Monitoring In A Western Canadian Shale Play With A Sparse Surface Network: Moment Tensor Analysis Implications

Kit Chambers\textsuperscript{1}, Bogdan Batlai\textsuperscript{2}, Brad Bialowas\textsuperscript{2}, John Nieto\textsuperscript{2}, Dario Baturan\textsuperscript{1}

1 - Nanometics Inc., 250 Hertzberg Av. Kanata, Ontario
2 - Canbriam Energy Inc., 2100, 215 2nd Street SW, Calgary, AB Canada

Summary

We present results from monitoring the stimulation of 4 wells using a sparse surface network of three-component instruments in a the western Canadian Montney formation. Focusing on the results from moment tensor inversion, we interpret this data set in the context of hydraulic fracture seismicity. During the treatment a total of 7237 events were identified based on P and S arrivals of which full moment tensors were computed for 1960 sources. The temporal and spatial distribution of the events along with their B-value is consistent with hydraulic-fracturing related rather than induced seismicity. The events partition into two groups separated by an aseismic gap. The largest group consists of events occurring near the wellbore, whilst the second group occurs to the north east. Throughout the entire data set we observe similar trends in terms of; event timing, relationship to stages, waveform characteristics and orientations, for both groups of events, which in turn is suggestive of a common causative mechanism for both groups.

The decomposition of computed mechanisms suggests that the sources are pure double-couple failures and that observed non-double couple components can be attributed to the influence of noise in the inversion process. The mechanisms are primarily dip-slip/horizontal-slip (DSHS) style sources with a consistent polarity, however, there are notable exceptions where the mechanism polarity is reversed. The existence of mechanism polarity reversals is shown to be robust through the analysis of station gathers. Whilst the observation of polarity reversals excludes a common interpretation for microseismic events, that they are consequent of a pre-existing stress field and their movement is triggered through the reduction of normal stress on a discontinuity. Instead our results are consistent with the source mechanisms being related to the stress field associated with the hydraulic fracture. As the hydraulic fracture grows it alters the stress state in the surrounding rocks, and as such creates favorable conditions for slip on weakness planes (such as bedding planes or joint surfaces) which would otherwise be stable. Our observations illuminate several aspects for this style of faulting. In particular, the separation of event groups could be due to fluid transfer along conduits where there is no seismic deformation, and the distribution of mechanism polarities may be related to the interaction of the local fracture and a regional stress field.
Introduction

As in other shale plays microseismic surveys have become an invaluable monitoring tool in the Western Canadian Sedimentary Basin. Typically, this region is considered emissive and is characterized by horizontal stresses equal to or greater than the vertical stress. Furthermore, the remote and quiet nature of the area makes the region ideal for surface microseismic monitoring using sparse networks.

Traditionally microseismicity resulting from hydraulic fracture stimulation has been interpreted in the following way; as the fracture proceeds the pore-pressure in the formation surrounding the frac is increased, and this increase in pore pressure causes a reduction in the normal stress on pre-existing pre-stressed discontinuities such that they fail and the resultant microseismic events are observed. Hereafter we will refer to this model as the pressure leak-off model. More recently, an alternative interpretation has been proposed by several authors (Rutledge et al. 2015, Stanek et al. 2013, Wilson 2013), whereby the observed microseismicity is related to the interaction of the stress-field associated with the hydraulic fracture with pre-existing weaknesses in the formation. We will refer to this model as the fracture-stress model for microseismic events.

The discussion of pressure leak-off vs fracture-stress is still very much active and it may be possible for both effects to be present in a dataset. However, their difference has important implications for the interpretation of microseismic events. In the pressure leak-off model microseismic events delineate a pressure cloud which encloses the fracture, and microseismic source mechanisms are unrelated to the behavior of the fracture since the source magnitude and orientation is determined by the projection of a regional stress tensor onto a pre-existing failure surface. Under the fracture-stress model the source positions reflect the extent and magnitude of the stress perturbation caused by the fracture and their mechanisms and magnitudes reflect the position of the source relative to the fracture and the orientation of the activated feature. Thus under the fracture-stress model the microseismic activity is more directly related to fracture properties such as height and width and furthermore this model predicts that the orientation of the source mechanisms reflects the orientation of the fracture stress field. In particular, the fracture-stress model has been used to interpret dip-slip/ horizontal slip style (DSHS) events, which are a feature of many microseismic datasets. These events typically show focal mechanisms with either vertical failure on a vertical plane or horizontal failure on a horizontal plane and as such could be either vertical slip on vertical features like joints or horizontal slip on bedding planes.

