Investigation of Observed Seismicity in the Horn River Basin

BC Oil and Gas Commission - August 2012

BC Oil & Gas COMMISSION

Table of Contents

About the

BC Oil and Gas Commission

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

The Commission's core roles include reviewing and assessing applications for industry activity, consulting with First Nations, ensuring industry complies with provincial legislation and cooperating with partner agencies. The public interest is protected by ensuring public safety, protecting the environment, conserving petroleum resources and ensuring equitable participation in production.

For general information about the Commission, please visit www.bcogc.ca or phone 250-794-5200.

Fort St. John
Fort Nelson
Dawson Creek
Kelowna
Victoria
www.bcogc.ca

Terms Used in this Report

'Seismicity', 'Seismic Events' and 'Events' – used interchangeably to describe seismograph recorded earthquakes caused primarily by fault movement.

'Micro-Seismicity' – very low magnitude events created by shear movement or tensile fracture during hydraulic fracturing not detectable by the Canadian National Seismograph Network (CNSN).

'Microseismic' – describes both the recording and processing of very small magnitude events produced by hydraulic fracturing.

'Induced Seismicity' – generally defined as earthquakes resulting from human activity.

'Stage' – refers to a hydraulically fractured interval along a horizontal wellbore, each stage is isolated and perforated prior to the injection of fluids to hydraulically fracture the reservoir rock.

Executive Summary

This report provides the results of the BC Oil and Gas Commission's (Commission) investigation into anomalous seismicity within geographically confined and remote areas in the Horn River Basin between April 2009 and December 2011. The investigation was commenced immediately after the Commission became aware of a number of anomalous, low-level seismic events which were recorded by Natural Resources Canada (NRCan) near areas of oil and gas development. Only one of the events under investigation had been reported by NRCan as "felt" at the earth's surface.

In undertaking the investigation, the Commission notes that more than 8,000 high-volume hydraulic fracturing completions have been performed in northeast British Columbia with no associated anomalous seismicity. None of the NRCan reported events caused any injury, property damage or posed any risk to public safety or the environment.

The investigation was completed by the Commission's geological and engineering staff within the Resource Development department, and they benefited from consultation with NRCan, the University of British Columbia and the Alberta Geological Survey. Data was obtained from numerous sources including open source information as well as proprietary data acquired by oil and gas companies working near the area of the investigation.

The Commission also acknowledges the professional, open and honest exchanges of information and analyses between the regulated industry and the investigation team.

The investigation has concluded that the events observed within remote and isolated areas of the Horn River Basin between 2009 and 2011 were caused by fluid injection during hydraulic fracturing in proximity to pre-existing faults.

Three sets of events are discussed in the report, the 38 events reported by NRCan, 216 events recorded by a dense array deployed at Etsho and 18 events recorded by a dense array deployed at Kiwigana. All these events are interpreted to be the result of fault movement.

The Etsho dense array monitored the d-1-D/94-O-8 pad. Events, recorded by this array, occurred on microseismic plots along linear trends interpreted to be faults. In only one instance did a linear seismic swarm overlay a fault mapped with 2D or 3D seismic.

Fault maps interpreted from 2D and 3D seismic were submitted for the investigation. These showed 12 mapped faults intersecting five of the 7 d-1-D pad wellbores. No events could confidently be linked to 11 of these faults, indicating that most of the faults intersected either did not slip or did move without generating a detectable event.

Disposal wells were ruled out as a source of the seismicity during the investigation. Four disposal wells were operating during the period of observed seismicity: three at Etsho and one in the Tattoo area. These wells were injecting recovered hydraulic fracturing fluids into the Mississippian Debolt Formation, 1800 metres above the Horn River Group. All event epicentres occurred within the Devonian Horn River Group and no fault movement was seen in the Debolt Formation.

The Commission makes seven recommendations based on the investigation, which include the submission of microseismic reports; establishment of a notification and consultation procedure; studying the relationship of hydraulic fracturing parameters on seismicity, and upgrading and improving B.C.'s seismograph grid and monitoring procedures. Improvements to the seismographic grid network have already begun through funding provided by Geoscience BC. The upgraded grid will provide improved monitoring for induced seismicity and will form the basis for the monitoring, detection, notification and consultation procedure.

In addition, the Commission has initiated a broader study with the University of British Columbia to examine factors related to the extent, magnitude, impact and control of induced seismicity in northeast B.C. The intent of this research is to provide insights into predicting the location and magnitude of seismic events based on hydraulic fracturing parameters and geomechanics and to establish protocols for prediction, detection, monitoring and mitigation of these events.

Event Summary

Between April 2009 and July 2011, 31 seismic events were recorded and located by NRCan in the Etsho area of the Horn River Basin in northeast British Columbia (Figure 1). Another seven events were recorded near the Tattoo area between Dec. 8 and Dec. 13, 2011. The observed events ranged in magnitude between 2.2 and 3.8 M_L on the Richter scale as recorded by NRCan (Table 1).

A search of the areas in the National Earthquake Database from 1985 to present shows no detected seismicity in the Horn River Basin prior to 2009. Two events (1985/09/04, 3.1M_L and 1986/09/28, 2.9M_L) located approximately 160 km south and southwest of Fort Nelson were detected by the Canadian National Seismograph Network (CNSN). This suggests that similar events occurring in the Horn River Basin could have been recorded. Two NRCan seismograph stations, part of the CNSN, are currently operational in northeast British Columbia. The Bull Mountain station near Hudson's Hope became operational in January 1998 and the Fort Nelson station came online in 1999. Magnitudes have been processed and reported down to approximately 2.0 M_L in the Horn River Basin since deployment of these two stations. Smaller events may have occurred and gone undetected due to the detection limitations of the CNSN. While the full extent of historical seismicity is not known, the April 2009 to December 2011 Etsho and Tattoo events are considered anomalous events when considered in full context.

Figure 1: Location of Etsho, Tattoo and Kiwigana areas in the Horn River Basin. Red triangles show NRCan reported epicentres, Bovie and Trout Lake Fault zones noted. Liard Basin to west of Bovie Fault. Blue star indicates location of Kiwigana seismograph array.

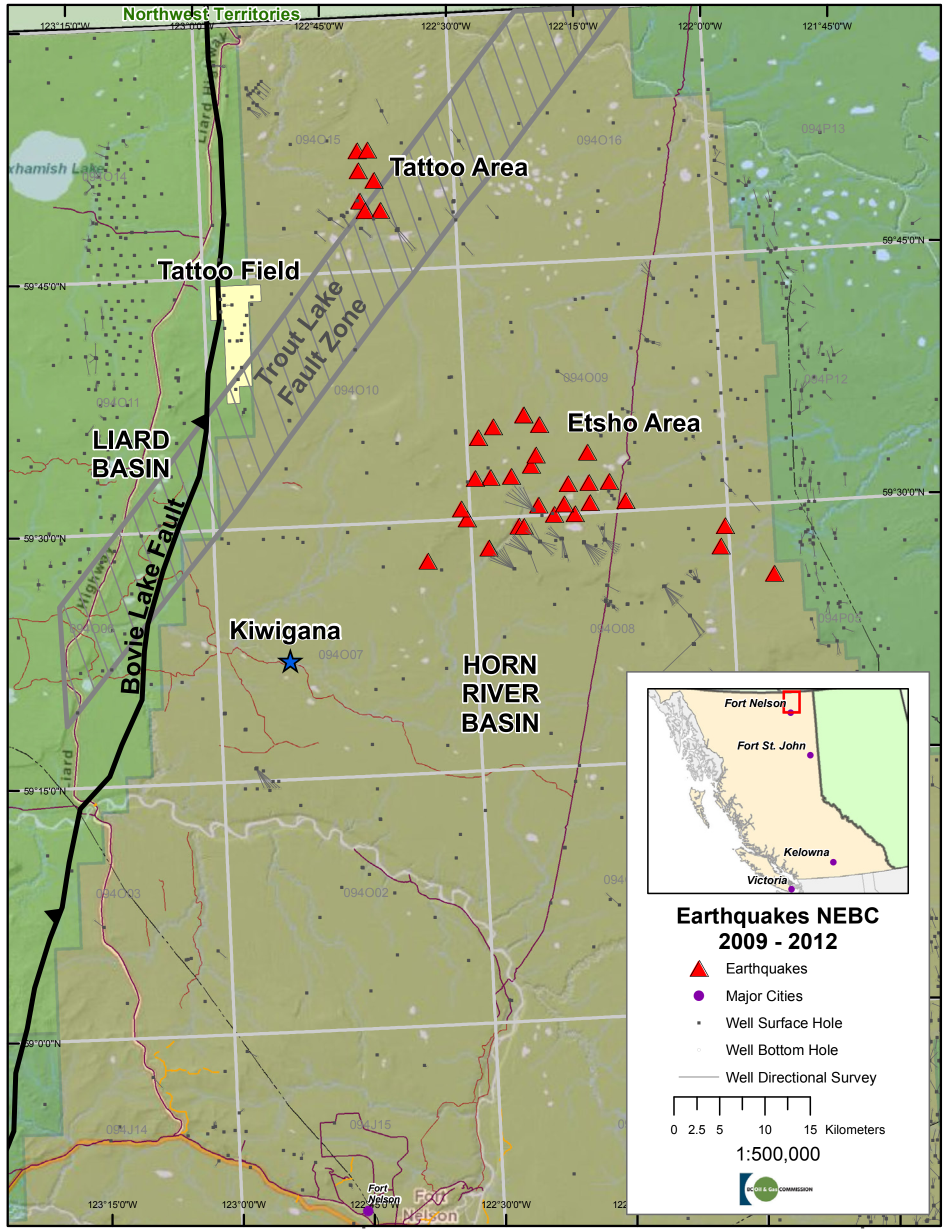


Table 1 provides a summary of the events recorded by NRCan in the Etsho and Tattoo areas that are plotted and shown on Figure 1.

The events in Table 1 were proximate to oil and gas activities employing hydraulic fracture operations when the events occurred.

Table 1 – Magnitude and Location of NRCan Seismic Events, with date and time.

Modified from NRCan report.

