Ⓔ

Monitoring the Earthquake Activity in an Area with Shale Gas Potential in Southeastern New Brunswick, Canada

by Maurice Lamontagne, Denis Lavoie, Shutian Ma, Kenneth B. S. Burke, and Ian Bastow

Online Material: Lists of earthquake locations and focal depths in the vicinity of the Stoney Creek Oil and Gas Field, interpretation of sonic log of velocities, velocity model, and events used in the velocity inversion.

INTRODUCTION

In recent years, there has been much interest in seismicity induced by hydrocarbon operations (e.g., Jones *et al.*, 2014). In the United States, it is mainly the reinjection of waste water that caused a major increase in the number of recorded earthquakes (Ellsworth, 2013). In contrast, lower magnitude earthquakes induced by hydraulic fracturing (HF) of tight reservoirs has attracted less interest. However, HF in western Canada has been associated with earthquakes of moderate magnitudes and more frequent occurrences. Three magnitude 3.5–3.6 events occurred in northeast British Columbia in 2010–2011 and a magnitude 4.4 in northern Alberta in January 2015. Both regions were only weakly seismic prior to the start of HF operations (see other articles in this issue; BC Oil and Gas Commission, 2012).

In eastern Canada, HF for shale gas has occurred only at an exploratory-scale in Quebec and New Brunswick. In the St. Lawrence Valley, multistage, slickwater HF of the Utica shale was done in 19 of the 29 wells drilled (Lavoie *et al.*, 2014). During that time period, very few earthquakes were detected in the surrounding areas. Although some of these earthquakes were shallow and within 10 km of wells, the hundreds of days between HF and the earthquakes rendered a causative link unlikely (Lamontagne and Ma, 2014). Since 2009, some HF has been conducted in southeast New Brunswick and is the topic of this article.

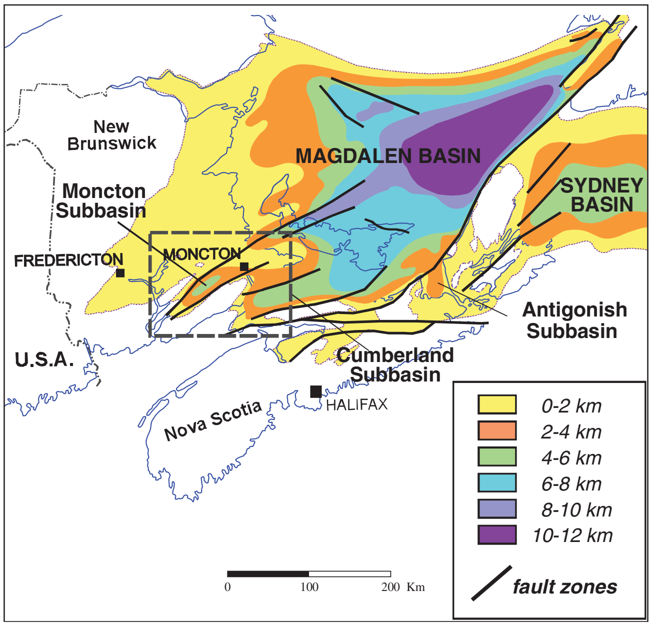
In many areas worldwide, natural seismicity is only recorded at regional distances before hydraulic activity started. For example, in northeast British Columbia, the Canadian National Seismograph Network had very sparse coverage before mid-2013, years after HF operations started (Farahbod *et al.*, 2015). In New Brunswick, we had the opportunity to gather this information prior to a proposed full-scale HF program. The New Brunswick project, initiated in 2012, aims to define regional natural seismicity of the Moncton sub-basin (Fig. 1). Here we review the regional geology and history of earthquake occurrences and monitoring. We define a regional velocity model, document the rate and depth distribution of natural seismicity, and also examine the criteria used to recognize induced earthquakes (Davis and Frohlich, 1993) in southeast New Brunswick. Based on our experience in the Moncton sub-basin, we offer some advice on some monitoring aspects of induced seismicity. We are confident that, for similar studies elsewhere, this analysis of natural seismicity provides a template of seismographic monitoring and studies in advance of shale gas development.

GEOLOGICAL AND TECTONIC SETTINGS

The Moncton sub-basin, part of the Maritimes basin, unconformably overlies diverse basement rocks of the Middle to Late Ordovician Taconian and Early to Mid-Devonian Acadian orogenies (Calder, 1998). In the Late Devonian, small fault-bounded basins opened up from the oblique convergence of Gondwana after the Middle Devonian Acadian orogeny (Gibling *et al.*, 2008); they are collectively known as the Maritimes basin. Regional strike-slip faults were active through most of the Maritime basin's development, resulting in local development of pull-apart basins and subsequent basin inversions and deformation (e.g., Bradley, 1982; Durling and Marillier, 1993). With time, these small continental basins expanded, and sedimentation was largely continental to marginal marine (Gibling *et al.*, 2008). The present day Maritimes basin is an erosional remnant of a more extensive cover of Upper Paleozoic strata (Fig. 1); it contains Middle Devonian to early Permian continental and shallow marine strata, with a maximum thickness of ~12,000 m in the east-central Magdalen basin (Fig. 1; Dietrich *et al.*, 2011).

The structural geology of the Moncton sub-basin (Fig. 2) comprises a number of uplifts (pre-Middle Devonian crystalline basement blocks) with the post-Middle Devonian

 doi: 10.1785/0220150051



▲ **Figure 1.** The regional isopach map of the Devonian–Permian successions of the western part of the Maritimes basin, based on marine seismic and selected offshore wells. The Moncton sub-basin is at the western reach of the Maritimes basin. The region discussed in this article is indicated by the rectangle (gray dashed lines). Modified from Lavoie *et al.* (2009).

succession either in faulted contact or unconformably overlapping these basement layers (St. Peter and Johnson, 2009). The depth of the basement–cover succession contact is variable in the Moncton sub-basin, from 0 to >3000 m over a relatively short distance (St. Peter and Johnson, 2009; their fig. 10). This level of complexity has implications for the velocity model for the region (see the Crustal Velocity Model section).

The New Brunswick stress regime is different from adjacent Quebec where compressive strike-slip type exists between depths of 250 and 4000 m (Konstantinovskaya *et al.*, 2012). In New Brunswick, shallow stress measurements are not available. The few (mostly upper-crustal) earthquake focal mechanisms show a strong reverse-faulting component but suggest a nonuniform maximum stress orientation (Bent *et al.*, 2003).

HISTORICAL HYDROCARBON EXPLORATION AND SHALE GAS

The Maritimes basin has numerous potential and proven hydrocarbon systems (Lavoie *et al.*, 2009; Dietrich *et al.*, 2011). In 1859, one of North America's first oil wells was drilled just outside Moncton, near the village of Dover (St. Peter and Johnson, 2009). Historic oil production from the Stoney Creek Field (about 20 km south of Moncton) was from the Lower Carboniferous lacustrine sandstones of the Albert formation of the Horton group (Fig. 3). Most oil and gas development in New Brunswick has focused on that formation.

