DEVELOPMENT OF NEW EXPERIMENTAL SYSTEM AND PERMEABILITY MEASUREMENTS OF FRACTURED ROCK AT 350-500 ^{o}C UNDER CONFINING STRESS

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1. INTRODUCTION

More recently, a new concept of EGS (Enhanced Geothermal System) in which a reservoir is created in ductile basement rocks (Figure. 1) has been proposed. This new type of EGS potentially has a number of advantages including: (1) nearly full recovery of injection water, (2) suppression of felt earthquakes from/around the reservoir, and so on. One of possible ways to create a fracture network in a ductile rock is thermal and/or hydraulic fracturing. The transition from brittle failure to ductile failure, or from elastic to plastic deformation, is expected to occur at ca. 380-400 ^{o}C for rhyolite or granite, although the required stress level is not so clear. Although creating fractures may be possible, there is concern about the fracture permeability after recovery of temperature and/or effective confining stress to the plastic condition. However, to the best of our knowledge, there is no clear way to quantitatively predict the permeability from a combination of temperature and effective confining stress.

The objectives in the present experimental study on permeability of fractured granite are therefore to clarify: (1) temperature and effective confining stress conditions of elastic-plastic transition for deformation of fracture, (2) influences of this transition on permeability, (3) a way to predict permeability at various combinations of temperature and effective confining stress, and (4) an optimum crust region, where can create artificial geothermal reservoir.

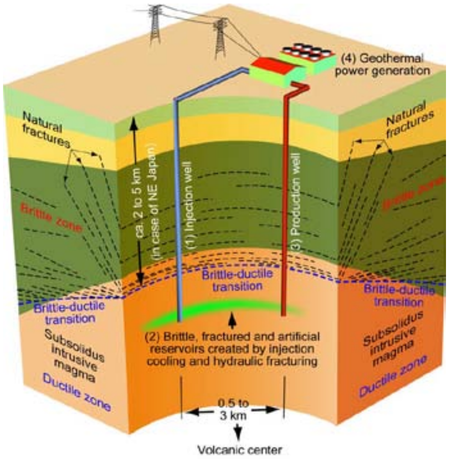

Fig.1 Concept of the new type of EGS in ductile zone.

2. PERMEABILITY MEASUREMENTS

Permeability measurements of fractured granite samples have been measured at effective confining stresses of 5-90 MPa, and temperatures of 350-500 ^{o}C. Figure 2 shows a representative photo and X-ray CT image of the samples (30 mm in diameter, and 25 mm in length). The X-ray CT image was taken at a resolution of 30 μm, with a X-ray tube voltage and current of 120 kV and 300 μA, respectively. The rock was Inada granite from Ibaraki Prefecture, Japan. At room temperature, this granite initially had a porosity of 0.6-0.9 % at atmospheric pressure, and a permeability of 10^{-19}-10^{-18} m^2 under confining stress. In this study, we made two kinds of rock samples. Creating fractures by heating at 570 ^{o}C for three hours and subsequent natural cooling was defined thermal fractured sample and tensile fracturing using splitting test was defined tensile fractured sample, seen as the blue lines in the X-ray CT images. Porosity of thermal fracture and tensile fracture are ca. 1.38 % and 0.75 % (on the average) at the atmospheric pressure and room temperature, respectively.

Figure 3 shows the experimental setup, which has been newly developed for the present study. The novelty of the system is the use of a high-viscosity molten plastic as a confining fluid, and a thin plastic film as a sleeve. The molten plastic is a molten PEEK (polyether ether ketone). PEEK has a melting point of 343 ^{o}C, and a high decomposition temperature of >450 ^{o}C. Because of the very high viscosity of 350 Pa·s even at 400 ^{o}C, it is possible to seal of a pore fluid and apply uniform confining pressure on the sample surface. Additionally, in order to prevent the molten PEEK adhere to the sample surface, we used a polyimide thin film having no melting point (i.e., it decomposes before the melting), and a quite high decomposition temperature of >500 ^{o}C. The molten PEEK is injected from inlet tube on the side of pressure vessel, and confining pressure is controlled by a pump. At a given temperature and confining stress conditions, flow rate measurement was conducted by using low pressure steam having low reactivity, so that water-rock chemical interactions can be negligible.

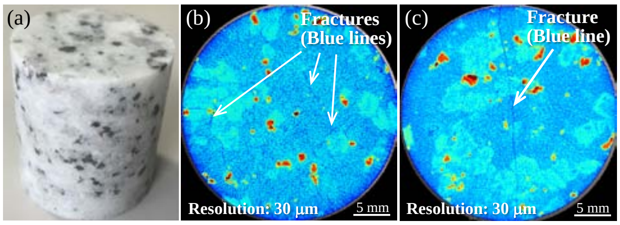

Fig. 2 (a) Representative photo and X-ray CT images of (b) thermal fractured granite sample and (c) tensile fractured granite sample.

