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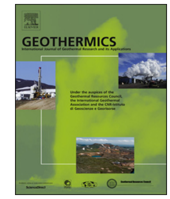

The variability of rock thermal properties in sedimentary basins and the impact on temperature modelling – A Danish example

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A B S T R A C T

Detailed knowledge of in situ formation thermal properties is a prerequisite for accurate temperature predictions from geothermal models of sedimentary basins. The value and regional variability of such formation thermal properties generally receive little attention: very few attention in petrophysical and even less in modelling studies. Consequently, the spatial variability of formation thermal properties is typically not considered, for neither the *a priori* model parameterisation nor the *posteriori* model calibration.

This basin study determines how the thermal properties of geological formations vary spatially and how this affects the quality of modelling results compared to the results of measured temperatures in the Danish Basin. Formation petrophysical properties (thermal conductivity, radiogenic heat production, thermal diffusivity, specific heat capacity, density, and porosity) and their spatial variability in the Danish Basin are exemplarily and systematically studied by well-log interpretation techniques. Therefore, the initial computations of the mean formation well-log values (and their variability) are presented for thermal diffusivity and specific heat capacity.

The analysis reveals that all the formation thermal properties display a larger variability than previously applied in geothermal or basin modelling studies. The observed maximum variability of the mean thermal formation values is up to approximately 50% (mean: 23 ± 11%) for thermal conductivity, up to approximately 65% (mean: 34 ± 16%) for thermal diffusivity, up to approximately 30% (mean: 16 ± 8%) for specific heat capacity, and up to more than 100% (mean: 64 ± 24%) for the radiogenic heat production.

A strong regional thermal-conductivity variability impact was quantified by the comparison of subsequently modelled geotherms with measured borehole temperatures. When basin-wide mean formation conductivities (representing the usual assumption of constant formation values in geothermal models) are applied to such models, the misfit between the predicted and measured temperatures at the maximum borehole depth of approximately 4 km is large and averages approximately 20% (range: −21 to 22 °C). Application of the observed but less representative formation conductivities in terms of the 'true' overall basin average yields maximum derivations between 27 and 66% (range: −38 to 90 °C). The application of local formation conductivities, in contrast, yields minimum deviations generally less than < 5 °C, depending on consideration of regional or location-specific heat-flow values.

Statistical data on the mean formation variability presented here can serve as guidelines to define reasonable variation ranges for the input or the post-processing calibration procedures for geothermal models of sedimentary basins with similar lithologies and genesis to the Danish Basin. In general, knowledge of the variability of formation thermal properties will lead to a significantly lower uncertainty in the temperature calculations, in particular but not exclusively for areas and depths where temperature observations are unavailable.

1. Introduction

In modelling the thermal fields of sedimentary basins, it is of paramount importance that the model parameterisation reflects the different rock thermal properties and their natural spatial variation in the subsurface. One of the most difficult and critical tasks is the assignment of reliable values to the different geologic units that compose the modelled domain. In the past, the majority of numerically studied geothermal models simplified the input of thermal properties of stratigraphic units or geological formations to laterally homogeneous average values. Some exceptional modelling studies have already mentioned the importance of considering the spatial variation in thermal conductivity (e.g., Fjeldskaar et al., 2008). Recent studies, however, clearly demonstrated that considering the variability in

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formation thermal properties significantly and systematically reduces the difference between predicted and measured borehole temperatures (Fuchs and Balling, 2016a,b). According to a lack of properly designed petrophysical studies, the values and variability of such formation parameters are commonly unknown and thereby not considered in the pre- or post-processing of the model computation (i.e., parameterisation and calibration).

The aim of this paper is to identify and quantify the variability of petrophysical properties, in particular of thermal formation properties in sedimentary basins that are relevant for geothermal modelling. For this purpose, the variability of thermal conductivity, radiogenic heat production, thermal diffusivity, specific heat capacity, density and porosity is studied on the example of Late Permian to Cenozoic geological formations in the Danish Basin applying well-log-driven analysis techniques. The resulting impact on modelled temperature is quantified by calculating geotherms for layered thermal borehole models and varying the layer parameters within the boundaries identified by the well-log analysis. This paper provides a comprehensive study of rock thermal properties in the Danish Basin and identifies reasonable parameter variability ranges that can either be used for stochastic parameterisation and/or inverse model calibration in the Danish Basin itself or can serve as boundaries when transferred to other sedimentary basins of similar geological genesis.

2. Background

The thermal state and the temperature regime of the Earth's crust is mainly shaped by the basal heat flow and spatial variation in subsurface rock thermal properties. For geothermal calculations, the most important rock thermal properties are thermal conductivity (TC; λ in W/[m·K]), radiogenic heat production (RHP; A, in $\mu W/m^3$) and the volumetric heat capacity (RHOC, ρc_p in kJ/[m^3·K]). The latter can be described as a product of the specific heat capacity (SHC, c_p in J/[kg·K]) and density (ρ in kg/m^3) or as a quotient of TC and thermal diffusivity (TD; α in $\cdot 10^{-6}$ m^2/s). While TC and RHP have a first-order effect on the terrestrial surface heat-flow density and the background steady-state temperature field, RHOC (and thereby SHC and TD) influences the transient change in heat and temperature in the crust (e.g., the paleoclimate effect, geothermal exploitation, storage of nuclear waste). As long these parameters are not well understood, accurate subsurface temperature predictions cannot be made; this is a fundamental problem for a wide range of applications (hydrocarbon maturation modelling, geothermal energy, subsurface storage of heat, nuclear waste repositories, etc.).

