A NEW GEOTHERMAL STUDY IN UNDERWATER BOREHOLES ON LAKE BAIKAL (Continental Rift Zone)

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ABSTRACT

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/m^2. 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 encountered 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 are 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 upon 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.

II. 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.

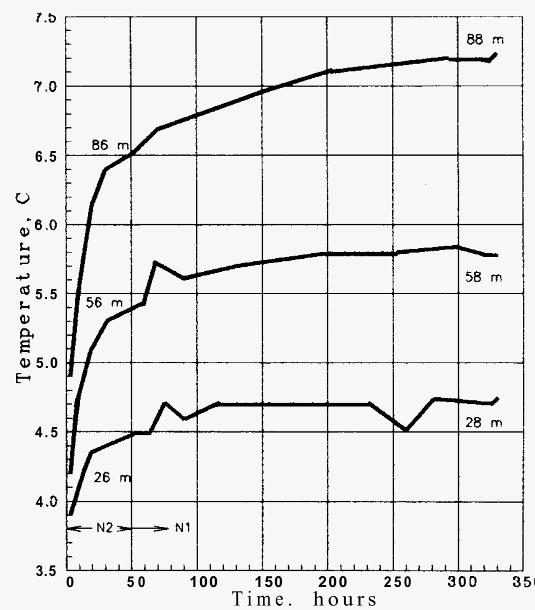
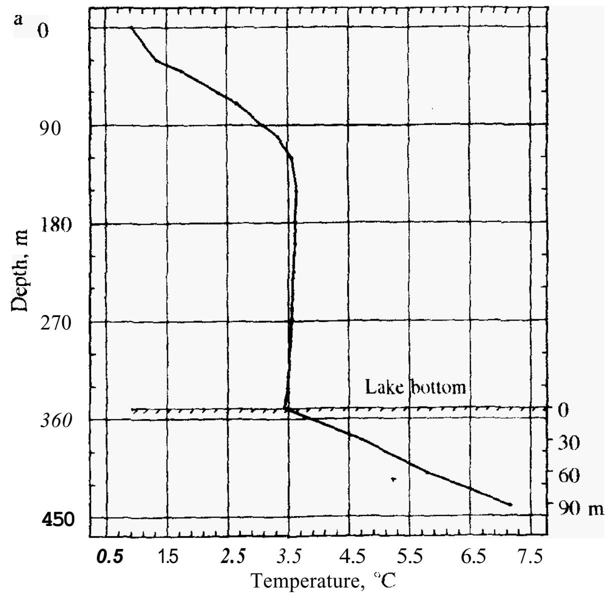


Fig.1. Return to equilibrium of the boreholes after the cessation of drilling

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 fist 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.2 (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 difference in mechanisms of heat transfer (conduction in the sediments and convection in the water).



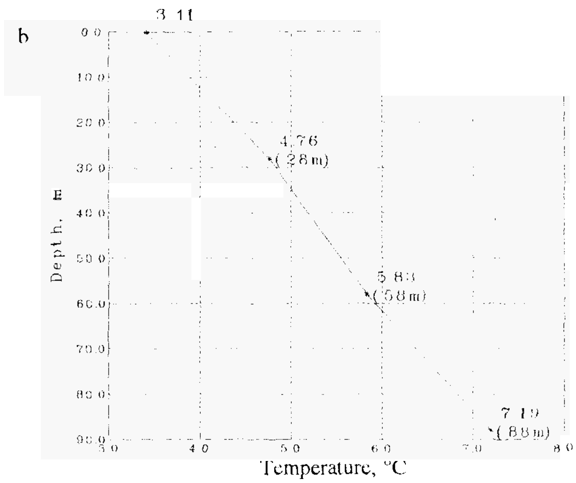


Fig.2. (a) Downward temperature distribution in the water and downhole. (b) Big scale for downhole temperature distribution

Equilibrium temperatures at depths of 0, 28, 58 and 88 m, (obtained about 280 hours after the beginning of measurements, Fig.1), wen: 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 hottom 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).

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

Number of measurement	number of cores	depth, m	T,°C	Geothermal gradient, mK/m	Thermal conductivity, W/mK by needle probe method	Thermal conductivity, W/mK by thermal comparator	Heat flow,mWt/m2
		0	341				
90	4 - 15			48	1.03	1 55±0 05	74
		28	4 76				
187	16 - 32			36	1.18	1 75 ±0 04	63
		58	5.83				
181	33 - 60			45	122	1.80±0.04	81
		88	7 19				
108	62 - 70					1 86±0.03	›
		102 23					
Mean				41	1.16±0.17	1 76±0.04	73

2.2. 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 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 bared on the comparative method of measurements and is calibrated against the standard conductivities within a range of

