1 **Characterization of damage processes in Montney siltstone under triaxial**
2 **compression using acoustic emission and diagnostic imaging**

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2 **Summary**

3 Crack nucleation and rock failure processes in a fine-grained siltstone (Montney
4 Formation) under triaxial compression are investigated using combined diagnostic
5 techniques, including ultrasonic-wave measurement, acoustic-emission (AE)
6 monitoring, computed tomography (CT) scanning, and thin-section imaging. The
7 sample displays a weak-to-moderate inherent seismic anisotropy and noticeable stress-
8 induced anisotropy prior to failure. No AE event was detected until the applied axial
9 stress reached 95% of the peak value. The signal-to-noise ratio is relatively low,
10 however, and detectable AE events are more diffuse than those observed in highly
11 brittle rocks. The AE locations correlate with a shear fracture zone imaged by CT
12 scanning. AE moment-tensor analysis reveals that events with larger relative
13 magnitudes are characterized by high volumetric (tensile or compressive) components,
14 and the initiation of the failure zone is dominated by combined shear-tensile failure.
15 Stress inversion of the AE events with high tensile components is in good agreement
16 with the known applied stress. Microscopic imaging of thin sections from the failed
17 sample shows that the failure zone is an *en echelon* structure consisting of a major
18 fracture with branching micro and minor cracks. This failure mechanism is consistent
19 with a shear-tensile source mechanism and is interpreted to be associated with the fine
20 granular structure and mineral composition of Montney siltstone.

21 **Keywords:** Induced seismicity; earthquake source observations; seismicity and
22 tectonics; fractures, faults, and high strain deformation zones

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1.0 Introduction

Fine-grained sedimentary rocks that exhibit inherent mechanical anisotropy (Shen et al., 2019), such as siltstone and shale, contain vast unconventional hydrocarbon resources. Many geomechanical studies of these units are limited by lack of observational constraints on the role of anisotropic properties in failure mechanisms (Weng, 2015), although previous experiments with anisotropic rocks from a deep mine environment (Lei et al., 2013) show that foliation-defined rock fabric exerts a strong influence on failure mechanism. In addition, triaxial experiments on shale samples from the Sichuan Basin (Li et al., 2017) and stress unloading after hydraulic fracturing of the Longmaxi shale (Zhai et al., 2020) show that fracture processes at the laboratory scale correlate strongly with anisotropic rock fabrics that are defined by bedding and fractures.

Acoustic emissions (AEs), defined as transient elastic waves created by energy release when microcracks undergo inelastic deformations inside a material (Lockner, 1993), can be recorded during laboratory experiments. Information that can be extracted from AE observations includes the onset, location and failure mechanism of microcracks, which can provide important insights into fracture nucleation and evolution processes (e.g., Lockner et al., 1991; Lockner, 1993; Benson et al., 2008; Thompson et al., 2009).

In general, AE activity reveals event statistics, such as event size distributions, that are similar to seismic field observations, but at a smaller scale and under controlled

1 laboratory conditions. AE experiments also provide opportunities for microscopic
2 examination of the damaged material, enabling further insights into underlying
3 fracturing processes. This type of analysis thus provides insights for understanding
4 earthquake nucleation processes associated with induced seismicity (Lockner et al.,
5 1991; Sellers et al., 2003; Bohnhoff et al., 2010; Goodfellow et al., 2015).

6 Previous AE tests have mainly been conducted on granites or sandstones, which
7 can store significant strain energy before detectable AE events are generated (Lockner
8 et al., 1982; Lockner, 1993; Reches & Lockner, 1994; Thompson et al., 2009). Recently,
9 laboratory research has demonstrated that AE analysis can be implemented on shale
10 samples, which are abundant in unconventional oil and gas reservoirs (Amann et al.,
11 2012; Stanchits et al., 2012, 2014; Li et al., 2015; Jin et al., 2017; Naoi et al., 2018,
12 2020). This laboratory analysis incorporates moment tensors and stress-inversion data
13 derived from AE techniques in samples of Montney siltstone, a fine-grained low-
14 permeability reservoir unit within a major unconventional hydrocarbon fairway in
15 northwestern Canada (Child & Mauger, 2019). Characterizing crack nucleation and
16 failure processes in shales is important, in general, for understanding induced seismicity
17 and deformation processes associated with unconventional hydrocarbon development
18 (Shimamoto & Logan, 1981). This is particularly the case for the Montney Formation,
19 which is noted for its relatively high geological susceptibility to induced seismicity
20 during hydraulic-fracturing operations (Mahani et al., 2017, 2019; Schultz et al., 2020;
21 Wozniakowska and Eaton, 2020).

22 With this motivation, the objective of this study is to investigate failure
23 mechanisms in Montney siltstone under triaxial compression, using diverse monitoring
24 systems and diagnostic imaging. The first part of the paper presents details of an

1 experiment in which the mechanical behaviour accompanied with ultrasonic wave
2 velocity and AE events were measured on a Montney shale sample. The second part
3 deals with data analyses and provides valuable insights into failure processes inside the
4 triaxial sheared sample.

