Monitoring and Risk Assessment of Anomalous Induced Seismicity Due to Hydraulic Fracturing in the Montney Formation, Northeastern British Columbia

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Introduction

Shale gas operations in northeastern British Columbia (NEBC) have induced the largest occurrence and magnitude of anomalous induced seismicity (AIS) due to hydraulic fracturing. Occurrences of AIS with magnitudes of up to M_L 4.6 have been recorded in seven clusters within the Montney play due to hydraulic fracturing (Figure 1). Two of these clusters have been linked to waste-water disposal and another five to hydraulic fracturing. Environmental and safety concerns associated with wellbore damage resulting from AIS are important, as are public concerns, especially as shale-gas extraction is expected to ramp up over the next several years.

The goal of this Geoscience BC research project is to better understand AIS due to hydraulic fracturing in NEBC. The project is designed to investigate the variables and processes controlling AIS and its associated ground motions, as well as to investigate and develop methods or protocols for the reduction and mitigation of the seismicity. The program has two objectives in order to accomplish these goals:

- build and deploy additional accelerograph and three-component (3C) seismometer sensors (up to 15 additional sensors during the tenure of the grant) to monitor hydraulic fracturing in the Montney Formation for the purpose of mitigating AIS through the development of a traffic-light/early-warning protocol based on ground motions, and to develop attenuation models (i.e., the relationship between magnitude and ground motions)
- develop probabilistic hydrogeomechanical models for the occurrence and magnitude of AIS due to hydraulic fracturing in the Montney Formation by integrating data from field studies and laboratory analysis into numerical simulations

Keywords: *British Columbia, hydraulic fracturing, induced seismicity, Montney Formation, attenuation model, traffic-light protocol, hydrogeomechanical modelling*

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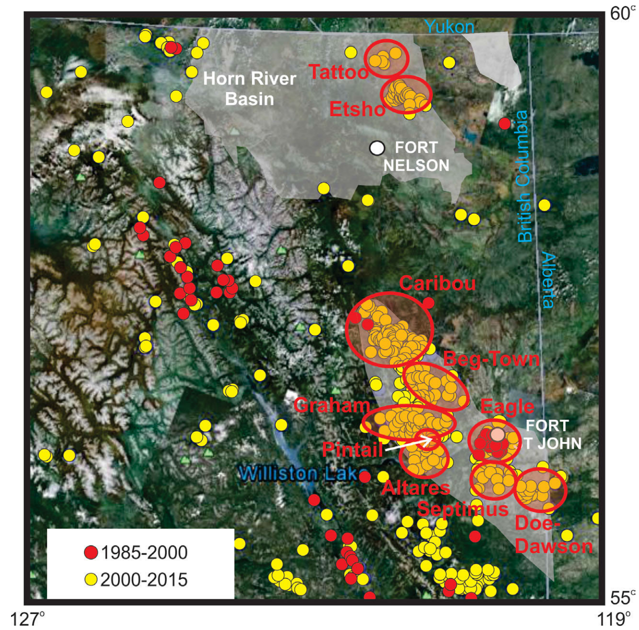

Figure 1. Anomalous induced seismicity in northeastern British Columbia from 1985 to 2000 (red circles) and from 2000 to 2015 (yellow circles). The Eagle cluster is related to conventional production and secondary recovery; the Graham and Pintail clusters are associated with waste-water injection; the Etsho and Tattoo clusters are linked to hydraulic fracturing in the Horn River Basin; whereas the remaining five clusters are linked to hydraulic fracturing in the Montney play.

The data necessary to develop an effective AIS traffic-light protocol (TLP) based on ground motions will be provided by expanding the currently operational five-sensor array. These sensors are low cost, mobile and easy to deploy (sensors need only be buried beneath any loose material using a shovel), consisting of both an accelerograph and 3C seismometer to cover the full frequency bandwidth necessary for monitoring both microseismicity and AIS, as well as accurately measure ground motions. The design for the sensors was modified from that developed at the University of British Columbia (UBC) and currently deployed for British Columbia's earthquake early-warning system and, hence, is extensively tested and proven technology. The sensors will be instrumental in providing industry with an efficient, accurate and inexpensive monitoring option for the BC Oil and Gas Commission's collaborative monitoring model. The array will be used to densely monitor the hydraulic fracturing of 3–5 multilateral well pads in the Montney play and to obtain a dataset of reliably located events and associated ground motions. The spatiotemporal and magnitude-frequency distributions of microseismicity, AIS and associated ground motions will be analyzed to develop TLP. The increased positional accuracy of source locations and magnitudes will be calibrated with, and integrated into, the Canadian National Seismograph Network (CNSN), as well as any commercial arrays put in place by industry partners. Monitoring of the array will provide a better understanding of the relationship between ground motions and magnitudes for induced events and assist in the development of an attenuation relationship for the Montney Formation.

