Characterization of the geomechanical properties of a reservoir rock from an integrated analysis of borehole data

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ABSTRACT

The importance of the reservoir characterization for addressing a broad range of geomechanics-related problems and the limitation of the deep core data necessitates tools to characterize the mechanical properties indirectly from borehole data. The novel approach of integrating various borehole and hydraulic data of the Soultz-sous-Forêts EGS field proposed in this study enables a characterization of the deep crystalline rock with respect to their role in affecting the failure processes during stimulation. Three zones in the reservoir are proposed based on the inherent structures present in a set of geophysical logs of GPK4 well. The occurrence of abundance fractures and breakouts in the two-mica granite indicate that this zone is weaker than the massive porphyritic granite. In between, a transition zone is identified by its high clay content. On the top of this, the slip tendency of all minor and major fractures in each zone is estimated. As most of the EGS target the crystalline rock, the understanding of the lithological controls on seismicity in granitic rock is crucial for the future development of the EGS.

1. INTRODUCTION

Enhanced Geothermal System (EGS) offer an attractive prospect for producing large quantities of energy from deep, low-porosity, hot crystalline rocks found in many places in the world. Often, the natural permeability of an EGS reservoir is too low for the requisite flow to circulate between the wellbores and is artificially enhanced. This enhancement is accomplished by a reservoir stimulation in which a large volume of fluid is injected into the rock mass at high flow rates that lead to the reactivation of the pre-existing fractures. In this case, good knowledge of the stress field and the mechanical properties of the fractured reservoir rock is essential for the reservoir management.

Mechanical heterogeneities play a significant role in affecting the response of rock masses to massive fluid injection (Zoback, 2007). The petrographical control on the frictional strength of granite is shown in experimental studies, e.g. Collins and Young (2000) and Sajid et al. (2016). Alteration also plays an essential role for geothermal reservoirs, where percolation by geothermal brine promotes the formation of hydrothermally altered zones around fluid pathways (André et al., 2006). The dissolution of primary rock-forming minerals and the precipitation of secondary minerals, such as quartz, clay, or carbonates, change the in situ conditions on the mechanical strength of the rock (Meller and Kohl, 2014). Hence, to characterize a geothermal reservoir and to assess its mechanics, it is important to understand the significance of each of those rock characteristics.

As deep core data and mechanical testing data on geo-reservoirs are limited, new tools are required to better characterize the stress heterogeneity and the mechanical properties indirectly from the geophysical well log and geological cutting data. In this study, we intend to improve the characterization of the mechanical properties of the Soultz deep reservoir and its response to fluid injection. This study is focused on the open-hole section of the GPK4 well from 4480 to 4980 m depth (here and subsequently, the depths cited are the True Vertical Depth (TVD) measured from the drilling platform). Herein, we first perform an integrated analysis of geological and geophysical borehole data measured in the GPK4 well. A neural-network clustering scheme is applied to identify inherent structures present in a set of geophysical logs of GPK4 well, i.e. magnetic susceptibility, fracture, alteration, and breakout. The reservoir characterization is made based on the distribution of neurons in the topology. This integrated analysis can provide key information on the reservoir characteristics to manage better the hydraulic stimulation.

2. DEEP RESERVOIR CHARACTERIZATION FROM BOREHOLE OBSERVATION

In this chapter, we propose an integrated analysis of the borehole data to better identify the rock characteristics of the deep geothermal reservoir in Soultz. Only the deep reservoir section penetrated by the open-hole of the GPK4 well at depths from 4437 to 4982 m is analyzed. As the reservoir rock experiences different phases of deformation, alteration, weathering processess, it requires a broad ranges of data to describe the induced effects and characterize the reservoir.

2.1 Input data

The lithology of the rock was derived from cutting data analysis (Dezayes et al., 2005) (Figure 1.a) with the help of the magnetic susceptibility measurements (Meller et al., 2014b) (Figure 1.c). Meller et al. (2014a) measured magnetic susceptibility of drill cuttings recovered during the drilling of the Soultz wells to distinguish the two granites in the deep reservoir.

