Injection- Induced Seismicity Assessment at the Alberta No.1 Geothermal Project

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ABSTRACT

Alberta No.1 is a geothermal project targeting deep carbonate, conglomerates and sandstone formations as the potential production and injection zone for geothermal energy exploitation within the Municipal District of Greenview south of Grande Prairie, Alberta, Canada. In geothermal systems without a steam fraction (typically systems under 170 C), rapid widespread pore pressure changes and slow temperature changes lead to increased deviatoric stresses, resulting in seismicity. This seismicity can damage infrastructure and shut down the geothermal project. A concern for the Alberta No.1 Geothermal Project is the fact that anthropogenic seismicity in Alberta displays some of the largest magnitudes reported globally. Thus, at the beginning of this type of project in Alberta it is prudent to review the potential for induced seismicity. In this study, a geomechanical study of the Leduc and Granite Wash formations, two potential injection zones, has been undertaken based on borehole geophysics and injection-induced earthquake data. Determining subsurface properties such as state of stress, pore pressure, and fault properties, however, poses uncertainties in the absence of actual data from the target formations. Geomechanical analysis results (with associated uncertainties) are used to assess the potential for injection-induced earthquakes. A Monte Carlo probability analysis is employed to estimate the likelihood of slippage of the known faults close to the Alberta No.1 Geothermal Project. A cumulative distribution function of the critical pore pressure on each fault is derived from the local tectonic stress state and the Mohr-Coulomb shear parameter analyses. The resultant probabilistic fault stability maps can serve as a baseline for future fluid injection projects in the region including wastewater disposal, hydraulic fracture stimulation, CO_2 sequestration, as well as geothermal energy extraction.

Introduction

One of the technical/environmental issues that needs to be addressed before starting a deep geothermal development in Alberta is the potential of induced seismicity as a result of fluid injection (Atkinson et al., 2016; Van der Baan and Calixto, 2017; Van der Baan et al., 2013; Zang et al., 2014). Upon injection of fluid into the fractured rock mass, pore pressure is increased along the pre-existing fault/fracture plane, and if the resolved shear stress on the plane exceeds normal stress, the fault slips and thereby triggers an earthquake (Van der Baan et al., 2013). The anthropogenic seismicity in Alberta includes some of the largest M_W values reported globally (Atkinson et al., 2016), including those of events near Fox Creek at Mw 4.1 on January 12, 2016 (Schultz et al., 2017), and Musreau Lake at ML 3.94 on December 25, 2019 (Li et al., 2021). In terms of distance, Fox Creek is approximately 200 kilometers southeast of the ABNo1 development site. Musreau Lake is approximately 100 km south (Figure 1). Thus, at the beginning of this type of project in Alberta a precautionary assessment is prudent. In Switzerland, The Deep Heat Mining Project taking place in a densely populated suburb of Basel, was shut down due to a M_L=3.4 injection-induced seismic event that occurred on December 8, 2006. The project was initiated for geothermal reservoir enhancement (“hot dry rock”) from the granitic basement. More than 13,000 induced earthquakes were detected during six- day’s following hydraulic fracturing (HF) stimulation at a depth of 5-6 km (Häring et al., 2008; Kraft and Deichmann, 2014; Mukuhira et al., 2013). Although, geological and operationally the ABNo1 project is very different than the Basel project, it is still important to assess the likelihood and risk of injection-induced seismicity.

Herein, using borehole geophysics data and earthquake focal mechanism reports from nearby locations, we establish a constraint for the region's state of stress in two target formations, the Leduc and Granite Wash formations. Similar geomechanically characterization has been observed in both formations. A set of uncertainties is also identified with regard to each effective uncontrollable geomechanical parameter, including stress tensors, pore pressure, faults/fractures orientations, and angles, etc. Then, we apply a probabilistic assessment to investigate the potential fault slip tendency due to fluid injection in the formations, incorporating the uncertainty distributions associated with Mohr-Coulomb strength parameters (normal and shear stress). A potential benefit of this study is the establishment of probabilistic fault stability maps that may provide a basis for any future fluid injection projects in the region, such as carbon sequestration or well field fluid disposal.

