The hydraulic fracturing mechanism under supercritical/superhot geothermal environment

Ryota GOTO

1. INTRODUCTION

These days, renewable energy is attracting a lot of attention because of global warming. In fact, Paris agreement has been adopted in COP21. Decreasing the amount of greenhouse gas emission is important subject. Therefore, developing renewable energy is known as an argent priority for all nations.

Especially, geothermal is expected as hopeful resources because it is not affected by weather (i.e. temperature, amount of solar radiation, etc.)

From 1970s, a new method of power generation with using geothermal resources, called EGS (Engineered/Enhanced Geothermal System), has been studied, in the US (Duchane, 1995). Nowadays, ongoing studies are conducted in many countries (Olasolo et al., 2015). But conventional EGS has difficulties such as induced seismicity. Especially, induced seismicity is serious problem. EGS project in Switzerland was stopped because of induced seismicity (Haring et al., 2005). On the other hand, accessing deeper and hotter geothermal systems which have magmatic roots and temperatures exceeding the critical temperature of water (374°C for pure water and 406°C for seawater) has been an ongoing challenge attracting a lot of attention. For example, drilling into such deep and superhot geothermal environments has been demonstrated all over the world, for example, Itally, Mexico, and so on (Batini et al., 1983 ; Espinosa-Paredes and Garcia-Gutierrez, 2003). Geothermal reservoir containing high-enthalpy supercritical or superheated water is called supercritical or superhot geothermal resources, and resources such as the resource of 450°C found in Iceland have a potential to generate electric power of an order of magnitude higher than conventional geothermal resources (Elders et al., 2014).

However, there has been a hypothesis that the continental granitic crust lacks permeable fractures because of the brittle-ductile transition (BDT). To explore the possibility that permeable fracture networks exist in ductile granitic crust. My research group previously performed a set of permeability measurements on fractured granite at 350-500°C and effective confining stresses of up to ~100 MPa (Watanabe et al., 2017a). The experimental results revealed that BDT is not the first-order control on rock permeability and therefore geothermal resources can be exist even in the nominally ductile crust. However, there is still a concern about insufficiency or the long-term viability of the permeability of the ductile granitic crust. Thus, developing methodologies to enhance or maintain the permeability such as hydraulic fracturing is important for successful developments of the new geothermal resources. Therefore, my research group recently started to explore the possibility of hydraulic fracturing and permeability enhancement in ductile granitic rocks (Watanabe et al., 2017b). We conducted hydraulic fracturing experiments on granite up to 450°C under conventional triaxial stress and obtained valuable information regarding the initiation and propagation of hydraulic fracturing in supercritical or superhot geothermal environments. In such geothermal environments, intensive fracturing can occur at a relatively low injection pressure probably as a result of the stimulation of preexisting microfractures with low-viscosity water at near-critical or supercritical temperatures and create a network of permeable microfractures densely distributed in a large rock body. In this study, I have tackled 3 problems (i.e. Can we creating a network of permeable microfractures under true triaxial stress condition? Can we predict the water pressure value at which fracturing occur? Can we create efficient artificial geothermal reservoirs by hydraulic fracturing ?)

2. HYDRAULIC FRACTURING UNDER TURE TRIAXIAL STRESS CONDITION AT 400℃ OR HIGHER

First of all, I sought the possibility that artificial reservoir in supercritical/superhot geothermal environment. In addition, I investigated that stress state (e.g. normal fault regime) and temperature can change breakdown pressure, distribution of permeable fractures. Therefore, a new experimental system that can conduct hydraulic fracturing experiment under supercritical/superhot condition (i.e. temperature is up to 500°C, and principle stress is up to 100 MPa.) was developed. And a series of experiment in 3 conditions were conduct. In Fig.1, an example of experimental result is shown. In Fig.1(a), the hysteresis of borehole pressure and water pressures that is measured on specimen surfaces are shown. The breakdown occurred at about 14 MPa. There was no big difference of breakdown pressure in each experimental condition.

