Isotropic versus Anisotropic Stress Field Effects on Hydraulic Fracture Mechanisms in Opalinus Shale

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ABSTRACT: Although hydraulic fracturing has been widely used for decades, and the technology to implement and interpret the induced fractures has been continuously evolving, many aspects are still not understood. Specifically, this includes hydraulic fracture initiation and propagation mechanisms and the effect of stress state and rock fabric. The objective of this study was to determine the differences between hydraulic fracturing under isotropic and anisotropic stress conditions.

Two experiments are presented, discussed in detail and compared: 1 - a specimen with a bedding plane orientation of 30° relative to horizontal is subjected to a vertical stress of 3 MPa and a lateral stress of 1 MPa (anisotropic stress). 2 - a specimen with the same bedding plane orientation of 30° is subjected to biaxial isotropic stresses of 2 MPa (isotropic stress). The results show that the combination of rock fabric and stress state affect the initiation and propagation of hydraulic fractures in shale. This adds to fundamental knowledge on how fractures behave and may provide insight into strategic hydraulic fracture treatments for field applications.

1. INTRODUCTION

Although hydraulic fracturing has been widely used for decades (Roberts, 1866, Bugbee, 1942, Clark, 1949), and the technology to implement and interpret the induced fractures has been continuously evolving (Yost, 1988, NRC, 2001, Fri, 2006, NETL, 2011, Trembath et al., 2012, Saldungaray & Palish, 2012), many aspects are still not understood. Specifically, this includes the fracture geometry and its interaction with natural features such as existing fractures, bedding planes, and various heterogeneities. The objective of this research is to gain a fundamental understanding of the hydraulic fracturing processes in shales through controlled laboratory experiments, in which the mechanisms underlying fracture initiation, propagation, and interaction with geologic features in the rock are visually captured and analyzed. Once these fundamental processes are properly understood, methods that allow one to induce desired fracture geometries in reservoirs can be developed.

Extensive work has been done at MIT to study fracture initiation, -propagation, and coalescence (Reyes, 1991, Bobet, 1997, Wong, 2008, Miller, 2008, Morgan, 2015, Gonçalves da Silva, 2016, AlDajani, 2017, AlDajani, 2018, Gonçalves da Silva, 2018). These studies were done on prismatic specimens with two pre-existing artificial fractures (flaws) without and with the influence of hydraulic pressure (Figure 1). Specimens were subjected to uniaxial or biaxial compressive loading, and fracture initiation and propagation mechanisms (tensile & shear) were captured using a high-speed camera and a high-resolution camera while simultaneously measuring the stress-strain behavior. These experiments were conducted on different materials: gypsum (artificial material), different marbles (metamorphic rock), granite (igneous rock), and different shales (sedimentary rock).

![Figure 1](image-url)
Hydraulic fracture geometries and mechanisms are affected by stress state (Perkins & Kern, 1961, Simonson et al., 1978, Cleary, 1980, Warpinski et al., 1982), rock fabric (Fisher & Warpinski, 2012, Suarez-Rivera et al., 2013), and other factors (Daneshy, 1978, Teufel & Clark, 1981, Biot et al., 1983, Blaire et al., 1989). In any given petroleum reservoir, the stress state can vary spatially, even along a single wellbore, due to the complex geologic structures such as salt domes and/or folds (Zoback, 2010). Rock fabric, i.e. bedding plane orientation, natural fractures, and localized heterogeneities, affect the local stress field and may influence the propagation of the hydraulic fractures, and thus play an important role in dictating the complexity of the induced fractures.

1.1. Specimen Mineralogy

The rock used in this study is Opalinus Shale from Mont Terri, Switzerland, which often has distinct alternating layers as shown in Figure 2.

The mineralogy was measured using X-ray diffraction and is presented in Table 1.

Table 1 – Bulk mineralogy analysis results of Opalinus Shale core sample from X-ray diffraction.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>33.0</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>3.4</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>1.8</td>
</tr>
<tr>
<td>Calcite</td>
<td>5.2</td>
</tr>
<tr>
<td>Dolomite</td>
<td>0.7</td>
</tr>
<tr>
<td>Siderite</td>
<td>1.8</td>
</tr>
<tr>
<td>Anatase</td>
<td>0.4</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.9</td>
</tr>
<tr>
<td>Muscovite</td>
<td>2.6</td>
</tr>
<tr>
<td>Chlorite (Tri)</td>
<td>2.3</td>
</tr>
<tr>
<td>I+I/S-ML</td>
<td>32.1</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>15.8</td>
</tr>
</tbody>
</table>

1.2. Mechanical Properties

The mechanical properties were measured through unconfined compression tests and are presented in Table 2. Although these results were for other Opalinus Shale cores, they fall within range of the extensive mechanical properties tested and presented by Bock (2001).