Earth models for the monitored regions will be developed to better understand the processes resulting in AIS, quantify the sensitivity of the occurrence and magnitude of the AIS to the hydrogeomechanical parameters, identify regions with higher probability of encountering critically stressed faults and provide estimates of maximum-event magnitudes, as well as test mitigation techniques. The modelling parameters will be obtained from the seismic monitoring as well as the analysis of well logs, injection fall-off tests and 'mini fracs', and combined with the hydraulic-fracture stimulation parameters provided by industry partners. The results from geomechanical tests being undertaken in sister studies at UBC will provide further metrics for the modelling. The field and laboratory data will be linked to numerical simulations incorporating advanced 3-D hydrogeomechanical bonded-block distinct-element modelling (3DEC™), which uses algorithms to estimate event magnitudes from simulated induced seismicity.

Background

British Columbia (BC) has tremendous resources of natural gas (estimated at ~8.5 x 10^{13} m^3) in mainly low-permeability rocks, which require hydraulic fracturing to achieve economic production rates (BC Ministry of Energy and Mines, 2011). It is estimated that natural gas will contribute some 100 billion dollars over the next 30 years to the BC economy and at the same time reduce greenhouse-gas emissions (BC Ministry of Energy and Mines, 2012). To supply five liquefied natural gas (LNG) export facilities would require an estimated 40 000 additional wells in NEBC by the year 2040 (Paulson, 2015). Reducing and mitigating AIS associated with hydraulic fracturing as well as other geohazards, minimizing water use, and developing more effective and efficient fracturing techniques are important challenges that must be met for this development to be economically and environmentally viable.

Anomalous induced seismicity is a known risk in any earth-engineering project that changes the effective stress in a rock mass. Such a change in effective stress can result from injecting or extracting fluids from the Earth during activities associated with energy technologies. The most notable example of fluid-disposal–induced seismicity occurred in Denver, Colorado, in the 1960s, when liquid-waste disposal at the Rocky Mountain Arsenal resulted in a series of magnitude 4 events. The largest was a magnitude 4.8 event in 1967, which caused half a million dollars in minor structural damages. Subsequent research (e.g., Healy et al., 1968; Van Poollen and Hoover, 1970; Hsieh and Bredehoeft, 1981) indicated a strong relationship between injection volumes and earthquake frequency; it was generally agreed that the seismicity could be described by the Hubbert-Rubey mechanism (Hubbert and Rubey, 1959), which is in accordance with the Mohr-Coulomb failure criterion ($\tau = \mu[\rho_n - p]$). In this mechanism, shear failure occurs on pre-existing failure surfaces as a result of fluid injection, which increases the pore pressure and, hence, reduces the effective normal stress. The reduction in effective normal stress lowers the critical shear stress on the failure surface, bringing the stress regime into a state of failure. This is the mechanism generally used to describe all fluid-injection–induced seismicity. In general, the fluid injection increases the pore pressure in the vicinity of the injection source, which then diffuses along natural and induced planes of weakness (e.g., fractures, faults, joints and bedding planes) into pre-existing faults that slip once the pore pressure exceeds the critical threshold.

The hydraulic fracturing of reservoirs typically only induces microseismicity (M<0). However, stronger events, up to magnitude 1, are known to occur when increased pore pressures penetrate pre-existing faults (e.g., Warpinski et al., 2012). There are four known exceptional regions where hydraulic fracturing has induced seismicity with greater magnitudes: Oklahoma (Holland 2011, 2013) and Ohio, United States (Skoumal et al., 2015); Blackpool, England (de Pater and Baisch, 2011; Clarke et al., 2014); and the Western Canada Sedimentary Basin (BC Oil and Gas Commission 2012, 2014; Schultz et al. 2015a, b).

