

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.

Keywords: acoustic emission, hydraulic fracturing, shale gas/oil, enhanced geothermal system

Highlights:

Hydrofracking-induced fractures assessed by acoustic emissions and fluorescent method

Fracturing patterns differed considerably between granite and shale samples

Permeability, grain size and/or mineralogy of rocks affect patterns of fractures
Aseismic areas where fluid penetrated without seismic events were clearly identified

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.

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 $85 \times 85 \times 170$ 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.

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 $0.80 \text{ mPa} \cdot \text{s}$ 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 (R15 α ; Physical Acoustic Corp.; 19 mm in diameter) with resonant frequency of 75–150 kHz onto a specimen, as shown in Fig. 1. Signals from each channel were continuously recorded at 10 MS/s by a 14-bit analog-to-digital converter (PXIe-5170R; National Instruments Corp.) after amplification by 52 dB and the application of a 0.02–3.00 MHz band-pass filter. The maximum range of the analog-to-digital converter was set to 2 Vpp. From these data, we created an AE catalog where hypocenter coordinates and relative magnitudes were listed based on the procedure described in Section 3. The 10-MS/s AE data recorded by the PXIe-5170R and the 100-kS/s pressure data recorded by the PXI-6251 were strictly synchronized with each other.

2.3 Observation of Induced Fractures with Fluorescent Resin

Nishiyama and Kusuda⁵ proposed a method for the observation of pore spaces and microfractures in rock samples using a thermosetting resin mixed with a fluorescent compound. Our previous studies have applied this approach to observe fractures induced by hydraulic fracturing.^{6,19,20} They soaked rock samples in resin after fracturing and then heated them to harden and fix the resin that had penetrated the pores and fractures. Observations were then performed on cut surfaces under UV light. Although this approach can clearly show the fractures within a rock sample, it is difficult to distinguish new fractures induced by the hydraulic fracturing from pre-existing cracks. This study overcame this problem via the use of the resin as the fracturing fluid; thus, highlighting only those regions in which the resin penetrated during fracturing.²¹

After fracturing, we put the samples in a pre-heated furnace to harden the penetrated resin. We maintained the temperature in the furnace at 90 °C for 1 h to promote the heating of the block, and then kept it at 80 °C for at least 12 h. Afterwards, we slowly cooled the sample to room temperature. Subsequently, the block was sliced into five sections parallel to the y - z plane (at approximately $x = -28.3, -14.2, 0.0, +14.2,$ and $+28.3$ mm) to observe the regions of resin penetration including the fractures. Photographs of the samples taken under UV light (all at the same exposure) are shown in

Section 5. The shutter speed was set to 2 s for the granite samples and 15 s for the shale samples.

The heating process was unlikely to affect our observation of regions where resin penetrated during hydraulic fracturing since the temperature used was too low to induce severe thermal cracking or shock. Even if new fractures were generated, the viscosity of the resin increased with temperature and it began to solidify at a lower temperature of ~ 60 °C; thus, it would have been difficult for the resin to penetrate newly induced fractures.

3. AE Catalog Development

3.1 Detection of AE Events

To identify AE events within the waveforms recorded continuously at 10 MS/s, we used ratios of the Short Term Average (STA) and the Long Term Average (LTA) of waveform amplitudes²² as described below.

Firstly, we decimated the recorded waveforms to 1 MS/s and calculated the STA for 20 samples and the LTA for 1000 samples from the decimated records of all 16 channels. We searched for intervals in which the STA/LTA ratios exceeded 3.5 continuously, and considered the timing of the maximum ratio in each interval as “trigger candidates.” When six or more channels had trigger candidates within a 50- μ s window, we defined the initial one as the “trigger time” of an AE event. We ignored all other trigger candidates within a 0.5-ms dead time following each identified trigger time. Around each trigger time, we acquired cutout waveforms of 2048 samples (204.8 μ s) in length for the following analysis.

3.2 Hypocenter Location

We applied the automatic *P*-wave arrival time detection algorithm suggested by Takanami and Kitagawa²³ to the cutout waveforms (Section 3.1), and located their hypocenters using a least square algorithm in which *P*-wave anisotropy was considered.²⁴ The details are described below.

First we calculated t^{med} , the median of the *P*-wave arrival times obtained by the automatic algorithm among all the 16 channels for each AE event, and removed arrival times whose differences to t^{med} were >30 μ s. This procedure allowed us to remove outliers that were impossible if the AE

hypocenters were situated within the specimen. Using the remaining arrival times, we estimated a hypocenter based on the iterative method of Rothman et al.²⁴. This procedure was repeated nine times for nine initial hypocenters distributed uniformly within each specimen.

Then we relocated a hypocenter again, using the result that provided the minimum residual of the nine hypocenters as the initial hypocenter. In this step, we used a biweight function to reduce the weight or to remove arrival times that had large residuals during the iterations.²⁵ We defined a weighting function that had only diagonal components:

$$w_i = \max^2 \left(0, 1 - \left(\frac{dr_i}{\alpha \sigma^{MAD}} \right)^2 \right), \quad (i = 1, \dots, 16), \quad (1)$$

where dr_i is the residual of an arrival time for an individual channel, α is a constant, dr^{MAD} is the median absolute deviation of the residuals, and σ^{MAD} is the median absolute deviation for Gaussian noise (=0.67449). Larger values of α accept arrival times that have larger residuals; here, we adopted a value of $\alpha = 6$.

From the results obtained, we chose “well-located events” that satisfy the following conditions: 1) eight or more arrival times remained after the final iteration, and 2) the maximum standard error was smaller than 40 mm among the three principal axes of an error ellipsoid calculated from the variance-covariance matrix. For the well-located AEs, the average location error was ~15 mm for the granite samples and ~25 mm for the shale samples.

As examples, we show the obtained hypocenter distributions of the well-located AEs for KJG07 in Fig. 2a–c and for INS03 in Fig. 3a–c. It can be seen that the hypocenters were distributed along the z -direction, consistent with the orientation of fracture propagation expected from the stress condition around the wellbore under the uniaxial condition.

The average location error of 15–25 mm is large, considering the size of the blocks used in our experiments. We also examined the hypocenter location accuracy using pulse radiation tests in which each of the 16 sensors were used as a pulsar and the other 15 received the radiated pulse. The pulsar position estimated from the arrival times at the 15 sensors, which could be read accurately due to a good signal to noise ratio, were typically 6–8 mm away from the actual position. Such large errors were due likely to the large size of the sensor (19 mm), which resulted in different arrival times

depending on the incident angles between the waves and the sensors. The large errors were also a result of the low-frequency resonance (75–150 kHz) of the sensor, which also prevented accurate detection of arrival times. Smaller sensors that can capture higher frequency waves are desirable in terms of achieving location accuracy. However, such sensors typically have a lower sensitivity, which causes fewer AEs to be detected. In the present study, we prioritized the number of detected events and choose to use an R15a sensor, which is large but very sensitive.

3.3 Hypocenter Relocation using the Double-Difference Method

As described above, large location errors were obtained for the hypocenter estimates. To improve the location accuracy, we relocated those hypocenters by applying the double-difference (DD) algorithm²⁵. In the conventional approach described in the previous section, a hypocenter of an event is estimated from the arrival times obtained for multiple stations; however, in the DD method, the hypocenters of multiple adjacent events were evaluated based on the “arrival time differences” at each station for many event pairs. By combining the cross-correlation travel time reading technique, which allows us to estimate travel time differences very accurately, the uncertainties of hypocenter estimates were sometimes improved by more than an order of magnitude compared to the originals²⁵.