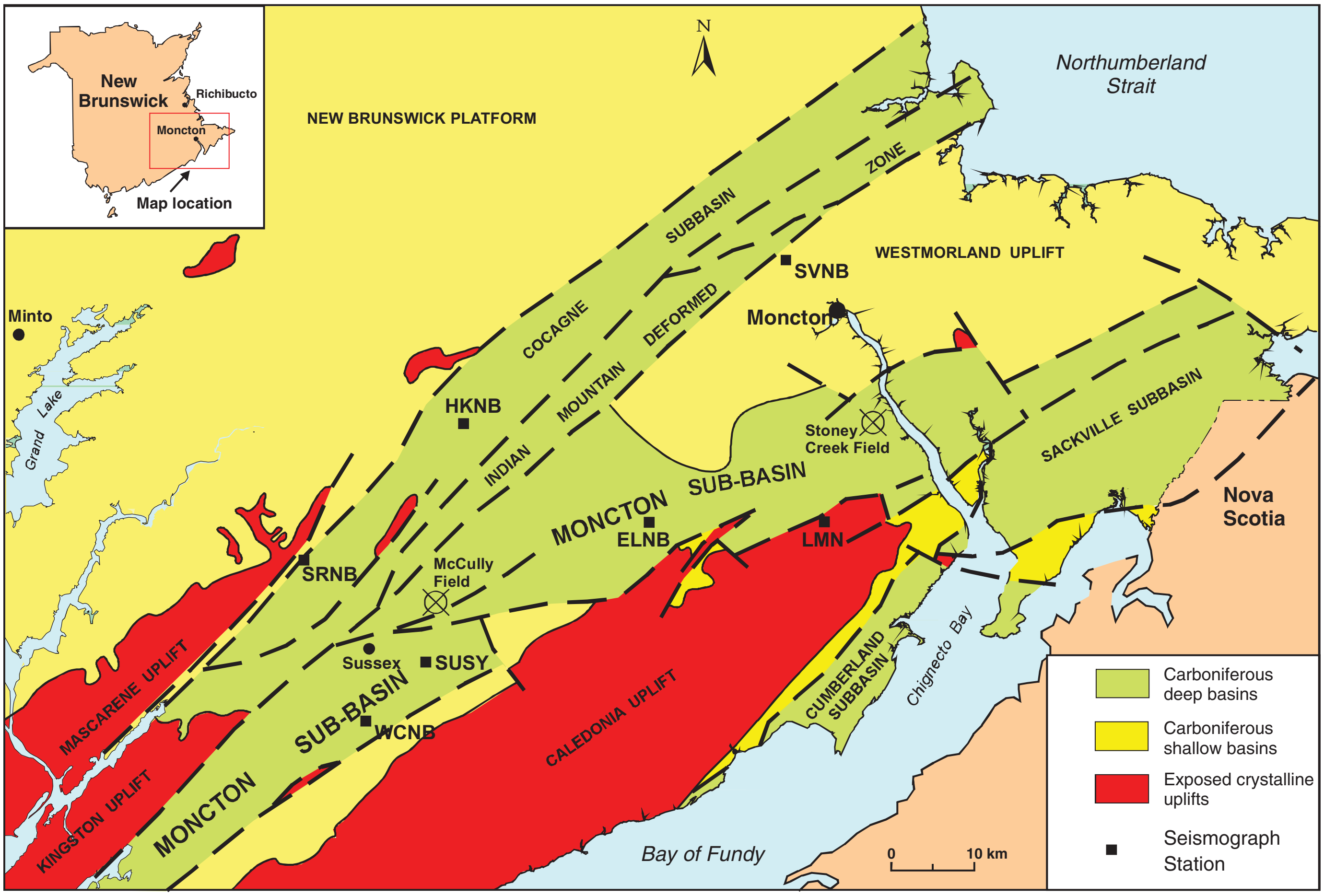
Corridor Resources currently produce natural gas at the McCully field near Sussex (Fig. 2). Production is from tight reservoirs that need HF to generate economic production; reservoirs primarily consist of tight sandstones of the Hiram Brook member (Albert formation), and one well is producing from the Frederick Brook shale member (Albert formation). Production is from vertical wells that were subjected to few stages and low-water-volume HF operations. Recently, propane gel was used for proppant carrying fluid.

HISTORY OF SEISMOGRAPH MONITORING AND EARTHQUAKES IN NEW BRUNSWICK

New Brunswick's seismicity can be divided into three periods: a historical period, a transitional period, and a seismograph network period. Before the twentieth century, earthquake listings were based mostly on historical references in newspapers, diaries, and letters. Seismographs were progressively used to detect earthquakes, albeit only teleseisms at first (Stevens, 1980). The first short-period seismographs were installed in Canada in 1927, but none were installed in New Brunswick until 1971. Only 67 earthquakes were reported from 1764 to 1960 (Fig. 4, Table 1). Events of magnitude ≤ 3 were mostly undetected. Five events had magnitudes estimated from felt area relationships in the m_{bLg} 5.4–6.0 range; two in the Central Highlands, two in the Passamaquoddy Bay region, and one near Moncton (in 1855, m_{bLg} 5.4; Burke, 2004). The latter, the only large event in the Moncton sedimentary sub-basin, damaged some chimneys and roads.

In the 1960s and 1970s, the Department of Energy, Mines and Resources, Canada, expanded the Canadian Seismograph Network with new and improved instrumentation. In 1971, a vertical-component, short-period analog seismograph was installed in Fredericton, greatly improving the monitoring of local small magnitude events. Digital (vertical) seismographs were installed in New Brunswick in 1980s, as part of the Eastern Canadian Telemetered Network. The introduction of this network permitted the province-wide location of small local earthquakes ($m_{bLg} \geq 2.0$). With this new recording capability, almost as many magnitude 2–3 earthquakes were recorded in 22 years, as in the previous 196 (Fig. 4; Table 1). Three m_N 5–6 earthquakes were recorded in the Miramichi region of the Central Highlands in early 1982; this region remains the most persistently seismically active in the province (Fig. 5). In the Moncton region, the earthquake reporting completeness was m_{bLg} 3.3 since 1826 and m_{bLg} 2.5 since 1972 (Halchuk *et al.*, 2004).

A seismograph station, Caledonia Mountain (LMN), was installed just southeast of the Moncton sub-basin in 1981 (Fig. 6). Events smaller than $m_{bLg} \approx 2.0$ were detectable by that station, but they could not always be located due to the large interstation spacing in New Brunswick. The short-period vertical station became a broadband three-component installation in 1993. Since 1980, the strongest earthquakes recorded in the sedimentary basin have been two felt events with $m_N \approx 3.6$; one occurred on 23 September 1984 and the other on 24 April



▲ **Figure 2.** The simplified geological map of the Moncton sub-basin in southern New Brunswick. The map illustrates the complex relationships between the Devonian–Permian succession and the pre-Devonian crystalline basement uplifts. The Stoney Creek (oil) and McCully (gas) fields are shown. The positions of the seven seismograph stations are shown. Modified from St. Peter and Johnson (2009).

