

APPENDIX K

Review of Potential Risks of Anomalous Induced Seismicity Associated with On-Shore Development of Multi-Stage Hydraulic Fracturing Operations in Western Newfoundland

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A Report to the Newfoundland and Labrador
Hydraulic Fracturing Review Panel

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Final Report
10 February 2016

EXECUTIVE SUMMARY

This report provides a high-level summary, from a seismology perspective, of potential risks of anomalous induced seismicity associated with hydraulic fracturing for shale gas development, with specific application to activities that may be undertaken during possible future land-based development of hydrocarbon resources in the Green Point shale (or other known targets) of Western Newfoundland. For the purpose of this report, "hydraulic fracturing" is considered to include all activities associated with the potential development of shale oil resources at depth, including surface and subsurface activities such as transportation, drilling, stimulation, production and well and site decommissioning.

The most common triggering mechanisms of injection-induced seismicity are an increase in stress acting on a pre-existing fault due to rock mass deformation, or an increase in pore-pressure, which leads to partial unclamping of a critically stressed fault thereby allowing it to slip. The U.S. midcontinent provides an example of a significant region where injection-induced seismicity has increased in recent years from oil and gas activities. In western Canada, there is evidence that induced seismicity from hydraulic fracturing is more prevalent than in the U.S. In the Horn River Basin, evidence suggests that the level of seismicity may be linked to the regionally aggregated volume of injected fluid.

The Green Point shale is an organic rich source rock that is prospective for unconventional oil and gas development. Unlike similar successions in other basins, its subsurface extent and configuration is complicated by significant structural reworking. Western Newfoundland is located in an area of low background seismicity and low seismic hazard. Seismograph network coverage is sparse and improved network coverage could enhance detection capabilities for low magnitude events and location capabilities for all earthquakes in this region.

The Canadian Association of Petroleum Producers has introduced an operational practice for anomalous induced seismicity. Together with a traffic light protocol that was recently developed by the Alberta Energy Regulator (AER), this provides a well-documented risk-management strategy.

The following recommendations are proposed to the Hydraulic Fracturing Review Panel:

1. The use by the operators of microseismic monitoring methods, especially during initial hydraulic fracturing tests, is recommended to verify the effectiveness of operations and containment of fractures. A summary report of the monitoring results should be submitted to the provincial regulator.
2. Enhancements should be made to seismograph network coverage in western Newfoundland in order to improve monitoring capabilities for baseline seismicity. Given the current station distribution, at least one new station north and east of Anticosti Island would provide a significantly better geometry for event detection. Since two or more years of data may be necessary to acquire baseline information, it is recommended that this should take place early in any development plan.
3. Implementation of a traffic light protocol for induced seismicity monitoring during treatment should be considered. The provisions of AER subsurface order #2 provide a well-documented template.
4. A geomechanical investigation that considers all available stress data and realistic structural models should be undertaken to address site-specific issues that pertain to the unique structural environment of the Green Point shale. It would be beneficial for this report (or at least a summary of key results) to be in the public domain.
5. In the event that deep disposal of waste fluids is considered as part of a future development plan, monitoring of pore pressure in the disposal formation should be undertaken prior to and during injection. This would enable the application of principles derived from the study of Raleigh et al. (1976) at the Rangely field to seismic risk management from wastewater disposal.

1. PURPOSE AND SCOPE OF THIS REPORT

This report summarizes current seismological knowledge pertinent to potential risks of induced seismicity from hydraulic fracturing (HF) for shale gas development, with specific application to activities that may be undertaken during possible future land-based development of hydrocarbon resources in the Green Point shale (or other known targets) of Western Newfoundland. Based on guidelines provided by the Newfoundland and Labrador Hydraulic Fracturing Review Panel, “hydraulic fracturing” is considered to include all activities associated with the potential development of shale oil resources at depth, including surface and subsurface activities such as transportation, drilling, stimulation, production and well and site decommissioning.

Although a preliminary assessment suggests that the probability of large-scale disposal of liquid wastes is improbable in the sedimentary sequences encountered in the region (CWN 2015), this report includes a summary of published results on deep well disposal of co-produced formation waters due to the strong association with induced seismicity that has been documented in other sedimentary basins, particularly within the U.S. Midwest region.

Considerations in this report include aspects of wellbore placement, HF treatment design, or production strategies to influence the probability and intensity of induced seismicity, procedures to establish baseline data and to monitor for induced seismicity, and procedures or practices to mitigate and respond to induced seismicity.

Specific questions that are addressed in this report include:

1. What is required to establish a reasonable baseline of the existing level of felt seismicity before any significant subsurface activity has taken place?
2. Do hydraulic fracturing (and production) activities, in general, lead to measurable seismic events that can impact communities in terms of infrastructure damage of any kind (Mercalli Modified Intensity of IV or higher)?
3. Could the surface intensity and frequency of induced seismic events be such that a high level of human annoyance and concern be expected, or are such events likely to be rare and below the threshold of common detection (Mercalli Modified Intensity of I or lower)?
4. Is the geology of Western Newfoundland distinct from and more at risk than other areas with respect to the potential triggering of induced seismicity as the result of hydraulic fracturing? (e.g. exceptionally large in situ differential stresses, sensitive ground conditions leading to greater surface intensity)
5. What actions/regulations/best practices can be applied to hydraulic fracturing activities to minimize induced seismicity and the felt intensity at the surface risks?

2. BACKGROUND ON INDUCED SEISMICITY

Induced seismicity refers to earthquakes or other seismic events that are attributed to human activities (e.g., NAS 2012; CAPP, 2013). Induced seismicity has been extensively studied for a number of different types of human activities, such as impoundment of water reservoirs (Gupta, 1992), mining (McGarr et al., 2002) and geothermal applications (Majer et al., 2007). There are also documented cases of earthquakes that have been triggered by poroelastic stress changes associated with withdrawal of hydrocarbons (Segall, 1989; Baranova et al., 1999).

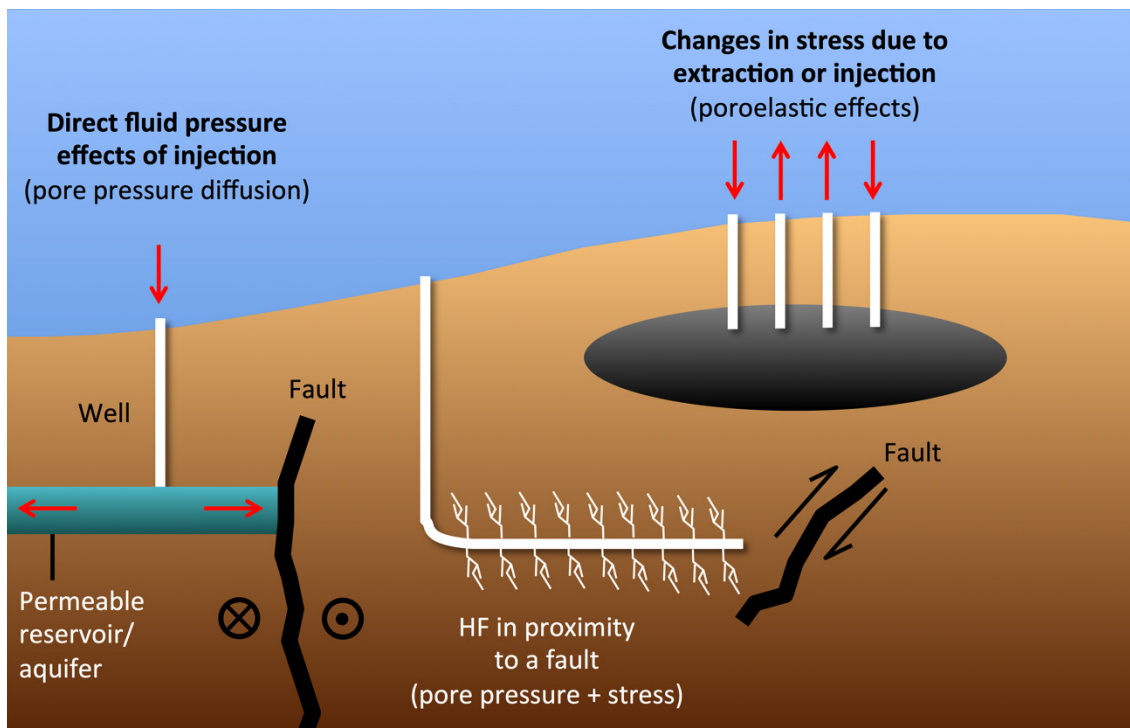


Figure 1. Mechanisms for fluid-induced seismicity (modified from Ellsworth, 2013). On the left, the disposal of waste fluids (e.g. formation water that is co-produced with oil) into a storage formation with a permeable pathway a fault can activate the fault due to pore pressure increase. On the right, poroelastic effects due to loading can also trigger slip on a fault with no direct hydrologic connection. Recent studies in western Canada highlight the induced seismicity potential of hydraulic fracturing (HF) in proximity to a fault.