1. Geology Setting

The stratigraphic columns in northwest Alberta are well established for the upper three quarters to two thirds of the section and have been the subject of many geology studies over the years (Dec et al., 1996; Glass, 1990; Porter et al., 1982). Top to bottom in northwest Alberta, the Devonian stratigraphy is made up of the Lower Devonian strata, the Elk Point Group, the Beaverhill Lake Group, the Woodbend Group, and the Winterburn Group (Dec et al., 1996; Glass, 1990; Porter et al., 1982). Figure 2 shows the stratigraphy column nearby the ABNo1 geothermal project. Based on the geothermal gradient, lithology, and hydrogeologic properties, Banks (2016) and Banks and Harris (2018) reported that two formations in Grande Prairie County and the Municipal District of Greenview region are suitable for geothermal energy extraction: the Leduc Formation and Granite Wash Formation. This work was corroborated by the studies of ABNo1 (Hickson et al., 2020).

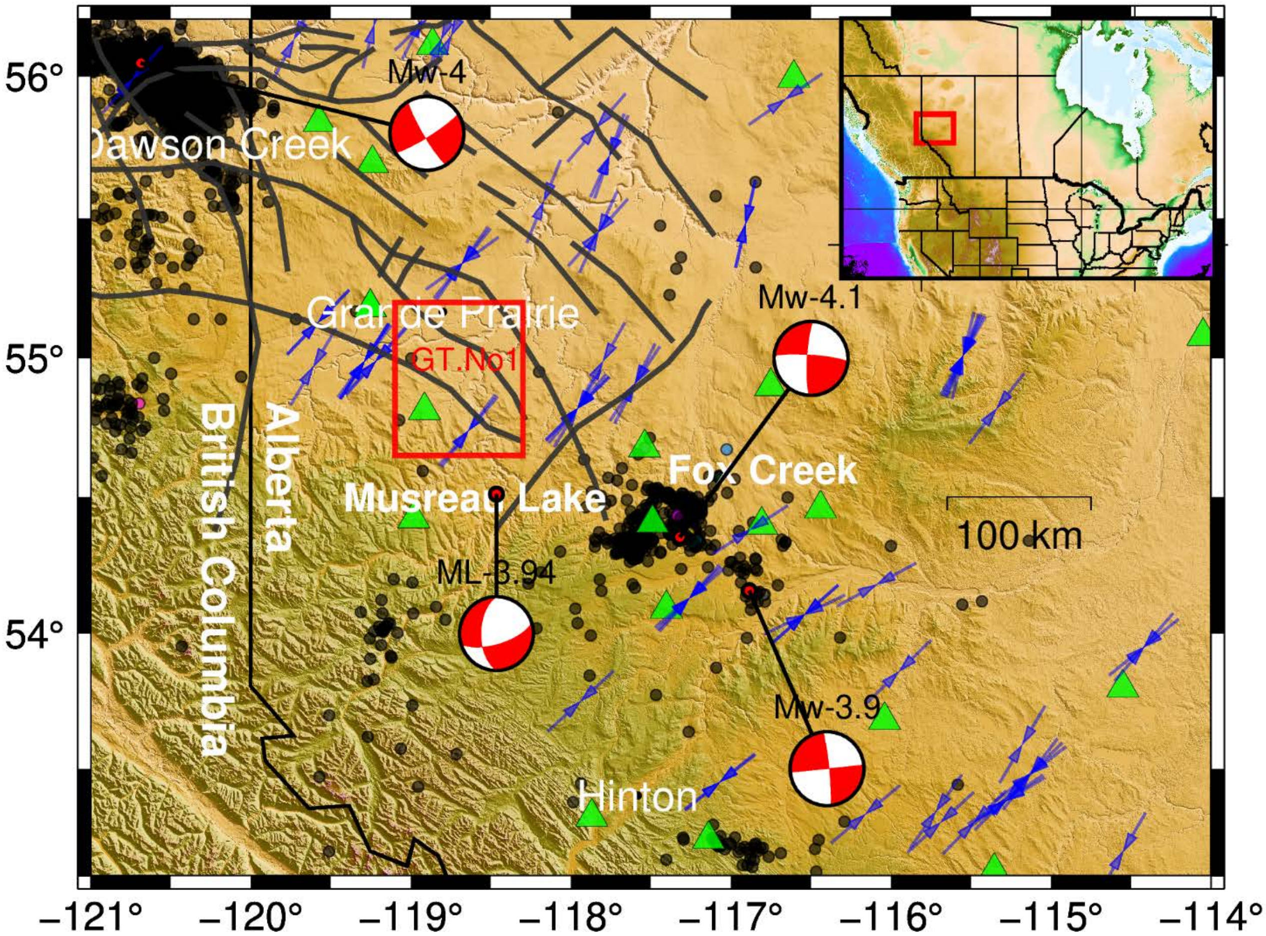

Figure 1. The location of Alberta No.1.geothermal project (red box). Black circles represent earthquakes reported in the area. The blue arrows, extracted from World Stress Map datasets (Heidbach et al., 2018), represent the maximum horizontal principal stress (S_{Hmax}) orientation. Grey thick lines are the main faults in the studied area. The green triangles represent the locations of seismic stations. The strike-slip focal mechanism events represent major earthquakes recorded in the area.

The Leduc Formation, which is approximately 175-300 m thick in the Grande Prairie area (from the Woodbend Group) contains limestone and dolomitized buildups (Banks and Harris, 2018). The formation is highly porous due to dolomitization during diagenesis (Amthor et al., 1994). Granite Wash Formation is another target