Event #	Date	Time (UT)	Time (Pacific)	Correct Date	Lat	Long	Mag	Approximate Location
38	2011/12/13	13:17:32	5:17:32		59.84	-122.66	3.1ML	114 km N of Fort Nelson
37	2011/12/12	23:34:12	15:34:12		59.81	-122.68	3.1ML	110 km N of Fort Nelson
36	2011/12/12	07:59:22	23:59:22	12/11/2011	59.82	-122.69	2.9ML	112 km N of Fort Nelson
35	2011/12/11	09:15:57	1:15:57		59.85	-122.69	2.4ML	114 km N of Fort Nelson
34	2011/12/11	02:37:53	18:37:53	12/10/2011	59.87	-122.67	2.9ML	116 km N of Fort Nelson
33	2011/12/10	02:52:34	18:52:34	12/9/2011	59.87	-122.69	2.9ML	117 km N of Fort Nelson
32	2011/12/08	15:28:37	7:28:37		59.81	-122.65	2.8ML	111 km N of Fort Nelson
31	2011/07/14	10:40:32	2:40:32		59.51	-122.20	2.5ML	82 km NE of Fort Nelson
30	2011/07/07	22:46:37	14:46:37		59.49	-122.40	3.1ML	76 km NNE of Fort Nelson
29	2011/07/01	09:32:46	1:32:46		59.54	-122.49	2.6ML	81 km NNE of Fort Nelson
28	2011/06/26	13:17:02	5:17:02		59.56	-122.37	2.7ML	84 km NNE of Fort Nelson
27	2011/06/18	23:02:03	15:02:03		59.82	-121.47	2.8ML	132 km NE of Fort Nelson
26	2011/05/29	08:09:47	0:09:47		59.54	-122.46	3.1ML	81 km NNE of Fort Nelson
25	2011/05/20	06:22:34	22:22:24	5/19/2011	59.51	-122.52	3.0ML	78 km NNE of Fort Nelson
24	2011/05/19	13:13:43	5:13:43		59.47	-122.47	3.3ML	74 km NNE of Fort Nelson
23	2011/05/19	13:05:15	5:05:15		59.49	-122.41	3.8ML	76 km NNE of Fort Nelson
22	2011/05/10	14:16:03	6:16:03		59.51	-122.37	3.5ML	79 km NNE of Fort Nelson
21	2011/05/03	12:56:29	4:56:29		59.51	-122.32	3.2ML	80 km NNE of Fort Nelson
20	2011/04/30	13:27:30	5:27:30		59.46	-122.59	3.1ML	72 km N of Fort Nelson
19	2011/04/28	22:34:51	14:34:51		59.47	-122.47	2.5ML	73 km NNE of Fort Nelson
18	2011/04/07	12:19:20	4:19:20		59.50	-122.51	3.2ML	76 km NNE of Fort Nelson
17	2011/03/04	03:09:05	19:09:05	3/3/2011	59.50	-122.34	3.3ML	78 km NNE of Fort Nelson
16	2010/10/12	21:01:11	13:01:11		59.55	-122.38	3.4ML	83 km NNE of Fort Nelson
15	2010/10/12	19:19:44	11:19:44		59.53	-122.31	3.0ML	83 km NNE of Fort Nelson
14	2010/10/12	17:09:40	9:09:40		59.59	-122.45	3.4ML	87 km NNE of Fort Nelson
13	2010/10/09	10:00:31	2:00:31		59.54	-122.42	3.1ML	82 km NNE of Fort Nelson
12	2010/10/05	22:01:14	14:01:14		59.60	-122.39	3.6ML	88 km NNE of Fort Nelson
11	2010/10/05	13:30:28	5:30:28		59.53	-122.27	3.1ML	83 km NNE of Fort Nelson
10	2010/10/04	11:09:34	3:09:34		59.59	-122.36	2.9ML	88 km NNE of Fort Nelson
9	2010/10/03	08:06:50	0:06:50		59.56	-122.27	3.5ML	86 km NNE of Fort Nelson
8	2010/09/30	12:33:36	4:33:36		59.58	-122.48	3.0ML	85 km NNE of Fort Nelson
7	2010/09/30	12:31:43	4:31:43		59.60	-122.39	2.9ML	89 km NNE of Fort Nelson
6	2010/08/22	09:30:20	1:30:20		59.53	-122.23	2.4ML	84 km NE of Fort Nelson
5	2010/08/03	20:15:35	12:15:35		59.51	-122.27	2.7ML	81 km NNE of Fort Nelson
4	2010/06/11	22:25:19	14:25:19		59.50	-122.30	3.4ML	79 km NNE of Fort Nelson
3	2009/04/09	16:34:00	8:34:00		59.48	-122.01	2.2ML	83 km NE of Fort Nelson
2	2009/04/08	21:30:23	13:30:23		59.43	-121.92	2.3ML	82 km NE of Fort Nelson
1	2009/04/08	21:27:37	13:27:37		59.46	-122.02	2.3ML	81 km NE of Fort Nelson

www.earthquakescanada.nrcan.gc.ca/

Investigation Overview

The Commission began a formal investigation in July 2011 into the anomalous events recorded by NRCan in the Etsho area. The investigation was extended to the Tattoo area when similar anomalous events were detected there in December 2011. The purposes of the investigation were to:

- Examine the available evidence to determine if there may be a linkage between oil and gas activities and the observed events.
- Review current research on induced seismicity and apply those results to the investigation.
- Consider possible mitigation methodologies, where appropriate, should a link be established between the observed events and oil and gas activities.

The Commission began the investigation with a review of hydraulic fracturing and well completion information on wells situated near the area of observed seismicity in the Etsho area. The dates and times of hydraulic fracturing operations were compared to the dates and times of recorded seismicity events.

To obtain additional information to assist in the investigation, the Commission issued formal Information Requests (IRs) to six operators within the study area. The IRs provided the Commission access to data not currently required to be submitted by the operators to the Commission. Much of this operator information obtained is proprietary and includes detailed completion statistics, microseismic reports, groundwater analyses and seismic mapping. In some cases, confidential data is used to support findings or analyses but not reproduced within the report.

Under British Columbia legislation and regulation, specified oil and gas information is required to be collected and submitted to the Commission. This includes geophysical logs, sample reports and drilling and completion information. Data is held confidential for a time period as defined in the regulation, dependent on well classification.

Through the course of the investigation, the Commission consulted with experts from industry, NRCan, the University of British Columbia and the Alberta Geological Survey.

A literature search was done as part of the investigation, focusing on science and analysis of induced seismicity as well as the geology of the Horn River Basin. Included in this search were a number of recent public reports on induced seismicity incidents in Oklahoma, England and Ohio.

Table 2: Richter Scale diagram showing range of magnitudes and effects. Based on US Geological Survey documents.

Event Frequencies courtesy of USGS (estimates).

Magnitude (M_L)	Description	Earthquake Effects	Natural Seismicity Occurences Worldwide
-3.0 – 0.5	Micro-Seismicity	Micro events created when hydraulic fracturing breaks rock, including micro shear movement and tensile fracturing, not felt	Very frequent. Detection reliability extremely varied. Frequency estimated at many millions of events per year.
0.5- 2.0	Micro earthquake	Very small earthquakes, not felt.	Very frequent. Detection reliability extremely varied. Frequency estimated at many millions of events per year.
2.0–2.9	Minor	Generally not felt, but recorded. (Not felt in Horn River Basin)	1,300,000
3.0–3.9	Minor	Often felt, but rarely cause damage.	130,000
4.0–4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	13,000

Background Information

Measuring Earthquakes

Unless otherwise noted, earthquake magnitudes reported in this investigation are Richter scale magnitudes (M_L) (Table 2) and occur throughout this report as both positive and negative numbers. The Richter magnitude scale was originally calibrated to a seismograph in 1935. At that time, zero on the scale was set as an event that would cause a one micrometre displacement on a seismogram 100 kilometres (km) from an epicentre. Instrument sensitivity has improved with time and modern seismographs are capable of detecting earthquakes that fall below the original zero value set by Richter. Negative Richter values account for this enhanced sensitivity.

Duration magnitude (Md) used by Holland (Holland, 2011) scales earthquakes using surface wave durations and is consistent with the Richter scale.

Station Coverage of the Canadian National Seismograph Network (CNSN)

The locations of earthquakes are generally referred to using the terms “epicentre” and “hypocentre” or “focus”. The epicentre is the location on the earth’s surface located directly above the “hypocentre” or “focus” where an event actually occurs underground.

The CNSN is designed to monitor moderate to strong magnitude earthquakes that pose a risk to public safety and not to detect low magnitude induced seismicity. Currently, the portion of the CNSN for northeast British Columbia consists of two stations, the Bull Mountain (Hudson’s Hope) and Fort Nelson seismograph stations. The limited station coverage in the region results in an uncertainty of 5 to 10km in the epicentral locations of detected earthquakes. The uncertainty in earthquake focal depths is even larger. Minimum magnitude detection by CNSN for earthquakes in the northeast BC region is estimated at 2.0 M_L but in the course of the investigation, it was found that the current grid had failed to detect 15 events greater than 2.0 M_L. From June 23 to August 14, 2011, an operator deployed local seismograph array at Etsho detected 19, 2.0 to 3.0 M_L events. Only four of these events were reported by NRCan.

Induced Seismicity in British Columbia

Induced seismicity may be caused by numerous factors including slippage along fault planes, ground subsidence from collapse of solution mines and stress release from reservoir depletion. Fault movement can occur when previously stable subsurface stress conditions are altered. Human activities that can alter these stress conditions include fluid injection for secondary recovery in hydrocarbon reservoirs, injection of waste fluids into deep rock formations, withdrawal of hydrocarbons from reservoirs and geothermal energy operations involving deep fluid injection.

Fluid injection may trigger induced seismicity. As fluid is injected, it flows into the existing pore system of the rock and into pre-existing fractures and faults. Across faults injection can increase pore pressure, counter-acting normal stress across the fault and may act to open an existing fault plane. This overcomes friction along the fault and can cause fault slippage.

In British Columbia, the only documented case of induced seismicity, linked to oil and gas activity, occurred in the Eagle Field area, approximately five km north of Fort St. John. Twenty-nine Richter magnitude 2.2 to 4.3 events were recorded from November 1984 to May 1994. Horner (Horner, 1994) used the Davis and Frohlich criteria (Davis and Frohlich, 1993) to conclude that the events were induced. High pressure fluid injection for secondary oil recovery was identified as a possible cause. High volume hydraulic fracturing was not employed in the area at that time.

In response to the Eagle Field incident, the regulator ordered the injection pressure be lowered. Since that time, reservoir waterflood and injection pressures within British Columbia are required to be maintained below levels capable of re-opening pre-existing fractures or faults. This requirement ensures the integrity of confinement boundaries and prevents fluid migration beyond the targeted formations.

Geology of the Horn River Basin

The Horn River Basin in northeast British Columbia lies between Fort Nelson and the Northwest Territories border (Figure 2). Basinal shales of the Horn River Group fill the Basin, bounded to the west by the Bovie fault and to the east by laterally equivalent Keg River and Slave Point Formations reef carbonates (Figure 3). The Muskwa, Otter Park and Evie Formations of the Horn River Group are highly siliceous, high organic content shale gas targets (McPhail et al, 2008). Overlying the Horn River Group are over 800 metres (m) of clay rich shales of the Fort Simpson Formation (Figure 3). As mineralogy transitions from the siliceous shales of the Muskwa Formation to the clay rich shales of the overlying Fort Simpson, a natural barrier to fracture propagation occurs and the growth of fractures caused by hydraulic fracturing is contained to the targeted Muskwa and Evie shales.

The Bovie Fault extends over 100 km from the northern British Columbia border south and then southwest into the foothills. This fault separates the Horn River Basin from the Liard Basin (Figure 1). Trending northeast from about 30 km south of Maxhamish Lake toward the Celibeta High is the Trout Lake Fault zone with a strike-slip component. (MacLean, Morrow, 2004).

