Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 59 (2014) 198 – 204

Energy Procedia

European Geosciences Union General Assembly 2014, EGU 2014

Deep geothermal energy for Lower Saxony (North Germany) – combined investigations of geothermal reservoir characteristics

Barbara Hahne[a,*], Rüdiger Thomas[a], and team gebo-Geosystem[a,b,c,d,e]

[a]Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hanover, Germany
[b]Geoscience Centre, University of Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany
[c]Section Hydrogeology, Technical University of Clausthal, Leibnizstraße 10, D-38678 Clausthal-Zellerfeld, Germany
[d]Institute for Geophysics and Extraterrestrial Physics, Technical University of Braunschweig, Mendelssohnstr. 3, 38106 Braunschweig, Germany
[e]Federal Institute for Geosciences and Natural Resources, Stilleweg 2, 30655 Hanover, Germany

Abstract

For the economic success of a geothermal project the hydraulic properties and temperature of the geothermal reservoir are crucial. New methodologies in seismics, geoelectrics and reservoir geology are tested within the frame of the collaborative research programme "Geothermal Energy and High-Performance Drilling" (gebo). Within nine geoscientific projects, tools were developed that help in the evaluation and interpretation of acquired data. Special emphasis is placed on the investigation of rock properties, on the development of early reservoir assessment even during drilling, and on the interaction between the drilling devices and the reservoir formation. The propagation of fractures and the transport of fluid and heat within the regional stress field are investigated using different approaches (field studies, seismic monitoring, multi-parameter modelling). Geologic structural models have been created for simulation of the local stress field and hydromechanical processes. Furthermore, a comprehensive dataset of hydrogeochemical environments was collected allowing characterisation and hydrogeochemical modelling of the reservoir.

Peer-review under responsibility of the Austrian Academy of Sciences

Keywords: deep geothermal; North German Basin; exploration; exploitation; characterisation; modelling

1. Introduction

In Germany, successful deep geothermal projects are mainly situated in Southern Germany in the Bavarian Molasse Basin, furthermore in the Upper Rhine Graben and, to a minor extent, in the North German Basin. Mostly they are hydrothermal projects with the aim of heat production. In a few cases, they are also constructed for the generation of electricity.

In the North German Basin temperature gradients are moderate. Therefore, deep drilling of several thousand metres is necessary to reach temperatures high enough for electricity production. However, the porosity of the sedimentary and crystalline rocks is not sufficient for hydrothermal projects, so that natural fracture zones have to be used or the rocks must be hydraulically stimulated. Furthermore, formation waters in the North German Basin are highly mineralised and can therefore cause compositional and structural alteration of well case materials. Precipitating minerals can even lead to clogging of wells and damage pumping equipment.

* Corresponding author. Tel.: +49-511-6433136; fax: +49-511-6433665.
E-mail address: barbara.hahne@liag-hannover.de

Peer-review under responsibility of the Austrian Academy of Sciences
doi:10.1016/j.egypro.2014.10.367

In order to make deep geothermal projects in Lower Saxony (Northern Germany) economically more attractive, the interdisciplinary research program “Geothermal Energy and High-Performance Drilling” (gebo) was initiated in 2009. It comprises four focus areas: Geosystem, Drilling Technology, Materials and Technical System. It aims at a significant increase of economic efficiency by introducing innovative technology and high tech materials as well as by optimising exploitation.

In this paper we give an overview of results of the focus area “Geosystem”, in which geological, geophysical, geochemical and thermo-hydraulic-mechanical (THM) modelling aspects of the geothermal reservoir are investigated. The nine sub-projects contribute to the research fields of geophysical exploration, drilling and stimulation, characterisation and THM-modelling of the reservoir. Thus, the projects offer different approaches leading to an improvement of geothermal exploration and exploitation as well as to a better understanding of the processes within geothermal reservoirs.

2. Projects on geophysical exploration

Among the main aims of our combined investigations is the development of an exploration strategy for fault systems. Combined seismic and geoelectrical investigations were carried out at the Leinetal Graben, a prominent fault system in the southernmost part of the North German Basin in Lower Saxony. This structure was chosen because it is cropping out at the surface, and it comprises typical rocks of the North German Basin. The measurements allow for a complex investigation of a North German setting for a geothermal reservoir, characterised by the presence of fault zones. Fault systems are considered as valuable hydrogeothermal reservoirs for energy extraction, as their permeability may be enhanced compared with the surrounding host rock.

