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New heat flow data from three boreholes near Bergen, Stavanger and Moss, southern Norway

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ABSTRACT

New heat flow data have recently been obtained for three boreholes, Fyllingsdalen, Ullrigg and Årvollskogen, which are located in southern Norway near Bergen, Stavanger and Moss, respectively. The obtained topographically and palaeoclimatically corrected values of average heat flow density are 51 mW/m^2 within the Ullrigg borehole, 72 mW/m^2 within the Fyllingsdalen borehole and 80 mW/m^2 within the Årvollskogen borehole, in the depth interval of 120–400 m. According to the preferred palaeoclimatic scenario, the highest tentative palaeoclimatic corrections vary from 21 to 26 mW/m^2 within the shallow parts of the investigated boreholes. Therefore, a significant decrease of the Earth's surface temperatures as a result of the continuous cooling during the two last glaciations in Weichselian and Saalian still affects the subsurface thermal field of the study areas in terms of the reduced heat flow density within the uppermost crystalline crust. Topographic corrections are characterised by rather minor values compared to the palaeoclimatic ones. Moreover, the groundwater flow can be a significant factor for the reduction of heat flow density in the Fyllingsdalen and Ullrigg boreholes, whereas hypothesised subsurface radioactive sources may have contributed to a higher heat flow density at Årvollskogen. The variation in heat production related to different lithologies appears to be one of the main reasons for the higher heat flow density in the Fyllingsdalen and Årvollskogen boreholes in comparison with the Ullrigg borehole.

1. Introduction

New heat flow data have recently been obtained for three boreholes, Ullrigg (5.71°E, 58.93°N), Fyllingsdalen (5.28°E, 60.34°N) and Årvollskogen (10.7°E, 59.42°N), which are located near Stavanger, Bergen and Moss, respectively (Fig. 1). The more than 1500 m vertically deep Ullrigg borehole near Stavanger was drilled as a test site for new drilling technologies of inclined boreholes in the 1980s and has a measured depth of around 2000 m. On the other hand, the Fyllingsdalen and Årvollskogen boreholes were drilled more recently. The 516 m-deep Fyllingsdalen borehole near Bergen was drilled in September 2011 as part of the Crustal Onshore–Offshore Project (COOP) at the Geological Survey of Norway (NGU) to investigate the uppermost crystalline crust onshore, and the 800 m-deep Årvollskogen borehole in Moss town was drilled in October–November 2012 to estimate the geothermal-energy potential in the Moss area. In general, all these three boreholes provide important data to investigate the geothermal potential of southern Norway in order to utilise the renewable and environmentally friendly, deep geothermal energy in the future.

At the regional scale, thermal measurements in the Ullrigg, Fyllingsdalen and Årvollskogen boreholes represent new heat-flow data for Norway in addition to existing ones which have already been summarised in Slagstad et al. (2009). In particular, Slagstad et al. (2009) have described the heat flow data from 14 boreholes in southern and central Norway. Based on all available data, they also constructed the heat flow density map, providing a regional overview of available data distribution and heat flow pattern over Fennoscandia and the Norwegian-Greenland Sea.

2. Geological settings

The investigated boreholes are situated within different geological and tectonic settings. The Ullrigg borehole is located within

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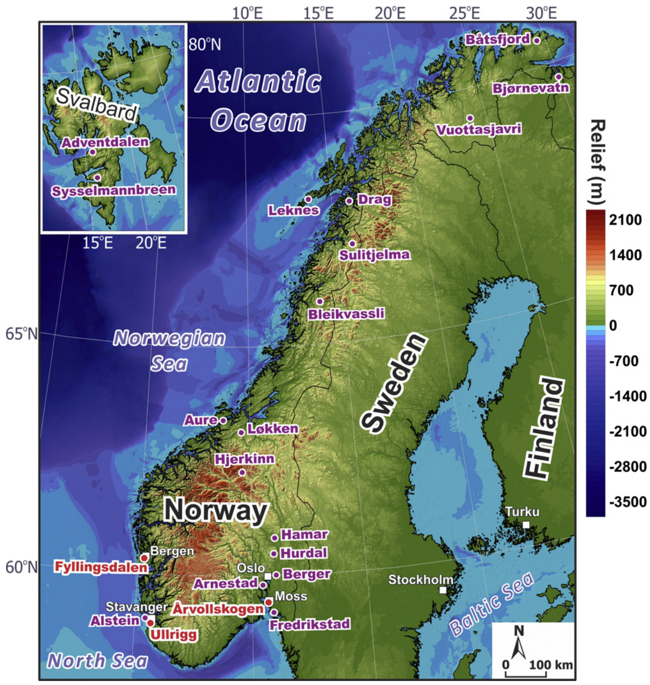

Fig. 1. Overview map with locations of all Norwegian boreholes on the mainland and Svalbard for which thermal data are available at the Geological Survey of Norway (NGU). Three boreholes from the present study are highlighted by red colour. Topography and bathymetry are from Norwegian Mapping Authority.

the western part of the Sveconorwegian Province, characterised by 1.5–1.0 Ga granitoids, granitoid gneisses and metasupracrustals (Tobi et al., 1985; Bingen et al., 2005; Slagstad et al., 2013). The borehole is located ca. 25 km north of the Rogaland Igneous Complex, consisting of anorthosites, mafic intrusive rocks and associated granitoids (Olesen et al., 2004; Vander Auwera et al., 2011), but it is unclear whether this complex extends to below the borehole. In the case of the Ullrigg borehole, the geological section consists of phyllites from the Earth's surface down to ca. 800 m, and gneisses are reported down to the hole bottom.

The Fyllingsdalen borehole has been drilled in vicinity of the Bergen Arc System through the Løvstakken granitic gneiss of the Øygarden Gneiss Complex. The Bergen Arc System initially formed during the Caledonian orogeny (Sturt and Thon, 1978; Fossen and Dunlap, 2006) and consists of a sequence of Caledonian nappes which overlie the Øygarden Gneiss Complex (Ragnhildstveit and Helliksen, 1997). According to rock-sample measurements in the vicinity of the Fyllingsdalen borehole, the Løvstakken granitic gneiss of the Øygarden Gneiss Complex is characterised by high values of the radiogenic heat production which reach more than 10 $\mu W/m^3$ locally (Rudlang, 2011).

The Årvollskogen borehole is located within the eastern flank of the Oslo Graben which formed as a result of a Late Carboniferous-Early Permian regional-scale extensional event (Heeremans and Faleide, 2004). The bedrock geology of this graben flank (Lutro and Nordgulen, 2008) is characterised by granites and different kinds of gneisses, including metagabbros and amphibolites. The drilled rocks of the Årvollskogen borehole comprise amphibolites and metagabbro within the upper interval of around 70–350 m, whereas granitic to quartz-dioritic biotite gneisses predominate down to more than 700 m. In addition, random interlayers of granitic pegmatites are present.

3. Data and methods

Thermal well logging was performed in the investigated boreholes in the period 2011–2013. Temperature was measured two times in the Ullrigg (in March 2011 and March 2013) and Fyllingsdalen (in March and June 2012) boreholes and only one time in Årvollskogen borehole (in January 2013). In the case of twice-measured temperatures in the Ullrigg and Fyllingsdalen boreholes, a good fit between measured temperatures at different time periods indicates that temperatures were obtained after reaching post-drilling thermal equilibrium in these boreholes and, therefore, are representative for the subsurface thermal regime. It has to be mentioned that there are also pronounced misfits within the uppermost 40–60 m of these boreholes but these are related to the seasonal changes of temperatures at the Earth's surface. According to results of measurements, the temperatures at the same depth are lower in the Ullrigg borehole compared to the Fyllingsdalen and Årvollskogen boreholes (Fig. 2). Low measured temperatures in the Ullrigg borehole are reflected by the low measured thermal gradient which is less than 13.0 °C/km (Fig. 4b). In contrast, the geothermal gradient is 16.5 °C/km in the case of the Fyllingsdalen borehole (Fig. 5b) and is 19.3 °C/km in the Årvollskogen borehole (Fig. 6a). The mentioned values of the geothermal gradients represent an average value which has been calculated for the whole borehole. In addition, the measured values of the thermal gradient were averaged by running-mean averages within fixed depth intervals of 20 and 100 m (Figs. 4b, 5b and 6a).

The same procedure has been applied for thermal conductivities in the Fyllingsdalen and Årvollskogen boreholes, where values of thermal conductivities (Figs. 5c and 6b) have been acquired by laboratory measurements of thermal properties on core samples from these boreholes. Distribution of the measured thermal conductivities with depth demonstrates that most of the measured values are around 3 W/mK in the case of these two boreholes. Details of the thermal conductivities for each major lithology of the Årvollskogen borehole have been provided in Maystrenko et al. (2014). Unfortunately, core samples were not available from the Ullrigg borehole. For this reason, average constant thermal conductivities for the Ullrigg borehole (Fig. 4c) have been derived from the national petrophysical database "Petbase" at NGU (Olesen et al., 1993), based on rock samples with the same lithology (Table 1) as those exposed at the surface in the vicinity of this borehole (Fig. 3). According to the rock-sample data, the assigned thermal conductivities can vary from 1.9 to 4.2 W/mK for phyllites and from 3.0 to 3.7 W/mK for augen gneisses. As it is shown in Table 1, the most of measured values of thermal conductivities for phyllites are in the range of 1.9–3.0 W/mK with only one much higher value of 4.2 W/mK which is outlying from the mentioned range. The arithmetic mean value of 2.6 W/mK has been considered as the average thermal conductivity for phyllites. The same has been applied for augen gneisses, for which the arithmetic mean value of thermal conductivity is equal to 3.3 W/mK. Therefore, these mean values have been used to be representative for the average thermal conductivities in further calculations of the heat flow densities and palaeoclimatic corrections.