Several different types of fluid injection processes are considered here (Figure 1). The primary focus of this report is on hydraulic fracturing; in a strict sense, this is a process of injecting fracturing fluids into a rock formation at a force exceeding the fracture pressure of the rock, thus inducing a network of fractures through which oil or natural gas can flow to the wellbore (CCA, 2014). Deep disposal of wastewater is also associated with certain types of oil and gas development (Rubinstein and Mahani, 2015). This type of fluid injection includes the disposal into an underground formation of produced water associated with the production of oil, bitumen, gas or coalbed methane, as well as fluids from solution mining operations, water containing polymers or other chemicals for enhanced recovery and waste fluids from circulation during well cementing.

It has long been understood that injection of fluids into the subsurface can activate slip on a fault (Healy et al., 1968); however, seismicity induced by fluid injection in association with oil gas operations has come into greater focus in recent years due to a sharp increase in the rate of earthquake activity in some areas, such as the U.S. midcontinent region (Figure 2). In the case of injection-induced seismicity, the primary physical mechanism for triggering an earthquake is increased pore pressure on a critically stressed fault, which effectively unclamps the fault so that shear stresses acting on the fault produce slip (e.g., LOGCC, 2015).

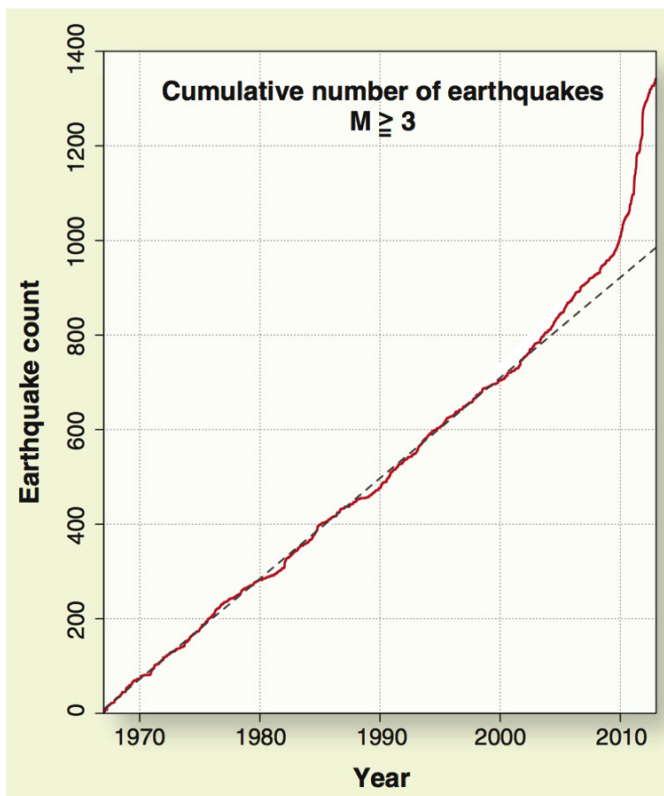


Figure 2. Cumulative number of earthquakes of magnitude $M \geq 3$ in the U.S. midcontinent region for the period from 1967-2013 (from Ellsworth, 2013), as a documented large-scale example of injection-induced seismicity. Until about 2003, the curve exhibits a clear trend indicative of the natural background seismicity rate; a further sharp increase in seismicity rate, related to accelerated oil and gas development, commenced in about 2010.

2.1 Effects of Pore Pressure

Figure 3 illustrates the basic physical processes for two well-documented examples of injection-induced seismicity, using Mohr diagrams. This type of diagram represents the state of stress using normal stress σ and the shear stress τ as co-ordinates. Increasing pore pressure leads to a reduction in the effective normal stress, which shifts the Mohr circle to the left. Fault slip occurs when the Mohr circle crosses the failure line. The first example, from the Rangely oil field in Colorado, was a unique experiment at a location where induced seismicity ($M < 3.1$) had previously been noted in association with secondary recovery by waterflood (Raleigh et al., 1976). Here, the initial reservoir pore pressure was ~ 17 MPa and water injection took place in a number of wells at depths of up to 2 km. During the experiment, it was determined that earthquakes could be turned off and on by varying the pore pressure relative to a critical value of 26 MPa (Figure 4). In terms of the Mohr diagram, increasing and reducing the pore pressure is equivalent to moving the circle to either side of the failure line. Similarly, Horner et al. (1994) documented the occurrence of earthquakes at the Eagle field near Fort St. John, B.C. due to injection of water for secondary recovery. A delay of ~ 4 years in the onset of seismicity represented the time required to move the effective stress within the reservoir to a state where some faults were at or above the failure line.

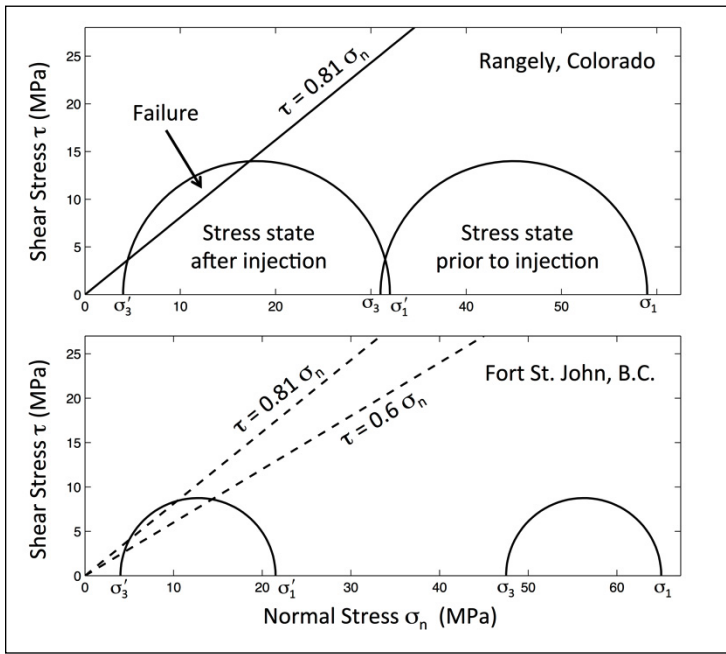


Figure 3. Mohr circle diagrams showing stress conditions at the bottom of injection wells at Rangely Field (Colorado) and the Eagle Field near Fort St. John, (British Columbia). σ_1 and σ_3 represent the unperturbed maximum and minimum in situ stress; σ_1' and σ_3' show effective stresses after hydrostatic stress and fluid injection are considered. Areas of the Mohr circle that are above the failure line are subject to failure due to fault activation. The failure conditions are not known at Fort St. John, so several possibilities are shown. Modified from Horner et al. (1994).

