Geomechanical Facies Concept in Exploration Techniques of EGS Sites, Soultz-sous-Forêts and Spa Urach

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ABSTRACT

Using the holisitic geomechanical facies concept as a framework, this paper compares techniques for major exploration, evaluation and field development at two European geothermal projects: Soultz-sous-Forêts, in the central part of the Upper Rhine Graben; and Urach Spa, in the South German crystalline complex.

Since 1971 the Hot Dry Rock/Hot Wet Rock (HDR/HWR) concept has been developed from the conceptual stage to the point where the feasibility of the technology has been demonstrated. The HDR concept has been adapted to fit the natural in-situ conditions of the rock and exemplifies one type of Enhanced Geothermal Systems (EGS) development. Significant developments have been made in drilling, borehole measurements and understanding the processes involved in the creation and operation of stimulated reservoirs, but little is yet known about how to influence joint opening so as to maximize productivity. Soultz, situated in granite rock and an active tectonic graben system, shows different conditions of lithology, temperature field, stress field, hydraulics and geochemistry than the Urach site. In contrast to Soultz, the Urach site is located in a very dense gneiss formation which shows comparatively more elastic behaviour and lies in a tectonically almost inactive strike slip stress field. The design and creation of HDR/HWR enhanced geothermal systems requires the development of simulation models predicting the extension behaviour of hydraulically induced fractures. This paper investigates key parameters for heat and fluid transport properties, coupled hydro-mechancial processes, the success of HDR heat exchanger development, and exploration techniques applicable to the different geomechanical facies, and suggests which technologies may be more or less successful for the development and use of the HDR technology.

Introduction

The feasibility of the Hot Dry Rock/Enhanced Geothermal System (HDR/EGS) concept for energy extraction from deep hot rocks was proven as early as 1995 and 1997 at the Soultz site (Baria et al. 1999; Baumgärtner et al. 1998; Jung et al. 1998). Currently the HDR/EGS projects at Soultz and Urach Spa are both nearing the point when pilot power plants could be installed (Baumgärtner et al., 2004; Tenzer et al., 2004).

The Soultz site for HDR/EGS research is located at Soultz-sous-Forêts in Northern Alsace around 50 km north of Strasbourg within the greatest geothermal anomaly in

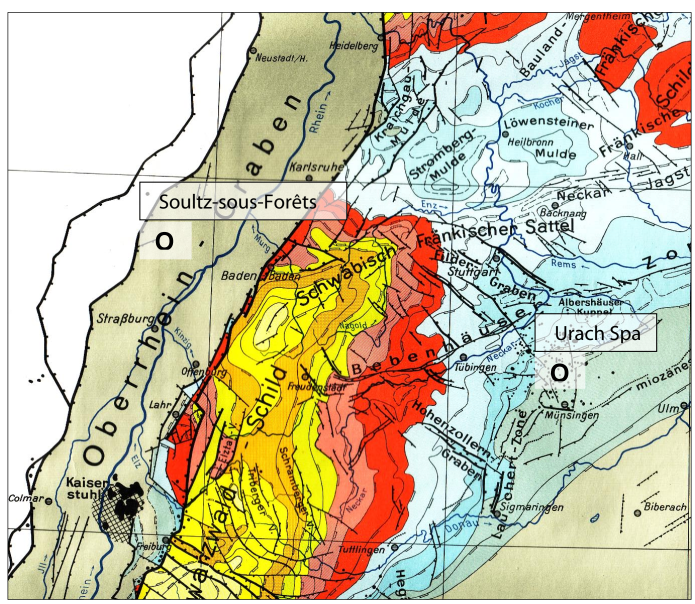


Figure 1. Location of the HDR/EGS locations Soultz-sous-Forêts and Urach Spa on the tectonic map of south Germany (amended after Carlé, 1950).

