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Monitoring Induced Seismicity in the Montney Play, Northeastern British Columbia

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Introduction

The limited availability of monitoring data to researchers is one of the greatest challenges limiting the advancement of the understanding of induced seismicity in northeastern British Columbia (BC) and, hence, the development of proactive mitigation schemes and frameworks for hazard assessment. Many of the recommendations regarding induced seismicity from the *Scientific Review of Hydraulic Fracturing in British Columbia* (Scientific Hydraulic Fracturing Review Panel, 2019) directly (6 of 18) or indirectly (4 of 18) refer to the need for increased monitoring and data sharing. While the regional broadband network in the Montney play is sufficient for larger events (M > ~1.8), a more complete catalogue is required for detailed modelling studies and proactive mitigation. Additionally, the coverage of accelerometers remains inadequate to understand whether events will be felt or cause damage. To address the data gap, an array of paired accelerographs plus geophone stations has been developed to densely monitor hydraulic-fracturing operations.

Three-component (3C) accelerographs are currently deployed at 15 sites in western Canada, 11 of which are telemetered and providing real-time data to an online interactive platform, Portae Terra (www.portaeterra.ca). In the past year (November 2018 to November 2019), two hydraulic-fracturing operations were monitored in the Montney play. Two stations, deployed within ~1 km of each other, recorded 33 of the 34 events with M > 1.5 that were induced by the two hydraulic-fracturing operations. Fourteen events with M < 1.5 were also recorded; however, ground-motion parameters for these events are of little use without event information for comparisons; such information is not available for these smaller events. Five of the 10 earthquakes that were not caused by the two fracturing operations being monitored by this project—but occurred within ~30 km of the aforementioned two stations and were reported by Natural Resources Canada (NRCan) with local magnitude (M_L) ranging from 1.4 to 2.6—were also recorded. The site-corrected, peak ground acceleration (PGA) of the geometric mean of the horizontal components ranged from 0.360 to 60.9 cm/s^2 (0.037–6.2% g) for events with M_L values of 1.57 to 4.5 and hypocentral distances of 2.46 to 17.8 km.

In order to obtain event information for smaller magnitude events, the stations have been upgraded to include 4.5 Hz, high-precision 3C geophones. The first paired station was deployed at one of the sites for the second of the project's monitoring operations. Data analysis is ongoing but, to date, in addition to recording all events with M > 1.5 during the hydraulic-fracturing operation, another 60 events were found from a quick visual inspection of the data. Portae Terra is currently being upgraded to provide real-time access to the geophone data and calculated automatic event information for smaller events. In addition, Portae Terra will provide access to public data from broadband stations in regional networks near the monitoring areas and calculated automatic event magnitudes and locations for larger events.

Dataset

Since 2017, accelerographs deployed at 29 sites across western Canada have been used to monitor seven hydraulic-fracturing operations, three disposal wells and a gas-storage facility. Five stations are currently deployed in the Montney play in BC: a telemetered, long-term accelerograph monitoring a disposal well; two long-term accelerographs in the Kiskatinaw Seismic Monitoring and Mitigation Area (KSMMA), one of which is telemetered; a temporary paired station in KSMMA; and a long-term accelerograph at Penalty Ranch.

During the past year, two hydraulic-fracturing completions were monitored in the Montney play. Two accelerographs were deployed within ~1 km of each other to monitor the first completion. For the second completion, one of the accelerographs was upgraded to a paired station with both

