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Injection-induced Seismic Hazard in Fox Creek Alberta

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Summary

Energy extraction from underground resources triggers or induces seismic events because it changes pore pressure and temperature, leading to stress perturbation along pre-existing faults and fractures. A fault or fracture reactivates when the critical shear stress on the discontinuity plane exceeds the Coulomb criterion, causing slippage to occur. Slip constitutes an environmental and potential risk issue if induced seismic events are large enough to damage subsurface or surface infrastructure. Assessing stress state, pore pressure and fault/fracture parameters as major input data for fault stability analysis is fraught because of a broad range of uncertainties. This paper applies a Monte Carlo probability assessment to estimate the potential slip tendency in a case study of Fox Creek, Alberta, Canada, involving seismic events induced by hydraulic fracturing (HF). Analyses of the local tectonic stress state and Mohr-Coulomb shear potential are displayed via a stability diagram, providing valuable insight for the fault slip tendency study. Probabilistic assessment is performed to identify the likelihood of induced seismicity and the slip tendency of faults crossing the Duvernay Formation shale. The results could provide useful input for seismic hazard assessments of local faults subjected to high-rate fluid injection, to mitigate risk.

Introduction

HF for energy extraction from underground conventional, unconventional and geothermal resources is typically accompanied by anthropogenic seismicity. Increasing pore pressure by fluid injection into pre-existing fractured media leads to slip/shearing of faults and fractures, with resulting detectable earthquakes *(van der Baan et al., 2013)*. The magnitude and rate of human-made earthquake are related to two sets of field parameters: controllable operational parameters including fluid injection pressure, rate, and volume *(Bao and Eaton, 2016)*; and, uncontrollable subsurface parameters including the state of stress, original pore pressure, size and density of pre-existing faults/fractures, fault/fracture orientation and frictional strength, permeability, compressibility and other geomechanics parameters. Each uncontrollable parameter is characterized by wide inherent uncertainties; these uncertainties in rock mass properties are the most important factors affecting the probability of fault/fracture slip.. In HF treatments, accounting for parametric uncertainty by using appropriate statistical probability distributions leads to better decision-making/risk management for user-controlled parameters such as injection pressure.

Since December 2013, noticeably increased seismicity rates have been observed in Alberta's previously quiescent Fox Creek area (Figure 1). More than 200 Mw>2.5

earthquakes in the area are associated with HF operations; and include MW 4.1 on January 12, 2016, and MW 3.9 on June 13, 2016. To predict the associated seismic risk due to fluid injection, the uncertainties associated with local geomechanics parameters must be incorporated in the evaluation process. Here, we apply a probabilistic assessment to investigate the potential slip tendency in a case study of Fox Creek, Alberta, Canada, involving seismic events induced by HF.

Seismicity in Fox Greek

The Duvernay Formation, which covers approximately 130,000 km^2 in west-central Alberta, is a source rock for conventional hydrocarbon resources. In recent years, shale gas and shale oil production from the formation has grown with the use of multi-stage HF technology. The formation is regionally heterogeneous; however, Fox Creek has been evaluated as the highest and optimal development site in the Devonian West Shale Basin *(Preston et al., 2016)*. Development in the Fox Creek area started in 2012, triggered by high oil prices and new HF technology availability; since then, the seismicity rate has also increased. Figure 1 shows the cumulative seismicity since 2004 in the Fox Creek area. Most earthquakes in the area occur during HF treatments and are spatially and temporally restricted to the region around the horizontal wells. Small white circles in Figure 2 represent earthquake clouds recorded in the area.

