From: Watson, Andrew
Sent: 2016, October 03 7:51 AM
To: Addo, Kofi
Subject: BC Hydro OGC Discussion.pptx
Attachments: BC Hydro OGC Discussion.pptx

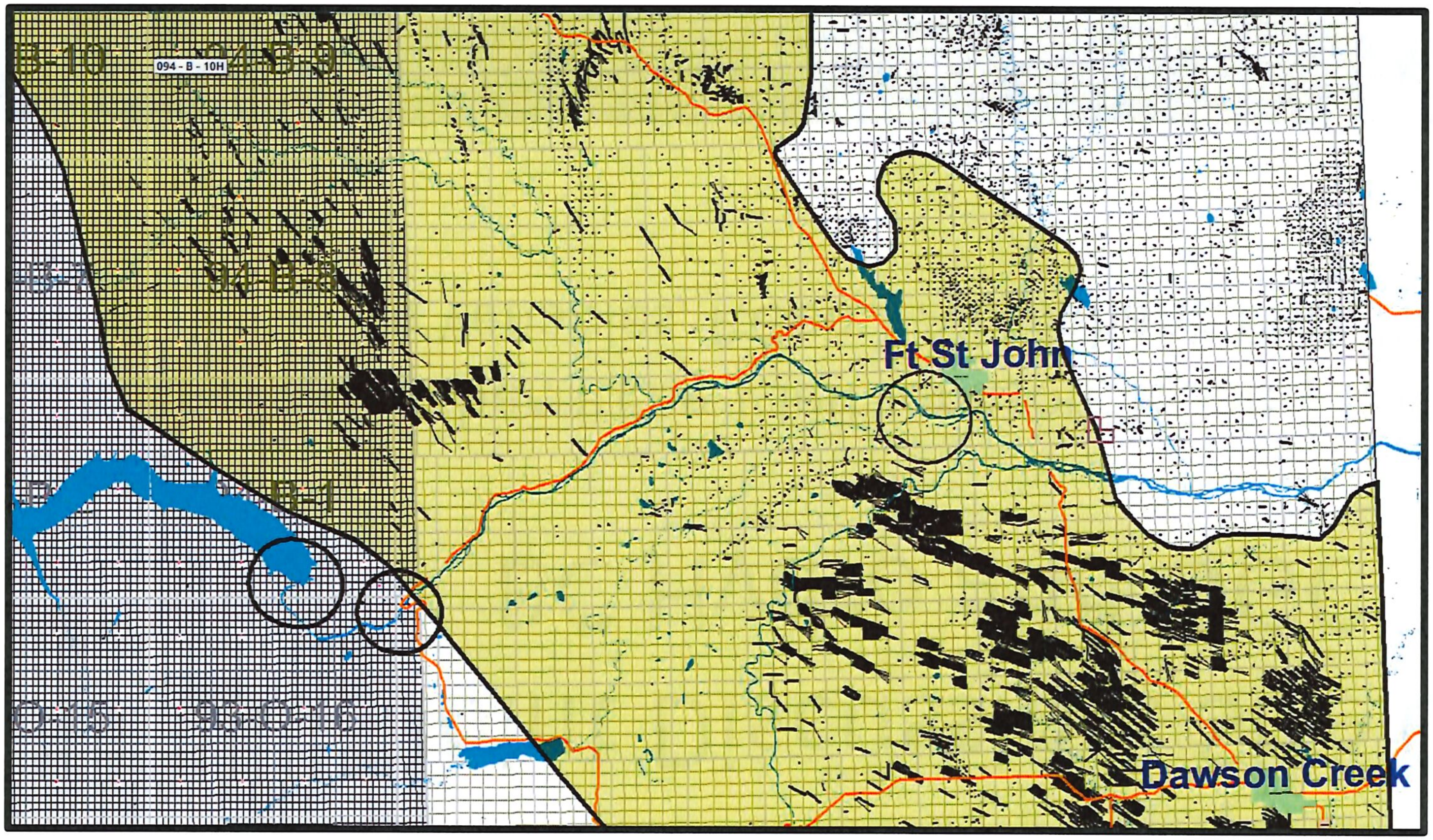
Joint Discussion: Site C
BC Hydro and OGC

Michelle Gaucher, P.Eng | Jeff Johnson, P.Geo | Ron Stefik, PEngL
Stu Venables, P.Geo | Ali Mahani, PhD, P.Geo

September 21, 2016

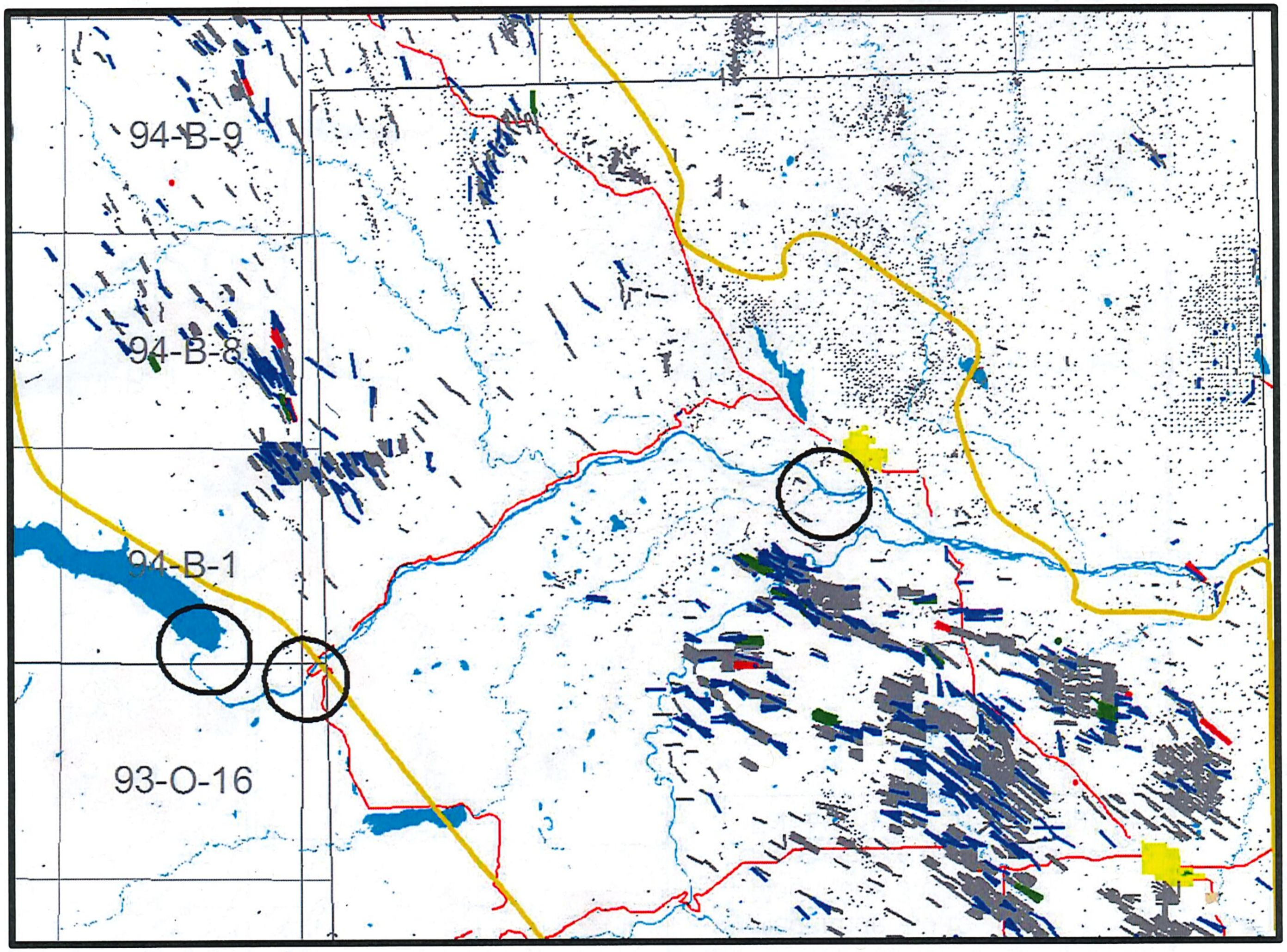
BC Oil & Gas COMMISSION

Peace Region



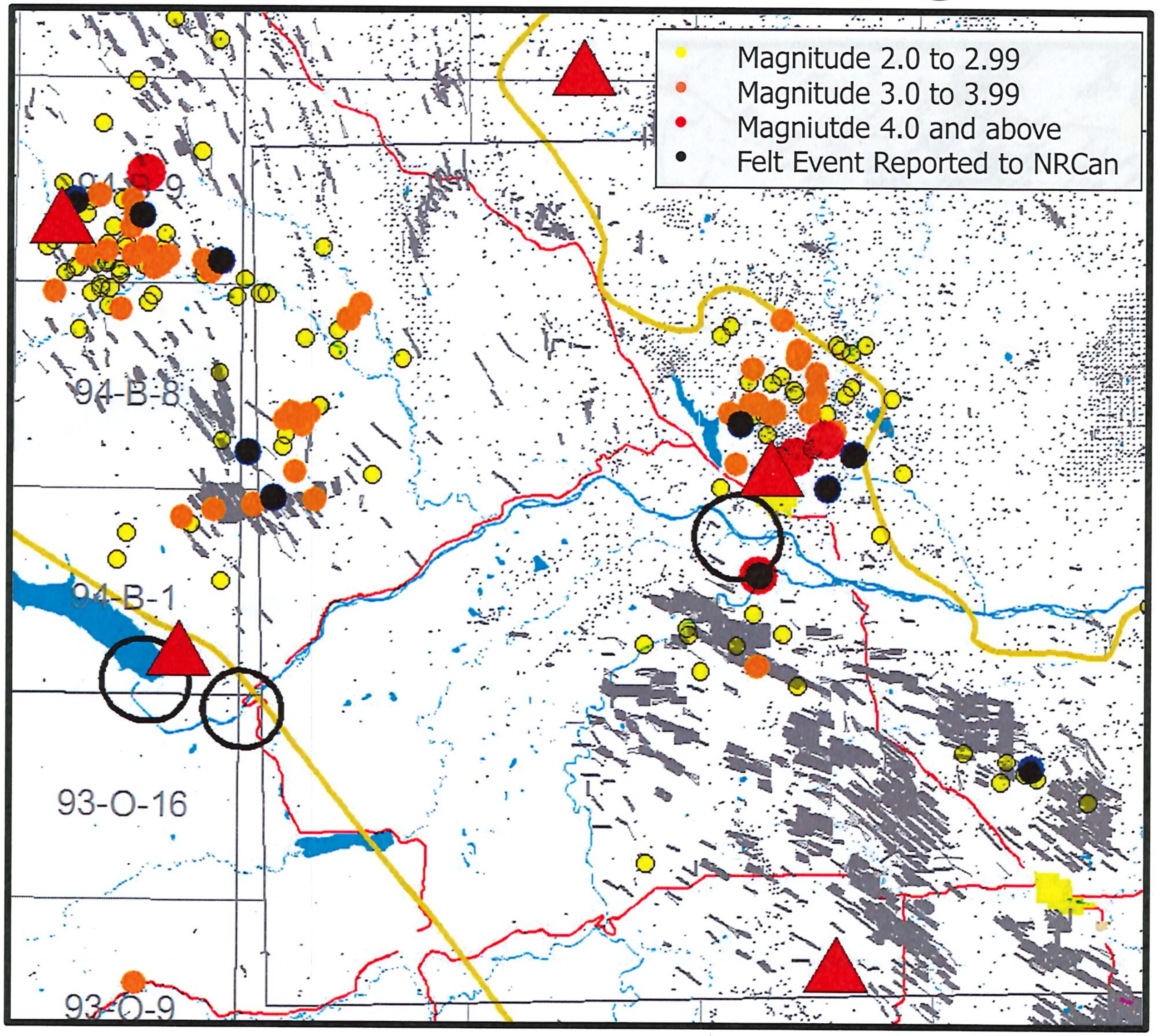
- Over 11,500 wells drilled to date
- Over 1,700 wells drilled since 2011

Peace Region



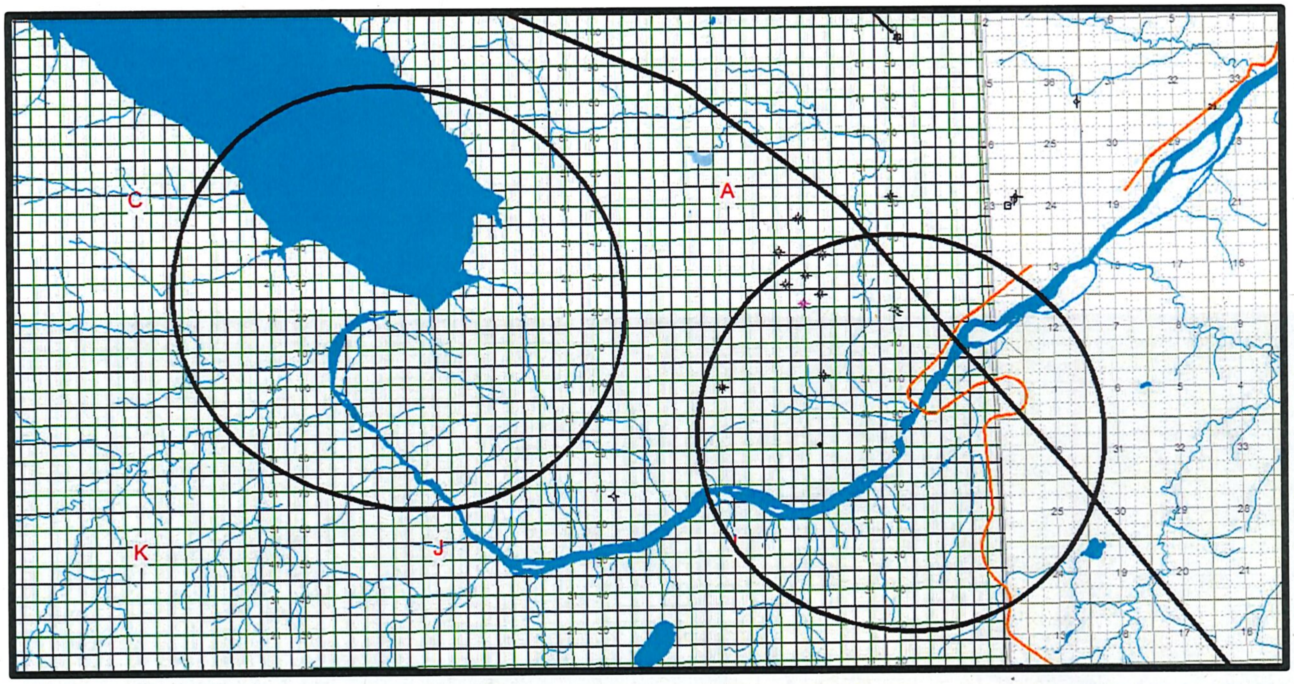
- Active Completion Operations
- Active Drilling Operations
- Future Activity (Locations)

