Investigation of Observed Seismicity in the Montney Trend

December 2014

BC Oil & Gas COMMISSION

ABOUT THE COMMISSION

The BC Oil and Gas Commission is the single-window regulatory agency with responsibilities for regulating oil and gas activities in B.C., including exploration, development, pipeline transportation and reclamation.

The Commission's core services include reviewing and assessing applications for industry activity, consulting with First Nations, cooperating with partner agencies, and ensuring industry complies with provincial legislation and all regulatory requirements. The public interest is protected by ensuring public safety, respecting those affected by oil and gas activities, conserving the environment, and ensuring equitable participation in production.

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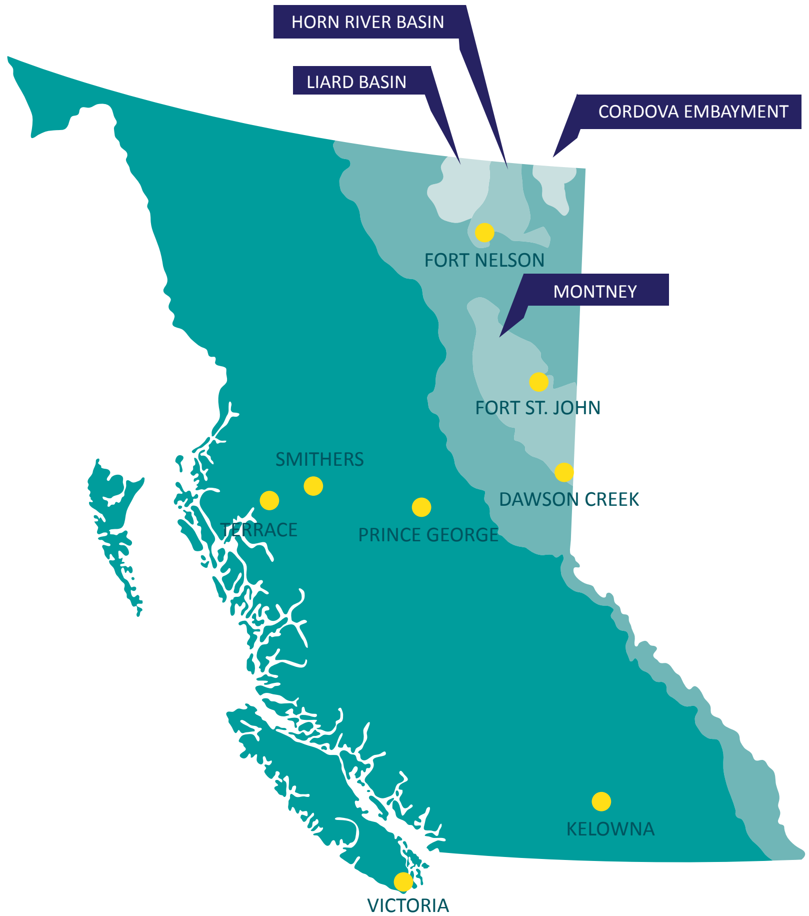

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Terms Used in this Report

Cluster
A group of seismic events linked to a common trigger mechanism. Usually these events are closely spaced in both area and time.

Dense Seismograph Array (Dense Array)
A localized array of seismographs with a minimum of three stations, deployed to monitor for induced seismicity in a particular area. These arrays are capable of locating event hypocentres to within 500 metres and recording magnitudes down to Magnitude 1.0.

Hypocentre
The point within the earth where an earthquake starts. Hypocentres include both the horizontal surface location and depth of an event.

Induced Seismicity
Earthquakes (events) resulting from human activity.

Microseismic
Describes both the recording and processing of very low magnitude events produced by hydraulic fracturing. Typically, these events range from -3.0 to 0.5 M_L.

Richter Magnitude (M_L) and Moment Magnitude (M_w)
Seismic events reported to the Commission are in either M_L or M_w magnitudes. Both values are approximately equivalent in northeast B.C. This report uses M_L.

Seismicity
Recorded earthquakes caused primarily by fault movement. Typically refers to events greater than 0.5 M_L.

Stage
A hydraulically fractured interval along a horizontal wellbore. Each "stage" is isolated prior to the injection of fluids to hydraulically fracture the reservoir rock. Unconventional wells in the Montney average about 14 hydraulically fractured stages per wellbore.

ABOUT THE MONTNEY TREND

The Montney Trend (Montney) is a 29,850-square-kilometre underground siltstone formation that stretches from the B.C.-Alberta border near Dawson Creek 200 kilometres (km) northwest to the B.C. Rocky Mountain foothills (Figure 1). Its depth ranges from 1,200 to 3,200 metres (m) below the surface. Overall the Montney represents about 37 per cent of B.C.'s recoverable natural gas reserves at15.7 Trillion Cubic Feet. A cross-section diagram of the Montney is shown in Appendix 1.

Unconventional gas development in the Montney began in the mid-2000s, and by 2014 the region has become B.C.'s single most important natural gas producing area, accounting for 56 per cent of the province's daily production, with 75 per cent from unconventional sources.

The Montney currently has over 1,700 active natural gas wells, nearly all of which are horizontal wells drilled after 2005. In 2013, 80 per cent of wells drilled in B.C. were completed in the Montney, rising to 89 per cent by the end of August 2014. Daily production levels are presently 2.3 Billion Cubic Feet/day, and significant gas liquids and condensates are also being generated.

In order to support unconventional gas development in the Montney, there has been an increase in demand for wastewater disposal capacity. Since 2005, the number of active wastewater disposal wells has increased from 89 to 104, and disposal volumes have increased 60 per cent over the same period (Figure 2, next page). Much of the increase is attributable to disposal of flowback fluids from hydraulic fracturing operations. In B.C., water used for hydraulic fracturing must ultimately be disposed underground at an approved wastewater disposal well.

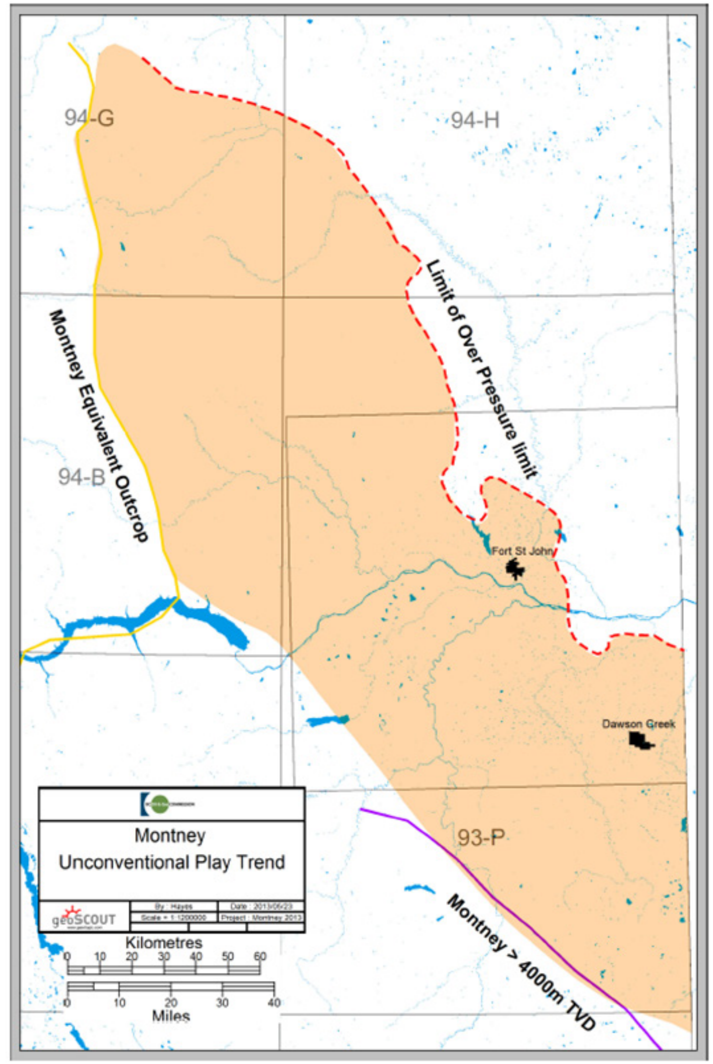
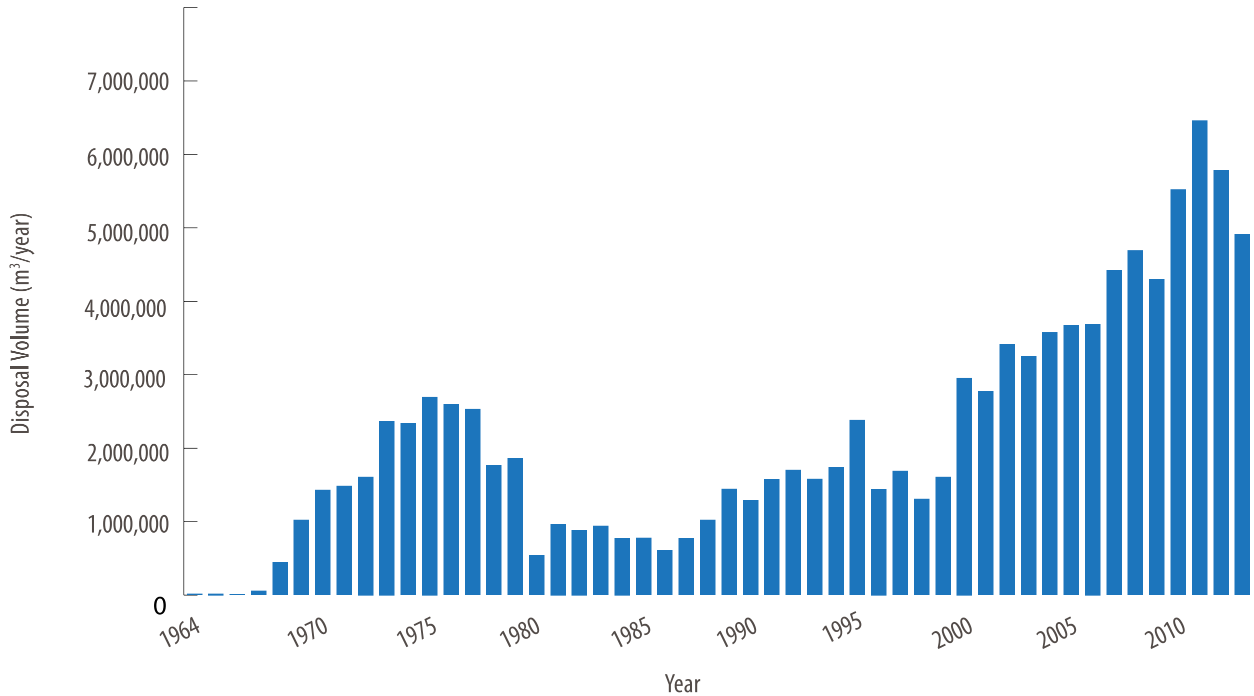


Figure 1 – The Montney Trend

Figure 2 – Annual Water Disposal Volumes for Northeast B.C.



Executive Summary

In 2012 the BC Oil and Gas Commission (Commission) released the results of its investigation into induced seismicity in the Horn River Basin. The report determined low-level seismic activity (2.2 to 3.8 M_L) was caused by fluid injection during hydraulic fracturing near pre-existing faults.[1] As noted in the 2012 report, the Commission distinguishes between the microseismic events caused by fracturing the rock during the hydraulic fracturing process (-3.0 to 0.5 M_L) and induced events caused by fault movement (events greater than 0.5 M_L).

As a result of recommendations from the investigation (Appendix 2), eight new seismograph stations (funded by the Commission, Geoscience BC, and the Canadian Association of Petroleum Producers) were added to the existing two Canadian National Seismograph Network (CNSN) stations to provide more accurate detection and location capabilities. Six went online in August 2013, and two in November 2014. With the new stations the CNSN began recording many more lower magnitude events than previously recorded, enhancing the Commission's ability to track seismicity. This report's primary focus is on the investigation into events recorded between August 2013 and October 2014 in the Montney.

The investigation found that during this period 231 seismic events in the Montney were attributed to oil and gas operations – 38 induced by wastewater disposal and 193 by hydraulic fracturing operations. None of the recorded events resulted in any injuries, property damage or loss of wellbore containment.

The report finds that events ranging from 2.5 to 4.4 M_L may produce actual fault movements in the range of one millimetre to centimetres within the target formation and at depth. Data also shows there is a higher occurrence of induced seismicity in certain areas due to the presence of pre-existing, stressed faults that are susceptible to reactivation.

As detailed in this report, the Commission identified five areas in the Montney where seismic events appear to have been triggered by hydraulic fracturing operations. Data shows that only 0.15 per cent of wellbore stage completions during the investigation period resulted in seismic events felt at surface.

Two additional areas of observed seismicity appear linked to two wastewater disposal wells. There are 104 active disposal wells in B.C.

1 Since release of the Horn River Basin Observed Seismicity Investigation report in August 2012 the Horn River and Liard Basins have been seismically quiet. Only four new seismic events have occurred in the basins over the past two years. This lack of recorded events, even after the upgrade to the CNSN, is believed to be due to a decline in the number of high-volume hydraulic fracturing operations.

Types of Induced Seismicity

Two types of induced seismicity are discussed in this report, wastewater disposal induced seismicity and hydraulic fracturing induced seismicity. In both types, the trigger mechanism is essentially the same – fluid is injected into or near an underground fault at high enough pressures for driving stresses to overcome normal stresses, resulting in fault movement. Although the trigger mechanism is the same, there are significant differences (Table 1).

Table 1 – Comparison of wastewater disposal induced seismicity to hydraulic fracturing induced seismicity

Comparison	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.

Seismic Monitoring in Northeast B.C.

The CNSN regional array is a reliable tool for locating new seismic event clusters and helping identify operations that may be triggering induced events. However, due to its spacing, it is incapable of providing accurate depths for events occurring in the upper crust.

To overcome this, dense seismograph arrays are used to provide more detailed locations. Dense array deployments collect accurate event locations and depths, and reliably record a wide range of magnitudes and detailed seismological data to monitor and mitigate induced seismic events.

