Natural Resources Canada   Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8335

A comprehensive earthquake catalogue for northeastern British Columbia and western Alberta, 2014–2016

R. Visser, B. Smith, H. Kao, A. Babaie Mahani,
J. Hutchinson, and J.E. McKay

2017

Celebrating 175 yrs

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8335

A comprehensive earthquake catalogue for northeastern British Columbia and western Alberta, 2014–2016

R. Visser[1], B. Smith[1], H. Kao[1,2], A. Babaie Mahani[3], J. Hutchinson[2], and J.E. McKay[4]

[1] Geological Survey of Canada, Pacific Division, Sidney, British Columbia
[2] School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia
[3] Geoscience BC, Vancouver, British Columbia
[4] Department of Physics, University of Victoria, Victoria, British Columbia

2017

Permanent link: https://doi.org/10.4095/306292

This publication is available for free download through GEOSCAN (**http://geoscan.nrcan.gc.ca/**).

Recommended citation
Visser, R., Smith, B., Kao, H., Babaie Mahani, A., Hutchinson, J., McKay, J.E., 2017**.** A comprehensive earthquake catalogue for northeastern British Columbia and western Alberta, 2014–2016**;** Geological Survey of Canada, Open File 8335, 1 .zip file. https://doi.org/10.4095/306292

Publications in this series have not been edited; they are released as submitted by the author.

Abstract

To gain a better understanding of induced seismicity in northeast British Columbia and western Alberta, we conducted an intensive analysis of seismic data to locate earthquakes that occurred within the area of 52˚N–61˚N, 126˚W–115˚W for the years of 2014 through 2016. Continuous seismic waveforms from as many as 43 stations operated by various organizations in the region were used in this study. A total of 5478 events were identified and located; but only 4916 solutions were deemed acceptable by our quality criteria. The number of earthquakes in our final catalogue is approximately three times the base level of the Canadian National Seismograph Network catalogue. In this report, we describe in detail our location procedures and how each source parameter (origin time, epicenter, focal depth, and magnitude) is determined. The earthquake catalogue is summarized in a table, while the phase picking data for individual events are presented in an ASCII file as a supplement to this report. The total numbers of events in 2014, 2015, and 2016 are 1287, 1575, and 2057, respectively. The overall magnitude of completeness of our catalogue is M_L 1.8, an improvement from the value of 2.3 for the CNSN catalogue.

1. Introduction

Northeastern British Columbia (BC) and western Alberta (AB) are part of the Western Canada Sedimentary Basin (WCSB) that contains many hydrocarbon-bearing formations. Historically, the WCSB was not considered a seismically active region because the vast majority of significant earthquakes (M≥4) in western Canada occurred near the coast or offshore in connection to plate boundary processes (Figure 1). As northeastern BC and western AB are located more than 800 km away from the western boundary of the North American plate, the pattern of low seismicity is consistent with the intraplate tectonic setting.

Recent engineering advances in horizontal drilling and hydraulic fracturing have enabled the economic development of unconventional oil and gas from shale formations. There are several major shale gas plays in the northeastern BC and western AB region, including the Horn River Basin (HRB), Cordova Embayment, Montney Play, Liard Basin, and Duvernay Play (BC Oil and Gas Commission 2015, Preston, et al. 2016). Many studies have indicated that a sharp increase in regional seismicity can be linked to the injection operations associated with the development of unconventional hydrocarbons (e.g., Atkinson, et al. 2016, Ellsworth 2013, Farahbod, et al. 2015b, Keranen, et al. 2014). This increase of injection-induced earthquakes (IIE) was observed in recent years as the unconventional oil and gas development in northeastern BC and western AB significantly expanded (Atkinson, et al. 2016, Farahbod, et al. 2015a, Schultz, et al. 2017).

The regional seismicity in northeastern BC and western AB is routinely monitored by Natural Resources Canada (NRCan) based on data from the Canadian National Seismograph Network (CNSN). Because of the relatively sparse station coverage in the region and the amount of human attention required to monitor seismicity Canada-wide, the magnitude of completeness for the WCSB was estimated to be M_L~2.3. This level of monitoring is inadequate for the study of induced seismicity as most IIE are small. Since 2013, NRCan has collaborated with a number of partners to increase the regional station density (Farahbod, et al. 2014). Performance analysis of the densified network has indicated that the magnitude of completeness could be improved to M_L~1.5 for places with good station coverage (Babaie Mahani, et al. 2016). Lowering the completeness of the earthquake catalogue by one magnitude unit, however, would require a significant increase in data analysis to locate thousands of small events, which was not available from the CNSN routine operation.

In order to obtain a complete regional seismic pattern for the study of IIE and the associated seismic hazard, the Induced Seismicity Research (ISR) Project, established under the Environmental Geoscience Program, decided to revisit seismic records collected by not only CNSN but also other regional and local seismograph networks between 1 January 2014 and 31 December 2016. The purpose of this effort is to establish a comprehensive earthquake catalogue for the region with a systematic approach and uniform processing criteria. This technical report represents the output of such an effort.

2. Data and Analysis

Our study area corresponds to the latitude and longitude ranges of 52˚N–61˚N and 126˚W–115˚W, respectively. A total of 43 seismic stations were included in this study to give the best azimuthal coverage for events within the study area (Figure 2). Prior to 2014, 30 of the total 43 seismic stations we used had data available. Station coverage was improved in 2014 by the installation of 9 stations in AB as part of the Regional Alberta Observatory for Earthquake Studies Network (RV), and the installation of CNSN station KITB in western BC. From 2015 to 2017 station coverage was further improved by the installation of 3 additional stations NAB2, NBC8, and FSJB (Table 1).

2.1 System Setup

To maintain compatibility with the existing NRCan catalogue, the computer setups and settings of earthquake processing software were made to match those that were used by the Canadian Hazard Information Service (CHIS). Three Linux workstations were set with CentOS 7 — a Linux distribution compatible with Boulder Real Time Technologies' (BRTT) Antelope software (Version 5.5). The Antelope software has a number of settings that must be modified prior to conducting analysis, including the velocity model, the magnitude calculation module, the hypocenter calculation module, and digital filters for waveform analysis.

2.1.1 Velocity Model Settings: The two-layer velocity model named CN01 was loaded into the Antelope velocity model library. This model is also the one used by CHIS analysts in routine location of regional earthquakes in the WCSB. In this model, depths up to 36 km have the corresponding *P* and *S* velocities of 6.2 km/s and 3.57 km/s, respectively. For depths below 36 km, *P* and *S* velocities are 8.2 km/s and 4.7 km/s, respectively.

2.1.2 Magnitude Settings: The calculation of local magnitude (M_L) is based on the maximum amplitude recorded on the vertical channel. Due to the generally smaller size of IIE, we had to adjust the threshold of the signal-to-noise ratio (SNR) from 3.0 to 1.5. The magnitude calculation was also set to take the median value as opposed to the mean used by the routine procedures.

2.1.3 Hypocenter Location Settings: The earthquake location algorithm settings file was modified to utilize the CN01 velocity model along with a limited depth range of 0–25 km.

2.1.4 Filter Settings: These settings are important since the filters utilized by the analyst will directly determine how earthquake signals are displayed on monitors and will subsequently influence the detection, phase picks, and the resulting location of earthquakes. Filter settings were adjusted from the default values to include the following filters: 1-Hz high-pass, 2-Hz high-pass integrated, 3-Hz high-pass, 5-Hz high-pass, 0.5–2-Hz band-pass, 0.8–3-Hz band-pass, 1–5-Hz band-pass, 1–10-Hz band-pass, and 2–20-Hz band-pass.

