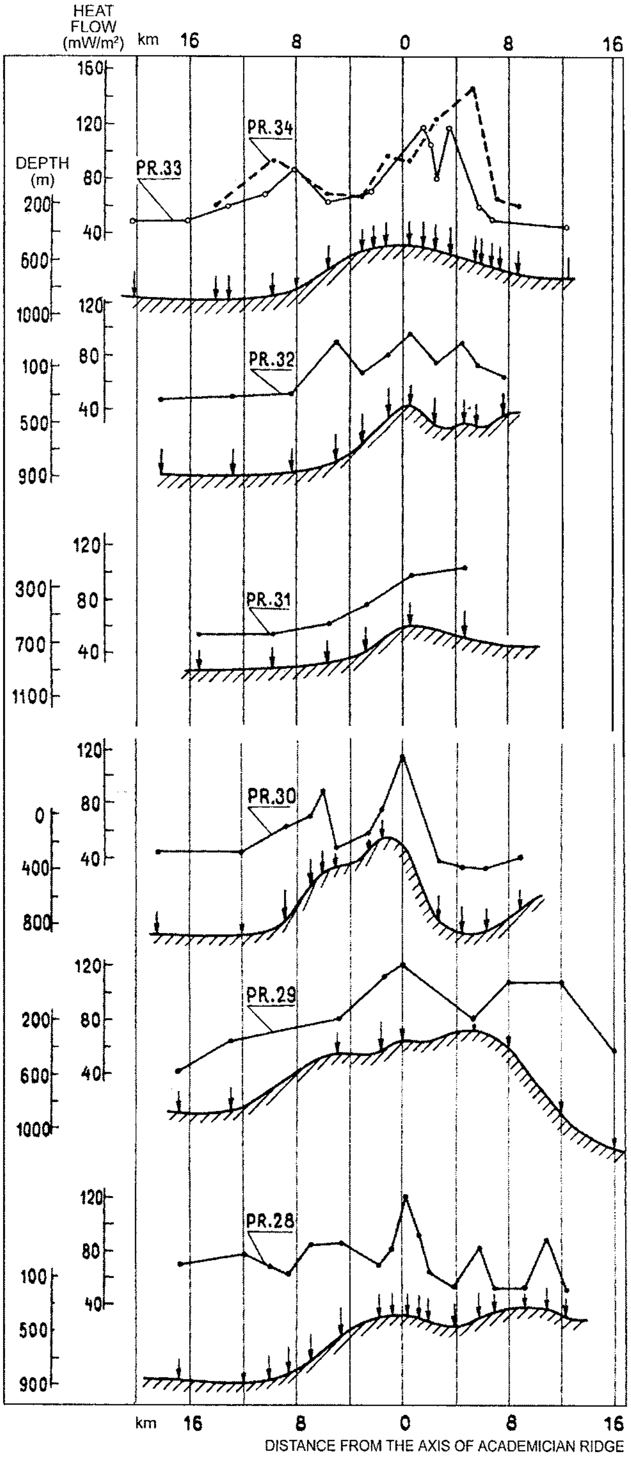


FIGURE 9

Heat flow pattern for Academician ridge from profiles across the ridge. Arrows point to measurement sites.

Distribution du flux thermique dans l'« Academician ridge », à partir de profils de mesure transversaux. Les flèches indiquent les points de mesure.

mated from undisturbed background heat flow compared to its values from profile ends which remain within 45 to 62 mW/m^2.

Calculations show that anomalous heat loss is the least (0.26 x 10^6 W/km) around profile 32 and the highest (0.72 x 10^6 W/km) around profile 29, its mean over the ridge being 0.38 x 10^6 W/km. For the whole length of the ridge it is:

$$Q = 0.38 \times 10^6 \text{ W/km} \times 140 \text{ km} = 53.2 \times 10^6 \text{ W}$$

As for North Baikal, we can assume that this value is produced by heat lost from ascending thermal water along active faults. Formula (1) shows that this amount of heat is related to linear discharge of thermal water at a rate of 0.95 l/km s. Total discharge is: 0.95 l/km s x 140 km = 133 l/s.

3.5. **CENTRAL BAIKAL**

On thirteen profiles across the deepest central part of the lake (Fig. 5, profiles 15 to 25, 27, 28), heat flow appears to be low and relatively constant (40 to 60 mW/m^2) along the basin axis and near its northwestern side, while it abruptly rises on approaching the southeastern side. On profiles 20 and 21 the flux increases up to 80 to 90 mW/m^2, and on profiles 19, 25 and 27 it reaches 140 to 280 mW/m^2. Closer to the southeastern shore, the flux becomes low again. Low values were obtained also in onshore boreholes. An extremely high heat flow (2500 mW/m$^{2)}$ was recorded in a limited area on the bottom of the Kukui canyon (Fig. 1 and 5) north of the Selenga delta (GOLUBEV, 1987; GOLUBEV *et al.*,1993). The Central Baikal anomaly varies from 5 to 10 km wide on different profiles (within 20% of the basin width). Maximum heat flows were obtained at depths of 800 to 1000 m corresponding to the lower and median parts of the underwater slope. Mean flux on the anomaly axis is 170 mW/m^2 (Fig. 10 top). This is three times as great as that in Central Baikal, except an anomaly of 57 mW/m^2. The local character of the anomaly is indicative of a shallow depth of its source which may have no direct relation to deep geothermal environments.

If we consider the case of an anomaly produced by an igneous source, for instance an intrusion of mantle material with a rectangular cross-section, an original temperature of 1200 °C and a temperature of the upper crust of 200 °C before intrusion, the calculations (GOLUBEV, 1987) give the following results. The intrusion-related distribution of heat flow would fit the confidence intervals of its observed pattern only provided that the intrusion occurred 0.3 My ago with a width of 1 km and its top as close as 2 km to the lake bottom. A positive magnetic anomaly should exist over such an intrusion, which would be about 7 km wide and 300 nT in magnitude (GOLUBEV, 1987). The axis location of the thermal anomaly and the results of hydromagnetic surveys along nine profiles across Central Baikal (ANISTRATENKO *et al.*, 1973) are shown in Figure 11. This figure also shows that at generally low intensity of the magnetic field, which is typical for the Baikal basin, the heat flow anomaly axis passes close to the magnetic highs in two cases only (hydromagnetic profiles 2 and 3). On the other seven intersections of the heat flow anomaly axis with hydromagnetic profiles, the intensity of the magnetic field is low. This independence between the thermal and magnetic fields contradicts the hypothesis of the existence of a Quaternary dike beneath the southeastern submarine slope of Central Baikal.

No intrusions were found in sediments of Central Baikal as well as in other areas of the lake by multichannel seismic reflection (HUTCHINSON *et al.*,1992; SCHOLZ *et al.*,1993). At the same time, the seismic profiles suggest the existence of a large fault, which was suspected long ago as a conduit for thermal waters (Golubev, 1987). The sediment thickness changes abruptly from > 2 km northwest down to < 1 km southeast of the fault (Fig. 2). The position of the fault almost coincides with the axis of the Central Baikal heat flow anomaly (Fig. 6).