Measurements of the thermal conductivities were made in the laboratory of the Geological Survey of Norway. Measurements for the Ullrigg and Fyllingsdalen boreholes were done in 2012 by use of a transient method according to Carslaw and Jaeger (1959) and Middleton (1993). Each sample has been prepared to have a thickness of around 1.9 and a diameter of the samples was around 3.8 cm for the Fyllingsdalen borehole and was around 3.4 cm for the Ullrigg borehole. During the measurements, a constant heat flow was induced to the top of the samples by the heat source which was placed 1 cm above the top of the sample and had a constant temperature of 300 °C. After that, thermal diffusivity was derived from

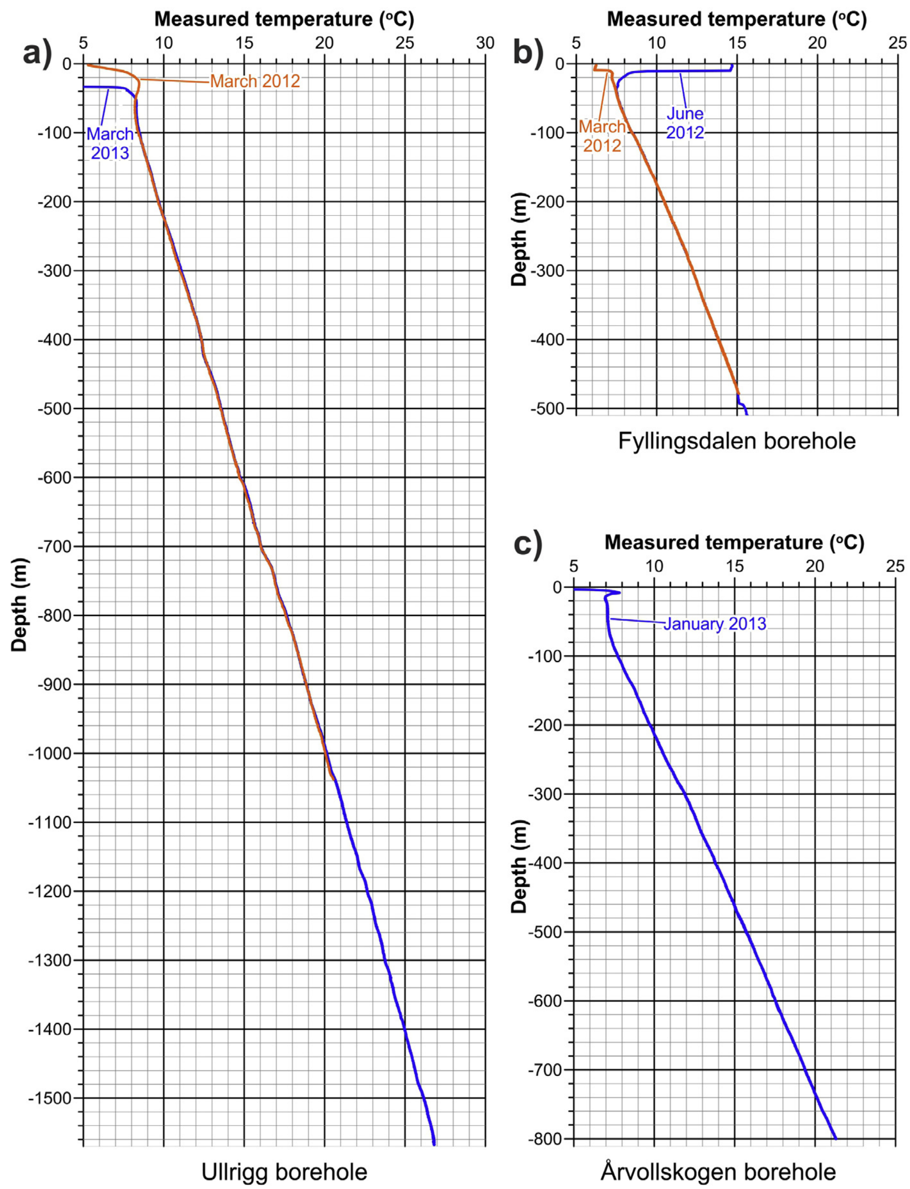

Fig. 2. The measured temperatures in the Ullrigg (a), Fyllingsdalen (b) and Årvollskogen (c) boreholes.

Table 1
Thermal conductivity, specific heat capacity and densities according to measurements on the rock samples from the Earth's surface near the Ullrigg borehole (see Fig. 3 for location).

N	Lithology	Thermal conductivity k (W/mK)	Estimated specific heat capacity C_p (J/kgK)	Density (kg/m^3)
1	Phyllite	3.1	850	2740
2	Phyllite	2.4	850	2710
3	Phyllite	4.2	850	2640
4	Phyllite	1.9	850	2770
5	Phyllite	2.4	850	2790
6	Phyllite	2.3	850	2880
7	Phyllite	2.6	850	2790
8	Phyllite	2.3	850	2760
9	Phyllite	2.7	850	2730
10	Phyllite	2.0	850	2860
Arithmetic mean	Phyllite	2.6	850	2767
11	Augen gneiss	3.0	850	2660
12	Augen gneiss	3.1	850	2640
13	Augen gneiss	3.7	850	2640
14	Augen gneiss	3.2	850	2640
15	Augen gneiss	3.3	850	2660
16	Augen gneiss	3.2	850	2640
Arithmetic mean	Augen gneiss	3.3	850	2647

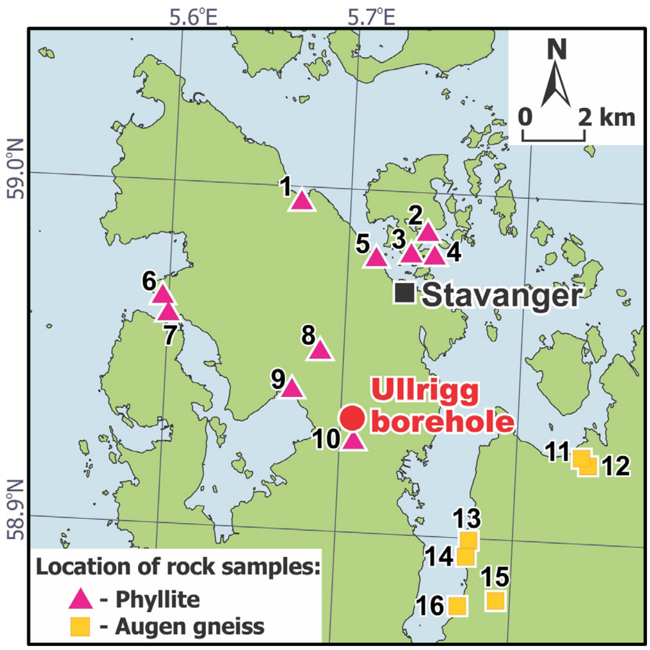

Fig. 3. Locations of rock sampling sites in the vicinity of the Ullrigg borehole. Numbering correspond to ordinal number in the first column of Table 1.

the temperature–time plot, obtained by the temperature measurements at the base of the sample. Finally, the thermal conductivity was calculated from thermal diffusivity, measured density and expected specific heat capacity. The specific heat capacity has been assumed to be 850 J/kgK. The estimated error of the thermal diffusivity measurements is within ±5%. In the case of the Årvollskogen borehole, thermal conductivities were obtained in 2013 by use of the recently installed thermal conductivity analyser C-Therm TVi TM. This instrument measures the thermal effusivity of rocks which has been used to derive the thermal conductivities. Samples had a diameter of around 5.0 cm and a thickness of 1.9–2.0 cm. In contrast to the previously described method, each sample was saturated by water before taking a measurement. Measurements were carried out four times to obtain a good statistical mean with the standard deviation in the range of 0.01–0.09 W/mK. The derived specific heat capacities of rocks are around 800 J/kgK for the drill cores from the Årvollskogen borehole. All measurements were done at room temperature and the quality of analysis was systematically controlled by measurements on the standard material Pyroceram.

The assigned values of the specific heat capacity have been set constant during the calculations of the topographic and palaeoclimatic corrections. For the Årvollskogen borehole, the average measured value is around 800 J/kgK and, therefore, this value has been taken to be representative for the drilled rocks in this borehole. In the case of the Fyllingsdalen borehole and Ullrigg boreholes, a constant value of 850 J/kgK has been used according to estimated values which have been used during measurements of the thermal conductivities.

The results of whole-rock chemical analyses of core samples (Table 2), natural gamma ray (Figs. 9a, 10a and 11a) and natural gamma spectrometry loggings (Fig. 11b–d) have been used to calculate the radiogenic heat production of rocks from the boreholes.