Peace Region



- 5 Seismograph stations located within the Peace Region
  - 1 operated by NRCan
  - 4 Operated by Geoscience BC
  - All tied into the CNSN Regional Array
  - Magnitude of Certainty at least 2.0 throughout Peace Region

WAC Bennett and Peace Dams



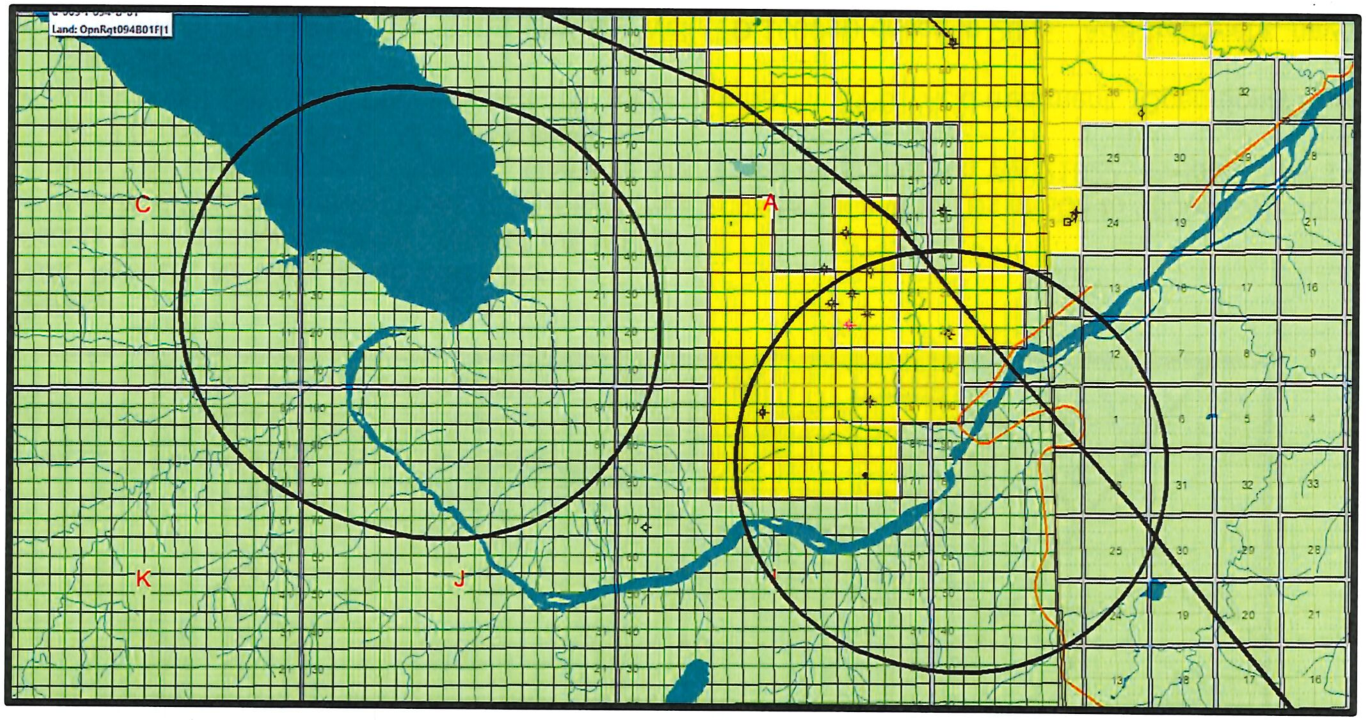
WELLS

- Limited Activity in the region
- No wells drilled within WAC Bennett Area
- 11 vertical wells drilled in the Peace Area

Details:
WAC Bennett: No wells drilled within 5km
Peace: 11 vertical wells drilled. NO ACTIVE WELLS

- 8 wells drilled for Gething COAL (CBG/CBM) from 2005 to 2008 with TDs of 500 to 950m TVD. All but one well fractured multiple times with 5 to 16 tonnes per treatment. One well was placed on production WA 21822. Produced for 14 months from January 2009 to April 2010 (Cum 63,693 Mcf). All wells suspended
- 1 Baldonnel Salt Water Disposal Well (TD 1600m) drilled in 2006. Acid treatment. Operational from December 2008 to April 2010. Currently Suspended.
- 1 Baldonnel POTENTIAL Salt Water Disposal Well (TD 1600m) drilled in 2006. Acid treatment, never used for disposal. Suspended (Potential SWD Well).
- 1 Bluesky gas well drilled in 2007 to 500m. Acid treatment, no production. Well is suspended.

WAC Bennett and Peace Dams



LAND

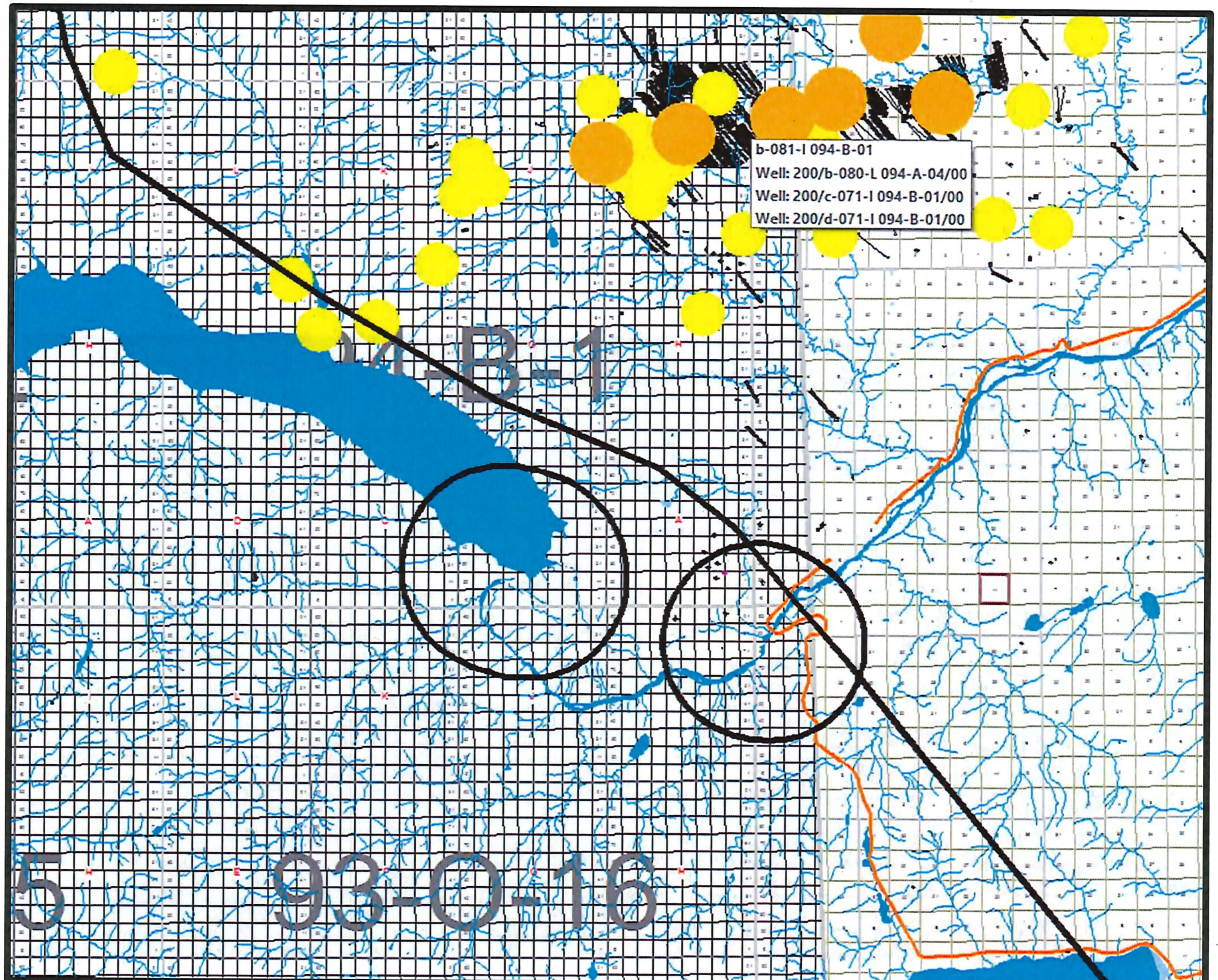
- No Tenure sold within WAC Bennett Area
- Tenure sold within Peace Area
  - Primarily for CBG

WAC Bennett and Peace Dams

LAND

- Limited Montney Rights sold
- Edge of currently mapped Montney Trend
- Some land coming up for expiry in October 2016

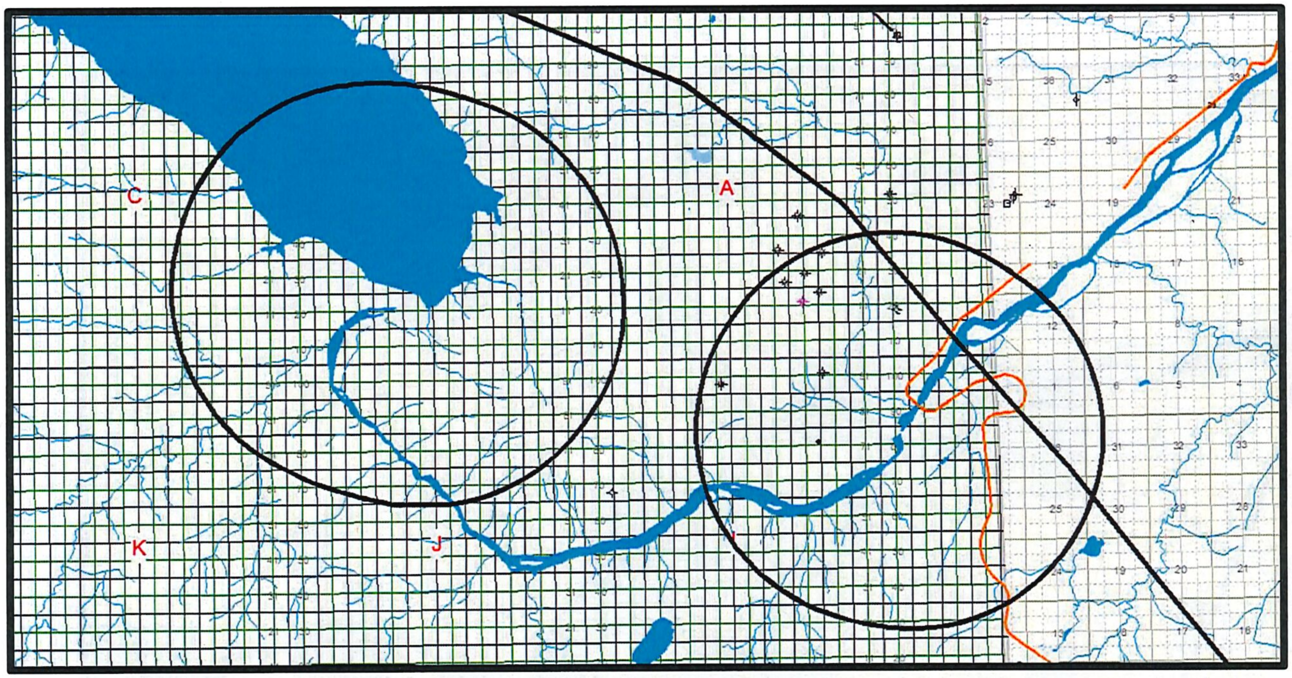
WAC Bennett and Peace Dams



SEISMICITY

- Quiet, to date, region
- CBG was not expected to induce seismicity (Ryan, 2010)

Site C Dam



WELLS

- **Active oil and gas region since 1950's**
- **64 wells drilled in Site C Area**
- **No Active Wells**
- **No current fracturing (no wells licensed)**
- **No Disposal or Injection**

Details:
64 wells. 33 have been fractured. Two (2) Montney wells (both suspended, poor production). Four (4) Terra Energy Wells. NO ACTIVE WELLS. Avg depth ~1800m. Shallowest well 978m.

