Regional Monitoring of Induced Seismicity in Northeastern British Columbia

A. Babaie Mahani, Geoscience BC, Vancouver, BC, ali.mahani@mahangeo.com

H. Kao, Natural Resources Canada, Geological Survey of Canada-Pacific, Sidney, BC

D. Walker, BC Oil and Gas Commission, Victoria, BC

J. Johnson, BC Oil and Gas Commission, Victoria, BC

C. Salas, Geoscience BC, Vancouver, BC

Babaie Mahani, A., Kao, H., Walker, D., Johnson, J. and Salas, C. (2016): Regional monitoring of induced seismicity in northeastern British Columbia; *in* Geoscience BC Summary of Activities 2015, Geoscience BC, Report 2016-1, p. 79–88.

Introduction

Northeastern British Columbia (NEBC; latitude 55–60°N, longitude 120–125°W) has hosted major hydrocarbon production since the early 1950s (National Energy Board et al., 2013). With the advancement in horizontal drilling and hydraulic fracturing (also known as fracking) in the mid 1990s, unconventional resources of natural gas have been developed within the Montney play and Horn River Basin of NEBC (BC Oil and Gas Commission, 2012b).

The relationship between fluid injection and occurrence of earthquakes has been studied extensively in the past (e.g., Davis and Frohlich, 1993; Ake et al., 2005; Shapiro and Dinske, 2009; Keranen et al., 2014; Dieterich et al., 2015; Hornbach et al., 2015). Injected fluid increases pore fluid pressure and reduces the effective normal stress on a fractured mass of rock. This effect causes shear slip on the pre-existing fault planes that are critically stressed (Davies et al., 2013; Holland, 2013). It should be noted that the fluid injected into a well need not travel the entire distance from the injection point to a fault to change the stress condition on the fault plane, as the increased pore pressure can be transmitted to greater distances than the fluid itself (Rubinstein and Babaie Mahani, 2015).

The continuous increase in the number of hydraulic fracturing completions in recent years and the occurrence of new clusters of seismicity have motivated the BC Oil and Gas Commission (BCOGC) to regulate oil and gas operations in NEBC. A fundamental goal of these regulations is to prevent the emergence of seismic hazards from larger magnitude events. Current permit conditions (traffic light system) require the immediate reporting of seismic events that are either felt or recorded with a magnitude of 4.0 and higher. Felt events have initiated deployments of several dense seismic networks and could lead to suspension of operations (BC Oil and Gas Commission, 2012a, 2014).

To improve the overall understanding of induced seismicity in NEBC, the British Columbia Seismic Research Consortium was initiated in 2012 with funding from Geoscience BC and the Canadian Association of Petroleum Producers and with technical support from Natural Resources Canada (NRCan) and BCOGC. As the first step of this joint effort, eight broadband seismograph stations have been established in NEBC since 2013 to complement the monitoring capability of the Canadian National Seismic Network (CNSN) for induced seismicity (Salas et al., 2013; Salas and Walker, 2014).

The aim of this paper is to evaluate the performance of the regional seismic network in NEBC, which is done by calculating the minimum magnitudes (smallest earthquakes) that can be detected by the network. For each seismic station, the level of background noise (signals due to sources such as traffic, wind, ocean waves), above which earthquake signals (primary [P], secondary [S], surface waves) can be distinguished, was analyzed and used for calculating the magnitude of an event. Then at each station, the peak ground-motion amplitude was simulated from earthquakes with different magnitudes across NEBC. By calculating the ratio of simulated ground motion to the background noise, maps of the minimum magnitudes that can be detected by the regional network were generated. The assessment of minimum detectable magnitude is important for future development of the regional monitoring network in areas with significant shale-gas production.

Evaluation Method and Results

Figure 1 shows seismicity in NEBC between 1985 and 2015 from the NRCan earthquake catalogue (Natural Resources Canada, 2015). Also shown on this figure are the locations of regional broadband seismic stations. The two stations BMBC and FNBB have been operating in this region since 1998 and 1999, respectively, whereas stations

Keywords: *induced seismicity, network performance*

This publication is also available, free of charge, as colour digital files in Adobe Acrobat® PDF format from the Geoscience BC website: http://www.geosciencebc.com/s/DataReleases.asp.

