Development of a numerical 3D geothermal model for Denmark

Niels Balling[1], Søren E. Poulsen[1,2], Sven Fuchs[1], Anders Mathiesen[3], Thue S. Bording[1], Søren B. Nielsen[1] and Lars H. Nielsen[3]

[1]Department of Geoscience, Aarhus University, Høegh–Guldbergs Gade 2, 8000, Aarhus C, Denmark

[2]VIA University College, Chr. M. Østergaards Vej 4, 8700 Horsens, Denmark

[3]Geological Survey of Denmark and Greenland, Ø. Voldgade 10, 1350 Copenhagen K, Denmark

niels.balling@geo.au.dk

Keywords: Regional subsurface thermal model, model construction, inverse parameter calibration, geothermal reservoirs, Denmark.

ABSTRACT

A regional 3D subsurface thermal model for Danish onshore areas is being developed. Structural and lithological information, data on rock thermal properties and current information on borehole temperatures and heat flow are integrated into a numerical model. By applying combined numerical forward modelling and inverse calibration methodology, model thermal parameters may be constrained to ensure consistency between temperature predictions and measured borehole temperatures. Some first results are presented and discussed including temperatures of potential geothermal reservoirs. Geothermal gradients across the country broadly range between 20 and 35 °C/km depending on location and depth. Variations are found to be largely due to differences in thermal conductivity between lithological units. In large parts of the country, sandstone reservoirs are found at depths and temperatures suitable for exploitation of low enthalpy geothermal resources. Thermal models, like the present, facilitate risk reduction in regional and local geothermal exploration, and model results are easily integrated into web-based platforms to provide information on subsurface geothermal conditions to a broader public.

1. INTRODUCTION

Subsurface thermal information is essential for the study and interpretation of many geoscience and technological problems, such as crustal dynamics, mapping and characterization of geothermal resources, formation and migration of hydrocarbons and thermal energy storage. Subsurface thermal information is basically obtained from two different sources: direct observations by measurements in boreholes and indirectly by numerical modelling.

Most of the Danish subsurface is characterized by thick successions of sedimentary rocks (e.g. Nielsen and Japsen, 1991). Geothermal research directed towards potential geothermal reservoirs has a relatively long history and has resulted in localization and characterization of a number of reservoir units, mostly sandstones, suitable for exploitation of low enthalpy geothermal energy (e.g. Balling and Saxov, 1978; Nielsen et al. 2004; Mathiesen et al. 2009). Three geothermal plants are in operation in Denmark, producing warm water for district heating purposes (Mahler et al. 2013; Røgen et al. 2015).

In this paper, a brief outline is given on main elements in the development of a numerical 3D subsurface thermal model for Danish onshore areas with some examples of first results. Model generation has been carried out as part of a national multi-disciplinary geothermal research project aiming at providing up-to-date knowledge of the geothermal energy potential and prospects of utilization. More information on model construction, as well as further results, is given in Poulsen et al. (2016).

2. GEOLOGICAL SETTING

Information about the deep subsurface geology in Denmark mainly originates from hydrocarbon exploration activities. Although with a highly uneven distribution, seismic reflection profiles and exploration wells cover most of the Danish areas. Combined with results of crustal seismological studies, these data provide knowledge on the regional structural setting as well as spatial distribution and lithology of main sedimentary units.

The Danish subsurface consists of five major structural elements (largely from north to south): the Skagerrak–Kattegat Platform, the Sorgenfrei–Tornquist Zone, the Danish Basin, the Ringkøbing–Fyn High, and the North German Basin (Fig. 1). The sedimentary basins contain Palaeozoic, Mesozoic and Cenozoic sedimentary successions of up to 5–10 km in total thickness. This is in contrast to sedimentary thicknesses of 1–2 km, and less, in areas of shallow basement highs (the Ringkøbing–Fyn High and Skagerrak–Kattegat Platform; cf. section 4.1 and Fig. 2). For most of the areas shown in Fig. 1, the crystalline basement consists of Meso– and Palaeoproterozoic Baltica crust, with only the southernmost part formed by Caledonian/Avalonian crust (Lassen and Thybo, 2012; Balling, 2013; Olivarius et al. 2015).

