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Improving the temperature predictions of subsurface thermal models by using high-quality input data. Part 2: A case study from the Danish-German border region

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ABSTRACT

We present a 3D numerical crustal temperature model and analyse the present-day conductive thermal field of the Danish-German border region. The model region covers the northernmost part of the North German Basin, a transition zone between the deep-reaching sedimentary rocks of the Glückstadt Graben (including complex salt structures) and the shallow crystalline basement of the Ringkøbing-Fyn High. The modelling approach is novel as it implements for the first time a comprehensive analysis of well-log data on a regional modelling scale. Those logs were used both to derive the spatial distribution of rock thermal conductivity across the study area, and to calculate heat flow values. New values of terrestrial surface heat flow are reported for eight deep boreholes in the North German Basin ranging from 72 to 84 mW/m^2 with a mean of 80 ± 5 mW/m^2. The values are computed from continuous temperature logs, carefully corrected BHT values, drill-stem tests and well-log derived rock thermal properties (thermal conductivity, radiogenic heat production) and were included in the setup of the numerical lower boundary conditions. New surface heat flow is up to 20 mW/m^2 higher than low values reported in some previous studies for this region. Heat flow from the mantle is 33–40 mW/m^2.

The model temperature predictions are validated against 59 temperature observations from 24 wells. The prediction uncertainties between observed and modelled temperatures at deep borehole sites are small (rms = 3.5 °C, ame = 2.1 °C). Pronounced lateral temperature variations are predicted and found to be caused mainly by complex geological structures, including a large amount of salt structures and marked lateral variations in the thickness of basin sediments. The associated variations in rock thermal conductivity generate significant variations in model heat flow and large variations in temperature gradients.

With regard to the utilization of geothermal energy, the Rhaetian and the Middle Buntsandstein sandstone reservoirs are found with temperatures within the range of 40–80 °C, suitable for low enthalpy heating purposes, in most of the area and locally also with higher temperatures. Temperatures above 120 °C, of interest for the production of electricity, are observed only in the very southeastern part of the study area.

1. Introduction

Well-constrained thermal models are important for the examination of the subsurface thermal structure and thus the geothermal resources of a region. In border regions like the Danish-German, located close to the northern margin of the North German Basin (NGB), such models can help to manage geothermal resources and to prevent conflicts of use between the wide range of possible subsurface applications that are technologically or economically affected by the thermal field (e.g. energy resources like geothermal heat or hydrocarbons, geological storage of energy or waste). Information on the geological structure, the configuration of the rock thermal properties and reliable boundary conditions are paramount for the setup of thermal models. While structural information are usually obtained from seismic analysis and borehole data, representative values of rock thermal properties for structural units are often taken over directly from previous modelling stud-

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ies or from literature. The latter fact generally implements large uncertainties in modelling studies.

In part one of this study (Fuchs and Balling, 2016; this issue), we demonstrated the importance of a high-quality thermal-conductivity (TC) parameterization on the uncertainty of predicted temperature in sedimentary basin models. We have demonstrated that a significant uncertainty reduction can be achieved (1) by using TC values determined from the analysis of lithological bore logs or even better from geophysical well logs instead of implementing literature values, and (2) by considering the spatial TC variability within modelled formations instead of using constant formation values. Considering both aspects resulted in a reduction of uncertainties of modelled temperatures by up to 80%.

In the present paper (part 2), we apply the findings of the first part and assess, in detail, the regional thermal field of the Danish-German border region. We present results from a 3D numerical thermal model which is developed to study the influences of the subsurface geological variability on the temperature field, in particular for the onshore zone between the crystalline basement high of the *Ringkøbing-Fyn High* (southern Jutland) and the northern part of the *Glückstadt Graben (Northernmost Germany)* area that is dominated by complex salt structures. New data on present-day surface heat flow (physically: heat-flow density) are presented and implemented in the verification of our 3D conductive thermal model. Modelled temperatures are compared with temperatures measured in boreholes. The final aim of this study is to generate a full 3D subsurface geothermal model and present new temperature maps for geological formations that are proper targets for geothermal exploration (e.g. Rhaetian/Gassum Formation and Middle Buntsandstein) as well as for selected constant depths levels (1 km, 2 km, etc.).

2. Study area and geological setting

The study area comprises the regions of Southern Jutland (Denmark), Schleswig-Holstein (northernmost Germany) and minor costal parts of the North Sea and of the Baltic Sea. It covers an area of *c.* 14,000 km^2 (roughly 115 × 130 km) and is located at the northern margin of the NGB, which is a part of the Central European Basin System (CEBS) (Fig. 1).

The NGB usually comprises up to, and locally more than 10 km sediments of Paleozoic, Mesozoic and Cenozoic age. The largest thickness (>12 km) is located in the central part of the *Glückstadt Graben*. The regional geology can be subdivided into five main elements: the *Westschleswig Block* in the northwestern part, the *Ostholstein-Westmecklenburg-Block* in the eastern part, the *Glückstadt Graben* area in the southeastern part and the NW–SE trending Tønder Graben and *Ringkøbing-Fyn High* in the North (Rodon and Littke, 2005; Maystrenko et al., 2005a; Michelsen and Clausen, 2002).