Table 2 – Mechanical properties of intact (no flaw) Opalinus Shale prismatic specimens subjected to unconfined compression tests (AlDajani, 2017).

<table>
<thead>
<tr>
<th></th>
<th>UCS, MPa</th>
<th>E, MPa</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>load ⊥ to bedding</td>
<td>17.26</td>
<td>1327</td>
<td>0.33</td>
</tr>
<tr>
<td>load ∥ to bedding</td>
<td>5.76</td>
<td>1947</td>
<td>0.26</td>
</tr>
</tbody>
</table>

1.3. Specimen Preparation

Prismatic specimens are prepared by dry cutting cored borings with various bedding plane orientations and a pre-cutting a flaw in the middle. The intricate preparation techniques used are described in AlDajani (2017) and are meant to preserve the shale’s chemical and mechanical integrity from in-situ conditions until testing.

In the previously mentioned studies, most experiments were conducted on specimens with double flaws to determine their interaction. In this study, only a single vertical flaw is cut to investigate the effect the stress state has on hydraulic fractures emanating from a single source, and observe the interaction of the produced hydraulic fractures with the rock fabric. The specimen dimensions and loading configuration are shown in Figure 3. Note that the specimens used in this study have a bedding plane orientation of 30° from horizontal.

Figure 2 - Image of Opalinus Shale showing two distinct alternating layers, a dark clay-rich layer & a light quartz- and carbonate-rich layer.

Figure 3 – Schematic of a prismatic specimen subjected to a constant biaxial load and a pressurized prefabricated flaw to induce hydraulic fractures to study fracture mechanisms.
2. EXPERIMENTAL SETUP

The novel and unique hydraulic fracture experimental setup introduced by Morgan et al. (2017) and described in detail by AlDajani (2018) is shown in Figure 4.

![Figure 4](image)

Figure 4 – Schematic of the experimental setup used in this study. The load frame subjects a constant biaxial stress on to the specimen and then the pressure volume actuator (PVA) injects fluid into the pre-cut flaw. The fractures are observed using a high-speed camera, a high-resolution camera, and an acoustic emission system, simultaneously. The fluid pressures were measured in the PVA as well as internally in the flaw. Modified from Morgan et al. (2017).

2.1. Testing Setup & Procedure

The main challenge and advantage of this setup was the ability to induce hydraulic fractures in an externally loaded rock specimen and be able to capture the fracture mechanisms in detail. This involved the flaw pressurization device (Figure 5).

![Figure 5](image)

Figure 5 – Three-dimensional rendering of updated flaw pressurization device components (isometric view) showing transparent polycarbonate window and larger flaw seal with front injection needle inserted into the flaw.

This device, its components, and operation were described in detail by AlDajani (2018). When placed into the load frame, it allows one to apply external stresses onto the specimen and pressurize the flaw to produce hydraulic fractures while simultaneously capturing visual and acoustic observations of the detailed fracture mechanisms.

After applying the external biaxial stresses, the device allows one to apply stress on the specimen face by clamping the front viewing window to the rear steel plate, i.e. creating a true triaxial stress state around the flaw. This stress ($\sigma_2$) was determined to be approximately 2 MPa by controlling the clamping screws’ torque and measuring the force on a load cell in place of the specimen. The same torque, and hence intermediate stress, was uniformly applied for all experiments.

Computer control is used to apply loads at specified rates in a synchronized fashion. Specifically:

- In the isotropic test, 2 MPa are simultaneously applied in the axial and lateral directions at a rate of 3.5 MPa/min, following an isotropic compressional stress path, and then to hold 2 MPa biaxially.

- In the anisotropic test, 1 MPa was applied simultaneously in the axial and lateral directions at a rate of 3.5 MPa/min, initially following an isotropic compressional stress path. After the lateral stress was held at 1 MPa, the axial stress was increased at the same rate until 3 MPa is achieved.
The stress paths for these two tests are shown in \( p-q \) space, where \( p = \frac{1}{2} (\sigma_1 + \sigma_3) \) and \( q = \frac{1}{2} (\sigma_1 - \sigma_3) \).