Central Europe in the Upper Rhine Graben (Figure 1). The site was chosen because of the high geothermal gradient (up to 65-100°C/km) in the sedimentary layers. A geothermal convection phenomena in the Upper Rhine Graben was described by Clauser & Villinger (1990). Thermal convection cells in the Upper Rhine Graben decrease the thermal gradient to near zero between depths of 2000 to 3000 m. Gradients increase again to around 30°C/km below ca. 3500 m depth. The granitic reservoir at Soultz is located about 5 km East of the western main fault zone of the tectonically active Upper Rhine Graben.

Very different conditions in lithology, temperature, stress field, hydraulics and geochemistry in are found at the Urach site, which has a reservoir in a very dense and more elastic gneiss formation in a tectonically almost inactive strike slip stress field. The Urach Spa site is situated around 50 km South East of Stuttgart (Figure 1) at the northern borderline of the Jurassic Swabian Alb. The area is almost tectonically inactive (only some natural low magnitude seismic events were recorded in recent past). The site is located in the centre of the second hottest geothermal anomaly of South Germany.

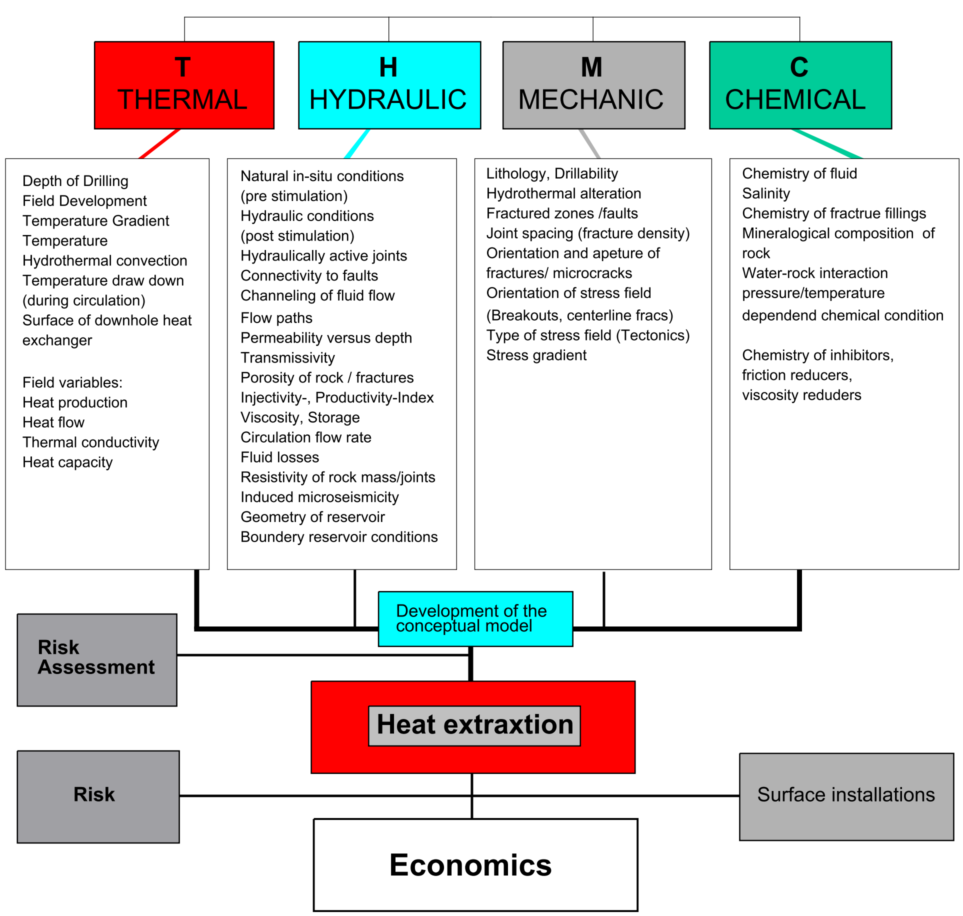
Geomechanical Facies Concept and the Application to HDR/EGS-Reservoir Exploration