Shale-gas operations in NEBC, within the Western Canada Sedimentary Basin, have induced the largest occurrence and magnitude of AIS due to hydraulic fracturing (BC Oil and Gas Commission, 2014). Occurrences of AIS have been recorded in seven clusters within the Montney play, with magnitudes of up to M_L 4.6. Two of these clusters have been linked to waste-water disposal and another five to regions where hydraulic fracturing of the Montney shale-gas play occurs (BC Oil and Gas Commission, 2014). Although some events have been felt, the remote location and magnitude of the seismicity did not cause any damage or pose any risk of harm to the public or the environment in NEBC. However, given the current public and media perception of hydraulic fracturing of shale-gas reservoirs, simply alerting the public to the issue can cause problems for the industry's development plans. The lower population in NEBC has helped industry avoid significant media attention, but safety and social concerns due to ground motions, in addition to environmental concerns associated with potential aquifer and wellbore damage (BC Oil and Gas Commission, 2012) resulting from AIS, are important issues, which are likely to worsen as more wells are drilled to meet proposed LNG commitments.

Regions where the risk is higher of inducing large events can be identified through hydrogeomechanical modelling and probabilistic risk assessment (e.g., Gischig and Wiemer, 2013; Hakimhashemi et al., 2014; Bommer et al., 2015; Hajati et al., 2015; Rutqvist et al., 2015; Tutuncu and Bui, 2016). Such assessments require a large quantity of data, which has yet to be integrated for the Montney Formation in NEBC. Even though research has provided a better understanding of the processes and parameters controlling the magnitude and occurrence of large induced events and identifying higher risk regions, it is currently impossible to measure or model the heterogeneity and scale necessary to prevent all induced events. Therefore, it is also necessary to develop and implement protocols for mitigating events. The events induced by fluid injection typically increase in magnitude and distance from the injector with time due to the diffusion of pore pressures (Figures 2, 3; e.g., Baisch and Harjes, 2003; Baisch et al., 2006; Baisch et al., 2010; Shapiro et al. 2011). The occurrence of events with increasing magnitude and distance from the injector can thus be considered precursor events and TLP are typically used to determine the nature and timing of the actions that should be taken in an attempt to mitigate larger future events (Figure 4; e.g., Bommer et al. 2006; Bachmann et al., 2011; Maxwell, 2013; Mignan et al., 2015). A TLP has yet to be developed for the Montney, where the current regulation simply requires all injected activities to stop after a magnitude 4 event. However, it is not the magnitude of an event, but the intensity of the ground shaking that controls whether an event is felt and causes damage. Therefore, the development of a traffic-light protocol requires an understanding of the ground motions and attenuation of seismic waves, in addition to understanding the spatiotemporal and magnitude-frequency distribution of events, and the nature of the actions that may help mitigate the increase in magnitude and occurrence of events.

Objectives

In order to investigate the hydrogeomechanical parameters and processes controlling AIS and its associated ground motions in NEBC, as well as to develop methods or protocols for reducing and mitigating AIS, this research program has two objectives, which are described in detail below.

Develop Protocols to Manage and Mitigate AIS

The main objective of this study is to develop effective TLP for mitigating AIS based on ground motions for the Montney Formation in NEBC. An array of five accelerograph and 3C-seismometer sensors with telemetry for real-time monitoring of fluid injection activities has been designed and built for this purpose. The design for the sensors was modified from those built for BC's earthquake early-warning system. The array will be expanded to densely monitor 3–5 hydraulic-fracturing stimulations in the Montney play to obtain a dataset of reliably located events and associated ground motions due to AIS. The spatiotemporal and magnitude-frequency distributions of microseismicity, AIS and the associated ground motions will be analyzed to develop TLP based on ground motions. The goal to developing TLP, and combining them with current research on

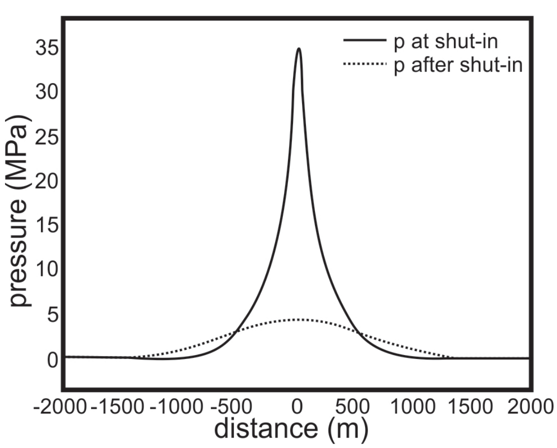

Figure 2. Graphical representation of pore pressure versus distance from an injector during injection (solid curve) and following shut-in (dotted curve), illustrating the process of pore-pressure diffusion. After shut-in, a larger area of a fault experiences elevated pore pressures resulting in larger magnitude events (modified from Baisch et al., 2006).

