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The geomechanical significance of clay in geothermal reservoirs

Carola Meller, Emmanuel Gaucher, Thomas Kohl

KIT-Institute of Applied Geosciences, Div. Geothermal Research, Adenauerring 20b, 76131 Karlsruhe, Germany

carola.meller@kit.edu

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ABSTRACT

25 years' experience during EGS development in the Upper Rhine Graben (URG) in Central Europe highlighted the importance of a sound reservoir characterization for the safety and success of a geothermal power plant, especially for enhanced geothermal systems (EGS). Especially seismic events with their immediate impact on the environment of a geothermal power plant have become a major task in EGS associated research. Being a direct effect of the geological and mechanical processes underground, controllability of induced seismicity can only be reached by a deep understanding of the reservoir geology and associated rock mechanical processes. Large mechanical contrasts in the crystalline geothermal reservoir of Soultz-sous-Forêts are expected between the primary granitic body and hydrothermally altered fracture zones. The present study aims on the investigation of relationships between the occurrence of hydrothermally altered, clay-bearing zones and observable geomechanical processes.

The basis for this study is synthetic clay content logs (SCCL) created with a neural network. These logs display the clay content inside fractures along a geothermal well. Their high resolution in the order of few decimeters allows detailed interpretation of induced seismicity. The basis for this study is the microseismic catalogue of the 1993 stimulation of the well GPK1. With a probabilistic model of fracture orientations in the open hole section of this well combined with a modification of their mechanical parameters according to their clay content, a model of the distribution of the critical pressure inside the reservoir is created. With a comparison between the probabilistic model and recorded seismicity during the 1993 stimulation it is demonstrated that the presence of weak fractures inside the reservoir can explain the evolution of induced seismicity.

1. INTRODUCTION

The granitic reservoir of the geothermal site in Soultz-sous-Forêts is characterized by a porphyritic monzo-granite with pronounced fracturing. Many fractures are affected by hydrothermal alteration involving the precipitation of clay minerals on the fracture surfaces. The mechanical weakness of clay-filled fractures has been demonstrated in several studies [e.g. *Dolan et al.*, 1995; *Schleicher et al.*, 2006; *Wu*, 1978]. Observations at the San Andreas Fault revealed the mechanical significance of clay minerals in terms of aseismic fault creeping. Several laboratory studies suggest that even small amounts of clay on fracture surfaces determine the mechanical properties of the fault zone, when an external stress is applied [*Tembe et al.*, 2010; *Zoback et al.*, 2012]. It has been shown by Meller and Kohl [2014] that the maximum magnitude seismic events induced during the GPK1 stimulation at Soultz is lower for clay-rich faults than for faults in unaltered rock. Also, the occurrence of aseismic movements in clay rich intervals is suggestive of a correlation between clay and the characteristics of fault slips. Therefore, it is assumed that the critical pressure, which is the pressure required to rupture a fault, depends significantly on the clay inside the fault. Therefore, the characteristics of induced seismicity should reflect the presence of weak faults. The present study aims at creating probabilistic models of the critical pressure of fractures in and around GPK1 taking into consideration the clay content of the fractures. These models are compared to induced seismicity recorded during the 1993 stimulation of GPK1.

2. METHODS

According to the Mohr-Coulomb failure criterion, the critical pressure of a fracture indicates its distance from the failure envelope, i.e. it represents the pressure, which is required to shear the fault during hydraulic stimulation, where only the pore pressure is assumed to vary. It can be calculated after

$$\boldsymbol{P_c = \sigma - \frac{(\tau - c)}{\tan\varphi}} \qquad (1)$$

where P_c is the critical pressure, σ is the effective normal stress acting on the fracture, τ is the effective shear stress acting on the fracture, c is its cohesion and φ the friction angle. The critical pressure is controlled by the orientation of the fracture in the prevailing stress field, the mechanical properties of the rock represented by its internal friction and cohesion, and by the pore pressure. The orientation of fractures in Soultz is known from borehole logging and the clay content can be derived from SCCL logs. Friction and cohesion parameters can be defined according to the clay content of a fracture. The creation of the probabilistic model of fracture orientations and clay content and the derived critical pressure is described in the following section.