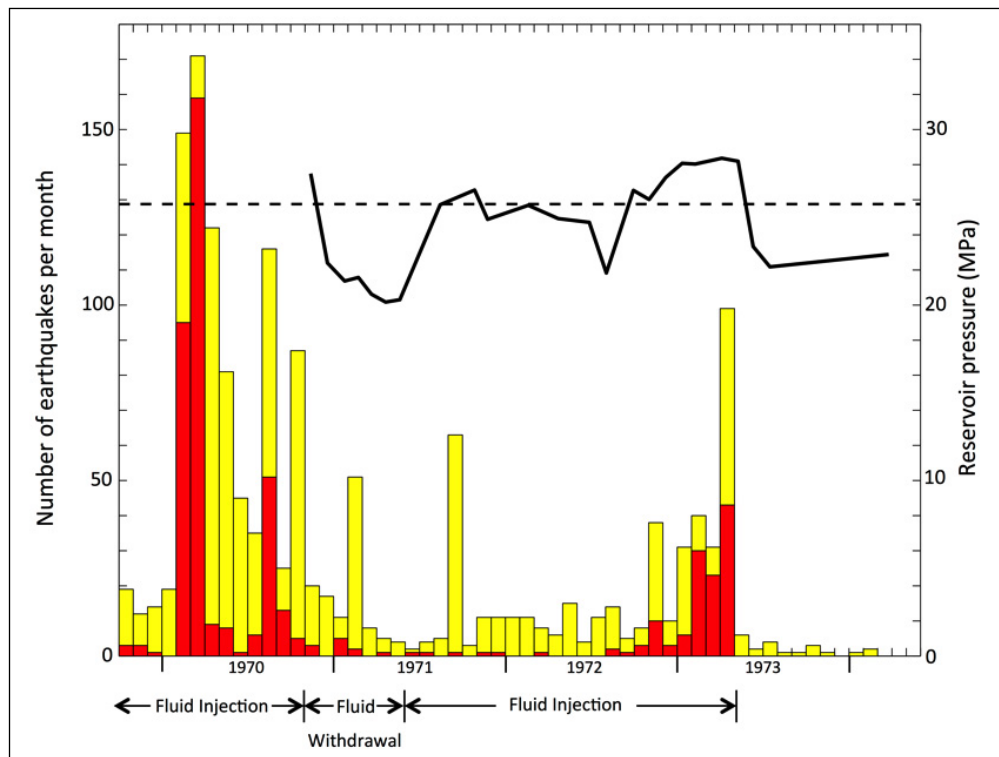


Figure 4. Pressure history (solid black line) and earthquake frequency (bars) at the Rangely field in Colorado, during more than one full cycle of fluid injection and withdrawal. The dashed line shows the calculated critical pressure required for fault activation. Stippled bars show earthquakes within 1 km of the injection wells. Modified from Raleigh et al. (1976).

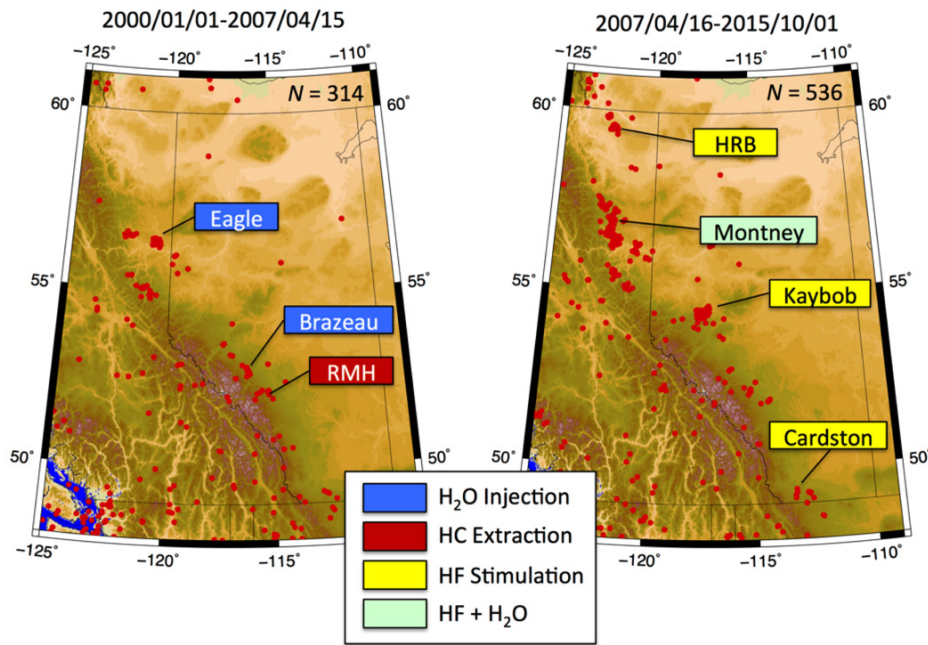


Figure 5. Seismicity map showing $M \geq 2.5$ earthquakes (red circles) in western Canada for two equal periods of time (data source: NRCan online earthquakes catalog). The first time interval is from 1 January 2000 until 15 April 2007, while the second time interval is from 16 April 2007 to 1 October 2015. In the Western Canada Sedimentary Basin, seismicity tends to occur in spatial clusters. During the first time period (left), seismicity clusters at the Eagle field and Brazeau River are associated with water injection, while a cluster near Rocky Mountain House (RMH) is linked to hydrocarbon (HC) extraction. During the second time period (right), studies of seismicity in the Horn River Basin (HRB), Kaybob and Cardston regions indicate an association with hydraulic fracturing (HF); in the Montney region, seismicity has been linked to both water injection and HF.

2.2 Injection-Induced Seismicity in Western Canada

Like the U.S. midcontinent region, induced seismicity in western Canada has increased in recent years (Figure 5). There is evidence that this increased seismicity has taken place as a result of oil and gas operations, including hydraulic fracturing in multi-stage horizontal wells (primarily since 2007). According to the Earthquakes Canada online catalog, for the time period from 1 January 2000 until 15 April 2007 there were a total of 314 $M \geq 2.5$ earthquakes within the region shown in Figure 5. East of the Rocky Mountains, within the Western Canada Sedimentary Basin, earthquakes are mainly localized into clusters of activity, of which several have been investigated. Induced seismicity during the first time interval in Figure 5 has been linked to conventional oil and gas operations. In particular, the Eagle cluster represents induced earthquakes arising from secondary recovery (waterflood) in the Eagle and Eagle West fields (BCOGC, 2014), a continuation of induced seismicity in this area that was studied by Horner et al. (1994). The Brazeau River cluster has been linked to deep disposal of wastewater near the Cordel Field (Schultz et al., 2014), whereas the Rocky Mountain House (RMH) cluster has been interpreted to be caused by gas production at the Strachan D-3A pool (Baranova et al., 1999; Eaton and Mahani, 2015).

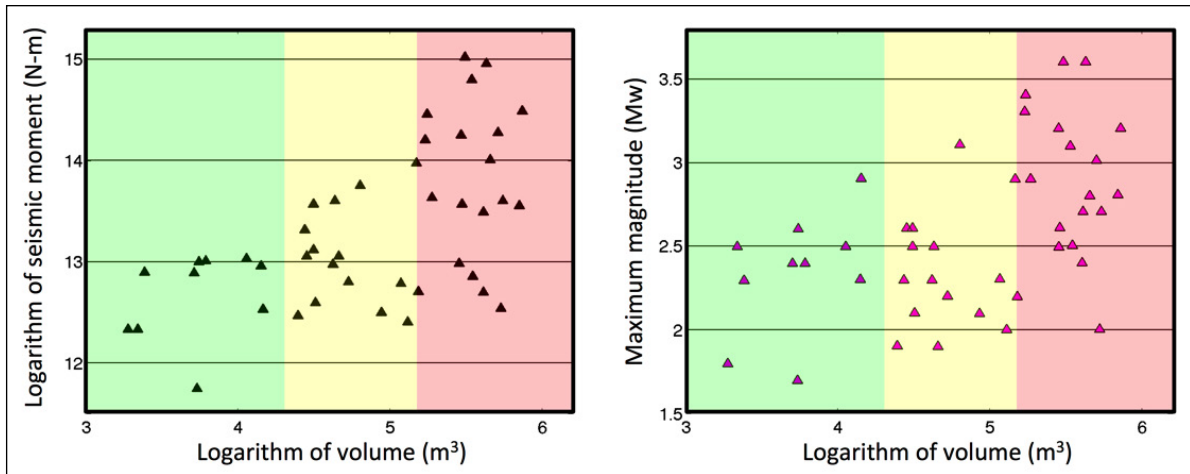


Figure 6. Induced seismicity response to the monthly injected volume of fluid used in hydraulic-fracturing operations in the Horn River Basin. Three levels of response are apparent. For total injected volume less than $\sim 20,000 \text{ m}^3$ (green zone), the maximum magnitude of induced events is ~ 2.5 . For total injected volumes in the range from $\sim 20,000$ to $\sim 150,000 \text{ m}^3$ (yellow zone), a modest increase in maximum magnitude is evident. For months where the total injected volume exceeded $\sim 150,000 \text{ m}^3$ (pink zone), events of magnitude greater than 3 are relatively common. Modified from Farahbod et al. (2015).

