European Geothermal Congress 2013
Pisa, Italy, 3-7 June 2013

# Outcrop Analogue Studies in Geothermal Exploration – 'AuGE' Project

René Grobe[1], Axel Wenke[1,2], John Reinecker[1], Torben Kissner[3], Georg Miernik[3], Dominik Soyk[3], Silke Meier[4], Johanna Bauer[4], Maria Fensterer[5], Thilo Bechstädt[6,7], Sonja Philipp[4], Harald Stollhofen[5], Horst Kreuter[1]

[1] GeoThermal Engineering GmbH, Baischstraße 7, 76133 Karlsruhe, Germany

[2] Statoil ASA Nord-Norge, Molnholtet 42, 9414 Harstad, Norway

[3] Institute of Earth Sciences, Heidelberg University, INF 234, 69120 Heidelberg, Germany

[4] Geoscience Centre Göttingen, Goldschmidtstr. 3, 37077 Göttingen, Germany

[5] GeoZentrum Nordbayern, Friedrich-Alexander Universität Erlangen-Nürnberg, Schlossgarten 5, 91054 Erlangen, Germany

[6] Jagiellonen University, ul. Gołębia 24, 31-007 Kraków, Poland

[7] GeoResources Steinbeis Transfer Center, INF 234, 68120 Heidelberg. Germany

Corresponding Author: Grobe@Geo-T.de

**Keywords:** Upper Rhine Graben, deep geothermal exploration, integrative outcrop analogue studies, reservoir characterization, seismic attribute analysis.

## ABSTRACT

Despite its undoubted deep geothermal potential projects in the Upper Rhine Graben and successful deep drillings are scarce compared with other geothermal regions in Germany (e.g. the Molasse Basin).

The current paper introduces the joint research project 'Outcrop Analogue Studies in Geothermal Exploration – AuGE'. The project aims to develop standardized workflows for outcrop analogue studies tailored to the needs of geothermal exploration. This will improve predictions of flow rate and heat transfer within the reservoir and decrease both exploration risk and cost to encourage geothermal project development within this region.

Project partners are the Universities of Erlangen, Goettingen and Heidelberg as well as the industrial partners GeoEnergy and GeoThermal Engineering. The project is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the framework of the 5th Energy Research Programme (FKZ 0325302).

The geologic structure of the Upper Rhine Graben exhibits deeply buried sediments within the centre of the Graben that are also exposed on the Graben shoulders within short distances. This offers ideal conditions for outcrop analogue studies.

The applied multi-method approach combines (i) lithofacies analysis and determination of petrophysical properties, (ii) examination of diagenetic processes, (iii) characterization of fault zones, (iv) LiDAR based 3D reservoir modelling, (v) seismic attribute analysis and (vi) analysis of well data.

Results will be integrated in 'shared earth models' enabling to conduct reservoir thermo-hydraulic simulations to predict fluid flow and heat transport for varying production scenarios. The extensive integration of methods applied and their implementation in geothermal exploration strategies enhances thermo-hydraulic simulations and therefore the reliability of predictions of both flow rate and heat transport. This will significantly reduce not only exploration risk but also cost and contribute to expand the development of geothermal projects in the Upper Rhine Graben.

## 1. INTRODUCTION

The Upper Rhine Graben (URG) exhibits a well-known deep geothermal potential supposedly bigger than that of the Alpine Molasse Basin. However the number of successful deep geothermal drillings in the Molasse Basin exceeds considerably the number of successful drillings in the URG.

Multiple prospective reservoir formations, a complex fault block structure and recent tectonic activity increase the exploration risk significantly yet open also chances and opportunities for geothermal use.

A successful geothermal use of the deep underground depends on the thermophysical and petrophysical properties of the reservoir rocks that determine i.a. heat capacity, heat flux and the circulation of thermal water.

Outcrop analogue studies are one powerful tool to characterize reservoir rocks and provide an integrative reservoir characterization from surface observations and should form part of each geothermal exploration concept if applicable. Consideration of outcrop analogues allows the basic assessment of the suitability of a formation as a reservoir rock, the choice of further suitable geophysical exploration concepts and parameters and gives ideas of the outcomes to be expected. Finally, a more robust input data base for thermo-hydraulic models will improve predictions of thermo-hydraulic simulations and provide evidence for sophisticated well path design.

The current joint R&D project represents an integrative approach to include comprehensive outcrop information directly and indirectly in geothermal exploration. Involved project partners are the Universities of Erlangen, Goettingen and Heidelberg as well as the industrial partners GeoEnergy and GeoThermal Engineering.