injection zone beneath Grande Prairie and consists of sandstone and conglomeratic sandstone with between 100-200 m thickness. This formation is also known for high porosity and permeability (Banks, 2016; Banks and Harris, 2018). Note that porosity is an important consideration when selecting formations/layers that can accommodate fluids with high storage capacity, such as geothermal resources.

Over 2920 wells were drilled in Grande Prairie County to extract fossil fuel primarily from the Montney and Duvernay formations (geoLOGIC™ Systems). Geomechanical parameters are available only for the Montney and Duvernay formations, although drilled wells provide information on depth, thickness, lithology, and rock physics properties of subsurface layers such as the Leduc and Granite Wash formations. The Duvernay and Montney formations are “tight” shales that require hydraulic fracturing in order to release hydrocarbons. HF (Hydraulic fracturing), informally referred to as “fracking,” is an oil and gas well development process that typically involves injecting water, sand, and chemicals under high pressure into a bedrock formation via the well operations. HF is rarely used in conventional geothermal operations, but in the case of “hot dry rock” (Enhanced or Engineered Geothermal Systems “EGS”), operations such as those carried out in Basel, Switzerland, the technique is used to create a fractured reservoir from which to extract the heat. In conventional geothermal, inject takes place under hydrostatic pressure and no proppants or other chemicals are added other than scale inhibitors might be necessary.

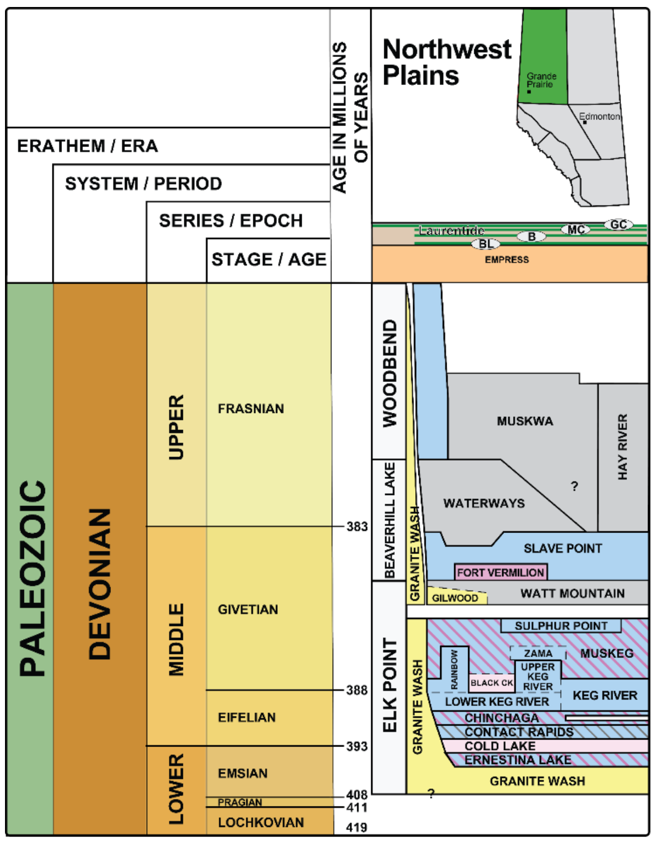

Figure 2: Stratigraphy column and table of formation in the Alberta No. 1 geothermal project in Grande Prairie in Northwest Alberta (Modified from Alberta Geology Survey, 2015).

