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

How Synthetic Clay Content Logs from Well Logs Can Help to Assess the Behaviour of a Geothermal Reservoir Upon Hydrothermal Stimulation

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Keywords: Soultz-sous-Forêts, neural network, clay, rock mechanics

ABSTRACT

Knowledge of the petrophysical and mineralogical parameters of a geothermal reservoir is essential for the estimation of rock mechanical behavior during hydraulic stimulation. The strength of a rock is determined by manifold petrophysical parameters. Clay bearing zones, which form during hydrothermal alteration, can affect not only the mechanical reservoir properties, but also the hydraulic properties, the stress parameters and the occurrence of induced seismicity.

We describe in this manuscript a neural network based method to identify clay bearing fracture zones from spectral gamma logs of the geothermal site at Soultz-sous-Forêts. With this method, synthetic clay content logs (SCCL) are obtained, which can be used as a basis for the interpretation of hydraulic, mechanical and seismic data in order to investigate the effects of hydrothermal alteration on the reservoir behavior.

By comparing SCCL logs of the five geothermal wells with hydro-mechanical and seismic data, it is shown that the precipitation of clay minerals locally lowers the frictional strength of the reservoir rock. Such weak zones can affect the orientation and magnitude of the principal stress components. In terms of hydraulic properties of the reservoir, the formation of secondary minerals as fracture fillings can increase, but also reduce fracture permeability. Fractures with high clay content seem to affect the evolution of induced seismicity during hydraulic stimulation and to promote the occurrence of aseismic movements. Thus, secondary mineral precipitation during hydrothermal alteration might have a great effect on the performance, the behavior and the evolution of a geothermal reservoir. The identification of hydrothermally altered zones is a first step towards understanding the relation between different processes determining the character of a geothermal reservoir.

1. INTRODUCTION

1.1. Motivation

In low-enthalpy regions like the Upper Rhine Graben in central Europe, geothermal energy can only be effectively used in enhanced geothermal systems (EGS). The development of EGS is restricted to highly permeable reservoirs with substantial flow rates. In order to reach the desired flow rates, the permeability of the reservoir has to be increased. This involves permeability creation by hydraulic stimulation of pre-existing fractures and is accompanied by the creation of microseismic events. In the past, people in Europe were frightened by the occurrence of small perceptible earthquakes caused by stimulation activities or during operation of geothermal power plants like the 3.4 earthquake in Basel in 2006 (e.g. Häring et al. 2008) or the 2.4 and 2.7 earthquakes near Landau in 2009 (Groos et al. 2013). In Soultz-sous-Forêts in contrast, the magnitude of seismic events induced by circulation of fluids is rather low (e.g. Baisch et al. 2010). An explanation of this behaviour is the presence of clay minerals inside fractures, which act as lubricants, thus promoting aseismic instead of seismic movements as it is for example observed on the San Andreas Fault (Moore and Lockner 2013). The effect of clay minerals on rock mechanics and hydraulics can be substantial. Therefore, the identification of clay-bearing zones is essential for the characterization and engineering of a reservoir. The objective of the present study has been to localize hydrothermally altered zones and to investigate the role of these zones on the hydro-mechanical behaviour of the Soultz geothermal site.

1.2. The Soultz-sous-Forêts geothermal site

The European geothermal project of Soultz-sous-Forêts targets a geothermal anomaly at the western border of the Upper Rhine Graben. Five wells have been drilled to a maximum depth of 5 km. The upper geothermal reservoir is hosted by a porphyritic monzogranite, which extends to a depth of ~4800 m forming the main granitic body of the Soultz geothermal system. It is characterized by large kalifeldspar crystals in a matrix of quartz, plagioclase, biotite, amphibole and accessories of magnetite, titanite, apatite, and allanite (e.g. Hooijkaas et al., 2006). The lower geothermal reservoir lies in fine-grained two-mica granite occurring at 4800 m depth with primary muscovite and biotite and only minor kalifeldspar.