In contrast to the earlier time period, recent studies have shown that clusters of seismicity that occurred during the second time interval (April 2007 to October 2015) are associated predominantly with hydraulic fracturing (Figure 5). Clusters of events where a specific association with HF stimulation has been determined include the Horn River Basin (HRB; BCOGC, 2012, Farahbod et al., 2015), the Duvernay play within the Kaybob/Crooked Lake area (Schultz et al., 2015a) and the Alberta Bakken play near Cardston, Alberta (Schultz et al., 2015b). A comparison of maximum magnitude values for induced seismicity with volume of injected fluids each month, aggregated over all HF operations in the Horn River basin, shows a step-like relationship. During months with low injected volumes ($< 20,000 \text{ m}^3$), the maximum induced earthquake magnitude is in the range from $2.5 \leq M \leq 3.0$, whereas for months with high injected volumes ($> 150,000 \text{ m}^3$) the maximum induced earthquake magnitude is in the range from $3.0 \leq M \leq 3.5$. This relationship suggests that there may be a cumulative effect from neighbouring operations.

In the Montney trend in B.C., earthquake clusters during the past few years have been identified that are associated with either HF stimulation or deep disposal of wastewater (BCOGC, 2014). At a smaller scale than Figure 5, the events in the Montney trend have been classified into 7 distinct clusters. The characteristics of seismicity associated with deep wastewater disposal are compared with those for hydraulic fracturing in Table 1.

Table 1. Montney trend: comparison of the characteristics of seismicity triggered by deep wastewater disposal with the characteristics of earthquakes triggered by hydraulic fracturing (from BCOGC, 2014).

PARAMETERS CONSIDERED	EVENTS TRIGGERED BY FLUID INJECTION INTO WASTEWATER DISPOSAL WELLS	EVENTS TRIGGERED BY FLUID INJECTION DURING HYDRAULIC FRACTURING ALONG HORIZONTAL WELLBORES
Injected Volumes	High cumulative volumes can be injected (typically over 100,000 m ³).	Injected volumes vary from 600 to 5,000 m ³ per stage
Flowback	Injected fluid volume is not commonly flowed back from the target formation.	On average, 50 per cent of injected fluid volume is flowed back when a well is put into production.
Injection Point	Fluid injection is at a single point through a set of perforations in a vertical well.	The injection point changes as new hydraulic fracture stages are completed along a horizontal wellbore.
Injection Zone	Injection is into a fair to good quality reservoir or aquifer.	Injection is into an unconventional gas zone to fracture the rock. Fluid left behind after flowback stays either in pre-existing faults or fractures, or in the newly created fracture network.
Distance of Triggered Events	Distant fault movement, several kilometres away from the injection point, can be triggered by injection at the disposal well.	Triggered events are usually close to the injection point as wellbore stages intersect faults. In some cases deeper events, up to 800 m below the injection point (Skoumal, 2014) or events up to 500 m horizontally from the injection point, have been triggered.
Injection pressures	Injection rates and pressures can be controlled to mitigate seismicity. Injection pressure is regulated to remain below formation fracture pressure.	Injection pressures are designed to momentarily achieve breakdown pressure. This is usually well above fault re-activation pressure. Afterward, pressure falls to the lower treating pressure.
Seismic Correlation	Seismicity generally correlates to either injection rate/pressure or volume.	Seismicity does not appear to correlate to either injection rate or volume.

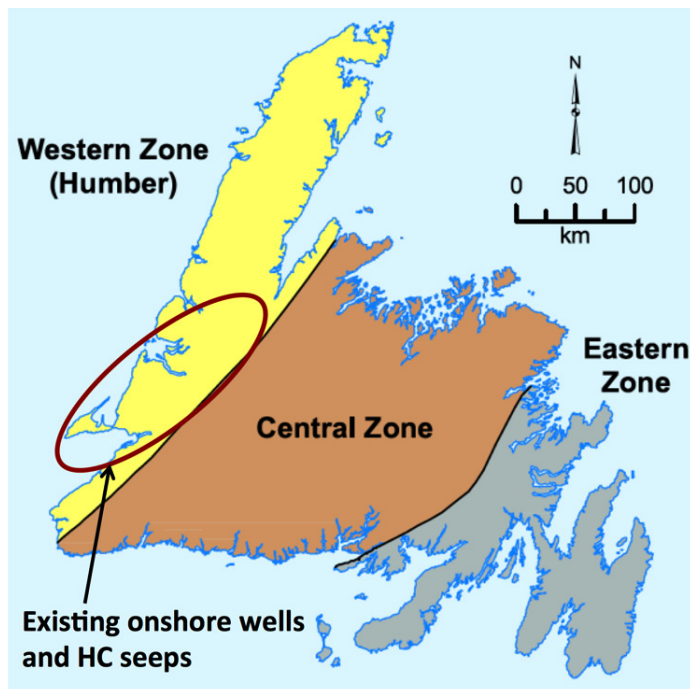


Figure 7. Simplified tectonostratigraphic domains of the Appalachian orogeny in Newfoundland, showing approximate region of existing onshore petroleum wells and hydrocarbon seeps. Modified from Hinchey et al. (2015).

3. WESTERN NEWFOUNDLAND STUDY AREA

The Humber Zone, which extends from western Newfoundland into the northern Gaspé Peninsula, is the westernmost of five major tectonostratigraphic domains of the Canadian Appalachians (Figure 7; Williams, 1979). Within this domain, the Green Point shale forms part of the Middle Cambrian to Early Ordovician Cow Head Group, which was deposited in an abyssal plain along the eastern edge of Laurentia on the northwestern margin of the Iapetus Ocean (Figure 8; Cooper et al., 2001).

This Green Point Formation includes thick, thermally immature to mature sequences composed of excellent hydrocarbon source rocks that could form potential targets for unconventional hydrocarbon development (Hamblin, 2006). Unlike unconventional shale resources that are currently being developed elsewhere in North America, the Green Point shale is not part of a simple, horizontally layered sequence; rather it has been structurally reworked by folding, overthrusting, thickening and thinning (Hinchey et al., 2015). Moreover, where it is exposed at the surface, the Green Point shale contains an interconnected network of fractures that likely served as migration pathways for abundant oil seeps and shows in western Newfoundland (Hinchey et al., 2015). The structural complexity, coupled with a general scarcity of subsurface constraints from seismic and drilling, hamper accurate prediction of the extent, structural configuration and rock characteristics of Green Point shale layers below the surface (Hinchey et al., 2015).