2.1. Detection of fault zones using P- and SH-wave seismics

Several high-resolution seismic P-wave surveys were carried out along and across the eastern margin of the Leinetal Graben. Imaging ranges in depths from ~50 m (base Jurassic) to ~1.5 km (inside Zechstein). A westward dipping reflector which is very prominent in the P-wave images down to 400 m below sea level was chosen as target for additional SH-wave surveys. S-waves image the subsurface at higher resolution compared with P-wave surveys due to the shorter wavelengths of S-waves. Furthermore, they give additional information on rock properties as they propagate through the rock matrix only and are unaffected by pore fluids or gases, thus allowing for the determination of the shear modulus. In combination with P-wave measurements, the bulk modulus can be computed, as well as an estimate of porosity could be deduced.

The P-wave profiles image the Eastern bounding fault of the Graben and its deformed forefront with very high resolution. Outcrop locations of major fault segments match with geological information and surface field mappings. The roll over structure in the strongly deformed (folded and faulted) foreland provides an indication of tectonic inversion in the Graben (from early extensional to compressional regime).

The SH-wave profiles carried out for comparison show quite different behaviour in their reflectivity in depths of 200 m to 400 m below sea level (Fig. 1). While the westward dipping reflector is clearly visible in the P-waves, the SH-waves show only discontinuous reflections.

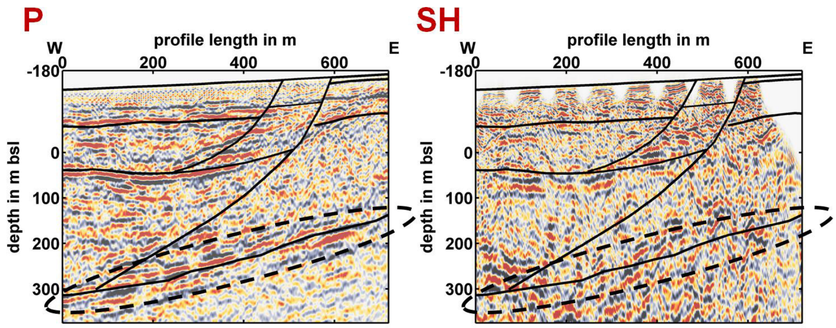

Fig. 1: Comparison of P- and SH-wave measurements along the same profile perpendicular to the eastern margin of the Leinetal Graben. While in the P-wave section a westward dipping reflector (marked by black dashed line) is very prominent, the same area in the S-wave section shows different reflection characteristics (also marked by black dashed line). Both profiles are shown unmigrated; bsl means below sea level.

2.2. Detection of fault zones with electric and electromagnetic methods

Fault systems are typically indicated by relatively low resistivity values if conductive minerals and/or brines within fractures are present. Electromagnetic methods are preferable to detect these zones, because they are highly sensitive to map these structures. Zones of maximum geoelectric "anisotropy" probably represent areas with strong fracturing or/and porosity containing hot mineral waters [1].

Very large-scale Direct Current (DC) measurements and transient electromagnetics were applied at the Leinetal Graben system for obtaining greater investigation depths. The electric and electromagnetic methods supplement the seismic method (see chapter 2.1) by imaging the underground structure with their ability to provide information about the resistivity, which is directly associated to the mineralisation of groundwater or hydrothermal fluids in the deeper subsurface.

The 2D inversion of the DC data reveals the main fault line of the Graben system but shows a smoothed resistivity distribution. Adding structural information to the inverse problem from reflection seismics, which is associated to lithologic changes, significantly improves the resistivity image. The DC resistivities show correlations to the fault segments and layers. The transient electromagnetic soundings approximate the local resistivity distribution and show especially layers with low resistivity. Due to this survey design the fault structure could be investigated up to depths of about 1 km. However, the DC method is not capable to resolve thin layers of low resistivity. To overcome this shortcoming, the combination with induction methods such as transient electromagnetic sounding is highly encouraged.