In the analysis, we used the average P -wave velocity in the xyz directions and we used the final location results obtained following the procedure in Section 3.2 as initial source locations. We used dt^{ct} , i.e., the arrival-time differences calculated from the automatic picking results that remained after the final iteration in Section 3.2, and we used dt^{cc} , i.e., the arrival-time differences measured by a waveform cross-correlation technique. For each event, dt^{cc} was calculated for up to 250 mates whose interevent distances were <40 mm for the granites and <80 mm for the shales, using filtered (20–400 kHz) waveforms of 55 μ s in length including the P -wave trains. In the relocation, we used dt^{cc} only for the waveform pairs whose cross-correlation coefficient was >0.75 at each station. Examples of the relocated results are shown in Figs. 2d–f and 3d–f for KJG07 and INS03, respectively. The resultant hypocenters were aggregated two-dimensionally better than the original results, indicating that location accuracy had improved.

The DD algorithm can minimize the influence of velocity modeling errors²⁵ by using the

differences in arrival time between neighboring events with an almost identical wave path. From this point of view, interevent distances of <40 mm and <80 mm are too large to assume nearly common paths. Although we selected those values to stably relocate AE events as many as possible, this likely impacted the resultant location accuracy. When we relocated AE hypocenters using the DD method with dt^{ct} only, the resultant hypocenter distribution did not change greatly from the original result obtained by the method described in Section 3.2. The improvement in location accuracy achieved by the DD method was likely due mainly to accurate readings of the differences in arrival time using the cross-correlation technique.

3.4 Relative Magnitude

Relative magnitudes for each event were estimated using the following equation:

$$M = \Sigma \log_{10} (r_i \times A_i) / N, \quad (2)$$

where A_i is the waveform amplitude [V] for the channel i -th AE sensor, r_i is the distance [mm] between sensor i and the hypocenter, and N is the number of sensors used in the magnitude calculation. The amplitude A_i was given by the peak-to-peak amplitude of the raw waveform in a 50- μ s window around a theoretical arrival time of the P -wave. We used only those channels remaining after the final iteration of the location procedure outlined in Section 3.2 and whose signal-to-noise ratio was <3. We did not remove saturated waveforms, and the upper limit of the obtained magnitudes was ~ 2.5 .

4. Experimental Results

4.1 Fluid Pressure History and AE Activities in Experiments of Kurokami-jima Granite

We list the details of all the fracturing experiments conducted in the present study in Table 2. In this section, we describe the results for KJG07 (Type V) as an example of fracturing of Kurokami-jima granite.

Figure 4a shows the wellbore pressure history and the cumulative number of well-located AEs as a function of elapsed time. The injection rate of water from the syringe pump was maintained at 2 mL/min for all the experiments involving granite. In the experiment on KJG07, the fluid pressure at the wellbore increased slowly with time from the initiation of injection ($t = 0$ s), and it increased

linearly from about $t \sim 360$ s and ~ 4 MPa. At $t = 438$ s and 9.77 MPa (i.e., $\sim 94\%$ of peak pressure), the pressurization rate started to decrease and it deviated from the linear trend. Peak pressure of 10.39 MPa was reached at $t = 455.7$ s. After attaining the peak magnitude, the pressure decreased slowly for several seconds and then dropped rapidly to ~ 7 MPa (breakdown). After reaching the bottom pressure, it then increased slowly again.

The AE rate started to increase from about $t \sim 435$ s and ~ 9 MPa (i.e., $\sim 86.7\%$ of peak pressure) and it reached a peak of ~ 165 events/s at $t = 443\text{--}460$ s (i.e., from 13 s before to 4 s after peak pressure). The relative magnitudes of the AEs increased with time until breakdown and then decreased (Fig. 4b). The region in which AEs occurred extended along the z -axis from the wellbore from about $t \sim 420$ s to $t = 455.65$ s at which point breakdown occurred (Fig. 5), indicating crack propagation. Large surface cracks were not recognized after fracturing, although a small crack of 10-cm length was found, which is consistent with the obtained AE distribution (Fig. 2). The lack of large cracks likely caused the small pressure drop at breakdown and its subsequent increase, probably because the supply rate of the fracturing fluid exceeded the discharge rate because of an insufficient volume of fluid path from the wellbore to the outside of the block.

4.2 Dependence of Fluid Pressure History on P -wave Anisotropy of Granite

We defined the following four parameters to characterize fluid pressure histories. 1) Pressure at which AE activity initiated (P^{AE}). We defined it as the pressure when the AE rate first exceeded five events/s. 2) Pressure at which the pressure–time curve deviated from a linearly increasing trend (P^{leak}). Stanchits et al.²⁶ interpreted this deviation as the result of the entry of the fracturing fluid into dry hydraulic fractures. Therefore, we called P^{leak} the “leak-off pressure.” 3) We called peak pressure (P^{BD}) the “breakdown pressure.” 4) The drop of wellbore pressure during breakdown was called P^{drop} .

Figure 6 shows the four pressure parameters against the ratio of the P -wave velocity in the z -direction and the velocity averaged in the x - and y - directions (i.e., $2V_z/(V_x + V_y)$). All four parameters were smaller for Type V, where ruptures propagate along a rift plane, than for Type H, where ruptures propagate across rift planes. The smaller values of P^{AE} , P^{leak} , and P^{BD} for Type V likely correspond to the lower tensile strength along the rift planes of granite (Section 2). Smaller values of

P^{drop} for Type V likely correspond to smaller fluid paths after breakdown. Actually, smaller surface cracks were observed for Type V blocks, suggesting smaller strain release in the experiments of Type V blocks, which was probably the result of smaller P^{BD} .

4.3 Results for Inai Shale

Figure 7 shows the pressure history and the cumulative number of well-located AEs for the INS03 experiment. The water injection rate from the syringe pump was 2 mL/min, as in the experiments on the Kurokami-jima granite. The obtained P^{BD} (18.74 MPa) was higher than in the experiments on the granites. Few AEs occurred before breakdown (Fig. 7), which resulted in similar values of P^{AE} and P^{BD} , different from the case of the granites where P^{AE} was 49.6%–93.2% of P^{BD} . For the shale samples, we also conducted experiments where the fluid was injected more slowly (i.e., at 0.5 or 0.2 mL/min) and the lack of AEs before breakdown was commonly observed in all cases, as shown in Fig. 8.

The increase rate of wellbore pressure was nearly constant from $t \sim 400$ s to 0.5 s before peak pressure, when the pressure reached P^{leak} of 18.72 MPa, i.e., nearly equal to the breakdown pressure (99.9% of P^{BD}). In addition, the peak AE rate of 10–20 events/s and the number of well-located AEs of 924 were significantly smaller than found in the granite experiments. These tendencies (i.e., greater P^{BD} , P^{leak} , P^{AE} , and P^{drop} and the smaller number of AE events compared with the granites) were commonly observed in all the experiments using Inai shale.

5. Fracture Observations using the Fluorescent Method

After fracturing, we observed regions of resin penetration under UV light irradiation (Section 2.3) for 10 samples (KJG07, 09–11, INS03, 06, 07–10) out of the 15 listed in Table 2. Figures 9–14 show corresponding photographs (in which the AE hypocenters relocated by the double-difference method are overlaid) for KJG07, KJG09, KJG10, INS03, INS08, and INS10. As described in Section 2.3, the photographs were taken for five sections parallel to the y – z plane. The bright and bluish-white parts correspond to areas of resin penetration. The principal region of resin penetration extended along the z -direction for all samples, as expected based on theory, although the region was inclined for some

samples. The locations of the AE hypocenters were approximately consistent with the regions of resin penetration.

