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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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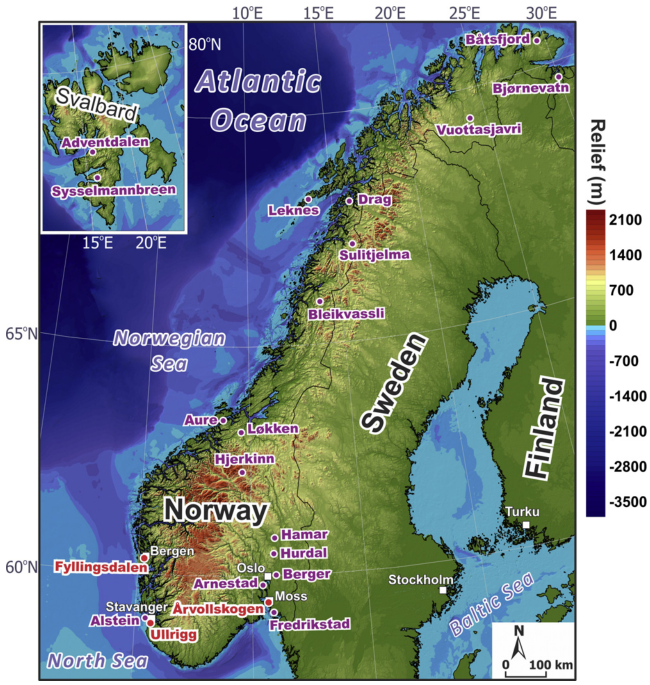

Fig. 1. Overview map with locations of all Norwegian boreholes on the mainland and Svalbard for which thermal data are available at the Geological Survey of Norway (NGU). Three boreholes from the present study are highlighted by red colour. Topography and bathymetry are from Norwegian Mapping Authority.

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 μW/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