The whole-rock chemical analyses of core samples in the Fyllingsdalen borehole (Table 2) and gamma spectrometry logging in the Årvollskogen borehole (Fig. 11b–d) have been used to calculate values of radiogenic heat production derived from uranium (U), thorium (Th), and potassium (K) concentrations. During the chemical analyses, powders of crushed rock were fused with a lithium metaborate/lithium tetraborate flux and analysed by inductively coupled plasma (ICP) atomic emission spectroscopy (AES) for major elements and ICP mass spectrometry (MS) for trace elements. The empirical relationship between radiogenic heat production and concentrations of the mentioned radiogenic elements (1) from Rybach (1988) has been applied to calculate the radiogenic heat production of rocks

$$S = \rho(9.52\,C_U + 2.56\,C_{Th} + 3.48\,C_K) \times 10^{-5}) \quad (1)$$

where S is the radiogenic heat production (μW/m^3), ρ is the density (kg/m^3), C_U and C_{Th} are the concentrations of U and Th in ppm, C_K is the concentration of K in wt.%.

The empirical relationship between total natural gamma and radiogenic heat production (2) from Bücker and Rybach (1996) has been applied to calculate the radiogenic heat production of rocks in the investigated boreholes

$$S = 0.0158(\mathrm{GR} - 0.8) \quad (2)$$

where S is the radiogenic heat production (μW/m^3) and GR is the total gamma (API units). The results of calculation are scaling values of the radiogenic heat production rather than precise ones. This is especially true for the total gamma higher than 350 API.

Based on the obtained data, heat flow density has been estimated for these boreholes. Uncorrected values of the heat flow density (W/m^2) in the boreholes (Figs. 4d, 5d and 6d) have been calculated using Fourier's law of heat conduction (3):

$$q = -k\nabla T \quad (3)$$

where k is the thermal conductivity (W/mK) and ∇T is the temperature gradient (K/m). The heat flow density, therefore, was calculated as the product of thermal gradients and conductivities and was also plotted with 20 and 100 m averaging. Afterwards, the calculated values of heat flow density have been corrected for topography and changes in palaeothermal regime at the Earth's surface during last 228,000 years.

The topographic and palaeoclimatic corrections have been calculated following the approach described by Slagstad et al. (2009), who performed heat flow density calculations in other Norwegian boreholes, drilled within the crystalline rocks onshore. As in Slagstad et al. (2009), the topographic corrections are based on topographic models with a horizontal resolution of around 100 m. Centred at the locations of the boreholes, 10,000 m × 10,000 m rectangular blocks were constructed by use of the "Heat Transfer in Solids" module of the commercial software package COMSOL Multiphysics. The constructed blocks have a vertical thickness of 5000 m plus the digital elevation data which represent the upper surface of these blocks (Fig. 7). The lower surface of the blocks is flat at a depth of 5000 m. The surface temperature has been set to represent the present-day annual average air temperatures according to Tveito et al. (2000) within the mainland and an average temperature of 8 °C has been chosen at the sea-bottom according to ICESCIEM (2012). The lower thermal boundary is represented by the constant heat flow density at the base of the blocks which has been set to be 40, 50 and 60 mW/m^2 in the case of the Ullrigg, Fyllingsdalen and Årvollskogen boreholes, respectively. These values of the basal heat flow density have been set to be close to the uncorrected heat flow in each borehole. It is obvious that the chosen values can differ from the real ones. On the other hand, topography is relatively smoothed in the close vicinity of the investigated boreholes (Fig. 7) and, therefore, the deviations of the topographic corrections due to a reasonable range of basal heat flow density, assumed to be not more than ±10 mW/m^2, are very small and can be neglected in the present study.

In the topographic models, average and constant thermal conductivities have been set according to the measured conductivities from each borehole. An average value of 3 W/mK was assigned for the Fyllingsdalen and Årvollskogen boreholes and 2.9 W/mK

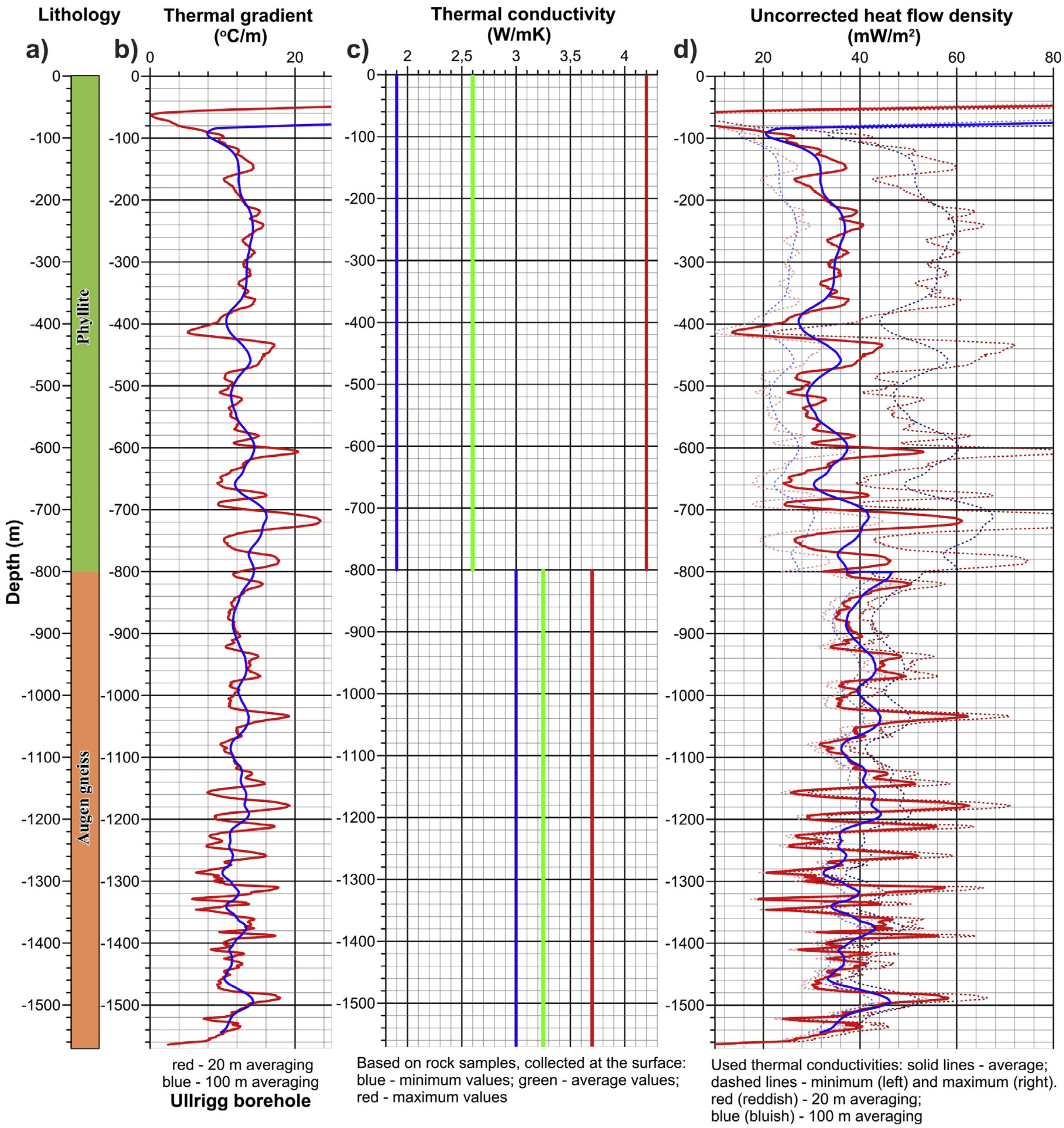

Fig. 4. Plots showing lithology (a), thermal gradient (b), thermal conductivity (c) and calculated uncorrected heat flow density (d) in the Ullrigg borehole.

Table 2
Radiogenic heat production in the Fyllingsdalen borehole according to measurements on the core samples (densities have been estimated; the uncertainty with respect to calculating heat production is negligible).

Depth (m)	Uranium U (ppm)	Thorium Th (ppm)	Potassium K_2O (wt.%)	Estimated density (kg/m^3)	Radiogenic heat production (μW/m^3)
6	42.1	51.9	4.76	2650	14.51
46	23.3	38.4	5.01	2650	8.87
101	6.64	54.3	5.35	2650	5.77
149	5.14	29.2	5.62	2650	3.71
200	5.08	39.8	5.08	2650	4.37
251	5.18	35.2	5.22	2650	4.09
300	4.46	43.9	5.12	2650	4.5
350	5.45	51.8	5.2	2650	5.29
400.5	3.15	38.2	5.27	2650	3.79
449.5	5.04	43.4	0.79	2650	4.28
499	7.68	46.7	5.48	2650	5.53

was used for the Ullrigg borehole. The topographic corrections on heat flow density were calculated to be negative (increased heat flow density) beneath topographic lows where thermal gradient is increased due to topography or positive (reduced heat flow density) beneath topographic highs where thermal gradient is decreased due to topography (Slagstad et al., 2008).