The Commission ordered the deployment of three dense arrays in 2013 at Altares, Graham and Doe-Dawson (Figure 3). Dense arrays are required to have hypocentre resolution to within 500 m and magnitude detection capability to 1.5 M_L. Industry operators in northeast B.C. also voluntarily deployed several dense arrays, including one in Septimus and an 18-station dense array in the northern Montney.

Bi-weekly reports are submitted by operators of dense arrays ordered by the Commission, as well as from several of the arrays independently deployed by operators. The reports include dates, times, locations, depths, and magnitudes of all recorded events.

Responding to Seismic Events

The Commission tracks northeast B.C. seismic events through the Natural Resources Canada (NRCan) website and industry-owned dense seismographic arrays. Events reported by the public are also investigated.

The Commission compares these seismic events alongside the locations of oil and gas operations, including hydraulic fracturing. If there is a temporal and geographic similarity, operators are contacted with a request for more data, including stage times and parameters, and microseismic and dense seismograph array monitoring data if available.

Action is then taken if required, and steps may include requesting the deployment of dense seismograph arrays, or changes to hydraulic fracturing parameters, which can include limiting well pressures or suspending operations.

Seismic Event Summary and Analysis

The Commission identified five areas within the Montney where seismic events were linked to hydraulic fracturing operations (Figure 3). Two additional areas where seismicity has been observed (Graham and Pintail) appear linked to deeper, sub-Montney wastewater disposal and not hydraulic fracturing.

From Aug. 1, 2013 to Oct. 10, 2014, NRCan recorded 231 events in the Montney, ranging from 1.0 to 4.4 M_L, attributed to oil and gas activities. Thirty-eight of these events (1.2 to 2.9 M_L) were triggered by wastewater disposal wells at Graham and Pintail (Figure 4, next page). Another 193 events (1.0 to 4.4 M_L) were triggered by hydraulic fracturing operations in the Montney (Figure 5, next page). Event cluster maps with hydraulic fracturing times are shown in Appendix 3, and a summary of the clusters is detailed in Tables 2 and 3 (Page 12).

Currently 450 wells are completed in the Montney each year. These wells average 14 hydraulic fracture stages per wellbore, totaling about 7,500 hydraulic fracture stages for the investigation period. Injected volumes of hydraulic fracturing fluid range from about 700-3,500 m^3 per stage, depending on area and operator. During the investigation period, hydraulic fracturing operations triggered 193 induced events. Therefore, approximately 2.6 per cent of pumped stages triggered events.

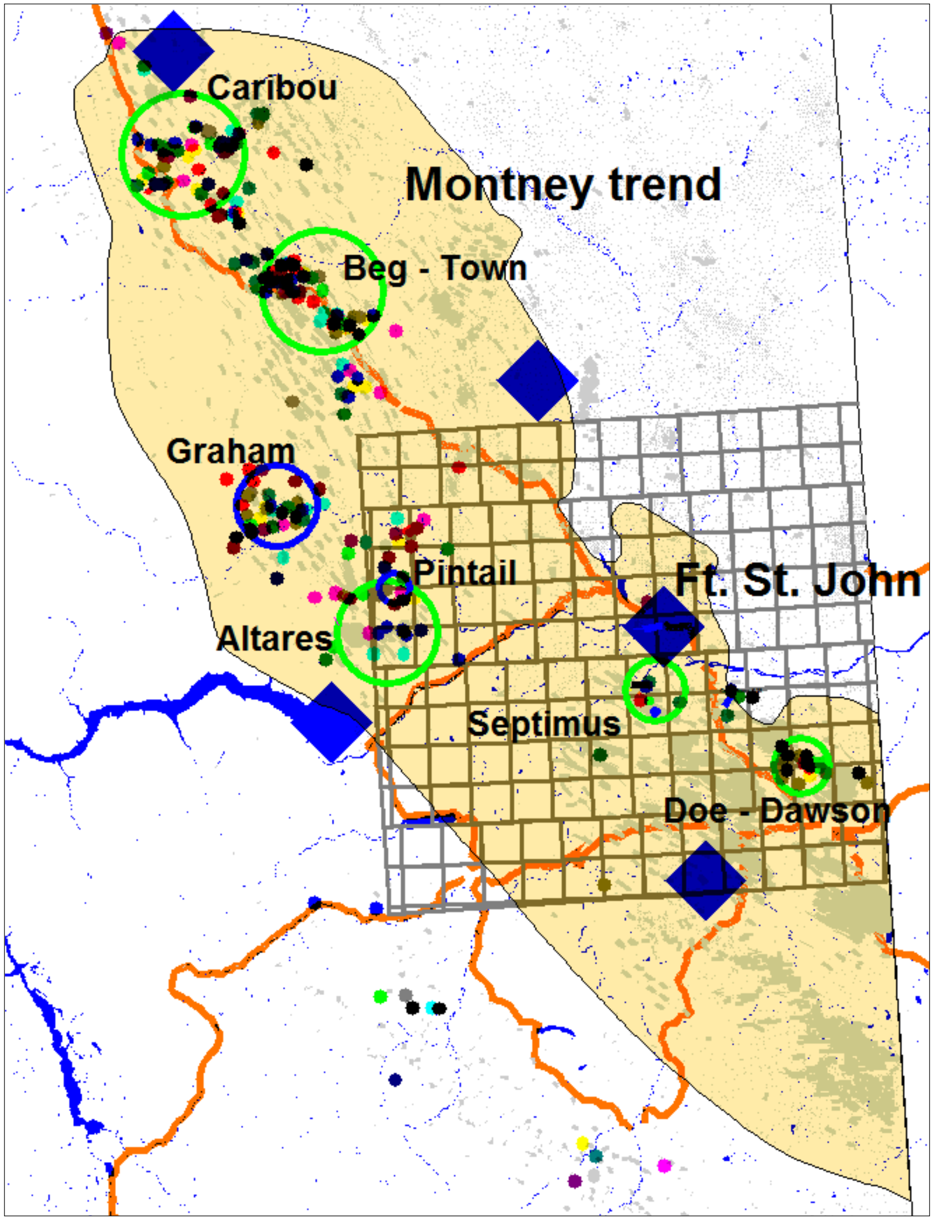


Figure 3 – The green circles on this map denote areas with hydraulic fracturing induced seismic events, and coloured dots represent NRCan events for Aug. 14, 2013 to Nov. 1, 2014. The two blue circles are wastewater disposal well induced seismicity areas. The blue diamonds are CNSN seismograph stations.

For wastewater disposal wells, of the 104 active in the province, only two have been linked to induced seismicity.

Recorded ground motions associated with these events shows they are below damage thresholds for surface structures and no injuries or property damages were reported. Data shows there is a higher occurrence of induced seismicity in the disturbed belt of the Rocky Mountain foothills and in proximity to the Fort St. John Graben complex. This is attributed to the presence of pre-existing, stressed faults that are susceptible to reactivation.

Hydraulic fracturing in the Lower Montney appears more prone to induced seismicity, although two events greater than 3.5 M_L have been recorded in the Upper Montney. Fluid injection at the Lower Montney level may reactivate older, underlying structures more readily than Middle and Upper Montney fracture stimulations. So far, dense array data has shown fault re-activation induced by hydraulic fracturing can occur within the Montney target zone or up to 700 m below the Montney as a result of fluid injection. On the horizontal plane, re-activation can occur within 100 to 400 m of the injection point.

Several instances of casing deformation have occurred within the horizontal portion of shale gas wellbores, but there was no loss of integrity with the wells and no impact on the vertical portions of wellbores.

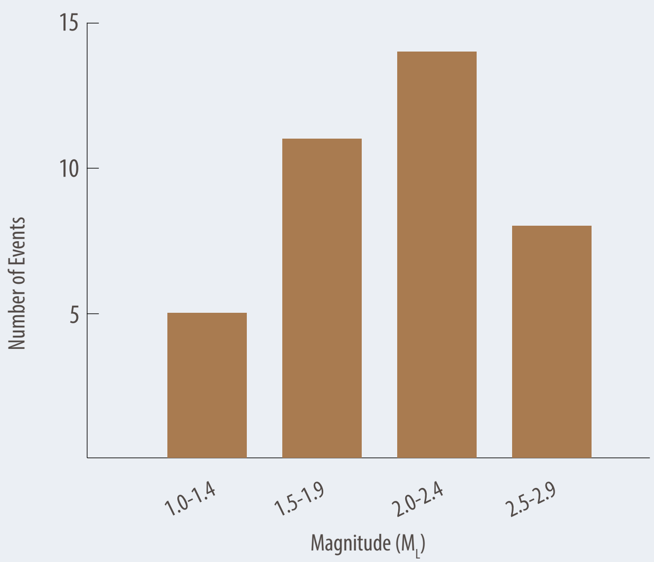


Figure 4 – Magnitude range frequency for wastewater disposal wells induced events

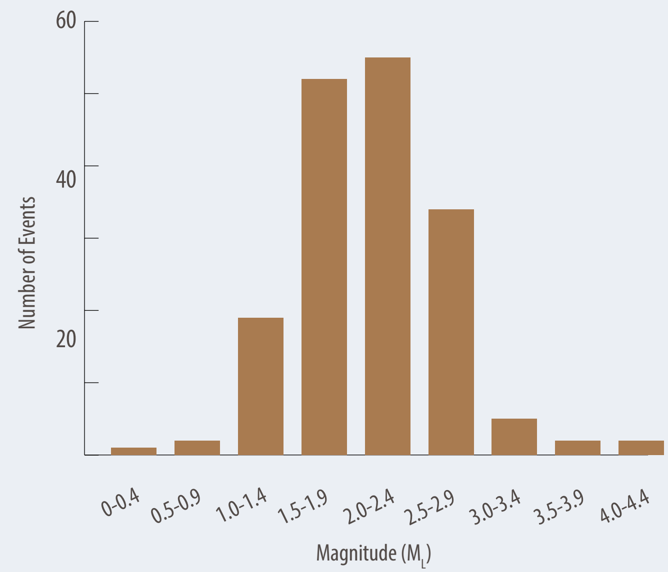


Figure 5 – Magnitude range frequency for hydraulic fracture induced events

Preliminary results indicate induced events triggered by injection at wastewater disposal wells may be mitigated by reducing disposal rate and pressure. Commission water disposal project approvals contain conditions limiting formation pressure to 120 per cent of original formation pressure.

Investigating Seismic Events

Determining whether a seismic event is induced is done by considering background seismicity, distance from hydraulic fracturing or disposal operations, and the timing of the event compared to the timing of operations.

As an example, for the Oct. 18-28, 2013 Doe-Dawson cluster (Appendix 3), there were no events previously recorded by the CNSN in that area. Ten events were located by the CNSN within five km of the 5-5-80-15W6 pad. These events were time coincident with hydraulic fracturing operations at the pad. There were no other active hydraulic fracturing or disposal operations within a five-km radius of the 5-5-80-15W6 pad.

Dense arrays provide precise event epicentres and depths, and often delineate the active fault. A strong case for induced seismicity can be made when mapped dense array hypocentres and event times are compared to hydraulic fracturing operational times.

Felt events have also been useful in verifying CNSN or dense array epicentres. Events greater than 3.5 M_L are often felt at the wellpad site with felt intensity dissipating away from the epicentre.

Table 2 – Summary of Montney Induced Seismic Event Clusters (Maps and graphs shown in Appendix 3)

Area	Cluster	Number of Events	Magnitudes	Dense Array (DA) coverage	Felt (Mercalli Scale)	Coincidence with hydraulic fracturing (HF)	Coincidence with water disposal operations	Distance from operations triggering events
1. Doe-Dawson	Oct. 18-28, 2013	16 NRCan events	1.2 to 2.8 M_L	Not at time of events; DA ordered	Yes – 6 felt events (III-IV)	All events occurred during or within 2 hours of HF	No evidence of wastewater induced activity	Within 3 km
2. Septimus	May 28, 2013	8 NRCan events	2.1 to 4.2 M_L	Not at time of events; DA ordered	Yes (III-IV)	All events occurred during or within 2 hours of HF	1 km from disposal well, cumulative 4,800 m^3 as of May 28. No evidence wastewater was trigger mechanism	Within 3 km
3. Altares	Nov. 5-6, 2013	14 DA events	1.2 to 2.2 M_L	Yes; DA monitoring HF	Yes (III-IV)	4 events within 2 hours of HF, 3 events during HF and 7 events within 7.5 hours of HF	No	Within 1 km
4. Beg-Town	Oct. 7-26, 2013	6 NRCan events	1.8 to 3.0 M_L	Not at time of events; DA now in place	None reported	Events vary from 2 hours to 12 days post-HF	No evidence of wastewater induced activity	1-3 km
5. Beg-Town	Aug. 18-31, 2013	10 NRCan events	1.5 to 3.4 M_L	Not at time of events; DA now in place	None reported	3 events occurred during HF. 3.0 ML event occurred 21 hours post HF	No evidence of wastewater induced activity.	1-3 km
6. Caribou	Jan. 15-23, 2014	9 NRCan events	1.3 to 3.0 M_L	Not at time of events; DA now in place	Yes (III-IV)	5 events occurred during or within 15 minutes of operations; 1 event 3 hours post-HF. 3 events within 48 hours	No evidence of wastewater induced activity	5 events within 1-3 km
7. Caribou	Mar. 2-13, 2014	11 NRCan events	1.2 to 3.2 M_L	Not at time of events; DA now in place	Yes (III-IV)	1 event occurred during HF. Other events 30 to 72 hours post-HF	No evidence of wastewater induced activity	500 m-3 km

Table 3 – Wastewater Disposal Induced Seismicity

Area	Cluster	#Events	Magnitudes	Dense Array Coverage	Felt	Coincidence with disposal operations	Distance
8. Pintail	Jan. 19, 2013 to present	5 NRCan events	2.9 to 3.1 M_L	DA in place	None reported	Events began six months after initiation of disposal	500 m-3 km
9. Graham	Mar. 2003 to present	>122 NRCan events	1.6 to 4.0 M_L	DA coverage since Mar. 2014	Yes (III-IV)	Events began 13 months after initiation of disposal	1-5 km of disposal well

Summary of Findings

- Induced seismicity has occurred in association with hydraulic fracturing in the Montney.
- Induced seismicity also occurred in association with two deep, sub-Montney wastewater disposal wells in northeast B.C.
- No injuries or property damage were linked to this induced seismicity. Ground motions recorded to date are below the damage threshold.
- There were no vertical wellbore integrity issues detected.
- Mitigation of induced seismicity related to wastewater disposal may be accomplished by limiting injection rates and pressures, and locating disposal wells distal from faults.
- The effectiveness of mitigation methods for induced seismicity related to hydraulic fracturing is difficult to assess given the many operational parameters involved. Additional study is underway to assess the impact of variations in pump rate, injected fluid volumes and sand concentration on induced seismicity.
- The occurrence of induced seismicity events within the Montney is much greater in the structurally deformed Rocky Mountain foothills belt and close to the pre-existing structures of the Fort St. John Graben complex.
- Induced seismicity is more commonly observed in wells undergoing hydraulic fracturing in the lower portion of the Montney formation. Stimulations in this setting are more likely to re-activate deeper, pre-existing faults.
- Identifying and predicting geohazards that may cause induced seismicity is challenging. In many cases, reflection seismic does not resolve small scale strike slip faulting, which may be susceptible to reactivation and generation of induced seismicity events.
- Dense array data indicates most induced events in northeast B.C. occur within the completion zone or in deeper horizons.