Fracture network

The orientation and distribution of fractures along the borehole GPK1 is well known from FMI, FMS and UBI logs. The fractures are generally oriented between N10°E and N170°E with a (sub-)vertical dip and are thus largely parallel to the principal stresses S_H, which is oriented N169±21°E [*Cornet et al.*, 2007] and S_v. A total of 1381 fractures have been identified in the granitic section below ~1400 m and 671 in the open-hole section between 2850 and 3590 m. The dip of the fractures in the open-hole section is representative of the dip in the whole granitic section with a more NNE-SSW oriented dip direction.

SCCL logs

In a study by Meller et al. [2014], spectral gamma ray logs and fracture density logs were used to create synthetic clay content logs (SCCL), which are a semi-quantitative model of the clay content along the Soultz boreholes. They were created with a neural network, which was previously trained on reference data derived from core material of the well EPS1. The application of the trained network on the deep wells generated logs, which represent the clay content inside fractures in five groups. SCCL group 1 represents the fractures without clay and SCCL group 5 applies to fractures with the highest amount of clay. The resolution of these logs is between several decimeters and 1 meter [*Meller et al.*, 2014] and they are thus a sound basis for detailed rock mechanical analyses. The synthetic log for the well GPK1 is presented in Figure 1. It clearly shows depth intervals of high and low clay content.

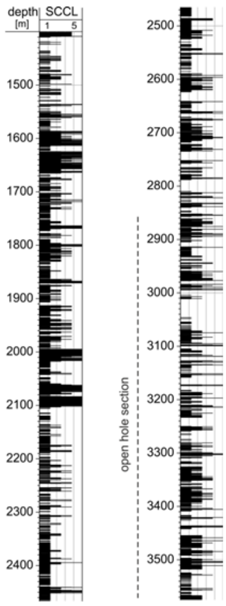

Figure 1: SCCL log for the well GPK1. SCCL group 1 represents the fractures without clay filling, whereas SCCL group 5 contains fractures with the highest amount of clay. The open-hole section of the well between 2847 and 3590 m is marked by the dashed line.

Probabilistic distribution of fractures and clay

The fractures identified on UBI logs of the open-hole section of the well GPK1 were used to determine the distribution of fracture orientations. Due to the large number of sub-vertical fractures, a Terzaghi-correction was applied [*Terzaghi*, 1965]. With this correction, the sampling bias of steeply dipping faults in borehole imaging logs is taken into account by weighting fractures according to their orientation to the borehole axis, thus giving subvertical fractures higher weights. It is supposed that the orientation distribution of fractures at the borehole wall is representative of fractures in the whole reservoir in the depth interval 2850-3590 m. It is therefore used to create a probability distribution of fracture orientations.

Figure 2, where the orientation of the fractures in GPK1 is illustrated together with the SCCL group of the fractures shows that there is no correlation between the dip, strike and clay content of the fractures. Therefore, it is reasonable to assume independently of fracture orientation and associated amount of clay a random distribution of SCCL groups over the fractures. Hence, in a probabilistic model, the proportion of fractures for each clay content can be derived from the SCCL logs. The relative proportion of fractures with different amounts of clay in the open-hole section of GPK1 is provided in Figure1. The SCCL groups 1-5 are randomly distributed to the fractures in 25 draws, whereas 42.85 % of the fractures are assigned to SCCL group 1, 32.69 % are assigned to SCCL group 2 and so on. On the basis of various rock mechanical laboratory studies, it is expected that clay rich fractures have lower friction coefficients than unaltered fractures. Therefore, the different SCCL groups are representative of fractures with different friction coefficients and presumably also cohesion.