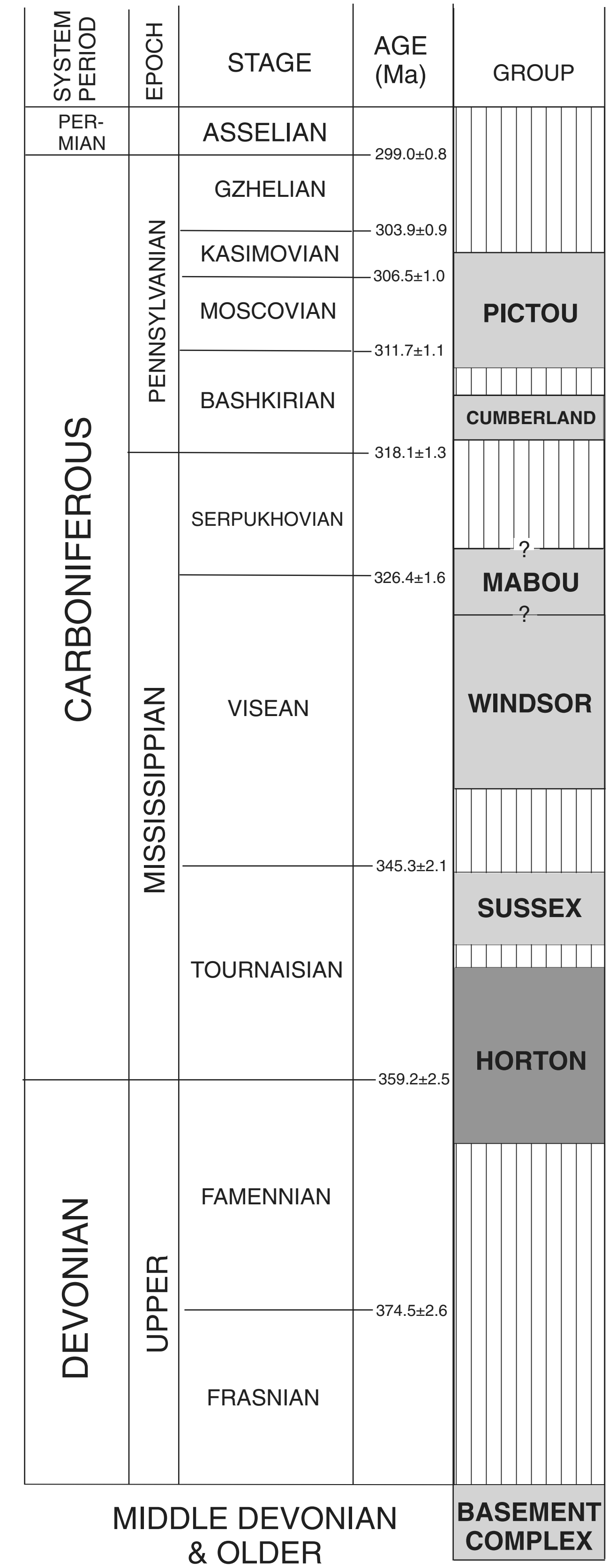
1988, both southwest of Moncton (Ⓔ Table S1, available in the electronic supplement to this article). Several earthquakes were located near the Stoney Creek Oil and Gas Field but none within 12 km of the production wells (Ⓔ Table S2).

To improve the detection and location capacity in the area with HF potential, a broadband station was installed at Elgin (ELNB) (Fig. 6). In October 2013, additional stations were installed (WCNB, SRNB, HKNB, and SVNB). Data from the six-component array are telemetered and archived at the Geological Survey of Canada (GSC); data from each station are analyzed in real time by an automatic event detection algorithm. The triggers are plotted as 30-s-long traces and examined by the analyst. A seismograph station equipped with a Güralp CMG-3TP broadband seismometer (SUSY) was installed by Imperial College, London, in September 2013. Finally, a microseismic network is in operation at the PotashCorp potash mine near Sussex.

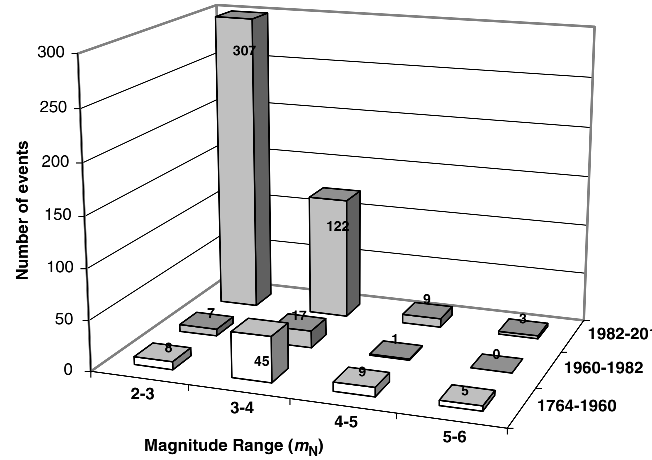
Quarry and construction blasts are detected almost daily. By comparing the detection with local earthquakes, we estimate our detection and location threshold of the network to be about m_N 1.0. Some computed locations of blasts slightly outside the network are within 5 km of the real positions. We believe epicenters within the network are better located and that a more representative velocity model could improve our locations.

CHARACTERISTICS OF THE NATURAL SEISMICITY OF NEW BRUNSWICK

To identify an induced earthquake, we must define the characteristics of the natural (tectonic) earthquakes, including focal depth. For this, it was decided to use regional depth phases (*sPg*, *sPmP*) that are often detectable at regional distances of <300 km in eastern Canada (Ma and Atkinson, 2006; Ma, 2010). A total of 22 $m_N \geq 2.8$ earthquakes were chosen in the period January 1980 to August 2014 in southeast New Brunswick (Ⓔ Table S1). Depth determinations for shallow earthquakes were checked against five surface quarry blasts. In addition, 37 events of all magnitudes within 100 km of station LMN were selected to model *sPg*, *sPmP*, and *Rg* phases (Ⓔ Table S3). Finally, we considered four small events that occurred within our local network in 2013 and 2014 (Ⓔ Table S4).



▲ **Figure 3.** Stratigraphic chart, at the group level, for the Moncton sub-basin in southern New Brunswick. Modified from St. Peter and Johnson (2009).