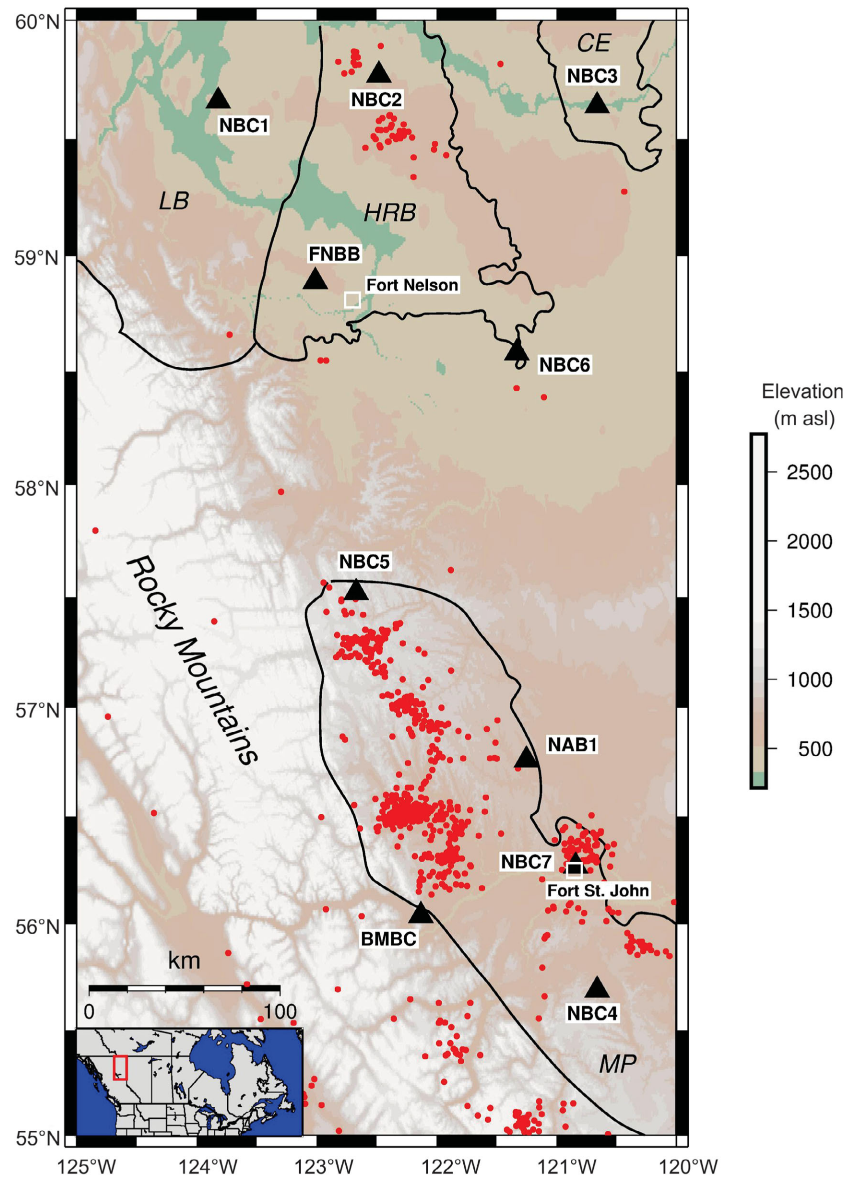

Figure 1. Map of seismic events (red dots) in northeastern British Columbia from 1985 to 2015. Black triangles indicate the locations of regional seismic stations in this area. Boundaries of the major shale gas plays are shown with black outlines. Abbreviations: CE, Cordova embayment; HRB, Horn River Basin; LB, Liard Basin; MP, Montney play. The inset shows the location of the study area (red box) on the national map. Background image from Lindquist et al. (2004).

NBC1–6 were established in 2013. Stations NBC7 and NAB1 were installed in 2014. In general, seismicity in NEBC appears to be clustered within specific areas to the east of the Rocky Mountains. These clusters coincide with the location of hydraulic fracturing completions and long-term disposal wells (Horner et al., 1994; BC Oil and Gas Commission, 2012a, 2014; Farahbod et al., 2015). Note that the earthquakes shown in Figure 1 were located using all the available stations in NEBC and environs.

The performance of a seismic network depends on many factors including sensor type, network geometry, instrumental and ambient noise level, and the condition of data transmission. D'Alessandro et al. (2011a) proposed the method of seismic network evaluation through simulation (SNES) to evaluate the performance of seismic networks. Based on the analysis of ambient noise level at each seismic station, the method simulates the regional distribution of ground motion to estimate variations in the source parameters of a seismic event (epicentre, depth, magnitude) as well as their uncertainties. The SNES method has been used to evaluate a variety of different seismic networks including those in Italy, Greece, Montana, Alaska, Romania and Spain (D'Alessandro et al., 2011a, b, 2012, 2013a, b;

D'Alessandro and Ruppert, 2012; D'Alessandro and Stickney, 2012). In this study, the SNES methodology has been followed to quantitatively evaluate the magnitude detection capability of the regional seismic network in NEBC.

Level of Ambient Noise

Evaluation of the ambient background noise is the first step in the assessment of the performance of a seismic network. It forms the baseline for detection of earthquake phases (P and S) used in magnitude calculations and event location.

There are different sources of noise that can affect seismic signals at different frequencies. Microseisms are ocean-generated noise that can be observed at all stations worldwide, although it is generally less at stations in the interior of continents. The predominant frequency range of microseisms is 0.06–0.25 hertz (Hz). On the other hand, cultural noise due to traffic and machinery has higher frequency content (1–10 Hz), which tends to attenuate quickly with distance and depth (Havskov and Alguacil, 2004).

