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Method for deep temperature estimation with regard to the paleoclimate influence on heat flow

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Abstract

New results of the study of the distorting effect of paleoclimate on the formation of the thermal field of the Earth's uppermost crust in the South Urals are presented. We discuss some consequences of taking into account the paleoclimate influence on estimates of deep heat flow and possible applications of these data. The dependence of the heat flow density on the studied depth of boreholes is considered, and deep heat loss and deep temperatures are estimated. A new method for deep temperature estimation is proposed, which takes into account the paleoclimate influence on the heat flow. The method is tested on the available high-quality temperature data for deep boreholes. Deep temperatures to a depth of –10,000 m are estimated for the platform part of the Republic of Bashkortostan using the proposed method. Isotherm schemes are constructed for elevations of –5000 and –10,000 m below sea level.

The necessity of using heat flow values corrected for the paleoclimate influence to estimate the Earth's thermal state is justified. Some examples illustrate that underestimation of heat flow values measured in shallow boreholes might lead to underestimation of deep temperatures and global heat losses.

Keywords: geothermics; heat flow; temperature; thermal conductivity; paleoclimate; conductive heat losses; South Urals

Introduction

Heat flow is the main source of information about the Earth's thermal state and the energy of the processes that go on within the Earth. Applied studies of the thermal field include the assessment of geothermal resources for their utilization as an energy source and the application of the geothermal method to prospecting and exploration works.

The distribution of heat flow is usually mapped using measured values of the heat flow, without any corrections, which can vary from region to region. Further use of data on the heat flow requires that the influence of distorting factors be excluded, if possible. Paleoclimate is one of these factors, whose influence can be taken into account and excluded.

The effect of climatic changes in the temperature of the Earth's surface on the distribution of temperature with depth in the near-surface rocks has been known since the 1930s, when the study of the Earth's heat flow began. Owing to the mechanism of thermal conductivity, surface temperature fluctuations penetrate into the Earth's interior with an attenuating amplitude and a delay in time, distorting the temperature field. Therefore, the present-day temperature distribution in the upper layers of the rocks depends on the climate prehistory. First and foremost, taking into account the influence of paleoclimate on the measured heat flow requires reliable data on past change in the temperature of the Earth's surface. For a long time, the effect of paleoclimate was considered an obstacle to heat flow measurements. There were attempts to take it into account using different climatic corrections, but there was no single technique. In the Urals, no corrections for past climate were made during the determination of heat flow for lack of exact data on the duration of climate epochs and the amplitude of temperature change over that time (Sal'nikov, 1984). Thanks to the paleoclimate studies of the last two decades, which were based on geothermal data, the knowledge of the change in the temperature of the Earth's surface, including the study region, has been considerably enriched (Demezhko, 2001; Demezhko et al., 2007; Golovanova, 2005; Golovanova et al., 2012; and others), which permits more substantiated corrections for the influence of paleoclimate on the measured heat flow. For the Urals and adjacent regions, a model for past climate changes has been proposed and a map for heat flow, corrected for the paleoclimate effect, has been compiled (Golovanova et al., 2008). For the European territory, a similar but somewhat simplified model was used

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to make regional corrections for the measured heat flow and to compile a map of the heat flow with regard to the influence of paleoclimate (Majorowicz and Wybraniec, 2010). It has been shown that corrections can be dramatic. In turn, this calls for a revision of the previous results of heat flow measurements in different regions and a refinement of the conclusions based on their analysis.

We discuss some implications of taking into account the influence of paleoclimate on estimations of great-depth heat flow and possible applications of the results obtained. The dependence of the density of heat flow on the studied depth of boreholes is considered, and losses of deep heat and deep temperatures in the platform part of Bashkortostan are estimated.

Effect of paleoclimate on estimations of great-depth heat flow

In our previous works, a model was proposed for past climate change in the South Urals and corrections were made for the influence of paleoclimate on the measured heat flow in the study region for all the boreholes in which it was measured (Golovanova et al., 2008). The heat flow of the Urals with paleoclimatic corrections was mapped. It was shown that paleoclimate has a considerable influence on the density of heat flow at depths of up to 1500–2000 m or more. The most important role in the distortion of the present-day heat field is played by the Wurmian–Holocene warming at ~10 ka and the cooling of the Little Ice Age (150–650 years ago). As a result, the geothermal gradient and, consequently, the heat flow within this interval are decreased. The correction for the measured values will be larger if the heat flow was determined in a shallow borehole or if the interval of the heat flow determination includes the upper part of the borehole section.

