FAULT EXPLORATION BASED ON THE MICROCRACK DISTRIBUTION PATTERN: THE EXAMPLE OF THE TSUKIYOSHI FAULT, CENTRAL JAPAN

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ABSTRACT

Faults are important conduits for the geothermal fluids in the crust. The boreholes for the geothermal exploration often need to penetrate faults to produce the hot water. If the cuttings or core samples could provide the information on the presence of the fault below the bottom of the drill hole, the decision to continue drilling would become easier. It is known by experimental studies that the microcrack distribution pattern is different near the fault from that of the intact rock. The purpose of this study is to understand the microcrack distribution pattern near a fault from that at other parts and to assess the applicability of microcrack distribution to fault exploration. The studied borehole is MIU-3 drilled by Japan Atomic Energy Agency (JAEA). MIU-3 borehole is c.1000 m length and penetrates the Tsukiyoshi fault at the depth of 707 m. The host rock of the Tsukiyoshi fault is the Late-Cretaceous Toki Granite. Several granite samples from the different depth of the MIU-3 borehole were used for this study. Attitude of healed and sealed microcracks developed in quartz grains in the granite are measured under the optical microscope with the universal stage. The previous study indicated that the microcrack pattern far from the fault forms two or three perpendicular planes. In this study, several granite samples from the different depth of the MIU-3 borehole show a different microcrack pattern that is combination of perpendicular planes and oblique planes. This suggests that microcrack pattern can be a potential tool to assess the presence of a fault.

INTRODUCTION

Fault zones are potential conduits for the geothermal fluids in the crust. For example, the Salton Sea geothermal area is located in the fault zone of the San Andreas fault (Tratt et al., 2011). The Ginyu fault in Japan constitutes the geothermal reservoir, and the fault is a target of the geothermal exploration (Goko, 2000). Thus, the boreholes for the geothermal exploration often need to penetrate faults to produce the geothermal fluids.

It is desired that the distribution of temperature and permeability below the bottom of the borehole is clarified on the basis of the logging and geological evidences. The estimation techniques of deeper temperature have been developed by e.g. Teng and Koike (2007). Deeper permeability structure, however, is difficult to estimate from the logging data. The fault zone is one of the important permeable structures. If the cuttings or core samples could provide the information on the presence of the fault below the bottom of the drill hole, the decision to continue drilling would become easier.

Moore and Lockner (1995) revealed the microcrack pattern from an experimental study to generate shear fracture in laboratory (Fig. 1). In this experiment, the microcracks that were formed during the experiment are principally tensile cracks of which orientations reflect the local stress field: those formed prior to the nucleation of the fault are roughly parallel to the cylinder axis (loading direction), whereas those generated in the process zone make angles averaging 30° to the overall fault strike (and 20° to the cylinder axis). The preferred orientation of microcracks in the process zone tends to pull the propagating fracture tip towards the dilational side, even though the trend is away from the overall fault strike. If the similar phenomena occur in a natural fault zone, the microcrack pattern near the fault is expected to be different from that in the intact rocks.

The purpose of this study is to clarify the microcrack distribution pattern near a natural fault and to assess the applicability of fault exploration by the microcrack observation.
Figure 1: Sketches of expected orientations of tensile cracks formed: (a) during initial loading of the cylinder, and (b) in the process zone in front of the fault (Moore and Lockner, 1995).

Figure 2: Geological map of the Tono area modified after Takagi et al. (2008), showing sample location of this study (open circle) and Takagi et al. (2008) (asterisk). MIU: Mizunami Underground Research Laboratory of Japan Atomic Energy Agency (JAEA).

GEOLOGICAL BACKGROUND OF THE MIU-3 BOREHOLE

The studied borehole is MIU-3 drilled in the Tono area, central Japan (Fig. 2). In this area, the JAEA has performed a comprehensive geological study to establish technical basis for the geological disposal of high-level radioactive waste (Yoshida et al., 1989; Sasamoto et al., 2004). MIU-3 is one of the boreholes drilled for this study. Although this area is not a geothermal region, it is suitable for this study because underground geology is well-known by extensive borehole surveys.

