APPENDIX: DATA, PROPERTIES AND METHODOLOGY

Structural data

Configuration of the middle and lower crystalline crust, Moho and the lithosphere-asthenosphere boundary have been taken from the 3D structural model of the northern North Sea and adjacent continent (Maystrenko et al., 2013), the 3D subsurface model of southern Norway and Sweden (Gradmann et al., 2013), and the Magnus-Rex deep seismic experiment (Stratford et al., 2009).

The structure of the upper crystalline crust is derived from the surface geology extrapolated to great depth and borehole data. In particular, 1:250 000 geological maps by Ragnhildstveit and Helliksen (1997), Jorde et al. (1995) and Lutro and Nordgulen (2008) have been used to define the structure of the upper crust within the Bergen, Stavanger and Moss areas, respectively.

Properties of rocks

Densities for the middle-lower crystalline crust and the upper mantle have been taken from the results of 3D density modeling (Maystrenko et al., 2013). The upper crustal densities and thermal properties are mainly derived from the NGU petrophysical electronic database "Petrbase" and have been also obtained by laboratory measurements of drillcore samples. Gamma-ray and gamma spectrometry logs have been used to estimate the radiogenic heat production of rocks in the boreholes. In addition, the thermal properties of the lithospheric mantle and crystalline crust are based on published values with similar lithological compositions (Čermak and Rybach, 1982; Clauser, 2011).

The results of natural gamma-ray and gamma spectrometry loggings have been used to estimate the radiogenic heat productions of rocks in the boreholes.

The empirical relationship between total gamma and radiogenic heat production (1) from Bücker and Rybach (1996) has been used to calculate the radiogenic heat production of rocks in the Fyllingsdalen and Ullrigg boreholes.

$$S=0.0158\ (GR - 0.8). \quad (1)$$

where S is the radiogenic heat production ($\mu W/m^3$) and GR is the total gamma (API units).

The empirical relationship (1) has been inferred based on the data from the following boreholes: Soultz-Sous-Forêts, Sancerre-Couy and BALAZUC- I, France; KTB, Germany; ODP 834B, Ocean Drilling Program; and three different NAGRA boreholes (Switzerland). The 160 data points cover the range of 0-350 API and, therefore, the results of calculation for the total gamma higher than 350 API are scaling values of the radiogenic heat production rather than realistic ones. The obtained radiogenic heat production in the Fyllingsdalen borehole varies mostly from 4 to 8 $\mu W/m^3$ with an average value of around 6 $\mu W/m^3$. In the case of the Ullrigg borehole, there is a clear difference in the calculated radiogenic heat production between phyllite and granitic gneiss. Phyllite is characterized by 0.5 $\mu W/m^3$ on average, whereas the radiogenic heat production of granitic gneiss increases with depth from 1.5 $\mu W/m^3$ to more than 5 $\mu W/m^3$ locally in the lower part of the borehole.

The results of natural gamma spectrometry logging in the Årvollskogen boreholes have been used to obtain values of the radiogenic heat production derived from uranium (U), thorium (Th), and potassium (K) concentrations. The empirical relationship between radiogenic heat production and concentrations of the radiogenic elements (2) from Rybach (1988) has been used to calculate the radiogenic heat production of upper crustal rocks.

$$S=\rho(9.52C_U + 2.56C_{Th} + 3.48C_K)*10^{-5}. \quad (2)$$

where S is the radiogenic heat production ($\mu W/m^3$), 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 obtained radiogenic heat production in the Årvollskogen borehole varies mainly from 0.5 to more than 8 $\mu W/m^3$ (Figure 8). These values of the radiogenic heat production clearly correlate with the predominant lithology. There is a clear difference in the calculated radiogenic heat production between the upper part of the borehole's section where amphibolites and metagabbro predominate, and the lower part of the borehole where granitic to quartz-dioritic gneisses are mainly present. Amphibolites are characterized by 1.2-1.5 $\mu W/m^3$ on average, whereas the radiogenic heat production of granitic to quartz-dioritic gneisses is much higher, reaching more than 8 $\mu W/m^3$ locally (Figure 8). An average value of 4.4 $\mu W/m^3$ has been assigned to the upper crustal granitic gneisses, assuming that radiogenic heat production decreases with depth. Local peaks with very high values of the calculated radiogenic heat production are related to the intervals where granitic pegmatites are mostly present.