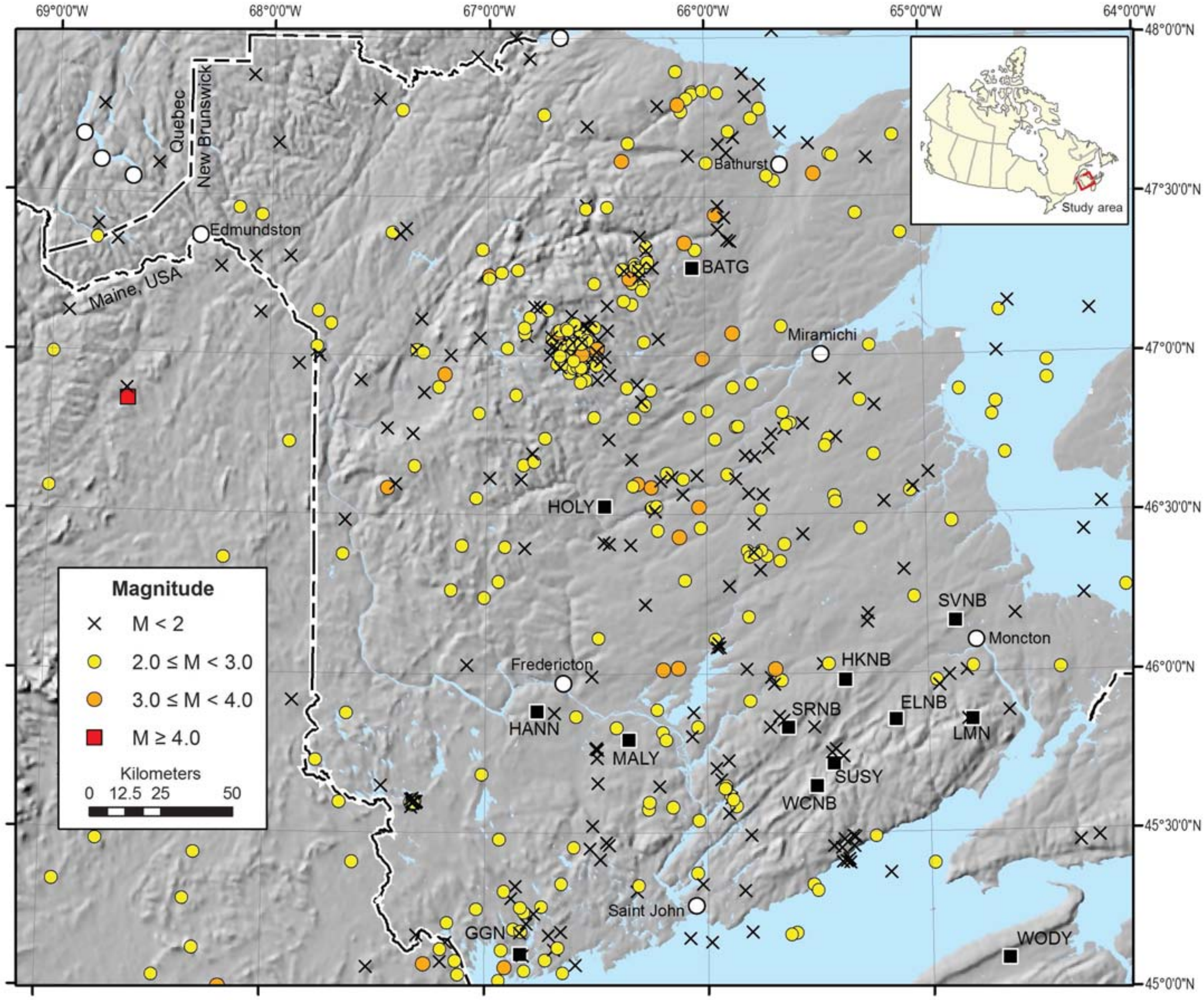


▲ **Figure 4.** The number of earthquakes in magnitude classes m_N 2.0–2.9, 3.0–3.9, 4.0–4.9, and 5+ reported in three different time periods (1764–1960, 1960–1982, 1982–2015).

The 22 focal-depth determinations for $m_N \geq 2.8$ earthquakes are shallower than 17 km (Fig. 7). About one-third of these events occur at depths shallower than 6 km, with a median of 7 km. Smaller earthquakes of the Moncton region are generally shallower (upper crustal, ≤ 12 km depth), with a median of 5 km (Fig. 8). Three events in the Sussex area (magnitude 0.4–1.9) are all within the upper 3 km (Ⓔ Table S4). The calculation of focal depths for the five quarry blasts in the Oromocto region all indicated shallow sources (0–3 km), indicating reliable results for upper crustal earthquakes. The same

Table 1
Number of Earthquakes in New Brunswick for Different Time Periods

Magnitude (m_N) Range	Number
Historical earthquakes (1764–1960)	
5–6	5
4–5	9
3–4	45
2–3	8
Subtotal	67
Earthquakes in transitional period 1960–1982	
4–5	1
3–4	17
2–3	7
Subtotal	25
Network earthquakes (1982–2015)	
5–6	3
4–5	9
3–4	122
2–3	307
Subtotal	441
Total (1764–2015)	**533**



▲ **Figure 5.** Earthquakes in New Brunswick and adjacent areas for the period 1980–2014. The positions of seismograph stations in operation in 2013 are also shown.

depth determination method applied for the Miramichi region earthquakes also yielded results consistent with those determined from previous aftershock field surveys (Ma and Motazedian, 2015).

