

PRELIMINARY RESULTS FROM UNDERWATER BOREHOLES ON LAKE BAIKAL: RELIABILITY OF GEOTHERMAL MEASUREMENTS

R.P. DOROFEEVA AND A.D. DUCHKOV

¹Senior Scientist, Academy of Sciences, Institute of the Earth Crust, Irkutsk, Russia

²Head of Laboratory, Academy of Sciences, ~~United~~ Institute of Geology, Geophysics and Mineralogy, Novosibirsk, Russia

SUMMARY - Geothermal measurements in two 100 m deep underwater boreholes in **Baikal** (52°31'05" N, 106°09'11" E) yielded a thermal gradient of **41 mK/m** and average heat flow of **73 mW/m²**. These values are different from earlier shallow measurements. The downhole temperature taken at depths 0, 28, **58**, and 88 m sub-bottom showed an increase with depth from **3.41** to **7.19°C**. Thermal conductivity determined by needle probe on 109 samples immediately after the core recovery tends to be lower than that measured on **553** samples several weeks later in the laboratory (1.16 against 1.76 W/mK). The systematic difference of about 30% between the two methods may be due to the effect of **outgassing** and consolidation of sediments. A sound resolution of the questions arisen can be obtained by repeated measurements in underwater boreholes to be drilled in 1995 - 1997.

I. INTRODUCTION

Heat flow studies in underwater boreholes on Lake Baikal were conducted in the frame of the multi-institutional **Baikal** Drilling Project (**BDP**) run by an international team of Russian, American and Japanese scientists to investigate past climatic changes and syn-rift tectonic evolution of the **Baikal** basin. Two boreholes, about 6 km seaward from the western coast of Baikal at 52°31'05" N, 106°09'11" E located within 1-2 m of each other, were drilled in March 1993 from a barge frozen into the ice. Water depth was **354** m and the holes reached a sub-bottom depth of about 100 m. The two recovered **cores** is being examined currently by several research teams **working** on diverse biological and geological **aspects** of the sedimentary record.

Temperature measurements were made in both holes for about 350 hours after the cessation of drilling but not repeated later on. Thermal conductivity was **measured** immediately on the core recovery from corehole N2, and then several weeks later in the laboratory on the core N1. The two data **sets** are consistent and permit joint interpretation.

The geothermal work is the first experience of measurements on long **marine** cores, never done before in **Baikal** studies.

2. TECHNIQUES OF MEASUREMENTS AND RESULTS

2.1. Temperature

Temperature **was** measured using a cable equipped with three thermistors (**output** resistance of **about** 12 kOhm) sensing the temperature of sediments downhole and one that recorded the lake's bottom temperature. The measurements **were** held by an automatic device as systematical sampling at preset time intervals, the information being saved and stored on a

hard disk. Further details concerning the design of the instrument are given in Fotiadi, 1987.

The drilling operation lasted for about ten days, or 250 - 270 hours, including hole flushing and tear-down. The **measurements** with the three thermistors set at 26, 56 and 86 m below the bottom in hole N2 were made for the time **period** 0 to 50 hours. Thermistors at 28.58 and 88 m in hole N1 recorded temperatures for the period 50 to 300 hours. The combined measurements with a small statistic adjustment for depth differences in N2 and N1 are shown in Fig.1.

At the three depth levels, temperature showed a characteristic increase with time indicating return to thermal equilibrium disturbed by **flushing** the **drillhole** with cold lake water during drilling. The greatest increment of **4 - 5°C** was gained in first 50 hours, then the growth slowed down. Near equilibrium was recovered in 300 hours. Systematic temperature increase was disturbed only two times: in 70 - 80 hours, when the temperature rose sharply by 0.2°C at the depths of 28 and 58 m, and in 250-270 hours when it dropped by 0.2°C at the depth of 28 m (Fig.1). The rise could be caused by the effect of water mixing during the recovery of the drill, and the drop could be due to downthrow of sediments from colder shallow horizons.