Significant differences were observed between the granite and shale samples. For the shale samples, a pair of wing-like main cracks, identifiable as thin luminous areas, the brightness of which contrasts considerably with the surrounding region, are evident in Figs. 12–14. Conversely, for the granite samples, a wider bright part (10–30 mm in width) is clearly observable in Figs. 9–11. This makes it difficult to identify the main path of the fluid corresponding to the main fracture, although thinner luminous parts likely representative of the main path can be identified in some granite samples (e.g., KJG10; Fig. 11).

6. Discussion

6.1 Implication for Fracture Evaluation by In-situ Microseismic Observations

Based on the results presented in Section 5, the following inferences regarding the relationships among the region influenced by fracturing fluid, fractures induced by hydraulic fracturing, and induced microseismic events in production fields can be proposed.

1) For the samples of Inai shale, we recognize the very thin (width < 1 mm) resin penetration regions correspond to the main crack induced by fracturing, but we obtained a wide distribution of AEs even for the DD results, probably the result of location errors (Figs. 12–14). Thus, the area of fractures induced by fracking could be overestimated if based only on microseismic observations without proper consideration of location errors.

2) For the samples of Kurokami-jima granite, the resin penetration region was significantly wider than the region in which the AEs occurred, as shown in Figs. 9–11. The hypocenter distribution obtained was always broader than the actual hypocenter distribution because any located hypocenters were accompanied by location errors. We therefore conclude that there exist aseismic regions where fluid penetrated into pores or preexisting/newly generated cracks without the corresponding seismic events. Thus, the extent of the region of fluid penetration could be underestimated if based only on the distribution of microseismic events.

3) We found resin penetration regions extended in both wings for all cases, indicating that

fractures propagated either side of the wellbore. However, in some cases, the AE hypocenters were concentrated only on one side (Figs. 10–12). Thus, based on microseismic observations only, it could be possible to believe mistakenly that fractures propagate on one side only, even if the actual fractures were generated on both sides.

4) There were cases in which the number of detected AEs differed considerably despite similar degrees of fracture creation indicated by the fluorescent method (e.g., Figs. 13 and 14). As stated in Section 1, to estimate the volume in which fractures are induced, engineers often calculate the SRV based on the spatial distribution of microseismic events and/or their density. Our results suggest that an accurate estimation of induced fractures from microseismic observations only is very difficult because of the unknown variations of AE activities.

6.2 Difference between Kurokami-jima Granite and Inai Shale

As described in Section 4, P^{AE} was 49.6%–93.2% of P^{BD} and P^{leak} was 87.2%–97.4% of P^{BD} for the granite samples, whereas P^{AE} and P^{leak} were nearly the same as P^{BD} for the shale samples. The small differences in the magnitudes of P^{BD} , P^{AE} , and P^{leak} for the shales indicate that significant fluid penetration into the rock did not occur until immediately before breakdown. The greater differences of P^{AE} and P^{leak} from P^{BD} for the granite samples were likely caused by higher permeability (Table 1), and likely consistent with the significantly wider regions of resin penetration (Section 5). In addition, the smaller P^{BD} for the granites is consistent with many previous studies that have found larger fluid penetration (i.e., using low-viscosity fracturing fluid or a low pressurization rate) resulted in lower breakdown pressure.^{20,26–29}

The sizes of the grains that constitute the rocks might also influence fracturing patterns. The average grain size of Inai shale (~0.04 mm) is much smaller than Kurokami-jima granite (~2 mm) (Fig. 15). The small grain size of Inai shale could possibly be the reason for the small number of AE events, especially before breakdown. The dependency of rupture progress on grain size has been studied in detail in laboratory experiments on fracturing of intact rock samples under triaxial compression. In such fracturing experiments, the two-dimensional aggregation of AEs on the plane of the future through-going rupture is often observed prior to macroscopic rupture.^{30–34} Such AE activities prior to

the through-going rupture are lower for rock samples with smaller grain sizes, indicating the main rupture occurs without a significant preparation process.³⁴ Such dependency on grain size is consistent with our results, observed in the lack of AEs prior to breakdown for the shale samples.

Differences in mineralogy also likely affected the results for Inai shale and caused fewer AEs. The clay minerals in shale could possibly have prevented the accumulation of the elastic energy necessary to generate seismic events. Those clays could also have caused inelastic decay of the seismic waves, which would also have prevented the detection of AEs, resulting in the small number reported.

7. Conclusions

In the present study, we conducted hydraulic fracturing experiments in the laboratory on Kurokami-jima granite and Inai shale with AE monitoring. We used a fluorescent resin as the fracturing fluid, and we observed resin penetration regions, including the induced fractures, on five cross-sectional planes cut orthogonally to the fracturing hole after fracturing. We obtained the following conclusions based on these experiments.

1) AE activities and pressure histories depended on *P*-wave anisotropy for the granite samples. This dependency was likely caused by the anisotropy of the tensile strength of granite, the relation of which to *P*-wave anisotropy has been reported in many previous studies.

2) The number of detected AEs was significantly smaller for the shale samples than for the granite samples. For the granite samples, AE activity and the deviation from a linearly increasing trend of wellbore pressure initiated significantly earlier than breakdown. For the shale samples, both changes occurred at almost the same time as breakdown. The fluorescent method revealed a large fluid penetration region for the granites, where the main fluid path was indistinguishable, whereas thin fluid paths were evident in the shales. These differences were likely caused by differences in permeability, grain size, and/or mineralogy of the rock samples.

3) The results obtained for the granite samples strongly indicate the existence of an aseismic zone where fluid penetrated but seismic signals were not radiated. Although such regions may be accompanied by the crack openings or shear slips that contribute to resource production, they cannot

be revealed by microseismic observation.

4) For some of the granite and shale samples, AE activity was concentrated on one side only despite resin penetration regions extending substantially on both sides of the wellbore. In addition, the number of detected AEs differed considerably when the experimental conditions including rock type and flow rate were the same and similar patterns of induced fractures were observed using the fluorescent method. In other words, a small number of AEs does not always correspond to a lack of induced fractures, at least in our experiments. This may highlight the difficulty of estimating induced fractures in production fields based only on microseismic observations.

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463

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 ^{1), 2)}	0.84 ³⁾	9×10 ^{-19, 3)}
Inai shale	10.87±5.27 ²⁾	0.6	< 5×10 ^{-20, 4)}

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¹⁾ Results of the Brazilian test for tensile strength along rift planes by Ishida et al.³⁵ ²⁾ The error was represented

465

by standard deviations. ³⁾ Ishida et al.³⁶ ⁴⁾ Smaller than the measurement limit (5×10^{-20} m²) of CMS-300, a

466

product of Core Laboratories.

467

Table 2. Sample information in the present study

Sample		V_x	V_y	V_z	Pumping rate	Well-located	P^{BD}	P^{AE}	P^{leak}	P^{drop}
Type										
No.		[km/s]	[km/s]	[km/s]	[cc/min]	AEs ¹⁾	[MPa]	[MPa]	[MPa]	[MPa]
KJG05	V	5.80	5.34	5.57	2.0	5329	11.77	5.84	10.26	3.22
KJG06	H	5.09	5.09	4.40	2.0	9437	15.50	13.33	14.28	15.02
KJG07	V	5.08	4.55	5.00	2.0	5290	10.39	9.58	9.77	3.43
KJG08	H	5.67	5.47	5.11	2.0	9806	15.43	14.38	15.03	5.83
KJG09	H	5.52	5.54	5.08	2.0	5288	15.00	13.12	14.60	5.03
KJG10	V	5.50	5.18	5.54	2.0	2803	12.20	10.67	11.74	3.92
KJG11	H	5.67	5.64	5.03	2.0	5843	12.90	10.87	11.83	8.77
INS03	H	6.20	5.91	6.01	2.0	924	18.74	—	18.72	18.30
INS04	H	6.10	5.64	5.72	2.0	260	18.64	—	18.62	18.50
INS06	H	6.08	5.67	5.82	0.2	5008	11.79	—	11.68	3.82
INS07	H	6.22	5.69	5.83	0.5	209	12.62	—	12.00	12.25
INS08	V	6.17	5.82	5.61	0.2	501	18.04	—	—	1.74
INS10	V	6.08	5.77	5.61	0.2	1502	18.54	—	18.53	3.40

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¹⁾ Events in which the maximum standard error was smaller than 40 mm and the number of arrival times

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remaining after the final iteration of the event location procedure (Section 3.2) was eight or more.

