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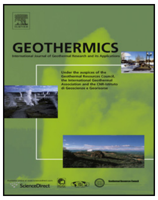

Full length article

Using seismic data to estimate the spatial distribution of rock thermal conductivity at reservoir scale

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ABSTRACT

Subsurface rock thermal conductivity predictions from laboratory measurements are limited by the number of available borehole data or of analogue outcrops. A method for spatially predicting subsurface rock thermal conductivity is demonstrated by using a combination of laboratory measurements on drill cores and *in-situ* geophysical measurements. Continuous measurements of thermal conductivity were performed on lower Permian Rotliegend drill cores of 80 m and 60 m length, respectively. The cores originate from the prominent Messel pit, Germany. In addition to the rock core measurements, numerous seismic sections of the study area as well as borehole geophysics from the respective boreholes are available. The seismic data is used additionally to the measured thermal conductivities and porosity as a secondary trend variable for interpolation by applying kriging with external drift (KED). Seismic data and thermal conductivity are physically related, mainly due to porosity, and can correlate strongly. Seismic data fulfils the main criteria required by KED as it varies smoothly and is known at all locations of the primary data and all locations to be estimated. In a primary study thermal conductivity interpolation in 1D along one of the two boreholes is studied. Finally in 2D along one seismic profile, which strikes through both boreholes, the method is tested. Results of interpolated dry thermal conductivity and porosity in 2D are geologically reasonable. The saturated bulk-rock thermal conductivity was determined using a geometric-mean model based on the interpolated porosity and dry thermal conductivity data. Both studies prove that the result is better while seismic data is used as secondary trend variable.

1. Introduction

Heat transport in sedimentary reservoir rocks is governed by the spatial variability of thermal and hydraulic properties. Evaluating geothermal reservoirs aims to investigate precisely the potential of accessible heat resources. The thermal conductivity of rocks is an important physical property for predicting heat flow and corresponding subsurface temperatures (*e.g.* Haenel et al., 1988; Rühaak et al., 2015; Rühaak, 2015). Thermal conductivity describes how well, but not how fast, heat is conducted through a material. It is still something of a challenge to estimate the thermal conductivities of rocks at a large scale required for geothermal applications (say 1000–10,000 m horizontally and up to a vertical depth of 6000 m) because no suitable tools and techniques are available. Direct measurements of the spatial distribution of the thermal conductivities of rocks within a reservoir are time consuming and expensive (Sundberg et al., 2009). Therefore advanced method, such as the integration of secondary data, like seismic velocity measurements can be a good option (*e.g.* Esteban et al., 2015 and Pimienta et al., 2014). Seismic data provide a non-invasive way of collecting information in 1-, 2- or even 3-dimensions.

A large amount of experimental and theoretical research has been undertaken and is still ongoing to improve our understanding of rock thermal conductivity. Reliable estimates using borehole data are constrained by the high cost of drilling boreholes. However, some previous studies derived thermal conductivity through well data (*e.g.* Hartmann et al., 2005; Teng and Koike, 2007; Sepúlveda et al., 2012; Vogt et al., 2013; Fuchs et al., 2015). Empirical/semi-empirical models (*e.g.*, Zamora et al., 1993; Wang and Yi, 2004; Wang et al., 2006) can only predict thermal conductivities for a small number of case studies. The *in-situ* thermal conductivity of rocks can also be inferred from temperature logs by calculating the

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heat-flow densities at different intervals and the average temperature gradients at particular depths (*e.g.* Blackwell and Steele, 1989; Sass et al., 1992; Fuchs and Förster, 2010; Ollinger et al., 2010). However, this method requires the boreholes to have reached thermal equilibrium, which has occurred in only particular cases and takes considerably long time. Furthermore, the heat flow has to be predominantly conductive. This approach is the subject of ongoing academic research and has not yet been used in the exploration of geothermal reservoirs (Fuchs et al., 2013).

Thermal conductivity can be measured in the lab on cores or cuttings (*e.g.* Popov et al., 1999; Hartmann et al., 2008; Bär et al., 2011; Sass and Götz, 2012; Rühaak et al., 2015; Schintgen et al., 2015) as the most common and direct way. However, *in-situ* thermal conductivity may deviate significantly from laboratory values, even if the influence of temperature, pressure and pore-fluid is considered (Clauser and Huenges, 1995). Laboratory work is usually performed on much smaller samples compared with *in-situ* measurements on an average of the samples' rock volume (*e.g.* Geothermal Response Tests). However, rocks are heterogeneous in many aspects, such as mineral composition, porosity, saturation and experimental conditions (Clauser and Huenges, 1995). Therefore, thermal conductivity can still vary considerably, even for the same rock type (Cermak and Rybach, 1982). An important shortcoming of all these approaches however, is that they only provide data in 1D along a borehole.

