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Technical note

Preliminary assessment of the highest potential transmissivity of fractures in fault zones by core logging

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A B S T R A C T

Fault zones are representative flow paths in rock masses, and the highest transmissivity of fractures in fault zones is important for conservative assessment of groundwater flow velocity for the purpose of radioactive waste disposal. Based on previous hydromechanical studies of fault zones, fault zones without tensile/hybrid damage-zone fractures are unlikely to have experienced faulting in a highly brittle manner, and the highest potential transmissivity of fractures in such fault zones is inferred to be relatively low (transmissivity (T) ≤ 10^{-8} m^2/s). To verify this inference, this study investigates the relationship between the failure mode (tensile/hybrid/shear) and the highest transmissivity of fractures in fault zones, using results from core logging and flowing-fluids electric conductivity (FFEC) logging in boreholes penetrating a Neogene siliceous mudstone (Wakkanai Formation) of the Horonobe area, northern Hokkaido, Japan. In 96% (35/36) of fault zones where tensile/hybrid fractures were not observed, the transmissivities of flow anomalies detected within the fault zones by FFEC logging are within the range of ≤10^{-8} m^2/s, whereas in 95% (145/153) of fault zones where tensile/hybrid fractures were observed, the transmissivities are within the range of ≥10^{-8} m^2/s. This result supports the above-mentioned inference, suggesting that core observations of whether tensile/hybrid fractures develop in fault zones allow preliminary assessment of the highest potential transmissivity of fractures in fault zones (i.e., potentially T ≥ 10^{-8} m^2/s or likely T ≤ 10^{-8} m^2/s). Such assessment increases the efficiency of hydrogeological borehole investigations of fault zones.

1. Introduction

Transmissivity of fault zones, which are representative flow paths in low-permeability rocks (e.g., Gutmanis et al., 1998; Mazurek et al., 1998; Follin and Stigsson, 2014; Ishii, 2015), can be directly measured by in situ hydraulic tests in boreholes that penetrate fault zones (Tsang et al., 2015). Such tests include packer tests, flowing-fluids electric conductivity (FFEC) logging (Tsang et al., 1990), and the Posiva flow log (PFL) measurements (Öhberg and Rouhiainen, 2000). The transmissivity data are important for site selection, design, and safety assessment of radioactive waste disposal areas (NAGRA, 1997; Japan Nuclear Cycle Development Institute, 2000; Nuclear Waste Management Organization of Japan, 2013; Tsang et al., 2015). However, when time and cost are somewhat limited in borehole investigations, abundant hydraulic tests may not be feasible, and hydraulic tests themselves may also be impossible, depending on borehole conditions (e.g., borehole diameter, dissolved gas, pore pressure, etc.). Although the aperture of fractures measured from borehole wall images can also be used to assess the transmissivity (e.g., using the parallel plate model (cubic law); Taylor et al., 1999; Flodin and Durlofsky, 2001; Jourde et al., 2002), the application of optical borehole-wall imaging for the precise measurement of fracture aperture requires limited borehole fluid and wall conditions (Williams and Johnson, 2004). Additionally, measurements of fracture aperture by acoustic/resistivity borehole-wall imaging have relatively poor detection limits (Genter et al., 1997). To efficiently conduct hydrogeological investigations of fault zones, even under such conditions, full utilization of core logging is necessary, as it enables geological information to be obtained easily and quickly.

To elucidate the relationship between geological information obtained by core logging and the permeability of fault zones, hydrogeological assessments have been conducted, and are based on results from laboratory experiments using core samples of matrices and fault rocks. In such studies, the fault core(s) and damage-zones are identified in drill core and the fault-parallel/normal bulk permeability is modeled (e.g., Evans et al., 1997; Lockner et al., 2009; Walker et al., 2013). However, to assess flow velocity in rock masses, the permeability of each conducting fracture in fault zones is important. The highest transmissivity of fractures in fault zones is significant for conservative assessments of groundwater flow velocity, which is key for safety assessments of geological sites for radioactive waste disposal. To evaluate the permeability of conducting fractures, detailed in situ hydraulic