2.2 Building the Database

Seismic station details and continuous waveforms in miniSEED format were obtained from the Incorporated Research Institutions for Seismology (IRIS) by using either the breq_fast request system or a Perl script created by IRIS called 'FetchData'. Station and waveform information that was not available from IRIS was supplemented by data available from CHIS. Waveforms obtained through IRIS were processed from their continuous yearly format into daily files by utilizing the *miniseed2days* program within Antelope. Waveforms were then sorted into folders and processed chronologically. Station data from IRIS and CHIS was consolidated into a master station file. Antelope databases were finalized for each year of data by creating a descriptor file, which pointed Antelope towards the master station table and the corresponding year of waveform data.

2.3 Location Analysis

Conducting the visual analysis of waveform data for three years of data for 43 stations was a very time intensive task. To effectively complete the analysis, the process is split into two main stages – scanning and location. During the scanning stage, the analyst searched each year of waveforms for earthquake signals. When earthquakes were found, rough phase selections were made that would be finalized during the location stage. While scanning, all available channels were visible, with 3–5 minutes of each channel's waveform data visible at any one time. This short time window allowed the analyst to confidently scan all traces on the screen for earthquake phases before advancing the time window. Earthquake phases picked for the catalogue were: *P*, *S*, *Pn*, *Pg*, *Sn*, and *Sg*. Two main filters were used during scanning to help identify seismic signals from local and regional events, as recommended by senior earthquake analysts at NRCan; the 2-Hz high-pass integrated filter was used during general scanning to remove unwanted low frequency noise while the 1–5-Hz band-pass filter was used to make phase picks on distant stations or stations with noise issues at higher frequencies. During the location phase, the phase selections for each earthquake were analyzed in greater detail with the application of other filters as needed. After preliminary earthquake locations were calculated (Pavlis, et al., 2004), travel-time residual for each observed phase were determined based on the predicted arrival time by the Antelope program *genloc*. The standard deviation of travel time residuals (SDOBS) for each solution was calculated by taking the square root of the sum of the squares of the time residuals, divided by the number of arrivals used in a solution minus either 4 (if depth is allowed to be free) or 3 (if depth is fixed). The max allowable SDOBS threshold was set at 1.0 s, and events with higher values were removed from the catalogue. Approximately 85% of our final solutions have SDOBS less than 0.6 s.

2.4 Magnitude Calculations

Event magnitudes were calculated in two steps. For each event, the first step was to calculate a magnitude value for each station with SNR above the prescribed threshold. Then the event magnitude was obtained by taking the median value of the station magnitudes. Magnitudes were calculated after all locations were completed by means of a batch processing script. The script allowed us to save time by conducting calculations all at once instead of individually, since otherwise an analyst would need to wait for each location and magnitude calculation to be completed before they could proceed to the next seismic event.

2.5 Fixing Systematic Magnitude Deviations

In general, the magnitude values derived from individual stations may vary due to a number of factors, including the radiation pattern of the source process, travel path effects, instrument response parameters, and spikes from data glitches. Upon close analysis of the magnitude calculation results, we found that some stations have magnitudes that are systematically higher or lower than the event magnitude. It is beyond the scope of this report to investigate the detailed cause of such deviations. However, the systematic nature of deviations between station and event magnitude values allowed us to determine correction factors for individual stations such that the systematic bias from station magnitude can be minimized.

The correction factor for a specific station was set to be the mean of the distribution of the difference between the station magnitude and the event magnitude (Table 2; Figure 3). After the correction factor was determined for all stations used in this study, we systematically re-calculated each event's magnitude with the application of the newly derived station correction factors. The corrected M_L values are presented in Appendix 1 next to the original M_L column. The improvement in the overall magnitude calculation is significant, as the average variance of station magnitudes is reduced from 0.16 to 0.11 after station correction factors are applied. The application of station magnitude correction is especially important for small events because the number of available magnitude measurement is usually very limited. There are 3 stations with fewer than 6 samples to estimate their magnitude correction factors (FLDN, MMPY, WTLY, Table 2). In Appendix 1, the corrected event magnitude is marked by an asterisk (*) if any of these less well constrained stations is used in the final magnitude calculation.

2.6 Comparison to the National Earthquake Database

Many of the seismic events we found had also been reported in the NRCan's National Earthquake Database, the de facto authority on earthquake location within Canada. Having the same earthquakes in both catalogues gave us the opportunity to verify the accuracy of our solutions. For each solution in our catalogue, we searched the NRCan catalogue for any events that occurred within ±8 seconds of the earthquake's origin time. The large time window ensured that no matching earthquakes were missed. Earthquakes in each catalogue that didn't match the other were added to tables of potentially missing seismic events. Any earthquakes found to be missing from our catalog were sought out and located to ensure the completeness of our results.

2.6.1 Location Comparisons

If matching events had differences in their epicentral locations of over 50 km, we tried to determine why such discrepancy may have occurred. We found that matching events with mislocation >50 km usually had different phase picks and stations used in their solutions or there were big differences in the timing of phase picks along with relatively poor azimuthal coverage. If the stations used for a solution were similar, individual arrival times and phase picks were compared and adjustments made to our dataset as required.

2.6.2 Curating Earthquakes

In order to produce an earthquake catalog with high quality solutions, location boundaries were implemented at margins where the station distribution was thought to affect the integrity of the solutions. Earthquakes were removed from the catalogue if they fell outside of the latitude and longitude ranges of 52–61˚N and 126–115˚W, respectively. Also, the solution was removed if an earthquake had an error ellipse that was too large – with the length of its major axis being greater than 10 km. Lastly, if an earthquake had been located but had no recorded magnitude, which would result from low SNR at all recording stations, the event was removed. In comparing with the NRCan catalogue, it is acknowledged that towards the edges of our study area, there is a potential of missing events due to inadequate station coverage. Our catalog is most complete within the bounds of 53.5-60.5˚N and 125-116˚W. Outside of this area yet still within the bounds 52-61˚N and 126-115˚W, the level of completeness gets worse due to inadequate station coverage and there is a greater potential for missing events. In the latitude range of 52–53.5˚N, there are events listed in the NRCan earthquake database but not present in our catalogue. Meanwhile, we also found many events not included in the NRCan catalogue. For readers who would like to achieve the highest level of completeness for this latitude range, it may be necessary to supplement our catalogue with solutions determined by various organizations.

3. Results

In focusing our efforts on seismic events in northeastern BC and western Alberta from 1 January 2014 to 31 December 2016, we managed to increase the number of reported seismic events by over 3 times from 1513 in the NRCan baseline catalogue to 4916 (Figure 4; Appendix 1; Appendix 2). Every event reported in the NRCan catalogue within the central part of our study area, as marked by the blue box in Figures 4–7, is included in our final catalogue. In between the boundary of our study area (i.e., 52–61˚N, 126–115˚W) and the boundary of our catalogue confidence area (i.e., 53.5-60.5˚N, 125–116˚N, blue box in Figures 4–7), there are 434 events in the NRCan catalogue that were missing from our final catalogue. This is mainly due to decreasing station coverage towards the edge of our study area.

Several key features of our final catalogue can be summarized. First, the magnitude of completeness is estimated to be 1.8. There were 5 earthquakes within the study area with

$M_w \geq 4$: the 4 August 2014 M_w 4.52 event located west of Fort St. John, the 23 January 2015 M_w 4.36 event located near Fox Creek, the 13 June 2015 M_w 4.59 event near Fox Creek, the 17 August 2015 M_w 4.55 event located west of Fort St. John, and the 12 January 2016 M_w 4.39 event located near Fox Creek.

