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Statistical characteristics of microseismic events and in-situ stress in the Horn River Basin

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Summary
Brittleness index, log-derived stress and microseismic statistics are commonly used in order to analyze the effect of a layered structure in the sedimentary infilling on hydraulic fracturing treatments. We compare and contrast these measurements. The analysis is applied to a case study in the Horn River basin. Vertical variations of the *b* and *D* values, the brittleness index and the in-situ stress are calculated and compared in order to highlight any possible relationships between fracturing, microseismicity and layering. We show that variations in *b* value correlate with the layered structure. This may be due to reactivation of preexisting fractures that are concentrated in some layers. However this is not confirmed by the *D* values that do not significantly change as a function of the layering. The *b* value is also linked to the in-situ stress. It is positively correlated to the minimum horizontal stress, and anti-correlated to the differential stress. Brittleness on the other hand is positively correlated to the differential stress and anti-correlated to the b-values.

Introduction
In hydraulic fracturing, a fluid is injected into a target formation in order to increase the inter-connected permeability. The increase in permeability results from fracture nucleation and the reactivation of pre-existing fractures. Identifying the characteristics of the fracture network and the underlying parameters leads to improved understanding of well performance. The characteristics of the fracturing may be assessed by studying the microseismic events that are induced by the fluid injection. Notably, the *b* and *d* values represent statistical characteristics in the distribution of magnitudes and spatial hypocenter locations of microseismic events, respectively. The *b* and *D* values are usually higher than 1 during hydraulic fracturing treatment. This indicates a relative abundance of small magnitude relative to large magnitude events, compared to naturally occurring earthquake populations ($b \approx 1$). In a specific site, *b* and *D* values may be correlated to the lithological layering due either to their dependence to the in-situ stress [*Scholz 1968*], or due to reactivation of preexisting fractures that may be concentrated in some layers [*Maxwell et al., 2009*]. In this paper, we assess the vertical variation of the *b* and *D* values for a case of hydraulic fracturing treatment in the Horn river Basin. We compare these variations to the in situ stress and the brittleness index calculated from well data in order to highlight relationship between fracturing, microseismicity and layering.

Case study
The field example is located northeast of Fort Nelson, British Columbia, in the Western Sedimentary Basin of Canada. Hydraulic fracturing treatment targets two shale members of the Horn River formation: the Evie, and the Muskwa members, separated by the Otter Park member (Fig. 1). The Horn River

formation lies above the carbonatic Keg River formation and under the shale of the Fort Simpson formation. The stimulations consist of alternated multiple stages of hydraulic fracture treatments for gas production. Microseismic data are acquired by real time monitoring by vertical sensors arrays. A total of 23,000 events have been mapped (Figure 1). Most of the stages show a well-defined planar structure with an average principal azimuth that is consistent with the direction of the maximum horizontal principal stress (N50°E to N55°E). The vertical event distribution is relatively homogeneous. The number of events is always great around the injection depths and decreases downward and upward (Figure 1). A large proportion of the events are concentrated in the Horn River Formation and their number drops in the Keg River and Fort Simpson Formations. The downward growth of the distribution of events into the Keg River is induced by the hydraulic stimulations performed into the Evie and it reaches greater depth than the upward growth. This may explain the slightly shorter fracture lengths in the Evie when compared to the Muskwa because less fluid volume is available to generate fracture length. Event magnitudes range from -3.5 to -0.5. They were noticeably higher in events located deeper in the Keg River formation.

