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Statistically reliable petrophysical properties of potential reservoir rocks for geothermal energy use and their relation to lithostratigraphy and rock composition: The NE Rhenish Massif and the Lower Rhine Embayment (Germany)

Rachel Jorand[a], Christoph Clauser[a], Gabriele Marquart[a,*], Renate Pechnig[b]

[a] Institute for Applied Geophysics and Geothermal Energy, E.ON Energy Research Center, RWTH Aachen University, Mathieustr. 10, D-52074 Aachen, Germany

[b] Geophysica Beratungsgesellschaft mbH, Lütticher Str. 32, D-52064 Aachen, Germany

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ABSTRACT

We present a comprehensive statistical analysis of petrophysical properties of rocks of the northeastern Rhenish Massif and the Lower Rhine Embayment in Germany. Properties measured comprise thermal conductivity, specific heat capacity density, porosity, hydraulic permeability, and compressional wave velocity. This robust and statistically reliable data is generally useful for numerical modeling of heat transport processes and helps, in particular, reducing the risk of failure in projects of geothermal energy use. We measured the thermophysical properties of rocks from two geological settings: (1) predominantly little consolidated Tertiary rocks forming the young sedimentary cover of the Lower Rhine Embayment in the condition they arrived in the laboratory; (2) well consolidated Paleozoic rocks from the northeastern Rhenish Massif in both dry and saturated condition. We tested a total of 476 samples from different lithologies in both settings in a comprehensive laboratory program consisting of mineralogical analyses and various petro- and thermophysical measurements at ambient and elevated p-T-conditions. This yields relations between composition and thermophysical properties of different sedimentary rock types and allows distinguishing between effects due to rock matrix and structure. The results are used to prove petrophysical rock models and allow predicting thermal properties of distinct rock types for greater depth. The results show that the thermophysical properties of Paleozoic rocks are mainly controlled by their mineralogical compositions, while thermophysical characteristics of Tertiary rocks are the result of a superposition of properties of their mineral content and the water-filled pore volume.

1. Introduction

Developing geothermal energy as an alternative source for heat and electricity requires estimating the resource and its uncertainty. In sedimentary formations, geothermal heat is produced from hot reservoir brines pumped to the surface. Therefore, thermal and hydraulic rock properties, apart from reservoir temperature, determine the thermal yield.

In the past, these properties have been determined on many individual samples by many authors (e.g. Čermák and Rybach, 1982; Clauser and Huenges, 1995; Clauser, 2006 for a review). However, physical properties in each type of rock vary with a number of factors, such as porosity, structure and geometry of the pore space, mineral composition and anisotropy of the solid rock, to name a few. Yet, to the best of our knowledge, there is no statistical analysis available based on measurements on specific rock types in a given region which would allow quantifying this uncertainty in thermal and hydraulic rock properties. Lack of this information, however, makes any resource assessment and prediction of producible thermal or electric energy difficult and questionable. For this reason, predictions are usually based on conservative assumptions which either result in oversized installations with associated unnecessary costs or in abandonment of projects due to unacceptable risk.

As an alternative, we propose and demonstrate a statistical approach for characterizing rock properties to be used as input for a (flow and transport) simulation-based analysis of uncertainty in predicted temperature and flow rate: for each rock type in a given geological setting, we parameterize the entire variability of

* Corresponding author. Tel.: +49 241 80 49895; fax: +49 241 80 49889.
E-mail address: gmarquart@eonerc.rwth-aachen.de (G. Marquart).

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a property derived from structural, mineralogical, and diagenetic differences by the statistical moments of the studied ensemble of samples.

We demonstrate this procedure in this paper on rocks from the NE Rhenish Massif. The area is one of the most densely populated regions of Germany and rising demands for geothermal energy are expected. This paper presents results from laboratory measurements on samples at ambient and elevated temperature and pressure. The data provided here can be complemented by data from borehole measurements from the same region reported in Hartmann et al. (2008) and in an internal report available via internet (Koch et al., 2009).

Apart from geothermal energy our results are relevant with respect to tight and shale gas reservoirs (Littke et al., 2011) as well as to underground gas and energy storage facilities.

2. Geological setting of study the area

The study area covers the Lower Rhine Embayment (LRE, German: Niederrheinische Bucht) and the adjacent parts of the Rhenish Massif (see Fig. 1). The Lower Rhine Embayment is an area of low relief surrounded to the east, south and partly to the west by the uplifted plateau of the Rhenish Massif. The embayment forms the southern part of a NW–SE trending rifting system which continues to the NW into the Roer Valley Rift and further onshore into structures of the southern North-Sea. Rifting has been active from the Tertiary up to the present day. The faults of the Lower Rhine Embayment are generally almost pure dip-slip normal faults forming a half-graben system of SE–NW trending elongated blocks (Reicherter et al., 2008). During different stages of rifting and subsidence, thick sequences of Tertiary and Quaternary clastic sediments were deposited within the blocks. Sediments of Late Oligocene age rest unconformably on Paleozoic and Mesozoic strata. The deepest half-graben of the Lower Rhine Embayment is the Erft Block with an accumulated thickness of Cenozoic sediments of 1000 m (Walter, 1995). The sediments are composed of alternating gravel, sand and clay layers of variable marine, deltaic and fluvial or lacustrine origin. The marine deposits are mainly composed of fine-to-medium sands. The terrestrial sediments, in contrast, cover a wider spectrum of grain sizes ranging from clay over silt and sand to fluvial gravels. Thick peat beds accumulated during the warm subtropical climate of the Miocene. They form up to 100 m thick lignite layers which are targets of an extensive open-pit mining activity.