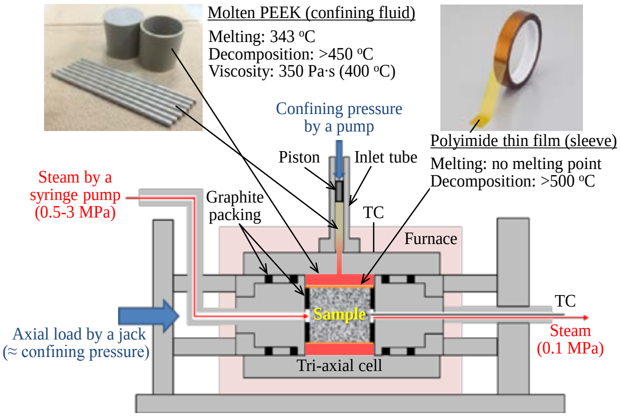

Fig. 3 Experimental system for permeability measurements.

3. PERMEABILITY OF FRACTURED GRANITE

Figure 4 shows the relations between permeability and effective confining stress for the thermal fractured samples at 350, 380, 400, 450 and 500 °C, and for the tensile fractured sample at 400 °C, where the results at the different temperatures were obtained for various samples. In general, at all temperatures and fractures, permeability first decreased and seemed to become almost constant with increasing effective confining stress at relatively low stress level, and then decreased again with increasing effective confining stress at relatively high stress level.

The stress dependency of permeability at the low stress level, which is similar to those of tensile fractures in granite at the room temperature, indicated occurrence of elastic deformation of the fracture, while the stress dependency of permeability at the high stress level indicated the fracture's plastic deformation. Indeed, at 350 °C, decreasing effective confining stress from 50 MPa to the initial stress level resulted in almost perfect recovery of the initial permeability, while decreasing the effective confining stress from 90 MPa to the initial value showed a significant permeability hysteresis. It can be therefore concluded that the change in stress dependency is caused by the transition from reversible (or elastic) to irreversible (or plastic) deformation of the fracture at the specific effective confining stress level, regardless of kinds of fracture type, which is hereafter called the reversible-irreversible (or elastic-plastic) transition stress.

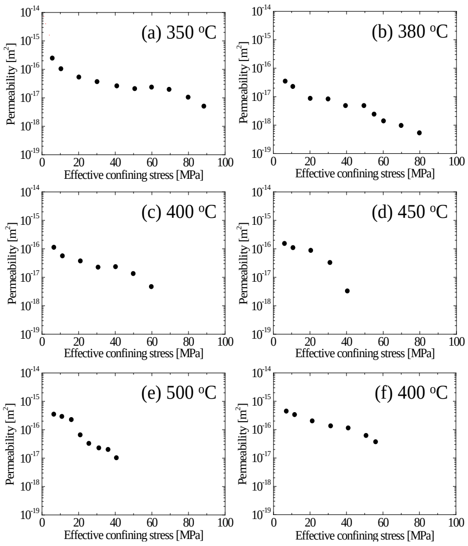

Fig. 4 Relations between permeability and effective confining stress for the thermal fractured samples at (a) 350, (b) 380, (c) 400, (d) 450, (e) 500 °C, and (f) the tensile fractured sample at 400 °C.

To clearly determine the reversible-irreversible transition stress at each temperature, the scale of the horizontal axis in Figure 4 was changed to logarithmic scale as shown in Figure 5. By doing so, the transition stress can be easily determined by finding an intersection of two linear curves at the low and high effective confining stress levels, where the slope of the linear curve is larger at the high stress level. As a result, the transition stresses were 70, 50, 40, 25, and 15 MPa, respectively, at 350, 380, 400, 450 and 500 °C. The transition stress is clearly temperature dependent. Additionally, it is found that the slope of the linear curve (i.e., stress dependency of permeability) is almost independent of temperature both below and above the transition stress, where the slopes at the elastic and plastic conditions are ca. -0.9 and -3.6, respectively.

