Inferring stress heterogeneities in fractured crystalline reservoir from an analysis of borehole breakout

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ABSTRACT

The mechanical properties variation, the fracture characteristic and the inclination of the well might perturb the development of wellbore failures. A comprehensive analysis of wellbore failures in the reservoir which related to various factors is performed based on detailed 1221 and 827 compressional and tensional wellbore failures, respectively, observed in a 3.5 km crystalline rock section of the GPK4 well in Soultz-sous-Forêts. Based on the different characteristics of the geometry of wellbore failures, two types of failures are observed: type I and type II. Type I failures show systematic deviation of wellbore failures orientation in the surrounding of major fracture zones, which might represent the large-scale stress heterogeneities. While type II has a characteristic of asymmetric failures shape and localized in the fracture zones. It is found that only type I failures can be used to estimate the in-situ stress field and its heterogeneity. As the development of type II failures is highly affected by the fracture characteristics, a careful analysis of type II failures can be used to qualitatively estimate the mechanical properties of the fracture zone. As most of the EGS target the crystalline rock, the understanding of the stress heterogeneity and fracture characteristics in granitic rock is crucial for the future development of the EGS.

1. INTRODUCTION

One of the key components of a comprehensive mechanical model in geosciences is knowledge of the current state of stress. The widespread use of wellbore imaging devices, e.g. ultrasonic borehole televiewers (Zemanek et al., 1970) and electrical imaging devices (Straub et al., 1991) yield detailed information about wellbore failure that is crucial in assessing stress orientation and magnitude at depth.

Often wellbore failures deviated from the principal horizontal stress orientation. Paillet and Kim (1987) and Barton and Zoback (1994) suggested that slip on active faults penetrated by boreholes was the source of such wellbore failures deviation. However, a large large fault plane is required to sufficiently alter the in-situ stress. A later study of Sahara et al. (2014) revealed that the rotation of the breakout orientations is also observed in the vicinity of minor fractures, which are too small to generate sufficient stress drop. They highlight the impact of fracture networks on borehole breakout heterogeneities in crystalline rock. Faulkner et al. (2006) showed that cracks influence the elastic properties of rock and, hence, the stress state of surrounding the damaged zone.

It has been long assumed that mechanical heterogeneities due to lithology, fractures and clay play an important role in the development of wellbore failures (e.g. Haimson, 2007). However, sound studies on the mechanical significance of those rock parameters on the estimation of in-situ reservoir stress state were missing.

A comprehensive study of the estimation of stress state that takes into account petrographical rock parameters and the well trajectory is performed in this study. Herein, we first identify all wellbore failures in 3.5 km crystalline section of the GPK4 well in the Soultz-sous-Forets geothermal field. Then, the orientation and magnitude of principal horizontal stresses and their heterogeneity are estimated from wellbore failures data. The mechanical properties of the crystalline rock used for stress inversion are determined directly from previous in-situ laboratory measurement (Valley, 2007) and indirectly from sonic log (Genter and Tenzer, 1995) run in the GPK2 well. Petrographic log which was derived from integrated cutting data and various geophysical logs (Dezayes et al., 2003; Dezayes et al., 2005; Genter et al., 1999) is used to extend the mechanical information of the rock from the laboratory scale to the reservoir scale. The results of this study explain the main parameters that affect the characteristic of the heterogeneities of wellbore failures in a fractured crystalline rock and give constraints in using them as a stress indicator.

2. SOULTZ-SOUS-FORETS GEOTHERMAL FIELD

The Soult-sous-Forêts enhanced geothermal system (EGS) field is located in the Upper Rhine Graben (URG). The present targets for heat exploitation are the fractured granite at 4.5–5 km depth, where temperatures reach 200 ◦C. In such a deep fractured reservoir, good knowledge of the stress field is essential for the optimization of borehole design (Moos et al., 2003), understanding of the flow distribution at depth (Barton et al., 1995) and mitigation of the seismic risk due to induced seismicity (Gaucher et al., 2015).

