Collecting Ground-Motion Data for the Mitigation and Prevention of Seismicity Induced by Hydraulic Fracturing in the Montney Formation, Northeastern British Columbia

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Introduction

Hydraulic fracturing stimulations in the Montney Formation in northeastern British Columbia (BC) have induced the largest ever reported rate and magnitude of anomalous induced seismicity (AIS), with events of magnitudes up to M_L 4.6 recorded in five clusters within the Montney play (Figure 1; BC Oil and Gas Commission, 2014). The goal of this Geoscience BC research project is to better understand the variables and processes controlling AIS and its associated ground motions due to hydraulic fracturing in the Montney Formation, with the ultimate goal of developing protocols to reduce and mitigate the rate and magnitude of events. The research program has two components: 1) a field component, whereby hydraulic fracture completions will be densely monitored; and 2) 3-dimensional (3-D) hydrogeomechanical modelling.

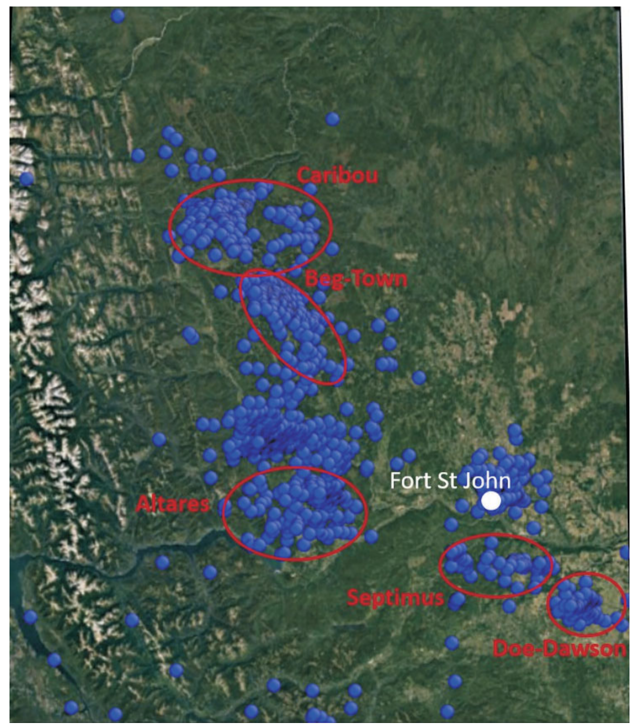

Figure 1. Seismicity recorded in the Montney Formation in northeastern BC from 1985 to present (blue circles). The five clusters linked to hydraulic fracturing are circled in red.

Over the past year, the original five-station array has been expanded to include 12 new stations in order to densely monitor operation in the Montney. Those five stations were deployed in the spring to monitor a multilateral stimulation, providing the first dataset. The first of the new stations were also deployed during the completions program in order to test their capabilities. All 17 stations are currently deployed, many around disposal wells, as steps are being taken to organize the first dense-monitoring project. The design for these low-cost, mobile, easy-to-install stations was modified from the early-warning earthquake detectors installed in BC schools for its earthquake early-warning system. In addition to providing real-time data and ground motion parameters, algorithms for calculating near real-time hypocentres and magnitudes are being developed.

In this study, the spatiotemporal and magnitude-frequency distributions of microseismicity, AIS, and the associated ground motions will be analyzed and different mitigation techniques will be tested through 3-D numerical simulations to develop an effective AIS traffic-light protocol (TLP) based on ground motions. Developing TLPs, and combining them with research on reservoir geomechanics, has the goal of developing real-time adjustments to completion programs to prevent AIS, at the same time as optimizing the completion. The data from the monitoring array will also be used to better understand site amplification and develop attenuation relationships for predicting ground motions from the magnitude of AIS in the Montney Formation. Additionally, Earth models will be created for monitored regions, by integrating the data from the field studies with ancillary data into a 3-D hydrogeomechanical model in order to better understand the processes resulting in AIS and to develop a probabilistic model for the seismic hazard and risk to the regions.

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Methods and Approaches

The two components of the research, monitoring and modelling, will be investigated in parallel with the field studies, combined with ancillary data provided by laboratory testing and industry collaborators providing metrics for the modelling portion of the study.

