Direct and Microseismic Observations of Hydraulic Fracturing in Barre Granite and Opalinus Clayshale

Bing Q. Li1,2 and Herbert H. Einstein1

1Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA, 2Now at Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

Abstract  While hydraulic fracturing is a well-established and widely implemented process, there are still some aspects that can be better understood. Specifically, researchers do not fully understand the relation between the hydraulic fracture network and the microseismic events induced during hydraulic stimulation. In this laboratory study, we address this knowledge gap by conducting hydraulic fracturing experiments where we directly observe microstructural changes using a high-speed camera attached to a 5X magnification lens and analyze the images using a digital image correlation code. These data are compared to simultaneously acquired acoustic emissions, from which we infer the location and focal mechanisms of induced microseismic events. Experiments were conducted on Opalinus clayshale and Barre granite, at injection rates of 0.019 and 0.39 ml/s for each rock. The simultaneous recording of microseismic and visual observations is unique and provides significant insight into the details of hydraulic fracturing. Our results show several interesting differences between granite and shale, and between injection rates. For example, we find that while the creation of hydraulic fractures is generally considered as tensile at the field scale, evidence of shearing can be observed to varying degrees at the microstructural scale. Specifically, we see that microstructural shearing is more evident in granite in the form of distinct en echelon microcracks. On the effect of the injection rate, we find that a reduced injection rate tends to create a more complex network of microcracks, along with a lower proportion of double-couple (shear) focal mechanisms in the microseismic data.

1. Introduction

Hydraulic fracturing is a frequently occurring natural process, and in the recent decades has also been employed by the petroleum industry and for enhanced geothermal systems (Norris et al., 2016). However, the physics behind hydraulic fracturing are not entirely understood and merit further study. Researchers have approached fracturing and hydraulic fracturing of rock and rock-like materials from multiple directions. At the laboratory scale, many studies have focused on the effect of injection rate. For example, Schmitt and Zoback (1992) and Schmitt and Zoback (1993) found, through internally pressurized hollow cylinders tests, that the tensile strength and deformation modulus of Westerly granite increases with the pressurisation rate. Other researchers, such as Bunger et al. (2005) and Lecampion et al. (2017), have conducted experiments and proposed models describing the relationships between fluid effects (e.g., viscosity, injection rate, and leakoff) and mechanical properties (e.g., fracture toughness, elastic moduli, and Poisson's ratio) in the context of hydraulic fractures. Other experimental studies have focused on acoustic emissions (AEs), which are elastic waves emanating from a rapid release of strain energy, and have been shown to correspond to the creation of microcracks (Li & Einstein, 2017; Nasseri et al., 2006). Yoshimitsu et al. (2014) have shown that these AEs, whose magnitudes are on the order of $M_w = -5$ to $-8.5$, are similar physical processes to the microseismic events ($M_w$ around 0) observed during field hydraulic fracture operations, and to large-scale earthquakes. As a result, researchers regard AEs as analogues to seismic and microseismic events seen in the field, and traditional seismic data processing workflows are applied to AEs. These studies (e.g., Li et al., 2019; Lockner et al., 1991; Moradian et al., 2016; Stanchits et al., 2011; Stoeckhert et al., 2015) have resulted in a wealth of information on the relationship between fracture processes and seismicity. However, AEs are an indirect source of information on the creation of fractures and hydraulic fractures, and in fact generally constitute less than 1% of the energy released from the fracture process (Goodfellow et al.,...
Consequently, it is important to directly observe fracture processes, in order to study their growth and geometries. Direct visual observation of fracture mechanisms have been performed in many earlier experiments by collaborators of the current author (Gonçalves da Silva & Einstein, 2018; Morgan et al., 2017; Wong & Einstein, 2009a) and others (Naoto et al., 2018; Nasseri et al., 2006). There have also been studies on rock fracture at a microstructural level (Tal et al., 2016), which have been compared to AEs (Li & Einstein, 2017), but not in the context of hydraulic fractures. Real-time visual monitoring of hydraulic fracturing is so far limited to fewer experiments because of the difficulty of applying hydraulic pressure while simultaneously visually observing the process (Miller, 2008). The combination of visual (direct) and AE (indirect) observations described in this paper is quite unique and makes it possible to better understand the hydraulic fracturing process.