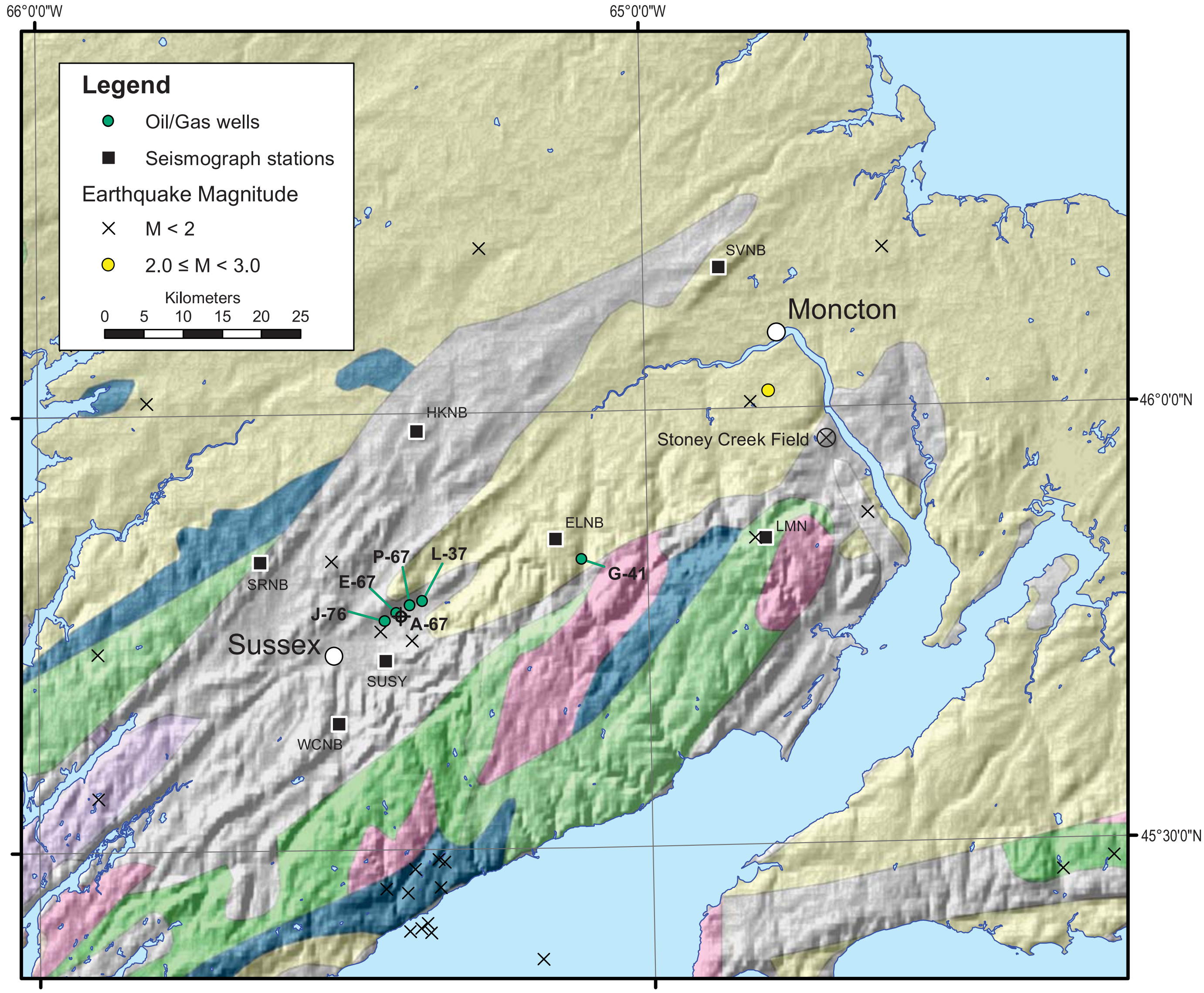
Rates of Earthquake Occurrences

For the purpose of seismic-hazard zoning, the Moncton sub-basin is part of the northern Appalachian zone (Adams and Halchuk, 2003). The rate of earthquake occurrences for the Moncton subzone of Burke (2004) was defined by Halchuk *et al.* (2004). The Moncton subzone is slightly larger than the region covered by our local seismograph network. For simplicity, we assume that seismicity in the Moncton sub-basin and Moncton subzones are similar. The rate of activity for the Moncton subzone is only half that of the northern Appalachian seismic zone. From the mean curve for the subzone, the cumulative annual rates of earthquakes are 0.3 events for m_N 2.0 (3.3 events per year); 0.5 events for m_N 3.0 (1 event per 20 years); 0.007 events for m_N 4.0 (one per 142 years); 0.0008 events for m_N 5.0 (one per 1275 years); and 0.0001 events for m_N 6.0 (one per 10,000 years). In the future, the seismic rates could be compared to the historical activity rate, keeping in mind the high uncertainty in the recurrence curve, especially for larger magnitudes.

MONITORING THE LOCAL EARTHQUAKE ACTIVITY

Crustal Velocity Model

Locating local earthquakes requires an adequate crustal velocity model. Unfortunately, there is only limited seismic velocity information for southeast New Brunswick, and most are owned

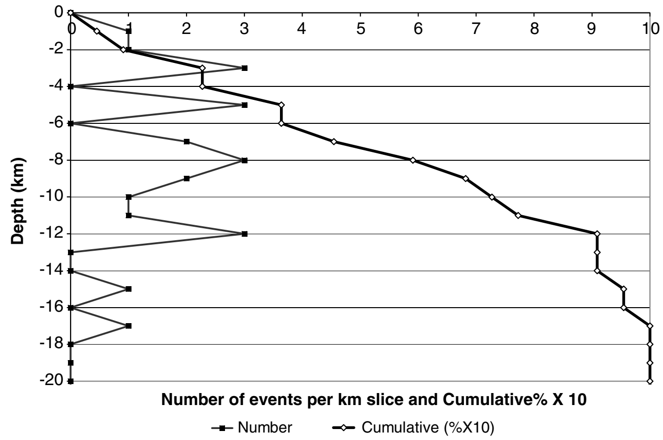


▲ **Figure 6.** Positions of the southeast New Brunswick seismograph stations and of the wells in which HF operations were performed during August and September 2014. Colors represent major geological units.

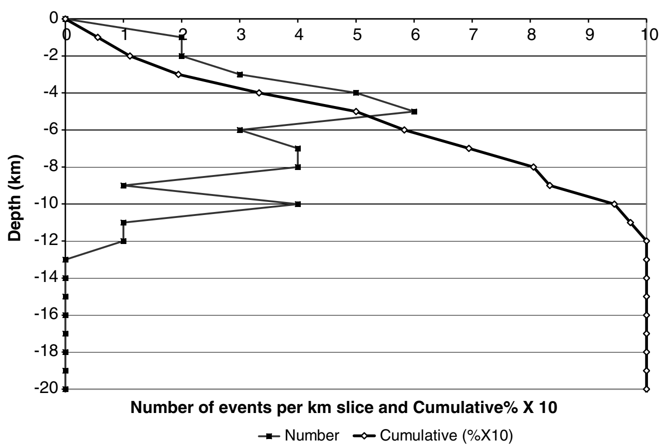
by exploration companies and contractors and remain confidential. Other available information includes results of receiver-function analysis (Kao *et al.*, 2014), shallow seismic data from late 1970s (Kingston and Steeves, 1979; Steeves and Kingston, 1981), and sonic logs from well A-67 (Fig. 6). The latter can constrain seismic velocity and the depths of contacts in the top 2.5 km (Ⓔ Table S5). In addition, *S*-wave velocity models were computed using crustal Rayleigh wave (*Rg*) dispersion data. Group velocities were estimated using the multiple filter technique (Dziewonski *et al.*, 1969) in the Computer Programs in Seismology package of Herrmann and Ammon (2002). Long paths of Rayleigh waves produced by the 23 June 2010 M_w 5.2 Val-des-Bois, Quebec, earthquake were used to define the regional velocity structure. Events in central New Brunswick and one recorded within the local network (defining paths in New Brunswick) were used to infer regional and local velocity models (Ⓔ Tables S6 and S7; Fig. 9). The computed model shows velocities systematically slower than those in the initial Canadian Shield model. At the local scale, vertical and lateral velocity variations remain poorly resolved. These velocity variations probably contribute to the complex seismic traces of shallow earthquakes (Fig. 10). Until an improved velocity model is defined, we cannot expect hypocenter precisions better than a few kilometers using such a simple 1D velocity model.