Monitoring Hydraulic Fracturing Completions

The seismicity data necessary for this research is being provided by an array of accelerographs. Working with the Earthquake Engineering Research Facility (EERF) at the University of British Columbia (UBC), the authors previously designed and built five stations and, as part of this study, have now deployed an additional 12 stations. The design for the stations was modified from that developed at UBC for BC's earthquake early-warning system (Azpiri, 2016). The original stations include custom-built Tetra 2 microelectromechanical systems (MEMS) accelerometers, whereas the sensors in the new stations are commercial MEMS accelerometers and are paired with a three-axis magnetometer. Using a series of ground-motion prediction equations for induced seismicity (Dost et al., 2004; Bobbio et al., 2009; Dost et al., 2013; Atkinson, 2015), it has been conservatively estimated that, given the ambient noise recorded, the detection threshold of the stations would be M1.5 within 5 km and M–0.2 within 0.5 km. In addition to three-component (3C) accelerometers, 3C geophones are currently in the process of being added to the stations. 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 units are powered by a solar panel with an absorbed glass mat deep cycle battery and an uninterruptible power supply (UPS) gel battery inside a protective (weather and animal proof) case for backup. The protective case also encloses a global positioning system for timing and location, as well as a computer to store the data and run the system. Whereas the original stations use a NUC (Next Unit of Computing) with Windows, the new stations use an Advanced RISC (reduced instruction set computer) Machine processor running Linux, which considerably reduces power consumption. The sensors have individual enclosures and need only be buried under any loose materials using a shovel. The enclosure for the sensors in the original stations is a box, approximately 10 by 5 by 20 cm in dimensions, and in the new stations is a sealed tube, 80 cm in length and 7.5 cm in diameter. Telemetry is currently provided by cell-phone modems, with antennas to boost the signal. Photos of the field setups are shown in Figure 2. Depending on the length of deployment and the anticipated weather conditions, the solar panels may be mounted on an in-house–designed aluminum frame, and the protective case and battery enclosed in a secondary weatherproof box.

In addition to obtaining real-time raw data, algorithms have been added to the stations to send an alert when a threshold acceleration is recorded and to calculate ground-motion parameters for the event in real time. The raw data is first run through a 4th order Butterworth filter with a high-pass cutoff frequency of 0.1 Hz. The peak ground acceleration (PGA) is then the maximum acceleration of the filtered data during the event. The filtered acceleration data is integrated to obtain velocities and the peak ground velocity is determined (PGV; equal to the maximum velocity during the

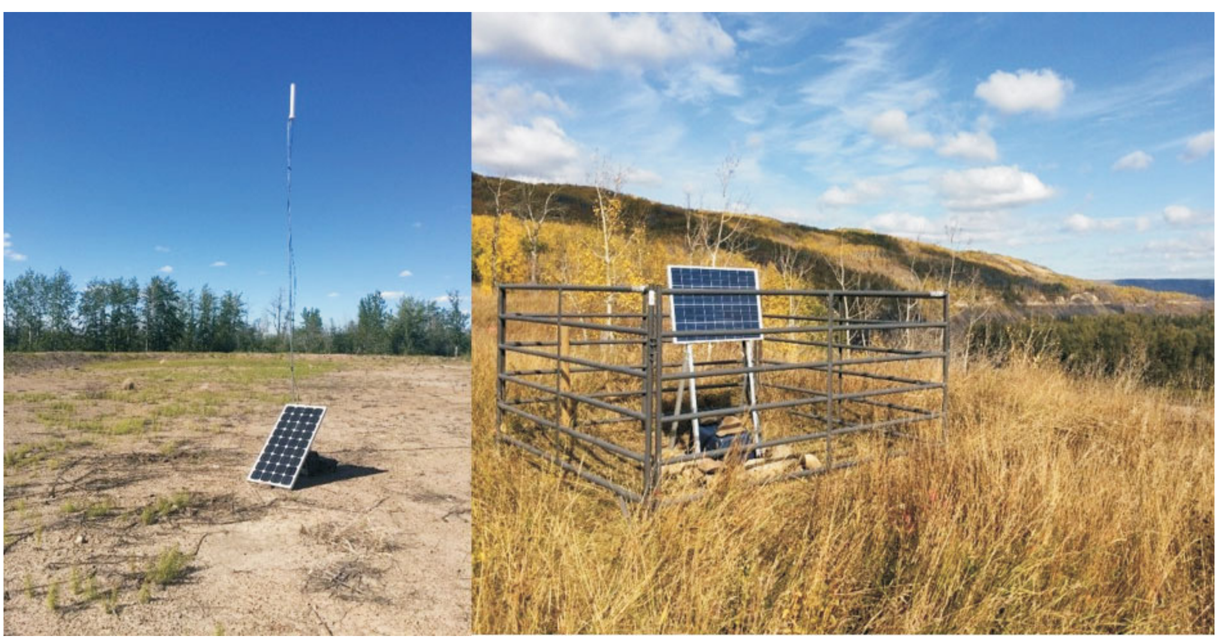

Figure 2. Field setup of a temporary (right) and a long-term station (left) used to monitor the Montney Formation.