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measurements are needed, such as short interval packer tests (e.g., Hamm et al., 2007), FFEC logging, and/or PFL measurements. These measurements have been performed at site investigations, including hydrogeological studies of fault zones. For example, Gutmanis et al. (1998) compared core logging data and permeability data obtained by short interval packer tests at the Sellafield site (Ordovician volcaniclastic rocks, United Kingdom), where fault zones are major potential conducting features (Gutmanis et al., 1998; Ishii, 2015), and indicated that the permeability increases with increasing frequency of fractures or potential flowing features of drill cores. Mazurek (1998, 2000) and Mazurek et al. (1998) compared core logging data and locations of flow anomalies detected by FFEC logging at the Wellenberg site (Cretaceous argillaceous marl, Switzerland) and the Northern Switzerland site (granite/gneiss), and reported no apparent systematic difference in the core logging data between fault zones that have or do not have flow anomalies, and found that marked hydrogeological heterogeneities (e.g., channeling) may exist within the fault zones. However, the relationship between the failure mode and the highest potential transmissivity of fractures in fault zones has not been well constrained quantitatively, although studies have shown, for example, that hybrid fractures tend to form the dilational portion (pull-aparts) of fractures in fault zones (Ferrill et al., 2012). Major fluid pathways can form if these open structures are then connected (Sibson, 1996; Holland et al., 2011). Previous studies have suggested that brecciated zones originating from numerous tensile fractures are potentially highly permeable features (Dholakia et al., 1998; Aydin, 2000, 2014).

Recently, Ishii (2015) proposed a rock mechanical indicator, ductility index (DI), which is defined by the effective mean stress of a rock mass normalized to the tensile strength of intact host rock, and showed that the highest potential transmissivity of fractures in fault zones can be uniformly predicted from DI, based on data from sedimentary rocks and crystalline rocks at six sites (Fig. 1). The studied fractures include all fractures in fault zones (e.g., damage-zone fractures and slip surfaces bounding fault rocks). The highest transmissivities of fractures in fault zones correspond to the transmissivities of flow anomalies detected by FFEC logging and/or PFL measurements. The correlation between the highest potential transmissivity and DI is given by the following equation:

$$\log T = -3.5\ \log \mathrm{DI} - 6.54 \quad (\text{standard error} = 1.25\ \text{in}\ \log T). \tag{1}$$