The pluton has been affected by the Upper Rhine Graben tectonics, which caused the formation of large sets of fracture zones, which are the main pathways for circulating fluids. Paleo-circulation of meteoric fluids from the Graben shoulders led to pronounced alteration of the Soultz granite. An earlier pervasive alteration, which involved the formation of mainly chlorite and hematite, affected the whole granitic matrix, but had no effect on the structural properties of the granite. A subsequent vein alteration event significantly changed the granite structure. During this alteration event, primary minerals were dissolved and secondary minerals precipitated. Alteration halos around the fractures are characterized by the transformation of mainly silicates and the precipitation of secondary clay minerals, quartz, carbonates, sulfates and iron oxides (Genter and Traineau, 1995).

The present paper provides a description and interpretation of the hydro-mechanical processes in Soultz related to hydrothermal alteration on the basis of synthetic clay content logs (SCCL) created from borehole logs.

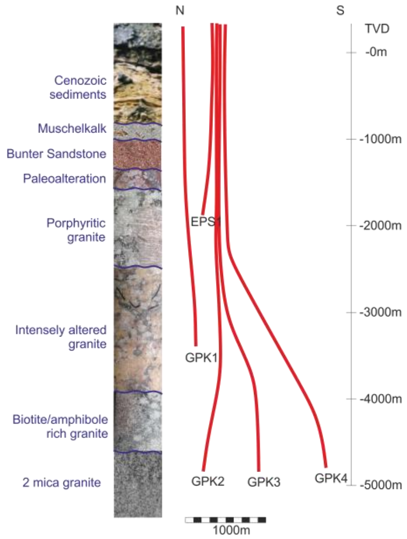

Figure 1: Trajectories of the five Soultz wells and the lithological profile (from Meller et al. 2014b)

2. METHODS

Meller et al. (2014) described a method to identify clay bearing fracture zones by applying a neural network on spectral gamma ray and fracture-density logs. The fully cored pilot well EPS1 at Soultz-sous-Forêts was used to create a reference dataset for the appearance of clay inside fractures on the basis of data from the drill core. By using a Kohonen algorithm (Kohonen, 1984) the neural network was trained on this reference dataset in order to learn, how the appearance of clay is related to the spectral gamma ray and fracture patterns. Figure 2 indicates the good quality of the reconstruction clay-bearing fractures for the reference well EPS1. After this procedure, the neural network has the knowledge about the relation between clay and logging data, and can be applied on the remaining wells. This way, SCCL for the deep wells are obtained, for which no core material is available. Calibration of these logs has been achieved with magnetic and mineralogical investigations of thin section from cuttings of the wells GPK1, GPK3 and GPK4 (for details see Meller et al., submitted).

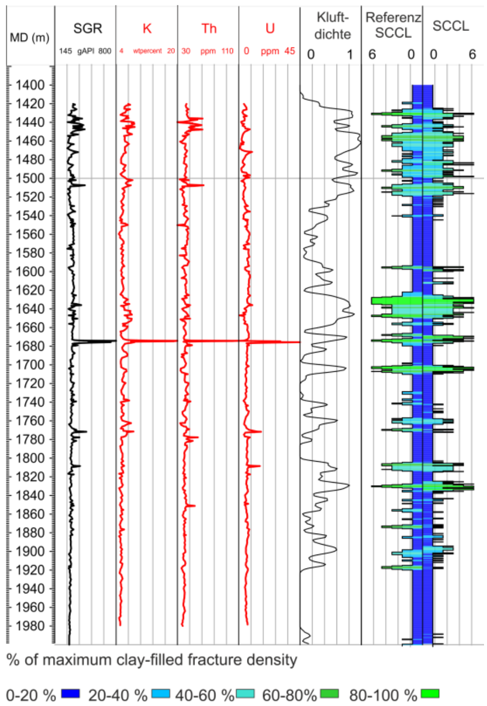

Figure 2: Input data, index log and synthetic clay content log (SCCL) for the reference well EPS1 (SGR = Spectral gamma ray, K = potassium log. Th = Thorium log, U = Uranium log, iSCCL = Index-SCCL). The clay content indicated by the SCCL group is explained by the legend. From Meller et al. (2014a).