Conventionally, the noise level is represented by the power spectral density (PSD) of ground acceleration for the frequency range of interest. It is common to represent the units of the PSD (originally in units of $(m/s^2)^2/Hz$) in decibels, which is a logarithmic unit from a ratio of two values. The noise level is therefore converted to decibels (Havskov and Alguacil, 2004) as

$$10 \log [PSD / (m/s^2)^2 / Hz] \quad (1)$$

To obtain PSD, one year of continuous waveform data (between May 1, 2014 and April 30, 2015) was downloaded from the Data Management Center of the Incorporated Research Institutions for Seismology (Incorporated Research Institutions for Seismology, 2015) for all newly established stations in NEBC (NBC1–7 and NAB1). The waveform data were then cut into one-hour segments. For each segment, PSD of acceleration were calculated using the PQLX software of McNamara and Boaz (2011). Probability density functions (PDF) of each power bin (in decibels, as given by the program) were then obtained at each frequency to better analyze the variation of noise and its probability of occurrence for each station and the three components of motion (two horizontal and one vertical; McNamara and Buland, 2004). Figure 2a shows an example of the noise PDF for the vertical component at station NBC7 in Fort St. John. Also plotted are the global low and high noise models of Peterson (1993) for comparison to the local noise. Since the continuous data was not screened for different types of waveforms, earthquake signals, system transients and instrumental glitches are all included in the calculated PSD. These signals, however, have low probability of occurrence (pink lines) compared to the higher-probability ambient noise (blue portion of the PDF, Figure 2a). For the purpose of this study, the ambient noise level of the vertical component for each station was extracted from their noise PDF, and the results are shown in Figure 2b.

Simulation of Ground Motion

Ground-motion amplitudes were generated for different earthquakes with a range of magnitude (0–4) and epicentral distance (from the earthquake to seismic station; 0–1000 km) values. The simulated values represent the velocity of ground motion in units of m/s (peak ground velocity, PGV). To generate the ground-motion amplitudes, a stochastic approach was followed for simulation of earthquake waveforms. In brief, this approach assumes that earthquake ground motion is a band-limited, finite-duration, white Gaussian noise that can be adjusted by a theoretical model of source (representing the shape and amplitude of the source spectrum), path (representing wave attenuation) and site (representing site amplification) to generate high-frequency motions from an earthquake (Boore, 2003). In this study, the stochastic simulation program SMSIM (Boore, 2003, 2009) was used to produce PGV using input models for western North America (Boore and Thompson, 2012, 2015).

The average level of ambient noise at each station was estimated for the frequency band of 0.5–12 Hz from the vertical components of PSD (Figure 2b). The frequency band of 0.5–12 Hz is used here because it represents the widest detectable frequency band for regional earthquakes (Atkinson and Kraeva, 2010). The PSD were converted from decibel to ground velocity (in m/s) using the conversion methods described in Havskov and Alguacil (2004). Specifically, the relationship between a spectral amplitude at a given frequency to a time domain amplitude in a given frequency band is defined as

$$a = 1.25a_{RMS} = 1.25(P(f_2–f_1))^{1/2} \quad (2)$$

where a is the true average peak amplitude, a_{RMS} is the root mean squared amplitude, and P is the power spectrum in the frequency range of f_1 to f_2. Here, P has the unit of m/s and is obtained by converting the acceleration PSD in decibels to their equivalent amplitude in m/s^2, then divided by the square of angular frequency. Equation (2) holds true under the assumption that the power spectrum is indeed a constant P if the frequency range of f_1 to f_2 is narrow (Havskov and Alguacil, 2004). For stations BMBC and FNBB the average ambient noise was obtained based on the nearby stations.

Theoretical Threshold for Locating Earthquakes in NEBC

In this step, a theoretical 100 by 100 grid was generated for the study area. By placing seismic sources of variable magnitudes (0–4 with 0.2 increments) at each grid point, the PGV was estimated at the location of each station using the simulated values as obtained above. For each grid point–

station pair, the ratio of simulated PGV to the average background noise was calculated for all magnitudes. The source signal at any given station was considered identifiable if the signal-to-noise ratio (S/N) exceeded 10. Figure 3a and b show the number of stations with S/N ≥10 when the magnitude of the source was 1.6 and 2.6, respectively. For an event to be considered locatable, it is required to have identifiable signals (i.e., S/N ≥10) at four or more stations. In the case of magnitude 1.6, the event can be located only if the source is within the areas that are well covered by the re-

