

GEOHERMAL RESERVIOR CREATION BY HYADRAULIC STIMULATION UNDER HIGH TEMPERATURE AND HIGH PRESSURE CONDITION

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1. Introduction

Usual EGS has problems such as low recovery rate of injected water, difficulties in establishing design and development method of geothermal reservoir, risk of induced earthquake due to water injection. It was suggested that there is limit to its development (Kaieda et al., 2005; Tenma et al., 2005; Majer et al., 2007; Häring et al., 2008).

However, a new concept of EGS that geothermal reservoir is created in ductile rock is proposed. It is expected that the new type of EGS solve the above problem. The new type of EGS may offer several advantages, including (1) simpler design and control of the reservoir, (2) nearly full recovery of the injected water, (3) sustainable production, (4) lower costs when developed in relatively shallow ductile rocks in compression tectonic settings, (5) large potential quantities of energy extraction from widely distributed ductile rocks, (6) the establishment of a universal design/development methodology, and (7) the suppression of felt earthquakes from/around the reservoir [Watanabe et al., 2017].

One possible way to create a fracture network in a ductile rock is utilizing thermal or hydraulic tensile fracturing. It is clarified that the fracturing characteristics in brittle region depend on differential stress, viscosity of fracturing fluid and injection rate (Solberg et al., 1980). However, the fracturing characteristics in a ductile region have not yet been clarified.

The purpose of this study is to experimentally explore the fracturing characteristics in a ductile rock by subjecting granite to hydraulic stimulation under high pressure and high temperature.

2. The Effect of Hydraulic Stimulation on Ductile Rock

In this chapter, hydraulic stimulation experiments were performed on granite specimen under brittle and ductile conditions to clarify generated fractures shape and hydraulic stimulation behavior. The experiment conditions were determined as follows. Byerlee [1968] and Fournier [2007] presumed that brittle-ductile transition temperature of granite is 380-400 °C. In addition, Watanabe et al. [2017] proposed elastic-plastic transition curves of granite. In this study, conditions

that satisfy both brittle-ductile transition temperature and elastic-plastic transition curves are considered as ductile condition (Fig. 1).

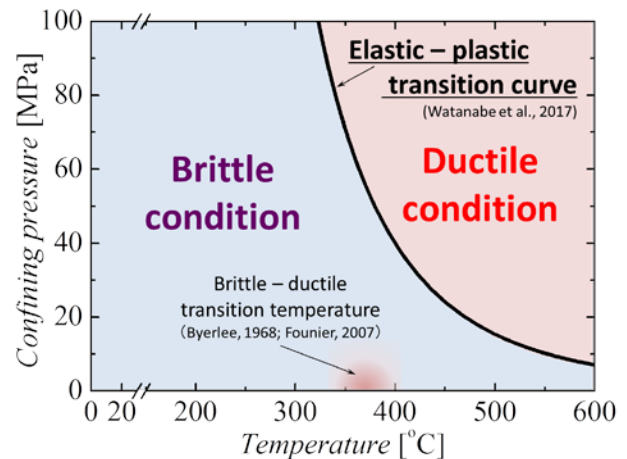


Fig. 1 Brittle – ductile condition

As a result of the experiment, it was found that a continuous fracture was generated under brittle condition (the room temperature and atmospheric pressure, 160 °C and confining pressure of 30 MPa) (Fig. 2). On the other hand, it was found that fracturing is possible even in ductile condition (450 °C and confining pressure of 30 MPa), and discrete fractures were generated under ductile condition (450 °C and 30 MPa) (Fig. 3). This is because the fracture development behavior differs depending on the viscosity of hydraulic stimulation fluid.

