Long term behavior of hydrogeological structures associated with faulting: an example from the deep crystalline rock in the Mizunami URL, Central Japan

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Abstract

Fracture zones around faults (damage zones) in crystalline rocks such as granite can act as significant transport pathways because the permeability of damage zones around active faults will likely be increased by the fracture network system. Understanding the characteristics and long-term behavior of damage zones along smaller scale faults is important for the safety assessment of deep underground facilities in the plutons of an orogenic belt; for example, facilities for the disposal of high-level radioactive waste. Therefore, this paper describes the features of a damage zone and the long-term behavior of its hydrogeological structures associated with faulting in an underground environment based on the results of geological and hydraulic investigations 300 and 500 m below ground level at the Mizunami Underground Research Laboratory, Central Japan. Detailed borehole and gallery wall investigations show the distributions of fractures, fracture fillings, predominant fracture orientations, groundwater inflow points, and hydraulic transmissivity in and around a damage zone. The results indicate that there are three stages in the development of hydrogeological structures. The first stage is the formation of background fractures that formed after the temperature of granitic plutons decreased through the ductile–brittle transition, forming fractures under brittle deformation conditions. The second stage is the formation of a damage zone and corresponding increase in hydraulic permeability as a result of the formation of relatively small fractures associated with faulting. The third stage is the formation of fracture fillings because of the infiltration of groundwater through the damage zone, decreasing the hydraulic permeability of the zone. In the late third stage, unconsolidated clayey fillings form in the large fractures associated with faulting resulting in decreased permeability of the fractures in the damage zone around the fault. These results underline the importance of understanding the development stages to evaluate the effect of faulting in orogenic belt plutons.

KEYWORDS: Fault; Fracture; Damage zone; Water-conducting fractures; High-level radioactive waste (HLW); Underground Research Laboratory (URL)

1. Introduction

Fractures in crystalline rock such as granite function as pathways for groundwater flow and mass transfer of solutes (e.g., Nagra, 1994; Mazurek et al., 2003; Yoshida et al., 2005, 2013a, 2013b; Svensk, 2006; Ishibashi et al., 2014). In particular, fracture zones associated with faulting (i.e., mechanical “damage zones”) are considered important hydrogeological structures because a damage zone may act as the main pathway connecting deep underground regions to the ground surface due to the development of interconnected fracture networks along the faults (e.g., Chester et al., 1993; JNC, 2000; Mazurek et al., 2003; Svensk, 2006; Faulkner et al., 2010; Yoshida et al., 2014). In an orogenic field such as Japan, small faults are inevitably distributed in the basement rocks, and it is known that smaller scale faults were formed every several hundred meters in the crystalline rocks (Yoshida et al., 2013a). Smaller scale faults can be more effective for hydrological and elemental migration in deep host rocks. Therefore, understanding the characteristics of damage zones along smaller scale faults is important for the safety assessment of underground facilities, such as those for the disposal of high-level radioactive waste (HLW) and the storage of liquefied petroleum gas (LPG).

Due to the influence of weathering, geological characterization of the damage zone based on fracture data obtained by geological investigations at the ground surface can be different from that based on data from the underground environment. Numerical and conceptual models constructed on the basis of detailed investigations of boreholes and galleries in underground facilities, such as the Grimsel Test Site in the central area massif of the Swiss alps, Äspö Hard Rock Laboratory in southeast Sweden, and ONKALO in western Finland, show that the faults act as significant water conducting features (Keusen et al., 1989; Nagra, 1994; Mazurek et al., 2003; Svensk, 2006; Sawada et al., 2015). The differing characteristics of water-conducting fractures (WCFs) in an orogenic field as compared with those of fractures observed in a stable continental region have also been described (Yoshida et al., 2005, 2009, 2013b). For example, WCFs in an orogenic field such as Japan constitute approximately 10% of all observed fractures due to the formation of fracture filling or sealing minerals related to the penetration of groundwater such as hydrothermal and low temperature fluids, although the total number of fractures in an orogenic field is larger than that in stable continental regions such as Europe and the United States (Yoshida, 2012; Ishibashi et al., 2014). Consequently, in-situ investigations of underground environments located in orogenic fields are needed to understand the characteristics of damage zones as they relate to their role as WCFs and also with respect to their long-term behavior.

Based on this background, detailed underground investigations are being conducted as part of the “Mizunami Underground Research Laboratory (MIU) project” (JNC, 2002) by the Japan Atomic Energy Agency (JAEA) in Central Japan. In this project, fracture data, such as their distribution, filling mineralogy, orientation, inflow points, and hydraulic transmissivity, in and around the fault related damage zones have been obtained at 300m and 500m below ground levels (GL). These data are useful for understanding the characteristics of damage zones as WCFs and for evaluating their long-term development. Furthermore, fracture data have been obtained at different scales, such as from boreholes and the mapping of gallery walls. Such approaches will provide insight into the water-conducting features in relation to the fractures in and around damage zones (including their long-term behavior) using data obtained at different scales of investigation in the underground environment at the MIU.