Geological deposits are not just random groups of deposits but rather there is both depositional and structural process control on the in situ properties. This consideration has led to the concept of architectural elements within geological deposits, particularly sedimentary deposits, e.g. (Hornung and Aigner, 2002; Klingbeil et al., 1999; Stephens, 1994). An architectural element defines a principal building block of the geological deposit being considered to which specific parameters are assigned. Additionally lithofacies constitute the fundamental building blocks of a reservoir model and geological profile (Röhrs, 1989). Lithofacies recognition provides an indication of reservoir quality and improve well-to-well correlation of litho-hydraulic units. An electrofacies log of the granite at Soultz between 1377 and 2000 m depth was compiled and calibrated on cores by Cautru in Traineau et al., 1990). The log enables the separation of zones of hydrothermal alteration from zones of sound granite as well as different geomechanical affected units. Adapting these main features for a hydrogeological and geo-mechanical situation, i.e. the coupling of hydraulic, mechanical and later thermal properties, allows the definition of geomechanical facies.

The geomechanical facies concept allows the description of separate architectural elements with definite flow, transport and mechanical characteristics. For example, McDermott et al., 2006a) divided the KTB (Kontinentales Tiefbohrprojekt of Germany) site into the geomechanical facies based on a number of different data sets at different scales. The shear zones defined were themselves divided into a core zone where flow and transport is more prevalent and a damage zone where there is an increase in micro-cracking. Between the shear zones there is an undisturbed zone where the action of shearing has not influenced the material. These concepts are here adapted to the evaluation of the site specific properties of the EGS sites Soultz sous Forêts in granite and the Urach Spa site in gneiss rock. Table 1 shows the complex exploration techniques related to the geomechanical facies concept of a holistic THMC coupled process modelling.

Of particular interest during heat extraction is the inclusion of the effect of thermal stress release. McDermott et al., (2006b) suggested that thermal stress, σ_t , induced in a rock due to cooling is approximately controlled by the coefficient of restraint (dimensionless), the elastic modulus the thermal coefficient of expansion and the change of temperature of the system. The coefficient of restraint, K_r , has a value of 1 in fully restrained systems where no movement is possible, and where movement is possible its value drops rapidly. This naturally introduces the concept of the scale of investigation and modelling. (illustrated in Figure 2 , after McDermott et al., 2005).

Table 1. Development of EGS exploration techniqies with respect to the geomechanical facies in-situ in THMC coupled procersses.



McDermott et al. (2006b) showed that depending on the thermal gradient, the flow paths, the viscosity and the size of the coefficient of restraint preferential flow paths may be developed within the reservoir during circulation. The concept behind the development of these preferential flow paths can be described as follows: As the temperature cold front advances in the reservoir the rock experiences thermal contraction. With increasing thermal contraction, there is an increase in the size of the fracture apertures due to a reduction in the normal effective stress across the fractures and an increase in the permeability of the system. This increases the quantity of fluid passing through the reservoir as the injection and extraction pressures are held constant and therefore the rate of heat extraction is also increased. The degree to which the thermal contraction effects the permeability is related to the mechanical restraint in the system.

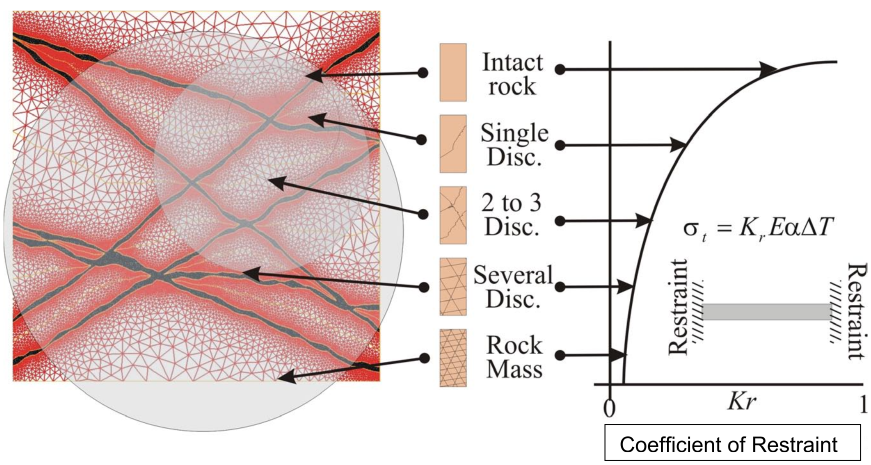


Figure 2. Coefficient of Restraint.