During the next step of this study, the palaeoclimatic corrections were calculated by use of the commercial software package

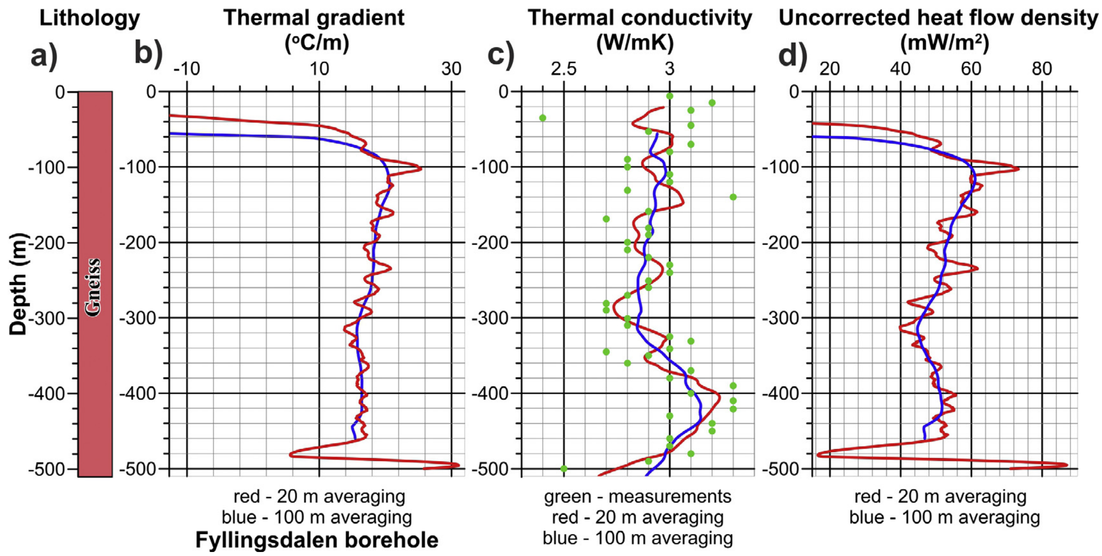

Fig. 5. Plots showing lythology (a), thermal gradient (b), thermal conductivity (c) and calculated uncorrected heat flow density (d) in the Fyllingsdalen borehole. Green dots are the measured thermal conductivities based on core samples data.

COMSOL Multiphysics. These calculations have been carried out based on physical principles of the conductive 2D thermal field by solving the heat equation (4):

$$\rho C(\delta T/\delta t) = \nabla \cdot (k\nabla T) + Q \quad (4)$$

where ρ is the density (kg/m^3), C is the heat capacity (J/kgK), T is the temperature (K), k is the thermal conductivity (W/mK), ∇T is the temperature gradient (K/m), t is the time (s), δT is the change in temperature per time interval δt, $\nabla\cdot$ is the operator giving the spatial variation in temperature and Q is the heat source (radioactive heat production, W/m^3). This has been done based on 15,000 m-deep 2D models with average thermal conductivities which have been taken to be 3 W/mK in the Fyllingsdalen and Årvollskogen borehole and 2.6 W/mK for phyllites and 3.3 W/mK for gneisses in the Ullrigg borehole. A constant basal heat flow density of 50 mW/m^2 has been set at the lower boundary at a depth of 15,000 m, and a surface temperature has been taken to vary according to the palaeoclimatic scenarios in Fig. 8 for each borehole. It is important to note

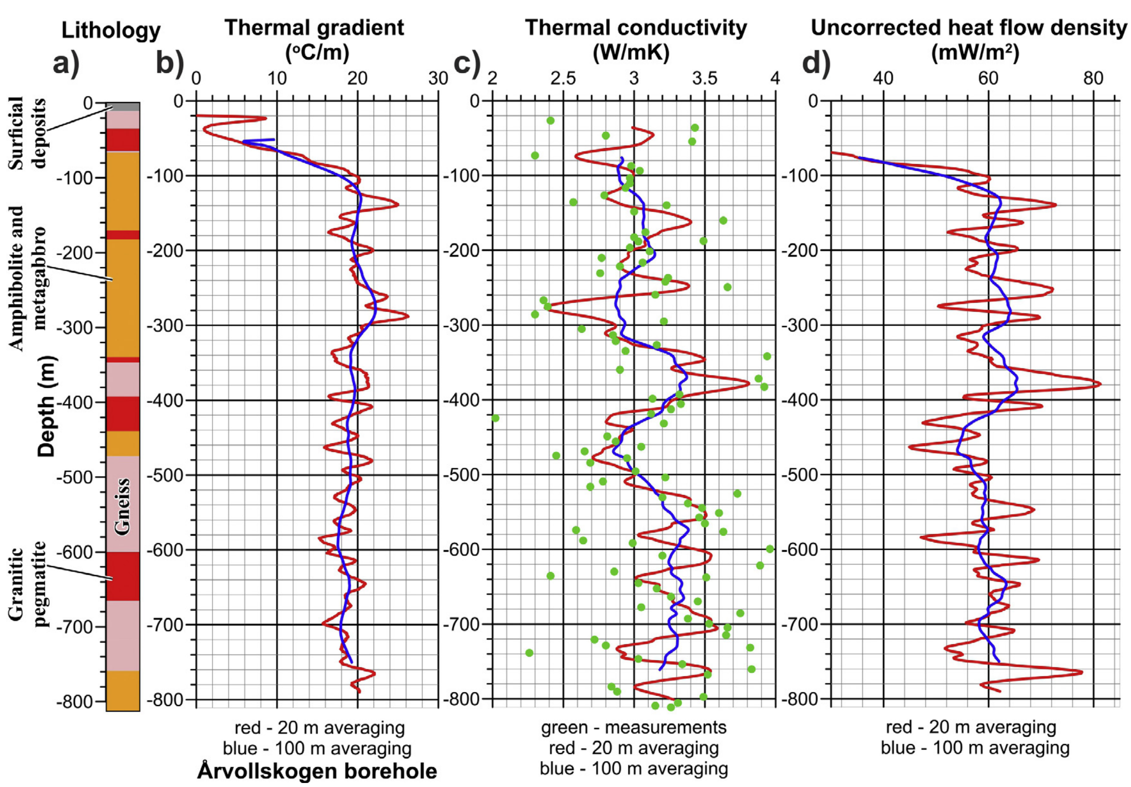

Fig. 6. Plots showing lythology (a), thermal gradient (b), thermal conductivity (c) and calculated uncorrected heat flow density (d) in the Årvollskogen borehole. Green dots are the measured thermal conductivities based on core samples data. Lithology is simplified after Maystrenko et al. (2014).

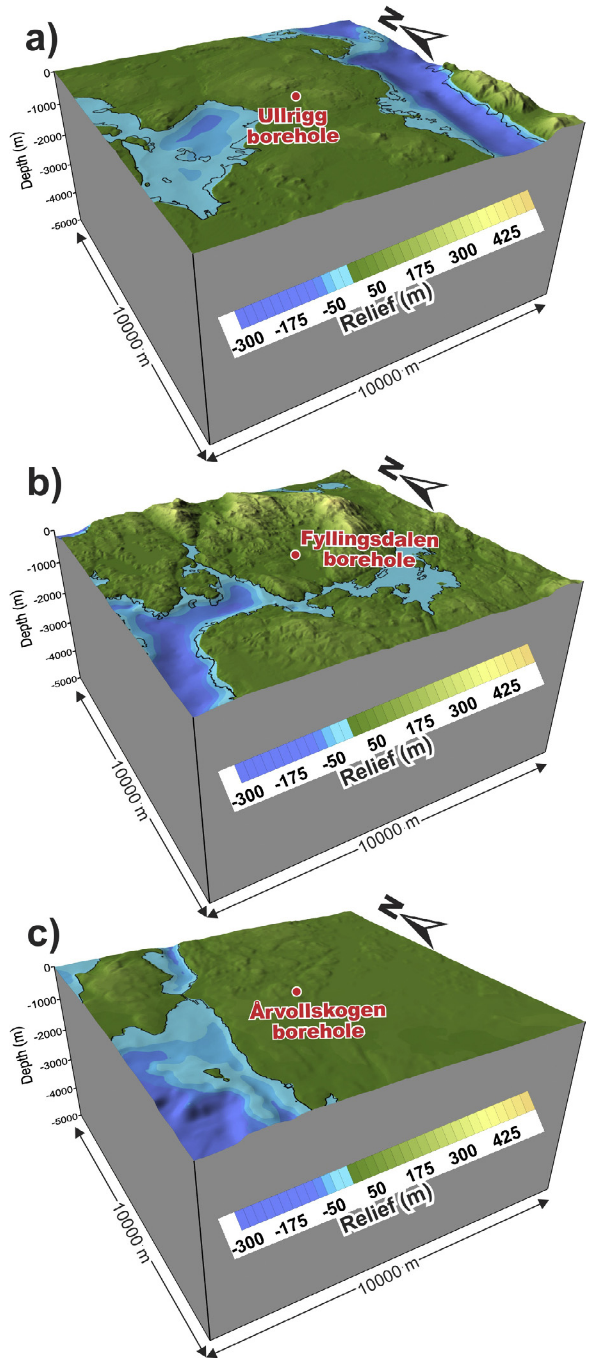

Fig. 7. Topographic models used to calculate the topographic corrections for the Ullrigg (a), Fyllingsdalen (b) and Årvollskogen (c) boreholes.

