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What Can Discrete Fracture Network Analysis Tell Us About Induced Seismicity In The Montney Formation?

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Introduction

The increasing occurrence of induced seismicity at felt magnitudes and above, is well documented (Atkinson et al. 2016, Bao and Eaton 2016). In the Western Canadian Sedimentary Basin and particularly the Montney Formation, the majority of the observed events have been related to hydraulic fracturing operations. This is in contrast to the widely reported events in Oklahoma, where sustained wastewater injection has been linked with seismicity up to magnitude 5.7 near Prague in 2011 (Walsh and Zoback 2015). In both cases, the larger induced events were associated with movement upon deeper faulting below the injection layer, with the the Precambrian basement in Oklahoma and Belloy and Debolt Formations in the Montney area being critical contributors.

Given that the geomechanics of pressured water injection related seismicity have been known about for nearly a century (Hitzman 2012), there still seems to be great difficulty in bringing clarity to the situation. The causal pathway behind induced seismic events during hydraulic fracturing is relatively clear (Davies et al. 2013). Pore pressure changes induce stress changes on existing geological structures, triggering shear failure and the generation of a seismic event. The causation process comprises a number of component requirements that are shown in Figure 1. (1) A structure (e.g. a fault) of sufficient size is required (~50m^2-1km^2) in size); (2) That structure needs to be orientated appropriately to experience relatively high shear stresses; (3) The fault has to have a shear strength (ϕ) that could result in slippage, i.e. not a locked ancient fault; (4) The fault needs to be located within a favourable stress field with an adequate pore pressure field; (5) The fault needs to be directly or indirectly connected to a well; and (6) The well has to operationally provide a pressure stimulation.

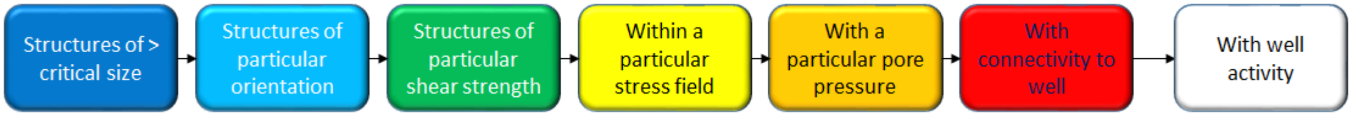

Figure 1: The causation process required to result in an induced seismic event

Given that we can measure many of these features or properties, why is it that understanding this issue remains so challenging? Obviously there is variability and uncertainty in all of the above components but their magnitude is relatively well defined. However the one component that is difficult to measure or predict is connection of the stimulated well to the fault. The source of a pressure perturbation is obvious if the stand off distance between a stimulation and known seismic fault is small. Yet, at greater distances when the connection is indirect as is often the case, understanding the hydraulic pathway becomes a challenge. Many studies of this connection use continuum modelling of poroelastic pressure diffusion (Shapiro 2015). These may be instructive for wastewater disposal but fail to account for the randomness observed in induced seismic events during hydraulic fracturing.

There is considerable anecdotal evidence for the presence of a conductive fracture network in parts of the Montney Formation with pressure connection being observed over scales of up to several kilometres, e.g. Rogers et al 2014. This is a critical component of the induced seismicity causation pathway that has not received significant study to date. There are several key natural fracture characteristics that impact upon the well-fault connectivity:

1. How hydraulic and natural fractures interact to extend the reach of the pressure signal
2. How variable properties of length and permeability within the natural fracture network result in a complex flow field that doesn't behave like a continuum poroelastic system
3. How sub-Montney faults extend up into the Montney and the variable nature of vertical connectivity between fractures in the Montney and these faults

Hydraulic Fracture - Natural Fracture Connection

When hydraulic fractures propagate within a naturally fractured reservoir, the initial induced fracture interacts with the natural structures in two primary ways. Those natural structures intersected by the growing induced fracture will dilate by inflation and take fluid when the pore pressure is greater than the normal effective stresses acting upon them. Additionally those fractures that are critically stressed will experience incipient shear failure and dilation, resulting in the generation of additional permeability. The sheared natural fractures will be less permeable than the inflated ones since their enhanced aperture is simply a function of their roughness and dilation angle (*i*). Thus the hydraulic stimulation can be considered to be comprised of two domains: a primary extensional zone consisting of both the induced fracture and inflated natural fractures and a compressional zone consisting of critically stressed fractures with more limited permeability enhancement due to shearing as illustrated in Figure 2.