2. Geological setting and study area

The primary aim of the MIU project is to establish methodologies for investigation, analysis, and assessment of deep geological environments and thus provide a basis for research and development on the geological disposal of HLW. The underground facilities of the MIU consist of two vertical shafts (Main Shaft and Ventilation Shaft), horizontal tunnels connecting the two shafts every 100 m depth, measurement niches (at GL−200 m and GL−300 m) and Access/Research Galleries (at GL−300 m and GL−500 m). At the present time (2016), the Main and Ventilation Shaft are about 500 m below GL, ranging in elevation from 200.9 m at the surface to −299.1 m at the shaft bottom. The shafts and galleries were constructed using the blast method.

The MIU site is situated on Miocene sedimentary rocks of the Mizunami Group, unconformably overlying Toki granite (Fig. 1). The vertical shafts penetrate through the Mizunami Group into the Toki granite at the unconformity, which is at about GL−170 m. The Toki granite of the Tono district, Central Japan, is a Late Cretaceous plutonic intrusive in the Sanyo Belt (Ishihara and Chappell, 2007).

The age of the Toki granite has been determined to be 68.3±1.8 Ma using the monazite chemical Th-U-total Pb isochron method (CHIME) (Suzuki and Adachi, 1998) , 72.3±3.9 Ma using whole-rock Rb-Sr (Shibata and Ishihara, 1979), and 76.3±1.5 Ma using mineral Rb-Sr (Nishimoto et al., 2014). Biotite K-Ar ages range from 78.5±3.9 to 59.7±1.5 Ma; similarly, zircon fission-track ages range from 75.6±3.3 to 52.8±2.6 Ma (Yuguchi et al., 2011). The primary mineral assemblage of the Toki granite is quartz, plagioclase, and K-feldspar, with accessory biotite and minor amounts of zircon, monazite, apatite, allanite, and opaque minerals (Nishimoto et al., 2008). Based on the cooling rate of the rock body, as estimated by thermochronology, Yamasaki and

Umeda (2012) suggested that the Toki granite was exposed at the land surface in the period between 33 and 24 Ma.

The Miocene Mizunami Group (20–18 Ma zircon fission-track age; Sasao et al., 2006) is divided into three units based on the presence of unconformities or disconformities. The oldest, the Toki lignite-bearing Formation, is composed of fresh water sediment; the intermediate aged unit, consisting of two formations, the Hongo and the Akeyo, is an intercalation of fresh water and marine sediment; and the youngest unit, the Oidawara Formation, consists of marine sediment (Itoigawa, 1974, 1980).

An almost vertical fault with N28–57^{o}W strikes (Main Shaft Fault; MSF) has been mapped from about GL−10 m to GL−500 m in the main shaft, which is a major fault in this area (Kuboshima et al., 2012; Tsuruta et al., 2013; Fig. 2). A high angle smaller fault with a NNW-SSE strike (secondary fault; SF) has been mapped about 50 m from the MSF in the GL−500 m gallery (Kawamoto et al., 2014; Fig. 2b). The MSF has a normal fault sense at the unconformity and a strike-slip sense in the Toki granite (Kubosihma et al., 2012). Previous studies indicate that the MSF has been reactivated and undergone several distinct fault movements (e.g., Tagami, 2012). The fault core of the MSF in the Toki granite consists of several fault gouges, fault breccia, a lamprophyre dyke, and strongly altered granite (Fig. 3a). The SF consists only of fault gouges (Kawamoto et al., 2014; Fig. 3b). The fault gouge thickness of the MSF is about 0.73 m at GL−300 m and about 0.43 m at GL−500 m; that of the SF is 0.03 m (Kawamoto et al., 2012, 2013, 2014; Fig. 3). An alteration halo, characterized by the chloritization of biotite and seritization of the plagioclase core, is observed in the wall rocks around fractures (several hundredths of meters to several tenths of meters from fractures) near the MSF (Nishimoto and Yoshida, 2010; Ishibashi et al., 2014).

Horizontal galleries, extending northward or northeastward from the Main Shaft, were constructed at GL−300 m and GL−500 m. The total length of galleries is about 100 m at the GL−300 m and 165 m at the GL−500 m (Fig. 1b and 2). Four horizontal boreholes with a total drill length of 360.6 m (08MI13: 62.5 m, 09MI21: 103 m, 10MI22: 85.4 m, and 10MI23: 110 m) were drilled into the Toki granite on the northeast side of the MSF at the GL−300 m level (Fig. 2a). Three horizontal boreholes with a total drill length of 246.1 m (12MI27: 37 m, 12MI33: 107 m, 13MI37: 102.1 m) were drilled at the GL−500 m level (Fig. 2b). The borehole directions, bearing clockwise from north, are: 08MI13, 19.6°; 09MI21, 358.2°; 10MI22, 260.7°; 10MI23, 279.5°; 12MI27, 39.5°; 12MI33, 349.8°; and 13MI38, 350.2°. Pre-excavation grouting was conducted to over 40 m from the Main Shaft in the GL−300 m gallery because a relatively high volume of groundwater inflow occurred when the 08MI13 borehole, which was a pilot boring for construction of the GL−300 m gallery, was drilled (Mikake et al., 2010).

