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Monitoring hydraulically-induced fractures in the laboratory using acoustic emissions and the fluorescent method

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ABSTRACT

We investigated the relation between seismic events and fractures induced by hydraulic fracturing in laboratory experiments under uniaxial loading conditions using granite and shale blocks by monitoring acoustic emissions (AEs). We used a thermosetting acrylic resin mixed with a fluorescent compound as the fracturing fluid and fixed it within the blocks by heating immediately after fracturing. This allowed observation of fluid penetration regions and fracturing patterns on cross-sectional planes under ultraviolet light irradiation. The obtained AE hypocenters and resin penetration regions observed after the fracturing extended on both wings along the loading axis from the fracturing hole for all the samples. This was as expected theoretically, although the AEs were concentrated primarily on only one side for some samples. Patterns of wellbore pressurization histories, AE activities, and resin penetration regions were significantly different between the two rock types. In the experiments using granite samples, wellbore pressure increased linearly until 87.2–97.4% of the peak pressure, followed by a gradual decrease of the rate and sudden drop of pressure (breakdown). AEs started to occur at 49.6–93.2% of the peak pressure, significantly before the breakdown. Resin penetration regions have a width of 10–30 mm and such wide penetration regions resulted in indistinguishable main fractures. For the shale samples, both the nonlinearity of the wellbore pressure–time curve and the AE activity were initiated immediately before breakdown. The number of detected AEs was much smaller than for the granites. Resin in the rock samples showed thin traces with widths of < 1 mm, corresponding to the main fracture. Such dissimilarities between the two rock types likely resulted from differences in their permeability, grain size, and/or mineralogy. We also found aseismic regions that lacked AEs despite evidence of fluid penetration. Although such regions were affected by the fracturing operations, they cannot be revealed by the microseismic observations used in shale gas/oil fields and enhanced geothermal systems.

1. Introduction

Hydraulic fracturing is commonly used to increase the permeability of reservoir rocks in unconventional reservoirs and enhanced geothermal systems (EGSs). Appraisal of a region in which fractures have been induced and fluid penetration has occurred is important for fracturing evaluation and production prediction. Although microseismic observations have often been used for such purposes, the relation between seismic activities and the fractures actually induced has not been clarified sufficiently. For example, in shale gas/oil fields, the concept of the “Stimulated Reservoir Volume” (SRV),[1] which is defined as a volume in which seismic events have occurred, has widely been used because some studies have reported that the SRV correlates well with gas/oil productivity.[1–3] This correlation is, however, not universal and other studies have reported negative correlation.[4] Negative correlation can be caused by fractures that accompany seismic events without contributing to production, or in contrast, by fractures behaving aseismically with contributing to production. It is necessary to understand the types of fractures that radiate seismic signals for advanced use of microseismic data in fracking evaluation.

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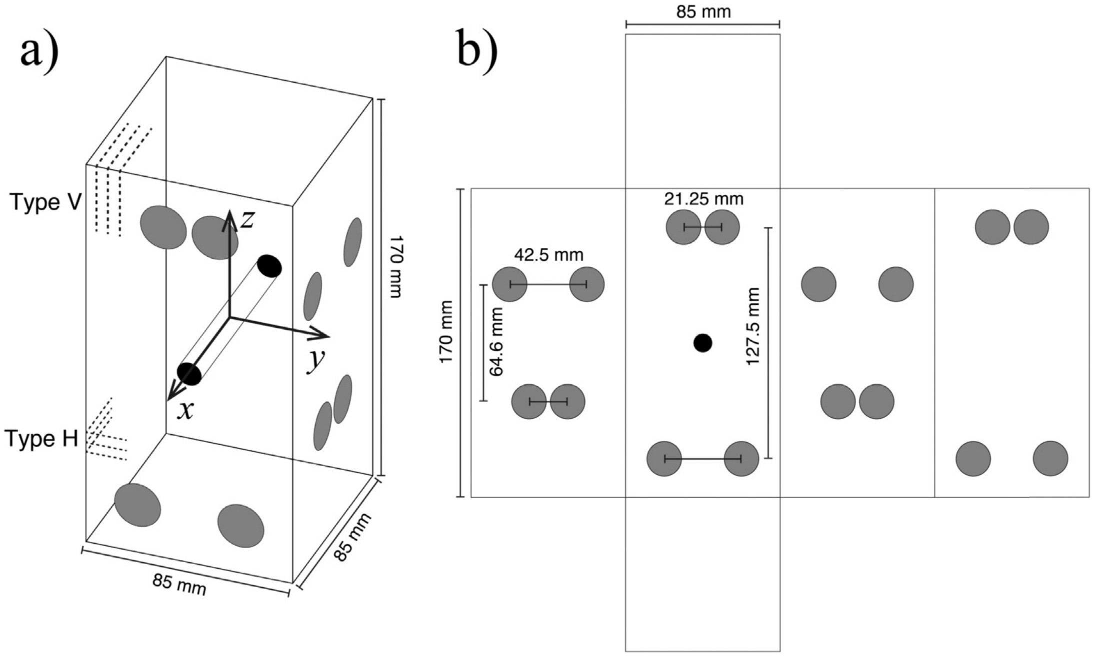

Fig. 1. a) Sample size, AE sensor position, and the coordinate system used in the present study. The origin of the coordinate system corresponds to the center of the specimen. Black circle represents a wellbore. A packer was inserted along the *x*-axis from the positive side. Gray circles represent the positions of the AE sensors (shown only on front side for clarity). b) AE sensor positions on the development projection.

