Induced Seismicity Monitoring Project (ISMP): April 2018-March 2019 Report

Alireza Babaie Mahani, Project Seismologist

May 2019

Contents

Executive Summary

The BC Seismic Research Consortium was established in 2012 by Geoscience BC, the Canadian Association of Petroleum Producers (CAPP), Natural Resources Canada (NRCan) and the BC Oil and Gas Commission (BCOGC). It followed a recommendation from the BCOGC in response to concerns regarding induced seismicity associated with hydraulic fracturing in the Horn River Basin. Initially funded by Geoscience BC and industry (CAPP, via the BC Oil and Gas Research and Innovation Society), project activities began with Geoscience BC and industry sharing the cost and maintenance of the seismic stations, with additional financial and technical support coming from the BCOGC and Natural Resources Canada, respectively. The Yukon Government was added as a consortium partner in 2016. The consortium is managed by a joint steering and technical committee comprising of representatives from each of the consortium partners.

During September and October 2018, 7 new seismographic stations were installed in the Montney Play of northeast British Columbia (NE BC). These public stations, funded by BC Oil and Gas Commission (BCOGC) and Natural Resources Canada (NRCAN), provide additional coverage for the area improving monitoring of induced seismicity and ground motion recording at close distances.

On November 30, 2018, a sequence of induced earthquakes occurred in the Septimus region of NE BC with the largest event having a moment magnitude (Mw) of 4.6. Ground motion from this relatively large induced earthquake was recorded by the dense public and private stations in the area providing an excellent database for ground motion analysis from shallow widely-felt induced earthquakes. Currently, automatic earthquake monitoring within the Montney Play is done using the in-house seismic monitoring software SeisComp3 using all the available stations along with a ShakeMap system that provides maps of ground motion amplitudes and shaking parameters for each earthquake.

There are several ongoing projects currently being conducted by the members of the BC Seismic Research Consortium including taking advantage of machine learning techniques for event identification, determination of local ground motion prediction equations, and velocity modeling for better earthquake location determinations.

Update on Seismic Monitoring in Northeast BC

In August 2018 a service trip was done for the maintenance of the seismographic station NAB1 (Figure 1) of the enhanced monitoring network. The batteries, solar panels, and 15 amp breaker were replaced in order to make the stations once again operational. During September and October 2018, 7 new stations, funded by BCOGC and NRCAN, were installed in the Montney Play of NE BC, which has increased the monitoring capabilities of the seismic network in the area. All the new stations were added to the SeisComp3 automatic earthquake monitoring for rapid identification of induced events. Figures 1 and 2 show the updated maps of the minimum detectable magnitude and epicentral uncertainty. In these maps, stations from different networks are shown with different colours; yellow: Regional Alberta Observatory for Earthquake Studies Network (5 stations), blue: Canadian National Seismic Network (3 stations), green: McGill University Network (9 stations), red: BCOGC Network (7 new stations), black: original BC Seismic Research Consortium Network (10 stations). With the exception of the McGill network, all stations are public. The dense coverage of seismographic stations, especially in the Septimus region to the south of Fort St. John where most activity is happening, provides a low detection threshold (Figure 1) and location uncertainty (Figure 2). Figure 3 provides an overview of the felt shaking area of the November 30, 2018 induced earthquake in NE BC with Mw of 4.6 (Babaie Mahani et al., 2019) as generated by a prototype near-real-time ground-motion analysis system being implemented for the region in collaboration among Western University, NRCAN, and BCOGC. Currently this system works in conjunction with the SeisComp3 earthquake monitoring software using the automatic solutions by SeisComp3 to generate the ShakeMaps.