In this study, we hydraulically fracture granite and shale specimens at two injection rates each and compare the captured AEs to micro–digital image correlation captured with a high-speed camera. These two rocks are chosen as they are analogous to the reservoir rocks used in the petroleum industry and enhanced geothermal systems. Different pressurization devices are used for the granite and shale as we were not able to design a single device capable of generally inducing hydraulic fractures in both materials. Specifically, the bolting forces applied to the granite pressure enclosure are too high for the shale, and the pressure-volume actuator in the shale pressurisation system does not reach sufficient pressure to induce hydraulic fractures in the granite. However, other experimental considerations such as load frame, fluid injection apparatus, imaging setup, and AE acquisition are kept the same in order to obtain test results that are comparable between materials.

2. Methodology

2.1. Rock Description and Physical Setup

The Barre granite was obtained from Vermont, and a previous study by the Vermont Geological Survey (Murthy, 1957) revealed that the mineralogy consists primarily of quartz, potash feldspar, plagioclase, biotite, and muscovite. The grain sizes generally fall within 2–4 mm. As shown in Figure 1, granite specimens were cut to dimensions $152 \times 76 \times 25$ mm, and a single vertical notch of length $12.7$ mm was cut with a water-jet. The Opalinus clayshale is obtained from the Mont Terri Underground Research Laboratory in the Jura Mountains in Switzerland, at a depth of $200$ m below the present surface. The mineralogy was analyzed by James Hutton Limited using X-ray diffraction, who reported $47\%$ quartz, $13.5\%$ calcite, $9.7\%$ kaolinite, and $16.2\%$ illite and illite/smectite. Shale specimens were cut to $102 \times 51 \times 25$ mm, and a single vertical notch of length $8.5$ mm was created by first drilling with a diamond bit, then cutting to the desired length with a steel blade. Note that given the small diameter of the available shale cores, the bedding plane orientation shown in Figure 1 is the only possible configuration. For each specimen, we intentionally create asymmetric notch tips by piercing the rock at the bottom, and cutting directly to the other end. In both materials, the pierced hole has a diameter of approximately $1$ mm. This creates a stress condition where the crack is more likely to initiate from the sharper (cut) edge. We then speckle at this sharper edge to consistently image the notch tip at which crack initiation occurs.

In all tests, the specimens were initially loaded to $3.5$ MPa in the axial direction, and then this load was maintained while hydraulic oil (viscosity $\mu = 3.89$ cP) is injected at a constant rate (see Morgan et al., 2017, for details). For each material, two tests were conducted: one at a nominal injection rate of $0.39$ ml/s and the other at a rate of $0.019$ ml/s. The setup can be seen in Figure 1.

Note that the thickness dimension of the specimens is relatively small compared to the width and height dimensions, and so we approximate a 2-D condition where the fracture patterns are consistent throughout the thickness dimension. Experimental investigations by Morgan and Einstein (2017) have shown that this is a reasonable assumption.