2. Seismicity in the region

In the Grande Prairie area, despite the large number of HF operations carried out as part of the oil and gas operations, no triggered seismic activity has been recorded. The number of seismic stations in a region will affect the level of seismic activity observed/reported in that region. The green triangles in Figure 1 show the location of regional seismic stations. One of these stations has been operating since 2009, 30 kilometers west of Grande Prairie and north of the Wapiti River (Stern et al., 2011). The seismic network in this area is sufficiently dense that it is certain that no seismic activity has resulted from fluid injection into different geological formations in the Grande Prairie area. However, in the region south and east of Grande Prairie, there are two seismogenic regions: Fox Creek and Musreau Lake (Figure 1), which, before the fluid injection projects, were both quiescent.

There has been a noticeable increase in seismicity rates in Fox Creek since December 2013. More than 200 earthquakes of magnitude >2.5 have occurred in this area in association with HF operations into the Duvernay Formation, including Mw 4.1 on January 12, 2016, and Mw 3.9 on June 13, 2016 (Bao and Eaton, 2016; Schultz et al., 2017). Most earthquakes in the Fox Creek area occurred during HF treatments and were spatially and temporally restricted to the region around the horizontal wells. Seismicity around Musreau Lake has also resulted from wastewater injection into the Winterburn Formation at a depth of 3 to 4 km. The largest event being M_L 3.94 on December 25, 2019. Like Fox Creek, seismicity in Musreau Lake was confined to the injection site spatially and temporally. A point that should be emphasized is that induced seismicity near Fox Creek is due to HF occurring in parts of the Duvernay Formation that lay near critically stressed faults unknown before the operation began (Figure 1). The result of this fact implies that there may be other, as-yet-unrecognized, critically stressed faults which are also susceptible to HF-induced earthquakes.

As a result of 706 multistage HF wells, 9×10^6 m^3 cumulative fluid (geoLOGIC™ Systems) was injected into both the Duvernay and Montney Formations in the Grande Prairie region . That is important to highlight because, in a multistage HF well in Fox Creek, fluid injections of 2.04×10^4 m^3 triggered 115 earthquakes with a magnitude from 1 to 2.9 (Yaghoubi et al., 2020). Although both regions have a comparable level of HF activity, there is a question as to why Fox Creek is a seismogenic region whereas Grande Parier is a quiescent area. This paper addresses this question as one of its objectives.

3. Pre-existing Faults in Grande Prairie

When evaluating fault slip, it is necessary to know the dip direction and dip angle of the faults that are laying beneath the region. Berger (1994) mapped faults around the Peace River Arch, a geological structure most prominant north of Grande Prairie using regional high-resolution aeromagnetic data (HRAM). Specifically, Berger (1994) explains that Grande Prairie is controlled by a northwest-southeast down-to-the-basin listric normal fault, as well as a northeast-southwest basement-involved strike-slip fault (see Figure 2 Berger (1994) for more information). The latter may be responsible for the induced seismicity in Musreau Lake as a result of wastewater injection. The interpreted wastewater injection focal mechanism shows consistency between nodal plane striking ENE with respect to regional orientation in the direction of basement-involved strike-slip fault.

Regional seismic sections indicate that down-to-the-basin listric normal faults are almost vertical (Berger (1994). In this study, the dip angle of each fault is described as a probability distribution with the mean value of 80° with 10° uncertainty. It should also be noted that no laboratory study or in-situ experiment has been conducted to estimate the coefficient of friction of reginal fault in the study area. Byerlee (1978) has demonstrated that the coefficient of friction of faults varies between 0.6 and 1.0 for different rock types based on experimental studies. In our study, we assumed that the coefficient of friction ranges from 0.6 to 0.8. A further important point to emphasize is that our study is based on known faults in the region. As mentioned above injection-induced seismicity around the Fox Creek area is a result of hidden critically stressed faults that had been unknown before the operation started.