3. RESULTS

3.1. SCCL creation

The resulting SCCL logs of the deep wells GPK1, GPK2, GPK3, and GPK4 allow distinguishing zones of different alteration intensity (Figure 3). The upper Interval I ends at about 1900 m depth and is characterized by high clay content. The following interval II contains ~150 m of SCCL groups 1 and 2 (low clay) with a central clay-rich interval at about 2100 m, which can be observed in all four wells. Interval III of the wells GPK1 and GPK2 is characterized by a succession of facies with changing claycontents, whereas interval III of the wells GPK3 and GPK4 has generally higher clay content. It can be subdivided into two sub-intervals IIIa and IIIb, whereas IIIa contains several broad and clay-rich structures alternating with intervals of little clay and Interval IIIb has high SCCL values in GPK3, but indicates less clay in GPK4. Interval IV is characterized by low SCCL in GPK2 and GPK3. In GPK1 and GPK4, broad intervals of intermediate clay content alternate with thick intervals poor in clay. At a depth of ~4600 m, interval V begins, which is again a clay-rich interval. At this depth, the transition between the porphyritic granite and the fine-grained two-mica granite is encountered.

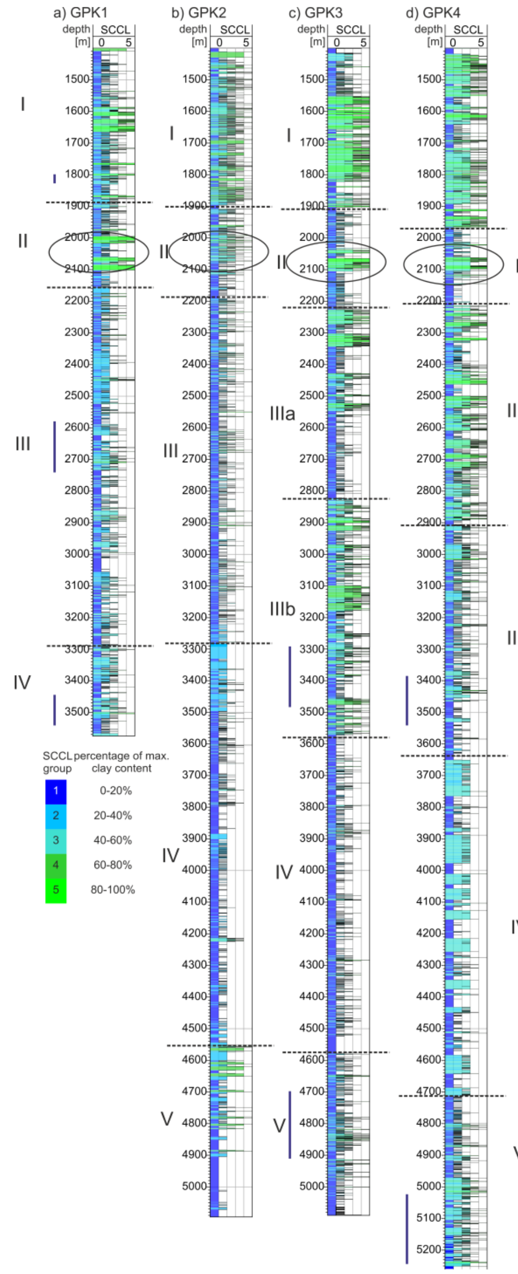

Figure 3: SCCLs for the wells GPK1-GPK4 created by the neural network application. The five different groups of increasing density of clay-filled fractures are explained by the legend. The logs are subdivided into four respectively five depth intervals I to IV or V, which are similar in each well. After Meller et al. (submitted).