After the breakdown, borehole pressure was decrease gradually and water pressures of outlet surfaces were rising. Fig.1(b) shows the displacement of pistons. If the specimen dilates, the displacement increase. Just after breakdown, the specimen dilated in all direction. But specimen shrank in maximum principle stress direction, finally. This specific deformation occurred in all experimental condition.

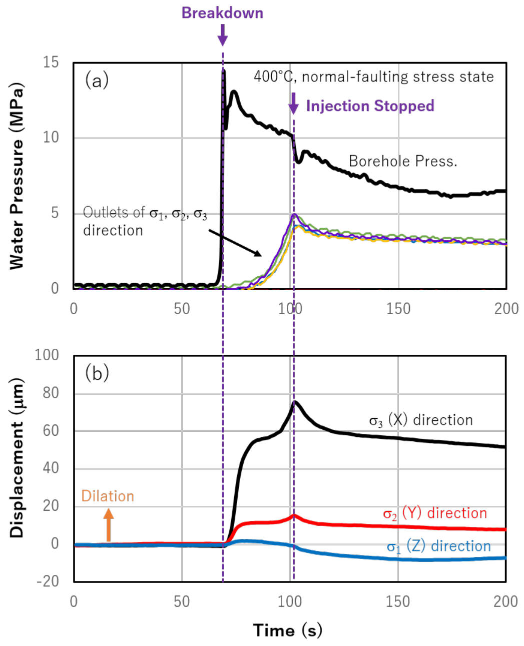

Fig. 1 Result of hydraulic fracturing under true triaxial stress condition. (a) water pressure hysteresis of borehole and other outlet surfaces. (b) displacement of pistons.

In Fig.2, the picture is microphotograph of thin section. The thin section is made from fractured specimen. Light blue lines mean that fractures exist. This result revealed the excellent fracture pattern which is created by hydraulic fracturing under supercritical/superhot condition. And microphotographs of thin sections made from fractured specimens and made from intact one are compared. These fractures are mainly created by crack propagation from preexisting micro fractures.

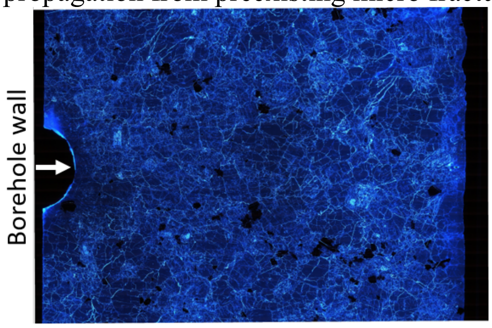

Fig. 2 Microphotograph of thin section under UV light.

3. APRLYING GRIFITH'S THEORY FOR HYDRAURIC FRACTURING UNDER SUPERCRITICAL/SUPERHOT CONDITION

In this chapter, I try to predict the borehole pressure at which the breakdown occurs. According to fracture mechanics, fractures propagate form preexisting fracture. It seems that this mechanism can be applied to hydraulic fracturing which I study. Based on this working hypothesis, hydraulic fracturing experiments under variety of differential stress state are conducted. And the experimental result and predicted breakdown pressure which is calculated from Griffith's criterion are compared. Also, our experimental system was developed. Namely, AE(Acoustic Emission) measuring system to monitor the fracturing phenomenon directly was newly installed.

In Fig.3, an example of experimental result is shown. Fig.3 (a), (b), (c-f) are the borehole pressure hysteresis, AE event hysteresis, X-ray CY images, respectively. According to borehole pressure hysteresis, the breakdown pressure was not decided because there is no sign that fracturing occurs (e.g. decline of borehole pressure.). But there is a clear peek in AE event hysteresis. This AE event must be caused by crack propagation. Therefore, the breakdown pressure was estimated to be about 4 MPa. Also, there is a complex fracture system in X-ray CT images. In addition, the shape of fracture is not strait. But it has many branches and bendings. This implies that the fracturing occurred from preexisting cracks. Both breakdown pressure and fracture shape support my hypothesis. In other words, it is reasonable to suppose that we can apply Griffith's theory to fracturing mechanism in supercritical/superhot geothermal condition.