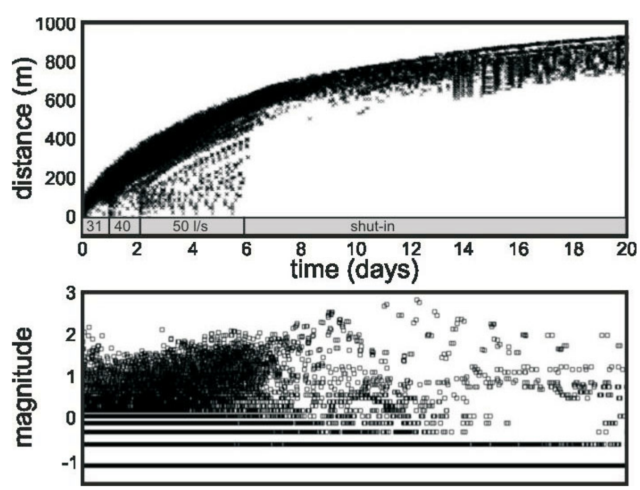

Figure 3. Example of the increase in distance from the injector (top) and the magnitude of earthquakes (bottom) during injection and following shut-in. Example is drawn from the enhanced geothermal project at Soultz-sous-Forêts in France (modified from Baisch et al., 2010).

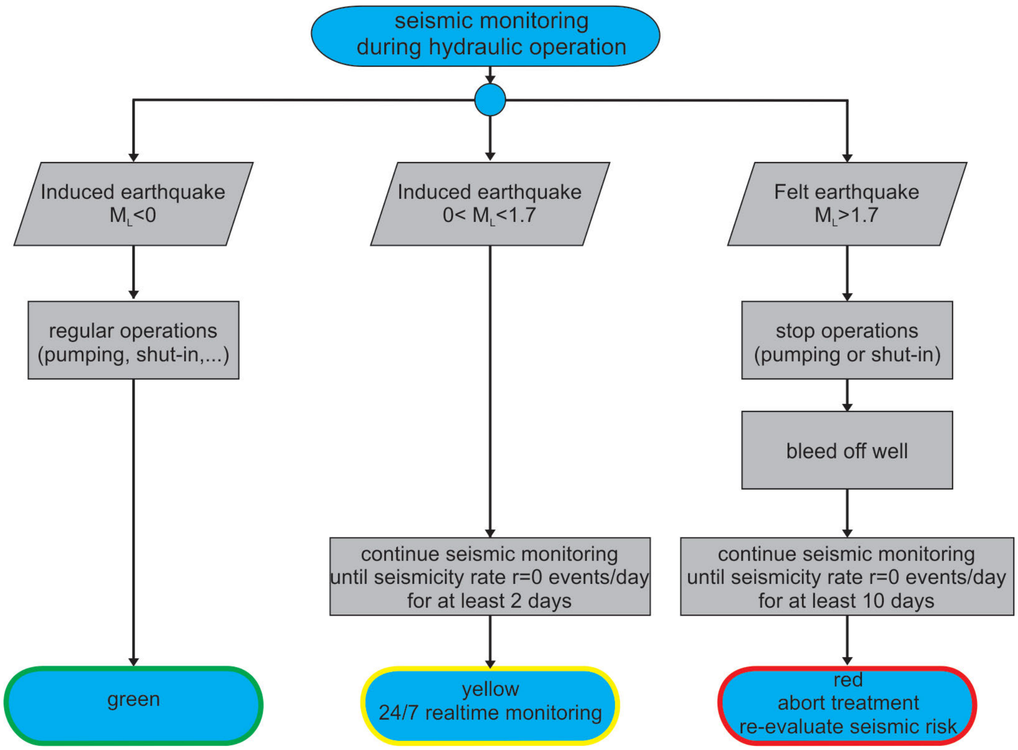

Figure 4. Example of a traffic-light protocol developed for mitigating anomalous induced seismicity due to hydraulic fracturing in the Bowland Shale in England (modified from de Pater and Baisch, 2011).

reservoir geomechanics, is to develop real-time adjustments to completion programs for mitigating AIS and, at the same time, optimize the stimulation. The data from the monitoring arrays will also be used to develop an attenuation relationship for predicting ground motions from the magnitude of AIS in the Montney Formation.