In this study we report on observations from a microseismic survey undertaken in the Western Canadian Sedimentary Basin with particular emphasis on the results and the interpretation of moment tensor data. We find that event locations delineate linear features trending away from the perforation positions, and that the mechanisms show DSHS style behavior, with little or no motion aligned with the regional stress field. Moment tensor decomposition shows that the events are pure-shear or double couple sources. We also see frequent polarity reversals in the mechanisms and investigate their robustness through the analysis of station gathers. We find that the results cannot be explained using the pressure leak-off interpretation of microseismic activity instead they are better explained as the interaction of the fracture stress field with pre-existing structures (the fracture-stress model). However, there are aspects to this dataset which complicate this interpretation. Firstly, the magnitude of the observed events is large compared to what might be expected from the fracture-stress model. Secondly, distribution of events together with the presence of an aseismic gap would suggest the effects of fracture stress can be transmitted a considerable distance from the injection point. Finally, we observe an asymmetric distribution of mechanism polarities which requires interaction of the fracture stress-field with either perturbations from previous stages or the regional stress field.
Data and Methodology

The dataset used in this study consisted of 25 3C Broadband sensors. Each sensor was installed in a shallow post hole (1-2 feet) and sanded in for mechanical and thermal stability. Sensors were deployed for a total of approximately 2 months of which there was a 10-day period with hydraulic fracture operations at a 4 well treatment pad in the center of the array. Typical inter-station distances for the array were around 500-1000m, with array aperture of approximately 5km. Thus although the array is sparse compared to some surface monitoring installations it still provides excellent coverage of the focal sphere for events in the target region, particularly when compared with local arrays utilized for induced seismicity monitoring. Initial modelling suggested that a magnitude of completeness of around -1 would be obtained for the array.

Two of the 4 monitored wells were completed using Plug and Perf whilst the others utilized Sliding Sleeve technology. The well pad sits within a relatively stable block bounded to the East by a thrust fault trending NS and strike-slip faults to the North and South trending NW-SE and SE-NW respectively. Figure 1 shows a several well logs for the formation of interest (the Upper Montney), the target intervals for the 4 wells were the C3 and C4 layers, are marked on the figure. Also marked on the figure is the organics layer in the lower C3 near the base of the Mid Montney which has a higher degree of horizontal lamination and is a potential zone for sub horizontal failures. Anisotropic analysis of 3D reflection data in the area also shows the presence of sub vertical natural fractures oriented NE-SW (perpendicular to the well path). Although it is worth noting that there are considerable lateral variations and in general the region around this pad is less fractured compared to other sites in the area.

During the treatment a total of 7237 events were identified using direct P and S picking as well as subspace analysis (e.g. Benz et al. 2015). These events were located using a 3D velocity model for the region based on P and S arrival times. Locations were further refined through the use a double difference re-location methodology (Waldhauser and Ellsworth, 2000). The double difference algorithm has the advantage that it the differences between arrivals times rather than the absolute times themselves in order to solve to hypocentral parameters. This means that the method is not sensitive to inaccuracies in the velocity model which affect neighboring events equally. Such inaccuracies can occur where the overburden is not effectively characterized. Full moment tensors were computed using picked P and S-wave amplitudes for the highest quality events. The amplitudes were picked automatically using the peak of the Hilbert transform, after a low pass filter at 50Hz and a Gaussian mute around the arrival. The picked amplitudes were then used as the input data for a least squares inversion for the 6 independent moment tensor components.

![Figure 1: Well logs for upper Montney formation in the region of interest. The target intervals of C3 and C4 are marked as is the organics layer at the base of the Upper Montney.](image-url)
Results

Event Observations

Figure 2 - Map view of the events used for moment tensor analysis. For reference red lines show the well paths and grey triangles show the position of sensors in the monitoring array.