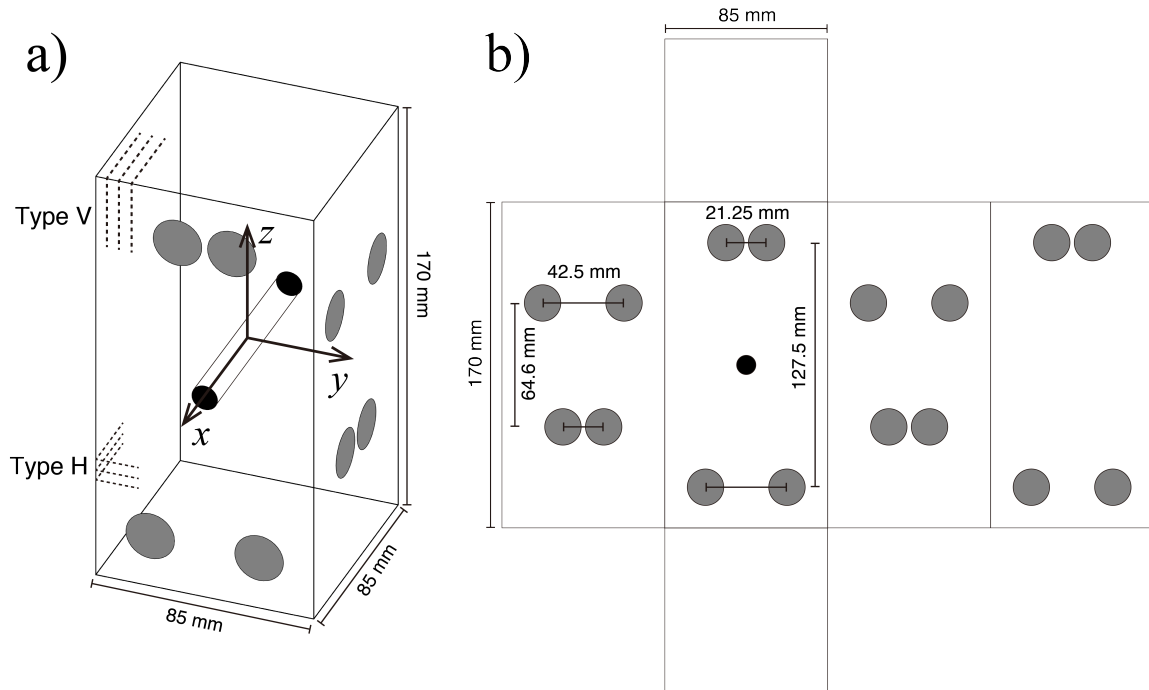


Figure 1. a) Sample size, AE sensor position, and the coordinate system used in the present study. The origin of the coordinate system corresponds to the center of the specimen. Black circle represents a wellbore. A packer was inserted along the x -axis from the positive side. Gray circles represent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

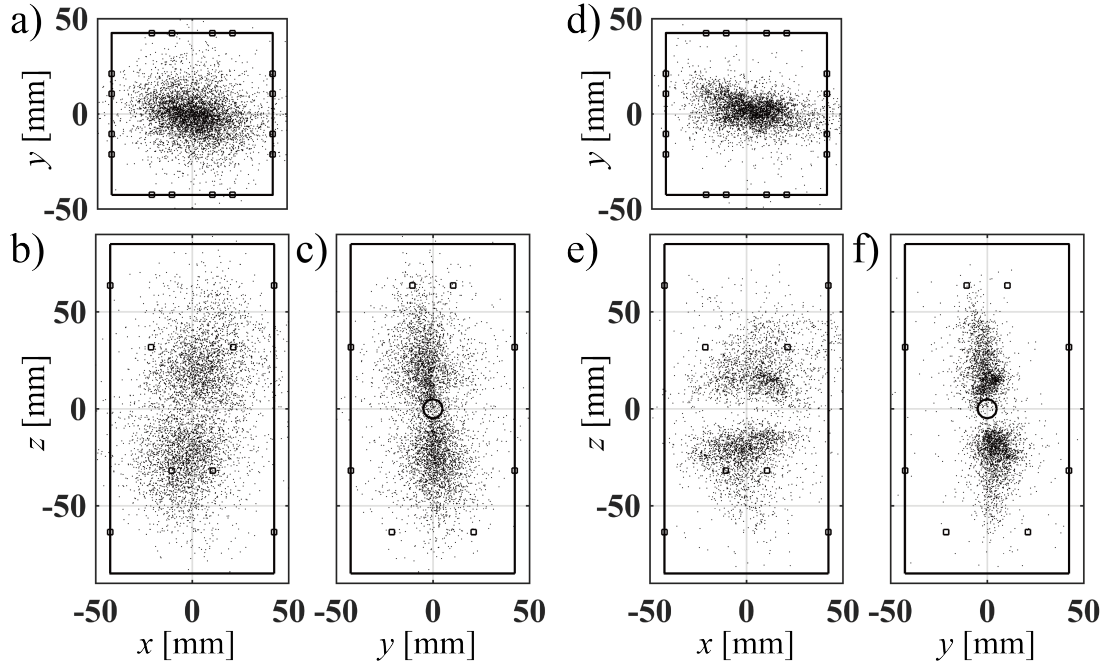


Figure 2. AE hypocenter distribution for KJG07. a)–c) Location results based on the method described in Section 3.2. d)–f) Relocation results obtained by the double-difference algorithm. a) and d) Projection to x – y plane. b) and e) x – z plane. c) and f) y – z plane.

