Slip Behavior of a Crack in Geothermal Reservoir Rock Cracks Induced by Supercritical CO_2

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1. INTRODUCTION

Carbon-recycling geothermal power generation technology using supercritical CO_2 is currently attracting attention. Carbon-recycling geothermal power generation is a geothermal power generation technology in which CO_2 is used to create geothermal reservoirs and CO_2 is used as a heat medium to generate electricity. This technology has the potential to improve heat extraction efficiency, contribute to carbon neutrality through the use of CO_2, and reduce induced seismic risk compared to conventional geothermal power generation.

In this study, pore-pressure-induced slip experiment of rock by supercritical CO_2 were conducted to investigate the characteristics of slip behavior with injected media for the purpose of realization of supercritical CO_2 geothermal power generation.

2. Experimental Methods, Conditions and Specimens

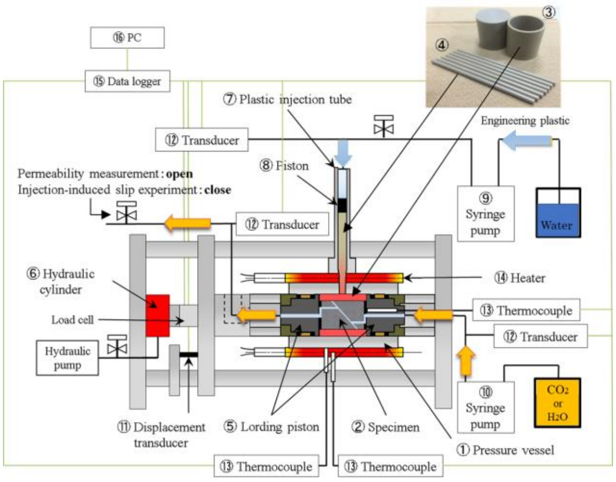

Fig. 1 Experimental system

In this study, experiments were conducted using the sealed-pressure triaxial experimental system shown in Figure 1. This system applies sealing pressure in the circumferential direction by means of a high-viscosity resin that melts at high temperatures, and in the axial direction, a piston is pushed in by hydraulic pressure using a hand pump to enable experiments under high temperature and high pressure. In this study, experiments were conducted under load control. For the specimens, Honkomatsu andesite was formed into a cylindrical shape and a 45-degree diagonal saw-cut crack surface was generated(Fig.2).

Experiments were conducted at 200°C for CO_2 and at 200°C, 400°C, and 450°C for H_2O. Stress conditions were set to 80 MPa axial stress and 40 MPa sealing pressure (59 MPa vertical stress and 19 MPa shear stress), and the fluid injection flow rate was 1.0 mL/min.

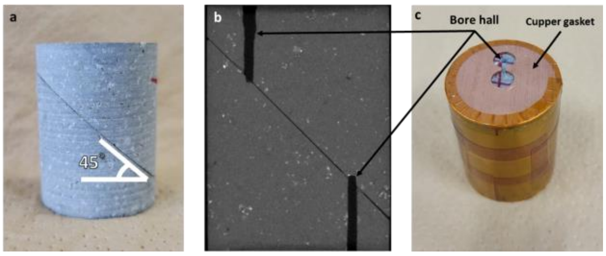

Fig. 2 Andesite specimen (a), X-ray CT image with bore hall (b) and with cupper gasket, stainless sheet and polyimide tape (c).

3. Pore pressure induced slip experiment with supercritical CO_2 and H_2O

Fig.3 and Fig.4 show the variation over time of inlet pressure (blue line), pore pressure (orange line), outlet pressure (green line), axial displacement (purple line), and AE energy (red line) in the pore pressure-induced slip experiments with supercritical CO_2 and subcritical H_2O using Honkomatsu andesite. Increasing axial displacement indicates contraction and decreasing axial displacement indicates expansion. The axial displacement tends to decrease at first. This indicates that the specimen is shear expanded. After the shear expansion of the specimen is completed, the axial displacement begins to increase. This indicates the occurrence of slip. In the case of supercritical CO_2, the occurrence of stick-slip was confirmed. For some time after the onset of slip, axial displacement increased nonlinearly, but the increasing trend changed to linear.

