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The mechanistical study of the effects of rock stiffness and wellbore orientation with respect to SHmax on induced seismicity: a numerical study

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Summary

In this extended abstract, we will examine different geological parameters including formation mechanical properties (Young's Modulus) and wellbore orientation with respect to the maximum horizontal stress affecting the induced seismicity magnitude frequency distribution.

These parameters are selected based on the results of an in-depth Machine Learning analysis; this analysis was carried out on a compiled dataset on geological and operational parameters throughout the Montney Formation in BC to find the effect of each parameter on the injection induced seismicity distribution recorded in BC for shale gas development. Finally, the goal of this paper is to give insight into the mechanistical reasoning behind each of these parameters. The generic base models are developed for the common geological setting in BC using a new 3-D hybrid lattice and particle-bonded code XSite™ (Damjanac at al., 2016).

Methodology

To better understand the mechanistical reasoning of the effects of each parameter on the magnitude frequency distribution we have developed two generic base models, figure 1. This will allow us to change the parameters and study them separate from each other. Model A (figure 1.a) is the generic model used to study the effects of formation stiffness on induced seismicity behavior. This model can generate large magnitude events (M3<), which happens rarely in during wellbore stimulation in the Lower Montney formation. Model B (figure 1.b) is designed to study the effects of wellbore orientation with respect to maximum horizontal stress. This model can produce typical hydraulic fracturing operation micorseismicity (<M2). The formation and the DFN properties are selected to represent the Lower Lower Montney formation reported by field measurements (wellbore image logging) and laboratory tests on Montney rock samples (Rogers et al., 2015). For a detailed model geometry see table 1.

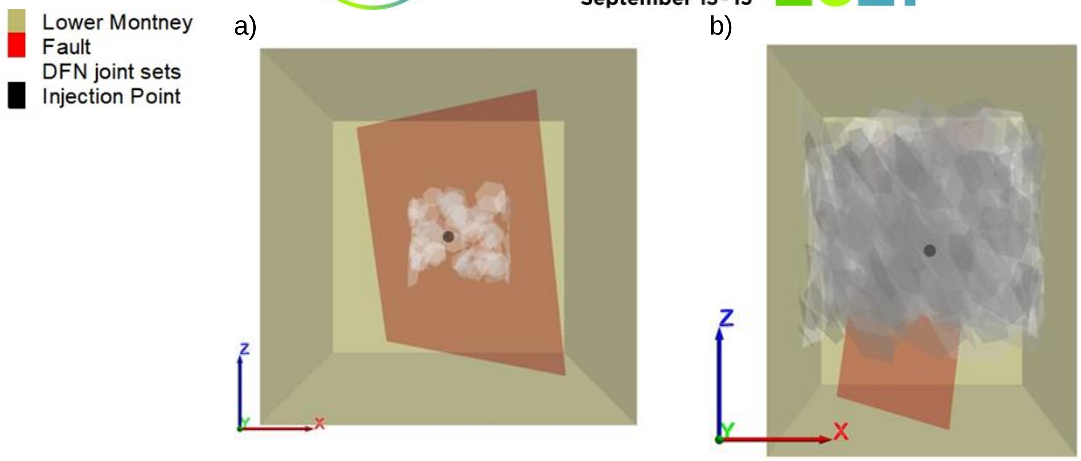

Figure 1. Cross sectional view of two generic models that are used for parameter senstivity analyses in this study.

Table 1. Model A and Model B properties and description (see figure 1).