5 **2.0 Material used**

6 The Montney Formation (Montney) is a Lower to Middle Triassic, siltstone-
7 dominated clastic unit in western Canada with a subsurface extent of approximately
8 130,000 km² (Fig. 1 - left). The Montney sample prepared for this test was recovered
9 at a depth of 3136.50 m from a vertical well located in the Kakwa area, Alberta, Canada.
10 The Montney Formation in this area is composed of nearly flat-lying siltstone with
11 grains cemented by dolomite and quartz, with a lower total organic content (TOC) than
12 typical of Montney materials elsewhere; therefore, compared to other fine-grained
13 materials, it is stronger and more brittle in terms of geomechanical behavior (Tak et al.,
14 2017).

15 A previous study by McKean (2017) indicates that the Kakwa Montney has a
16 Young's modulus of approximately 50 GPa and a peak strength of ~300 MPa under a
17 confining pressure of 15 MPa. The inherent anisotropy is weak-to-moderate with both
18 the anisotropic P-wave and S-wave parameters of ϵ and $\gamma \ll 1$ (Thomsen, 1986). In
19 terms of porosity, a wide range has been recorded for different facies of Montney (from
20 5% to over 20%; Davies et al., 1997) and, according to Gareth et al. (2012), the average
21 porosity for Kakwa Montney around the study area is roughly 5%.

22 Cylindrical samples used in this study are 125.8 mm in length and 50.29 mm in
23 diameter (length-diameter aspect ratio of 2:5) and were cored using an automated rotary
24 drill, with end faces ground to within 0.01-mm parallelism using a diamond grinding

1 wheel. The vertical cores were oriented perpendicular to the horizontal subsurface
 2 bedding orientation. The X-ray computed tomography (CT) scan and X-ray diffraction
 3 (XRD) analysis (Table 1) show that the tested sample has an average porosity of 9.6%,
 4 and a grain density of 2.72 kg/m^3 , respectively. Some light spots (Figure 1) that
 5 represent grains of pyrite are found, which have higher densities and are significantly
 6 stiffer than the siltstone matrix. Although the CT image does not indicate the presence
 7 of bedding planes, ultrasonic-wave survey (Section 4.2) shows the existence of elastic
 8 anisotropy.

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11 Figure 1. Left: Map of seismicity with a minimum magnitude of 2.5. related to
 12 development of the Montney unconventional play for the period of October 2006 to
 13 September 2017 (red dots) based on a compilation of catalogues in British Columbia
 14 (B.C.) (Mahani & Kao, 2017; Mahani et al., 2017, 2019; Visser et al., 2017). Seismicity
 15 in the Montney Formation related to hydraulic fracturing is generally confined to areas
 16 to the north and west in British Columbia (B.C.). Black dots show hydraulically

1 fractured wells within the Montney Formation and white rectangle shows location of
2 the Kakwa field. Black outline shows extent of the Montney Formation in the
3 subsurface of B.C. and Alberta, Canada. Middle: CT scan image shows the whole
4 length (125.8 mm); Right: four slices of the sample (each slice has a diameter of 50.29
5 mm). The locations of those four slices are indicated by the blue line. For the right part
6 of the figure, the brighter color indicates a higher density (pyrite).

1 Table 1. Mineral composition of the Montney sample examined by X-ray diffraction
2 analysis.

Mineral	Weight percentage (%)
Quartz	33
Dolomite	35.1
Plagioclase	15.2
K-feldspar	13.8
Pyrite	2.1
clays	0.8

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4 **3.0 Experimental setup and procedures**

5 This AE experiment was conducted inside a triaxial geophysical imaging cell
6 (GICA cell). The axial load was delivered by the MTS axial hydraulic actuator, and the
7 confining pressure was maintained by silicone oil outside of a rubber jacket using a
8 servo-control Teledyne system. Two linear variable differential transformers (LVDTs)
9 were used to measure axial deformation, but no radial strain was recorded. Previous
10 work with this type of experimental configuration is described by Goodfellow et al.
11 (2015, 2016) and Jia et al. (2018a).

12 Inside the GICA cell, sixteen single-component piezoelectric transducers were
13 used for passive monitoring of the AE signals emitted from the sample as it was
14 compressed. Three AE sensors were mounted on the top loading platen, two were on
15 the bottom platen, and the other 11 lateral sensors were mounted on the rubber jacket

(Fig. 2). All the sensors were in direct contact with the sample surface under the applied confining stress. The geometrical configuration of the sensors provided sufficient coverage around the sample to provide sufficient geometrical constraints for stable moment-tensor inversion (Eaton and Forouhdeh, 2011). Each of the AE sensors was calibrated in the frequency range 200 KHz to 1 MHz on an aluminum block with a rubber jacket.

An Applied Seismology Consultants (ASC) system was used for pre-amplifying and sampling the AE signals, which contain the information of wave arrival times, amplitudes and first-motion polarities. The data were first amplified by 40 dB with a 100 kHz - 1 MHz bandpass filter, and then digitized using an ASC Richter system with a sampling rate of 10 MHz and digitized at 12-bit resolution. Amplified waveforms were recorded using the IMAge Richter acquisition system with a dynamic range of 10 V. Picked arrival times were inverted to estimate the origin times and hypocenter locations of the AE events. The preamplifiers included a switching mechanism that allowed AE transducers to act as both a source and receiver, in order to conduct repeated P-wave velocity surveys. After the experiment, continuous acoustic-emission waveforms were extracted for detected AE events based on a simple triggering threshold. A sample length of 1,024 points were recorded for each channel, using a triggering threshold voltage of 80 mV.