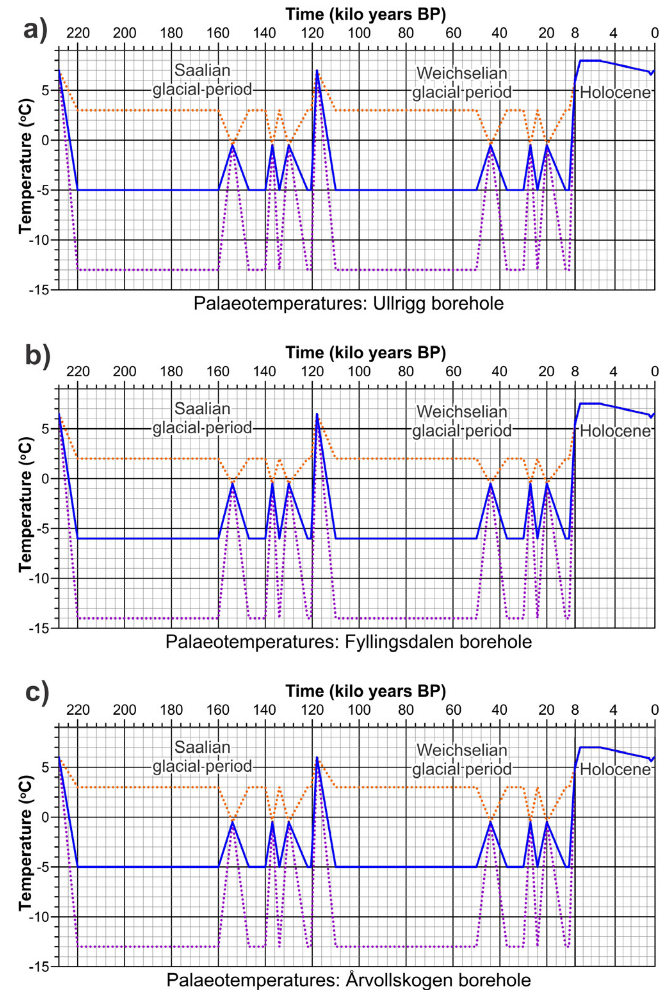

Fig. 8. Time-dependent surface temperatures according to the simulated mean annual temperatures for the Younger Dryas (Renssen and Isarin, 1998). Palaeotemperatures for the Ullrigg (a), Fyllingsdalen (b) and Årvollskogen (c) boreholes. Upper (+8 °C) and lower (−8 °C) dashed lines are possible deviations of the preferred palaeotemperatures (solid line) within the ice-free areas.

that the chosen value of the heat flow density does not represent the existent heat flow density at depth of 15,000 m within the study areas. In contrast to the topographic corrections, the magnitude of the basal heat flow density is not really important in the case of the flat upper surface. We calculate the palaeoclimatic corrections as a difference between the constant basal heat flow density and the palaeoclimatically disturbed one. Therefore, from the mathematical point of view, the value of the basal heat flow can be chosen randomly in the case of flat upper and lower boundaries. In this case, the important point is to set the basal heat flow density to be constant value.

The palaeoclimatic scenarios have been mainly derived again according to the approach of Slagstad et al. (2009). The palaeoclimatic history during the last glacial period is based on a regional-scale model of temporal ice-cover changes in Scandinavia during the Weichselian glaciations according to Olsen (2006). Based on these data (Olsen, 2006), the heat flow sites (boreholes) were temporally covered by a Weichselian ice sheet. The temperature at the surface has been assumed to be −0.5 °C, at times when the boreholes were covered by an ice sheet. A near-melting point temperature around 0 °C is in agreement with published estimates of the subglacial thermal regime beneath the large polar ice cover in Antarctica, which can be taken as a suitable analogue for ice sheets developed during the Quaternary glacial cycles in NW Europe. The main aspects of the Antarctic subglacial conditions have been discussed by Pattyn (2010), showing that the mean ice basal temperature is in the range between −1 and 0 °C for the greater part of Antarctica. Furthermore, an airborne radar survey has detected approximately 100 lakes under the Antarctic ice cap (Price et al., 2002), the largest of which, Lake Vostok, has already been drilled in 2012 (Lake Vostok Drilling Project, 2012). At times when the boreholes were ice free, a temperature lower than the present-day annual average air temperatures 1961–1990 (Tveito et al., 2000) has been taken for each borehole according to simulated mean annual temperatures for the Younger Dryas (Renssen and Isarin, 1998). In particular, a constant temperature of −5 °C has been assumed for the Ullrigg and Årvollskogen boreholes and

−6 °C for the Fyllingsdalen borehole (Fig. 8). The Weichselian glacial (∼110,000–10,000 years BP) and Holocene interglacial (10,000 years BP to present day) palaeoclimatic settings were also applied for the Saalian glacial/Eemian interglacial period (220,000–110,000 years BP), considering that climatic conditions were relatively similar during the Weichselian glacial/Holocene interglacial and the Saalian glacial/Eemian interglacial periods (Andersen and Borns, 1994; Slagstad et al., 2009). The reconstructed, annual, average palaeotemperatures at the Earth's surface according to our palaeoclimatic scenarios are shown in Fig. 8. It should be mentioned that the most reasonable palaeoclimatic correction is indicated by blue solid line in Fig. 8, although corrections with ±8 °C are shown for the sake of completeness of the present study. The palaeotemperatures during the last 8000 years is represented by 1 °C below the present-day average air temperature at 8000 years BP (Davis et al., 2003), by 1 °C above the present-day average air temperature during the Holocene Climate Optimum at 7500–5500 years BP (e.g. Seppä et al., 2009) and by almost 0.4 °C below the present-day average air temperature during the Little Ice Age (Nesje et al., 2008; Mann et al., 2009).

4. Results and discussion

The calculated uncorrected heat flow density is shown in Figs. 4d, 5d and 6d. The uncorrected heat flow density in the Ullrigg borehole demonstrates a clearly recognisable decrease in the depth interval of 100–800 m compared to more stable values between 800 and 1200 m depth (Fig. 4d). This decrease is possibly related to the assigned low thermal conductivity of phyllites which are drilled in the upper part of this borehole. As it was mentioned above, core samples are not available from this borehole, and the assigned thermal conductivity can vary from 1.9 to 4.2 W/mK for phyllites and from 3.0 to 3.6 W/mK for gneisses according to sample measurements of these rocks (Table 1) which are exposed in vicinity of the borehole (Fig. 3). Therefore, the variable thermal conductivity may change calculated values of the heat flow density in a reasonable range, reaching −10 and +20 mW/m^2 within the upper part of this borehole if the minimum and maximum thermal conductivities of the phyllites are considered (Fig. 4). The uncorrected heat flow density in the Ullrigg borehole ranges from 14 to 63 mW/m^2 within the most part of the borehole and the average value is 37 mW/m^2 (Table 3). In the case of the Fyllingsdalen borehole, the calculated uncorrected heat flow density is characterised by a general increase towards the upper part of the borehole (Fig. 5d), ranging from 39 to 63 mW/m^2 with an average value of 50 mW/m^2 (Table 3). The uncorrected heat flow density in the Årvollskogen borehole (Fig. 6d) varies around 60 mW/m^2 without long wavelength undulations compared to the previously described boreholes.

In order to compare the heat flow density in these three boreholes correctly, the uncorrected heat flow density has been calculated within the same depth intervals in all three boreholes, avoiding an influence of general decrease of the heat flow density with depth within the crystalline crust (Table 4). Reduction of the heat flow with depth is mostly related to the fact that the deep heat flow from the mantle can be represented by a constant value and the general increase of the heat flow within the crystalline crust is due to a presence of radioactive elements which act as an additional heat source. In Table 4, the heat flow density has been calculated for the depth interval 120–400 m for all boreholes, showing that the highest values of the heat flow density are observed in the Årvollskogen borehole, whereas the lowest heat flow density is in the Ullrigg borehole. Heat flow data have been excluded at depths which are shallower than 120 m in order to minimise the influence of present-day seasonal changes of temperature at the Earth's