The Late Cretaceous Toki Granite is intruded into the Jurassic Mino accretionary complex and the Late Cretaceous Nohi Rhyolites. This granite is distributed in the area of 14 km (north-south) by 12 km (east-west), and consists of medium- to coarse-grained biotite granite and biotite monzogranite, partially intruded by quartz porphyry. The Miocene Mizunami Group and the Mio-Pleistocene Seto Group unconformably overlie the basement rocks. The Toki Granite and the Mizunami Group are cut by an E-W trending Tsukiyoshi fault, which dips about 70° to the south. The apparent vertical displacement of the fault is estimated to be 30 m from the dip-slip of overlying sediment along the fault. Because the fault does not displace the Seto Group, its activity was terminated until the late Miocene (Onishi and Shimizu, 2005). The sense of shear is mainly reverse, although the evidence of normal and strike-slip was also reported (Niizato, 2003).

Onishi and Shimizu (2005) divided the 300-707 m interval into four domains based on core-scale deformation features (Fig. 3): they are (A) undeformed granite, (B) granite with cataclastic seams, (C) fault damage zone (highly fractured granite), and (D) foliated cataclasite at the center of the Tsukiyoshi fault toward the depth of 707 m.

MIU-3 is a 1014 m vertical borehole (Fig. 3). The Toki Granite distributed from the depth of 91.4 m to the bottom of the hole. The Tsukiyoshi fault is penetrated at 707 m. The cataclastic seams are ubiquitously distributed from 500 m to the bottom (Onishi and Shimizu, 2005). Four studied samples (498, 623, 662 and 698 m depths) are collected from the coarse-grained biotite granite in the hanging wall. The samples are reoriented by the comparison of the fracture patterns in the core sample with those on the borehole wall images from the borehole TV.

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MICROCRACKS IN THE GRANITE

Occurrences of the Microcracks

The target mineral for the microcrack analyses is quartz in this study due to its homogeneous physical property and no cleavage and twinning planes. Healed microcracks are recognized as aligned fluid inclusions, while sealed microcracks are brown colored precipitate, probably iron oxides. The relationship of these two types of microcracks is not clear due to very small scale features. Because mode of occurrence that healed microcracks cut sealed ones has not been observed, the formation of healed microcracks is probably prior to that of sealed microcracks (Fig. 4).

Measurements of the Microcrack Orientation

The measurement of the microcrack orientation is according to Vollbrecht et al. (1991). For this method, thin sections with the thickness of c. 200 μm are prepared. The reason why the sections for this study are thicker than the standard ones is to make the microcrack observation easier. The U-stage measurements with the optical microscopy are carried out in three orthogonal thin sections from each sample: horizontal, N-S vertical and E-W vertical. This enables to measure all possible microcrack orientations. Composite pole figures are plotted for the horizontal plane (equal area, lower hemisphere) using the computer program StereoWin 1.2 developed by R. W. Allmendinger. Crack pole densities resulting from the overlap of stereonet sectors of the three sections are statistically compensated by doubling the number of crack poles for areas of no overlap. Triple overlap is avoided by limiting the tilt angle at the U-stage to approximately 35° (Fig. 5).

Figure 3: Stratigraphic column of the borehole MIU-3 (Onishi and Shimizu, 2005). The Tsukiyoshi fault is located at the depth of 707m. Solid circles shown in the left side are sampling points.

Figure 4: Occurrence and crosscutting relationship of healed and sealed microcracks (PPL: Plane Polarized Light mode, MIU-3, 698 m depth).

Figure 5: Explanation of the superposition of orientation data from three orthogonal thin sections (Vollbrecht et al., 1991). Pole orientations of healed and sealed microcracks in the cross-hatched areas are measured with “normal weighting”, whereas those in the hatched areas with “double weighting”. 
Results of Measurements

Results of healed microcracks

The measurement results of healed microcrack orientations are shown in Fig. 6. One of the characteristics of the healed microcrack orientations is that the orientation is preferred to subhorizontal to gentle dip. This is observed in all samples, however, the samples of 623 and 698 m show the strong concentration to N-S strike with gentle dip to the east, while those of 496 and 662 m exhibit the weak concentration with different strikes: E-W strike with gentle dip to the north in 496 m and N-S with dip to west in 662 m.