event); then the velocities are integrated to obtain displacements and the peak ground displacement is determined (PGD; equal to the maximum displacement during the event). The ratio of the short-term average (STA) to the long-term average (LTA) is also calculated, as it provides a measure of the signal-to-noise ratio and can be used to set up the trigger threshold. The short- and long-term averages are calculated as the average squared acceleration between 1 and 10 Hz, giving a measure of the short- and long-time energy of the vibration. The raw data is first filtered through two cascading 4^{th} order Butterworth filters, one low-pass filter at cutoff frequency of 1 Hz and one high-pass filter at 10 Hz, then the exponential average is found over 0.3 s (STA) and 30 s (LTA) time windows. Additionally, the spectral intensity (SI), which provides a measure of the damage potential to structures by events, is calculated according to A. Rosenberger (unpublished report, 2010). The authors define SI as the maximum velocity of two 20% damped single degree-of-freedom systems with resonant frequencies of 1.5 s and 2.5 s.

Currently, additional algorithms are being developed for real-time calculation of ShakeMaps, magnitudes and hypocentres. Whereas the data recorded by the geophones will allow for the calculation of magnitudes comparable to other networks, the geophone and accelerometer data will be used in conjunction to better define phases and first arrivals for estimating hypocentres.

The original five stations were deployed in the spring to monitor a multilateral stimulation, providing the first dataset, which contains 11 events recorded on multiple stations with a PGA =0.2%g. The largest recorded event had a PGA of 2.2%g (220 mm/s^2), a PGV of 2.7 mm/s, a PGD of 1 mm and a SI of 4.3 mm/s. Figure 3 shows an example of a raw waveform recorded for one of the events. The first of the new stations were also deployed during the completion program in order to test their capabilities. The original and new sensors produced very similar results, with an average difference between the PGAs for two co-located stations within 0.09%g and the new sensors producing slightly lower ambient noise measurements (Figure 4). All 17 stations are currently deployed, seven of which around disposal wells, in preparation for the first dense-monitoring project. In addition to sites obtained through operator agreements, stations have also been deployed at research sites and on a private ranch. The locations for these three sites are shown in Figure 5. It is also anticipated that the sensor package will play a role in providing reservoir surveillance against hydraulic fracturing in adjacent areas. To this end, experiments have been undertaken whereby sensors are directly mated to a suspended well in a producing field to monitor reservoir impact from adjacent operations.

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. The modelling parameters will be obtained