Temperature-dependent values of the thermal conductivities for the uppermost crust have been calculated according to the empirical equations (3) and (4) from Sass et al. (1992):

$$k(T) = k_o / (1.007+T(0.0036-0.0072/k_o)). \quad (3)$$

$$k_o = k_r(1.007+25(0.0037-0.0074/k_r)). \quad (4)$$

where k(T) is the thermal conductivity (W/mK) at temperature T in (^oC), k(0) is the thermal conductivity (W/mK) at 0 ^oC, k_r is the thermal conductivity (W/mK) at room temperature of 25 ^oC and T is the temperature (^oC).

The empirical equations (5) and (6) from Vosteen and Schellschmidt (2003) have been used to calculate the temperature-dependent thermal conductivities for the rest of the crystalline crust where temperatures are higher than 300 ^{o}C:

$$k(T) = k_o / (0.99+T(a-b/k_o)). \quad (5)$$

where k(T) is the thermal conductivity of crystalline rocks (W/mK) at temperature T in (K), k_o is the thermal conductivity (W/mK) at 0 ^{o}C, k_r is the thermal conductivity (W/mK) at room temperature of 25 ^{o}C, T is the temperature (K), a and b are constants: a = 0.0030±0.0015 and b = 0.0042±0.0006.

$$k_o = 0.53k_r +1/2(1.13(k_r)^2-0.42k_r)^{1/2}. \quad (6)$$

where k_o is the thermal conductivity of crystalline rocks (W/mK) at 0 ^{o}C and k_r is the thermal conductivity (W/mK) at room temperature of 25 ^{o}C.

To define the temperature- and pressure-dependent thermal conductivities within the lithospheric mantle, the empirical equations (7) and (8) from Hofmeister (1999) have been taken:

$$k(T,P) = k_r(298/T)^a\exp(-(4\gamma+1/3)\alpha(T-298))(1+K'_oP/K_o) + k_{rad}. \quad (7)$$

$$k_{rad} = 4.7(0.01753-0.00010365T+2.2451T^2/10^7-3.407T^3/10^{11}). \quad (8)$$

where k(T,P) is thermal conductivity (W/mK) at temperature T in (K) and under pressure in (Pa), k_r is the thermal conductivity (W/mK) at room temperature, T is the temperature (K), γ is Grueneisen parameter (γ =1 to 1.4), a is the phonon fitting parameter (a = 0.25 to 0.45), α(T-298) is the volume coefficient of thermal expansion as a function of temperature, K_o is the bulk modulus (Pa)(K_o=261 GPA), K'_o is the pressure derivative of the bulk modulus (K'_o=5) and k_{rad} is the radiative component of the thermal conductivity, enhanced according to van den Berg et al. (2001).

Permeability of the crystalline rocks is mainly associated with the size of fractures and their connectivity. Unfortunately, the Ullrigg borehole is cased, whereas drilling and logging in the Fyllingsdalen borehole indicate the presence of joints and fractures. The uppermost 120 m of the Fyllingdalen borehole are represented by highly fractured bedrock. Besides, the Fyllingsdalen borehole was stopped at 516 m because strongly fractured bedrock caused problems for further drilling operations. In the absence of information about the distribution of joints and fractures within the Bergen and Stavanger areas, regional compilation of permeability measurements in boreholes from the Baltic Shield and other areas (Juhlin et al., 1998) has been used. Permeabilities of the crystalline rocks have been set to decrease rapidly with depth from 5.0E-015 m^2 at shallow levels to less than 1E-018 m^2 in the deeper crust. Porosities of crystalline rocks have been taken to be 1.5% at relatively shallow levels and 0.98% at the deeper levels according to porosity measurements in crystalline rocks of Sweden (Tullborg and Larson, 2006).

Fluid properties (density, thermal conductivity, specific heat capacity and dynamic viscosity) have been set to be dependent on temperature, based on the thermodynamic properties of water and steam according to the International Association for Properties of Water and Steam Industrial Formulation 1997 (Wagner and Kretzschmar, 2008).