- 28 Abandoned wells
- 8 Gas Wells (Halfway, Baldonnel, Boundary Lake) – None currently producing
- 1 boundary lake oil producer – not producing
- 23 Suspended wells
  - 2 Suspended Montney Gas Wells – shut-in due to poor performance
    - WA26652 (D&C 2011) | WA23686 (D&C 2008)
- 3 wells not completed
- 1 suspended Water Disposal (WA697 – Penn West)

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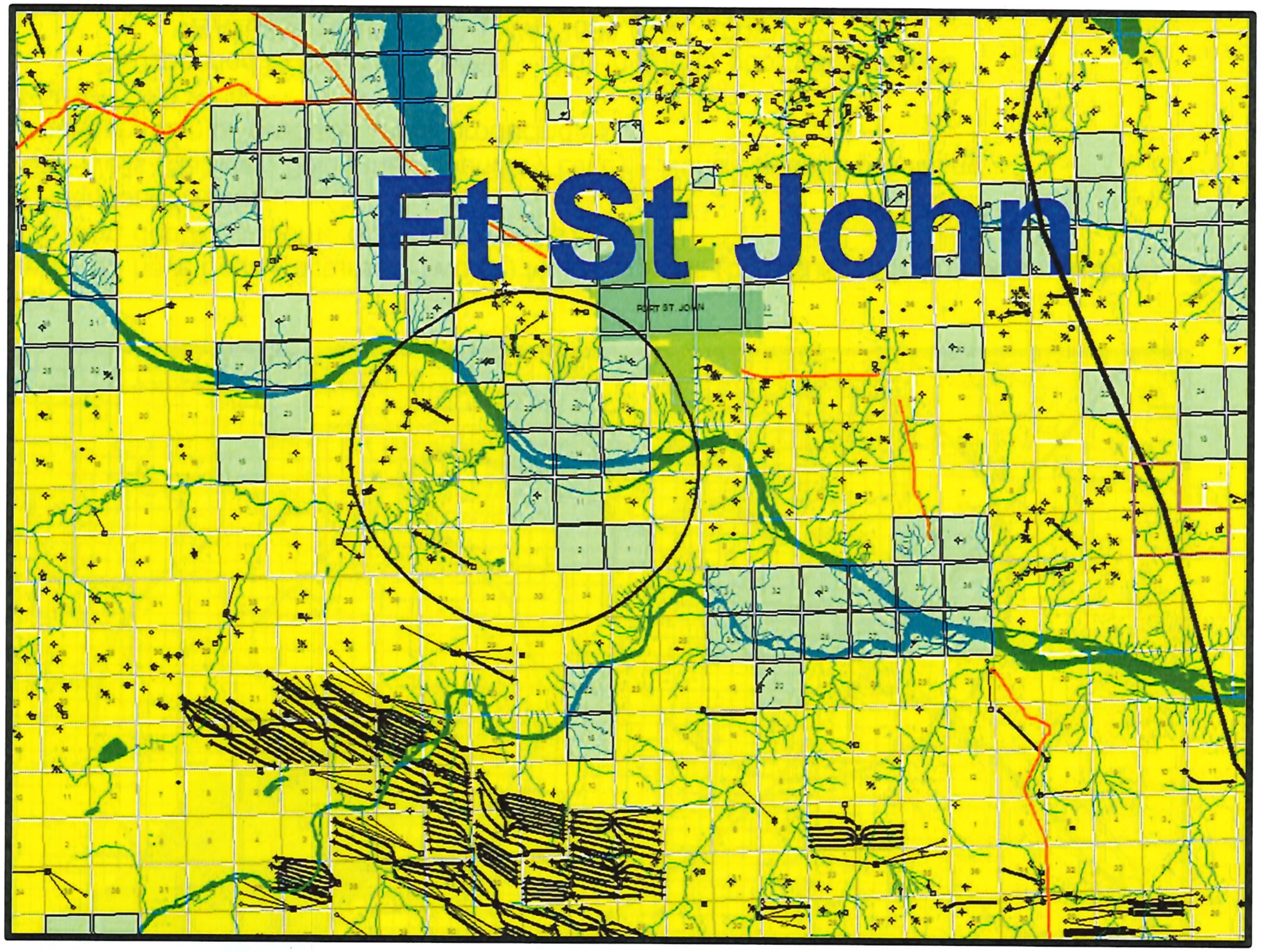
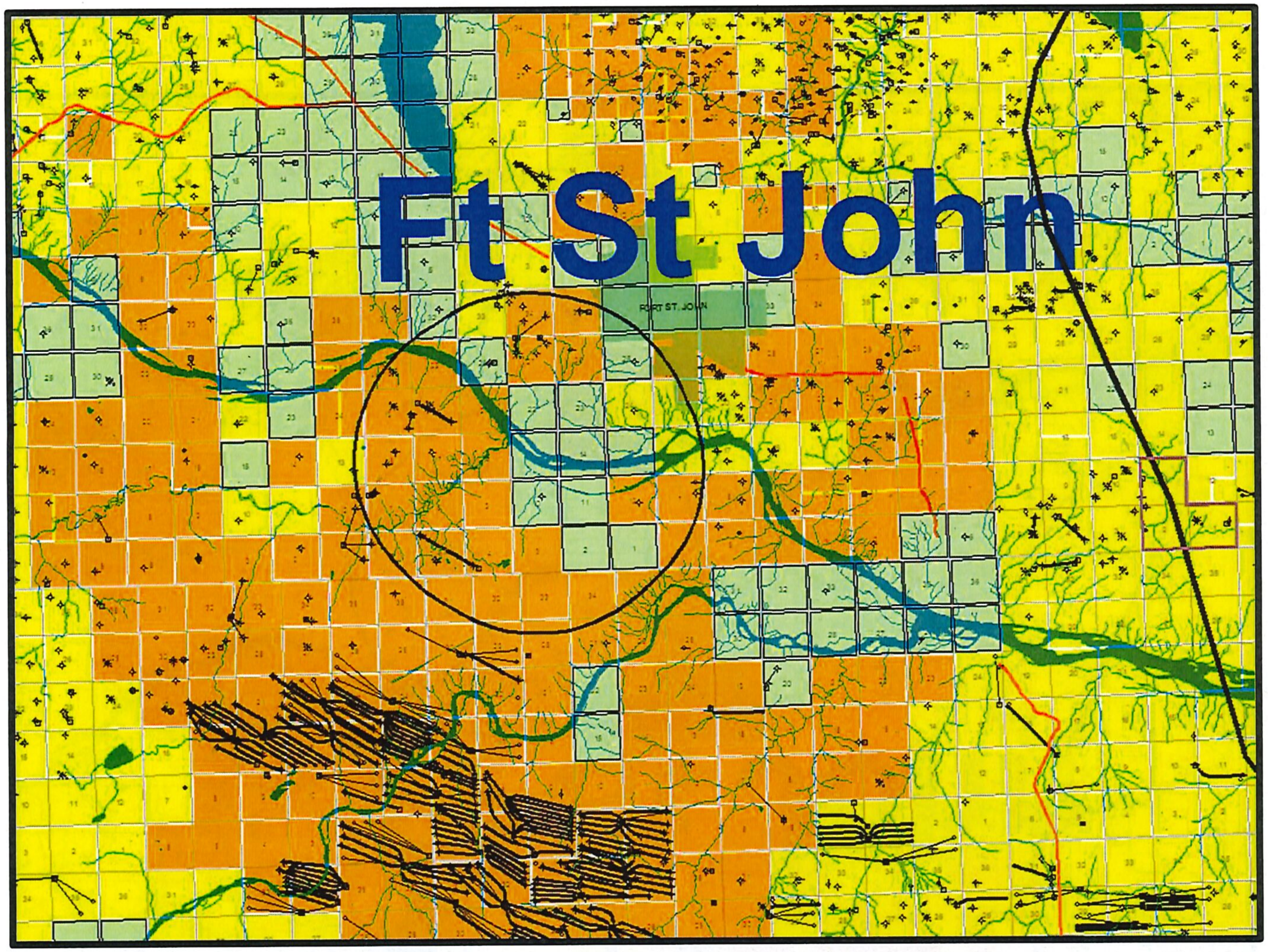
Site C Dam



LAND

- Mix of Tenure sold targeting variety of geological formations

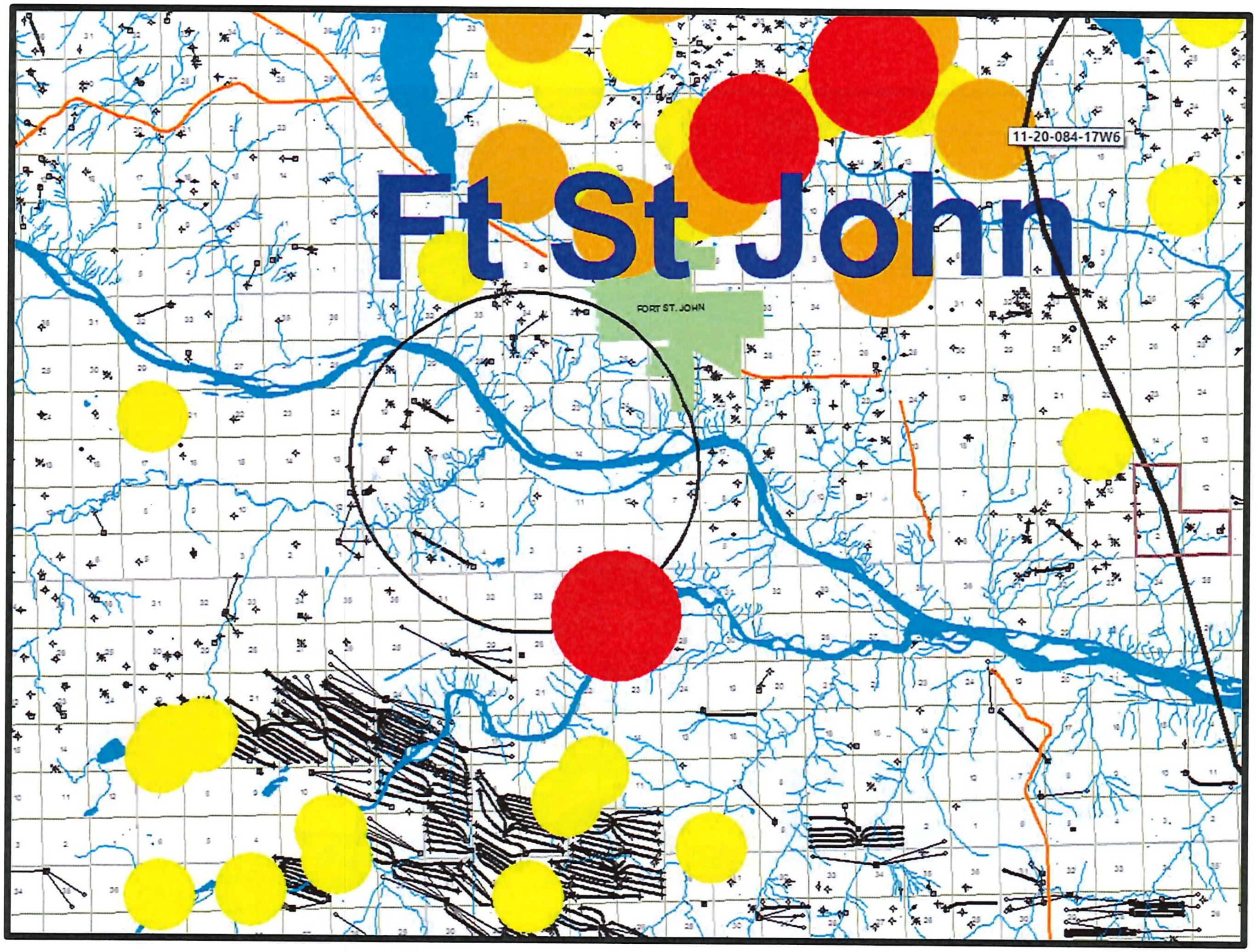
WAC Bennett and Peace Dams



LAND

- Several blocks of Montney Rights sold
- Site C wholly contained within Montney fairway
- Area get into the oil window and can be under-pressured and uneconomic

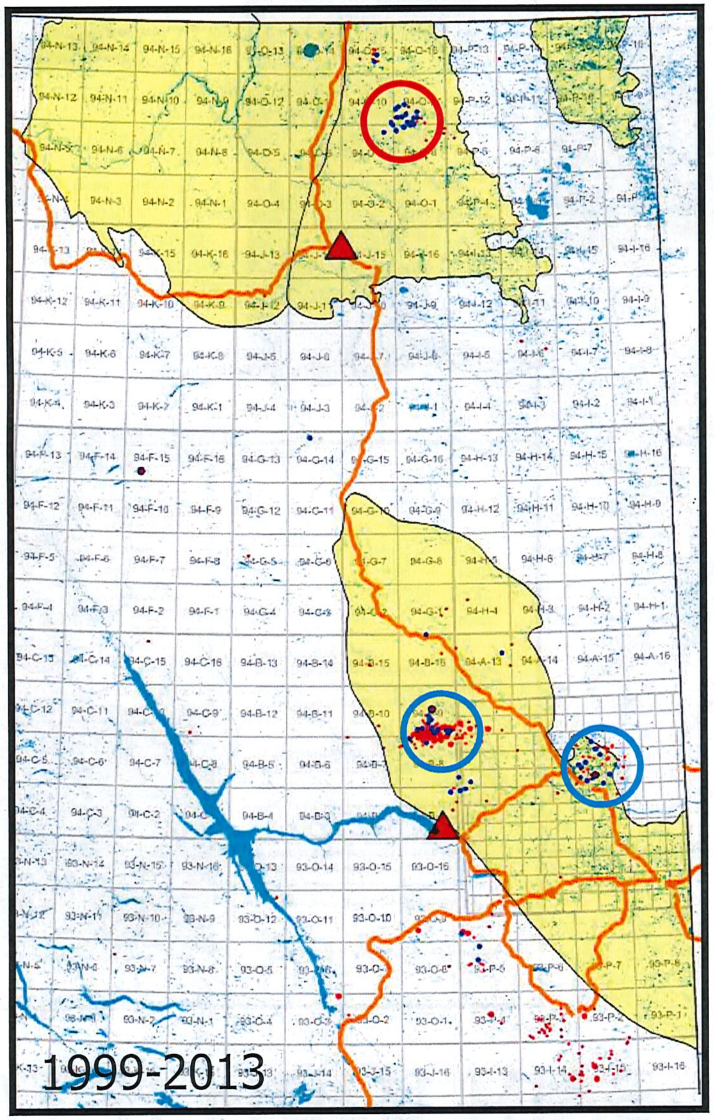
Site C Dam



SEISMICITY

- Active seismic area
- Seismicity to NE linked to injection, which has been contained
- Seismicity to South and SE linked to fracturing
  - High frequency, low magnitude to date
- Significant event possibly linked to shallow (Cadomin Age) fault