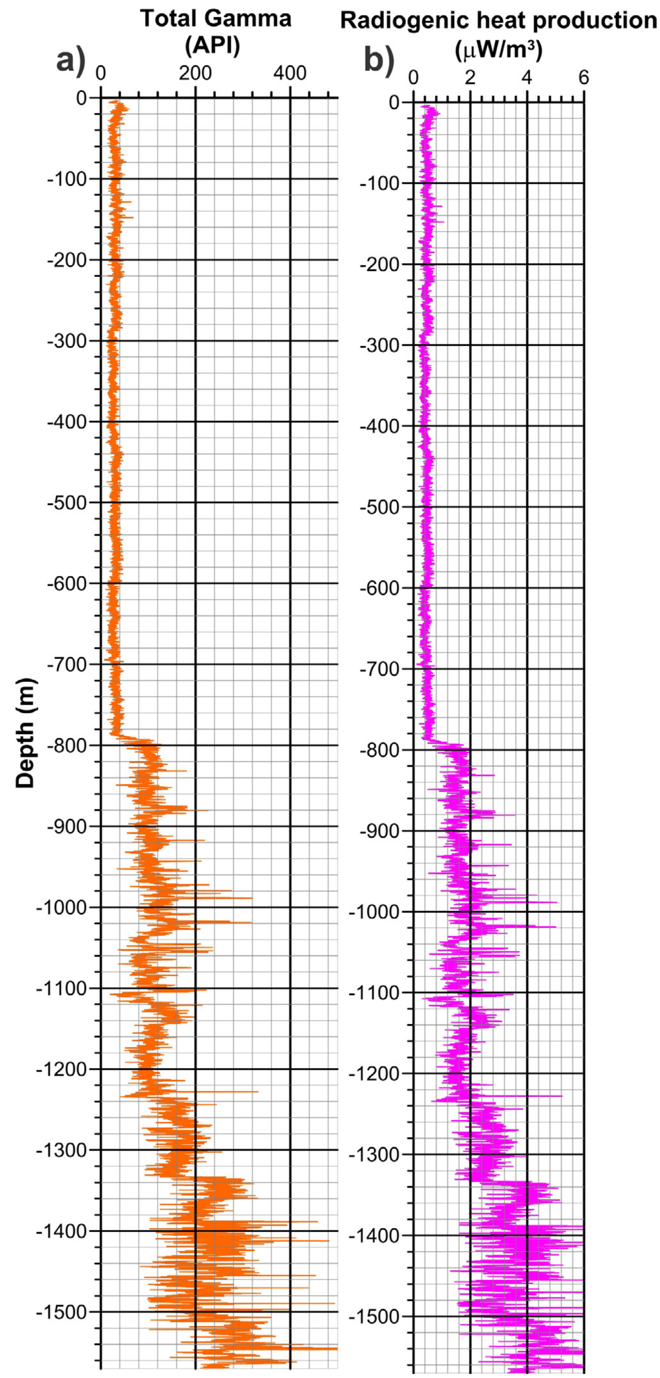

Fig. 9. Plots showing measured total natural gamma (a) and derived radiogenic heat production (b) in the Ullrigg borehole.

surface. These seasonal temperature changes are clearly recognisable on the temperature logs (Fig. 2) by the presence of strong decreases or increases of temperatures in the depth interval 0–60 m, depending on the season when temperature was measured. A relatively low heat flow density in the Ullrigg borehole correlates with low heat production, which is only 0.5 μW/m^3 on average for phyllites and varies from 1.5 to 3 μW/m^3 for large parts of the gneisses with local increases to more than 3–4 μW/m^3 in the lower part of the borehole according to measured total gamma (Fig. 9). In contrast, the average heat production of granite in the Fyllingsdalen borehole is around 6 μW/m^3 according to measured total gamma (Fig. 10), similar to that obtained from whole-rock chemical analyses of core samples yielding an average heat

Table 3
Uncorrected and corrected heat flow density for the investigated boreholes.

Borehole name	Averaging interval (m)	Depth interval (m)	Data range: uncorrected heat flow density (mW/m²)	Average uncorrected heat flow density (mW/m²)	Data range: corrected heat flow density (mW/m²)	Average corrected heat flow density (mW/m²)
Ullrigg	20	120–1500	14–63	37	22–74	48
	100	120–1500	27–47	37	35–58	48
Fyllingsdalen	20	120–450	39–63	50	60–85	72
	100	120–450	44–61	50	65–83	72
Årvollskogen	20	120–750	45–81	60	62–99	77
	100	120–750	54–65	60	71–83	77

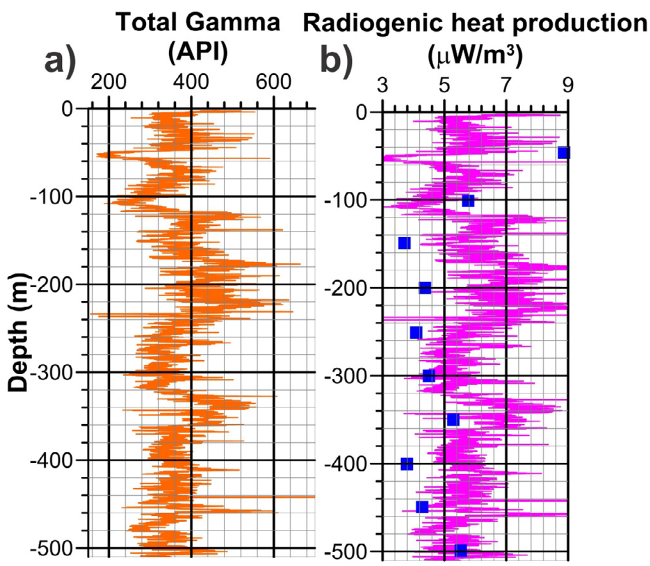

Fig. 10. Plots showing measured total natural gamma (a) and derived radiogenic heat production (b; rectangles are values of the radiogenic heat production obtained according to measurements of core samples in Table 2) in the Fyllingsdalen borehole.

production of 5 μW/m^3 (Table 2, one sample with anomalously high heat production omitted from average). To compare independently obtained values of radiogenic heat production, values according chemical analyses of core samples has been superimposed onto plot of radiogenic heat production obtained based on natural gamma data (Fig. 10b). There are three core samples in Fig. 10b which are located outside of the gamma-ray-based plot of radiogenic heat production whereas seven core samples demonstrate that our gamma-ray-based radiogenic heat production is in agreement with more reliable results from whole-rock analyses of core samples. Three mentioned mismatches can be related to difference in resolvability of the methods. Based on gamma spectrometry logging, heat production is 2 μW/m^3 for gabbros and amphibolites and 4.5 μW/m^3 on average for gneisses in the Årvollskogen borehole, reaching more than 12–14 μW/m^3 locally (Fig. 11f). The reason for these peaks is probably associated with a presence of granitic pegmatites which are characterised by increased content of uranium, thorium and potassium. The value for the gneisses at Årvollskogen is somewhat higher than that found by Slagstad (2008) using a regional bedrock geochemical dataset, yielding values typically <3 μW/m^3. To verify the reliability of radiogenic heat production obtained from the gamma ray log according to the empirical equation (4) from Bücker and Rybach (1996), two curves of radiogenic heat production, calculated based on both natural gamma ray and gamma spectrometry loggings, have been plotted together in Fig. 11f, demonstrating a very good qualitative fit as shapes of both graphs are very similar. On the other hand, these two graphs differ quantitatively in some places where values of radiogenic heat production obtained from the natural gamma log are locally lower compared to those obtained from gamma spectrometry in the case of the Årvollskogen borehole. These local mismatches are mainly related to difference in resolvability of the two methods and, therefore, radiogenic heat production based on gamma ray logging is representative for the drilled rocks in the Årvollskogen borehole. Unfortunately, we do not have gamma spectrometry logs for the Ullrigg and Fyllingsdalen boreholes to clarify if it is also true for these boreholes and, therefore, we can only assume that the obtained values of radiogenic heat production in the Ullrigg and Fyllingsdalen boreholes (Figs. 9b and 10b) also represent values which are very close to the real ones. This suggestion is also supported by the fact that most of values of radiogenic heat production according to chemical analyses of core samples are in the range of radiogenic heat production derived from gamma ray log in the Fyllingsdalen borehole (Fig. 10b).

The calculated topographic corrections are rather minor in all boreholes, ranging from −1 to 1 mW/m^2 in the Ullrigg borehole (Fig. 12a). In the Fyllingsdalen borehole, topographic correction is also −1 to 1 mW/m^2 (Fig. 13a) and ranges from less than −3 to 0 mW/m^2 in the Årvollskogen borehole (Fig. 14a). Very low magnitudes of topographic corrections in the Ullrigg, Fyllingsdalen and Årvollskogen boreholes are due to very smoothed relief in the vicinity of these boreholes, which are located at slightly positive landforms, at 40, 17 and 36 m a.s.l., respectively (Fig. 7).

In contrast to topographic corrections, the calculated palaeoclimatic corrections are characterised by rather high values, reaching more than 23–26 mW/m^2 in the upper part of the Fyllingsdalen borehole and 21–22 mW/m^2 in the Ullrigg and Årvollskogen boreholes (Figs. 12a, 13a and 14a). Therefore, the topographic corrections are rather minor compared with the palaeoclimatic ones for the investigated boreholes. The calculated magnitude of the

Table 4
Uncorrected and corrected heat flow density within the upper part of the investigated boreholes.

Borehole name	Averaging interval (m)	Depth interval (m)	Data range: uncorrected heat flow density (mW/m²)	Average uncorrected heat flow density (mW/m²)	Data range: corrected heat flow density (mW/m²)	Average corrected heat flow density (mW/m²)
Ullrigg	20	120–400	14–45	33	40–59	52
	100	120–400	27–37	33	45–55	51
Fyllingsdalen	20	120–400	40–63	51	60–85	72
	100	120–400	45–61	51	65–83	72
Årvollskogen	20	120–400	50–81	62	69–99	81
	100	120–400	59–65	62	77–83	80