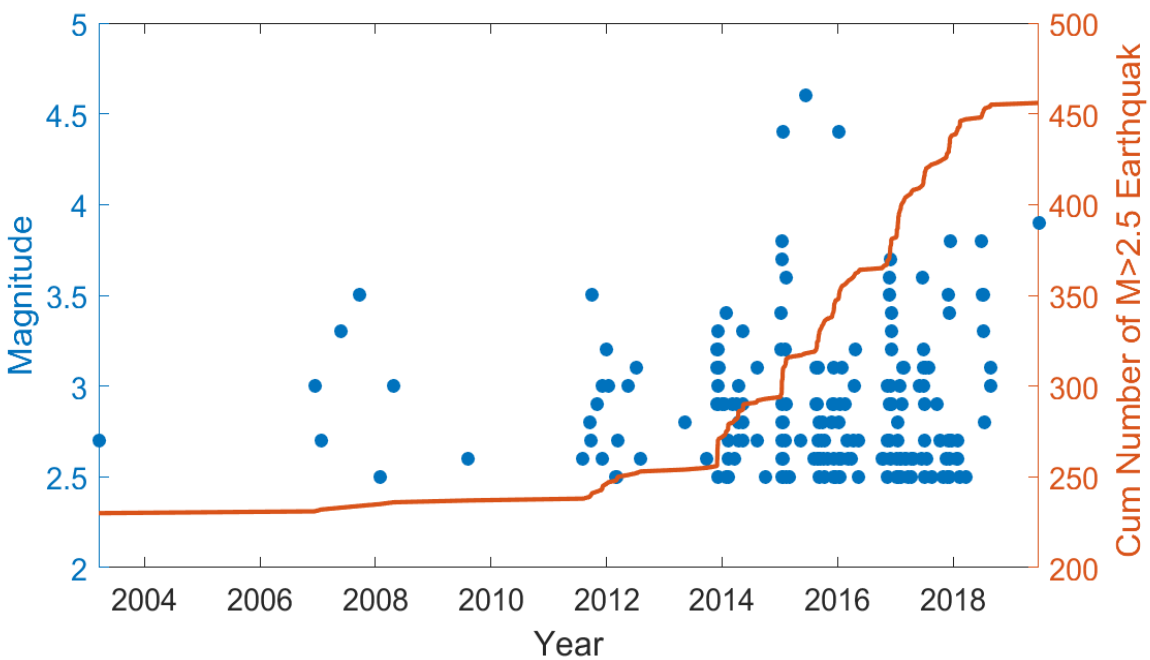

Figure 1: Cumulative number of earthquakes with Mw>2.5 around Fox Creek, Alberta; a rapid increase since 2012.

Probabilistic fault slip assessment
Fault/fracture slip depends on the relative stress magnitude, the angle between the principal stress directions and the fault plane, and the coefficient of friction μ. The slip tendency on a pre-existing cohesionless fault can be defined in terms of the Mohr-Coulomb shear failure $\tau = \mu\sigma_n$. Slip on a fault plane is likely to occur when the resolved shear stress, τ, equals or exceeds the frictional resistance of the fault surface ($\tau/\sigma_n \geq \mu$), and then the fault is called “critically stressed”.

The studies on the state of stress in the Fox Creek area have revealed that a strike-slip fault system is dominant in the area. Drilling-induced tensile fractures and borehole breakouts observed in wellbore image logs indicate that the maximum horizontal stress (S_{Hmax}) orientation is NE-SW in the region. The black lines with inward-pointing arrow line in Figure 2 show S_{Hmax} orientations around Fox Creek *(Haug and Bell, 2016).* A high pore pressure gradient with a mean value of 15 kPa/m in the Duvernay Formation plays an important role in seismicity generation during HF treatment.

Prior to HF activity in the Fox Creek area, little was known about the possible existence of a fault in the HF stimulation area. Neither 3D seismic image nor geological mapping initially detected diagnostic structural features in the Duvernay Formation in Fox Creek. However, existing faults can now be inferred from induced seismic events. Using the focal mechanisms of earthquakes, which provides two nodal planes, we can derive the possible fault plane. Having applied a strike-slip faulting regime with S_{Hmax} orientation 45^o, we investigate which of two nodal planes of the earthquake focal mechanisms were geometrically optimal for the inferred fault plane.

Figure 2.b includes a Mohr Diagram with a representative strike-slip focal event (Mw=3, 2015-08-19). The stress magnitudes in the diagram are defined based on the study performed by *Shen et al. (2019)*. The uncertainties associated with three principal stress magnitudes are shown with green error bars. The circular points in Figure 2.b correspond to the shear and normal stresses acting on nodal planes. As shown, for this example, the fault plane is striking N-S and dipping $11°$ to the E is most likely to slip, and is the preferred nodal plane. The same analysis has been performed for the other earthquake focal mechanisms shown in Figure 2.a. The red line crossing each focal beachball represents the preferred fault plane. As illustrated, most fault planes in the area are in the N-S direction, already in a critically stressed situation.