Figure 2: Provincial map of British Columbia showing locations and outlines of Horn River and Liard Basins and Cordova Embayment

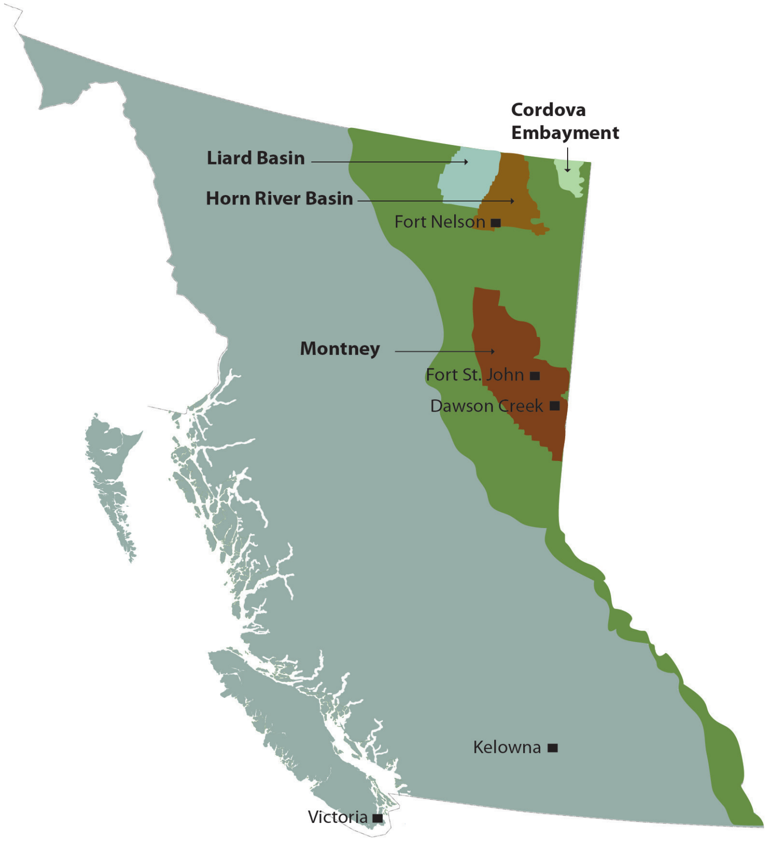
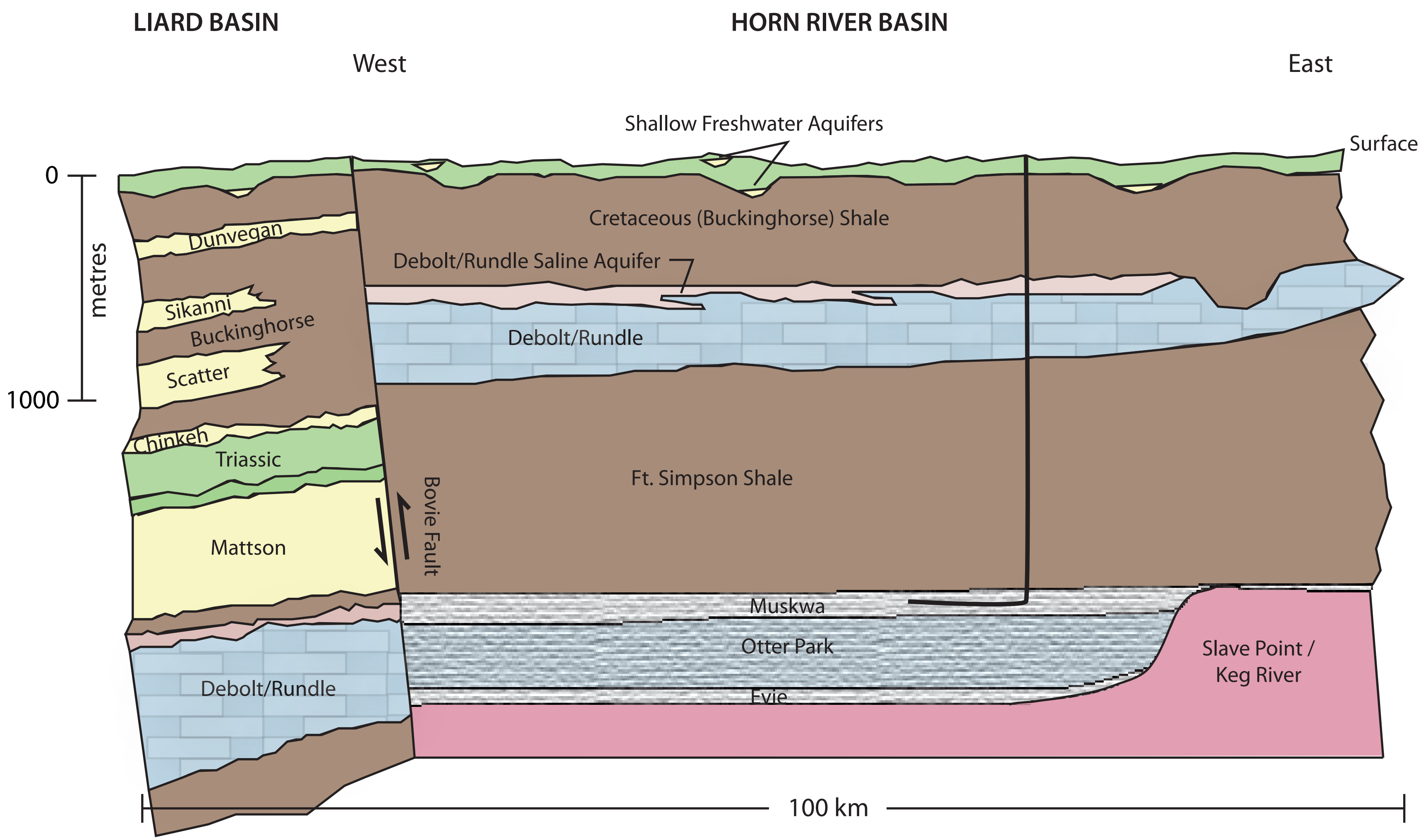


Figure 3: Cross-section of Horn River Basin showing Muskwa, Otter Park and Evie formation shale gas targets. Horizontal wellbores target the Muskwa, Otter Park and Evie zones. Diagram modified from Geoscience BC Horn River Basin Subsurface Aquifer Characterization Project schematic cross-section.



Hydraulic Fracturing in the Horn River Basin

In the Etsho study area, horizontal wells targeting the Horn River shales were hydraulically fractured using multiple stages of slickwater and sand. The horizontal leg of each well was cemented with casing and a “perf and plug” technique was used to initiate the fractures, starting at the toe of the well and proceeding to the heel. Each hydraulic fracture stage was isolated with bridge plugs and received multiple perforations prior to pumping the stage. Once all the stages were complete, the bridge plugs were drilled out and the hydraulic fracture fluid was flowed back to surface.

Analysis of microseismic data shows that fracture growth within the study area is confined to the target Horn River shales. It appears that the overlying Ft. Simpson shale acts as a highly effective fracture barrier during hydraulic fracturing.

Hydraulic fracturing operations in the Etsho area have been ongoing from February 2007 to late July 2011. During this period, 14 different drilling pads were used to drill over 90 wells with more than 1,600 hydraulic fracturing stage completion operations (Table 3).

Table 3: Pad Hydraulic Fracturing Statistics for Etsho (non-confidential pads). Minimum, maximum and average numbers are calculated from all pad data reviewed. Only non-confidential pads are listed in the table.

Well Pad	Wells/Pad	Stages/Well	HZ Completed (m)	Fluid/Well (m^3)	Sand/Well (Tonnes)	Avg Pump Rate (m^3/minute)	Fracs/Pad	# of Seismic Events
b-100-G	5	5	1,176	11,505	710	12	26	0
c-1-J	9	16	1,837	52,429	3,072	14	147	0
b-76-K	13	15	1,752	58,386	2,454	15	180	1
d-70-J	7	14	1,391	53,800	2,692	15	74	3
d-1-D	7	27	2,727	138,005	5,484	15	176	6
c-34-L	9	18	2,200	63,000	3,200	15	162	7
b-63-K	14	23	2,452	107,738	4,505	14	347	13
Average	**8**	**17**	**1,846**	**61,612**	**3,107**	**13**	**149**	**3**
Min.	**4**	**5**	**1,176**	**11,505**	**710**	**8**	**26**	**0**
Max.	**16**	**27**	**2,727**	**138,005**	**5,484**	**15**	**347**	**13**

Literature Review

Recently, two international cases of induced seismicity have been documented linking hydraulic fracturing to seismic events. In the first case, Dr. C.J. de Pater and Dr. S. Baisch (de Pater and Baisch, 2011) directly tie hydraulic fracturing in the Bowland Shale near Blackpool, England to local seismicity. In the second case, Holland (Holland, 2011) suggests a relationship between hydraulic fracturing in Garvin County, Oklahoma and local seismicity.

Other studies considered during the investigation include Shale Gas Extraction in the UK: A Review of Hydraulic Fracturing published by the Royal Academy of Engineering in June 2012 and Induced Seismicity Potential in Energy Technologies (Pre-Publication) by the US National Research Council.

Blackpool, UK

Near Blackpool, England, the Preese Hall–1, spudded Aug. 16, 2010, targeted gas in the Bowland shale. The Bowland shale was encountered at 1,993.3 m (metres) (6,540 feet) MD (Measured Depth) and was drilled to 2,744.4 m (9,004 feet) MD. Hydraulic fracturing ran from 2,337.8-2,727.6 m (7,670 – 8,949 feet). From March 28 to May 27, 2011 five hydraulic fracturing (slickwater) stages were run. Stage volumes ranged from 596.2–1,669.4 cubic metres (m^3) (5,000-14,000 bbls) water and 52-117 metric tonnes proppant. Bottom-hole pressures reached a gradient of 21.4 KPa/m (0.95 psi/ft).

Fifty events, magnitude -2 to 2.3 M_L, (generally considered to be below the threshold for detection as a "felt" event at the surface) were recorded from March 28 to May 28, 2011. Seismicity is focused around stages 2, 4 and 5. Events began early in stage operations and the strongest event occurred 10 hours after shut-in. The occurrence of events some time after hydraulic fracturing operations is interpreted to be the effect of a pressure front spreading out from the hydraulic fracturing injection point. De Pater and Baisch (de Pater and Baisch, 2011) conclude that seismicity magnitude can be mitigated by "rapid fluid flow back after the treatments and reducing the treatment volume".

Sufficient movement occurred to deform well casing within the target formations on the horizontal leg. The casing deformation was attributed to "distributed, small magnitudes of bedding plane slip".

Garvin County, USA

In Garvin County, Oklahoma, hydraulic fracturing operations began at the Picket Unit B Well 4-18 on Jan 17, 2011. This is a vertical well located in the Eola field at the northern edge of the Ardmore basin. The geology of the area consists of numerous, major, parallel faults running west-northwest to east-southeast. Several northwest to southeast trending faults intersect the major faults. The Eola field is block faulted and fault dips are near vertical.

Fifty events, magnitude 1-2.8 Md (Duration Magnitude), occurred on Jan. 17-18, 2011. The events began seven hours after hydraulic fracture operations started.

Thirty-nine of the events occurred within 16 hours after hydraulic fracturing operations began. Although this area of Oklahoma has considerable natural seismicity, seismological evidence indicates a unique origin different from naturally occurring earthquakes.

Holland used the seven question Davis and Frohlich criteria (Davis and Frohlich, 1993) to help determine if the events were induced. The following summarizes Holland's answers:

1. Are these events the first known earthquakes of this character in the region? (UNKNOWN) It was difficult to determine if the events were uniquely different from previously recorded earthquakes in the area.
2. Is there a clear correlation between injection and seismicity? (YES) There was a clear correlation between hydraulic fracturing and earthquake times.
3. Are the epicenters near wells (within 5 km)? (YES) The epicentres are within five kilometres of the Picket well.
4. Do some earthquakes occur at or near injection depths? (YES) Most earthquakes occurred near injection depths. Depth uncertainty on seismic recording is about 630 m.
5. If not, are there known geologic structures, that may channel flow to sites of earthquakes? (YES) Faults exist that could channel injection fluid to epicentre locations.
6. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity? (YES) Hydraulic fracturing pressures are sufficient to encourage seismicity.
7. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity? (UNKNOWN) Pressure diffusion could not be adequately modeled within the Eola Field.

Holland concluded that timing and location of the events suggested a possible connection to hydraulic fracturing.