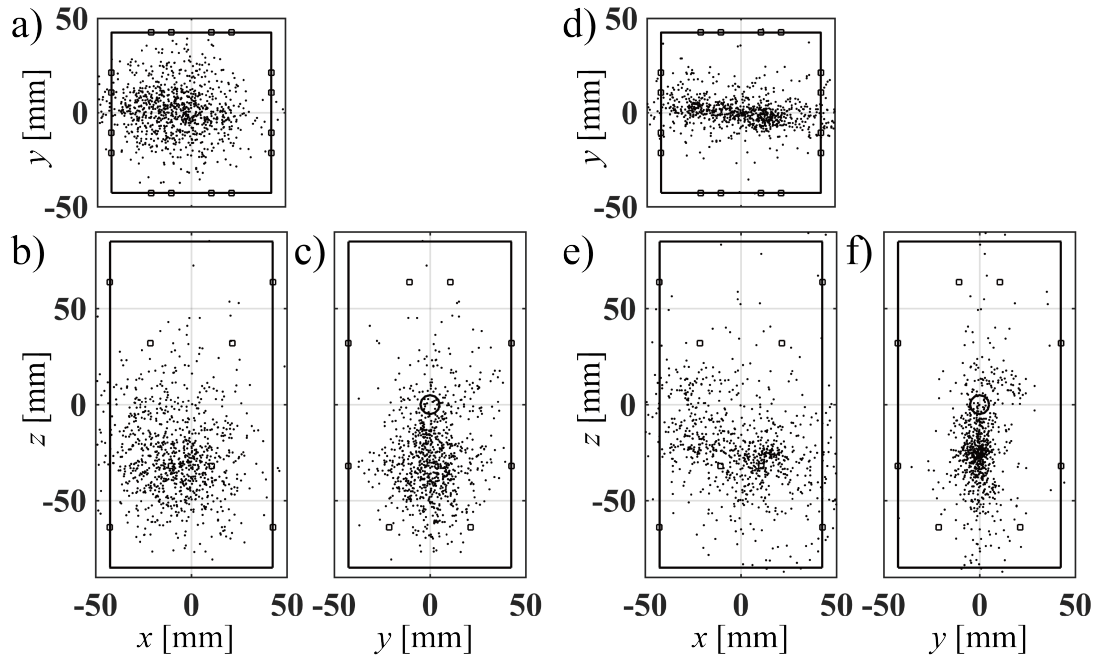


Figure 3. AE hypocenter distribution for INS03. a)–c) Location results based on the method described in Section 3.2. d)–f) Relocation results obtained by the double-difference algorithm. a) and d) Projection to x – y plane. b) and e) x – z plane. c) and f) y – z plane.

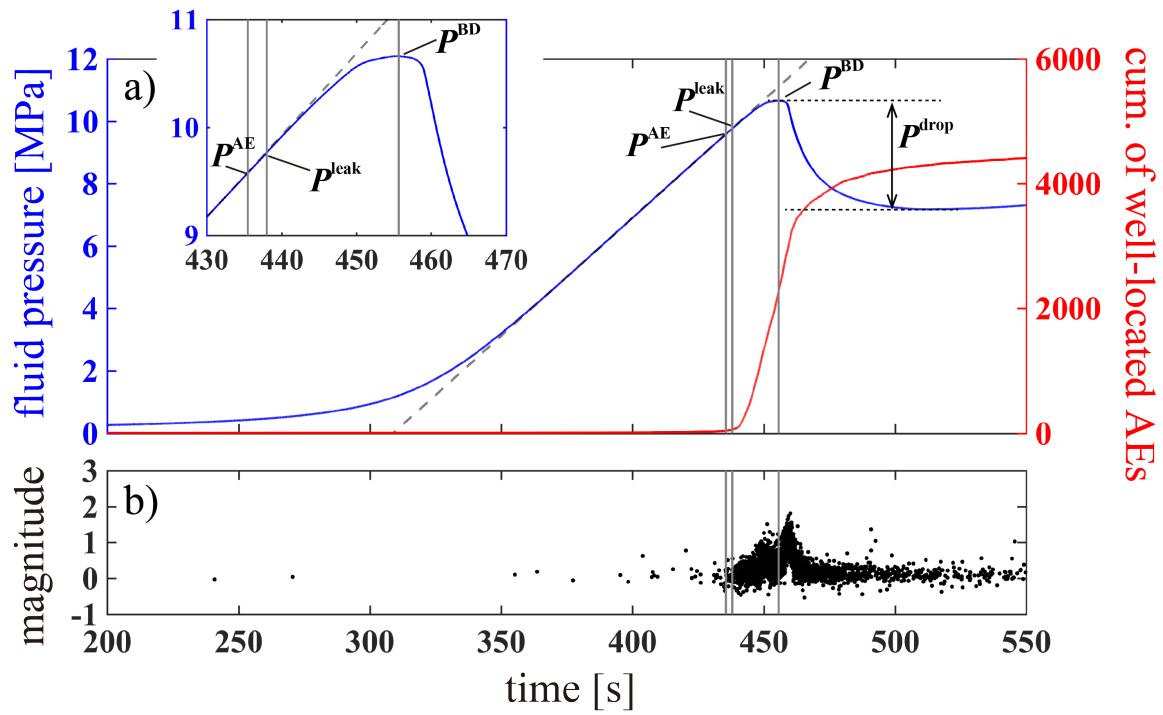
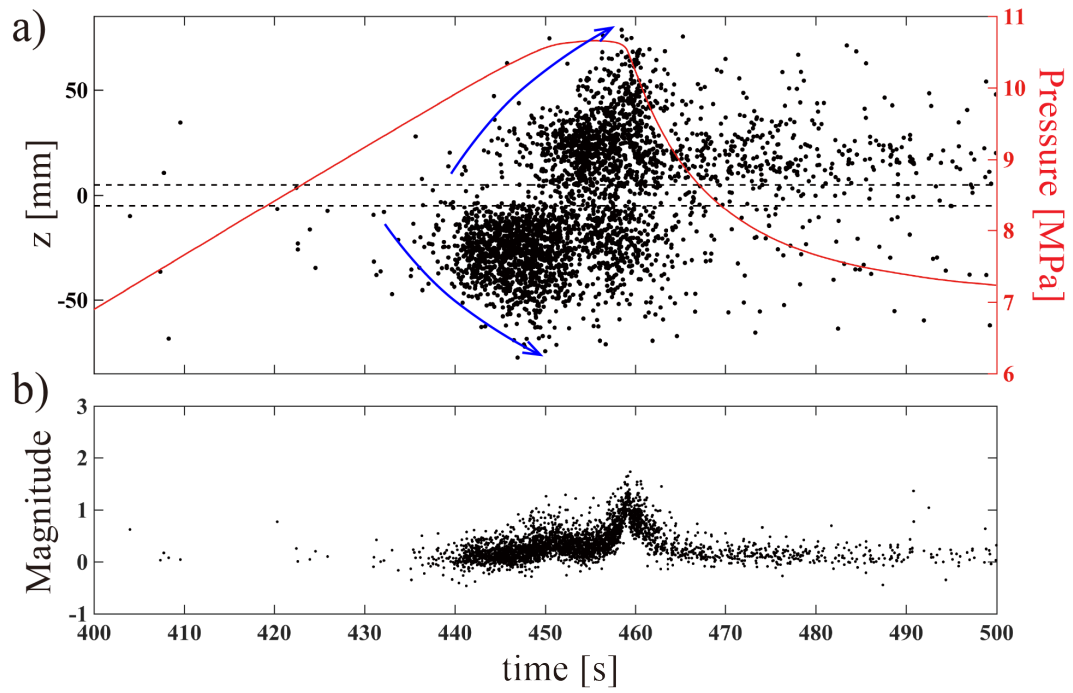


Figure 4. a) Wellbore pressure history (blue line) and the cumulative number of well-located AEs as a function of time (red line) for the experiment of KJG07. Black dashed line represents the approximation line of the part of the linear increase of pressure. Inset) Pressure history around breakdown. b) Magnitude–time diagram.



489

490 Figure 5. AE activity around the breakdown for KJG07 (DD results). a) z coordinates of the AEs

491 plotted against time in a 100-s interval around breakdown. Dashed line represents the position of the

492 wellbore. Red line shows wellbore pressure. b) Magnitude–time diagram.