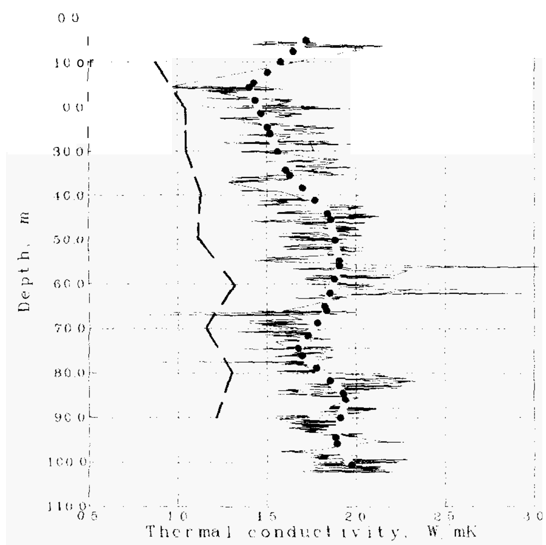


Fig.3. Thermal conductivity plotted against the sub-hottom depth in BDP-93/1 determined on 553 samples in the laboratory by the comparative method. Dotted line is thermal conductivity averaged over every 10 m of the core. Dashed line on the left is mean conductivity from measurements by needle probe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

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

An attempt was made to observe the hehaviour 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 3X on clay silt (10 to 50% of sand and ahove 50% of silt) to 15 I on clays. Individual anomalously low values helong to the sediments containing organic cells, and the ahove-normal peaks correspond to consolidated sandy and silty lenses.

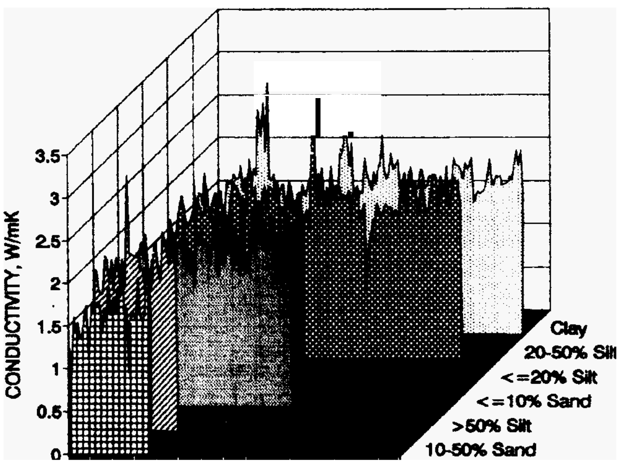


Fig.4. Thermal conductivity of sediments (BDP-93/1) as function of lithology. The six datasets are: clays, 151 samples (a): under 10%sand, 7X samples (b): 10-50% sand, 38 samples (c): more than 20% silt, 72 samples (d), 20-50% silt, 132 samples (e); more than 50% silt, 3X samples (I). On X axis are portions of each lithology per the total core

The heat flow in the drilling site, calculated on the basis of newly ohtained thermal conductivities, is 73 mW/m^2 that is some 30%higher than the previous estimates of ahout 50-52 mW/m^2 from measurements in near-hottom sediments (Sites NN 953, 954 in the Catalogue of heat flow data in Siberia, Duchkov, 1985).

III. DISCUSSION

Heat flow in Baikal has heen so far calculated from numerous samples of temperature. geothermal gradient and thermal conductivity of the uppermost sediments measured hy 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 heen of common use to speculate about the temperatures and heat flow at greater depths though it has heen questioned how could the heat flow behave in its downward distrihution.

The question arose again after we had ohtained first results from the BDP-93 experiment. As noted ahove, the thermal conductivity measured hy a needle probe inserted into the hutt-ends of the cores is in average 304 lower than that taken several weeks later in the lahoratory 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/m^2) which cannot he accounted for hy mere instrumental bias. Quite apparently, the lower conductivity ohtained immediately alter the core recovery may he 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 - 10cm 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 horeholes in lake Biwa, carried out by Japanese scientists (Fujisawa et al., 1985; Hone, 1987). They obtained a long record of hottom 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-hottom 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 hottom (Fig.5). The gradient hecame fairly stable below 150 m from the *lake* surface and averaged 55 mK/m between

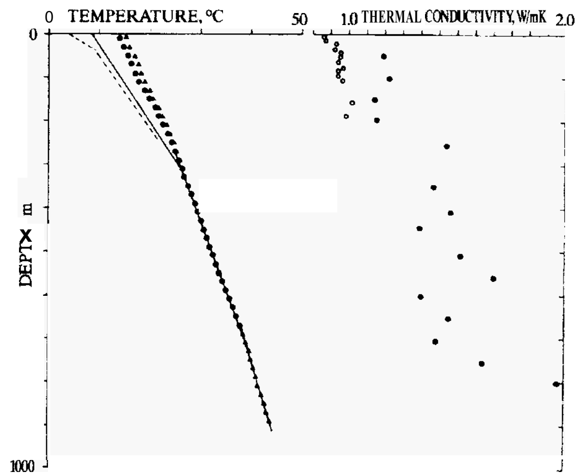


Fig.5. Observed temperature gradient and thermal conductivity, (after Fujisawa et al.,1985). Dotted line in the left upper corner is the result of Uyeda et al. (1973). Solid lines show estimated original temperature profiles. Solid circles and solid triangles show measurements on X May and on 2 May.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

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-hottom (Fujisawa et al., 1985).The mean thermal conductivity of sediments in the layer where the gradient becomes stable (150 to *250* m), showed to k 0.92±0.04 W/mK, as measured hy 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 (Fujisawa et al., 1985). Note, however, that the thermal conductivity could k 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/m^2 (Horie, 1987).

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

IV. CONCLUSION

Geothermal studies of 100 m horeholes 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/m^2. 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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