In the pore pressure induced slip experiment with supercritical H_2O, no slip onset was observed.

A detailed analysis of the experimental results is given in Chapter 4.

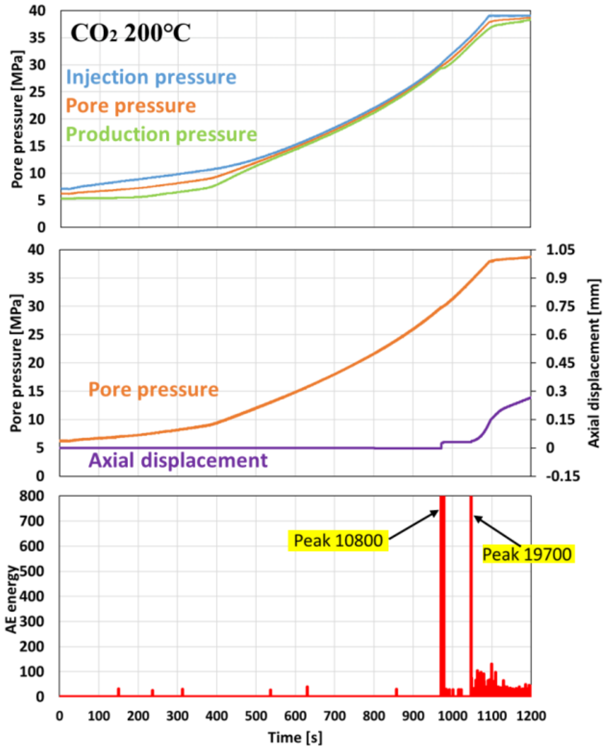

Fig.3 Time-dependent changes in injection pressure, pore pressure, production pressure, axial displacement, AE energy (injection CO_2)

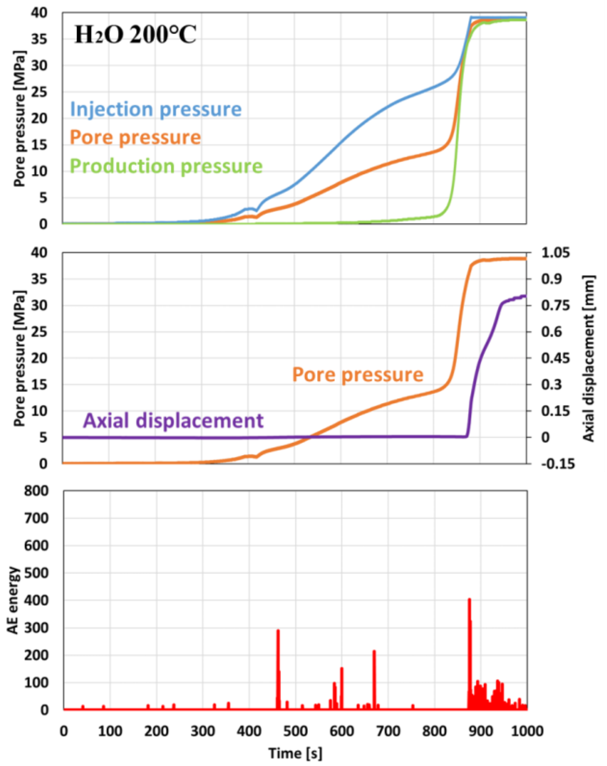

Fig.4 Time-dependent changes in injection pressure, pore pressure, production pressure, axial displacement, AE energy (injection H_2O)

4. Characteristics of Slip due to Pore Pressure Induced Slip

4.1. Characteristics of Slip Behavior

The slip observed in the experiments showed a common trend of slip behavior. In this study, referring to the definition in Takeyama et al. (2021), the zone between boundaries I and II is defined as the initial slip zone, the zone between boundaries II and III as the steady slip zone, and the slip and its average velocity in the former are defined as initial slip and initial slip velocity V_{initial} and those in the latter are defined as steady-state slip and steady-state slip velocity V_{stable} . It was suggested that no difference exists in the slip behavior (shear expansion→initial slip→steady slip) due to the difference in the properties of crack surface and injection media (water and CO_2).