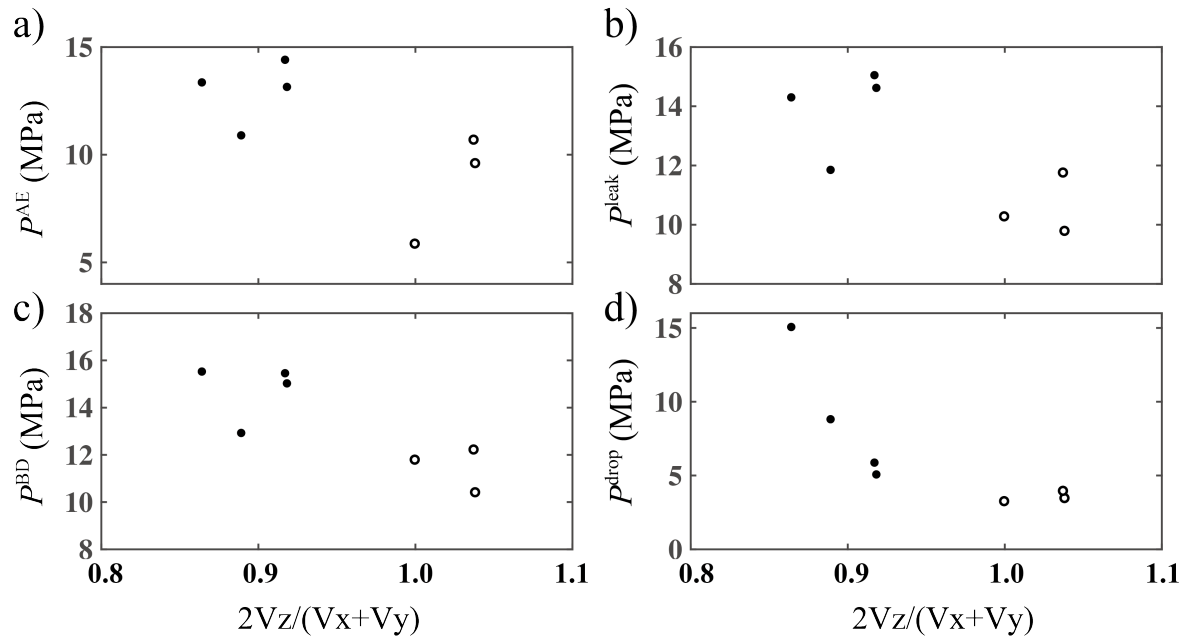


Figure 6. Relation between wellbore-pressure parameters and P -wave anisotropy of the granite samples. Each pressure parameter is plotted against the ratio between V_z and the average of V_x and V_y . Black circles show the results for Type H samples. White circles show the results for Type V samples. a) P^{AE} , b) P^{leak} , c) P^{BD} , and d) P^{drop} .

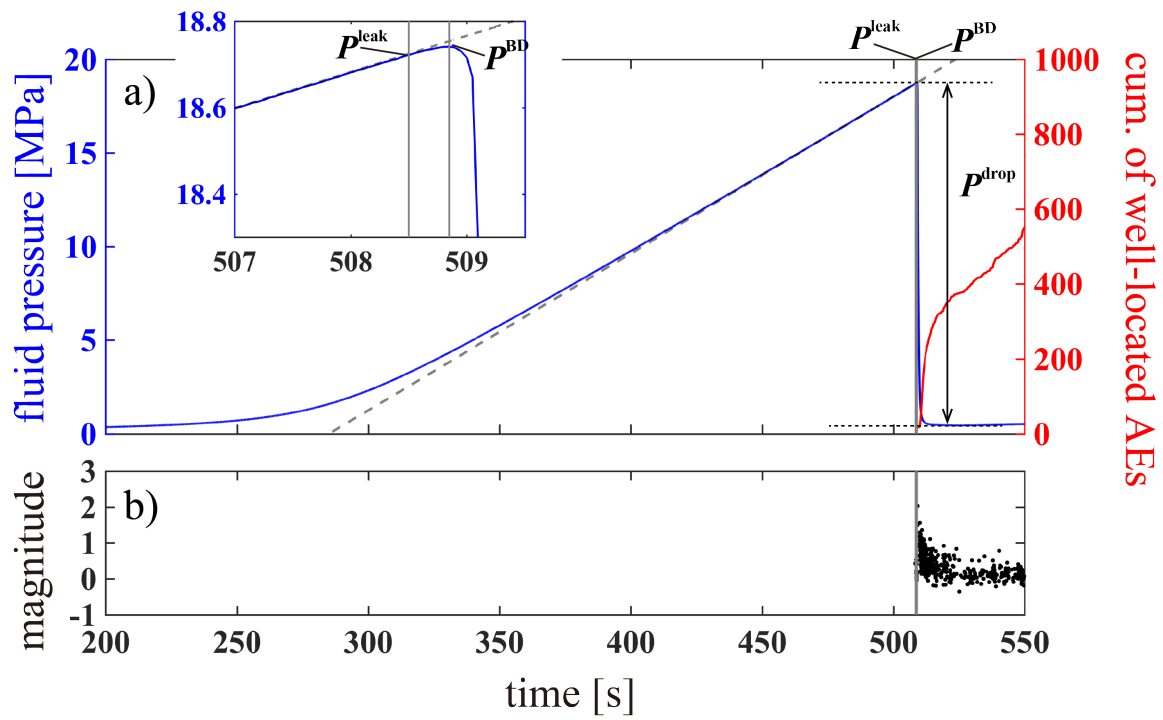


Figure 7. a) Wellbore pressure history of the INS03 experiment and cumulative number of the well-located AEs. b) Magnitude–time diagram.

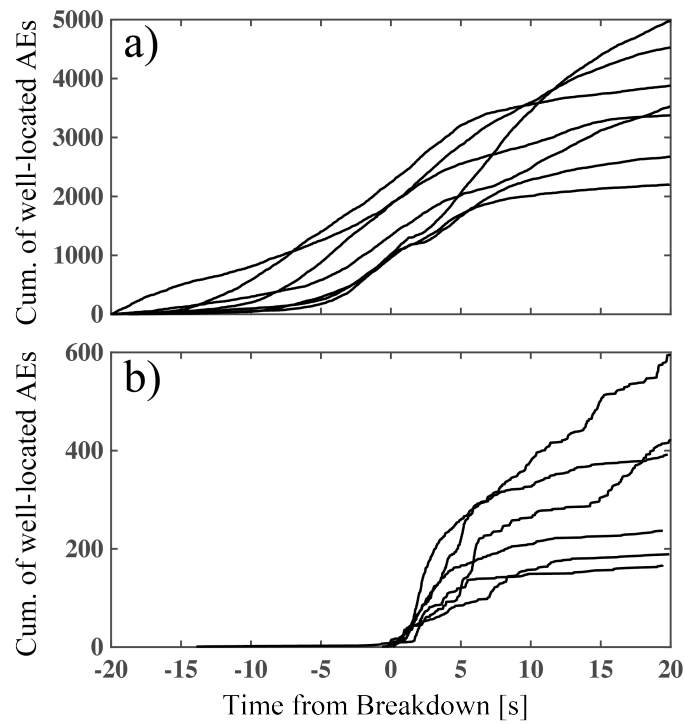


Figure 8. Cumulative number of well-located AEs in a 40-s window around peak pressure. a) Results for the granite samples. b) Results for the shale samples.

