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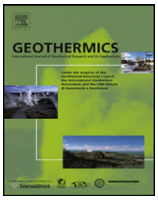

Subsurface temperature distribution in Germany

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ABSTRACT

Data from approximately 10,500 wells and more than 700 ground level data sets were used to develop a three-dimensional (3D) estimate of the subsurface temperature distribution in Germany. The temperature model was realized with universal kriging, and extends from ground level to 5000 m below sea level. Conventional two-dimensional (2D) mapping algorithms are often used to estimate subsurface temperature at certain depths. The major limitation of any 2D mapping is the possibility of inconsistencies between different depths due to the loss of information from shallower levels. A different approach is used in this paper. The application of 3D-kriging in the context of subsurface temperature estimation is described in detail and variation of data density and quality are also discussed. Kriging employs customized prediction parameters for an unbiased estimate of the subsurface temperature distribution. The kriging variance predicts the uncertainty of the temperature estimate and provides a local probability interval of the temperature estimate.The developed temperature model is part of the Geothermal Information System for Germany (GeotIS).

1. Introduction

Although geothermal energy constitutes only a minor portion of renewable energy sources in Germany, the geothermal industry in Germany has been developing rapidly since the government enacted the Renewable Energy Act in April 2000. The total installed electric power generated from geothermal sources increased from 0.2 MW to 8 MW in the last three years (Schellschmidt et al., 2010). Geothermal heat and power production in Germany relies on reservoirs of low to moderate temperature. Temperatures above 60 °C are considered to be sufficient for district heating purposes. Geothermal power generation requires temperatures above 100 °C. The hottest water available for a geothermal plant in Germany is 160 °C and located at Landau in Rheinland-Pfalz (Rhineland-Palatinate). Geothermal power plants in Germany use conversion techniques such as the Organic Rankine Cycle (ORC) or the Kalina cycle method.

The crucial parameters for geothermal energy use are production rate Q and the temperature at the wellhead $\mathrm{T_i}$ which depends on temperature T_A in the aquifer. In general, $\mathrm{T_i}$ is a function of the production rate Q, the reservoir temperature T_A, and the production duration Δt. During long periods of production at high rates, there is only a negligible difference between the wellhead temperature and the reservoir temperature. This gives rise to the following general relationship for the installed output P of a geothermal plant:

$$P \propto Q \cdot T_\mathrm{A} \tag{1}$$

Therefore, knowledge of the subsurface temperature is crucial for planning geothermal plants for heat and power production. Higher temperatures provide better yields and increase the cost-effectiveness of a geothermal site. Mapping subsurface temperature distribution from available measurements is an important prerequisite for geothermal reservoir evaluations.

Prior investigations produced a limited number of maps for certain depths using 2D-mapping algorithms like for instance a distance-weighted estimator (Schulz et al., 1992; Hurter and Schellschmidt, 2003). The major disadvantage of 2D algorithms is the loss of information from shallower levels since the deep subsurface is much less explored. A sequence of maps may suggest geothermal gradients which are not consistent with our understanding of a predominant conductive thermal regime. In practice, it is difficult to tackle inconsistent vertical temperature steps at unsampled locations.

In order to estimate the geothermal potential of a geological body at any depth, it is necessary to determine the temperature at any point in a consistent 3D-temperature model. A 3D interpolation method suitable for developing such a model is kriging. There are several types of kriging, e.g. simple kriging, ordinary kriging, indicator kriging, etc. (Deutsch and Journel, 1998). In this study we applied universal kriging. Universal kriging makes it possible to accommodate a trend in data which is essential for the estimation of subsurface temperatures. Generally, kriging estimates are

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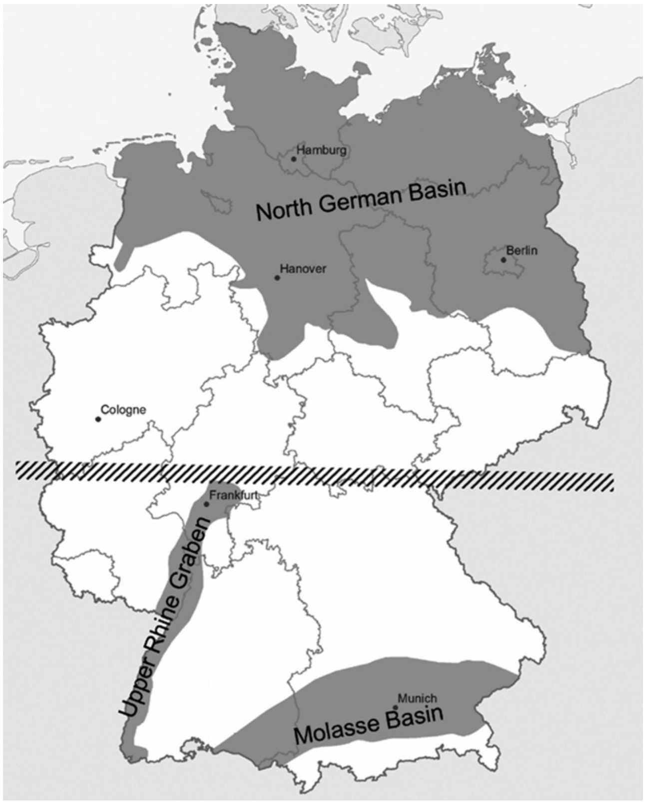

Fig. 1. Regions in Germany suitable for geothermal exploitation (shaded area). Two subsurface temperature models that have been developed are merged along a 20 km wide zone (hatched area).

weighted linear or non-linear combinations of the available data. It is the only method which allows the inclusion of measured spatial variability in the estimation process. Another major advantage of kriging is the calculation of the uncertainty associated with the predicted values.

