Seismic Assessment of Geothermal Potential of Crystalline Crust

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ABSTRACT

On the basis of seismic and petrophysical data collected at the 9.1 km deep Continental Deep Drillhole (KTB) we are presenting a stochastic approach to estimate geothermal and hydraulic properties of deeply fractured crystalline crust. The work is an approach to realistically estimating the geothermal potential of faulted crystalline crust. Its seismic part consists of applying new techniques of data analysis to 3D seismic reflection data in order to identify and statistically quantify complex networks of fractures and their relation to major fault planes. Concentrating on a 10x10x10 km crustal cube this analysis is combined with vertical seismic profiling, geophysical logging, petrophysical laboratory and mineralogical data in order to estimate crack porosity values in situ. In order to determine model uncertainties distribution functions are derived for all geophysical properties involved on the basis of borehole measurements and seismic modelling. Attributing the resulting crack porosities and permeabilities to the 3D seismic fracture patterns leads to a hydraulic model of the brittle upper crust which is evaluated and calibrated in two ways: (1) by the outcome of the hydraulic injection experiments performed previously at the KTB site, and (2) by geothermal modelling.

1. INTRODUCTION

Within the project MeProRisk (Neuartige Methodik zur Aufsuchung, Erschliessung und Nutzung geothermischer Lagerstätten. Toolbox zur Prognose und Risikobewertung), five institutes, each with a different field of expertise, have been developing strategies for better understanding of the thermal regime and heat transport processes in great depths in order to enable a better quantitative estimation of uncertainties and financial risks involved in the geothermal reservoir prediction. One of the locations chosen for the development of new and improved methods of geothermal reservoir assessment was the site of the Continental Deep Drillhole (KTB) in S Germany. At this site, one shallower pilot hole (KTB-VB) and one deep main hole (KTB-HB) have been sunk into the rock of the Southern German crystalline (Emmermann and Lauterjung, 1997). The temperatures measured in the KTB-HB at the final depth of 9101 m (265°C) and the geological settings make this location interesting from the geothermal point of view. KTB as one of the largest and most expensive programs in geosciences undertaken in Germany, with the huge amount of gathered data, provides a great database for further research. Aim of this study was to analyse the available seismic cross-sections together with borehole measurements and evaluate the input which seismic data can contribute to the topic of geothermal reservoir assessment.

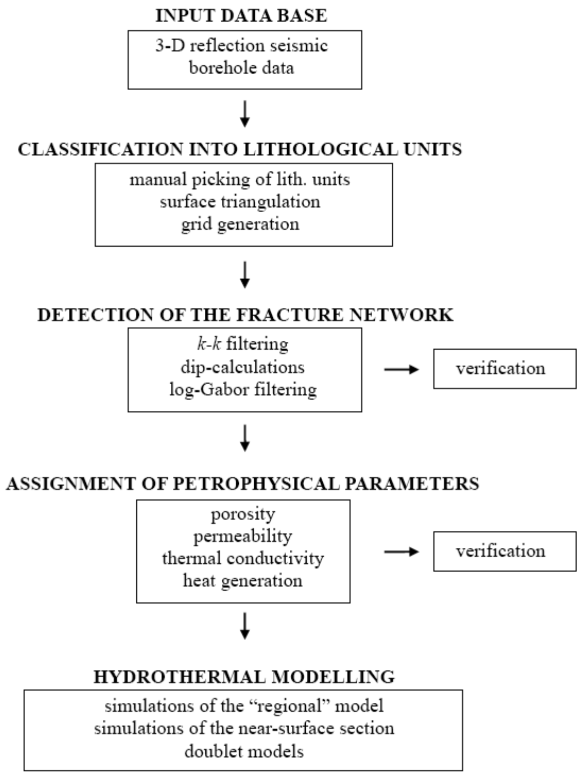

Figure 1: Concept of structural model construction for coupled thermal and hydraulic simulations on the basis of seismic data. The concept has been applied to the test-location of the Continental Deep Drllhole (KTB).