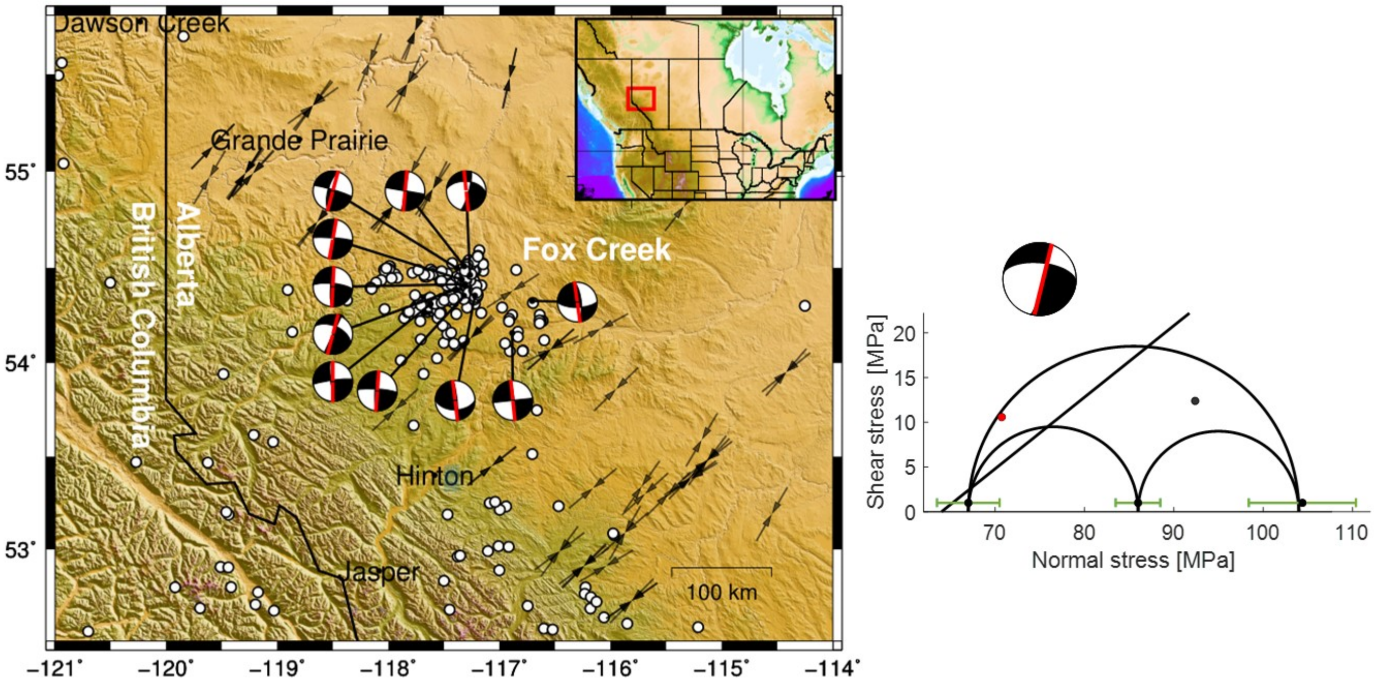

Figure 2: a) Seismicity around Fox Creek, Alberta. White circles represent earthquakes recorded in the area. The eleven interpreted Focal mechanisms are compiled from *Schultz et al.(2017)*, b) 3D Mohr's circle showing representative strike-slip earthquake focal plane (Mw=3, 2015-08-19). *Schultz et al.(2017)*

The deterministic fault slip tendency is expressed as the ratio of normal stress to shear stress on a potential sliding surface ($\tau/\sigma_n \geq \mu$). The deterministic approach considers just one single analysis as finite and therefore underestimates the potential risk. The slip tendency in a probabilistic analysis, however, considers inherent uncertainties for each input variable, including stress magnitudes and orientation, fault dip direction, angle, and frictional strength. Probabilistic slip tendency analysis is therefore comprehensive and suitable for evaluating multiple scenarios. In this work, a Monte Carlo simulation with 10000 scenarios has been applied to explore uncertainties associated with geomechanics parameters.

Figure 3 shows the statistical geomechanics variables used in the Monte Carlo simulation. Probabilistic assessment is then performed to identify the likelihood of induced seismicity and the slip tendency of faults detected from the earthquake focal mechanism. The probability of faults slipping as a function of pressure injection is illustrated in Figure 4. The results show a high likelihood of slip due to HF in faults crossing the Duvernay Formation shale. For faults inferred from the earthquake focal mechanism at an injection pressure of 60 MPa, the probability of slip is between 60% to 80%. The result shows that N-S faults in Fox Creek are likely to slip with even a small increase in pressure.