Discussion

Underground fault movement can create seismic waves that propagate through the subsurface to the surface, resulting in ground motion. Ground acceleration values have been recorded for three events in northeast B.C. Two 2.9 M_L events in the Horn River Basin had peak acceleration values of 0.017 g (acceleration due to gravity) and 0.0166 g. A peak ground acceleration of 0.038 g and a mean ground acceleration of 0.013 g were calculated from a 3.1 M_L event recorded in the Montney.

Fault Movement

Moment magnitude, equating roughly to Richter magnitudes in northeast B.C., is a function of fault slip area, the distance the fault slipped and rock rigidity. In northeast B.C. felt events have ranged from 2.4 M_L to 4.4 M_L. Fault slippage for these events can be estimated using Figure 6. Estimated fault displacement resulting in 3.0 to 4.0 M_L induced events in northeast B.C. is in the one- to 10-centimetre range for faults one to four km long. Fault movement from lower magnitudes is measured in the millimetres.

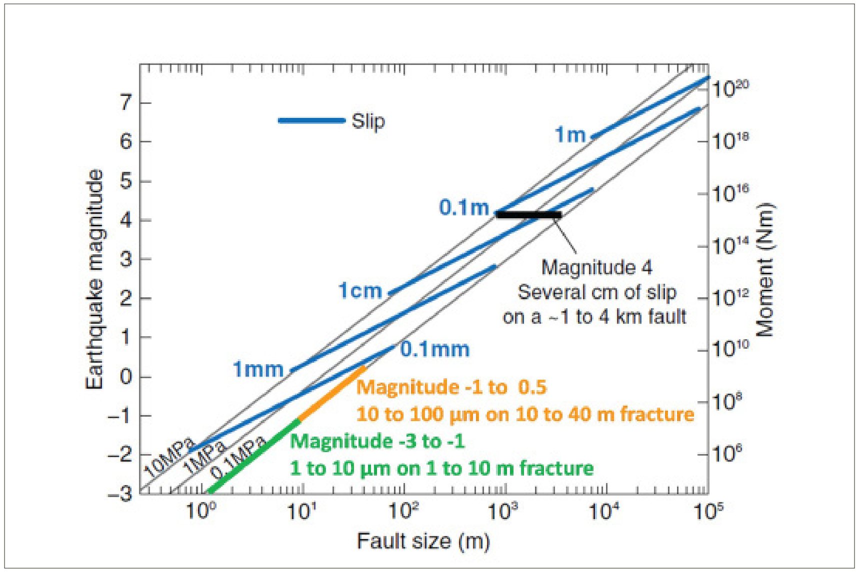


Figure 6: Fault slip for various magnitudes and fault movement areas. Refers to earthquake stress drops ranging from 0.1 to 10 MPa. (Zoback and Gorelick, 2012; modified by Maxwell, 2013)

Wellbore Integrity

The Commission has found no evidence of wellbore damage in the vertical sections of shale gas multi-laterals that can be linked to induced seismicity. The potential exists to reduce the productive flow capacity of wells by restricting access to completion stages due to casing damage in the horizontal portion of wellbores.

Shallow aquifer isolation

Hydraulic fracture completion depths in the Montney and Horn River Basin range from approximately 1,800 to 2,500 m. Maximum freshwater aquifer depths, conservatively estimated, range from 300 to 600 m, with most potable water wells in northeast B.C. occurring from 25 to 120 m. This leaves, at a minimum, 1,200 m of mixed lithology sediments as a barrier to hydraulic fracture fluid infiltration. In addition, shale gas wellbores are flowed back to initiate gas production, and a significant portion of fracture fluid is recovered in this process. Fluids and gas are continuously drawn toward the wellbore as the lowest point of pressure in the reservoir.

Felt events

There are seven induced seismicity areas in northeast B.C. where events have been felt. Generally, people close to the epicentre experience a few seconds of shaking. Shaking intensity dissipates with distance from the epicentre. No surface damage linked to induced seismicity has been reported. These felt events are III to IV (weak to light) on the Mercalli Intensity Scale (Figure 7).

In the areas of Graham, Doe-Dawson, Altares and Eagle, residents reported felt events to the Commission. In each case the Commission investigated and provided responses. At Eagle, almost 90 events, linked to waterflood injection, were recorded from March 1985 to July 2013. Horner (1994) cataloged 29 events from November 1984 to March 1993 and reported that 19 of these events were felt by Fort St. John residents. The operating company has reduced injection rates and the induced seismicity has been effectively mitigated.

At Doe-Dawson, during hydraulic fracturing operations in the Lower Montney, 16 events were recorded from Oct. 16-28, 2013. Reports of six felt events were received by the Commission from nearby residents. These felt events were Mercalli III to IV (weak to light). The Commission ordered the deployment of a dense seismograph array to monitor future hydraulic fracturing operations in the area. In October 2014 fracturing operations resumed two km to the southeast. The new fracturing operations triggered only a few minor events in the Upper Montney, but higher magnitude and felt events began occurring with hydraulic fracturing in the Lower Montney. Active faults were delineated on the dense array seismicity plots. The Commission is working with the operator on mitigation options.

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	< 0.0017	< 0.1	Not felt	None
II-III	0.0017 - 0.014	0.1 - 1.1	Weak	None
IV	0.014 - 0.039	1.1 - 3.4	Light	None
V	0.039 - 0.092	3.4 - 8.1	Moderate	Very light
VI	0.092 - 0.18	8.1 - 16	Strong	Light
VII	0.18 - 0.34	16 - 31	Very strong	Moderate
VIII	0.34 - 0.65	31 - 60	Severe	Moderate to heavy
IX	0.65 - 1.24	60 - 116	Violent	Heavy
X+	> 1.24	> 116	Extreme	Very heavy

Figure 7 – Mercalli intensity scale with ground accelerations. (Modified from the USGS Instrumental Intensity Scale.)

Induced Seismicity Permit Conditions

1. During fracturing operations on this well, the operator shall immediately report to the Commission Emergency Contact 1-800-663-3456 any seismic event
    a. recorded by the operator or any source available to the operator as being magnitude 4.0 or greater and within a 3 km radius of the drilling pad, or
    b. felt on the surface within a 3 km radius of the drilling pad.
2. In the event that a pad is identified, either by the operator or the Commission, as being responsible for the seismic event described in section 1(a) above, the operator, subject to section 3 below, will suspend fracturing operations on this well immediately.
3. Fracturing operations at this well, suspended under section 2 above, may continue if:
    a. the operator presents to the Commission a plan for mitigation aimed at reducing the seismicity or eliminating well operations related to the induced seismicity,
    b. the Commission is satisfied with this plan, and
    c. the operator implements this plan.

Analysis of Mitigation Options

In B.C., the Commission has responded to induced seismicity by improving the regional CNSN array to better locate new induced seismic event clusters; deploying dense arrays to obtain precise depths and locations for a wide range of event magnitudes; implementing new well permit conditions requiring the reporting of felt events, and the suspension of operations triggering a 4.0 M_L event or greater. Following in this section is an analysis of other mitigation options currently being implemented and/or studied by the Commission.

Several other jurisdictions have developed, or are developing, procedures to address induced seismicity. For example, Colorado employs a traffic-light system based on the Modified Mercalli Scale whereby companies are required to modify operations if triggered events are felt at surface, and suspend operations in the event of a 4.5 M_L event. Ohio has responded by establishing buffer zones around higher risk areas, and operators are required to have a seismicity mitigation plan in place and monitor hydraulic fracture operations inside the buffer zone. The monitoring must have resolution down to at least 1.0 M_L, and if a 1.0 M_L event is detected the company meets with the Ohio Conservation Commission to discuss a plan to resume operations. The Canadian Association of Petroleum Producers has an induced seismicity operating practice that has recommendations for assessing seismicity potential, drilling design and responding to induced seismicity (http://www.capp.ca/canadaIndustry/naturalGas/ShaleGas/Documents/natural-gas-operating-practice-7.pdf).

Wastewater disposal well induced seismicity mitigation steps

The Commission responded to wastewater disposal well induced seismicity by working with the well owner in increasing seismic monitoring and decreasing injection rates. Disposal well approvals contain specific conditions for well operation, monitoring, testing and reporting to ensure the geologic containment of fluids, including:

- Maximum injection and ultimate reservoir pressure limits.
- Continuous monitoring and recording of tubing and casing pressure.
- Reporting monthly disposal volume, pressure and operating hours.
- Annual reservoir pressure and packer isolation testing.
- Periodic wellbore integrity and zonal isolation logging.

Applications to the Commission for wastewater disposal in zones near pre-existing faults or in areas with known induced seismicity may be denied.

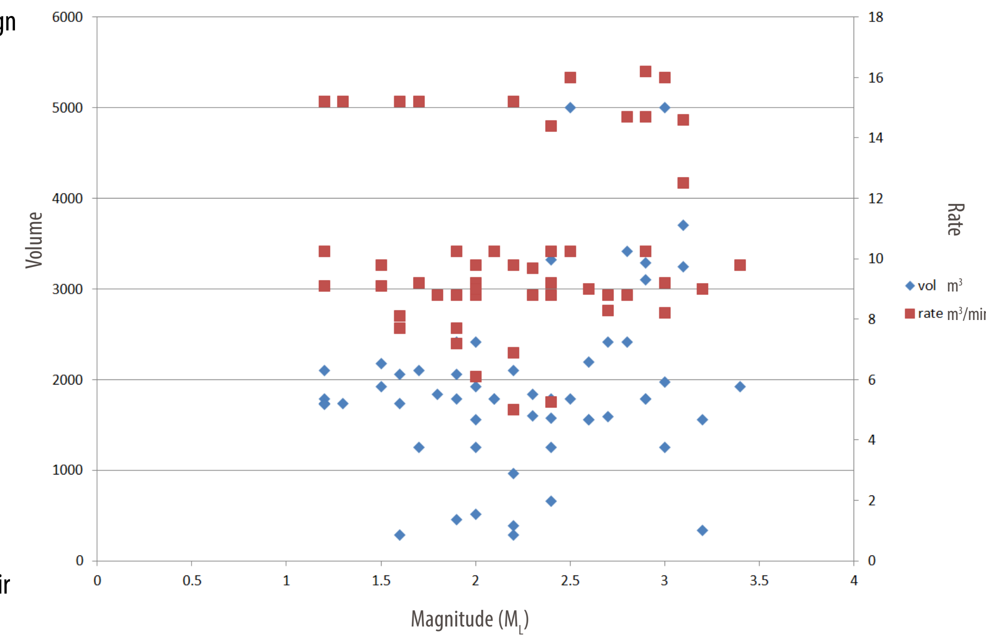


Figure 8 – Comparison of magnitude to causal hydraulic fracturing stage pump rate and volume.

Hydraulic fracturing induced seismicity mitigation steps

In northeast B.C., operators have tried several methods to prevent or mitigate hydraulic fracturing induced seismicity, including reducing hydraulic fracture stage volumes, reducing pump rates, reducing proppant concentration, skipping hydraulic fracture stages and flowing back fracture fluids. The success of these mitigation procedures is difficult to ascertain given the many hydraulic fracture operational parameters at play and the anecdotal nature of the results. High-resolution dense array deployments have proven useful for detecting very low magnitude events and the early fault identification needed to initiate mitigation.

Fault Delineation and Dense Seismograph Arrays

A key to induced seismicity mitigation is early active fault identification. This may be achieved by real-time dense array monitoring or real-time microseismic monitoring. In both the Horn River Basin and the Montney, many of the active faults are strike-slip and difficult to detect with reflection seismic. Snelling (2013) demonstrates that the location and orientation of active faults may be resolved with microseismic monitoring. In some dense array submissions to the Commission, the active fault type along with the strike, rake and dip were obtained using dense arrays. Often individual seismic events could be linked to separate hydraulic fracturing stages.

Reductions of Injected Volumes and Pump Rates

Several attempts have been made to mitigate the seismicity through reducing volumes and/or pump rates, but results are inconclusive. In the Horn River Basin, the operator at the d-1-D pad reduced pump rates from 16 m^3/min to 13 m^3/min and reported a slight reduction in event frequency. At Kiwigana in the Horn River Basin the operator pumped at a consistent 13 m^3/min, and while events were triggered at reactivation zones, magnitudes did not exceed 1.9 M_L.

Event magnitudes are correlated to the volume and pump rate for the fracture stage considered to have triggered the event (Figure 8). No clear correlation is apparent between pump rate or volume and magnitude. The magnitudes on the x-axis are the events triggered by the overlying volume and rate. For example, Magnitude 3.0 events can be seen to have been triggered by pump rates of eight to 16 m^3/min with corresponding volumes of 1,100 to 5,000 m^3.

In Caribou and Beg-Town, the operator reduced pump rates and volumes in an effort to mitigate induced events. In some cases it appeared frequency and magnitude of induced events were reduced. The success of these measures is anecdotal. No dense array was deployed to monitor fault reactivation.