Reducing AIS through Hydrogeomechanical Modelling

Hydrogeomechanical modelling will help prevent AIS due to hydraulic fracturing in NEBC by providing a better understanding of the relative importance of hydrogeomechanical parameters, by identifying regions with a higher probability of hosting critically stressed faults, and by providing insights into the maximum magnitude of events. Mitigation techniques will also be investigated through modelling. The modelling parameters will be obtained from the results of the seismic monitoring and the analysis of well logs, injection fall-off and mini-frac tests, combined with the hydraulic-fracture stimulation parameters provided by industry partners and geomechanical tests being undertaken in sister studies at UBC. The field and laboratory data will be integrated into numerical simulations using 3DEC™, a discontinuum-modelling code based on distinct-element method (DEM) software developed by Itasca™ Consulting Group, Inc.

Methods and Approaches

There are two components to the research: a field component, whereby the array will allow hydraulic-fracture completions to be densely monitored, and a hydrogeomechanical modelling component. These approaches will be investigated in parallel, with results from the field studies being combined with ancillary data provided by laboratory analyses and industry collaborators providing the metrics for the modelling portion of the study.

Densely Monitoring Hydraulic Completions

Working with the Earthquake Engineering Research Facility (EERF) at UBC, the authors designed and built a five-station array of sensors, which include an accelerograph (Tetra 2) and a 3C seismometer. The design for the sensors was modified from the EERF's early earthquake detectors installed in BC schools for BC's earthquake early-warning system (http://globalnews.ca/news/2429129/early-warning-system-successfully-detects-b-c-earthquake/). The Tetra 2 accelerometers, which consist of 78 microelectromechanical systems (MEMS), are custom built based on the Tetra 1 sensors designed, built and installed for BC's earthquake early-warning system. The units are powered by a solar panel with an absorbed glass mat (AGM) deep-cycle battery and an uninterruptible power supply (UPS) gel battery inside the pelican box for backup. The pelican box also encloses a GPS as well as a next unit of computing (NUC) to store the data and run the system. The configuration and a photo of the field setup of one of the units are shown in Figure 5. The accelerograph and seismometer have individual enclosures, which are approximately 10 by 5 by 20 cm and need only be buried under any loose material using a shovel.

The first test-monitoring project for the array is complete and the data is currently being processed. Following the first test, the stations were upgraded to include the 3C seismometers and telemetry by cell-phone modem to enable real-time monitoring. Additional modifications to reduce power consumption, due to the remoteness of the deployment areas, are currently underway. Following the next deployment, the array of inexpensive and easily deployable stations will be expanded in such a way as to allow 3–5 completions to be densely monitored (ideally 10 stations over a 10 by 10 km area) in real-time over a short period of time to obtain a dataset of reliably located events and the associated ground motions. The goal is to monitor hydraulic-fracturing stimulations of pads in the Montney play operated by industry collaborators, as well as by operators of nearby pads, through a collaborative model. The arrays will be integrated with downhole or surface (depending on the operators' preference) microseismic monitoring arrays. A major hydraulic-fracturing service company operating in NEBC has also offered to work with them on operations with certain clients. The design criteria of the arrays will depend on the surface geology, microseismic monitoring array, the location of nearby monitoring arrays, as well as the number of sensors that are available.

The spatiotemporal and magnitude-frequency distributions of microseismicity, AIS and the associated ground motions will be analyzed to develop TLP. Similar waveforms from the same fault system will first be grouped together through cross-correlations (events rupturing the same fault system will have similar waveforms), then the post-injection time-lag and magnitude increase will be quantified to better understand pore-pressure diffusion and the resulting spatiotemporal distribution. In addition to developing TLP for regions of NEBC, the data will be used to develop an attenuation relationship for NEBC, to better understand the relationship between ground motions and recorded magnitudes.