Figure 2 shows a map view of the event locations for the 1960 largest events used for moment tensor analysis. These events represent the largest (Mw -0.5 to +1) and highest quality events in the dataset with arrivals recorded on 21 or more stations. Nearly all (98%) of the observed seismicity occurred during fracture treatments, in particular activity was correlated with the stimulations in the 3 more northern wells, which together with the observed B-value of 1.6 suggest that these events are related to hydraulic fracturing rather than induced seismicity.

The events are organized into linear features trending away from the perforation of the relevant treatment stage. This trend is approximately parallel to the orientation of vertical fractures determined from 3D seismic surveys in the region. The events can also be partitioned into two groups based on their locations. The largest group consists of events near the wellbore (referred to as near well events here after), whilst another group (the isolated group) is separated by seismic gap around Y=1000m.
Mechanisms

Figure 3: Focal mechanism results from the moment tensor inversion. A) map view of the 50 largest events in the near well (black) and isolated (green groups). Orange arrows show the direction of the regional SHmax. B) Histograms of strike dip and rake orientations.

Figure 3 shows histograms of focal mechanism parameters obtained as well as the focal mechanisms for the 50 largest events in each of the groups in map view. We see that the fault plane for both groups are described by a similar style of failure, namely dip-slip/ horizontal slip. That is, vertical slip on a near vertical plane aligned with the orientation of the event distribution to the north east. Alternatively, failure is consistent with horizontal motion on a horizontal plane in a SE or NW direction.

Figure 3 only displays the double-couple portions of the moment tensors. However, a full 6 component moment tensor was solved for for each source allow us to investigate the possibility of failures not consistent with fault plane slip in the results. Figure 4 shows the results of moment tensor decompositions on a lune diagram (Tape and Tape 2012) for each of the two groups. Lune diagrams show the decomposition of the moment tensor into isotropic (explosion/ implosion), CLVD (compensated linear vector dipole) and double couple portions. Isotropic sources plot at the poles, whereas sources with zero volume change are restricted to the equator. Double-couple (or pure shear) sources plot in the center. We see that the population of both events is centered around the pure double couple coordinate. It is also worth noting that in the near well dataset higher magnitude (and hence more robust) events tend to plot closer to the true double couple position.
Figure 4: Lune plots showing the results of moment tensor decomposition. A) shows the near well events whilst B) shows events in the isolated group. Events are colored by magnitude in each group with red being higher.

Example Stages

We now investigate the results in more detail by showing subsets of corresponding to specific stages, in the hydraulic fracture treatment. Figure 5 shows the locations and mechanisms for events in two example stages in the northernmost well. In most of the cases examined events tend to occur on the heel side of the perforations. However, this could be due to velocity model calibration error rather than representative of fracture behavior.

We see that the fault plane orientations are consistent with the overall trend for the dataset, and there are frequent polarity reversals of the mechanisms. The majority of mechanisms are consistent with vertical slip with downward motion to the southeast (or the equivalent horizontal slip mechanism). However, there are a smaller but still significant number showing motion consistent with downward motion to the northwest. These polarity reversals occur abruptly between neighboring events with some intervals of the order of 50m.
In order to investigate the robustness of the mechanism polarity reversals we show vertical component station gathers for two stations using events from stage 9 in the northernmost well (figure 6). In each case the records have been aligned on the P-wave arrivals time at 0 seconds. From the figure we can see that the P-wave polarity changes between events in the dataset. It is also worth noting the presence of a weaker coda arrival some 0.1s after the P-wave. This is most likely related to a multiple or shear wave conversion, in the case of the latter we might expect the conversion discontinuity to be near the source position since the arrival is seen at multiple receivers.

Figure 5: Focal mechanisms for two example stages in the treatment. Red circles show the perforation positions.

