Permeability change of rock fractures estimated from the scale of microearthquakes in geothermal reservoir

Takuya Ishibashi[1], Noriaki Watanabe[2], Satoru Ishikawa[2], Hiroshi Asanuma[1], and Noriyoshi Tsuchiya[2]

[1]Fukushima Renewable Energy Institute, AIST, 2-2-9 Machiikedai, Koriyama, Fukushima, 963-0298, Japan

[2]Graduate School of Environmental Studies, Tohoku University, 468-1 Aramaki-aza-Aoba-ku, Sendai, Miyagi, 980-0845, Japan

e-mail: takuya.ishibashi@aist.go.jp

ABSTRACT

Despite its importance, the relation between microearthquakes (MEQs) and changes in fracture permeability during hydraulic stimulation of a geothermal reservoir has rarely been explored, and it is still not well understood. To investigate this relation, we first formulate a plausible scale dependence in fracture permeability for joints and faults. By combining this formulation with the concept of the seismic moment, we derive quantitative relations between the moment magnitude (M_w) of MEQs and the fracture permeability change in the directions orthogonal to ($k_{fault,\perp}/k_{joint}$) and parallel to ($k_{fault,//}/k_{joint}$) the shear displacement, in the form $k_{fault,\perp}/k_{joint} = 116.4 \times 10^{0.46 M_w}$ and $k_{fault,//}/k_{joint} = 13.1 \times 10^{0.46 M_w}$. Despite the simplicity of the derivation, these relations have the potential to explain the results of field experiments on hydraulic stimulation, such as the enhanced geothermal systems at Soultz-sous-Fôret and Basel. Additionally, we briefly introduce our recent project on exploring the link between MEQs and permeability change on the basis of rock deformation experiment under HP-HT conditions.

Keywords: rock fracture/fault, permeability, moment magnitude, microearthquake, surface roughness

1. INTRODUCTION

Traditionally, geothermal reservoirs are stimulated hydraulically for the purpose of improving or maintaining their permeability [*Evans et al.*, 2005; *Häring et al.*, 2008]. During this stimulation, a massive amount of pressurized fluid is injected into the reservoir and, as a result, pre-existent fractures undergo slip which induces microearthquakes (MEQs) [*Guglielmi et al.*, 2015]. In-situ data on such MEQs are generally recorded, since they can be good indicators of active processes within the reservoir. However, the relation between MEQs and changes in hydraulic properties has rarely been explored and is still poorly understood.

In the present study, our main focus is achieving a quantitative relation between the magnitude of a MEQ and the change in permeability during hydraulic stimulation of a geothermal reservoir. Based on the results of numerical modeling, we derive the scale dependences of hydraulic properties of subsurface rock fractures (joint/fault), where the shear displacement of the fracture is treated as a variable parameter rather than having a fixed value. Consequently, the dependence of hydraulic properties of rock fractures on scale (length) and shear displacement can be successively determined. By introducing the concept of the seismic moment, which relates the magnitude of a MEQ to the fracture scale, we then obtain the relation between the MEQ magnitude and the permeability change.

2. METHOD

Based on the method developed by *Ishibashi et al.* (2015), heterogeneous aperture distributions for effective confining stresses of up to ~100 MPa are simulated for rock fractures with various combinations of length l [m] and shear displacement δ [m]. In their method, a pair of synthetic fractal surfaces were placed together, so that the fractures had a scale-independent contact area (see *Ishibashi et al.* (2015) for details). We numerically paired surface topographies of square fractures with fracture lengths of 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 m, using a 250-μm square-shaped grid. Heterogeneous aperture structures of fractures with shear displacement (i.e., faults) and without shear displacement (i.e., joint) were then modeled over various scales. To imitate natural faults, δ/l was kept constant (2.5×10^{-3}, 5.0×10^{-3}, 1.0×10^{-2}, and 2.0×10^{-2}). Thus, a total of 35 aperture distributions were considered in this study.

For each distribution, unidirectional fluid flow was simulated by solving the Reynolds equation [*Brush and Thomson*, 2003]. In the simulations, flow both orthogonal and parallel to the imposed shear displacement direction was considered. Based on the fluid flow simulations, changes in the fracture permeability was evaluated for different fracture lengths and shear displacements.

Finally, the scale dependence of fracture flow was combined with equations defining the scale of earthquakes [*Aki and Richards*, 2002; *Hanks and Kanamori*, 1979], and the relation between MEQs and the change in the fracture permeability was investigated.