DI was calculated using the tensile strengths of intact rocks determined from laboratory indirect tension (Brazilian) tests, and the mean stress and pore pressure of the rock mass were determined from in situ measurements in boreholes. Although the rock strengths in fault zones may be partly reduced by fault deformation, the DI model uses the strengths of intact host rocks due to the following reasons: (1) as a harder rock is likely to allow a larger dilation, the strength of intact rock is a more important factor when considering the prediction of the highest potential transmissivities; and (2) the strengths of intact rocks can be more consistently defined and measured (Ishii, 2015). Although the mean stresses around faults can be perturbed by failure within the damage zone (e.g., Segall and Pollard, 1980), the DI model uses the mean stresses calculated from the far-field stresses (Ishii, 2015). Furthermore, Ishii (2016) indicated that DI is closely related to the failure mode of damage-zone fractures in fault zones, as shown by theoretical analysis based on the Griffith-Coulomb failure criterion, laboratory experiments, and core logging. Ishii (2016) reported that: (1) only tensile/hybrid damage-zone fractures form when faulting occurs at DI < 2; and (2) shear damage-zone fractures can form when faulting occurs at DI > 2, which suppresses the formation of tensile/hybrid damage-zone fractures. These damage-zone fractures result from stress concentrations at the asperities/tips of slip surfaces in fault zones (Ishii, 2016), and the tensile/hybrid damage-zone fractures are typically wing/splay cracks (e.g., Kim et al., 2004) that propagate from the slip surfaces (Fig. 2a). The shear damage-zone fractures are typically synthetic/antithetic shear fractures (e.g., Kim et al., 2004) that branch from the slip surfaces (Fig. 2b), and they strictly initiate from other preceding/preexisting structures such as micro shear bands (e.g., Ishii, 2012, 2016) or tensile microcracks (e.g., Petit and Barquins, 1988; Healy et al., 2006). Shear fractures/slip surfaces do not nucleate and self-propagate alone (e.g., Crider and Peacock, 2004; Aydin et al., 2006). During the evolution of fault zones, the initial slip surfaces form along other preexisting structures such as deformation bands (e.g., Aydin and Johnson, 1978; Shipton and Cowie, 2001; Schultz and Siddharthan, 2005; Ishii, 2012) or joints (e.g., Martel and Pollard, 1989; Crider and Peacock, 2004; Myers and Aydin, 2004; Walker et al., 2012). During the evolution of the fault zone, all fractures can be reactivated (sheared) (e.g., Crider and Peacock, 2004; Aydin, 2014), and reactivated fractures may newly develop their own damage-zone fractures (e.g., Davatzes et al., 2003; Flodin and Aydin, 2004; Myers and Aydin, 2004; Aydin, 2014; Ishii, 2016). If faulting occurs at DI < 2, these new damage-zone fractures would be tensile/hybrid fractures, according to the model of Ishii (2016). Thus, integrating the above-mentioned findings of Ishii (2015, 2016), it is inferred that fault zones in which tensile/hybrid fractures do not develop are unlikely to experience faulting at DI < 2, and the highest potential transmissivities of fractures in such fault zones are likely to be $\leq 10^{-8}$ m^2/s (Fig. 2). This range of transmissivity corresponds to a range of the highest potential transmissivity of fractures in fault zones at DI > 2, according to Eq. (1).

To verify the above-mentioned inference, this study investigates the relationship between the failure mode (tensile/hybrid or shear) and the highest potential transmissivity of fractures in fault zones, based on the

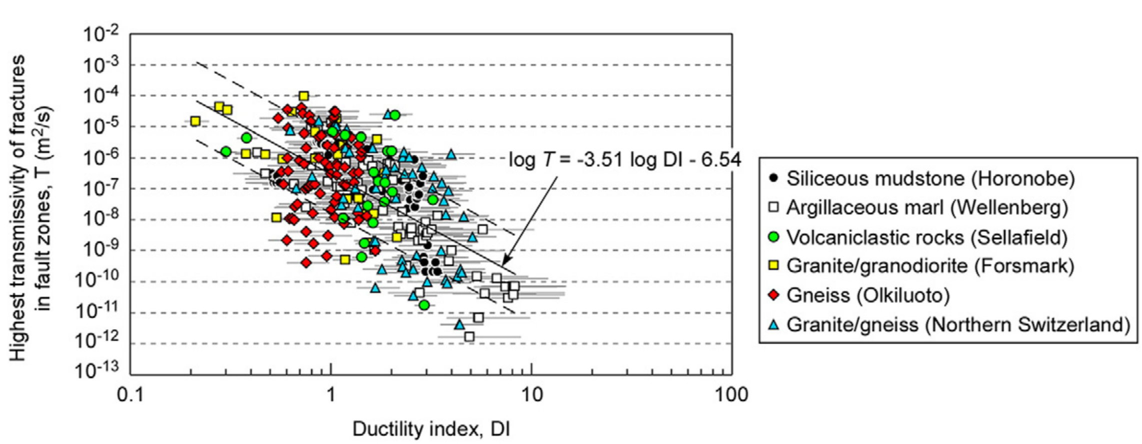

Fig. 1. Transmissivities of the flow anomalies detected in fault zones, and the corresponding DI for the six sites of interest (Ishii, 2015). Horizontal error bars show estimation errors due to uncertainties in tensile strength. Also shown is the best fit line (solid line) with the standard error (= 1.25 in log$T$: broken lines) from regression analysis, using the data for all the sites.