Temperature Field

A data base of temperatures available for a part of the middle Upper Rhine Graben were compiled by the Geological Survey of Lower Saxony (Schellschmidt and Schulz, 1989). The mean geothermal gradient for the entire Graben corresponds to a vertical temperature gradient of 60 °C/km. The maximum gradient for the sedimentary graben fill was determind to 110 °C/ km. The gradient decreases in the Buntsandstein aquifer and approaches zero in the upper part of the granitic basement. Below 4 km depth, the gradient of around 30°C/km is close to the average value for conventional crust. A very low gradient between 2000 and 3200 m depth indicates thermal convections cells between the granite basement and the sedimentary overburden in the vicinity of the Soultz site (Baria et al., 2002). A temperature of 200 °C was determined at 5000 m depth.

At the Urach site a high geothermal anomaly of 11° C/km was detected to depth of around 300 m. Between 300 and 1600 m the gradient was determined to 4 °C/km . The mean geothermal gradient in the crystalline basement (metamorphic gneiss rock) was determined to be around 2.8 °C/km (Tenzer, 1997). A temperature of 170 °C was determined at 4400 m depth.

Stress Field, Tectonics, Faults and Joint Network

The stress regime is a dominant factor for the development of a downhole heat exchanger. The hydraulic properties at large depth are controlled by the fracture systems, the rock matrix and the stress field. Laboratory investigations of the pressure dependence of the permeability of artificially fractured Soultz-sous-Forêts-granite samples yield an rough estimation of the permeability of the reservoir at 5 km depth. The minimum horizontal stress at 3,2 km is 40 MPa. Linear extrapolation of the stress regime at 5 km depth yields a value of S_h of about 70 MPa. Assuming no variation in the rock material (neglecting the temperature dependence of permeability and the size-effect by using the laboratory results for the pressure dependence), a decrease of rock mass permeability by half a decade can be expected. For example, permeability for samples with a fracture oriented in the same direction as fluid flow decreased from 10^{-16} to 5^{-17} m² (Hettkamp et al., 2002).

At Spa Urach, it was shown that the orientation of the joint system (strike direction around North-South) below 3750 m depth is controlled by the orientation of the major horizontal stress direction of N 172 °E. As the direction of the fracture system in the reservoir between 3750 m and 4445 m is sub-vertical and approximately north south, the minor horizontal stress can be taken as being the total normal stress across the fractures dominating flow. Subvertical sinistral strike-slip shears and faults which correspond to the most intense cataclastic structures, strike N 170° E (Genter, 1997 ;Tenzer et al., 1997). Stress measurements at 3352 m depth yield values of S_{hmin} between 41-50 MPa (Rummel, 1997). Estimated stress magnitudes of Anelastic Strain Recovery (ASR) measurements on cores from around 4425 m depth yields values of S_h = 63 MPa (Tenzer et al., 1997).

Tectonic investigations on a regional scale at Soultz-sous-Forêts and experience from borehole measurements and testing at several sites indicate that the basement can be considered as a mosaic of more or less rigid blocks that are devided by faults or fracture zones along which large lateral of vertical displacements can occur (Jung, 1990; Jung et al., 1997). At Spa Urach and Soultz-sous-Forêts the direction of the major horizontal stress S_H, was found to be NS- to NNW-SSE (Tenzer et al., 1991; Tenzer et al., 2002). In contrast to Spa Urach, at Soultz-sous-Forêts the stress regime shows considerably lower horizontal stresses typical for graben tectonics ($S_H < S_V$). This implies a crossover from a normal faulting regime ($S_h < S_H < S_V$) to a strike slop regime ($S_h < S_V < S_H$) in the section of 3000 -4000 m depth (Baumgärtner et al., 2004).