The line of empirical flow distribution roughly fits the model, considering that thermal waters rise from a depth of 4 km and discharge at a rate of 0.8 l/km s. However, the theoretical distribution somewhat under-estimates the real magnitude of anomalous heat loss (solid line in Fig. 10, top). As calculated for individual profiles, it is on average 0.5 x 10^6 W/km; the total loss over the 170 km length of Central Baikal is Q = 0.5 x 10^6 W/km x 170 km = 85 x 10^6 W. According to formula 1 (paragraph 3.2.) such an amount of heat is produced by hydrothermal discharge at a total rate of 212 l/s or 1.25 l/s per km. These are minimal values as they neglect the amount of heat brought by thermal waters directly into the near-bottom water.

The dashed line in Figure 10 represents a theoretical pattern of surficial heat flow produced by cooling thermal waters, which flow up from the base of the crust, at about 40 km deep (Golubev, 1987) and discharge at a rate of 0.8 l/km s. However, the crustal-scale ascent of fluids is not consistent with the small width of the observed anomaly. According to this model, it should be roughly as wide as the basin, which is actually not the case.

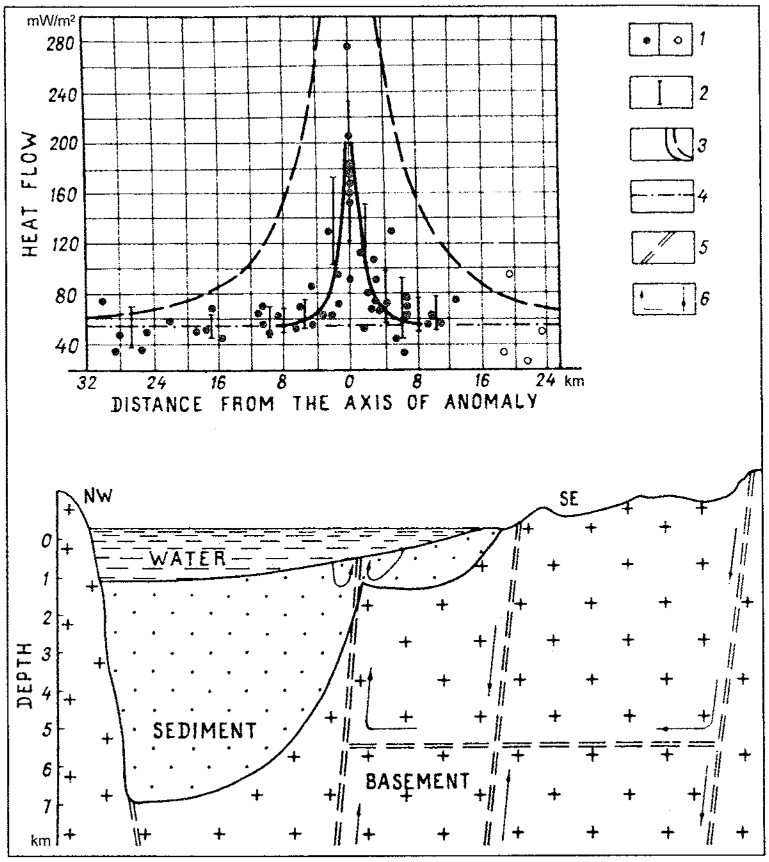


Figure 10

Model of formation of a thermal anomaly in Central Baikal. 1 = heat flows measured on the bottom (dots) and in on-land boreholes (circles); 2 = confidence intervals of averaging; 3 = heat flow variations with distance from the vertical fault along which thermal waters ascend from a depth of 4 km (solid line) and 40 km (dashed line) and discharge at a rate of 0.8 l/km² s; 4 = mean regional heat flow; 5 = faults; 6 = direction of ground water movement.

Modèle de formation d'une anomalie thermique dans le bassin central du lac Baïkal. 1 = flux thermique mesuré sur le fond (points) et à terre (cercles) ; 2 = intervalle de confiance pour la moyenne ; 3 = variation du flux thermique en fonction de la distance à une faille verticale de montée des eaux, depuis une profondeur de 4 km (trait plein) et de 40 km (tireté) avec un écoulement de 0,8 l/km² s ; 4 = flux de chaleur régional moyen ; 5 = faille ; 6 = direction d'écoulement des eaux souterraines.

3.6. SELENGA DELTA AND SOUTH BAIKAL

South Baikal and the area around the Selenga delta constitute the oldest part of the Baikal rift (Logatchev *et al.*,1974; Logatchev, 1993). Heat flows measured near the Selenga delta may be considerably disturbed by episodes of redeposition due to high sedimentation rate and high local seismicity (Golubev, 1982a). Redeposition must be responsible for nearly zero heat flows obtained on the southeastern end of profile 18, where a strong earthquake in 1959 caused an underwater landslide and changed the surrounding depths by more than 20 m (Solonenko & Treskov, 1960). Submarine landslides and downthrows may have caused changes of flux from 0 to 442 mW/m² on profiles 1 and 2 which follow canyon thalwegs on either side of the Murin Bank (Fig. 1 and 5).

Geothermal measurements were the most detailed on profiles 5 to 8 (Fig. 5). It is worth noting that only two of them (NN 7 and 8, across the Posol'sk Bank) record the southeastern flank of the South Baikal anomaly. Figure 12 shows a generalised heat flow pattern from measurements on the four profiles and data from boreholes on the northwestern shore of Baikal. Corrections were applied to the heat flow values to allow for topography and sedimentation effects. According to the averaging curve, low flux on the northwestern side of about 40 mW/m² increases towards the lake axis up to 107 mW/m², or 2.7 times. Owing to a large scattering of the available heat flow values near the southeastern slope, it is uncertain whether the anomaly extends on to the Khamar-Daban foothills (Fig. 1) or is confined to the lake. Anomalous heat loss was calculated with respect to the background flux which varies between 40 and 61 mW/m². The former value (40 mW/m²) corresponds to the mean in the northwestern shore of Lake Baikal and the latter one (60 mW/m²) is the bottom heat flow 5 km offshore (Fig. 12). For the former case, the linear magnitude of anomalous heat escape is 1.85 x 10^6 W/km, and for the latter it is 1.05 x 10^6 W/km. If these values are representative for the full 220 km length of South Baikal, the anomalous heat loss through its bottom must be 1.85 x 10^6 W/km x 220 km = 407 x 10^6 W, and 1.05 x 10^6 W/km x 220 km = 231 x 10^6 W, for the lower and higher values of heat flow, respectively.