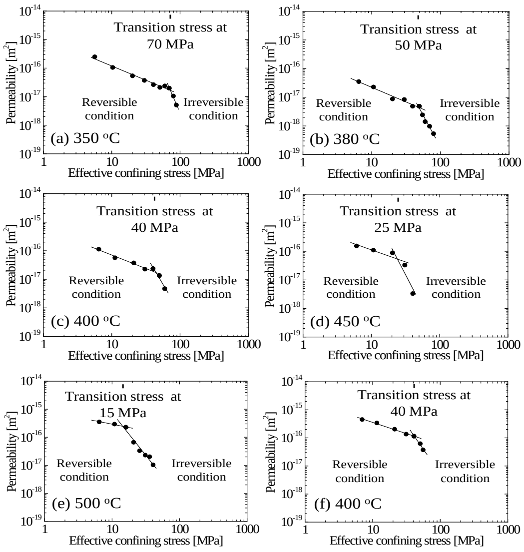

Fig. 5 Determination of the transition stresses for the thermal fractured samples at (a) 350, (b) 380, (c) 400, (d) 450, (e) 500 °C, and (f) the tensile fractured sample at 400 °C.

Figure 6 shows the relations between permeability and effective confining stress during increasing stress level from 5 MPa to 50 MPa (as shown in (i) and (ii)) and decreasing stress level from 50 MPa to 5 MPa (as shown in (iii)) at 400 °C. At the increasing stress level, reversible-irreversible transition appeared between (i) and (ii), which is similar to the preceding results. On the other hand, at the decreasing stress level, permeability recovered while keeping the stress dependency, same as (i). For these results, at the stress level of (i), which was in reversible condition, all fractures caused elastic deformation. At the stress level of (ii), which was in irreversible condition, a part of fractures caused plastic deformation, which indicated occurrence of permanent strain at the fracture surfaces, and stress dependency of the whole granite sample increased. At the stress level of (iii), because of the permanent strain, the fractures have occurred plastic deformation couldn't recover by decreasing confining pressure, and only the fractures have occurred elastic deformation recovered. Therefore, permeability of granite sample recovered while keeping the stress dependency, same as (i).

Figure 7 summarizes the above discussion, in which temperature-effective confining stress regimes of the elastic and plastic deformation of the fracture, divided by an empirical reversible-irreversible transition stress curve, are shown together with the stress dependencies of permeability of the fractured granite for both types of deformation. The equation of the reversible-irreversible transition stress curve can predict the depth of the boundary between the hydrothermal convection and heat conduction zones (i.e., the depth on the brittle/elastic-ductile/plastic transition). In the Kakkonda geothermal field in Japan, the transition was observed at 3.1 km (temperature is 380 °C) within the Kakkonda granite in a well, WD-1a. According to the equation, the reversible-irreversible transition occurs at 3.1 km because the effective confining stress of 52 MPa at that depth exceeds the transition stress of 48 MPa at the temperature of that depth (380 °C), based on the temperature profile of the well, and an effective confining stress (difference between lithostatic confining stress and hydrostatic pore pressure). Based on Fig. 7, one may roughly assess the permeability of the fractured granite such as an artificially created geothermal reservoir, when assuming initial permeability just at fracturing, where the effective confining stress for fracture is nearly zero. At the same fracture porosity, the near-zero-stress log permeability is almost independent of temperature as seen in Fig. 5. Therefore, the permeability change with effective confining stress at each temperature may be calculated based on the near-zero-stress log permeability, the reversible-irreversible transition stress curve, and the relation between log permeability-log effective confining stress.

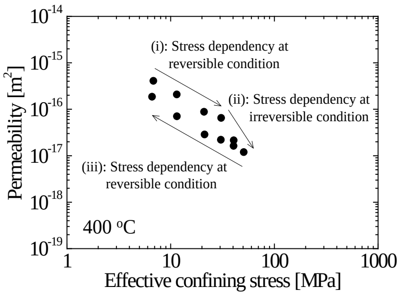

Fig. 6 Relations between permeability and effective confining stress for increasing confining pressure and decreasing confining pressure at 400 °C.

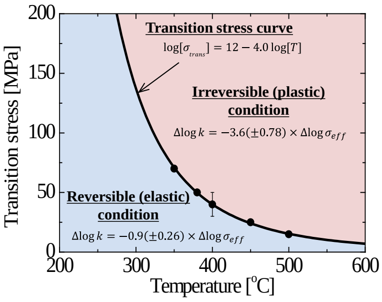

Fig. 7 Temperature (*T*)-effective confining stress (σ_{eff}) regimes of the permeability transition of the fracture, divided by an empirical transition stress curve, together with the stress dependencies of permeability (*k*) of the fractured granite for the permeability deformation.