The NGB itself was formed as an intra-cratonic basin during the Permo-Carboniferous linked to the Variscan orogeny (rifting and igneous activity) (Ziegler, 1990; Henk, 1999; Benek et al., 1996). The subsidence of the NGB during the Permian (Rotliegend and Zechstein) results in *c.* 1500 m thick claystones and evaporite rock units (rock salt, anhydrite, gypsum, etc.). Fig. 2 shows the main stratigraphic units and the generalized lithology.

The *Glückstadt Graben* is one of the deepest post-Permian sub-basins of the CEBS. The sedimentary filling mainly consists of Permian to Cenozoic rocks that overlays a Devonian-Carboniferous sequence and a Caledonian consolidated crystalline crust (Bayer et al., 2002). Its Mesozoic evolution is mainly controlled by a Middle-Late Triassic (Keuper) extension (Rodon and Littke, 2005; and references therein). Mobilized salt in the form of pillows, diapirs and roughly N-S striking parallel aligned salt walls, mainly determines the inner structural setup of the *Glückstadt Graben*. The depth of the evaporite Zechstein base is varying between 2 and 10 km. Around salt structures, thickness maxima of Cenozoic and Mesozoic sediments occur in primary and secondary rim synclines. Jurassic sediments, which were often targeted by oil exploration, occur in very deep rim synclines only (cf. Fig. 3). Further details of the evolution of the *Glückstadt Graben* are summarized in Ziegler (1992), Maystrenko et al. (2005a,b), and Maystrenko et al. (2006).

The *Ringkøbing-Fyn High* is a NW-SE trending basement ridge which separated the Southern Permian Basin from the Northern Permian Basin during Late Carboniferous to Early Permian times. It consists of a series of shallow fault blocks of Precambrian crystalline rocks (spanning between North Sea and Baltic Sea) and is subdivided by N–S striking graben systems (Brande Graben, Horn Graben), generated in relation to movements along the Sorgenfrei-Tornquist Zone and the Trans European Suture Zone during the Late Carboniferous to Early Permian (Thybo, 1997, 2001; Bergerat et al., 2007; Sorgenfrei and Buch, 1964). The Early-Middle Jurassic major updoming of the North Sea area (Ziegler, 1990) caused a progressive uplift of the *Ringkøbing-Fyn High*. Above the *Ringkøbing-Fyn High*, thin sections of Triassic to Lower Cretaceous sediments are present in the northern part of the study area (Nielsen, 2003).

The area between *Glückstadt Graben* and *Ringkøbing-Fyn High* is structurally determined by the NW-SE trending *Tønder Graben*, which forms a narrow tectonic depression extending from Flensborg Fjord to the island of Rømø (Michelsen and Clausen, 2002). This area, similar to the *Westschleswig Block*, is characterized by weak halogenetic elements, and therefore, can be clearly separated from the *Glückstadt Graben*. Minor salt pillows are known in several areas, e.g. from the Tønder area (Fig. 1). Further details on the general regional geology can be found in Rodon and Littke (2005) and Kaufhold et al. (2011). Examples of depth and thickness distributions of selected geological units are shown in Fig. 3. Detailed values of thickness and depth of the modelled geological units are summarized in part one of this study (Fuchs and Balling, 2016; this issue).

More than 200 deep boreholes have been drilled in the study area and provide valuable insight into the structural and sedimentary evolution of this region. Most of these boreholes were drilled for the exploration of potential geological traps for oil and gas nearby salt structures in the *Glückstadt Graben* (cf. Fig. 1). Constrained by borehole data and seismic information, a 3D structural model was developed by LLUR (State Agency for Agriculture, Environment and Rural Areas Schleswig-Holstein, Germany) and GEUS (Geological Survey of Denmark and Greenland) (Kirsch et al., 2015). Lithological, stratigraphical, petrophysical, and geophysical borehole data of good quality available for more than 70 wells are implemented in this study. Further details to the amount and quality of the used database are reported in part one of this study (Fuchs and Balling, 2016; this issue).

3. Previous modelling studies

The NGB was target of several modelling studies over the past two decades. A broad range of scientific issues was examined, with special emphasis on the analysis of the present day thermal structure (e.g. Scheck, 1997; Bayer et al., 1997; Ondrak et al., 1999; Vosteen et al., 2004; Norden et al., 2008; Noack et al., 2010; Norden et al., 2012; Balling et al., 2013; Sippel et al., 2013; Scheck-Wenderoth et al., 2014), thermal maturity studies (e.g. Friberg et al., 2000; Rodon and Littke, 2005), type and configuration of basement and lower boundary (e.g. Scheck, 1997; Marotta et al., 2000; Cacace et al., 2010; Noack et al., 2012), reservoir production and lifetime (e.g. Ondrak et al., 1998; Ollinger et al., 2010; Mottaghy et al., 2011; Blöcher et al., 2010), processes of advective and convective heat