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Impact of fracture networks on borehole breakout heterogeneities in crystalline rock

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ABSTRACT

This study describes a systematic analysis of breakout occurrence, variation of breakout orientation and fracture characteristics. We infer the impact of fracture networks on the development of breakouts from detailed analysis of 1221 borehole elongation pairs in the vicinity of 1871 natural fractures observed in the crystalline section of the GPK4 well of the Soultz-sous-Forêts geothermal field (France). Breakout orientation anomalies are found to concentrate in the immediate vicinity of fault cores and to decrease with distance to the fault core. Patterns of breakout orientation in the vicinity of natural fractures suggest that the breakout rotation, relative to the mean S_{hmin} direction, is strongly influenced by the fracture orientation. Even a direct relationship between fracture and breakout orientations is found in some depth intervals. In highly fractured zones, with different fracture families present, breakout orientations are especially heterogeneous, resulting from the overlapping effects of the fracture network. Additionally, breakouts are typically found to be asymmetrical in zones with high fracture density. Borehole breakout heterogeneities do not seem to be related to the principal stress heterogeneity only, but also to the effect of mechanical heterogeneities like weak zones with different elastic moduli, rock strength and fracture patterns. Consequently, care has to be taken when inferring the principal stress orientation from borehole breakout data observed in fractured rock.

1. Introduction

Ensuring wellbore stability is one of major problems for drilling in hydrocarbon and geothermal industries, depending on the state of stress and the rock strength [1]. The present day state of stress has a key influence on fluid flow through fractured geo-reservoirs. For example, hydraulically active fractures tend to be critically stressed in the contemporary stress field [2]. Current investigations of stress orientations and magnitudes are based on various methods including analysis of hydraulic fracturing, borehole breakouts [3], drilling induced tensile fractures (DITF), focal mechanism inversion and many others.

Borehole breakouts are cross-sectional elongations in the minimum horizontal stress direction, which are caused by localized failure around a borehole due to stress concentrations [4,5]. Breakouts are one of the direct indicators of the contemporary tectonic stress field [6]. However, breakout orientations can vary and differ from the mean minimum horizontal stress orientation. We call these localized breakout orientations which differ significantly from the mean minimum horizontal stress "orientation anomalies". Those orientation anomalies are commonly observed in the vicinity of fracture zones [7].

Paillet and Kim [8] suggested that slip on active faults penetrated by boreholes was the source of breakout anomalies. Barton and Zoback [7], Shamir [9], and Shamir and Zoback [10] compute the local stress perturbation in the vicinity of fractures, which is required to distort the breakout orientation based on slip on the fault plane. In their studies near complete stress drop on the fracture plane (around 26 MPa at 5400 m depth) is required to match the observed breakout orientation anomalies by this model.

In this paper we consider the changes in mechanical properties affecting the breakout orientation, in particular in the Young's modulus and the Poisson's ratio, induced by the high microcrack density of the fault zone. Fault zones have a high microcrack density near the fault core. This microcrack density decreases exponentially with distance from the fault core [11,12]. Changes of rock mechanical parameters due to changing crack density could lead to local heterogeneous zones around the fault core [13,14]. Faulkner et al. [15] showed that crack density influences the elastic properties of rock and, hence, the stress state of surrounding faults. Furthermore, they found that the mean stress as well as the

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magnitude of the highest principal stress decrease and the least principal stress increase as the fault core is approached, resulting in overall decrease in the differential stress. Thus, the breakout orientation anomalies might also be attributed to varying crack density. Zang et al. [16] investigated the petrophysical properties of drill cores of the Continental Deep Drilling Program (KTB) and the relation of foliation, microcrack and stress anisotropy.

Valley [17] analyzed breakouts and drilling-induced tensile fracture (DITF) patterns in two 5 km deep wells of the enhanced geothermal system in Soultz-sous-Forêts (France). He clearly identified a breakout orientation rotation by 50° with a wavelength of about 250 m in the vicinity of a fracture zone supposed to be 400 m in width and length intersecting the well [18]. However, the origin of this deviation remains unclear. He suggests that it might be related to fracture zones that intersect the wells or to lithology changes. In other publications, it is also suggested that such heterogeneity might also be related to minor fracture densities [19], or to fluid pressure [20]. Crack closure pressures have been examined by Zang et al. [21] using ultrasonic P-wave velocities and helped to identify the SH orientation at the KTB site in addition to breakout investigation by Mastin et al. [22].