To aid in the source location analysis (Lockner et al., 1991), three pairs of dedicated ultrasonic transducers measuring the compressional wave (P) and two polarized shear wave velocities (S_h and S_v) were located along three orthogonal x, y and z axes (purple triangles in Fig. 2) on the sample in the cell to conduct velocity surveys and analyze shear-wave splitting. However, as the single-component AE

1 transducers are not well suited for recording shear-wave motions, shear-wave splitting
2 analysis was not carried out for the AE waveforms.

3 During the experiment, no internal pore pressure was applied to the siltstone
4 sample, and the sample contained only atmospheric moisture, i.e., no additional fluid
5 was used to saturate the sample. It was allowed to deform under a constant confining
6 pressure of 10 MPa. The triaxial system was first gradually loaded to 10 MPa
7 hydrostatic pressure ($\sigma_1 = \sigma_3 = 10$ MPa) under load control. Then, the MTS axial
8 actuator was held under constant displacement control mode with a rate of 0.2 $\mu\text{m/s}$ to
9 increase the deviatoric stress ($\sigma_1 - \sigma_3$) with the constant confining pressure until the
10 sample failed. Ultrasonic wave velocity measurements were carried out every
11 increment of 10 to 20 MPa in the axial stress until reaching 260 MPa, results of which
12 provided the velocity field used in the location algorithm to compute the AE hypocenter
13 positions. As the AE sensors cannot send and receive signals at the same time, no
14 seismic survey was made when the sample was close to failure.

15 Prior to and after the triaxial compression test, the sample was CT scanned to
16 examine the internal structure. In addition, thin sections at different locations were
17 made on the failed sample to reveal the fracture configuration.

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2 Figure 2. Left: Schematic illustration showing locations of AE sensors. The solid and
3 open blue dots indicate the locations of AE sensors at the front and back of the sample,
4 respectively. Ultrasonic transducers for velocity survey are located along the three
5 orthogonal axes and are shown as purple triangles. Modified from Jia et al. (2018a).
6 Right: Locations of AE sensors (blue dots) and ultrasonic transducers (purple triangles)
7 on the side of the sample (cylindrical coordinates).

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9 **4.0 Experimental results and analyses**

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11 **4.1 Mechanical characteristics**

12 The sign convention used in this paper is that compressive stresses and strains
13 are positive. The stress-strain curve for the triaxial compression test is illustrated in Fig.
14 3. Note that all the red points are rough estimations based on the linearity of the curve.
15 The hydrostatic loading part of the test is shown in the curve up to Point A, and after

1 that, the deviatoric stress starts to increase. Portion A-B has a low slope, indicating the
2 closure of pre-existing micro-cracks. For portion B-C, the sample displays a linear
3 primary loading curve (elastic behaviour). Point C represents the onset of crack
4 initiation, and from Point D, the curve starts to inflect, indicating permanent axial
5 deformation as defined by Martin (1997). Once the stress condition reached a peak, at
6 a deviatoric stress and axial strain of about 280 MPa and 0.8% respectively, the sample
7 underwent an unstable macroscopic failure with significant strain-softening. Based on
8 the linear portion of the stress-strain curve, the static Young's Modulus E is
9 approximately 50 GPa, which is consistent with the modulus obtained by McKean
10 (2017).

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2 Figure 3. a) Deviatoric stress ($\sigma_1 - \sigma_3$) versus axial strain under a confining stress of 10
3 MPa. The red letters mark the beginning of the following process: deviatoric loading
4 (Point A), linear primary loading (Point B), inelastic micro-crack growth (Point C), and
5 unstable deformation (Point D). A shear fracture cross-cutting the specimen was formed

1 after the peak stress, resulting in a large drop in deviatoric stress. The black dashed line
 2 crosses Point B. (b) P-wave velocity along all three orthogonal axes and S-wave
 3 velocities polarized in the vertical (V_{sv}) and horizontal (V_{sh}) directions along the x axis
 4 when subjected to axial stress change. (c) Anisotropy parameters estimated from the
 5 elastic wave velocities using a vertical transversely isotropic model (Thomsen, 1986),
 6 where ϵ characterizes the P-wave anisotropy and γ characterizes the S-wave anisotropy.

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8 A shear fracture formed during the test, with an inclination angle of 70° with
 9 respect to the top surface (Fig. 4). To map the internal structure of the failure zone, the
 10 sample was CT scanned again after the test, and the images were imported into
 11 MATLAB for visualization (Fig. 5). Based on the microscopic image of a thin section
 12 as shown in Fig. 6, the shear fractured zone consists of sub-vertical cracks that are
 13 connected by the bedding-parallel side-steps, thus leading to a shear dilation behavior
 14 coalescing to form a steeply inclined apparent shear fracture (Niandou et al., 1997;
 15 Amann et al., 2012).

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18 Figure 4. Photographs of the sample before and after the triaxial compression test.

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2 Figure 5. Processed CT results showing shear fractured zone, in which the blue color
3 represents the fracture surface (x and y axes are along horizontal or radial directions,
4 and the z axis is along vertical or axial direction).

5

6 Figure 6. Microscopic image of the thin section with unpolarized (natural white) light
7 taken around the shear fracture of the tested sample showing *en echelon* micro-fractures.
8 The sample contains angular to sub-rounded grains (white). Black color can be organic
9 matter or cements. The white linear features indicate fractures.