The basement of the Lower Rhine Embayment is formed by Paleozoic rocks of the Variscan basement, which also built the surrounding uplift plateaus of the Rhenish Massif. The Paleozoic rocks of this part of the Variscan mountain belt are dominated by folded sediment series of Devonian and Carbonifereous age. Clastic rock spectra range from quartzitic sandstones and graywackes to shales and argillaceous shists of epicontinental and hemipelagic origin. Into this, thick limestone series are intercalated which belong to Middle and Upper Devonian reefs and Lower Carbonifereous carbonate platforms (Walter, 1995).

The Variscan basement architecture is formed by large WSW to ENE striking synclines and anticlines (Fig. 1) which are overprinted by axes undulations orientated in N–S direction. Most of the folds show asymmetric geometries with a tendency to a north-directed vergence. Devonian and older sequences form the deeper subsurface. They outcrop at the surface south of the Ruhr area in the anticlines of the "Bergisches Land" and "Eifel". Thick Carboniferous series are found in the synclines. Most prominent are the synclines of the Ruhr area (NE Rhenish Massif) comprising up to 5 km thick Upper Carboniferous series with interlayered coal beds which made the area the most important coal mining district of Europe (Walter, 1995). During the last century numerous underground mines were constructed down to levels of more than 1300 m. Data and rock samples gained during exploration activities are one of the most important data sources used for this study.

3. Rock samples and sampling routine

In this paper, we determine the variability of petrophysical properties of the main lithologies of Tertiary rocks from the Lower Rhine Embayment and Paleozoic formations in the NE Rhenish Massif in Germany. The studied samples derive from 18 boreholes in this region (see Fig. 1). One of these (B-00, Fig. 1) comprises a continuous sequence of unconsolidated sediments and little consolidated Tertiary rocks from an exploration borehole of RWE Power AG at the edge of the open pit lignite mine Hambach. With a depth of 741 m, it reaches almost to the Paleozoic surface and covers a wide range of sediments from Tertiary formations in the Lower Rhine Embayment.

Up to now, the cores available from the core archives for this period had not been suitable for laboratory testing due to significant alteration caused by moisture loss during prolonged storage. This causes irreversible modifications of sample structures resulting in inaccurate estimates of petrophysical properties why these samples are no longer representative for the studied formations (Jorand et al., 2011). Recently, with the support of RWE Power AG, we obtained a number of fresh core samples, a rare opportunity for studying virtually undisturbed sediments of the Tertiary. The data set is completed with measurements performed on about 219 core samples, taken from 17 additional wells. Unlike the Tertiary samples, these samples characterizing the Paleozoic formations, are well consolidated cores obtained from the core archives of the Geological Survey of North Rhine-Westphalia, Germany. They were selected according to availability and a good spatial coverage of the Paleozoic lithology. Also information from drilling reports was analyzed for a proper rock sample preselection. The geologic sequence sampled ranges from the Middle Devonian to the Upper Carboniferous (Table 1). The sampling depth for these Paleozoic cores varies between 53.9 m and 1759.6 m. Cretaceous rocks, which overlay the Paleozoic unconformably, are only represented locally, reaching a maximum depth of about 400 m. These rocks are of only minor importance for geothermal reservoirs and therefore not included in our study.

3.1. Tertiary rock samples

260 'fresh' Tertiary samples were studied right after recovery according to their textures. The texture refers to the size of the particles that make up the rock sample. The terms sand, silt, and clay refer to sizes of the soil particles given by the diameter ($Ø_{grains}$): (1) sand, 50 μm < $Ø_{grains}$ < 2 mm, (2) silt, 2 μm < $Ø_{grains}$ < 50 μm, (3) clay, $Ø_{grains}$ < 2 μm. Some measurements were performed on lignite samples but these were difficult because of the high brittleness of the samples, leaving only 4 useful plugs. Only thermal conductivity and matrix density were measured on these lignite cores which derived from the Upper Oligocene at depths between 71.13 m and 71.53 m.

3.2. Paleozoic rock samples

The Paleozoic samples were studied according to their lithology: mudstone (i.e. clay with a calcitic component), siltstone, sandstone, and conglomerate (see Fig. 2). This macroscopic classification is based, as for the Tertiary samples, on grain size fractions and on general geological information from the archives of the Geological Survey of North Rhine-Westphalia.

First, we grouped the sample data base according to lithology. The first group consists of sandstones, siltstones and mudstones.