Indication of deep groundwater flow through the crystalline rocks of southern Norway

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ABSTRACT

We assess the major aspects of the subsurface thermal regime within crystalline rocks of southern Norway. Results of two-dimensional modeling of coupled groundwater flow and heat transfer demonstrate that advective cooling due to groundwater flow is an important factor for the reduction of subsurface temperatures in southwestern Norway (the Bergen and Stavanger areas) where the normal annual precipitation is high on the western (windward) side of the Scandes mountains. On the other hand, the influence of groundwater flow on subsurface temperatures is most likely relatively low in southeastern Norway (the Moss area), which represents the rain-shadow area with light precipitation and is characterized by smoothed landforms. Therefore, where the reduced subsurface temperatures are associated with high atmospheric precipitation and complex surrounding topography, deep groundwater flow is most likely present within crystalline rocks. In this case, the observed low values of the thermal gradient within crystalline rocks can be used as groundwater flow tracers.

INTRODUCTION

Knowledge about the temperature distribution within the upper crystalline crust is an important issue in the geosciences because changes in temperature control the major properties of crystalline rocks as a result of generally increasing temperature with depth. The amplitude of this increase varies locally, depending on many factors such as thicknesses of the lithosphere, crystalline crust and sediments and their ratio of thickness to each other, lithological composition, temperature at Earth's surface, and features of groundwater flow. Actually, regional thermal anomalies created by large-scale groundwater flow are well documented within permeable sediments, showing that variability in geothermal heat can be used as a groundwater flow tracer (e.g., Anderson, 2005; Saar, 2011). Traditionally, during modeling within sedimentary basins, regional-scale groundwater flow through the crystalline crust was considered to be unimportant due to the fact that the greater part of fluid flow occurs within sediments. Deep drilling, however, has shown that groundwater is still present at great depths within crystalline rocks (Emmermann and Lauterjung, 1997), and groundwater flow through crystalline rocks also has a significant impact on the geothermal pattern of the subsurface (Komninou and Yardley, 1997). Furthermore, long-term monitoring of groundwater flow in deep boreholes of the Volga-Ural region (Russia) has indicated a regional-scale active fluid flow regime within upper-crustal crystalline rocks (Plotnikova, 2008). Therefore, processes of groundwater flow within crystalline rocks require better understanding.

Here, we assess the major controlling factors of the subsurface temperature distribution in the Fyllingsdalen, Ullrigg, and Årvollskogen boreholes, which were drilled within crystalline rocks near Bergen, Stavanger, and Moss, respectively, in southern Norway (Fig. 1A). Temperature well logging was recently carried out in these three boreholes. The measured average thermal gradient is unexpectedly low (13.0 °C/km and 16.5 °C/km, respectively) in the Ullrigg and Fyllingsdalen boreholes. In contrast, the thermal gradient is 19.3 °C/km in the Årvollskogen hole. Consequently, the low values of the thermal gradient in the Fyllingsdalen and Ullrigg boreholes require an explanation.

REGIONAL AND LOCAL SETTINGS

Topographic relief (Fig. 1A) is present in the form of smoothed landforms in the close vicinity of the Årvollskogen borehole. In contrast, the northeast-southwest–trending Scandes mountains, with altitudes reaching to more than 1500–2000 m a.s.l. (above sea level), are to the east of the Ullrigg and Fyllingsdalen boreholes. These mountains act as barriers to the flow of moist Atlantic air over southern Scandinavia, causing increased annual precipitation along their western slope, whereas the eastern part of southern Norway is affected by a rain-shadow effect and, therefore, has low annual precipitation (Fig. 1B).

The 516-m-deep Fyllingsdalen borehole is situated in the Løvstakken granitic gneisses of the Bergen arc system which formed during the Caledonian orogeny. The granitic gneisses (layer 4 in Fig. 2) are characterized by relatively high radiogenic heat production that locally reaches more than 10 $\mu W/m^3$. The structure of this arc system is expressed by a structurally complex sequence of Caledonian nappes, the main three of which are the Lindås nappe (layer 1 in Fig. 2), the Hardangerfjord nappe (layer 2 in Fig. 2), and the Blåmanen nappe (layer 3 in Fig. 2).