Second, the number of earthquakes per each month appears to have some interesting trends related to local oil and gas activities. For examples, the peaks in seismicity (September 2015 and July 2016) also correspond to increased number of injection operations in the study area (Figure 8). Months with low number of injection operations had relatively fewer events.

Third, the distribution of regional seismicity shows a clear spatial preference. Earthquakes mainly occurred near the western edge of the WCSB along a similar regional trend as the eastern margin of the Canadian Cordillera in BC and AB (Figure 4). The number of events decreases in general as the distance from the Canadian Cordillera increases. It is beyond the scope of this report to determine the cause of individual earthquakes, but some clusters of events were likely to be associated with industrial activities. For examples, seismicity found to the southwest of the WCSB can often be connected to blasts from a number of mining operations in the area. In the WCSB, clusters of local seismicity coincide remarkably well with areas of unconventional oil and gas development.

Finally, the average M_L decreases from 1.81 in 2014, 1.71 in 2015, to 1.65 in 2016. This is probably due to the continuing installation of new seismograph stations in the study area. Similarly, the number of earthquakes detected each year increases from 1287 in 2014, 1575 in 2015, and finally to 2057 in 2016.

3.1 Results from 2014

In 2014, we found 1287 seismic events compared with the 368 baseline events reported in the NRCan catalogue (Figure 5). The majority of events in 2014 are located in clusters on the eastern edge of the Canadian Cordillera. Locations of seismicity in our catalogue tend to be scattered slightly more than the NRCan catalogue, likely due to the generally small magnitude of earthquakes in our catalogue and subsequently the fewer number of stations with visible arrivals. Significant clusters of seismicity in 2014 occurred in the Horn River Basin, west of Fort St. John, near Peace River, near Dawson

Creek, and near Fox Creek; all of these areas are known to be sites of IIE. The average M_L for events within 2014 is M_L 1.81 and the average depth for events in 2014 is 4.3 km.

3.2 Results from 2015

We found 1575 seismic events in 2015, a significant increase from the 559 baseline events originally reported in the NRCan catalogue (Figure 6). The majority of events in 2015 are located in clusters on the eastern edge of the Canadian Cordillera. Significant clusters of seismicity occurred in known areas of IIE: west of Fort St. John, near Peace River, near Dawson Creek, and near Fox Creek. The average M_L for events within 2015 is 1.71 and the average depth for events within 2015 is 6.8 km.

3.3 Results from 2016

In 2016, we located 2057 seismic events, whereas the routine NRCan catalogue has 586 events (Figure 7). Similar to 2014 and 2015, the majority of events in 2016 are located in clusters on the eastern edge of the Canadian Cordillera. Significant clusters of seismicity occurred west of Fort St. John, near Peace River, near Dawson Creek, and near Fox Creek. The average M_L for events within 2016 is 1.65 and the average depth for events within 2016 is 4.0 km.

4. Acknowledgements

We are thankful to Jaden Rowley and Taimi Mulder for their technical help on GIS and Antelope systems. Critical review by Taimi Mulder is very much appreciated. The operation and maintenance of all the seismograph networks in our study area, including CNSN, RV, and NY, are gratefully acknowledged. This study is partially supported by the ecoEnergy Innovation Initiative, the Office of Research and Development of NRCan, the Energy Innovation Program, and the Environmental Geoscience Program of NRCan.

5. References

Atkinson, G. M., D. W. Eaton, H. Ghofrani, D. Walker, B. Cheadle, R. Schultz, R. Shcherbakov, K. Tiampo, J. Gu, R. M. Harrington, Y. Liu, M. van der Baan, and H. Kao (2016). Hydraulic fracturing and seismicity in the Western Canada Sedimentary Basin, *Seismol. Res. Lett.*, **87,** 631-647, doi:10.1785/0220150263.

Babaie Mahani, A., H. Kao, D. Walker, J. Johnson, and C. Salas (2016). Performance evaluation of the regional seismograph network in northeast British Columbia, Canada, for monitoring of induced seismicity, *Seismol. Res. Lett.*, **87,** 648-660, doi:10.1785/0220150241.

BC Oil and Gas Commission (2015). British Columbia's Oil and Gas Reserves and Production Reprot, 35pp. https://www.bcogc.ca/node/13607.

Ellsworth, W. L. (2013). Injection-induced earthquakes, *Science*, **341,** 1225942, doi:10.1126/science.1225942.

Farahbod, A. M., J. F. Cassidy, H. Kao, and D. Walker (2014). Collaborative studies of regional seismicity in northeast British Columbia, *Can. Soc. Explo. Gephys. Recorder*, **39,** 40-44.

Farahbod, A. M., H. Kao, J. F. Cassidy, and D. Walker (2015a). How did hydraulic fracturing operations in the Horn River Basin change the seismicity patterns in northeast British Columbia, Canada?, *The Leading Edge*, **34,** 658–660, 662–663, doi:10.1190/tle34060658.1.

Farahbod, A. M., H. Kao, D. M. Walker, and J. F. Cassidy (2015b). Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia, *Can. J. Earth Sci.*, **52,** 112-122, doi:10.1139/cjes-2014-0162.

Keranen, K. M., M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection, *Science*, **345,** 448-451, doi:10.1126/science.1255802.

Pavlis, G. L., F. Vernon, D. Harvey, and D. Quinlan (2004). The generalized earthquake-location (GENLOC) package: an earthquake-location library, *Computers & Geosciences* **30**, 1079-1091.

Preston, A., G. Garner, K. Beavis, O. Sadiq, and S. Stricker (2016). Duvernay Researves and Resources Report, 75 pp., http://aer.ca/documents/reports/DuvernayReserves_2016.pdf.

Schultz, R., R. Wang, Y. J. Gu, K. Haug, and G. Atkinson (2017). A seismological overview of the induced earthquakes in the Duvernay play near Fox Creek, Alberta, *J. Geophys. Res. Solid Earth*, **122,** 492-505, doi:10.1002/2016JB013570.

Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe. (2013). Generic Mapping Tools: Improved version released, *EOS Trans. AGU* **94**, 409-410.