2.2. Imaging Setup

The experiments were imaged with a Phantom v2511 high-speed camera operating at $4,000$ fps for the $0.39$-ml/s tests, and $600$ fps for the $0.019$-ml/s tests. The camera was coupled to a Laowa $25$ mm f/2.8 2.5–5X Ultra Macro lens at 5X, giving a field of view of approximately $7.2 \times 4.5$ mm ($800 \times 1,280$ pixels). The lens was directed toward the area at the tip of the precut notch, which was speckled by first painting a solid black base layer using Krylon Colormaster paint + primer, and then applying white speckles using Krylon Colormaster paint + primer held approximately $50$ cm from the rock surface. The white spray paint was applied
Figure 1. Schematic of test setup for (a) Barre granite and (b) Opalinus clayshale. Black solid lines denote specimen boundaries, red indicates acoustic emission sensors, green denotes steel loading platens, blue indicates area to which fluid pressure is applied, and purple indicates area that is in contact with a rubber seal, which applies 2 MPa of stress. Dotted lines in the shale denote bedding plane orientation. Both specimens are 25.4 mm in thickness, and the fluid pressure is applied to the inside of the notch, which is cut throughout the thickness of the specimen. The boundary conditions are the same on the reverse side. Specific details of the pressure enclosure used to apply the fluid pressure can be found in studies by Gonçalves da Silva and Einstein (2018) and Morgan et al. (2017).

Image analysis was conducted using digital image correlation, which is a class of methods to extract displacement fields from a series of images. This is calculated by comparing the location of a unique pixel pattern across images. The Ncorr code (Blaber et al., 2015) is used in the majority of this work. The code performs correlation, based on subset deformation, where for each subset in the reference image a best fit subset is found in the current image. The difference, in the x and y directions between the current and reference subsets are considered to be the \( u \) and \( v \) displacements, that is, displacements in the x and y directions, respectively. Given that an image is divided into a large number of subsets, a displacement field can then be

Figure 2. Image of shale specimen with speckling. Inset shows high-speed video frame of speckled region.
Figure 3. Images of the bare rock used in each test, at 5X magnification.

generated for each current image. This is illustrated schematically in Figure 4, where we see that a subset (the red circle) is considered in the reference image, and the subset radius where the pattern most resembles that seen in the reference image is found in the current image. The difference in the position of the center of this subset is the displacement. This is calculated for each pixel (one can also calculate at each n-th pixel by applying a subset spacing) to generate a displacement map. The reference image is compared to each current image independently, to generate a series of displacement maps.

The displacements can then be transformed into strain fields $\varepsilon_{xx}$, $\varepsilon_{xy}$, and $\varepsilon_{yy}$ as specified in equation (1), and these strain fields can be used to better understand the process zones and cracks created during loading.

Figure 4. Illustration of process to calculate displacement map.
In this study, we use a subset radius of 15 pixels for displacement, and radius of 2 pixels for strain. The code has been shown to work well for geotechnical materials (Li & Einstein, 2017; Stanier et al., 2015; Zhang et al., 2016), and a similar approach has been used successfully on the microscale in marble (Tal et al., 2016).

2.3. Acoustic Emissions Setup

Each test was instrumented with eight Micro30S sensors from Physical Acoustic Corporation, sampled at 5 MHz using four PCI-2 data acquisition cards. The sensors were coupled with honey to the specimen, and sensors in the load path were emplaced within an inset in the loading platens. Sensor locations are shown in Figure 1. The 20 and 60 dB of preamplification were used in the granite and shale tests, respectively. The sensors exhibit a frequency range of 125 to 400 kHz, with a resonant frequency of 225 kHz. Locations are calculated in granite using a $P$ wave velocity of 4,500 m/s and error tolerance of 5 mm, and in Opalinus clayshale using an elliptical velocity distribution, with a $P$ wave velocity of 3,500 m/s along the bedding plane, and 2,000 m/s across bedding planes, to an error tolerance of 10 mm. In our algorithm, the location error is defined, per channel, as the $P$ wave velocity multiplied by the difference between the observed arrival time and the predicted travel time between the inverted source location and the sensor. The location error must be less than the error tolerance on all detected channels, and be detected by a minimum of four channels to be considered an event. The $P$ wave velocities were measured under experimental conditions.

More details of the AE setup can be found in (Li et al., 2019).