After loads are applied, the flaw is initially saturated by pumping fluid from the pressure-volume-actuator (PVA) through the tubing into the flaw (see Figure 4), and out through the flaw pressure measurement needle (see Figure 5). Once saturated, a pressure transducer is attached to this needle to close the system. The flaw is then pressurized at a constant injection rate of 1.33 mL/min for both tests. Pressure and volume measurements are taken at the PVA, and internal flaw pressure is measured with the pressure transducer probing the flaw. The fluid injected is hydraulic oil to prevent the hydration of clays, and has a dynamic viscosity of approximately 4 cP.

Imagery acquisition was done with a high-speed (HS) camera at 1,000 frames per second (fps) on a 1 megapixel (MP) sensor and a high-resolution (HR) camera at 0.5 fps on a 20 MP sensor. The HS camera is manually triggered to capture the failure of the specimen, i.e. the end of the test. The HR camera captures time lapses of the test from beginning to end. The acoustic acquisition system samples data at 5 MHz from 8 acoustic sensors, which are spring-loaded in specialized platens surrounding the specimen. Acoustic observations are not discussed in this paper.

Imagery acquisition was done with a high-speed (HS) camera at 1,000 frames per second (fps) on a 1 megapixel (MP) sensor and a high-resolution (HR) camera at 0.5 fps on a 20 MP sensor. The HS camera is manually triggered to capture the failure of the specimen, i.e. the end of the test. The HR camera captures time lapses of the test from beginning to end. The acoustic acquisition system samples data at 5 MHz from 8 acoustic sensors, which are spring-loaded in specialized platens surrounding the specimen. Acoustic observations are not discussed in this paper.

To show practical relevance, the concept of this experiment is similar to bringing the rock to in-situ stress conditions, the saturation phase is analogous to drilling mud in the wellbore, and the pumping phase follows what is done in field operations to induce hydraulic fractures. In our tests, the following data are acquired to be analyzed:

a. HS video
b. HR images
c. Internal flaw pressure
d. PVA pressure and volume
e. Acoustic emissions (not discussed in this paper)

The imagery is then analyzed, and what is visually captured is analyzed and drawn into sketches for a clearer graphical representation of what happened.

### 3. RESULTS AND DISCUSSION

Recall that two stress states investigated: anisotropic and isotropic (Figure 7).

#### 3.1. Anisotropic Stress State \( (\sigma_1 = 3 \text{ MPa}, \sigma_2 \approx 2 \text{ MPa}, \sigma_3 = 1 \text{ MPa}) \)

The data collected from the anisotropic hydraulic fracture experiment are shown in Figure 8. The internal flaw pressure is the red curve, and the injected volume is the blue curve. The black triangles indicate where sketches were taken for image analysis. A sketch is taken from the HS or HR images when a significant event occurs such as fracture initiation or a specific interaction of the hydraulic fracture with features in the rock.
pressures/times/volumes in Figure 8 (designated by the labeled black triangles).

![Figure 9](image-url) – Sketches of fracture progression throughout pressurization of the flaw in the anisotropically loaded specimen. Sketch numbers refer to numbered black triangles on pressure curve in Figure 8. Fracture initiation is denoted with red letters. The flaw seal boundary is indicated by the rounded square. (T) indicates opening in tension, and subscript \( \text{bp} \) indicates propagation along a bedding plane.

The final sketch (Sketch 10) is enlarged and shown in Figure 10.

![Figure 10](image-url) – Final sketch (Sketch 10 in Figure 8) of the anisotropic stress hydraulic fracture test.

As shown in Figure 8, fluid is injected at a constant flow rate, and the internal flaw pressure response is measured. The maximum pressure was 4.32 MPa, but the first fracture \( \text{A(T)}_{\text{bp}} \) initiated at the top flaw tip at 3.49 MPa (Sketch 1 in Figure 9) and started propagating along the bedding plane. A second fracture \( \text{B(T)}_{\text{bp}} \) initiated at a bedding plane intersecting the middle of the flaw at 3.92 MPa (Sketch 2) while \( \text{A(T)}_{\text{bp}} \) continued to propagate. As propagation of \( \text{A(T)}_{\text{bp}} \) and \( \text{B(T)}_{\text{bp}} \) continued, \( \text{C(T)}_{\text{bp}} \) branched from \( \text{A(T)}_{\text{bp}} \) (Sketch 3). At this point, \( \text{A(T)}_{\text{bp}} \) arrested and propagation continued along the intersecting bedding plane \( \text{C(T)}_{\text{bp}} \) (Sketch 4). The non-linear pressure response between sketches 3 and 4 reflects the dilation as a result of fracture propagation while the drastic pressure drop shortly afterwards is due to the fracture reaching the seal boundary (Sketch 5). Despite that, the fractures continued propagating until they reached the specimen boundaries (Sketch 10 in Figure 10). The pressure record shows that the pressure to initiate fractures is greater than that needed to propagate fractures, as was established by Irwin (1956) and Feng & Gray (2017). An image taken at the end of the test is shown in Figure 11 which corresponds to the final sketch in Figure 10.