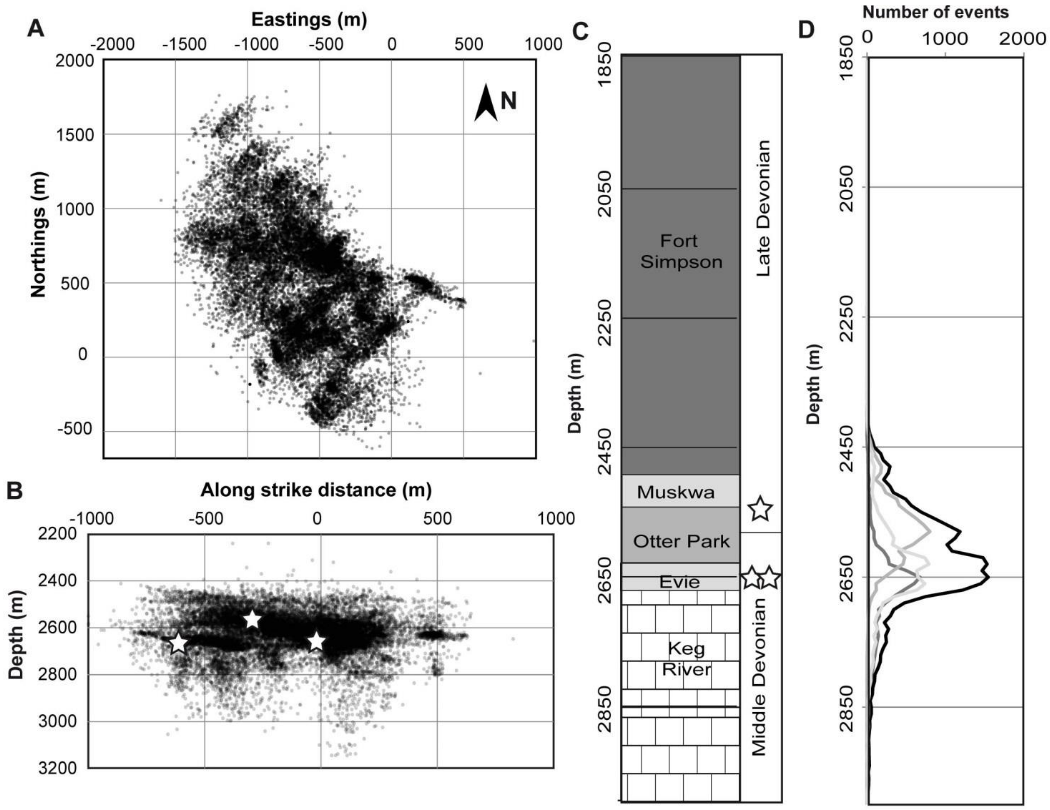

Figure 1: Distribution of the microseismic events and lithological layering of the field example. A and B show the distribution of the microseismic events in map view and cross-section along the direction of longest elongation of the microseismicity (N050), respectively. C: Stratigraphic section showing lithological sequence. D: Depth distribution of the microseismic events. The grey curves representes the ditributions for the 3 wells and the black curve represntent the totality of the events. In B and C the perforation zones are indicated with white stars.

Theory and Method

Magnitude and spatial distributions of microseismic events are described by power-laws and quantified by the *b* and *D* coefficients of these power-laws, respectively [*Grob and Van der Baan, 2011*]. The vertical variations of the *b* and *D* values are computed using moving windows of 800 events with a step of 200 events after sorting all events according to depth. The *b* and *D* values are calculated by fitting in a least-square sense the magnitude and spatial distribution curves of the 800 events in each window with the adequate power-law. The depth dependence of the dynamic elastic parameters, Young's modulus and Poisson's ratio, are calculated from the density and the compressional and shear wave velocities, assuming isotropic properties and following the methodology presented in *Roche et al, [2014]*.

The dynamic elastic parameters are used to calculate the vertical variation of the brittleness index, following the methodology presented in *Rickman et al., [2008]*. They are also used to assess the in-situ stress profile assuming a normal stress regime. The calculation takes into account the overburden, the pore pressure and a horizontal tectonic solicitation. The tectonic effect is calculated using a model of strain solicitation [*Blanton and Olson 1999*]. We postulate that the tectonic solicitation only occurs in the direction of the minimum horizontal principal stress and the tectonic solicitation in the direction of the maximum horizontal principal stress is negligible. The magnitude of the tectonic solicitation is calibrated on in-situ stress measurements. We assume an initial lithostatic state of stress before the tectonic solicitation. This is different from the standard method that used an initial uniaxial state of stress [*Blanton and Olson 1999*]. Similar trends are obtained assuming an initial uniaxial, or a lithostatic state of stress, but the magnitude of the layer to layer stress changes due to tectonic effects are maximized in the case of an initial lithostatic state of stress.

Results

The Keg River Formation exhibits a higher brittleness index than the Horn River Formation (Figure 2A) and should therefore better promote fracturing. Conversely, the Fort Simpson Formation should inhibit fracturing because of a lower brittleness index than in the Horn River Formation. Although the magnitude of the variation is weak, the Otter Park should also act as a mechanical barrier compared to the Muskwa and Evie formations.

The extensive strain regional solicitation applied in the direction of the minimum principal stress is equal to -0.94 mm, assuming an initial lithostatic state of stress and calibrated with the in-situ stress measurement. The minimum horizontal stress therefore decreases due to the tectonic solicitation. These decreases are more important in the Keg River (-47 MPa) than in the Horn River formations (-32 MPa) and the Fort Simpson formations (-20 MPa) (Figure 2B). Likewise, the decrease is slightly lower in the Otter Park member than in the surrounding Muskwa and Evie members. Hence, the tectonic solicitation involves a decrease in stress downward from the Horn River Formation to the Keg River Formation and an increase upward in the Fort Simpson Formation. Likewise, the intermediate Otter Park member exhibits a higher stress than the surrounding target formations. Conversely, the differential stress (that is the vertical stress minus the minimum horizontal stress for a normal stress regime) increases downward through the layered section. These variations of the in-situ stress are coherent with the mechanical behavior highlighted by the brittleness index.

