Regional shallow heat flow in Denmark from borehole temperatures and thermal conductivities of main lithologies

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ABSTRACT

Exploitation of shallow geothermal energy requires knowledge of the geothermal conditions like the temperature field, thermal conductivity of the earth materials and the heat flow. New and existing temperature data from 50 wells of 100-300 m depth, covering the Danish onshore areas have been analysed for temperature gradient variations and correlation with lithology and thermal conductivity. The temperature gradients were grouped according to lithology over which they were measured. Similarly, thermal conductivity data measured on outcrop and core material were grouped into main sediment classes. Following Fourier's law of heat conduction (heat flow = thermal conductivity x temperature gradient) a regional estimate of characteristic shallow heat flow in Denmark was obtained by linear regression of mean temperature gradient and the inverse of mean thermal conductivity for the main sediment classes. An estimated heat flow value of 35 mW/m^2 is in good agreement with local, classically heat-flow determination from shallow borehole data. Due to long-term palaeoclimatic effect, this value is significantly below deep background heat flow.

1. INTRODUCTION

For the exploitation of geothermal resources, general knowledge of the thermal structure of the subsurface is of great importance. This applies to deep as well as shallow geothermal energy. Information about the amount of heat flowing out of the Earth is an important boundary condition for subsurface thermal modelling and for the characterisation of any subsurface thermal anomalies.

Classically, heat flow at a specific site is determined from measured temperature gradients in sections of a borehole in combination with information of thermal conductivity from the same interval, preferably from laboratory core measurements (Powell et al. 1988). Heat flow is then determined as the product of temperature gradient and thermal conductivity (Fourier's law).

Here, we present an approach by which an estimate of characteristic near surface heat flow may be obtained for a certain area or region by combining information of mean temperature gradients from a number of different lithologies with information of characteristic mean thermal conductivity of the same lithologies. Our data cover main near surface lithologies from the whole of the Danish onshore area and were collected and analysed as part of a research project on ground source heating and cooling from closed loop boreholes (Ditlefsen et al. 2013; Møller et al. 2014).

2. GEOLOGY OF THE DANISH STUDY AREA

Most of the subsurface geology of Denmark is characterised by deep sedimentary basins formed since the Carboniferous and Permian. The shallow subsurface consists primarily of soft sediments spanning from Cretaceous chalk, Paleogene limestone, marls and clays, Neogene clay and sand to Quaternary glacial and interglacial deposits. Only at the island of Bornholm, the shallow subsurface consists of crystalline rocks and sediments older than Cretaceous. The Pre-Quaternary sediments (Figure 1) are covered by up to 100-300 m Quaternary deposits composed mainly of clay till and meltwater sediments deposited during a number of glacial periods.

3. MATERIAL AND METHOD

3.1 Lithological data

Borehole lithological data were obtained mainly from the Danish national geological and hydrological database Jupiter (http://jupiter.geus.dk; Hansen and Pjettursen 2011), to which lithological sample description are reported. Age and depositional environment were determined, and samples were classified into a lithostratigraphic framework. For a minority of the boreholes, in particular deeper boreholes, the lithological data were found in scientific reports and well completion reports (Møller et al. 2014).

Two examples of lithological logs displaying the geological settings in a Quaternary buried valley and a clay-rich Neogene and Paleocene sequence are shown in Figures 2c and 2f, respectively. For the present heat flow analysis, the lithostratigraphic units were grouped into ten main sediment classes.

3.2 Temperature data

High quality, “undisturbed” temperatures are available from temperature logs in about 50 boreholes covering the depth range of 100-300 m. The temperature data were collected in a number of different projects, the oldest measurements dating back to about 1980 (Balling et al. 1981). Different temperature logging equipment have been used. The oldest data in shallow boreholes were acquired by thermistor probes and discrete point sampling of typical 5 m distance. From the deep wells, data were acquired using quartz oscillator probes and continues dense sampling. Most of the recently measured temperature data were acquired with conventional logging tools and also with continues dense sampling. Sensitivity of the applied temperature probes is generally better than 0.01 °C and absolute accuracy better than 0.1°C. Temperature data are available from boreholes distributed across most of the country and different geological environments are represented (Figure 1). Examples of temperature logs from two different geological settings are displayed in Figure 2.