2.3. Hydraulic parameters from Induced Polarisation

Induced polarisation (IP) is a method to investigate the electrical parameters of the subsurface. The measurements are carried out with alternating current. Compared to the conventional DC method, an additional parameter, the phase shift between injected current and measured voltage, is obtained.

Laboratory studies and theoretical investigations suggest that the information obtained from IP measurements might be used to estimate hydraulic conductivity (e.g. [2], and references therein). Therefore, the method might be useful for geothermal exploration.

The transfer to geothermal problems requires an understanding of the IP effect at the pore scale itself, and the consideration of temperature dependence in particular. We carried out calculations of an analytical membrane polarisation model (based on the model of Marshall and Madden [3]) with the aim to evaluate existing equations and refine them for geothermal application. The work is based on earlier numerical simulation efforts [4,5] and on existing laboratory investigations which include temperature as a variable parameter [6].

Fig. 2 shows the phase shift of the spectral induced polarisation, depending on frequency and temperature for a polarisation model developed by Bücker and Hördt [7,8] and for a measurement at a sandstone sample. Both results show the same characteristics: there exists a maximum, and the frequency with the highest phase shift is increasing with increasing temperature. This means, the measurements can be explained qualitatively with the extended membrane polarisation model.

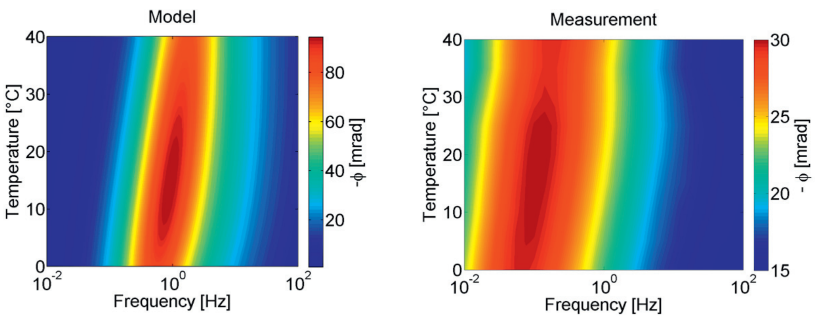

Fig. 2: Phase shift of the spectral induced polarisation, colour coded versus frequency and temperature. Left: modelled for a membrane polarisation model. Right: measured at a sandstone sample.

3. Projects on drilling and stimulation

3.1. Heterogeneous rock properties, drilling efficiency and fracture propagation

Heterogeneous rock properties in terms of layering and fault zone infrastructure are typical phenomena in sedimentary basins such as the North German Basin. To better adapt the drilling strategy for deep geothermal wells to the geological situation it is important to know the mechanical rock properties and the hydromechanical infrastructure of fault zones. Therefore, these properties were quantified by performing detailed structural geological field studies in outcrop analogues of all lithostratigraphic units from Permian to Cretaceous – supplemented by laboratory analyses of rock physical (mainly rock mechanical) properties and petrographic thin sections analyses.

The sub-project played a central role in the research association because for all the other projects it provided information on geological and rock physical topics. In particular, it was involved in planning the geophysical field measurements in the Leinetal

Graben (see chapter 2), provided data about the geological situation, the stratigraphy and typical rocks in the North German Basin and helped to create realistic geometries for numerical models.

Field studies on fault zones and layering show that there are clear differences between fault zones in sandstone and limestone, the most obvious being that limestone fault zones form wider damage zones than those with equal displacements in sandstones. The damage zone width seems to be related to the orientation of the fault zone within the regional stress field, and in terms of parallelism to major fault systems. That means, an outcrop-scale fault zone parallel to a major fault system develops a wider damage zone than one with perpendicular orientation.

Quantitative analysis of heterogeneous (i.e. layered) rocks shows that in rocks with distinctive layering fractures are often restricted to individual layers. This implies that the fractures are shorter than in more homogeneous rocks and are less likely to form a well-connected fracture network creating a continuous flow path through several layers. The probability of arrest/termination seems to depend on the stiffness contrast between two single layers and on the thickness of the softer layer [9].

The results of laboratory analyses of rock samples show that mechanical properties vary considerably between these samples due to differences in lithology, compaction, and cementation. Data are compiled in a database providing geomechanical and geophysical information on rocks of the North German Basin. Applicability of strengths data, derived from outcrop samples, for geothermal applications is checked using triaxial testing of core samples and equivalent samples from outcrops. Data show that geomechanical properties of outcrop samples are comparable to the properties of core samples if equivalence regarding facies and porosity is ensured [9,10].