4.2. For supercritical CO_2 (200°C)

The supercritical CO_2 case is characterized by stick-slip and a stair-step transition behavior in the axial displacement transition. In addition, the increase in pore pressure was gradual and no rapid pressure increase was observed. The initial slip velocity V_{initial} after the onset of slip was 2.0 μm/s, and the steady-state slip velocity V_{stable} was 4.2 μm/s. This slip rate is comparable to the slow non-seismic slip (4 μm/s) observed by Guglielmi et al (2015) in their study of fault slip and seismic activity induced by fluid injection into natural faults to elucidate the mechanism by which fluid injection is involved in induced earthquakes, and It is suggested that even if slip were to occur, it could be non-seismic slip.

4.3. For subcritical H_2O (200°C)

The subcritical H_2O case is characterized by the absence of stick-slip and smooth transition behavior of axial displacement. The initial slip velocity V_{initial} after the onset of slip was 8.6 μm/s, and the steady-state slip velocity V_{stable} was 28.4 μm/s.

4.4. For supercritical H_2O (400°C, 450°C)

For supercritical H_2O, no slip was observed. The reason why slip was not observed under the supercritical H_2O temperature condition was considered to be that the specimen changed from a brittle to a ductile state. Comparing the results of uniaxial and triaxial compression tests on Honkomatsu andesite), the specimen showed a large volume expansion under a sealed pressure loading of 10 MPa compared to uniaxial compression, suggesting that the specimen tends to become ductile. In particular, under the experimental conditions in this study (sealing pressure of 40 MPa and temperatures of 400°C and 450°C), both sealing pressure and temperature were higher, suggesting that the specimen rock is ductile. The ductile state of the specimen rock softens the specimen and makes the crack surface adhere to the specimen, making it less likely to slip.

4.5. Consideration of the characteristics of sliding behavior depending on the pressurized fluid

4.5.1. Characteristics of sliding behavior and sliding velocity of supercritical CO_2 (200°C) and subcritical H_2O (200°C)

Regarding the trend of transition behavior of axial displacement, the process of transition behavior of sliding behavior showed similar trend. Comparing the details of the sliding behavior, stick-slip was observed in the case of supercritical CO_2, whereas subcritical H_2O exhibited smooth sliding without stick-slip. In addition, the transition of the axial displacement of the initial slip between Boundary I and Boundary II in supercritical CO_2 was slow and abrupt, and the graph showed a staircase-like transition, whereas in subcritical H_2O, the axial displacement increased smoothly. One possible cause of these differences may be the difference in viscosity of the pressurized fluid. The viscosity of supercritical CO_2 under the experimental conditions is approximately 0.025~0.04 mPa·s, and that of water in liquid state at around 200°C is 0.134 mPa·s, indicating a difference in viscosity of 3~5 times between supercritical CO_2 and water. Since fluids tend to penetrate small cracks with decreasing viscosity, it is considered that supercritical CO_2 penetrates from the crack surface into the existing crack due to its low viscosity, and that the crack surface, which was widened by the supercritical CO_2 injection, is closed again and the rocks are in contact with each other. Therefore, the supercritical CO_2 escapes into the low pore pressure area in the specimen and the increase in pore pressure acting on the crack surface occurs simultaneously, which may be the cause of the staircase-like transition in the graph of axial displacement transition. On the other hand, subcritical H_2O is in a liquid state and has high viscosity, which may make it more difficult for the fluid to penetrate from the crack surface into the existing crack than supercritical CO_2. Therefore, the fluid could not penetrate into the existing crack in time for the pressure to increase, and the crack surface was not blocked as in the case of supercritical CO_2, resulting in smooth sliding behavior.