The >1500-m-deep Ullrigg borehole was drilled through phyllites (layer 6 in Fig. 2) and gneisses (layer 9) near the northwestern part of the Sveconorwegian Rogaland igneous province.

The 811-m-deep Årvollskogen borehole is located within the eastern flank of the late Carboniferous–Early Permian Oslo graben (Fig. 1). The geological section of the Årvollskogen borehole consists of amphibolites and metagabbro (layer 8 in Fig. 2) in the upper part, whereas gneisses (layer 9 in Fig. 2) predominate in the lower part of the borehole.

DATA AND METHODS

Configuration of the deep crystalline crust, Moho, and lithosphere-asthenosphere boundary were taken from lithosphere-scale, three-

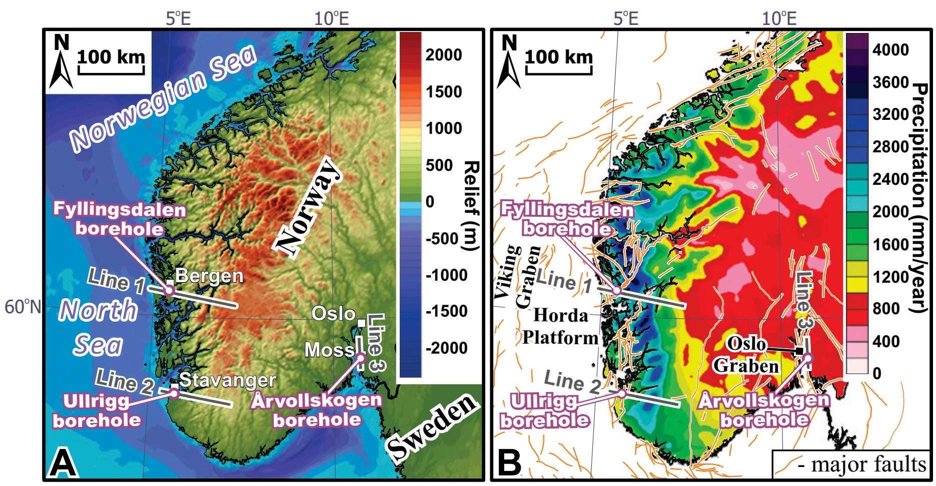

Figure 1. A: Topography (IOC, IHO, and BODC, 2003) of study area. B: Normal annual precipitation (NMI, 2013) with locations of major faults (Sigmond, 2002). Locations of the modeled lines 1, 2, and 3 are also shown.

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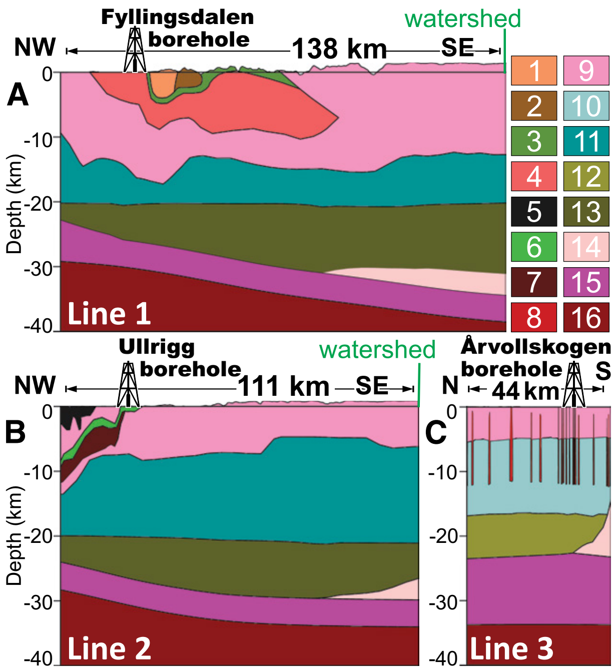