As a basic geophysical tool, refraction seismic surveying convert the time-distance information into the format of velocity variation with depth. The penetration capability of refraction seismic directly depends on the velocities of different materials in the subsurface. Seismic velocities are obtained from geophysical surveys of 2D sections or 3D volumes but can also be obtained by borehole geophysical logging like Vertical Seismic Profiling (VSP) or by lab measurements. Previous studies presented the regression analysis between thermal conductivity and compressional wave velocities. For example, Hartmann et al. (2005) used bulk density and sonic velocity linear regressions to predict the thermal conductivities of rocks in 1D from logging data, and determined the thermal conductivity with an average deviation of less than $0.2\,\mathrm{W\,m^{-1}\,K^{-1}}$. Gegenhuber and Schoen (2012) also described the correlation by considering the two important factors for thermal conductivity – mineral composition and cracks/fractures in an inclusion model (nonlinear) and a defect model (linear). The defect model is simple, but measured thermal conductivity values fit well. Similar correlation for thermal conductivity and different geophysical rock properties, such as density, porosity, permeability and compressional wave velocity, are independently found or used by other numerous studies (*e.g.* Joeleht et al., 2002; Popov et al., 2003; Özkahraman et al., 2004; Alishaev et al., 2012; Fuchs et al., 2013; Pimienta et al., 2014; Esteban et al., 2015). Typically thermal conductivity cannot simply be estimated by a regression calculation with any single parameter except in rare cases, *e.g.* in a study of Balling et al. (1981). Their study based on the precondition that the mineralogy of the sampled lithotypes do not vary too much; this way the thermal conductivity can be sufficiently expressed by the porosity correlation only. In most other cases the correlation between thermal conductivity and other petrophysical properties generally depend besides of porosity also on mineralogy and texture. However, the occurrence of a similar general trend between thermal conductivity and compressional wave velocity is demonstrated sufficiently in all of the mentioned studies, which is the base of this study.

Kriging with external drift (KED) is suited to improve an interpolation by supporting the rock thermal conductivity measurements with the trend of a secondary variable (like compressional wave velocity data).

Because of the KED model takes the information from a secondary variable into account. KED model requires that a general trend (not necessarily a strong linear correlation) exists between primary and secondary variables. Thermal conductivity and compressional wave velocity are in general physically related. KED requires two conditions to be fulfilled: (a) the secondary variable must be varied smoothly in space; (b) the external variable must be known at all locations of the primary data (Deutsch and Journel, 1997). Both of the two criteria are fulfilled with respect to the compressional wave velocity data. Several authors have used KED to incorporate other factors as the secondary information. For example, Hudson and Wackernagel (1994) mapped subsurface temperature with elevation drift in Scotland; Bourennane et al. (2012) improved the soil water content estimation from electrical resistivity data by KED; Rühaak et al. (2014) used the KED method to improve subsurface temperature interpolations by consideration of a conductive numerical model result.

The objectives of this study are to combine thermal conductivity from lab measurements and seismic velocity of *in-situ* borehole geophysics and 2D seismic profiles to explore the capability of KED. The estimation of the saturated thermal conductivity is not straightforward; however, the interpolated porosity and dry thermal conductivity are calculated by geometric mean model. To our knowledge, no study about the incorporation of geophysical data as an auxiliary variable for the prediction of spatial thermal conductivity distributions was performed before.

Finally, an interpolation in both 1D and 2D is performed and the predicted results of KED are analysed. For a comparison, ordinary kriging is also applied.

2. Data and methods

2.1. Study area

The study area is located (Fig. 1) on the Sprendlinger Horst in the Messel pit (Schaal and Ziegler, 1992; Harms, 2002). The pit is a maar within the paleozoic horst structure which is separating the northern Upper Rhine Graben in the west from the Gersprenz Graben in the east (Fig. 1). Permian to Carboniferous volcanic and sedimentary rocks as well as Middle Eocene sedimentary rocks has been deposited on crystalline Variscan basement bedrock. Permian Rotliegend sediments in the adjacent Upper Rhine Graben are found at depths of 3 to 5 km and are considered to form a hydrothermal reservoir with a geothermal potential sufficient for binary geothermal power plants (Bär, 2012; Aretz et al., 2013, 2015).

The Messel pit is well known because it contains oil shales that are rich in fossils, particularly of mammals and plants. It came on the UNESCO World Heritage list in 1995. The pit was formed as a maar structure 47 Ma ago following phreatomagmatic explosions (Schulz et al., 2002, 2005; Nix, 2003; Mezger et al., 2013). Volcanic activity occurred in this region along fault systems that formed during the Variscan orogeny and were reactivated as normal and oblique normal faults in the Permian and Tertiary periods. Magma pierced through Permian Rotliegend clastic sediments and crystalline rocks of the Paleozoic basement, the latter cropping out mostly to the south of the Messel Pit (Fig. 1). Older Permian basaltic to andesitic volcanic rocks (with the regional name melaphyres) presumably erupted along similar fault segments as did the Tertiary basalts. Tertiary black shales (Messel Oil Shale) appear as isolated spots throughout the region, and are associated with the assumed SW–NE orientated "Messel Fault Zone" (Nitzsche, 2007).

Boreholes GA1 and GA2 were drilled to 68 and 80 m respectively in 2004, and were completely cored. The locations of the boreholes are shown in Fig. 1. Several 2D seismic sections, one of which passes through both boreholes, were also recorded by the Leibniz Institute for Applied Geophysics (LIAG) in 2003 and 2004.