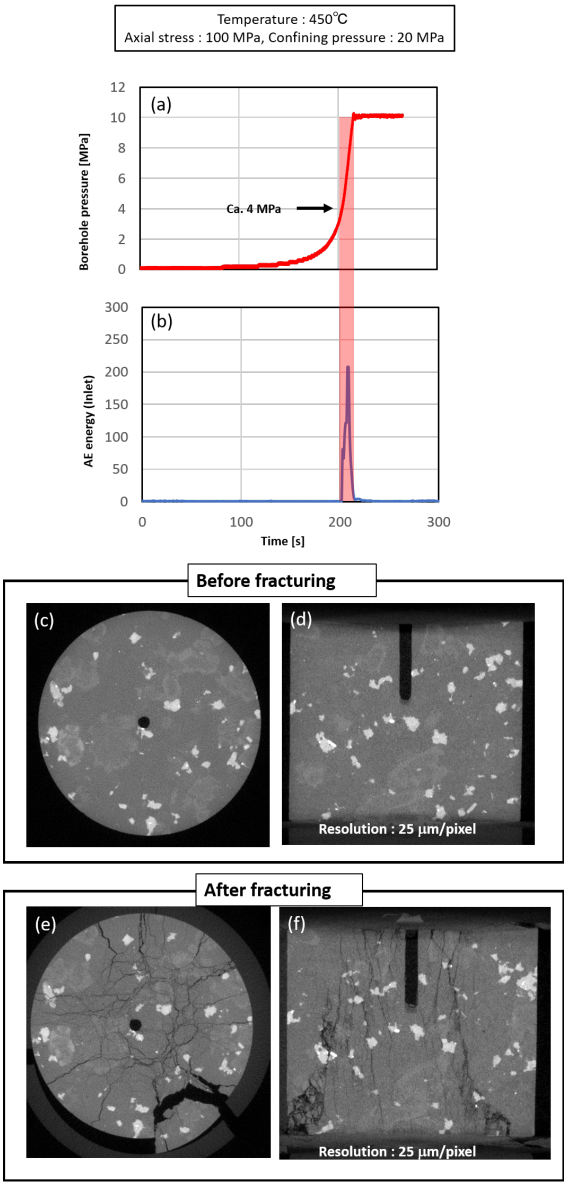

Fig. 3 Result of hydraulic fracturing under tri axial stress state.

Fig. 4 shows the relationship between experimental result and predicted breakdown pressure. if the dots are close to the diagonal red line, it means that predicted values agree to experimental result. In some results, for example 3-A and 3-D, predicted value mostly correspond to experimental result. On the other hand, some results are a little far from red diagonal line. It can be caused by the distribution of preexisting micro crack. Griffith's criterion supposes that brittle rock which has homogeneous crack distribution. In addition, the cracks are same length. But in fact, rock specimen has a variety of fractures. Their length and angle are different each other. Thus, some results are a little far from predicted value. And it implies that we can predict the breakdown pressure with Griffith's criterion.

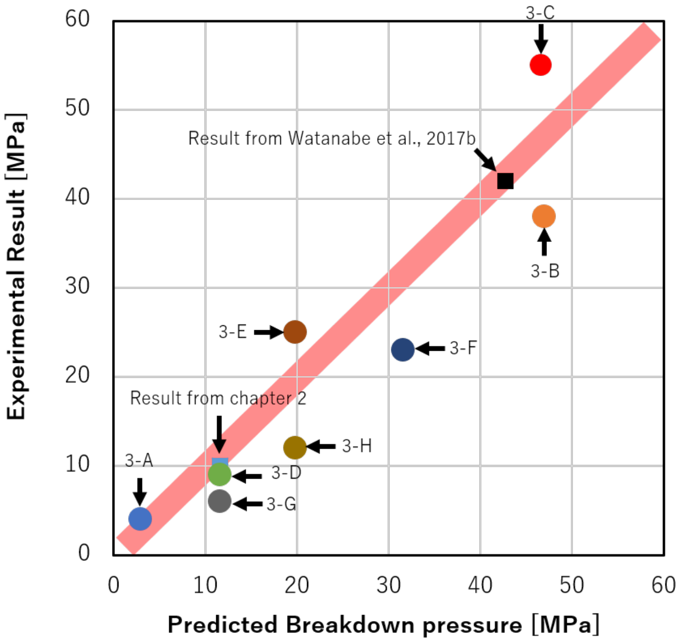

Fig.4 The relationship between experimental result and predicted breakdown pressure.