3. Results

3.1. General Observations

The results are first presented in terms of pressure and AE amplitude over time, as seen in Figure 5. First, we note that within the same material, a higher injection rate results in a higher maximum pressure. We also note that, in general, maximum pressure was lower in Opalinus clayshale than in granite. This difference in maximum pressure is most likely related to the difference in tensile strength between the two materials, where Opalinus clayshale is reported to have a tensile strength of 1 to 2 MPa (Bossart & Thury, 2008), and

$$
\varepsilon_{xx} = \frac{1}{2} \left( \frac{\partial u}{\partial x} + \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2
$$

$$
\varepsilon_{yy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial y} + \frac{\partial u}{\partial y} \frac{\partial v}{\partial y} + \frac{\partial v}{\partial y} \frac{\partial v}{\partial y} \right)
$$

$$
\varepsilon_{xy} = \frac{1}{2} \left( \frac{\partial v}{\partial y} + \frac{\partial u}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2
$$

(1)
the tensile strength of Barre granite is reported between 10 to 15 MPa (Dai & Xia, 2010). In three of the four tests, we also note that peak AE rate corresponds to the maximum pressure, which suggests that the creation of the hydraulic fractures is most closely related to release of significant seismic energy. The exception, when only considering Figure 5, is the 0.39-ml/s Opalinus test, where peak AE rate occurs at approximately 7 MPa, while the maximum pressure during the test was 10 MPa. As will be seen in subsequent sections, this is likely due to cracks taking time to propagate to the seal boundaries, at which time the pressure drops. In order to compare results between tests, we denote a normalized time \( t_{\text{norm}} \) for each test, where \( t_{\text{norm}} = 0 \) is the start of injection, and \( t_{\text{norm}} = 1 \) is the time of highest AE rate.

### 3.2. Strain and Displacement Maps

Here, we present and describe the strain and displacement maps for each test over time, to gain a better understanding of the development of microcracks seen at the 100–500-\( \mu \)m scale. These microcracks are defined as a region of relatively high localized and linearized strain, seen either in the \( \varepsilon_1 \) or \( \gamma_{\text{max}} \) contours, such as the newly developed microcrack shown in the blue ellipse in Figure 6a. We presume that these microcracks initially follow a cohesive model behavior (Broek, 1985; Li & Einstein, 2017), where the two faces of the microcrack are not entirely debonded until significant opening displacement occurs. We consider
Figure 7. Maximum ($\varepsilon$) and shear strain ($\gamma_{\text{max}}$) contours shown in the (a–f) top and bottom rows, respectively, presented at various stages during granite 0.019-ml/s test. Arrows overlying the contour plots show displacement field, with rigid body translation subtracted such that the mean displacement of the entire area is 0. Displacement field is the same for top and bottom rows. Red circles indicate locations of fracture branching.

We also note that the fracture development appears to be more continuous in the 0.39-ml/s test, as the final microcrack patterns consists of a well connected series of three microcracks, whereas in the 0.019-ml/s test the network appears to be somewhat more complex. For example, significant strain first shows at a distance from the notch tip (circled in A in Figure 7a), as opposed to right at the notch tip (Figure 6b) as occurred at 0.39 ml/s. Additionally, there is a secondary microcrack branching off (circled as B in Figure 7f) at approximately $x = 2.2$ mm, $y = 0.7$ mm, and a gap between microcracks (circled as C in Figure 7f) at $x = 2.3$ mm, $y = 1.3$ mm. This indicates that there is a higher tendency for microcrack arrest in the lower injection rate test.