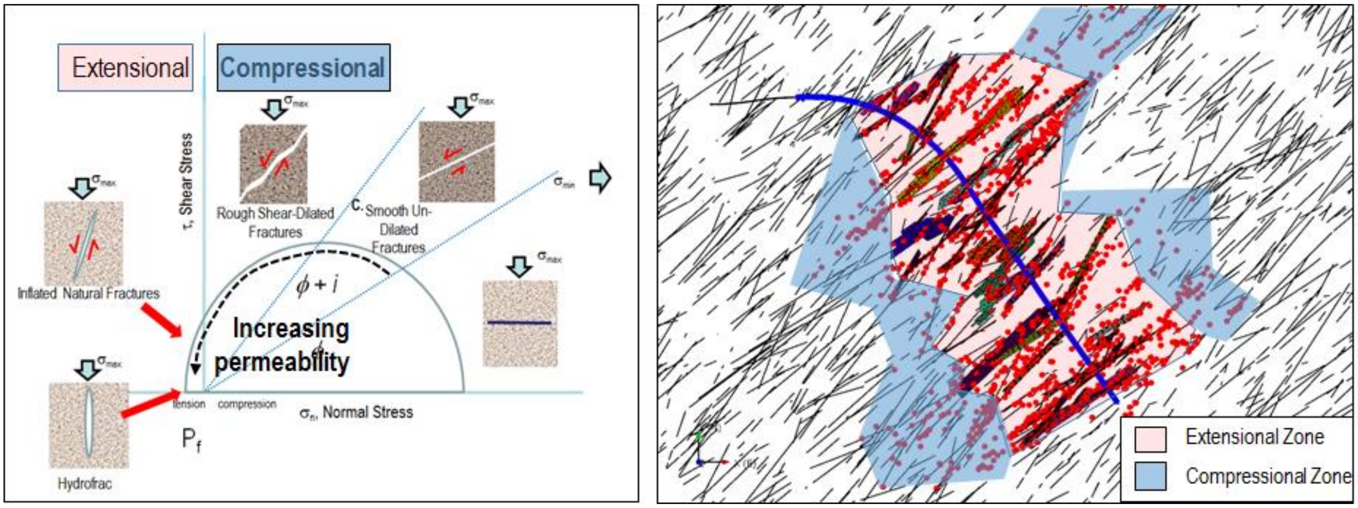

Figure 2: Left, the Mohr circle showing the different fracture components under stimulation conditions and Right, a hydraulic fracture simulation showing the induced inflated fractures (coloured objects) with simulated microseismicity in red. Those points without fracture objects represent the compressional zone of only critically stressed fractures

This implies that the stimulated reservoir volume primarily reflects the extensional zone of the stimulation with an extended fringe of microseismicity representing the compressional zone. This concept is analogous to the concept of 'wet' and 'dry' microseismicity (Maxwell et al. 2015). A wide range of fracture orientations may be critically stressed close to the main induced fracture. However with increasing distance and reducing pore pressure, the range of reactivated fracture orientations becomes quite restricted. Figure 3 shows a Montney example of pressure perturbations far from the well are able to reactivate natural structures. These triggered events are actually quite predictable when a Mohr Circle assessment of critically stress features, the orientation of those features, and the trends of microseismic lineaments resulting from a single stage simulation are considered.