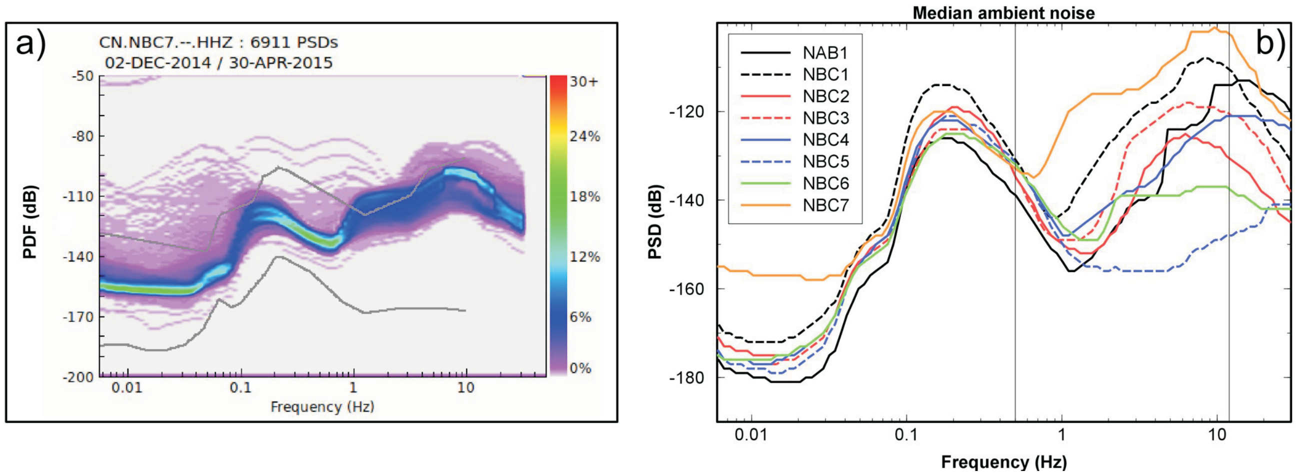

Figure 2. Noise spectra of seismic stations in northeastern British Columbia: **a)** Vertical component of probability density function (PDF) of each acceleration power bin (in decibels [dB]) at station NBC7. The colour bar shows noise probability at each frequency. **b)** Median power spectral density (PSD; vertical component) of all newly established stations (NAB1, NBC1–7) versus frequency. The two vertical lines mark the frequency range used in simulation of ground-motion amplitudes and averaging of the ambient noise. Abbreviation: Hz, hertz.

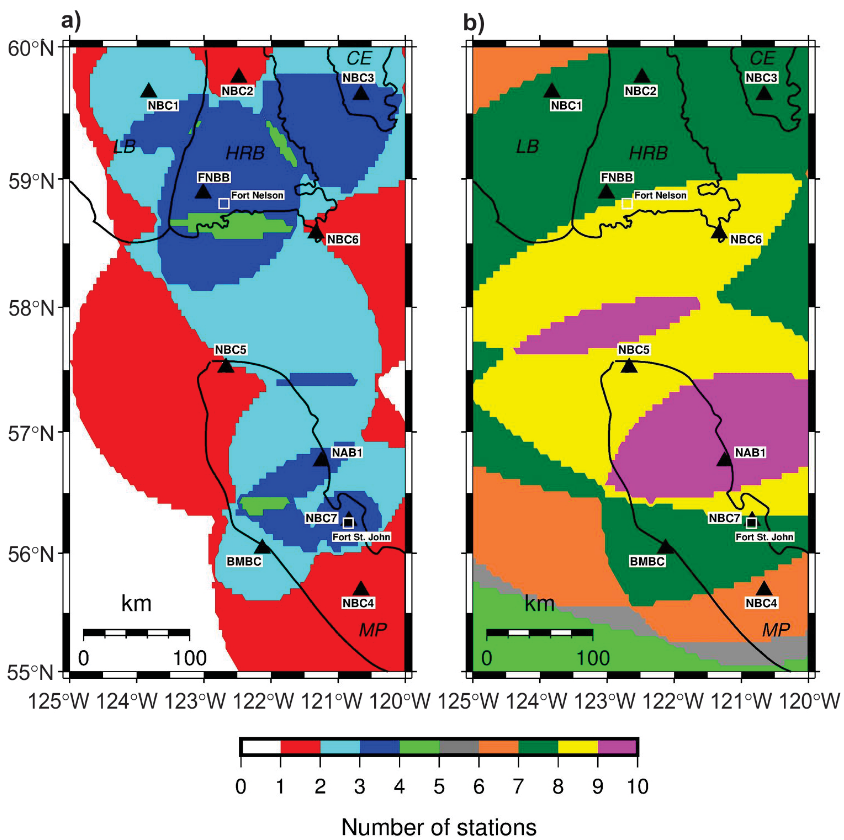

Figure 3. Number of stations with signal-to-noise ratio of ≥10 for **a)** magnitude 1.6 and **b)** magnitude 2.6. Black triangles indicate the locations of regional seismic stations in northeastern British Columbia. Boundaries of the major shale gas plays are shown with black outlines. Abbreviations: CE, Cordova embayment; HRB, Horn River Basin; LB, Liard Basin; MP, Montney play.

gional network. In contrast, a magnitude 2.6 event anywhere inside the study area can be detected and located as at least four stations with identifiable signals are available.

Based on the same criterion, the variability of minimum detectable magnitude of regional earthquakes in NEBC was mapped and the results are shown in Figure 4. The minimum detectable magnitude can be considered as the theoretical threshold for any seismic event to be located by the regional seismic network. Overall, the theoretical magnitude threshold for NEBC is below 2.6 and it can be as low as 1.6 for areas of the Montney play and Horn River Basin that are well covered by the regional network.

Future Improvement of the Regional Network

The seismic network in NEBC plays a critical role in detecting and locating seismic events that are potentially linked to hydraulic fracturing or deep injection for the purpose of wastewater disposal. The data of earthquake source parameters (e.g., epicentre, depth, magnitude) obtained from the regional network are used for regulatory purposes. The uncertainties in source parameters, however, make hazard mitigation a challenging task. In this section, some options are considered to improve the capability of the current regional seismic network.