Figure 2. Lines 1, 2, and 3 across the investigated boreholes in southern Norway (see Fig. 1 for location of lines). Upper part of line 1 is modified after Rudlang (2011) and based on the geological cross section from Ragnhildstveit and Helliksen (1997). Legend: 1—anorthosite, gneiss, and amphibolite; 2—diorite, gabbro, and metabasalt; 3—mainly schist; 4—Løvstakken granitic gneiss; 5—plutonic rocks; 6—phyllite; 7—anorthosite and norite; 8—amphibolite and (meta)gabbro (intrusions); 9—upper-crustal granites and gneisses; 10—part of the middle and the upper crust; 11—middle crust; 12—lower and part of the middle crust; 13—lower crust; 14—high-density crust; 15—high-density lower crust; 16—lithospheric mantle.

dimensional (3-D) structural models and deep seismic data (detailed information is provided in the GSA Data Repository[1]). The structure of the upper crust is based on the surface geology and borehole data. In order to obtain self-consistent 2-D structural models as shown in Figure 2, we merged the deep and shallow data sets with the help of 2-D density and magnetic modeling.

The values of the densities and thermal properties are shown in Table 1. The thermal conductivities have been set to be temperature dependent for the crystalline crust and temperature and pressure dependent for the lithospheric mantle.

We used the permeabilities of the crystalline rocks adjusted according to the regional compilation of permeability measurements from Juhlin et al. (1998).

A 2-D temperature distribution was modeled by use of the software package COMSOL Multiphysics. The heat equation was used to calculate the conductive heat transfer, and we applied Darcy's law to model the flow of water through the subsurface.

The base of the lithosphere was chosen as a lower thermal boundary, which corresponds to the 1300 °C isotherm. For the upper thermal boundary, constant and time-dependent temperatures at the Earth's surface were applied. This was done by taking into account paleoclimatic changes during the past 228 k.y. according to the approach of Slagstad et al. (2009). Present-day surface temperatures are represented by annual average air temperatures during the period A.D. 1961–1990 (Tveito et al., 2000). In particular, temperatures at ~6.7 °C, 7 °C, and 6.2 °C were set near the locations of each borehole within the Bergen, Stavanger, and Moss areas, respectively. The influence of paleoclimatic changes was included in the modeling process in terms of a time-dependent variable temperature at the upper thermal boundary. The paleotemperatures were inferred based on temporal ice-cover variations in Scandinavia during the Weichselian glaciations as reported by Slagstad et al. (2009). At times when the modeled lines 1, 2, and 3 (for location, see Fig. 1) were covered by ice, the temperature at the surface along the lines is assumed to have been –0.5 °C. For times when the lines were ice free, the temperature was derived from Renssen and Isarin (1997) who modeled the mean annual temperatures for the Younger Dryas (ca. 11,000–10,000 yr B.P.). In particular, a constant temperature of –5 °C was set in the Stavanger and Moss regions, and –6 °C for the Bergen area.

RESULTS AND DISCUSSION

The starting point of the 2-D thermal modeling was the initial thermal models that have been calculated assuming present-day annual average air temperatures (Tveito et al., 2000) as the upper thermal boundary. Comparison of the results with measured temperature-depth plots in the boreholes (Fig. 3) indicates that there are large misfits between the measurements and the results of the modeling.