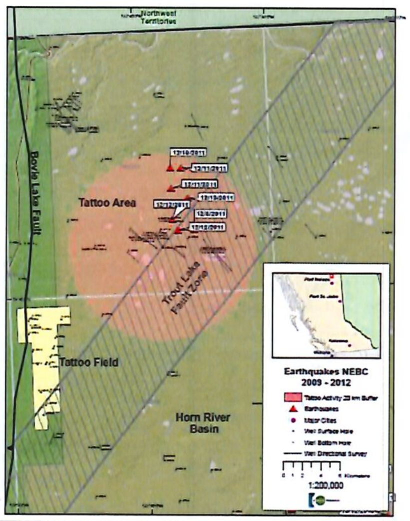
Seismograph Network



- Stations added to NE B.C. in 1998 and 1999
- Bull Mountain added 1998
- Fort Nelson added 1999
- In 2011, this network assisted with locating Horn River Basin seismic events

2012: Horn River Basin Investigation

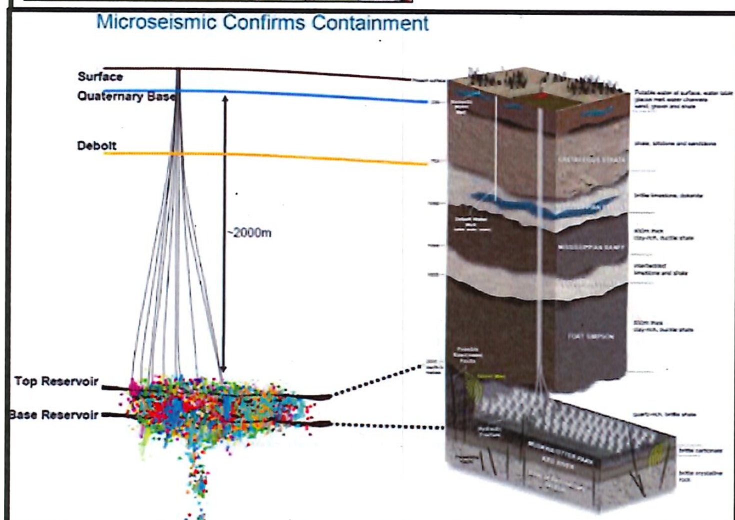
Figure 6: Tattoo area NRCan event epicentres and Multi-well Pads, shown within "20km buffer", 10km radius red circle.

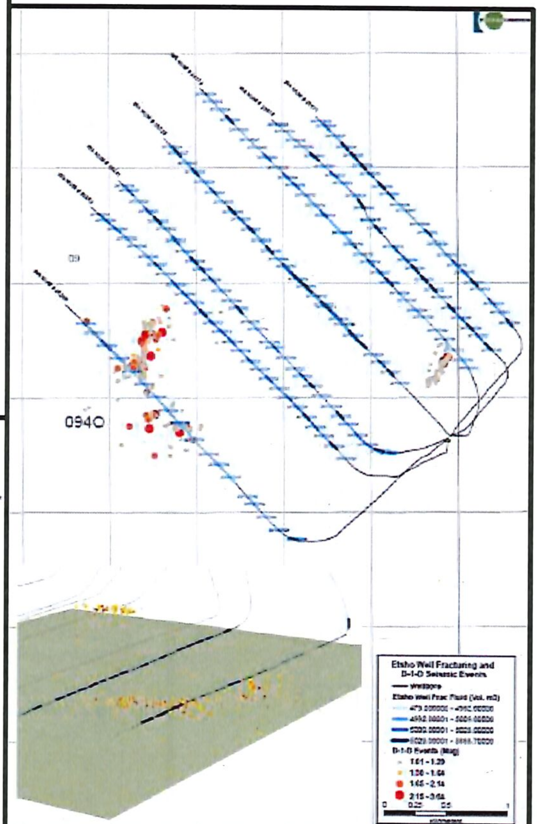


Seismicity Event Locations and Depth – Proximity to Hydraulic Fracturing

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).

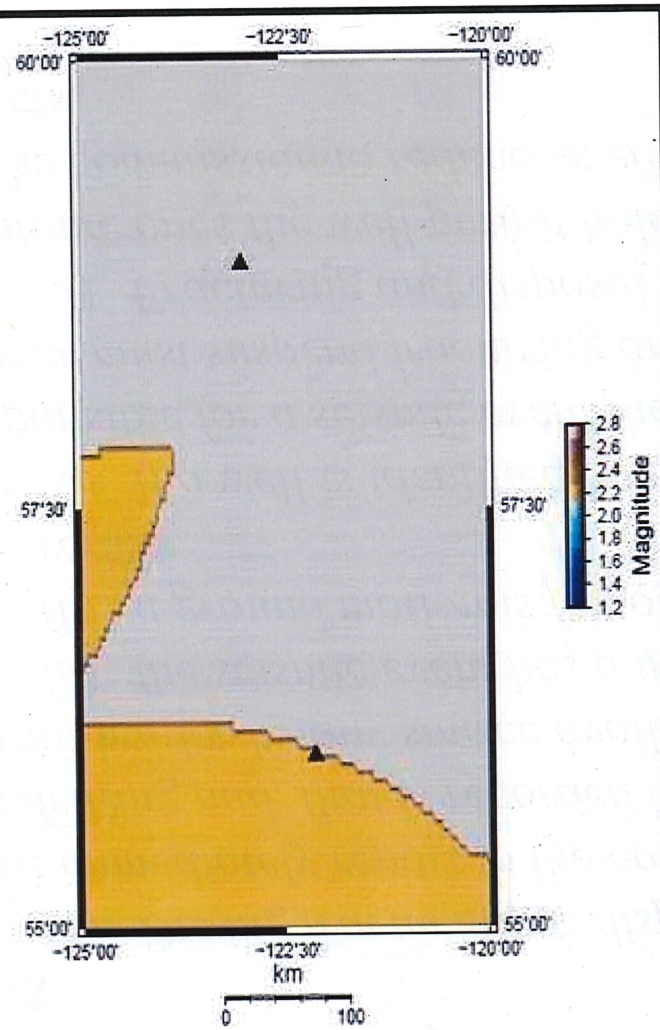
Figure 7 shows the horizontal wellbores for the d-1-D drilling pad, volumes injected at each hydraulic fracturing stage and the magnitude >1.0M_L events occurring from June 23 to August 14, 2011.



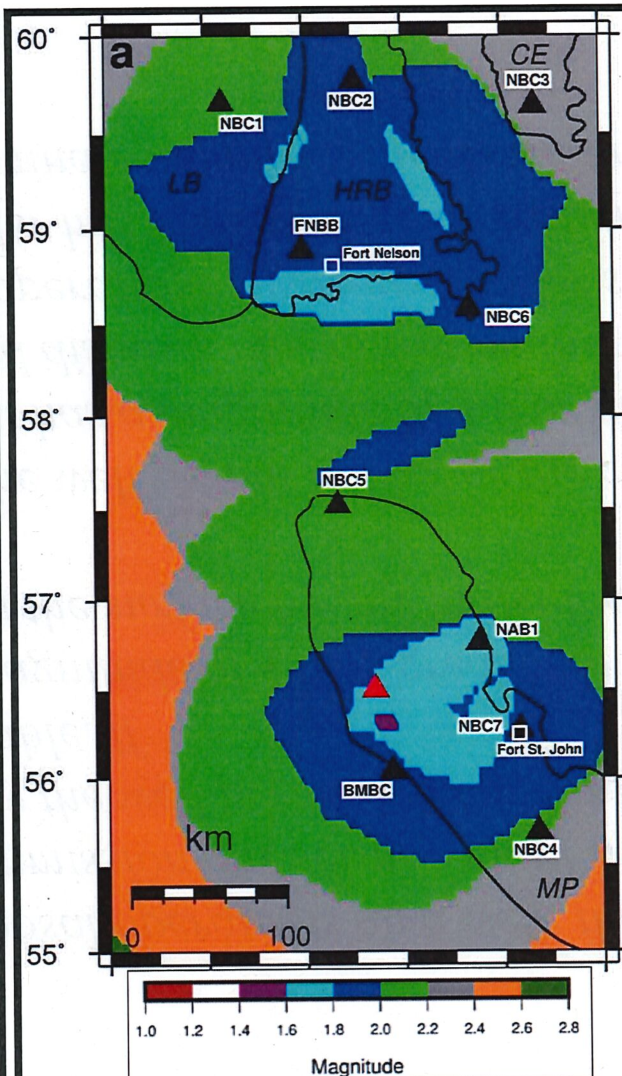


- Incident: Connection between seismicity and hydraulic fracturing activities
- Report: "Investigation of Observed Seismicity in the Horn River Basin"
- Result: Well Permit Conditions placed on all new and existing permits operating in Horn River Basin
- Actions: Improvement of CNSN from 2 stations to 11

CNSN - 1999



CNSN - 2016



- Horn River Investigation lead to an increase from 2 to 11 seismograph stations in NE BC
- Seven stations installed in 2013, two in 2014 and one in 2016
- A partnership between GeoScience BC, CAPP and NRCan
- New grid allowed for the 2014 Montney Report

Current Seismicity Regulations

Induced seismicity
21.1

(1) During fracturing or disposal operations on a well, the well permit holder must immediately report to the commission any seismic event within a 3 km radius of the drilling pad that is recorded by the well permit holder or reported to the well permit holder by any source available, if

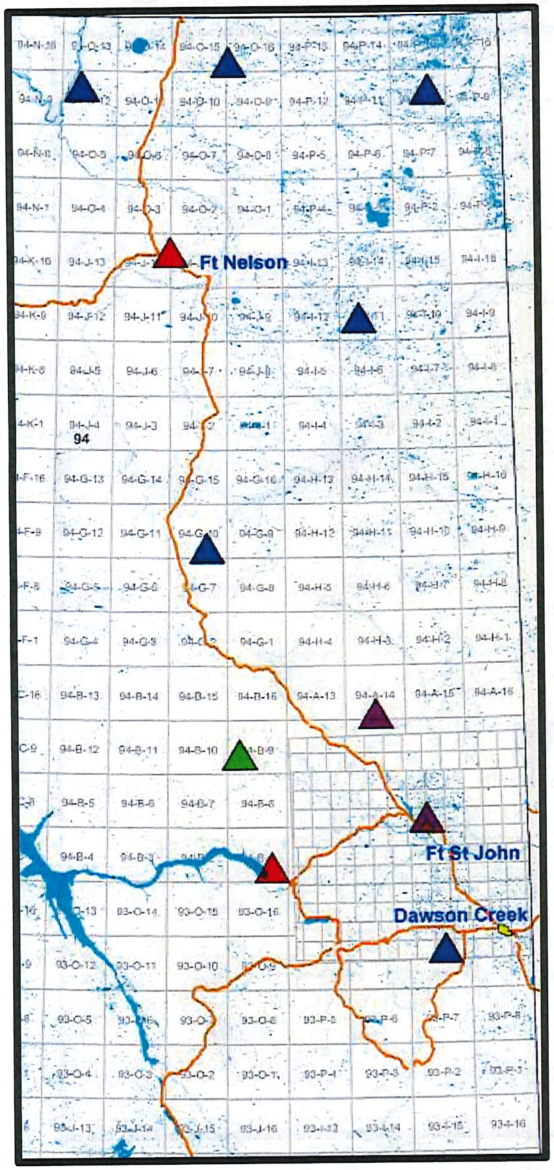
(a) the seismic event has a magnitude of 4.0 or greater, or

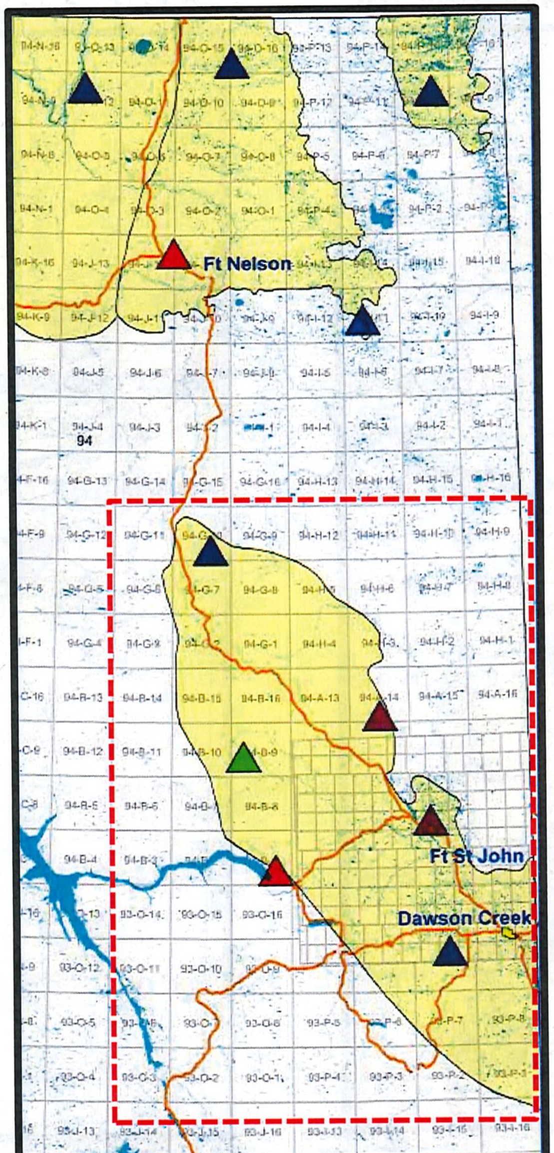
(b) a ground motion is felt on the surface by any individual within the 3 km radius.