Exploration Techniques to Determine Parameters for Reservoir Development: Installation and Operation of a Seismic Monitoring Network

Seismic measurements are currently the only means by which direct information about the state of the reservoir can be obtained at locations distant from the boreholes. Observing the development of the downhole heat exchanger necessitates a network of seismic monitoring wells. The optimal placement of the monitoring wells has to be determined by modeling. Based on the experience of the investigated sites drillholes for seismic monitoring can be either shallow wells (200 –300 m depth) at Spa Urach or deep wells into the sound crystalline rock (at least 100 m below the fossil weathering surface) as installed at the Soultz site.

Realtime microseismic observation enables the verification of the down hole heat exchanger surface development concurrently to the hydraulic injection operation. This is a technique also increasingly used in the exploitation of hydrocarbon reservoirs (Jupe et al., 2002). As the injection into the ground can induce seismic activity (especially in active seismic regions) it is important to monitor seismic background proving the real size of magnitude of seismic signals in case of seismic hazards. Additionally, the calculation of magnitudes of the seismic events in nearly real time operation helps to reduce seismic hazard risks. This technique was used first in geothermal applications during the massive stimulation of Spa Urach 3 borehole in 2002 (Weidler et al., 2002 a).

Field Development of Soultz-sous-Forêts: Drilling and Hydraulic Testing

The European HDR/EGS project preparations at Soultz-sous-Forêts site started in 1986, and by 2006 Soultz-sous-Forêts comprises five main boreholes, GPK1, GPK2, GPK3, GPK4 and EPS1. GPK1 was drilled in 1987 to a depth of 2002 m. During 1992 –1993 the existing drillhole GPK1 was extended from 2000 to 3590 m depth. A large number of geophysical and other scientific measurements were carried out (Genter and Tenzer, 1995; Baria et al., 2000). The second deep well GPK2 well is located approximately 450 m south of GPK 1 and reached in 1995 a depth of 3876 m at a temperature of 170°C. The drillhole GPK 2 was stimulated in 1995 and 1996 in a depth section of around 3500 m with a maximum flow rate of 78 l/s to improve the permeability. The productivity (and injectivity) of both drillholes is proportional to the applied injection rate during the frac-experiments. This result is essential especially because is makes the effect of frac-experiments predictable (Jung et al., 1998).

First HDR Circulation System at Great Depth in Central Europe

A hydraulic connection and a first circulation system was created in 1995 at depth of around 3350 and 3500 m between GPK1 & GPK2. In 1997, a 4 month circulation test was successfully performed. During this experiment a total of 244.000 tons of brine at temperatures of 142 °C at a flow rate of up to 25 kg/s were circulated. The feasibility of the HDR concept in the Upper Rhine Graben was proven with this test (Jung et al., 1998). Based on the experience of operating Neustadt-Glewe heat plant, the long-term hydraulic circulation test in 1997 at EGS Soultz site was driven under pressure and avoiding oxygen entry into the system. For the operational design of an EGS power plant the determination of the maximum injection pressure. for fluid circulation should be determined by modelling of coupled processes.

Deepening of GPK 2 and Wells GPK 3 and GPK4, Drilling and Testing

According to the prerequisites of an economic power production borehole, GPK 2 was extended in 1999 to a depth of 5048 m to reach a temperature of 200°C. Following to the extension of GPK2 to 5000 depth an additional stimulation was carried out. Evaluating the microseismic monitoring a separate lower reservoir between 4500 m and 5000 m depth had been created without a hydraulic connection to the upper reservoir around 3500 m. In 2002, from a wellhead location 6 m from GPK2, the well GPK 3 was drilled vertically to a depth of around 2700 m and then deviated 600 m to the south of GPK 2 to a depth of 5000 m using downhole motors. Drillhole GPK3 was stimulated in the years 2000-2003. Fully automatic data processing algorithms provide a key to the real-time analysis of this kind of data set (Baisch et al., 2004). As a result it could be shown that both the orientation and the overall shape of this seismic cloud is in good agreement with the existence of a wide extending fault zone postulated from the analysis of the stimulation of GPK2 in the year 2000 (Weidler et al., 2002 b). Following the results of the testing program in GPK 2 and GPK 3 (stress field, joint system and microseismic clouds), the third 5000 m deep drillhole GPK 4 was drilled vertically to 2100 m and then deviated to the landing point around 600 m south of GPK3. The well reached a length of 5260 m and a vertical depth of 4982 m. The final completions of all wells used a floating casing installation (Baumgärtner et al., 2004 ; Baria et al., 2002)