The increased positional accuracy of source locations and magnitudes will be integrated and calibrated with the

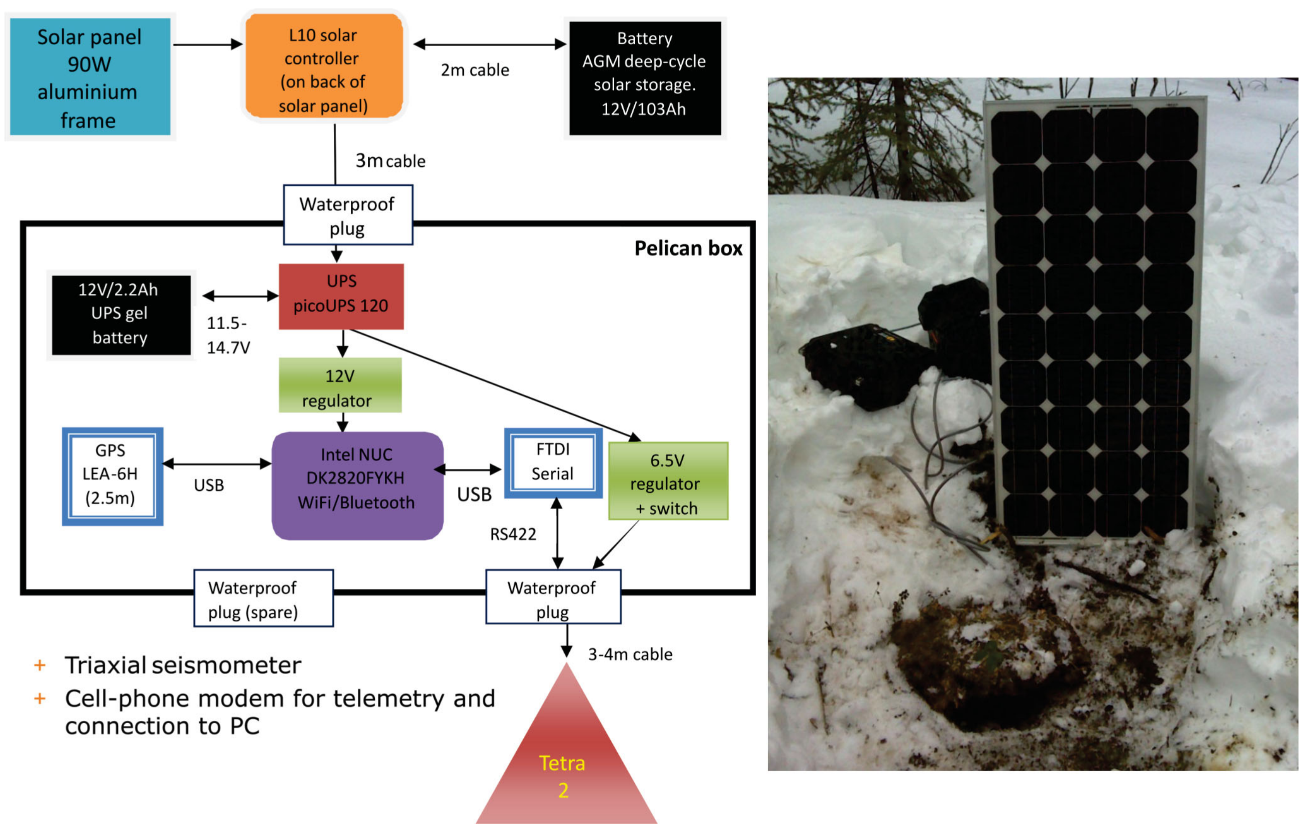

Figure 5. Configuration (left) and photo of the field setup (right) of one of the accelerograph and 3C-seismometer sensors used to monitor hydraulic fracturing in the Montney Formation. Abbreviations: AGM, absorbed glass mat; Ah, amp hour; FTDI, Future Technology Devices International; GPS, global positioning system; NUC, next unit of computing; UPS, uninterruptible power supply; USB, universal serial bus; V, volt.