4. State of stress around Grande Prairie

An integral part of a region's stress state is the pore pressure. Formation pore pressure can be directly measured from direct wellbore tests such as Drill Stem Test, Repeat Formation Test, or predicted from borehole geophysics data. For this study, we intend to determine pore pressures within two target formations, the Leduc and Granit Wash Formations. The datasets are extracted from geoLOGIC™ Systems. Of 856 direct pore pressure measurements in the Leduc Formation in the WCSB, six wells including 30 tests are in the region of study.

Since the late 1970s, extensive studies have been conducted on the principal stress orientations in British Columbia and Alberta (Bell and Bachu, 2004; Bell and Grasby, 2012; Bell and McCallum, 1990; Dusseault, 1977; Gough and Bell, 1981; Haug and Bell, 2016). Various methods have been used to determine the S_{Hmax} orientations in the region, including borehole failures (borehole breakouts and tensile-induced fractures) and earthquake focal mechanisms. Compilations of maximum horizontal compressive orientation (S_{Hmax}) and relative stresses are available in the 2018 edition of the World Stress Map (WSM) databases (Heidbach et al., 2018). The blue arrows in Figure 1 indicate the S_{Hmax} azimuth (including all quality rankings) within the region, derived from borehole breakouts and tensile-induced fractures provided by the World Stress Map. We have assigned a mean of 45° and a standard division of 5° to S_{Hmax} azimuth in all stress areas.

The Vertical Stress is assumed to be equal to the average specific weight of the geomaterials multiplied by the depth. S_v can be obtained from the typical density logs that are abundant for most drilled wells. Because of density log availability, less uncertainty is associated with the vertical stress component in stress tensors. Several studies have investigated the vertical stress variation in the Western Sedimentary Basin (Bell and Gough, 1979; Bell and Grasby, 2012; Bell et al., 1990; Haug and Bell, 2016). The study of the Kiskatinaw area reported in Enlighten Geoscience (2021) indicates vertical stresses ranging from 24.6 to 25.5 MPa/km at Montney Formation. The same values were reported in Hayes et al. (2020) and Shen et al. (2018). In our study, we consider an S_v range of between 24 and 26 MPa/km.

The 706 multistage HF wells drilled in Grande Prairie have been subjected to a Diagnostic Fracture Injection Test (DFIT) or mini-frac, which can provide reliable determinations of minimum in situ stress magnitude. Only one DFIT well has been completed in the Granite Wash formation, indicating a closure pressure of 16.55 MPa/km. The majority of the HF wells were completed in the Montney and Duverney formations in the Grande Prairie region. There are DFIT tests available in the Watt Mountain and Muskeg Formations, both of which are situated vertically between the Leduc and Granite Wash Formations, but laterally remote from the Grande Prairie area. In the Muskeg Formations, 28 measurements of closure pressure indicate a S_{hmin} gradient of between 17 and 23 MPa/km. Having undergone 30 DFITs, the Wat Mountain Formation shows a S_{hmin} gradient of 16 to 25 MPa/km. Weides et al. (2014) use a range of 13.6 to 19.7 MPa/km for S_{hmin} as input for the likelihood of fault slip due to fault injection in the

Granite wash formation around the town of Peace River. In our study, we consider a S_{hmin} range of between 16 and 24 MPa/km in both the Leduc and Granite Wash Formations.

When determining a strike-slip (or thrust) stress state tensor, the most difficult parameter to determine is the maximum principal stress magnitude. However, borehole failure data, together with knowledge of horizontal and vertical stresses, can be utilized to limit the range of S_{Hmax} magnitude (Yaghoubi et al., 2021). Additionally, earthquake focal mechanisms provide helpful information on the magnitude of the relative stress as well as the maximum principal stress. To constrain the maximum principal stress magnitudes, we used injection-induced earthquake focal mechanisms recorded around the Grande Prairie region. The dataset includes 11 HF-induced earthquakes around Fox Creek, and 39 wastewater-induced earthquakes near Musreau Lake, Alberta (Li et al., 2021).