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2 **4.2 Ultrasonic wave velocities**

3 Measurements of ultrasonic wave velocity during geomechanical testing have
4 been applied in AE experiments to monitor deformation-induced changes in wave
5 velocities in response to the increasing deviatoric stress (Hadley, 1976; Fortin et al.,
6 2006; Stanchits et al., 2006). In general, the wave velocities are reduced substantially
7 at the onset of crack development. The speed of waves propagating normal to the crack
8 planes is reduced more than the speed of waves travelling along the plane (Nur, 1971;
9 Lockner et al., 1977; Stanchits et al., 2006; Li et al., 2018).

10 Fig. 3b illustrates measured P-wave velocities (V_P) along the three orthogonal
11 axes and the two polarized S-wave velocities (V_{Sh} and V_{Sv}) along the x axis as a function
12 of the axial strain. Note that the S_h wave propagating in the x direction is polarized
13 along the y axis (in-plane) and S_v is polarized along the z direction (out of plane). As
14 the sample exhibits transversely isotropic (TI) symmetry, the S_h wave polarized
15 parallel-to-bedding has a higher speed than S_v (Sarout et al., 2007). Similar phenomena
16 are also observed in the other two directions.

17 The initial P-wave velocity (without loading) in the z direction is significantly
18 lower than that in the horizontal directions, and V_P in the x direction travels faster than
19 that in the y direction, indicating a slightly inclined anisotropic symmetry axis
20 (assuming transversely isotropic system). The velocity increase is greatest in the axial
21 direction before the onset of linear primary loading (Point B in Fig. 3a), inferred to be
22 the result of closure of pre-existing cracks (Mayr & Burkhardt, 2006), and then the
23 slope of the curve decreases considerably. In the post-peak time window, velocities in

1 the x and y directions decrease more significantly than that in the z direction, confirming
 2 that stress-induced cracks are mainly formed (sub-) normal to the x - y plane.

3

4 The anisotropic parameters of the velocity field for TI materials can be
 5 expressed using Thomsen parameters as (Thomsen, 1986)

$$6 \quad \epsilon = \frac{V_{P,radial}^2 - V_{P,axial}^2}{2V_{P,axial}^2}, \quad (1)$$

$$7 \quad \gamma = \frac{V_{Sh}^2 - V_{Sv}^2}{2V_{Sv}^2}, \quad (2)$$

8 where ϵ measures the P-wave anisotropy and γ measures the S-wave anisotropy. The
 9 radial P-wave and the shear waves used in this case propagate in the x direction. Fig.
 10 3c shows the change of anisotropy parameters as a function of the axial strain. The
 11 initial anisotropic parameters of the sample (without loading) are relatively low,
 12 indicative of a weak-to-moderate inherent anisotropy (Thomsen, 1986). During
 13 hydrostatic loading (before Point A) and the initial crack closure stages (before Point
 14 B), ϵ decreases from 0.17 to -0.06 indicating a velocity increase in the axial direction
 15 as a result of the pre-existing crack closure. The shear-wave anisotropy increases as γ
 16 changes from 0.07 to approximately 0.15. After Point B, both ϵ and γ only change
 17 slightly. This is similar to behavior observed in sandstone, indicating that elastic
 18 anisotropy is not strongly induced in the elastic deformation regime (Fortin et al., 2006).
 19 On the other hand, in the post-peak, due to the formation of the shear band, the P-wave
 20 anisotropy parameter changes significantly, thus producing a stronger anisotropy
 21 between the axial and radial directions.

22 4.3 AE data

4.3.1 Hypocenter locations and moment tensor inversion

P-wave first arrivals were picked manually, and the velocity model was assumed to be homogeneous and transversely isotropic (Itasca Consulting Group Inc., 2014). An example of the filtered waveforms (low band pass filter) for one AE event is shown in Fig. 7, in which each trace displays the signal from one AE sensor channel. The first arrivals are not as clear as those evident in the granitic samples (Lei et al., 1992), which makes the data processing and interpretation challenging.

Figure 7. Record section showing waveforms from one AE event. The sampling frequency is 10 MHz, and a total of 1024 sampling points are shown. Green lines indicate the pick time on each AE recording channel. The mean peak amplitude for this event is ~ 2 V, and the estimated moment magnitude is approximately -6.5.

Because most events occurred close to the time of peak activity, the last velocity survey measured at the axial stress of 260 MPa (axial strain of $\sim 0.7\%$) was used to

define a time-invariant VTI velocity model. The source locations were calculated using a collapsing-grid search method, in which the minimum of the P-wave first arrival residuals is searched through a progressively refined grid until a user-defined resolution is achieved (Itasca Consulting Group Inc., 2014). The AE sensors detected roughly 470 AE events, of which locations were determined for 149 high quality events. The screening criteria for hypocenter determination are (Grosse & Ohtsu, 2008): (1) confident arrival time picking on waveforms with good signal quality of signal-to-noise ratio ($\text{SNR} \geq 1$), and (2) number of sensor picked (at least 4) to provide sufficient sensor coverage and improve AE event localization. Unlike granite, the waveforms generated from Montney siltstone do not always show a clear first arrival (Fig. 7). Moreover, reflections from the sample's surface can make the picking process especially challenging (Aker et al., 2014). In this case, the overall SNR is 12.5, which is defined as (Itasca Consulting Group Inc., 2014):