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an accelerometer and a geophone. The accelerometers recorded 33 of the 34 events detected by the local, operator-deployed array with moment magnitude (M_w) > 1.5 that were induced by the two hydraulic-fracturing operations. The event that was missed by the sensors is the smallest of the events. Fourteen additional events, presumably with M_w < 1.5, were recorded by the accelerometers during the operations; however, ground-motion parameters for these events are of little use without event information for comparisons; such information is not available for these smaller events. Seven of the events detected by the local array were reported by NRCan. NRCan reported 10 additional events, with M_L ranging from 1.4 to 2.6, within 35 km of the two stations in the past year. The accelerometers detected 5 of the 10 events. The largest of the events was missed by the accelerometers; however, smaller events at greater hypocentral distances were detected. In total, 53 events were recorded during the past year by the accelerometers, with pre–site-corrected PGAs (for geometric mean of horizontal components) ranging from 0.030% g to 8.1% g. The measured PGAs were corrected for each event to a reference site-class with a time-averaged shear-wave velocity over the top 30 m (V_{s30}) of 760 m/s, following the procedure outlined in Bustin et al. (2019). The site-corrected PGAs range from 0.037% g to 6.2% g for events with magnitudes of 1.57–4.5 and hypocentral distances of 2.46–17.8 km.

In addition to these two accelerometers, the first of the project's geophones was deployed for the second of the monitoring operations. Data analysis is ongoing but, to date, in addition to recording all events with M > 1.5 during the hydraulic-fracturing operation, another 60 events were found from a quick visual inspection of the data.

Attenuation

The site-corrected PGAs versus hypocentral distances for events recorded by the stations were overlain on the data and predictive model presented for the South Montney play by Babaie Mahani and Kao (2017). The results, which are plotted in Figure 1, show that the datasets are consistent. However, the PGAs for many of the magnitude 2–2.5 events are higher than predicted by the ground-motion prediction equation (GMPE). This may be a result of the simple method used for correcting site effects (i.e., amplification), the combination of local and regional solutions being used, or the effects of radiation patterns resulting from the source mechanisms. The plot also shows the minimum threshold for detection as a result of digital noise. The MEMS sensors that are currently being deployed allow detection of events with PGA > ~0.03% g.

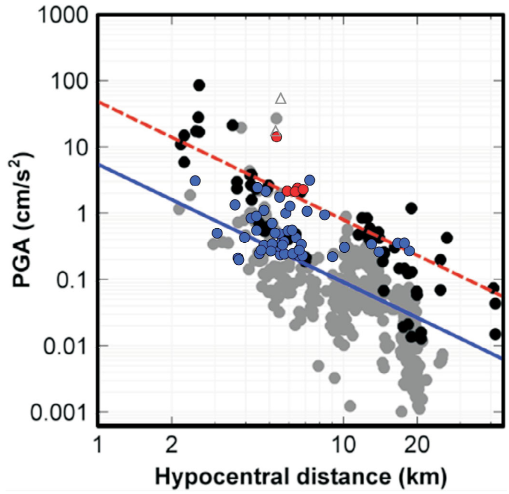

Figure 1. Site-corrected PGA versus hypocentral distance for events recorded by the project's array, with 1.5 < M < 2.5 events plotted as blue dots, 2.5 < M < 3.5 events plotted as red dots and M > 3.5 events plotted as grey triangles on GMPE and data from Babaie Mahani and Kao (2017).

Magnitude of Completeness

To investigate the magnitude of completeness for the sensors, magnitude versus hypocentral distance has been plotted for events that were detected by one or more of the stations (blue dots in Figure 2) and events that were not (grey dots). The results indicate that M > 1.55 events are consistently detected within ~7 km and M > 2 events within ~18 km of the stations. Events with M < 1.5 are being detected, but access to information for these events is not available because the local, operator-deployed array does not provide sufficient solutions for smaller events. Based on its magnitude and hypocentral distance, the M_L 2.6 event on January 19, 2019, reported by NRCan, should have had sufficient ground motions to be detected by the sensors.