3. RESULTS AND DISCUSSION

The predicted fracture-length dependence of hydraulic properties is shown in Figure 1. Figure 1(a) shows that fracture permeability ($k_\perp$) in the direction orthogonal to the shear displacement increases with fracture length for both joints and faults. For joints, the permeability can be approximated by

$$k_{joint} = 9.8\times10^{-13} l^{0.16}, \tag{1}$$

where k_{joint} is the joint permeability [m^2]. For faults, the permeability can be approximated by

$$k_{fault,\perp} = 2.3\times10^{-6}\left(\frac{\delta}{l}\right)^{1.18}\cdot l^{1.08}, \tag{2}$$

where $k_{fault,\perp}$ is the fault permeability [m^2]. Figure 1(b) shows fracture permeability ($k_{//}$) in the direction parallel to the shear displacement. The line and the shaded region represent the $k_\perp$ values shown in Figure 1(a). The permeability anisotropy is significantly small for the joint, whereas the permeability anisotropy is large for the fault. Considering this fact, the fault permeability ($k_{fault,//}$) in the direction parallel to the shear displacement is approximated by

$$k_{fault,//} = 2.6\times10^{-7}\left(\frac{\delta}{l}\right)^{1.18}\cdot l^{1.08}. \tag{3}$$

The permeability anisotropy may be due to the fact that contacting asperities grouped along the direction orthogonal to the shear displacement partially block the fluid flow.

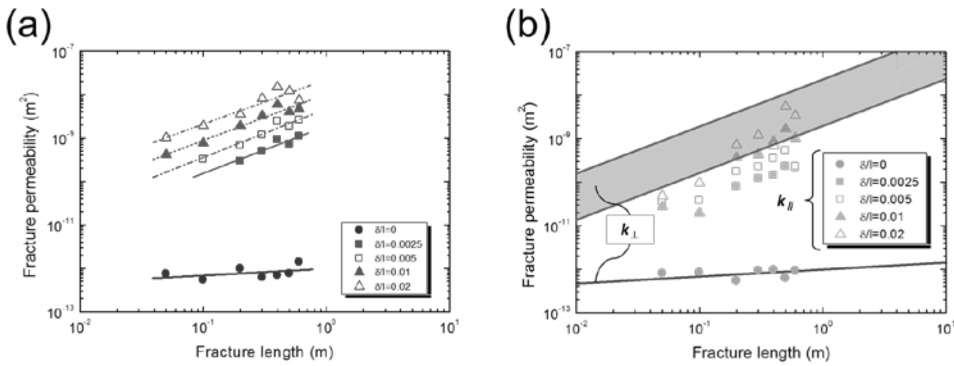

Fig. 1 Predicted fracture length dependence of (a) fracture permeabilities in perpendicular direction to shear displacement, $k_{\perp}$ and (b) fracture permeability in parallel direction to shear displacement, $k_{//}$.

Having established the dependence of the fracture permeability (k) on the fracture length (l) and shear displacement (δ), we introduce the concept of seismic moment. This concept relates the scale of an earthquake to the fracture length, allowing a quantitative relationship between the change in permeability and the magnitude of MEQs. First, we consider a simple configuration of hydro-shear failure for the MEQs generated during stimulation of fractured reservoirs (see Figure 2(a)). With the definitions related to the moment magnitude (M_w) [*Leonard*, 2010], M_w, l, and δ can be quantitatively correlated as following:

$$l = 10^{0.5M_w + 1.00} \tag{4}$$

$$\delta/l = 3.72\times10^{-5} \tag{5}$$

For a fracture that has not experienced shear failure (i.e., a joint prior to hydraulic stimulation), we assume zero shear displacement. This allows the initial values for fracture permeability (k_{joint}) for a fracture with a given length to be estimated using Equations (1). In contrast, for a fracture that has experienced a MEQ (i.e., a fault after hydraulic stimulation), the permeability ($k_{fault,\perp}$) in the direction orthogonal to the shear displacement and the permeability ($k_{fault,//}$) in the direction parallel to the shear displacement can be estimated using Equations (2) and (3). In this manner, the quantitative change in fracture permeability can be expressed in terms of M_w for a MEQ. By combining Equations (1), (2), (4), and (5), the corresponding change in the fracture permeability in the orthogonal direction to the shear displacement can be formulated as

$$k_{fault,\perp}/k_{joint} = 116.4\times10^{0.46M_w}. \tag{6}$$

In contrast, by combining Equations (1), (3), (4), and (5), the change in the fracture permeability in the parallel direction to the shear displacement is

$$k_{fault,//}/k_{joint} = 13.1\times10^{0.46M_w}. \tag{7}$$

Note that the generality of these expressions is clearly limited.