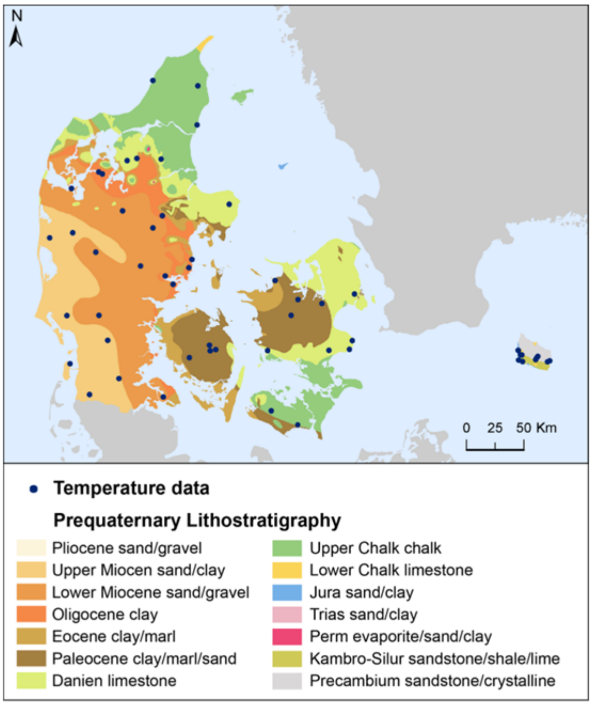

Figure 1: Map of Denmark showing Pre-quarternary Danish deposits (Håkansson and Pedersen 1992) and location of boreholes with temperature data applied in this study.

3.3 Temperature gradients

Temperature gradients were estimated using a linear least squares approach, with a gradient fitted to all data point within a 5 or 20 m interval. Gradients were calculated for every 2.5 m for the continuous logs and at the sampling point for the discrete logs (generally larger than 2.5 m). The 5 m interval gradients depict more lithological variations than the 20 m gradient (Figures 2b and 2e). In order to limit uncertainties

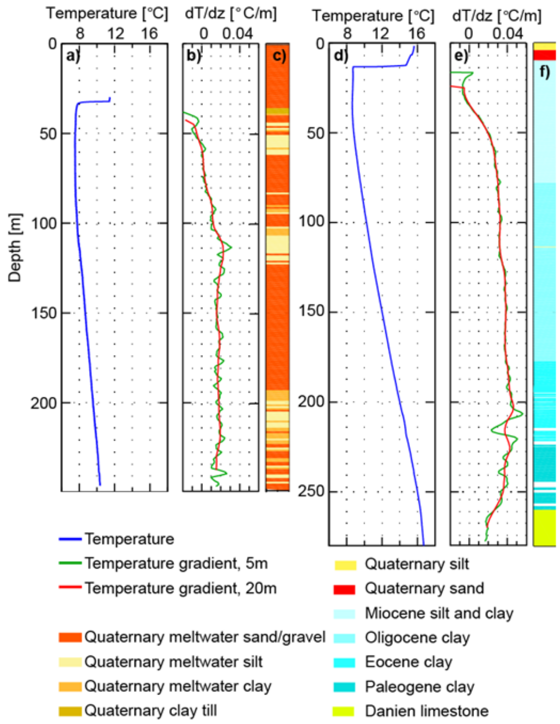

Figure 2: Temperature (a, d), temperature gradient (b, e) and lithological log (c, f) from a borehole in a Quaternary buried valley (a, b, c) and a clay-rich Neogene to Paleogene setting (d, e, f).

within the positioning of both the lithological sampling and the temperature sampling, the 20 m temperature interval gradients were used for the heat flow analysis.