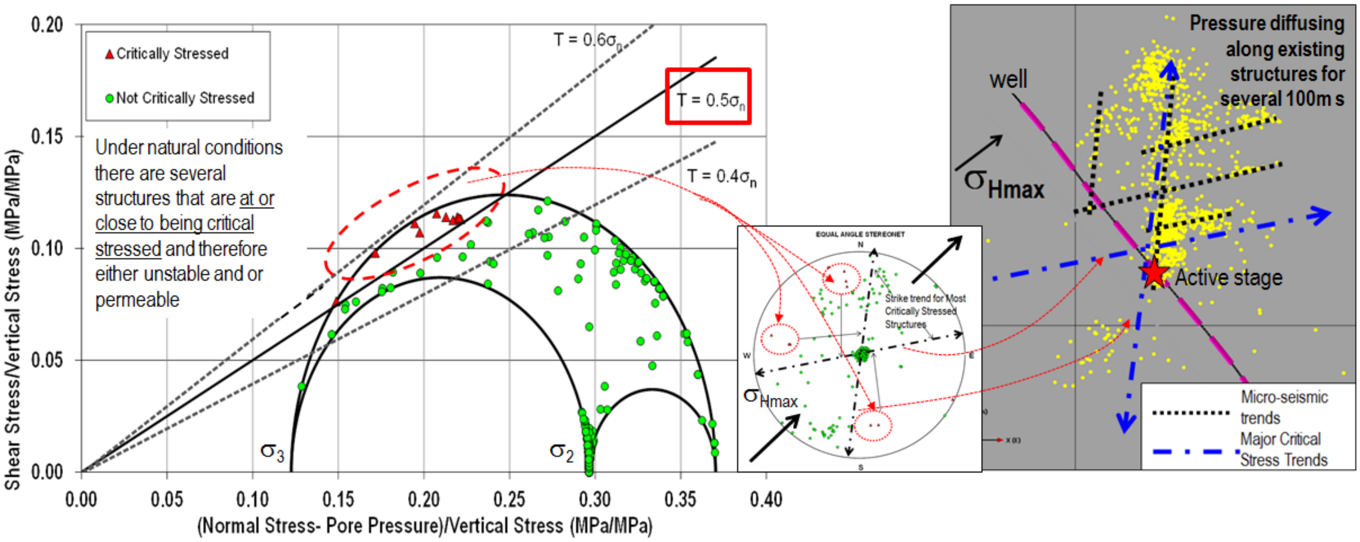

Figure 3: Montney example showing under natural conditions, certain fracture orientations are at or close to being critically stressed, left. When the orientations of those fractures are plotted they can be seen to define two trends, centre, that agree with the main orientation trends seen within the distal microseismic event lineaments (Rogers et al. 2014).

Not all fractures are equal

Conductive structures allow the conduction of elevated pore pressures over considerably longer distances than the actual hydraulic fracture. If the subsurface comprises an extensive and connected fracture network, the pressure perturbation would be wide spread, and induced seismicity more predictable. However fractures in the subsurface have variable permeability, often correlated with fracture length, which results in a very heterogeneous distribution of pressure. A significant difference between matrix and fracture communication is the highly diffusive nature of the fracture connections (high permeability, low storage). This means that strong pressure signals can be transmitted rapidly over considerable distances compared to matrix transmission, where the higher matrix volume means that the pressure signal is slow and diffusive.

Vertical Connectivity to the Deeper Faults

Virtually all of the large induced seismic events reported in the Montney are associated with faulting within the Belloy or Debolt Formations underlying the Montney. This is consistent with the need for a large fault area (50 m^2 to >1 km^2) to generate a magnitude 3 or greater quake (Abercrombie 1995).

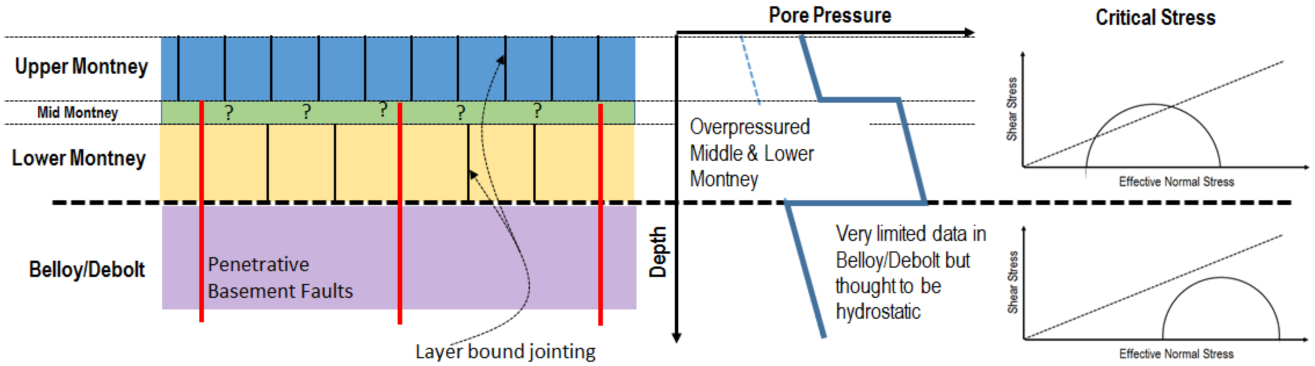

Figure 4: Example generalised conceptual fracture model for the Montney, left and representative pore pressure curve, right

So how does the Montney connect to these deeper faults? Natural fractures of different styles have been observed within both the Upper and Lower Montney Formations. However the larger penetrative faults are typically found to extend downwards from the Middle Montney to various depths several hundreds of metres below as show in Figure 4. This is consistent with observations that larger induced events have typically resulted from stimulation of the Lower Montney.

Whilst the faults may extend downwards into the Belloy/Debolt, the stability of these faults becomes more complex when we consider typical regional pore pressures. Since most of the Montney is overpressured, the effective normal stresses acting on faults tend to low enough to make them critically stressed. However a lower pore pressure gradient prevails below the Montney, meaning that the faults are much further from being critically stressed and require a far larger reactivation pressure prior to slipping (Zoback 2010). The actual reactivation pressure will also vary depending on the local fault orientation as relatively subtle changes in fault plane topography as illustrated in Figure 5.