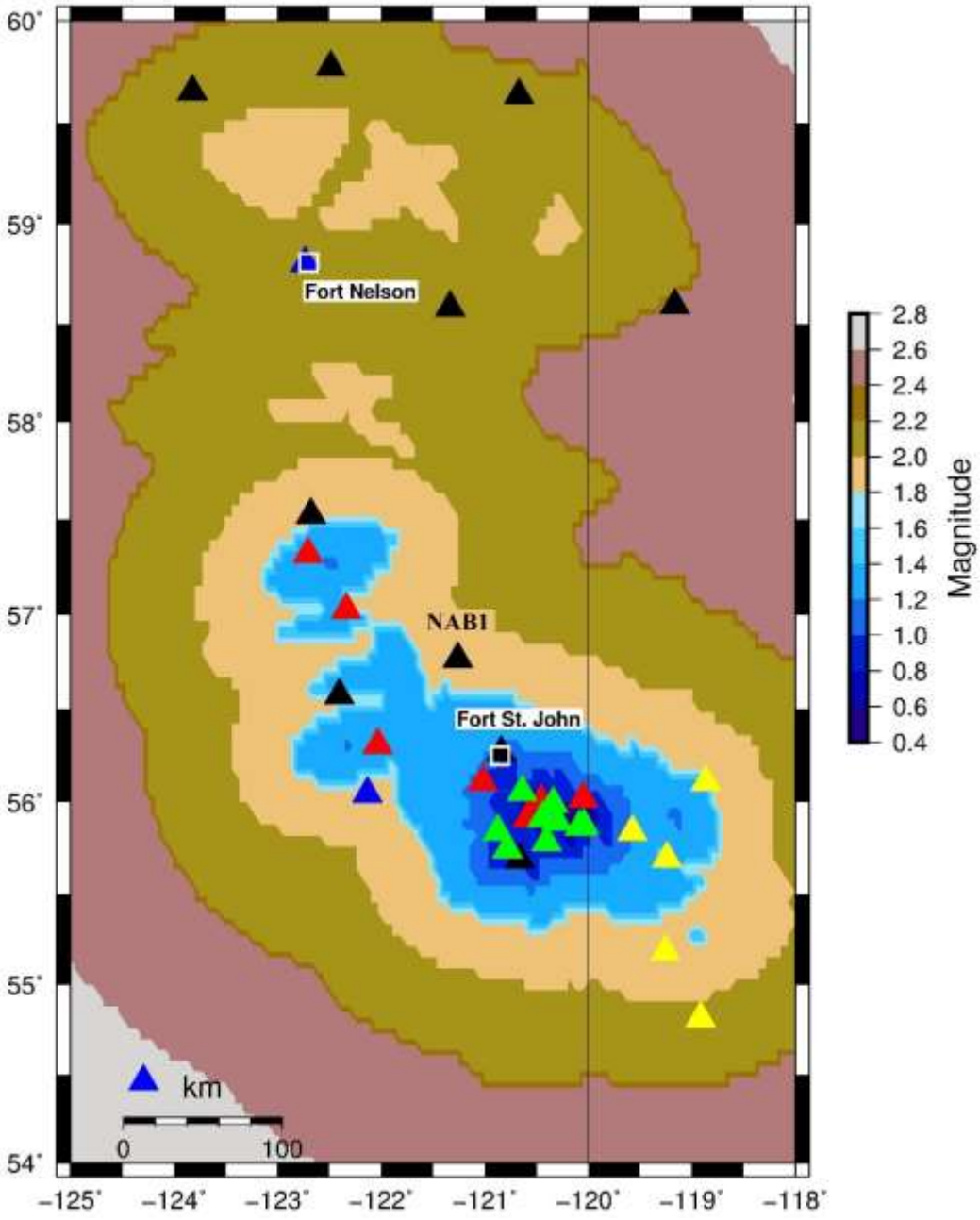


Figure 1. Map of the minimum detectable magnitude in NE BC and western Alberta. Triangles show the seismographic stations; yellow: Regional Alberta Observatory for Earthquake Studies Network (5 stations), blue: Canadian National Seismic Network (3 stations), green: McGill University Network (9 stations), red: BCOGC Network (7 new stations), black: original BC Seismic Research Consortium Network (10 stations).