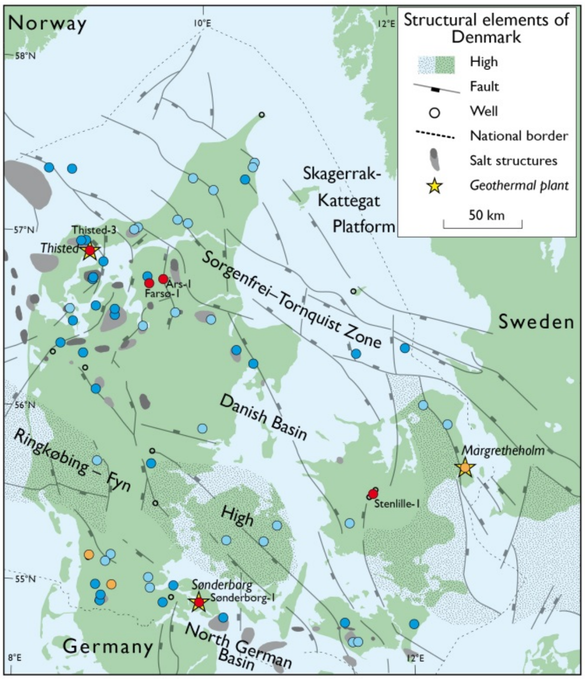

Figure 1: Map showing main structural elements of Denmark and locations of deep wells with stratigraphic and temperature information. Read circles indicate wells with accurate equilibrium temperature logs; orange, wells with formation test temperatures; dark blue, wells with corrected bottom-hole temperatures (BHT; equilibrium estimates); light blue, wells with uncorrected BHTs (only minimum temperature estimates); small open circles, wells with no temperature information. Also shown are locations of geothermal heating plants (Thisted, Margretheholm and Sønderborg). Structural cross-sections are shown in Fig. 2 and temperature-depth plots in Fig. 4.

The above main structural differences, with deep basins and structural highs, play an important part in determining the distribution, thicknesses, facies types and burial depths of sedimentary units including the potential geothermal reservoirs (Nielsen, 2003; Nielsen et al. 2004).

In particular five lithological units are found to contain geothermal reservoirs: the Lower to Upper Triassic Bunter Sandstone and Skagerrak Formations, the Upper Triassic–Lower Jurassic Gassum Formation, the Middle Jurassic Haldager Sand Formation, and the Upper Jurassic–Lower Cretaceous Frederikshavn Formation. These formations contain sandstones of potential reservoir quality (Mathiesen et al. 2009).

3. METHODOLOGY

The heat equation describes the transport of heat and variation of temperature in a given region. For a subsurface volume, it defines a link between temperature and petrophysical properties. A fundamental element in model generation is solving the heat equation. Focussing on thermal conduction (no mass transfer) this equation reads:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + H$$

where T is temperature, t is time, ρ is density, c is specific heat capacity, k is thermal conductivity, H is the rate of heat generation, and (x, y, z) are the three spatial variables.

Important input data comprise information on rock thermal properties, background heat flow as well as measured borehole temperatures. This information is integrated into a detailed 3D structural model. Borehole temperatures are included as data by applying an inverse parameter calibration procedure. Such model optimization procedures are generally not applied in regional subsurface thermal modelling studies, but are well known in groundwater modelling (e.g. Hill and Tiedeman, 2007) and are found to be of great value.

Various numerical procedures exist for solving the heat equation. For the model examples presented here, a modified version of the groundwater flow code MODFLOW was applied. This is a finite difference code developed by U.S. Geological Survey (Harbaugh, 2005). Applying this thoroughly tested and flexible code is possible due to the mathematical similarity between groundwater flow (Darcy's law) and heat flow (Fourier's law). Application of the finite-element modelling software FEFLOW (Diersch, 2014) is similarly well suited for this type of problem (cf. Fuchs and Balling, 2016a,b).

Inverse parameter calibration was carried out with the universal parameter estimation software PEST (Doherty, 2010). Here a Gauss-Marquardt-Levenberg algorithm is implemented to minimize an objective function comprised of a weighted sum of the squared differences between modelled and measured temperatures (cf. Poulsen et al. 2016). Thermal conductivity of the various geological units is the main model calibration parameter to be adjusted.

In the present models, for computational resource reasons, modelling was carried out in two steps. The first phase, including full 3D steady-state numerical solutions of the heat equation, is followed by the superposition of a point-wise 1D transient model to account for a long-term palaeoclimatically induced thermal perturbation of the upper subsurface layers (see below).

4. MODEL CONSTRUCTION

The main elements of model construction include defining a suitable structural geological model followed by quantification of model parameter values. Furthermore, as observed borehole temperatures are integrated into the thermal model as model constraints, this information has to be included as well as a heat flow boundary condition.

4.1 A 3D structural geological model

The regional subsurface mapping of the Danish area carried out by the Geological Survey of Denmark and Greenland (GEUS) is based on interpretation of all available seismic data and information from deep wells. The seismic data are mainly 2D transects of different age and quality and with highly variable density across the country.

By integrating information from all available regional seismic horizons, including those outlined in Mathiesen et al. (2009), and additional horizons interpreted and mapped for the present purpose, a comprehensive 3D digital structural model has been produced (Fig. 2). The deepest observed seismic reflector of regional coverage is the Top Pre-Zechstein horizon (Vejbæk and Britze, 1994). For deeper layers, information is available from different sources, including Lassen and Thybo (2012). Above the crystalline basement a total of 13 lithological units are included which, together with the basement, are defined as model layers.

Seismic resolution is highly variable, in several areas with a limit around 50 ms, corresponding to c. 50–75 m, depending on seismic velocities. In areas were the seismic units are below seismic resolution, information from nearby wells was used to estimate thickness of layers. Where not locally constrained by accurate well information, the mapped and depth-converted horizons are estimated to have an uncertainty between 5 and 15 %, generally increasing with depth. The regional seismic horizons were interpolated to a regular 2000 by 2000 m grid.

The model includes the spatial distribution, burial depth and thickness of formations containing geothermal reservoirs. Among the formations of special interest is the Gassum Formation which is present in large areas at depths (Fig. 3) and temperatures (section 6.4) suitable for exploration. The thickness of the formation is generally within the range of 50–300 m and it typically contains several successions of reservoir sandstones.