2. CONCEPT

The amount of heat extracted from a geothermal reservoir is controlled by a number of properties, such as temperature gradient, porosity and permeability of the rock, rock petrophysical properties, water stored in the underground, etc. These factors influence not only the process of heat extraction itself but also play a role in the economical component of geothermal energy production. In order to estimate hydrothermal characteristics of a reservoir correctly, it is necessary to combine the information about geological and tectonic settings of the site provided by the interpretation of seismic sections with petrophysical properties of the rock matrix and finally complement it with coupled hydrothermal simulations. The corresponding workflow is illustrated in Fig. 1.

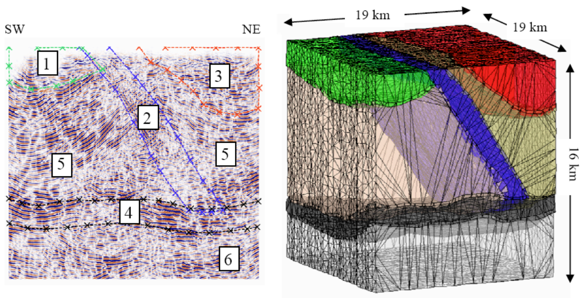

Figure 2: Lithological units identified at the KTB site projected onto a seismic cross-section (left) and the triangulated surfaces of the units forming the complete volume of the data block (right). 1- sediments, 2- fault zone, 3- granite, 4- mafic layer, 5- biotite-gneiss and amphibolites of the Zone of Erbendorf-Vohenstrauss (ZEV), 6- middle crust

2. LITHOLOGICAL UNITS

The primary dataset, which is in the centre of this work, is a depth-migrated 3-D reflection seismic dataset recorded in 1989 within the frame of the Integrated Seismic Oberpfalz (ISO89) survey (Harjes et al., 1997). Covering the area of about 19 km x 19 km and reaching up to 16 km depth, this dataset provides a three-dimensional picture of the complex structures in the continental crystalline crust. The data has been processed and migrated by the DEKORP group in the DEKORP Processing Centre (DPC) Clausthal (Thomas et al., 1996) and were provided by the GFZ Potsdam. The lithological units identified in the data volume are shown in Fig.2. The major volume of the data cube corresponds to the metamorphic Zone of Erbendorf-Vohenstauss (ZEV) which is composed of interlayered biotite-gneisses and amphibolites. The internal composition of the ZEV was estimated by waveform modelling of the seismic reflection data (Szalaiova, 2012).

3. FAULTS AND FRACTURES

At the KTB site, fault families of different scales have been detected. We distinguish two groups which are treated differently in the further processing according to the expected influence of the particular fracture group on the flow field. The so-called Franconian Lineament is a major fault zone. It falls under the group of large-scale faults. As one of the most distinct features of the KTB site, it separates foreland sediments in the SW from the crystalline rock. Its image could be extracted from the data cube by wave number filtering combined with three-dimensional dip calculations. Middle-scale faults are characterized by horizon shifts accompanied by low reflectivity. These could be located and separated from the background signals with the help of log-Gabor filtering and image processing. We applied several tests to check their reliability, for example, visual inspection, fractal dimension calculations, and comparison with focal planes of induced seismicity. The results of the fracture detection procedures are shown in Fig.3.

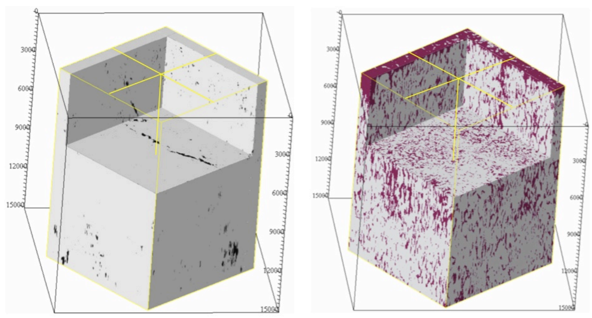

Figure 3: Major fault zone (left) and middle-scale fault and fractures extracted from the 3D seismic data cube by wave number- and log-Gabor-filtering