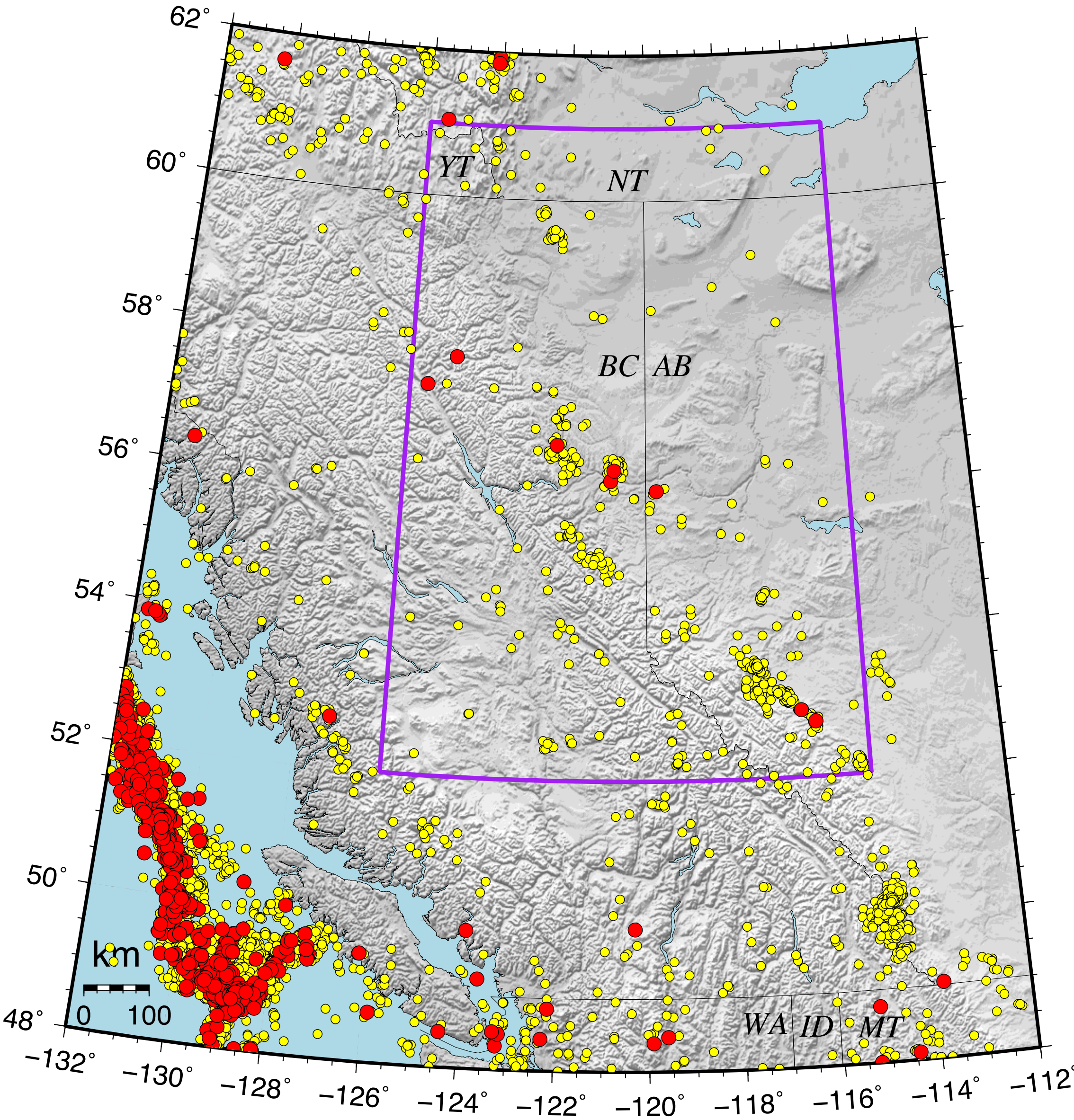

Figure 1. Distribution of seismic events with an M_L of at least 2.5 (yellow circles), and at least 4.0 (red circles), as located by NRCan from 1985 through 2013. The study area is outlined in purple, the black lines represent provincial and national borders, and light blue features represent water bodies.

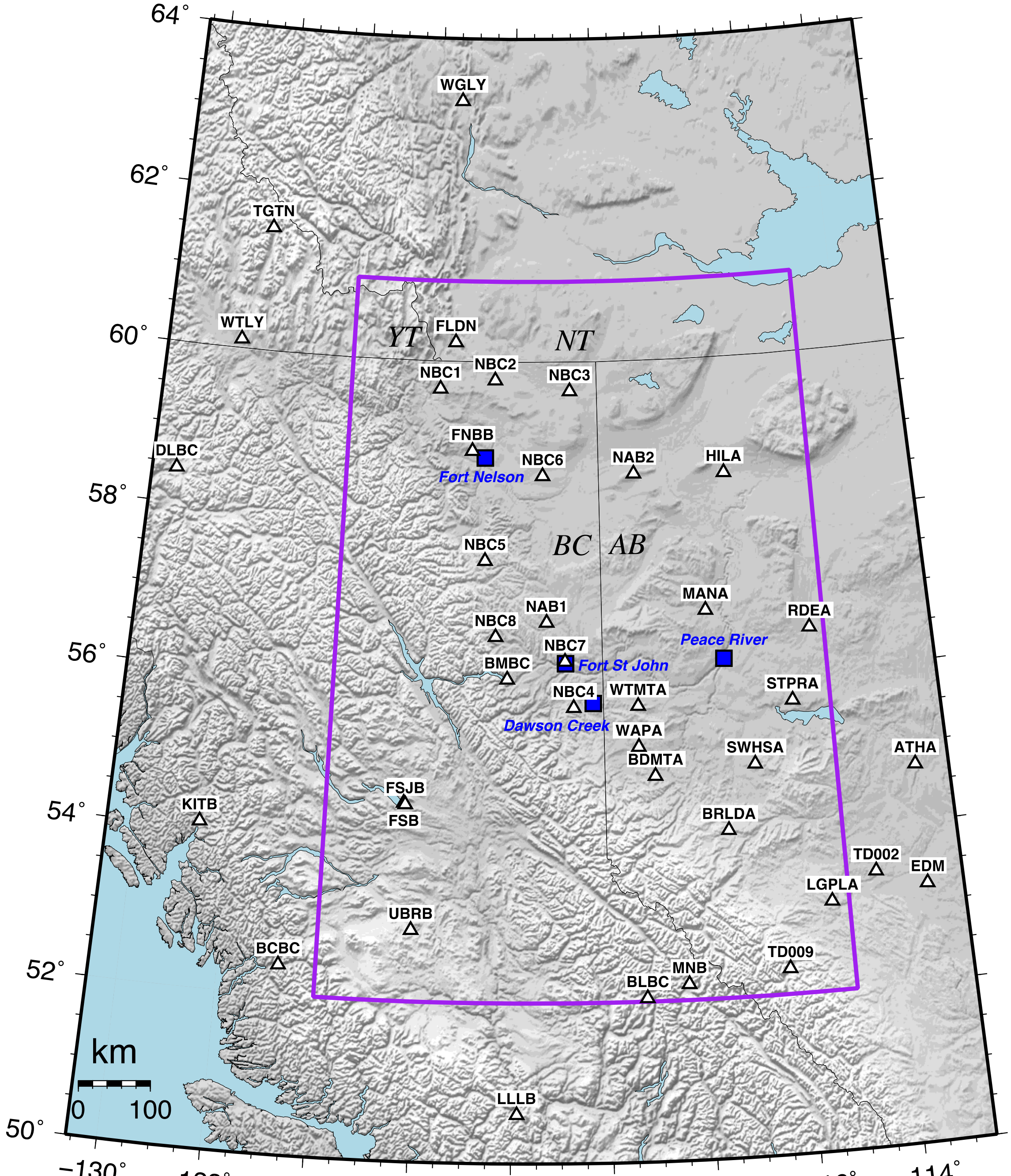

Figure 2. Distribution of seismic stations used to complete the analysis of seismic events in and around the WCSB from 2014 through 2016. FARO, MAYO, and WHY are further west in the Yukon Territory than can be shown by the bounds of the map. Stations are plotted as white triangles, with major communities as blue squares, and the study area is outlined in purple. The black lines represent provincial and national borders, and light blue features represent water bodies.