Operator Dense Array Deployments

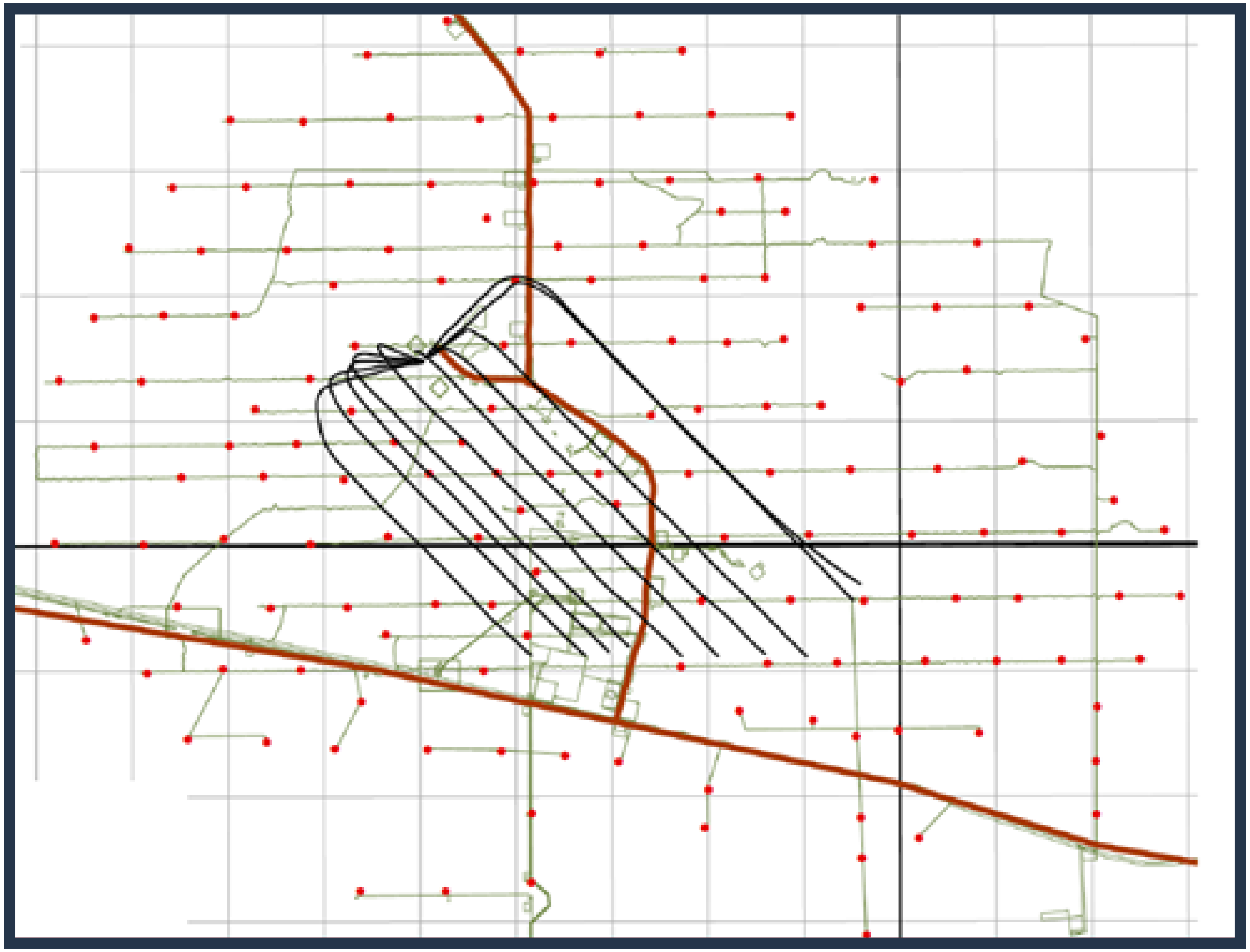
Etsho

A 20-seismograph dense array was deployed in the Etsho area to record, locate and study the seismicity in greater detail than possible with NRCan data. This array, surrounding the d-1-D/94-O-8 pad, was operated from June 16 to Aug. 15, 2011.

Kiwigana

A second dense array was deployed at Kiwigana, 40 kilometres to the southwest of the Etsho area (Figure 1). This 151-station seismograph array was located over the ECA HZ KIWIGANA c-15-D/94-O-7 multi-well pad and operated from Oct. 25, 2011 to Jan. 27, 2012 (Figure 4).

Figure 4: Map of Kiwigana dense array, surrounding c-15-D/94-O-7 pad, showing horizontal wellbores (black lines) and seismograph locations (red dots).



Analysis

Induced Seismicity

Hydraulic fracturing is the process of creating cracks (fractures), in buried geological formations to create pathways along which hydrocarbons trapped within the formation can flow into the wellbore at higher rates than otherwise possible. The hydrocarbons then flow to the surface under controlled conditions through the wellhead and are collected for processing and distribution.

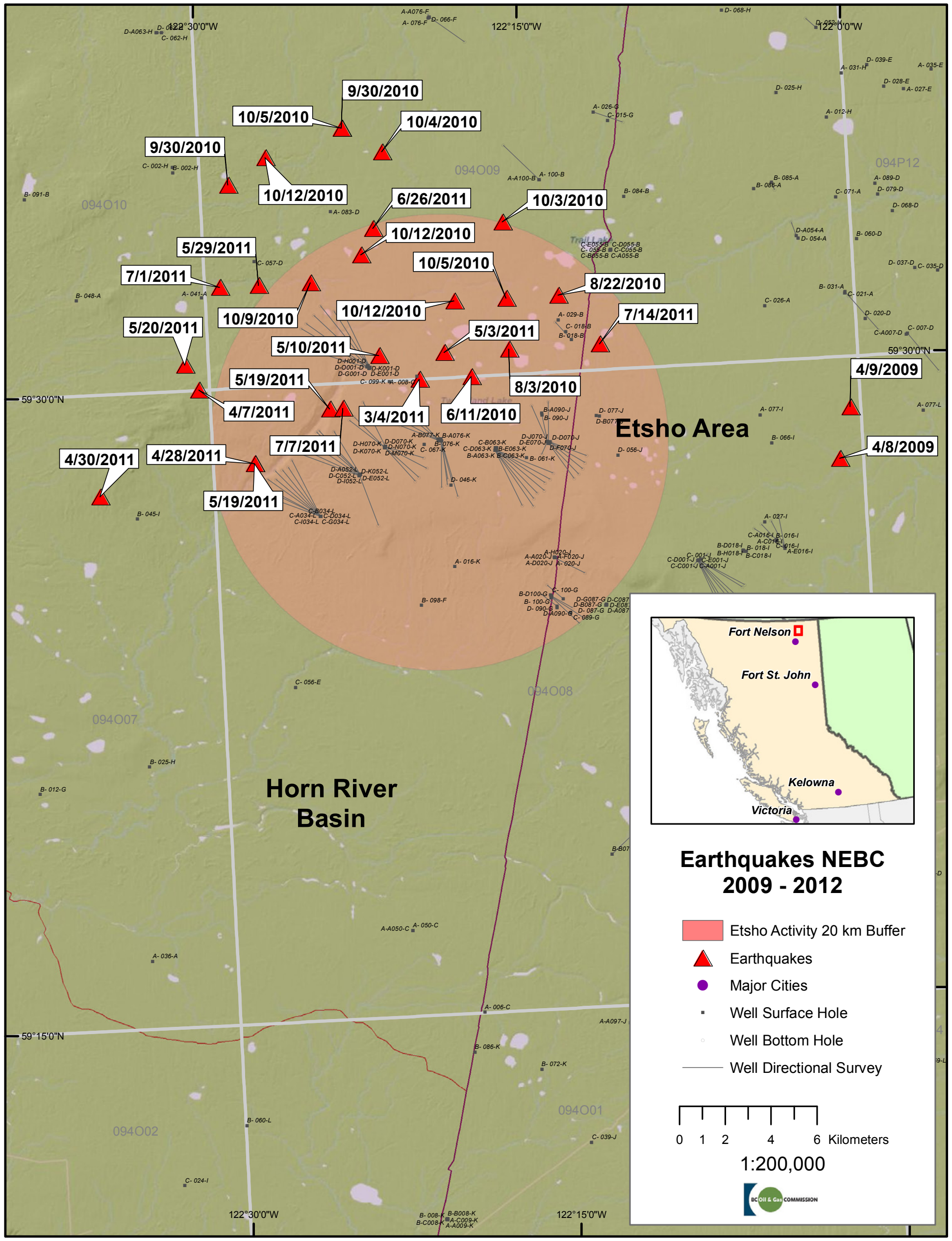
During the hydraulic fracturing process, a mixture of water, sand and other chemical additives designed to protect the integrity of the wellbore and enhance production is pumped under high pressure into the formation to create fractures. The fractures are kept open by sand or "proppant", which provides pathways to allow the natural gas to flow into the wellbore.

As hydraulic fracturing fluids are injected into intact gas bearing shales, thousands of micro-seismicity events (approx -3.0 to 0.5 M_L) are created as the rock is fractured. These events are caused by micro shear movement and tensile fractures and by the re-opening of existing fractures and faults. The micro-seismicity created by fracture development is often monitored during hydraulic fracturing by a borehole or surface seismograph array to assess the effectiveness of the fracture program. Special equipment is used as these events are far below the detection threshold of the seismographic monitoring networks in place for earthquake detection. For the purposes of this report, the focus is on seismicity that would not normally occur when performing hydraulic fracture completions (such as seismicity resulting from fault movement). Larger magnitude events may occur when fluid injected during hydraulic fracturing triggers movement along pre-existing stressed faults.

Only one event studied within this investigation was reported felt at surface. NRCan's report on the May 19, 2011, 3.8 M_L event indicates that the event was "felt by workers in (the) bush". No injuries or damage to surface structures were reported for this or any of the events studied within this investigation.

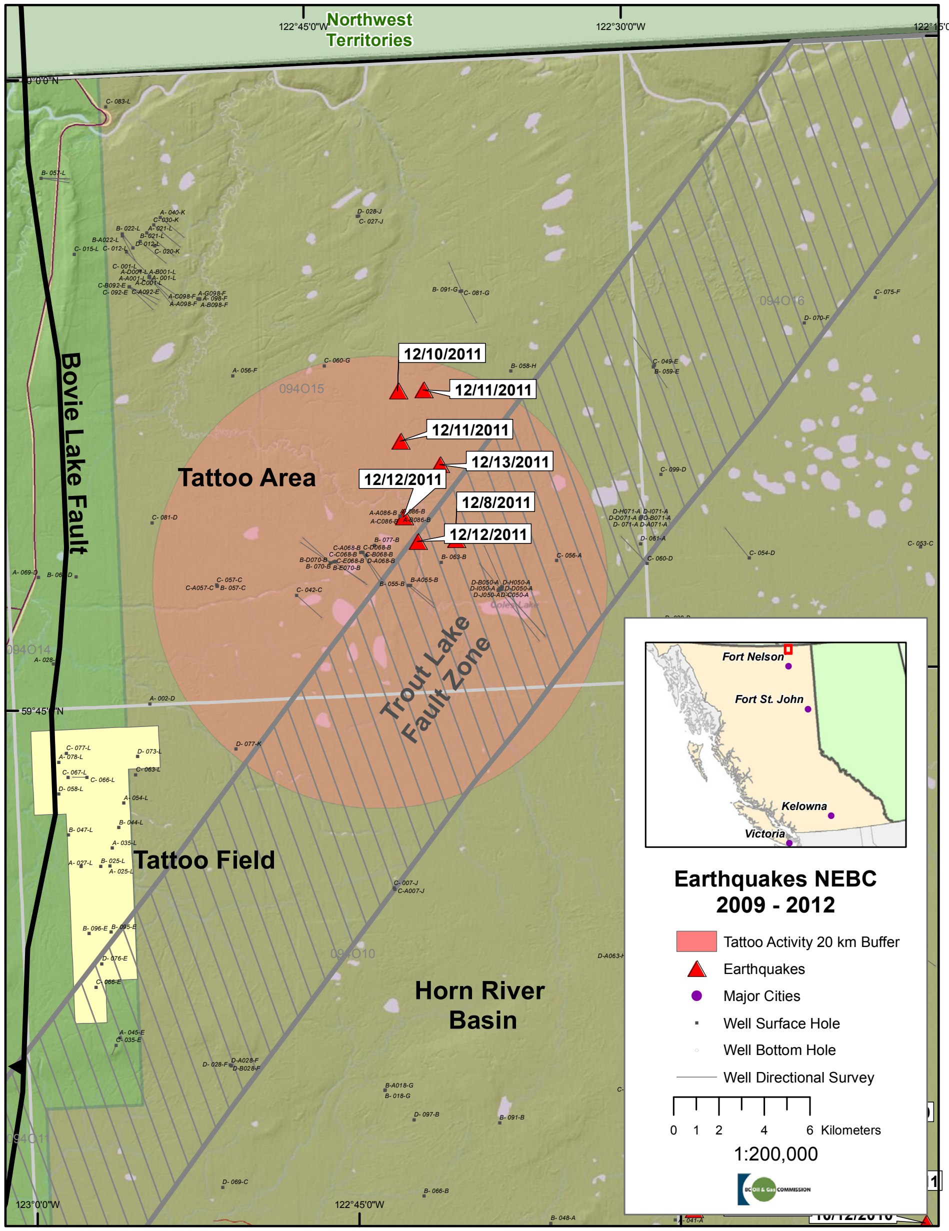
Twenty-seven of the recorded Etsho events lie within a 10 km radius circle (Figure 5). Within this same circle are seven multi-lateral drilling pads. Five of these pads were conducting hydraulic fracturing operations when events occurred.