3.2. Determination of seismic attenuation in geothermal reservoirs using induced seismicity

Within the scope of this project the monitoring of micro-seismic events and ambient seismic noise is investigated and extended in terms of exploring geometries and positions of hydraulically induced fractures and fracture systems.

Fluid injection causes perturbations of the pore pressure, which in turn provoke a change of effective stress. Exceeding a critical value such anthropogenic activities trigger or induce failures along pre-existing zones of weakness, which are accompanied by a release of elastic energy; that is the induced seismicity. Besides the use of microseismic monitoring as primary tool for fracture imaging (exact identification of the location of the geothermal reservoir), high-frequency seismograms of passive recordings also contain information on source mechanism, site amplification and propagation path (heterogeneity of the reservoir and intrinsic absorption within the reservoir).

We developed a new technique to extract useful information from the records of induced seismicity using the radiative transfer theory. The smoothed trace of the squared velocity seismogram – the “envelope” - is jointly inverted for the source, site and path effect. The approach is based on a physical model of the scattering process that considers the transport of energy through a statistically inhomogeneous medium. Estimating attenuation may significantly contribute to reservoir engineering by providing the geomechanical model with complementary parameters, whereas source parameters and site response might be capable to improve the reservoir model. By use of envelope inversion we are able to separate frequency-dependent contributions of intrinsic and scattering attenuation, which are differently sensitive to attributes such as lithology, fluid saturation, permeability or porosity.

To demonstrate the feasibility of this technique we analyzed passive seismic data acquired during a hydraulic fracturing treatment at the German Continental Deep Drilling Programme (KTB) site in 2000 (Fig. 3). For the North German Basin, unfortunately there exist no suitable data yet that we could analyze with this method.

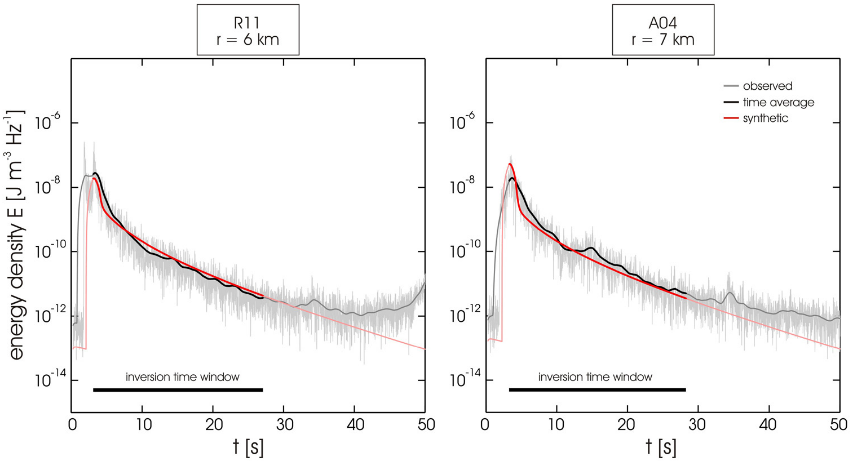

Fig. 3: Comparison of theoretical model curves, based on Radiative Transfer Theory, with measured seismogram envelopes obtained from fluid-induced seismicity at the KTB.

4. Projects on the characterisation of the reservoir

4.1. Hydrogeochemical processes in geothermal systems

The effectiveness of geothermal energy production from deep aquifers or hot dry rocks strongly depends on the natural hydrogeochemical characteristics of the reservoir (fluid-rock interaction) and the alteration of geothermal water induced by the interaction within the technical systems. The prediction of scaling and corrosion effects according to the composition of geothermal waters, their temperature and pressure gradients is based on the knowledge of the hydrogeochemical behaviour of the fluids. This behaviour strongly depends on the surrounding matter such as minerals, gases, organic material as well as technical equipment.

The natural and the technically influenced hydrogeochemical environments in deep aquifers of the North German Basin (useable for geothermal energy production) are characterised within this project, and the controlling hydrogeochemical processes within these environments are identified on the basis of hydrogeochemical thermodynamic modelling using the code PHREEQC [13] and appropriate thermodynamic data bases.