Monitoring of the Hydraulic Fracturing

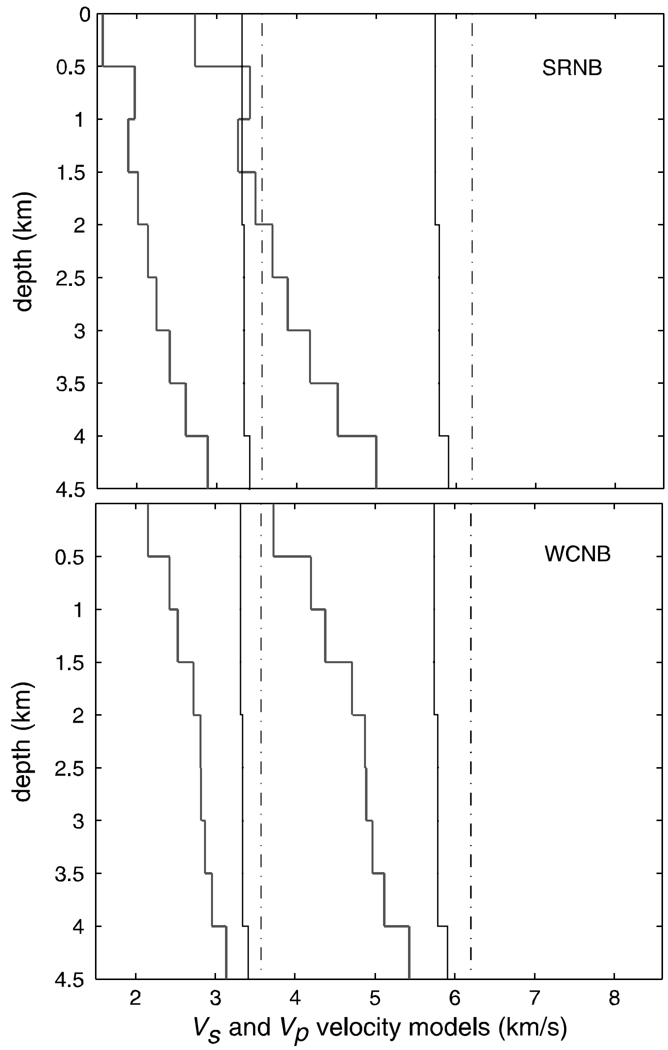
Hydraulic fracturing was performed in the McCully gas field area between September 2009 and November 2010 and again between August and September 2014. In 2014, four of the five



▲ **Figure 7.** Focal-depth distribution of $m_N \geq 2.8$ earthquakes in terms of absolute numbers per 1 km slices and cumulative number (maximum 10) for the southern part of New Brunswick. See Ⓔ Table S1 for details.



▲ **Figure 8.** Focal-depth distribution of $m_N < 2.8$ earthquakes in terms of absolute numbers per 1 km slices and cumulative number (maximum 10) for the southeastern part of New Brunswick near our local seismograph network. See Ⓔ Table S2 for details.

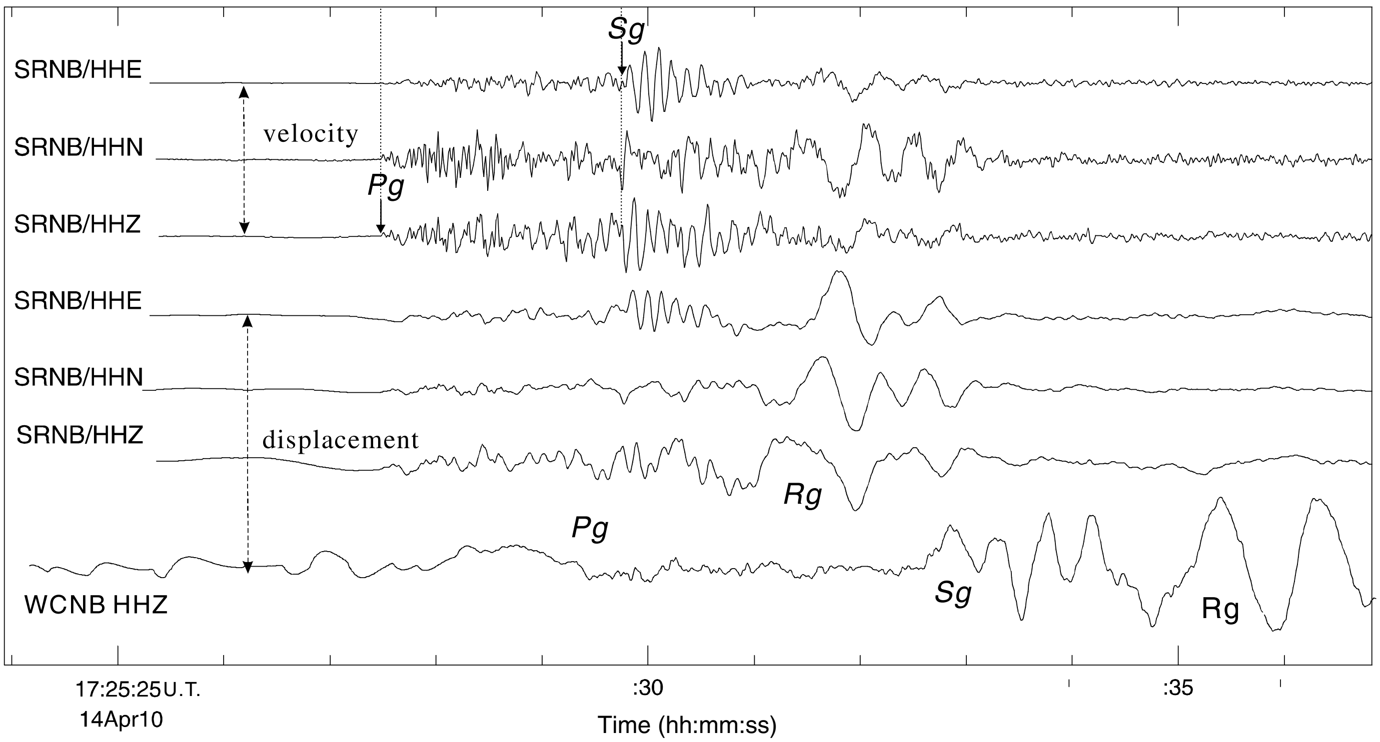


▲ **Figure 9.** Velocity models for the *P* and *S* waves for the upper 4.5 km of the Moncton sub-basin as inverted at two stations (top) SRNB and (bottom) WCNB. The other lines are the initial *P*- and *S*-wave velocity models (black solid lines) and those of the standard Geological Survey of Canada (GSC) velocity model used to locate earthquakes (dashed-dotted lines).

wells were fracked with liquid petroleum gel and one with slickwater; four wells tested shales and had one-stage HF, the other well stimulated the sandstones with two-stage HF. All HF stages had low volume (14–55 tons) of proppant emplacement (Corridor Resources, 2014). No induced activity was recorded during these periods on the surface stations. Although our stations are sufficiently sensitive to detect $\mathbf{M} \geq 1$ earthquakes in the immediate region, no microearthquake was detected (Lamontagne and Lavoie, 2015).