4.2 Model parameterization

The individual model units (the lithological layers), must be ascribed characteristic physical properties. The properties in question are those included in the heat equation (ρc, k, H). For a steady-state model, information on rock thermal conductivity (k) and heat generation (H) is needed. For modelling including transient elements, also information on volumetric heat capacity (ρc) is required.

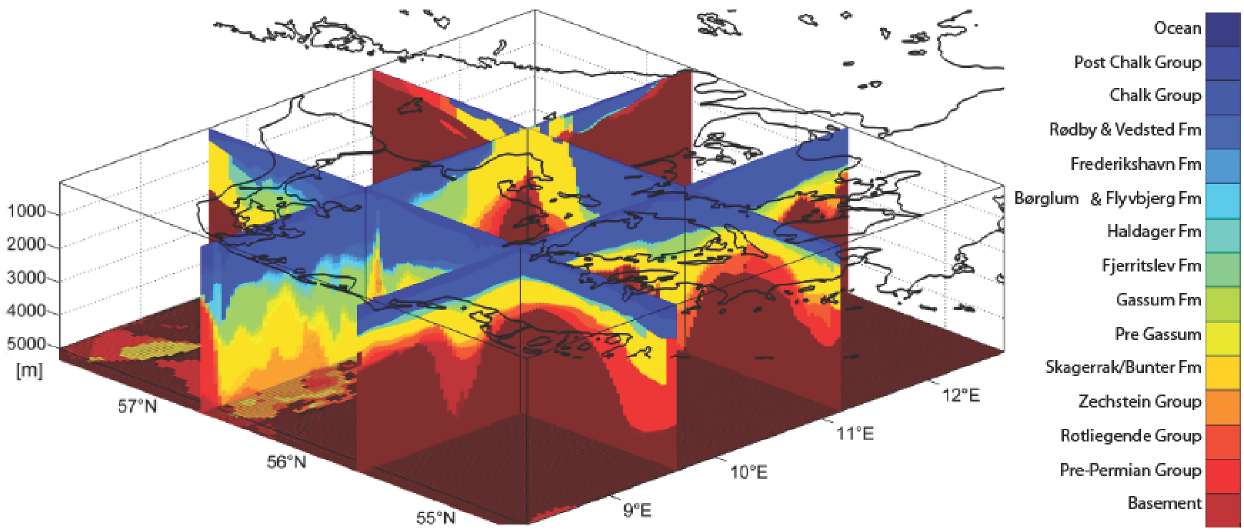

Figure 2: The 3D structural model covering onshore Denmark, illustrated by two north-south and two east-west cross-sections. Deep basins and structural basement highs are clearly recognized (cf. Fig. 1). Main lithological units (indicated), represented as model layers, are assigned characteristic petrophysical properties. Potential geothermal reservoirs are found within the Frederikshavn, Haldager, Gassum, Skagerrak and Bunter Formations. (For stratigrafic reference, the Chalk Group and Rødby/Vedsted Formations are Cretaceous; the Frederikshavn Formation is Lower Cretaceous–Upper Jurassic; the Gassum Fomation is Lower Jurassic–Upper Triassic, and the Skagerrak/Bunter Formations extends over most of the Triassic period. For further details, see Mathiesen et al. 2009).

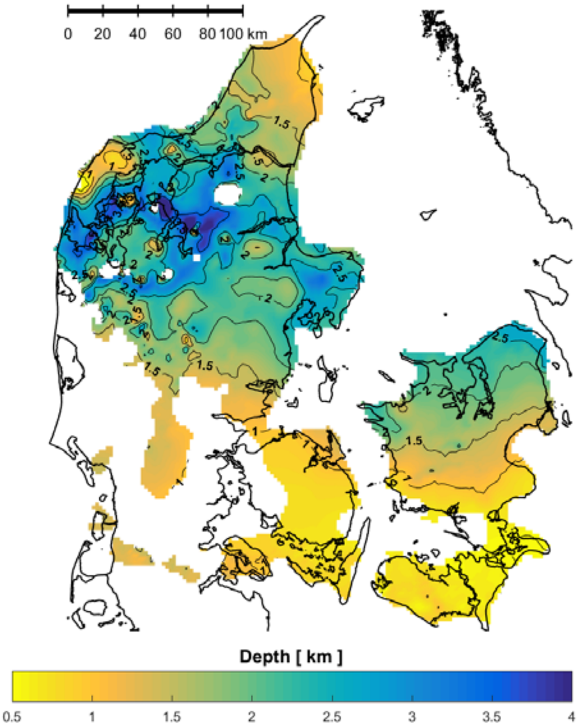

Figure 3: Map showing depth to the Gassum geothermal reservoir. Mid-formation depth and areas of interpreted thickness of more than 20 m.

Thermal conductivity is defined by characteristic matrix values for individual lithological units and calculated from exponential porosity-depth relations using the geometric mean formula. Temperature and pressure dependence on conductivity is included. Even if thermal conductivity is treated as a calibration parameter, it is of critical importance that a reliable range of variation is quantified (cf. Fuchs and Balling, 2016a). Current estimates are based on a combination of information from laboratory core measurements, calculations from temperature logs and lithological information. Heat production is estimated based on measured radiogenic isotope concentrations for different lithological units (Balling et al. 1981).