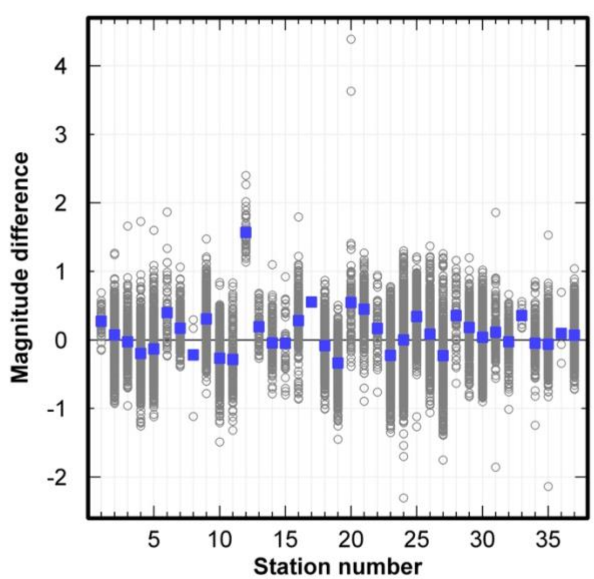

Figure 3. Station correction factors are determined using recorded differences in station magnitude and event magnitude. Stations are indexed by the station numbers given in Table 2. Each grey circle corresponds to a difference value between a recorded station magnitude and the corresponding event magnitude (i.e., $M_{station} - M_{event}$). Blue squares mark the mean values, corresponding to station correction factors listed in Table 2.

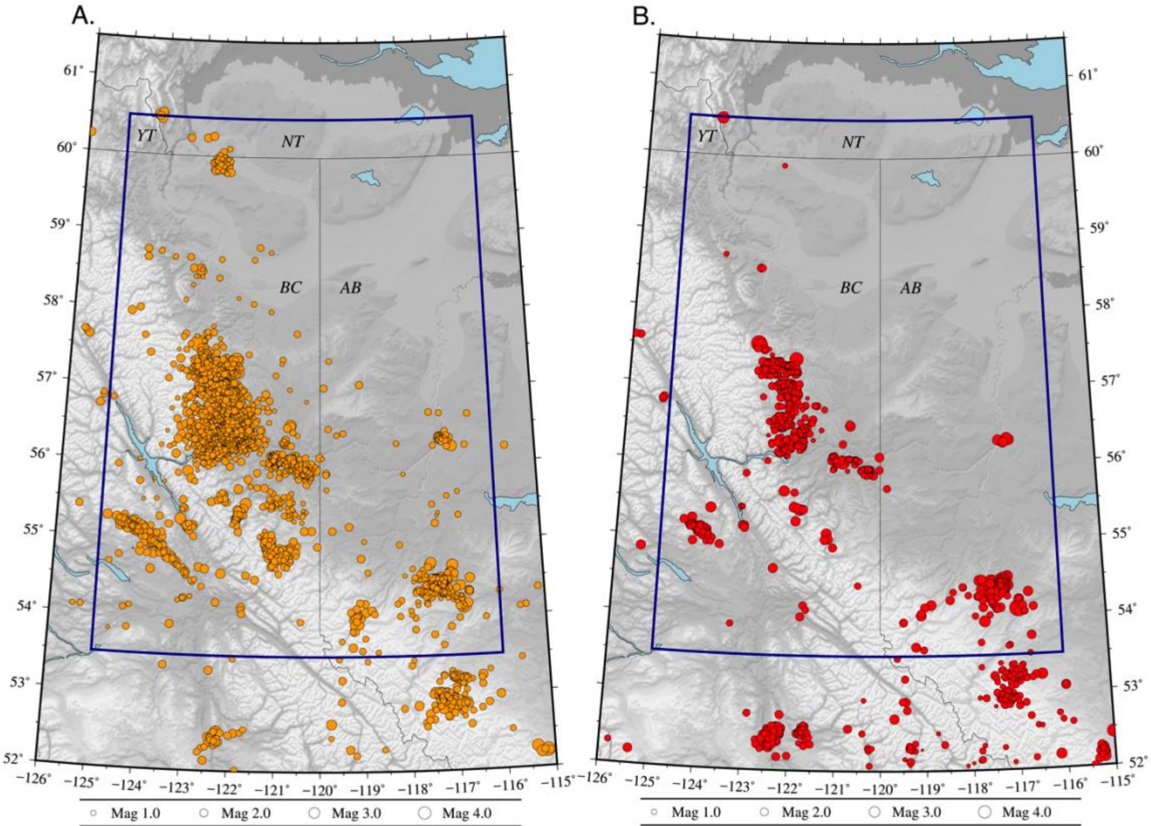

Figure 4. Maps showing the distribution of earthquakes in northeastern BC and western AB as determined by this study (A, yellow circles) and by routine processing of CNSN data (B, red circles). The time period spans from 1 January 2014 to 31 December 2016. The blue box indicates the area with the best station coverage. Black lines mark provincial and territorial boundaries. The size of each circle is proportional to the magnitude of the event.

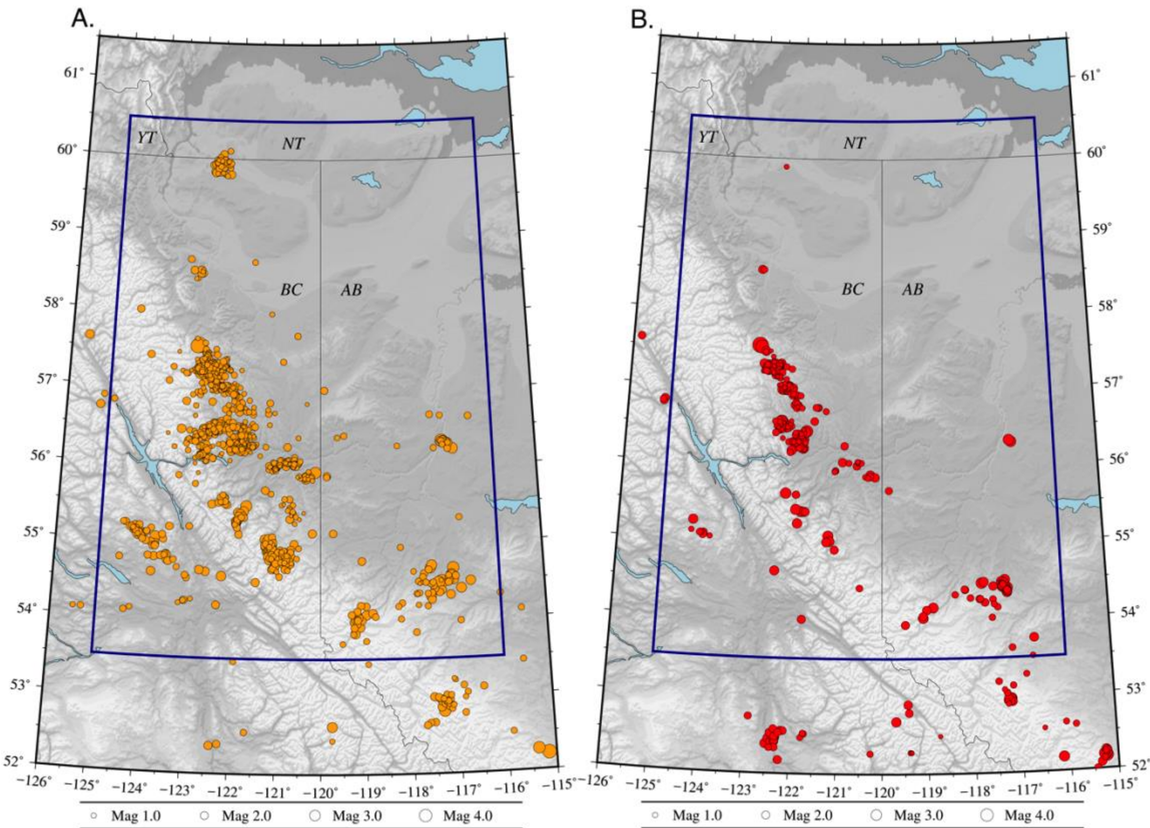

Figure 5. Maps showing the distribution of earthquakes in northeastern BC and western AB as determined by this study (A, yellow circles) and by routine processing of CNSN data (B, red circles) for the year of 2014. Layout and symbols are the same as those in Figure 4.