Figure 6: Station gathers for events in stage 9 of the northernmost well (figure 5B). Each section shows vertical component traces for each event aligned on the P-wave arrival (just after 0 seconds). Note the frequent polarity reversals in first motion between events. This indicates mechanism reversals between proximal hypocenters. A) and B) show traces sorted by channel offset for two different sensors in the array.
Discussion

During the survey 7237 events were identified and analyzed of which the 1930 highest quality events were used for moment tensor analysis. The timing and B-value observations of the recorded seismicity are consistent with the events being related to the fracture treatment rather than induced seismicity. We find that event locations are concentrated in two broad areas, those near the well and an isolated group, which are separated by an aseismic gap. However, despite their separate locations both groups show similar trends for timing, relative orientation, mechanism and the presence of polarity reversals. This in turn is suggestive of common driving mechanism for both groups.

The moment tensor decompositions show a distribution centered around pure-double couple failure with seemingly random scatter in the non-double couple portions of the decomposition. From previous studies it is well known that the primary effect of noise in the moment tensor inversion process is to create apparent non-double couple components. That in this case we see the distribution of events decompositions centered around a pure double couple mechanism with higher magnitude events showing smaller amounts of non-double couple behavior, suggests that the events in this study are in fact pure shear or double-couple sources and observed non-double couple components can be attributed to the influence of noise in the inversion process.

The determined moment tensors show remarkably consistent fault plane geometries. However, the polarities of the source mechanisms are not consistent, meaning that we observe a smaller but still significant number of mechanism polarity reversals. Whilst, it is tempting to dismiss this observation of polarity reversals as an artifact of inaccuracies in data processing or amplitude picking, these polarity reversals are also visible in the P-wave arrival at stations for neighboring events. This phenomenon is not limited to a particular station or event geometry and occurs throughout the data set, thus we consider the observations of mechanism polarity reversals to be robust. Furthermore, this observation is incompatible with the pressure leak-off interpretation of microseismicity, since it requires the projection of a regional pre-existing stress field onto a fault surface to be reversed. In order to create the polarity reversals we require the presence of a gradient and or rotation in the governing stress-field active over length scales comparable with the event distribution.

However, the fracture-stress interpretation of microseismicity is compatible with the presence of polarity reversals. Since in this case the source for the stress-field is proximal and we would expect to see gradients and rotation of the stress tensor depending on the relative orientation of event to the fracture. Under this interpretation, as the hydraulic fracture grows it alters the stress state in the surrounding rocks, and as such creates favorable conditions for slip on weakness planes which would otherwise be stable. Thus the observed DSHS mechanisms are related to movement on vertical weakness planes such as joint surfaces or horizontal planes such as the bedding planes.

In the case of bedding plane slip it might be expected that event depth would correlate with a specific boundary. In this case the most likely candidate is the organics layer at the base of Upper Montney, which is known to be a zone of weakness. In this experiment typical location accuracy is 50m laterally and 75m in depth, however, this includes errors due to the velocity model and static corrections which do not influence the relative position of events. Thus the precision of the locations after double difference is improved to approximately 30m. However, this level accuracy is still in insufficient to place activity at a specific boundary, so we are unable to confirm or deny the hypothesis that the failures are related to bedding plane slip at the base of the Upper Montney. Hopefully future studies will be able to address this question.

Nonetheless our observations illuminate several aspects for this style of faulting. The magnitude range of the observed events (Mw=-0.5 to +1.0), whilst large compared to other plays, is typical for events associated with hydraulic fracturing in this area observed using sparse surface networks. Together with standard scaling relationships the magnitude range suggests failure dimensions of around 10-100m and slips of 1mm for these events. In the case of slip on a horizontal plane, this would be related to the seismic signature of horizontal fracture expansion, and vice versa for a vertical plane.

The distance of events from the injection point and their separation by an aseismic zone is also unexpected. In the case of a fracture-stress model, we would expect the events to mark out the sides of the fracturing region and form a continuous progression of events away from the injection point. However, this is not observed, instead we see near
well events and isolated event groups with very similar features separated by an aseismic gap. One possible explanation is that there was fluid transfer through the aseismic region along pre-existing conduits where there is little or no seismic deformation. If this is the case then the isolated events could mark a transition to a region more prone to brittle failure with favorably oriented weakness planes. That the position of the isolated group matches with a region of increased vertical fracturing determined from 3D seismic may support this.