Operators are testing different rates and volumes to mitigate induced events along active faults closely delineated with dense arrays.

Flowback

Flowback occurs when the hydraulically fractured zones are opened up to production. Fluid and gas flow to surface, reducing the elevated formation pore pressure needed to trigger fault movement. Flowback appears to be effective in reducing seismicity. In one northeast B.C. case, following multiple events along a wellbore and a felt 2.7 M_L event, hydraulic fracturing operations were suspended and the wellbore was flowed back. No additional events occurred after flowback.

Stage Skipping

Two operators reported skipping completion stages near fault reactivation zones in an effort to reduce the magnitude and frequency of induced events. This effort is also inconclusive. In some cases no additional events occurred, while at other times after skipping a stage, new events occurred. In one recent case, dense array results (Figure 9) showed events were being triggered at almost every stage along a wellbore and up to 350 m from where the wellbore intersected the active fault.

In the Horn River Basin, fault re-activation zones are well defined. It appeared injection had to be very close or within the fault reactivation zone for fault reactivation to occur. Dense array evidence in the Montney suggests events can be triggered from outside the reactivation zone, perhaps up to 200 to 300 m away from the fault with fluid pressure being transmitted through fracture networks. There is also dense array evidence that fault movement may occur several hundred metres below the Montney completion zone.

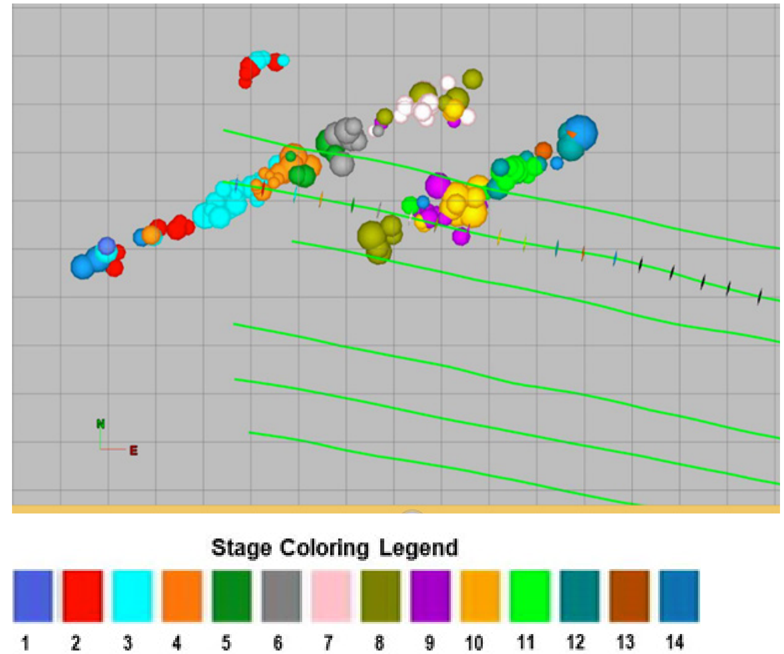


Figure 9: Event locations delineating faults and stage that triggered fault movement. Events sized by Mw and coloured by stage. Magnitudes range from 1.1 to 3.2 Mw. (Grid 100 m by 100 m.)

Recommendations

1. Increase regulatory scrutiny for disposal wells
The vast majority of wastewater disposal wells in northeast B.C. do not generate induced seismic events. Induced seismic events have been noted at two disposal wells, occurring in marginal reservoir quality rock in proximity to existing faults.
ACTION: Evaluation of wastewater disposal well applications will incorporate a geological and geophysical analysis to identify pre-existing faults near the proposed site. Approval conditions may include seismic monitoring to detect and accurately locate seismic events and previously unrecognized fault reactivation zones.

2. Encourage deployment of high-resolution dense arrays
The improved CNSN grid has significantly improved the Commission's ability to monitor for induced seismicity in northeast B.C. However, the improved CNSN epicenter resolution varies with location and is inadequate to confidently locate events. Event depths cannot be resolved with the CNSN. Current dense array deployments by operators, either ordered or voluntary, provide precise locations and depths and, at times, the active fault delineation needed to implement mitigation procedures.
ACTION: The Commission will continue to monitor events recorded by the CNSN to locate induced seismicity areas. Dense array deployments will be requested in areas where more detailed information is required, including areas with felt events, higher magnitude clusters and high-frequency clusters.

3. Continue to improve regulations to address induced seismicity
Currently, the Commission employs well permit conditions to regulate induced seismicity. Permit conditions were initially used in the Horn River Basin to address concerns in what was believed to be a geographically confined area of induced seismicity. The recognition of induced seismicity related to wastewater disposal and hydraulic fracturing within the Montney indicates a more uniform application of regulations is appropriate.
ACTION: The current permit conditions used by the Commission to respond to induced seismicity will be placed in regulation.

4. Increase public availability of data necessary to study induced seismicity
Dense array data provides precise induced event locations and depths as well as the detailed seismological data required for research into induced seismicity. The Commission currently supports research projects at UBC and NRCan and has requested support from industry for several international research projects.
ACTION: The Commission will continue to promote and support the sharing of dense array data with researchers and the publication of research results. In addition, the Commission will promote awareness of the extensive hydraulic fracturing operational database it maintains and is available to the public.

5. Assess the use of hydraulic fracturing buffer zones to protect sensitive infrastructure and subsurface projects
In addition to increased seismicity monitoring, it may be prudent in some circumstances to implement buffer zones near subsurface disposal or storage facilities.
ACTION: The Commission will identify disposal and storage projects that could be adversely affected by fault reactivation and investigate whether conditions on hydraulic fracturing in these project areas or zones is appropriate.

Conclusion

The Horn River Basin report recommendations resulted in an increased emphasis on the detection of potential geohazards, enhanced seismicity monitoring and implementation of effective notification and consultation procedures. In collaboration with the University of British Columbia (UBC), NRCan, Geoscience BC and industry partners, the Commission has studied geomechanical and operational controls on induced seismicity in order to develop and optimize detection, monitoring and mitigation strategies.

The Commission has been proactive in dealing with induced seismicity and has taken numerous steps since 2012 to improve understanding, monitoring and mitigation. Induced seismicity related to hydraulic fracturing has now been detected in northeast B.C.'s Horn River Basin and Montney. It has also occurred at two sub-Montney wastewater disposal sites.

Regional and detailed monitoring of seismic events in northeast B.C. indicate "felt" induced seismicity is uncommon. Of the approximately 7,500 hydraulic fracture stages performed during the August 2013 to October 2014 investigation period, only 11 triggered events felt at the surface. None of the events resulted in damage to surface structures, and only minor horizontal wellbore effects have been noted. The investigation found no loss of wellbore containment.

The mechanism for inducing seismic events is the reactivation of faults via the injection of fluids either from short term, high-pressure hydraulic fracturing or longer term, higher cumulative volume wastewater disposal. Mitigation of wastewater disposal induced seismic events may be accomplished by reducing injection rates, limiting the increase in reservoir pressure and locating distal from faults. Mitigation of induced seismicity related to hydraulic fracturing is more difficult to assess given the many operational parameters involved, but the Commission has identified fault zone avoidance and early flow-back of fracture fluids are probably the best mitigation techniques.

Dense array data is critical to understanding induced seismicity. Recent deployments have precisely delineated active faults and provided detailed structural and seismological data that can be applied to risk assessment and mitigation of induced seismicity.

A comprehensive regulatory framework is in place ensuring continued responsible development of unconventional resources in B.C. The Commission has also formed research partnerships with NRCan, UBC and Geoscience BC to study the effects and relationships between seismicity and hydraulic fracturing and water disposal.

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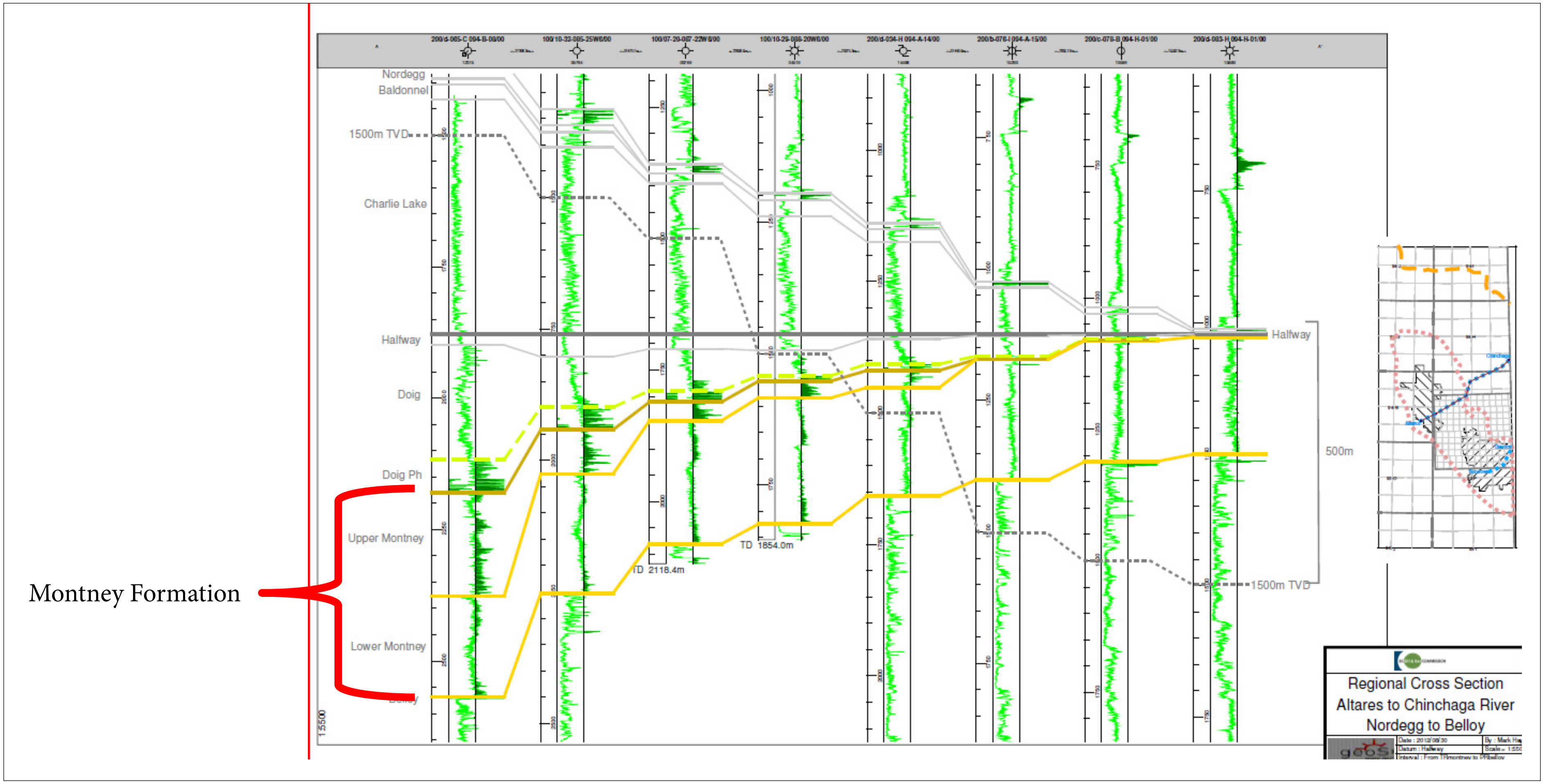
Appendix 1

Montney Cross-Section (Altares to Chinchaga River)



Appendix 2

Investigation of Observed Seismicity in the Horn River Basin

In 2012 the Commission released the report Investigation of Observed Seismicity in the Horn River Basin. The investigation concluded that seismic events observed within remote and isolated areas of the Horn River Basin in northeast B.C. between 2009 and 2011 were caused by fluid injection during hydraulic fracturing in proximity to pre-existing faults. As a result, the Commission made seven recommendations to enhance seismic monitoring, industry best practices and regulations. In the past two years, significant progress was made in implementing the recommendations, as detailed below.

1 Improve the accuracy of the CNSN in northeast B.C.

Six new seismograph stations, funded by the Canadian Association of Petroleum Producers (CAPP) and Geoscience BC, were installed and connected to the CNSN in August 2013. An additional two stations (funded by NRCan and the Commission) were brought online in 2014 (Figure 12). These additions have significantly improved CNSN resolution. Before the improvements, epicentre resolution uncertainty was five to 10 km. Current epicentre resolution varies from one to five km depending on event location. A comparison of same-event epicentres recorded by dense arrays and the CNSN show many CNSN located events are within three km of dense array epicentres.

2 Perform geological and seismic assessments to identify pre-existing faulting

Since 2012, most of the high-volume hydraulic fracturing and almost all of the new CNSN-recorded seismicity has occurred within the Montney. Operators commonly use 3D seismic to interpret geological structures and are developing a good understanding of structural trends and fault orientations.