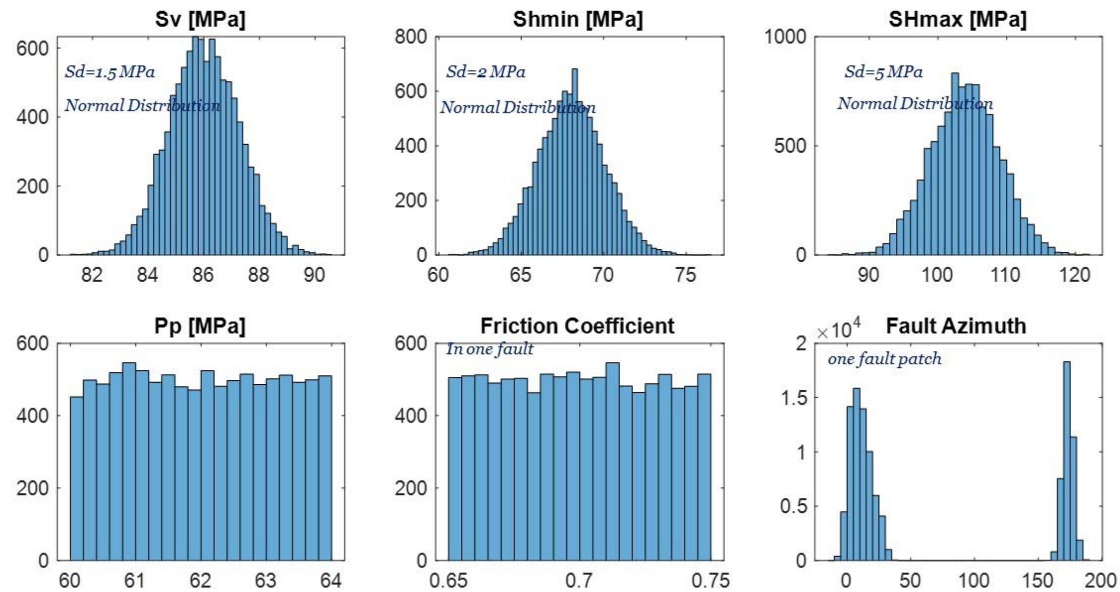

Figure 3: Statistical variables used in Monte Carlo simulation.

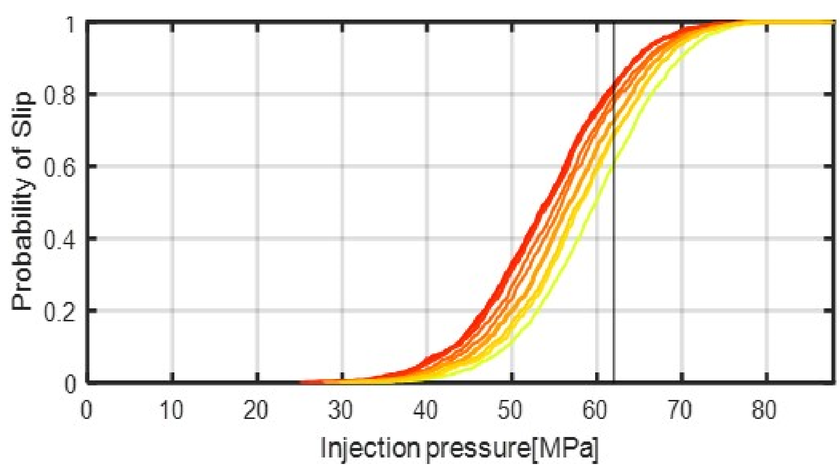

Figure 4: Cumulative probability function for fault slip as a functions injection pressure. Each curve represents one fault patch.

Conclusions

We use a probabilistic approach to determine the likelihood of fault slip as a function of injection pressure due to HF treatment near Fox Creek. The approach allows us to account for the inherent uncertainties associated with geomechanics parameters. Using the interpreted focal mechanics and induced seismicity, faults oriented approximately N-S were detected in the Fox Creek area. The analysis demonstrates almost all the faults planes examined would become unstable with a modest change of pore pressure. Therefore, there is a heightened risk of induced earthquakes as a result of HF in the region.

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