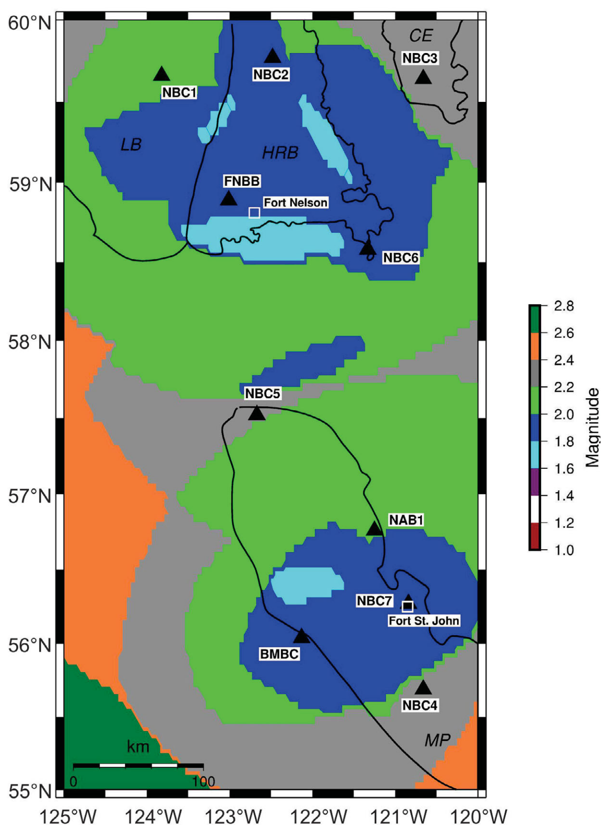

Figure 4. Spatial distribution of the minimum detectable magnitude in northeastern British Columbia based on signal-to-noise ratio of ≥10 at four or more stations. Black triangles indicate the locations of regional seismic stations in this area. Boundaries of the major shale gas plays are shown with black outlines. Abbreviations: CE, Cordova embayment; HRB, Horn River Basin; LB, Liard Basin; MP, Montney play.

The improvement of the regional seismic network in NEBC can be achieved from different approaches in order to reduce the uncertainties in the earthquake parameters. One of the most straightforward ways is to increase the S/N at existing stations such that signals from smaller events can be clearly identified. This is possible by replacing the near-surface sensors with deep borehole ones or by relocating noisy stations to places with better site conditions. Figure 5 shows the hypothetic results if the level of background noise is reduced by 10, 25 and 50%. In comparison to the current network configuration (Figure 4), an overall reduction of noise by 10% (Figure 5a) would lower the detection threshold by ~0.2 magnitude unit for most of the Liard Basin, northeast of the Horn River Basin, southern Montney play, and the area to the west of Montney play. For a 25% noise reduction (Figure 5b), the magnitude detection threshold could be improved to ~2.0 magnitude unit for almost the entire NEBC. The Horn River Basin and central Montney play could have a value down to ~1.6 magnitude. When the noise level is reduced by 50% (Figure 5c), the regional network could detect seismic events with magnitude ≥1.8 for most of NEBC. The area with a magnitude detection threshold of ~1.6 would expand to cover the entire Horn River Basin, most of the Liard Basin and the central Montney play (i.e., the Fort St. John area).

The performance of the regional seismic network in NEBC can also be improved by installing additional stations at critical locations. The exact location of new stations depends on the expected goal of the earthquake monitoring. Given the relatively higher injection activity in the Montney play in recent years, one desirable improvement is to lower the local earthquake detection threshold for more effective monitoring and mitigation of seismic hazard. In Figure 6, the hypothetical scenarios of improvement are presented with up to four additional stations in the Montney play. The area corresponding to the detection threshold of ~1.6 magnitude could expand significantly even with the addition of just one station in the central Montney play (Figure 6a versus Figure 4). Moreover, the addition of this station might help to reduce the azimuthal gap between stations NBC5 and BMBC for events that occurred in the northern and central Montney play. By adding stations to the south and east of station NBC5 in the northern Montney play (Figure 6b, c), the network's monitoring capability could be dramatically improved for the entire Montney play from 1.6–2.2 magnitude to 1.2–1.8 magnitude. The regional network would require four additional stations in the central and northern Montney play to achieve an overall magnitude detection threshold of ~1.2 magnitude (Figure 6d).