The temperature profiles in the water column and the sediment column are shown in Fig.1 (a, b). The first 120 m of water below the ice surface show a fast warming up from 0.7 - 0.9°C to 3.65°C. The subsequent very slow decrease by no more than 0.24°C (from 3.65 to 3.41°C) through the remaining 234 m of the water column till the lake bottom is indicative of the thermal stability of this water layer. Fig. 2a illustrates how the temperature behaviour changes drastically at the water/lake bottom interface due to the

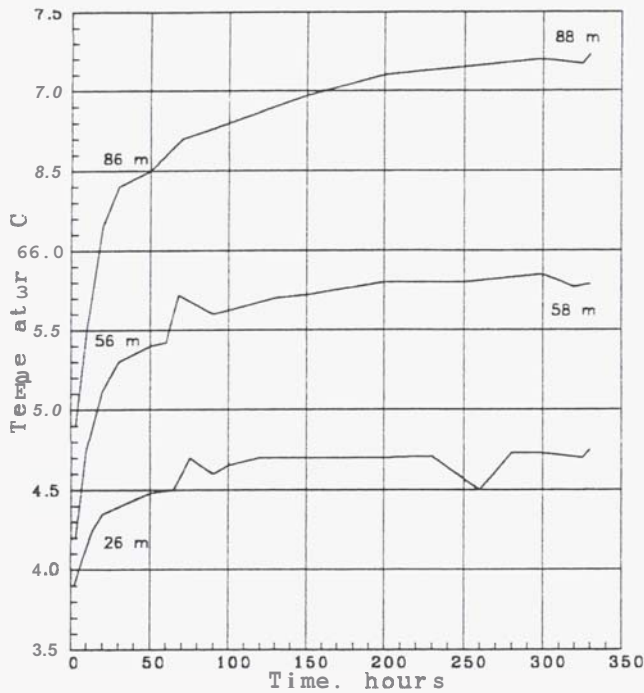


Fig. 1. Return to equilibrium of the boreholes after the cessation of drilling

difference in mechanisms of heat transfer (conduction in the sediments and convection in the water).

Equilibrium temperatures at depths of 0, 28, 58 and 88 m, (obtained about 280 hours after the beginning of measurements, Fig. 1), were used to calculate the geothermal gradient. Unfortunately, the lowest thermistor could not be set deeper than 88 m for technical reasons, and thus temperature at the bottom of the hole was not sensed. The geothermal gradient varies from 36 to 48 mK/m, with a mean value of 41 mK/m (Table 1).

22 Thermal conductivity

A total of 662 thermal conductivity values were determined by two different methods and at different time. First, 109 measurements on core N2 were made on the barge immediately after the core was recovered, entering the probe