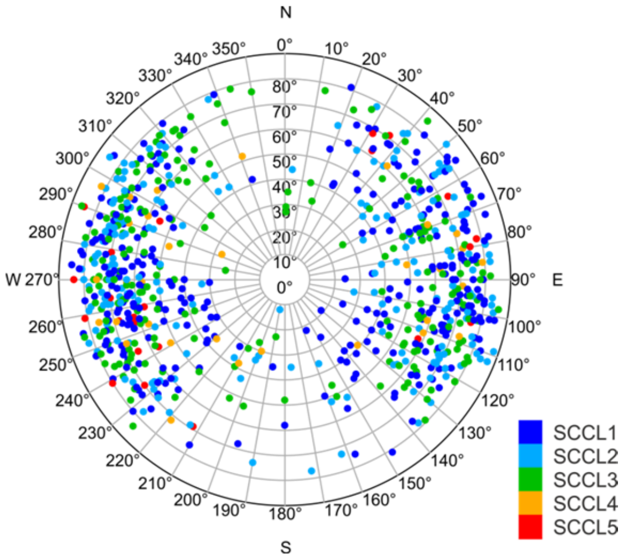

Figure 2: Fracture orientations in the well GPK1. The SCCL group of each fracture is color-coded as indicated by the legend. There is no visible correlation between fracture orientation and SCCL.

Stress field

In addition to the fracture orientation, the orientation and magnitude of the principal stress components are required to calculate the critical pressure for a fracture. The stress field in Soultz has been thoroughly investigated by various techniques including borehole breakouts, drilling induced fractures, leak-off tests and fault plane solutions of microseismic events. Valley [2007] and Cornet [2007] provided the most recent solution for the stress field magnitude and orientation at Soultz, which is used in this study.

Seismicity induced during GPK1 stimulation

The critical pressure represents the overpressure, which is required to shear a fracture. During stimulation a pressure is applied to the reservoir. This pressure acts on a fracture in addition to the prevailing pore pressure. Therefore, the overpressure in a reservoir corresponds to the wellhead pressure, which has been corrected for a frictional term related to friction of the stimulation fluid along the borehole. Provided that the overpressure in the reservoir corresponds to the critical pressure of fractures, each fracture with a P_c smaller than the applied overpressure shears. If it is assumed that the overpressure inside the reservoir corresponds to the downhole pressure and each shearing fracture induces exactly one seismic event, the previously calculated distribution of P_c can be directly transferred to a seismic event curve with increasing stimulation pressure. This allows investigating the role of clay for the evolution of microseismicity during GPK1 stimulation. In this chapter, the frictional characteristics of the fractures around GPK1 are assessed by comparing the characteristics of recorded seismic events with the probabilistic curves of the distribution of P_c.

The well GPK1 is 3580 m deep with an open-hole section spanning the lowermost 730 m of the borehole. In September 1993, hydraulic stimulation of the open-hole section has been performed in 8 steps approaching a maximum injection rate of 37.8 ls^{-1}. During and shortly after the stimulation operations downhole, which continued 15 days from 2nd September, the downhole seismic network recorded ~12'000-13'000 seismic events. Shut-in was on September 17th, but the record of pressure and induced seismicity continued for another 13 days until the wellhead pressure reached zero.

To be able to compare the critical pressure with induced seismic events, the wellhead pressure applied during stimulation has to be converted into downhole pressure. The correction for the wellhead pressure is derived from the pressure gradient and the downhole overpressure (Bhp) can be calculated from the wellhead pressure (Whp) after

$$Bhp = Whp - \frac{4f\rho v^2}{2D} \qquad (2)$$

Hereafter the term bottom hole pressure or downhole pressure refers to the overpressure produced in the reservoir during injection. In order to create a cumulative number of events vs. overpressure curve, only the increasing pressure steps during stimulation are considered as well as the total number of events, which occurred until the pressure levels were reached.

3. Results and discussion

Comparison between recorded seismicity and the probabilistic curves of Pc may deliver insight into the frictional properties of the reservoir, yet several assumptions have to be made for such a comparison. One of the strongest is that time variation of the pressure is not taken into account here. Indeed, to do so, a correct model of pressure propagation would be necessary, which is not a simple task, as identified by Cornet [2012].