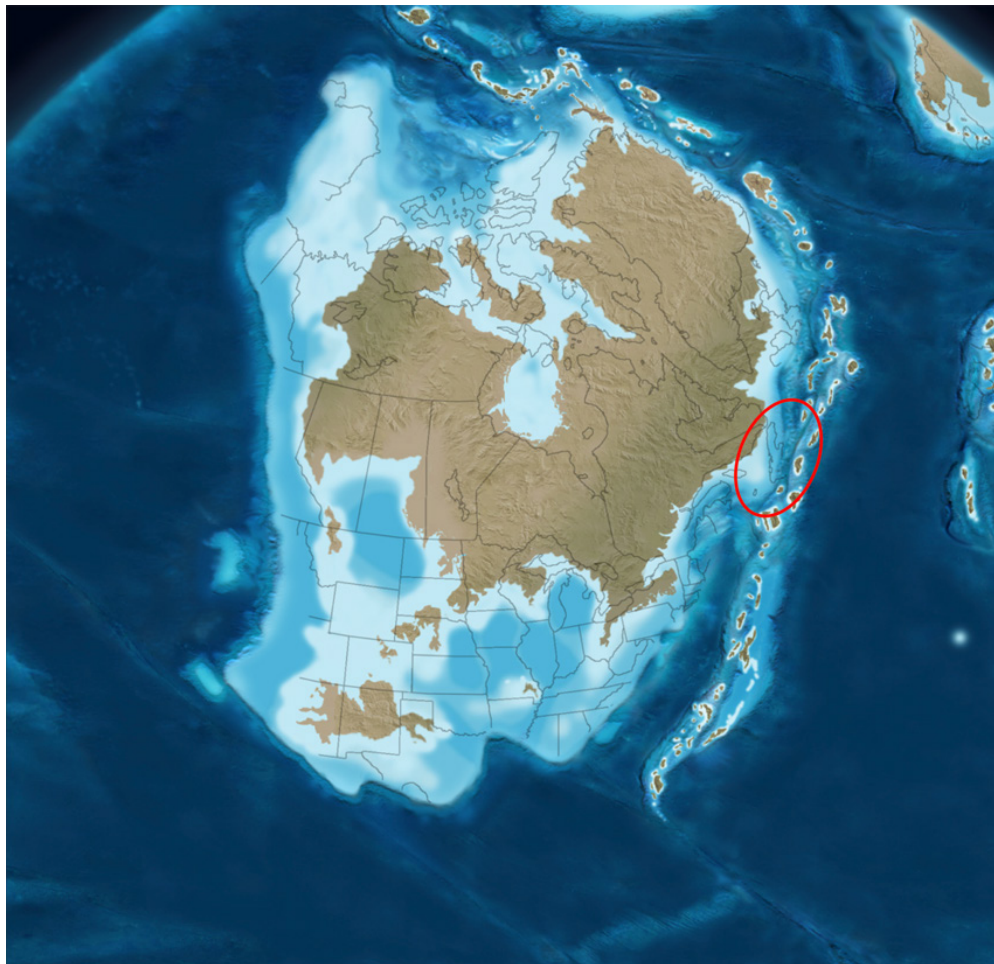


Figure 8. Early Ordovician paleogeography of North America (from www2.nau.edu/rcb7/nam.html), shown in the present-day geographic frame of reference including coastlines and political boundaries. The study area is circled.

On the basis of monitoring by the Canadian National Seismograph Network (CNSN), operated by Earthquakes Canada, western Newfoundland has relatively sparse natural background seismicity. Figure 9 shows a map of currently operating CNSN stations and seismicity in the region since 1 January 2000. In the onshore region of western Newfoundland, there are only 4 events in this nearly 16-year time period. In contrast, the most seismically active zone in this region is the Lower St. Lawrence Seismic Zone, located east of Anticosti Island. As a cautionary note, the sparse distribution of seismograph stations in this area implies that the magnitude of completeness (i.e. the magnitude level at which every earthquake is detected by the network, at a high level of confidence) is likely to be higher than areas where the station distribution is more dense.

A simplified seismic hazard map of Canada is appended to the end of this report (see page 18). This map is based on spectral acceleration at a 0.2 second period (5 Hz), which represents the ground motions that might damage one- or two-storey buildings. Together with a suite of maps at other frequencies, this information provides input to the seismic provisions of the National Building Code of Canada (Mitchell et al., 2010). Western Newfoundland is situated within in the lowest hazard zone, which means that there is less than a 1 per cent chance in a 50-year time period of shaking from an earthquake that is sufficient to cause significant damage in a fraction of this type of building. In the highest hazard zone, the chance of strong ground shaking is increased by a factor of 30.

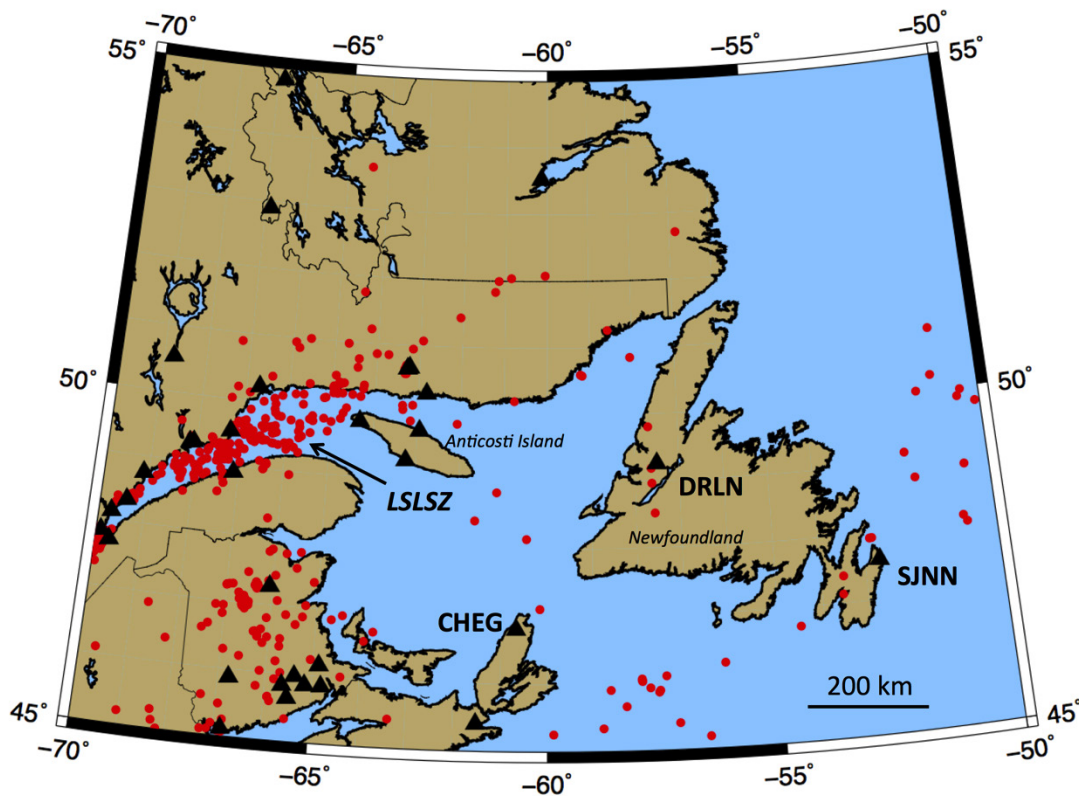


Figure 9. Seismicity map showing $M \geq 2.5$ earthquakes (red circles) in western Newfoundland and environs for the period 2000/01/01 to 2015/11/26. Currently operating CNSN stations are indicated by black triangles. Labeled stations: CHEG denotes Cheticamp, DRLN denotes Deer Lake, SJNN denotes St. John's. LSLSZ denotes the Lower St. Lawrence Seismic Zone. Data source: Earthquakes Canada.

4. CURRENT PRACTICES FOR MONITORING AND MITIGATION

Microseismic events are very small earthquakes, generally having negative seismic magnitudes, that are often associated with hydraulic fracturing (fracking) in unconventional reservoirs. The microseismic cloud can provide a proxy for the extent of the stimulated rock volume (Mayerhofer et al., 2010). Microseismic monitoring techniques have been extensively used by the oil and gas industry to monitor hydraulic stimulation of “tight” (very low permeability or ultralow permeable) hydrocarbon reservoirs; as such, microseismic methods represent one of the technologies underpinning the development of unconventional resources in western Canada (van der Baan et al., 2013).

Microseismic methods can also provide a surveillance technology for monitoring out-of-zone growth of fractures. Figure 10 shows an example of microseismic monitoring data. This dataset was acquired using a downhole toolstring during the hydraulic-fracture stimulation of a tight gas field in central Alberta (Eaton et al., 2014). The treatment used an open-hole packer system, which can be advantageous by making use of natural permeability pathways from existing fracture networks (Reynolds et al., 2012). In this case, upward growth of the microseismic cloud during the stimulation of well A has been interpreted as activation of natural fractures above the treatment zone (Rafiq et al., 2015).