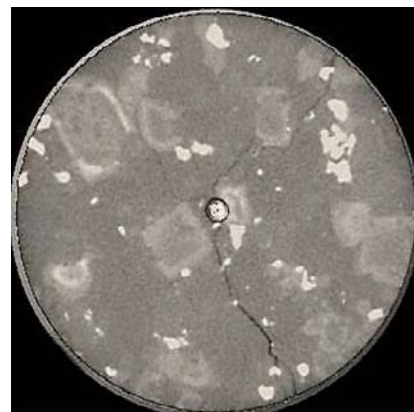


Fig. 2 X-ray CT image of specimen after experiment under brittle condition (160 °C, 30 MPa).



Fig. 3 X-ray CT image of specimen after experiment under ductile condition (450 °C, 30 MPa).

The hydraulic stimulation behavior differs depending on the generated fracture shape. When continuous fractures were generated, sudden breakdown occurred and borehole pressure decreased greatly (Fig. 4). On the other hand, when discrete fractures were generated, borehole pressure was slowly released (Fig. 5).

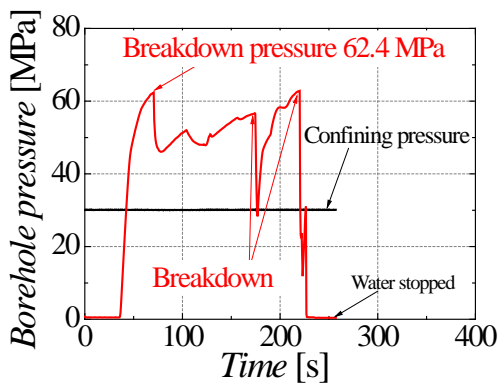


Fig. 4 Borehole pressure hysteresis of hydraulic stimulation experiment under brittle condition (160 °C, 30 MPa).

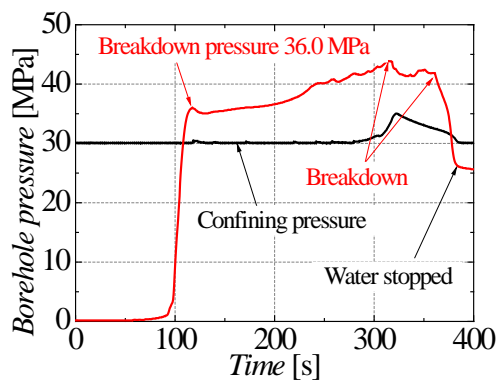


Fig. 5 Borehole pressure hysteresis of hydraulic stimulation experiment under ductile condition (450 °C, 30 MPa).

3. Fracture Shape, Hydraulic Stimulation Behavior and Permeability

In this chapter, hydraulic stimulation experiments were performed under various conditions in order to consider the results of chapter 2 in more detail. Moreover, permeability measurements were performed to evaluate permeability of generated fracture.

As a result of X-ray CT imaging, continuous fractures are generated under 200 °C (Fig. 6), and discrete fractures were generated under 450 °C (Fig. 7). Furthermore, in the experiment at 360 °C, intermediate fractures between continuous and discrete fracture were generated (Fig. 8). From this result, it was found that the shape of generated fractures is determined by the hydraulic stimulation fluid viscosity.

In order to observe the discrete fractures in more detail, the aperture width of the fracture was calculated from the CT value [Watanabe et al., 2013], and the distribution of the aperture width of the fracture was presented three-dimensionally in Fig. 9. It was found that discrete cracks spread in a cloud shape (cloud fracture).