3.2. Log calibration

Magnetic measurements on the EPS1 core (Just, 2005; Rummel and König, 1991) revealed an inverse correlation between magnetic susceptibility and granite alteration, which is shown in the logs of Figure 4. This suggested using magnetic susceptibility as a tool to calibrate the SCCL logs of the deep wells, for which cutting material is available. Magnetic susceptibility measurements together with magnetic mineralogical investigations allowed to distinguish between zones of different alteration grades and to calibrate the SCCL logs for the deeper parts of the reservoir. Details of this procedure are beyond the scope of this manuscript and can be found in Meller et al. (submitted).

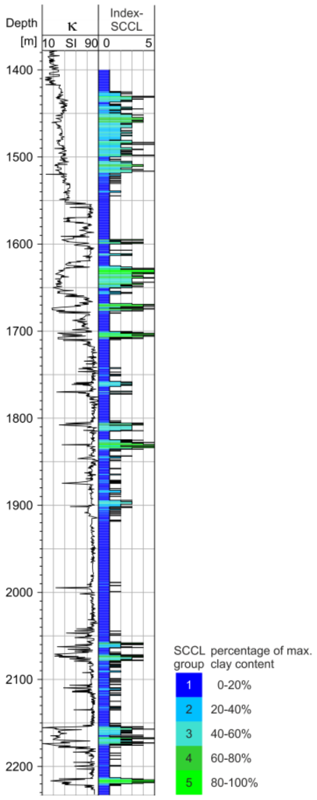

Figure 4: Magnetic susceptibility of the well EPS1 versus the SCCL log. An inverse correlation between magnetic susceptibility and clay content is obvious and suggests magnetic susceptibility as a marker to calibrate SCCL logs.

4. DISCUSSION

4.1. Hydro-mechanical relevance

Experiments of Valley and Evans (2003) on samples of different alteration grades from the revealed an anti-correlation between alteration grade and UCS, respectively the E-modulus of the samples (Figure 5). Thus, we expect lower friction coefficients for altered rock than for fresh granite. This assumption is supported by the accumulation of breakouts in clay-rich zones (Figure 6).

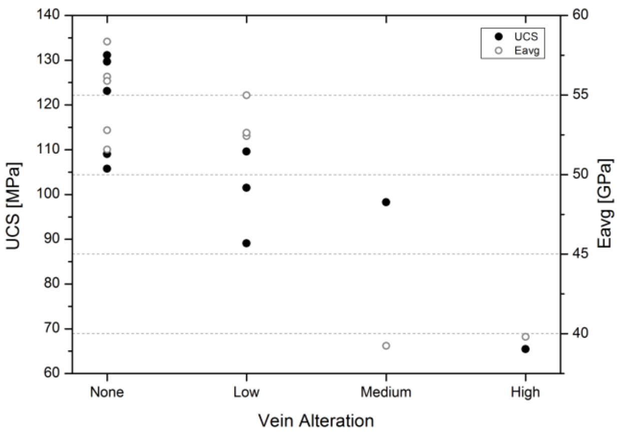

Figure 5: E-moduli and uniaxial compressive strength (UCS) of samples with different vein alteration grades from none to high alteration. Data is taken from Valley& Evans (2003).

The occurrence of breakouts and their size seems to be correlated to the clay content, which is obvious, as the occurrence of breakouts is controlled by the mechanical strength of the rock. As clay minerals are weaker than the intact granite, the formation of more and larger breakouts is promoted in hydrothermally altered zones.

The orientation of breakouts gives evidence about the orientation of the principal stress components, as they form parallel to the minimum horizontal stress. We can see from Figure 6 that large deviations from the mean breakout orientation can be observed below 4800 m in the well GPK4. These deviations coincide with high amounts of clay, encountered at these depths. It is well known that a change in the elastic properties of rocks can change the orientation and the magnitude of the stress components (e.g. F. H. Cornet and Roeckel, 2012). Large hydrothermally altered zones might therefore also change the ambient stress field at Soultz.

