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Kyoto University
Acoustic emission monitoring of hydraulic fracturing laboratory experiment with supercritical and liquid CO₂

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Carbon dioxide (CO₂) is often used for enhanced oil recovery in depleted petroleum reservoirs, and its behavior in rock is also of interest in CO₂ capture and storage projects. CO₂ usually becomes supercritical (SC-CO₂) at depths greater than 1,000 m, while it is liquid (L-CO₂) at low temperatures. The viscosity of L-CO₂ is one order lower than that of normal liquid water, and that of SC-CO₂ is much lower still. To clarify fracture behavior induced with injection of the low viscosity fluids, we conducted hydraulic fracturing experiments using 17 cm cubic granite blocks. The AE sources with the SC- and L-CO₂ injections tend to distribute in a larger area than those with water injection, and furthermore, SC-CO₂ tended to generate cracks extending more than three dimensionally rather than along a flat plane than L-CO₂. It was also found that the breakdown pressures for SC- and L-CO₂ injections are expected to be considerably lower than for water. Citation: Ishida, T., K. Aoyagi, T. Niwa, Y. Chen, S. Murata, Q. Chen, and Y. Nakayama (2012), Acoustic emission monitoring of hydraulic fracturing laboratory experiment with supercritical and liquid CO₂, Geophys. Res. Lett., 39, LXXXXX, doi:10.1029/2012GL052788.

2. Experimental Method

2.1. Specimens and Confining Pressure

Four cubic (17 cm × 17 cm × 17 cm) samples of Kurokami-jima granite were used as specimens. Two of the four, the specimens G1009 and G1010, were subjected to SC-CO₂ injection, while the other two, the specimens G1011 and G1012, were subjected to L-CO₂ injection. The samples had a 2 cm diameter central hole, and the inherent rift plane of the granite specimen was oriented so as to correspond to the YZ-plane in the Cartesian coordinate system, as shown in Figure 1a. P-wave velocities measured along the X- and Z-directions were around 5.0 km/s, while that along the X-direction normal to the rift plane was around 4.3 km/s. To monitor AE events induced with the injection, sixteen cylindrical PZT elements in total were glued on the six surfaces of the specimen. To apply confining pressures, the specimen, together with the PZT elements on its surfaces, was encapsulated in plaster.

[5] The specimen was placed in a cylindrical pressure cell. Four bow-shaped spacer blocks were inserted between the specimen and the inner wall of the pressure cell, and a flat jack was placed between the specimen and each spacer block to apply pressure in the X- and Y-directions. In the Z-direction, flat jacks were placed between the specimen and loading plates supported by the end caps on the top and bottom of the pressure cell. In all experiments, confining pressures of 1 MPa were applied in the X-, Y- and Z-directions to provide the hydrostatic stress condition. Figure 1b shows the packer used to inject CO₂ which was inserted into the center hole of the samples. The packer had a 60 mm pressurizing section sealed with two O-rings at each end. The pressurizing section was centered along the hole.
2.2. CO₂ Injection Method

To control the experimental conditions, the injection system shown in Figure 2 was made especially for these experiments. The CO₂ was fed from a bomb to a cylinder of the syringe pump, which has a capacity of 266 mL. To fill the cylinder as full as possible, the CO₂ was cooled and kept in liquid form by circulating coolant in a cooling unit located above the cylinder. L-CO₂ was discharged from the cylinder of the syringe pump at a constant flow rate of 30 mL/min, to be injected into the packer placed in a hole in the center of the specimen. The injection was stopped just after hydraulic fracturing was induced, which was indicated by a sudden pressure drop. CO₂ becomes supercritical when the temperature is higher than 31.1°C and the pressure is greater than 7.38 MPa, while it is liquid at lower temperatures. For SC-CO₂ induced fracturing, the L-CO₂ discharged from the syringe pump was passed through a heater unit and the temperature was maintained at 55°C by bandaging electric resistance heating ribbon along the pipe connecting the heater unit to the packer as shown in Figure 2. In addition, the cell in which the specimen was contained was filled with hot water at a temperature of around 45°C to prevent the injected CO₂ from cooling. Although the specimen was soaked in hot water for around one hour, we believed that water does not infiltrate into around the injection hole due to its low permeability and the hydraulic fracturing was induced in dry condition from our experience on previous similar experiments. Thus, for the L-CO₂ injection, L-CO₂ was fed to the packer without heating and the cell was kept at room temperature without filling water.