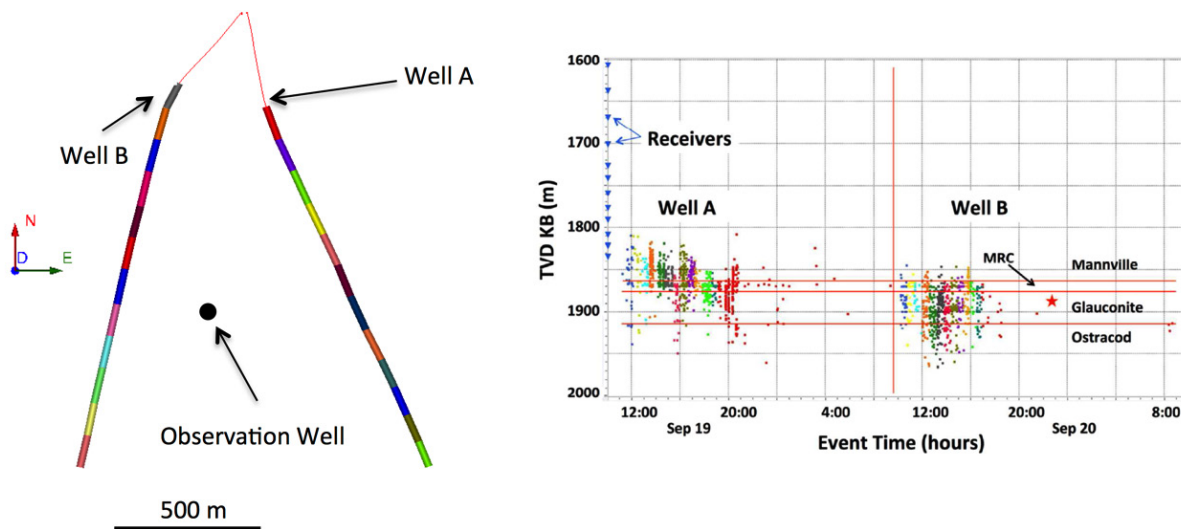


Figure 10. Example of downhole microseismic monitoring during hydraulic fracturing stimulation of a tight sand reservoir in central Alberta. Left: map view of horizontal treatment wells A and B, as well as location of the vertical monitor well. Coloured bars show individual treatment stages. Right: cross section showing locations of 1660 recorded microseismic events ($-3 \leq M \leq -0.5$), coloured by stage. During the early stages of well A, events above the injection zone (Glauconite member of the Cretaceous Mannville Group, indicated by the star) are interpreted as activation of a pre-existing fracture network. MRC denotes Medicine River Coal. From Eaton et al. (2014) and Rafiq et al. (2015).

Anomalous induced seismicity (AIS) represents seismic activity, such as activation of fault movement, that is atypical of hydraulic fracture completions. AIS is generally characterized by significantly higher magnitude levels than the operationally induced microseismicity that is typically observed during a HF completion, such as shown in Figure 10. To date, the highest-magnitude AIS event occurred on 18 August 2015 in the Montney trend; according to Earthquakes Canada, this event measured M_L (local magnitude) 4.6. The Canadian Association of Petroleum Producers has developed an operating practice for its members that “outlines the requirements of companies to assess the potential for anomalous induced seismicity and, where necessary, establish appropriate monitoring

procedures, and procedures to mitigate and respond to AIS in shale gas, tight gas and tight oil development areas” (CAPP, 2013). The operating practice comprises the following steps:

1. **Assess the potential for AIS.** This step is undertaken using available engineering, geologic and geophysical data to characterize the geological setting of the site, including pre-existing faults and historical seismicity. It also includes communication with other operators to share data and experiences, and understanding the local context including the local population and built environment.
2. **Design considerations.** This aspect of the operating practice includes evaluation of wellbore placement to account for local surface and geological conditions, in addition to communication with onsite personnel to recognize and be prepared for the possibility of AIS. It also includes establishment of appropriate monitoring procedures and authorization of onsite personnel to suspect operations if anomalies conditions are experienced or suspected.
3. **Mitigation and response procedures.** This aspect of the operating practice may entail situational assessment, increased monitoring activities, temporary suspension of operations, review of available subsurface data, engineering trials to adjust operating procedures, reporting and discussion with the regulator, and sharing learnings with other area operators. If AIS escalates to site-specific threshold levels that could present harm, onsite personnel are expected to suspend operations immediately and report to the regulator. The company is then expected to consult with the regulator to establish amended procedures for restarting operations.

In relation to the first step, above, a study to assess the potential for AIS in the Moncton sub-basin of New Brunswick was undertaken by Lamontagne et al. (2015). This study included careful examination of recorded earthquakes using available seismograph stations, including the development of an improved velocity model and screening small events to distinguish quarry blasts and road construction from natural or induced earthquakes. Over a 4 year period that included small-scale hydraulic fracture trials, only one earthquake was detected, but it was concluded that this event was unrelated to the well stimulation. A set of criteria developed by Davis and Frohlich (1993) was invoked by Lamontagne et al. (2015) as a way to distinguish natural seismicity from injection-induced seismicity. These criteria can be summarized as a set of seven questions forming a profile of a seismic sequence:

1. Are the events the first known earthquakes of this character in the region?
2. Is there a clear (temporal) correlation between injection and seismicity?
3. Are epicenters near wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic features that may channel flow to the sites of earthquakes?
6. Are changes in well pressures at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

If an affirmative response is found for most of these questions, the sequence can be considered as induced. A traffic light protocol (TLP) is a site-specific, real-time, risk management system with multiple discrete risk levels. Each TLP level is determined using observable criteria and invokes specific actions designed to mitigate risk. In relation to the second and third steps listed in the CAPP operating practice, on 19 February 2015 the Alberta Energy Regulator (AER) issued Subsurface Order #2 (aer.ca/documents/orders/subsurface-orders/SO2.pdf) as a TLP in response to a marked increase in seismicity level within the Kaybob/Crooked Lake area (Figure 5). On the basis of observed associations to hydraulic fracturing, AER subsurface order #2 is applicable only to completions within the Duvernay zone in this region. Notwithstanding the site-specific application, these provisions provide a useful TLP template for other regions where vulnerability (remote region with relatively sparse population density) is similar. Broadly similar requirements exist in other jurisdictions, including British Columbia.

Subsurface order #2 calls for operators:

- to implement a plan to monitor for, mitigate, and respond to induced seismicity, and to submit the plan to AER upon request;
- to ensure that seismic monitoring is sufficient to detect a 2.0 local magnitude (M_L) seismic event within 5 kilometres (km) of any affected well;
- to report immediately any seismic event of 2.0 M_L or greater within 5 km of the affected well, and then to implement mitigation procedures in a manner that eliminates or reduces further seismic events from the hydraulic fracturing operation;
- to report immediately any seismic event of 4.0 M_L or greater within 5 km of the affected well, and then to cease hydraulic fracturing operations at the affected well and return the well to a safe state

Finally, hydraulic fracturing operations that are suspended under this order can only be recommenced with written consent of the AER. Given typical focal depths and site conditions for AIS, according to T. Shipman (pers. comm., 2015), the choice of M_L 2.0 and M_L 4.0 as “yellow” and “red” TLP thresholds was based upon a view that M_L 2.0 corresponds approximately to the minimum event magnitude that may be felt at the surface and M_L 4.0 corresponds approximately to the minimum event magnitude that could result in superficial damage to built structures.

5. GROUND MOTIONS AND INTENSITY

Magnitude constitutes a quantitative measure of the size of an earthquake based on seismograph recordings. Several magnitude scales have been defined, but the most commonly used are (1) local magnitude (M_L), also referred to as “Richter magnitude,” (2) surface-wave magnitude (M_s), (3) body-wave magnitude (m_b), and (4) moment magnitude (M_w) (USGS, 2015). On the other hand, *intensity* is a scale used to quantify the effects of earthquake ground motion on the natural or built environment (NRCan, 2015). In North America, intensity is usually quantified using the Modified Mercalli Scale (Table 2).