$$\text{SNR} = W_{\text{RMS}}/L_{\text{RMS}} \quad (3a)$$

where L_{RMS} is the RMS noise level calculated before the first arrival of each event, and W_{RMS} is the RMS waveform amplitude of the event over a time window consisting of N sampling points:

$$W_{\text{RMS}} = \sqrt{\frac{\sum_{i=1}^{i=N} W_i^2}{N}} \quad (3b)$$

Figure 8 shows cumulative triggered AE events versus time as well as the hypocenter locations of locatable events in different time intervals. Each event is colored by its corresponding location magnitude, M_L , determined based on the relative magnitudes of events recorded on the same array (Itasca Consulting Group Inc., 2014):

$$M_L = \log \left(\frac{\sum_{m=1}^{m=N} (W_{RMS_m} \cdot d_m)}{N} \right) \quad (4)$$

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2 where W_{RMS_m} is the RMS waveform amplitude of each sensor for the m^{th} event as
 3 described by Eq. (3b), d_m is the ray path length, and N is the number of events. It should
 4 be noted that although it is valid in a relative sense, the location magnitude used here is
 5 not calibrated in an absolute sense. A time residual, which is the difference between the
 6 measured and theoretical arrival times (Itasca Consulting Group Inc., 2014), is
 7 calculated for each locatable event (Fig. 9) with an overall average value of 0.34 μs .

8 Results show that before the inelastic deformation stage, there were no detected
 9 AE events. When approaching the peak stress, events started to occur and persisted
 10 until the end of the test. However, no events were analyzed or located in the post-peak
 11 time window, due to the low SNR of the waveforms. A localized failure plane can be
 12 seen from the hypocenter plot, and the nucleation process was initiated from the upper
 13 side of the sample as illustrated by the red arrow in Fig. 8. The AE cluster expanded
 14 from the top-to-bottom, forming a band cross-cutting the sample. The orientation of the
 15 failure plane shows a close correspondence with the CT results, but with a lower
 16 inclination angle from the top surface ($\sim 60^\circ$).

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2 Figure 8. Upper: Cumulative AE event count (red curve) and axial strain (blue curve)
3 versus time. Points A – D correspond to those in Fig. 3. Inset shows top view of
4 hypocenter locations for 149 locatable AE events. Lower: Temporal evolution of AE
5 events, where times are indicated by the black dashed lines. Symbol colors correspond
6 to the location magnitude, a relative AE magnitude scale defined by Eqn. 4. The red
7 arrow indicates the direction of fracture propagation.

8

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2 Figure 9. All locatable AE events coloured based on the average time residuals.

3 To evaluate the source mechanism, moment tensors (MTs) were inverted based
 4 on P-wave first-motion polarities and amplitudes (Eyre & Van Der Baan, 2015; Zhang
 5 et al., 2019), which were picked manually from the recorded waveforms to determine
 6 the failure modes of crack. This inversion process can generate a full moment tensor,
 7 which includes non-double-couple source mechanism. No S-wave was identified,
 8 mainly due to the small distance between the source and receivers that resulted in
 9 interference with the P wave (Aker et al., 2014). The Green's functions for a point
 10 source were calculated using isotropic velocities measured by the ultrasonic velocity
 11 surveys (Itasca Consulting Group Inc., 2014). At least 8 channels with good coverage
 12 of the focal sphere (Eaton & Forouhideh, 2011) were used, so that the inversion
 13 problem is overdetermined. In total, fifty-seven (57) events were inverted for MTs. The
 14 condition numbers, which characterize the stability of matrix inversion (a lower number
 15 indicates the inversion is more stable), are all lower than 10 with one exception, for
 16 which the condition number was ~ 15 . These values are indicative of well constrained

1 inversion results (Eaton and Forouhdeh, 2011).

2 In Figure 10, the source mechanisms are projected onto a Hudson T - k plot
3 (Hudson et al., 1989), in which DC denotes double-couple, CLVD is compensated
4 linear vector dipole, T and K denote the deviatoric and volumetric components,
5 respectively. Symbol colors indicate the time of occurrence in seconds after the
6 beginning of the test (upper panel), and moment magnitude (lower panel). The temporal
7 pattern looks similar to those observed in the field (Foulger et al., 2004), indicating that
8 this experiment may provide a useful proxy for field observations. The early events
9 (dark blue) are mainly indicative of tensile opening, but subsequently mixed-source
10 mechanisms are evident. This indicates that the initiation of shear fracture is dominated
11 by tensile crack opening, similar to previous observations (Stanchits et al., 2006;
12 Reches & Lockner, 2010; Aker et al., 2014). The events are nearly equally distributed
13 in the upper and lower half of the Hudson plot, indicative of roughly equal proportions
14 of opening and closing fractures.

15 Following Collins et al. (2002) and Thompson et al. (2009), when K is in the
16 range of -0.22 to 0.22, as illustrated by the grey shaded area in Fig. 10, the source type
17 is considered to be a shear (double couple) source. The remaining sources are classified
18 here as shear-tensile (ST) events, since they are characterized by non-negligible
19 volumetric component (either tensile opening or compressive closing). In total, 23
20 events are classified as ST, and 34 events belong to the shear source type. Another
21 source-type classification method (by the inclination angle α) gives similar results, as
22 discussed in Section 4.3.2 of stress inversion.