Fig. 4 shows a hydrogeochemical characterisation of North German formation waters with their typically high mineralisation. Total dissolved solids (TDS) in the formation waters of the North German Basin exhibit an increase with depth and temperature. Formation waters in deep aquifers of the North German Basin are characterised by pH values lower than 7 and dominated by the ions Na^+ and Cl^- or Na^+, Ca^{2+}, and Cl^-. Compared with surface groundwaters, they are also strongly enriched in most of the other elements, even trace metals such as Pb and Zn. Groundwaters in deep aquifers of the North German Basin contain high amounts of dissolved gases (e.g., N_2, CO_2, and CH_4) and are exposed to strongly reducing environments indicated by high concentrations of ammonium. The collected data base serves as a basis for hydrogeochemical modelling. In [18] modelling was performed for five wells of the North German Basin. The modelled results generally fit the measured concentrations in the sampled formation water, the residual sampled gas amount and contents, as well as the observed types of scaling.

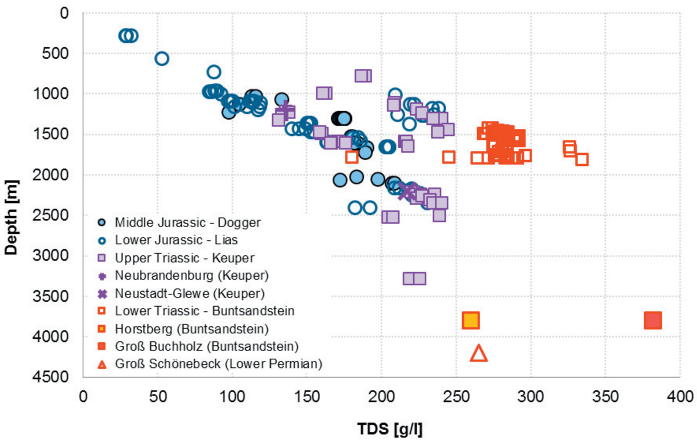

Fig. 4: Hydrogeochemical classification of geothermal systems in the North German Basin: TDS (total dissolved solids) versus depth. GeotIS data from [14], Neubrandenburg and Neustadt-Glewe: [15], Groß Schönebeck: [16], Horstberg and Groß Buchholz Gt1: [17].

4.2. Hydraulic, heat and tracer tests at wellbore and reservoir scale

Tracer techniques are relatively new in the deep geothermal field in Germany. The focus of this project is on the design and dimensioning of tracer tests of single-well and inter-well type, aimed at (1) early reservoir characterisation at 'new-wellbore' testing stages, (2) evaluating the performance of fracturing/stimulation treatments and (3) reservoir monitoring during long-term operation. Main questions are the determinability of important transport parameters and of their changes with time, the predictability of thermal breakthrough from early inter-well tracer test signals, and the contribution of tracer tests to assessing not only the thermal, but also the hydrogeomechanical and hydrogeochemical lifetime of a geothermal reservoir. More details on the use of artificial tracers as a tool for matrix and fracture characterisation are given in [12] in this issue. Therein it is shown how a tool for quantifying the individual frac discharge can be derived using only stable conservative tracers.

4.3. Hydromechanics of Geothermal Reservoirs

The stress field and the hydromechanical behaviour of a fracture in the vicinity of complex geological structures are characterised here on the basis of a geological 3D model. The structures are representative for North-West Germany, e.g. salt layers, salt diapirs and fault zones. Our objective is to improve the understanding of the hydromechanical processes during drilling and stimulation as these are essential for geothermal energy exploitation.

One aspect of the project was numerical modelling of fracture propagation during stimulation for diverse scenarios such as multiple layers with varying properties. Several layering and material properties encountered at the drill site “GeneSys” Groß-Buchholz Gt1 (Hanover, Northern Germany) were implemented with a single fracture and multiple fractures. The behaviour of a stimulated reservoir after fracturing is of great importance for the exploitation. The pressure needed to run continuous heat/power production depends on the hydromechanical interaction of the fracture with the surrounding rock.