![Figure 11](image-url) – Image of hydraulically fractured specimen subjected to anisotropic stress at the end of the test.

### 3.2. Isotropic Stress State \( (\sigma_1 = \sigma_2 \approx \sigma_3 = 2 \text{ MPa}) \)

The data collected from the isotropic stress hydraulic fracture experiment are shown in Figure 12. The plotted curve colors and symbols are the same as in Figure 8 (section 3.1.).
As shown in Figure 12, fluid is injected at a constant rate, and the internal flaw pressure response is measured. The maximum pressure in this test was 7.70 MPa. It is worth noting that no fractures were detected in the image analysis prior to the drastic pressure drop, which is a sign that a hydraulic fracture(s) has propagated past the seal boundary. The likeliest explanation was that the fracturing started on the rear face of the specimen before becoming visible on the front (imaged) face. The front and rear faces of the specimen were photographed after the test and they show good correspondence (Figure 13). The earlier fracturing at the rear is supported by the wider wet region around the fractures on the rear face, indicating longer exposure to the injected fluid.

Regardless of this fact, the visual observations on the imaged face of the rock throughout the test were analyzed as this test still shows the entire fracture behavior of this specimen under isotropic loading.

The fracture progression is shown in Figure 14, where each sketch number corresponds to the image of the specimen at the denoted pressures/times/volumes in Figure 12 (designated by the labeled black triangles).

The final sketch (Sketch 6) is enlarged and shown in Figure 15.
• The maximum pressure reflects how much pressure is required to propagate a fracture to the seal boundary, and it is significantly higher in the isotropic test. One initial explanation is that in an anisotropic stress field, the stress concentrations around the flaw are more extreme than in an isotropic stress field. However, further work is necessary to determine how stress concentration and rock fabric interact.

4. SUMMARY & CONCLUSIONS
The objective of this paper was to study the differences between hydraulic fractures produced in shale specimens subjected to isotropic and anisotropic stress conditions. The hydraulic pressure testing setup at MIT allowed real-time analysis of fracture initiation and propagation by utilizing a transparent flaw pressurization device and imagery equipment.

The anisotropic stress test applied and held the following external stresses: \( \sigma_1 = 3 \text{ MPa}, \sigma_2 \approx 2 \text{ MPa}, \sigma_3 = 1 \text{ MPa}, \) and the flaw was pressurized at a constant flow rate of 1.33 mL/min. This resulted in hydraulic pressure opening up bedding planes and propagating along them.

The isotropic stress test applied and held the following external stresses: \( \sigma_1 = \sigma_2 \approx \sigma_3 = 2 \text{ MPa}, \) and the flaw was pressurized at the same constant flow rate of 1.33 mL/min. This resulted in one hydraulic fracture propagating along a bedding plane and the other across bedding layers.

For both stress conditions, the first hydraulic fracture to initiate was at the flaw tips where the tensile stress is highest and at the intersection with a bedding plane. The fracture continued to propagate along the same bedding plane. Thus, the rock fabric has a strong effect in dictating fracture initiation and propagation. However, the characteristics of the secondary hydraulic fracture and the pressures were different between the two tests.

While the combined effect of stress state and fabric may explain the differences in hydraulic fracture initiation and propagation, more work is needed to fully understand their interaction.

The results from such experiments can be very insightful to interpret fracture complexity in past field operations or in the planning stage for future treatments, where the stress state can vary spatially, even along the same wellbore. They can also be used as a validation tool for theoretical and numerical models.

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REFERENCES


12. Fri, Robert W. "From Energy Wish Lists to Technological Realities.” Issues in Science and Technology 23, no. 1 (Fall 2006).


