Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Fluid-Rock Interaction in Deep Fault Systems and the Influence on Permeability in Typical Rocks of the Upper Rhine Graben, Southwest Germany

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Keywords: fluid-rock interaction, Upper Rhine Graben, Black Forest, fault systems, geothermics

ABSTRACT

Deep-seated fault systems play an important role for deep geothermal applications, particularly in volcanically inactive regions with low matrix permeability. Faults can be significant for convective heat transport. Therefore, the permeability within a fault zone is a crucial parameter for an efficient geothermal usage, if the matrix permeability of the aquifer is low. Its magnitude varies substantially with depth and pressure, rock composition, fluid chemistry, and thermal properties. Additionally, permeability can vary significantly through a cross section of a fault.

A selection of typical aquifer rocks of the Upper Rhine Graben (URG) were chemically-mineralogically investigated and characterized. Additionally, we examined the hydraulic properties (i.e., porosity and permeability) of undeformed rock material. Mechanical rock investigations were carried out to determine the physical rock features and delineate fresh and/or artificial faults. Chemical and mineralogical investigations are performed, since mineral precipitation and roughness have a significant influence on the geomechanical model, the permeability of the fault zone and consequently on the efficiency of geothermal applications. Fluid-rock interaction experiments were conducted with an autoclave on fresh fracture surfaces. We used synthetic fluids similar to fluids of the Upper Rhine Graben in greater depth. The results gathered from laboratory experiments will be compared with the observations of natural fault systems by cores from deep boreholes and abandoned mines of the Black Forest. Further experiments on the samples of the fault systems will be conducted in the laboratory and in-situ. We present here the first results of an ongoing project.

1. INTRODUCTION

Deep-seated fault systems play an important role in deep geothermal application, particularly in volcanically inactive regions with low natural permeability. Faults can be significant for convective heat transport. Therefore, the permeability within a fault zone is one of the crucial parameters for an efficient geothermal usage.

Analyzing a cross section through a fault demonstrates significant variation in permeability and rock strength. Generally outer parts of a fault consist of coarse rock fragments, whereas inner parts are mostly composed of fine ground-altered rock material. Furthermore, parameters to characterize fault zones are influenced by fluid-rock interaction such as dissolution, replacement reactions, and mineral precipitation. Previous research in this tectonic setting (URG) proved that the hydraulic and geomechanical behavior of geothermal reservoirs mainly depend on the lithology, structural evolution, and alteration processes.

In our research, typical aquifer rocks will be chemically-mineralogically characterized and hydraulic properties (i.e., porosity and permeability) of undeformed and deformed rock material will be examined. Fluid-rock interaction experiments will be carried out to investigate alteration processes. The results of the laboratory experiments will be compared with observations on natural fault systems in pits and adits of the Black Forest. Additional experiments with samples from the fault systems will be conducted in the laboratory and in-situ. This ongoing research serves a purpose for a better understanding and prediction the efficiency of geothermal applications in the Upper Rhine Graben.

2. AQUIFERES IN THE UPPER RHINE GRABEN

In the URG in southwestern Germany mainly three different types of aquifers are relevant for geothermal applications. The usually low permeable crystalline bedrock mainly consists of granites and gneisses. Sedimentary rocks of the Lower Triassic Buntsandstein are primarily composed of clayey-calcitic and silica-cemented medium- to coarse-grained sandstones. Shell-bearing as well as crystalline and micritic limestone of the Muschelkalk occurs in the Middle Triassic. A minor aquifer is the Middle Jurassic Hauptrogenstein, which is also a limestone unit. In the northern part of the Upper Rhine Graben deeper laying Cenozoic sediments could also be of importance (Stober, 2013).