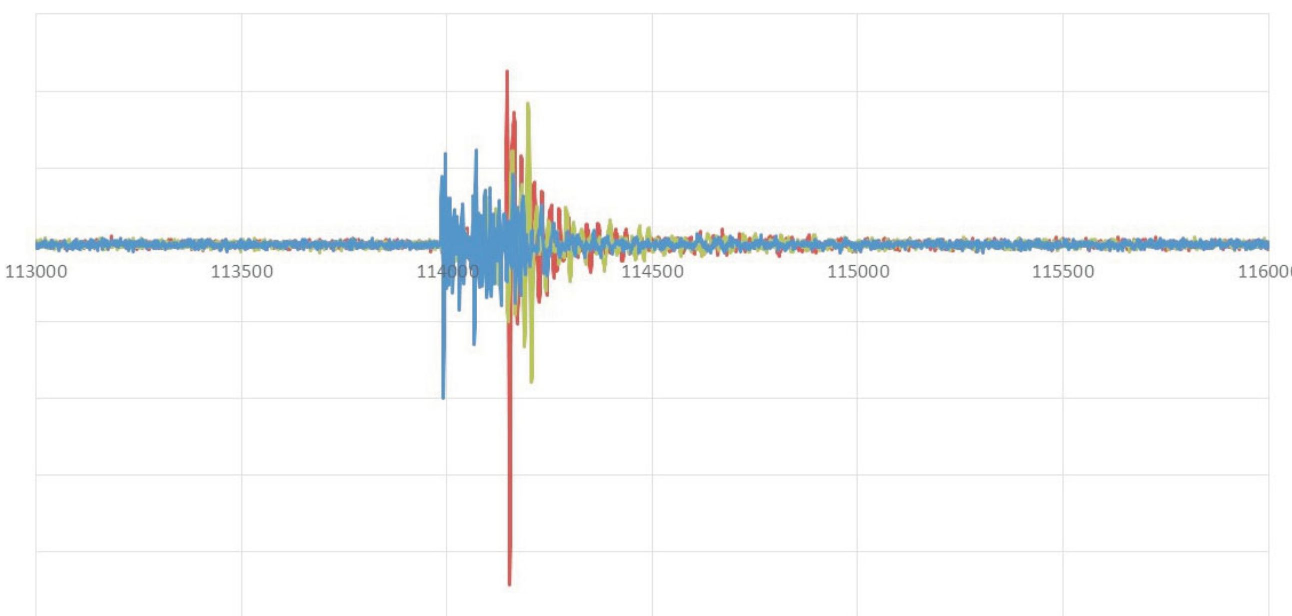

Figure 3. Example of acceleration data recorded for an event by a 3-axis accelerometer at one of the monitoring stations deployed in the Montney play. Scale and legend not included for confidentiality.

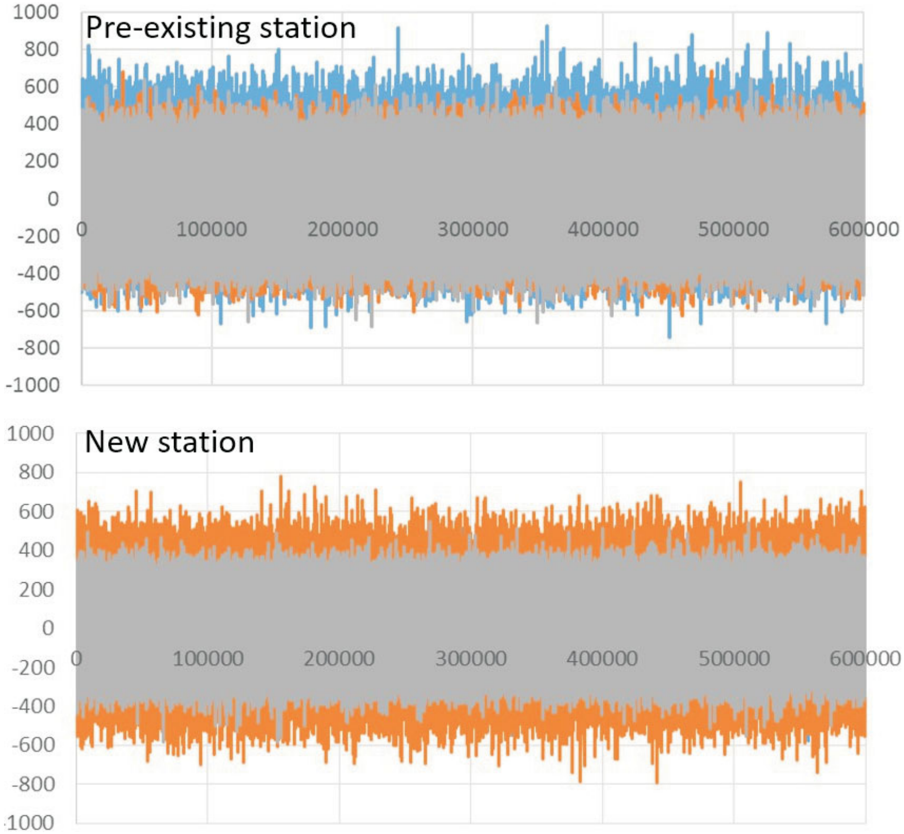

Figure 4. Example of the ambient noise recorded in µg by sensors at one of the original monitoring stations (top) and at one of the new stations (bottom), which were co-located in the Montney play.