23

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2 Figure 10. Hudson diagram (Hudson et al., 1989) showing AE source mechanisms
 3 calculated from moment tensor inversion. Events in the grey shaded area are considered
 4 to contain mainly double-couple component. DC denotes double couple, CLVD
 5 denotes compensated linear vector dipole, which is characterized by no change in
 6 volume. Events are colored according to the occurred time in seconds since the
 7 beginning of the experiment.

8

9 4.3.2 Stress inversion

10 Stress information obtained from the earthquake focal mechanisms makes up
 11 the majority of data recorded in the World Stress Map project (Barth et al., 2008). In
 12 this study, the moment tensors were utilized to conduct formal stress inversions, and
 13 reduced stress tensors consisting of only four components (three principal stress
 14 orientations and their relative magnitudes) can be calculated (Vavryčuk, 2014). Two
 15 stress inversion methods were used: the original STRESSINVERSE MATLAB code
 16 developed by Vavrycuk (2014), and the STESI code developed by Jia et al. (2018b).

1 STRESSINVERSE was developed using the traditional Bott hypothesis assuming all
 2 events are double-couple (DC) sources (Vavryčuk, 2014); whereas, STESI couples the
 3 tensile or compressive motion of crack by including the shear-tensile (ST) source model
 4 proposed by Vavrycuk (2011), in which the inclination angle α (the angle between the
 5 slip vector and the projection of slip vector on the fault plane) becomes the fourth
 6 parameter of focal mechanisms other than strike, slip and rake (Fig. 11). Therefore,
 7 STESI provides improved accuracy when dealing with sources that have volumetric
 8 changes. For a detailed description of these methods, refer to papers by Vavryčuk (2014)
 9 and Jia et al. (2018b).

10 Double-couple (DC) source Shear-tensile (ST) source

11 Figure 11. Schematic diagram of a double couple (DC) source model (left) and shear-
 12 tensile (ST) source model (right), where $\mathbf{u}$ is the slip vector, $\mathbf{n}$ is the fault normal vector,
 13 and α is the inclination angle. The main difference between these two source models is
 14 that the slip vector of a DC source is constrained within the fault plane ($\alpha = 0$).

15 The events were separated into a shear dominated domain and a ST dominated
 16 domain based on their corresponding α values (Jia et al., 2018b):

17 $|\alpha| \geq 30^\circ$ indicates ST source

18 $|\alpha| < 30^\circ$ indicates shear-dominated source.

19 Note that, depending on the polarity, a ST source can contain either tensile opening or
 20 compressive closing. Out of the 57 inverted MTs, 21 are ST source, and the rest are

1 shear-dominated sources. This is in a good agreement with the result revealed by the
 2 Hudson's plot in the previous section, confirming that 30° is a suitable selection for the
 3 classification boundary between the ST and shear dominated sources.

4 Figure 12 displays event locations colored by the source domains. The ST
 5 dominated events (light blue) mainly occur in the upper portion of the shear band,
 6 whereas the shear dominated events (dark blue) are more scattered. As the shear failure
 7 zone formed from the top to the bottom, this again demonstrates that ST events
 8 dominate the failure-initiation process.

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11 Figure 12. Locations of events with moment tensors, colored by the failure modes: blue
 12 indicates shear tensile dominated events and red indicates shear dominated events.

13

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Shear Dominated Events ST Dominated Events

Figure 13. Rose diagrams of strike direction for the shear-dominated events (left) and shear-tensile (ST) dominated events (right). Strike is measured as the angle between the inferred failure plane and the $+x$ -axis.

Based on the Griffith and Mohr Coulomb failure criteria, the nodal plane that has a higher tendency to fail out of the two nodal planes is selected as the fault plane (Jia et al., 2018b; Vavryčuk, 2014). The strike directions, signifying the angle between the selected failure plane and the $+x$ -axis shown in Fig. 2, are plotted in the rose diagrams in Fig. 13. The strikes of shear-dominated events are scattered, whereas the strikes of ST dominated events show a pattern: a majority of the events are orientated within the azimuth ranges of 120° to 150° and 300° to 330° from the $+x$ direction. The large variation in terms of the strikes of shear-dominated events is possibly due to: (1) the deformation-induced local stress fluctuations, and (2) the interactions between the main failure plane and pre-existing weak planes (especially the sliding of weak planes).

Fig. 14 shows stereoplots of the principal stress orientations for shear dominated events calculated by STRESSINVERSE (top), and ST dominated events obtained from STESI (bottom). The scatter in pole directions provides an indication of uncertainty and is produced by the noise sensitivity analysis (Jia et al., 2018b) aiming at quantitatively

1 assessing the susceptibility of the dataset when subjected to noise. Random disturbance
2 acting as arbitrary noise with an average deviation angle of 5 degrees are added to the
3 fault normal ($\mathbf{u}$) and fault slip ($\mathbf{n}$) vectors of each event to create ‘noisy’ dataset,
4 followed by the stress inversion process. This runs repeatedly for 100 times, and each
5 iteration generates one reduced stress tensor. Therefore, an overall of 100 stress tensors
6 are produced to form the clusters defining the confidence limit as shown in Fig. 14
7 (Vavrycuk, 2014).