2.3. Methods to Monitor AE, Pressure and Temperature

The PZT elements glued onto the specimen were cylindrical, 3 mm in diameter and 4 mm in length, and had a resonance frequency of 300 kHz. They were covered with aluminum sheet to avoid electromagnetically induced noise. They were also covered with heat shrinkable tubes and silicon rubber to provide a waterproof barrier for the plaster encapsulation. The detected AE signals were amplified by 66 to 84 dB in total (36 dB in a pre-amplifier and 30 to 48 dB in a signal conditioner), and recorded on a hard disk through an A/D converter. For each event, the record length and sampling time of the A/D converter were selected to be 2048 words and 0.1 ms, respectively. The dead time was set to be 1 ms after recording an event, to prevent the hard disk from recording too much noise due to “ringing,” which is the vibration following a large AE event. The recording of an AE event was triggered when one of the signals from 16 AE sensors exceeded 0.3 V. In addition, the number of AE events per second was counted for each AE sensor when the signal exceeded 0.3 V.

Every 0.1 s, the injected CO₂ pressure was measured through transducers set at the top of the packer, and the flat jack pressures in the three directions, X, Y and Z, were measured through transducers set on the connecting pipes of opposing pairs of flat jacks. Temperature changes were measured with a thermocouple glued on the injection pipe just above the packer in the hole. Thermocouples were also

Figure 1. Specimen and straddle packer used to inject CO₂. (a) Specimen, loading condition and positions of AE sensors. (b) Photo and illustration of a sectional view of the packer.

Figure 2. Injection system for SC-CO₂ and L-CO₂.
placed at the both ends of the section of a pipe covered with electric resistance heating ribbon, as shown in Figure 2.

3. Results and Discussion

3.1. Change of Fluid Pressure, Temperature and AE Count Rate

Figure 3a shows changes of the injected fluid pressure, the AE count rate and the temperature when SC-CO₂ and L-CO₂ were injected into the specimens G1010 and G1012, respectively. In the left plot, the temperature measured with a thermocouple glued onto the injection pipe just above the packer was 40.2°C, which indicates that the fracturing was induced by SC-CO₂. On the other hand, in the right plot, the temperature was 16.1°C, indicating that the fracturing was induced by L-CO₂. In both cases, the temperature decreased along with the breakdown pressure. This is most likely due to adiabatic expansion of CO₂ by leakage through the cracks created by the fracturing. The AE occurrence rose sharply just after the fracturing and events continued to occur for several seconds.

Figure 3b shows change of the injected fluid pressure for 50 s just before and after the breakdown in all the experiments. The breakdown pressures of 8.44 and 9.56 MPa recorded for SC-CO₂ are lower than those of 10.56 and 11.56 MPa for L-CO₂. A possible explanation is that a slick fluid, like SC-CO₂, having lower viscosity infiltrates into defects in the matrix around the hole more easily than L-CO₂. This inference is also supported by the fact that the difference in the pressure change becomes noticeable after the pressure reached around 7.38 MPa where the CO₂ becomes supercritical at the temperature of the SC-CO₂ experiments. The steep increase in the pressure may help the breakdown pressures for L-CO₂ to become larger than those for SC-CO₂.

3.2. Induced Visible Cracks and Located AE Sources

After the experiments, we closely observed the induced cracks on the specimen surfaces with the naked eye. Figures 4a and 4b show the visible cracks sketched on the unfolded planes of the specimens. The figure shows that the cracks were induced along the inherent rift plane for both SC-CO₂ (G1010) and L-CO₂ (G1012) injection. This also occurred in the other two specimens, G1009 and G1011, not shown in the figure. Figures 4c and 4d show the distribution of 95 and 78 AE sources for SC-CO₂ (G1010) and L-CO₂ (G1012), with an accuracy expected to fall within a few mm satisfying certain conditions [Ishida and Sasaki, 2011].

The fractal dimensions of the distributions of the located sources were obtained by the correlation function method, following Hirata et al. [1987] and Grassberger...
Theoretically, the fractal dimension for infinite numbers of points distributed on a line, on a flat plane and three dimensionally should be one, two and three, respectively. Since a number of points distributed is limited, the fractal dimensions obtained with the method tend to be a little bit lower than the respective dimensions. However, the dimension still can measures fracture behavior, and in the case, the larger fractal dimension indicates that AE sources distributes the more three dimensionally rather than along a flat plane, suggesting the induced fracture extending the more three dimensionally. The fractal dimensions, \( FD \), for SC-CO\(_2\) fracturing were 2.20 in specimen G1010, while those for L-CO\(_2\) were 1.64 in G1012. The fractal dimensions obtained in the other two experiments showed the same tendency (see Table 1).