CNSN, as well as any commercial arrays deployed by industry partners. The calibration of the data from the study's monitoring arrays with that provided by other sensor types will aid in understanding hypocentre accuracy and magnitude distributions and thresholds, as well as serve as a comparison to illustrate the advantages provided by these sensors. Additionally, the monitoring projects will help optimize the design criteria for monitoring arrays in NEBC.

Hydrogeomechanical Modelling

Hydrogeomechanical modelling provides the opportunity to evaluate the potential response of naturally stressed rock to fluid injection under various conditions. The first step of the modelling is to create a database of the parameters needed to create a hydrogeomechanical model. The necessary parameters include: 3-D stress profiles; pore pressure; rock mechanical properties (including those for fault characterization); spacing, geometry, and orientation of natural and induced fractures and faults; and bedding thickness and orientation. In order to determine the above parameters, agreements are in place with many operators in NEBC to provide data and/or interpretations from well-pressure tests, well logs, and seismic and microseismic monitoring. Information on completions, including wellbore pressures, injected volumes and rates, type and amount of proppant, and flow-back volumes and rates, in addition to well designs, are also being obtained.

To establish metrics for the hydrogeomechanical and reservoir models, laboratory tests will be combined with interpretation and analysis of well logs and well tests, in addition to the results of the seismic monitoring. Part of the research will involve characterizing the relationship between the lithostratigraphy, rock moduli (mechanical stratigraphy) and the established or estimated in situ stress field to better predict the fracture fabric that will be induced with various drilling and hydraulic-fracturing strategies. Therefore, a necessary component of the research involves the detailed analysis and integration of petrophysical properties, including stress-dependent permeability and porosity, measurement of rock moduli from triaxial tests on core, and stress-dependent acoustic P- and S-wave velocities at various degrees of saturation and pore pressure. These data, when combined with analysis of calibrated wireline dipole sonic and dipole shear logs and well tests, will contribute to upgrading the regional stress map of NEBC at a scale that can be integrated into a geohazard map. Using EXbase[1] and UBC data allows access to a broad sampling of rock mechanical data that provide a starting point for the study.

Once the hydrogeomechanical parameters are collected, they will provide inputs for simulating seismicity induced by the monitored hydraulic completions using a 3-D modelling program. Each recorded event with a magnitude >1 will first be associated with a stage of hydraulic fracturing, by allowing for large time windows to account for post-injection seismicity and by considering the event's location with respect to the perforations and previous events. The hydrogeomechanical and completion parameters from those stages, laterals, regions and fields that induced seismicity will be compared with the parameters from those that did not. Relating each induced event with a period of fluid injection will also allow the spatial and temporal distribution of the events to be examined. Understanding the migration in time and space of the occurrence and magnitude of the seismicity will provide insight into the pore-pressure diffusion taking place.

The first stage of the hydrogeomechanical modelling will involve history matching specific hydraulic-fracturing stages to match the spatial and temporal pattern of the seismicity and microseismicity as well as the wellbore-pressure variations that were monitored. The history matching will provide insight into the source parameters of the induced seismicity as well as into the mechanisms taking place. A complete parametric analysis will then be conducted on the best-fit models by comparing the occurrence and maximum magnitude of induced seismicity for variations in the hydrogeomechanical parameters, including the stress field, rock mechanical properties and structural setting. Parametric analysis will be used to determine which variables are controlling the induced seismicity, to identify regions with a higher probability of hosting critically stressed faults and to provide insights into the maximum possible magnitude of events. For comparison, stages which only induced microseismicity will also be history matched and the sensitivity of the parameters will be analyzed.

Different mitigation techniques will also be tested using hydrogeomechanical modelling, such as the impact of reducing or stopping injection at different thresholds and flow-back volumes, and controlling leak-off rates by modifying the completion-fluid chemistry. Another technique involves varying the hydraulic-fracturing parameters (i.e., wellbore pressures, injected volumes and rates, type and amount of proppant, and flow-back volumes and rates) and well designs, which can help optimize disposal and completions. For example, the effect of zipper fracturing, simultaneous fracturing, number of stages, injection rates and pressures, fluid viscosity, as well as orientation, spacing and pattern of laterals can also be examined.