The 20 m temperature gradients were grouped according to main sediment classes, as known from borehole sample descriptions. A temperature gradient value was assigned to a specific sediment class, only if at least 90 per cent of the sediment samples belong to that class within the 20 m interval in question. The temperature gradient distribution for each main sediment class was displayed as histograms and a gradient mean value determined. As an example, the clay sediment class is shown in Figure 3.

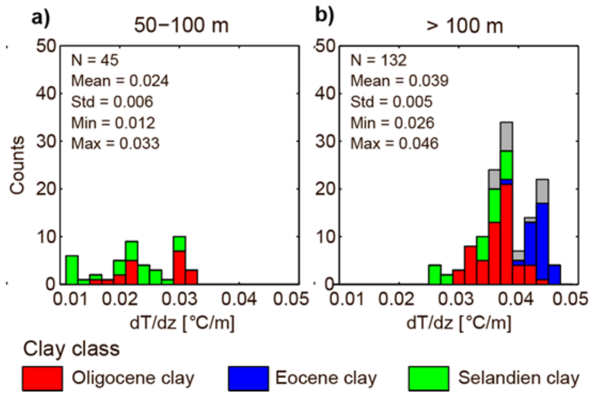

Figure 3: Temperature gradient distribution of the clay sediment class displayed with sub-clay classes on top for a) the depth interval of 50-100 m and b) for depth greater than 100 m.

3.4 Thermal conductivity

Thermal conductivities originate from new laboratory measurements on samples, largely from outcrops (Ditlefsen et al. 2014), and from a compilation of previously published measurements, mainly from core materials (e.g. Balling et al. 1981; 1992; Kristiansen et al. 1982). All samples were measured water-saturated using needle-probe techniques. The thermal conductivity data were also grouped according to main sediment classes and a mean thermal conductivity value determined for each main class.

3.5 Heat flow estimation

According to Fourier's law of heat conduction (heat flow = thermal conductivity x temperature gradient), temperature gradients and inverse thermal conductivity are linearly related, if heat flow is a constant and the heat flow is given by the slope of the regression line. Heat flow may then be estimated by defining the least squares linear regression line from the set of data containing mean temperature gradient and mean thermal conductivity for the main sediment classes.

4. RESULTS

The seasonal temperature variations penetrate to a depth of 20-30 m. However, the temperature gradients in the uppermost 50-100 m of the ground are found to be influenced by recent short-term climatic changes (in particular past c. 40 years). This influence can be seen in the temperature logs and their temperature gradients (Figure 2). Temperatures are almost constant (gradients close to zero) to depths of c. 100 m in the sandy sediments and c. 50 m in the clayey sediments, respectively. Deeper penetration in sand is due to a higher thermal diffusivity compared with clay.

Consequently, the data set used for the heat flow analysis was divided into two groups, one for the depth interval of 50-100 m below the ground surface and one for depths greater than 100 m to ensure that temperature gradients unaffected by the short-term climatic changes are not mixed with the potentially affected ones.

Temperature gradient versus inverse thermal conductivity for the available sediment classes are displayed in Figure 4. The "disturbance" from short-term climatic changes explains the lack of a clear linear relation for the shallow group of data. For the deeper levels of 100 - c. 300 m a much clearer linear relationship is observed, in particular when not including the 'silty clay' sediment class.

Silty clay can be explained as an outlier due to unrepresentative sampling: Fine sand and silt are known to be difficult to sample with drilling methods applying drilling mud. The fine sand and silt fraction may be taken up by the mud, and only the clay cuttings are left for sampling, and the sediment sample may thus be described as silty clay. However, the mean temperature gradient for the silty clay class indicates that sediments at the logged boreholes actually mainly consist of sand. Thermal conductivity was measured on samples from outcrops correctly described as silty clay.