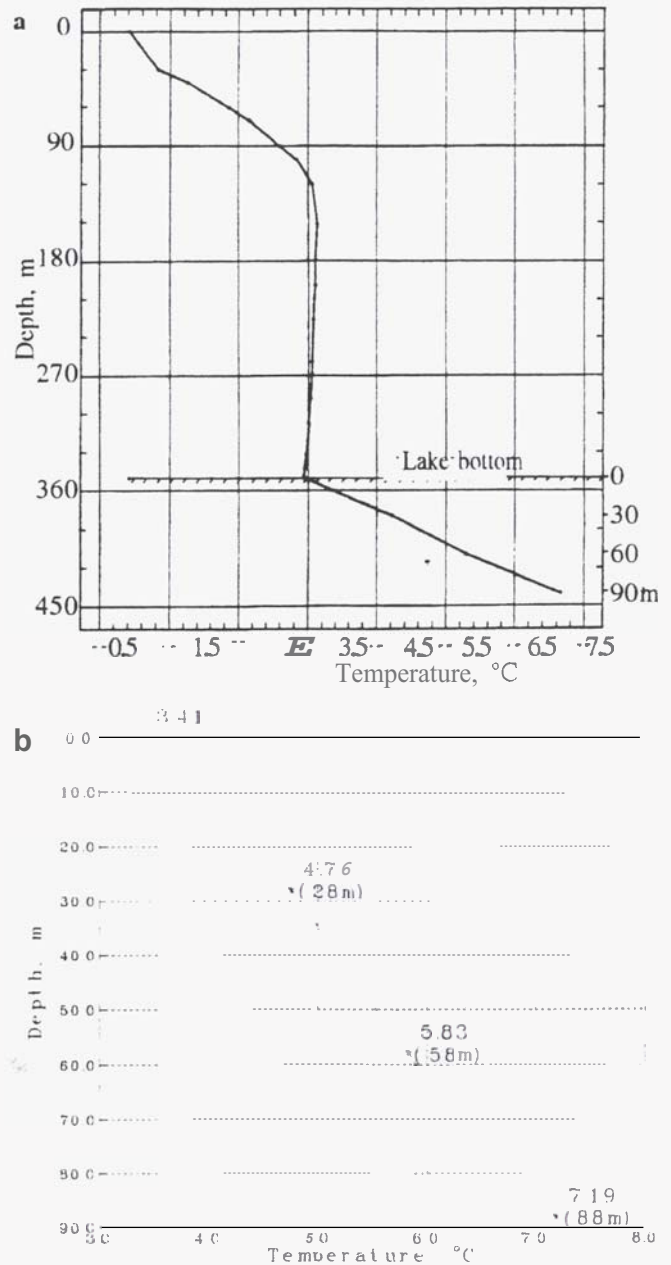


Fig. 2. (a) Downward temperature distribution in the water and downhole. (b) Big scale for downhole temperature distribution

Table 1- Results of geothermal measurements in BDP/93-1 borehole

Number of measurements	number of cores	depth, m	T, °C	Geothermal gradient, mK/m	Thermal conductivity, W/mK		Heat flow, mW/m
					by needle probe method	by thermal comparator	
90	4 - 15	0	3.41	48	1.03	1.55±0.05	74
187	16 - 32	28	4.76	36	1.18	1.75±0.04	63
181	33 - 60	58	5.83	45	1.22	1.80±0.04	81
108	62 - 70	88	7.19			1.86±0.03	,
		102.23	-				
Mean				41	1.16±0.17	1.76±0.04	73

into its butt-ends. The sensing device was semi-automatic, designed on the basis of the constant-power needle probe method (Fotiadi, 1987). The measurements yielded a spread of values from 0.73 to 1.61 W/mK. Relatively low conductivity of 0.8-0.9 W/mK is appropriate of shallowest sediments within a range of 5 to 18 m depth. Below 18 m conductivity increases steeply due to decrease in the water content of sediments and averages 1.16 ± 0.17 W/mK (Table 1).

Several weeks later thermal conductivity was measured in the laboratory by a thermal comparator designed by Siberian engineers. The instrument is based on the comparative method of measurements and is calibrated against the standard conductivities within a range of 0.2 to 14.7 W/mK (Kalinin, 1981). The core samples were split axially into two halves, and their surfaces were sensed (553 determinations on 70 samples). Thermal conductivity results are shown in Figure 3. An increase from 1.4 to 1.8 W/mK was observed downward to a depth of 50 m sub-bottom, which was followed by a decrease down to 1.6 W/mK between 50 and 80 m depth and then by another increase starting from below 80 m. The arithmetic mean of the laboratory-examined conductivities is 1.76 ± 0.01 W/mK, 30% higher than that measured aboard the barge on non-split samples by the needle probe method (Fig.3, Table 1).

Lithologically the recovered sediments are diatom and pelitic silt with some sand admixture. The portion of pelitic material decreases downhole and the portions of silt and sand grow accordingly. The section shows a sharp line of demarcation between fine- and coarser-grained sediments

