HEAT FLOW THROUGH THE BOTTOM OF LAKE BAIKAL

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Abstract

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HEAT FLOW THROUGH THE BOTTOM OF LAKE BAIKAL

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The Baikal region is the region of greatest seismicity on the continent, characterized by a sharp isostatic disequilibrium of the Earth' s crust and by intense modern movements (^{1}). About 2000 earthquakes are recorded here every year. The frequency of earthquakes of magnitude 10 reaches 15 per 100 years. Since the ridges of the Baikal region are still rising and the basin is subsiding, it may be considered that the isostatic anomalies are increasing and the disequilibrium is becoming greater. Volcanism is predicted to awaken here (^{2}). In this connection, an estimate of the energy parameter of this region in the form of the magnitude of the heat flow is of particular interest.

Method. We applied the oceanographic method (^{3}, ^{4}) for determining heat flow by inserting a gradient-probe into the bottom sediments of Baikal. The work was organized by the Institute of Physics of the Earth of the Academy of Sciences of the USSR jointly with the Limnological Institute and the Institute of the Earth' s Crust of the Siberian Branch of the Academy of Sciences of the USSR on the research vessel "G. Yu. Vereshchagin" in 1965. A gradient-probe with sensitive semiconductor sensors mounted on it was lowered from the side of the ship in free drift. The design of the thermogradientograph is described in (5). The heat-flow measurement was made at depths > 700 m; on the bottom a horizontal site about 600 m long was selected. Near the bottom, a stop was made and a "zero line" was recorded for reading off the temperature gradient. Thermistors MMT-1 were used as sensors, and direct-current bridges with a lower sensitivity threshold of 0.005 were used. Recording was carried out by burning electrosensitive paper. The form of the record is shown in Fig. 1. The gradient was recorded through two channels. The temperature gradient, from the obtained record of the temperature difference at a distance l between the sensors, was determined by the formula:

Fig. 1. Record of the thermogradientograph

$$\operatorname{grad} T = \frac{\Delta S_2 \Delta R_1}{\Delta S_1 \cdot k \cdot l}, \tag{1}$$

where ΔR_1 is the change in the resistance of the calibrator, ΔS_2 is the amplitude of the working record corresponding to the difference in the thermistor readings, l is the distance between the sensors, k is the temperature coefficient of the thermistor, and ΔS_1 is the amplitude of the record from the calibrator. Table 1 gives the mean values of the parameters entering formula (1) and their errors, as well as the total error in determining the temperature gradient for both channels.

Sampling of the sediment for measuring its thermal conductivity was carried out with a special sediment tube immediately before lowering the thermogradientograph. The thermal conductivity of the sediment column was measured at several levels; the thermal-conductivity data for each station were reduced to a depth of 1 m. For the first time in oceanographic investigations, the "spherical probe" method was used to determine the thermal conductivity of sediments* . The calculation formula is as follows [5]

Table 1

	1st channel	2nd channel
ΔR_1, ohm	2.71 ± 0.01	10.72 ± 0.01
ΔS_2, mm	32 ± 0.3	10 ± 0.1
ΔS_1, mm	5 ± 0.1	3 ± 0.1
l, m	1 ± 0.02	2 ± 0.03
k, ohm/deg	86 ± 1	86 ± 1
$\operatorname{grad} T$, deg/m	0.200 ± 0.014	0.200 ± 0.008
Error, %	7	4

$$\lambda = \frac{q\,(\sqrt{t_2} - \sqrt{t_1})}{4\pi a\,(T_2\sqrt{t_2} - T_1\sqrt{t_1})}, \tag{2}$$

where λ is the thermal conductivity, T the values of the probe temperature, t the time of temperature reading, a the radius of the spherical probe, and q the specific power of the probe heater. The results obtained were checked by the Ratcliffe method, which is based on the empirical dependence of the thermal conductivity of bottom sediments on their moisture content. Satisfactory agreement of the results was obtained; the total error in measuring λ was estimated at 7%.

Results of measurement. The instrumental value of the heat flow was determined as $Q = \lambda \operatorname{grad} T$. Table 2 presents the results for each of the 11 stations (their locations are shown in Fig. 2).