4.5.2. Behavior in the case of supercritical pore fluid

Comparisons are made for the cases of supercritical CO_2 (200°C) and supercritical H_2O (400°C, 450°C). When both pore fluids were supercritical, slip occurred in the case of supercritical CO_2 (200°C), while no slip was observed in the case of supercritical H_2O (400°C, 450°C). This difference in behavior may be due to the different conditions of the specimen rock, Honkomatsu andesite, which is likely to be ductile at 400°C and 450°C, as described in Section 4.4. In contrast, at 200°C, the specimens are considered to be in a brittle state. As a result, it is thought that the difference between the experiments with supercritical CO_2 (200°C) and those with supercritical H_2O (400°C and 450°C) is that the specimens become ductile and soft, and the crack surfaces adhere to each other and no slip occurs, compared to the experiments with supercritical CO_2 (200°C). The difference was due to the softer specimen in the ductile state and the absence of slip.

4.5.3. Axial expansion of specimens in supercritical H_2O

The expansion of the specimen before the pore fluid injection was stopped was 12.1 μm in supercritical H_2O (400°C) and 4.3 μm in supercritical H_2O (450°C), indicating that the expansion in supercritical H_2O (400°C) was larger. The reason for this difference in expansion is considered to be that the specimen becomes ductile and easily deforms at high temperatures between 400°C and 450°C. It is known that the viscosity decreases at 450°C due to the higher temperature compared to supercritical H_2O at 400°C.. Therefore, it is possible that the effective stress acting on the specimen is lower at 450°C than at 400°C because more fluid flows into the specimen and the pore pressure inside the specimen increases. As a result, the specimen was less deformed at 450°C, which may have resulted in a difference in the amount of expansion.

5. CONCLUSIONS

In Chapter 1 describes the background of the study, previous studies, and the objective of this study. In Chapter 2, an overview of the experimental apparatus, specimens, experimental method, and experimental conditions for conducting pore pressure induced slip experiments are described. In Chapter 3, the obtained experimental results, X-ray CT images of the specimens before and after the experiment, and images of the specimens after the experiment are presented, and it is found that slip occurred in the supercritical CO_2 and subcritical H_2O experiments. In Chapter 4, we first summarized the common slip behavior when slip occurred. The characteristics of the slip behavior in supercritical CO_2, subcritical H_2O, and supercritical H_2O are summarized, and the slip behavior is compared and discussed. The results suggest that supercritical CO_2 has lower viscosity than subcritical H_2O, which allows the pressurized fluid to penetrate the existing crack more easily, and that supercritical CO_2 may change from smooth slip