Field Development at Spa Urach, Drilling and Hydraulic Testing

The first phase of the Hot Dry Rock (HDR) Project in Spa Urach began in 1977/78 with the Urach 3 drill hole. The aim was to investigate the origin of the geothermal anomaly of the Spa Urach-Kirchheim area and determine the possible utilisation of geothermal energy from deep hot rocks in a gneiss formation. This large research programme is documented in detail in Hänel, 1992). It was the first HDR/ EGS - Geothermal program performed at great depth and high temperatures within Europe. In the first project phase, a depth of 3334 m in high metamorphic gneiss rock (Anatexites, Diatexites) was reached (Dietrich, 1982a). Basic hydraulic testing programm and hydraulic fracturing were carried out and is documented in detail by Dietrich, (1982b), by Schädel and Dietrich, (1982).

In 1982/83 Urach 3 was extended to a depth of 3488 m (Phase 2) and a temperature of 147° C was reached. During this phase a single hole circulation system was tested.

In order to reach higher temperatures for realizing a HDR pilot plant, the Urach 3 drillhole was extended in 1992 from 3488 m to 4445 m (true vertical depth 4394.72 m), where the bottom hole temperature was found to be 170°C (Phase 3). As main lithological units, metamorphic rocks such as biotite-gneiss, anatexite and diatexite were determined in the extended drill hole (Tenzer et al., 1997). The different crystalline units are effected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulphates). The aperture of fractures is in the range of some 0.1 to 10 mm.

An extensive hydraulic program was carried out in the Urach 3 during 2002 with the aim of developing and identifying the potential HDR/EGS heat exchanger (Phase 4). During a massive hydraulic stimulation, fluid was injected into the well Urach 3 at flow rates of up to 50 l/s. A newly developed software for automatic hypocenter determination enabled the monitoring of induced seismicity in real-time, providing a maximum control about efficiency and spatial impact of the stimulation. Micro-seismic activity was focused in the center of the open hole section (3320 – 4445 m, 170 °C bottom hole temperature), and extents vertically from ca. 3400 m to 4400 m depth. The lateral extension in NNW-SSE direction is up to 1000 x 500 m (Weidler et al., 2002a). Post-stimulation injection tests demonstrated that the hydraulic permeability was enhanced by a factor of roughly 100 due to the main stimulation. The dominating hydraulic flow paths within the reservoir have been determined by a new technique that integrates seismic and hydraulic data into a combined model ("seismo-hydraulic modelling"). Based on predictions from this model the subsurface heat exchanger was further improved and extended by a long term and low rate (2 l/s) hydraulic stimulation and the target of the directional drilling was determined. The transmissivity of the reservoir was increased additionally by a factor of 2. During a second low rate injection test in 2004 the reservoir was extended and the permeability improved to a transmissibility of 0.3 mD. These results were the first proof that the metamorphic crystalline gneiss rock in south Germany at the Spa Urach location could be significantly stimulated**.** The results are representative for the south German crystalline complex and can be applied to various regions in Europe.

Recent results of holistic THM coupled process modelling McDermott et al., 2006a/b suggest that for long term heat production and because of the potential to develop preferential flow paths, the distance between the drillholes at Spa Urach should be increased.

Reservoir Characterization by Borehole Measurements: Exploration Logging at Soultz-sous-Forêts and Spa Urach

Data from borehole logs vary considerably all along the drillhole, representing variations in the physical properties of the different rock facies. In order to determine any correlation between these variations, frequency histograms with arithmetic mean and standard deviation of the values of parameters measured for each of the three different type of lithological facies where evaluated (Genter and Tenzer, 1995). HNGS (Hostile Natural Gamma Spectrometry) data can help in recognition of igneous rock type (Schlumberger, 1982).