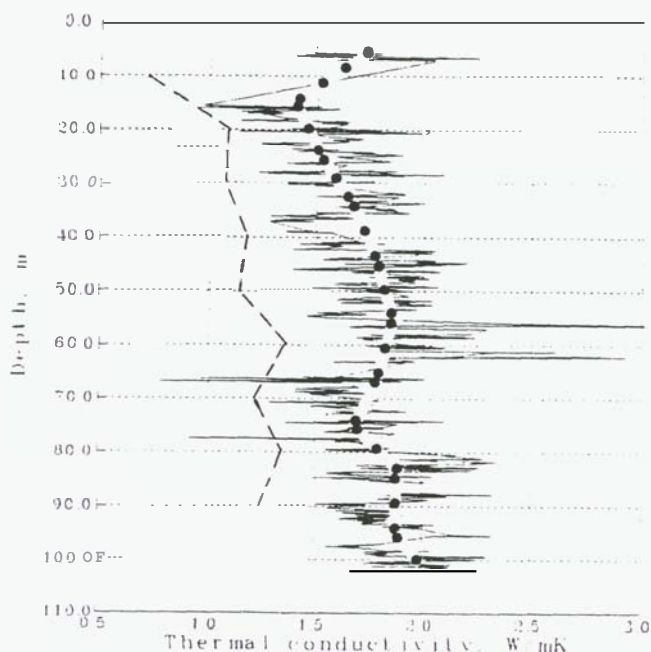


Fig.3. Thermal conductivity plotted against the sub-bottom depth in BDP-93/1 determined on 553 samples in the laboratory by the comparative method. Dotted line is thermal conductivity averaged over every 10 m of the core. Dashed line on the left is mean conductivity from measurements by needle probe method made on the barge immediately following core retrieval.

at 50 m depth, with fine-grained in the upper and coarser-grained in the lower unit.

An attempt was made to observe the behaviour of thermal conductivity of the sediments as a function of their lithology. The thermal conductivity diagrams shown in Fig.4, are plotted separately for six lithological groups discriminated according to silt and sand percentages they contain. The number of measurements varied from 38 on clay silt (10 to 50% of sand and above 50% of silt) to 151 on clays. Individual anomalously low values belong to the sediments containing organic cells, and the above-normal peaks correspond to consolidated sandy and silty lenses.

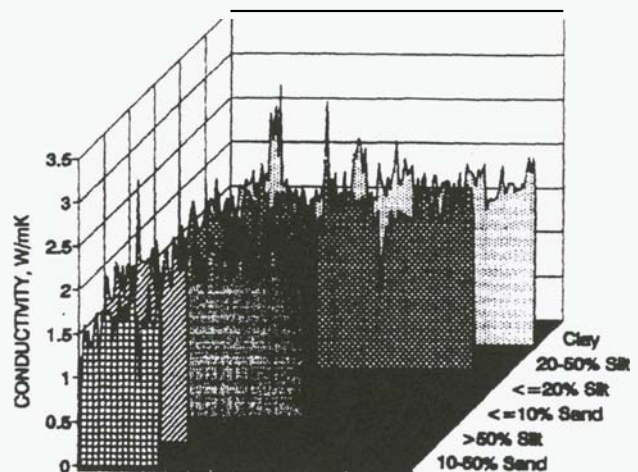


Fig.4. Thermal conductivity of sediments (BDP-93/1) in function of their lithology. The six datasets are: clays, 151 samples (a); under 10% sand, 78 samples (b); 10-50% sand, 38 samples (c); more than 20% silt, 72 samples (d), 20-50% silt, 132 samples (e); more than 50% silt, 38 samples (f). On X axis are portions of each lithology per the total core

The heat flow in the drilling site, calculated on the basis of newly obtained thermal conductivities, is 73 mW/m² that is some 30% higher than the previous estimates of about 50-52 mW/m² from measurements in near-bottom sediments (Sites NN 953, 954 in the Catalogue of heat flow data in Siberia, Duchkov, 1985).

3. DISCUSSION

Heat flow in Baikal has been so far calculated from numerous samples of temperature, geothermal gradient and thermal conductivity of the uppermost sediments measured by standard lake and marine heat flow probes penetrating no deeper than 3-3.5 m below the lake bottom (Golubev, 1982; Duchkov, 1985; Fotiadi, 1987). These shallow measurements have been of common use to speculate about the temperatures and heat flow at greater depths though it has been questioned how could the heat flow behave in its downward distribution.

The question arose again after we had obtained first results from the BDP-93 experiment. As noted above, the thermal conductivity measured by a needle probe inserted into the butt-ends of the cores is in average 30% lower than that

taken several weeks later in the laboratory on split samples. This systematic difference, the input temperatures remaining the same, causes the respective spread of the heat flow values (from 63 to 81 mW/m²) which cannot be accounted for by mere instrumental bias. Quite apparently, the lower conductivity obtained immediately after the core recovery may be due to dilution of the sediments as they were lifted through the water. Moreover, gases were observed at the time of coring as expansion pockets of 3 - 10 cm of core liner length. The gas pockets were not sampled or analysed and their chemistry and exact amount remained unknown. Thus, the sediments could have consolidated later and increase in conductivity due to the ensuing outgassing.