3. Methodology

Borehole investigations (core logging, borehole television (BTV) survey, hydraulic packer tests) and geological investigations in the galleries (scan-line survey and gallery wall mapping) were conducted at the GL−300 m and GL−500 m levels (Table 1). The investigations were focused on the northeast side of the MSF after all fractures on the gallery wall had been mapped and hydrological information had been obtained from the MSF to the relatively low fracture density (intact) zone (Fig. 2).

Core logging, BTV surveys, and hydraulic packer tests were carried out for the borehole investigations (Table 1). Geological investigations in the galleries were conducted after each blast round; each blast round length was 1.6–1.7 m. Geological investigations in the galleries consisted of two complementary methods. One was the scan-line investigation, in which all fractures crossed by a tape measure placed parallel to a gallery axis (the scan-line) are recorded with respect to fracture distribution, filling mineralogy, and fracture orientation (Table 1). Scan-line investigations were performed along both sides of the galleries at GL−300 m and GL−500 m. The height of the scan-line was either 1.25 or 2.50 m from the gallery floor, depending on the gallery size (Fig. 2). The other method was wall rock mapping in the galleries (gallery wall mapping), in which all fractures were sketched to obtain the fracture distribution and trace length of each fracture along the gallery wall. In the wall rock mapping, the fractures with groundwater inflow (WCFs) were also recorded to develop an understanding of their distribution and inflow rate (Table 1).

To understand the effect of faulting, fracture data, such as fracture frequency and orientation, were organized systematically by horizontal distance from the MSF (Figs. 2, 4, and 5). In addition, we use the high- and middle- angle fractures as a dataset because the investigations were in an almost horizontal direction and the target fault was a vertical structure. Fracture orientation data acquired by BTV surveys are invariably biased (Terzaghi, 1965). The probability of intersection between fractures and boreholes depends on factors such as the number of fractures in the sampling region, the fracture orientation with respect to the borehole, the size of the fractures, the positions of fractures relative to the position of the borehole, the length of the borehole, and the diameter of the borehole (Martel, 1999). Therefore, the fracture orientation distribution obtained by BTV survey is corrected by a Terzaghi weighting factor (Terzaghi, 1965). The trace length distribution provides an indication of fracture size distributions such as fracture radius (Piggott, 1997). Understanding fracture trace length is important for evaluating groundwater flow because fracture size distribution may correlate with the hydraulic permeability of the region being investigated (Ijiri et al., 2001). The cumulative distribution of fracture trace lengths generally follows a power-law distribution (e.g., Turcotte, 1986; Scholz and Cowie, 1990; Ijiri et al., 2001). The cut-off of longer and shorter portions of the fracture trace length is known as ‘truncating’ and ‘censoring’ (e.g., Ijiri et al., 2001; Raymond and Svensk, 2004). Truncating leads to non-measured information caused by the bias resulting from the size of the observation domain. Large fracture planes may extend beyond the rock exposure. Measurements are therefore truncated at some value dependent upon the size of the observation domain. Censoring also leads to non-measured information and is the result of a physical inability to detect fractures shorter than a specific threshold value. The cumulative distribution of fracture trace lengths obtained by gallery wall mapping at GL−300 m and GL−500 m follows a power-law distribution in the range 1.0 to 7.0 m; therefore, the “all fracture frequency” sampled by mapping is assigned trace lengths in this range (Figs. 4c and 5c). The WCFs were recorded as “wet” (less than 0.1 L/min), “dripping” (between about 0.1–1.0 L/min), and “flowing” (greater than about 1.0 L/min (Figs. 4g and 5g). In addition, fractures with grout were assumed to be WCFs because they likely had sufficient apertures to allow injection of the grout (Fig. 4g). Fracture fillings are useful indications of past fluid flow and possibly illustrate patterns of groundwater flow (Yoshida et al., 2013b). Unconsolidated clayey fillings (detailed occurrence described in section 4.6) are observed in this gallery. This filling material has the propensity to be washed out by drilling fluid during borehole drilling; therefore, the fracture filling data used are those obtained by scan-line investigations (Figs. 4f and 5f). Fractures induced by drilling can be difficult to discriminate from natural fractures; therefore, fractures observed in both the drill core and BTV images were used as the fracture data for borehole investigations (Figs. 4g and 5g). The hydraulic transmissivity acquired by hydraulic packer tests was used to understand rock mass permeability (Figs. 4h and 5h). In addition, petrographic study of thin sections and X-ray diffraction (XRD) analyses were used to determine the occurrence and mineral species of the fracture fillings.