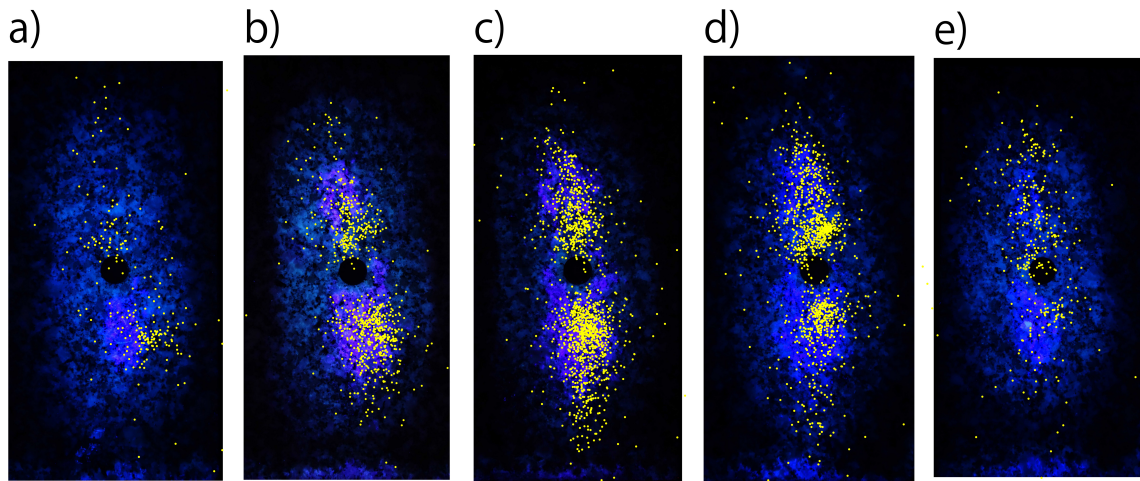


Figure 9. Resin penetration areas revealed by the fluorescent method on y - z planes for KJG07. a) Cross section at $x = -28.3$ mm, b) $x = -14.2$ mm, c) $x = 0.0$ mm, d) $x = +14.2$ mm, and e) $x = +28.3$ mm. AE hypocenters (DD results) located within 7 mm from each plane are projected onto each figure.

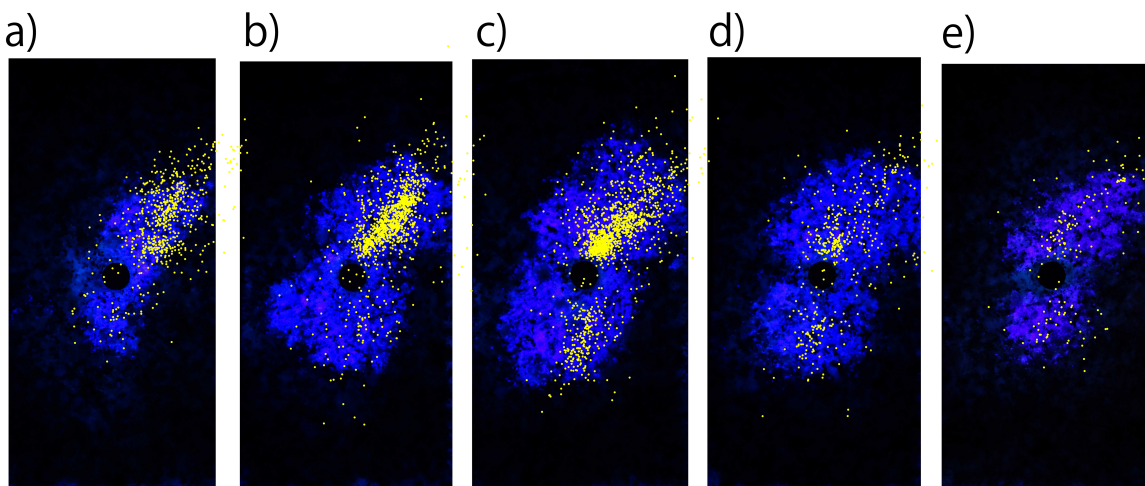


Figure 10. Resin penetration areas revealed by the fluorescent method (y - z plane) for KJG09.

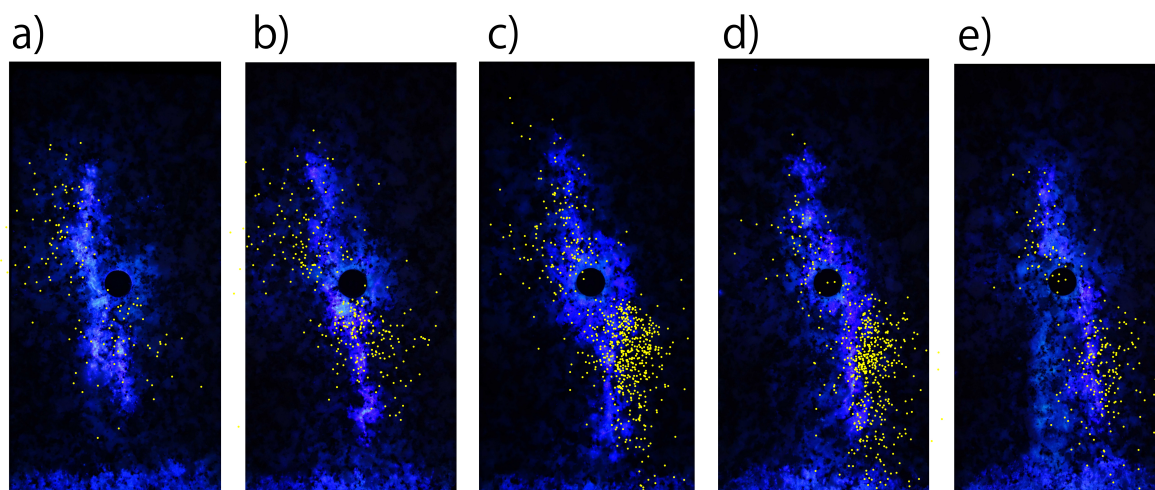


Figure 11. Resin penetration areas revealed by the fluorescent method (y - z plane) for KJG10.

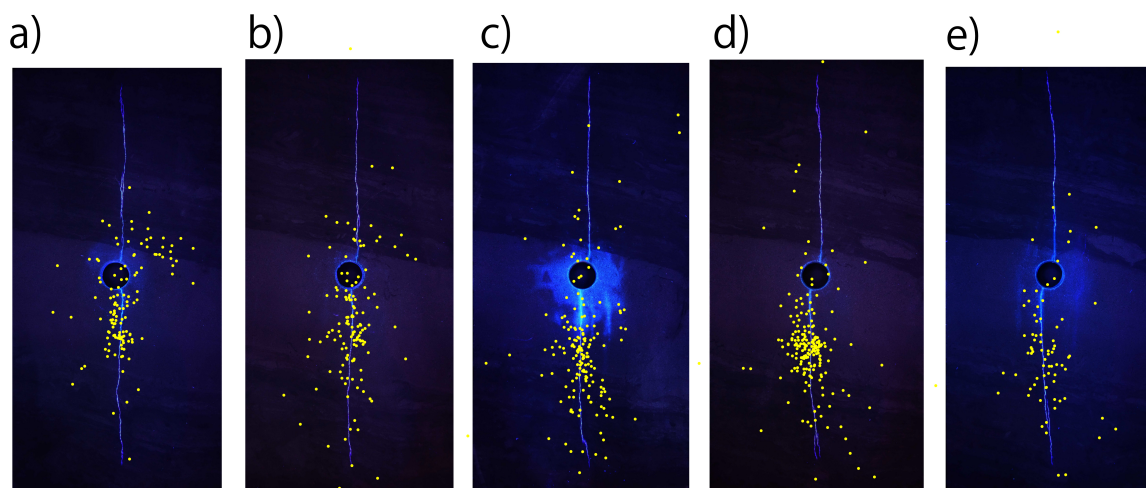


Figure 12. Resin penetration areas revealed by the fluorescent method (y - z plane) for INS03.