Property	Description
Model Geometry	1.5x1.5x1.5 km^3 (Model A), 0.6x0.6x0.8 km^3 (Model B)
Fault size	1.3x1.3 km^2 (Model A), 0.4x0.7 km^2 (Model B)
Fault strength prop.	μ = 0.5, c = 0MPa
Injection	Located on the fault (Model A*), Different locations (distanced from the fault) (Model B**)
Sv (Z-axis)	48 MPa ± 0.025 MPa/m
SH(Y-axis)	57 MPa ± 0.017 MPa/m
Sh (X-axis)	42 MPa ± 0.013 MPa/m
Pore pressure gradient	10 MPa/km**
Depth at top of the model	1.9 km
Elastic Properties	E = 32 GPa**, ϑ= 0.22
Matrix Permeability	50 nD
*This is the worse case scenario to inject directly into the fault **These are the properties for the base models and are changed for the sensitivity analysis purposes.	

Results and Discussion

The effect of the formation stiffness on induced seismicity

Using model A, we have studied the effects of the Young's modulus on the seismic slip behavior by keeping all the other parameters fixed. The values for the Montney formation stiffness are reported within a range in the literature (see for example McKean & Priest, 2019). Therefore, we selected E = 16, 24, 32, 48, 64 GPa. Figure 2 shows the frequency magnitude distribution of events larger than M0. As the rock gets stiffer the number of events with relatively larger magnitudes (M1<), as well as the total number of events (M0<) are increasing. As the rock gets stiffer the stored strain energy gets larger, and consequently larger amount of seismic energy may be radiated due to sudden shear slip. Figure 3 compares the shear stress drop for all the models (the blue symbols). All the stress drops are also compared with their maximum possible stress drop calculated from the cap cumulative moment release proposed by McGarr (2014). The amounts of stress drop ($\Delta\tau$) and the average shear displacement (D) are larger for the stiffer rock. This observation also confirms that the injection into stiffer rocks would result in larger seismic events.

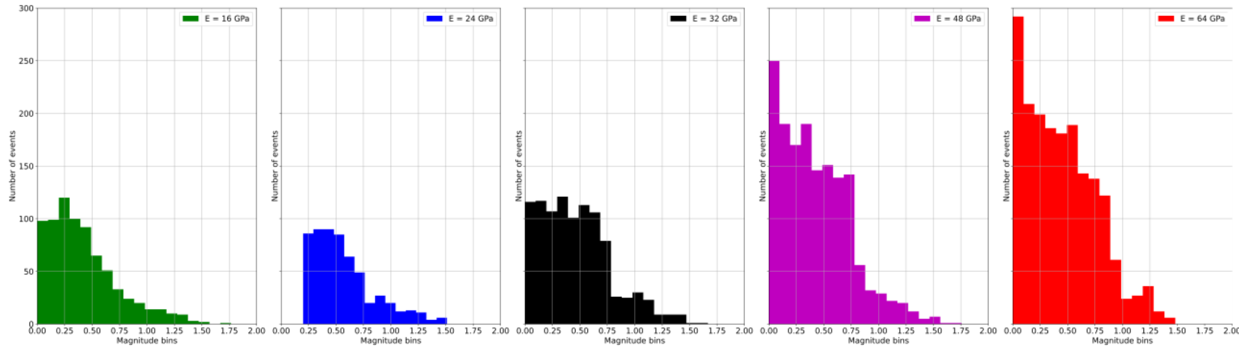

Figure 2. The magnitude-frequency distribution resulted from numerical simulation studies of different Young's modulus for model A.