Flow logs are the main logging methods to determine hydraulically active joints before and after hydraulic stimulation. Additionally resistivity measurements (Dual Latero Log) to determine the resistivity on the borehole wall and a certain distance (1m) inside the rock can be applied. Hydraulically open joints (Tenzer et al., 2001) can be detected by the difference of the measured values of the Dual Latero Log Shallow to Dual Latero Log Deep.

Intense logging programs were carried in the Soultz-sous-Forêts project, described in detail by Traineau et al., (1990), Genter and Tenzer, (1995), Genter et al., (1997), Homeier and Baumgärtner, (2004). The direction of the major horizontal stress S_H was assessed from borehole images such as the Formation Micro-Imager/scanner and acoustic Borehole Televiewer.

Beside classical measurements, sonic wave measurements enables the calculation of Poisson's ratio and determination of the dynamic elastic properties of the rock. This data is important for the application of the geomechanical facies concept in THMC coupled process modeling. Various standard open-hole well logs (caliper, resistivity and gamma ray logs) were performed in the wells in order to determine the main distribution of the petrographic facies in terms of facies variations, standard granite and hydrothermally altered and fractured zones.

Data from electrical ARI-log enables the verification of hydrothermal altered zones. The strike direction of a major part of joints is around NNW-SSE. The comparison between acoustic and electrical borehole imagery measurements indicated that electrical tools did not perform as well as expected in hydrothermally altered zones. The high conductivity of the drilling fluid or natural brine dominates the measuring results and joints are so less clearly visible.

Very intense logging programs were carried out in different project phases of the Spa Urach 3 drillhole between 3320 and 4445 m depth (Tenzer et al., 1997). The composite log shows that different lithological units are separated by different units of sonic velocities and zones of different geomechanical properties can be defined. The logs show that different geomechanical facies can be applied.

Tracer Tests

A newly identified class of candidate fluorescent tracers for the use in hypersaline hydrothermal environments, the polyaromatic sulfonates, have been shown to be resistant to thermal decay under simulated reservoir conditions at 300 °C. Due to their strong anionic character, these refractory compounds also promise to be resistant to absorption (Rose, 2002). Not only are these fluorescent compounds thermally stable, but they are also very detectable. The polyaromatic sulfonates were used in hydraulic tests at the Soultz site and in a push pull tracer test as EGS site Spa Urach to verify the inner surface of a rock volume under high temperature conditions. These tracer tests are intended for a quantitative characterization of the hydraulically active fracture systems, i.e. to determine the fracture area accessible to fluid flow and important for heat exchange processes. Renner and Sauter, 1997 showed that the combined analysis of unsteady state discharge and temperature change in the discharge water allows the evaluation of fracture geometries, i.e. the ratio of volume to contact area.

The tracer test and results for Urach 3 were reported by Sauter et al., (2004). The inner surface of a rock mass of 1 m^3 was calculated as being 5-30 m^2.

Conclusions

Applying experience gained in the development of two key HDR research locations, Soultz-sous-Forêts and Spa Urach, it is possible to identify the key factors which need to be addressed during development of further programs. A geomechanical facies approach is applied to allow the comparison of these sites. Such an approach defines geological units as not just random groups of deposits but rather thee is both depositional and structural process control on the in-situ properties. Each geomechanicl facies then forms a principal building block of the geological sequence being considered to which specific parameters are assigned. This approach provides a conceptual framework upon which the application of various reservoir investigation, characterization, development and predictive modeling techniques can be applied. Issues such as the key parameters for the flow and heat transport properties, coupled hydro-mechanical process identification, the success of the HDR reservoir as a heat exchanger, and exploration techniques applicable to the different facies were addressed.

The very successful results of the HDR-Soultz-sous-Forêts project are representative for the region of the Upper Rhine Graben. Due to the very promising results of the investigations at the Spa Urach site, it is proposed that the Spa Urach site located in a widespread tectonic strike-slip system is suitable for a HDR demonstration project. The results can be applied in Southern German and Northern Swiss regions and in many other areas of Europe.

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