Simpson's approach (Simpson, 1997)was applied to the 50 compiled focal mechanisms, showing that a strike-slip fault system dominates the area, with an average Anderson fault parameter of $A_{\varphi} \approx 1.20$ around Musreau Lake and $A_{\varphi} \approx 1.5$ around Fox Creek. In this study, we consider $A_{\varphi} \approx 1.2$ to 1.5 for slip tendency of fault located around Grande Prairie. That means Vertical Stress is closer to minimum horizontal stress than maximum horizontal stress magnitude.

5. Assessment of fault-slip potential

Fault or 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 based on Coulomb faulting theory (Morris et al., 1996). The slip tendency in a pre-existing cohesionless fault can be defined in terms of the Mohr-Coulomb shear criterion, where σ_n is the effective normal stress across the slip surface $\tau = \mu\sigma_n$. Fault plane slippage is more likely to occur when the resolved shear stress, τ, equals, or is very close to, the frictional resistance of the fault surface; the fault is then called “critically stressed”. The deterministic fault slip tendency is expressed as the ratio of effective 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 potential risks. Based on the evidence provided in the previous section, each parameter of geomechanics in the Grande Prairie region is associated with some level of uncertainty. A probabilistic analysis, on the other hand, examines slip tendencies by considering uncertainties inherent to each input variable, such as stress magnitudes and directions, fault dip directions, angles, and friction coefficients (Jones and Hillis, 2003; Walsh III and Zoback, 2016; Wang et al., 2010). Various input variables can be assigned as random samples with specific statistical parameters in Mohr-Coulomb shear failure. The Probabilities of failure can be described as follows:$P_f = P[\, \tau - \mu\sigma_n \leq 0]$.

Probabilistic slip tendency analysis is, therefore, more comprehensive and is more appropriate for assessing risk in a variety of scenarios. In this study, for each fault segments, a Monte Carlo simulation has been applied to evaluate the slipping tendency of faults in the injection formations. Uncertainties associated with uncontrollable subsurface parameters, such as the state of stress, pore pressure, fault/fracture orientation, and frictional strength, are involved in the analysis. Considering that both the Leduc and Granite Wash formations exhibit relatively similar geomechanical behavior, a single analysis has been conducted to examine fault slip potential in both formations.

The result is the cumulative distribution function of the critical pore pressure on each fault derived from the local tectonic stress state and the Mohr-Coulomb shear parameter analyses. As shown in the Mohr-Coulomb diagram, the mean of the principal stress magnitudes is accompanied by the associated uncertainty (green error bar). We calculated the shear stress and normal stress acting on each fault plane based on the state of stress and fault dip direction and angle. Then, we calculated the probability of slip for each fault segment in response to a change in pore pressure of 2 MPa ($\Delta P(P_{inj}-P_p)$ = 2 MPa). The cumulative distribution of the injection pressure on each fault is shown in Figure 3b.

Figure 4 illustrates faults colored according to their slip probability. According to the results, there is a low probability of slippage of the faults as a result of fluid injection. The northeast-southwest basement-involving strike-slip fault in the study region has a higher probability to slip. The current result is consistent with a low level of seismicity in the region. It is important to point out that our analysis is based on 2 MPa pore pressure perturbation. Increasing pore pressure increases the probability of the slip of each fault. Our findings are consistent with less seismic activity reported around Grande Prairie, despite numerous multistage hydraulic fractures having been conducted in this area. However, Fox Creek, about 200 km southeast of Grande Prairie, was reported to have experienced some large HF induced earthquakes. HF seismicity occurred in Fox Creek as a result of multistage HF in the Duvernay Formation. The Duvernay Formation differs significantly from other formations in the region in terms of pore pressure gradients, one of its primary geomechanics properties. Pore pressure measurements indicate a gradient of 18 MPa/km in the Duvernay Formation around Fox Creek, which is twice as great as that in the Leduc and Granite Wash Formations.