The displacement vectors are not particularly telling in the granite tests, as the face of the rock is subject to fluid pressure and thus the vectors are dominated by the Poisson effect generated by this pressure, such that the vectors spread outward from the center of the specimen (Gonçalves da Silva, 2016). In contrast, a seal is
Figure 8. Maximum ($\varepsilon_1$) and shear strain ($\gamma_{\text{max}}$) contours shown in the (a–e) top and bottom rows, respectively, presented at various stages during Opalinus 0.39-ml/s test. Arrows overlying the contour plots show displacement field, with rigid body translation subtracted such that the mean displacement of the entire area is 0. Displacement field is the same for top and bottom rows. Bedding planes are oriented parallel to $y$ axis. Red dashed line indicates wedge of opening displacement whose vertex is at a distance from the notch tip.

directly applied to the face of the rock in the Opalinus setup, and so fluid pressure is only directly applied to the inside of the notch, resulting in displacement vector fields that are more descriptive of the localized deformation resulting from expansion of the notch.

The analogous figures are shown for the Opalinus clayshale tests in Figures 8 and 9. Here the time evolution of the displacement vectors are more interesting. In the 0.39-ml/s test (Figure 8), we can see that initially the vectors are mostly random except beside the notch and that over time a wedge of opening displacement (shown in red dashed lines) emanates from the notch tip, and then moves upward along with the microcrack tip. This somewhat represents plumose fracture patterns, which are indicative of tensile fracture (Figure 10).

The behavior at 0.019 ml/s, shown in Figure 9, is markedly different from the test at 0.39 ml/s (Figure 8). Initially (Figure 9a) at $t_{\text{norm}} = 0.66$, the displacement vectors look similar to the initial state of the 0.39-ml/s test, but by $t_{\text{norm}} = 0.96$ (Figure 9f) we can see that the displacements are largely in the $x$ direction, with the exception that there is a narrow zone of displacement along the eventual microcrack (shown in the red dashed lines labeled A in Figure 9c). In subsequent frames we still see that the displacement vectors ahead...
of the zone of significant strain are much narrower (circled as B in Figure 9d) and do not exhibit the same wedge shape seen in the 0.39-ml/s test. We also see a more complex microcrack network in the 0.019-ml/s test, with multiple bedding planes showing significant strain (circled as C in Figure 9e). Specifically, we see that one bedding plane opened near the notch, but multiple bedding planes open at further distance from the notch (circled as C in Figure 9e). With increasing pressure, one bedding plane dominates, as seen at \( t_{\text{norm}} = 0.99 \).

### 3.3. Statistical Distribution of Strains

Figure 11 shows the histograms of principal strains, based on the entire high-speed video frame such as shown in the inset of Figure 2. Specifically, we consider the strain at each pixel in the window of analysis (such as in Figure 6) and present the distribution of these strains at approximately \( t_{\text{norm}} = 1 \) for each test. We note that the distribution of strains is generally similar between materials and injection rates, in that the \( \epsilon_3 \) values are generally compressive, \( \epsilon_1 \) are generally tensile, and thus the Mohr's circle is almost centered at 0 stress. We may conclude, then, that in a general sense the state of strain at a notch or flaw tip does not differ significantly between materials or injection rate. We also consider \( \epsilon_v = \epsilon_1 + \epsilon_3 \) for each test and plot results for each test as shown in Figure 11 alongside \( \epsilon_1 \) and \( \epsilon_3 \). We can see that the Opalinus tests are closest to showing zero volume change, while the granite hydraulic fracturing (HF) tests show slightly positive \( \epsilon_v \) (volume expansion). We can see that the 0.39-ml/s granite HF test shows marginally higher \( \epsilon_v \) compared to the 0.019-ml/s granite HF test, while this trend does not appear to be evident in the Opalinus HF tests.
3.4. Displacement and AE Activity Over Time

In this section, we present quantitative results regarding the shear and normal displacements across the microcrack at various points along the microcrack, as shown in Figures 12 and 13. These are presented alongside the rate of AE hits, to gain an understanding of the relationship between the displacements and AE activity. In the 0.39-ml/s granite test, we can see that initially the displacements are close to 0 and that there is an increase in the displacement rate at approximately $t_{\text{norm}} = 0.825$. We suggest that this represents a transition from elastic to inelastic deformation, as the timing corresponds well, albeit slightly later, to an increase in the rate of AEs. In making this statement, we are assuming that inelastic deformation is caused by irrecoverable damage occurring between and/or within mineral grains (Morgan et al., 2013; Wong & Einstein, 2009b), which produces elastic waves detected as AEs (Li & Einstein, 2017). We also note that there is a decrease in the AE rate at around $t_{\text{norm}} = 0.84$ (Figure 12a), which corresponds to the creation of the microcrack located at Query Point 2 (Figure 12b). The real-time development of this microcrack can be seen in Figures 6c and 6d.