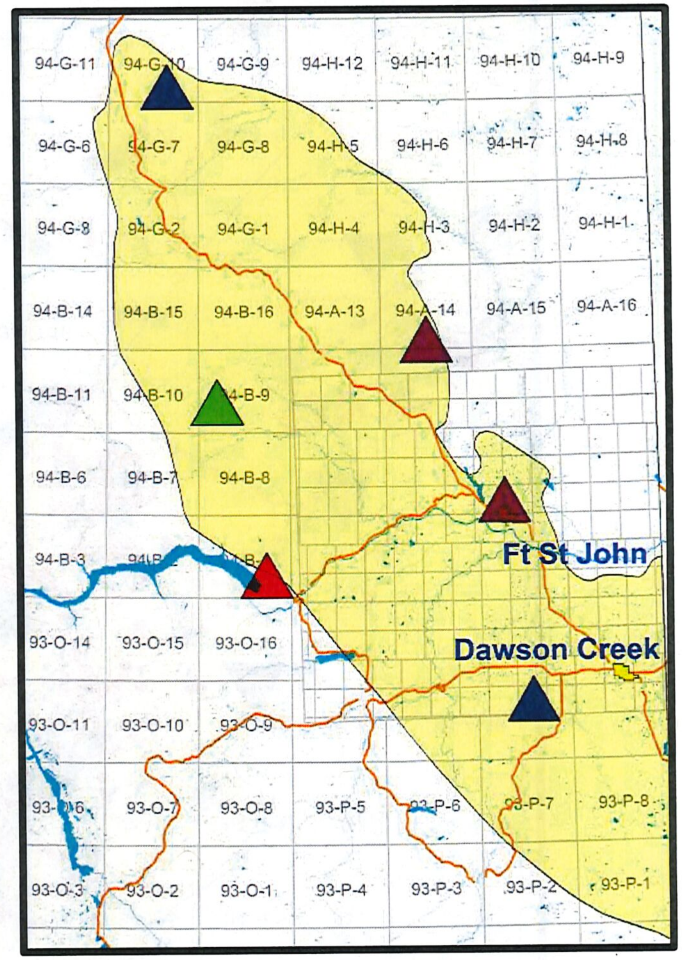
(2) If a well is identified by the well permit holder or the commission as being responsible for a seismic event that has a magnitude of 4.0 or greater, the well permit holder must suspend fracturing and disposal operations on the well immediately.

(3) Fracturing and disposal operations suspended under subsection (2) may continue once the well permit holder has implemented operational changes satisfactory to the commission to reduce or eliminate the initiation of additional induced seismic events.

Base Maps for NEBC







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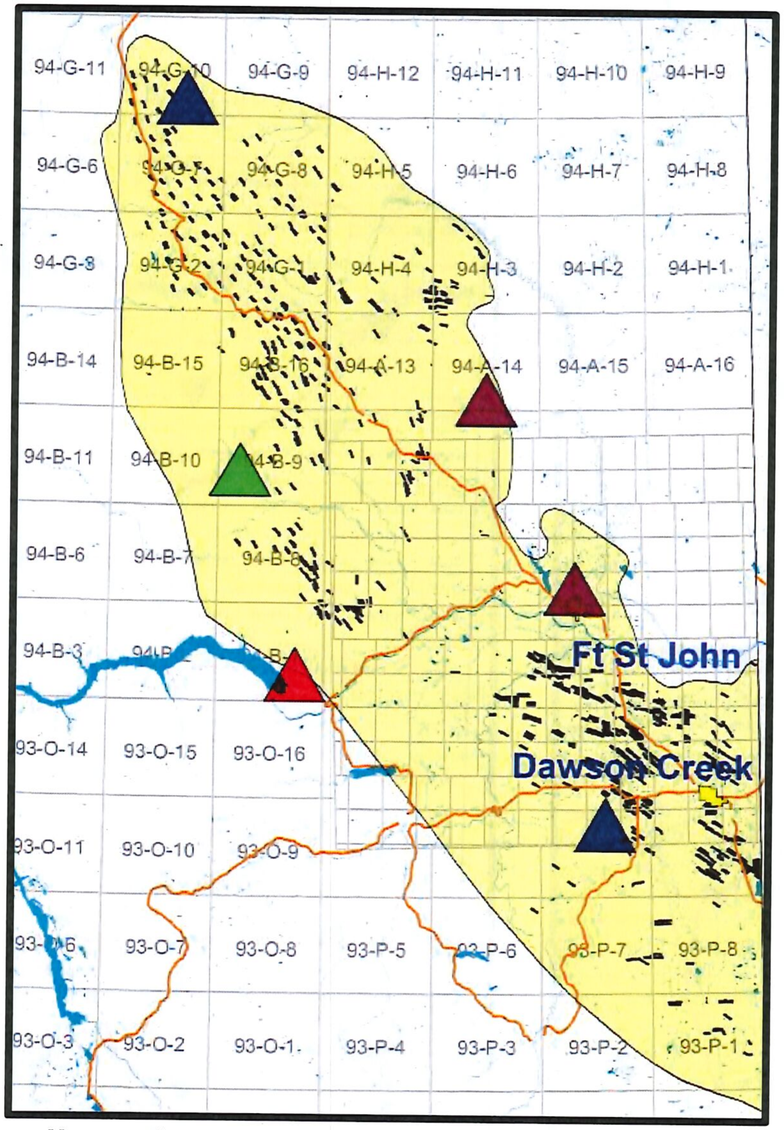
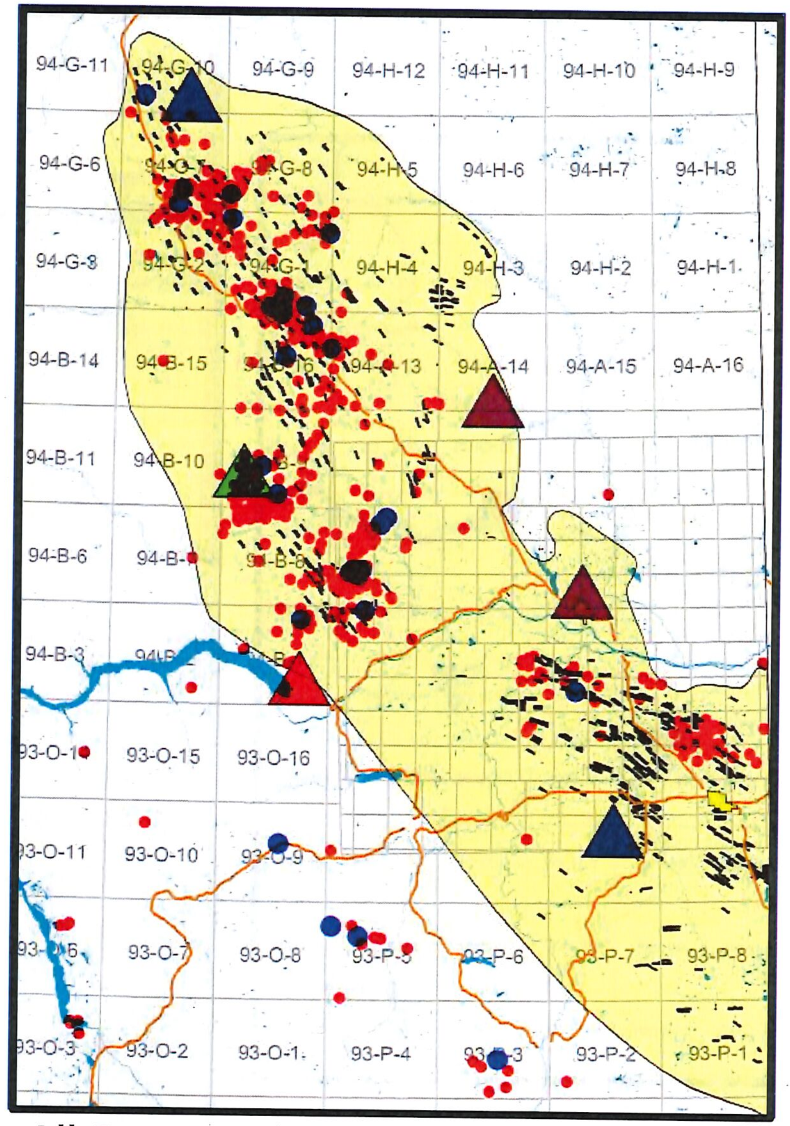
Montney Base Maps

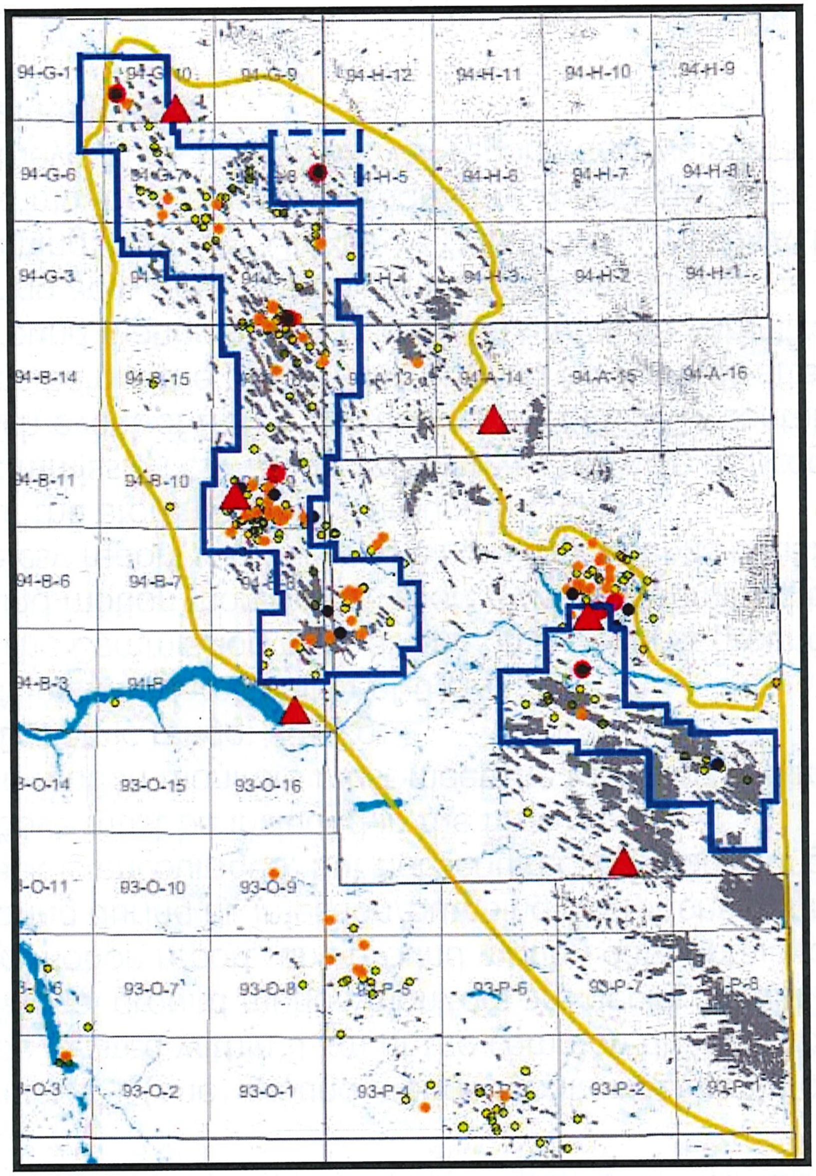


All Hydraulic Fracturing 2013-2015



All Reported Events 2013-2015

Ground Motion Monitoring



- Came into force as a permit condition on June 1, 2016
- Applies to wells permitted after June 1, 2016 within ground motion monitoring areas only

Ground Motion Parameters

- Minimum of 1 (one) ground motion monitor per common drilling pad location
- Must be located within 3 km of the common drilling pad
- If additional ground motion monitors are deployed within 5km of the common drilling pad, include, in the ground motion report, any ground motion data obtained from these monitors
- Monitoring during all injection/pumping operations during hydraulic fracturing activities. Monitoring during flowback is encouraged, but not required. If monitoring is on-going during flowback, any events of 0.02g and above must be included in the final report.
- Ground motion monitors must meet the following minimum criteria:
  - Dynamic range: +/- 2g
  - Minimum detectability of 0.02g
  - The Commission may, at any time, request ground motion monitoring data
- A ground motion monitoring report must be submitted to the Commission in electronic format consisting of one csv report summarizing all ground motions equal to 0.02g and greater and one SEED format file for each of the aforementioned ground motions
- The Commission csv report template is available at bcogc.ca
- For each event of 0.02g and above, the SEED file containing instrument response and waveform from 30 seconds before the observed event and 60 seconds after must be submitted
- The ground motion monitoring reports must be submitted within 30 days of the completion of hydraulic fracturing activities via email to welldatamail@bcogc.ca
- File naming: WANUM_GMMR_YYYYMMDD_OPTIONALDESCRIPTION.CSV/SEED
- Ground motion monitoring reports are considered to be information obtained from or about a well. As such, they will be treated as well reports and well data, as per 17 (1) of the Oil and Gas Activities Act General Regulation.


Thank You – Questions?

From: Oswell, Terry
Sent: 2017, November 17 12:39 PM
To: Ahlfield, Kay
Cc: Addo, Kofi
Subject: FW: Crew Energy Meeting - 16 Nov 2017 Notes

FYI – Stephen wants us to have a short meeting (without him), depending on what you learn in Calgary. To talk about potential conditions for Crew Energy, perhaps or the information that we want from them.

From: Oswell, Terry
Sent: 2017, November 17 8:41 AM
To: Watson, Andrew; Rigbey, Stephen; Addo, Kofi; (19), (22) [redacted] Gilliss, Scott
Subject: RE: Crew Energy Meeting - 16 Nov 2017 Notes

This time with pad numbers corrected.