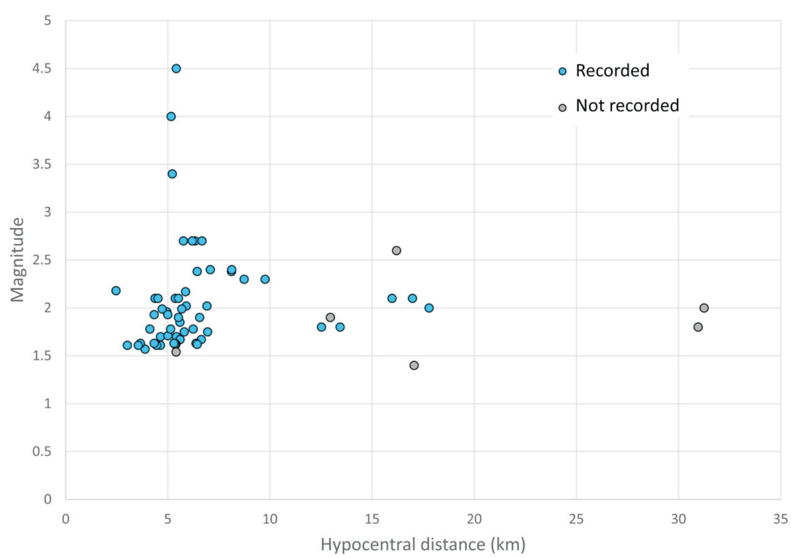

Figure 2. Magnitude versus hypocentral distance for events that were detected (blue) and were not detected (grey) on the study's stations.

The data recorded from one of the stations at the time of the event, showing the usual digital noise, is shown in Figure 3. For comparison, the data recorded from the same station for the M_L 2.1 event on January 27, 2019, reported by NRCan, is also shown. Although the events have similar hypocentral distances (16.0 km for M_L 2.1 versus 16.2 km for M_L 2.6), the smaller event shows clear P- and S-wave arrivals and the larger event does not. A denser array of accelerometers would have been required to understand why this event was not recorded. A possible explanation is that the M_L 2.6 event has a source that radiated asymmetrically with a minimum axis in the direction of the study's stations.

Depth of Burial

To investigate any possible impacts that depth of burial of the sensors might have on recorded ground motions, four sensors were installed at different depths (30, 60, 90, and 120 cm) at a single site in a seismically active area for a 3-month period. The sensors were a maximum of 5 m apart, with the 30 and 90 cm sensors and the 60 and 120 cm sensors within 1 m of each other. Eighteen events were recorded by the four sensors, with no correlation observed between sensor depth and PGA.

Portae Terra

The telemetered stations are providing real-time data to an online interactive platform, Portae Terra (www.portaeterra.ca). When new data are received by the study's server and an alert has been triggered, the raw data are automatically transferred to Portae Terra. Proprietary data are selectively available to operators through a unique passcode to access Portae Terra. Passcode '111111' provides open ac-