Continuous coring was conducted in EPS1, providing 810 m of granite core for structural analysis and petrographic examination (Genter and Traineau, 1996). In the other wells, however, only cutting samples were collected in the granite section and were used to realize a petrographic log. Geophysical measurements, i.e. caliper, spectral gamma ray and Ultrasonic Borehole Image (UBI) logs, were also carried out in the granite section and were analyzed in order to help to determine the lithology and the characteristics of the fractured zones. Based on those integrated data obtained from borehole, the main petrographic interpretation of the deep crystalline can be described as follows (Dezayes et al., 2003; Dezayes et al., 2005; Genter et al., 1999; Genter and Tenzer, 1995)

1. From 1400 to 2100 m a porphyritic MFK-rich granite with fracturing, characterized by high average content of Th and U but low K content is observed

2. The same granite but poorly fractured with moderate radioactive element content was penetrated from 2100 down to 3000 m.

3. From 3000 to 4000 m the dominant facies is the porphyritic MFK-rich granite but with a high intense fracturing and vein alteration and a high K-content.

4. From 4000 to 4700 the porphyritic MFK-rich granite shows a low average content of the radioactive elements.

5. From 4700 to the bottom depth, there are some petrographic variations with the MFK-rich granite and a younger two-mica granite.

The elastic properties variation in the reservoir is consistent with the lithology characterization proposed by cutting and log data, i.e. significantly lower dynamic Young’s modulus and higher Poisson’s ratio for fractured porphyritic granite. Assuming that crystalline rock is mechanically isotropic, and the perturbation of its mechanical properties can be attributed only to the occurrence of fractures and accompanying alteration, this information can be prolonged with the help of the petrographic log into the deeper part of the well. Furthermore, the elastic properties information can also be laterally distributed among the wells following the lithology boundary.

3. IN-SITU STRESS ESTIMATION

Wellbore failures were identified from the high-quality acoustic borehole televiewer (UBI) log that was run in the granite section of the deep well GPK4. GPK4 is the most deviated well in the Soultz-sous-Forêts geothermal field, its deviation from vertical exceeds 15° in the depth range of 2490 -4740 m TVD and reaches a maximum deviation of 35° at 4220m depth. Wellbore failures can be grouped into two main features, tensile failure (DITF) and compressive failures (breakout). On the UBI image, wellbore failures appear as zones of increased borehole radius on the travel time log and low amplitude on opposite sides of the borehole on the amplitude log.

Figure 1 shows an overview of the DITF and breakout observation as discussed subsequently. DITF were observed mainly in the upper section of the well between 1500 to 2500 m TVD while breakouts were seen in the lower section starting at a depth of 2900 m TVD. The orientation and width of wellbore failure trends seen on UBI images were then measured every 20 cm. Both sides of the DITF and the breakouts were picked. A total of 1221 and 827 breakouts and DITF pairs, respectively, were identified. Each pair is then considered an individual DITF or breakout with a uniform length of 20cm. This approach enables us to examine the characteristics of stress heterogeneities estimated from wellbore failures on deviated wells in fractured crystal.

3.1 Estimation of the in-situ stress field and its heterogeneitiesine rock

An iterative forward modeling of the orientation of wellbore failures at each depth section is performed for a selected range of the magnitude and orientation of SHmax. Stress profile of Sv and Shmin obtained by Cornet et al. (2007) is used as an input for this stress inversion. The misfit, $\Delta\theta$, is defined as the angle between modeled wellbore failures orientation and observed data. Root mean square (RMS) is then used to represent the misfit for each SHmax orientation and magnitude.

Figure 2 shows the $\Delta\theta$ values for all data set as a function of SHmax orientation and magnitude. White areas define stress regimes with $\Delta\theta$ values lower than 20°. Gray to black areas indicates high $\Delta\theta$ values of up to 70°. Consequently, the white areas represent stress regimes with the best agreement of observed and modeled data. The best fit is marked by the gray line. The results of the inversion using three different set of data show a consistent pattern; SHmax is oriented toward N168°E±15°.

However, the misfits are independent of the SHmax orientation. Therefore, it is not possible to deduce a preferential SHmax magnitude. It might be because the deviation of the wellbore failures from the orientation of principal horizontal stresses caused by the well inclination is not significant. Hence it could not be used to determine the magnitude of the principal stress.