Heat flow anomalies of the whole Lake Baikal were interpreted earlier with the use of a model of transient geothermal field (Golubev, 1982a; Zorin & Osokina, 1984). According to this model, the stage of slow rifting (Logatchev *et al.*,1974; Logatchev, 1993) was associated with the rise of an asthenos-

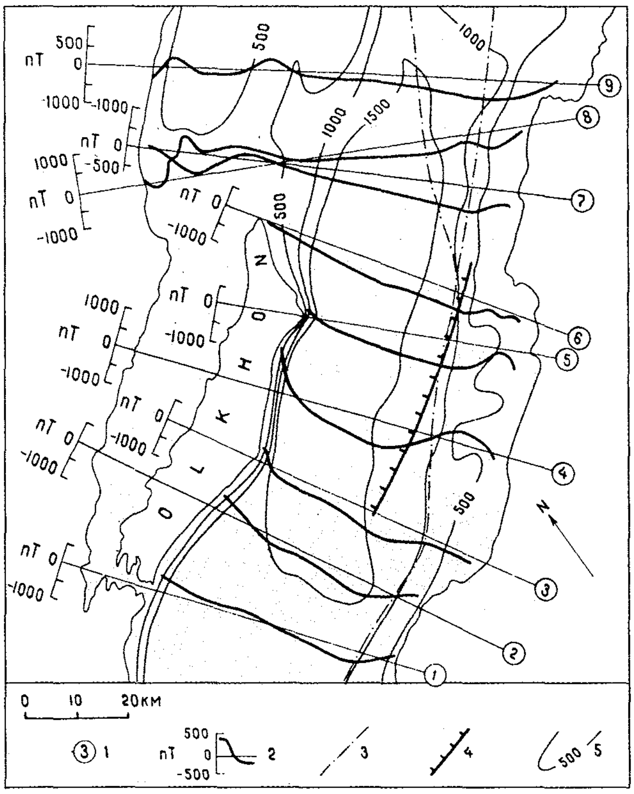


Figure 11

Results of hydromagnetic and other geophysical surveys on Central Baikal. 1 = numbers of profiles; 2 = variation of excess intensity of the magnetic field (nT) on different profiles, after Anistratenko *et al.*,1973; 3 = axis of heat flow anomaly; 4 = fault in the basement detected by multichannel reflection [Hutchinson *et al.*,1992]; 5 = bathymetry (m).

Relation entre champ magnétique et anomalie thermique dans le bassin central du lac Baïkal. 1 = numéro de profil ; 2 = variation de l'anomalie du champ magnétique (nT) le long de différents profils d'après Anistratenko et al.*, 1973 ; 3 = axe de l'anomalie du flux thermique ; 4 = faille du socle détectée par sismique réflexion [*Hutchinson et al.*, 1992]* ; 5 = *courbe bathymétrique (m).*

pheric diapir from a depth of 120 km up to the crustal base. Fast rifting started 3 My ago when the diapir injected into the crust beneath South Baikal as a dike trending along the rift axis. Zorin and Osokina (1984) showed that the theoretical distribution of heat flow would be consistent with the empirical one obtained at that time, if the dike were 10 km wide and its top were at depth of 6 km. Background flux on the flanks of the anomaly and maximum on its axis were assumed in the model to be 61 and 92 mW/m^2, respectively.

On the basis of analytical relationships (Carslaw & Jaeger, 1959; Golubev, 1982a), the parameters of a dike which would fit the updated heat flow pattern shown in Figure 12 were calculated. They turned out to be somewhat different: time of intrusion 2 My ago, width of the dike 12 km, depth of its top 3 km.

However, explanation of Baikal heat flow anomalies by the existence of shallow fissure intrusions is unlikely for the following two reasons:

— field observations and modelling results show that hot intrusives inevitably induce hydrothermal systems (Norton & Knight, 1977; Carrigan, 1986; Cathless, 1990). Thermal waters provide intense convective outflow of heat in addition to its conductive release that considerably speeds up cooling of the intrusion.

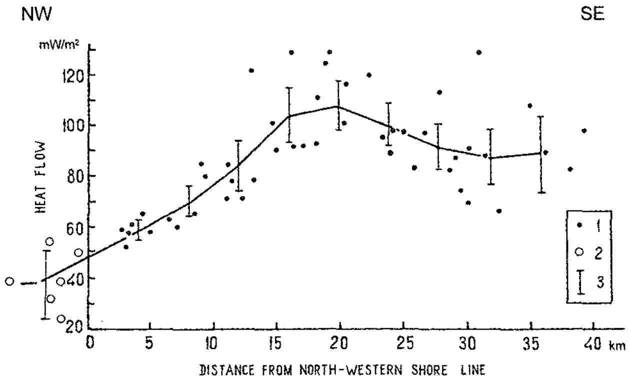


Figure 12

Heat flows along a synthetic profile based on four profiles across South Baikal. 1 = heat flows measured on the bottom (corrected for topography and sedimentation); 2 = heat flows measured in on-land boreholes; 3 = confidence intervals of averaging.

Flux thermique le long d'un profil synthétique d'après quatre profils transversaux du lac Baïkal Sud. 1 = flux thermique mesuré au fond du lac (après correction pour la topographie et la sédimentation) ; 2 = flux thermique dans des forages à terre ; 3 = intervalle de confiance pour la moyenne.

Hydraulic permeability (K) is a key parameter to determine the relationship between conductive and convective heat output. For the upper 10 km of the crust of the Baikal rift it is at least 5 x 10^{-17} m^2 (Golubev, 1990). A relationship between maximum conductive and convective heat over a dike similar to the one beneath South Baikal is shown in Figure 13 (Norton & Knight, 1977, fig. 7). It follows that even with the lowest permeability of 5 x 10^{-17} m^2, the convective component of heat loss over the intrusive must be 2 to 3 times higher than the conductive one. Hence, due to the joint action of conductive and convective heat transfer, the dike should cool down three or four times faster. If the dike and the host medium are as permeable as 10^{-15} m^2, we obtain a few dozen times faster cooling than with pure conduction (Cathless, 1990). The presence of intrusion-induced hydrothermal systems disturbs the surrounding conductive thermal field as well. Thus, the position of its lows and highs depends rather upon the size and geometry of the hydrothermal systems than upon the distance from the intrusive.

— in accordance with the above, if the South Baikal heat flow anomaly does result from an igneous source, the latter should have intruded less than 1 My ago. The intrusive pierces almost the entire crust, and its width is 10 to 12 km, so a single episode of intrusion would cause respective crustal extension for 10 to 12 km. At the same time, total extension over the 40 to 50 My history of rifting in South Baikal amounts 15 to 20 km according to Logatchev & Zorin (1992), and just a few kilometres according to Artiushkov *et al.* (1990), i.e. the amount of extension is comparable to the width of the surmised dike. But it is very unlikely that extension was restricted to the last million years of rift evolution. This is supported by the existence of strong thermal anomalies in the younger Central and North

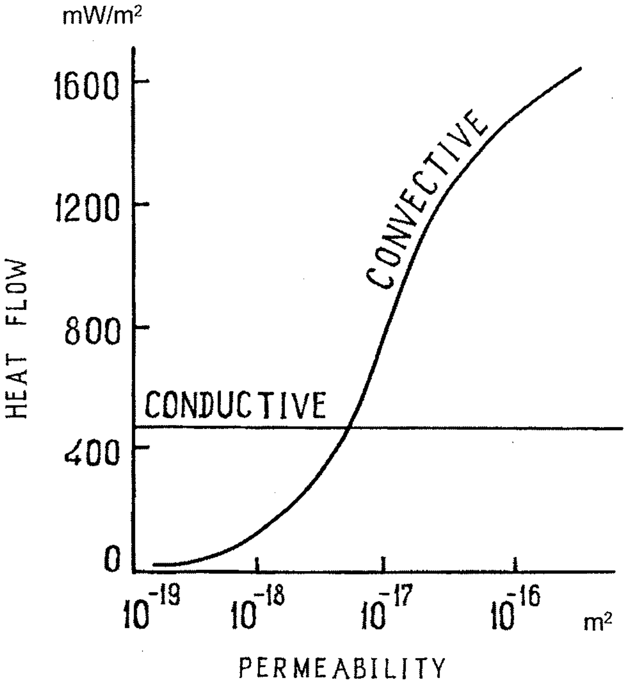


FIGURE 13

Variations of convective heat flow over the central part of a dike as a function of permeability of host medium. Note that the conductive output remains invariable (after NORTON & KNIGHT, 1977, fig.7).