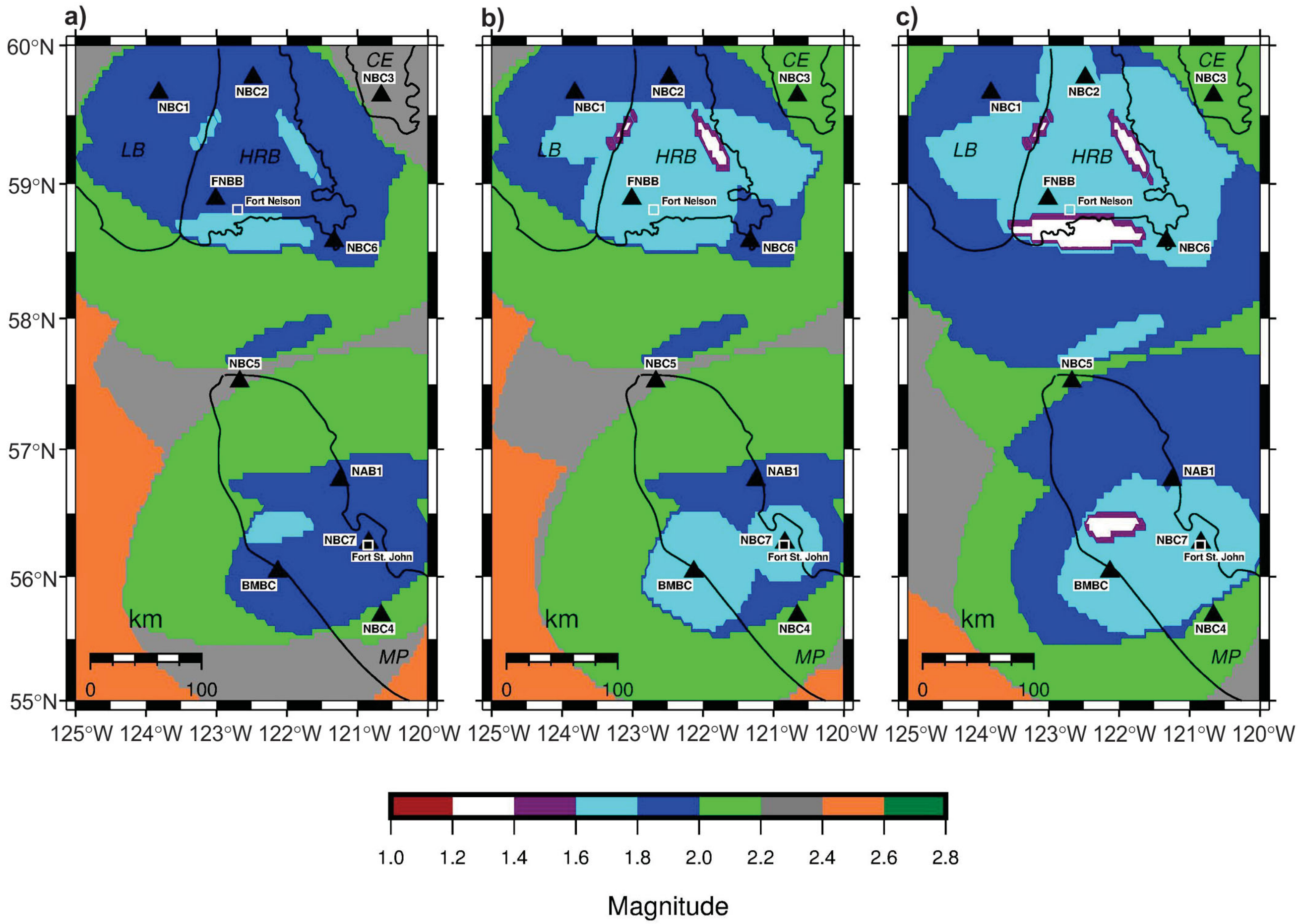

Figure 5. Spatial distribution of minimum detectable magnitude in northeastern British Columbia after reducing the ambient noise levels by **a)** 10%, **b)** 25% and **c)** 50%. Black triangles indicate the locations of regional seismic stations in the area. Boundaries of the major shale gas plays are shown with black outlines. Abbreviations: CE, Cordova embayment; HRB, Horn River Basin; LB, Liard Basin; MP, Montney play.