To account for lateral variations in rock matrix thermal conductivity (facies variations; generally more sandy lithologies in north-eastern areas etc.), some geographical subdivision of layers was introduces. Rock matrix thermal conductivity varies between 1.5-2 W/m/K for units dominated by clay and claystone and about 6 W/m/K for quartz-rich sandstone.

The climatic effects were accounted for by point-wise 1D transient thermal modelling using constant matrix values for density and specific heat capacity (2650 kg/m^3 and 840 J/kg/K, respectively) for all layers. Further information on model parameterization and values of parameters is given in Poulsen et al. (2016).

4.3 Borehole temperatures and heat flow

Subsurface temperature data are available from different sources: Densely spaced accurate equilibrium temperature logs (five deep wells; measurements by the present research group), industrial bottom-hole temperatures (Poulsen et al. 2012, 2013) and a few additional temperatures measured during reservoir tests. Positions of wells, with type of data information, are indicated in Fig. 1, and temperature-depth plots are shown in Fig. 4. Temperature gradients generally vary between 20 and 35 °C/km depending on location and depth.

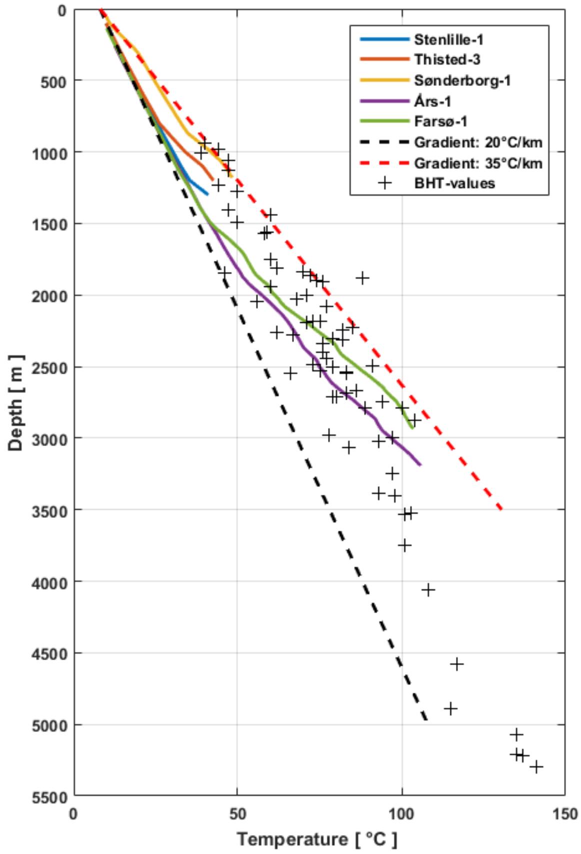

Figure 4: Subsurface temperature information from onshore Denmark. Accurate equilibrium temperature logs (five deep wells, locations in Fig. 1) and bottom hole temperatures (BHTs); here only values corrected to equilibrium estimates. Temperature gradients are within the approximate range of 20-35 °C/km. These data are integrated into the thermal model serving as model parameter constraints.

In model calibration, the temperature data are assigned different weights reflecting their individual accuracy in terms of estimated standard deviation (varying from less than 1°C for equilibrium temperature logs to typically around 3–5°C for corrected BHT-data, locally up to about 10°C).

Information on heat flow is a highly important boundary constraint for solving the heat equation. In the Danish area, below the depth of significant palaeoclimatic perturbations, terrestrial heat flow seems to show only minor variations at around 70–75 mW/m^2 (Balling, 1992; 2013). Considering the contribution from radiogenic heat production from the uppermost layers, background heat flow at 5000 m depth (current lower model boundary) is estimated at c. 65 mW/m^2, and this value defines the lower boundary condition.

The upper boundary, at Earth surface, is a temperature boundary. By superimposing the 3D steady-state temperature field modelled for a fixed surface temperature (below zero) with the point-wise 1D transient temperature profiles, we achieve consistency between observed temperatures and temperature gradients also in the shallow subsurface. The transient model includes long-period surface climatic temperature variations for the past c. 200.000 years. For the temperature difference between last glacial maximum, c. 20.000 years before present, and postglacial times, a relatively high value of 15°C is applied (cf. discussion below)

5. MODEL RESULTS

The thermal model provides information on model temperature at densely spaced subsurface grid points (horizontal distance, 2500 m by 2500 m, and vertical distance, 10 m) covering Danish onshore areas down to a depth of 5000 m.

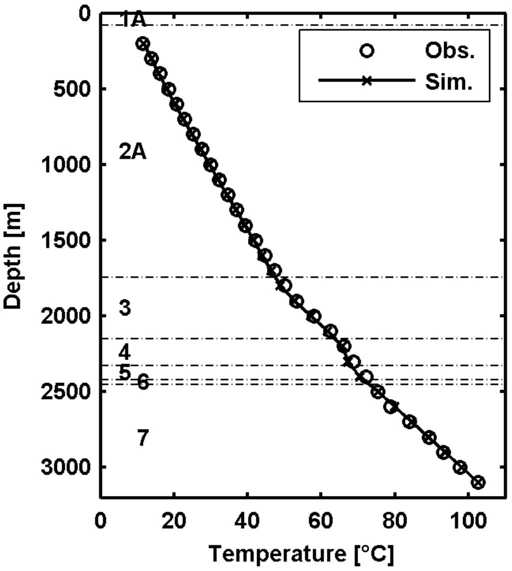

Fig.5. Comparison of measured temperatures and model simulated values for the deep well Års-1. Numbers indicate different model lithological units. Unit 2A represents the thick Chalk Group (Cretaceous carbonates) with relatively low temperature gradients, and unit 7 is the Lower Jurassic Fjerritslev Formation of low thermal conductivity and associated high temperature gradients.