Methodology

A 2D temperature distribution has been simulated with the help of the commercial software package COMSOL Multiphysics.

During the purely conductive 2D thermal modelling, the module of "Heat Transfer in Solids" has been used to simulate the stationary and time-dependent heat transfer by heat conduction, which is assumed to be the dominant mechanism of heat transfer at the regional

scale within the study area. Therefore, these simulations have been carried out based on physical principles of the conductive 2D thermal field by solving the heat equation (9):

$$\rho C (\delta T/\delta t) = \nabla \cdot (k \nabla T) + Q. \quad (9)$$

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), Q is the heat source (radioactive heat production) (W/m^3), δT is the change in temperature per time interval δt, and $\nabla \cdot$ is the operator giving the spatial variation in temperature. Accordingly, the solution of the heat equation (9) is sensitive to the values of the thermal properties (C, k and Q) as well as to the thermal boundary conditions.

The heat flow q (W/m^2) has been calculated according to Fourier's law of heat conduction (10):

$$q = - k\nabla T. \quad (10)$$

where k is the thermal conductivity (W/mK) and ∇T is the temperature gradient (K/m).

Furthermore, two COMSOL modules of "Heat Transfer in Porous Media" and "Porous media and Subsurface Flow/Darcy's Low" have been used to carry out a fully coupled thermal modelling with taking into account the advection heat transfer due to groundwater flow.

To model the flow of water through a subsurface porous medium, Darcy's law (11) has been applied:

$$u=-\kappa /\mu\nabla P. \quad (11)$$

where u is the Darcy velocity or discharge per unit area (m/s), ∇P is the pressure gradient vector (Pa/m), κ is the permeability of the porous medium (m^2) and μ is the fluid's dynamic viscosity (Pa*s). The value of permeability represents the ability of fluid to flow through a porous medium.

In order to calculate the heat transfer in the porous medium, a sophisticated version of the heat equation (9) has been applied:

$$\rho_{eq}C_{eq}\,(\delta T/\delta t)+ \rho_f\,C_f\,u\nabla T = \nabla\cdot\,(k_{eq}\,\nabla T) + Q. \quad (12)$$

where ρ_{eq} is the density of the solid-fluid system (kg/m^3), C_{eq} is the heat capacity of the solid-fluid system (J/kgK), T is the temperature (K), t is the time (s), ρ_f is the density of the fluid (kg/m^3), C_f is the heat capacity of the fluid (J/kgK), u is the fluid velocity field (m/s), ∇T is the temperature gradient (K/m), k_{eq} is the thermal conductivity of the solid-fluid system (W/mK), Q is the heat source (radioactive heat production) (W/m^3), δT is the change in temperature per time interval δt, and $\nabla\cdot$ is the operator giving the spatial variation in temperature. In this particular case, the fluid velocity field (u) is represented by the Darcy velocity from equation (11).

It is important to note that ($\rho_{eq}C_{eq}$) is the so-called equivalent volumetric heat capacity of the solid-fluid system and can be calculated according to the equation (13):

$$\rho_{eq}C_{eq} = \theta_s\,\rho_s\,C_s + \theta_f\,\rho_f\,C_f. \quad (13)$$

where ρ_s is the density of the solid material (porous matrix) (kg/m^3), C_s is the heat capacity of the solid material (porous matrix) (J/kgK), ρ_f is the density of the fluid (kg/m^3), C_f is the heat capacity of the fluid (J/kgK), θ_s is the solid material's volume fraction, which is related to the volume fraction of the fluid θ_f as in the following:

$$\theta_s + \theta_f = 1. \quad (14)$$

The equivalent thermal conductivity of the solid-fluid system k_{eq} is the so-called equivalent thermal conductivity and can be inferred by use of this equation:

$$k_{eq} = \theta_s\,k_s + \theta_f\,k_f. \quad (15)$$

where k_s is the thermal conductivity of the solid material (porous matrix) and k_f is the thermal conductivity of the fluid.

During the modeling, it was assumed that the groundwater flows in the same direction as that of rainwater at the Earth's surface. To take into account this assumption, the modeled lines have been restricted to the drainage basin of the river where the investigated line is located. This has been done by use of a spatial distribution of discharge areas in Norway according to Borgvang et al. (2005). Consequently, Line 1 is located within the drainage basin of the Suldaslågen river and Line 2 is located within the drainage basin of the Oreelva river. Consequently, both lines have been vertically restricted to the places where the watersheds are located.