Figure 5: NRCan event locations, event sequence and drilling pad locations, shown within 10km radius red shaded circle.



At Tattoo all seven of the recorded events can be encompassed within a 10 km radius circle that encloses two multi-well shale gas drilling pads. One pad at Tattoo had ongoing hydraulic fracturing operations when the seismicity occurred (Figure 6).

Figure 6: Tattoo area NRCan event epicentres and Multi-well Pads, shown within "20km buffer", 10km radius red circle.

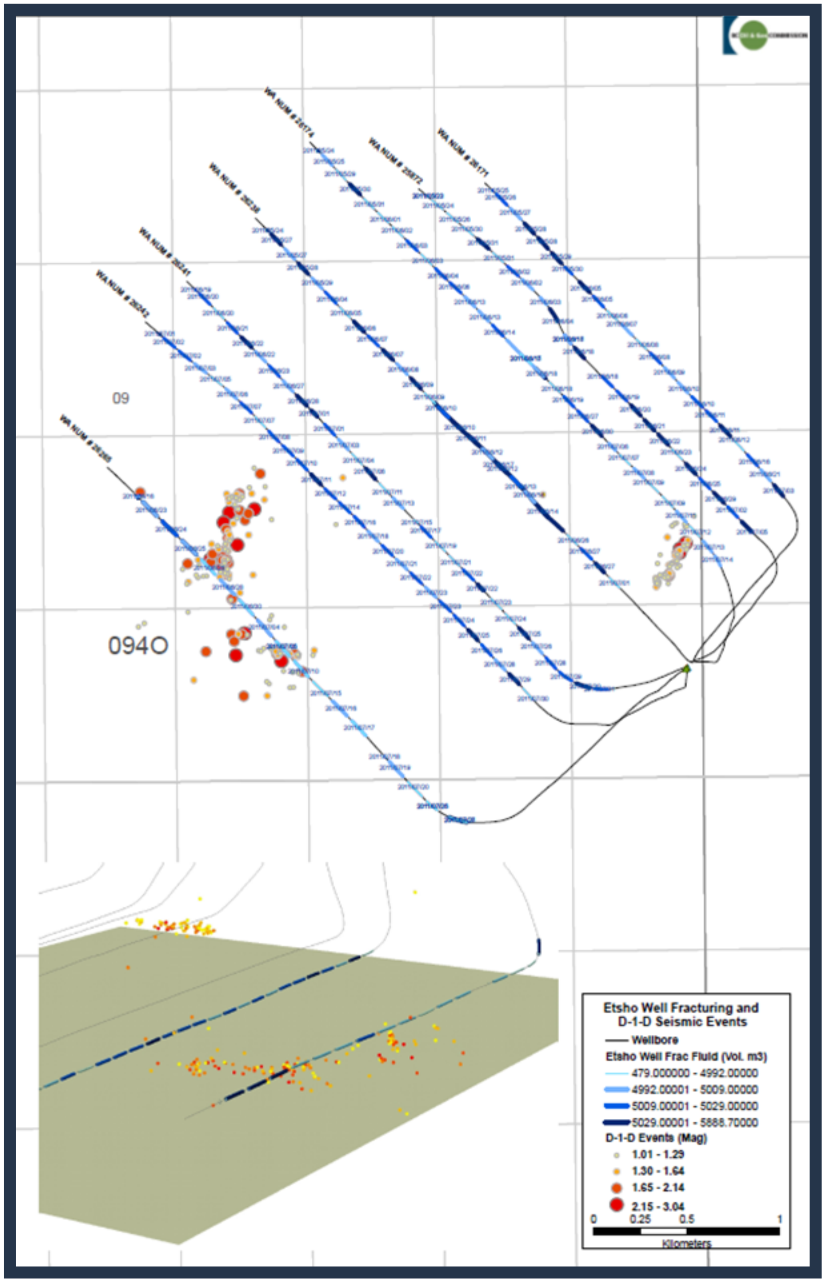


Seismicity Event Locations and Depth – Proximity to Hydraulic Fracturing

A number of events, ranging from magnitude -0.8 to 3.0 M_L, were recorded by the Etsho dense array during hydraulic fracturing. Of these, 216 are interpreted to be related to fault movement (197 events, magnitude 1.0 – 2.0M_L and 19 events magnitude 2.0-3.0 M_L). Operator provided b-value analysis indicated that magnitudes from 0.5M_L to 1.0M_L indicate the transition from fracture driven seismicity to seismicity driven by fault movement. For the dense array's operational date range, June 23 to August 14, the two northeast B.C. stations in the CNSN recorded four events (mag. 2.5 to 3.1 M_L).

Figure 7 shows the horizontal wellbores for the d-1-D drilling pad, volumes injected at each hydraulic fracturing stage and the magnitude >1.0M_L events occurring from June 23 to August 14, 2011.

Figure 7: Diagram showing d-1-D wellbores and events >1.0. Wellbores are black lines and stages with relative injection volumes are thickened blue sections.

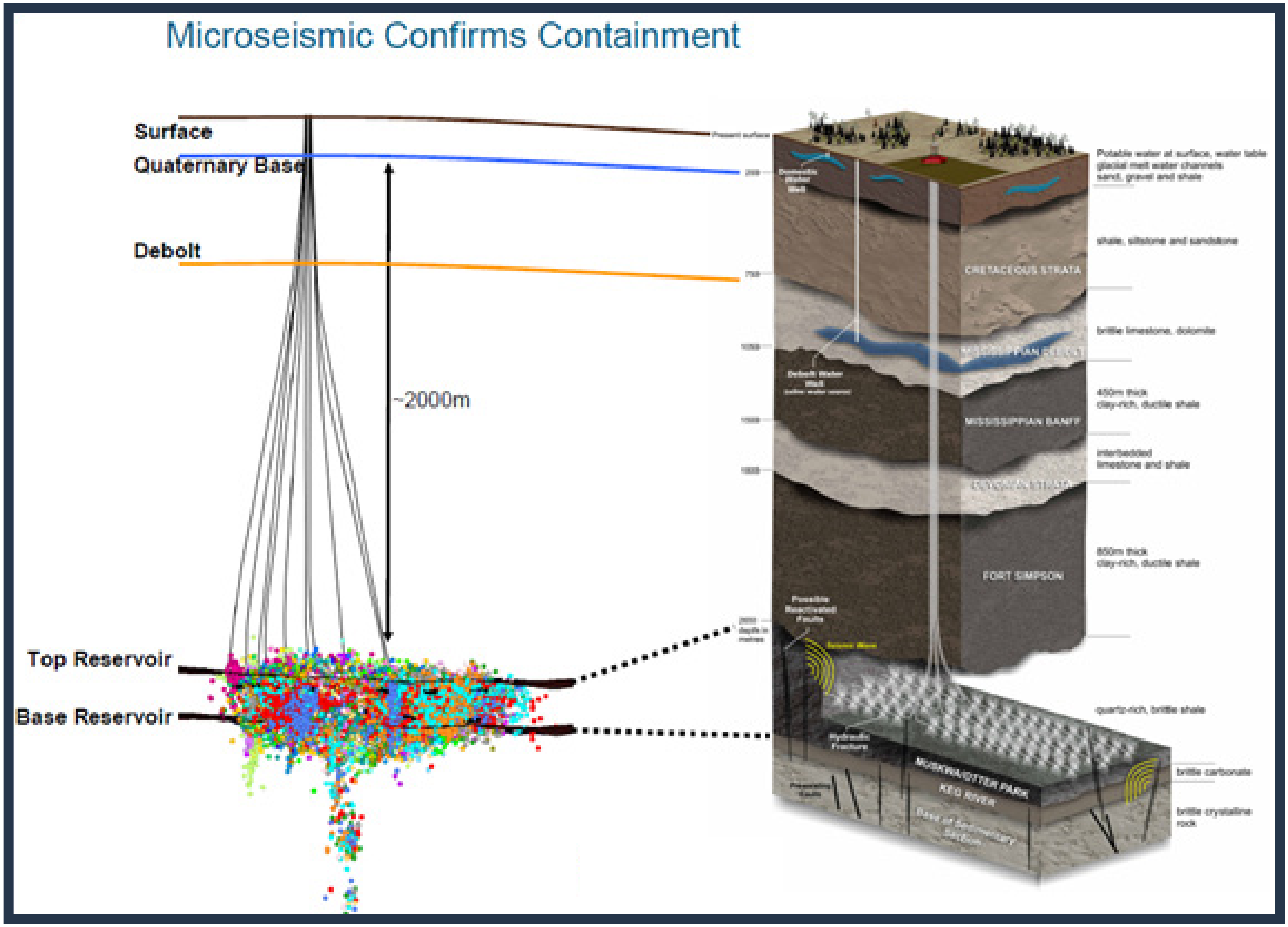


The horizontal and vertical locations of several events at Etsho detected by NRCan were relocated by the operator using data obtained from the dense array. The results of this work placed event hypocentres within 200 m, vertically and horizontally, of hydraulic fracturing stages. In cases where events could be confidently linked to hydraulic fracturing stages, events occurred during the event stage or prior to the following stage beginning. Associated faults, identified on microseismic plots as linear swarms, could be seen intersecting stage locations. True vertical depths (TVD) of hydraulic fracturing completions at the Etsho d-1-D pad range from approximately 2,650 to 2,889 metres TVD. Of the 69 magnitude 1.5 to 3.0 M_L seismic events recorded by the dense array and linked to this pad, all fall within the targeted formations. Sixty-six of these events occur between 2,800 and 2,870 metres.

At Kiwigana, numerous micro-seismicity events, ranging from -1.7 to 0.5 M_L, were detected between Oct. 25, 2011 and Jan. 27, 2012 by the operator deployed dense array. These micro-seismicity events resulted from tensile failure and shear movement during the normal process of hydraulic fracturing to develop the reservoir. An additional 18 events ranging from 1.0 to 1.86 M_L were detected and are interpreted to be the result of injection fluids triggering movement along pre-existing faults.