2.1 Crystalline Basement

The crystalline basement of the URG and the Black Forest is mainly composed of Variscan granites and gneisses. Subordinate Permian rhyolitic volcanics and porphyroblasts are also present. For this study the Malsburg granite from the southern Black Forest is presumed as a representative lithology for the crystalline basement. It has a homogeneous structure and an equigranular grain size distribution with relatively small grain sizes (1–2 mm). The intensity of wall-rock alteration is usually low. The Malsburg granite is a biotite granite to granodiorite, composed of quartz, plagioclase, K-feldspar, and biotite (Figure 2a,b) with accessory apatite and zircon, and minor hornblende. Secondary phases are muscovite, chlorite, epidote, and magnetite (Zimmerle, 1958). The age of the intrusion is determined as 309 Ma (Emmermann, 1977).

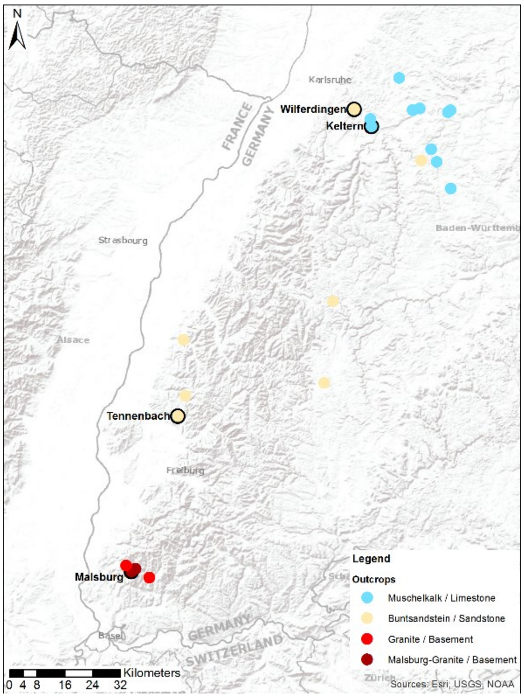

Figure 1: Locations of rock samples for this study. Malsburg granite is from Malsburg, southern Black Forest. Tennenbacher sandstone is from Tennenbach near Emmendingen, southern Black Forest. Pfinztäler sandstone is from Wilferdingen, northern Black Forest. Limestone is from Keltern near Pforzheim, northern Black Forest.

2.2 Buntsandstein

The reservoir layers of the Buntsandstein are composed mainly of sandstones with local gravel and clay layers. For our investigations we selected two sandstones, the Tennenbacher sandstone and the Pfinztäler sandstone (Figure 1).

The Tennenbacher sandstone is a silica-cemented sandstone of the Lower Buntsandstein. The lower layers of the quarry are composed of thick homogenous bands without any cross-bedding with almost no clay inclusions. It is a coarse- to medium-grained sandstone with an equigranular grain size distribution of 1–2 mm (Figure 2c). Its components are mostly quartz with small amounts of sericitized feldspar and accessory hematite. The quartz grains are well-rounded and bounded on relatively small areas of the grain surfaces (Figure 2d). Thus, the porosity of the rock is high and the hardness is limited. The Tennenbacher sandstone is reddish in color due to very low amounts of hematite, which is concentrated in few areas between the quartz grains.

The second sandstone unit is the Pfinztäler sandstone from the Upper Buntsandstein. It is finely cross-bedded. The composition is quartz, relatively high amounts of feldspar (sericitized), and muscovite. The quartz and feldspar grains are not well-rounded and they are elongated along bedding planes (Figure 2e), similar to the muscovite grains. The red color originates from hematite which is more commonly present in the Pfinztäler sandstone compared to the Tennenbacher sandstone. The Pfinztäler sandstone is highly compacted, has a low porosity (Figure 2f) and is consequently relatively hard.