In the 0.019-ml/s granite test, this transition appears to be more gradual, and we see that the AE hit rate only increases after significant slip has occurred along multiple microcracks. We note that in the 0.39-ml/s test, the elevated AE rate occurs for approximately 4–5 s prepeak and that in the 0.019-ml/s test the period of elevated AE occurs over approximately 3–4 s. Given that the peak rate of AE at both injection rates is in the range of 1,800–2,000 hits per second and that the period of elevated AE is also relatively similar, we suggest that the AE behavior resulting from the initiation and propagation of a hydraulic fracture are similar despite the 20X difference in injection rate. This implies, at least in the context of this experimental setup, that the microcracks develop at a rate that is dependent on the injection rate (as seen in Figures 6 and 7) but that the process of macrocrack initiation and propagation (recall discussion in section 3.2), which corresponds to connection of these microcracks (see, e.g., Ashby & Hallam, 1986; Wong & Einstein, 2009b), does not...
Figure 12. (a) Plot of normal and shear displacements across the microcrack at three points along the microcrack. This is plotted alongside the rate of acoustic emission hits during the test. Top x axis shows real-time axis in seconds; bottom x axis shows $t_{\text{norm}}$. (b) Image showing the three points along the microcrack, at which normal and shear displacements are calculated in (a). Blue arrows show the direction along which shear and normal displacements are resolved. Panels (a) and (b) show the granite 0.39-ml/s test, and panels (c) and (d) show the granite 0.019-ml/s test. Erroneous data points in (c) around $t_{\text{norm}} = 0.945$ (shown in orange circle) likely correspond to external factors such as a bubble. Note that distinction of elastic and inelastic are based on the image data only.

Figure 12. (a) Plot of normal and shear displacements across the microcrack at three points along the microcrack. This is plotted alongside the rate of acoustic emission hits during the test. Top x axis shows real-time axis in seconds; bottom x axis shows $t_{\text{norm}}$. (b) Image showing the three points along the microcrack, at which normal and shear displacements are calculated in (a). Blue arrows show the direction along which shear and normal displacements are resolved. Panels (a) and (b) show the granite 0.39-ml/s test, and panels (c) and (d) show the granite 0.019-ml/s test. Erroneous data points in (c) around $t_{\text{norm}} = 0.945$ (shown in orange circle) likely correspond to external factors such as a bubble. Note that distinction of elastic and inelastic are based on the image data only.

 depend on the injection rate for the tested range of injection rates. This difference between the microcrack and macrocrack behavior may be attributed to fracture mechanics (Irwin, 1958), which predicts stable crack propagation (microcracking) when the energy release rate $G$ is less than the critical energy release rate $G_c$, and unstable propagation of a crack at the global scale when $G = G_c$. However, further study is needed to determine if this explanation is correct.

In the shale, we first note that in all cases it appears that the normal displacements are larger than the shear displacements, whereas in the granite this varied on a case-by-case basis. Second, we observe a phenomenon
Figure 13. (a) Plot of normal and shear displacements across the microcrack at three points along the microcrack. This is plotted alongside the rate of acoustic emission hits during the test. Top x axis shows real-time axis in seconds; bottom x axis shows \( t_{\text{norm}} \). (b) Image showing the three points along the microcrack, at which normal and shear displacements are calculated in (a). Blue arrows show the direction along which shear and normal displacements are resolved. Panels (a) and (b) show the Opalinus 0.39-ml/s test, and panels (c) and (d) show the Opalinus 0.019-ml/s test.