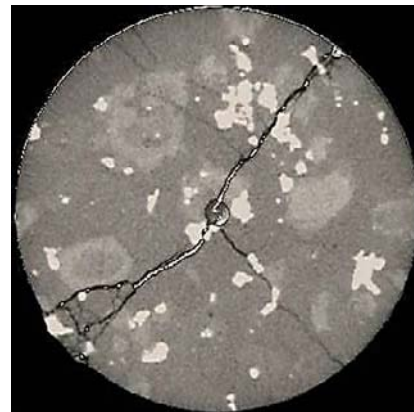


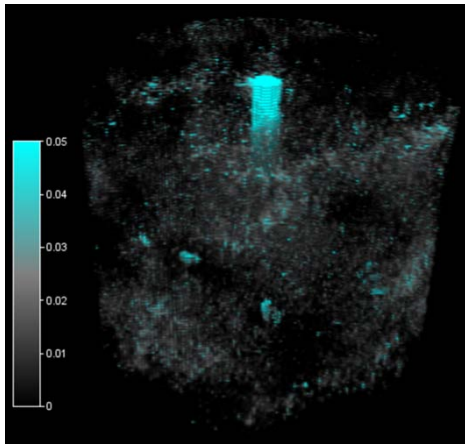
Fig. 6 X-ray CT image of specimen after experiment under brittle condition (200 °C, 40 MPa).



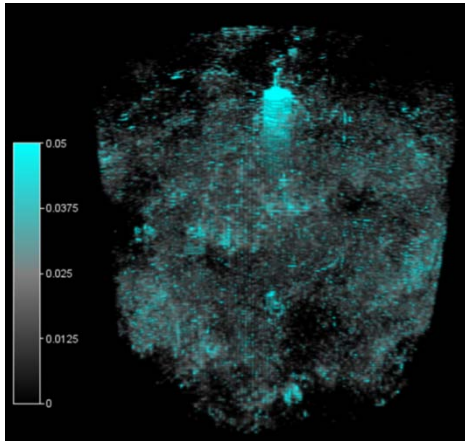
Fig. 7 X-ray CT image of specimen after experiment under ductile condition (450 °C, 40 MPa).



Fig. 8 X-ray CT image of specimen after experiment under brittle condition (360 °C, 40 MPa).



(a) Before experiment.



(b) After experiment.

Fig. 9 Aperture distribution of specimen(450 °C, 40 MPa).

As a result of the hydraulic stimulation experiment, it was found that the hydraulic stimulation behaviors differed depending on the shape of the generated fractures. When continuous fractures were generated, a rapid breakdown occurred (Fig. 10). This is because the fractures develop linearly and the borehole pressure is released at once. When cloud fractures were generated, a slow breakdown occurred (Fig. 11).

This is because the fractures develop while branching and the borehole pressure is slowly released. When intermediate fractures were generated, hydraulic stimulation behavior also showed intermediate behavior (Fig. 12).

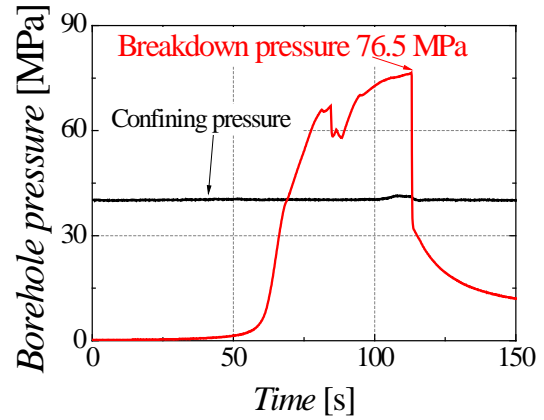


Fig. 10 Borehole pressure hysteresis of hydraulic stimulation experiment under brittle condition (200 °C, 40 MPa).

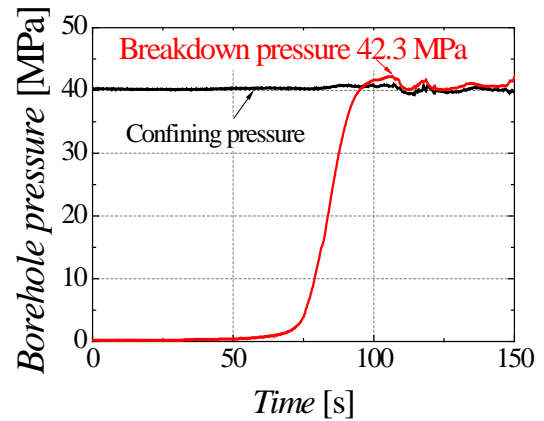


Fig. 12 Borehole pressure hysteresis of hydraulic stimulation experiment under ductile condition (450 °C, 40 MPa).