The current model of choice is 3DEC™, a discontinuum-modelling code based on DEM software The utility of this program was evaluated by first using UDEC™ (Universal Distinct Element Code), the two dimensional version of the numerical software developed by Itasca™ Consulting Group, Inc., to model both pore-pressure buildup and its

[1]*EXbase is a proprietary historical database of mainly geochemical data.*

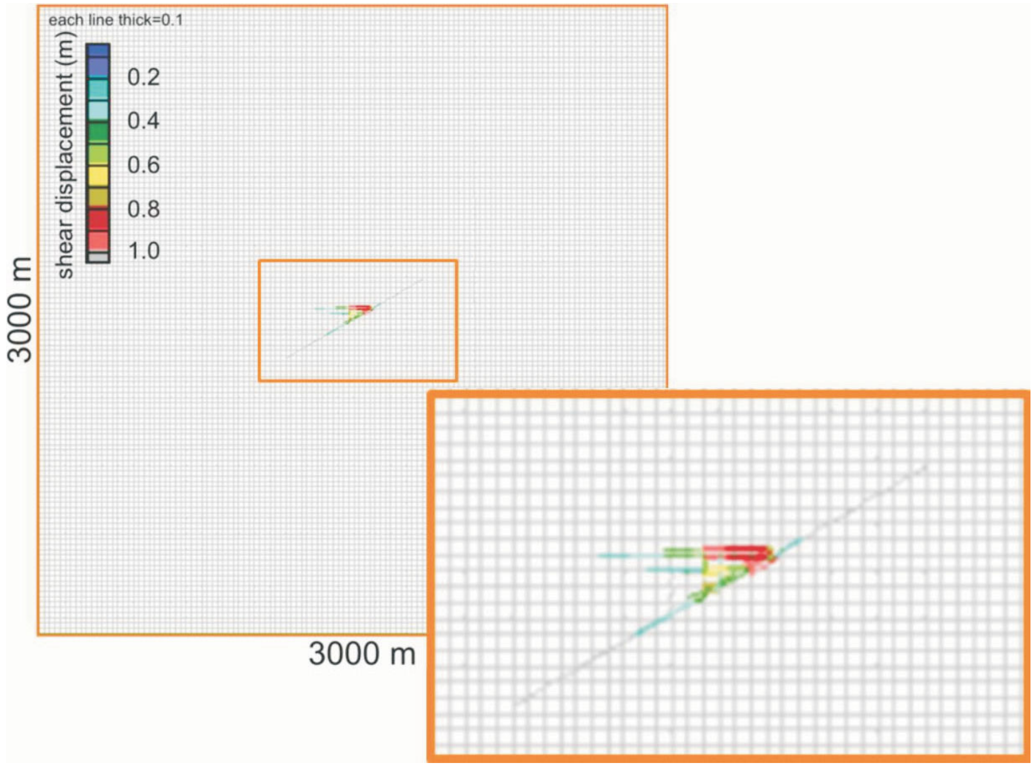

Figure 6. Example of the results from modelling using UDEC™ (Universal Distinct Element Code), the two dimensional version of the distinct-element method (DEM) numerical software chosen for the hydraulic fracturing monitoring project in the Montney Formation. The plot shows the shear displacement along a 1500 m fault and fractures surrounding the hydraulic fracture caused by injection 100 m from the fault.

diffusion along rock discontinuities into a critically stressed fault in response to fluid injection and the subsequent changes to the effective stress field (Figure 6). The problem domain is discretized into blocks, where the boundaries represent fractures/joints/faults or planes subject to possible failure. Failure occurs by both shear slip and dilation along the pre-specified surfaces; therefore, both shear and normal displacements can be quantified. The Mohr-Coulomb slip model with residual strength is used to quantify the displacements. The blocks are subdivided into a mesh of finite difference elements and their deformation is modelled based on the basic Mohr-Coulomb slip criterion. A coupled hydrogeomechanical analysis models the fluid flow through the discontinuities, whereas the blocks are impermeable.

Legacy

In addition to the development of methods and protocols for the reduction and mitigation of AIS in the Montney Formation in NEBC, the legacy of this research will be the commissioning of up to 15 mobile sensors that can be optimally positioned throughout field development as needed. In addition, a world-class research nexus is being created at UBC–Geoscience BC dealing with AIS and hydraulic fracturing that will serve the province during the exploration and exploitation of its vast shale-gas and shale-oil resources during the next 40 years.

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