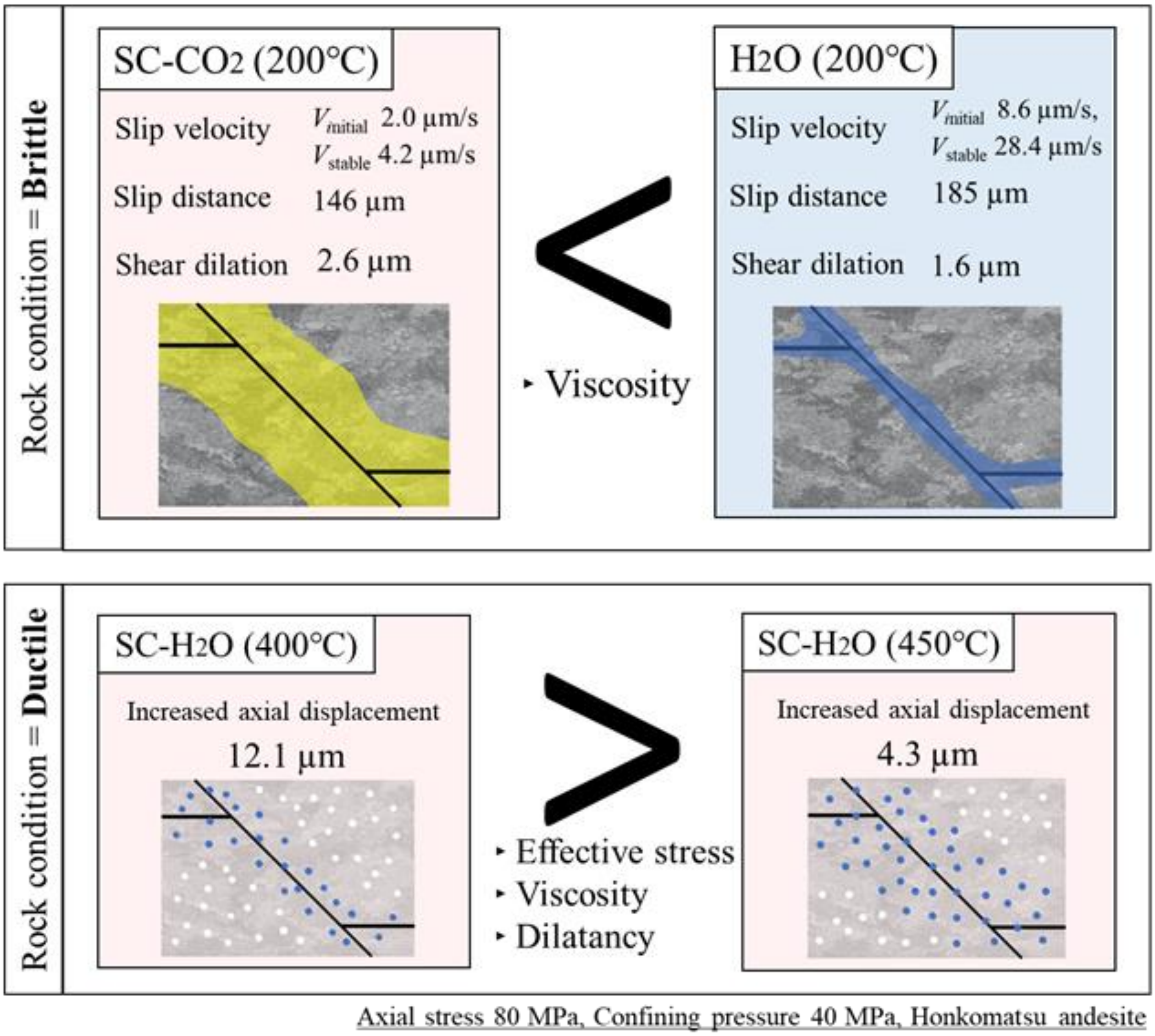

Fig.5 Correlation diagram of Honkomatsu andesite slip behavior due to pore pressure induced slip.

behavior to a stepwise slip behavior with a stair-step transition in axial displacement. Regarding the slip velocity and axial displacement after the onset of slip, the initial and steady-state slip velocities and axial displacement of supercritical CO_2 were found to be lower than those of subcritical H_2O, suggesting that the difference in viscosity contributed to this change. It is suggested that the difference in behavior between the supercritical CO_2 and supercritical H_2O experiments is related to the state of the rock. The axial expansion of the specimen during the supercritical H_2O experiment was suggested to be related to the decrease in effective stress due to the penetration of pore fluid into the specimen and to the state of the rock. In addition, the slip velocity measured in the experiments with supercritical CO_2 in this study was comparable to the slow non-seismic slip observed in Guglielmi et al (2015), suggesting that even if slip did occur, it might be non-seismic slip.

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