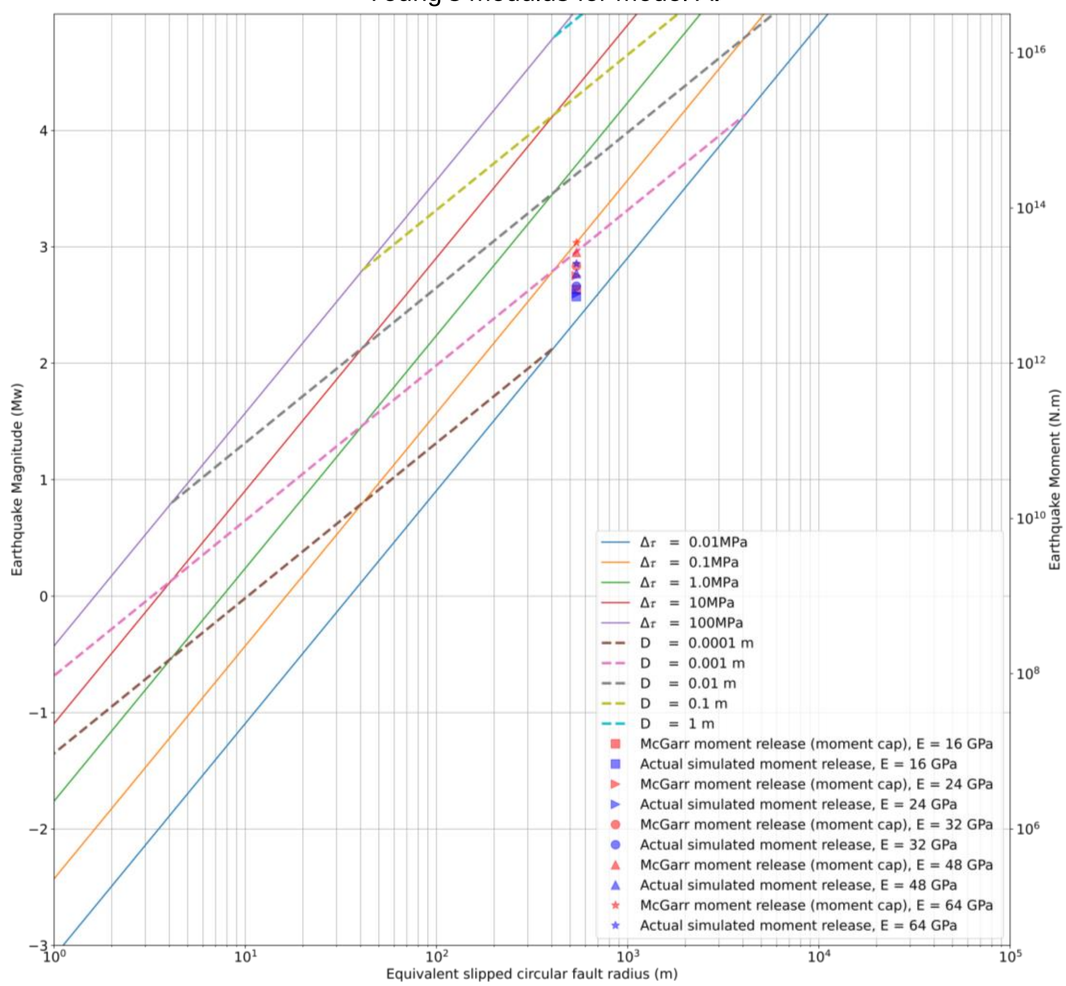

Figure 3. Stress drop ($\Delta\tau$, solid lines) as a function of equivalent circular fault size, moment release (moment magnitude), and average displacement (D, dashed lines).

In addition to the above discussion, looking into the injection pressure profiles (figure 4), one could argue that under the same condition the injection pressure for the stiffer rock is higher since it takes larger amount of stress to deform the stiffer rock (i.e., $E = \frac{\sigma}{\varepsilon}$). The buildup of a larger injection pressure results in a larger pressure gradient inside the fault which in turn results in larger flow rate inside the fault (i.e., $q \propto \Delta P$). Considering that the injected volume in all 5 models is the same, and due the conservation of mass (assuming the water as almost incompressible fluid) the injected volume must be equivale to the perturbed volume inside the fault. Due to high pressure gradient and smaller normal displacement in the stiffer rock, the pore pressure perturbation front diffuses more extensively and affecting a larger area in comparison with softer formations. The larger perturbated area (A) and larger shear stiffness (G) increases the total moment release (i.e., $M_o = GAD$) and thus the largest magnitude, see figure 5.