The paleoclimatically corrected results of the 2-D thermal analysis demonstrate an almost perfect fit in the case of the Årvollskogen borehole (Fig. 3A). However, results along lines 1 and 2 indicate that considering a paleoclimatic effect does not provide a good fit between measured (blue lines in Figs. 3B and 3C) and modeled temperatures (magenta lines) in the Fyllingsdalen and Ullrigg boreholes. In fact, the paleotemperatures used were estimated only for the Younger Dryas (Renssen and Isarin, 1997) and, therefore, could have varied during the other time intervals of the Weichselian and Saalian glacial periods. However, in order to remove the misfits recorded in the Fyllingsdalen and Ullrigg boreholes, further attempts employing decreasing paleotemperatures resulted in a large misfit within the middle part of the 1500-m-deep Ullrigg borehole if the modeled temperatures coincide with the measured ones within the deep part of this borehole. This indicates that there are some restrictions regarding to what extent the paleoclimatic effect is involved in the reduction of temperatures. Therefore, another process must

TABLE 1. DENSITIES AND THERMAL PROPERTIES OF THE TWO-DIMENSIONAL CRUSTAL MODELS

Layer number	Layer description	Density ρ (kg/m³)	Specific heat capacity C_p (J/[kg×K])	Thermal conductivity (scale value) k_r (W/[m×K])	Radiogenic heat production *S* (μW/m³)
1	Anorthosite and amphibolite	2800	790	3.00	1.5
2	Diorite, gabbro, and metabasalt	3030	790	2.90–3.00	0.3
3	Schist and mylonitised gneiss	2774	790	2.80–2.90	1–2.7
4	Løvstakken granitic gneiss	2620	820	3.10	4.5–6.0
5	Plutonic rocks	2820	880	2.90–3.00	0.5
6	Phyllite	2810	880	2.55	0.5
7	Anorthosite and norite	2840	880	2.91	0.3
8	Amphibolite and (meta)gabbro	2850–3050	790	2.90	0.4–1.2
9	Upper-crustal granites and gneisses	2610–2730	800–910	3.00–3.30	2.0–4.4
10	Middle-upper crust of line 3	2740	930	3.10	1.6
11	Middle crystalline crust	2743	950	3.20	0.7
12	Lower-middle crust of line 3	2830	1050	3.20	0.7
13	Lower crust	2856	1050	2.90	0.3
14	High-density crust	2940	1050	3.10	0.3
15	High-density lower crust	3056	1100	2.75–2.85	0.2
16	Lithospheric mantle	3222	1200	4.79	0.03

Note: Layer number refers to the layer numbering in the two-dimensional crustal model (see Fig. 2).

[1]GSA Data Repository item 2015119, data, properties of rocks, and methodology, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

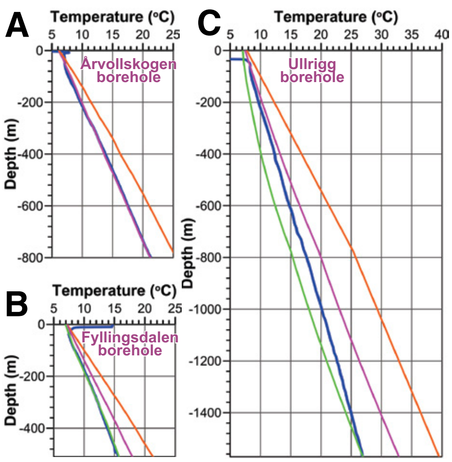

Figure 3. Measured versus modeled temperatures. A: Årvollskogen borehole. B: Fyllingsdalen borehole. C: Ullrigg borehole. Blue shows measured temperature, orange is assuming steady-state conditions, magenta is with paleoclimatic corrections, and green is with the influence of the groundwater flow in addition to paleoclimatic corrections.

be responsible for the lowering of temperatures. This process is suggested to be most reasonably related to groundwater circulation through cracks and fractures in the crystalline rocks.

In this case, the question arises: Do we have enough fractures or microfractures within our study areas for groundwater flow? At the regional scale, the Bergen Arc shear zone is the most pronounced tectonic feature within the Bergen region, and basement shear zones are also reported within the Stavanger area (Fossen and Hurich, 2005). Furthermore, the entirety of Fennoscandia is currently being uplifted due to post-glacial isostatic rebound (Balling, 1980), and there is also pronounced recent seismic activity within southwestern Norway (Fjeldskaar et al., 2000), indicating that this area is not tectonically quiet and, consequently, some previously active fractures or faults could have been reactivated to have apertures large enough to allow fluid flow through the crystalline rocks.