Local Earthquakes in the Moncton Sub-Basin

During the period September 2009 (onset of limited HF) to September 2013 (the onset of our six-station monitoring network), only one earthquake was detected within the sub-basin (20 October 2011; Ⓔ Table S4). Although the epicenter is within a few kilometers of the McCully field, this event does not appear related to the HF campaigns: its focal depth was calculated to be 5 km by the modeling of regional depth phases, and the event occurred almost a year after the conclusion of the fracturing operations. Between September 2013 and January 2015, four small magnitude events (m_N 1.9, 0.9, 0.4, and 1.3) have been located with the local network (Ⓔ Table S4). The largest of these events occurred in the middle of the network. The complicated geology and the inherent imprecision of the hypocenter locations make a correlation with precise faults difficult. No HF had been done for at least three years prior to the first three events. The time interval of two months between the August and September HF operations and the 18 November 2014 earthquake suggests that these events are not associated with each other.



▲ **Figure 10.** Vertical velocity and displacement records of the 10 April 2014 m_N 1.9 earthquake recorded (top) at station SRNB and (bottom) at station WCNB.

DISCUSSION AND CONCLUSIONS

We defined several characteristics of the seismicity of southeast New Brunswick where full-scale HF operations could eventually take place. In the Moncton sub-basin, most earthquakes occur in the top 5 km, but some are as deep as 12 km (Ⓔ Table S4). Some faults of the upper crust may be more susceptible to reactivation in the presence of increased pore-fluid pressure. In the sub-basin, the current network can detect and locate $m_N > 1.0$ earthquakes. Better surveillance of the earthquakes requires additional stations to increase redundancy and a local velocity model to improve hypocenter locations.

If the shale gas and tight oil development proceeds in the Moncton sub-basin, can we distinguish between natural and induced earthquakes? For this, Davis and Frohlich (1993) defined a series of criteria to help diagnose the nature of an earthquake sequence (Table 2). First, natural earthquakes occur in New Brunswick; however, based on modern and historical data, the occurrence rate is extremely low. Between September 2012 and January 2015, only five earthquakes ($m_N \leq 1.9$) have been recorded in the Moncton sub-basin. Natural earthquake swarms are possible (e.g., as occurred in McAdam, New Brunswick, in 2012; Butler *et al.*, 2013) and are not necessarily induced by human activity. The current network appears sufficient to locate $m_N \geq 1.0$ earthquake hypocenters within a few kilometers and could help determine a possible link with HF. The correlation with local faults requires hypocenters to be determined with greater precision. The aspects of fluid pressures and how they diffuse with distance would be difficult to calculate with certainty. Because of the many uncertainties in seismological, geological, and pore-fluid diffusion parameters, the criteria of Davis and Frohlich (1993) may not provide a clear diagnostic of induced seismicity in southeast New Brunswick. To provide diagnostic evidence, we recommend that a microseismic array be established near HF operations to monitor earthquake activity at close distances.

Finally, we offer some advice on the monitoring aspects of induced seismicity based on our experience in southeast New Brunswick. Real-time transmission of seismographic data greatly simplifies the analysis. Detecting very-small-magnitude earthquakes requires more time than analyzing larger events. In the lower magnitude range, earthquakes and noise bursts are similar and require time-consuming analysis. Often, very small events recorded by one station are not always locatable unless the less precise method of determining *S*–*P* time and the direction of the incoming *P* wave is used. Although shallow events often give clear Rayleigh waves (*Rg*) shortly after the *S* wavetrain, such an event could be an earthquake or a blast at a mine, quarry, or construction site. Confirming that an event is a blast can be very time consuming, but prior knowledge of recurring blast sources and corresponding contact information greatly helps. Road construction blasts are especially difficult to confirm. The enhanced level of attention by the public and the media for unusual rumbles and vibrations can generate additional work.

Table 2
Seven Questions Forming a Profile of a Seismic Sequence (Davis and Frohlich, 1993)

Question	Earthquakes Clearly Not Induced	Earthquakes Clearly Induced	1. Applicability to the Moncton Sub-Basin 2. Current Situation
Background seismicity			
1. Are these events the first known earthquakes of this character in the region?	No	Yes	1. Background seismicity is present with very low rates; one known damaging earthquake 2. No; earthquakes occur there naturally
Temporal correlation			
2. Is there a clear correlation between injection and seismicity	No	Yes	1. No at this time 2. Recently, small-scale hydraulic fracturing did not produce events within reasonable time frame
Spatial Correlation			
3a. Are epicenters near wells (within 5 km)?	No	Yes	1. The local network allows determination of sources within a couple of kilometers, which should fulfill this condition 2. Yes; some earthquake activity is within 5 km
3b. Do some earthquakes occur at or near injection depths?	No	Yes	1. For earthquakes larger than m_N 1.5, the local network allows depth determination of sources within 1 km precision. 2. Yes, most earthquakes are shallow focus.
3c. If not, are there known geologic structures that may channel flow to sites of earthquakes?	No	Yes	1. Yes; numerous faults are present; very local conditions near wells are poorly known. 2. To be determined
Injection practices			
4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?	No	Yes	1. To be determined 2. Unknown
4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	No	Yes	1. Would be hard to determine 2. Unknown

ACKNOWLEDGMENTS

We thank Veronika Peci, seismological analyst at the Geological Survey of Canada (GSC), for her dedicated work at analyzing New Brunswick earthquakes; Tim Côté (GSC) for help analyzing seismograph data; members of the Energy Institute of New Brunswick and the New Brunswick Department of Energy and Mines for their support; the technologists of Canadian Hazards Information Service (CHIS); collaborators at PotashCorp and at Corridor Resources; and the owners and employees of the properties where our stations are located. I.B. acknowledges support from Leverhulme Trust Grant RPG-2013-332. This article is Earth Sciences Sector Publication Number 20150044.

REFERENCES

Adams, J., and S. Halchuk (2003). Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada, *Geol. Surv. Canada Open-File 4459*, 155 pp.

BC Oil and Gas Commission (2012). *Investigation of Observed Seismicity in the Horn River Basin*, BC Oil and Gas Commission, 29 pp., http://www.bcogc.ca/node/8046/download (last accessed May 2015).

Bent, A. L., J. Drysdale, and H. K. C. Perry (2003). Focal mechanisms for eastern Canadian earthquakes, 1994–2000, *Seismol. Res. Lett.* **74,** 452–468.

Bradley, D. C. (1982). Subsidence in Late Paleozoic basins in the northern Appalachians, *Tectonics* **1,** 107–123.

Burke, K. B. S. (2004). Historical seismicity in the Central Highlands, Passamaquoddy Bay, and Moncton regions of New Brunswick, *Seismol. Res. Lett.* **75,** 419–434.

Butler, K. E., S. Hayek, K. B. S. Burke, J. Adams, A. Bent, J. J. Brown, and S. Halchuk (2013). The extremely-shallow 2012 earthquake swarm in McAdam, New Brunswick, Canada (abstract), *The IAHS–IAPSO–IASPEI Joint Assembly*, Gothenburg, Sweden, 22–27 July 2013, Abstract S301S3.02.