In this study, the subsurface temperature model for Germany was created as a part of the Geothermal Information System for Germany (Agemar et al., 2007; Pester et al., 2010). Subsurface temperatures were estimated for depths ranging from ground level to 5000 m below sea level.

2. Hydrothermal resources of Germany

Today, geothermal exploration and production for direct use in Germany focus on deep aquifers in sedimentary basin and graben structures at depths of 2–4 km. The most important regions for geothermal exploitation are the North German Basin, the Molasse Basin in southern Germany, and the Upper Rhine Graben (Fig. 1).

The North German Basin is the central part of the Central European Basin. The present-day sediment thickness ranges from 2 to more than 11 km (Maystrenko et al., 2006). Halokinetic movements of the Zechstein halite layers are responsible for the intense and complex deformation of Mesozoic and Cenozoic formations (Franke et al., 1996). These movements are locally active up to recent times and the disturbance strongly influences the local conditions.

The Mesozoic deposits of the North German Basin consist of siltstones and sandstones, clays, carbonates, and evaporites. Sandstone aquifers most suitable for the direct use of geothermal energy are confined to the Permian and Mesozoic stratigraphic column: Rotliegend, Middle Bunter, Keuper, the Lias-Rhaetian Aquifer Complex, Dogger, and Lower Cretaceous (Katzung et al., 1992; Feldrappe et al., 2008). The sediments of the Mesozoic are generally 2–3 km thick and have sunk to depths of 4 km and more in the basin center (Baldschuhn et al., 1996; Katzung et al., 1992). Locally, much higher thicknesses and greater depths occur as a result of tectonic movements. In the Glückstadt Graben in Schleswig-Holstein for instance, the Triassic sediments are 3.5–6.5 km thick (Maystrenko et al., 2006). Salt tectonics cause great lateral depth and thickness variations over relatively short distances, and contribute to the uncertainty of any structural model. Therefore, the geothermal potential of individual aquifers varies strongly at a local scale.

The Molasse Basin in southern Germany is an asymmetrical foreland basin of the alpine mountain belt which was filled during the uplift of the Alps (Lemcke, 1988). It extends over more than 300 km from Switzerland in the southwest to Austria in the east. The basin is mainly filled by Tertiary sediments overlying Cretaceous, Upper Jurassic and Triassic sediments. Eight aquifers in these sedimentary layers are of interest for direct geothermal energy exploitation: Burdigalian sands, Aquitanian sands, Chattian sands, Baustein-Schichten, Ampfing-Sandstein, Gault/Cenoman-Sandstein, Malm and Upper Muschelkalk (Fritzer et al., 2010). The Upper Jurassic karstified limestone (Malm) is one of the most important geothermal energy reservoirs in Central Europe due to its high productivity and presence beneath almost the whole Molasse Basin. South of the Danube, the Malm aquifer dips from north to south and reaches depths of more than 5 km along the northern margin of the Alps.

The Upper Rhine Graben is part of a large rift system which traverses the north-western European plate (e.g. Villemin et al., 1986). The graben is 30–40 km wide and runs from Basel, Switzerland, to Frankfurt, Germany. The structure was formed during the Tertiary about 45–60 Ma. It is interpreted as a doming of the crust-mantle boundary due to magmatic intrusions at 80–100 km depth. The stressed induced by folding and thermo-mechanical effects have given rise to extensional tectonics with a maximum vertical offset of 4.8 km. Six Tertiary, Jurassic, Triassic and Permian aquifers are of interest for the exploitation of geothermal energy for direct use: Hydrobien-Schichten, Grafenberg-Schichten, Hauptrogenstein, Upper Muschelkalk, Bunter Sandstone and Rotliegend Sandstone (Haenel and Staroste, 1988; Hurter and Haenel, 2002). The most promising geothermal energy reservoirs in the Upper Rhine Graben are the Triassic Upper Muschelkalk and Bunter Sandstone (Haenel and Staroste, 1988). The base of the Upper Muschelkalk reaches depths of more than 4 km, whereas the base of the Bunter reaches depths of more than 5 km.

Other areas, such as the Central German Uplands, may also prove suitable for geothermal exploitation. The introduction of enhanced geothermal systems (EGS) would utilize the geothermal energy from deep crystalline basement rocks. The joint French-German project at Soultz-sous-Forêts (Alsace) successfully demonstrates the general feasibility of an EGS in Central Europe (Fritz and Gérard, 2010).

3. Data

The Geophysics Information System (Kühne et al., 2003) was the most important data source for this study. It contains a large amount of geophysical data, primarily within Germany, consisting of a main system and various subsystems. The geothermal subsystem (Schulz and Werner, 1989) contains subsurface temperature data from 10,559 wells (Fig. 2). Equilibrium temperature logs and reservoir temperatures are considered to be optimal data which require no corrections. Because of the regular monitoring of production wells over many years, reservoir temperatures are available in time series; the fluctuation in these temperatures is mainly less than 1 K.

Bottom-hole temperature data (BHT) are also stored in the geothermal subsystem. These BHT values are recorded in almost all