4. Results from tunnel wall and borehole investigations

4.1. Fracture orientations

The predominant fracture directions are NW–NNW, NE, and EW striking high-angle fractures in the both the GL−300 m and GL−500 m galleries (Figs. 4a, b and 5a, b). The predominant fracture directions from the borehole investigations in the rock mass (Figs. 4a and 5a) correspond to observations from the gallery wall mapping (Figs. 4b and 5b). The NW-NNW striking fractures, i.e., similar to the strike of the MSF, are mainly observed within about 80–100 m of the MSF in the GL−300 m gallery and within about 60 m of the MSF in the GL−500 m gallery; on the other hand, NE and EW striking fractures are more common beyond 80–100 and 60 m from the MSF in each gallery, respectively.

4.2. Distribution of all fractures, water-conducting fractures, fracture fillings, and transmissivities

Fracture frequencies based on the results of gallery wall mapping at GL−300 m decrease gradually, in intervals, with distance from the MSF (Fig. 4c); although all fracture frequencies based on the results of scan-line and borehole investigations are relatively constant until about 100 m from the MSF (Figs. 4d and e). Based on results of borehole investigations, the all fracture frequencies are about 1/m beyond 100 m from the MSF (Fig. 4e). Calcites, hydrothermal minerals such as sericite and chlorite, and unconsolidated clayey fillings occur as fracture fillings in this gallery (detailed occurrence is described in section 4.6). The distribution of fracture fillings based on scan-line investigations and analyzed as a percentage of fracture fillings per 5 m interval (Fig. 4f) indicate that fractures filled with calcite and hydrothermal minerals occur in high proportions everywhere. Clayey fillings are relatively common until about 60 m from the MSF. Figure 4g shows the frequency distribution of WCFs based on the results of gallery wall mapping. The WCFs comprise 11.4% of all fractures (191 of 1670 fractures) at GL−300 m. Trace lengths of the WCFs are relatively long compared with those of closed or sealed fractures (i.e., those fractures without groundwater flow) (Fig. 2a). In about the first 30 m from the MSF, the frequency of WCFs and the inflow rates are both lower than beyond 30 m (Fig. 4g). In addition, the number of WCFs as a percentage of the number of all fractures also increases with distance from the MSF. Hydraulic transmissivities obtained from the borehole investigations are relatively low (less than 10^{-9} m^2/s) until about 25 m from the MSF at GL−300 m (Fig. 4h). In the rock mass between 25 and 100 m from the MSF, hydraulic transmissivities increase, but the transmissivities of individual fractures are not as high as those in the region more than 100 m from the MSF. This is because fracture frequency is higher between 25 and 100 m than beyond 100 m from the MSF (Figs. 4e and h).

As determined by gallery wall mapping, fracture frequencies are consistently high for about the first 60 m from the MSF at GL−500 m; beyond this, they decrease as distance from the MSF increases (Fig. 5c). Fracture frequencies determined by both scan-line and borehole investigations are relatively high around the MSF, although this trend is not as clear as with the gallery wall mapping (Figs. 5d and e). Around the SF (at about 50 m from the MSF), fracture frequencies based on scan-line and borehole investigations are the highest. After about 50 m, all fracture frequencies decrease. Calcite, hydrothermal minerals, or hydrothermal minerals with calcite as fracture fillings are generally observed at the GL−500 m level (Fig. 5f). Clayey fillings constitute more than 10% (with and without other minerals) of the filling minerals until about 65 m from the MSF (Fig. 5f). The number of WCFs is 7.3% of the total fracture population (146 of 2002) at the GL−500 m level. The trace lengths of the WCFs are also relatively long compared with those of fractures without groundwater inflow (Fig. 2b). Up to about 50 m from the MSF, the inflow rates from WCFs are low compared with the rates more than 50 m from the MSF (Fig. 5g). Hydraulic transmissivities are relatively low (less than 10^{-9} m^2/s) until about 30 m from the MSF at the GL−500 m level (Fig. 5h). At distances greater than 30 m from the MSF, hydraulic transmissivities increase, but the values are not as high as in the fractures more than 60 m from the MSF, where fracture frequency is lower than around the MSF (Figs. 5e and h). Hydraulic transmissivity around the SF is 10^{-7} m^2/s. However, the transmissivity of individual fractures around the SF is not high compared with other locations because the fracture frequency around the SF is over 10/m (Figs. 5e and h).

In addition, transmissivities in the highly fractured area are relatively constant; although in the less fractured area, these show variability at both the GL−300 m and GL−500 m levels (Figs. 4h and 5h).

4.3. Distribution of fractures according to trace length

Figure 6a shows the frequency distribution of fracture lengths at one meter intervals plotted versus distance from the MSF. Fracture frequencies for the relatively short trace length fractures are highest around the MSF. Note that the frequencies of fractures under 2 m in trace length at the GL−500 m level are relatively high up to 60 m from the MSF, at which point they abruptly decrease (Fig. 6a). On the other hand, the frequencies of fractures having relatively long trace lengths are reasonably constant throughout the sample distance.