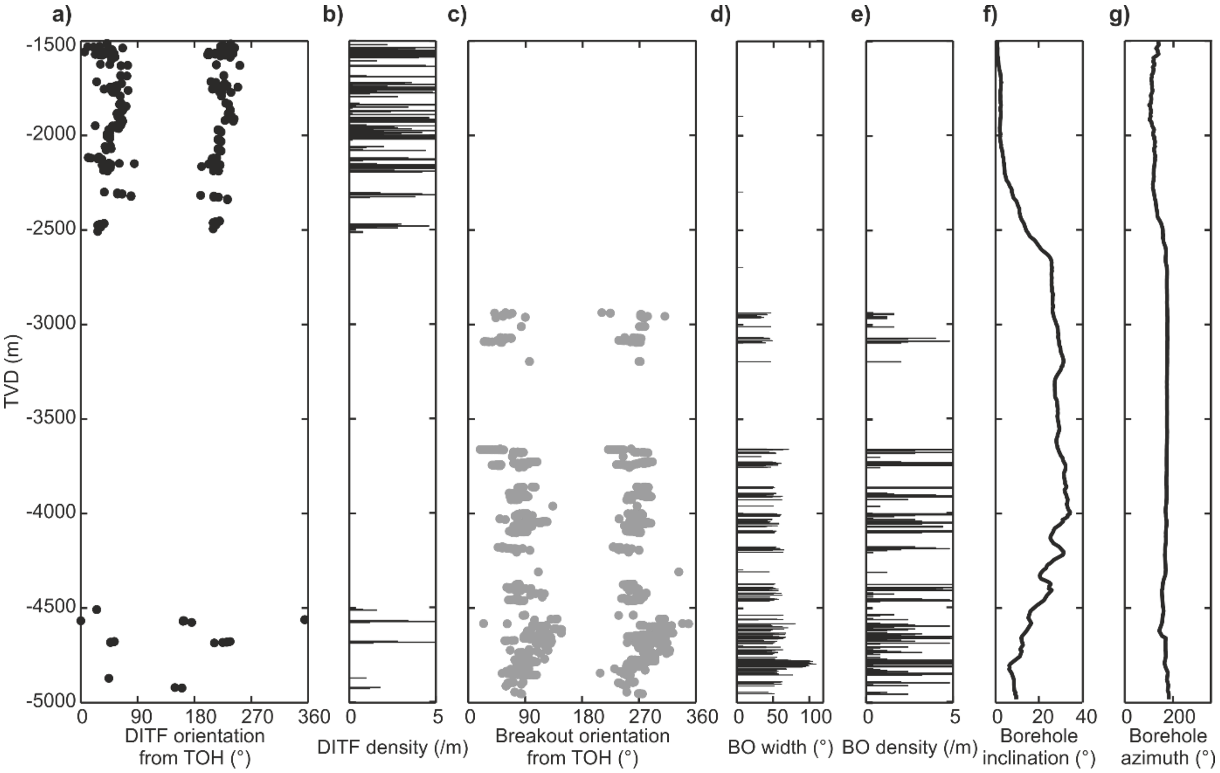

Figure 1: Comparison of various geophysical and geological data of the GPK4 well open-hole section. a) Geological lithology log of the GPK4 well from the interpretation of cutting data, b) synthetic clay content log of GPK4 derived from spectral gamma ray and natural fracture data, c) magnetic susceptibility 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.

Figure 3 shows the $\Delta\theta$ values of breakout widths in GPK4 as a function of SHmax and Shmin magnitude. The best fit is obtained when SHmax = 0.9 – 1.15 Sv and Shmin = 0.62 Sv. Interestingly, the magnitude of Shmin determined from the breakout width is comparable to the one from hydraulic data at a shallower depth which shows Shmin = 0.67 Sv (Cornet et al., 2007). In the absence of hydraulic data, this suggests that by carefully selecting the input breakout data this method might provide a reliable alternative for estimating the magnitude of Shmin.