The natural fracture data of the GPK4 well used in this study were obtained from the French Geological Survey (BRGM) on the GPK4 image logs (Dezayes et al., 2005). Major fracture zones derived from the geological analysis, induced microseismicity and vertical seismic profiles modeled by Dezayes et al. (2010) and Sausse et al. (2010) are also incorporated in this analysis. The alteration degree was estimated from synthetic clay content analysis performed in fractured granite (Meller et al., 2014a) (Figure 1.b).

Breakout data is used to infer the in-situ stress field and its heterogeneities in the reservoir (Sahara et al., 2014) (Figure 1.d-f). The orientation and width of borehole elongation trends seen on UBI images run in the granite section of the GPK4 well were measured every 20 cm by Sahara et al. (2014).

2.2 Neural network clustering

Clustering is a common technique in identifying inherent structures present in a set of objects based on a similarity measure. In this study, we use a Self-Organizing Map (SOM) neural network clustering methodology (Kohonen, 1984) for grouping similar parameters obtained from log data of GPK4 into distinct subsets. The clustering process is performed from top to bottom, i.e. the general pattern is resolved before going to the details of the lowest levels.

From the results of clustering, we can conclude that three distinct zones can be distinguished

1. The uppermost zone, from 4400 to 4630 m depth, has a relatively low density of fractures and low clay content. It consists of porphyritic granite, which is only slightly affected by the hydrothermal alteration process.

2. The middle zone corresponds to a transition from porphyritic to two-mica granite, between 4630 and 4780 m. It has low to medium density of fractures and breakouts, and a medium to high clay content. In addition, the width of breakouts is found to be very narrow in this zone.

3. The lowermost zone, from 4780 to 4980 m, consists of a younger two-mica granite that intrudes into the porphyritic granite. This zone has a medium to high fracture density and a moderate clay content.

The boundaries of those lithologies are also found at similar depth in the GPK2 and GPK3 deep well (Dezayes et al., 2003; Genter et al., 1999); hence, it can be assumed that the deep reservoir consists of several lithologies with horizontal boundary.