Most of the stations are located at the southern end of Baikal—at the foot of the eastern slope of the Baikal depression. Stations Nos. 10 and 11 are situated on the margins of the depression north of the Ushkany Islands; stations Nos. 3, 5, and 8 form a profile opposite Cape B. Kolokolnya.

Table 2

No.	N lat.	E long.	grad T, deg/m	λ, cal/(cm · deg · sec) $\times 10^{-4}$	Q, μcal/(cm^2 · sec)
1	54°57$ ‘24’ ’ $	109°33$ ‘00’ ’ $	0.110	20	2.2
2	53°55$ ‘36’ ’ $	109°08$ ‘00’ ’ $	0.210	12	2.5
3	52°12$ ‘30’ ’ $	105°53$ ‘30’ ’ $	0.142	18	2.5
4	51°36$ ‘30’ ’ $	104°35$ ‘00’ ’ $	0.120	18	2.1
5	52°15$ ‘00’ ’ $	105°49$ ‘30’ ’ $	0.126	19	2.4
6	51°38$ ‘40’ ’ $	104°13$ ‘00’ ’ $	0.112	27	3.0
7	51°38$ ‘30’ ’ $	105°44$ ‘50’ ’ $	0.154	20	3.0
8	52°11$ ‘30’ ’ $	105°52$ ‘50’ ’ $	0.104	19	2.0
9	51°40$ ‘20’ ’ $	105°12$ ‘30’ ’ $	0.170	20	3.4
10	54°12$ ‘30’ ’ $	108°57$ ‘50’ ’ $	0.110	20	2.2
11	54°00$ ‘00’ ’ $	108°52$ ‘20’ ’ $	0.105	20	2.1

Calculation of the heat flow. The arithmetic mean from the instrumental data is equal to $2.6 \cdot 10^{-6}$ cal/cm^2 · sec. A histogram of the measured heat-flow values is given in Fig. 3. Calculation of the true value of the heat flow in the complex structural zone of Baikal requires consideration of the following factors.

1. Influence of relief irregularities

Mountains located in the vicinity of the lake may be the cause of significant curvature of the deep isotherms. To calculate the topographic correction it is necessary to find a solution of Laplace’ s equation $\nabla^2 T = 0$ that satisfies the conditions: $T \to \gamma z$ as $z \to \infty$, $T = T_s(xy)$ at the surface; $z = -h(xy)$, where h is the height above sea level. The simplest solution of this problem

Fig. 2. Outline of Lake Baikal with the location of stations and the ellipsoid replacing it

Figure 2: Fig. 2. Outline of Lake Baikal with the location of stations and the ellipsoid replacing it

was proposed by Lees [6]. According to the Lees correction, the increase in the geometric gradient at the lake shore, caused by the influence of a mountain range located in the southern part of Baikal, to the east of it, at a distance of 10 km from the shore and having a height of about 2 km, should amount to $6 \cdot 10^{-6}$ deg/cm near the ground surface. This value ex– negligibly small in comparison with the geothermal gradient. Therefore it may be considered that the mountain massif under consideration has no influence on the temperature distribution beneath Baikal.

2. The Role of the Cold Water Mass

The cooling of the Earth' s crust near large water basins was pointed out by V. I. Vernadskii (^{7}). To calculate the correction, the form of Lake Baikal may be represented by one half of an ellipsoid cut by a plane passing through two of its axes and situated so that the plane of the section coincides with the Earth' s surface (^{8}). It is necessary to take the length $2b = 660$ km, the width $2a = 50$ km, and the greatest depth $c = 1700$ m. Then the relation between the true γ and measured dT/dn gradients is determined as

$$\frac{dT}{dn} = \frac{4}{z_0} \gamma z \times$$

$$\times \frac{1}{c_2} \frac{1}{\sqrt{\frac{x^2}{a^4} + \frac{y^2}{b^4} + \frac{z^2}{c^4}}}.$$

Thus, the increase in heat flow and the geothermal gradient at constant thermal conductivity, caused by the presence of cold water, should amount to a maximum of 7%, i.e., the measured value of the heat flow should be reduced by approximately 7%; taking into account that the observation stations are shifted from the center toward the southern and northern parts, for the mean value of the flow we obtain $2.4 \cdot 10^{-6}$ cal/cm^2 • sec. A more detailed calculation of the correction can be carried out by electrical modeling.