Variation du flux thermique de convection au-dessus de la partie centrale d'un dyke en fonction de la perméabilité de la roche encaissante. Remarquer que le flux de conduction reste invariable (d'après NORTON & KNIGHT, 1977,fig.7).

Baikal sub-basins. Their heat flow field may be a model of earlier stages of the geothermal evolution of South Baikal. So, keeping to the version of the dike-induced heat flow anomaly in South Baikal, we would have to assume that intrusions occurred repeatedly and before 1 My ago. But, for instance, three such episodes would extend the basement by 30 to 36 km and it would be composed mainly of the mantle material. With such a composition, it should be considerably denser than a normal crust. However, gravity data indicates a noticeable density excess only in the lower crust beneath Baikal (ZORIN & OSOKINA, 1984). No support for a young intrusion into the upper crust comes from hydromagnetic data. Multichannel seismic profiling detected no dikes in the 6 km thick sediment fill of the Baikal basin either (HUTCHINSON *et al.*,1992; SCHOLZ *et al.*,1993).

In conclusion, on the one hand, intrusion in a single episode can hardly be reconciled with the long history of the Baikal rift, while repeated intrusions are not proved valid by the available geological and geophysical data. This imposes the particular requirement on sources of heat flow anomalies in Baikal, that they should be renewable. Renewal of heat sources in localised zones beneath the Baikal bottom may evidently occur in two ways. The first is the crustal-scale ascent of mantle fluids, providing heat and mass transfer for the Baikal thermal anomalies, though the data available so far is not enough for quantitative estimates. The other mechanism will be considered in detail hereafter.

4. — REGIONAL INFILTRATION OF GROUND WATERS AND ITS EFFECT ON THE GEOTHERMAL FIELD OF THE BAIKAL RIFT

4.1. MODEL OF INFILTRATION. LATENT DISCHARGE

The observed pattern of the geothermal field in the Baikal rift with colder rift shoulders, hotter rift basins and local thermal highs within them, can be accounted for by redistribution of heat by advection of ground water. Absorbing terrestrial heat beneath the rift shoulders, thermal waters transfer it to the rift basins on their way upwards through faulted basin floors. Such redistribution provides renewal of heat resources in the fault zones within the rift basins.

More than 50 springs have been discovered since then within the Baikal rift. Most of them are Si-rich nitric waters, generated beyond magmatic or metamorphic processes, which discharge at a temperature of up to 84 °C and a total output of about 800 l/s. Calculations with the use of SiO_2 and Na-K-Ca geothermometers show that the temperature of thermal water at its depths of origin varies for the different hot springs from 31 to 159 °C (GOLUBEV, 1982b). As suggested from marine geothermal data, latent hydrothermal discharge in North Baikal may be many times higher than that observed. This is valid for other rift basins as well. Low-temperature thermal waters originating at depths shallower than 2 km remain unidentified while their total discharge is evidently several times as high as that of the known hot springs formed at greater depths (GOLUBEV, 1991).

For evaluation of the effect of the run-off in depths on the geothermal field of the Baikal rift, the first step was to calculate depths of formation of thermal water (**H**) for each of 53 hot springs, from the known mean geothermal gradient (**grad t**) and temperatures (**t**) at those depths (GOLUBEV, 1982b):

$$H = \frac{t - t_0}{\text{grad t}} \qquad 2$$

where t_0 is the temperature of the Earth's surface (about 0 °C). The mean geothermal gradient observed in shallow boreholes in the rift shoulders (17 °C/km; LYSAK, 1995) was taken as its lowest value since the water exchange becomes less intense away from the Earth's surface and hence exerts less influence on the conductive flux. The latter, like **grad t**, must increase with depth. As is shown below, the gradient increases by 1.5 times and attains about 25 °C/km. Inserting the two values (17 °C/km and 25 °C/km) into equation 2, we obtain respectively two depth ranges of formation of thermal waters: 1.3 to 6 (version 1) and 2 to 9 km (version 2). The respective mean depths will be 3.9 and 5.4 km with the mean temperature at these depths of 99 °C (GOLUBEV, 1982b).

The next step was to estimate volumes of thermal water generated at different depths. For this, the upper crust of the Baikal rift was conventionally divided into horizontal layers. In the two versions of the model the layers were 400 metres (version 1) and 600 metres thick (version 2). Rates of discharge measured on the Earth's surface for each of the 53 known hot springs were assigned to one or the two layers according to their depths of origin (**H**). Then the flow rates were totalled over each layer.

The two sets of resulting histograms (Fig. 14) show that most of the apparent thermal water (about 240 l/s) originates

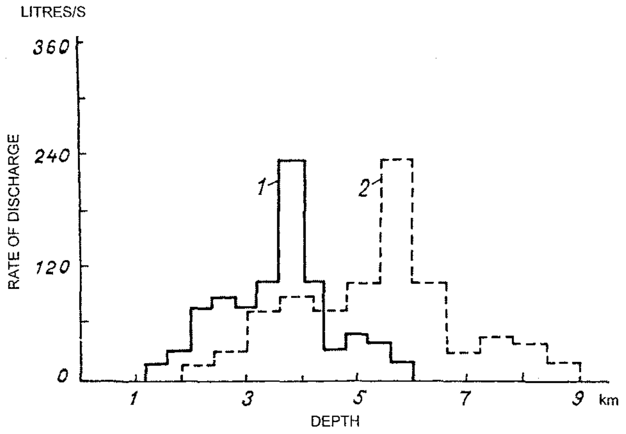


FIGURE 14

Histograms of apparent hydrothermal discharge totalled over upper crustal layers with thicknesses 400 metres (1) and 600 metres (2); the former value was calculated at regional temperature gradient of 25 °C/km, the latter at 17 °C/km.

Histogrammes de la décharge hydrothermale apparente cumulée, au-dessus d'une tranche de croûte supérieure de 400 mètres (1) et de 600 mètres (2) ; la première valeur a été calculée avec un gradient géothermique régional de 25 °C/km et la seconde avec un gradient de 17 °C/km.