2.3 Muschelkalk

The limestone descends from a quarry in the northern Black Forest near Keltern (Figure 1). Thick layers (tens of centimeters thick) are composed of three different types of limestone, which is not really distinguishable in the scale of broken blocks. On fresh sawed surfaces and under the microscope we identified shell-bearing parts (Figure 2g) from parts with no shells. The shell pieces are embedded in an extremely fine-grained matrix. There are two varieties of shell-free limestone; coarse-grained (0.5 mm) and fine-grained (< 0.3 mm), which are also clearly separated from each other (Figure 2h). The color of the rock is dark grey with yellowish schlieren, independent of the type of the grains. The rock is relatively hard and cracks splintery.

2.4 Fluid chemistry

Groundwaters in the URG above 500 m depth are low mineralized. The chemistry is strongly influenced by the rock geochemistry, such that the composition of the water in the limestone aquifers is dominated by Ca and HCO_3. The amount of total dissolved solids (TDS) increases with increasing depth and individual waters of different aquifers develop into a Na-Cl-type, independent of the surrounding rock. The high salinity of the aquifers has different sources and is linked to deep circulation-systems. Therefore, deep Buntsandstein waters are strongly influenced by upwelling deep waters of the crystalline basement, which are rich in NaCl (Figure 3). Deep waters within the Upper Muschelkalk aquifer are influenced by upwelling waters from the Middle Muschelkalk with halite deposition. All waters are saturated with respect to calcite and some other minerals such as quartz or barite (Stober & Bucher, 1999; Stober, 2013).