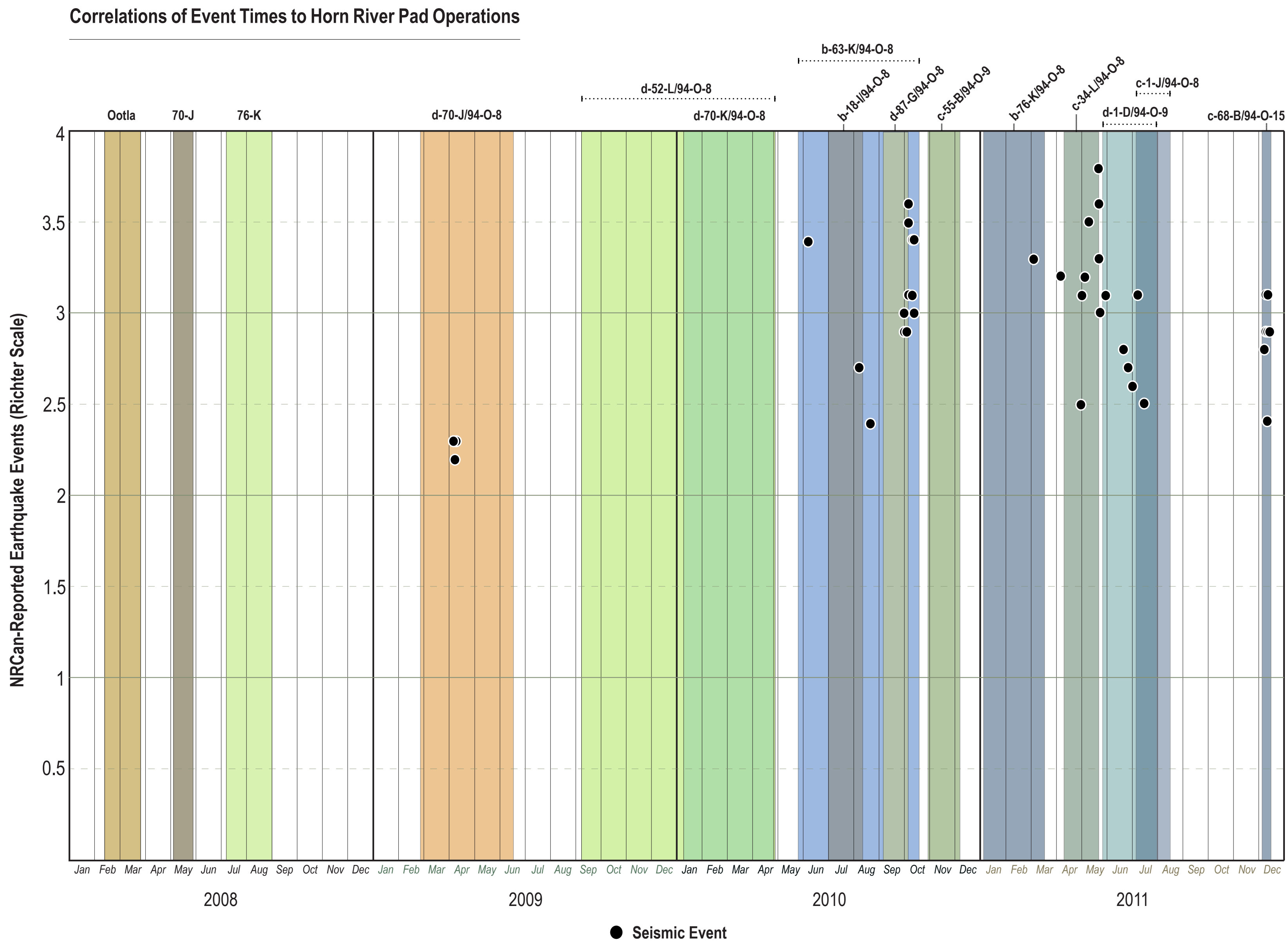
Figure 8 is a cumulative microseismic plot showing a vertical profile of the Kiwigana wellbores at the c-15-D pad. Coloured dots indicating micro-seismicity show that hydraulic fracturing operations are successfully contained to the Horn River shale target horizons and that the overlying Ft. Simpson shale provides an effective barrier to vertical fracture growth. A fault is suggested near the centre of the wellbores by the downward trending collection of microseismic points.

Figure 8: Cumulative microseismic plot for Kiwigana, coloured dots indicate contained micro-seismicity events caused by tensile and shear failure of intact shale. Trail of coloured dots suggest reopening or movement of pre-existing fault. Generalized stratigraphic column to right.



Hydraulic fracturing dates and times were compared to seismicity event times (Figure 9). At Etsho and Tattoo, all 38 NRCan reported events occurred either during a hydraulic fracturing stage or sometime after one stage ended and another began. No events were recorded before hydraulic fracturing operations began or after the last hydraulic fracturing operations ended.

Figure 9: Timing of NRCan reported Events (black dots) vs. Magnitude. Timing of hydraulic fracturing operations (coloured columns).

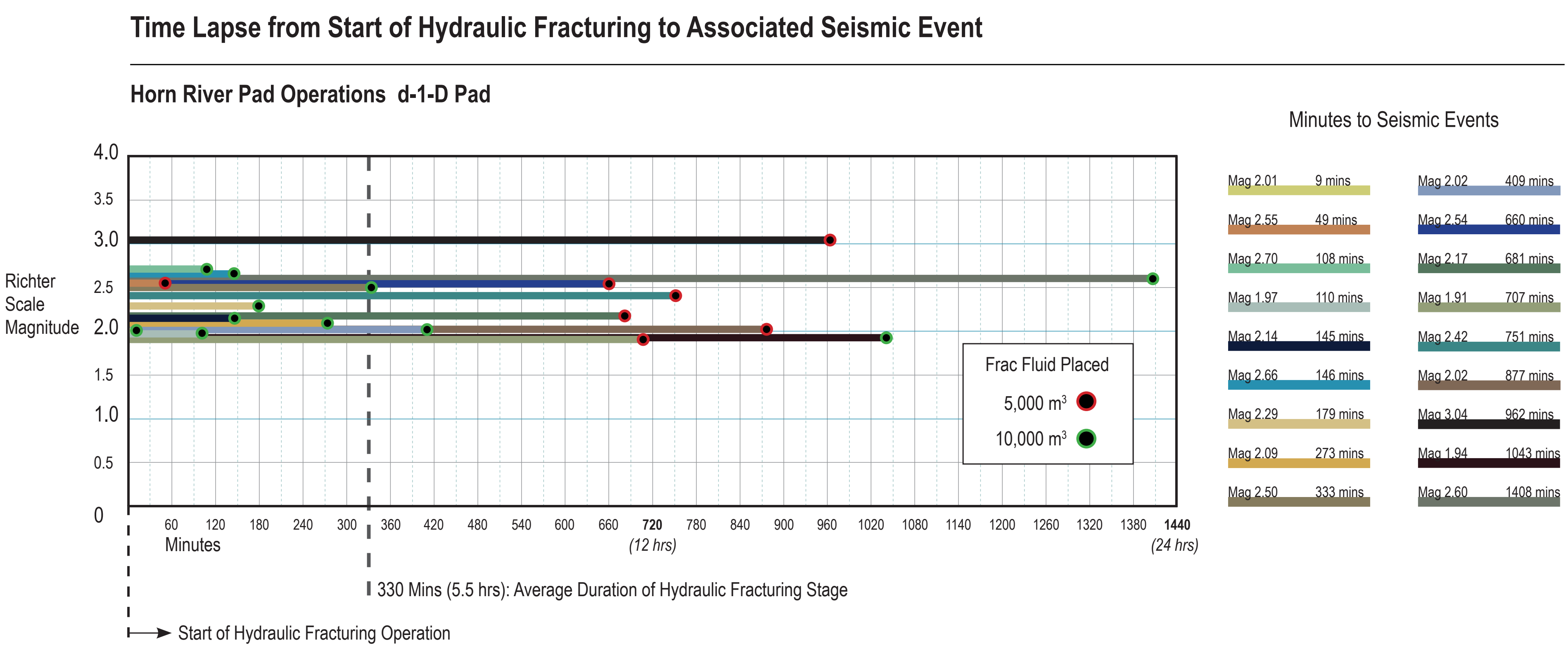


Hydraulic fracturing and NRCan event timing were compared at 15 Etsho and Tattoo drilling pad sites. Nine pads had ongoing hydraulic fracturing operations when the NRCan events occurred (Figure 9). The other multi-well drilling pads in the Etsho area could not be linked to the NRCan events by location or timing.

Eighteen magnitude 1.9 to 3.0 M_L events were selected from dense array microseismic plots. These events were selected because they were located adjacent to hydraulic fracturing stages and could be connected to a single stage fluid injection with some confidence. Evidence strongly suggests that all events were triggered by fluid injection at adjacent stages. Figure 10 shows the time lapse from the beginning of the selected stage to the seismicity event time. One stage was linked to 3 events, four stages to 2 events each and 7 stages had one event. On average, stage start time to stop time was 5 ½ hours. Eight events occurred during stage operations. Seventeen events occurred within 17 ½ hours and all events had occurred within 24 hours of assigned stage start times.

All stages along the d-G1-D (southwestern most) wellbore had 10,000 m^3 total hydraulic fracturing fluid placed. For these stages, two injections of 5,000 m^3 were placed at the same stage interval separated by about one hour. Eight of the events connected to the 11 stages graphed with 10,000 m^3 total fluid placed, occurred prior to the second injection of 5,000 m^3.

Figure 10: Timing of seismicity events, resulting from fluid injection at selected hydraulic fracturing stages. Green dots designate events linked to stages with 10,000 m^3 total 'Fracturing Fluid Placed' (two injections of 5000 m^3 separated by one hour). Red dots are events linked to stages with 5,000 m^3 total 'Fracturing Fluid Placed'.



Controls on Seismicity

Proximity to pre-existing faults, injection volumes, breakdown pressures and hydraulic fracture pump rates were examined as possible controls on seismicity.

Dense array data was used by an operator to compare pumping rates and fault proximity to seismicity frequency and magnitude at the d-1-D pad. The operator study concluded that seismicity was greatest near pre-existing faults and subsided away from the mapped fault fairway. As hydraulic fracturing proceeded from toe to heel along horizontal wellbores, seismicity magnitude increased as wellbore stages encountered micro-seismically visible faults. Higher magnitude events, caused by fault movement, declined or fell off completely as completion stages moved away from faulting. According to the operator study, as hydraulic fracturing stages continued along the horizontal legs and pump power was reduced, events became less frequent. This indicates either no faults were being intersected or additional faults encountered were not critically stressed or injection was insufficient to trigger fault movement. The operator analysis concluded that proximity to faulting appeared to have a greater effect on seismicity than pump rates.

Faulting was identified on microseismic plots and 3-D seismic supported fault mapping provided by operators. In only one case did a linear seismicity swarm clearly coincide with a 3-D seismic mapped fault. A much larger linear swarm of events mapped at d-1-D, interpreted to be occurring along a single reactivated fault, had no supporting 3-D mapped faulting. Microseismic plots were not available for the May 19, 2011 3.8 M_L event. The maximum event verified by dense array and visible on microseismic plot was the July 7, 2011, 3.1 M_L (NRCan) event located within the large linear swarm at d-1-D (figure 7).