E-W strike healed microcracks with steep dip occurred in all samples. The degree of the concentration is different among samples; that of 623 and 662 m is clearer than that of 496 and 698 m. NE-SW to E-W strike cracks with steep dip exist in all samples except 623m. WNW-ESE strike ones with steep dip are recognized in 496 and 698 m samples.

Healed microcracks with moderate dip occurred in all samples except 496 m sample. The concentration is very strong in 623 and 698 m, and weak in 662 m. Dominant strike with moderate dip cracks is different each other; E-W with dip to south in 623 m, N-S with dip to west in 662 m, and NNE-SSW with dip to east in 698 m.

Two or three orthogonal patterns are observed in all samples, but moderately dipping cracks also appear except 496 m.

Results of sealed microcracks

The measurement results of sealed microcrack orientations are shown in Fig. 7. Common characteristics in all samples are E-W to WNW-ESE strike cracks with steep dip. The other characteristics are different among the samples. Subhorizontal cracks are developed in all samples except 623 m. Moderate dip cracks occurred only in 698 m; those strike to E-W and NNE-SSW. Steep dip cracks with N-S strike are in 496 and 698 m. NW-SE and NE-SW strike cracks with steep dip are in 623 and 662 m.

Three orthogonal patterns are clearly developed in 496 m. In 662 m, three orthogonal patterns are developed, but different strikes. In 698 m, orthogonal patterns are similar to those of 496 m, but moderately dipping cracks also appear.

Figure 6: Orientations of healed microcracks in quartz grains of the borehole MIU-3. 1% area contour. Contour Interval is 2.0% per 1% area.

Figure 7: Orientations of sealed microcracks in quartz grains of the borehole MIU-3. 1% area contour. Contour Interval is 2.0% per 1% area.
DISCUSSIONS

Comparison with Previous Microcrack Studies
Microcrack orientation has been studied to estimate the regional paleostress directions. Kowallis et al. (1987) showed that microcrack orientation is related to paleostress direction. Vollbrecht et al. (1991) reveals healed microcrack pattern with two orthogonal sets. Takeshita (1995) exhibits three orthogonal patterns. The patterns are interpreted that since the formation of a first set of healed microcracks perpendicular to the $\sigma_3$-axis causes a stress decoupling of the quartz from the external $\sigma_3$, further contraction of quartz produces microcracks perpendicular to the $\sigma_2$-axis.

Takagi et al. (2005) studied microcrack pattern of the borehole DH-15, located 2.5 km away from MIU-3 (Fig. 2), and several surface samples to estimate regional paleostress direction in this area (Fig. 8). The result of healed microcrack orientation pattern of the DH-15 and the surface samples from two outcrops near the MIU-3 (Garaishi and Akeyo outcrops: Fig. 2) showed two or three orthogonal distribution and the preferred orientation of NNW-SSE strike with steep dip and subholizontal. Microcracks with ENE-WSW strike and steep dip was also recognized in some samples of DH-15.

Based on these previous studies, two or three orthogonal sets are a common pattern for the preferred orientation of healed microcracks. In this study, three orthogonal pattern of healed microcracks is recognized only in 496 m. The other samples show different pattern of preferred orientation, that is not only the combination of subvertical and subhorizontal cracks but also moderately dipping crack distribution. This combined set of healed microcracks might be a distinct feature near the fault.

Takagi et al. (2005) also reported the sealed microcrack orientations of the DH-15 (Fig. 8). The preferred orientation of the sealed cracks is dominant to E-W strike with steep dip. The other principal orientations are subhorizontal and N-S strike with steep dip. These three preferred orientations are orthogonal sets without moderate dip.