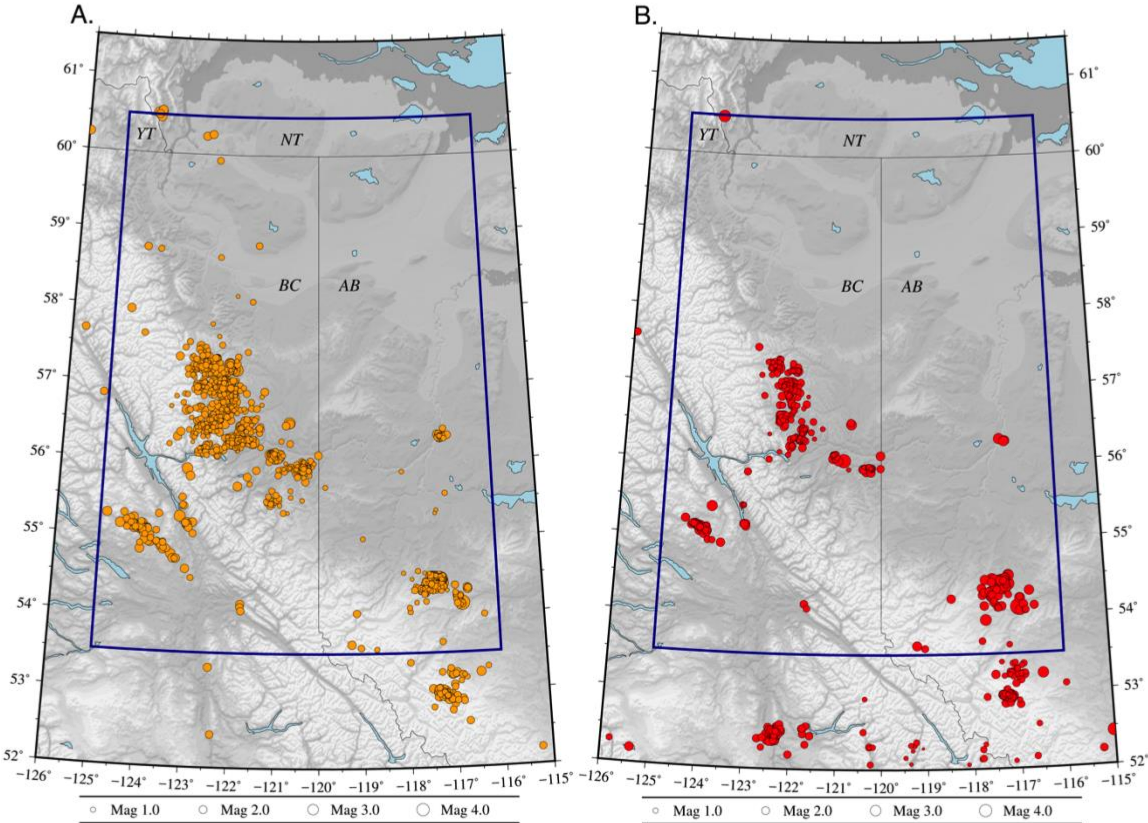

Figure 6. Maps showing the distribution of earthquakes in northeastern BC and western AB as determined by this study (A, yellow circles) and by routine processing of CNSN data (B, red circles) for the year of 2015. Layout and symbols are the same as those in Figure 4.

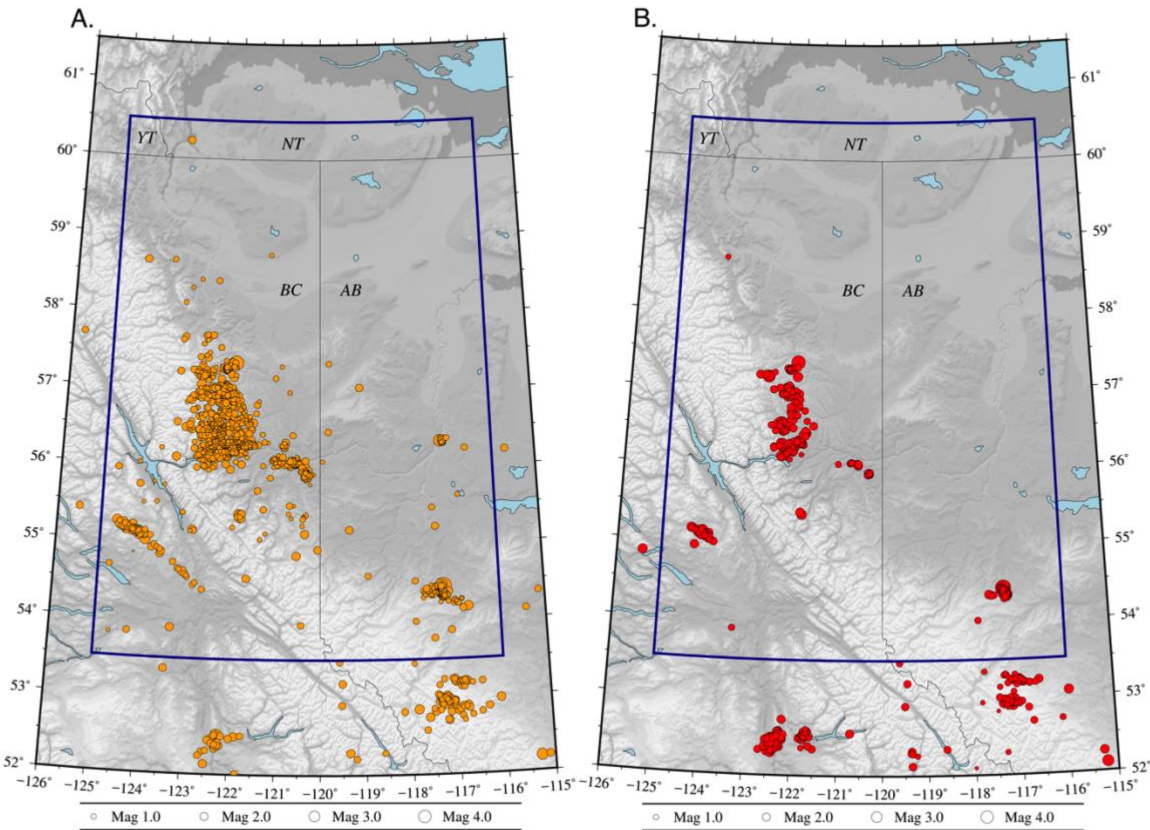

Figure 7. Maps showing the distribution of earthquakes in northeastern BC and western AB as determined by this study (A, yellow circles) and by routine processing of CNSN data (B, red circles) for the year of 2016. Layout and symbols are the same as those in Figure 4.