4. FEASIBILITY STUDIES FOR CREATING ARTIFICIAL GEOTHERMAL RESERVOIRS

Based on our previous results, I will discus about the feasibility of creating artificial geothermal reservoirs with hydraulic fracturing.

To begin with, the actual geothermal condition (i.e. temperature and stress state.) was estimated from previous works which was conducted in Kakkonda (Ikeuchi et al., 1998 ; NEDO, 1996). And the stress and temperature condition under 3000m are calculated. In Fig.5, the breakdown pressure which is calculated from Griffith's criterion and calculated from other theory (i.e. it is the water pressure value when the borehole wall is broken.) are compared. As you can see, the breakdown pressure which is calculated from Griffith's criterion is clearly lower than the other. In addition, the breakdown pressure become lower when the depth become deeper. These result support the superiority of hydraulic fracturing with supercritical water.

Also, I conducted two types of fracturing experiment, additionally. The first experiment is re-injection/pressurization experiment. From this result, I confirmed that the fracture permeability can reach to 10^{-12} m^2. The second experiment is fracturing with fracturing CO_2 at 300°C. The result shows that we can create complex fracture system at lower temperature. Based on this result, it is possible to create artificial fracture system which has efficient fracture pattern to extract geothermal energy even if the borehole is cooled to protect drilling tools (i.e. supercritical/superhot condition is too hot to dig the borehole with conventional tools.)

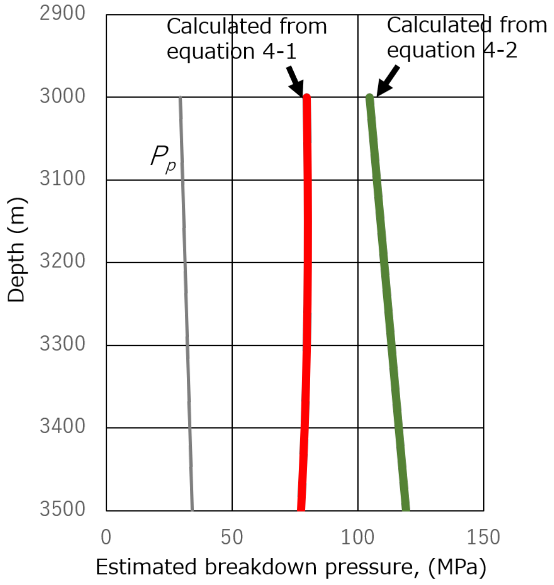

Fig. 5 The estimated breakdown pressure under 3km.

5. CONCLUSIONS

The conclusions of our study are as follows :

1. It is possible to create a homogeneous fracture system in supercritical/superhot geothermal environment (i.e. true triaxial stress state at 400°C or higher.) and fracture distribution is not affected by stress regime and temperature.
2. The permeability of fracture system can reach to 10^{-15} m^2.
3. The mechanism of hydraulic fracturing in supercritical/superhot geothermal condition is mainly crack propagation from preexisting cracks which are stimulated by low-viscosity fluid (e.g. supercritical water).
4. It is possible to predict the breakdown pressure from Griffith's criterion.
5. Based on previous work, actual stress state and temperature in supercritical/superhot geothermal condition were estimated. And the breakdown pressure was calculated. In result, fracturing will occur at lower water pressure than conventional fracturing mechanism (i.e. breaking the borehole wall).
6. The fracture permeability can reach to 10^{-12} m^2 by pressurizing borehole again, after the breakdown.
7. It is possible to create a complex fracture system at temperature lower than 400°C with low-viscosity fluid such as supercritical CO_2.

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