8 For shear dominated events, σ_1 and σ_2 deviate from the vertical and horizontal
9 directions by approximately 30° , indicating a non-Andersonian faulting regime
10 (Anderson, 1951) that differs from the actual stress condition that was applied to the
11 sample. This discrepancy could be resulted from the varying strike orientations of
12 shear-dominated events that are not representative of the applied stress directions for
13 inversion (Jia et al., 2018b). On the other hand, for ST events, the inversion results
14 reflect the applied stress orientations more closely: the principal stresses only slightly
15 deviate from the vertical and horizontal planes, and σ_1 is in the sub-vertical direction.
16 The clusters of the two horizontal principal stresses are scattered because the algorithm
17 cannot distinguish them as the confining pressure is constant around the sample.

18

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4 Figure 14. Stereoplots showing scatter of the principal stress directions retrieved by
5 STRESSINVERSE for shear dominated events (top) and STESI for ST dominated
6 events (bottom). The actual σ_1 is applied in the vertical direction and the confining stress
7 ($\sigma_2 = \sigma_3$) is in the horizontal direction.

8

9 **5.0 Discussion**

10 The shear fracture generated in this experiment does not follow the typical orientation
11 of shear plane defined by Mohr-Coulomb failure criterion i.e., $45^\circ + \Phi/2$ with respect
12 to σ_3 , where Φ is the angle of internal friction, estimated as approximately 35° from
13 previous experiments conducted on this type of materials (McKean, 2017). As signified
14 by the microscopic image (Fig. 6), this slightly more inclined fracture plane could arise

1 from the influence of the pre-existing weak planes, or from the interactions between the
2 tensile and compressive fractures which tends to occur under a low confining stress
3 (Yang et al., 2012). On the other hand, the AE hypocenters exhibit a slightly different
4 inclination angle (Fig. 8). This discrepancy may be caused by the relatively low signal-
5 to-noise ratio of the waveforms and the use of a time-invariant velocity model.

6 The sensors were calibrated on an aluminum block, which means that the
7 sensitivity of the sensor was best suitable for aluminum instead of the rock sample;
8 however, we remark that similar setups have been used in previous studies (Sellers et
9 al., 2003; Goodfellow et al., 2015). Additionally, the accuracy of moment tensor
10 solutions (especially those with large non-double-couple components) may be affected
11 by various factors, such as the noise, the intrinsic and stress-induced anisotropic effects
12 (Aker et al., 2014). Sample anisotropy was neglected when constructing the Green's
13 function, which is a source of uncertainty in our analysis. Other sources of error for this
14 AE analysis include sensor (mis)calibrations, anisotropic/heterogeneous properties of
15 the sample, the use of a time-invariant velocity model in the presence of time-dependent
16 changes in the velocity field, inaccuracy of the velocity along the axial direction of the
17 sample, uncertainties in first-arrival and amplitude picking, and the use of single-
18 component (versus three-component) sensors.

19 Under in situ conditions in the subsurface, the medium would most likely be in
20 a fully saturated state with formation brine, hydrocarbons or some combination of these
21 fluids filling the pore space. The influence of pore fluids on the bulk properties of a
22 poroelastic material are well established (Biot, 1962). A recent lab study shows that
23 water saturation state also influences the initiation and propagation of hydraulic
24 fractures in granite, with higher AE count before and after breakdown in the saturated

1 samples compared to unsaturated samples (Zhuang et al., 2020). For upscaling results
2 of this study, these effects should therefore be considered.

3 The progression of failure in the Montney siltstone observed in this study is
4 notably different from previously published results in granite and sandstone (Lockner
5 et al., 1991, 1992). The fractures that formed in the siltstone contained some small
6 fractures that deviated in orientation from the main failure plane. In addition, the AE
7 cluster that formed after crack nucleation in Montney is spatially diffuse, whereas in
8 granite the AE hypocenter distribution typically indicates a clear planar shear fracture.
9 Possible explanations for these discrepancies are discussed below: (1) the shale material
10 is anisotropic under a low confining stress (10 MPa), which may affect the orientation
11 of fracture growth (Yang et al., 2012); (2) the high-density grains (bright spots in Fig.
12 1) forming heterogeneity can influence stress distributions and strain localization
13 processes (Saroglou & Tsiambaos, 2008). It is possible that the location uncertainty can
14 could be a factor in the diffuse nature of AE activity. However, as the maximum
15 hypocenter uncertainty is within 2 mm, considering the uncertainties in origin time and
16 the RMS residual of 0.34 μ s between the measured and theoretical arrival times, this
17 means the diffuse event distribution cannot be entirely explained by location
18 uncertainty.

19 Other distinct characteristics of AE activity in Montney siltstone include the
20 following: no event was detected until approaching the peak stress; and, the AE signals
21 from fine-grained sedimentary rocks showed a lower signal-to-noise ratio than that of
22 granitic rock and sandstone. Similar phenomena were reported in other studies. Liang
23 et al. (2016) found out the energy and signal-to-noise ratio of AE events were low from
24 shale samples. In the AE tests conducted by Li et al. (2015), no significant AE activity

1 was recorded before the nucleation and fracturing phases from shale. This could be
2 improved by reducing machine background noise, implementation of more accurate
3 sensor calibration (e.g., calibrated on the rock sample, not on aluminum), and higher
4 sensor coverage.