Fig. 2. Outline of Lake Baikal with the location of stations and the ellipsoid replacing it

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* Measurements of thermal conductivity were carried out by A. K. Popova.

Fig. 3. Histogram of heat-flow values for Lake Baikal (I) and graph of the increase of Q with the rise of the melting boundary (II). a—melting temperature $T_m = 1000$°K, b—$T_m = 2000$°K.

Figure 3: Fig. 3. Histogram of heat-flow values for Lake Baikal (I) and graph of the increase of Q with the rise of the melting boundary (II). a—melting temperature $T_m = 1000$°K, b—$T_m = 2000$°K.

3. The Role of River Deposits

The northwestern part of Baikal is characterized by periodically recurring catastrophic floods, as a result of which, in a short time, through downpours and the melting of snow on the crests of the ridges, the stream from the mountains carries out and deposits hundreds of thousands of cubic meters of suspended material (^{9}). This catastrophic sedimentation may be the cause of a strong disturbance of the regional gradient. Since the growing layer of sediments must absorb part of the heat, as a result of measurements we obtain an underestimated heat flow. Its initial value may be found from the formula: $\gamma = \gamma_0 \operatorname{erfc}[vt/\sqrt{4kt}]$, where v is the sedimentation rate.

Unfortunately, at present we do not have sufficient information on the history, age, and rate of the sedimentary formations of Baikal to obtain a numerical estimate of the effect. The correction may reach 30%. It is quite possible that the observed decrease in the magnitude of the heat flow in the northwestern part of Baikal can be explained by this effect.

4. Influence of glaciations

The fact of ancient glaciation in the Baikal region is not denied; there is only no unanimity on the question of the number of glacial epochs. All views agree that the glaciers approached the very waterline of Baikal (^{9,10}). On the southern shore the glaciation was comparatively slight, while in the northeastern part it was the strongest.

Fig. 3. Histogram of heat-flow values for Lake Baikal (I) and graph of the increase of Q with the rise of the melting boundary (II). a—melting temperature $T_m = 1000$°K, b—$T_m = 2000$°K.

If the glaciation lasted from time t_2 to t_1 and the temperature was maintained equal to $T_1 = -V_1$, then the geometrical gradient at the surface is

$$\gamma_0 = \gamma + V_1 \left[(\pi k t_1)^{-1/2} - (\pi k t_2)^{-1/2} \right].$$

For $V = 5^\circ$, $k = 0.01\ \mathrm{cm}^2/\mathrm{s}$, $t_1 = 10^4$ years, $t_2 = \infty$, the perturbation of the geothermal gradient must reach 5°/km, and the correction to the heat flow up to 30%. This means that the equilibrium values of the heat flow in the northeastern part must be increased to $(2.8 \div 3.0) \cdot 10^{-6}$ cal/cm$^2 \cdot$ s. The correction for glaciation apparently exceeds all the others.

Taking all corrections into account, the mean value of the heat flow must be increased by 23%, i.e., it should amount to $3.2 \cdot 10^{-6}$ cal/cm$^2 \cdot$ s. We cannot vouch for the accuracy of the corrections because of the uncertainty of the geological information. However, within the limits of the estimated corrections, there exists beneath Baikal a thermal anomaly characterized by an increased heat flow and due in its origin to deep horizons of the mantle. The conclusion about a thermal anomaly is in complete agreement with the results of deep electromagnetic sounding ([11]), which indicate a sharp increase in electrical conductivity beneath Baikal. The origin of the high temperature in the mantle and of the anomaly in the heat flow can be explained by invoking the effect of zonal melting of the upper layers of the mantle ([12]). As is evident from Fig. 3, the flow Q increases rapidly as the upper boundary of melting approaches the base of the crust.

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Note: Figure translations are in progress. See original paper for figures.