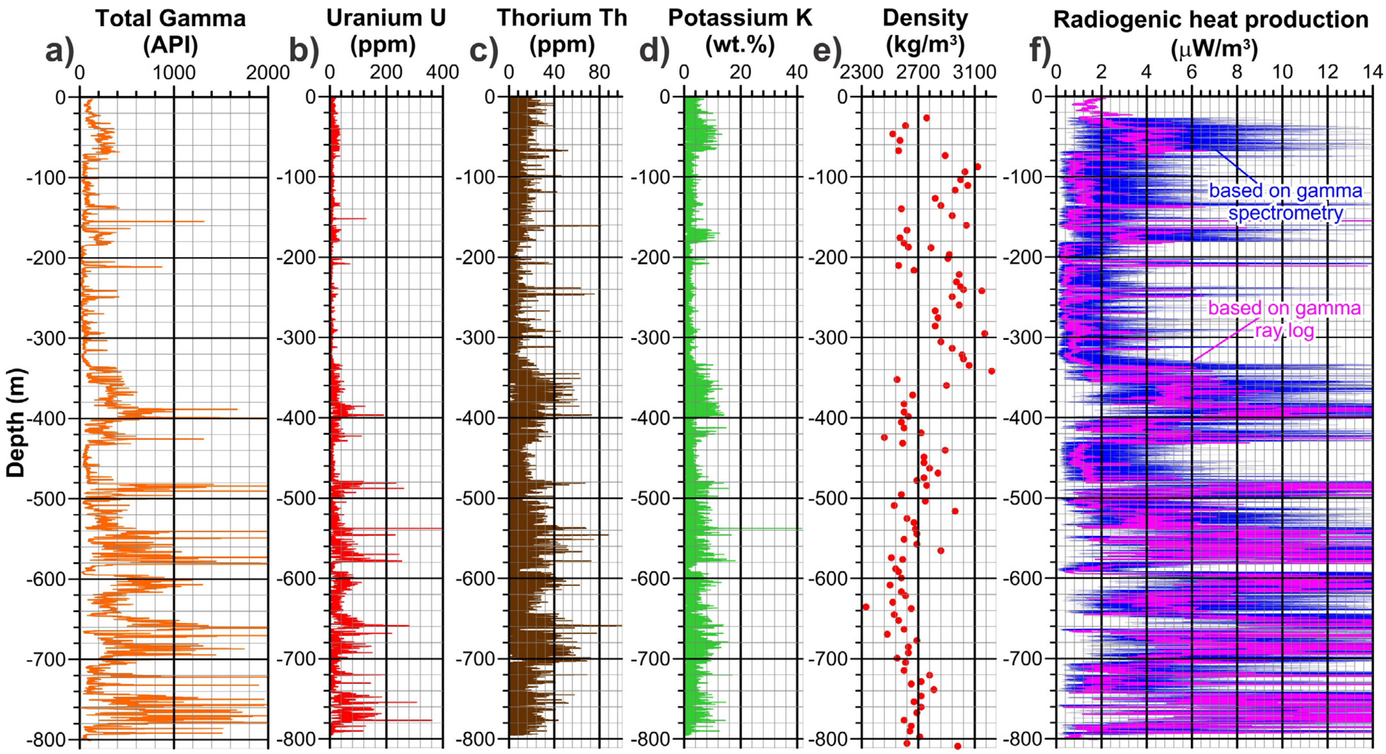

Fig. 11. Plots showing measured total natural gamma (a), natural gamma spectrometry (b–d; concentrations of uranium (b), thorium (c) and potassium (d), obtained by use of running-mean averages at depth intervals of 5 m), density (e) and calculated radiogenic heat production (f; magenta plot is based on natural gamma ray log in (a) and blue plot is based on natural gamma spectrometry in (b–d) in the Årvollskogen borehole. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

palaeoclimatic influence is in agreement with the regional-scale estimates for these parts of Scandinavia, calculated by Majorowicz and Wybraniec (2010). In detail, our palaeoclimatic corrections are higher by 2–4 mW/m^2 on average than those published by Majorowicz and Wybraniec (2010). This difference is most likely related to the errors in heat flow calculations, the uncertainties in the values of thermal conductivities and the variations in the used surface palaeotemperatures.

Consequently, the calculated corrected heat flow density (Figs. 12b, 13b and 14b) is considerably higher than the uncorrected values (Figs. 4d, 5d and 6d), reflecting a fact that a considerable drop in the Earth's surface temperatures during the last 228,000 years, in the Weichselian and Saalian glacial periods (Fig. 8), still strongly affects the subsurface thermal regime of southern Norway in terms of reduced heat flow density within the uppermost crystalline crust. As in the case with uncorrected heat flow density, the topographically and palaeoclimatively corrected heat flow density is the highest in the Årvollskogen borehole, ranging from 69 to 99 mW/m^2 with an average value of 80–81 mW/m^2 between 120 and 400 m depth (Table 4). The lowest heat flow density values are again in the Ullrigg borehole, where the average corrected heat flow density is only 51 mW/m^2 at a depth interval of 120–400 m. An average value of 72 mW/m^2 has been calculated for the Fyllingsdalen borehole.

According to our calculations, the values of the heat flow densities in the Ullrigg borehole are partially uncertain due to a fact that thermal conductivities of the drilled rocks (phyllites and augen gneisses) are unknown in detail compared to the Årvollskogen and Fyllingsdalen boreholes. As it has been already mentioned, deviations of the calculated uncorrected heat flow density in the Ullrigg borehole can vary from −10 to +20 mW/m^2. Therefore, the uncertainty of the calculated heat flow density of this borehole is in the range of −20 to +40%. This range is definitely very large on one hand. On the other hand, the Ullrigg borehole is associated with low to moderately heat producing phyllites, granitoids and granitoid gneisses (Slagstad, 2008), which may have contributed to the relatively low thermal gradient in this borehole compared to higher thermal gradients in the Årvollskogen and Fyllingsdalen boreholes. There, the drilled rocks are characterised by higher values of the radiogenic heat production and, therefore, that rocks produce larger amounts of heat than the drilled ones in the Ullrigg borehole. In this case, it would be reasonable to suggest that the heat flow density in the Ullrigg boreholes has to be significantly lower than in the Årvollskogen and Fyllingsdalen boreholes, implying that the maximum value of uncertainties has to be lower than +40%. Thus, the relatively low corrected heat flow density in the Ullrigg borehole is reasonable in spite even of the large uncertainties in the values of the uncorrected heat flow density. The calculated palaeoclimatic correction is also relatively uncertain due to a large range of possible values for thermal conductivities in the Ullrigg borehole. In this case, the possible deviation of the palaeoclimatic correction is in range of −3 to +6 mW/m^2. On the other hand, this discrepancy in thermal conductivities can be neglected in the case of the topographic correction due to a very low value of this correction itself.

In the Årvollskogen and Fyllingsdalen boreholes, thermal conductivities of rocks are, on average, similar to each other and thicknesses of the crust and the lithosphere are also similar in both cases. Radiogenic heat production of the Løvstakken granitic gneiss in the Fyllingsdalen borehole is comparatively high (cf., Slagstad, 2008) and it appears likely that the relatively high heat flow density observed in the Fyllingsdalen borehole results from this local, radioactive contribution. A similar scenario was suggested by Slagstad et al. (2009) for anomalously high heat flow density observed in a borehole in the high heat-producing Iddefjord granite in SE Norway In contrast, the even higher heat flow density observed at Årvollskogen appears to be unsupported by known local, radioactive sources. There are several possible answers to this conundrum.

The Fyllingsdalen borehole is located in southwestern Norway where the normal annual precipitation is very high (NMI, 2013), reaching roughly 4000 mm/year on the western side of the Scandes mountains. There, the results of the modelling of coupled groundwater flow and heat transfer (Maystrenko et al., 2015) demonstrate that the advective cooling due to groundwater flow is an additional factor for the reduction of subsurface temperatures. This scenario is also applicable for the Ullrigg borehole which is also located in southwestern Norway (Maystrenko et al., 2015). On the other