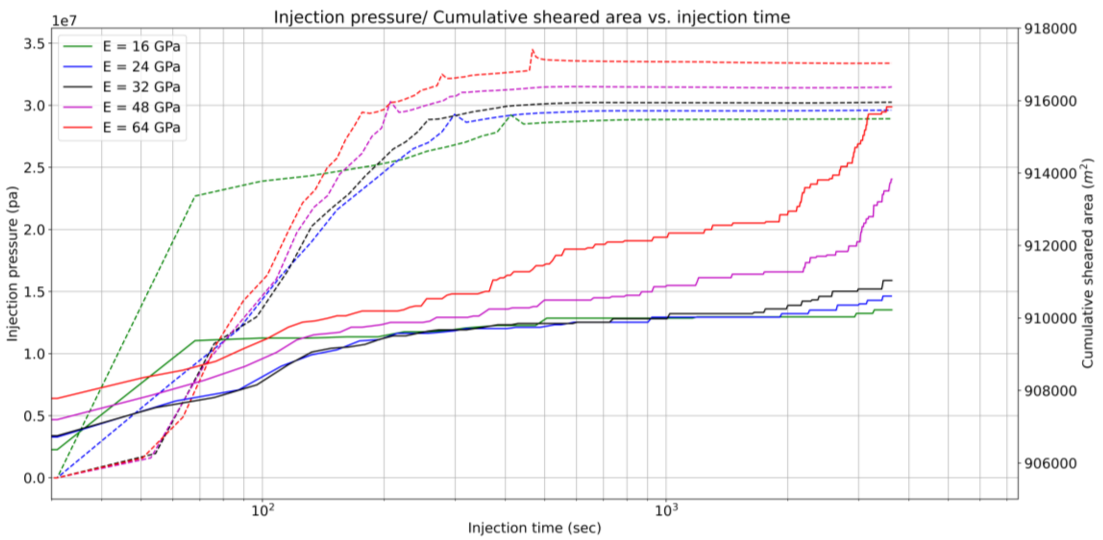

Figure 4. Bottom hole injection pressure (dashed lines) and stimulated area versus shear simulated area.