The most likely flat plane for the distribution of the AE sources was also estimated for each experiment, by minimizing the sum of squares of distances from a located source to the flat plane. The average distance from a source to the estimated flat plane, \( L_{av} \), was 8.82 mm in the specimen G1010 (SC-CO\(_2\)), while that for G1012 (L-CO\(_2\)) was 7.80 mm. The average distances in the specimens G1009 (SC-CO\(_2\)) and G1011 (L-CO\(_2\)) showed the same pattern, being 24.2 mm and 7.80 mm, respectively. The large value of \( L_{av} \) in G1009 is due to a three dimensional AE source distribution particularly in a lower part of the specimen (not shown here). The most likely flat plane cuts across the four out of the six surface planes of the specimen. The intersection lines are also shown in Figures 4a and 4b. The intersection lines for L-CO\(_2\) (Figure 4b) almost coincide with the visible cracks on the surfaces, while those for SC-CO\(_2\) (Figure 4a) 252

Table 1. Number of Located AE Sources, the Fractal Dimension, \( FD \), and the Average Distance to the Most Likely Flat Plane, \( L_{av} \), Which Were Obtained for Each Experiment

<table>
<thead>
<tr>
<th>Injectant</th>
<th>Specimen Number</th>
<th>Located AE Sources</th>
<th>( FD )</th>
<th>( L_{av} ) (mm)</th>
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<tbody>
<tr>
<td>SC-CO(_2)</td>
<td>G1009</td>
<td>79</td>
<td>2.64</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td>G1010</td>
<td>95</td>
<td>2.20</td>
<td>8.82</td>
</tr>
<tr>
<td>L-CO(_2)</td>
<td>G1011</td>
<td>103</td>
<td>1.62</td>
<td>5.30</td>
</tr>
<tr>
<td></td>
<td>G1012</td>
<td>78</td>
<td>1.64</td>
<td>7.80</td>
</tr>
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</table>

Figure 4. Cracks and AE source distributions for typical examples of SC-CO\(_2\) and L-CO\(_2\) injection. Cracks (bold lines) observed on the specimen surfaces and intersection lines (thin chain lines) of the most likely flat plane estimated from the source distribution: (a) SC-CO\(_2\) (G1010) and (b) L-CO\(_2\) (G1012). Projections of AE sources onto the \( xy \), \( yz \) and \( zx \)-planes: (c) SC-CO\(_2\) (G1010; \( FD = 2.20, L_{av} = 8.82 \) mm) and (d) L-CO\(_2\) (G1012; \( FD = 1.64, L_{av} = 7.80 \) mm).
do not show such a close correspondence. The wide variance
of the source distribution for SC-CO\(_2\) probably causes the
larger gap between the intersection lines and the visible
cracks. Although the observed difference in the distance
Lav, 1.02 mm, between SC-CO\(_2\) (G1010) and L-CO\(_2\)
(G1012) is not large, it is consistent with the differences in
the fractal dimensions and in the gaps between the visible
cracks and the intersection lines. Thus, it seems to be sig-
nificant and meaningful, suggesting the fracture induced
with SC-CO\(_2\) extends three dimensionally than that with L-
CO\(_2\), for example, wavelike with more secondary branches
rather than along a flat plane.