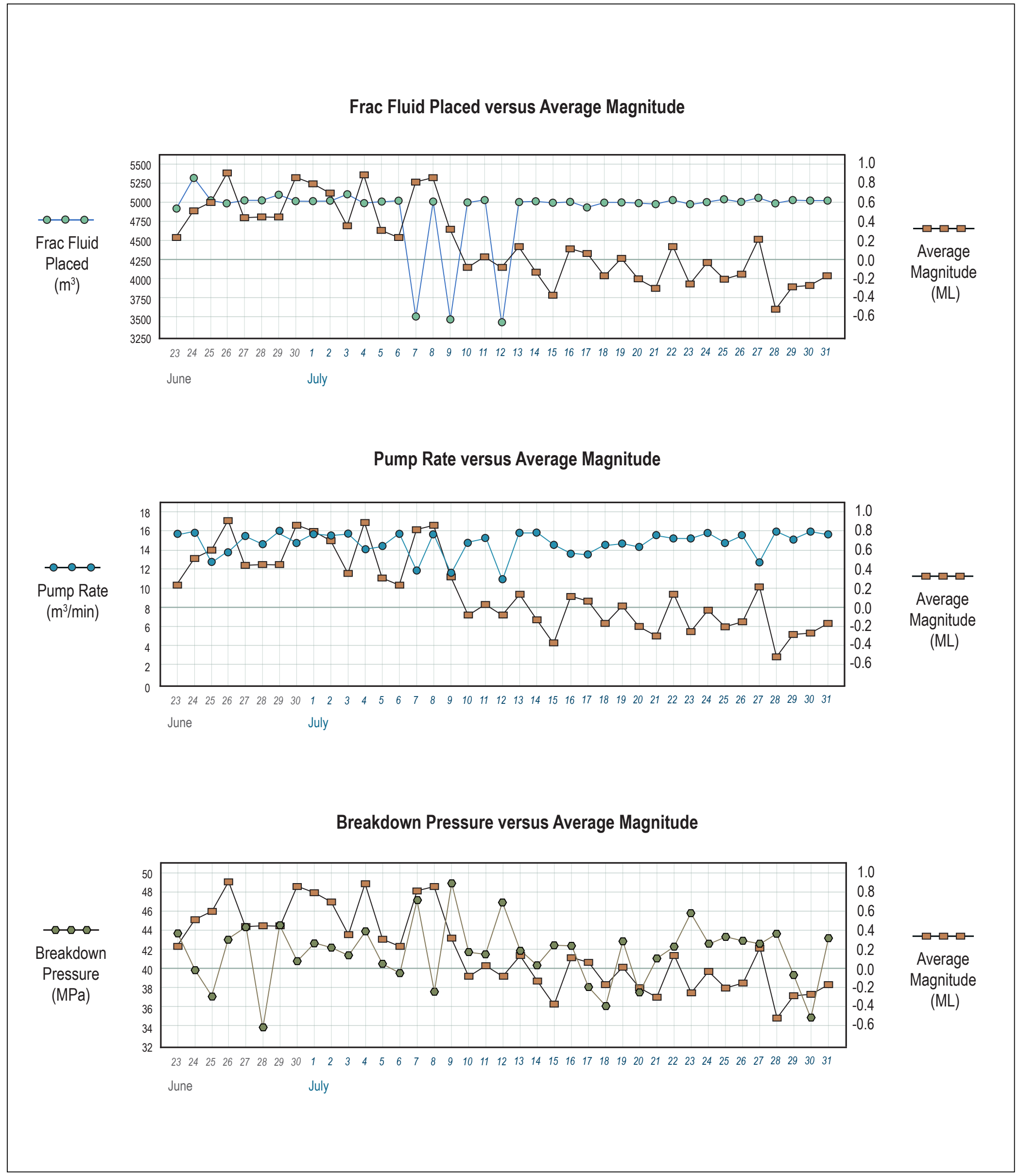
At Etsho, an operator analysis showed a slight correlation between hydraulic fracture pumping rates and event magnitude and frequency. Pump rates were reduced from16 m^3/min to 13 m^3/min on July 19, 2011. In this operator analysis, after the July 19 pump rate reduction, the frequency of higher magnitude events decreased.

Figure 11 shows the results of a Commission analysis. Event magnitudes, collected from the dense array, from June 23 to July 31 are compared to pump rates, breakdown pressures and injection volumes for the corresponding period. Magnitudes are averages of all events occurring on the date. Pump rates, pressures and volumes were averaged by date for all the wells on the d-1-D/94-O-8 pad. The magnitude drop around July 9 (Figure 11) indicates a decline in magnitude as hydraulic fracturing stages moved away from pre-existing faults that became active as a result of fluid injection. Although pump rates were below average from July 15–20, no corresponding decline in magnitudes is seen in this analysis. Some periods of direct relationship can be seen between breakdown pressures and magnitudes. As stated previously, magnitudes decline around July 9 as completions move away from the active faulted interval. Magnitudes after July 9 suggest few events past that date are related to fault movement.

Within the active faulted zone (June 23 to July 9) magnitudes show some correlation to breakdown pressures.

Figure 11: Change in average magnitude with changes in daily fracture volume, pump rate and breakdown pressure over time. Frac fluid placed, pump rates and breakdown pressures are daily averages taken from d-1-D pad completions report. Magnitudes are also daily averages.

2011 Horn River Pad Operations d-1-D Pad



Hydraulic fracturing pump rates at Kiwigana were maintained at slightly below 13 m^3/min. Micro-seismicity frequency and magnitude were fairly consistent during the Oct. 2011 to Jan. 2012 hydraulic fracturing operations, with magnitudes ranging from -1.7 to 1.9 M_L.

Eighteen events were above 1.0 M_L for a period from Nov. 6-10, 2011 suggesting minor fault movement. A review of microseismic plots for this time period shows that as the initial hydraulic fracturing stages were completed in the c-A15-D wellbore, a trailing swarm of microseismic points, indicating fault slippage, extended below and to the southwest of the completion interval and stage location. Here again, fluid injection at a fracturing stage while proximal to a critically-stressed fault appears to trigger seismicity.

At Kiwigana, a consistent, relatively low pump rate may have been effective in mitigating seismicity magnitude and frequency. Only 18 events were interpreted to be the result of fault movement. None of these very low magnitude events were detected by NRCan or felt at surface.

Davis and Frohlich Criteria

The Davis and Frohlich induced seismicity criteria (Davis and Frohlich 1993) is a generally accepted methodology for the identification of induced seismicity. These criteria strongly suggest the Horn River Basin seismicity was induced by hydraulic fracturing.

Davis and Frohlich Criteria – related to Horn River Basin

1. Timing

a. *Are these events the first known earthquakes of this character in the region?* Probably, only some mag >2.5M_L events would have been detected in the Horn River Basin back to 1999. Prior to 1999, magnitude 4.0M_L events would have been detected as far back as the 1960's. No events were recorded by NRCan in the Horn River Basin prior to April 2009
b. *Did the events only begin after hydraulic fracturing had commenced?* Yes, all the Horn River Basin events, recorded by both NRCan and the operator deployed dense array, began after hydraulic fracturing commenced.
c. *Is there a clear correlation between hydraulic fracturing and seismicity?* Yes, all the seismic events in Horn River Basin occurred during or between hydraulic fracturing stages.

2. Location

a. *Are epicenters within five kilometres of wells?* Yes, all epicentres occurred within five kilometres of hydraulic fracturing operations.
b. *Do some earthquakes occur at or near hydraulic fracturing depths?* Yes, the dense array report shows seismicity occurring within 300 metres of hydraulic fracturing stages.
c. *Do epicenters appear spatially related to the production region?* Yes, all the NRCan reported events were located within five kilometres of hydraulic fracturing operations in the Horn River Basin. Dense array hypocentres locate the events within 1 km.

3. Fluid pressures, etc.

a. *Did hydraulic fracturing cause a significant change in fluid pressures?* Yes, hydraulic fracturing must increase localized pressures to breakdown pressure in order to fracture the reservoir rock. This pressure is greater than original formation pore pressure.
b. *Did seismicity begin only after the fluid pressures had increased significantly?* Yes, the events occurred after hydraulic fracturing commenced and fluid pressures had increased significantly.
c. *Is the observed seismicity explainable in terms of current models relating hydraulic fracturing to fault activity?* Yes, current induced seismicity models relate increased pore pressure from fluid injection to overcoming friction along a fault resulting in fault slippage.

Wellbore Integrity

Horizontal portions of wellbores at Etsho are roughly 2500 to 3000 metres long. Five of the six operators covered by the Information Request reported no wellbore integrity issues in 91 of the 93 wellbores at Etsho. Two instances of wellbore deformation along horizontal sections were reported by one operator. These occurred over a short interval beginning at 3,011 m KB (Kelly Bushing) in the d-A1-D/94-O-9 well. In this instance, casing deformation was minor and did not hinder completion operations. At d-1-D/94-O-9, the deformation was encountered at 4,245 m KB and the casing distortion blocked completion efforts at 4,288 m KB. Neither incident posed any risk with respect to safety, containment or fluid migration.

The operator reported that the deformation occurred in the horizontal section of the wellbores only and no wellbore issues were reported in the vertical sections of any wells.

This deformation was detected in July 2011. Hydraulic fracturing stages for the two affected wellbore measured depths were completed from June 16 to July 3, 2011. All geophysical logs, containing wellbore caliper and image data, were run in Sept. and Oct. 2010, prior to the deformation occurring.

The bit (117.5mm) used to drill out the stage packers is very close to the inside diameter of the casing (121.0mm) and would have detected any vertical wellbore casing distortion. As a result of not encountering any further distortion, no subsequent casing or cement evaluation tools were run.

Pre-Existing Faults

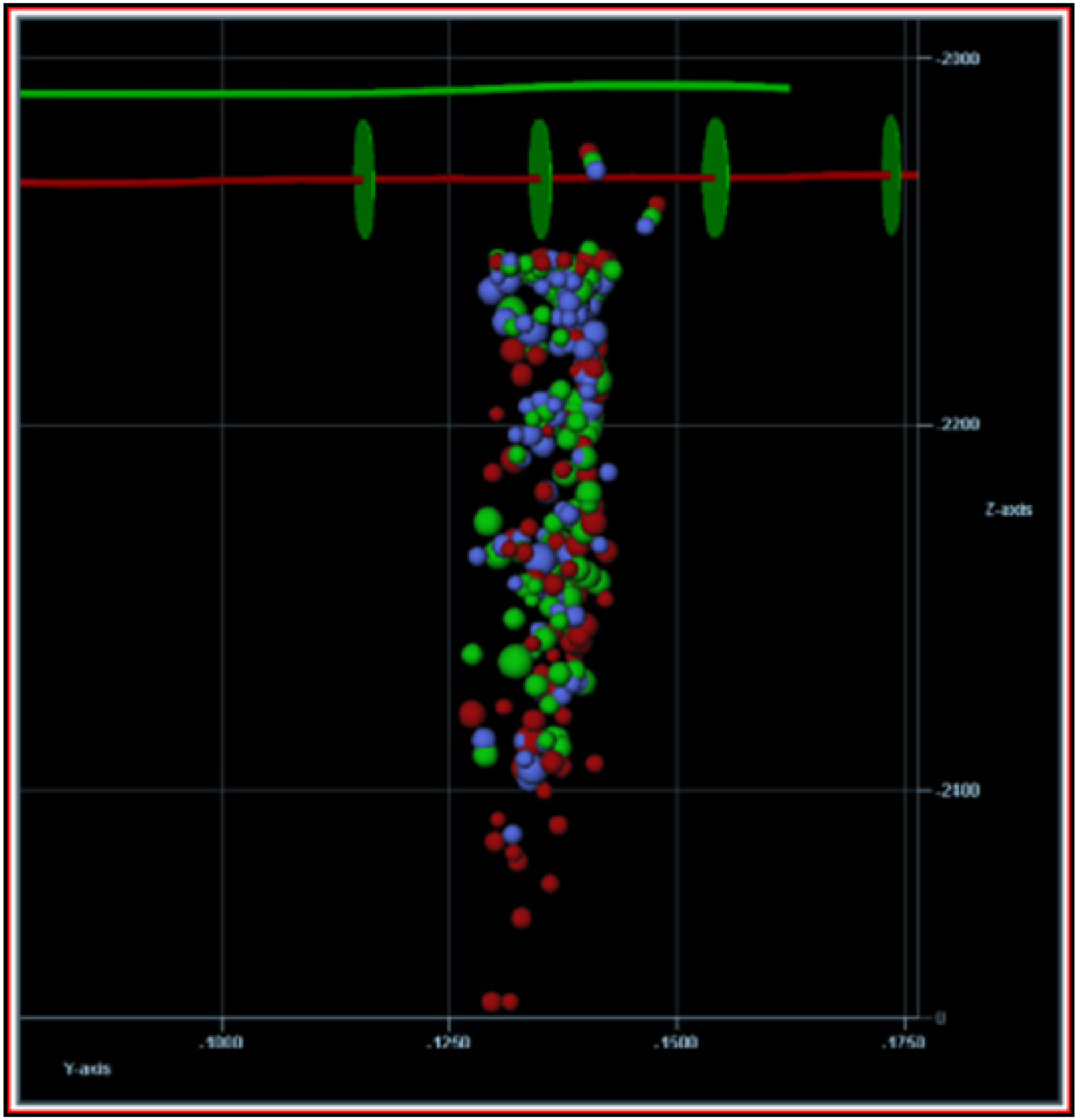
All Etsho operators conducted two and three dimensional seismic surveys and interpreted faulting before conducting hydraulic fracturing operations.