Together with possible differences in climate history, different depths of heat flow determinations complicate paleoclimatic correction and cause mistakes in the determination of great-depth heat flow. Analysis of data shows that the measured heat flow increases with depth. This problem was widely discussed, and authors made the conclusion that the heat flow for boreholes less than 2 km deep had been underestimated and paleoclimatic corrections were necessary. For example, in (Gosnold et al., 2005), a brief survey of literature is carried out and a linear dependence between the measured heat flow in Europe and the studied depth of boreholes is presented, according to different authors (database of the International Heat Flow Commission, http://www.geophysik.rwth-aahen.de/IHFC). In the South Urals and adjacent areas, it was also observed that boreholes up to 4–5 km deep are marked on the map by higher heat flow values than those of the surrounding shallower boreholes (Golovanova, 2005; and others).

In this paper, analysis of all published data on the heat flow of the Urals and adjacent territories also showed an increase in the heat flow density with depth. Published data on the densities of heat flow in the Urals and adjacent territories (Golovanova, 2005), measured by the classical method depending on the studied borehole depth, are shown in Fig. 1*a*. The figure clearly illustrates the foregoing dependence between the measured heat flow and the studied borehole depth.

The paleoclimatic corrections applied to the measured heat flow (Golovanova et al., 2008) almost eliminate the depth dependence of the heat flow (Fig. 1*b*). This fact can confirm the correctness of the proposed model for past climate changes in the Urals and of the way the paleoclimatic corrections were applied.

No realistic geodynamic theory can be developed without analyzing the Earth's thermal field. Determinations of the density of conductive heat flow serve as a basis for the solution of the problem concerning the origin of heat flow. The obtained average estimates of the heat flow are used for the estimation of the planetary conductive heat losses and energy balance.

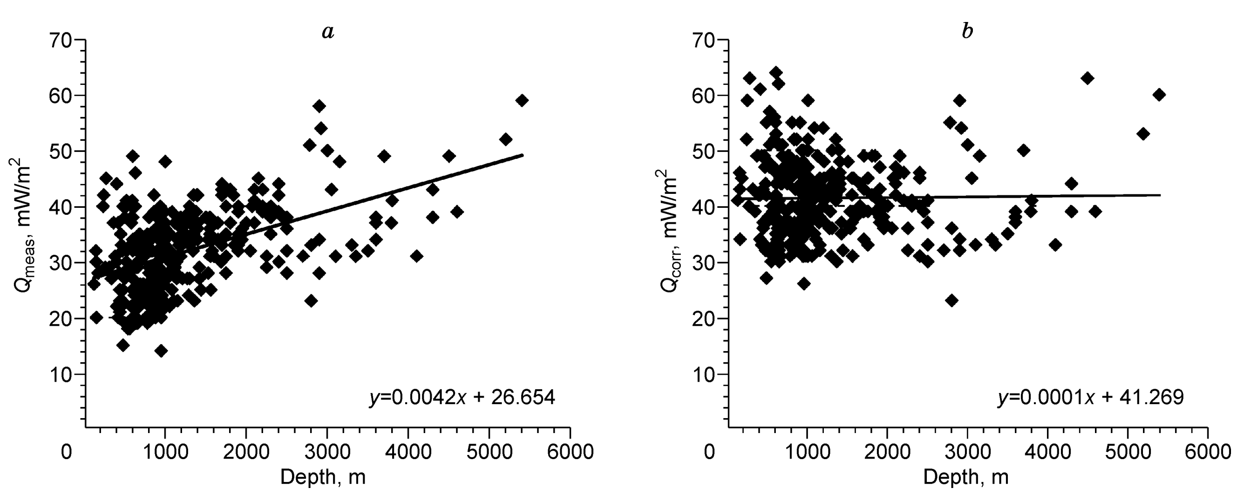

Fig. 1. Dependence of the heat flow density in the Urals and adjacent territories on the studied borehole depth. *a*, For values measured by the classical method (Q_{meas}) (Golovanova, 2005); *b*, for values with paleoclimatic corrections (Q_{corr}) (Golovanova et al., 2008); straight line shows a linear trend.