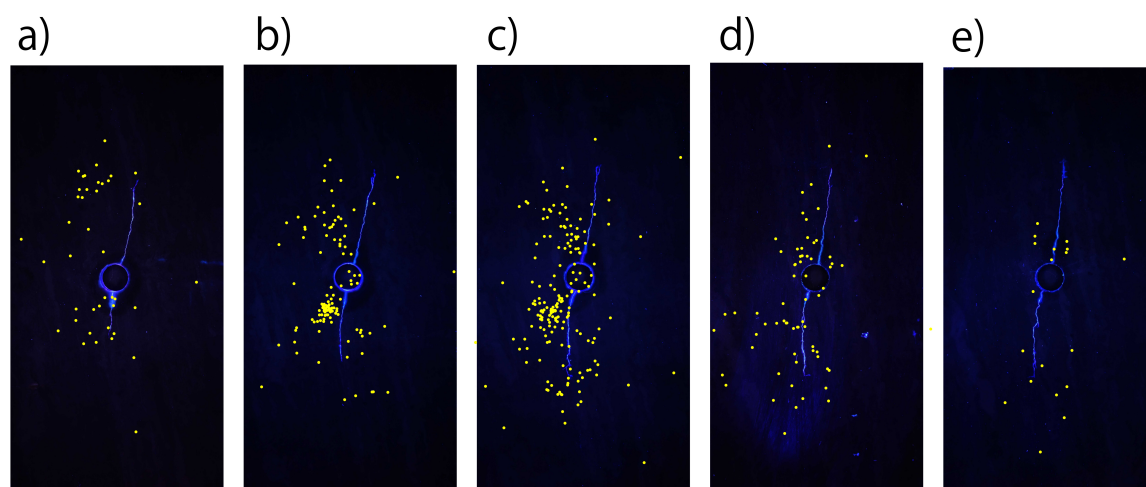
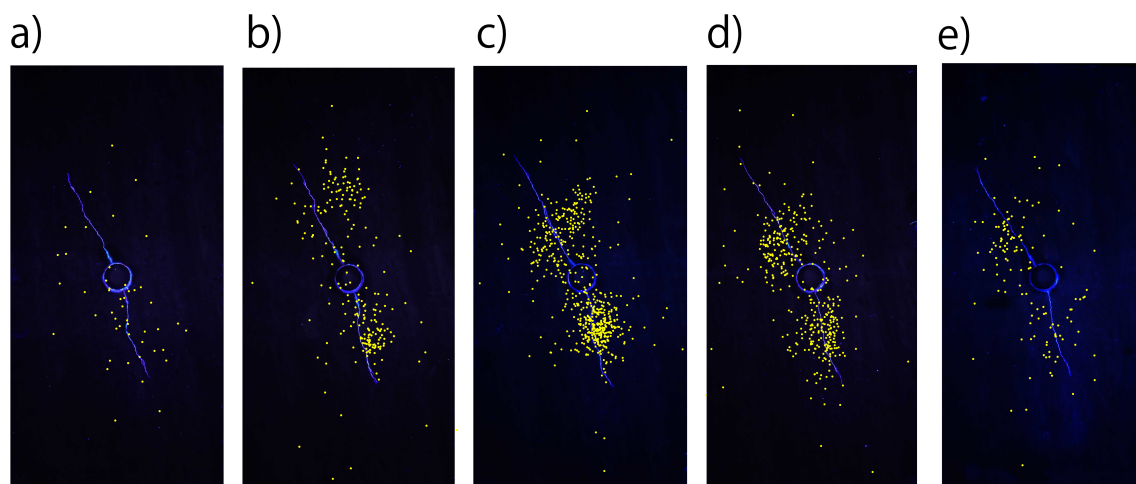


Figure 13. Resin penetration areas revealed by the fluorescent method (y - z plane) for INS08



518

519 Figure 14. Resin penetration areas revealed by the fluorescent method (y - z plane) for INS10.

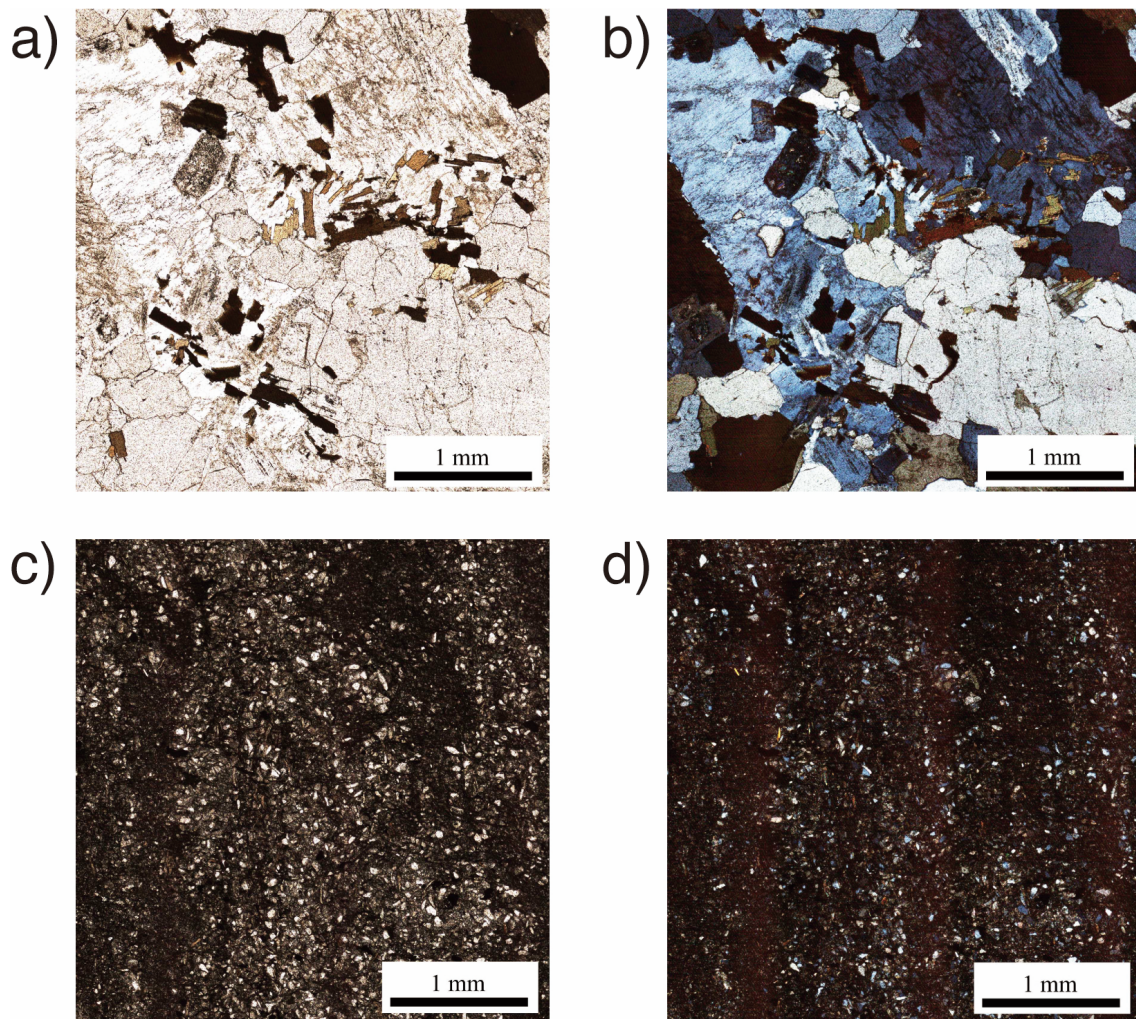


Figure 15. Photographs of polarization microscope for Kurokami-jima granite and Inai shale. a) Kurokami-jima granite (single nicol), b) Kurokami-jima granite (crossed nicols), c) Inai shale (single nicol), and d) Inai shale (crossed nicols).