Model results may be presented as temperature-depth profiles at any selected location of interest, as temperature maps for selected constant depth or for specified geological horizons, such as potential geothermal reservoirs. For illustration, such results are shown in Figs. 5–7. Also model cross-sections may be extracted.

An assessment of the model quality may be obtained by comparing measured equilibrium temperatures with temperature predictions. For all five wells of equilibrium temperature logs (Figs. 1 and 4), the agreement between observed and predicted temperatures is very good and similar to that shown in Fig. 5 for the deep Års-1 well. Differences between modelled and measured temperatures are generally within 1–2°C and with a maximum of 4°C. Achieving this agreement requires that vertical variations in temperature gradients associated with differences in thermal conductivity between lithological units be well resolved.

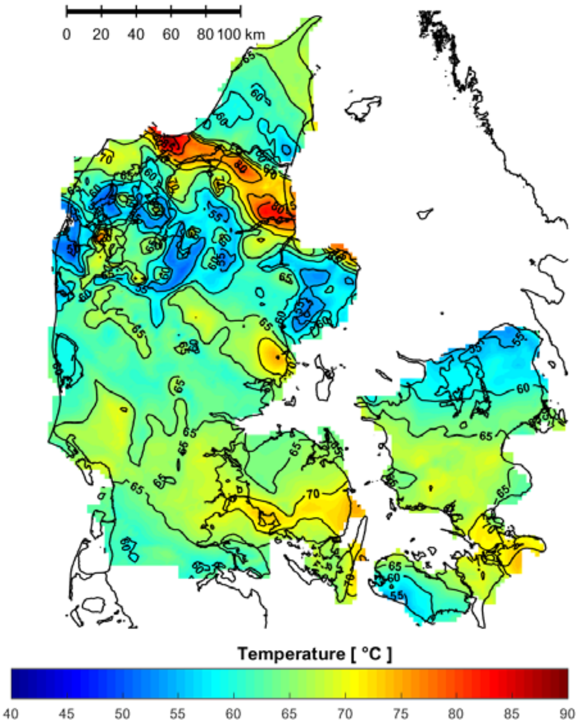

Figure 6: Model temperatures for the constant depth of 2000 m.

Due to the general significant reduction in porosity and permeability of potential geothermal reservoirs with increasing depth (Mathiesen et al. 2009; Weibel et al. 2016), the main geothermal exploration interest is currently limited to depths of up to 2500–3000 m. The modelled temperature field for the constant depths of 2000 m (Fig. 6) shows a temperature range of 55–85°C, with large areas at around 60–65°C. For the deeper level of 3000 m, temperatures of 85–120°C are predicted. Mean temperature gradients from surface to depths of 2000–3000 m are typically within the range of 25–30 °C/km, locally up to about 35 °C/km, in good agreement with observations (Fig. 4).

For the Gassum reservoir (Fig. 7), characteristic temperatures range from about 40–55°C, at 1000–1500 m depth, to about 80–110°C at its deeper levels of around 2500–3500 m (central and northern part of

Danish Basin). Reservoir temperature differences are mainly related to large differences in burial depth (Fig. 3), but lateral variations in thermal conductivity also play an important part.

The northwestern basin areas are characterized by many salt structures. Reservoir formations, including the Gassum reservoir, may be elevated above salt pillows or deposited in deep rim synclines, resulting in large depth and temperature variations over small distances (Figs. 1, 3 and 7). Furthermore, local temperature anomalies, both positive and negative, are generated by the salt structures due to the higher thermal conductivity of rock salt compared with that of the surrounding sediments (Balling et al. 1981; Jensen, 1990).

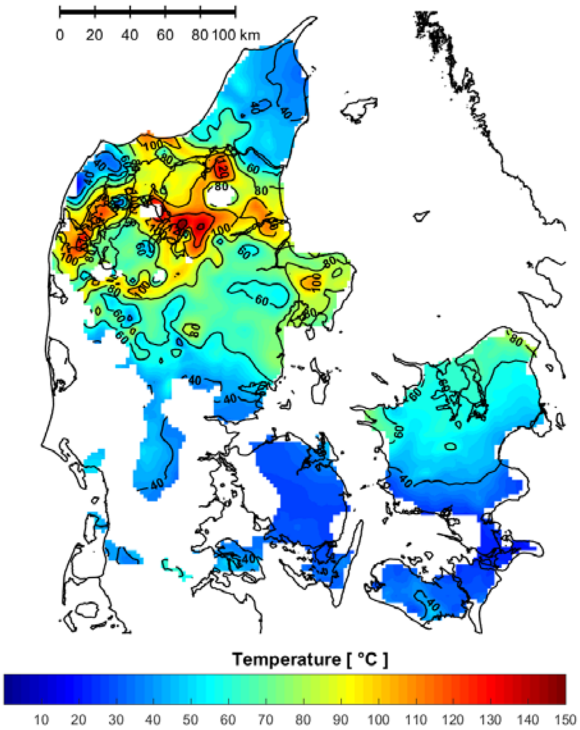

Figure 7: Model temperatures for the Gassum geothermal reservoir (mid-formation level, cf. Fig. 3).