Finally, the asymmetrical distribution of mechanism polarities presents another puzzling aspect of this dataset. A local stress field source (such as a hydraulic fracture) acting in isolation might be expected to produce equal proportion of the different polarity mechanisms. That we are seeing different portions of the positive and negative polarity events might be explained in a number of ways; if the failure occurs on very shallow dipping boundary then we might expect that failure in the down dip direction would be promoted. However, although this dip might be to subtle to be resolvable in an individual source mechanism we would expect to see such a pattern in the population of the nodal planes shown in figure 3B. Another possible explanation would be that the reversed polarity events are related to a small amount of fracture closing towards the end of the treatments. However, no such relationship was observed.

Instead we believe that it is more likely that the asymmetry in the event polarities is created by stress shadow effects. For example, the stress perturbation from prior completions may have created conditions which favor a particular orientation over the other. A similar effect could be caused by the presence of a regional stress field. Although the regional SHmax is in the null space of the double couple stress tensors for the events, there may still be other components to the regional stress field which result in a non-isotropic shear stress in the plane of the event failures. Such a residual regional shear stress might create conditions which promotes failure in one direction at the expense of the other direction.

Conclusions

We have analyzed data recorded during the treatment of a 4 well pad in the Western Canadian Sedimentary Basin. Based on the analysis of event timings, magnitudes and B-values we established that the observed seismicity was related to the hydraulic fracture treatment rather than being fault reactivation or induced seismicity. The event geometries show that they are organized into linear features trending perpendicular to the well bore and parallel to the regional trend for vertical fractures and maximum horizontal stress.

We find that the event mechanisms are consistent with pure shear or double-couple sources and we believe that the presence of non-double couple components can be attributed to the influence of noise in the inversion process. The fault planes associated with the event mechanisms show a high degree of consistency being dominated by DSHS style sources with the orientation of the mechanisms such that the vertical plane strikes NE/SW in a direction parallel to the event distribution.

We also see frequent cases where mechanisms show reversed polarity and the presence of these features is shown to be robust though the analysis of station gathers using groups of closely spaced events. The presence of mechanism polarity reversals is not consistent with the pressure leak-off interpretation of microseismic events, and instead suggests that the microseismic events are related to the interaction of the stress field from the fracture with pre-existing discontinuities. However, despite the fracture stress interpretation’s success in explaining mechanism polarity reversals there are several other aspects to this dataset which are illuminating. Firstly, although the observed magnitudes are in the typical range for events associated with hydraulic fracturing in this area, standard scaling relationships the magnitude range suggests failure dimensions of around 10-100m and slips of 1mm, which would be related to the seismic signature of horizontal fracture expansion and vice versa for the vertical plane. Secondly, the distance of events from the injection point and their separation by an aseismic zone is unexpected and might be explained by fluid transfer through a region along pre-existing conduits where there is little or no seismic deformation. In which case the isolated events mark a transition to a region more prone to brittle failure with favorably oriented weakness planes. Finally, the asymmetrical distribution of mechanism polarities presents another puzzling aspect of this dataset as a local stress field source (such as a hydraulic fracture) acting in isolation might be expected to produce equal proportion of the different polarity mechanisms. In order to produce a biased distribution such as that observed we invoke the interaction of the local fracture stress-field with perturbations from pre-existing fractures and or regional stresses.
In summary, we present a data set from the monitoring of 4 well pad in the Western Canadian Sedimentary Basin during hydraulic fracturing. Observations from moment tensor inversion results are consistent with the stress field associated of the hydraulic fracture being the primary causative mechanism for the events, whilst aspects such as the magnitude range, the event distribution, and the distribution of mechanism polarity reversals provide further constraints on the dynamics of the fracturing process. As such our dataset provides valuable information for the ongoing discussion of the interpretation of microseismic events and their relationship to the hydraulic fracturing process.

Acknowledgements
The authors would like to thank Canbriam Energy Inc for permission to publish this work and also Emrah Yenier, Andrew Reynen, Michael Laporte, David Shorey and William Parrales for assistance and constructive discussions in preparing this work.

References

Stanek et al. 2013, “New model explaining inverted source mechanisms of microseismic events induced by hydraulic fracturing”, SEG expanded abstracts.