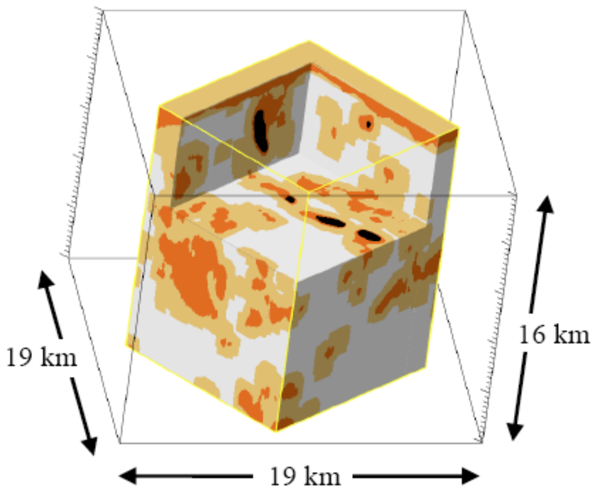

Figure 4: Distribution of relative permeability values based on the fracture density detected in 3D seismic reflection data. White: likely to be impermeable (<30% of volume elements containing fractures), coloured likely to be permeable (>30% of volume elements containing fractures)

4. HYDRAULIC PERMEABILITY

In order to enhance rock permeability, the mere presence of a fracture is not sufficient. Only fractures interconnected in a way that allows hydraulic communication can result in pathways affecting the thermo-hydraulic flow field. With increasing density of fractures, also the probability of fracture connectivity increases. Percolation theory states that if a medium consists at least to 30% of fractured volume, fluids start to percolate. Following this theory, we defined zones of different fracture densities and relate them to relative fracture permeabilities which can be regarded basically as a fracture density distrbution. Since fracture may be closed by tectonic stress, the orientation of the detected fractures with respect to the principal staress axes has to be considered. The volume distribution of the resulting relative permeabilities is, therefore, basically a density distribution of seismically detected fractures considered to be open. Absolute hydraulic permeability values were then attributed to this distribution function based on values estimated by injection tests at the KTB drillhole. The rage of permeabilities applied lies between 10^{-14} and 10^{-18} m^{-2}. The distribution of relative permeabilities resulting from this procedure is shown in Fig.4.

Rock porosity was assumed to be correlated with fracture density, too. Therefore, the same distribution function was applied as for the relative permeability values, but calibrated with porosity values observed at the KTB drillhole.

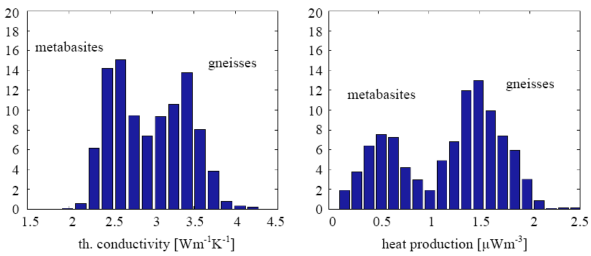

Figure 5: Thermal conductivity and heat production distribution (number of samples in %) within the ZEV unit penetrated by the KTB-HB. The bimodal behaviour can be explained by the presence of two different rock units: metabasites with lower values of thermal conductivity and heat production, gneisses with higher values.

5. THERMAL CONDUCTIVITY AND HEAT PRODUCTION

The Zone of Erbendorf-Vohenstrauss is filling out the major part of the rock volume at the KTB site. It represents the lithological unit in which the hydrothermal processes of interest take place. For this reason, the ZEV was analysed in much more detail compared to the other tectonic units. It has been subdivided into the two main components: gneisses and metabasites. Joint analysis of seismic cross-sections and borehole data enabled the calculation of synthetic seismograms, which give an overview about the location of the particular layers within the ZEV. Due to the considerable differences in rock thermal properties (Fig.5), this processing step yields important input required for coupled hydrothermal simulations. Thermal conductivity of gneisses is due to the pronounced foliation highly anisotropic. We combined the determined gneiss locations with calculations of structural dip. According to the specific foliation orientation, different values of thermal conductivity could be assigned to the particular volumes.