From: Oswell, Terry
Sent: 2017, November 17 8:40 AM
To: Watson, Andrew; Rigbey, Stephen; Addo, Kofi; (19), (22) [redacted] Gilliss, Scott
Subject: Crew Energy Meeting - 16 Nov 2017 Notes

Notes from our meeting with Crew Energy yesterday

Attendance at the meeting was (19), (22) [redacted] and myself from BC Hydro; Paul Dever and Kevin Evers from Crew Energy

(19), (22) [redacted] gave an update of the status of construction at Site C, with emphasis that the right bank in general is very sensitive with 20-30 mm of movement seen so far (displacements are similar in magnitude as predicted displacements) and that the inlet portal excavation is also very sensitive. Movements of the slopes are observed with small blasts and rainfall events. The inlet portal excavation is starting now and is expected to continue through winter. Less concerned about seismic induced ground motions with regards to the earthfill structures and tunnels.

(19) [redacted] noted that BC Hydro is looking into the withstand of the inlet portal structure, beyond the level to which it was designed to.

Paul gave a summary of the June 9 meeting with BC Hydro, noting that they now have Well Authorization from the OGC for Pad 3-32 which is fully within the 5 km buffer zone. There will be 10 wells from this pad. This Well Authorization requires that Crew Energy notify between 21 and 45 days (before drilling and before completion). They will send this notification to the DSOP email address with copy to my address. I need to check that the DSOP Process contains the information the DSOP needs to act on the notification email (post-meeting check – it does contain instructions to forward the email to me). They also have authorization to drill from Pad 4-21 which is immediately adjacent to the buffer zone and although the Well Authorization doesn't require they notify us for this pad, they plan to because some wells may cross the 5 km buffer zone by a few meters. They may drill from this pad first. Work is expected to start in January.

Kevin gave a hard copy presentation on well activity since the June meeting. They have completed 7 pads and for each pad, they showed a map with the location of all measured seismic events for the period of well activity, in addition to the location of major faults (publically available information) and smaller faults that they have identified. The highest recorded event was magnitude 1.92. Only one event was measured within the buffer zone, magnitude 0.78 on

November 4. Crew Energy have two ground motion accelerometers that are moved around as required and buried in the ground in a concrete vault. They are required to submit a record of ground motions exceeding 0.02g to the OGC within 30 days after operations complete. It's possible that the requirement for movements to report on will decrease to anything over 0.008g starting in January but apparently this date is a moving target. The set of slides is not available until Kevin gets permission to share them – they may decide to provide us with a summary of the significant events and distance from the well.

With work possibly starting in or near the buffer zone in January, we should expect our first formal notification to arrive in December. If BC Hydro wants to have any conditions other than what Crew Energy is already doing, we will need to decide what we want fairly soon and then inform the OGC.

As interest, Paul and Kevin noted that there is an Induced Seismicity Workshop being held in Calgary on December 4.

Terry Oswell | Dam Safety Program Engineer, Dam Safety

BC Hydro
6911 Southpoint Dr, 10th floor
Burnaby, BC V3N 4X8

(22) [redacted]

E terry.oswell@bchydro.com

bchydro.com

Smart about power in all we do.

From: (19), (22) [redacted]
Sent: 2017, March 21 9:35 AM
To: Oswell, Terry; Rigbey, Stephen; Addo, Kofi; Watson, Andrew
Subject: RE: Crew Energy Slides

We don't have a withstand for the cofferdams.

Below are the results of some of the stability analyses. For the post-seismic analysis, it is assumed that liquefaction of the alluvium occurs. Some liquefaction may occur, but it wouldn't be widespread.

(19), (22) [redacted]

SITE C CLEAN ENERGY PROJECT

STAGE 1 COFFERDAM STABILITY ANALYSIS RESULTS - FACTORS OF SAFETY

Loading Condition	Minimum Required Factor of Safety	Slip Surface		Section						
				S1-DIC-0200	S1-DIC-0320	S1-DOC-0400	S1-LCD-0160	S1-LCD-0470	S1-RCD-0180	S1-RCD-
1. End of Construction Normal Maximum Water Level + B-Bar	FOS > 1.2	River side	Embankment	Note 1	2.37	1.87	2.08	1.94	1.80	1.9
		Dewatered (dry side)	Embankment	2.56	2.41	1.98	2.07	2.43	2.43	2.1
			Along BP25	1.67	1.69	Note 3	Note 3	Note 3	Note 3	Note
			Along BP27	1.93	2.17	Note 3	Note 3	Note 3	Note 3	Note
			Along BP28	2.33	Note 3	1.41	3.38	1.41	NA	1.41
			Along BP30	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP31	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP33	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
2. Long-Term Steady Stage Seepage Static Normal Maximum Design Water Level	FOS > 1.3	River side	Embankment	Note 1	2.40	1.80	2.20	1.91	1.74	2.0
		Dewatered (dry side)	Embankment	2.61	2.30	2.00	1.95	2.47	2.43	2.1
			Along BP25	1.72	1.64	Note 3	Note 3	Note 3	Note 3	Note
			Along BP27	1.97	2.12	Note 3	Note 3	Note 3	Note 3	Note
			Along BP28	2.35	Note 3	1.44	3.56	1.34	Note 3	1.3
			Along BP30	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP31	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP33	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
3. Long-Term Steady Stage Seepage + Seismic Normal Maximum Design Water Level	FOS > 1.0	River side	Embankment	Note 1	1.44	1.27	1.21	1.72	1.44	1.7
		Dewatered (dry side)	Embankment	1.34	1.15	1.33	1.76	2.15	2.10	1.8
			Along BP25	0.836 (0.1045 - Note 2)	1.06	Note 3	Note 3	Note 3	Note 3	Note
			Along BP27	1.07	1.53	Note 3	Note 3	Note 3	Note 3	Note
			Along BP28	1.26	NA	0.762 (0.08 - Note 2)	2.86	1.17	Note 3	1.1
			Along BP30	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP31	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
			Along BP33	Note 3	Note 3	Note 3	Note 3	Note 3	Note 3	Note
4. Post Seismic Normal Maximum Design Water Level	FOS > 1.1	River side	Embankment	Note 1	1.64	1.15	1.43	1.21	1.62	1.1
4a. Rapid Drawdown										

From: Oswell, Terry
Sent: 2017, March 21 9:11 AM
To: (19), (22) [redacted] Rigbey, Stephen; Addo, Kofi; Watson, Andrew
Subject: RE: Crew Energy Slides

Have there been any analyses carried out on the cofferdams to see what they would actually withstand under seismic loading?

From (19), (22) [redacted]
Sent: 2017, March 21 8:47 AM
To: Rigbey, Stephen; Oswell, Terry; Addo, Kofi; Watson, Andrew
Subject: Crew Energy Slides

Attached are PowerPoint slides for use in the meeting with Crew tomorrow, for comment.

(19), (22) [redacted]

From: (19), (22) [redacted]
Sent: 2017, March 09 2:54 PM
To: Watson, Andrew; Rigbey, Stephen; Addo, Kofi; Oswell, Terry (terry.oswell@bchydro.com)
Subject: Proposed Agenda Crew Energy Induced Seismicity Site C

All,
Below is the agenda for a meeting with Paul A. Dever, Director, Government & Stakeholder Relations Crew Energy Inc. and others, in response to the requirement for notification (see attached).
For comments.

Agenda for discussion with Crew Energy regarding induced seismicity:

1. OGC requirements: 5 km buffer at Site C and need for notification.
2. Sensitivity of Site C to induced seismicity during construction.
3. Crew Energy preliminary work plan during Site C construction.
4. Monitoring array.
5. Sharing of data.
6. Proposed protocol: see BC Drilling and Production Regulation 21.1 below.

BC Drilling and Production Regulation 21.1

Induced seismicity

21.1 (1) During fracturing or disposal operations on a well, the well permit holder must immediately report to the commission any seismic event within a 3 km radius of the drilling pad that is recorded by the well permit holder or reported to the well permit holder by any source available, if

(a) the seismic event has a magnitude of 4.0 or greater, or

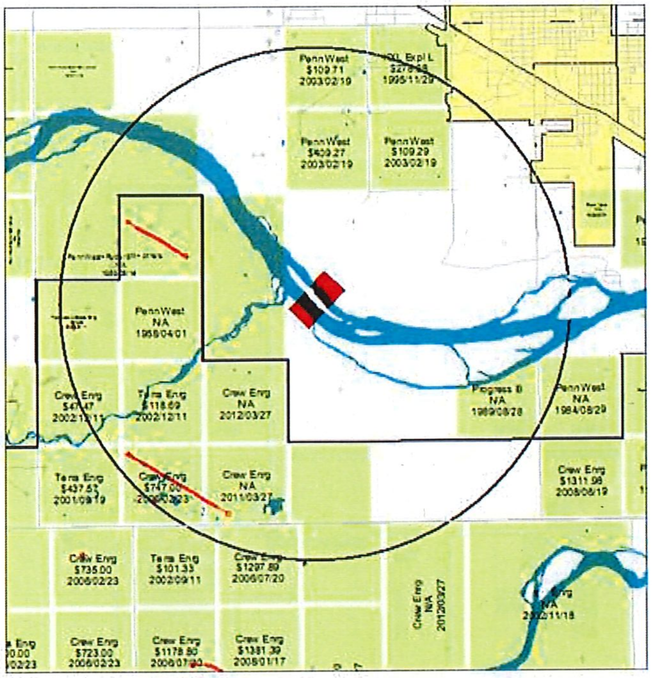
(b) a ground motion is felt on the surface by any individual within the 3 km radius.

(2) If a well is identified by the well permit holder or the commission as being responsible for a seismic event that has a magnitude of 4.0 or greater, the well permit holder must suspend fracturing and disposal operations on the well immediately.

(3) Fracturing and disposal operations suspended under subsection (2) may continue once the well permit holder has implemented operational changes satisfactory to the commission to reduce or eliminate the initiation of additional induced seismic events.

[en. B.C. Reg. 159/2015, s. 5; am. B.C. Reg. 165/2015.]

Site C - 5 km radius



Nearest Montney Activity

- 2.5 km to closest well
- 4 km to closest production

5 KM

- Montney P&NG tenure very close (Penn West & Crew Energy)

Montney oil focus may bring development in mid term but no indication of near term drivers.

- Crew not LNG linked

High liquids/oil and lower pressures = less desirable

From: Watson, Andrew
Sent: 2016, June 20 12:54 PM
To: Addo, Kofi
Cc: Rigbey, Stephen
Subject: RE: Fracking Discussion with OGC

Anytime after Sept 6 should be ok
thx

From: Addo, Kofi
Sent: 2016, June 20 12:50 PM
To: Watson, Andrew
Cc: Rigbey, Stephen
Subject: RE: Fracking Discussion with OGC

Andrew,

I suggest we postpone the meeting to September (as alternatively proposed by the OGC) so you can attend. The OGC also wants to discuss Site C Construction (you are most knowledgeable on this) and how it may 'regulate' operations to reduce adverse impacts.

Which week in September are you able to meet?

Kofi

From: Rigbey, Stephen
Sent: 2016, June 18 6:52 AM
To: Addo, Kofi
Cc: Watson, Andrew
Subject: Re: Fracking Discussion with OGC

It looks like I am. Please block the time through Fran.

Sent from my iPhone

On Jun 17, 2016, at 1:56 PM, Addo, Kofi <Kofi.Addo@bchydro.com> wrote:

> FYI –
>
> Are you available on July 25th to meet with the OGC, per their e-mail below?
>
> **From:** Addo, Kofi
> **Sent:** 2016, June 17 10:55 AM
> **To:** 'Venables, Stuart'
> **Cc:** Johnson, Jeff
> **Subject:** RE: Greetings
>
> Good Morning Stu,

We are very interested in meeting with you and your colleagues at BCOGC on this and other matters related to oil & gas exploration near the dams and appurtenant structures.

I will discuss timing with our Director of Dam Safety and the Site C Project Engineer and get back to you early next week.

Kind regards,
Kofi

From: Venables, Stuart [mailto:Stuart.Venables@BCOGC.ca]
Sent: 2016, June 17 8:52 AM
To: Addo, Kofi
Cc: Johnson, Jeff
Subject: Greetings

Morning Kofi,

I hope this note finds you well. Earlier this year I sent you a variety of maps and tenure info for operators around both the WAC and Peace Dams along with the proposed Site C location. MNGD has a policy in place to not sell any tenure within 5km of the WAC and Peace Dams, however there is tenure already sold within 5km of the proposed Site C location. I'd like to get together with you and any of your colleagues that are interested to discuss the timing of Site C construction, understand the concerns that BC Hydro may have with oil and gas development during both the construction and operational phases of the Site C dam and work towards establishing well permit conditions for operators to follow that would work towards alleviating potential safety concerns.

The summer is quickly approaching, so I understand that availability may be difficult. Right now, the week of July 25th works well for us and we can come to your offices in Vancouver. If there are no dates that will work for you that week, then we'll make plans to get together in September.

Take care,

-Stu

<image001.jpg>

Stuart Venables P.Geo
Senior Petroleum Geologist
Stuart.Venables@BCOGC.ca

Victoria BC
Office Address Directory
bcogc.ca

T. 250 419-4472
F. 250-419-4403
(22) [redacted]

<image002.jpg> <image003.jpg>

From: (19), (22) [redacted]
Sent: 2019, February 08 1:20 PM
To: Addo, Kofi
Cc: (19), (22) [redacted] Oswell, Terry; Watson, Andrew
Subject: RE: Ground motions from OGC

Good afternoon Kofi,

Have you had a chance to process the data from the most recent induced earthquake?