Modelling results show that differences in elastic parameters such as Young’s modulus and Poisson’s ratio between the sedimentary layers do not seem to arrest fracture growth for the considered scenarios [11]. However, differences in elastic properties of material may reduce fracture aperture while traversing from a “softer” sedimentary rock layer into a “stiffer” sedimentary layer. Modelling results reveal that fracture toughness is a key parameter controlling fracture path. Scarce data on this parameter in the respective modes are available. Numerical modelling demonstrates that for low ratios of fracture toughness in mode I and II fracture deflection and switch of modes may occur at material interfaces and in general at material heterogeneities and discontinuities. Moreover, pre-existing fractures seem to heavily affect the spatiotemporal evolution of hydraulic fractures. In particular, pre-existing fractures initially inactive and oriented in some preferred direction appear to reactivate and overtake main fluid flow conduits as well as to grow in the direction of maximum shear.

5. Projects on modelling

5.1. Modelling of coupled thermo-hydro-mechanical processes in georeservoirs

Prediction of reservoir performance following stimulation and operation relies to a major extent on the modelling of groundwater flow, heat transport and the mechanical response of the reservoir to variable stresses. The interaction between the fluid conducting fractures and the rock matrix with the stored heat, the response of the borehole to the drilling process, the evaluation of hydraulic and transport characterisation tests, the optimisation of the well configuration, and the simulation of the long-term performance of the reservoir are typical modelling tasks.

Fig. 5 shows results for a flow regime of a model containing typical sedimentary layers of the North German Basin as well as a fault zone. Streamlines originating from outer boundaries are given in blue colour, while red streamlines indicate the circulating flow from the injection into the permeable layer to the production in the fault zone. Obviously a complex doublette flow is initiated, which follows the course of the layers.

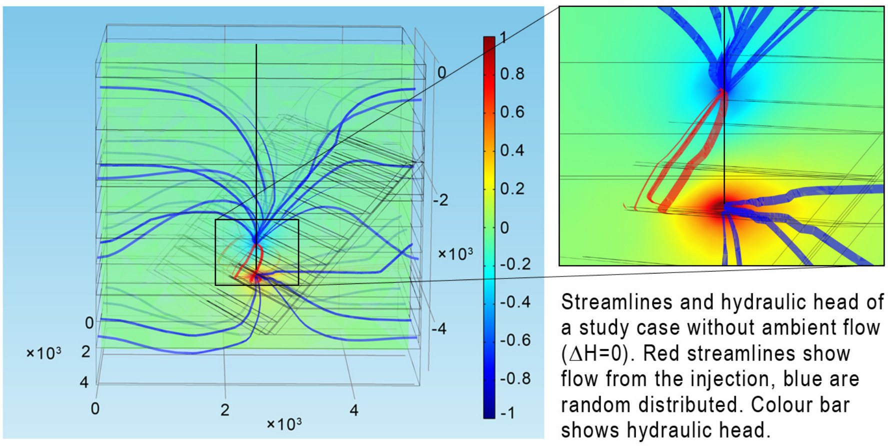

Fig. 5: Simulated flow regime for a single borehole “pump & inject” installation in connection with a fault zone. The model is a block of 5 km x 5 km x 5 km with sedimentary layers. The vertical line at the center is the borehole which penetrates the dipping fault zone.

6. Conclusions

We present the work of nine geoscientific sub-projects of the research association gebo. These sub-projects investigate geothermal reservoirs and the role of fault systems with various geophysical, geological, geochemical and numerical methods. The geological project plays a central role as it supplies all other projects with information on geological and rock physical aspects typical of the North German Basin. The projects are interconnected in terms of providing e.g. structural information from seismic measurements as constraint for inversion of geoelectrical data, geochemical information that influence tracer propagation, or co-operation concerning fracture and deformation modelling.

Thus, the projects offer diverse approaches that lead to an optimisation of the exploration and exploitation of deep geothermal reservoirs as well as a better understanding of the complex processes within the reservoir itself.

Acknowledgements

The collaborative research association gebo is funded by the Ministry of Science and Culture of the Federal State of Niedersachsen and the industry partner Baker Hughes (Celle, Germany).