The next question arises: What is the long-term regional-scale source of the water? Actually, there is a direct relationship between the intensity of precipitation and the long-term average groundwater recharge (Döll and Fiedler, 2008). According to data from the Norwegian Meteorological Institute (NMI, 2013), the normal annual precipitation in southwestern Norway reaches >4000 mm/yr locally (Fig. 1B). Meteoritic water can penetrate to great depths according to Menzies et al. (2014) who showed that fluids circulating to ~6 km depth in the Southern Alps of New Zealand are dominantly surface derived. In general, the penetration depth is mostly controlled by the permeability of crystalline rocks, which rapidly decreases with depth (e.g. Ingebritsen and Manning, 2010), implying that the greater part of groundwater flow should be localized within the uppermost crystalline crust.

Deelstra et al. (2013) reported that the groundwater contribution to surface and subsurface runoff is on the order of 10% in the agriculture-dominated Norwegian catchment. During the modeling, we chose 2.5%–5% of the normal annual precipitation to represent the possible average amount of rainfall water that can penetrate down to the deep subsurface. Therefore, the upper boundary condition for the groundwater flow simulation was taken as the mass flux, which is equal to 2.5%–5% of the annual precipitation along lines 1 and 2. These values were assumed to be constant during the past 10 k.y. The influence of groundwater flow has been neglected during the glacial periods due to a lack of information concerning groundwater flow when the study area was affected by permafrost.

The results of the 2-D modeling of coupled groundwater flow and heat transfer demonstrate that advective disturbance of heat by the groundwater flow helps to move the modeled temperatures (green lines in Figs. 3B and 3C) closer to the measured ones. A good fit is obtained for the Fyllingsdalen borehole (Fig. 3B). A partial mismatch in the case of the Ullrigg borehole (Fig. 3C) can be related to vertical fluctuations of permeabilities in contrast to the assigned values, which simply decrease with depth. Modeled influence of groundwater flow on the subsurface thermal regime beneath these two boreholes is strongest at a depth interval of 1000–2000 m where a consideration of the advective disturbance due to groundwater flow decreases the conductively modeled temperatures by almost 6 °C. This influence declines down to depths of ~2500–3000 m where the thermal effect of groundwater flow becomes insignificant. A lack of detailed information concerning the sizes and densities of fractures within the crystalline rocks does not allow us to estimate a precise magnitude of the groundwater influence on the subsurface thermal regime.

Moreover, values of radiogenic heat production can vary within a reasonable range, implying that modeled temperatures accounting for this variation may deviate from the obtained values. The thermal effect of possible variations has been examined and indicates that the deviations of the modeled temperature can be ~±12% on average at 6000 m depth, decreasing toward shallower depths where the 2-D thermal models are well constrained by structural and sampling data. Another influencing factor is related to the regional late Neogene uplift and subsequent erosion, which led to a temporary uplift of isotherms within the upper crystalline crust of southwestern Norway.

Therefore, the impact of groundwater flow may be greater than the one modeled here if the presence of regional-scale permeable fractures could be confirmed by independent data, if the radiogenic heat production decreases more slowly with depth than predicted by our models, and if the magnitude of a positive thermal anomaly due to the late Neogene uplift is still significant. On the other hand, the magnitude of the expected Neogene thermal anomaly could be already smoothed by paleogroundwater that was possibly circulated through the crystalline rocks of southwestern Norway during the Neogene uplift and erosion. In this case, the potential thermal effect of a deep paleogroundwater flow through crystalline rocks has to be considered for geological interpretations of time-temperature models based on fission-track and (U-Th)/He data.