As there is a gap in seismic recording above ~9.3 MPa and therefore the number of seismic events is biased between the period before and after this technical problem, the stimulation phase between 0 and 9.3 MPa wellhead pressure is selected for this analysis. In order to better characterize the evolution of seismicity at low pressures, semi-logarithmic curves are used to illustrate the amount of seismic events versus downhole pressure, which can be compared to the amount of fractures shearing vs. their critical pressure as described in the previous section. Figure 3a shows the evolution of seismicity during the 1993 stimulation between 0 and 9.3 MPa. It is compared to 5 probabilistic curves, which have been obtained using different friction and cohesion parameters (Figure 3b-f).

The cumulative curve of seismic events during the September 1993 stimulation of GPK1 reveals an onset of seismicity at around 6 MPa downhole pressure. Between 6 and 8.3 MPa the number of events is approximately exponentially increasing, resulting in a sub-linear curve in the semi-logarithmic plot. Noticeable are the 5 steps of increasing event numbers followed by a pressure increase without or with very few seismic events. The five steps are attributed to large structures inside the reservoir, which affect the propagation of fluid and seismicity. These structures could be either large fracture zones focusing fluid flow and microseismicity as postulated by Evans [2005] or very clay-rich zones, which hamper the spreading of the seismic cloud [*Meller and Kohl*, 2014].

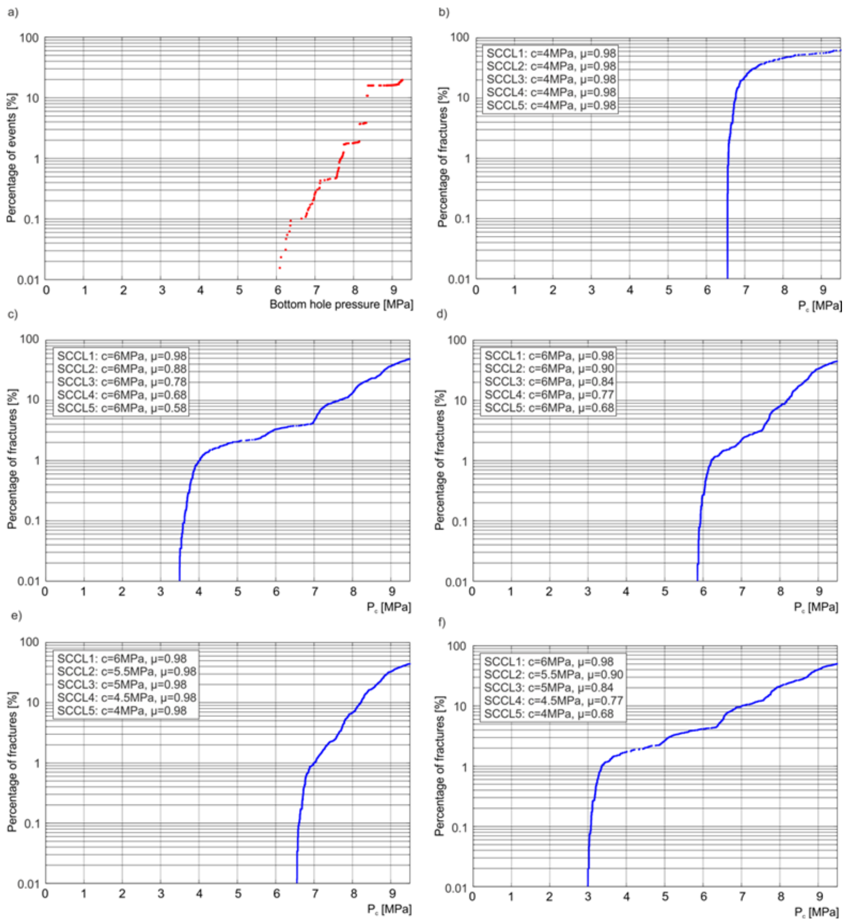

Figure 3: Semi-logarithmic cumulative curves of the events during the September 1993 stimulation of GPK1 (a) and fractures vs their critical pressure calculated with the probabilistic fracture model (b-f) between 0 and 9 MPa. In curve b), the friction coefficient and cohesion are constant. In c) and d), the friction coefficient is decreasing with increasing clay content. In e), cohesion is decreasing with increasing clay content and in f) both, cohesion and friction coefficient, are decreasing with increasing clay content.