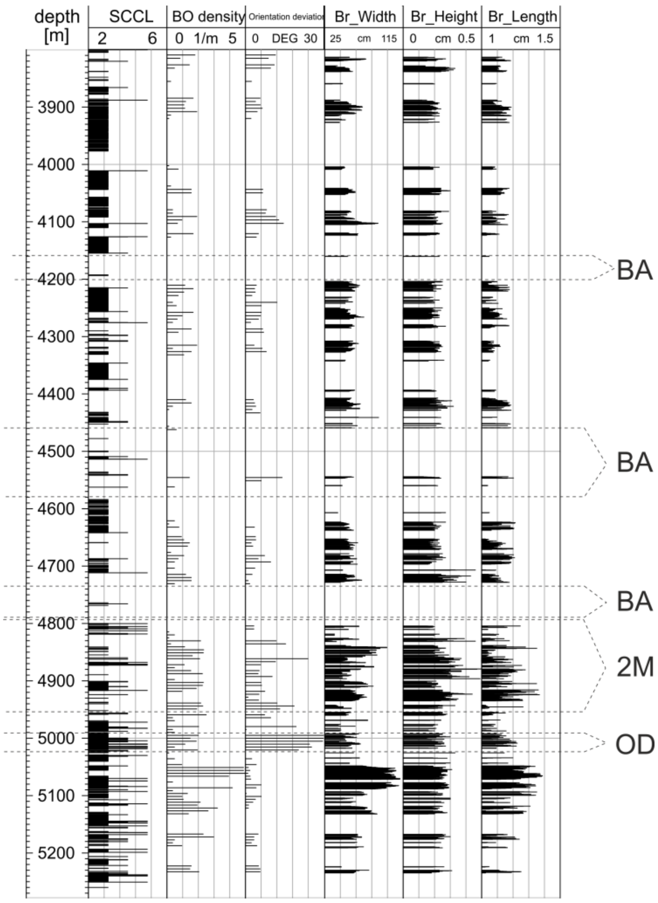

Figure 6: SCCL 2-5 of the well GPK4 compared to the breakout density, orientation deviation and the dimensions of the breakout. There is a clear correspondence between breakout appearance and size and the SCCL (Meller & Kohl 2014). BA=breakout absence; 2M=2-mica granite; OD=orientation deviation.

However, such changes are only local phenomena and therefore, it is a good approximation to use the linear stress model established by Cornet et al. (2007) and Valley and Evans (2007). By combining the knowledge of the ambient stress field, the orientation of fractures and their clay content, we can calculate their critical pressure, which is the pressure increased needed to cross the Mohr-Coulomb failure envelope, i.e. to shear the fracture. Fracture orientation of the fractures in Soultz are known from borehole image logs. The stress model we use for our calculation is described by Equations 1-4.

$$S_V=-1.3+0.0255\cdot z \quad (1)$$

$$S_H=0.98(-1.3+0.0255\cdot z) \quad (2)$$

$$S_h=-1.78+0.01409\cdot z \quad (3)$$

$$P_P=0.9+0.0098\cdot z \quad (4)$$

where Sv is the vertical stress, SH the maximum horizontal stress with an orientation of N169°E and Sh the minimum horizontal stress. Pp is the pore pressure. The frictional parameters for the different SCCL units 1-5 are:

SCCL1: $\mu=0.98$, c=6 MPa

SCCL2: $\mu=0.88$, c=5 MPa

SCCL3: $\mu=0.78$, c=5 MPa

SCCL4: $\mu=0.68$, c=5 MPa

SCCL5: $\mu=0.58$, c=5 MPa.

The minimum cohesion of 5 respectively 6 MPa has been derived from calculations, which revealed that a minimum cohesion of 5 MPa is needed that fractures do not show negative critical pressures, which is physically not possible. The maximum and minimum friction coefficients are derived from studies of Cornet et al. (2007) and Blanpied et al. (1995). The linear dependence of μ with clay content has been shown in studies of Zoback et al. (2012). For all fractures encountered at the Soultz site, the distribution of the critical pressure magnitudes is shown in Figure 7. Almost 50 % of the fractures have a critical pressure lower than 10 MPa, a pressure which is easily reached during hydrothermal stimulation.