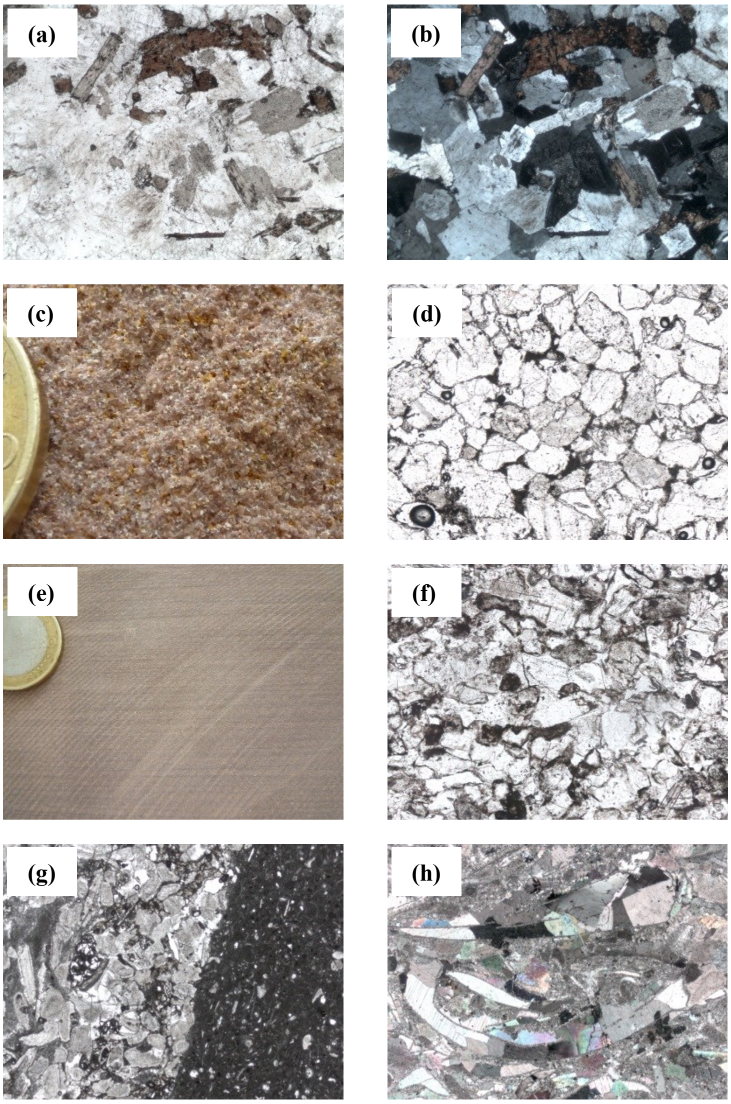

Figure 2: Photos of rock samples analyzed in this study: (a) microphotograph of the Malsburg granite (polarized light, image width: 4.8 mm), (b) microphotograph of the Malsburg granite (cross-polarized light, image width: 4.8 mm), (c) macroscopic image of the Tennenbacher sandstone, (d) microphotograph of the Tennenbacher sandstone (polarized light, image width: 3.0 mm), (e) macroscopic image of the Pfinztäler sandstone, (f) microphotograph of the Pfinztäler sandstone (polarized light, image width: 1.2 mm), (g) microphotograph of the fine and coarse crystalline parts of the Keltern limestone (polarized light, image width: 4.8 mm), (h) microphotograph of the shell-bearing part of the Keltern limestone (cross-polarized light, image width: 4.8 mm).

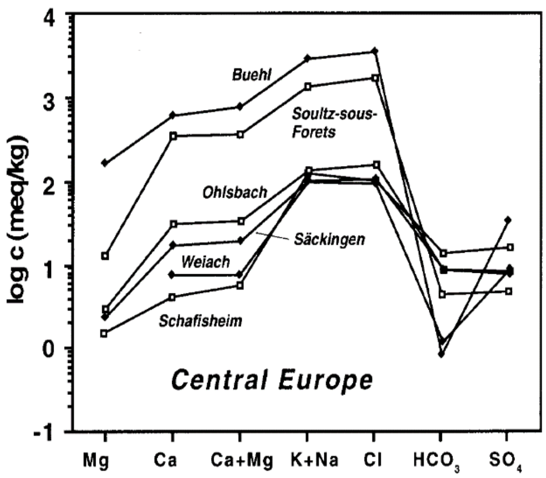

Figure 3: Hydrochemistry of waters in deep crystalline basement rocks in central Europe (URG, Black Forest, N Switzerland), which are dominated by Na and Cl (Bucher & Stober, 2000).

3. HYDRAULIC TESTS

The permeability and porosity of the rock samples representing typical reservoir rocks of the URG were measured to obtain the starting values of the hydraulic behavior of ideal, homogenous, non-fractured and undeformed rock samples, and matrix permeability. We compare these results with the permeability and porosity measurements of artificially-produced faults in the laboratory (high p-T triaxial tests, autoclave experiments) and the values of different natural fault zones in drilling cores and mines in the Black Forest. The aim is to get an idea of the hydraulic properties of fault systems in greater depth with the background of a usage as reservoir for deep geothermal applications.

The permeability of the sandstones were determined by water permeameter tests. First results are $4.3x10^{-9}$ m/s for the Tennenbacher sandstone. The Keltern limestone and the Malsburg granite have permeability values lower than 10^{-10} m/s but the exact values could not be determined by the water permeameter tests. Our results fit well with the permeability data of the URG (Figure 4) carried out by the oil industry and evaluated by Jodocy & Stober (2011).

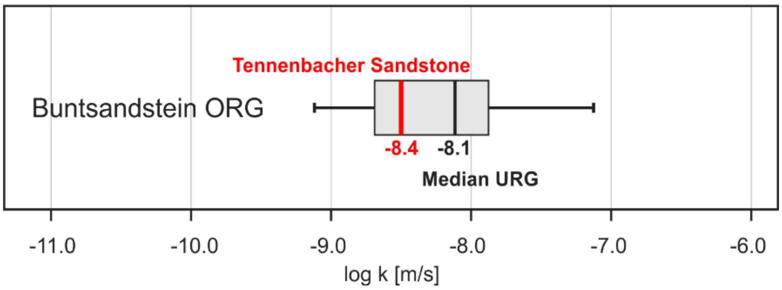

Figure 4: Permeability of the Buntsandstein (core samples) in the URG (data from Jodocy & Stober 2011).