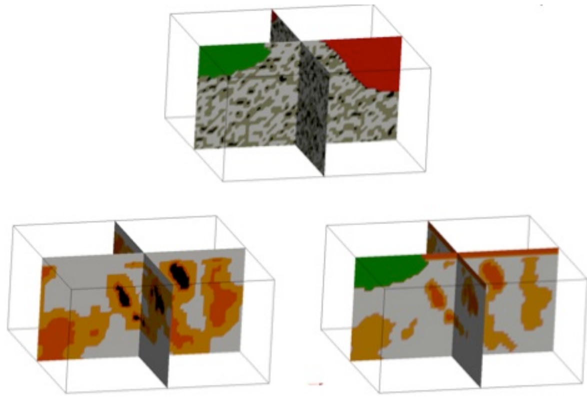

Figure 6: Qualitative images of the distribution functions of physical parameters used as input for thermal modeling. Top: Thermal conductivity and heat production rate based on lithological units and waveform modelling. Bottom: Relative hydraulic permeability (left) and porosity (right) based on seismic fracture analysis.

6. STEADY-STATE HYDROTHERMAL MODEL

The hydrothermal modeling was performed with the SHEMAT code (Clauser et al., 2003). We searched for steady state solutions of an equidistantly discretised model with no-flow lateral boundary conditions, a fixed surface temperature and an adjustable bottom heat flow density. The hydraulic boundary conditions of the upper boundary are given by the hydraulic head characterised by the local topography. In several steps, we computed the thermal effect of the main KTB lithological units separately and in combination and compared the resulting reduced temperature profiles with values measured in the KTB-HB borehole. To reproduce the thermal field of the site correctly, it was necessary to keep the porosity values very low. During the process of modelling, it became clear that the thermal field of the area can be explained by a relatively simple conductive model. Low permeabilities and porosities cause low Darcy velocities with the highest values reaching only 10-12 m/s. One of the findings of the modelling process is that permeabilities prevailing in this particular crystalline environment are of values too low to generate a hydraulic flow which would affect the thermal field notably. The only exception might be one of the major fault zones (the so-called SE2- fault), which seems to have an effect on the thermal field. The general fit of the measure temperature depth-curve is of the order of 0.2°C.

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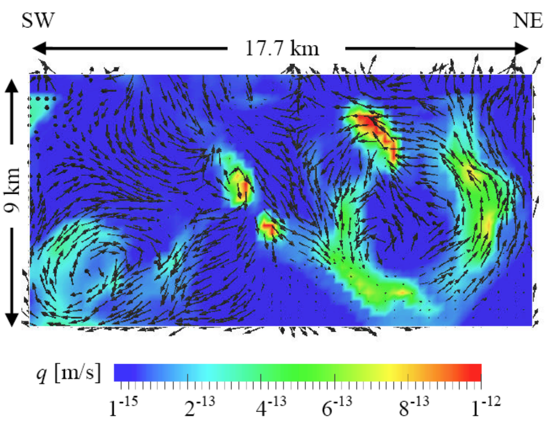

Figure 7: Calculated flow field of the final model consisting of all rock units identified at the KTB site including inhomogeneous porosities and permeabilities. The resulting temperature-depth distribution is in excellent agreement with the observed temperature field (Szalaiova, 2012).

7. CONCLUSIONS

In order to estimate the amount of heat available for extraction at the KTB site, it was necessary to consider not only the lithological composition but also the fracture inventory of the site. For this purpose we develop a suite of data analysis algorithms the results of which were checked versus borehole and other information in manifold ways. The final test for calibrating and evaluating the seismic model was based on hydraulic modelling and comparison with the temperature-depth distribution observed at the KTB deep drillhole. Modeled and observed data fit well within 0.2°C bounds. In a crystalline environment which is characterised by low matrix permeability, fluids tend to percolate through fractures. Therefore length of the travel path is closely related to the time available for heat exchange between the rock matrix and the circulating fluid. Based on three-dimensional reflection seismic data, it was possible to prepare a 3-D structural model of the KTB site which incorporates the lithological units as well as the complex network of fractures of different scales. Indispensable were also information concerning petrophysical rock properties. In the case of the KTB site, these data were at hand thanks to the huge amount of downhole measurements recorded in the two available boreholes.

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Acknowledgements

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