l and δ are estimated for a MEQ with a M_w of 0-2, and the fracture permeability are calculated before and after the earthquake. Figure 2(b) shows the relation between l and M_w and between δ and M_w. Figures 2(c) shows the change in the fracture permeability due to MEQs with a specific M_w. Though the mechanisms of fracture shear are much more complicated than is assumed here, we feel that the proposed approach is valuable as a first step towards linking MEQs to fracture permeability change.

Finally, we compare the permeability increases predicted using the proposed method with the results of actual field experiments. According to *Evans et al.* (2005), the hydraulic stimulation for creating an enhanced geothermal system (EGS) at Soultz-sous-Fôret, France, caused several MEQ events with local magnitudes of 2.3-2.9, and, as a result, the reservoir transmissivity increased from ~$10^{-16.8}$ to ~$10^{-14.5}$ m^2 (approximately 200 times). Similar transmissivity gains (400 times) were reported at the EGS project in Basel, Switzerland, where the local magnitude of observed MEQs was ≥ 2.5 [*Häring et al.*, 2008]. In comparison, for a MEQ with M_w=2.5, Equations (14) and (15) respectively predict permeability gains of 1,640 and 185 times. Since these equations represent extreme cases with regard to the slip direction, the actual permeability increase would be expected to be between these values. This is consistent with the results of the field experiments, and thus supports the validity of the approach proposed here.

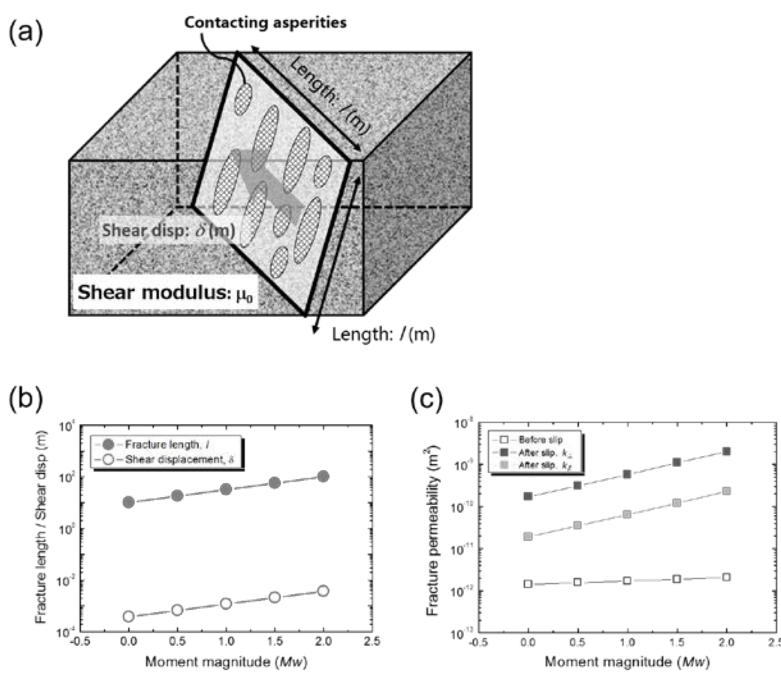

Fig. 2 (a) Model for linking MEQ to permeability change during hydraulic stimulation, and estimated relations between moment magnitude and (b) fracture length and shear displacement, and (c) fracturepermeablity.

Thus, we suggested the possible link between MEQ and the change in the hydraulic properties of rock fracture, in term of the moment magnitude of MEQ, during hydraulic stimulation on a geothermal reservoir. Though our suggested link is useful due to its simplicity, for the practical use, this link should be sophisticated on the basis of the rock deformation experiments under high temperature and high pressure (HTHP) conditions. For this purpose, we recently install the new experimental apparatus, which enable us to shear rock fractures under HTHP conditions, into FREA, AIST (Figure 3). The detail of our apparatus is explained in our presentation. This system will help us to understand the physics of MEQ during the stimulation and related phenomena.