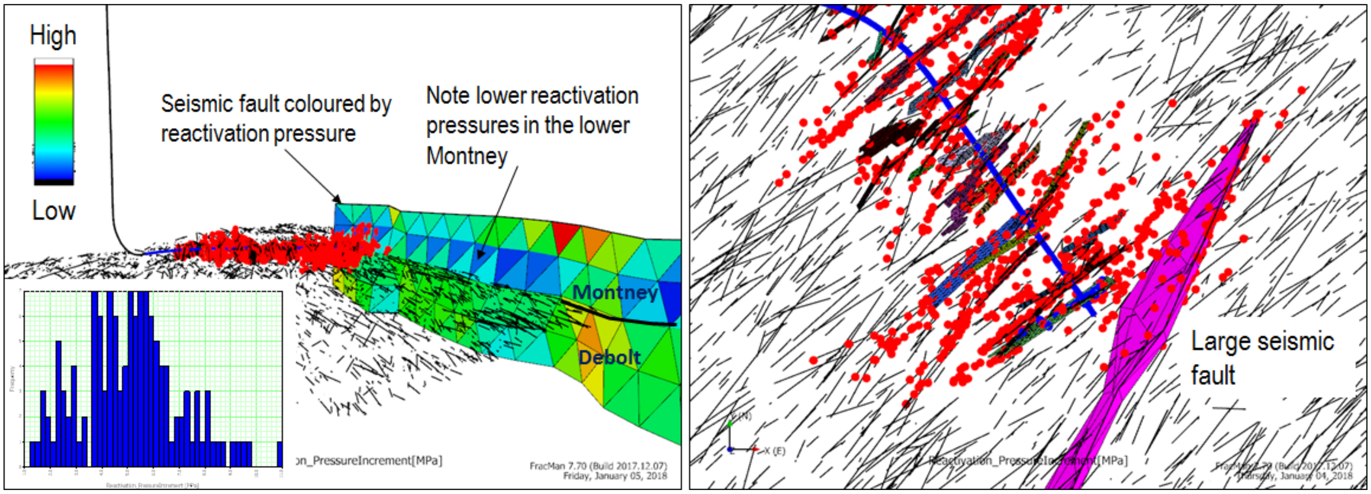

Fig 5: Reactivation pressure on fault to cause slippage as a function of depth and orientation, shown also on the histogram (left) and view of how the fault (purple) may interact with the frac in a complex way (right)

Therefore the response of the fault to elevated pore pressure is dependent on which part of the fault connects back to the well and how permeability is distributed across the fault surface. As mentioned earlier, if the stand-off distance is low, the injection pressure is high relative to the reactivation pressure and the pore pressure is therefore less important. However with increasing distance, the local pore pressure gradient becomes more important.

Summary

The causation process for induced seismicity has been well studied. The largest uncertainty in the process is associated with the pressure communication between the well and larger faults though a connected system of fractures and faults. The nature of this connectivity needs to be evaluated in a discrete way and helps to explain the seemingly unpredictable response of the reservoir to pressure perturbations from well activities. More emphasis needs to be placed on the characterisation and understanding of this structural connectivity as a significant step in the quest to reduce and ultimately mitigate induced seismic events.

References

Abercrombie, R. E., 1995, Earthquake source scaling relationships from -1 to 5 ML using seismograms recorded at 2.5-km depth: Journal of Geophysical Research, v. 100, no. B12, p. 24015–24036, doi:10.1029/95JB02397.

Atkinson, G. M. et al., 2016, Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin: Seismological Research Letters, v. 87, no. 3, p. 631–647, doi:10.1785/0220150263.

Bao, X., and D. W. Eaton, 2016, Fault activation by hydraulic fracturing in western Canada: Science, v. 354, no. 6318, p. 1406–1409, doi:10.1126/science.aag2583.

Davies, R., G. Foulger, A. Bindley, and P. Styles, 2013, Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons: p. 171–185, doi:10.1016/j.marpetgeo.2013.03.016.

Hitzman, M. W., 2012, Induced Seismicity Potential in Energy Technologies: 1-240 p., doi:10.17226/13355.

Maxwell, S. C., M. Mack, F. Zhang, D. Chorney, S. D. Goodfellow, and M. Grob, 2015, Differentiating Wet and Dry Microseismic Events Induced During Hydraulic Theory of Shear Failure, *in* Unconventional Resources Technology Conference: doi:10.15530/urtec-2015-2154344.

Rogers, S., P. McLellan, and G. Webb, 2014, Investigation of the Effects of Natural Fractures and Faults on Hydraulic Fracturing in the Montney Formation, Farrell Creek Gas Field, British Columbia, *in* DFNE 2014.

Shapiro, S. A., 2015, Fluid-Induced Seismicity: 1-276 p., doi:10.1017/CBO9781139051132.

Zoback, M. D., 2010, Reservoir Geomechanics: Cambridge, U.K., Cambridge University Press, 503 p.

Walsh, F. R., and M. D. Zoback, 2015, Oklahoma’s recent earthquakes and saltwater disposal: Science Advances, v. 1, no. 5, p. e1500195–e1500195, doi:10.1126/sciadv.1500195.