Table 2. Modified Mercalli Intensity Scale (earthquake.usgs.gov/learn/topics/mercalli.php)

Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

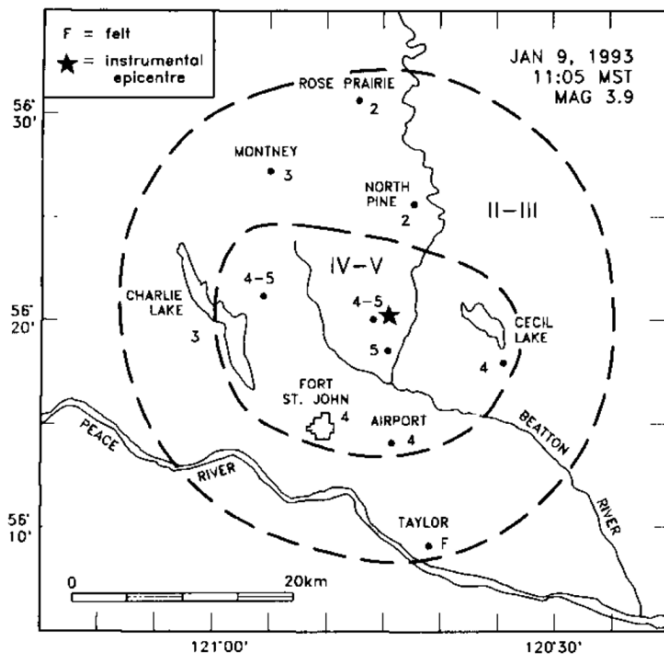


Figure 11. Isoseismal map showing Modified Mercalli Intensity (MMI) for the 9 January 1993 M3.9 event in the Eagle Field near Fort St. John, B.C. Focal depth is 5 km. From Horner et al., 1994.

Figure 12. Observations of the fall-off in Modified Mercalli Intensity (MMI) level with epicentral distance for the 31 December 2011 induced M3.9 earthquake near Youngstown Ohio. The focal depth of this event was 5 km. From Hough (2014).

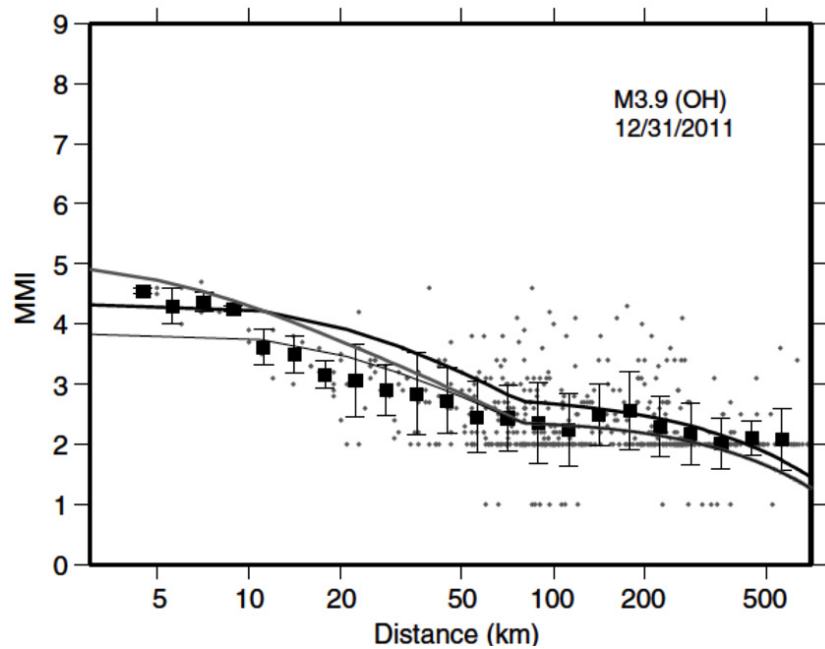


Figure 11 shows an isoseismal intensity map for the 9 January 1993 M3.9 earthquake in the Eagle Field near Fort St. John, B.C. (Horner et al., 1994). This event produced intensities levels up to MMI V within a few km of the epicentre, indicative of moderate shaking that is likely to have been felt by most people. Figure 12 shows the decay in intensity with distance for a M3.9 earthquake on 31 December 2011 near Youngstown, Ohio. This event produced similar intensity levels in the epicentral region, and was weakly felt by some people to distances of up to 500 km.

Conclusions and Recommendations:

The following questions have been considered in light of the foregoing information.

1. What is required to establish a reasonable baseline of the existing level of felt seismicity before any significant subsurface activity has taken place?

In view of the seismic monitoring that has already been undertaken in New Brunswick (Lamontagne et al., 2015), a prudent approach would be to upgrade existing seismograph network capabilities for a period of several years before any significant subsurface activity has taken place. This would result in improved detection capabilities for background seismicity and thus would provide a higher margin of public safety by either assuring that the background seismicity levels are indeed low, or enabling the identification of potentially seismogenic structures that should be avoided during development.

2. Do hydraulic fracturing (and production) activities, in general, lead to measurable seismic events that can impact communities in terms of infrastructure damage of any kind (Mercalli Modified Intensity of IV or higher)?

The ground-motion intensity studies by Horner et al. (1994) and Hough (2015), applied to earthquakes with magnitude near to the M_L 4.0 "red" threshold magnitude in the recently introduced traffic light protocol in Alberta, show that MMI IV or higher is possible from AIS. There have been several recent events in Alberta and B.C. that are of similar or greater magnitude compared to the events depicted in Figures 11 and 12.

3. Could the surface intensity and frequency of induced seismic events be such that a high level of human annoyance and concern be expected, or are such events likely to be rare and below the threshold of common detection (Mercalli Modified Intensity of I or lower).

Many studies have shown that induced earthquakes that are felt are rare events (e.g. NAS 2012). It is therefore likely that hydraulic fracturing could proceed with no incidence of induced seismicity, as seen during small-scale hydraulic fracturing tests in New Brunswick (Lamontagne et al., 2015). However, there is no guarantee of this and events may be triggered by hydraulic fracturing with intensity and/or frequency to cause annoyance and concern.

4. Is the geology of western Newfoundland distinct from and more at risk than other areas with respect to the potential triggering of induced seismicity as the result of hydraulic fracturing? (e.g. exceptionally large in situ differential stresses, sensitive ground conditions leading to greater surface intensity)

More data is required to determine if there are any specific site conditions in western Newfoundland that could amplify surface intensity. It is worth noting that the USGS National Earthquake Hazards Reduction Program (NEHRP) has defined site classes that depend on the average shear velocity in the top 30 m, such that high velocity sites (e.g. those on bedrock) have reduced ground motion amplification relative to those with low velocity (e.g. those on very soft sediments). The folding and faulting characteristics of the Green Point shale are distinct from other unconventional plays in North America, which tend to be in areas that are flat-lying and undeformed. This consideration suggests that targeted geomechanical modeling may be warranted to address this issue. The discontinuous nature of the formation may represent more of an economic risk than a seismic risk, since the maximum magnitude is related to the fault area

5. What actions/regulations/best practices can be applied to hydraulic fracturing activities to minimize induced seismicity and the felt intensity at the surface risks?

The CAPP (2013) operating practice for Anomalous Induced Seismicity, together with the traffic light protocol defined by AER's subsurface order #2 provide very effective guidance for risk management from induced seismicity.

To summarize, the Traffic Light Protocol colours of green, yellow and red would indicate the following:

GREEN (Go)

No earthquake felt. This would correspond to no event, or to an event with a local magnitude M_L of 2 or smaller, and a Modified Mercalli Intensity (MMI) scale value of II or smaller. **Action:** No action need be taken.