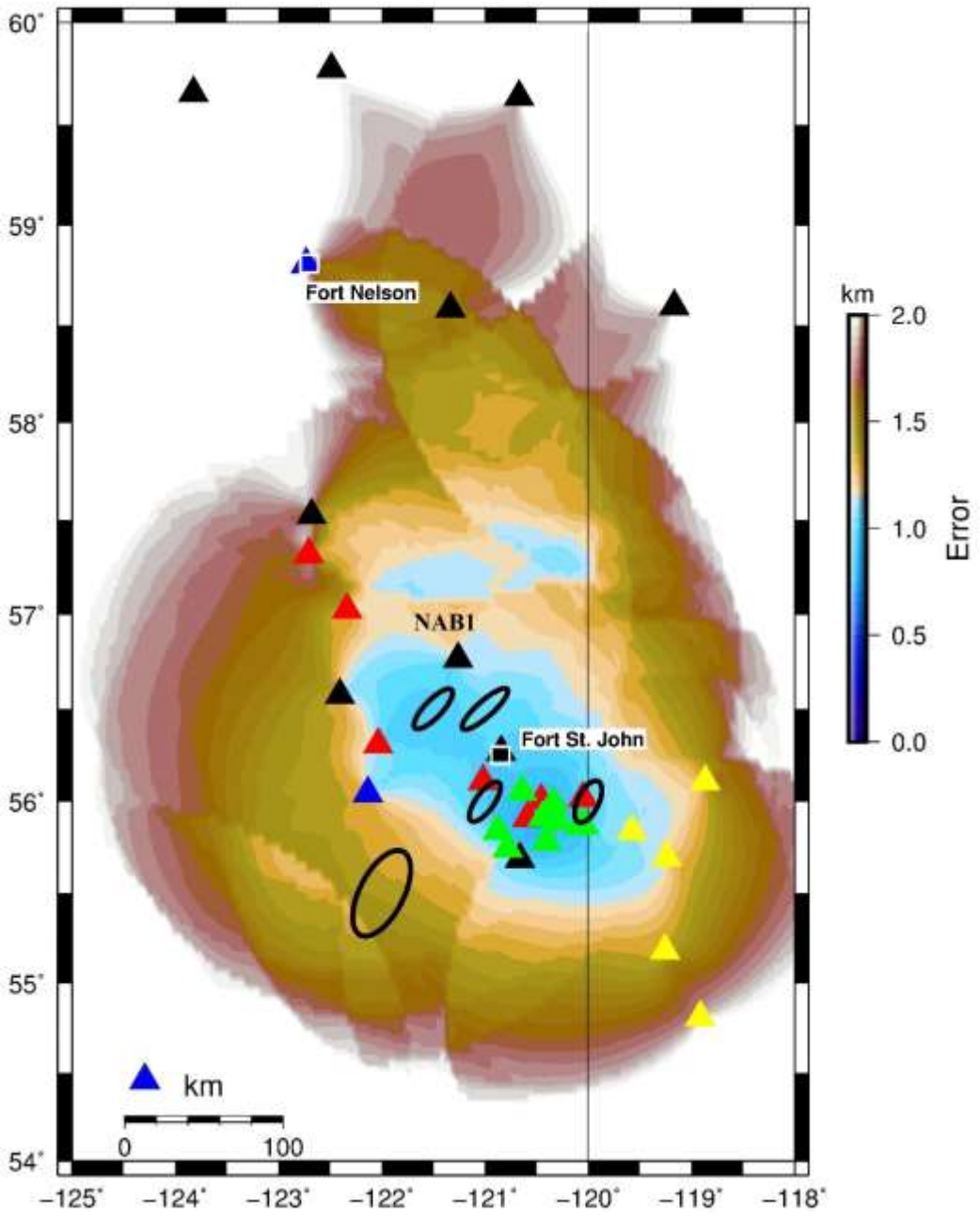
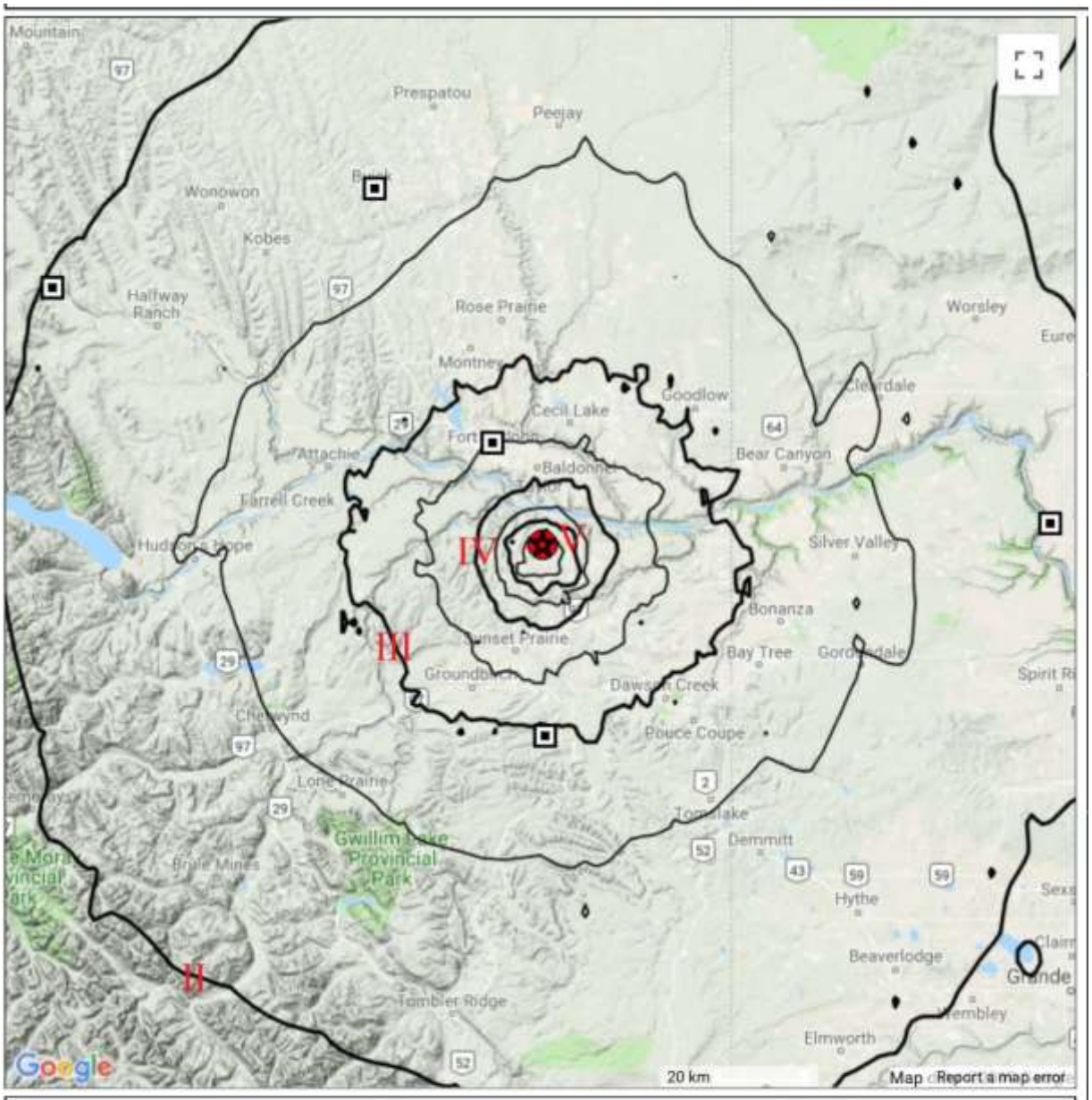


Figure 2. Map of the epicentral uncertainty for earthquakes with magnitude of 2 in NE BC and western Alberta. Ellipses show the uncertainty at some locations. Triangles show the seismographic stations; yellow: Regional Alberta Observatory for Earthquake Studies Network (5 stations), blue: Canadian National Seismic Network (3 stations), green: McGill University Network (9 stations), red: BCOGC Network (7 new stations), black: original BC Seismic Research Consortium Network (10 stations).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	*<0.02*	*0.1*	*1.4*	*4.7*	*9.6*	*20*	*41*	*86*	*>178*
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2012)

Figure 3. Automatically-generated near-real-time ShakeMap of the ground shaking distribution for the mainshock on November 30, 2018 in NE BC with Mw of 4.6, based on real-time public stations (squares). The associated ground acceleration and velocity for each MMI level are the average values.