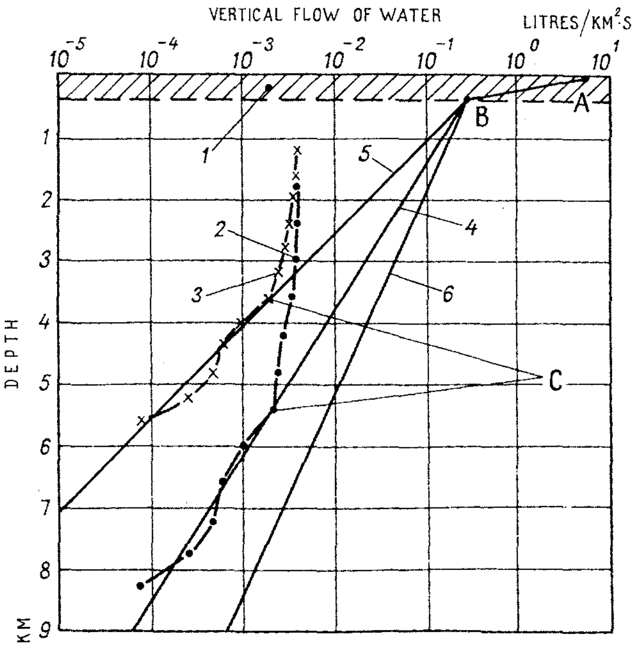


FIGURE 15

Infiltration rate of ground water at different depths in mountain regions of the Baikal rift. *Vitesse d'infiltration des eaux souterraines à différentes profondeurs, dans les parties montagneuses du rift du Baïkal.* 1 = zone of intense water exchange - *zone à échange d'eau intense ;* 2 and 3 = depth-dependent variations in infiltration rate (M) with regard to only apparent (identified) hydrothermal discharge corresponding to patterns 2 and 1 in Figure 14 - *variations de la vitesse d'infiltration dépendant de la profondeur, seulement en fonction de la décharge hydrothermale apparente correspondant aux histogrammes 1 et 2 de la Figure 14 ;* 4, 5, 6 = depth-dependent variations of total (apparent and latent) infiltration rate according to equation: - *variations de la vitesse d'infiltration totale (apparente et latente) dépendant de la profondeur selon l'équation :*

$$M(Z) = M_L \exp [-a(Z-L)]$$

for the cases when - *dans les cas où :*

$M(Z = 5.4 \text{ km}) = 2.7 \times 10^{-3}$ l/km² s (line 4);
$M(Z = 3.6 \text{ km}) = 2.7 \times 10^{-3}$ l/km² s (line 5);
$M(Z = 5.4 \text{ km}) = 3 \times 2.7 \times 10^{-3}$ l/km² s (line 6);
$M_L = M(Z = 0.3 \text{ km}) = 0.25$ l/km².

respectively within depth ranges of 3.6 to 4 km (version 1) or 5.4 to 6 km (version 2). The histograms allowed the assessment of the regional mean infiltration rate. Doing this for a certain depth **Z**, the total output of thermal waters over all the layers below this depth was found. The values thus obtained were divided by 200 x 10^3 km², corresponding to the feeding area of the rift shoulders which occupy about four fifths of the total rift area (about 250 x 10^3 km²). The plots for different depths (curves 2 and 3 in Fig. 15) show that the growth in apparent portion of hydrothermal discharge ceases above 2 to 3 km. At the same time, the total discharge, including its unidentified low-temperature component, should keep increasing towards the Earth's surface.

The motion of ground water is strongly controlled by the permeability of the crust (**K**). It was recognised (ANDERSON *et al.*,1985; NEHLIG & JUTEAU, 1988), that permeability of crystalline rocks shows an exponential downward decrease. For the stretched upper crust of the Baikal rift, vertical permeability must greatly exceed its horizontal component ($K_v >> K_h$, where K_v and K_h are vertical and horizontal components of permeability). In this case the respective decrease in infiltration rate (**M**) starting at some depth **Z = L** can be described as (GOLUBEV, 1991):

$$M(Z) = M_L \exp [-a(Z-L)] \qquad 3$$

Infiltration rate 2.7 x 10^{-3} l/km² s (0.27 x 10^{-11} m/s) at depths of 5.4 km or 3.6 km can be taken as one of the points of the sought infiltration rate *vs* depth plot (Fig. 15, point C on curves 2 and 3). Another point (Fig. 15, point B) comes from the infiltration rate at the base of the zone of intensive water exchange, the assumed thickness of which for the Baikal rift (**L**) is 300 metres. The infiltration rate at this depth was taken to be 0.25 l/km² s (0.25 x 10^{-9} m/s), less than 1% of the coastal run-off in the mountains around Baikal (PISARSKY, 1987).

Figure 15 gives several versions of depth-dependent variations of infiltration rate. The relationships are shown linear in semi-logarithmic scale. Two lines pass through the discussed points corresponding to values of 0.25 l/km² s at a depth of 0.3 km and 2.7 x 10^{-3} l/km² s at depths of 3.6 or 5.4 km. It is seen from the figure that the total rate of discharge involving its latent portion within depths of 0 to 3 km is one or two orders of magnitude higher than the apparent portion.

This result is possibly underestimated as well, especially for depths greater than 5.4 km, since point C on line 4 corresponds to only the apparent portion of the total amount of discharged deep thermal water. The real discharge of thermal water from depths greater than 5.4 can also be a few times higher than assumed (line 6 in Figure 15). It corresponds to the case where M(Z = 5.4 km) = 3 x 2.7 x 10^{-3} l/km² s = 3 x 0.27 x 10^{-11} m/s, or 3 times as great as that obtained for the apparent discharge.

4.2. MODEL OF THE GEOTHERMAL FIELD

The effect of regional-scale infiltration of meteoric water on the Baikal rift geothermal field has been modelled by a one-dimensional steady-state temperature field with an upper limit at 0.3 km (Z = L = 0.3 km) and a lower limit at the Moho (Z = 40 km). The crust was assumed to have a two-layered structure. Within the upper 10 km, thermal conductivity and heat production of rocks were taken to be 2.5 W/m°C and 1 x 10^{-6} W/m^3, respectively; below 10 km, at 2.7 W/m°C and 0.3 x 10^{-6} W/m^3. For the upper limit, the following boundary constraints were set: temperature (**t_L**) of 4 °C, measured heat flow for the rift shoulders (**q_L**) of 43 mW/m^2, and infiltration rate (**M_L**) of 0.25 l/km^2 s. For the need of calculations, the crust was divided into horizontal layers 0.2 km -thick (in the upper crust) and 1 km (in the lower crust). Temperatures and heat flows for each subsequent layer were derived from those of the preceding one, in function of heat balance between infiltrated water and ascending conductive flux:

$$t_{i+1} = \frac{t_i + \left(Z_{i+1} - Z_i\right)\left(q_{i+1} + q_i\right)}{2\,k_{i+1}} \qquad 4$$

$$q_{i+1} = \frac{q_i + c\,M_{i+1}\left(t_{i+1} - t_i\right) + c\left(M_i - M_{i+1}\right) \times \left(t_{i+1} - t_i\right)}{2 - \left[A_{i+1}\left(Z_{i+1} - Z_i\right)\right]} \qquad 5$$

where **k_{i+1}** and **A_{i+1}** are thermal conductivity and heat production of the i+1 layer, and **c** is water heat capacity. The second item in the sum **5** is the amount of heat taken from the i+1 layer by ground waters on their way down through the layer; the third item is the amount of heat lost by the i+1 layer by lateral basinward movement of ground water. Formula **5** can be simplified as follows:

$$q_{i+1} = \frac{q_i + c\left(t_{i+1} - t_i\right)\left(M_{i+1} + M_i\right)}{2 - \left[A_{i+1}\left(Z_{i+1} - Z_i\right)\right]} \qquad 6$$

Inserting equation **6** into formula **4**, we obtain (GOLUBEV, 1991):

$$t_{i+1} = \frac{4\left\{\left[q_i\left(Z_{i+1} - Z_i\right) + t_i k_{i+1}\right] - c t_i\left(M_{i+1} + M_i\right)\left(Z_{i+1} - Z_i\right) - 2A_{i+1}\left(Z_{i+1} - Z_i\right)^2\right\}}{\left[4k_{i+1} - c\left(M_{i+1} + M_i\right)\left(Z_{i+1} - Z_i\right)\right]} \qquad 7$$

Infiltration rate at depths **Z_i** was calculated by formula **3** (paragraph 4.1.). The **a** coefficient which enters the index of its exponent, was derived from the expression:

$$a = \frac{\ln\left(M_L / M_{Z^*}\right)}{Z^* - L} \qquad 8$$

obtained from formula 3 at fixed values of M_L = 0.25 l/km^2 s and M(Z) = M(Z*) = M(Z = 3.6 km), or M(Z) = M(Z*) = M(Z = 5.4 km) considered above.