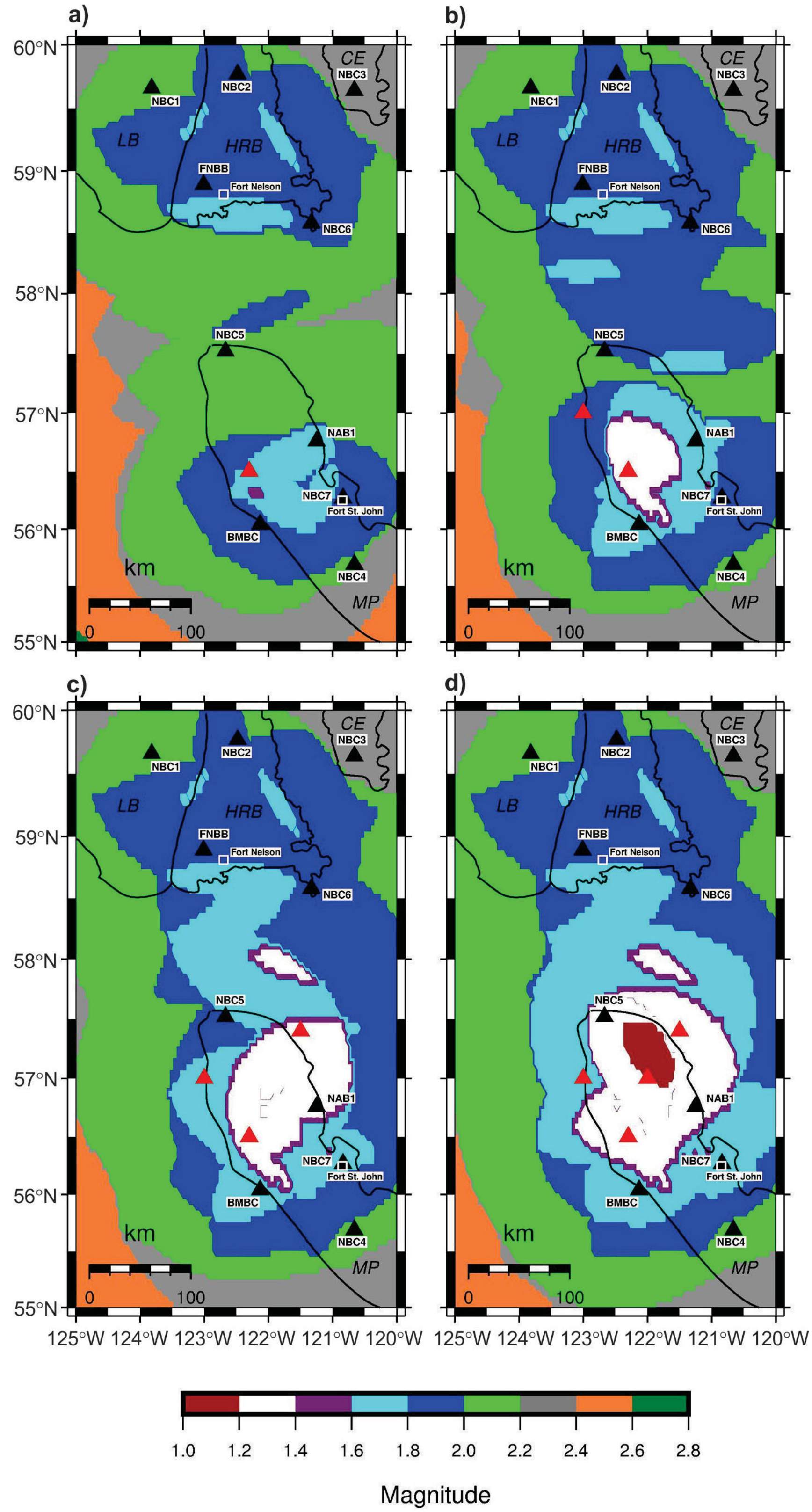

Figure 6. Spatial distribution of the minimum detectable magnitude in northeastern British Columbia after addition of up to four hypothetical stations (red triangles): **a)** one station; **b)** two stations; **c)** three stations; and **d)** four stations. Black triangles indicate the locations of regional seismic stations in the area. Boundaries of the major shale gas plays are shown with black outlines. Abbreviations: CE, Cordova embayment; HRB, Horn River Basin; LB, Liard Basin; MP, Montney play.

Acknowledgments

Financial support for this project was partially provided by Canadian Association of Petroleum Producers.

References

Ake, J., Mahrer, K., O'Connell, D. and Block, L. (2005): Deep-injection and closely monitored induced seismicity at Paradox Valley, Colorado; Bulletin of Seismological Society of America, v. 95, p. 664–683.

Atkinson, G.M. and Kraeva, N. (2010): Ground motions underground compared to those on the surface: a case study from Sudbury, Ontario; Bulletin of Seismological Society of America, v. 100, p. 1293–1305.

BC Oil and Gas Commission (2012a): Investigation of observed seismicity in the Horn River Basin; BC Oil and Gas Commission, technical report, 29 p., URL <https://www.bcogc.ca/node/8046/download> [November 2015].

BC Oil and Gas Commission (2012b): Montney Formation play atlas NEBC; BC Oil and Gas Commission, technical report, 36 p., URL<https://www.bcogc.ca/node/8131/download> [November 2015].

BC Oil and Gas Commission (2014): Investigation of observed seismicity in the Montney trend; BC Oil and Gas Commission, technical report, 32 p., URL <https://www.bcogc.ca/node/12291/download> [November 2015].

Boore, D.M. (2003): Simulation of ground motion using the stochastic method; Pure and Applied Geophysics, v. 160, p. 635–676.

Boore, D.M. (2009): Comparing stochastic point-source and finite-source ground-motion simulations: SMSIM and EXSIM; Bulletin of Seismological Society of America, v. 99, p. 3202–3216.

Boore, D.M. and Thompson, E.M. (2012): Empirical improvements for estimating earthquake response spectra with random-vibration theory; Bulletin of Seismological Society of America, v. 102, p. 761–722.

Boore, D.M. and Thompson, E.M. (2015): Revisions to some parameters used in stochastic-method simulations of ground motion; Bulletin of Seismological Society of America, v. 105, p. 1029–1041.

D'Alessandro, A. and Ruppert, N.A. (2012): Evaluation of location performance and magnitude of completeness of the Alaska regional seismic network by the SNES method; Bulletin of Seismological Society of America, v. 102, p. 2098–2115.

D'Alessandro, A. and Stickney, M. (2012): Montana seismic network performance: an evaluation through the SNES method; Bulletin of Seismological Society of America, v. 102, p. 73–87.

D'Alessandro, A., Badal, J., D'Anna, G., Papanastasssou, D., Baskoutas, I. and Ozel, N.M. (2013a): Location performance and detection threshold of the Spanish national seismic network; Pure and Applied Geophysics, v. 170, p. 1859–1880.

D'Alessandro, A., Danet, A. and Grecu, B. (2012): Location performance and detection magnitude threshold of the Romanian national seismic network; Pure and Applied Geophysics, v. 169, p. 2149–2164.