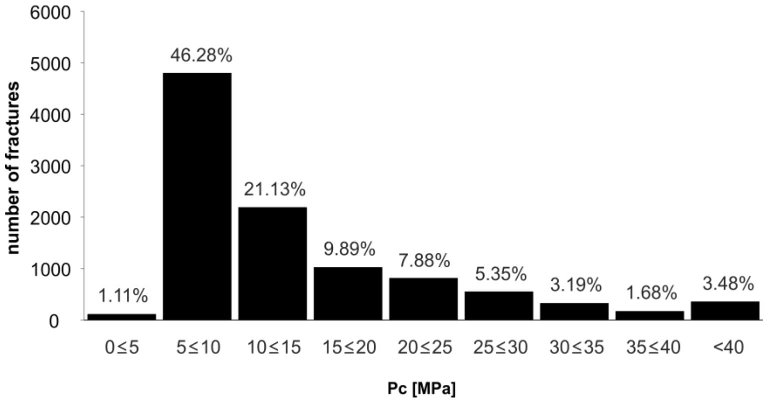

Figure 7: Distribution of the critical pressure for the Soultz wells. A total of 10379 fractures have been used for calculation. About 47 % of all fractures have a critical pressure of <10 MPa.

The occurrence of large numbers of critically stressed fractures at Soultz has been observed earlier by Evans (2005). In his study, he also found, that the critically stressed fractures are those, who showed flow prior to or after hydraulic stimulation. By comparing the location of flowing zones in the well GPK1 (Figure 8a) with the critical pressure calculated for this well (Figure 8c), we can see that a large scatter of critical pressure is observed in intervals around flowing zones, and critical pressures <5 MPa are often seen in flowing zones. It is also obvious from Figure 8b, that the flowing zones are surrounded by intervals with large amounts of clay.

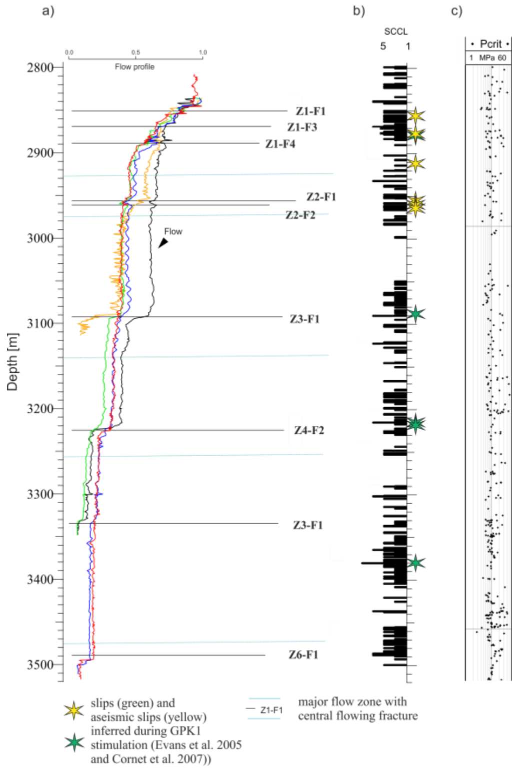

Figure 8: a: naturally permeable fractures in GPK1 and the corresponding flow logs. Flowing fractures are designed Zn-Fm, 'n' is the zone number and 'm' is the fracture number in the zone. Modified after Evans et al. (2005b). b: SCCL versus the location of (aseismic) slips during GPK1 stimulation identified by Cornet et al. (1997) and Evans et al. (2005a). c: critical pressure for each fracture using the stress field after Cornet (2007) and Valley (2007). Friction coefficients used are 0.89 for SCCL1, 0.88 for SCCL2, 0.78 for SCCL3, 0.68 for SCCL4, 0.58 for SCCL5. The cohesion is 6 MPa for SCCL 1 and 5 MPa for SCCL2-5.