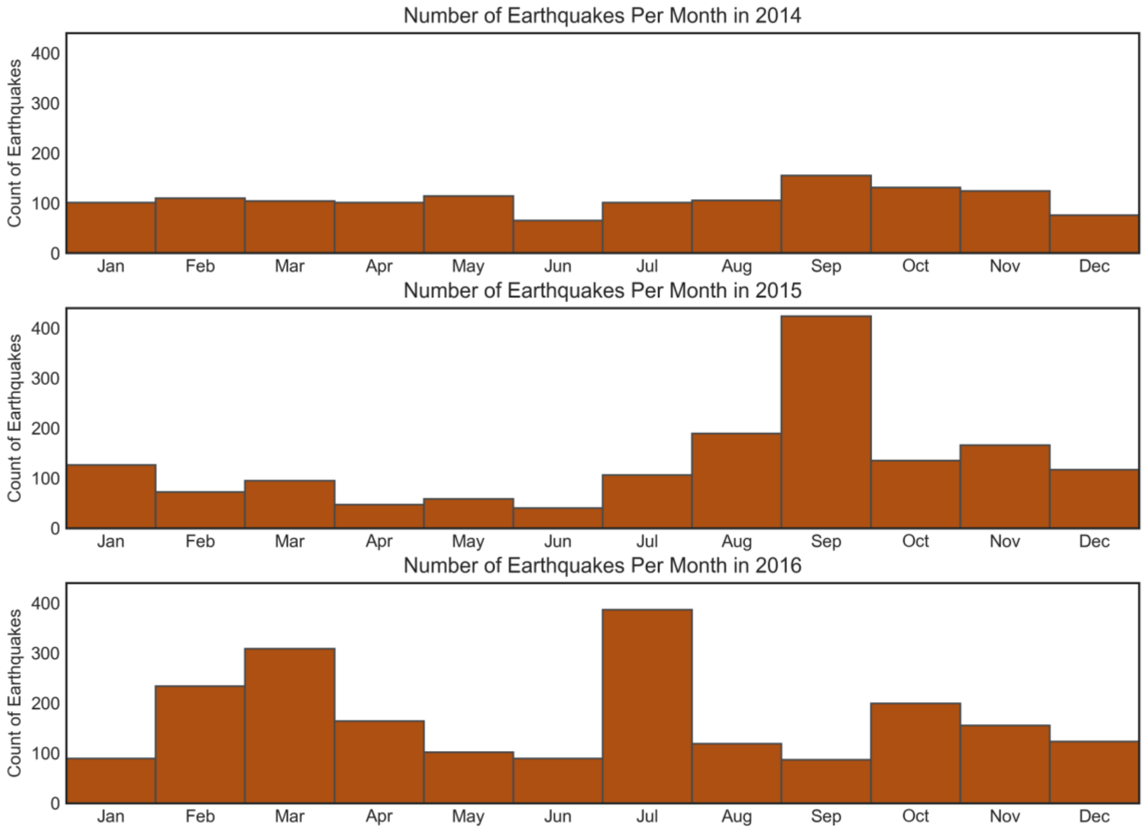

Figure 8. Histograms showing the count of earthquakes during each month of 2014, 2015, and 2016 as determined by this study.

Table 1. List of Seismograph Stations Used in This Study.

Network[1]	Station	Active Since[2]	Active Until	Latitude (˚N)	Longitude (˚E)	Instrument Type	Sampling Rate[3]
CN	EDM	1992155	present	53.2217	-113.3500	Broadband	100
CN	DLBC	1994271	present	58.4372	-130.0272	Broadband	40
CN	WHY	1994276	present	60.6597	-134.8806	Broadband	40
CN	BLBC	1997168	present	52.0440	-119.2439	Short-period	100
CN	MNB	1997168	present	52.1976	-118.3887	Short-period	100
CN	BMBC	1998030	present	56.0449	-122.1336	Broadband	40
CN	LLLB	1998321	present	50.6090	-121.8815	Broadband	100
CN	FNBB	1999297	present	58.8903	-123.0099	Broadband	40
CN	FSB	2000046	present	54.4767	-124.3283	Short-period	100
CN	UBRB	2007289	present	52.8918	-124.0832	Broadband	100
CN	BCBC	2007340	2014155	52.3720	-126.7550	Broadband	100
CN	NAB1	2013001	present	56.7550	-121.2500	Broadband	100
CN	NBC1	2013001	present	59.6559	-123.8200	Broadband	100
CN	NBC2	2013001	present	59.7730	-122.4800	Broadband	100
CN	NBC3	2013001	present	59.6370	-120.6600	Broadband	100
CN	NBC4	2013001	present	55.6870	-120.6600	Broadband	100
CN	NBC5	2013001	present	57.5230	-122.6700	Broadband	100
CN	NBC6	2013001	present	58.5830	-121.3300	Broadband	100
CN	NBC7	2013001	present	56.2670	-120.8420	Broadband	100
CN	KITB	2014079	present	54.0779	-128.6368	Broadband	100
CN	NAB2	2015244	present	58.5950	-119.1656	Broadband	100
CN	FSJB	2015308	present	54.4588	-124.2945	Broadband	100
CN	NBC8	2016001	present	56.5731	-122.4044	Broadband	100
NY	FARO	2013182	present	62.2296	-133.3481	Broadband	100
NY	FLDN	2013182	present	60.2390	-123.4754	Broadband	100
NY	MAYO	2013182	present	63.5958	-135.8921	Broadband	100
NY	MMPY	2013182	present	62.6189	-131.2625	Broadband	100
NY	TGTN	2013182	present	61.5267	-128.2727	Broadband	100
NY	WGLY	2013182	present	63.2281	-123.4584	Broadband	100
NY	WTLY	2013182	present	60.1133	-128.7961	Broadband	100
RV	ATHA	2012293	present	54.7137	-113.3137	Broadband	40
RV	LGPLA	2013300	present	53.1165	-115.3551	Broadband	100
RV	BDMTA	2014227	present	54.8129	-118.9149	Broadband	100
RV	BRLDA	2014227	present	54.0920	-117.4038	Broadband	100
RV	STPRA	2014227	present	55.6606	-115.8323	Broadband	100
RV	SWHSA	2014227	present	54.8994	-116.7518	Broadband	100
RV	WTMTA	2014227	present	55.6942	-119.2398	Broadband	100
RV	HILA	2014309	present	58.5561	-117.0203	Broadband	40
RV	RDEA	2014310	present	56.5513	-115.3179	Broadband	100
RV	MANA	2014311	present	56.8554	-117.6367	Broadband	40

RV	WAPA	2014314	present	55.1833	-119.2536	Broadband	40
TD	TD002	2013301	present	53.4394	-114.3876	Broadband	100
TD	TD009	2013356	present	52.3206	-116.3234	Broadband	100

[1] CN: Canadian National Seismograph Network, RV: Regional Alberta Observatory for Earthquake Studies Network), TD: TransAlta Monitoring Network, NY: Yukon-Northwest Seismic Network. Stations are sorted firstly by 'Network,' and secondly by 'Active Since.'

[2] Year (4-digit) and Julian day (3-digit).

[3] Sampling rate is in number of samples per second.

Table 2. List of Station Magnitude Correction Factors.

Station No.	Name*	Correction Factor	No. of Events
1	ATHA	0.274	46
2	BDMTA	0.076	1121
3	BLBC	-0.026	335
4	BMBC	-0.196	1697
5	BRLDA	-0.129	650
6	DLBC	0.400	50
7	EDM	0.173	236
8	FLDN	-0.218	3
9	FNBB	0.310	579
10	FSB	-0.266	511
11	FSJB	-0.284	174
12	HILA	1.569	40
13	KITB	0.193	58
14	LGPLA	-0.043	139
15	LLLB	-0.045	40
16	MANA	0.285	343
17	MMPY	0.556	1
18	MNB	-0.081	495
19	NAB1	-0.335	634
20	NBC1	0.548	82
21	NBC2	0.451	254
22	NBC3	0.169	63
23	NBC4	-0.222	1694
24	NBC5	0.001	1998
25	NBC6	0.342	1438
26	NBC7	0.085	823
27	NBC8	-0.227	796
28	RDEA	0.356	58
29	STPRA	0.182	410
30	SWHSA	0.040	755
31	TD002	0.113	154
32	TD009	-0.024	150
33	TGTN	0.358	7
34	UBRB	-0.045	213
35	WAPA	-0.060	532
36	WTLY	0.095	3
37	WTMTA	0.072	1166

* Stations are sorted alphabetically. There were no magnitude calculations available to create correction factors for: BCBC, FARO, MAYO, NAB2, WGLY, and WHY due to low signal-to-noise ratios for events or distances between stations and events being greater than the 600km distance threshold, beyond which magnitudes are not calculated.