The spatial variation in rock thermal properties in sedimentary basins is caused by the complex interplay between the structural and lithostratigraphic, and thereby the lithofacies-dependent configuration of the geological units. Depending on the depositional environment, these changes may be random or systematic. For the TC of many lithotypes, the effect of substantial regional variations has long been known from many regional studies of well data (e.g., Chapman et al., 1984; Powell and Chapman, 1990; Deming et al., 1990; Fjeldskaar et al., 1993; Gallardo and Blackwell, 1999; Norden and Förster, 2006; Fjeldskaar et al., 2008; Fuchs and Förster, 2010; Schütz et al., 2012a,b; Norden et al., 2012; Homuth et al., 2014; Götz et al., 2014). In contrast, for TD, SHC and RHP, much less effort has been spent on similar regional well studies, although the basic interrelation of matrix minerals and pore fluid for these properties raises the expectation of a commensurate variability in sedimentary rocks and formations. However, in regard to geothermal modelling, data on the variability of thermal properties is frequently either not available or not considered as input for model parameterisation. This approach might be sufficient for the rare case of geologic formations of a uniform lithology over large distances, where it may be possible to characterize the TC from a few laboratory measurements, but this approach fails when geological formations are subject to even moderate lateral or vertical changes in lithology (cf. Deming et al., 1990; Fuchs and Balling, 2016a).

In addition to this common negligence on the modelling side, the use of 'standard' lithotype values or laboratory measurements on material from selective borehole depths introduces further drawbacks. Upscaling from selective point data to a 'representative' mean formation value creates significant uncertainties (Fjeldskaar et al., 2008). Upscaling requires an adequate number of rock samples for laboratory studies, increasing the coring costs of a well. Even if a sufficient number of measurements are available for each rock type, it remains unclear whether the studied rock samples reflect the 'true' variation in mineralogy and petrography within the geological formation in question. As soon as the changes in rock composition between wells are taken into account, the number of measurements required increases tremendously to a number of samples generally not available without incurring the costs of numerous laboratory measurements.

An alternative to laboratory measurements is the indirect determination of rock thermal properties from geophysical well logs, which is limited to a 1D sampling volume along the borehole instead of point data in selected core sections. The well-log-based determination of rock thermal properties offers high vertical resolution and thereby a more accurate understanding of the vertical parameter distribution. A successful approach in this regards is the inversion of continuous temperature logs to borehole profiles of in situ TC (Blackwell and Steele, 1989; Fuchs and Förster, 2010; Sippel et al., 2013; Schütz et al., 2013; Fuchs et al., 2015). The computation requires stable (unperturbed) heat-flow conditions and the existence of continuous temperature logs recorded under thermal borehole equilibrium, which are very rare in most sedimentary basins. However, interpreting standard geophysical well logs is applicable far more often. For both RHP (e.g., Rybach, 1986; Bücker and Rybach, 1996) and TC (with many more methods, cf. Fuchs and Förster, 2014) this is a long-known and often-applied workflow, but only recent approaches allow the determination of TC, TD and SHC in sedimentary rocks from combinations of the most common standard log types (cf. Fuchs and Förster, 2014; Fuchs et al., 2015). However, the application of any of these well-log-driven approaches allows the calculation of reasonable mean formation values – as primarily demonstrated for inverted temperature logs by Blackwell and Steele (1989) – considering the full variability of the recorded parameter profiles and thereby the vertical changes in lithology, mineralogy and porosity. On these terms, Vogt et al. (2010) and Mottaghy et al. (2011) interpreted well logs for a TC profile and were among the first to calculate statistical values for stratigraphic units as a basis for 3D stochastic parameter realizations in a Monte-Carlo computation of a temperature model. They demonstrated that this approach is generally helpful in reducing the width (and thereby the uncertainty) of computed temperature distributions. However, as long as TC is determined at one well only, the stochastic 3D parameter distribution for each formation merely reflects the vertical variability within the formation, but not between different well locations or within a basin. When the variation in TC is also considered among different well locations in recent modelling studies, significantly lower uncertainties in temperature prediction were reported (Fuchs and Balling, 2016a,b).

Taking all these aspects into account reveals that the magnitude of variation in rock thermal properties for geological formations in sedimentary basins is often unknown but very important for the parameterisation of thermal models. Knowledge of basin-wide variations would be helpful for all geothermal numerical modelling approaches (stochastic, forward, and inverse modelling) but generally suffer from lack of data.

3. Geological setting and stratigraphy

The Danish Basin (DB) constitutes a major part of Denmark (Fig. 1). It is a WNW-ESE trending intracratonic basin in the eastern part of the North Sea system of sedimentary basins (Ziegler, 2005) and is bounded by the Precambrian basement blocks of the Ringkøbing-Fyn High (RFH)