Fault mapping at Etsho shows abundant faulting. Interpretations vary but it appears most of this faulting (including the larger, regional faults in this grouping) is deep seated and concentrated in a north-south trending fault fairway centered at Etsho. Minor, secondary faulting is evident, generally trending northwest to southeast, at approximately 45 degrees.

From the data reviewed, faulting appears to be confined below the lower Fort Simpson shale extending into the basement (Precambrian) or within the shallower Debolt Formation. No faulting was seen to extend through the Fort Simpson Formation and no evidence was found that Middle Devonian aged faulting, in this area, could provide a conduit for fluids to zones above the Fort Simpson shale.

Faults were also interpreted from available microseismic plots. In the case of the dense array at Etsho, daily microseismic plots (June 16 – July 31, 2011) that showed high magnitude events were submitted for the investigation. Along with higher magnitude seismicity, dates and the stages hydraulically fractured for that date were highlighted. Event dates could be compared to the plots and fault mapping. In all cases examined, faulting could be seen on the plots as linear swarms or a smaller bundle of events with a large signature event represented by a large dot. Faults can also be seen as long, trailing legs of dots on microseismic vertical profiles (Figure 12). In this case, hydraulic fracturing fluids or a pressure front appear to have migrated along the fault creating micro-seismicity events that reach the underlying Keg River formation.

Figure 12: Micro-seismicity events (coloured circles) and hydraulic fracture stages (green ellipses) along horizontal wellbore legs.



Findings

1. The seismicity observed and reported by NRCan in the Horn River Basin between April 2009 and December 2011 was induced by fault movement resulting from injection of fluids during hydraulic fracturing.

2. No injuries or property damage were reported as a result of the induced seismicity. Only one event was reported by NRCan to have been felt at the ground surface.

3. The fractures developed during the hydraulic fracturing operations studied within the investigation were effectively confined to the target Horn River shales by the overlying Ft. Simpson shales. No effects on shallow aquifers or the environment were identified.

4. The magnitude and frequency of the induced seismicity investigated by the Commission may be influenced by numerous factors including pump rate, breakdown pressure and proximity to pre-existing faults.

5. No casing deformation was reported in the vertical portion of wellbores and no reservoir containment issues were identified. Minor casing deformation within the horizontal well portion of target shale formations occurred in 2 instances. The cause of the casing deformation could not be conclusively linked to the seismicity.

6. Fault mapping provided by operators shows abundant sub parallel north-south trending faulting through the Etsho and Tattoo areas. These faults are generally deep seated and do not show displacement above the Ft. Simpson shale. The Ft. Simpson shale is considered to be a ductile fracture barrier. Fault reactivation in this structural setting is not considered a threat to shallow overlying aquifers.

7. Seismograph station additions are needed to the CNSN to improve monitoring for induced seismicity in northeast British Columbia.

Recommendations

1.Improve the accuracy of the Canadian National Seismograph Network in northeast B.C.

During the investigation it became evident that the existing coverage of the CNSN, operated by NRCan for northeast B.C. is adequate for large conventional earthquake detection but could not reliably provide the spatial accuracy necessary to positively identify smaller seismic events associated with induced seismicity. The current grid did not detect 15 magnitude 2.0 to 3.0 M_L events which were detected by the more accurate dense array temporarily installed at Etsho.

The Commission has been working with NRCan and the Alberta Geological Survey to determine what enhancements to the existing detection grid are needed to provide accurate and timely identification of induced seismicity.

Action: Geoscience BC has organized funding for a five year project to install and operate six additional seismograph stations for the CNSN. NRCan has completed site surveys and installation is scheduled for late 2012. The enhanced grid will reliably identify induced seismicity, providing detection sensitivities below 2.0 M_L and surface location accuracy to within one kilometre.

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

While several faults were believed to have been intersected by wellbores at Etsho, only a few of these faults slipped resulting in seismicity. In one case a mapped fault coincided with a microseismic plot event swarm. In other areas, seismicity occurred where faults had not been mapped. It currently cannot be determined which intersected fault will move or what injection pressure or volume will trigger the event. Operators do identify as many pre-existing faults as practical and can tailor their hydraulic fracture programs to include enhanced monitoring for seismicity when completing near these faults

Action: Operators should review geological and seismic data to identify pre-existing faulting. If induced seismicity is detected, the active fault could be located and avoided in subsequent wellbores. Additional mitigation procedures, such as bypassing stages adjacent to a known active fault might also be considered. Monitoring for events will be done by the Commission under Recommendation 3.

3. Establish induced seismicity monitoring and reporting Procedures and Requirements.

A notification and consultation procedure provides a means for the Commission to respond to induced seismicity in northeast B.C. If seismicity is detected on the CNSN or an operator deployed dense array, the Commission would contact the operator to investigate the occurrences and determine appropriate mitigation options when required.

Action: Each case will require a unique response. Incidents will be evaluated on the basis of event frequency, magnitude, ground motion, depth and proximity to populated areas. In the case of the Horn River Basin area, the Commission will commence consultations regarding additional monitoring requirements or mitigation as soon as induced seismicity is detected.

Specific to the Horn River Basin, with the additions to the CNSN, induced events should be reliably and consistently detected and reported at magnitude 2.0 M_L. Mitigation discussions with the operator will begin immediately. Mitigation steps taken will vary dependent on the risk posed by the events and may include enhanced data recovery for research purposes.

An order to suspend hydraulic fracturing specific to the well under completion could be issued dependent on an evaluation of the previously stated criteria of event frequency, magnitude, ground motion, depth and proximity to populated areas. Operators will immediately suspend hydraulic fracturing operations for a well upon detection of a 4.0 M_L or greater event.

4. Station ground motion sensors near selected NEBC communities to quantify risk from ground motion.

Along with location and depth, it is important to know how much the ground actually moved at a given location during a seismic event. Ground motion sensors record ground acceleration and enable a correlation between magnitude and ground acceleration. This has implications for human safety and infrastructure integrity.

Action: NRCan experts will be consulted to determine equipment selection, location, installation and operation of ground motion sensor stations.

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

A dense array, separate from the regional grid, is necessary to determine event depth, a key to diagnosing induced seismicity. Depth is required to fully understand the range of fault movement and risk to shallow aquifers. Focal mechanism determination, improved location resolution and lower magnitude detection are also possible benefits of a dense array. They can be designed to be quickly deployable, placed on the ground, and may require as few as five seismographs.

Action: Two operators have deployed three dense arrays in the Horn River Basin and an additional research dense array is being considered by NRCan for the Basin. The Commission will seek funding for a portable dense array to be deployed as needed for induced seismicity research and data collection.

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

Microseismic data can identify geological features such as faults where there may be increased risk of inducing seismicity beyond magnitude 2.0 M_L. In addition, microseismic plots can verify that hydraulic fracturing is confined to the target zone by outlining both the vertical and lateral extent of the fracturing.

Action: The Commission will develop requirements for submission of information gathered from microseismic monitoring during hydraulic fracturing. Data gathered will be limited to that which is necessary to show fracture containment and faulting. The format shall be determined in consultation with stakeholders including other regulators outside of British Columbia. Consideration of the proprietary nature of microseismic data must be included in the development of submission requirements.

7. Study the relationship between hydraulic fracturing parameters and seismicity.

At Etsho and Kiwigana magnitudes may have declined as pump rates were reduced or held low. This investigation found weak correlations between pump rates and magnitude and breakdown pressure and magnitude. The historical response to induced seismicity from fluid injection has been to either stop operations or reduce injection rates. Seismicity frequency at the Rangely oilfield in Colorado (Gibbs et al, 1972) directly corresponded to the amount of water injected per year.

Action: The Commission is continuing its analysis of hydraulic fracturing data to attempt to find correlations between hydraulic fracturing parameters and event magnitude. Reducing pump rates or injection volumes will be considered if induced seismicity is detected beyond the criteria set out under recommendation three.

Conclusion

Horn River Basin seismicity events, from 2009 to late 2011, were caused by fluid injection during hydraulic fracturing. All events occurred during or between hydraulic fracturing stage operations. Dense array data accurately placed the depth and location of events at or near hydraulic fracturing stages. Only one event was reported as “felt” and no events were felt beyond 10 km of the epicentres.

Faulting transecting horizontal wellbores can be identified on microseismic plots. Some events greater than 2.0 M_L were located at the intersection of faults and wellbores when adjacent hydraulic fracturing stages were being completed. In other circumstances, faults intersected wellbores yet no anomalous events were detected. Fault movement is dependent on numerous factors such as in-situ stress and there is no reliable method to identify which faults will slip or under what conditions. Further research is needed to determine if induced seismicity from hydraulic fracturing can be controlled by either altering hydraulic fracturing parameters or by fault characterization and avoidance.

The current coverage of the CNSN was designed as part of a national large earthquake preparedness system and is inadequate for the reliable detection of induced seismicity. Only four of the 19 (2.0 to 3.0 M_L) events detected by the dense array at Etsho between June 23 and Aug. 15, 2011 were detected by the current regional grid. Recommended improvements to the CNSN will improve location resolution to within one km and magnitude detection to <2.0 M_L. Site surveys for the additional seismograph stations being added to the CNSN have been completed. Installation of the new stations is tentatively scheduled for late 2012. Dense arrays will be deployed where appropriate to determine event depth and precise location.

None of the events under investigation resulted in any injury or property damage and only 1 event was recorded by NRCan as having been “felt” at the surface. The recommended ground motion sensors will accurately record any ground acceleration from future events. This enables a correlation between magnitude and any ground motion and eliminates the need to rely on ‘felt’ reports to gauge possible effects at surface.

Recommended improvements to the CNSN and implementation of a notification and consultation procedure will provide the necessary early detection and mitigation action as well as for additional research on mitigation methods. It is essential to take pre-emptive steps to ensure future events are detected and the regulatory framework adequately provides for the monitoring, reporting and mitigation of all seismicity related to hydraulic fracturing thereby ensuring the continued safe and environmentally responsible development of shale gas within British Columbia.

References

Davis, S.D. and Frohlich, C., 1993. Did (or will) fluid injection cause earthquakes? – Criteria for a Rational Assessment, Seismol. Res. Lett. 64(3-4), 207-224

De Pater, C.J. and Baisch, S., 2011 Geomechanical Study of Bowland Shale Seismicity, Synthesis Report commissioned by Cuadrilla Resources Ltd.

Gibbs, J., Healy, J., Raleigh, C., Coakley, J. 1972 Earthquakes in the Oil Field at Rangely, Colorado, U.S. Geological Survey, Open File Report 72-130

Holland, Austin, 2011, "Examination of Possibly Induced Seismicity from Hydraulic Fracturing in the Eola Field, Garvin County, Oklahoma", Oklahoma Geological Survey Open File Report OF1, 2011.

Horner, R.B., Barclay, J.E. and MacRae, J.M. ,1994, Earthquakes and Hydrocarbon Production in the Fort St. John Area of Northeastern British Columbia, Canadian Journal of Exploration Geophysics, Vol. 30, No. 1, (June 1994), P. 38-50

MacLean, B.C., Morrow, D.W., 2004, Bulletin of Canadian Petroleum Geology, Vol. 52, No. 4 (December 2004, P. 302-324

McPhail, S., Walsh, W., Lee, C., Monahan, P.A., 2008, British Columbia Energy and Mines, Open File, Report # 2008-1

Nicholson, C. and R.L. Wesson, 1990, Earthquake Hazard Associated With Deep Well Injection – A Report to the U.S. Environmental Protection Agency, U.S. Geol. Surv. Bull, 1951.

Hayes, B.J., 2010, HORN RIVER BASIN Subsurface Aquifer Characterication Project, Presentation to Unconventional Gas Technical Forum, Geoscience BC project