Thanks,
(19), [redacted]

(19), (22) [redacted]
Owner's Design Representative, GSS Civil Works Contract
Site C Clean Energy Project

P 236 455 6659
(19), (22) [redacted]@bchydro.com

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From: Addo, Kofi
Sent: 2019, January 16 6:27 PM
To: Watson, Andrew
Cc: Stevenson, Garry; Oswell, Terry; (19), (22) [redacted]
Subject: RE: Ground motions from OGC

Andrew,

I was able to reach the OGC yesterday. Based on the clarification received, I converted the raw waveform data to ASCII. I still have to go back to the OGC for metadata needed for additional processing. I will touch base with Gail before doing so.

Regards,
Kofi

From: Watson, Andrew
Sent: Wednesday, January 16, 2019 5:14 PM
To: Addo, Kofi
Cc: Stevenson, Garry; Oswell, Terry; (19), (22) [redacted]
Subject: Ground motions from OGC

Kofi,

The data provided by OGC is also not something gail can work with or at least not without additional work. Can you call her and combine request to OGC? We should get OGC to provide the data in suitable form so we can quickly review the ground motions. Sounds like Gail is also looking to extrapolate to expected bedrock motions but I want to ensure we have the best data and minimize uncertainty. I assume with all the monitoring in place there must be some recordings in rock. Listening to crew they periodically have downhole movements. Others must as well so there must be some nearby recordings in rock.

Can you follow-up with Gail and let me us know if you need assistance getting anything from OGC?

You point on increased monitoring at the site is increasingly important. (19) [redacted] will get back to you on that one.

Thx
ANdrew

Andrew Watson, P.Eng., M.Eng.
Director, Design Engineering
Site C Clean Energy Project
BC Hydro
Suite 1200 745 Thurlow Street
Vancouver, BC V6E 4M3
Tel: 236-455-6715 (direct)
(22) [redacted]
Web: www.sitecproject.com

From: Addo, Kofi
Sent: 2016, August 19 3:16 PM
To: Addo, Kofi
Subject: RE: Induced Seismicity Site C

Advisory Board No. 14, May 2015

Section 10 Induced Seismicity

Recommendation/Comment
The Board recommends that this issue receive more attention, based upon its experience with related considerations elsewhere. To advance this, BC Hydro should undertake dynamic analyses with earthquake records, scaled to the near field and interrogate whether significant slip along weak bedding planes might develop and create excessive cracking of the concrete structures. The Board does not perceive any risk associated with the earthfill dam.

Status
In Progress: Discussions have been ongoing with TransAlta (regarding the Brazeau Dam) and BC Oil and Gas Commission (regarding data and methods of analysis for induced seismicity from both water injection and fraccing operations). The next steps for BC Hydro are as follows:

- Continue discussions with TransAlta to obtain information that they are willing to release; as it stands there are issues with release of information.
- Evaluation of state of practice from other jurisdictions
- Re-calculate ground motions for Site C taking into account induced seismicity as it relates to operations in the field. This work will be reviewed by a qualified Specialist Consulting Engineer or Seismologist.
- Recalculate the response on the structures
- Re-evaluation the 5km consultation buffer in place for tenure sales around the Peace River dams.

From: (19), (22) [redacted]
Sent: 2016, August 19 2:02 PM
To: Addo, Kofi
Subject: Induced Seismicity Site C

Kofi,
Text below.
Is it possible to send me the proposal you sent to Andrew?

Thanks,
(19), (22) [redacted]

125	Advisory Board No. 14, May 2015 Section 10 Induced Seismicity	The Board recommends that this issue receive more attention, based upon its experience with related considerations elsewhere. To advance this, BC Hydro should undertake dynamic analyses with earthquake records, scaled to the near field and interrogate whether significant slip along weak bedding planes might develop and create excessive cracking of the concrete structures. The Board does not perceive any risk associated with the earthfill dam.	**In Progress:** Discussions have been ongoing with Transalta regarding the braz dam and BC Oil and Gas Commission regarding data and methods of analysis fo induced seismicity from both water injectic and fraccing operations. The next steps fo BCHydro are as follows: • Continue discussions with Transa to obtain information that they are willing to release; as it stands ther are issues with release of information. • Evaluation of state of practice fron other jurisdictions • Re-calculate ground motions for S C taking into account induced seismicity as it relates to operatior in the field. This work will be reviewed by a qualified Specialist Consulting Engineer or Seismolog • Recalculate the response on the structures • Re-evaluation the 5km consultatio buffer in place for tenure sales around the peace dams.

From: [redacted]
Sent: 2018, October 29 2:08 PM
To: Watson, Andrew
Cc: [redacted]; Addo, Kofi
Subject: RE: Seismicity Update:

Andrew,

Just got off the phone with Kofi. Here is a summary of our discussion (Kofi, feel free to correct my understanding where applicable).

1) STC Seismic Hazard
   a. Seismic hazard for STC was completed in 2012, before the work on the PSHA was completed.
   b. Some assumptions were made in order to complete the seismic hazard for STC.
   c. The memo stated that these assumptions should be confirmed at some point in time.
   d. Kofi would like to confirm these assumptions by studying current geological information (especially when shear wave velocities are available).
   e. [redacted] to help coordinate collection of information.
2) Seismic Instrumentation at STC
   a. [redacted] to check with [redacted] what are the plans for seismic instrumentation in and around STC.
   b. Kofi interested to capture:
      i. Natural earthquakes
      ii. Induced earthquakes
      iii. Reservoir filling triggered seismicity
   c. Two to four instruments could be available at no cost through GSC.
   d. Would need four more instruments to get adequate coverage. Can we use STC's instruments to that effect?
   e. Monitoring would have to be in place two years ahead of reservoir filling.
   f. If done soon (next few months), we could 'piggy back' on some work GSC is doing in the area and have them monitor the data and simply upload it for our use.

In summary:
1) [redacted] to help coordinate collection of information.
2) [redacted] to check with [redacted] what are the plans for seismic instrumentation in and around STC.
3) Can STC's instruments to that effect?

Let's discuss when you have a moment.

Thanks,
[redacted]

[redacted]
Owner's Design Representative, MCW and GSS Civil Works Contracts
Site C Clean Energy Project

P 236 455 6659
[redacted]@bchydro.com

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From: Addo, Kofi
Sent: 2018, October 29 9:23 AM
To: Watson, Andrew; (19), (22) [redacted]
Cc: (19), (22) [redacted]
Subject: RE: Seismicity Update:

Andrew - thanks for letting me know.

(19), (22) [redacted] I'll be at my desk: 7-7725

From: Watson, Andrew
Sent: 2018, October 29 9:19 AM
To: Addo, Kofi; (19), (22) [redacted]
Cc: (19), (22) [redacted]
Subject: RE: Seismicity Update:

Kofi

Something has come up I have to deal with.

(19), (22) [redacted] can you catchup with Kofi today and get an update on the seismicity work? We can followup with a proper update as needed,

thx

-----Original Appointment-----
From: Addo, Kofi
Sent: 2018, October 28 10:42 AM
To: Addo, Kofi; Watson, Andrew
Subject: Seismicity Update:
When: 2018, October 29 9:30 AM-9:45 AM (UTC-08:00) Pacific Time (US & Canada).
Where: Do you have 5-10 minutes for a quick call?

From: Watson, Andrew
Sent: 2016, September 19 1:30 PM
To: Roby, Misti; Thomas, James; Fourchalk, Doug
Cc: Rigbey, Stephen; Addo, Kofi
Subject: RE: Well in new substation WA 02082

Misti, can you see if doug fourchalk is available to the oil and gas meeting on Wednesday. Need him from 1 to 2.

Steven Rigbey also needs to call in at 3pm. Can you also send this invite to Steven Rigbey so he can call in at this time as well. Also pls setup agenda

Priobably best to send one appointment with the two different call in times.
Agenda:
1:00 to 1:30 Discussion on existing oil and gas infrastructure on right bank : Richard Tuohey
1:30 to 2:30 OGC update on activities, seismic monitoring, controls, discussion of evolving issues (1 hour) Jeff/OGC
2:30 to 3:00: Site C update on construction, schedule (30 min) Andrew
3:00-3:30: Discussion on Site C update on further seismic studies underway and formalising the current buffer and controls for existing tenures. (30 min) Andrew/Rigbey/Kofi
330 to 5 (likely not needed but will hold for discussion)

thx

From: (19), (22) [redacted]
Sent: 2016, September 19 11:15 AM
To: Watson, Andrew
Subject: RE: Well in new substation WA 02082

Forward me the meeting invite, and I shall call in

(19), (22) [redacted] Construction Manager, Site C
Capital Construction - Generation

BC Hydro
Site C Office
Fort St. John, BC

From: Watson, Andrew
Sent: 2016, September 19 11:13 AM
To: (19), (22) [redacted]
Subject: RE: Well in new substation WA 02082

Meeting with oil and gas commisiion tomorrow, can you call in?

From: (19), (22) [redacted]
Sent: 2016, September 19 11:12 AM

To: Watson, Andrew
Subject: FW: Well in new substation WA 02082

FYI. We have two sets of coordinates for the well within the substation.

(19), (22) [redacted] Construction Manager, Site C
Capital Construction - Generation

BC Hydro
Site C Office
Fort St. John, BC

From: (19), (22) [redacted]
Sent: 2016, September 19 9:21 AM
To: Thomas, James
Subject: FW: Well in new substation WA 02082

Good Day
We have another gas well that is within the Substation footprint of the Site C project. This area has been cleared and the surficial organics have been removed. There does not seem to be any type of markers in the field to mark this well.
Supposedly it did/does belong to Direct Energy, but I am not sure if this company is still in business.

(19), (22) [redacted] Construction Manager, Site C
Capital Construction - Generation

BC Hydro
Site C Office
Fort St. John, BC

From: (19), (22) [redacted]
Sent: 2016, September 19 9:16 AM
To: (19), (22) [redacted] Routledge, Robin
Subject: Well in new substation WA 02082

Here's the information to get you started.
Some things to note:

1. If you compare both attachment you will notice the same well number but different UTM coordinates given. I would assume that WA(1)02082 pdf is probably the more accurate coordinate as it references NAD 83 whereas the other does not have a referenced datum.
2. It is not obvious out in the field the few times I have passed by and actually looked for it.
3. I have also include an AutoCAD pdf snapshot of where WA 02082 is located based on both coordinates which are about 162m apart
4. Let me know what you find out!

Cheers
(19), (22) [redacted]

---

(19), (22) [redacted] | Construction Officer, Site-C

BC Hydro
Site C BC Hydro Construction Management Project Office.
7007 269 Rd, Charlie Lake, BC V0C 1H0

M 250 794 0717
(19), (22) [redacted]@bchydro.com

bchydro.com

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From: (22) [redacted]@telus.net>
Sent: 2015, February 19 4:24 PM
To: Watson, Andrew
Cc: Rigbey, Stephen; Addo, Kofi
Subject: Seismicity Induced by Hydraulic Fracturing
Attachments: Induced Seismicity.zip

Andrew,
Thinking ahead to our May 2015 Site C Technical Advisory Board meeting, one topic that might come up again is seismicity induced by hydraulic fracturing. Just thought I would pass on some recent info and ask if you have anything new on this topic.

In January 2015, there were several earthquakes near the community of Fox Creek Alberta, the largest being M3.8 on 14 Jan and M4.4 on 22 Jan. The latest info seems to be that these events are induced and related to hydraulic fracturing, not to waste injection wells. If so, I believe the M4.4 would be the largest magnitude of that type to date (BC has had up to about M4.3). In any case, these earthquakes have been widely reported in Alberta newspapers so Dr. Morgenstern will be aware of them.

By copy of this note to Stephen and Kofi – has Dam Safety had any recent contact with the BC Oil & Gas Commission regarding potential protocols related to induced seismicity near dams?

I happened to be in touch with John Cassidy a few days ago, and he provided copies of 2 recent papers on NE BC induced seismicity; copies are attached for your reference.

(22) [redacted]

NRC Research Press

ARTICLE

Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia

Amir Mansour Farahbod, Honn Kao, Dan M. Walker, and John F. Cassidy

Abstract: We systematically re-analyzed historical seismograms to verify the existence of background seismicity in the Horn River Basin of northeast British Columbia before the start of regional shale gas development. We also carefully relocated local earthquakes that occurred between December 2006 and December 2011 to delineate their spatiotemporal relationship with hydraulic fracturing (HF) operations in the region. Scattered seismic events were detected in the Horn River Basin throughout the study periods. The located seismicity within 100 km of the Fort Nelson seismic station had a clearly increasing trend, specifically in the Etsho area where most local HF operations were performed. The number of events was increased from 24 in 2002–2003 (prior to HF operations) to 131 in 2011 (peak period of HF operations). In addition, maximum magnitude of the events was shifted from M_L 2.9 to M_L 3.6 as the scale of HF operation expanded from 2006–2007 to 2011. Based on our relocated earthquake catalog, the overall *b* value is estimated at 1.21, which is higher than the average of tectonic/natural earthquakes of ~1.0. Our observations highly support the likelihood of a physical relationship between HF operation and induced seismicity in the Horn River Basin. Unfortunately, due to the sparse station density in the region, depth resolution is poor for the vast majority of events in our study area. As new seismograph stations are established in northeast British Columbia, both epicentral mislocation and depth uncertainty for future events are expected to improve significantly.

