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 crystal-
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 $m_{lg}$ 5.4–6.0 range; two in the Central Highlands, two in the Passamaquoddy Bay region, and one near Moncton (in 1855, $m_{lg}$ 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. Digital (vertical) seismographs were mostly undetected. Five $m_{lg}$ 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 $m_{lg}$ 3.3 since 1826 and $m_{lg}$ 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 $m_{lg}$ ≥ 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 $m_N$ ≥ 3.6; one occurred on 23 September 1984 and the other on 24 April.
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 ($sP_g$, $sP_{m}P$) 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 $sP_g$, $sP_{m}P$, and $R_g$ phases (Ⓔ Table S3). Finally, we considered four small events that occurred within our local network in 2013 and 2014 (Ⓔ Table S4).
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, \( \leq 12 \) 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 (Fig. 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

![Figure 3](image)

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

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![Figure 4](image)

**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).

<table>
<thead>
<tr>
<th>Magnitude (( m_N )) Range</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical earthquakes (1764–1960)</td>
<td></td>
</tr>
<tr>
<td>5–6</td>
<td>5</td>
</tr>
<tr>
<td>4–5</td>
<td>9</td>
</tr>
<tr>
<td>3–4</td>
<td>45</td>
</tr>
<tr>
<td>2–3</td>
<td>8</td>
</tr>
<tr>
<td>Subtotal</td>
<td>67</td>
</tr>
<tr>
<td>Earthquakes in transitional period 1960–1982</td>
<td></td>
</tr>
<tr>
<td>4–5</td>
<td>1</td>
</tr>
<tr>
<td>3–4</td>
<td>17</td>
</tr>
<tr>
<td>2–3</td>
<td>7</td>
</tr>
<tr>
<td>Subtotal</td>
<td>25</td>
</tr>
<tr>
<td>5–6</td>
<td>3</td>
</tr>
<tr>
<td>4–5</td>
<td>9</td>
</tr>
<tr>
<td>3–4</td>
<td>122</td>
</tr>
<tr>
<td>2–3</td>
<td>307</td>
</tr>
<tr>
<td>Subtotal</td>
<td>441</td>
</tr>
<tr>
<td>Total (1764–2015)</td>
<td>533</td>
</tr>
</tbody>
</table>
depth determination method applied for the Miramichi region earthquakes also yielded results consistent with those determined from previous aftershock field surveys (Ma and Mota-zedian, 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...
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 ($R_g$) 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
wells were fracked with liquid petroleum gel and one with slick-water; 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 $M \geq 1$ 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 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.
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 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 (\( R_g \)) 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.

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

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

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