The **team gebo-Geosystem** are: E. Holzbecher, S.L. Philipp, D. Reyer, I. Ghergut, M. Sauter (University of Göttingen), D. Fielitz, U. Wegler, (BGR, Hanover), K. Bairlein, A. Hördt (TU Braunschweig), E. Bozau, W. van Berk (TU Clausthal), H. Buness, M. Grinat, T. Günther, B. Hahne, E. Meneses Rioseco, G. Schaumann, R. Schellschmidt, R. Thomas, B. Wawerzinek (LIAG, Hanover).

References

[1] Bujakowski W, Barbacki A, Czerwinska B, Pajak L, Pussak M, Stefaniuk M, Trzesniowski Z. Integrated Seismic and Magnetotelluric Exploration of the Skierniewice, Poland, Geothermal Test Site. Geothermics 2010; 39:78–93.
[2] Hördt A, Blaschek R, Binot F, Druiventak A, Kemna A, Kreye P, Zisser N. Case Histories of Hydraulic Conductivity Estimation with Induced Polarisation at the Field scale. Near-Surface Geophysics 2009; 7:529-545.
[3] Marshall D, Madden T. Induced polarization, a study of its causes. Geophysics 1959; 24(4):790816.
[4] Blaschek R, Hördt A. Numerical modelling of the IP-effect at the pore scale. Near-surface Geophysics 2009; 7:579-588.
[5] Volkmann J, Klitzsch N. Frequency dependent electric properties of microscale rock models from one millihertz to ten kilohertz. Vadose Zone Journal 2010; 858-870.
[6] Zisser N, Kemna A, Nover G. Dependence of spectral induced polarization response on temperature and its relevance to permeability estimation. J. Geophys. Res. 2010; 115, B9, DOI: 10.1029/2010JB007526.
[7] Bücker M, Hördt A. Analytical modelling of membrane polarization with explicit parametrization of pore radii and the electrical double layer. Geophys. J. Int. 2013; doi: 10.1093/gji/ggt136.
[8] Bücker M, Hördt A. Long and short narrow pore models for membrane polarization. Geophysics 2013; 78:E299-E314.
[9] Reyer D, Bauer JF, Philipp SL. Fracture Systems in Normal Fault Zones Crosscutting Sedimentary Rocks, Northwest German Basin. Journal of Structural Geology 2012; 45:38-51. doi:10.1016/j.jsg.2012.06.002.
[10] Reyer D. Outcrop Analogue Studies of Rocks from the Northwest German Basin for Geothermal Exploration and Exploitation: Fault Zone Structure, Heterogeneous Rock Properties, and Application to Reservoir Conditions. PhD thesis, University of Göttingen, 2014.
[11] Meneses Rioseco E, Reyer D, Schellschmidt R. Understanding and Predicting Coupled Hydro-Mechanical Fracture Propagation. European Geothermal Congress, Pisa, Italy, 2013.
[12] Ghergut I, Behrens H, Sauter M. Tracer-Based Quantification of Individual Frac Discharge in Single-Well Multiple-Frac Backflow: Sensitivity Study. Energy Procedia 2014; this issue.
[13] Parkhurst DL, Appelo CAJ. User's guide to PHREEQC (version 2)—a computer program for speciation, batch-reaction, one dimensional transport, and inverse geochemical calculations. US Geological Survey, Water Resources Investigations Report 99-4259, Washington, DC 1999.
[14] Schulz R, GeotIS-Team. Der Endbricht zum Projekt „Aufbau eines geothermischen Informationssystems für Deutschland". 2009; http://www.geotis.de/homepage/Ergebnisse/GeotIS_Endbericht.pdf.
[15] Kühn M, Niewöhner C, Isenbeck-Schröter M, Schulz H-D. Determination of major and minor constituents in anoxic thermal brines of deep sandstone aquifers in Northern Germany. Wat. Res. 1998; 32:265-274.
[16] Seibt A. Die Zusammensetzung des Reservoir-Fluids. GFZ-Report STR04/16, 25-27, 2004.
[17] Hesshaus A, Houben G, Kringel R. Halite clogging in a deep geothermal well – geochemical and isotopic characterisation of salt origin. Physics and Chemistry of the Earth 2013; 64:127-139.
[18] Bozau E, van Berk W. Hydrogeochemical Modeling of Deep Formation Water Applied to Geothermal Energy Production. Procedia Earth and Planetary Science 2013; 7:97-100, doi: 10.1016/j.proeps.2013.03.006.