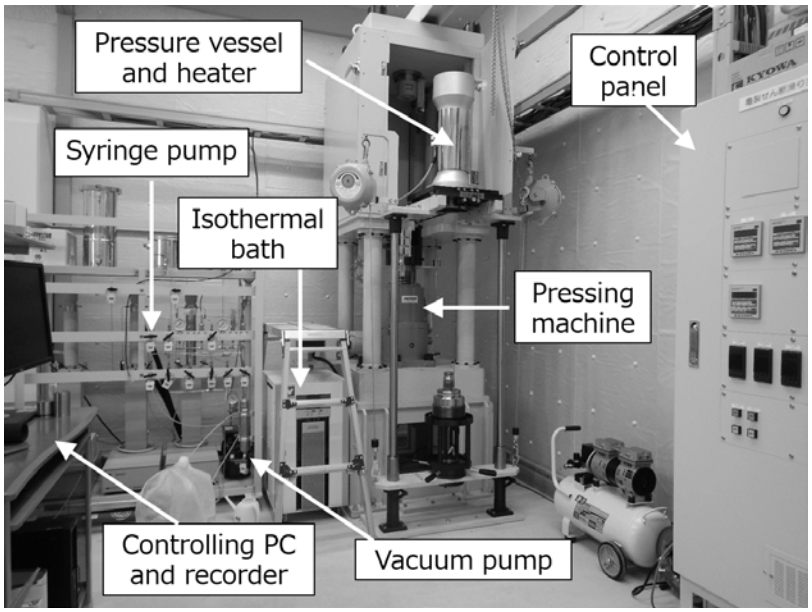

Fig. 3 New experimental system for evaluating permeability change during fracture shearing under HP-HT conditions. This system has been installed to FREA, AIST, in 2016.

4. CONCLUSIONS

- We explore the linkage between MEQs and a fracture permeability change during hydraulic stimulation of a fracture reservoir.
- We derive a quantitative relation between the moment magnitude of MEQs and the fracture permeability change.
- We suggest the potential of in-situ MEQ data that allow inverse mapping of permeability change.
- We recently install the new experimental apparatus, which enable us to shear rock fractures under HTHP conditions, into FREA, AIST. This apparatus will help us to understand the physics of MEQ, the change in hydraulic properties during MEQ, and so on.

ACKNOWLEDGEMENT

The present study was supported in part by JSPS through Postdoctoral Fellowships for Research Abroad, No. 26-709 (to T.I.) and by METI, Japan through International Research Program for Innovative Energy Technology (to H.A.).

REFERENCES

Aki, K. and P. G. Richards (2002), Quantitative Seismology, 2nd ed., 700 pp., University Science Books, Sausalito.

Brush, D. J., and N. R. Thomson (2003), Fluid flow in synthetic rough-walled fractures: Navier-Stokes, Stokes, and local cubic law assumptions, *Water Resour. Res.*, **39(4)**, 1085, doi:10.1029/2002WR001346.

Evans, F. E., A. Genter, J. Sausse (2005), Permeability creation and damage due to massive fluid injections into granite at 3.5 km at Soultz; 1. Borehole observations, *J. Geophys. Res.*, **110, B04203**, doi:10.1029/2004JB003168.

Guglielmi, Y., F. Cappa, J. F. Avouac, P. Henry, and D. Elsworth (2015), Seismicity triggered by fluid injection-induced aseismic slip, *Science*, **348(6240)**, 1224-1226

Hanks, T. C., and H. Kanamori (1979), A moment magnitude scale, *J. Geophys. Res.*, **84(B5)**, 2348-2350.

Häring, M.O., U. Schanz, F. Ladner, and B.C. Dyer (2008), Characterisation of the Basel 1 enhanced geothermal system, *Geothermics*, **37**, 469-495.

Ishibashi, T., N. Watanabe, N. Hirano, A. Okamoto, and N. Tsuchiya (2015), Beyond-laboratory-scale prediction for channeling flows through subsurface rock fractures with heterogeneous aperture distributions revealed by laboratory evaluation, *J. Geophys. Res.*, **120**, doi:10.1002/2014JB01555.

Leonard. M. (2010), Earthquake fault scaling: Self-consistent relating of rupture length, width, average displacement, and moment release, *Bull. Seism. Soc. Am.*, **100(5A)**, 1971-1988.