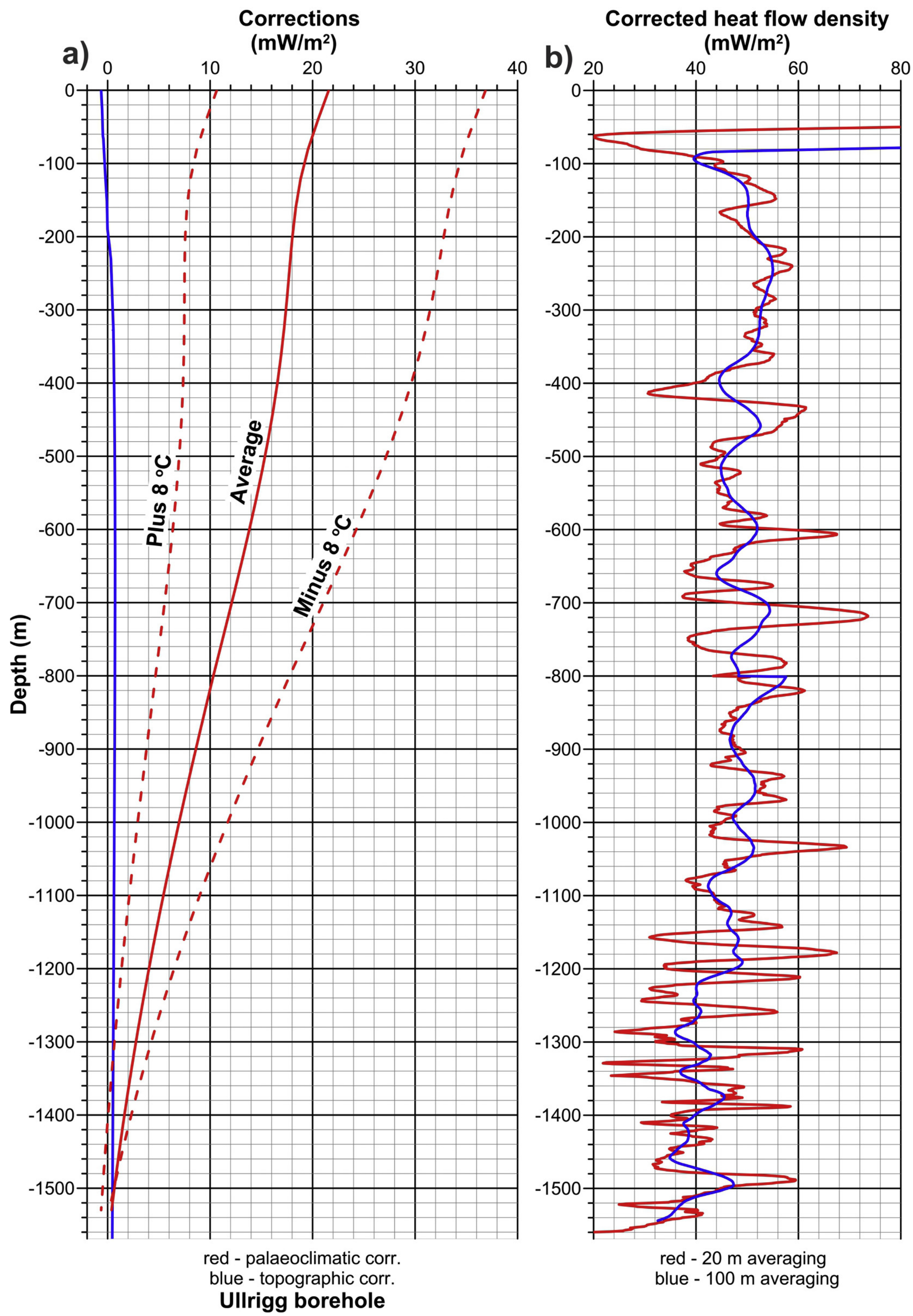

Fig. 12. Plots showing topographic and palaeoclimatic corrections (a) and calculated corrected heat flow density (b) in the Ullrigg borehole. Uncorrected heat flow density, calculated by use of arithmetic mean values of the thermal conductivities in Fig. 4c, has been used.

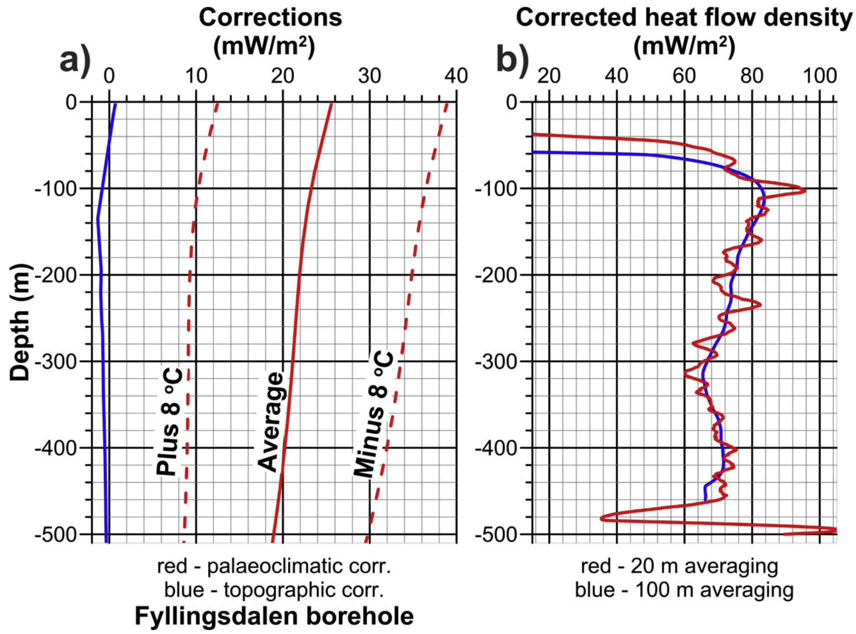

Fig. 13. Plots showing topographic and palaeoclimatic corrections (a) and calculated corrected heat flow density (b) in the Fyllingsdalen borehole.

hand, the influence of the groundwater flow on subsurface thermal field is most likely relatively low in the Årvollskogen borehole, which is located in the rain-shadow area with light precipitation and smoothed landforms. Therefore, the heat flow density in the Fyllingsdalen and Ullrigg boreholes may be additionally reduced due to advective cooling by groundwater flow as a result of high rates of precipitation and complex relief at the regional scale (Maystrenko et al., 2015). In this case, an additional correction due to heat transfer by groundwater circulation within fractured crystalline rocks has to be considered in order to obtain the undisturbed

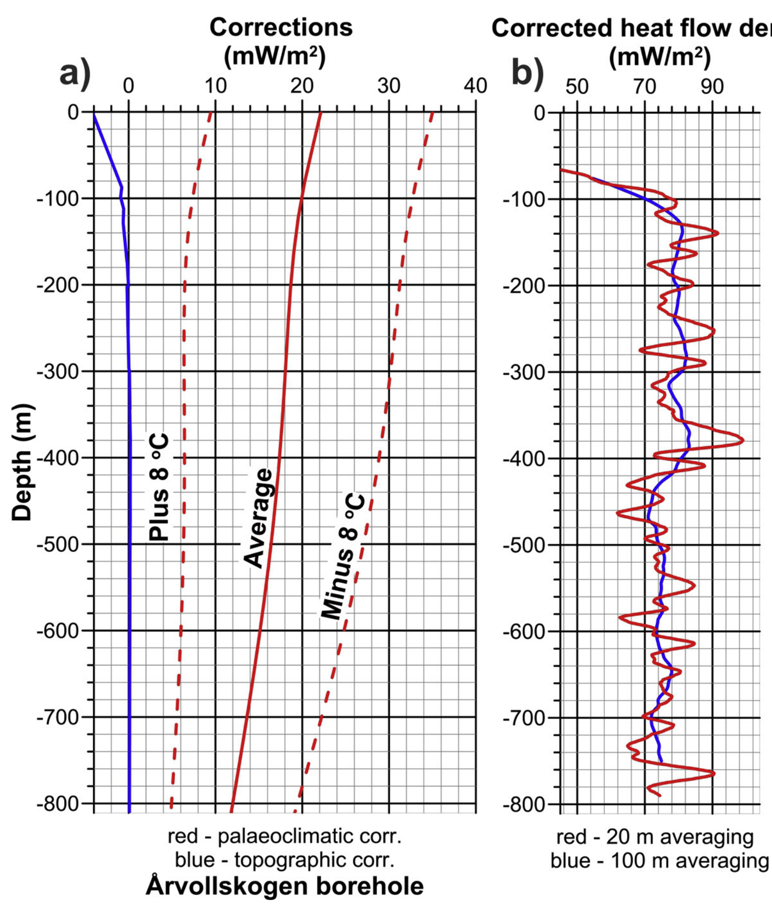

Fig. 14. Plots showing topographic and palaeoclimatic corrections (a) and calculated corrected heat flow density (b) in the Årvollskogen borehole.

values of the heat flow density in these two boreholes. However, there are not enough structural and hydrogeological constraints and, therefore, the groundwater flow related correction cannot be calculated accurately during the present study.

Another possible explanation of the (for Norway) unusually high heat flow density observed at Årvollskogen is that unseen, high heat–producing granites exist at depth in the area. The Årvollskogen borehole is located less than 20 km north of the Iddefjord/Bohus granite, which is one of numerous, Precambrian high heat-producing granites in SE Norway (Slagstad, 2008). Slagstad (2006) postulated the existence of several other, similar subsurface granites, and suggested that their presence could be detected by high heat flow densities unsupported by local, radioactive sources. However, a denser heat flow dataset is needed to determine whether the region is characterised by local, unsupported positive perturbations in heat flow densities, consistent with localised sources such as granite bodies, or if heat flow is higher in general in this region, which might point to a different interpretation.

5. Conclusions

In summary, it can be stated that the average heat flow density within the investigated boreholes has been calculated from a depth of 120 m to 400 m, where the thermal gradient is not strongly affected by seasonal changes of the Earth's surface temperature. This depth interval of 120–400 m has been chosen for all boreholes to consider general decrease of heat flow density with depth. The obtained corrected values of average heat flow density are 51 mW/m^2 within the Ullrigg borehole, 72 mW/m^2 within the Fyllingsdalen borehole and 80 mW/m^2 within the Årvollskogen borehole according to the preferred palaeoclimatic scenario (Fig. 8).

Highest tentative palaeoclimatic corrections vary from 21 to 26 mW/m^2 within the shallowest parts of the investigated boreholes (Figs. 12–14). Topographic corrections are characterised by rather minor values compared to palaeoclimatic corrections. Furthermore, the groundwater flow can be considered as an additional factor for the reduction of heat flow density in the Fyllingsdalen and Ullrigg boreholes, whereas hypothesised subsurface radioactive sources may have contributed to a higher heat flow density at Årvollskogen.

There is a clear difference in the calculated values of the heat flow density in the Ullrigg borehole and in the Fyllingsdalen and Årvollskogen boreholes. The obtained heat flow density is much lower in the case of the Ullrigg borehole compared to the Fyllingsdalen and Årvollskogen boreholes. This large difference may be related to the higher content of radioactive elements within the crystalline crust of the Fyllingsdalen and Årvollskogen boreholes as compared with the Ullrigg borehole. Therefore, the variations in heat production related to different lithologies is one of the main reasons for the higher heat flow density in the Fyllingsdalen and Årvollskogen boreholes in comparison to the Ullrigg one.

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