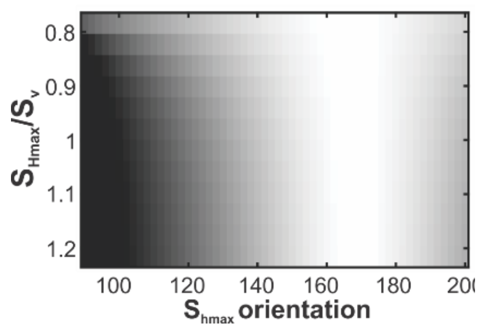

Figure 2: The RMS misfit of wellbore failures orientation between modelled and observed wellbore failures.

The magnitude of the principal horizontal stresses is then estimated from the width of borehole breakouts. The information of the elastic moduli and the uniaxial compressive strength of the rock used for this stress inversion is obtained based on the results of the laboratory measurement and sonic log run in GPK2. The compressional strength and Young modulus of the massive granite are 100 MPa and 54 GPa, respectively, and 30% lower each for fractured rock.

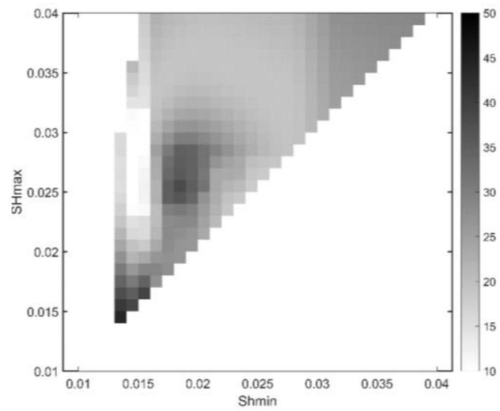

Figure 3: The RMS misfit of borehole breakout width between modelled and observed wellbore failures for each SHmax and Shmin magnitude.

Iterative forward modeling is performed to minimize the misfit ($\Delta\theta$) between the observed and modeled breakout width. In this calculation, SHmax and Shmin are varied while Sv is fixed. We sample all SHmax and Shmin that fall within the stress polygon (Zoback et al., 2003a) assuming that the friction coefficient is 1. However, a satisfactory result of the SHmax magnitude estimation could not be achieved, i.e. magnitude uncertainty of SHmax greater than 30%. It might be caused with the high variation of the breakout width, especially, in the fractured zone.

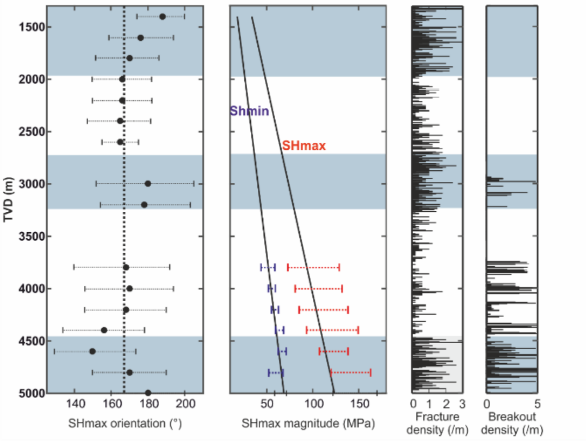

Figure 4: Stress profile based on the wellbore failures orientation and width observed in the GPK4 well. (from left to right) SHmax orientation, SHmax magnitude, fracture density, breakout density.

The procedure of the estimation of the orientation and magnitude of SHmax is repeated for every 200 m depth interval to analyze the stress heterogeneity along the well for all type of wellbore failures observed in each depth section. The results of the SHmax orientation profile is shown in Figure 4. It is shown that the orientations of SHmax are aligned with the mean SHmax orientation in the massive granite and are shifted by approximately 15° in the fractured granite section. Apparently, the uncertainty of the orientation of SHmax is greater in the fractured zone.