To compare the fracture frequency distributions of fractures with traces increasing in one meter intervals, we normalized the fracture frequencies and conducted multivariate analysis. To normalize the data, the expected value and variance were estimated for exponential distributions because the probability density distribution of fracture frequencies is an exponential distribution (Fig. 6b). The normalized fracture frequencies are given by the following equation.

$$f_n(x_i) = (x_i - E)/\sqrt{V} \qquad (1)$$

where $f_n(x_i)$ is the normalized fracture frequency, x_i is the fracture frequency every meter from the MSF, E is the expected value of the exponential distribution, and V is the variance of the exponential distribution. The normalized values are calculated using equation (1) for the multivariate analysis. The results of the multivariate analysis show that the trend of the fracture frequency distributions can be divided based on biplot analysis into two groups at the boundary of the 4 m fracture length (Fig. 6c). Based on normalized fracture frequencies divided by the 4 m fracture trace length, fracture frequencies that include relatively short trace lengths decrease toward the MSF and fracture frequencies with relatively longer traces are relatively constant (Fig. 6d).

4.6. Relationship between fracture trace length and fracture filling

Figure 7a shows the relationship between fracture filling and (a) fractures of less than 4 m in length and (b) fractures of greater than or equal to 4 m in length. Fractures with relatively short traces tend to be filled by hydrothermal minerals alone (Figs. 7b-1 and b-4), calcite and hydrothermal minerals (Fig. 7b-2), or calcite (Fig. 7b-3) and clayey fillings (Figs. 7b-5, b-8, and a). Fractures with relatively long traces are filled by several minerals; the percentage filled by clayey fillings is high compared with relatively short fractures (Fig. 7a).

There are two types of calcite. Type I calcite coexists with hydrothermal minerals (Fig. 7b-2). This calcite is anhedral or has cleavage that may be either parallel or oblique to the fractures. Calcite I sometimes displays a layered structure with hydrothermal minerals (Fig. 7b-2; Ishibashi et al., 2014). Type II calcite can be either rounded or rectangular in shape and only slightly elongated parallel to the c-axis (Fig. 7b-3; calcite II; Ishibashi et al., 2014). Alteration haloes signify biotite chloritization and seritization of plagioclase cores in wall rocks around fractures filled by calcite I. However, this is almost never observed in wall rocks around fractures filled by calcite II. Fragments of quartz and feldspar are observed both with hydrothermal minerals (Fig. 7b-4) and in clayey fillings (Figs. 7b-5 and 8b). Results of XRD analysis and microscopy show that clayey fillings are composed of smectite, calcite, and other fragments (Figs. 7b-5 and 8). Clayey fillings occur in fractures at the visual scale and microscopic scale (micro-cracks; Figs. 7b-5 and 8b). Micro-cracks filled by clayey fillings are not sheared cracks because the shape of each fracture surface is similar and the minerals are not displaced around micro-cracks (Fig. 8b). The long axes of fragments in clayey fillings have similar orientations around the surfaces of fractures, which is similar to an imbricate structure (Fig. 8b-2). In addition, the size of fragments in clayey fillings differs with distance from the micro-crack surface; small fragments are observed near the micro-crack surface and large fragments are observed in the core of clayey fillings (Fig. 8b-3).

5. Discussion

5.1. Fracture distribution around the major fault

All fracture frequencies are higher in close proximity to the MSF, as shown by the results of gallery wall mapping (Figs 4c and 5c). In particular, at the GL−500 m level, all fracture frequencies are clearly higher within 60 m of the MSF than at distances further away (Fig. 5c). Similarly, at the GL−300 m level, the trend in fracture frequencies is clearly shown by the gradual decrease in the moving average with distance from the MSF (Fig. 4c). The frequencies of relatively short length fractures are higher in areas of high fracture frequency compared with areas of lower fracture frequency (Figs. 5c and 6a; Table 2). The frequencies of fractures with relatively long traces are almost constant in all areas (Figs. 6a and c). A similar increase in the frequency of fractures with relatively short traces was also observed in surface investigations of the Atera Fault, one of the major active faults in the northeastern part of the Chubu area, Central Japan (Yoshida et al., 2014). This was also observed around small scale (decameter-size) faults in Äspö Hard Rock Laboratory, southeast Sweden (Bossart et al., 2001). Fracture orientations are similar to the orientation of the MSF in areas of high fracture frequency at both the GL−300 m and GL−500 m levels (Figs. 4a and b and 5a and b). This suggests that the fractures in the highly fractured zone in close proximity to the MSF were formed in association with the activity of the MSF. It is also an indication that this highly fractured zone is a mechanical damaged zone of the MSF. Therefore, fractures with relatively short traces are considered to have formed as a direct result of fault activities on the MSF, and the resultant damage zone around the MSF is mainly composed of relatively short fractures.