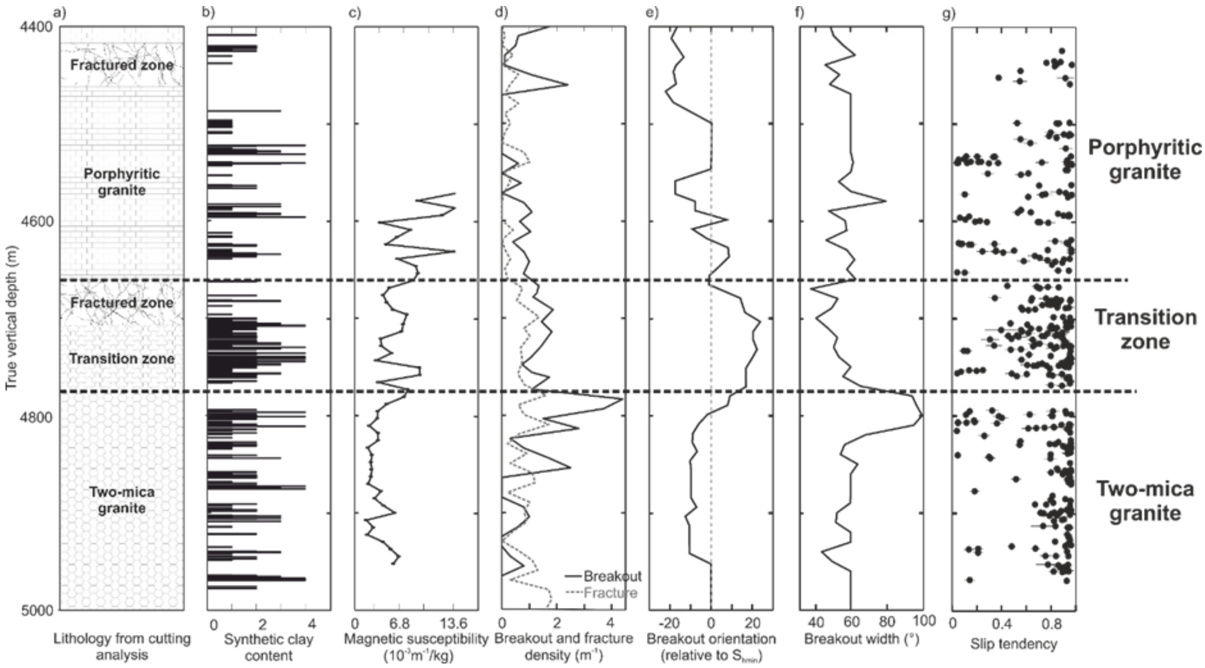

Figure 1: Comparison of various geophysical and geological data of the GPK4 well open-hole section. a) Geological lithology log of the GPK4 well from the interpretation of cutting data, b) synthetic clay content log of GPK4 derived from spectral gamma ray and natural fracture data, c) magnetic susceptibility measured from cutting data, d) breakout and fracture density, e) breakout orientation, f) breakout width, and g) slip tendency of natural fractures observed in the well.

2.3 Mechanical properties interpretation

The interpretation of the variation of the mechanical properties of the reservoir is made based on the previous in-situ laboratory measurements of Soultz reservoir. Petrophysical analysis of the samples taken from the roller reamer after drilling has revealed that the two-mica granite has a lower density, 2.52 kg m-3, compared to the porphyritic granite, 2.62 kg m-3 (Baillieux et al., 2012). It has been shown empirically that rock with lower density tends to have lower elastic moduli (Brocher, 2005). Hence, lower elastic moduli are expected for two-mica granite.

The process of alteration is usually accompanied by an enrichment of clay minerals in the veins and rock matrix, which might act as a zone of weakness (Sausse et al., 2006). It was found that altered samples in Soultz are characterized by smoother surfaces of fractures (Sausse, 2002), suggesting a lower frictional strength of altered rock. In-situ laboratory measurements have been performed by Valley (2007) to analyze the effect of fractures and alterations on rock mechanical parameters. He showed that the Young's modulus of massive porphyritic Soultz granite is around 54 GPa, and significantly reduced for altered granite. An inverse correlation is found between alteration grade (in terms of clay content) and the mechanical properties of the rock (Table 2). In the other fields, it is also shown that the uniaxial compressive strength is also found to decrease with increasing fracture density (Alm et al., 1985). These observations suggest that the two-mica granite, which has a lower density, higher alteration grade, and higher fracture density, is less stiff compared to the porphyritic granite.

The higher number of borehole breakout occurrence in the two-mica granite compared to the porphyritic granite section (Figure 1.d) is also consistent with a reduction of the compressional rock strength as suggested by Haimson and Chang (2000). Additionally, the asymmetry of the breakouts formed in the two-mica granite is also higher (Sahara et al., 2014), which might be the effect of the higher mechanical heterogeneity of the two-mica granite.

It is always helpful to summarise your findings and present them in a conclusion chapter. After this chapter, list the references, and check that all literature listed is actually cited in the text. The references should follow the style shown below.

3. CONCLUSIONS

This study demonstrates that the analysis of the rock characteristics from borehole data proposed in this study is essential to improve the understanding of the geomechanical processes due to hydraulic stimulation. Three zones in the reservoir are identified based on the neural network clustering using various geophysical logs data of the GPK4 well. We are successfully infer the mechanical zonation of the Soultz crystalline reservoir based on the magnetic susceptibilities, fractures, and breakouts

The results of this study provide a better understanding of the significance of the mechanical properties characterization in fractured rocks. Careful analysis of log data can help us learn about the mechanical properties of the fractured granite. The impact of the fracture network on mechanical heterogeneities is very pronounced in crystalline rock, which is mechanically isotropic. This is why we could attribute the variation of the mechanical properties to the occurrence of fractures and accompanying alteration of mechanical properties only. As most of the EGS target the crystalline rock, the understanding of the lithological controls on seismicity in granitic rock is crucial for the future development of the EGS.

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