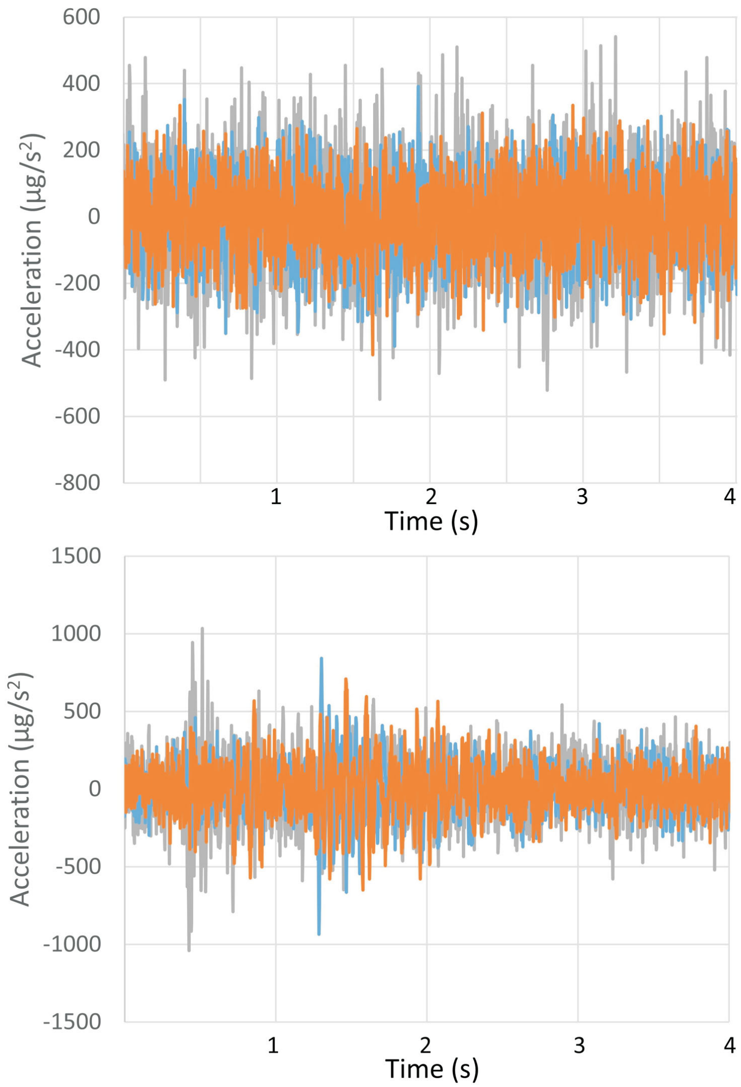

Figure 3. Data recorded on one of the study's accelerometers from the M_L 2.6 event reported by NRCan on January 19, 2019 **(top)**, compared to data recorded on the same station from the M_L 2.1 event reported by NRCan on January 27, 2019 **(bottom)**.

cess to data from the telemetered stations on public land as well as other public stations. Upon entering the site, a map is provided showing the location of all stations available for the specific passcode. Stations with new data since the last login appear with a different icon marker. To view the data from a specific event, the desired station is first chosen by either clicking the station on the map or choosing the station name from the drop-down list. The data file can then be chosen based on date and time from the drop-down list. The data with removed instrument response are then plotted with the event time and calculated ground-motion parameters printed below and next to the plot. A sample screenshot from Portae Terra is included in Figure 4. Waveforms for up to six events can be viewed at once. If the download button is selected, a zipped folder can be downloaded containing CSV files with the data in µg and cm/s^2, the calculated ground-motion parameters and the calculated response spectral accelerations (PSA) at periods of 0.05, 0.1, 0.3, 0.5, 1.0, 2.0 and 3.0 s. The zipped folder also contains the raw data in miniSEED format and dataless SEED volume for the station.

Ongoing Upgrades and Future Work

Systems are being set up for automatic solutions for small-magnitude events using the study's geophone data and for large-magnitude events using data from regional broadband networks available through Incorporated Research Institutions for Seismology (IRIS; https://www.iris.edu/hq/). Earthworm is being used to process the data from the geophone arrays, whereas the procedure of the BC Oil and Gas Commission (BCOGC) for automatic solution using Seiscomp3 is being mimicked for the data from the regional broadband stations. The regional stations for which real-time data are currently being received from IRIS can be viewed on Portae Terra by choosing 'All Stations'. The data from the study's geophone stations and the regional broadband stations in the areas being monitored by the study will be available to view and download through Portae Terra. The automatic solutions calculated by the system will also be plotted on the map. A module is also being prepared for real-time monitoring of hydraulic-fracturing operations through frequency-magnitude, probability and 3D event distributions, and temporal variations in b-value, number of events and maximum magnitude. The upper-limit maximum magnitude estimated from the methods of Shapiro et al. (2010) and van der Elst et al. (2016) will be included on the plot of maximum magnitude versus time, to enable comparisons. A module including basic information on induced seismicity, a glossary and links to sites for additional information is also being prepared.