The question arises why not all critically stressed fractures and not all hydrothermally altered zones are flowing. The reason for that might be found in the nature of the fracture fillings. Hydrothermal alteration can enhance permeability of fractures by dissolution of silicates. However, large amounts of clay minerals, quartz or carbonates can also clog fractures and reduce their permeability. In terms of hydraulic performance of a reservoir, not only the occurrence of hydrothermal alteration is important, but also its intensity and character.

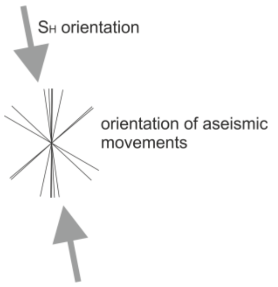

Figure 9: Strike of the aseismic movements observed by Cornet (1997) vs. the orientation of SH. Not all fractures, which sheared aseismically lie optimally oriented towards SH.

In terms of induced seismicity, the occurrence of clay inside fractures might play an important role, which attains more and more importance. Studies on the San Andreas Fault showed that weak minerals on fracture surfaces can promote aseismic creep (e.g. Carpenter et al., 2011; Schleicher et al., 2006). Obviously this can also be observed at Soultz. The stars beside the SCCL log in Figure 8b mark the positions of aseismic movements, which have been observed by Cornet et al. (1997) from borehole image logs. All of these slips occurred in intervals, where the SCCL indicates large amounts of clay. This supports the assumption of clay minerals acting as lubricants on fracture surfaces promoting aseismic creep. This is important for hydraulic stimulation as creep can also happen on fractures, which are not optimally oriented in the ambient stress field. Figure 9 shows the orientation of the aseismic creeps observed in the well GPK1. We can see that some of these creeps are at a large angle to SH, which is a very unfavorable orientation for shearing.