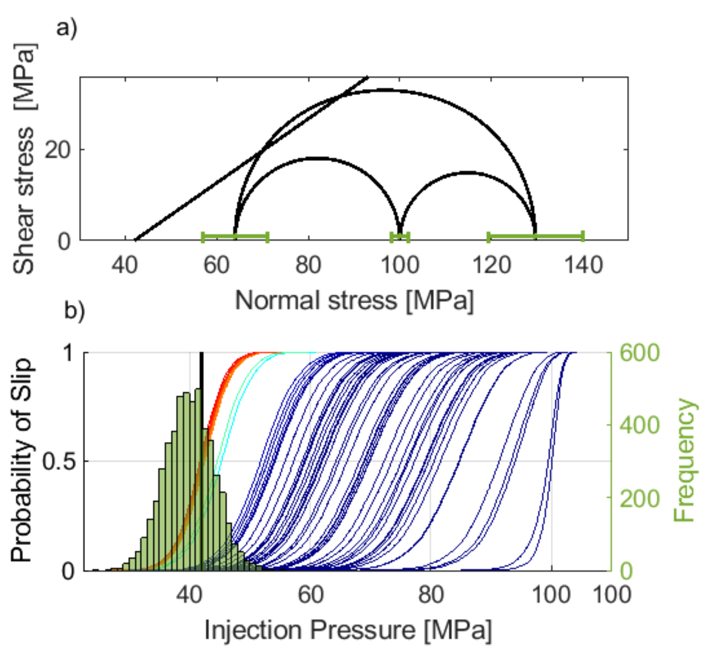

Figure 3: 3D Mohr diagram presenting principal stress magnitudes acting on known faults located in the Grande Prairie area. The cumulative probability function of the required injection pressure to cause slip on each fault segment.

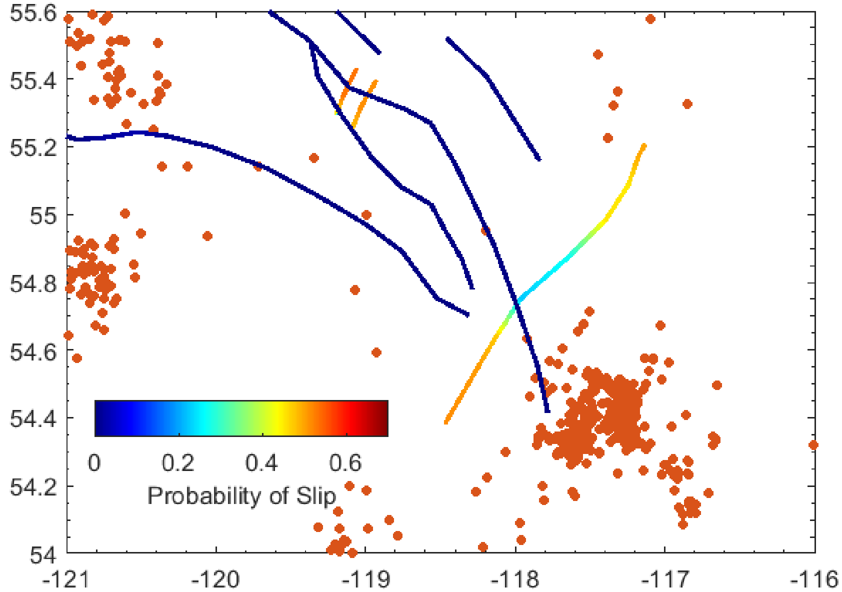

Figure 4: Map of faults in the Grande Prairie colored according to the probability of slip. The red circles represent seismicity reported by Visser et al. (2017).

6. Conclusion

A potential fault slip assessment has been performed on Alberta's No.1 geothermal project site. Geomechanical analyses have been performed on the Leduc and Granite Wash Formation, potential injection zones in the Grande Prairie area. This study area is characterized by strike-slip faulting as the dominant stress state in both target formations. The result of cumulative injection pressure shows a low probability of known faults located around the Grande Prairie. This finding is consistent with less seismic activity reported around Grande Prairie, despite numerous multistage hydraulic fractures having been drilled in this area. Our result shows that nearly vertical faults orientated in NEN and ENE, which are critically stressed orientations, are stable after 2 MPa pore pressure perturbations. Nevertheless, as Pp/injection pressure increases, the likelihood of fault reactivation and subsequent injection-induced earthquakes increases.

Acknowledgements

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