6 DISCUSSION

6.1 Model accuracy

As noted above, a very good agreement is obtained between predicted and measured temperatures (Fig. 5). Although the model is calibrated by applying these temperature data, it does not apply to layer thermal conductivity locally at individual sites, but regionally over larger areas. Still, with increased distances from and beyond the depth of wells with temperature logs, accuracy will decrease. From detailed model uncertainty analysis (Poulsen et al. 2016), general model temperature uncertainty at specified depths is estimated at 5–10%. If uncertainty in depth (e.g. to a geothermal reservoir) is added, temperature uncertainty will increase accordingly.

6.2 Comparison with previous models

Previous regional subsurface thermal models for the Danish area (e.g. Balling et al. 1981; 2002) were generated from a layered model using a grid of densely spaced 1D steady-state forward solutions. The present thermal model, being 3D with combined forward and inverse calibration modelling, and based on a more detailed structural geological model, represents significant improvements.

A comparison of model results reveals similar main temperature levels and main trends of anomalies. The present model generally shows additional details and higher temperature anomalies. Differences are observed particularly in areas of local complex structures, such as around salt structures and close to structural boundaries. In some areas, the present model shows up to 10–20°C higher temperatures at depths of 2000–3000 m.

6.3 Temperature variations

Temperature observations from deep wells and modelling results consistently show marked differences in mean geothermal gradients. Significant temperature variations are observed at any selected constant depth as illustrated by Fig. 6. As a constant lower boundary heat flow is applied (65 mW/m^2 at 5000 m, cf. above), any marked local temperature anomalies as well as regional temperature variations almost entirely originate from lateral variations in thermal conductivity. Differences in radiogenic heat production play a very minor role.

Relatively high temperatures and high mean temperature gradients are predicted for NW–SE trending zones in the northern and deeper parts of the Danish Basin. This is explained by thick successions of Lower Cretaceous – Jurassic clay-rich formations of low thermal conductivity. For the Lower Jurassic Fjerritslev Formation, high resolution temperature logs show local temperature gradients of 5–6 °C/100 m (Fig. 5; Balling and Bording, 2013). The lower temperatures and temperature gradients are found in areas of thick limestones and/or sandy lithologies of relatively high thermal conductivity.

6.4 Geothermal reservoirs

Of special interest are the Gassum, the Bunter and the Skagerrak sandstone reservoirs, with large regional coverage across the Danish area (Fig. 3; Mathiesen et al. 2009; Kristensen et al. 2016; Olivarius and Nielsen 2016). Currently being exploited, the Gassum and the Bunter sandstone reservoirs have demonstrated production quality. At the geothermal plant at Thisted (north-western Danish Basin, Fig. 1) warm water is being extracted from the Gassum reservoir, locally elevated above a salt pillow (depth, c. 1250 m; temperature, 44°C; capacity, 7 MW). Also at the heating plant at Sønderborg (northern part of North German Basin, Fig. 1), production is from the Gassum reservoir (depth, c. 1150 m; temperature, 48°C; capacity, 12 MW). In the Copenhagen area, at the

Margretheholm geothermal plant, sufficient productivity is found in the deeper Triassic Bunter sandstone reservoir (depth, c. 2550 m; temperature, 73°C; capacity, 14 MW). All geothermal plants are of the doublet type with combined production and reinjection and energy production for district heating purposes (Mahler et al. 2013; Røgen et al. 2015).

Most geothermal reservoirs are subject to marked variations in burial depth (Figs. 2 and 3) and large variations in temperature. At the deeper levels, towards 3000 m, and at temperatures of around 90–100°C, compaction and diagenetic processes seem to result in porosity and permeability mostly too low for production (Kristensen et al. 2016; Weibel et al. 2016). This result was also the outcome of Gassum reservoir production tests at about 3000 m depths in the deep geothermal exploration wells Års-1 and Farsø-1 (Fig. 1). The possibilities and potential of reservoir stimulation have so far not been tested.

The Gassum reservoir is present in large areas at depths of around 1000–2500 m (northern and central Jutland and most of Zealand, including the Copenhagen area) with temperatures at 40–80°C (Figs. 3 and 7). In the southern part of the country (Ringkøbing-Fyn High and the northern part of the North German Basin), this reservoir is generally either absent, thin or present at shallow depth with low temperatures.

The Skagerrak reservoir, present in the northern and central part of the Danish Basin, has large depth and thickness variations and seems generally too deep for exploitation with current technology. The Bunter sandstone reservoir has a large regional coverage in the southern and south-eastern parts of the country at depths (c. 1300–2500 m) and model temperatures (range 45–75 °C) of interest for exploitation.