Reconstruction of the seismic event curve is tried by selecting different friction and cohesion parameters for the probabilistic curves of critical pressure. In Figure 3b, homogeneous friction coefficients and cohesion is used for the calculation of P_c. It is obvious that the evolution of seismicity as illustrated by Figure 3a and b are totally different. Whereas the number of seismic events is exponentially increasing in Figure 3a, the uniform friction and cohesion curve of Figure 3b shows a rapid increase in the number of sheared fractures with increasing pressure. In this curve, 40 % of all fractures have a critical pressure between 6.5 and 7.5 MPa, implicating that 40 % of all fractures would shear within a pressure increase of 1 MPa at the beginning of the stimulation. In Figure 9 9c, the friction coefficient is decreasing linearly between 0.98 for SCCL1 and 0.58 for SCCL5. With these parameters, 1 % of the fractures would shear within a pressure increase from 3.5 to 4 MPa, followed by an exponential increase in the number of shear events. The gradient of the linear section in the semi-logarithmic plot is smaller than that of the real seismic event curve of Figure 3a. A steeper gradient is obtained, when the range of friction coefficients between SCCL1 and SCCL5 is smaller. In Figure 3d, the friction coefficient was linearly interpolated between 0.98 for SCCL1 and 0.68 for SCCL5. A similar result is obtained, when the friction coefficient is kept constant, but the cohesion decreases with increasing clay content (Figure 3e). The gradient of the linear section in this curve is depending on the range between maximum and minimum cohesion. If both, cohesion and friction coefficient are decreasing with increasing clay content, the gradient of the linear section in the semi-log plot is even smaller.

From these curves, it is obvious that the evolution of seismicity can not be explained by a uniform friction and cohesion throughout the reservoir. With uniform cohesion and friction, seismic events would be induced above a certain pressure level, which is depending on their mechanical strength. All seismic events would happen within a small pressure range in the order of 1 MPa. This is not observed during the September 1993 stimulation. The exponential increase in the number of seismic events, which has been recorded during stimulation, can only be reconstructed by distinguishing between fractures with different cohesion/friction. This highlights the importance of weak zones for the evolution of seismicity, especially at low stimulation pressures.

A common feature of the probabilistic curves created with distinct friction and cohesion parameters is the step at the onset of the curve, where the number of fractures is quickly increasing to ~1 % within a small pressure increase of 0.3-0.5 MPa, which is not observed in the real seismic event curve. Several reasons for the absence of this section are following discussed. When comparing the probabilistic curves to the evolution of seismicity during GPK1 stimulation, it is assumed that all fractures inside the reservoir shear and produce a seismic event. This is not necessarily the case. Fractures with high clay contents for example might shear without producing microseismicity. The existence of such movements has been constrained for GPK1 stimulation by Cornet et al. [1997] on the basis of borehole image logs run before and after stimulation.

A second reason for the absence of this section in the recorded seismic events could be the Terzaghi correction applied on the fracture distribution model. Very steeply dipping fractures are weighted maximum 5-fold, which increases the number of sub-vertical fractures in the model. A comparison between the curves created with Terzaghi-corrected fracture models and uncorrected models, however, showed that the curves are not much different and the vertical section in the semi-log plot is only insignificantly reduced by less than 0.01 %. Therefore, it is concluded that the Terzaghi correction is not generating the steep increase in shear events at the onset of the probabilistic curves.

A further possible reason is a packer test conducted in GPK1 in August 1993, before stimulation activities started. Water was injected into a fault at 3500 m with a maximum pressure of 20 MPa and 158 seismic events were recorded between 3410 and 3576 m depth. This stimulation started on 19th of August and continued for only 20 hrs. Although the pressure of this packer stimulation was much higher than in the following stimulation of the whole open hole section, it is assumed that only a small part of the reservoir around the packered fault zone was affected by the high pressure.