In the 0.019-ml/s test that the bedding plane at Point 2, between \( t_{\text{norm}} = 0.95 \) and \( t_{\text{norm}} = 0.985 \), first closes in response to the opening of the adjacent bedding plane at Point 3. This reinforces the earlier notion that the lower injection rate results in opening of the bedding planes prior to the propagation of the microcrack, which in turn causes closure of adjacent bedding planes. With regard to the AE rate, we can see that at both injection rates the AE tend to occur after the onset of inelastic deformation. It also appears that the AE rate is less intense and occurs over a longer period at the lower injection rate, which differs from the previously observed phenomenon in granite. This suggest that the microseismic properties of hydraulic fracture initiation and propagation, in the context of this experimental setup, depend on the injection rate for shale but not in granite, that is, it is possible that, for the tested injection rates, unstable fracture propagation occurs.
in the granite but not the shale. Do note, however, that the differences in the experimental setup between the granite and the shale, specifically the amount of fluid available to the fracture at the time of initiation, may also contribute to the differences in behavior.

Overall, we also note that measurable inelastic deformation begins to occur around $t_{\text{norm}} = 0.95$ of peak fluid pressure at 0.019 ml/s in both granite and shale, while at 0.39 ml/s the damage begins to occur around $t_{\text{norm}} = 0.8$ to 0.85 in both granite and shale.

3.5. AE Hypocenter Locations

AE hypocenter locations are shown in Figure 14. We see that, in general, the hypocenters are more spread out in the granite than in the Opalinus tests, which suggests that the process zone is larger in granite than in shale. This is in agreement with a recent study by Naoi et al. (2018), where they also observe a much larger process zone in granite HF than shale HF.

The relative proportions of focal mechanisms are shown in Figure 15, which shows that, in general, the faster injection results in a higher proportion of double-couple events and that there tend to be more implosion/compaction type events in the Opalinus than the granite tests. This corresponds well to Figures 9 and 13, which show that various bedding planes open and close as the microcracks propagate through the specimen. As a matter of curiosity, we present in Figure 16 the cumulative isotropic component (ISO) over time for the 0.019-ml/s Opalinus clayshale test, which increases when explosive non-double-couple events occur.
**Figure 16.** Cumulative amount of isotropic component (ISO) over time during 0.019-ml/s Opalinus clayshale experiment, where an increase is expansion and moves the cumulative value toward positive, and decrease is compaction and moves the cumulative value toward negative.

**Figure 17.** Images of rock surface prior to the HF experiment, overlaid with the microcrack paths.
and decreases when implosive non-double-couple events occur. We can see that it is relatively stable between 78-80s, likely because few AE are detected. A significant inflection occurs around 80.5 s, which, when compared to Figure 13, is around the time when bedding plane opening begins at Query Point 4, and so the compression is likely occurring on along adjacent bedding planes.

4. Effect of Fabric

Figure 17 shows the microcracks overlaid on an image of each rock surface taken prior to each experiment. In the granite, we can see that the microcracks generally form around the dark grains, which we presume are biotite (Murthy, 1957), as shown in the regions circled A, and also tend to avoid the translucent gray grains circled in B, which we presume are quartz grains (Murthy, 1957). The majority of the microcracks, then, occur in the white feldspar minerals (Murthy, 1957). In the Opalinus clayshale, there are generally fewer petrographic features that we can distinguish, although it appears that the microcracks generally form along the bedding plane direction and form along the dark mineral. We see one instance, circled C, where the light colored grain exhibits much less strain than the surrounding dark mineral. This is in general agreement with an internal nanoindentation study (O. AlDajani, personal communication, April 2019), which showed that the $K_{IC}$ value is much higher among the light compared to the dark mineral regions.