Curve 1 in Figure 16 was plotted for the case where M(Z) = 0 at any Z, which corresponds to the case of "pure conduction". Curve 2 was obtained for the case where M(Z = 5.4 km) = 2.7 x 10^{-3} l/km^2 s (0.27 x 10^{-11} m/s), which conforms to pattern (2) in Figure 15 calculated at grad t = 17 °C/km. Heat flow grows with depth (see Figure 16, curve 2) and, at the greatest depths of formation of thermal water (7 to 9 km), it is 62 mW/m^2 or 1.5 times in excess of the observed shallow flux. The geothermal gradient at these depths must be about 25 °C/km if it grows at the same rate. As already mentioned, this value of the geothermal gradient was used to plot histogram 1 in Figure 14 and curves 3 and 5 in Figure 15. The respective infiltration rate M = 2.7 x 10^{-3} l/km^2 s should be expected to occur at a depth of 3.6 km. Curve 4 was obtained for the case where M(Z = 5.4 km) = 3 x 2.7 x 10^{-3} l/km^2 s discussed above.

Analysis of the curves from Figure 16 shows that the uppermost crust in the Baikal rift cools due to diffuse regional infiltration of meteoric water and its localised discharge through hot springs. The conductive component of heat flow rapidly grows with depth as the infiltration rate decreases. The heat flow increases up to depths of 3 to 5 km where it is 1.3 to 1.6 times higher than the mean flux measured in shallow boreholes in the rift shoulders.

Measurements in deep boreholes in the Baikal rift do show evidence of a downward growth of the heat flow (LYSAK, 1995). Of greatest importance are geothermal and hydrogeological data obtained during the construction of the North Muya tunnel located 100 km northeast of Baikal (YAS'KO & SHABYNIN, 1984). Following on from Figure 17, geothermal gradient beneath the central part of the North Muya ridge remains within 5 to 7 °C/km even at a depth of 1 km. The strong downflow of groundwater provides almost perfect vertical equalising of temperatures. The ground waters heat up at great depths and discharge through faults separating the ridge from the neighbouring basins. Like heat flows, temperatures calculated with regard to infiltration of ground water are considerably higher than those obtained for the case of "pure conduction" and the measured flux. Figure 16 shows Moho temperatures which can also be expected to be 1.5 to 2 times in excess of those for "pure conduction".

5. — DISCUSSION AND CONCLUSION

The geothermal field of the Baikal basin and of the surrounding rift shoulders is formed by both conductive and convective heat transfer. Great thicknesses of sediments seal up active faults in the basement, thus hindering them from serving as conduits for thermal waters. Figure 6 shows faults detected by multichannel reflection (HUTCHINSON *et al.*,1992) together with the axes of positive heat flow anomalies and faults revealed by geothermal studies. Having compared their location, it can be inferred that the convective outflow of heat in North and Central Baikal is mostly restricted to the areas where vertical displacements of the basement along faults reach a few kilometres and the sediment thickness decreases down to 1 km or less. On the eastern edge of North Baikal, sites of hydrothermal discharge are attributed to intersections of major rift faults with minor transverse faults.

The most difficult to interprete is the South Baikal anomaly, which is the greatest found in Baikal. The absence of extreme highs (5 to 10 times and more, above the background flux) means the absence of localised hydrothermal venting while diffuse discharge may be suggested. In earlier studies (GOLUBEV,

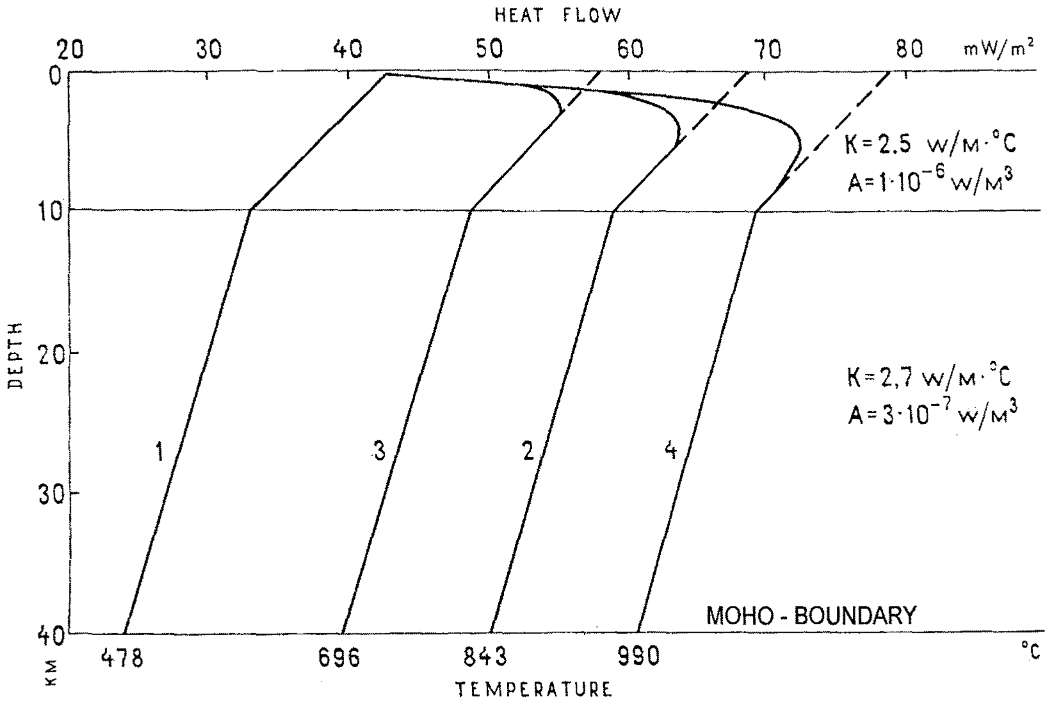


FIGURE 16

Depth-dependent variations of conductive heat flow beneath rift shoulders at different values of infiltration rate obtained with the use of equation :
– Variations du flux thermique conductif en fonction de la profondeur, sous les épaulements du rift pour différentes valeurs de la vitesse d'infiltration, obtenues avec l'équation :

$M(Z) = M_L \exp[-a(Z-L)]$

1 = no infiltration at all depths; *pas d'infiltration à toute profondeur ;*

2 = $M(Z = 5.4 \text{ km}) = 2.7 \times 10^{-3}$ l/km² s;
3 = $M(Z = 3.6 \text{ km}) = 2.7 \times 10^{-3}$ l/km² s;
4 = $M(Z = 5.4 \text{ km}) = 3 \times 2.7 \times 10^{-3}$ l/km² s;
$M_L = M(Z = 0.3 \text{ km}) = 0.25$ l/km² s.