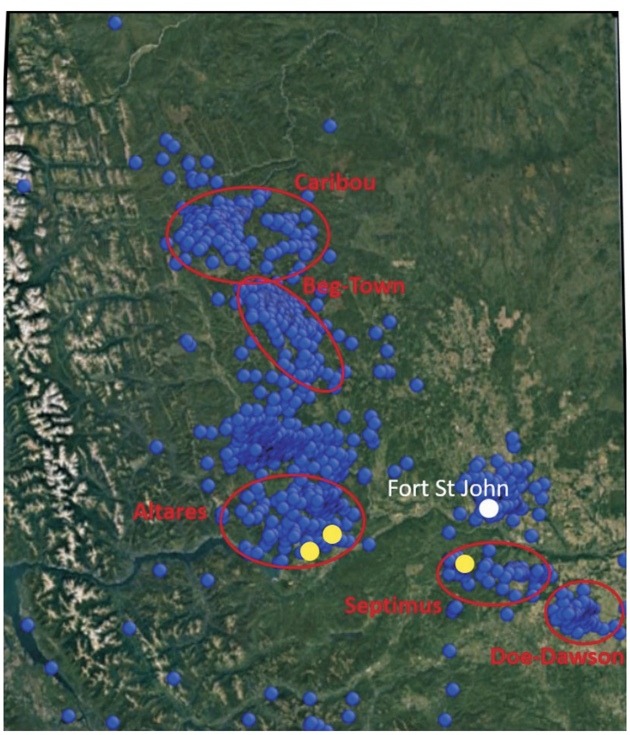

Figure 5. Locations in the Montney play where three of the new monitoring stations are deployed (yellow circles).

from the results of the seismic monitoring as well as the analysis of well logs, injection falloff tests and 'mini fracs', combined with the hydraulic-fracture stimulation parameters provided by industry partners collaborating on this project. The results from geomechanical and leakoff/imbibition 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.

For the modelling, the preferred program is 3DEC™ (version 5.2), a discontinuum-modelling code based on distinct-element method (DEM) software developed by Itasca™ Consulting Group Inc. The utility of this program was evaluated by first using UDEC™ (Universal Distinct Element Code), the two-dimensional version of the software, , to model both pore pressure build-up and its diffusion along rock discontinuities into a critically stressed fault in response to fluid injection and the subsequent changes to the effective stress field (Bustin and Bustin, 2015). 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 and between the discontinuities and the matrix blocks.

Objectives

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

Develop Protocols to Manage and Mitigate AIS

One of the main objectives of this study is to develop effective TLPs for mitigating AIS based on ground motions for the Montney Formation in northeastern BC. 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. The spatiotemporal and magnitude-frequency distributions of microseismicity, AIS and the associated ground motions will then be analyzed, and different mitigation techniques, such as the impact of reducing or stopping injection at different thresholds and flow-back volumes, and controlling leakoff rates by modifying the completion-fluid chemistry, will be tested through 3-D numerical simulations. The goal of developing TLPs, when combined with current research on reservoir geomechanics, is to develop real-time adjustments to completion programs for mitigating AIS, yet, at the same time, optimize the stimulation.

The impact of site conditions on amplifying the ground motion will be investigated by estimating shear-wave–velocity profiles (e.g., Wair et al., 2012). To fully understand the ground motions resulting from AIS due to hydraulic fracturing, data will be collected from sites with varying ground conditions (i.e., bedrock to till). Comparing the geophone and accelerometer datasets will lead to a better understanding of the amplification factors, as well as the relationship between ground motions and magnitudes. The amplification and attenuation data will then be used to develop ground-motion–prediction equations.

Reducing AIS through Hydrogeomechanical Modelling

Hydrogeomechanical modelling will help prevent AIS due to hydraulic fracturing in northeastern BC by leading to a better understanding of the processes resulting in AIS, quantifying the sensitivity of the rate and magnitude of AIS to the hydrogeomechanical parameters, and by identifying regions with higher probability of hosting critically stressed faults, as well as providing insights into the maximum magnitude of events. The first stage of the hydrogeomechanical modelling involves history matching specific hydraulic-fracturing stages, laterals and/or well pads to match the spatial and temporal pattern of the seismicity and microseismicity as well as the wellbore-pressure variations that were monitored. Complete parametric analyses will then be performed on the best fit models. The modelling will investigate the re-activation of faults both inside and outside the reservoir zone. The results of the modelling will be integrated with the shake maps calculated from the monitoring data and the amplification factors to develop seismic hazard and risk maps. Earth models will also be used to test completions and well designs to optimize production; 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 be investigated.

Summary

The array of inexpensive and easily deployable stations has been expanded from 5 to 17, such that it is now possible to densely monitor completions in real time. Algorithms were added to send an alert when a threshold acceleration is recorded and to calculate real-time ground-motion parameters (i.e., PGA, PGV, PGD, STA/LTA, SI). The first dataset was recorded by the original five-station array and the new stations have been thoroughly tested. All 17 stations are currently deployed, many around disposal wells, in preparation for the first dense-monitoring project. The data recorded by the monitoring projects will be integrated with ancillary data into 3-D hydrogeomechanical models to develop methods and protocols for the reduction and mitigation of AIS in the Montney Formation in northeastern BC. In addition to methods and protocols, the legacy of this research is the development of the mobile sensors that can be optimally positioned throughout field development as needed.

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