6.5 Palaeoclimatic effect

Observed temperature gradients and heat flow in upper layers are lower than might be expected. Information from heat-flow determinations in shallow and deep boreholes in the Danish Basin (Northern Jutland) shows a marked increase in heat flow with depth, from c. 30–40 mW/m^2 at shallow depths (100–400 m) to 70–75 mW/m^2 at depths of about 2000 m and below (Balling, 1992; 2013: Fig. 5.9). From a recent regional analysis of shallow temperature gradients and associated thermal conductivity, similar low characteristic shallow heat flow is obtained for the country as a whole (Møller et al. 2016).

This increase of heat flow with depth is interpreted as due to long-term palaeoclimatic surface temperature variations, of which the increase of temperature from last glacial maximum to post-glacial times plays an important part. The relatively high temperature rise of 15°C applied here, yields good agreement between observed heat flow and temperature gradients at shallow depth (example in Fig. 5). Our model is approximate in terms of not including latent heat (freezing and melting processes). Including this effect is likely to reduce somewhat the required surface temperature increase (cf. model results in Mottaghy and Rath, 2006).

6.6 Further model development

The present first model results present very good agreement between temperature predictions and observed borehole temperatures. However, potential for improvements exists, and further model development is in progress. Project co-workers at GEUS are about to finish a comprehensive reinterpretation of all available reflection seismic surveys, a project which will provide new, more accurate depth and thickness data for main lithological units to be integrated into the structural geological model.

Furthermore, high resolution records of rock thermal properties are currently been calculated from petrophysical well-log data for most onshore wells using the procedure of Fuchs et al. (2015). These data will provide more detailed information on the thermal conductivity parameter, including a better resolution of lateral variations. As shown by Fuchs and Balling (2016a,b), the thermal conductivity parameterization is of special importance. Better constraints on thermal conductivity may also reveal some lateral variation in background crustal heat flow.

7 CONCLUSIONS

A model construction procedure has been applied, which allows for integrating detailed structural geological information, rock thermal properties and borehole temperatures into a regional numerical 3D subsurface thermal model. The heat equation has been solved by applying combined numerical forward solution and inverse calibration methodology.

Model thermal parameters are constrained, and the model is optimized to ensure consistency between predicted temperatures and measured borehole temperatures within their uncertainty limits. As the available borehole temperature data often are of highly variable quality (equilibrium temperature logs, corrected and uncorrected BHTs etc.), different weights are applied to individual temperature data.

This methodology is applied to the Danish onshore areas, and examples of first results are presented and discussed. The thermal model includes depth and thickness of main lithological units and temperature predictions in a densely spaced 3D grid of subsurface points, thereby providing easily accessible information on the subsurface thermal field. Temperature information may be extracted in terms of temperature-depth profiles, temperature maps for a selected constant depth, for specified geological horizons or layers, such as potential geothermal reservoirs or as model cross-sections.

Such models improve our understanding of the subsurface thermal field, including sources of temperature variations and anomalies, and facilitate risk reduction in regional and local geothermal exploration. Furthermore, model results are easily integrated into any flexible subsurface web-based platform to provide information on subsurface geothermal conditions to a broader public (cf. http://DybGeotermi.geus.dk).

REFERENCES

Balling, N.: Denmark. In: Hurtig, E., Haenel, R. and Zui, V. (Eds.). Geothermal Atlas of Europe, (1992), 25-28, *Hermann Haack, Gotha*, Germany.

Balling, N.: The Lithosphere beneath Northern Europe: Structure and Evolution over Three Billion Years. Contributions from Geophysical Studies, Doctoral dissertation, *Aarhus University*. ISBN 9788790400620, (2013), 195 pp.

Balling, N., Bording, T.S.: Temperatur, temperaturgradienter og varmeledningsevne i den geotermiske boring Sønderborg-1/1A, Research report, *Department of Geoscience, Aarhus University*, (2013) 16 pp.

Balling, N. and Saxov, S.: Low enthalpy geothermal resources in Denmark, *Pure and Applied Geophysics*, **117**, (1978), 205-212.

Balling, N., Hvid, J.M., Mahler, A., Møller, J.J., Mathiesen, A., Bidstrup, T. and Nielsen, L.H.: Denmark. In: Hurter, S. and Haenel, R. (Eds.), Atlas of Geothermal Resources in Europe. Publication No. EUR 17811, *The European Commission*, 27-28 and plates, (2002), 15-16.

Balling, N., Kristiansen, J., Breiner, N., Poulsen, K.D., Rasmussen, R. and Saxov, S.: Geothermal Measurements and Subsurface Temperature Modelling in Denmark, *GeoSkrifter*, **16**, *Aarhus University*, (1981), 172 pp.

Diersch, H.-J.: FEFLOW - Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media, *Springer*, (2014), 996 p.

Doherty, J.: PEST - Model independent parameter estimation, User Manual. 5th Edition, *http://www.sspa.com/pest/download/pestman.pdf,* (2010).

Fuchs, S. and Balling, N.: Improving the temperature predictions of subsurface thermal models by using high-quality input data. Part 1: Uncertainty analysis of the thermal-conductivity parameterization, *Geothermics*, **64**, (2016a), 42-54.

Fuchs, S. and Balling, N.: Improving the temperature predictions of thermal models by using high-quality input data. Part 2: A case study from the Danish–German border region, *Geothermics*, **64**, (2016b), 1-14.