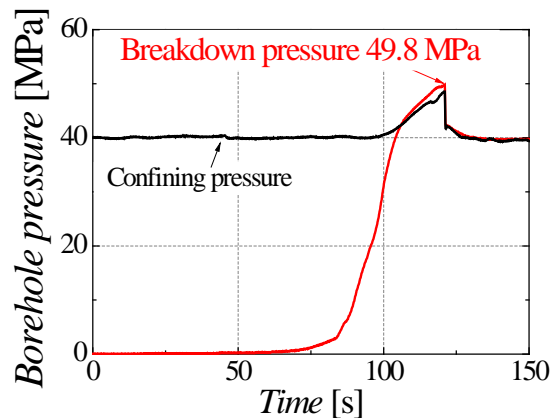


Fig. 11 Borehole pressure hysteresis of hydraulic stimulation experiment under brittle condition (360 °C, 40 MPa).

As a result of the permeability experiment, it was found that the permeability increases by 2 to 5

orders by generated fractures, and the permeability increased 3 orders by cloud fractures generated in the ductile rock. From this, it was suggested that heat extraction is possible using this cloud fractures in ductile rock.

Based on the above results, the possibility of creation of a crack network (cloud fractures) which could be a geothermal reservoir in ductile rocks was shown.

4. Clarification of Fracture Opening Mechanism in Ductile Rock

In this chapter, hydraulic stimulation experiments were performed under the ductile condition (450 °C and confining pressure of 40 MPa) using a large specimen with the purpose of clarifying the fracture opening mechanism in ductile condition. As a result of measurement of the P-wave velocity, it was found that the P-wave velocity decreased from before breakdown (Fig. 13). From this, the fracture opening mechanism was discussed as follows. When the hydraulic stimulation fluid viscosity is low, the hydraulic stimulation fluid permeates into isolated pore. Then, pressure of isolated pores increases with the borehole pressure. Consequently, fractures generated from isolated pores, and cloud fractures are generated by connecting isolated pores.

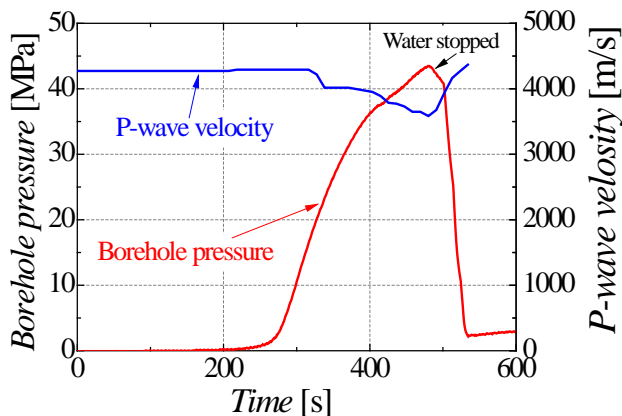


Fig. 13 Change of P-wave velocity and borehole pressure hysteresis.

5. Conclusion

This study experimentally explored fracturing characteristics of ductile rock by subjecting granite to hydraulic stimulation under ductile condition. The main results obtained in this study are summarized as follows.

- (1) Even in the ductile rock, it is possible to create fractures by hydraulic stimulation.
- (2) As the hydraulic stimulation fluid viscosity decreases, the shape of the generated fractures changes from a continuous fracture to a cloud fractures.

- (3) The shape of the generated fractures is reflected in the hydraulic stimulation behavior.
- (4) Cloud fractures are created by the connection of isolated pores.
- (5) Cloud fractures having a three-dimensional spread in a rock have permeability which can be a geothermal reservoir.

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