3 Establish induced seismicity monitoring and reporting procedures and requirements

Seismic monitoring and reporting have been addressed in three ways. First, a notification and consultation procedure was implemented to facilitate communication between operators and the Commission, to improve seismic monitoring and explore possible mitigation options. Second, the Commission has ordered the deployment of dense seismograph arrays in three separate locales to collect detailed seismological data on probable induced event clusters. Third, well permit conditions are in place for all of northeast B.C. requiring operators to immediately report events within three km of their operations that

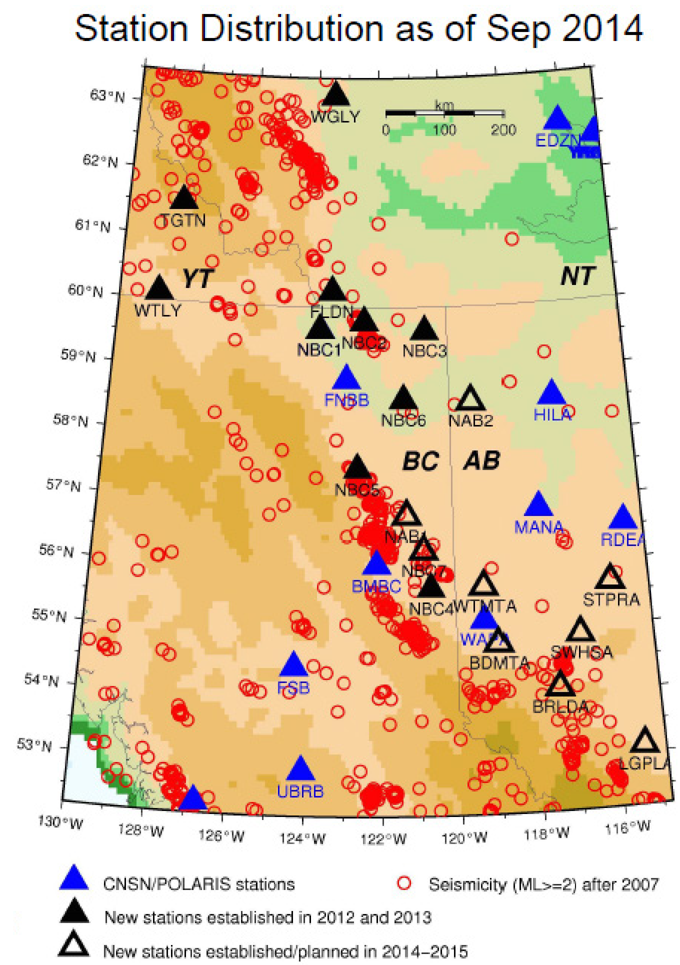


Figure 12: Locations of CNSN stations in northeast B.C., new stations (blue triangles)

are felt or are equal to or exceed 4.0 ML. Permit conditions require the suspension of operations on the wellbore linked to any 4.0 ML event. Operations can be resumed with a Commission-approved mitigation plan.

4 Station ground motion sensors near selected northeast B.C. communities to quantify risk from ground motion.

One strong motion detector was installed in Fort St. John. In addition, dense arrays were deployed or will be in place to monitor future operations within the Montney. Velocities from these near surface seismographs can be used to calculate ground motion at the station location.

5 The Commission will study the deployment of a portable dense seismograph array to selected locations where induced seismicity is anticipated or has occurred.

The Commission studied and identified a portable dense array option; however, the combination of ordered seismicity monitoring and voluntary deployment has provided the data necessary to understand the clusters of events detected by the CNSN.

6 Require the submission of microseismic reports to monitor hydraulic fracturing for containment of micro-fracturing and to identify existing faults.

The requirement for mandatory submission of microseismic reports is currently under review. It is recognized microseismic monitoring is a key technology in understanding the propagation of hydraulic fractures and induced seismicity. Making a subset of that information more widely available is desirable to facilitate academic study and increase dissemination of this data.

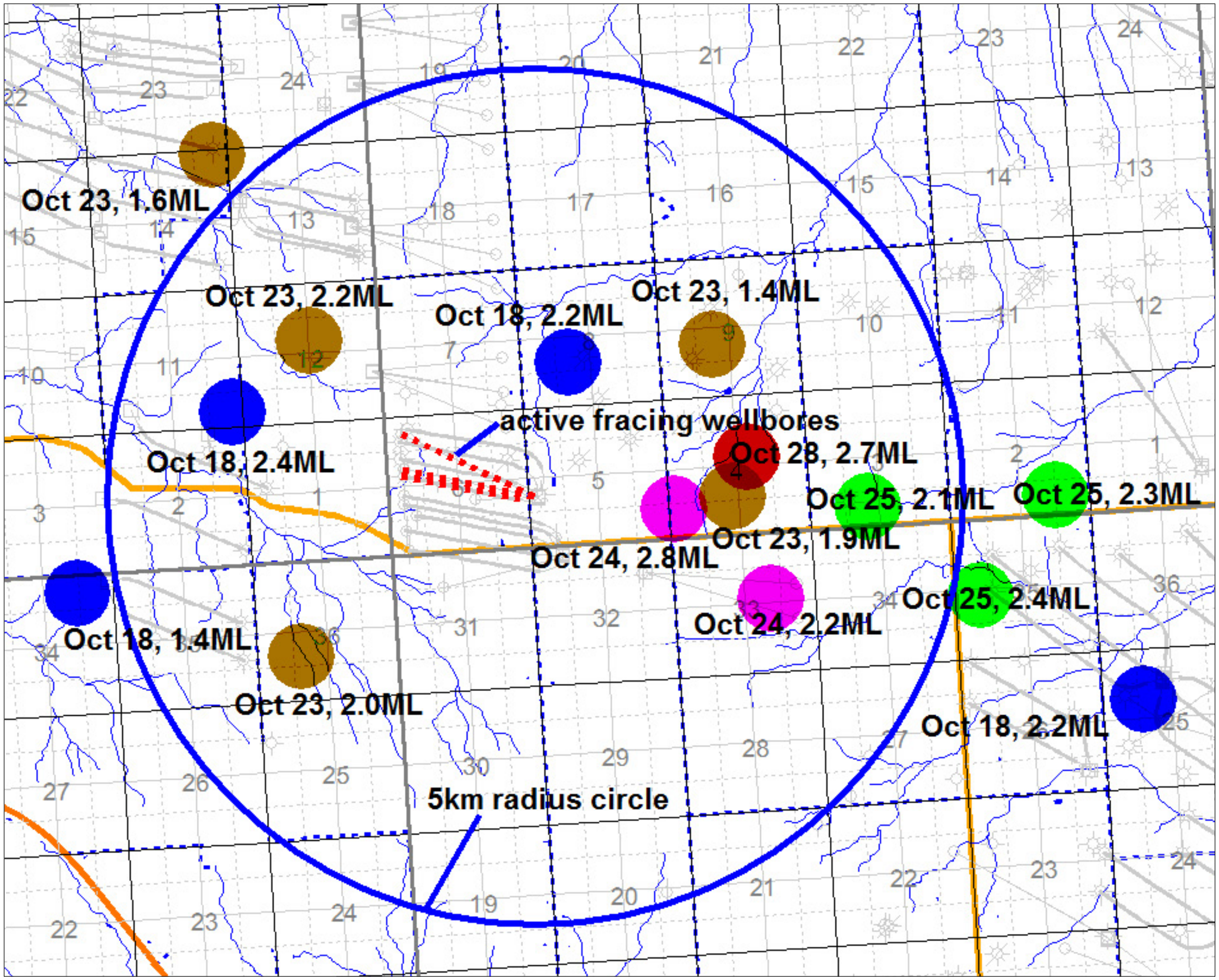
7 Study the relationship between hydraulic fracturing parameters and seismicity.

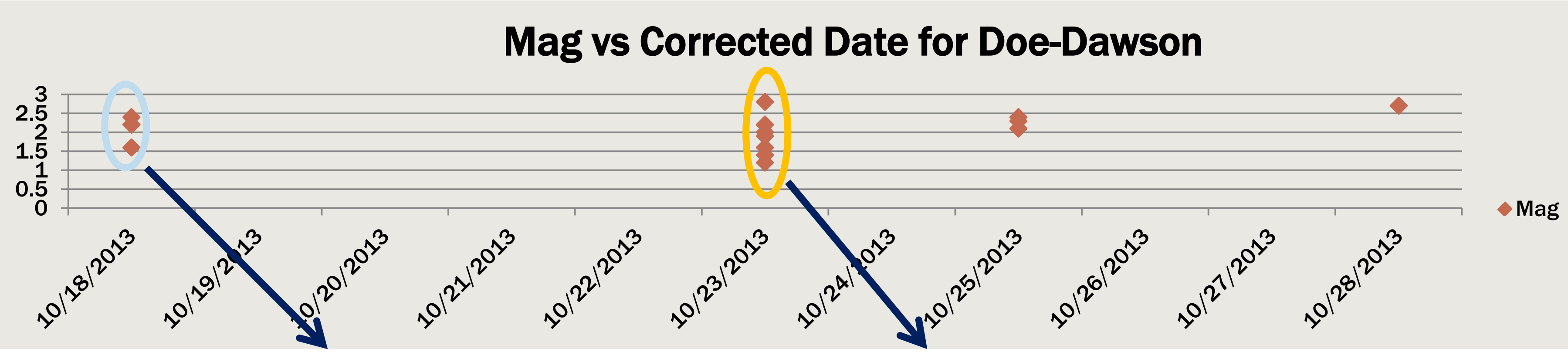
Research projects investigating injected volume and magnitude relationships are ongoing at UBC and NRCan. Several operators have experimented with hydraulic fracturing parameters to mitigate detected seismicity. No clear relationship has been found between event magnitude or frequency and pump rate, injected volume, proppant concentration or fracture stage omission. Induced seismicity associated with wastewater disposal wells shows a relationship between injection rate and event frequency.

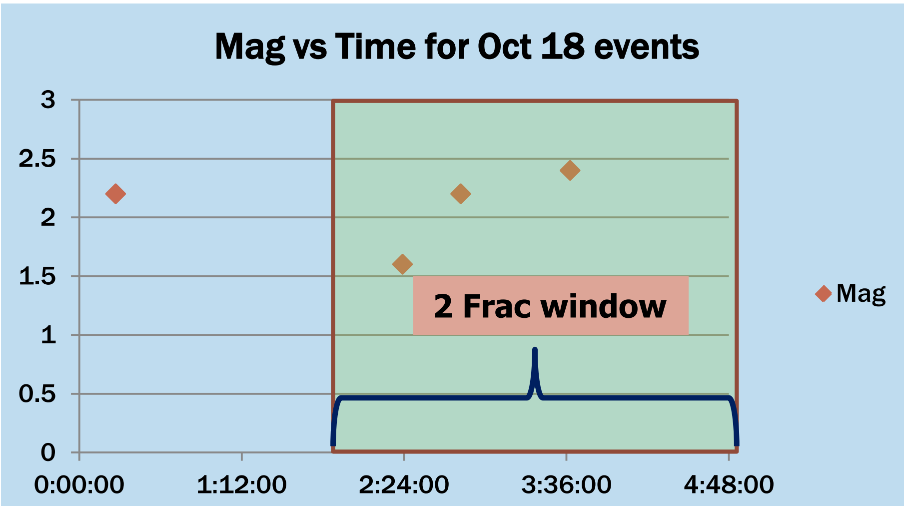
Appendix 3
Cluster Maps and Magnitude/Time Graphs

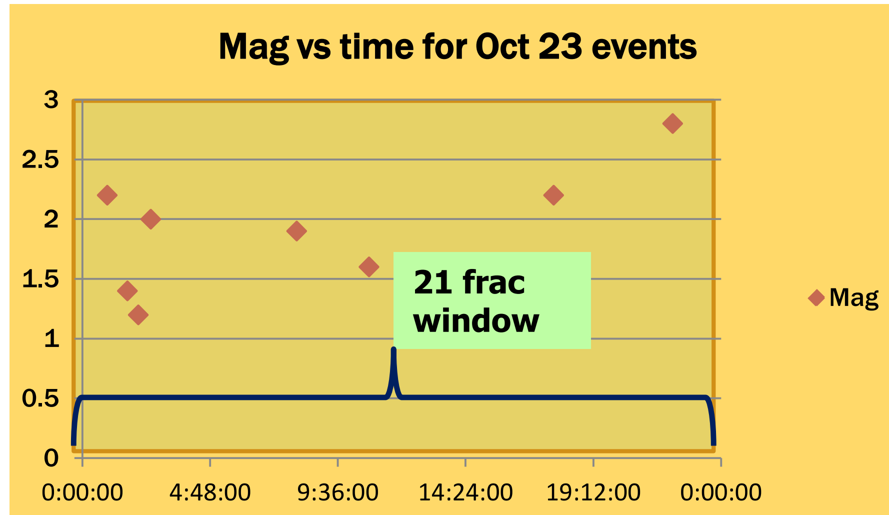
The following maps show examples of individual seismic event clusters by location (from Figure 3), and the charts show hydraulic fracturing timelines highlighted over magnitude versus time graphs. Coloured dots indicate NRCan recorded events.