Calder, J. H. (1998). The Carboniferous evolution of Nova Scotia, *Geol. Soc. Lond. Spec. Publ.* **143,** 261–302.

Corridor Resources (2014). *Corridor Announces Initial Results of 2014 Capital Program*, http://www.marketwired.com/press-release/corridor-announces-initial-results-of-2014-capital-program-tsx-cdh-1961709.htm (last accessed May 2015).

Davis, S. D., and C. Frohlich (1993). Did (or will) fluid injection cause earthquakes: Criteria for a rational assessment, *Seismol. Res. Lett.* **64,** 207–224.

Dietrich, J., D. Lavoie, P. Hannigan, N. Pinet, P. Castonguay, P. Giles, and A. P. Hamblin (2011). Geological setting and resource potential of conventional petroleum plays in Paleozoic basins in eastern Canada, *Bull. Can. Petrol. Geol.* **59,** 54–84.

Durling, P. W., and F. J. Y. Marillier (1993). Structural trends and basement rock subdivisions in the western Gulf of St. Lawrence, northern Appalachians, *Atl. Geol.* **26,** 79–95.

Dziewonski, A., S. Bloch, and M. Landisman (1969). A technique for the analysis of transient seismic signals, *Bull. Seismol. Soc. Am.* **59,** no. 1, 427–444.

Ellsworth, W. L. (2013). Injection-induced earthquakes, *Science* **341,** no. 6142, doi: 10.1126/science.1225942.

Farahbod, A. M., H. Kao, D. M. Walker, and J. F. Cassidy (2015). 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.

Gibling, M. R., N. Culshaw, M. C. Rygel, and V. Pascucci (2008). The Maritimes basin of Atlantic Canada: Basin creation and destruction in the collisional zone of Pangea, in *The Sedimentary Basins of the United States and Canada*, A. D. Miall (Editor), Chapter 6, Sedimentary Basins of the World, Vol. 5, Elsevier Science, Amsterdam, The Netherlands.

Halchuk, S., K. B. S. Burke, and J. Adams (2004). Note on the magnitude recurrence relationships for the Central Highlands, Passamaquoddy Bay, and Moncton subzones of New Brunswick, Canada, *Seismol. Res. Lett.* **75,** 432–434.

Herrmann, R., and C. Ammon (2002). *Computer Programs in Seismology, version 3.30*, Saint Louis University, St. Louis, Missouri, http://www.eas.slu.edu/eqc/eqc_cps/CPS/CPS330/cps330s.pdf (last accessed May 2015).

Jones, G. A., J.-M. Kendall, I. Bastow, D. Raymer, and A. Wuestefeld (2014). Imaging of fractures and faults: A microseismic study from the Ekofisk reservoir, *Geophys. Prospect.* **62,** 779–796, doi: 10.1111/1365-2478.12139.

Kao, H., S.-J. Shan, J. F. Cassidy, and S. A. Dehler (2014). Crustal structure in the Gulf of St. Lawrence region, eastern Canada: Preliminary results from receiver function analysis, *Geol. Surv. Can. Open-File Rept. 7456*, 48 pp.

Kingston, P., and B. Steeves (1979). Shallow seismic data from the eastern part of the New Brunswick platform: Stratigraphic and structural implications, *New Brunswick Department of Natural Resources Open File 79-14*, 31 pp.

Konstantinovskaya, E., M. Malo, and D. A. Castillo (2012). Present-day stress analysis of the St. Lawrence Lowlands sedimentary basin (Canada) and implications for caprock integrity during CO_2 injection operations, *Tectonophysics* **518/521,** 119–137.

Lamontagne, M., and D. Lavoie (2015). Report on the monitoring of micro-earthquakes during the hydraulic fracturing conducted in New Brunswick in August and September 2014, *Geol. Surv. Can. Open-File Rept. 7815*.

Lamontagne, M., and S. Ma (2014). Monitoring earthquakes in eastern Canadian areas with shale gas exploration potential (abstract), *Second European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey, 25–29 August 2014, Abstract 2980.

Lavoie, D., N. Pinet, J. Dietrich, P. Hannigan, S. Castonguay, A. P. Hamblin, and P. Giles (2009). Petroleum resource assessment, Paleozoic successions of the St. Lawrence platform and Appalachians of eastern Canada, *Geol. Surv. Can. Open File 6174*, 275 pp.

Lavoie, D., C. Rivard, R. Lefebvre, S. Séjourné, R. Thériault, M. J. Duchesne, J. Ahad, B. Wang, N. Benoit, and C. Lamontagne (2014). The Utica shale and gas play in southern Quebec, geological and hydrogeological synthesis and methodological approaches to groundwater risk evaluation, *Int. J. Coal Geol.* (special issue on potential environmental impacts of unconventional fossil energy development) **126,** 77–91.

Ma, S. (2010). Focal depth determination for moderate and small earthquakes by modeling regional depth phases *sPg*, *sPmP*, and *sPn*, *Bull. Seismol. Soc. Am.* **100,** 1073–1088.

Ma, S., and G. M. Atkinson (2006). Focal depth distribution for earthquakes with $m_N \geq 2.8$ in western Quebec, southern Ontario and northern New York, *Bull. Seismol. Soc. Am.* **96,** 609–623.

Ma, S., and D. Motazedian (2015). Focal depth distribution of the 1982 Miramichi, New Brunswick, earthquake sequence, retrieved by analyzing regional depth phases (abstract), *2015 Joint Meeting of the AGU-CGU-GAC-MAC*, Montreal, Quebec, May 2015, Abstract S44A-0318.

Steeves, B., and P. W. Kingston (1981). Carboniferous seismic survey, *Department of Natural Resources of New Brunswick, Open-File Rept. 81-1*, 145 pp.

Stevens, A. E. (1980). History of some Canadian and adjacent American seismograph stations, *Bull. Seismol. Soc. Am.* **70,** 1381–1393.

St. Peter, C. J., and S. C. Johnson (2009). Stratigraphy and structural history of the late Paleozoic Maritimes basin in southeastern New Brunswick, Canada, *New Brunswick Department of Natural Resources, Memoir 3*, 348 pp.

Maurice Lamontagne
Geological Survey of Canada
615 Booth Street
Ottawa, Ontario
Canada K1A 0E9
maurice.lamontagne@nrcan-rncan.gc.ca

Denis Lavoie
Geological Survey of Canada
490 de la Couronne
Québec City, Québec
Canada G1K 9A9

Shutian Ma
Department of Earth Sciences
Carleton University
1125 Colonel By Drive
Ottawa, Ontario
Canada K1S 5B6

Kenneth B. S. Burke
Department of Earth Sciences
University of New Brunswick
Fredericton, New Brunswick
Canada E3B 5H5

Ian Bastow
Imperial College
London SW7 2AZ
United Kingdom

Published Online 10 June 2015