Following the work from Valley [17], details of stress perturbations associated with small natural fractures, not only with major fracture zones, are studied for a better understanding of the impact of the natural fracture network on breakout heterogeneities in granite rock. Herein, we first identify all faults and fractures accompanied by stress-induced breakouts in the crystalline section of the GPK4 well at the Soultz-sous-Forêts geothermal field. Then, we investigate the possible relationship between the breakouts and the mechanical perturbation due to the presence of faults and fractures. We outlined the influence of fracture density to the material heterogeneity, inferred from the detailed analysis of breakout shape. Furthermore, the importance of material heterogeneity resulting from fracture occurrence to breakout development is examined.

2. State of stress in the Soultz-sous-Forêts geothermal field

2.1. Geological context

The Upper Rhine Graben (URG) forms the central part of the European Cenozoic rift system, which consists of a rift-related sedimentary basin bounded by the Rhenish Massif and Vogelsberg volcano in the north and the frontal thrust of Jura Mountains in the south [23]. Major faults in the intra-graben and the shoulder areas, which were derived mainly from 2D seismic interpretation [24], are shown in Fig. 1.

The intra-graben faults predominantly strike in N10°E direction parallel to the main border faults, whereas faults in the shoulder areas are bimodal with a main strike orientation towards N45°E and N115°E. These fracture trends are known as the Variscan and Hercynian, respectively. The kinematics of the intra-graben faults is predominantly extensional [25,26], which suggests that the current maximum principal horizontal stress is oriented parallel to the orientation of those faults (NNE). This is confirmed by the world stress map on a regional scale [6]. Furthermore, it is suggested that the stress regime in the URG varies from normal faulting in the northern part to strike slip faulting in the south [27,28].

Soultz-sous-Forêts is located in the URG and hosts a deep Enhanced Geothermal System (EGS) test site (Fig. 1). Its reservoir is in crystalline rocks which are characterized by low matrix porosity. Natural and forced fluid circulation takes place through the fracture network. At its current state of development, the EGS consists of five boreholes, including three deep wells which extend to more than 5000 m depth (Fig. 1b). More information about the Soultz-sous-Forêts EGS can be found in Gerard et al. [29].

In-situ stress orientation and magnitude of the Soultz-sous-Forêts geothermal field were inferred from borehole log and hydraulic methods in previous studies. Cornet et al. [30] reviewed various reports and analyses on hydraulic tests, borehole images and induced seismicity. Furthermore, breakouts and drilling-induced tensile fracture (DITF) patterns in GPK3 and GPK4 were analyzed by Valley [17] and Valley and Evans [31]. In general, the mean maximum horizontal stress orientation values fall within the range of N164°E to N185°E.

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. Azimuth and dip angle were determined for a total of 1871 fractures along the depth range between 2800 and 5000 m TVD. It can be summarized that most of the fractures appear to be members of a nearly vertical system of a conjugated fracture set with a symmetry axis striking NNW-SSE.

In addition to the BRGM dataset, major fracture zones derived from the geological analysis, induced microseismicity and vertical seismic profiles modeled by Dezayes et al. [32] and Sausse et al. [18] are also incorporated in this analysis. Their notations derived from measured depth are used throughout this study. All fractures and breakouts are presented in TVD (True Vertical Depth), as a result of which the depth of the major fractures plotted in the figure might differ from the depth indicated by their name. Hereinafter, all the natural fractures observed on borehole images and the modeled major structures will be referred to as fractures and fracture zones, respectively.

2.2. Principal horizontal stress orientation inferred from breakout observation

To identify breakouts, we examined 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 mTVD and reaches a maximum deviation of 35° at 4220 m depth. The UBI tool provides detailed images of the ultrasonic reflectivity of the borehole wall along with the borehole geometry at an angular resolution of 2° inferred from the travel time. The logs were acquired in two runs 15 and 18 h after the completion of drilling, respectively. Hence, the effect of time-dependent breakout growth [33] was probably still insignificant.

On the UBI image, breakouts appear as broad zones of increased borehole radius on the travel time log and low amplitude on opposite sides of the borehole on the amplitude log. Typical breakouts observed on the UBI image are shown in Fig. 2. Median filtering with a kernel half width of seven samples (corresponding to 14°) was applied to remove noise in the image data through a one-dimensional linear filter. Stress-induced borehole elongations are not always observed symmetrically in opposite directions. In some cases, they might be confused with key seat or washout phenomena [4]. Elongation pairs separated by at least 130° with an increase of the borehole radius of more than 2% were picked as breakouts.

Fig. 3 shows an overview of the borehole breakout observation as discussed subsequently. Breakouts were observed starting at a depth of 2900 mTVD. The orientation and width of borehole elongation trends seen on UBI images were then measured every 20 cm. Both sides of the breakouts were picked. A total of 1221 borehole elongation pairs were identified. Each elongation pair is then considered an individual breakout with a uniform length of 20 cm. This approach enabled us to examine the detailed breakout shape on both sides and its correlation with the occurrence of fractures.