1. Doe-Dawson – Oct. 18-28 cluster (NRCan recorded events)





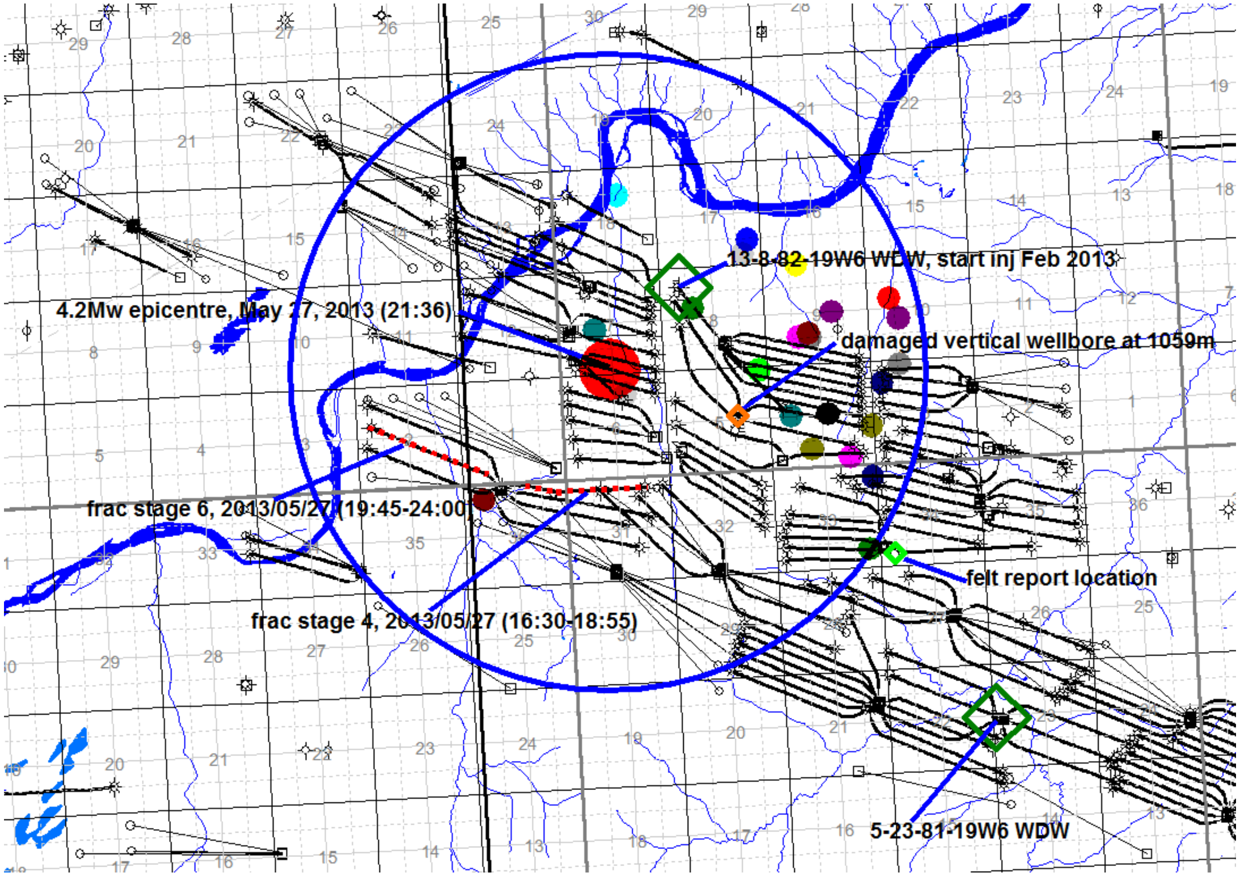


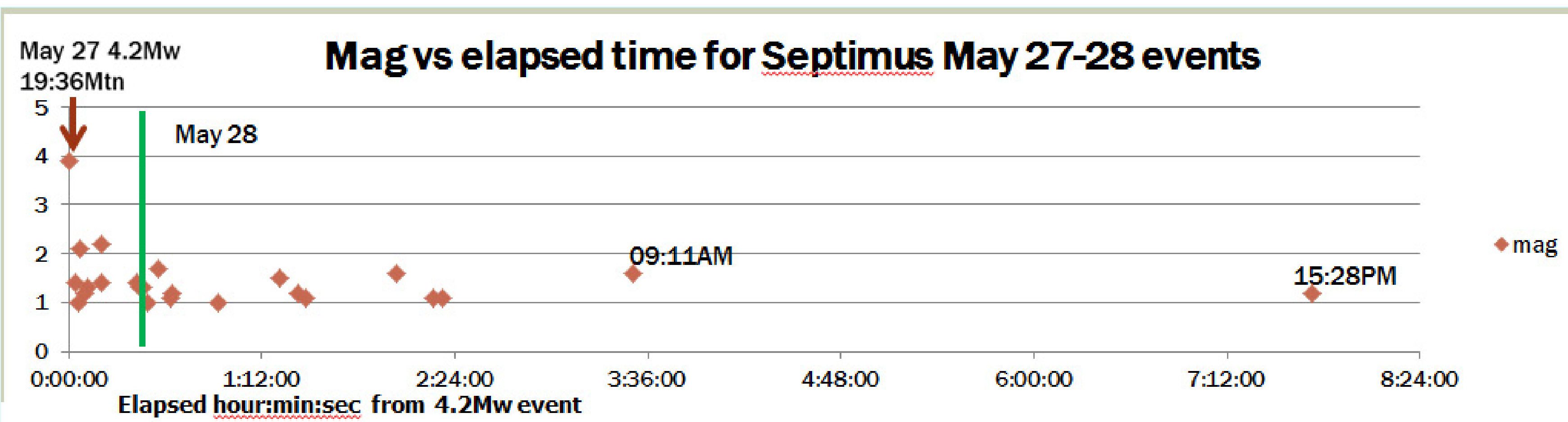


- 2 fracs prior to Oct 17 events, start 21:20 & 23:45; 2 fracs Oct 18, start 02:00 and 4:15.
- Avg frac duration 2hrs
- Avg Rate 5.0 m3/min
- Max Press 61.1 MPa
- Vol 144m3 to 662m3

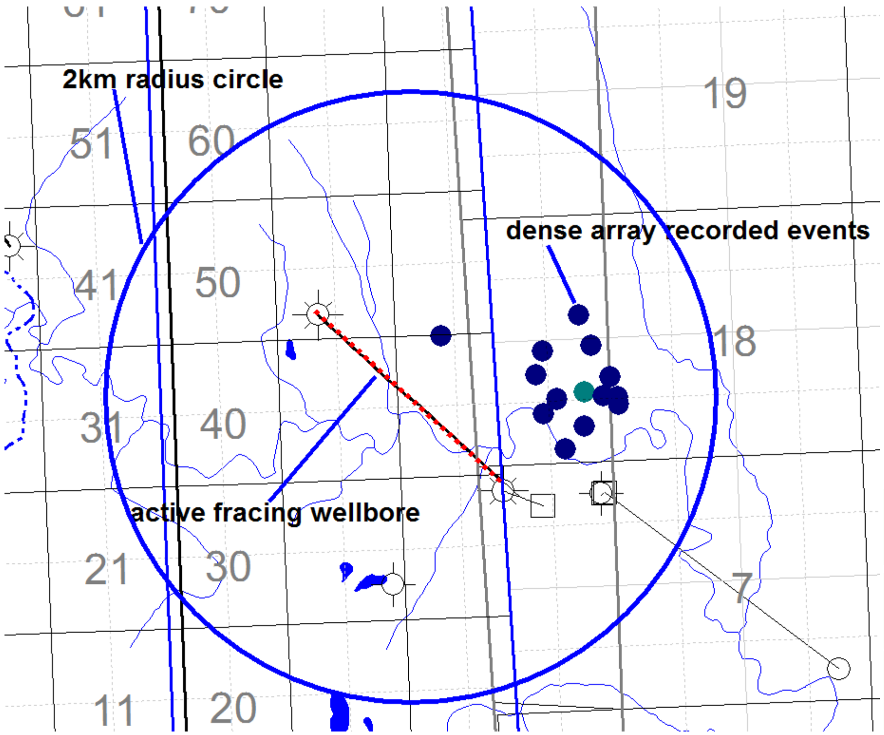
- 21 fracs start 23:15, Oct 22 to 22:50 Oct 23 in two wellbores
- Avg frac duration 45 min
- Rates vary from 6.6m3/min to 10.5 m3/min
- Max Press 64MPa
- Vol 244m3 to 524m3

2. Septimus Field – May 27-28, 2013 cluster (All events shown recorded by dense array on May 27-28, 2013)





3. Altares – Nov. 5-6, 2013 cluster

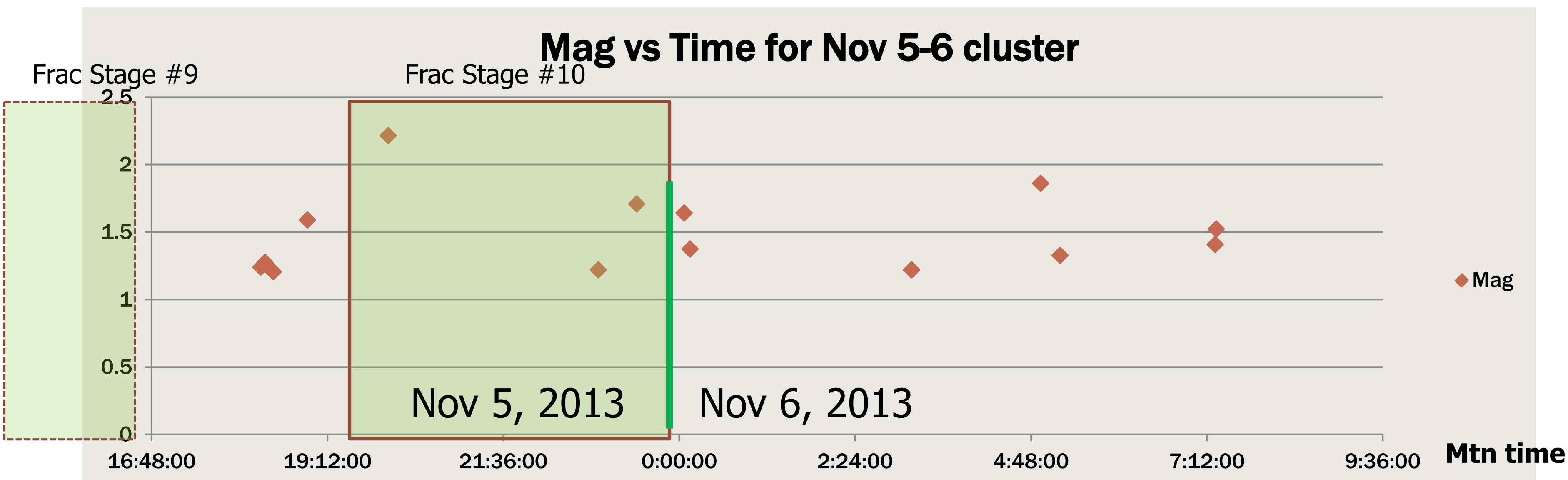


Altares, Nov 5-6 cluster

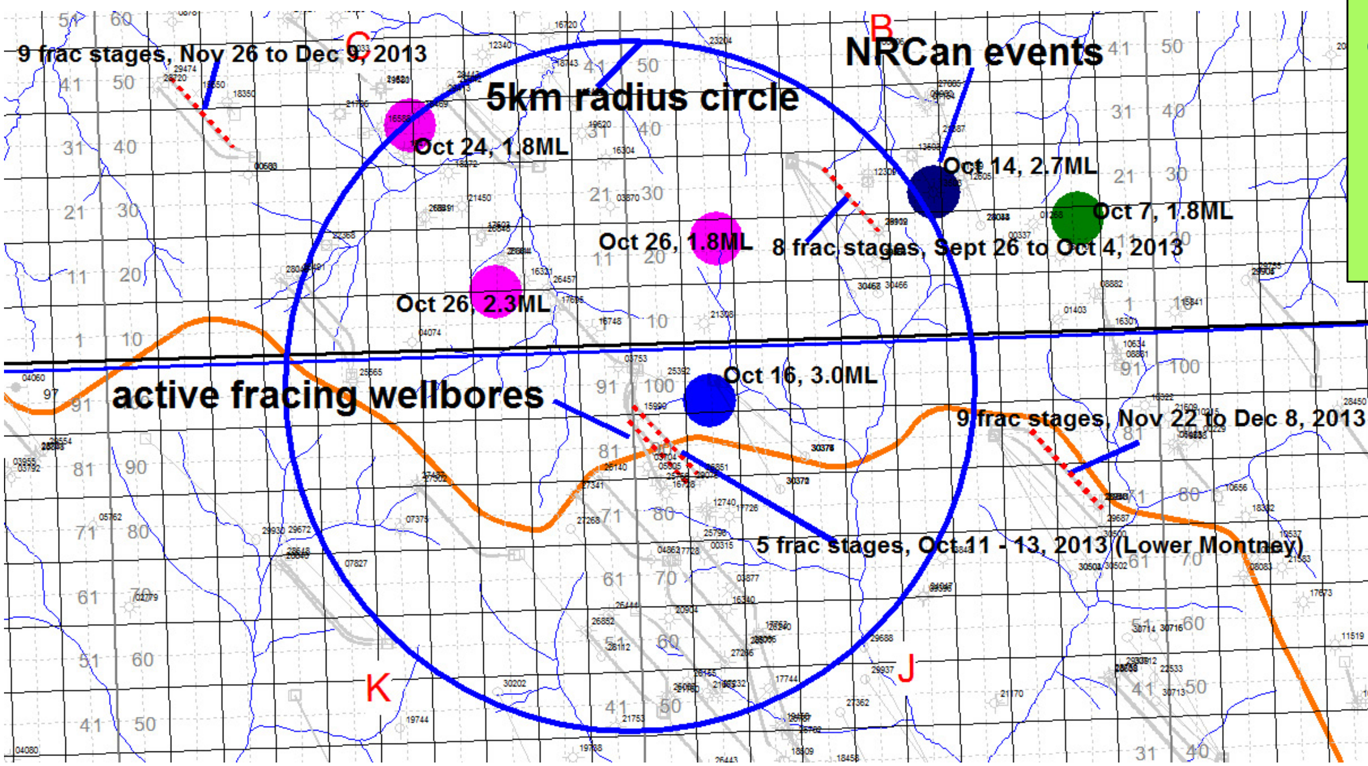
14 events, Mag 1.2 to 2.2ML over 13 hours. Recorded by dense array

- Three fracs before and during some events
- Avg brkdwn 57MPa
- Avg rate 15.1m3/min
- Avg vol 1880m3

Frac Stage #8	**08:02-10:52 (mtn), Nov 5, 2013**	**14 events on Nov 5-6 (mtn) inside blue circle**
Frac Stage #9	**13:35-16:18(mtn) , Nov 5, 2013**	**1st event 18:17 (mtn), Nov 5**
Frac Stage #10	**19:35-23:30(mtn) , Nov 5, 2013**	**Last event, 07:20 (mtn) , Nov 6**