Once the upgrade of the current accelerographs to paired stations with 3C 4.5 Hz geophones has been completed, up to five hydraulic-fracturing operations in the Montney play can be monitored to obtain a more comprehensive catalogue of events, complete with ground-motion parameters. The recorded monitoring data will be investigated to better understand frequency-magnitude and spatiotemporal distribution, and how they can be used to forecast maximum magnitude, aid in the development of proactive mitigation plans and map seismic susceptibility. In addition, the ground-motion data from the dense monitoring will be investigated to better understand whether ground motions will be felt or pose a risk to critical infrastructure or well-

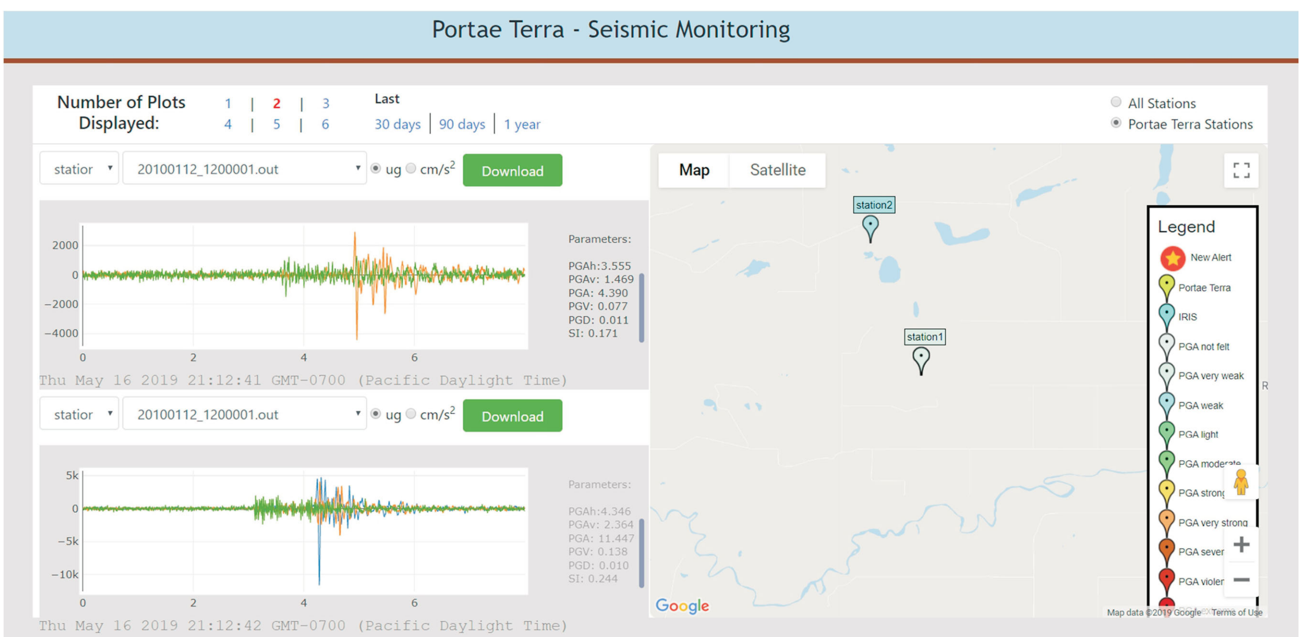

Figure 4. Example of an event recorded on two stations viewed on Portae Terra (www.portaeterra.ca).

bore integrity, to reduce the variability in ground-motion prediction equations due to radiation patterns, and to compare approaches for quantifying their hazard/risks. Finally, the data will be integrated into 3D Earth models to quantitatively rank mitigation strategies and better understand the processes and parameters controlling anomalous induced events.

Summary

The study's accelerographs, which are now providing real-time data to an online interactive dashboard (Portae Terra), were deployed to monitor two hydraulic-fracturing operations during the past year. Fifty-three events were recorded, with site-corrected PGAs for the geometric mean of the horizontal components ranging from 0.037% g to 6.2% g for events with magnitudes of 1.57 to 4.5 and hypocentral distances of 2.46 to 17.8 km. The values obtained are consistent with the data and prediction models previously presented for the south Montney play. The first paired station with both a 3C accelerometer and a 3C geophone was deployed for the second hydraulic-fracturing operation and recorded 60 events not detected by the accelerometers. A system is currently being developing for automatic solutions for smaller events from the geophone data and larger events from regional broadband networks. The data and automatic event information will also be made available through Portae Terra.

Acknowledgments

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