Figure 4 shows the $\Delta\theta$ values of breakout widths in GPK4 as a function of SHmax and Shmin magnitude. The best fit is obtained when SHmax = 0.9 – 1.15 Sv and Shmin = 0.62 Sv. Interestingly, the magnitude of Shmin determined from the breakout width is comparable to the one from hydraulic data at a shallower depth which shows Shmin = 0.67 Sv (Cornet et al., 2007). In the absence of hydraulic data, this suggests that by carefully selecting the input breakout data this method might provide a reliable alternative for estimating the magnitude of Shmin.

4. DISCUSSION

As weak zones might perturb the initiation and the development of wellbore failures, the critical question arise, can we use failures data observed in fractured rock as stress indicator? This discussion is missing in publications of wellbore failures as a stress indicator. One might argue that it is related to the scale of heterogeneity, claimed that the uncertainty is smaller with greater data wavelength (Cornet et al. (2007)). A detailed analysis of breakout occurrences and orientations pattern is performed in the highest density breakout area between 4600 – 4850 m. Within this depth section, GPK4 well intersected massive porphyritic granite up to approximately 4700 m and highly fractured two-mica granite in the lower part.

A low-pass filter is applied to select orientation data which has a wavelength of more than 20 m. This filtered data is then subtracted from the original data to obtain the lower wavelength anomaly which might be related to the material heterogeneity in the reservoir. A sinusoidal pattern of the breakout orientation deviation, with a center at a depth of around 4720, coincidences with two major fracture zones that intersect the GPK4 well around that depth (Sausse et al., 2010). At a greater depth breakout orientation is shifted counterclockwise with the similar amplitude, which also coincide with the occurrence of GPK4-FZ5100 major fracture zone. Hence, it can be concluded that the major fracture zones significantly affect the large scale stress heterogeneities in the Soultz crystalline reservoir.

Based on these observations, a hypothesis of the breakout orientation rotation in the vicinity of a fracture could be developed as follow. If a fracture has an associated fractures damaged zone, the stresses are expected to be perturbed and rotated depending on the change in elastic properties of the damaged material. As the fractured core bears the most damage, the stress perturbation is assumed to be concentrated in that zone and to decrease with distance to the core. Wellbore failures will then develop according to this local stress perturbation. Hence, a gradual wellbore failures orientation rotation centered at the fault core is observed. This gradual rotation trend starting from the fault core is also observed in the other studies, e.g. Barton and Zoback (1994), Shamir and Zoback (1992). The orientation rotation observed at a depth of around 1500 m, and 3000 m in this well could also be addressed with the same process. The stress heterogeneities stem from the wellbore failures that we defined as stress-related failures and, apparently, those data are a good indicator of the in-situ stress field and its heterogeneity.

In addition, a random pattern of orientation rotations is observed. This might well represent the wellbore failures orientation rotation due to material heterogeneity. The maximum amplitude of breakout orientations deviations is around 35°. We interpret those random stress heterogeneities represent the wellbore failures orientation perturbation due to material heterogeneity, or fractured-related wellbore failures as defined previously. Hence, despite those data could not be used for the estimation of the principal horizontal stresses, they could give us a hint about the mechanical properties of the rock in the surrounding of the well.

5. CONCLUSION

Analyzing state of stress from wellbore failures at a great depth is a challenging task, in particular because of the occurrence of highly fractured granite which makes the orientation of wellbore failures is highly heterogeneous. Two type of wellbore failures is distinguished from detailed wellbore failures data of 1221 and 827 breakouts and DITF pairs observed in the 3.5 km crystalline section of GPK4 well: stress-related and fracture-related wellbore failures. Based on the characteristics of each wellbore failures type, only the stress-related wellbore failures can be used as a stress indicator. The orientation of SHmax is found to be N168°E±15° and the magnitude of the two principal horizontal stresses are SHmax = 0.9 – 1.15 Sv and Shmin = 0.62 Sv. Those are in agreement with the previous stress investigations, e.g. Cornet et al. (2007), Valley (2007). Furthermore, the magnitude of Shmin determined from the breakout width is comparable to the one from hydraulic data at a shallower depth which shows Shmin = 0.67 Sv (Cornet et al., 2007). In the absence of hydraulic data, this suggests that, by carefully selecting the input data, this method could provide a reliable alternative for estimating the magnitude of Shmin.

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