Excluding the silty clay sediment class, a heat-flow value of 35 mW/m^2 is obtained from linear regression with a regression coefficient of 0.90 (Figure 4b). This value is low, but in good agreement with independent measurements from a number of shallow boreholes across the Danish area, using conventional techniques of combining local temperature gradients and measured thermal conductivities on core samples (Balling et al. 1981; 1992). By combining information on heat flow observations from shallow depth and that from deep boreholes, a marked increase of heat flow

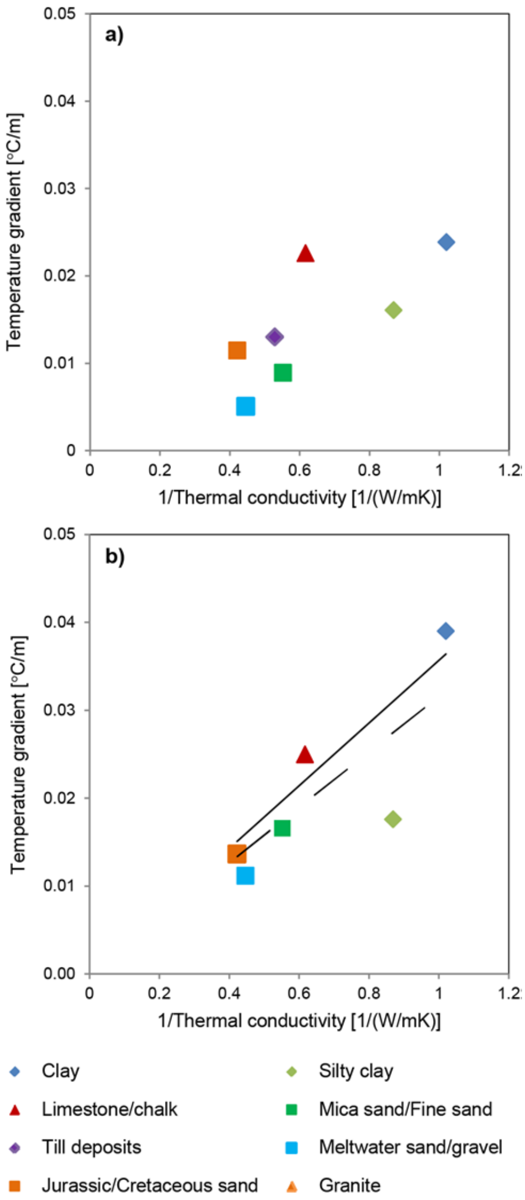

Figure 4: Mean temperature gradients plotted versus inverse mean thermal conductivity for main sediment classes from onshore Denmark. Depth intervals, a) 50-100 m, and b) more than 100 m. For the deeper level, an approximate linear relationship is found from which a heat flow estimate is obtained. Dashed line, all data, and solid line, excluding the silty clay outlier.

with depth is observed, from about 30-40 mW/m^2 at shallow depth to about 70-75 mW/m^2 at depths of c. 2000 m and deeper (Balling 1982; 2013: Figure 5.9). The reduction of shallow heat flow is interpreted to be due to long-term palaeoclimatic influence, similar to that described by Kukkonen et al. (2011) and Mottaghy and Rath (2006).

The low heat flow value represents current actual flow of heat at shallow depth to be considered for shallow geothermal problems, but should not be applied as a boundary constraint for deep thermal modelling (cf. Balling et al. 2016; Poulsen et al. 2016).

From the observed linear relation in Figure 4b, thermal conductivity of a specific drilled section may be estimated, when temperature gradients are measured. This is of interest in relation to estimating the amount of heat to be extracted from borehole heat exchangers.

5. CONCLUSIONS

A regional shallow heat flow estimate is obtained by linear regression of independently determined temperature gradients and thermal conductivity measurements represented by their mean values for main sediment classes. The estimated heat flow value of 35 mW/m^2 is in good agreement with traditionally determined heat flow values from shallow borehole observations in the Danish area. This low value, compared with those obtained from deep boreholes, is due to long-term palaeoclimatic effect.

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