4. APPLICATION FOR CONTINENTAL FIELD

To examine the validity of the way to predict permeability, we checked consistency between two kinds of permeability-depth relations in the continental crust, which have been reported in Manning and Ingebritsen (2010), and predicted in the present study, as shown in Figure 8. The predicted permeability-depth relation was obtained by assuming a near-zero-stress log permeability of -15, a temperature gradient of 25 °C/km, and an effective confining stress as a difference between lithostatic confining stress and hydrostatic pore pressure, respectively. As seen in Fig. 8, the predicted permeability values were similar to the reported permeability values at all depth, and the predicted depth of the reversible-irreversible transition (10.2 km at which temperature and effective confining stress were 275 °C and 170 MPa, respectively) was within the range of the predicted brittle-ductile transition zone in the continental crust (10-15 km by Manning and Ingebritsen). Therefore, it can be concluded that the prediction method can roughly predict permeability of fractured granite at various combinations of temperature and effective confining stress.

Moreover, we examined the chemical relations at the occurrence of the boundary between the hydrothermal convection and heat conduction zones, and/or the reversible-irreversible transition. In

Kakkonda geothermal field in Japan, Saishu (2015) reported that dissolution of quartz is a dominant reaction at around 2 km depth where the density of the fluid-filled fractures is high, and that the depth of precipitation-dominant of quartz corresponds to that of the permeable-impermeable boundary at the depth of 3.1 km by drillhole data of WD-1a, as shown in Figure 9. Therefore, the reversible-irreversible transition may be corresponding to the precipitation condition of silica.

Based on these results and considerations, the boundary between the hydrothermal convection and heat conduction zones are formed by hydraulic, dynamic, and chemical reactions, which are reversible-irreversible transition, brittle-ductile transition, and silica precipitation. Conventional knowledge says that heat conduction can be dominant without flowing of pore fluid at deeper than the bottom of hydrothermal convection, where indicates the boundary. However, the stress dependency of permeability only increases by the reversible-irreversible transition, so pore fluid can flow through the fracture. In addition, silica precipitation can be prevented by drop of the quartz solubility beyond the transition. These can be therefore concluded that if it is possible to create an artificial fracturing in the plastic condition, the crust region at just after the reversible-irreversible transition is the most suitable for creating an artificial geothermal reservoir.

5. CONCLUTIONS

The present experimental study has explored permeability of the thermally fractured granite at the various combinations of temperature (up to 450 °C) and effective confining stress (up to 90 MPa). The main results obtained in this study are summarized as follows:

(1) It has been found that transition from reversible (or elastic) to irreversible (or plastic) deformation occurs at a specific stress level (i.e., elastic-plastic transition stress), depending on temperature. The elastic-plastic transition stress decreases with increasing temperature.

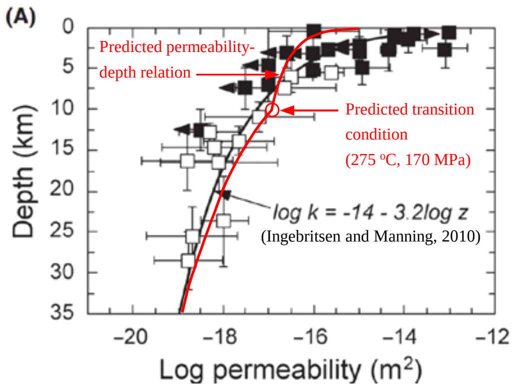

Fig. 8 Comparison of the reported permeability-depth relation and the predicted permeability-depth relation using the present study in the continental crust.

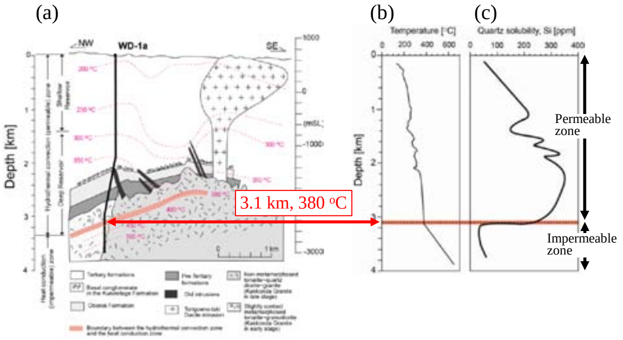

Fig. 9 (a) Schematic cross-section through the Kakkonda geothermal system. (b) Temperature-depth curve obtained for the drillhole WD-1a. (c) Quartz solubility with depth.

(2) At both elastic and plastic conditions, the relation between log permeability-log effective stress (i.e., effective confining stress dependency of permeability of the fractured granite) is linear and independent of temperature.

(3) the permeability change with effective confining stress at each temperature may be calculated based on the near-zero-stress log permeability, the reversible-irreversible transition stress curve, and the relation between log permeability- log effective confining stress.

(4) If it is possible to create an artificial fracturing in the plastic condition, the crust region at just after the reversible-irreversible transition is the most suitable for creating an artificial geothermal reservoir.

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