Seismicity between April 2018 and April 2019

Figure 4 shows 107 events that occurred in NE BC between April 2018 and April 2019. With the exception of the mining blast events in the gray area to the left of the Cordilleran deformation front (solid black line), seismicity was confined within the Montney Play. The largest event was the Mw 4.6 earthquake on November 30, 2018 in the Septimus region (star). Although, the Septimus region experienced larger earthquakes in the period April 2018 to April 2019 than other periods (January 2016 to October 2017 (Figure 5; left) and October 2017 to April 2018 (Figure 5; right), distribution of seismicity is similar and confined within the Montney region, with the exception that the Septimus region seems to be more active than other areas such as Altares, Graham, Beg-Town, and Caribou. This difference is probably due to the more oil and gas activities in the Septimus region than other parts of the Montney Play.

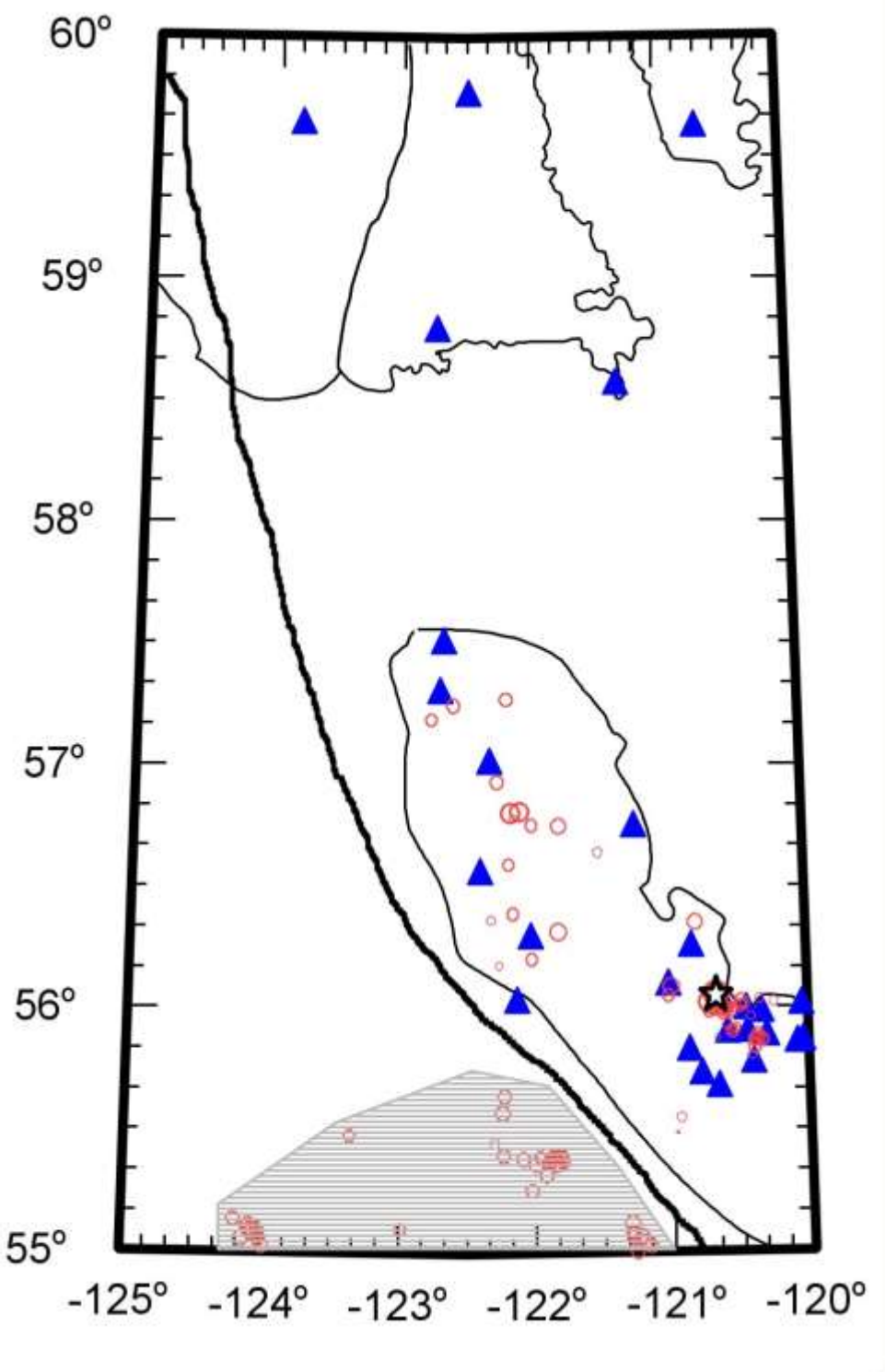


Figure 4. Events reported in the NRCAN earthquake catalogue in NE BC between April 2018 and April 2019 (circles). Triangles show the seismographic stations. Events in the gray area are mining blasts. Star shows the location of the earthquake on November 30, 2018 with moment magnitude of 4.6. Solid black line shows the approximate eastern limit of the Cordilleran deformation front.