It is pertinent to compare our results with a similar study of underwater boreholes in lake Biwa, carried out by Japanese scientists (Fujisawa et al., 1985; Horie, 1987). They **obtained** a long record of bottom sediments from a 197.2 m deep borehole drilled in 1971 and a super-deep borehole cored in early **80-ies**, which reached the sub-bottom depth of 1422.5 m, having passed through about 65 m of water (Fujisawa et al., 1985). The temperature variation, and thus the temperature gradient, in the upper 50 m of the sediment was greater than that at the lake bottom (Fig.5). The gradient **k a m e** fairly stable below 150 m from the lake surface and averaged **55 mK/m** between 150 and 250 m (Uyeda et al., 1973). Then it decreased down to 32 mK/m in a range of 310 to 710 m and further down to 26 mK/m between 730 and 890 m sub-bottom (Fujisawa et al., 1985). The mean thermal conductivity of sediments in the layer where the gradient becomes stable (150 to 250 m), showed to be 0.92 ± 0.04 W/mK, **as** measured by the needle probe **method** (Uyeda et al., 1973). On the other hand, its arithmetic **mean** between the depths of 250 and 800 m was estimated **as** 1.85 ± 0.28 W/mK from **QTM** (Quick Thermal Conductivity Meter) measurements, or about 38% higher

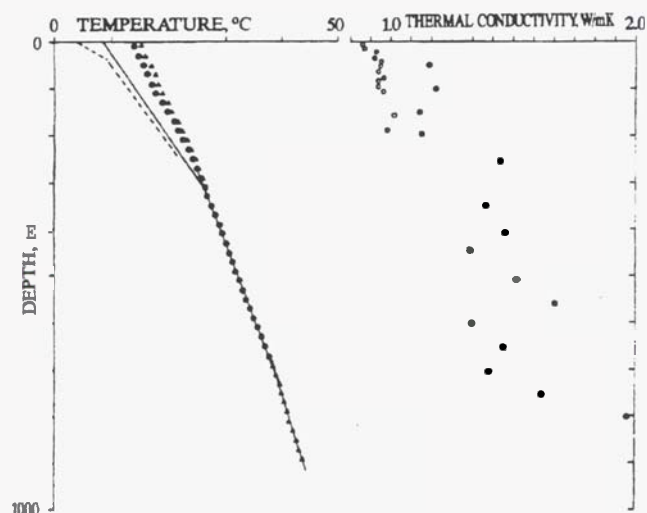


Fig.5. Observed temperature gradient and thermal conductivity, (after Fujisawa et al., 1985). Dotted line in the left upper corner is the result of Uyeda et al. (1973). Solid lines show estimated original temperature profiles. Solid circles and solid triangles show measurements on 8 May and on 2 May, respectively. Solid circles are thermal conductivities measured by the QTM and open ones **are** those by the needle probe by Uyeda et al. (1973)

(Fujisawa et al., 1985). Note, however, that the thermal conductivity could be disturbed by freezing the sediments during storage and thawing before measurements, and this effect is still uninvestigated. Uncorrected heat flow in lake Biwa **was** estimated as 56 mW/m² (Horie, 1987).

Therefore, our results from the 100 m deep holes agree with those of the Japanese scientists obtained on a far longer core but on less number of samples.

4. CONCLUSION

Geothermal studies of 100 m boreholes and long marine cores from Baikal, the continental rift lake in the center of Asia have yielded a thermal gradient of **41 mK/m** and average heat flow of 73 mW/m². This study also raises a number of questions. Previous shallow measurements have yielded high geothermal gradients and low thermal conductivities. The new results showed 30 - 40% higher conductivity values, though the effect of degassing of sediments remained uninvestigated. So, it can be hypothesized that the heat **flow** is underestimated and the respective correction is probably needed with regard to higher thermal conductivity. Moreover, the heat flow may vary with depth, some of the variations being related to past climatic changes.

These problems can find a sound resolution only if a reliable collection of statistic data is gathered to provide a solid ground for geophysical interpretation of the preliminary results. The collection of deep-water measurements is expected to **be** amplified soon due to laboratory examination of the second core **and** to further drilling experiment through 1995 - 1997 in three more drilling sites at the Academician ridge **and** the Selenga delta.

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