D'Alessandro, A., Gervasi, A. and Guerra, L. (2013b): Evolution and strengthening of the Calabrian regional seismic network; Advances in Geosciences, v. 36, p. 11–16.

D'Alessandro, A., Luzio, D., D'Anna, G. and Mangano, G. (2011a): Seismic network evaluation through simulation: an application to the Italian national seismic network; Bulletin of Seismological Society of America, v. 101, p. 1213–1232.

D'Alessandro, A., Papanastassiou, D. and Baskoutas, I. (2011b): Hellenic unified seismological network: an evaluation of its performance through SNES method; Geophysical Journal International, v. 185, p. 1417–1430.

Davies, R., Foulger, G., Bindley, A. and Styles, P. (2013): Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons; Marine and Petroleum Geology, v. 45, p. 171–185.

Davis, S.D. and Frohlich, C. (1993): Did (or will) fluid injection cause earthquakes? – criteria for a rational assessment; Seismological Research Letters, v. 64, p. 207–224.

Dieterich, J.H., Richards-Dinger, K.B. and Kroll, K.A. (2015): Modeling injection-induced seismicity with the physics-based earthquake simulator RSQSim; Seismological Research Letters, v. 86, p. 1102–1109.

Farahbod, A.M., Kao, H., Walker, D.M. and Cassidy, J.F. (2015): Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia; Canadian Journal of Earth Sciences, v. 52, p. 112–122.

Havskov, J. and Alguacil, G. (2004): Seismic noise; *in* Instrumentation in Earthquake Seismology, Modern Approaches in Geophysics, v. 22, p. 70–77.

Holland, A. (2013): Earthquakes triggered by hydraulic fracturing in south-central Oklahoma; Bulletin of Seismological Society of America, v. 103, p. 1784–1792.

Hornbach, M.J., De Shon, H.R., Ellsworth, W.L., Stump, B.W., Hayward, C., Frohlich, C., Oldham, H.R., Olson, J.E., Magnani, M.B., Brokaw, C. and Luetgert, J.H. (2015): Causal factors for seismicity near Azle, Texas; Nature Communications, v. 6, p. 1–18.

Horner, R.B., Barclay, J.E. and Macrae, J.M. (1994): Earthquakes and hydrocarbon production in the Fort St. John area of northeastern British Columbia; Canadian Journal of Exploration Geophysics, v. 30, p. 38–50.

Incorporated Research Institutions for Seismology (2015): Data management center; Incorporated Research Institutions for Seismology, URL <http://ds.iris.edu/ds/nodes/dmc/> [November 2015].

Keranen, K.M., Weingarten, M., Abers, G.A., Bekins, B.A. and Ge, S. (2014): Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection; Science, v. 345, p. 448–451.

Lindquist, K.G., Engle, K., Stahlke, D. and Price, E. (2004): Global topography and bathymetry grid improves research efforts; Eos, Transactions, American Geophysical Union, v. 85, no. 19, p. 186, URL <http://www.agu.org/pubs/crossref/2004/2004EO190003.shtml> [November 2015].

McNamara, D.E. and Boaz, R.I. (2011): PQLX: a seismic data quality control system description, applications, and user's manual; United States Geological Survey, Open-File Report 2010-1292, 41 p.

McNamara, D.E. and Buland, R.P. (2004): Ambient noise levels in the continental United States; Bulletin of Seismological Society of America, v. 94, p. 1517–1527.

National Energy Board, BC Oil and Gas Commission, Alberta Energy Regulator and BC Ministry of Natural Gas Development (2013): Energy briefing note: the ultimate potential for unconventional petroleum from the Montney Formation of British Columbia and Alberta; National Energy Board, BC Oil and Gas Commission, Alberta Energy Regulator and BC Ministry of Natural Gas Development, 17 p., URL <https://www.neb-one.gc.ca/nrg/sttstc/ntrlgs/index-eng.html> [November 2015].

Natural Resources Canada (2015): Earthquakes Canada; Natural Resources Canada, URL <http://earthquakescanada. nrcan.gc.ca/> [November 2015].

Peterson, J. (1993): Observations and modeling of seismic background noise; United States Geological Survey, Open-File Report 93-322, 94 p.

Rubinstein, J.L. and Babaie Mahani, A. (2015): Myths and facts on wastewater injection, hydraulic fracturing, enhanced oil recovery, and induced seismicity; Seismological Research Letters, v. 86, p. 1060–1067.

Salas, C.J. and Walker, D. (2014): Update on regional seismograph network in northeastern British Columbia (NTS 094C, G, I, O, P); *in* Geoscience BC Summary of Activities 2013, Geoscience BC, Report 2014-1, p. 123–126.

Salas, C.J., Walker, D. and Kao, H. (2013): Creating a regional seismograph network in northeast British Columbia to study the effect of induced seismicity from unconventional gas completions (NTS 094C, G, I, O, P); *in* Geoscience BC Summary of Activities 2012, Geoscience BC, Report 2013-1, p. 131–134.

Shapiro, S.A. and Dinske, C. (2009): Fluid-induced seismicity: pressure diffusion and hydraulic fracturing; Geophysical Prospecting, v. 57, p. 301–310.