Dashed lines show theoretical heat flow values if infiltration were not existing. Moho temperatures are given for the respective versions of the model.
Les lignes en tireté indiquent les valeurs théoriques du flux thermique en l'absence d'infiltration. Les températures au niveau de la Moho sont données pour les différents cas du modèle.

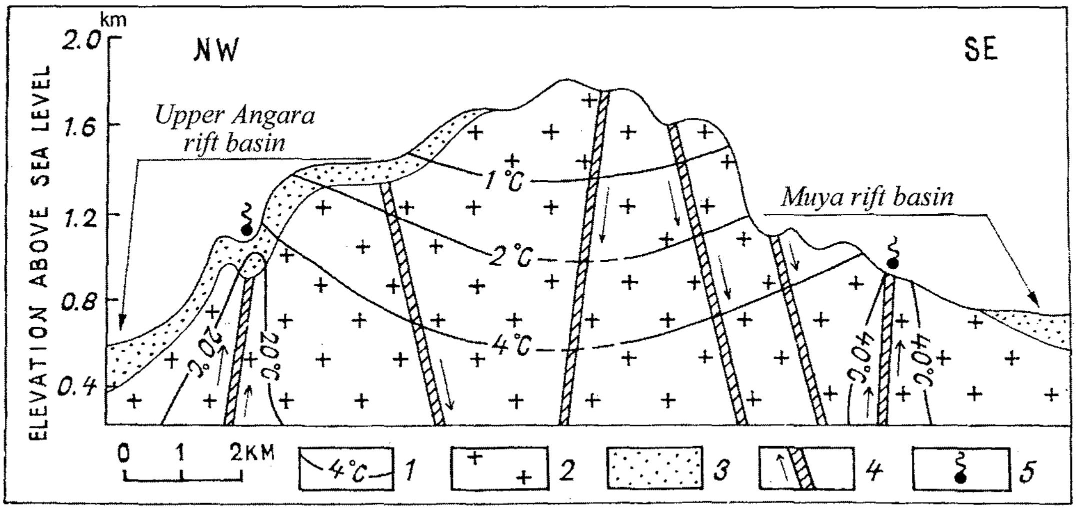


FIGURE 17

Geothermal profile of the North Muya ridge. 1 = temperature contour lines; 2 = crystalline rocks; 3 = sediments; 4 = faults and direction of ground water movement; 5 = hot springs (after YAS'KO & SHABYNIN, 1984).

Profil géothermique de la « North Muya Ridge ». 1 = isothermes ; 2 = roches cristallines ; 3 = sédiments ; 4 = failles et direction de mouvement des eaux souterraines ; 5 = sources chaudes (d'après YAS'KO & SHABYNIN, 1984).

1982a; ZORIN & OSOKINA, 1984) the anomaly was modelled by a large (about 10 km wide) intrusion of mantle material extended along the lake axis and only conductive heat was regarded. However, considering the existing permeability of the upper crust of the Baikal rift, convection of ground water induced by such an intrusion would have cooled it in less than 1 My. Such an anomaly with a short life span is inconsistent with the long history of rifting which has acted upon this segment of Baikal, while repetitive intrusions of such size and depth do not agree with the available geophysical results. This inference does not rule out a possibility of recent shallow injections of minor dikes, the heat input of which must be of secondary importance. The presence of dikes in the lower crust, indicated by gravity data (ZORIN & OSOKINA, 1984), may account for some elevation of heat flow. But the size and intensity of such anomaly suggest that its source is located in the upper half of the crust anyway, no matter whether the anomaly is interpreted in terms of transient or steady temperature field.

In this respect, the best explanation would be that the anomaly has been produced by diffuse discharge of thermal waters, recharged beneath the Khamar-Daban ridge. This idea is substantiated by the presented model of regional infiltration of ground water responsible for redistribution of heat. The model accounts for low heat flows in the surrounding rift shoulders.

According to the model, temperatures at crustal base beneath the ridges approach melting points for rocks. Therefore, the absence of regional-scale high heat flow in the Baikal rift is related not only to the transient behaviour of its geothermal field as was suggested before, but also to the regional redistribution of heat by infiltration of ground water.

I am grateful to all my collegues who helped me in my geothermal studies on Baikal. I wish to thank academician N.A.LOGATCHEV, D. DELVAUX and D. BARDIN for their editorial efforts. Thanks are extended to Mrs. T. PEREPELOVA who translated the paper into English and to Ms. T. LESHKEVICH and Mrs. S. BOCHAROVA for technical aid.

6. — REFERENCES

ANDERSON, R.N., ZOBACK, M.D. & HICKMAN, S.N. (1985). — Permeability versus depth in the upper oceanic crust: *in situ* measurements in DSDP hole 504 b, Eastern equatorial Pacific. — *J. Geophys. Res.*, **90**, B5, 3659-3669.

ANISTRATENKO, A.G., BELUGINA, V.N. & KOROSTIN, P.B. (1973). — Magnetic field of Lake Baikal. — *Geomagnetism and aeronomia,* **13**, 2, 387-388 (in Russian).

ARTYUSHKOV, E.V., LETNIKOV, F.A. & RUZHICH, V.V. (1990). — The mechanism of formation of the Baikal basin. — *J. Geodyn.*, **11**, 277-291.

CARSLAW H.S. & JAEGER, J.C. (1959). — Conduction of heat in Solids, 2nd ed. — *Oxford University Press. Amen House,* Oxford, 510 pp.

CARRIGAN, C.R. (1986). — A two-phase hydrothermal cooling model for shallow intrusions. — *J. Volcanology and Geothermal Res.,* **28**, 1-2, 175-192.

CATHLESS, L.M. (1990). — Scales and effects of fluid flow in the upper crust. — *Science,* **248**, 4953, 323-329.

CRANE, K., HECKER, B. & GOLUBEV, V. (1991a). — Heat flow and hydrothermal vents in Baikal. — *EOS Transactions.* AGU, **72**, 52, 585.

CRANE, K., HECKER, B. & GOLUBEV, V. (1991b). — Hydrothermal vents in Lake Baikal. — *Nature,* **350**, 281.

DUCHKOV, A.D., KAZANTSEV, S.A. & VELINSKY, V.V. (1979). — Heat flow in Lake Baikal. — *Geologia i Geofizica,* **9**, 137-142 (in Russian).

GOLDYREV, G.S. (1982). — Sedimentation and evolution of the Baikal basin. — Nauka, Novosibirsk, 181 pp. (in Russian).

GOLUBEV, V.A. (1982a). — Geothermics of Baikal. — Nauka, Novosibirsk, 150 pp. (in Russian).

GOLUBEV, V.A. (1982b). — Thermal and chemical characteristics of hydrothermal systems in the Baikal rift zone. — *Sovetskaya Geologia* **10**, 100-108 (in Russian).

GOLUBEV, V.A. (1987). — Geothermal and hydrothermal studies in Central Baikal. — *Izvestia AN SSSR, Fizika Zemli,* **7**, 14-26 (in Russian).