Hydrothermal minerals such as chlorite and sericite were formed at this site soon after brittle deformation (Ishibashi et al., 2014). Fracture fillings of almost all fractures with relatively long traces include the hydrothermal minerals (Fig. 7a). This indicates that fractures with relatively long traces were formed during the early stage of Toki granite intrusion. Yoshida et al. (2005, 2013b) showed that brittle tensile fractures (background fractures) formed soon after brittle deformation after the temperature of granitic plutons decreased through the ductile-brittle transition. In addition, Yoshida et al. (2014) showed that the frequency of background fractures in Japanese plutons of different ages (ranging from 1 to 120 Ma) is almost the same. The frequency of fractures with relatively long traces is constant in all areas with respect to the MSF (Figs. 6a and d). It is probable that those fractures with relatively long traces correspond to background fractures; therefore, they formed before faulting.

Fracture frequencies determined in borehole investigations at the GL−300 m level are low. They fall in a range below about 3/m and are commonly about 1/m at distances greater than 100 m from the MSF (Fig. 4e; Table 2). This is interpreted as an indication that fractures formed due to faulting developed within 100 m of the MSF in the rock mass around the GL−300 m level. Therefore, the damage zone at this depth does not extend beyond 100 m from the MSF.

The relationship between the width of a mechanical damage zone (W_{dz}) formed due to faulting and the length of a fault (L) has been suggested as follows.

$$W_{dz} = 0.016*L \qquad (2)$$

(Vermilye and Scholz, 1998).

The relationship between the maximum displacement on a fault (d) and the length of a fault has been suggested as follows.

$$d = L^{1.5}/200 \qquad (3)$$

(Cowie and Scholz, 1992).

In addition, field observations indicate that the correlation between the width of a fault gouge (W_g) and the displacement on a fault is as follows.

$$W_g = 10^{-2}*d \qquad (4)$$

(Scholz, 1987).

Based on the fault gouge width, the damage zone widths of the MSF are estimated to be about 96 and 67 m at the GL−300 m and GL−500 m levels, respectively, while that of the SF is estimated to be about 11 m. These widths correspond to the width of damage zones estimated by fracture frequency based on borehole investigations and geological investigations in the gallery. Yoshida et al. (2009) also showed that the scale of the damage zone of the Atera Fault is consistent with the scale calculated by equation (2).

The extent of a damage zone must be understood as soon as possible before the construction of an underground facility because it is an important design consideration and must be taken into account in any decisions regarding the layout of the facility. However, evaluating the extent of a damage zone is difficult based on the results of a one-dimensional investigation such as a borehole or scan-line investigation (Figs. 4d and e and 5d and e). This is because large fractures are more likely to be intersected by the borehole or scan-line, whereas small fractures are less likely to be intersected, potentially leading to their under-representation in any analysis (Ohnishi and Kagimoto, 1988; Martel, 1999). Therefore, an indication of damage zone width calculated using the above equations is useful for estimating the scale of the fault damage zone in an underground environment.

5.2. Fracture filling process

Sericite, chlorite, calcite, and smectite occur as fracture fillings at the GL−300 m and GL−500 m levels. Sericite and chlorite are hydrothermal minerals (e.g., Hedenquist, 1996; Nishimoto et al., 2008; Utada et al., 2003; Nishimoto and Yoshida, 2010). Seritization of plagioclase cores and chloritization of biotite are characteristically observed at centimeter to decimeter distances from fractures filled with sericite or chlorite, respectively. Therefore, sericite and chlorite are considered to be associated with hydrothermal fluids. Hydrothermal minerals are occasionally observed in a fracture, with fragments such as quartz or feldspar (Fig. 7b-4). Such occurrences have been previously reported by J´ebrak et al. (1997), Branquet et al. (1999), and Fujii et al. (2000), although the scales are different. These reports suggest that sericite and chlorite formed during a fluidization process in which hydrothermal fluid, along with fragments of quartz or feldspar, was injected into the fractures.

Calcite I is mainly observed with hydrothermal minerals, often displaying a layered structure (Figs. 7b-1 and b-2), and the wall rock around fractures has an alteration halo. Calcite associated with hydrothermal alteration is considered to have formed with Ca that is available after the seritization of anorthite (Hamasaki et al., 1999). This indicates that calcite I formed in association with hydrothermal fluid. The calcite II is only observed in fractures without clear alteration halos. Calcite II shows a slight elongation parallel to the *c*-axis (Fig. 7b-3). The shape of calcite is known to be dependent on groundwater condition (Folk, 1974; Iwatsuki et al., 2002; Mizuno et al., 2010). Ishibashi et al. (2014) suggested that calcite II collected at GL−300 m was precipitated from groundwater at the time of the Mizunami Group deposition.