## 2. METHODS AND TECHNIQUES

Research area is the URG with its reservoir formations Muschelkalk, Bunter Sandstone, Permo-Carboniferous and basement rocks. Focus is on (i) reconstruction of basin development and facies distribution, (ii) intra-formation petrophysical properties of individual reservoir formations (micro-, macroporosity/permeability, thermal properties, fracture propagation and shearing behaviour) (iii) investigation of diagenetic processes and their impact on the properties of individual reservoir formations, (iv) fracture behaviour of individual reservoir formations within fault zones and with regard to recent local tectonic stress, (v) correlation of outcrop data with geophysical borehole and seismic data and (vi) determination of thermo-hydraulic parameters.

It is intended to integrate results of the following key techniques in ‘shared earth models’ of key outcrops and to transfer to and compare with the models of several ongoing geothermal projects in different stages in the URG.

### 2.1 Lithofacies analysis and petrophysical properties

A certain reservoir formation can be build-up of varying lithofacies types with varying thermophysical and petrophysical properties that in turn affect all favoured and non-favoured rock properties for geothermal use. One of the first steps in the current outcrop analogue studies is a detailed appraisal, mapping and classification of the present lithofacies types.

In the next steps petrophysical and thermophysical properties are conducted. Were applicable both in-situ and by lab measurements as well as in different scales (outcrop scale, sample scale, micro scale). We measure ultrasonic velocities, gamma ray, porosity, permeability and thermal conductivity.

Dependencies of petrophysical properties and lithofacies types are evaluated and a comparison between in-situ and lab measurements is carried out. Objective is to test if robust data of certain rock properties can be acquired by large-scale in-situ measurements rather than by extensive and costly lab measurements.

### 2.2 Diagenesis

Diagenetic processes of lithofacies types also affect the geothermal suitability of a reservoir formation. Therefore, this part of the current project aims at the understanding of diagenetic processes and potential fluid migration between faults and reservoir (hydraulic linkage).

We use thin-section, cathodoluminescence and scanning electron microscopy as well as fluid inclusion analysis, X-ray diffractometry, stable and radiogenic isotopes (C, O, Sr) analysis.

These techniques contribute to facies analysis, petrography, zonation analysis, revelation of cementation sequences, microthermometry, compaction and pore space analysis.

Outcomes provide information i.a. on cementation sequences as proof for hydraulic linkage, regional diagenesis trends and temperature gradient from cementation sequences, microthermometry and fault zone-specific diagenesis.

### 2.3 Characterization of fault zones

Hydrothermal geothermal projects within the URG rely on sufficient flow rate governed by increased permeability of the fractured reservoir rocks. In most cases matrix permeability alone will not be able to provide the flow rates necessary.

Thus, comprehension and characterization of fault zones with respect to the accordant reservoir formation and even lithofacies type is one key step in understanding and characterizing the reservoir.

Infrastructure and structural composition of fault zones is performed by outcrop observations. We classify fault zones into hydromechanical units (i) fault core, (ii) damage zone with increased fracture density and (iii) transition zone to host rock (Braathen and Gabrielsen 2000, Caine et al. 1996). The fracture network is characterized by orientation, fracture density with respect to fault core considering hanging wall and footwall, interconnectedness of fractures, termination of fractures (ratio of stratabound to non-stratabound fractures).

Also the mechanical properties are assessed by in-situ tests and lab experiments on representative rock samples. We address compression tests for uniaxial compressive strength and static Young´s modulus as well as Brazilian test to determine the tensile strength.

Rebound hardness is measured in-situ with a “Schmidt-Hammer” and is empirically transformed to compressive strength. These predictions of compressive strength from in-situ measurements are compared with robust results from lab experiments to evaluate their accuracy. Measuring the rebound hardness allows to compile detailed maps for mechanical properties of fault zones.

Measured data will be used for numerical models of fault zones and integrated in 'shared earth reservoir models' in the further course of the project.

### 2.4 LiDAR based 3D reservoir modelling

Terrestrial LiDAR scanning of key outcrops combined with photography provides high-resolution 3D Digital Outcrop Models (DOMs) on which interpretation of depositional planes, geometries and fractures will be performed. In addition development of automated fracture detection is in progress. Results will be compared and calibrated with field observations from structural analysis and serve as additional input quantity for integrated models, i.e. hydraulic simulations and final reservoir models.

### 2.5 Seismic attribute analysis

At the latest from the advent of considerable computing power sophisticated seismic attribute analysis is a default tool in the exploration and production (E&P) of hydrocarbons. It goes therefore without saying that the use of seismic attributes could add value to seismic interpretation for geothermal exploration. An extensive amount of publications is available on description and classification of seismic attributes. Chopra and Marfurt (2005) is one of numerous publications as introduction to this field.

However, all seismic attributes are based on the primary attributes stored in seismic information, i.e. time, amplitude, frequency and phase. Taner et al. (1994) suggested a division of attributes in two general categories: (i) geometrical and (ii) physical. Combining various attributes by displaying them at the same time (composite attributes) or in a more sophisticated approach by further weighting them using geostatistics, neural networks or other technology (meta attributes; Chopra and Marfurt 2005) increases the number of available attributes almost indefinitely.