The calculated distribution of temperatures along lines 1 and 2 (Figs. 4A and 4B) is also characterized by an increase in the modeled

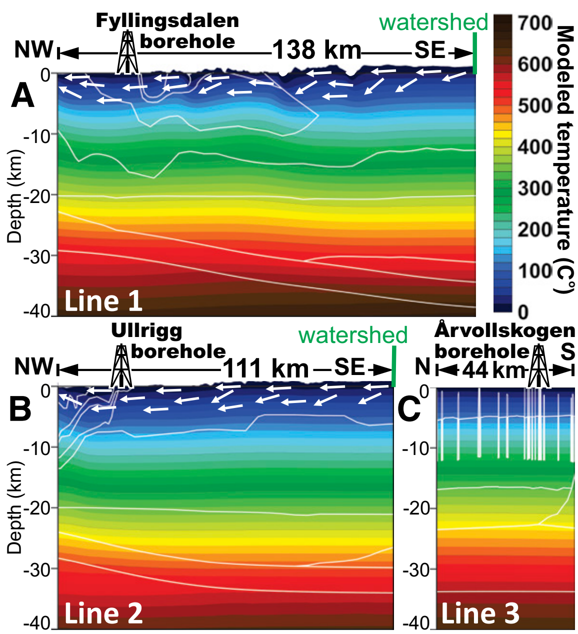

Figure 4. A,B: Distribution of modeled temperatures along lines 1 and 2 (model with influence of groundwater flow). C: Modeled temperatures along line 3 (model without influence of groundwater flow). White arrows indicate approximate groundwater flow directions within uppermost crystalline crust.

temperatures toward the northwestern terminations of the profiles. The presence of the regional topographic low of the North Sea causes a discharge of relatively heated groundwater which results in positive thermal anomalies near the coast, demonstrating an opposite effect in comparison with cooling in the places where the boreholes are located. In contrast, the modeled isotherms are almost horizontal within the Moss area (Fig. 4C).

The relatively low present-day temperature at Earth's surface (<7 °C on average along lines 1 and 2), the pronounced changes in relief (from sea level to >1000–1500 m over a distance of <50–60 km), and the associated high precipitation (2500 mm/yr on average), together with the presence of fractures within the crystalline rocks, create favorable conditions for advective cooling of the uppermost crystalline crust within the Bergen and Stavanger areas by groundwater flow.

Therefore, we have shown that atmospheric precipitation–derived groundwater flow through the crystalline rocks can affect the regional conductive thermal field of the upper crust in terms of reduced temperatures within the uppermost crust of southwestern Norway. Thus, the observed thermal anomalies within the crystalline rocks can also be used as groundwater flow tracers similarly to those that are commonly observed within the sediments (Anderson, 2005; Saar, 2011). Furthermore, our results are in agreement with previous studies (Menzies et al., 2014), showing also that surface-derived groundwater can reach down to relatively deep levels of the crystalline crust.

At the global scale, topography-induced orographic rainfalls can also affect the subsurface geothermal field within other areas of the world where a steep topographic gradient coincides with a high atmospheric precipitation rate, such as along the western slopes of the Coast Mountains in the Pacific Coast Ranges and the southernmost part of the Alaskan Mountain Range in North America; the Southern Andes in South America; and the southern slope of the Himalaya in Asia. In those areas, intensity of atmospheric precipitation is very high (Hijmans et al., 2005) and changes in relief are even more extreme than in southwestern Norway (IOC, IHO, and BODC, 2003).

CONCLUSIONS

Results of the 2-D modeling of coupled groundwater flow and heat transfer demonstrate that advective cooling due to groundwater flow through crystalline rocks is an important factor for the reduction of temperatures within the crystalline rocks of southwestern Norway (the Bergen and Stavanger areas) where the normal annual precipitation is one of the highest in Europe. On the other hand, the influence of the groundwater flow on subsurface temperatures is most likely very low within the Moss region, which is located in the rain-shadow area south of Oslo.

According to our results, the association of the low values of the geothermal gradient within the upper crystalline crust with high atmospheric precipitation and pronounced changes in topography, like in southwestern Norway, can also be used as a possible indication of surface-derived, deep groundwater flow through crystalline rocks in other areas of the world.

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