The fractures with clayey fillings are mainly observed in extension joints. The clayey fillings are accompanied by fragments, such as quartz, feldspar, and calcite, together with smectite formation (Figs. 7b-5 and 8). This occurrence is similar to the filling of hydrothermal fractures with minerals and fragments (Fig. 7b-4). In underground environments, smectite is formed either from hydrothermal fluids or due to the water-rock interactions of sericite and relatively low temperature groundwater (Taboada and Garcia, 1999; Meideno and Alistair, 1996; Yoshida et al., 2008; Nishimoto and Yoshida, 2010). Based on O-isotopic analysis, Yoshida et al. (2013b) showed that calcites in clayey fillings at the GL−300 m gallery were precipitated from groundwater at about 30 °C. The calcite present in clayey fillings is considered to have formed prior to the formation of the clayey filling because it occurs as fragments. In addition, hydrothermal fluids did not penetrate the Toki granite after decreasing to a relatively low temperature (Yamasaki et al., 2013; Ishibashi et al., 2014). These findings indicate that smectite was formed due to water-rock interactions with sericite and relatively low temperature groundwater. The occurrence of clayey fillings in micro-cracks shows a structure similar to the imbrication of sedimentary rocks (Fig. 8b-2). This structure forms in association with material flow. In Figure 8b-3, small fragments are observed near the micro-crack surface, and large fragments are distributed in the inner region of the fracture filling. Such an occurrence can be thought of as being associated with decreasing flow velocity near the fracture surface due to frictional forces between the fracture surface and the filling minerals. Therefore, these occurrences indicate that such clayey fillings formed due to the injection of fragments within the smectite. Clayey fillings are mainly observed in damage zones of the MSF and SF (Figs. 4f and 5f; Table 2). Multiple reactivations of the MSF are indicated by the different displacements observed on the MSF (Tagami et al., 2012). The process of clayey filling formation consists of smectite formation due to water-rock interactions between sericite and relatively low temperature groundwater and due to the injection of fragments with smectite (associated with fault activity).

5.3. Water-conducting fractures (WCFs) in fault damage zones

Generally, the relationship between a major fault and hydraulic permeability is that the fault core is composed mainly of fault gouges and has low permeability and the damage zone has higher permeability (e.g., Chester et al., 1993; JNC, 2000; Faulkner et al., 2010). Several investigations at other underground facilities have reported faults as high permeability structures (e.g., Keusen et al., 1989; Nagra, 1994; Mazurek et al., 2003; Svensk, 2006). However, the permeability of each fracture in the damage zone around the MSF in this gallery is low, even though a fracture network has developed at the GL−300 m and GL−500 m levels (Figs. 4 and 5; Table 2). Fractures with relatively short traces were sealed by fracture fillings formed by a single type of groundwater (hydrothermal fluid or low temperature groundwater), and these became non-WCFs in their present condition. However, these fractures had open spaces, allowing groundwater to flow in the past. On the other hand, fractures with relatively long traces are mainly WCFs in their present condition, even though they are filled with several minerals such as hydrothermal minerals, calcite, and smectite, which are formed by different types of groundwater. Thus, fractures with relatively long traces (background fractures) are considered to have been WCFs until the present day.

The percentage of fractures filled by clayey fillings is high compared with the other fillings in fractures with relatively long traces (Fig. 7a). Clayey fillings have a high potential for decreasing the hydraulic transmissivity of fractures because they not only coat the fracture surface but also fill micro-cracks in the matrix (Figs. 7b-5 and 8b). Therefore, the hydraulic transmissivity of fractures with relatively long traces is lowered as a result of being filled by clayey fillings formed due to fault formation. Similar clayey fillings are also observed in fractures that are not shear cracks at Kamaishi Mine in the northern part of Honshu (Tohoku area) and at the LPG storage facility located under the Seto Inland Sea in the western part of Japan (JNC, 1999; Maejima and Nakajima, 2010). However, they are not reported in the tension cracks in stable continental regions (Yoshida et al., 2012). Therefore, clayey fillings are identified as one of the features of an orogenic field such as Japan. From the above considerations, the development of hydrogeological structures related to faulting in an orogenic field can be divided into three stages. The first stage is the formation of background fractures, the second stage is formation of a damage zone due to faulting, and the third stage is the formation of fracture fillings associated with the penetration of groundwater, such as hydrothermal fluid and relatively low temperature water, through the high permeability fracture network developed in a damage zone (Fig. 9). In the first stage, background fractures are formed after the temperature of the granitic plutons decreases through the ductile-brittle transition zone. The hydraulic transmissivity of granitic rock is largely controlled by the heterogeneity of fracture distributions (Fig. 9). Fault activity leads to the formation of a damage zone, in which a fracture network develops as a result of the formation of relatively small, interconnected fractures in the second stage. In addition, hydraulic transmissivity of the damage zone increases as the fracture network develops (Fig. 9). As a result of increased hydraulic transmissivity, hydrothermal fluid and low temperature water, such as meteoric water, selectively penetrate into a damage zone during each penetration event. The small fractures formed by faulting are then sealed by fracture fillings and the large fractures (background fractures) are filled by several fracture fillings that are formed by different types of groundwater penetrating during different ages in the damage zone during the third stage (Fig. 9). In this late stage, the clayey fillings were injected into mainly large fractures in the damage zone associated with faulting. Therefore, the hydraulic transmissivities of the damage zone and each fracture are reduced. The second and third stages are considered to have occurred repetitively in the study area. The reactivation of faults, such as older structures (e.g., mylonites and cataclasites), representing the pre-existing mechanical heterogeneities of younger deformation events, such as the formation of fault gouges and breccias, has also been reported at other underground facilities (e.g., Keusen et al., 1989; Mazurek et al., 2003). The MSF was formed (early second stage) after the formation of background fractures, and fractures in the damage zone were filled and sealed by hydrothermal minerals and calcite I (early third stage). Calcite II and clayey fillings were formed in association with the penetration of meteoric water in the damage zone (late third stage) after the MSF was reactivated (late second stage) and the hydraulic transmissivity was reduced. As a result, the percentage of WCFs present in this area is about 10%.