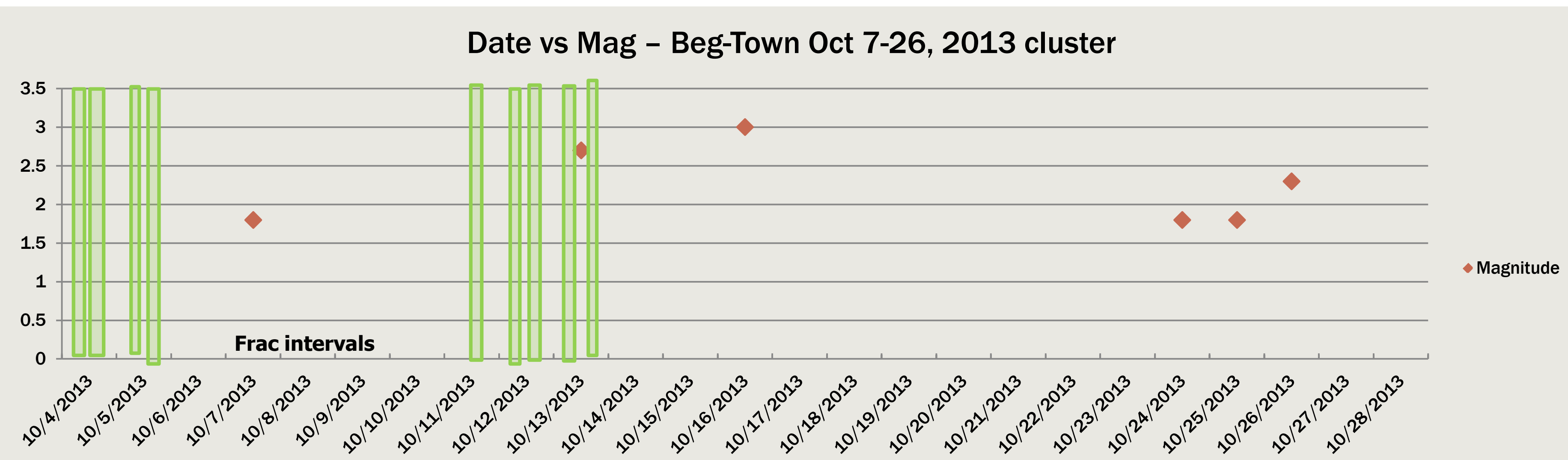


4. Beg-Town – Oct. 7-26, 2013 cluster

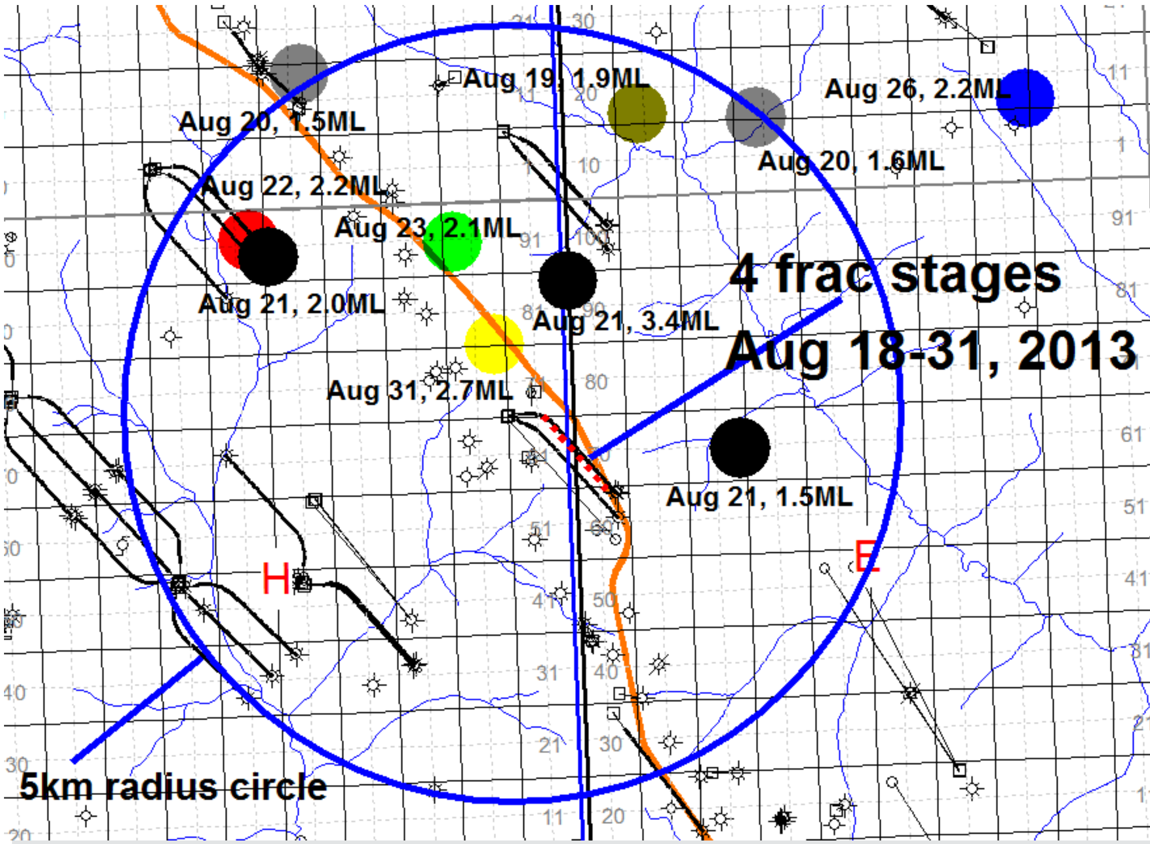


Beg-Town, Oct 7-26 cluster

- 6 NRCan recorded events, Mag 1.8 to 3.0ML over 20 days



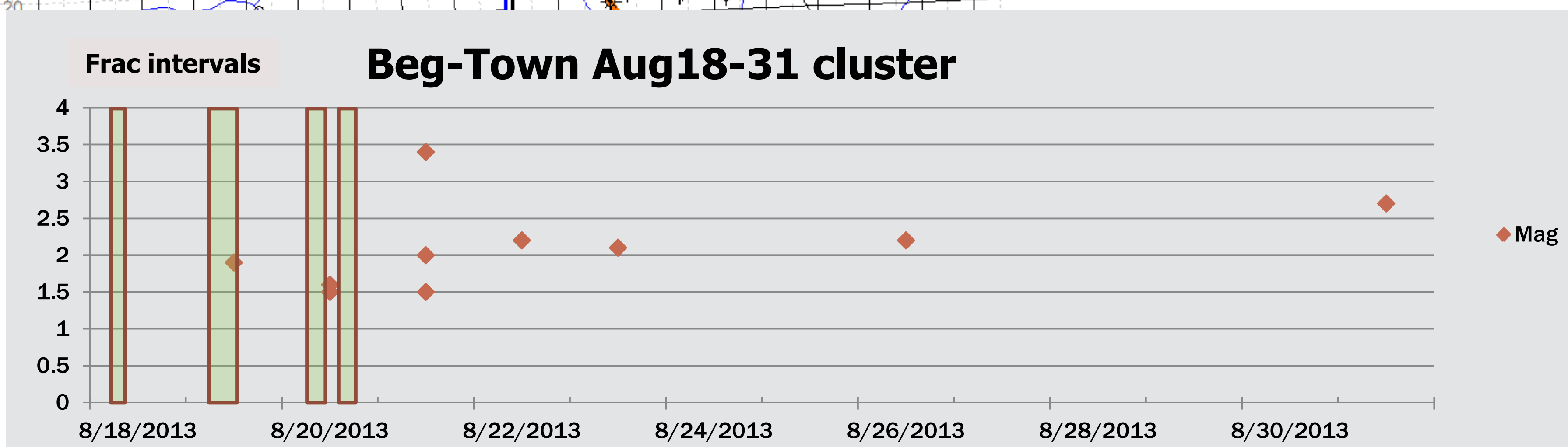
5. Beg-Town – Aug. 18-31, 2013 cluster



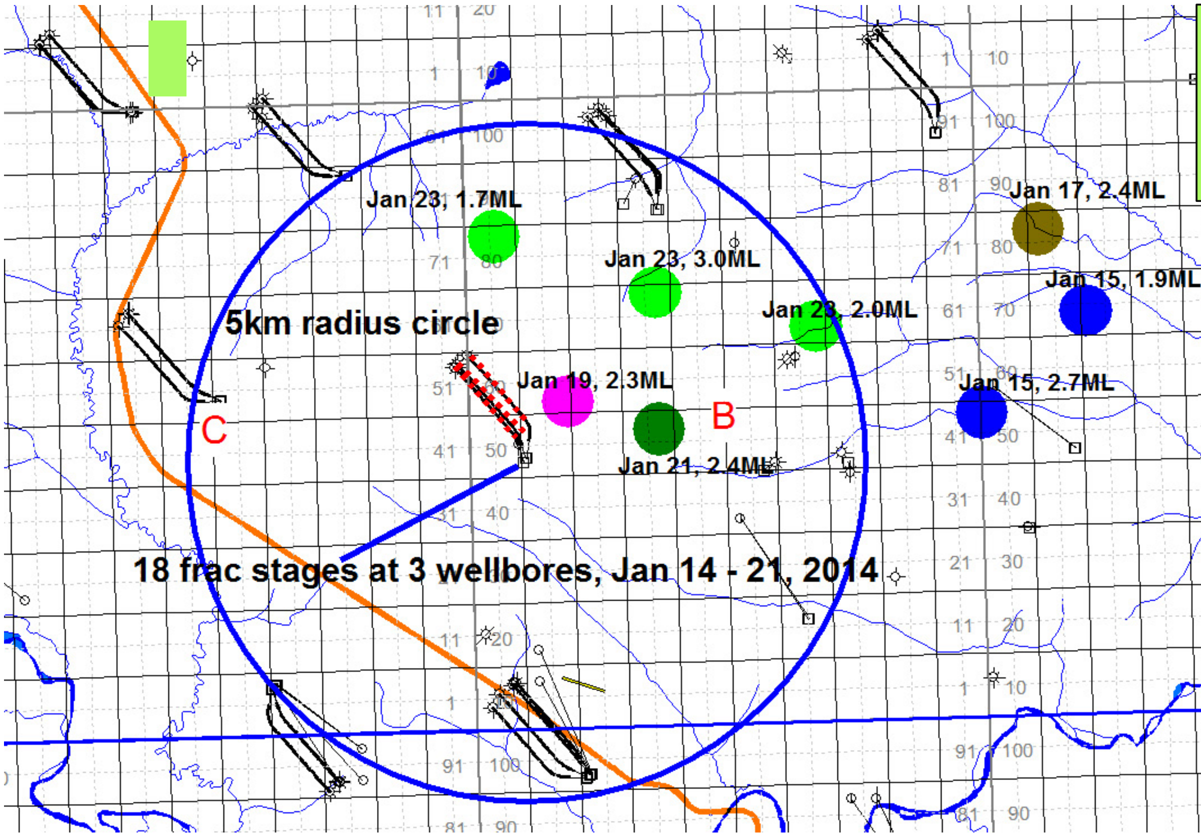
NRCan recorded events

Lower Montney fracs

- **Aug 18, frac #7**
  - •Start 07:00, end 08:45
  - •Brkdwn 60.1MPa
  - •Avg rate 6.9m3/min
  - •Vol 444.2m3
- **Aug 19, frac #7, second attempt**
  - •Start 07:30, End 13:15
  - •Brkdwon 50.7MPa
  - •Avg rate 7.7m3/min
  - •Vol 2059m3
- **Aug 20, frac #8**
  - •Start 07:45, end 11:30
  - •Brkdwn 59MPa
  - •Avg rate 9.1m3/min
  - •Vol 2178m3
- **Aug 20, frac #9**
  - •Start 15:30, end 18:30
  - •Brkdwn 54MPa
  - •Avg rate 9.8m3/min
  - •Vol 1920m3

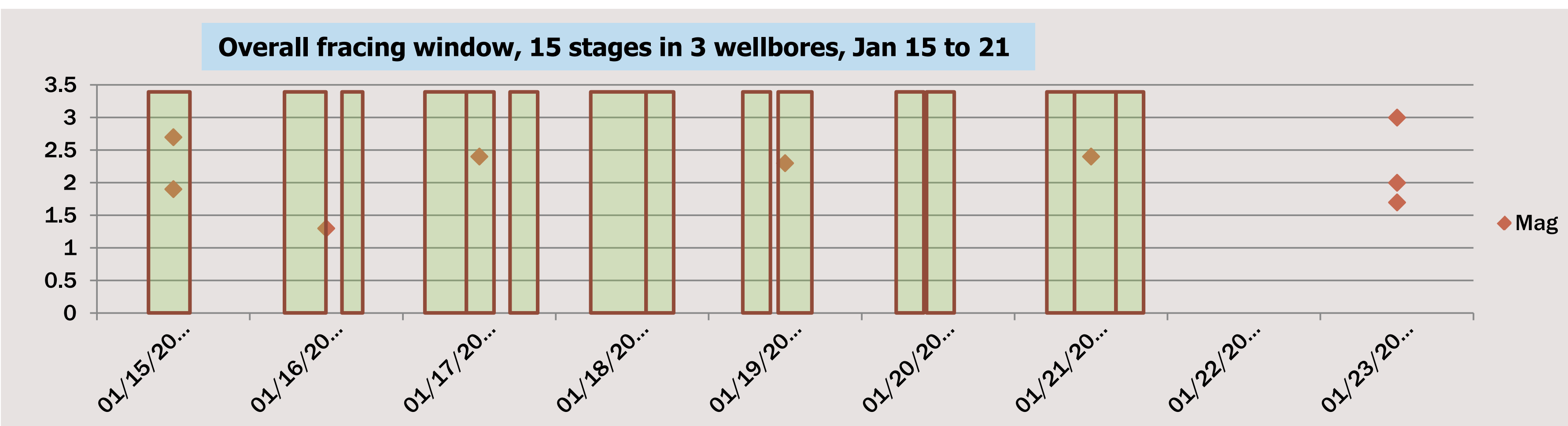


6. Caribou – January 15-23, 2014 cluster

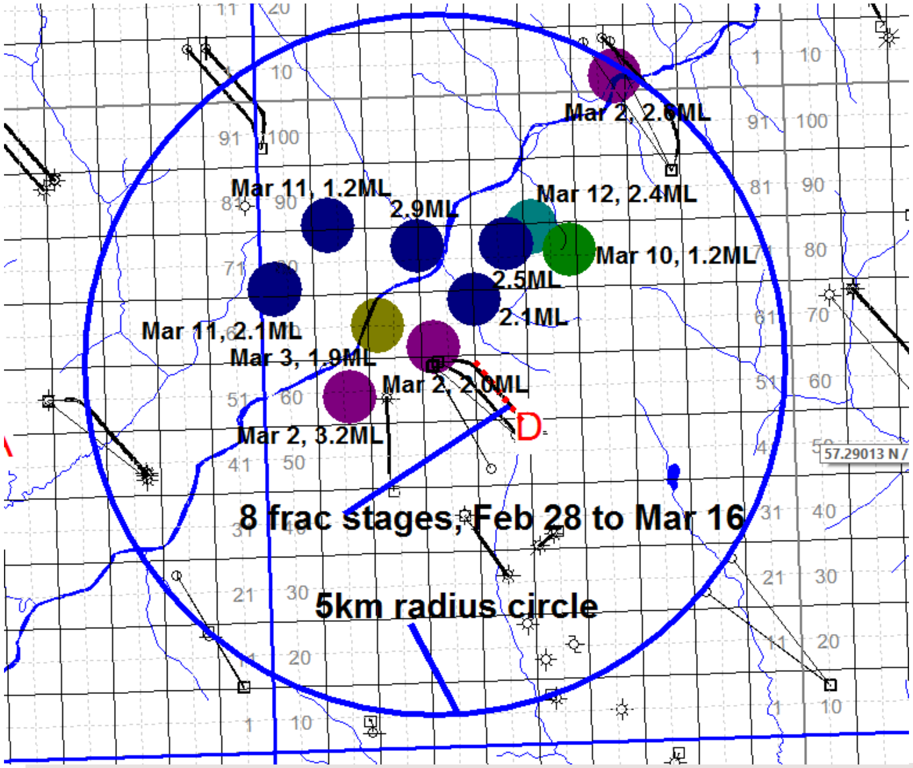


Caribou, Jan 15-23, 2014 Cluster, 9 NRCan recorded events, Mag 1.3 to 3.0ML over 9 days