In this study, we conducted hydraulic-fracturing laboratory experiments under uniaxial loading conditions and monitored the resulting acoustic emissions (AEs). We used a thermosetting acrylic resin mixed with a fluorescent compound as the fracturing fluid.[5,6] This permitted the observation under ultraviolet (UV) light irradiation of fluid penetration regions on cross-sectional planes cut after the fracturing. These regions were then compared with AE hypocenter distributions. For the fracturing experiments, we used intact samples of Inai shale to mimic tight reservoirs of shale gas/oil and Kurokami-jima granite to mimic EGS reservoirs. Although the use of intact rock samples might not correspond to the most recent concept of an EGS, where shear stimulation of pre-existing fractures is usually assumed, fracturing of very tight reservoirs similar to shale gas/oil fields is potentially applicable to future fracturing design of EGSs.[7,8]

2. Experimental methods

2.1. Specimen and experimental setup

We used seven blocks of Kurokami-jima granite (KJG05–11) and six blocks of Inai shale (INS03–10) with dimensions of 85 × 85 × 170 mm (Fig. 1). Kurokami-jima granite is Cretaceous granite found in Kurokami-jima Island in the Seto Inland Sea in southwestern Japan. Inai shale is found in the Triassic Inai group in Miyagi Prefecture in northeastern Japan. Table 1 presents the porosity, permeability, and tensile strength of a number of samples as measured by the Brazilian test.

For all samples, we measured the *P*-wave velocities along the *xyz* directions before fracturing (Table 2). The coordinate system used is shown in Fig. 1. Most granite has orthogonal anisotropy of *P*-wave velocities, which is associated with the anisotropic distribution of pre-existing microcracks,[9–13] and their *P*-wave velocities become lowest in the direction normal to the plane within which most of the microcracks exist.[10] This plane is called the rift plane, and tensile strength is lowest along this plane.[14–17] Kudo et al.[16,18] have reported that Kurokami-jima granite has these features. Based on the *P*-wave anisotropy, we classified the granite blocks used in the present study into two types (Fig. 1a): Type V, which has vertical rift planes (normal to the *x*–*y* plane) and Type H, which has horizontal rift planes (parallel to the *x*–*y* plane). For the shale blocks, we defined Type V as having vertical sedimentary planes and Type H as having horizontal sedimentary planes.

Table 1
Physical properties of Kurokami-jima granite and Inai shale.

	Tensile strength [MPa]	Effective porosity [%]	Intrinsic permeability [m^2]
Kurokami-jima granite	8.38 ± 0.86[a,b]	0.84[c]	9×10^{-19}[c]
Inai shale	10.87 ± 5.27[b]	0.6	$< 5 \times 10^{-20}$[d]

[a] Results of the Brazilian test for tensile strength along rift planes by Ishida et al.[35].
[b] The error was represented by standard deviations.
[c] Ishida et al.[36].
[d] Smaller than the measurement limit (5×10^{-20} m^2) of CMS-300, a product of Core Laboratories.

Fracturing was conducted under uniaxial loading of 5 MPa along the *z*-axis. Uniform loading was confirmed before fluid injection based on data from four strain gauges attached to the samples. Samples had a wellbore of 10 mm in diameter, as shown in Fig. 1a, and a packer was inserted into the wellbore to inject the fracturing fluid. The packer had a 30-mm pressurizing section, which was centered along the wellbore (corresponding to the origin of the coordinate system), sealed with two O-rings at each end. We used methyl methacrylate (MMA), a thermosetting acrylic resin, which has a viscosity of 0.80 mPa s at room temperature, as the fracturing fluid. The MMA was mixed with a fluorescent compound to allow us to observe fluid penetration regions after fracturing. The MMA was injected into the packer using a cylindrical piston, which was pressurized by water injected from a syringe pump at a constant flow rate. The wellbore pressure was measured by a pressure gauge near the packer, and its data were recorded continuously at a rate of 100 kS/s using a PXI-6251 (National Instruments Corp.)

2.2. Measurement of acoustic emissions

We attached 16 AE sensors (R15α; Physical Acoustic Corp.; 19 mm in diameter) with resonant frequency of 75–150 kHz onto a specimen,