GOLUBEV, V.A. (1990). — Hydrothermal systems, permeability and thermal models of the crust in the Baikal rift zone. — *Izvestia AN SSSR, Fizika Zemli,* **11**, 23-33 (in Russian).

GOLUBEV, V.A. (1991). — The model of the run-off in depths and its influence on the geothermal field of the Baikal rift zone. — *Geologia i Geofizica,* **12**, 102-109 (in Russian).

GOLUBEV, V.A. (1993). — Sources of subaquaeous discharge and heat balance of North Baikal. — *Dokl. Akad. Nauk Rossii,* **328**, 3, 315-318 (in Russian).

GOLUBEV, V.A., KLERKX, J. & KIPFER, R. (1993). — Heat flow, hydrothermal vents and static stability of discharging thermal water in Lake Baikal (South-Eastern Siberia). — *Bull. Centres Rech. Explor. - Prod. Elf Aquitaine,* **17**, 1, 53-65.

HERZEN, R.P. VON & UYEDA, S. (1963). — Heat flow through the eastern Pacific ocean floor. — *J. Geophys. Res.*, **68**, 14, 4219-4250.

HUTCHINSON, D.R., GOLMSHTOK, A.J., ZONENSHAIN, L.P., MOORE, T.C., SCHOLZ, C.A. & KLITGORD, K.D. (1992). — Depositional and tectonic framework of the rift basins of Lake Baikal from multichannel seismic data. — *Geology,* **20**, 589-592.

HUTCHISON, J. (1985). — The effects of sedimentation and compaction on oceanic heat flow. — *Geophys. J. r. astron. Soc.,* **82**, 3, 439-459.

KLERKX, J., GOLUBEV, V. & KIPFER, R. (1993). — Preliminary investigation of the hydrothermal site of Frolikha Bay (Lake Baikal). — Mus. Roy. Afr. Centr., Tervuren (Belg.), Dept. Geol. Min., Rapp. ann., 73-81.

LACHENBRUCH, A.H. (1968). — Rapid estimation of the topographic disturbance to superficial thermal gradients. — *Rev. Geophys.*, **6**, 3, 365-400.

LACHENBRUCH, A.N. & MARSHALL, B.V. (1966). — Heat flow through the Arctic Ocean floor: the Canada basin - Alpha rise boundary. — *J. Geophys. Res.*, **77**, 4, 1223-1249.

LOGATCHEV, N.A. (1993). — History and geodynamics of the Lake Baikal rift in the context of the Eastern Siberia rift system: a review. — *Bull. Centres Rech. Explor. - Prod. Elf Aquitaine* **17**, 2, 353-370.

LOGATCHEV, N.A., GALKIN, V.I. & GOLDYREV, G.S. (1974). — Basins of the Baikal system. Highlands of Baikal and Trans-Baikal areas. — Nauka, Moscow, 21-162 (in Russian).

LOGATCHEV, N.A. & ZORIN, Yu. A. (1992). — Baikal rift zone: Structure and geodynamics. — *Tectonophysics,* **208**, 1-3, 273-286.

LUBIMOVA, E.A. & SHELIAGIN, V.A. (1966). — Heat flow through the bottom of Lake Baikal. — *Dokl. Akad. Nauk SSSR,* **171**, 6, 1321-1325 (in Russian).

LYSAK, S.V. (1978). — The Baikal rift heat flow. — *Tectonophysics,* **45**, 87-93.

LYSAK, S. (1995). — Terrestrial heat flow and temperatures at upper crustal depths in southern East Siberia. — *Bull. Centre Rech. Explor.- Prod. Elf Aquitaine,* **19**, 1, 39-57.

NEHLIG, P. & JUTEAU, T. (1988). — Flow porosities, permeabilities and preliminary data on fluid inclusions and fossil thermal gradients in the crustal sequence of the Sumail ophiolite (Oman). — *Tectonophysics*, **151**, 1-4, 199-221.

NORTON, D. & KNIGHT, J. (1977). — Transport phenomena in hydrothermal systems: cooling plutons. — *Amer. J. Sci.*, **277**, 8, 937-982.

PISARSKY, B.I. (1987). — Regularities of formation of ground waters in the catchment of Lake Baikal. — Nauka, Novosibirsk, 154 pp. (in Russian).

SCHOLZ, C.A., KLITGORD, K.D., HUTCHINSON, D.R., TEN BRINK, U.S., ZONENSHAIN, L.P., GOLMSHTOK, A.Y. & MOORE, T.C. (1993). — Results of 1992 Seismic reflection experiment in Lake Baikal. — *EOS Transactions. AGU*, **74**, 41, 465.

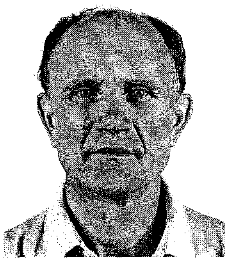
SOLONENKO, V.P. & TRESKOV, A.A. (1960). — Middle Baikal earthquake of August 29, 1959 in Central Baikal. — Irkutsk Publ. House, 34 pp. (in Russian).

TADA, R. (1991). — Compaction and cementation in siliceous rocks and their possible effect on bedding enhancement. — *In:* EINSELE, G., RICKEN, W. & SEILACHER, A. (eds): Cycles and events in stratigraphy. — Springer-Verlag, 480-491.

WEISS, R.F., CARMACK, E.C. & KOROPOLOV, V. M. (1991). — Deep water renewal and biological production in Lake Baikal. — *Nature*, **349**, 665-669.

YAS'KO, V.G. & SHABYNIN, L.L. (1984). — North-Muya ridge. — *In:* I.S.LOMONOSOV (ed.): Geology and Seismicity of the BAM zone. Hydrogeology. — Nauka, Novosibirsk, 116-132 (in Russian).

ZORIN, Yu.A. & OSOKINA, S.V. (1984). — Model of transient temperature field of the Baikal rift lithosphere. — *Tectonophysics*, **103**, 193-204.



Vladimir Artemievich GOLUBEV holds a degree in Physics from the Irkutsk State University (1968) and a doctorate in Physics and Mathematics from the Institute of Physics of Earth in Moscow (1978). Since 1970 he has worked at the Institute of the Earth's Crust for the Siberian Branch of the Russian Academy of Sciences. Since 1982, he has been a senior Researcher at the Laboratory of Geophysics. His main scientific interests focus on geothermics, theory of conductive and convective heat transfer in the Earth's crust, studies of the heat output by thermal waters and gases in the continental rifts and especially through the bottom of the deep rift lakes.

***Vladimir Artemievitch GOLUBEV** est diplômé en Physique de l'Université d'Irkutsk (1968) et docteur en Physique et Mathématiques de l'Institut de Physique du Globe de Moscou (1978). Depuis 1970, il est chercheur à l'Institut de Physique du Globe de la section Sibérie de l'Académie russe des Sciences. En 1982, il devient Maître de Recherches au Laboratoire de Géophysique. Ses recherches portent sur la géothermie, l'étude théorique des transferts de chaleur par conductivité et convectivité dans l'écorce terrestre et l'étude de l'apport de chaleur par les eaux thermales et les gaz dans les rifts continentaux, en particulier au fond des lacs profonds dans les rifts.*