The *D* values range from 1.86 to 2.56 with an average value of 2.14 (Figure 2C). The *D* value is barely related to the layering. It may slightly decrease in the lower section of the Otter Park Formation and the Evie members may exhibit more oscillation than the rest of the section. The *b* values range from 2.94 to 0.87 with an average value of 1.7. A similar range has been described in the Horn River basin [*Hurd and Zoback 2012*]. Contrary to the *D* value, the *b* value is correlated to the layering. The *b* value steeply decreases with depth. The maximum value, equal to 2.86 on average, is obtained in the Fort Simpson formation. The Horn River formation is characterized by an intermediate value with significant vertical variations. The *b* value is high (between 2.32 and 2.27 on average) in the Muskwa and the upper section of the Otter Park. It significantly decreases to 1.5 and 1.4 on average in the lower section of the Otter Park and the Evie members, respectively. The minimum *b* value, equal to 1.1 on average, is obtained in the Keg River Formation.

In the case study, the *b* value decreases downward from values around 3 to values around 1. The main decrease occurs in the lower section of the Otter Park Formation, where *b* values decrease from 2.3 to 1.5. This decrease may indicate that the events are associated to reactivation of preexisting fractures in the Evie members and the Keg River Formations, whereas fracture nucleation occurs in the upper section. However, the *D* value is approximately constant at ~2 throughout the section. This indicates an event distribution shaped over a 2D plane. The lack of variation of *D* values along depth might indicate that the event spatial distribution is constrained by the layering (events mainly happening along interfaces between layers) and/or happen mainly along fracture planes. Likewise, no significant difference in the distribution of microseismicity is observed between the treatments of the Muskwa and the Evie members.

The changes in *b* value might also be correlated to the in-situ stress variation. Higher *b* values are obtained in layers with lower minimum principal stress and higher differential stress, like in the Keg River formation. Conversely, lower *b* values are obtained in layers with higher minimum principal stress and lower differential stress, like in the Fort Simpson formation. These results are consistent with those obtained by *Scholz et al. [1968].* The slight decrease in *b* values that occurs between the Otter Park and the Muskwa members also corresponds to a decrease in the minimum horizontal stress. The exception is the Evie member that exhibits low *b* values for a relatively high minimum principal stress.

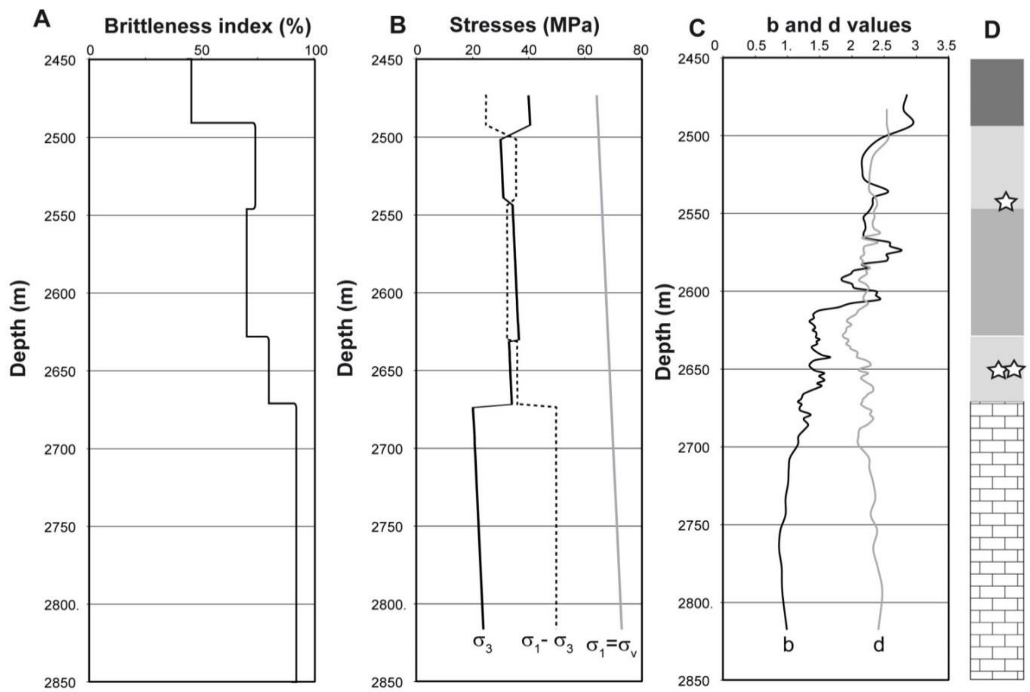

Figure 2: Depth variation of the brittleness index (A), the in-situ stress (B) and the *b* and *D* values. The lithological section is presented in D.

Conclusion

In our case study of a Horn River reservoir the increase of the differential stress with depth favours fracturing. The corresponding decrease in *b* value indicates that this favoured fracturing happen mainly through the reactivation of faults, whereas at shallow depth induced microseismicity is the dominant behaviour. The lack of variations in the spatial distribution of events as quantified by the *D* value steady around 2 seems to indicate a constraining effect of the layering in the top part of the reservoir and is consistent with fault reactivation in the lower part. To confirm the results, future work will include stress inversion from event moment tensors to compare with the stress variations inferred from log data.

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