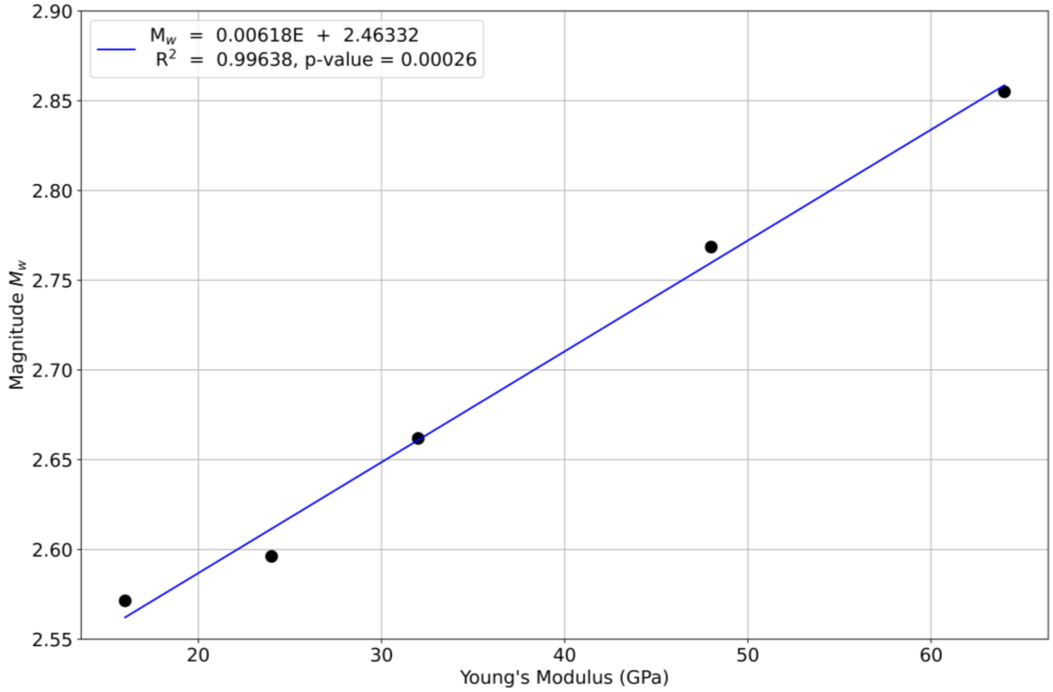

Figure 5. The linear relationship between the largest magnitude and the stiffness of the rock formation.

The results of our sensitivity analysis of wellbore orientation with respect to SHmax using model B shows that the largest possible induced seismicity could happen when the wellbore is drilled along with the SHmax orientation (figure 6, 0° means the wellbore is completed parallel to SHmax and 90° normal to SHmax). This could be explained by the fact that larger fluid pressure is required to open the fault in mode 1 (in the case of wellbore completed parallel to SHmax, i.e., 0°). Considering that the injected volume is the same (injected volume = aperture x length of the fault), the pressure diffusion front would perturb a larger area and therefore larger magnitude events would occur as the simulation results suggest.

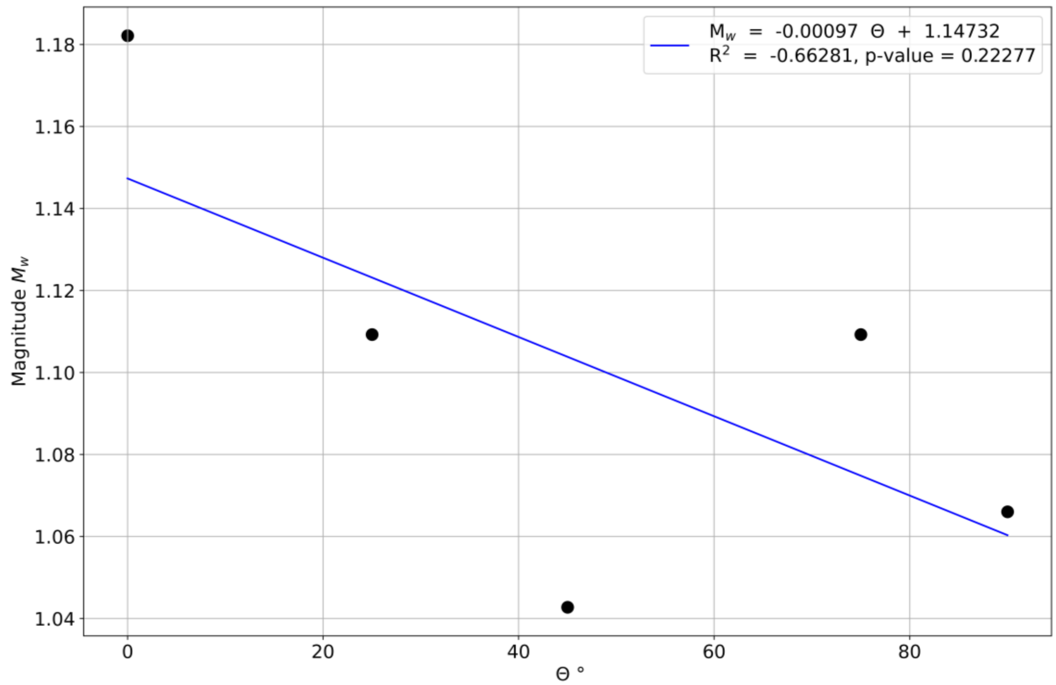

Figure 6. The largest magnitude versus the wellbore completion orientation with respect to SHmax (θ = 0° represents the wellbore parallel to the SHmax, and the rest are counterclockwise from SHmax).

Acknowledgements

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