The sealed microcracks in the MIU-3 are characterized by two (623 m) or three orthogonal sets (496 and 662 m). The sample of 698 m shows the combination of three orthogonal sets and moderately dipping cracks. This combined set of sealed microcracks as well as that of healed microcracks might be a distinct feature near the fault.

Comparison with the Result of Laboratory Experiment
Moore and Lockner (1995) demonstrated that the microcracks formed prior to the nucleation of the fault are roughly parallel to the loading direction, whereas those generated in the process zone make angles 30° to the overall fault strike, and the preferred orientation tends to pull the propagation fracture tip towards the dilational side (Fig. 1). If the similar phenomena occur at the generation of the Tsukiyoshi fault, the microcrack pattern in the process zone should be different from those away from the fault. The healed microcracks in the sample of 496 m depth show the typical orthogonal pattern, suggesting that this is outside of the process zone. The samples of 623, 662 and 698 m depths exhibit an extraordinary pattern of healed microcrack orientations. Especially, the existence of the microcracks with moderate dip is a characteristic feature.

Figure 8: Contour diagrams of maximum orientations ($\sigma_3$) of (a) mesocracks, (b) healed microcracks, and (c) sealed and open microcracks in each sample in the DH-15 core. Equal-area and lower hemisphere projections. n: Number of core samples (Takagi et al., 2008).
Formation of the moderately dipping cracks in the process zone of the Tsukiyoshi fault is also estimated from the angle relationship of the experimental result by Moore and Lockner (1995). The Tsukiyoshi fault is a reverse fault, which dips about 70° to the south. Moore and Lockner (1995) revealed the angle relationship of 30° between the fault and microcracks in the process zone, and the preferred orientation tends to pull the propagation fracture tip towards the dilatational side. If this angle relationship recognized in the laboratory sheared sample is also applied to the natural faults, the microcracks in the process zone of the Tsukiyoshi fault should be developed with 40° dipping to the south (Fig. 9). The existence of moderately dipping cracks in the samples of 623, 662 and 698 m support this idea, however strike is different each other.

Sealed microcracks with moderate dip are only recognized in 698 m sample. This means that the zone of the sealed microcracks influenced by the fault is thinner than that of the healed microcracks (Fig. 9). The microscopic features show that the formation of the healed microcracks is prior to that of the sealed microcracks, so that the thicker influenced zone was developed at the earlier stage of the faulting history, and thinner was at the later. The Tsukiyoshi fault had been activated from Late Cretaceous to Miocene, and uplifted in this period. The rocks measured in this study should be located at the deeper part when the healed microcracks were generated, and at shallower when the sealed microcracks were formed. The difference of the formation period and depth would result in the difference of thickness of the moderately dipping crack zone. The first formation of the healed microcracks would occur at the time of onset of the Tsukiyoshi fault. Before that, the intact rocks were accompanied with no cracks. The possible reason why the healed microcrack zone influenced by the fault is thicker is that more rupture energy was needed to fracture the intact rock at the deeper part. The first formation of the sealed microcracks would occur in the preexisting fault zone at the shallower part. The fault zone had been recovered after the formation of healed microcracks, but probably become weaker than the intact rock. The reason why the sealed microcrack zone influenced by the fault is thinner is that the necessary rupture energy in the preexisting fault zone is smaller than that in the intact rock. The difference of the rupture energy may be related to the difference of thickness of the microcrack zone influenced by the fault.

CONCLUSIONS

The orientation measurements of the healed and sealed microcracks in the MIU-3 reveal that:

1) Away from the Tsukiyoshi fault, the preferred orientations of the healed and sealed microcracks are two or three orthogonal sets combined with subhorizontal and subvertical microcracks.

2) Near the fault, the preferred orientation of microcracks is characterized by the combination of the two or three orthogonal sets and moderately dipping set.

3) Compared the distribution of healed and sealed microcracks, distribution of healed microcracks is thicker than that of sealed microcracks, suggesting that the necessary rupture energy was different between healed and sealed microcracks due to the different formation depth.

4) These lines of evidence suggest that the fault exploration is possible by the measurements of the preferred orientation of healed and sealed microcracks.

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REFERENCES


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