4. WATER-ROCK INTERACTION IN THE LABORATORY

Water-rock interaction will be simulated in laboratory experiments to investigate the influence of fluid chemistry, temperature, and pressure on the permeability of fault zones within the three reservoir lithologies, respectively. We recently carried out experiments with a maximum temperature of 200°C as observed in some reservoirs in the URG (e.g., geothermal power plant of Soultz-sous-Forêts; Pauwels et al., 1993). Additionally, we plan to increase temperatures and pressure, and change the fluid chemistry (i.e., carry out experiments with CO_2 saturation), amount of total dissolved solids, and ion composition. During our first experiments pressure was not adjusted manually, but was defined by the increase of the fluid volume in the autoclave due to heating.

The rock sample will be analyzed to determine solution of mineral phases, ion exchange of existing crystals, precipitation of additional phases, change in the bulk chemistry, and modification of the surface roughness. Changes in fluid characteristics will also be determined in terms of solutes, TDS, and pH.

The preliminary test of fluid-rock interaction of the Malsburg granite with 2 molar NaCl-solution was conducted over a period of 34 days to get an idea of the kinetics of the chemical reactions. The rock sample consists of a cylinder with a diameter of 4.5 cm, which was broken to get a fresh surface representing an artificial fault surface. The roughness of the sample after the autoclave experiment will be compared with the negative piece of the cylinder. As a first result, the granite sample shows a slight alteration of biotites with precipitation of a light greenish phase onto biotite crystals (Figure 5). Future experiments will involve other rock samples, and will be conducted with changing temperature and pressure values, CO_2 saturation, fluid solutes, and concentrations.

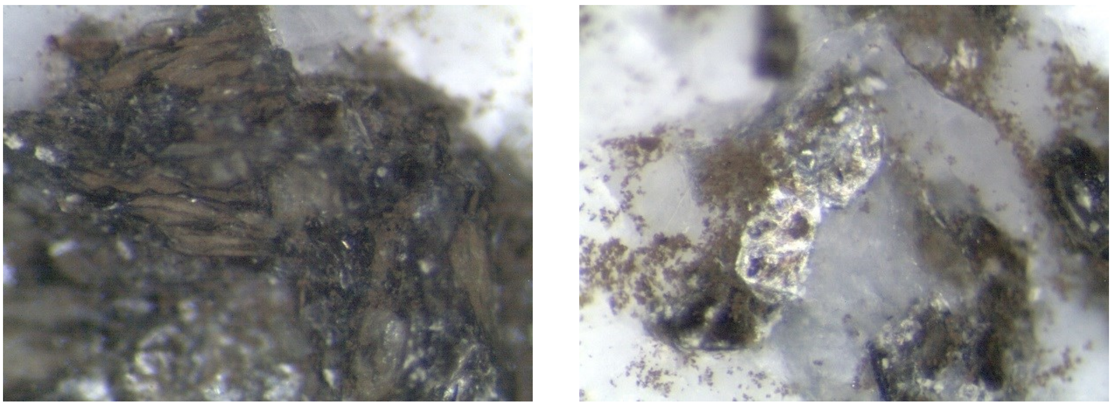

Figure 5: Binocular images of the Malsburg granite after the autoclave experiment with 2 molar NaCl fluid at 200°C and about 15 bars for 34 days. Left: Alteration of biotite (image width: 2 mm). Right: Precipitation/replacement reaction of a light greenish secondary mineral phase on a biotite crystal (image width: 1.5 mm). The brown particles are unconsolidated alteration products of the autoclave vessel.

5. CONCLUSIONS

The sample selection and preliminary experiments give us starting values for the upcoming experiments during the ongoing research project. The results will be compared with the results of future experiments and with in-situ experiments in natural fault systems. Current results will be presented in the conference.

AKNOWLEDGEMENTS

The project StörTief (deep fault zones) is supported by the German Federal Ministry for Economic Affairs and Energy (BMWi, no: 0325623C).

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