- at least one event felt in camp

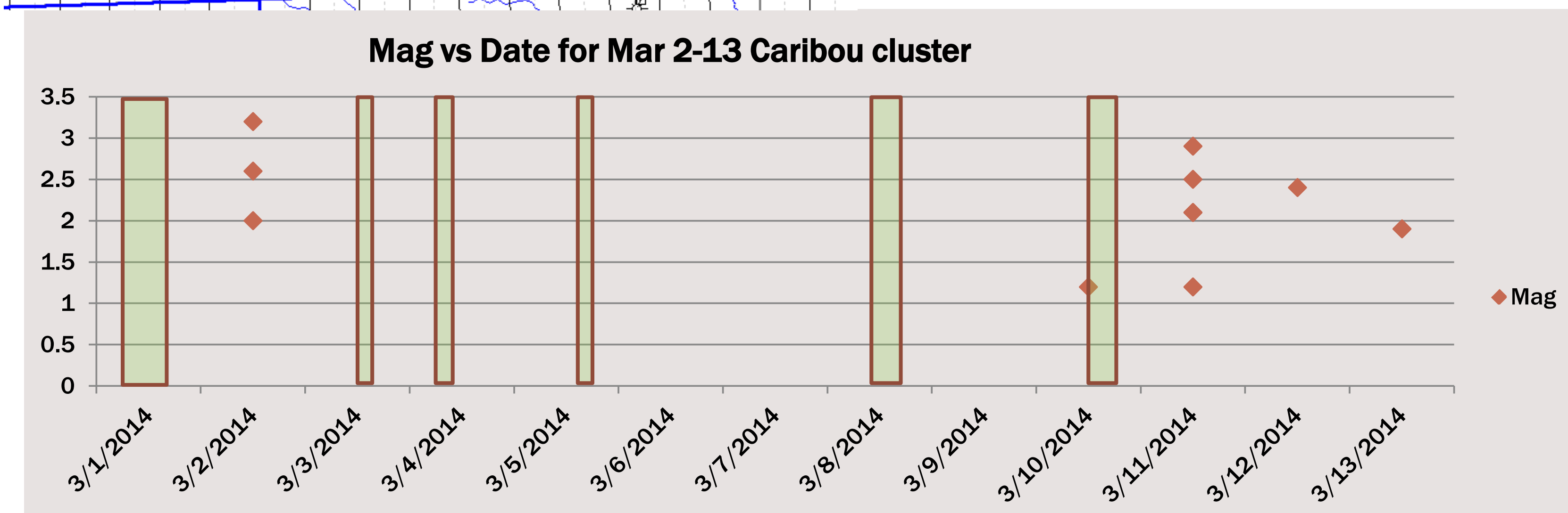


7. Caribou – March 2-13, 2014 cluster

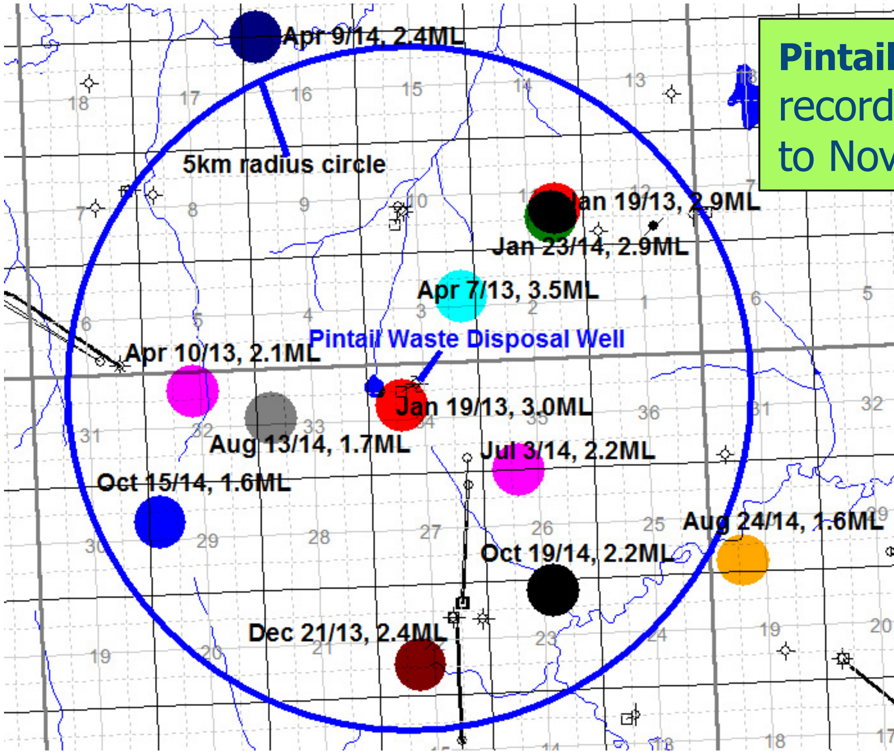


Caribou, Mar 2-13, 2014 Cluster, 11 events, Mag 1.2 to 3.2ML over 11 days

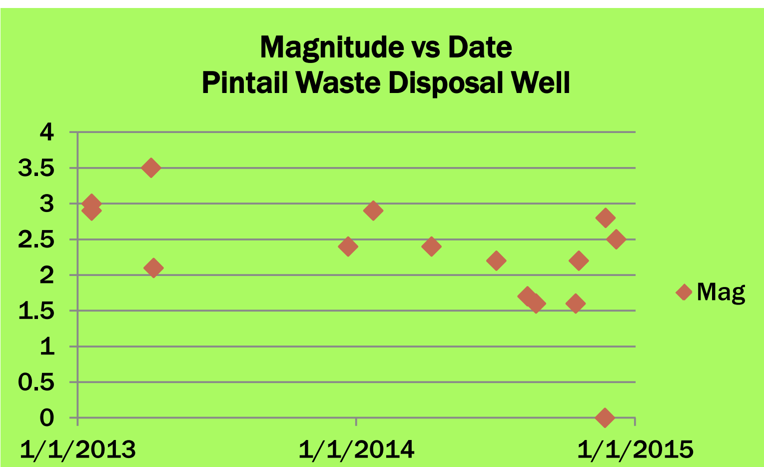
- One event felt in camp
- NRCan recorded events

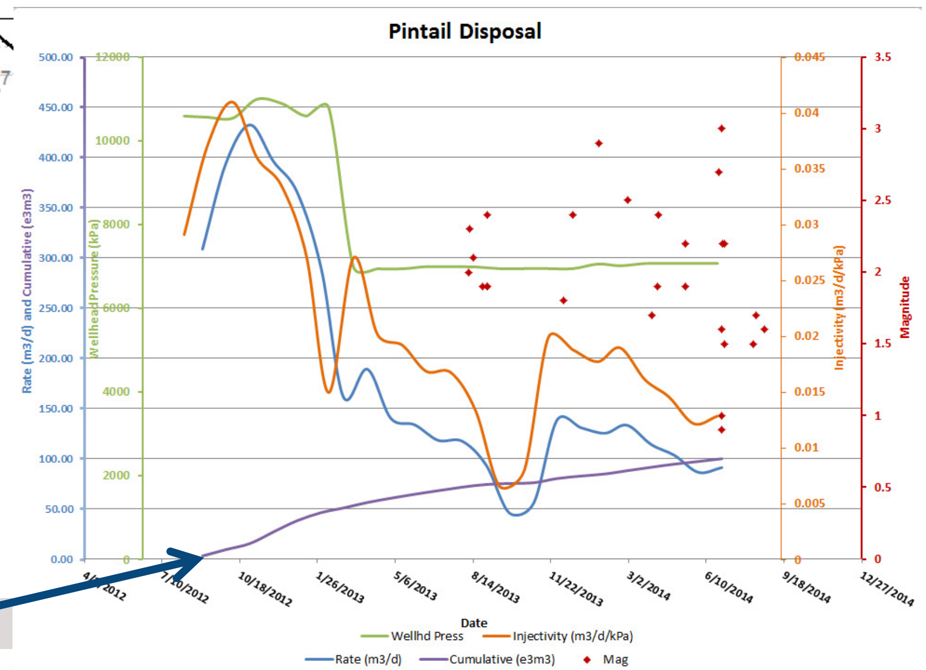


8. Pintail – Jan. 9, 2013-Nov. 1, 2014 (Wastewater Disposal Induced Seismicity)



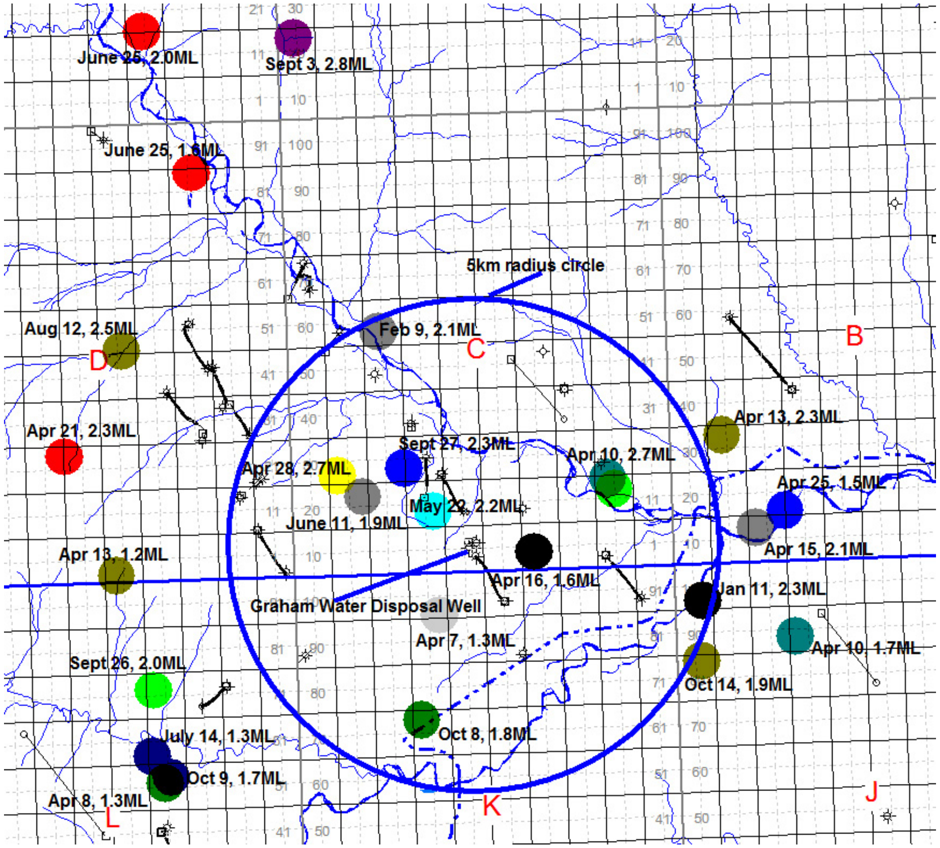
Pintail– 12 NRCan recorded events recorded near Pintail (Jan 19, 2013 to Nov 1, 2014)



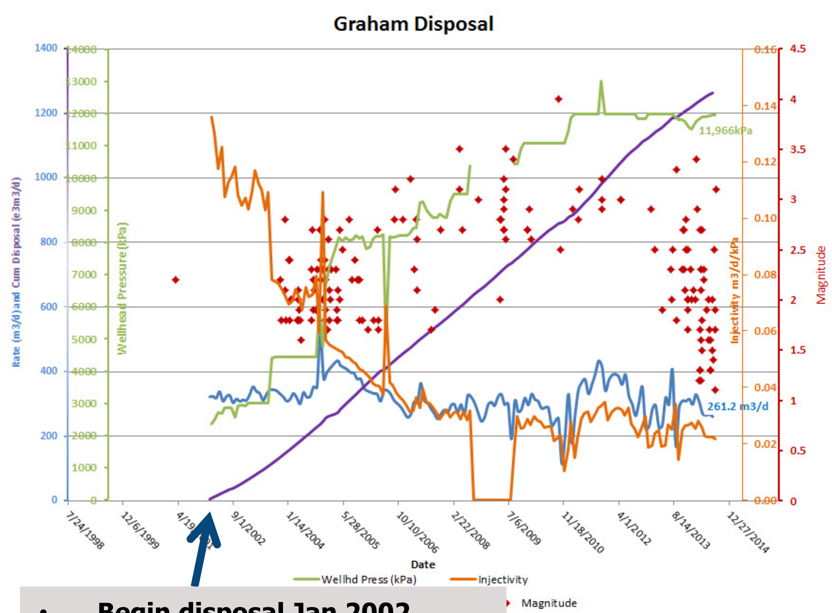


Begin disposal Aug 2012

9. Graham – March 2001-December 2014 (Wastewater Disposal Induced Seismicity)



Graham area, 197 NRCan recorded events, mag 1.1 to 4.0ML, Nov 2, 2003 - Dec 2014 (only 2014 events shown on map)



- **Begin disposal Jan 2002**
- **First induced event recorded Nov 4, 2003**

Events red diamonds