5 However, based on the discrete element model developed by Jia (2019), AE
6 events started to occur at approximately 50% of the peak stress, indicating the energy
7 of these early cracking events might not be sufficient to trigger the recording system.
8 Naoi et al. (2018) experimentally proved that with the same extent of fracturing activity,
9 less AE events were detected in shale compared to granitic rocks. These may be due to
10 different material compositions and stiffness of materials (Sone & Zoback, 2013). The
11 Montney siltstone sample contains a high percentage of dolomite (Table 1), and
12 dolomite has a relatively low hardness as compared to other minerals (Hurlbut, 1957).
13 This contrast in hardness may reduce the overall stiffness (modulus) and brittleness of
14 the rock. In addition, presence of K-feldspar and plagioclase may contribute to the less
15 brittle behaviour due to their cleavage nature (Hurlbut, 1957). Diffuse AE events of low
16 SNR may be associated with such less brittle behaviour.

17 Analysis of source mechanisms shows that tensile-dominated events occurred
18 first, possibly because a shear failure mode alone is inefficient at generating new
19 fractures without the involvement of tensile failure (mode I) (Petit and Barquins, 1988).
20 Shear faults can originate from the interaction and coalescence of tensile microcracks,
21 causing macroscopic failure (Scholz, 2002; Healy et al., 2006). Compressive closing
22 with a negative α value may have resulted from the collapse of pore space (Vajdova et
23 al., 2004). In addition, the relatively low confining pressure could contribute to
24 generation of tensile fractures followed by shear slippage.

1 In this experiment, shear-tensile events have a higher average magnitude than
2 that of shear events, which is different from some other studies. For example, Kwiatek
3 et al. (2014) discovered events occurred approaching the slip onsets with double-couple
4 source mechanism exhibited higher magnitudes in saw-cut samples. The difference
5 could due to two factors: (1) The sample in Kwiatek et al. (2014) has saw cut, so the
6 majority of events could be caused by slippage along the pre-existing failure plane; in
7 our case, creating a new failure plane will involve bond breakage, leading to a large
8 component of shear-tensile events; (2) No event was recorded at the early stage of our
9 experiment, which could be due to the sensitivity of the AE sensors.

10 This laboratory-scale experiment provides a proxy for understanding failure
11 processes that can ultimately lead to felt induced events in sedimentary rocks, including:
12 (1) the AE events recorded in the laboratory can be related to macroscopic seismicity
13 through empirical scaling relations (Bunger et al., 2005); (2) in particular, waves
14 emitted by laboratory-scale fractures have higher frequencies than those in the field,
15 implying that sensors used in laboratory experiments should be different than those
16 employed for field studies (Goodfellow and Young, 2014). Although the laboratory-
17 scale fracturing processes have generally similar failure and propagation behaviors as
18 at the field-scale, shear-tensile events with significant tensile components may be more
19 abundant at the laboratory scale as the laboratory sample behaves more homogeneous
20 under a controlled applied stress field whereas the behavior in the field is influenced by
21 presence of natural fractures and localized differential stress (Fisher and Guest, 2011).

22 **6.0 Concluding remarks**

23 Laboratory experiments were performed to examine the nucleation and
24 propagation of failure process inside a Montney siltstone sample under triaxial

1 compression. Ultrasonic-wave measurement, acoustic-emission (AE) monitoring,
2 computed tomography (CT) scanning, and thin section imaging were used as diagnostic
3 tools. The elastic-wave velocity survey indicates that the inherent anisotropy is weak to
4 moderate in the Montney siltstone sample. Stress-induced anisotropy was detected
5 during triaxial loading. Changes in ϵ and γ parameters are more significant in the
6 loading stage of closure of pre-existing cracks compared to other loading stages. The
7 observed AE activity in Montney shale is distinct from the published AE studies in
8 brittle geomaterials such as granite. No AE event was detected until the applied axial
9 stress reached 95% of the peak value. The lack of AE events could be due to the low
10 seismic energy emitted from siltstone, which might be insufficient to reach the system
11 triggering threshold. This could also be the reason for the low signal-to-noise ratio of
12 the waveforms in Montney siltstone.

13 AE data analyses include AE hypocenter determination, source mechanism
14 analysis (moment tensor inversion), and stress inversions based on an isotropic model.
15 The AE hypocenter distribution approximately reproduces the location of the major
16 shear fractured zone, which is consistent with CT images of the failed sample. The
17 failure zone is a diffused, step-like structure consisting of a major shear fracture and
18 branched micro and minor cracks. The inclination angle of the failure zone is steep,
19 which may arise from the induced shear dilation inside the failure zone at low confining
20 pressure.

21 In terms of source mechanisms, the number of crack-opening (tensile) events is
22 almost equal to the number of crack-closing (compressional) events. Nucleation and
23 growth of a prominent shear fracture are initially dominated by microcracks that failed
24 under tensile, opening from the upper portion of the sample. Stress inversion analysis

1 indicates that the shear-tensile (ST) dominated events provide a better representation of
2 the principal stress orientations imposed by the applied stress, whereas for shear
3 dominated events, the results deviate from the true stress condition as the orientations
4 of shear fractures are quite scattered.

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15 **Data Availability**

16 The data underlying this article will be shared on reasonable request to the
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