Fuchs, S., Balling, N. and Förster, A.: Calculation of thermal conductivity, thermal diffusivity and specific heat capacity of sedimentary rocks using petrophysical well logs, *Geophysical Journal International*, **203**, (2015), 1977-2000.

Harbaugh, A.W.: MODFLOW-2005, the U.S. Geological Survey modular ground-water model – the Ground-Water Flow Process, *U.S. Geological Survey Techniques and Methods,* **6-A16, (**2005).

Hill, M.C. and Tiedeman, C.R.: Effective Groundwater Model Calibration: With analysis of data, sensitivities, predictions and uncertainty. *John Wiley & Sons*, New York, (2007), 455 pp.

Jensen, P.K.: Analysis of the temperature field around salt diapirs. *Geothermics*, **19**, (1990), 273-283.

Kristensen, L., Hjuler, M.L., Frykman, P., Olivarius, M., Weibel, R., Nielsen, L.H., and Mathiesen, A.: Pre-drilling assessments of average porosity and permeability in the geothermal reservoirs of the Danish area, *Geothermal Energy*, **4, (**2016), DOI 10.1186/s40517-016-0048-6.

Lassen, A. and Thybo, H.: Neoproterozoic and Palaeozoic evolution of SW Scandinavia based on integrated seismic interpretation, *Precambrian Research*, **204–205**, (2012), 75-104.

Mahler, A., Røgen, B., Ditlefsen, C., Nielsen, L.H., Vangkilde-Pedersen, T.: Geothermal Energy Use, Country Update for Denmark, *Proceedings European Geothermal Congress 2013*, Pisa, Italy (2013).

Mathiesen, A., Kristensen, L., Bidstrup, T. and Nielsen, L.H.: Vurdering af det geotermiske potentiale i Danmark, *Geological Survey of Denmark and Greenland*, *Report* **59**, (2009), 30 pp and appendix.

Mottaghy, D. and Rath, V.: Latent heat effects in subsurface heat transport modelling and their impact on palaeotemperature reconstructions, *Geophysical Journal International*, **164**, (2006), 236-243.

Møller, I., Balling, N, Rasmussen, P. and Ditlefsen, C.: Regional shallow heat flow in Denmark from borehole temperatures and thermal conductivities of main lithologies. *Proceedings European Geothermal Congress 2016*, Strasbourg, France, (2016).

Nielsen, L.H.: Late Triassic–Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, J.R and Surlyk, F. (Eds): The Jurassic of Denmark and Greenland, *Geological Survey of Denmark and Greenland Bulletin*, **1**, (2003), 459-526.

Nielsen, L.H. and Japsen, P.: Deep wells in Denmark 1935–1990. Lithostratigraphic subdivision. *Geological Survey of Denmark, Series* A **31**, (1991), 179 pp.

Nielsen, L.H., Mathiesen, A. and Bidstrup, T.: Geothermal energy in Denmark. *Review of Survey activities 2003, Geological Survey of Denmark and Greenland Bulletin*, **4**, (2004), 17-20.

Olivarius, M. and Nielsen, L.H.: Triassic paleogeography of the greater eastern Norwegian-Danish Basin: constraints from provenance analysis of the Skagerrak Formation, *Marine and Petroleum Geology,* ***69***, (2016), 168-182.

Olivarius, M., Friis, H., Kokfelt, T.F. and Wilson, J.R.: Proterozoic basement and Palaeozoic sediments in the Ringkøbing–Fyn High characterized by zircon U–Pb ages and heavy minerals from Danish onshore wells. *Bulletin of the Geological Society of Denmark*, **63**, (2015), 29-44.

Poulsen, S.E., Balling, N., Bording, T.S., Mathiesen, A. and Nielsen, S.B.: Regional-scale subsurface temperature modelling with inverse calibration methodology: application to Danish sedimentary basins. *Geothermics*, (2016), submitted.

Poulsen, S.E., Balling, N., Nielsen, S.B.: Analysis of bottom hole temperatures on- and nearshore Denmark, Research report, *Department of Geoscience, Aarhus University*, (2013), 23 pp.

Poulsen, S.E., Nielsen, S.B. and Balling, N.: Estimation of the equilibrium formation temperature in the presence of bore fluid invasion, *Geophysical Journal International*, **190**, (2012), 1551-1561.

Røgen, B., Ditlefsen, C., Vangkilde-Pedersen, T., Nielsen, L.H. and Mahler, A.: Geothermal Energy Use, 2015 Country Update for Denmark, *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, (2015).

Vejbæk, O.V. and Britze, P.: Geological map of Denmark 1:750.000. Top pre-Zechstein (two-way traveltime and depth). *Geological Survey of Denmark, Map Series* **45**, (1994), 8 pp.

Weibel, R., Olivarius, M., Kristensen, L., Friis, H., Hjuler, M.L., Kjøller, C., Mathiesen, A. and Nielsen, L.H.: Predicting permeability of low enthalpy geothermal reservoirs: A case study from the Upper Triassic–Lower Jurassic Gassum Formation, Norwegian–Danish Basin. *Geothermics*, (2016), submitted.

Acknowledgements

This study was carried out within the framework of a national geothermal energy project supported by the Danish Council for Strategic Research (project 2104-09-0082).