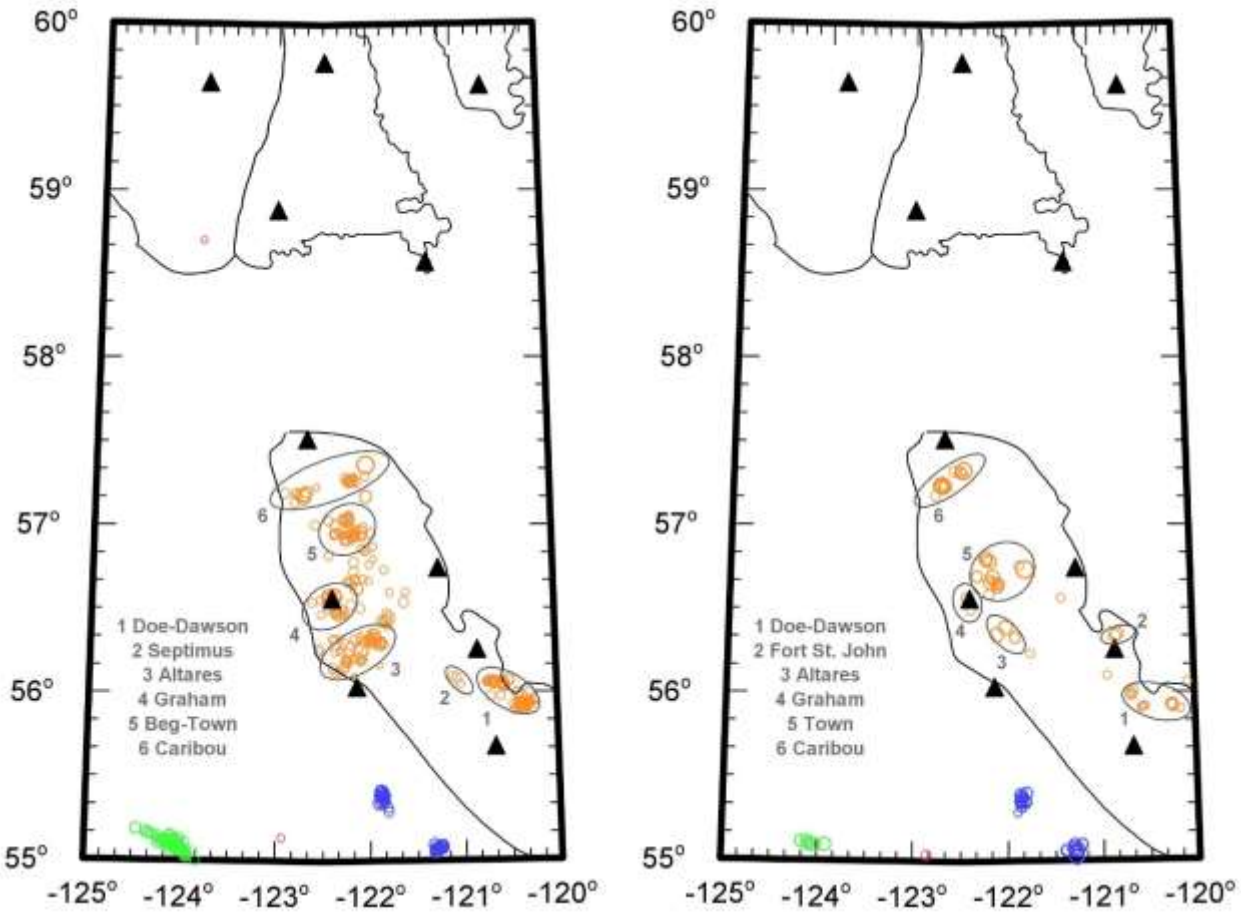


Figure 5. Events reported in the Natural Resources Canada earthquake catalogue in northeast British Columbia between January 2016 and October 2017 (left) and October 2017 to April 2018 (right). Events shown with green, red, and blue circles to the southwest of the Montney Play are mining blasts. From Babaie Mahani (2018).

The November 30, 2018 Septimus Earthquake

On November 30, 2018 at 01:27:06 (UTC), a felt event was detected in the Septimus region of NE BC where hydraulic fracturing was in progress. The initial report by NRCAN gave a local magnitude (ML) of 4.5. This event was followed by two other earthquakes, less than an hour later, at 02:06:02 and 02:15:00, with ML of 3.4 and 4.0, respectively (Babaie Mahani et al., 2019). A fourth event with ML of 2.7 occurred on December 7, 2018 at 13:49:26 within the epicentral area of the November sequence. The maximum intensity level at the epicentral area of the mainshock was in the range of IV to V (Modified Mercalli Intensity; MMI) with felt reports mostly within 100 km of the epicenter (Figure 3).

Babaie Mahani et al. (2019) obtained Mw for these events using the Atkinson et al. (2014) estimation based on distance-corrected vertical pseudo-response spectral acceleration (PSA) amplitudes averaged over all stations, as modified by Novakovic et al. (2018, 2019) for Oklahoma and Alberta. The estimated Mw values are shown in Table 1. Figure 6 shows the three-component peak ground acceleration (PGA)

and peak ground velocity (PGV) versus hypocentral distance for all the events described in Table 1. PGA is a good measure of high-frequency ground motions (5 to 10 Hz), whilst PGV is indicative of motions at intermediate frequencies (1 to 2 Hz). Thus, high-frequency structures tend to be sensitive to PGA and low-frequency structures tend to be more sensitive to PGV. The dashed horizontal line in Figure 6 corresponds to the associated lower-bound ground motion threshold, in acceleration (46 cm/sec^2) and velocity (3.8 cm/sec), for an MMI of VI based on the relationships provided by Worden et al. (2012). At distances less than 6 km, PGA is clearly higher than the MMI VI threshold for the two largest events. However, the PGV values are mostly below the MMI VI threshold at all distances. For distances larger than 6 km, some PGA values are still close to the MMI VI threshold up to distances ~25 km whilst PGV values are well below the MMI VI threshold for distances above 6 km. As subsequently discussed, the PGA values for the two largest events may have been reduced by non-linear site response at many stations within 20 km. The intensity of shaking in different frequency bands and its duration are important considerations in the assessment of structural response to ground motion.