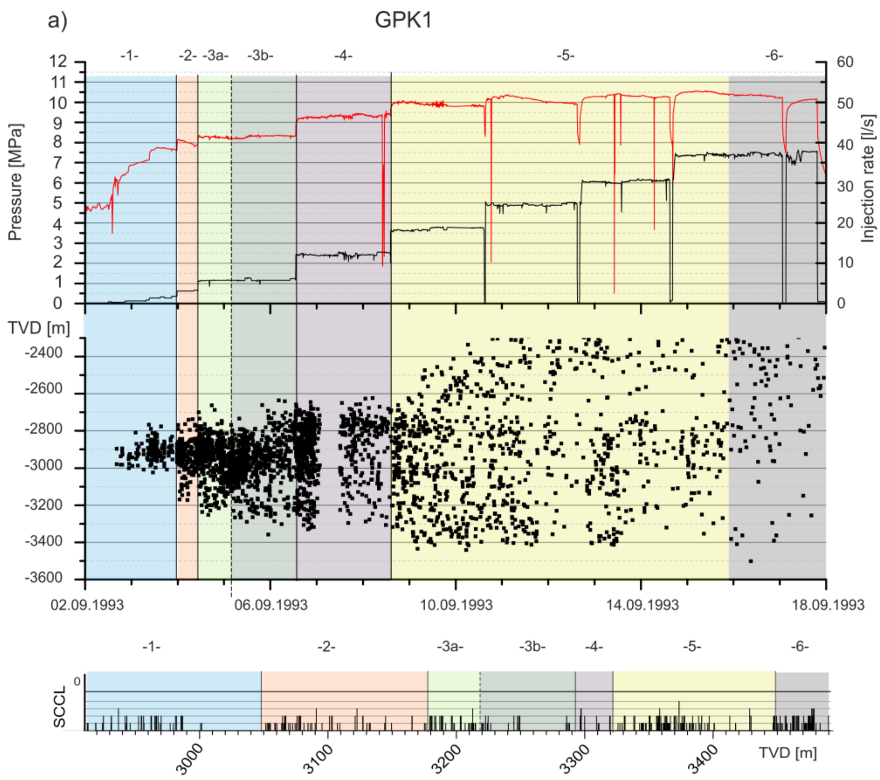

Figure 10: Evolution of seismicity in a radius of 100 m around the boreholes during stimulation. The upper part of the diagrams show the stimulation pressure and below, the time-evolution of induced seismicity is shown versus depth. The lower part of the diagram shows the SCCL for the respective depth intervals and flow logs run after stimulation. Different sections are marked by numbers and colors indicating certain pressure steps of injection. With increasing stimulation pressure, seismicity migrates upwards and downwards respectively. The steps might be caused by clay-rich intervals, which rather promote creep than seismic shearing. After each pressure increase, seismicity only begins at depths, where the clay-content is lower until a clay-rich interval is reached. This interval is overcome during the next pressure increase and seismicity starts just after the clay-rich zone migrating towards the next clay-rich zone and so on.

Analyses of the evolution of induced seismicity at Soultz suggest that aseismic movements might play a larger role than previously assumed. During stimulation of the well GPK1, induced seismicity around the borehole evolved stepwise with increasing stimulation pressure (Figure 10). A possible explanation of this behavior is the distribution of clay rich zones along the well. With each pressure increase, seismicity moves downwards. However, if a clay rich interval is reached, no seismicity occurs until the pressure front has transcended this interval and encounters fresh granite, where seismic events are induced. With the next pressure increase the next clay-rich interval is overcome until seismicity is induced in the lower unaltered rock and so on. From the 4th pressure step on this is no more clearly visible as the pressure front migrated into the reservoir, where we do not have information about the clay content. During the overcoming of the clay-rich interval, there is either no event induced at all or the induced movements are aseismic. Aseismic in this context means that this event is so small that it cannot be detected by a seismic network. This can be explained by the fact that weak rocks can not build up large differential stresses, so that no large seismic events can happen (c.f. Schorlemmer et al., 2005).

4.2. Relevance for hydraulic stimulation

During hydraulic stimulation, the hydraulic and mechanical conditions in a reservoir are changed. Models predicting the behavior of a reservoir upon such changes mostly base on linear stress models and homogeneous hydraulic and mechanical properties for the reservoir. However, the above findings show, that especially in zones, which are of interest for hydraulic stimulation, these linear and homogeneous models are no longer valid. The stress field can be changed in magnitude and orientation, the mechanical strength of the rock is reduced, hydraulic properties might no longer be explained by Darcian flow and fractures might behave ductile instead of brittle.

SCCL logs are a powerful tool to identify hydrothermally altered zones inside a reservoir. Such logs could be used as a basis for the planning of hydraulic stimulations as they can help identifying target zones. Furthermore, information about the location of hydrothermal alteration in a reservoir should be used to update mechanical and hydraulic models of reservoirs in order to better assess the reservoir behavior. In order to prevent large seismic events they can help restricting stimulation activity to clay- rich zones, where aseismic creep is the dominating failure mechanism and no large seismic events can evolve.

5. CONCLUSION

The findings of the previous sections highlight the importance of hydrothermal alteration for the performance and behavior of a reservoir.

Using a neural network, we could create synthetic logs, which indicate the clay content along boreholes from logging data. On the basis of these logs, phenomena related to the appearance of clay inside boreholes could be analyzed. It was shown that

1) Clay inside the geothermal reservoir lowers its mechanical strength.

2) The resulting mechanical contrast inside the reservoir can change the magnitude and orientation of the stress field.

3) Clay inside fractures affects the hydraulic performance of the reservoir

4) The evolution of induced seismicity might be controlled by clay-rich intervals

5) Hydrothermal alteration can foster aseismic creep on fractures due to the formation of clay minerals.

6) Clay content logs could be used as a basis for a better planning of hydraulic stimulation to increase its effectiveness while keeping the risk for large seismic events as small as possible.

6. ACKNOWLEDGEMENTS

This research was conducted within the portfolio topic GEOENERGIE of the Helmholtz Association of German Research Centers and was funded by Energie Baden-Wuerttemberg (EnBW), Germany. The authors are grateful to GEIE Exploitation minière de la chaleur for providing the Soultz borehole data and to the French geological survey (BRGM) in Orléans, for the cutting material.

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