REFERENCES CITED

Borgvang, S.A., Stålnacke, P., Johansen, S.W., et al., 2005, Riverine inputs and direct discharges to Norwegian coastal waters - 2005: Norwegian Institute for Water Research, Report TA-2245/2007, 152 p.

Bücker, C., and Rybach, L., 1996, A simple method to determine heat production from gamma-ray logs. Marine and Petroleum Geology, v. 13, 373–375.

Čermak, V., and Rybach, L., 1982, Thermal properties: Thermal conductivity and specific heat of minerals and rocks, *in* Angenheister, G., ed., Landolt-Börnstein, New Series, Geophysics and space research: Berlin, Springer, v. 1(A), p. 305–343.

Clauser, C., 2011, Thermal storage and transport properties of rocks, *in* Gupta, H., ed., Heat capacity and latent heat, Encyclopedia of Solid Earth´s Geophysics, 2nd ed., v. 2, p. 1423–1431.

Gradmann, S., Ebbing, J., and Fullea, J., 2013, Integrated Geophysical Modeling of Boundary Zone in Lithospheric Mantle under Norway and Sweden: Geophysical Journal International, v. 194, p. 1358–1373, doi:10.1093/gji/ggt213.

Hofmeister, A.M., 1999, Mantle values of thermal conductivity and the geotherm from phonon lifetimes: Science, v. 283, p. 1699–1706.

Jorde, K., Sigmond, E.M.O., and Thorsnes, T., 1995, Geologisk kart over Norge, berggrunnskart Stavanger: Norges geologiske undersøkelse, Trondheim, Norway, scale 1: 250 000, 1 sheet.

Juhlin, C., Wallroth, T., Smellie, J., et al., 1998, The Very Deep Hole Concept - Geoscientific appraisal of conditions at great depth: SKB Technical report 98-05, Svensk Kärnbränslehantering AB, Sweden, 124 p.

Lutro, O., and Nordgulen, Ø., 2008, Oslofeltet, berggrunnskart Oslo: Norges geologiske undersøkelse, Trondheim, Norway, scale 1: 250 000, 1 sheet.

Maystrenko, Y., Olesen, O., and Ebbing, J., 2013, Deep structure of the northern North Sea and adjacent areas according to regional-scale 3D density and thermal modeling: EGU General Assembly, memory stick: Geophysical Research Abstracts, v. 15, abstract EGU2013-2159.

Rybach, L., 1988, Determination of heat production rate, *in* Hänel, R., Rybach, L., Stegena, L., eds., Handbook of Terrestrial Heat-Flow Determination: Dordrecht, Kluwer Academic Publishers, p. 125–142.

Sass, J. H., Lachenbruch, A. H., Moses, T. H., Jr., and Morgan, T., 1992, Heat flow from a scientific research well at Cajon Pass, California: Journal of Geophysical Research, v. 97, p. 5017–5030.

Stratford, W., Thybo, H., Faleide, J.I., Olesen, O., Tryggvason, A., 2009, New Moho Map for onshore southern Norway: Geophysical Journal International, v. 178, p. 1755–1765, doi:10.1111/j.1365-246X.2009.04240.x.

Tullborg, E.-L., and Larson, S.Å., 2006, Porosity in crystalline rocks - A matter of scale: Engineering Geology, v. 84, p. 75–83.

van den Berg, A.P., Yuen, D.A., and Steinbach, V., 2001, The effects of variable thermal conductivity on mantle heat-transfer: Geophysical Research Letters, v. 28, p. 875–878.

Vosteen, H.-D., and Schellschmidt, R., 2003, Influence of temperature on thermal conductivity, thermal capacity, and thermal diffusivity for different types of rock: Physics and Chemistry of the Earth, v. 28, p. 499–509.

Wagner, W., and Kretzschmar, H.-J., 2008, International Steam Tables – Properties of Water and Steam Based on the Industrial Formulation IAPWS-IF97: Springer-Verlag, Berlin, 388 p.