3.3. Feature of Fracture Behavior in Comparison

With Water Injection

[Ishida et al. (2004)] conducted hydraulic fracturing
experiments on the same kind of cubic Kurokami-jima
granite using normal water and viscous oil, with viscosities
of 1 and 80 mPa\(\cdot\)s, respectively. The results indicate that
viscous oil tends to generate thick and planar cracks with
few branches, while water tends to generate thin and wave-
like cracks with many secondary branches. The viscosities of
SC-CO\(_2\) and L-CO\(_2\) at the fracturing are 0.025 and 0.088
mPa\(\cdot\)s respectively. These values were calculated using the
equation of state for CO\(_2\) of T. Ohmori (http://hp.vector.
co.jp/authors/VA030090/) based on the theory by Fenghour
et al. [1998]. For the calculation, a temperature and pres-
sure of 40.2\(\degree\)C and 8.44 MPa were used for SC-CO\(_2\), while
16.1\(\degree\)C and 10.56 MPa were used for L-CO\(_2\). Considering the
difference of viscosities, it seems to be consistent that the
fractal dimension and the average distance for located AE
sources associated with SC-CO\(_2\) injection are larger than
those for L-CO\(_2\). Furthermore, we compare the source dis-
tributions with the SC- and L-CO\(_2\) injections to those with
water and oil injections in Ishida et al. [2004, Figures 6 and
7], we can easily find the distributions with SC\(_2\) and L-CO\(_2\)
extend in a larger area than those with water and oil on projec-
tions of respective planes. On the other hand, Warpinski
et al. [2005] produced hydraulic fracturing using gel and slick water
in a shale gas reservoir, and compared the microseismic maps
associated with the two fracturings. The map associated with
slick water fracturing outlines a much larger area than that
achieved with the gel fracturing. Our results including those in
Ishida et al. [2004] are consistent with the field experience,
from the viewpoint of the difference in the fracturing fluid
viscosity.

In the experiments by Ishida et al. [2004], the mag-
nitude of the breakdown pressure for the viscous oil was
16.5 and that of water was 17.9 MPa, which was inconsistent
with the fact that viscosity of the oil is 80 times larger than
that of water. In this case, variation in the strengths of the
specimens might cover the difference. Since the condition of
confining pressures and flow rates are different between the
experiments in this paper and those in Ishida et al. [2004],
let’s compare tensile strengths at the breakdown with sub-
tracting the compressive stress induced at the fracturing
point along the hole wall by the confining pressures using
Kirsch’s [1898] solution, without considering pore pressure.
The tensile strength in the SC- and L-CO\(_2\) injections were
6.44 and 8.56 MPa, subtracting 2 MPa induced by the con-
fining pressures that \(S_h = 1\) and \(S_h = 3\) from the breakdown
pressure 8.44 MPa and 8.56 MPa, as shown in Figures 3a
and 3b. On the other hand, the tensile strength in the water
and oil injections in Ishida et al. [2004] were 14.9 and
around 13.5 MPa, subtracting 3 MPa by \(S_h = 6\) and \(S_h = 3\)
from the breakdown pressure 17.9 for water and 16.5 MPa
for the viscous oil. Thus, the tensile strengths for the SC- and
L-CO\(_2\) injections are quite lower than those for the water and
oil injections. Furthermore, the order of the tensile strengths
almost follows the order of the injectant viscosities, with a
slight reversal between water and the viscous oil. The results
are consistent with the facts elucidated in experimentally by
Schmitt and Zoback [1993] and theoretically by Burger et al.
[2010]. On the other hands, the difference in flow rates
between 30 mL/min for the SC- and L-CO\(_2\) injections and 10
mL/min for water and the oil injections does not seem to
affect the results, because the larger flow rate should make the
larger breakdown pressure [Schmitt and Zoback,1993; Garagash
and Detournay, 1997]. Thus, under the same condition of in situ rock stress and flow rate, the breakdown
pressure with CO\(_2\) injection is expected to be considerably
lower than with usual water injection due to its lower
viscosity.

4. Conclusions

Using SC- and L-CO\(_2\) as the fracturing fluid, we con-
ducted hydraulic fracturing experiments in cubic granite
blocks. The results can be summarized as follows.

1) The fractal dimensions of the located AE source dis-
tributions with the SC-CO\(_2\) injection were larger than
those for L-CO\(_2\) injection. Furthermore, the average dis-
tances from a source to the most likely flat plane estimated for
the AE source distribution were also larger for SC-CO\(_2\) than
those for L-CO\(_2\). These differences suggest that, due to its
lower viscosity, SC-CO\(_2\) tends to generate cracks extending
more three dimensionally than rather than along a flat plane than
L-CO\(_2\). The AE source distributions were compared with
those with water and viscous oil injections in the previous
similar experiments. The AE sources with the SC- and L-CO\(_2\)
junctions distributed in larger area more three dimensionally
than those with water injection. The same difference was also
observed in microseismic maps with hydraulic fracturing
using gel and slick water in a shale gas reservoir, and our
results is consistent with the filed experiences.

2) A tendency for the breakdown pressures to be lower for SC-
than for L-CO\(_2\) was observed. Comparison with water and the viscous oil injections elucidated that the breakdown
pressures with SC- and L-CO\(_2\) injections are expected to be considerably lower than with water injection
due to their lower viscosities under the same in situ rock
stress and flow rate.

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