YELLOW (Caution)

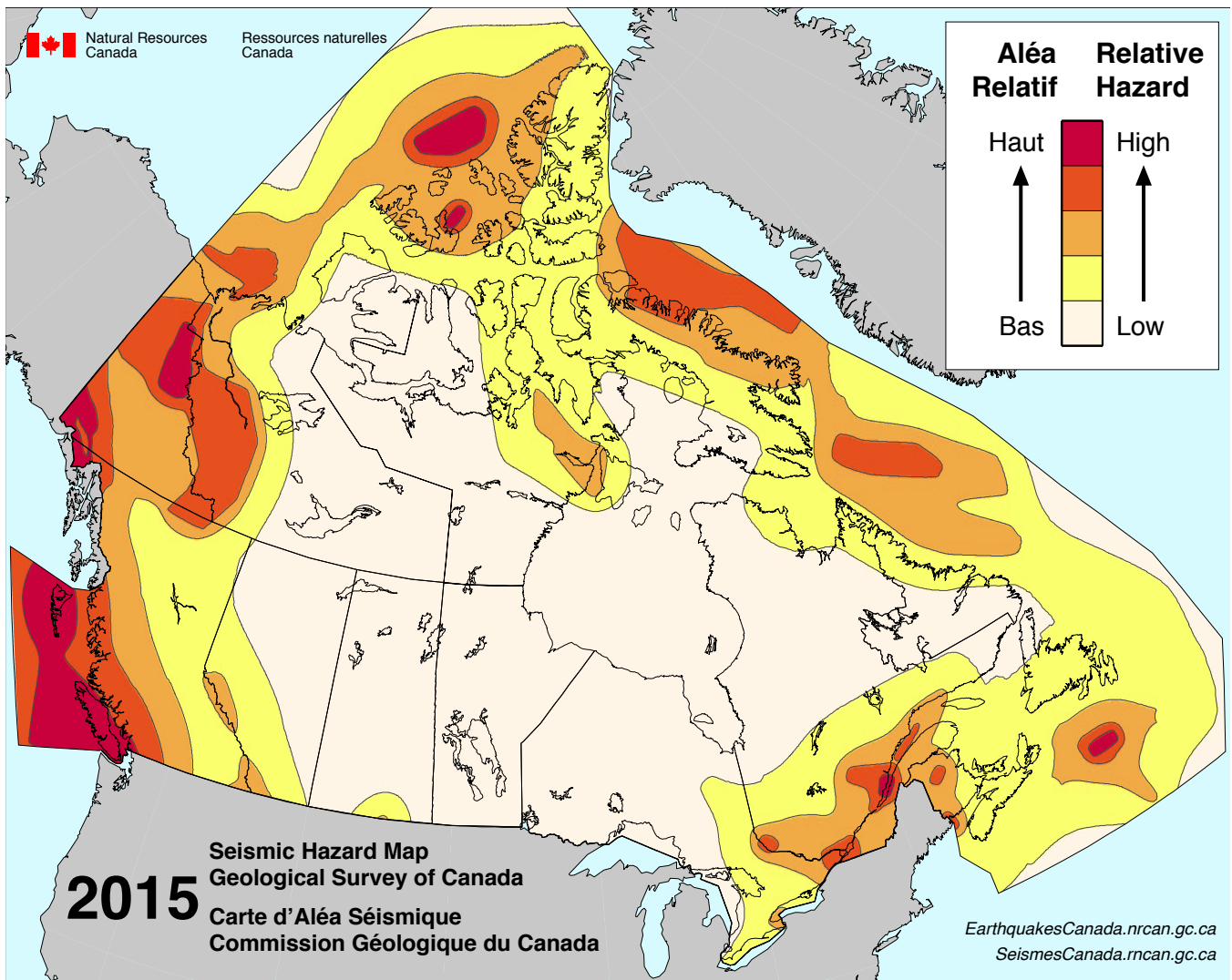
An earthquake event that may be felt at the surface. This would correspond to an event with a local magnitude M_L between 2 and 4, and a Modified Mercalli Intensity scale value between II and IV. An event at the low end, i.e., of local magnitude $M_L = 2$, would be barely felt, whereas an event at the high end, i.e., of local magnitude $M_L = 4$, would likely be felt by many (windows and items on shelves may rattle slightly). **Action:** Inform the provincial energy regulator, and put into action a response plan that would reduce or eliminate further seismic activity due to the fracking operation.

RED (Stop)

An earthquake event that is felt by many, and may produce damage to infrastructure. This would correspond to an event with a local magnitude M_L of 4 or greater, and a Modified Mercalli Intensity scale value of IV or greater. For an event at the low end, i.e., of local magnitude $M_L = 4$, the damage would be slight. **Action:** Inform the provincial energy regulator, stop fracking operations immediately, and return the well to a safe state.

Further to these points, the following measures are recommended to the Hydraulic Fracturing Review Panel:

1. The use by the operators of microseismic monitoring methods, especially during initial hydraulic fracturing tests, is recommended to verify the effectiveness of operations and containment of fractures. A summary report of the monitoring results should be submitted to the provincial regulator.
2. Enhancements should be made to seismograph network coverage in western Newfoundland in order to improve monitoring capabilities for baseline seismicity. Given the current station distribution, at least one new station north and east of Anticosti Island would provide a significantly better geometry for event detection. Since several years of data may be necessary to acquire baseline information, it is recommended that this should take place early in any development plan.
3. Implementation of a traffic light protocol for induced seismicity monitoring during treatment should be considered. The provisions of AER subsurface order #2 provides a well documented template.
4. A geomechanical investigation that considers all available stress data and realistic structural models should be undertaken to address site-specific issues that pertain to the unique structural environment of the Green Point shale.
5. In the event that deep disposal of waste fluids is considered as part of a future development plan, monitoring of pore pressure in the disposal formation should be undertaken prior to and during injection. This would enable the application of principles derived from the study of Raleigh et al. (1976) at the Rangely field to seismic risk management from wastewater disposal.



A simplified seismic hazard map of Canada.

GLOSSARY OF TERMS

Anomalous induced seismicity: Seismicity that would not normally occur when performing hydraulic fracture completions, such as activation of slip on a fault (CAPP, 2013).

Class II injection well: Defined by the U.S. Environmental Protection Agency (EPA) as wells that inject fluids associated with oil and natural gas production. Most of the injected fluid is salt water (brine), which is brought to the surface in the process of producing oil and gas. Well types include disposal wells, enhanced recovery wells and hydrocarbon storage wells (EPA, 2015).

Disposal well: A type of class II injection well used to inject brines or other fluids associated with the production of hydrocarbons. In the U.S., disposal wells represent about 20% of 151,000 class II injection wells (EPA, 2015).

Effective stress: The normal stress on a fault plane reduced by the fluid pressure (NAS, 2012).

Focal depth: Depth below the surface of an earthquake's focus.

Focus: The point in the subsurface where earthquake rupture initiates.

Ground motion prediction model: A relationship that predicts the amplitude of a specified ground-motion parameter (e.g. PGA, PGV) as a function of magnitude, distance, focal depth and site conditions (Majer et al., 2012).

Hazard: The probability that a given event will produce damage or harm. Hazard (H) is related to Risk (R) and Vulnerability (V) by the risk equation: $R = H \cdot V$.

Hydraulic fracturing (strict definition): Injecting fracturing fluids into a rock formation at a force exceeding the fracture pressure of the rock, thus induces a network of fractures through which oil or natural gas can flow to the wellbore (CCA, 2014).

Induced seismicity: Seismic events that can be attributed to human activities (BCOGC, 2012; CAPP 2013). Examples of activities that can cause induced seismicity include geothermal development, mining, reservoir impoundment and subsurface fluid injection and withdrawal.

Intensity: The effects of earthquake ground motion on the natural or built environment. In North America, intensity is usually quantified using the Modified Mercalli Scale. Intensity is specified in Roman numerals and ranges from I (not felt except by a very few under especially favourable conditions) to XII (total damage) (NRCAN, 2015).

Magnitude: A quantitative measure of the size of an earthquake based on seismograph recordings. Several scales have been defined, but the most commonly used are (1) local magnitude (M_L), also referred to as "Richter magnitude," (2) surface-wave magnitude (M_s), (3) body-wave magnitude (m_b), and (4) moment magnitude (M_w) (USGS, 2015).

Operationally induced seismicity: Defined here as seismicity that typically occurs when performing hydraulic fracture completions. The distribution of operationally induced events is often used as a proxy for the extent (height, length) of a hydraulic fracture.

Seismic moment: A measure of the size of an earthquake based on the product of the rupture area, the average amount of slip, and the force that was required to overcome fault friction. Seismic moment can also be calculated from the amplitude spectra of seismic waves. (USGS, 2015).

Seismicity: Earthquakes or other seismic activity within a given area.

Triggered seismic event: A seismic event that is the result of failure along a pre-existing zone of weakness, e.g. a fault that is already critically stressed and is pushed to failure by a stress perturbation from natural or manmade activities (Majer et al., 2012).

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