A further point, which could affect the cumulative curve at minimum stimulation pressures, is the magnitude of completeness of the seismic catalog, which is ~-2. There are big differences in magnitudes recorded during the 1993 stimulation and a significant number of small events might have been missed by the seismic network. As a previous study showed (Figure 8 7), the magnitude of seismic events is affected by the clay content. In the probabilistic analysis, the magnitude of seismic events was not taken into account. The probabilistic analysis showed that fractures with high clay contents exhibit the lowest critical pressure. If those fractures produce seismic events with magnitudes below the detection limit, they are not recorded and are missing in the cumulative curve. 7.6 % of the fractures are in SCCL groups 4 and 5, and 50 % of them are optimally oriented in the stress field. Thus, they could affect the cumulative curve below 3.9 % of the fractures and could therefore be responsible for the missing steep part at the beginning of the real seismic event curve.

Model uncertainties

(1) Homogeneous pressure in the whole reservoir

Homogeneous pressure throughout the reservoir is not very likely, as the propagation of the pressure front into the reservoir is controlled by the reservoir permeability. In fractured reservoirs, the main fluid pathways are fractures. As the stimulation fluid is preferentially migrating along fractures, the pressure front is certainly not isotropic throughout the reservoir and the pressure is not necessarily homogeneously distributed around the borehole.

(2) Single friction coefficient for each fracture

This would require a homogeneous fracture structure over its whole length. In reality, the parameters characterizing fracture surfaces vary over distance, and therefore the friction coefficient of the fracture can also vary locally inside fractures and thus its critical pressure.

(3) Depth reference taken for the model

As the stress field is varying several MPa between the top of the open-hole section and its bottom, the resulting DFM curves are very different. If for example a fracture with dip direction N104°E, dip 72° at the top of the open-hole section has a critical pressure of 9.6 MPa the same fracture would shear at 11.1 MPa at the bottom of the open-hole section. Therefore, the modeled curves can be shifted by several MPa depending on the depth at which the stress field is considered.

Despite the modelling uncertainties and simplifications, the results show that there have to be several fractures with a friction coefficient below 0.98. Even a low number of such weak fractures significantly affect the evolution of induced seismicity. Considering that only 8 % of all fractures are SCCL4-5 and three thirds of the fractures are SCCL1-2, the effect of this small proportion of clay rich fractures completely changes the increase of induced seismic events, especially for low overpressures. One of the goals of this study was to find out, if the critical pressure significantly depends on the clay inside the fault. The results have shown that most of the fractures with low critical pressure are SCCL4-5 and therefore fractures with high amounts of clay inside. Without these weak fractures, the minimum Pc would be ~3-5 MPa higher and the evolution of induced seismicity would be most likely different from what is observed during the 1993 stimulation of GPK1. The onset of induced seismicity at low overpressures and the slow increase in the seismic rate until 8.5 MPa clearly indicate that weak fractures dominate the evolution of induced seismicity in the initial stage of hydraulic stimulation.

4. Conclusion

It has been shown that probabilistic curves of the distribution of the critical pressure around the well GPK1 are a reasonable approximation to the distribution of Pc in the reservoir. The Pc distribution can be directly transferred to the overpressure required to induce shear on fractures during hydraulic stimulation. The comparison between the model and recorded seismicity implicates the presence of weak fractures inside the reservoir. The study shows that 1) clay-filled fractures are most likely a weak link inside the reservoir, exhibiting much lower frictional and/or cohesive parameters than unaltered rock and 2) the presence of such clay rich fractures significantly affects the pressure dependent evolution of induced seismicity. This indicates that the role of clay and the lowering of the mechanical friction can not be neglected in models of induced seismicity. Specifying the frictional properties of fractures according to their clay content is a new approach to explain the characteristics of induced seismicity. In future, this approach could be integrated into more complex structural and hydraulic models in order to develop stimulation strategies for geothermal wells. Especially for soft stimulation, where large seismic events are supposed to be mitigated, the Pc distribution in time and space is a necessary input to fix the stimulation pressure.

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