5. Summary and Conclusions

While hydraulic fracturing is a well-established and widely implemented process, there are still some aspects that need to be better understood. For example, it is difficult to capture the geometry of the created fracture network, and to understand their relation to the induced microseisms. This relationship is important since resource extraction efficiency is dependent on the fracture network, which is in turn inferred from interpretation of microseisms. However microseismic catalogues only serve as indirect observations. In this laboratory study, we address this knowledge gap by conducting hydraulic fracturing experiments where we directly observe microstructural changes and compare these to corresponding microseismic data. Experiments were conducted on Opalinus clayshale and Barre granite at two injection rates for each rock. We observe the following effects of injection rate:

- Lower injection rates tended to result in a more complex microfracture network, due to the increased number of arrested microcracks. Lower injection rates were also associated with a lower proportion of double-couple (shear) focal mechanisms.
- Between 0.019- and 0.39-ml/s injection rates in the Opalinus, it appears that the behavior transitions from bedding planes opening at the microcrack tip, to the bedding planes opening along with the microcrack tip. No equivalent transition in behavior was observed in the granite.
- For the given experimental setup, inelastic deformation begins to occur around 95% of peak fluid pressure at 0.019 ml/s in both granite and shale, while at 0.39 ml/s the damage begins to occur around 80–85% of peak fluid pressure in both granite and shale.
- For the injection rates tested, the injection rate affects both the microseismic behavior and development of microcracks in both Barre granite and Opalinus clayshale.

We also observe the following differences between hydraulic fracturing in Barre granite compared to Opalinus clayshale. Note, however, that these observations may be limited as the grain size of the granite is relatively large compared to the shale and to the window size.

- Microcracks in granite tend to form as a series of oblique en echelon (shear) cracks, whereas microfractures in Opalinus tend to form directly along bedding plane boundaries. Specifically, in Opalinus all microcracks open in tension before shearing. In granite, the order of tension and shearing depends on the specific microcrack.
- In the Opalinus clayshale tests, the displacement field ahead of the crack tip tends to closely resemble a plumose fracture (see Figure 10), where the material immediately ahead of the crack tip displaces in the direction of the crack path, and there is a gradual transition on either side to a displacement field that is normal to the crack. This transition appears to occur within a smaller area for the Opalinus than the granite, suggesting that the process zone is smaller in Opalinus. A plumose structure is generally associated with tensile fractures, again reinforcing the notion that the shale material initially has a higher tendency toward tensile cracking.
The data set can be found online (https://doi.org/10.17632/gd59th44b9.1).

Acknowledgments
The authors would like to thank Total SA and the Abu Dhabi National Oil Company for funding this research. We would also like to thank the Mont Terri rock laboratory for their generous donation of Opalinus clay shale. Additionally, many thanks to two anonymous reviewers and editor Doug Schmitt for excellent suggestions on the manuscript. Finally, we would like to thank Wei Li and Omar Aldajani for their assistance with experiments, and John Germaine, Brian Evans, and German Prieto for invaluable advice. The data set can be found online (https://doi.org/10.17632/gd59th44b9.1).

- Statistical analysis of the strain data suggest that the granite tests display more volumetric expansion than the shales.
- Generally, the AE shows many more implosive non-double-couple-type events in the Opalinus tests than the granite. The AE hypocenters in Opalinus also tend to be much closer to the notch tips compared to the granite, indicating a smaller process zone in the shale.

Overall, we find several interesting differences between granite and shale, and between injection rates. For example, we find that while the creation of hydraulic fractures is generally considered as tensile at the field scale (Gonçalves da Silva & Einstein, 2018; Sileny et al., 2009), evidence of shearing can be observed to varying degrees at the microstructural scale. Specifically, we see that microstructural shearing is more evident in granite in the form of distinct en echelon microcracks. On the effect of the injection rate, we also find that a reduced injection rate tends to create a more complex network of microcracks, along with a lower proportion of double-couple (shear) focal mechanisms in the microseismic data.

References