Table 1. Parameters of the earthquakes occurred on November 30, 2018 and December 7, 2018. Mcat is the reported magnitude in the NRCAN earthquake catalogue, which is either Mw or ML. The columns with the header Mw and Δσ are the moment magnitude and stress drop obtained by Babaie Mahani et al. (2019). For event number 1-3 depth was reported by Canadian Natural Resources Limited while for the 4th event depth is assumed as 2 km.

Event No.	Time (UTC)	Latitude	Longitude	Depth (km)	M_{cat}	M_w	Δσ (bars)
1	2018-11-30 01:27:06	56.05	-120.69	1.1	4.5 (M_w)	4.6	85
2	2018-11-30 02:06:02	56.05	-120.71	1.7	3.4 (M_L)	3.5	
3	2018-11-30 02:15:00	56.05	-120.69	1.8	4.0 (M_L)	4.0	75
4	2018-12-07 13:49:26	56.04	-120.68	2.0	2.7 (M_L)	2.9	

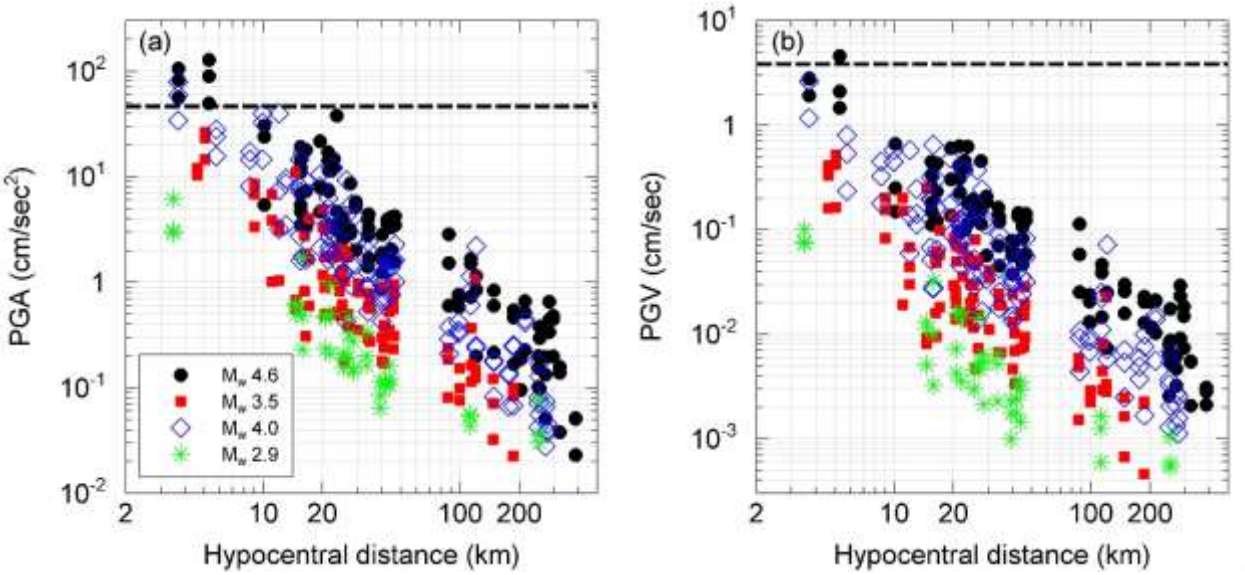


Figure 6. Three-component PGA (a) and PGV (b) versus hypocentral distance for the earthquakes considered in Table 1. The dashed horizontal line corresponds to the lower bound of MMI of VI based on the relations in Worden et al. (2012).

Communication and Extension Plan

The members of the BC Seismic Research Consortium have presented the following papers or presentations throughout April 2018 to March 2019.

Presentations:

- Tectonic Strain Rate as a Controlling Factor of Injection-Induced Earthquakes in Western Canada, H. Kao, R. D. Hyndman, Y. Jiang, R. Visser, B. Smith, A. B. Mahani, L. J. Leonard, H. Ghofrani, and J. He, American Geophysical Union annual meeting, December 10-14, 2018, Washington, D.C. (oral presentation). Ali Mahani, Project Seismologist
- Near-Field Ground-Motion Amplitudes from Induced Earthquakes in the Western Canada Sedimentary Basin, CSUR Induced Seismicity Workshop, Banff Alberta, October 24-26, 2018 (poster presentation and expanded abstract). Ali Mahani, Project Seismologist

Technical Papers:

- Babaie Mahani, A., H. Kao, G. M. Atkinson, K. Assatourians, K. Addo, and Y. Liu (2019). Ground motion characteristics of the November 30, 2018 injection-induced earthquake sequence in northeast British Columbia, Canada, submitted to Seismological Research Letters.
- Babaie Mahani, A. and H. Kao (2019). Local Magnitude Scale for Earthquakes in the Western Canada Sedimentary Basin, Northeastern British Columbia and Northwestern Alberta; in Geoscience BC Summary of Activities 2018, Geoscience BC, Report 2019-2, p 47-54.