Appendix 1. Regional Earthquake Catalogue for Northeastern BC and Western AB (1 January of 2014 – 31 December 2016)

Appendix 1 lists all seismic events included in the final version of our earthquake catalogue. It is given as an Excel spreadsheet for easy data manipulation. The event origins and parameters were determined using the software program *genloc* (Pavlis et al., 2004) and magnitudes were determined by *Mlriche*r and *evproc*, both part of the *Antelope 5.5* software suite. There are 11 columns and the corresponding parameters are:

Y-M-D: The origin date in the format of "year-month-day" (YYYY-MM-DD).

H:M:S: The origin time in the format of "hour:minute:second" (HH:MM:SS).

Lat. (N): The latitude of the epicenter in decimal degrees using the NAD83 coordinate system.

Lon. (E): The longitude of the epicenter in decimal degrees using the NAD83 coordinate system.

M_L: The uncorrected local magnitude.

CM_L: The corrected local magnitude as originally calculated by genloc then corrected according to the method described in section 2.5 of this technical report (Figure 3, Table 2.). An asterisk (*) denotes the use of a station correction factor derived from less than 6 samples.

M_W: The moment magnitude when available.

Depth: The focal depth in km.

MajorAxis Err: The major axis distance error in km from the ellipse of the epicentral uncertainty.

MinorAxis Err: The minor axis distance error in km from the ellipse of the epicentral uncertainty.

Azimuth: The azimuth for the major axis of the ellipse of the epicentral uncertainty.

Depth Err: The depth error in km of the hypocentral uncertainty. If the depth of the earthquake is fixed in place by the analyst, this parameter is marked by an 'f' in the column.

Appendix 2. Arrival Picks for Seismic Events Listed in Appendix 1.

Appendix 2 is provided as an ASCII file that lists detailed source parameters (origin time, epicentral location, focal depth, picked phase arrival times, and magnitudes) for each event contained in the final catalogue. Parameters for individual events are given in the format adopted by the CNSN routine operation. Whenever available, moment magnitude values are chosen preferentially over other magnitude types. Local magnitude values after applying station correction factors are chosen preferentially over the uncorrected ones.

For each event, the first column indicates the content of the rows. ‘C’ indicates a row or section of data with column headers or location names. ‘S’ indicates a row with solution information such as origin time, location, depth, and other details. ‘E’ indicates a row containing error information. ‘M’ indicates a row containing magnitude information. Each calculated magnitude is given as a separate line.

Included location columns:

TF:	The type classification of the earthquake. Null for all earthquakes in our catalogue since determination of earthquake types was outside the scope of this report.
YearMoDy:	Year, month, and day of the origin time, in the format: YYYYMMDD
HrMn:	Hour and minute of the origin time, in the format: HHMM
Secnd:	The seconds of the origin time. Precision to two decimal places: SS.SS
Latitude:	Latitude of the earthquake hypocenter in decimal degrees in the NAD83 coordinate system and rounded to four decimal places.
Longitude:	Longitude of the earthquake hypocenter in decimal degrees in the NAD83 coordinate system and rounded to four decimal places.
Depth:	Depth of the earthquake hypocenter in kilometers rounded to two decimal places.
#St-:	Number of stations used to locate the earthquake.
#Ph:	Number of phase arrivals used in the earthquake location.
-Magnitude--:	For our catalogue, contains either local or moment magnitude

(M_L or M_W) and also the value of the magnitude in the given magnitude scale.

Agncy: The agency who conducted the analysis. In this particular catalogue, the code "ISR" (an acronym for the Induced Seismicity Research Project) is used for all events.

Included error columns:

VM: Velocity model. For our study, the velocity model used was CN01, indicated by "01."

L: The program used to determine location. For our study, the location program used was *genloc* and is indicated by an 'N.'

Weight: When determining the location of an origin, this option specifies whether the stations used had weighted contributions to a given solution. For our study, weights are on (WT ON) and location weights are assigned by the program *genloc.*

RMS-: The standard deviation of travel time residuals for each solution rounded to two decimal places. Calculated by taking the square root of the sum of the squares of the time residuals, divided by the number of arrivals used in a solution minus either 4 (if depth is allowed to be free) or 3 (if depth is fixed).

TErr-: Time error as determined by the program *genloc* and rounded to two decimal places.

LatErr--: Latitude error as determined by the program *genloc*, given in km and rounded to three decimal places.

LonErr--: Longitude error as determined by the program *genloc*, given in km and rounded to three decimal places.

DErr-: Depth error in km as determined by the program *genloc* and rounded to two decimal places.

MajE: Length of the major axis given in km of the ellipse of the epicentral uncertainty as determined by the program *genloc*.

MinE: Length of the minor axis given in km of the ellipse of the epicentral uncertainty as determined by the program *genloc*.

VerE: Error in the vertical component given in km of the ellipse of hypocentral uncertainty as determined by the program *genloc* and rounded to two decimal places .

AzHor: Azimuth of the major axis of the ellipse of the epicentral uncertainty as determined by the program *genloc.*

Agncy: The agency who conducted the analysis. The code "ISR" is used for all events listed in this report.

Included magnitude columns (described in order of appearance):

Magnitude Type: Either M_L or M_W, the chosen event magnitude is indicated by an asterisk (*) preceding its type.

Magnitude: The value of the magnitude in its given type.

Mag Error: The error of the calculated magnitude as determined by *evproc* if available.

Stations used: The number of stations used in the magnitude determination if available.

Agncy: The agency who conducted the analysis. The code "ISR" is used for all events listed in this report.

Location details (described in order of appearance):

Language: Either E (English) or F (French).

Location: The province or territory where the event occurred in the language indicated.

Agncy: The agency who conducted the analysis. The code "ISR" is used for all events listed in this report.

Included location arrival columns:

Statn: The station name of the picked phase.

I: Instrument type (H: high-gain broadband; B: broadband; E: high-gain short-period).

C: Channel (Z: vertical; N: north; E: east).

nHHMM: The hour and minute of the arrival time in the format of HHMM.

SSSSS: The second component of the arrival time in the format of SS.SS.

TCorr: Time correction in seconds. In this report, all time corrections are set to 0.

Q-Phase: The phase of the arrival selected by the analyst.

IUW: Whether an arrival is location determining (0) or not (x0). Arrivals that are not location determining are still used in magnitude calculations if they meet the SNR and distance threshold requirements.

TTres: The travel time residual for the arrival in seconds.

LocW: The weight assigned to the picked arrival by the program *genloc*.

StDly: Station time delay in seconds. In this report, all station time delays are set to 0.

EDistnc: The distance between the epicenter and the recording station in km.

Azm: The azimuth from the epicenter to the recording station.

Agncy: The agency who conducted the analysis. The code "ISR" is used for all events listed in this report.

Included magnitude arrival details:

Statn: The name of the station used in magnitude calculation.

-Magnitude--: The type of magnitude and the magnitude value. In this report, the corrected local magnitude (as described in Section 2.5) is reported.

Agncy: The agency who conducted the analysis. The code "ISR" is used for all events listed in this report.