The results of this study indicate that faulting decreases the hydraulic permeability of the damage zone in the long term. In addition, clayey fillings are effective in the containment of material within an underground environment proposed for the geological disposal of HLW because these are often of low hydraulic permeability and composed of smectite, which has high adsorption properties (JNC, 1999). These results emphasize the importance of understanding the development of hydrogeological structures related to faulting for evaluating the effect of faulting in plutons in an orogenic field.

6. Conclusions

The distributions of fractures, fracture fillings, and hydraulic transmissivity in and around a fault damage zone in Central Japan have been studied in order to understand the features and long term behavior of WCFs in and around such a damage zone.

The development of hydrogeological structures related to faulting in an orogenic field can be divided three stages. The first stage is the formation of background fractures that have acted as WCFs from past to present (long-term WCFs); the second stage is the formation of a damage zone due to faulting (hydraulic transmissivity in the damage zone is increased as a result of the formation of relatively small fractures) (temporal WCFs); and the third stage is the formation of fracture fillings associated with the penetration of groundwater, such as hydrothermal fluid and relatively low temperature water, through the high permeability fracture network developed in a damage zone. In addition, unconsolidated clayey fillings, which are characteristically observed in long-term WCFs in the damage zone, behave as a natural grout and reduce the hydraulic permeability of long-term WCFs.

Overall, this study indicates that faults in underground environments in an orogenic stress field have the potential to decrease the long term hydraulic permeability of fractures via the formation of fracture fillings.

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Figure captions

Fig. 1 Location map of the Mizunami Underground Research Laboratory in the Tono district, Central Japan, together with (a) a general map of the site showing the distribution of the Toki granite (after PNC (1994)); and (b) a schematic figure of the underground facilities at the URL, showing the location of the study areas (ground level (GL) −300 m and GL−500 m levels).

Fig. 2 Layout of galleries and boreholes, and the distribution of fractures (faults and joints), based on borehole investigations and gallery wall mapping at the (a) GL−300 m and (b) GL−500 m levels.

Fig. 3 Photographs of rock core samples showing faults and adjacent wall rocks: (a) major fault crossing the main shaft (MSF), with Lamprophyre dike and strongly altered granite in the 10MI22 borehole; and (b) secondary fault (SF), with altered granite at the GL−500 m level in the 12MI33 borehole.

Fig. 4 Distribution of fracture orientations (a, b), all fracture frequencies based on geological investigations in the gallery (c, d), average of all fracture frequencies based on borehole investigations (e), fracture fillings (f), and water conductiong fractures (WCFs; g) based on investigations in the gallery and transmissivities (h) around the MSF at the GL−300 m level. Horizontal axis shows horizontal distance from MSF.

Fig. 5 Distribution of fracture orientations (a, b), all fracture frequencies based on geological investigations in the gallery (c, d), average of all fracture frequencies based on borehole investigations (e), fracture fillings (f), and WCFs (g) based on investigations in the gallery and transmissivities (h) around MSF at the GL−500 m level. Horizontal axis shows horizontal distance from MSF.

Fig. 6 Frequency distribution of fracture trace lengths increasing in one meter intervals (a); probability density of fracture frequencies assumed as an exponential distribution (b); biplot of principal component analysis based on normalized frequency distribution of fractures (c); distributions of the normalized frequency of fractures per trace length of one meter, where upper charts show frequency of fractures with relatively short trace lengths and lower charts show that of fractures with relatively long trace lengths (d).

Fig. 7 Relationships between fracture fillings and trace length (a) and occurrence of fracture fillings (b).

Fig. 8 Results of XRD analysis of unconsolidated clayey fillings (a) and microscopic occurrence (b). Clayey fillings are present in micro-cracks (b-1). The long axes of fragments show similar orientations around the fracture surface (b-2). The size of fragments differs with distance from the micro-crack surface, with small fragments observed near the micro-crack surface and large fragments observed in the core of clayey fillings (b-3).

Fig. 9 Conceptual model showing the development of a fault damage zone as a hydrogeological structure.