- Babaie Mahani, A., and H. Kao (2018). Accurate Determination of Local Magnitude for Earthquakes in the Western Canada Sedimentary Basin, Seismological Research Letters, Vol. 90, No. 1, p. 203-211, doi: 10.1785/0220180264.
- H. Kao, R. D. Hyndman, Y. Jiang, R. Visser, B. Smith, A. B. Mahani, L. J. Leonard, H. Ghofrani, and J. He (2018). Induced Seismicity in Western Canada Linked to Tectonic Strain Rate: Implications for Regional Seismic Hazard, Geophysical Research Letters, Vol. 45, No. 20, p. 11, 104-11, 115, doi:10.1029/2018GL079288.

Current Research

There are several ongoing projects being conducted by the members of the BC Seismic Research Consortium. These projects include:

- Artificial intelligence or machine learning techniques in earthquake monitoring and event identification.
- New ground motion prediction equations or calibration of existing models for NE BC and the ShakeMap system for the area.
- Local velocity structure of the Montney Play for better earthquake location determinations.

Conclusions

Seven new seismographic stations, funded by BCOGC, were installed during September and October 2018, in the Montney Play of NE BC. These public stations provide increased coverage for the area, thereby improving monitoring of induced seismicity and ground motion recording at close distances. On November 30, 2018, a sequence of induced earthquakes occurred in the Septimus region of NE BC with the largest event having an Mw of 4.6. Ground motion from this relatively large induced earthquake was recorded by the dense public and private stations in the area providing an excellent database for ground motion analysis from shallow induced earthquakes that are felt within a large area. Currently, automatic earthquake monitoring within the Montney Play is done using the in-house seismic monitoring software SeisComp3 using all the available stations along with a ShakeMap system that provides maps of ground motion amplitudes and shaking parameters for each earthquake. There are several ongoing projects currently being conducted by the members of the BC Seismic Research Consortium including taking advantage of machine learning techniques for event identification, determination of local ground motion prediction equations, and velocity modeling for better earthquake location determinations.

References

Atkinson, G. M., D. W. Greig, and E. Yenier (2014). Estimation of moment magnitude (M) for small events (M < 4) on local networks, Seismological Research Letters, 85, 1116-1124.

Babaie Mahani, A. (2018). Induced Seismicity Monitoring Project (ISMP): October 2017-March 2018 Report, 16 pages.

Babaie Mahani, A., H. Kao, G. M. Atkinson, K. Assatourians, K. Addo, and Y. Liu (2019). Ground motion characteristics of the November 30, 2018 injection-induced earthquake sequence in northeast British Columbia, Canada, submitted to Seismological Research Letters.

Novakovic, M., G. M. Atkinson, and K. Assatourians (2018). Empirically calibrated ground-motion prediction equation for Oklahoma, Bulletin of Seismological Society of America, 108, 2444-2461.

Novakovic, M., G. M. Atkinson, K. Assatourians, and Y. Gu (2019). Empirically calibrated ground-motion prediction equation for Alberta, Bulletin of Seismological Society of America, in review.

Appendix A: Earthquakes recorded between April 1 2018 and March 31 2019

Date	Time (UTC)	Latitude	Longitude	Depth (km)	Magnitude
2019-03-18	01:54:04	55.082	-121.313	0.0	2.1
2019-03-17	22:08:05	55.365	-122.001	0.0	2.7
2019-03-17	01:14:27	55.403	-122.239	1.0	2.5
2019-03-12	22:14:09	55.074	-121.241	5.0	2.5
2019-03-10	23:12:27	55.396	-121.880	5.0	2.6
2019-03-07	18:31:09	55.118	-124.079	0.0	2.5
2019-03-07	01:35:28	55.578	-122.243	0.0	2.7
2019-03-06	02:19:20	55.404	-121.862	5.1	2.5
2019-02-27	16:41:02	56.819	-122.109	9.6	3.3
2019-02-21	23:05:40	55.375	-121.838	1.8	2.7
2019-02-20	16:22:39	56.811	-122.180	11.4	3.4
2019-02-17	22:33:57	55.093	-124.068	6.8	2.7
2019-02-13	20:31:31	56.794	-122.156	8.3	1.6
2019-02-12	07:27:23	55.967	-120.420	7.5	1.7
2019-02-04	19:47:49	55.368	-121.855	12.1	3.0
2019-02-03	02:01:19	57.198	-122.772	12.6	2.2
2019-02-02	22:53:13	55.051	-124.010	8.8	2.3
2019-01-29	01:11:58	55.991	-120.608	9.9	2.0
2019-01-28	14:45:50	55.996	-120.589	10.0	2.1
2019-01-27	23:09:54	55.376	-121.916	25.0	2.2
2019-01-27	18:35:12	55.029	-123.982	16.2	2.5
2019-01-27	18:33:44	55.991	-120.633	9.7	1.8
2019-01-27	09:40:52	56.010	-120.493	15.2	2.1
2019-01-24	10:50:33	56.020	-120.476	14.0	1.4
2019-01-24	10:28:45	56.008	-120.542	3.7	1.9
2019-01-24	05:37:36	56.005	-120.681	10.7	2.1
2019-01-24	02:42:03	56.003	-120.611	5.1	2.3
2019-01-23	20:26:01	56.651	-121.532	5.0	1.9
2019-01-22	06:57:25	55.995	-120.605	3.1	2.3
2019-01-19	14:28:54	56.036	-120.354	13.2	1.8
2019-01-19	07:14:28	56.027	-120.491	7.5	2.6
2019-01-18	07:33:27	56.026	-120.252	5.0	1.8
2019-01-17	21:10:24	55.883	-120.661	10.0	1.3
2019-01-17	09:31:12	56.057	-120.695	7.9	2.7
2019-01-17	08:47:37	56.017	-120.464	13.1	2.0
2019-01-16	18:12:07	55.391	-122.090	0.0	2.6
2019-01-15	22:49:23	55.081	-121.305	10.0	2.3
2019-01-15	00:11:00	55.083	-124.058	7.4	2.8
2019-01-14	22:50:35	57.254	-122.607	5.0	2.6
2019-01-14	03:32:21	56.942	-122.278	16.1	2.5
2019-01-10	09:14:57	55.494	-120.970	10.0	0.8
2019-01-10	01:57:27	55.896	-120.372	6.8	2.2