Identifying a proper attribute as property predictor that actually correlates with the (rock) property of interest in the seismic data by avoiding false correlation is the challenge of attribute analysis. Typically two types of errors are associated with attribute analysis (Chambers et al. 2002):

(i) Type I error: attribute is selected but correlation is not given.

(ii) Type II error: attribute is not selected although true correlation exists.

Another particular challenge in geothermal exploration and the use of seismic attributes analysis is the commonly much less extensive data set in terms of borehole data in contrast to hydrocarbon E&P. Sparse borehole data increases difficulties in calibrating results from attribute analysis.

Currently we focus our approach on using geometric attributes, i.e. polar dip, similarity and curvature for advanced fault and fracture detection. In a subsequent step we test to combine geometrical with physical attributes that expectedly best correlate with the physical properties of areas with high structural permeability. We assume these areas to be highly fractured with the presence of a fluid phase both affecting the seismic signal.

It is intended to compare results with predicted areas of increased permeability in extensive/transtensive fault zones from geomechanical modelling as independent control as far as borehole or other independent data are not available.

### 2.6 Well data

We analyse vintage and recent borehole geophysical data as well as drill cores data to obtain robust subsurface information on petrophysical, thermophysical and structural properties of reservoir rocks. Application of additional non-standard tools for geophysical data acquisition during current exploration drillings will allow a more detailed and broader structural analysis as well as a clear identification of extensive/transtensive and potentially permeable fracture systems. Well data form therewith the required link to get from surface to subsurface and are essential to calibrate and transfer outcrop observations to reservoir conditions.

### 2.7 Integration / 'Shared Earth Models'

Finally the entire information collected is integrated in 'shared earth models' of key outcrops and geothermal reservoirs. Shared earth models contain static geological model as well as reservoir simulation model enabling to conduct reservoir thermo-hydraulic simulations to predict fluid flow and heat transport for varying production scenarios.

## 3. CONCLUSIONS & OUTLOOK

Outcrop analogue studies are well established in the E&P of hydrocarbons and provide valuable information for improved reservoir characterization. The extensive integration of methods applied and their implementation in geothermal exploration strategies within the frame of the current project enhances thermo-hydraulic simulations and therefore the reliability of predictions of both flow rate and heat transport. This will significantly reduce not only exploration risk but also cost and contribute to expand the development of geothermal projects in the Upper Rhine Graben.

## REFERENCES

Braathen, A. and Gabrielsen, R.H.: Bruddsoner i fjell - oppbygning og definisjoner, *Gråsteinen*, **7**, (2000), 3-22 (in Norwegian).

Bauer, J. F., Meier, S., Philipp, S. L.: Infrastruktur von Störungszonen im Buntsandstein des Oberrheingrabens – Aufschlussanalogstudien, *Tagungsband „Der Geothermiekongress 2012“*, Karlsruhe, Deuschland, (2012).

Caine, J.S., Evans, J.P. & Forster, C.B.: Fault zone architecture and permeability structure, *Geology*, **24**, (1996), 1025-1028.

Chambers, R.L. and Yarus, J.M.: Quantitative Use of Seismic Attributes for Reservoir Characterization, *CSEG RECORDER*, **27**, 6, (2002), 14-25.

Chopra, S. and Marfurt, K.J.: Seismic attributes – A historical perspective, *Geophysics*, **Vol. 70**, No. 5, (2005), 3-28.

Fensterer, M., Schöner, R., Stollhofen, H.: Einfluss der Faziesarchitektur auf die Petrophysik geothermischer Reservoir-Analoga (Buntsandstein), *Tagungsband „Der Geothermiekongress 2012“*, Karlsruhe, Deuschland, (2012).

Kissner, T., Miernik, G., Zühlke, R.: Projekt AuGE – LiDAR basierte 3D Reservoirmodellierung zur Analyse geothermischer Potentiale. Tagungsband „Der Geothermiekongress 2012“, Karlsruhe, Deuschland, (2012).

Meier, S., Bauer, J. F., Philipp, S. L.: Charakterisierung von Störungszonen im Muschelkalk des Oberrheingrabens – Aufschlussanalogstudien, *Tagungsband „Der Geothermiekongress 2012“*, Karlsruhe, Deuschland, (2012).

Soyk, D., Bechstädt, T.: Diagenese von Geothermie-Reservoiren im Oberrheingraben und deren Aufschlussanaloga, *Tagungsband „Der Geothermiekongress 2012“*, Karlsruhe, Deuschland, (2012).

Taner, M. T., J. S. Schuelke, R. O'Doherty and Baysal, E.: Seismic attributes revisited: *64th Annual International Meeting*, SEG, Expanded Abstracts, (1994), 1104–1106.

## Acknowledgements

We thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) for funding the current project within the framework of the 5th Energy Research Programme (FKZ 0325302).