Date	Time (UTC)	Latitude	Longitude	Depth (km)	Magnitude
2019-01-09	23:15:53	55.872	-120.386	5.0	2.1
2019-01-09	23:13:34	55.870	-120.393	5.0	2.4
2019-01-09	22:31:12	55.843	-120.392	9.9	2.5
2019-01-09	22:25:10	55.809	-120.415	20.0	1.7
2019-01-08	01:33:04	55.868	-120.340	8.7	2.4
2019-01-07	22:26:43	55.875	-120.372	9.9	2.7
2019-01-07	22:12:34	55.395	-121.834	6.7	2.9
2019-01-04	22:21:33	55.028	-121.174	9.1	2.4
2019-01-04	21:08:30	56.186	-122.264	12.7	1.6
2019-01-03	23:03:16	55.648	-122.226	6.3	2.6
2018-12-30	23:13:42	55.382	-121.803	5.0	2.5
2018-12-30	18:40:57	55.101	-124.057	10.0	2.7
2018-12-27	18:09:11	55.395	-121.967	5.1	2.3
2018-12-24	22:22:07	55.123	-121.307	1.0	2.9
2018-12-20	12:31:51	56.043	-120.683	8.0	1.7
2018-12-20	10:22:35	55.991	-120.689	10.8	1.8
2018-12-17	07:54:58	56.759	-121.820	4.5	2.8
2018-12-15	22:21:47	55.390	-121.879	6.1	2.5
2018-12-08	12:27:48	57.282	-122.207	15.0	2.4
2018-12-07	13:49:26	56.042	-120.678	8.0	2.7
2018-12-04	18:49:07	55.092	-124.020	0.0	2.4
2018-12-02	16:02:38	56.213	-122.025	6.7	2.3
2018-11-30	02:15:01	56.029	-120.718	2.2	4.0
2018-11-30	02:06:02	56.057	-120.687	5.6	3.4
2018-11-30	01:27:06	56.060	-120.677	5.0	4.5
2018-11-24	22:13:50	55.050	-121.214	16.0	2.4
2018-11-18	18:19:05	55.405	-121.852	10.0	2.3
2018-11-14	22:12:27	55.366	-121.848	0.0	2.3
2018-10-25	02:28:31	56.060	-121.019	9.9	2.3
2018-10-24	16:42:26	56.397	-122.164	7.8	2.3
2018-10-12	11:26:08	55.996	-120.688	10.0	1.6
2018-10-12	06:28:42	55.998	-120.631	6.2	1.6
2018-10-10	23:06:29	55.323	-121.926	2.0	2.6
2018-10-09	14:40:37	55.997	-120.688	2.0	2.3
2018-10-08	21:53:13	55.141	-124.188	1.0	2.4
2018-10-08	07:07:44	55.990	-120.723	9.0	2.3
2018-10-02	20:39:00	55.979	-120.581	3.4	2.0
2018-09-18	18:50:12	55.984	-120.546	11.7	1.7
2018-09-17	19:07:10	55.058	-121.256	13.8	2.0
2018-09-13	10:41:42	55.983	-120.617	5.5	2.4
2018-09-06	05:11:46	56.761	-122.026	6.3	2.3
2018-08-16	19:03:25	55.453	-122.305	11.5	2.0
2018-08-14	21:32:49	55.057	-124.129	0.0	2.7
2018-08-14	14:17:58	55.557	-120.940	19.5	1.9

Date	Time (UTC)	Latitude	Longitude	Depth (km)	Magnitude
2018-07-24	18:06:13	55.391	-121.884	3.0	2.7
2018-07-03	21:55:47	55.110	-124.094	0.0	2.3
2018-07-01	03:42:34	55.100	-122.987	14.6	2.1
2018-05-30	10:11:56	56.371	-122.326	15.0	1.7
2018-05-29	18:24:30	55.484	-123.360	0.0	2.1
2018-05-29	18:12:16	55.258	-122.029	10.0	2.4
2018-05-19	07:56:45	56.321	-121.827	9.2	3.1
2018-05-05	11:38:11	56.035	-120.569	8.5	2.3
2018-05-05	03:18:57	55.903	-120.559	5.0	2.1
2018-05-02	15:40:06	55.932	-120.593	0.1	2.0
2018-04-30	05:05:57	56.096	-120.997	6.7	3.0
2018-04-17	13:47:39	55.919	-120.556	4.2	1.9
2018-04-17	09:52:07	55.923	-120.536	5.0	1.9
2018-04-17	06:08:58	55.913	-120.570	5.0	1.9
2018-04-16	23:25:48	56.358	-120.814	4.7	2.8
2018-04-16	02:21:43	55.923	-120.532	3.3	1.9
2018-04-13	01:51:55	55.068	-121.302	0.0	2.5
2018-04-13	01:36:21	56.600	-122.192	5.0	2.1
2018-04-08	19:46:20	55.009	-121.276	1.0	2.5
2018-04-07	19:18:44	55.404	-121.817	10.0	2.5
2018-04-01	17:42:17	55.063	-124.005	8.3	2.5