Résumé : Nous analysons à nouveau et de manière systématique des sismogrammes historiques dans le but de vérifier l'existence d'une sismicité de fond dans le bassin de Horn River, nord-est de la Colombie-Britannique, avant le début d'un développement régional de gaz de shale. Nous avons aussi soigneusement relocalisé les séismes locaux survenus entre décembre 2006 et décembre 2011 afin de délimiter leurs relations spatiotemporelles par rapport aux opérations de fracturation hydraulique (FH) dans la région. Des événements sismiques dispersés ont été détectés dans le bassin de Horn River durant toutes les périodes d'étude. La sismicité localisée dans un rayon de 100 km de la station sismique de Fort Nelson montrait nettement une tendance croissante, surtout dans le secteur d'Etsho où se déroulaient la plupart des opérations de FH. Le nombre d'événements a crû de 24 en 2002-2003 (avant les opérations de FH) à 131 en 2011 (période de pointe des opérations de FH). De plus, la magnitude maximale des événements est passée de M_L 2,9 à M_L 3,6 à mesure qu'augmentait l'échelle des opérations de FH de 2006-2007 à 2011. En se basant sur notre catalogue des séismes relocalisés, la valeur *b* générale est estimée à 1,21, ce qui est supérieur à la moyenne des séismes tectoniques/naturels de ~1,0. Nos observations supportent fortement la possibilité d'une relation physique entre les opérations de FH et la sismicité induite dans le bassin de Horn River. Malheureusement, en raison de la faible densité des stations dans la région, la résolution de la profondeur est mauvaise pour la plupart des événements dans notre secteur d'étude. À mesure que de nouvelles stations sismiques seront établies dans le nord-est de la Colombie-Britannique, l'erreur de positionnement de l'épicentre et l'incertitude quant à la profondeur des événements futurs devraient diminuer de façon significative. [Traduit par le Rédaction]

Introduction

The Horn River Basin (HRB), located in northeast British Columbia (Fig. 1), is one of the largest shale gas fields in North America (US Department of Energy 2011). As the shale gas exploration and development significantly expanded over the past decade, there have been increasing concerns from governments and local communities on a variety of environmental and public safety issues. Among them, the possibility of increasing seismic hazards due to earthquakes induced by the hydraulic fracturing (HF) treatment of shale gas formations is one of the most discussed topics and has generated serious anxiety in the affected areas (e.g., Green and Styles 2012; Hayes 2012).

It is well known that fluid overpressure would reduce the effective normal stress and thus facilitate shear failures (e.g., Hubbert and Rubey 1959; Pearson 1981). While HF stimulations are very successful in creating flow channels within shale gas formations, there is growing evidence that high-pressure fluid injection could also induce local earthquakes in areas where historical seismicity is rare (e.g., Horner et al. 1994; Deichmann and Giardini 2009; Frohlich et al. 2011; Holland 2011; Avouac 2012; Frohlich 2012; Ellsworth 2013; Frohlich and Brunt 2013; Maxwell 2013; Keranen et al. 2013, 2014; Schultz et al. 2014). In the HRB, limited HF operations started in late November 2006, became much more active in 2009 as the shale gas development expanded, and increased again in 2010 and 2011 (British Columbia Oil and Gas Commission 2012). In terms of regional seismicity, earthquake catalogues compiled by Natural Resources Canada (NRCan) indicate that the HRB area had only one event before 2009 (15 February 2004, M_L 2.4). Since then, however, more than 40 local earthquakes have been detected and reported (Fig. 2). Among them, seven events in 2010 were determined with $M_L \geq 3$. Such a dramatic change in the pattern of background

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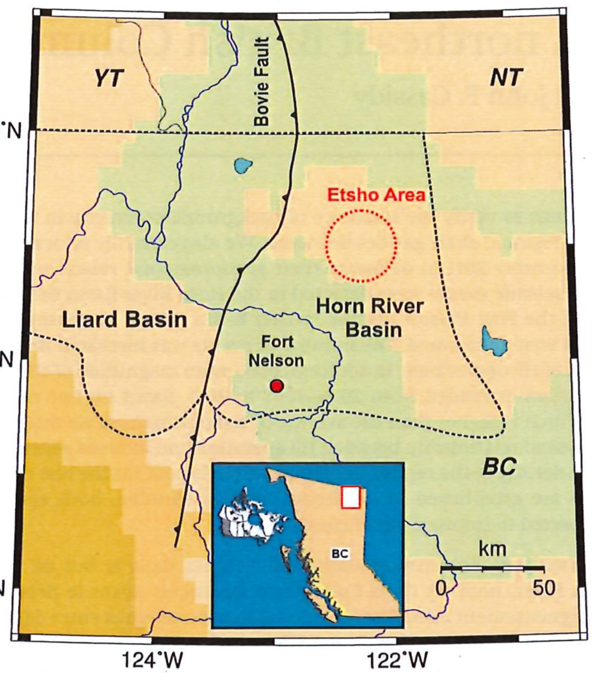
Paper handled by Associate Editor Andrew Calvert.

A.M. Farahbod, H. Kao, and J.F. Cassidy. Geological Survey of Canada, Pacific Geoscience Centre, 9860 West Saanich Road, Sidney, BC V8L 4B2, Canada.
D.M. Walker. British Columbia Oil and Gas Commission, 300, 398 Harbour Rd., Victoria, BC V9A 0B7, Canada.
Corresponding author: Amir Mansour Farahbod (e-mail: Amir.Farahbod@NRCan-RNCan.gc.ca).

Fig. 1. A map showing the location of the Horn River Basin and Fort Nelson in northeast British Columbia (BC). The Bovie Fault separates the Horn River Basin from the neighboring Liard Basin. Dashed lines mark the outline of the basin system. YT and NT correspond to Yukon and Northwest Territories, respectively.

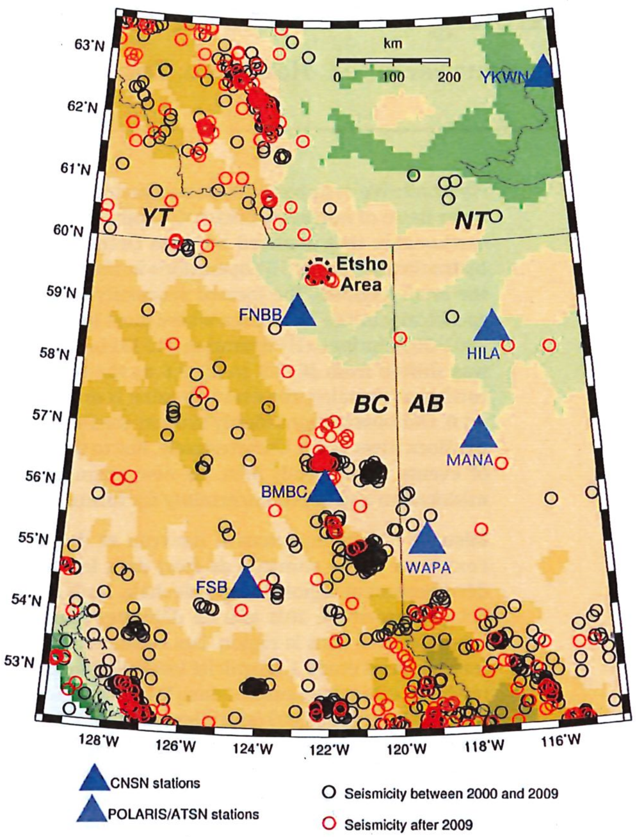


seismicity is unusual. Moreover, areas immediately to the north or west of the HRB, where no shale gas HF was performed, show no discernible variation (Fig. 2).

Delineating possible relationships between local HF operations and the change of seismic pattern in the HRB requires accurate assessment of earthquake distribution both before and after the regional shale gas development. Unfortunately, the Canadian National Seismograph Network (CNSN), which is the primary data source for NRCan's earthquake catalog, had very sparse station coverage for northeast British Columbia before mid-2013. There was only one station in the HRB (at Fort Nelson, FNBB, Fig. 2), and stations to the east, west, and south were all located at least 350 km away. The station distribution was even worse to the north where no seismograph station was available between Yellowknife in the Northwest Territories and Whitehorse in the Yukon. Thus, the apparent lack of historical background seismicity in the HRB could be an artifact due to the poor detection threshold of the CNSN.

To clarify the above issue, we conducted a systematic investigation of the background seismicity for the HRB. Because the conventional earthquake location methods are inapplicable to smaller events whose seismic signals fail to reach multiple stations at distance, we had to take a totally different approach with a very limited dataset. We randomly chose a one-year window (from July 2002 to July 2003) that is well before the start of local HF operations to verify the apparent aseismic nature of the HRB. Also, we applied the same procedure to analyze continuous waveforms from December 2006 until the end of 2011 to better define the spatiotemporal distribution of local seismicity after the beginning of shale gas development in the HRB. These results are then compared to the timing and locations of HF operations in the area, available from the British Columbia Oil and Gas Commission, to investigate their possible relationship.

Fig. 2. Seismicity (circles) between 2000 and mid-2014 and seismograph stations (triangles) in the Horn River Basin and neighboring regions. CNSN, Canadian National Seismograph Network; POLARIS, Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity; ATSN, Alberta Telemetered Seismograph Network.

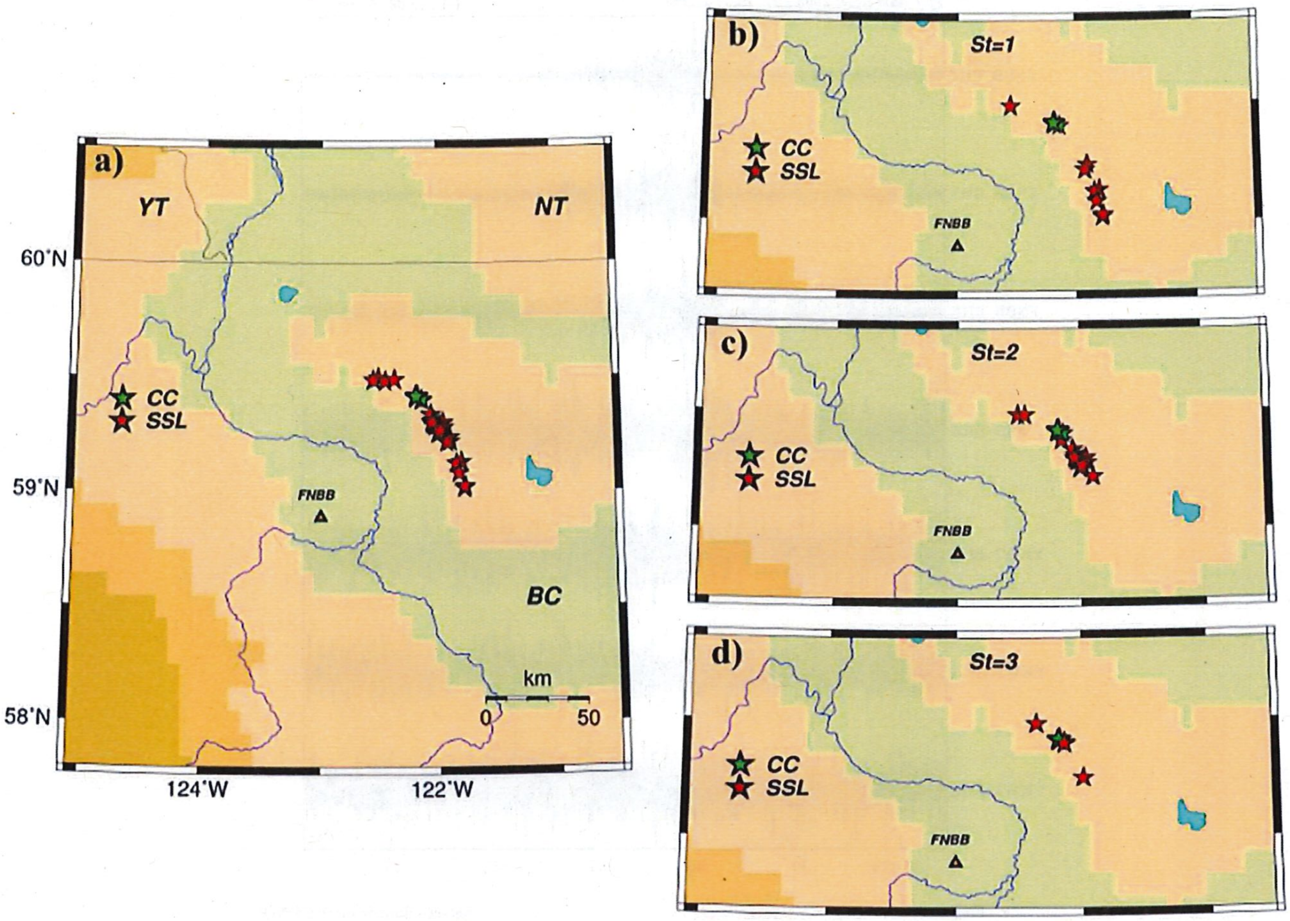


Data and analysis

Our primary dataset is the continuous three-component broadband waveforms from the CNSN station at Fort Nelson (FNBB, Fig. 2). P and S phases were picked by visual inspection of bandpass-filtered (1–5 Hz) seismograms. Whenever corresponding arrivals could be identified, waveforms from other nearby stations in the region (Fig. 2), including Bull Mountain (BMBC), Fort St. James (FSB), Yellowknife (YKWN), and three stations of the Alberta Telemetered Seismograph Network (HILA, MANA, and WAPA), were also included to maximize the constraint.

We use the single-station location (SSL) method to locate hypocenters of local events. Here, we briefly explain how the SSL method works. Readers are referred to the original paper (Roberts et al. 1989) and the user manual for the Seismic Analysis software package (SEISAN, Ottemöller et al. 2012) for more technical details. The principle concept of SSL is to determine the source's hypocenter by tracing back the corresponding ray path. The first step of our analysis is to pick a short time window that contains P arrival on the vertical component seismogram. Cross correlation functions are then calculated respectively between the vertical component and the two horizontal components. The ratio between the two cross correlation functions is used to estimate the back azimuth (i.e., the direction from station to the source). The incident angle is subsequently estimated from the ratio between the cross correlation between the radial and vertical components and the autocorrelation of the vertical component. Finally, the ray path is traced backward from the recording

Fig. 3. Comparison of epicenters determined by the cross-correlation method (CC) and single-station location (SSL) method for local earthquakes in the Horn River Basin. Data from a dense local array are used to derive the CC solutions, whereas SSL solutions use only Canadian National Seismograph Network stations. (*a*) All 26 events that occurred during July and August of 2011. (*b*) Small events with $M_L \leq$ 2.1. Seismic signals of these events can be identified at only one station. (*c*) Solutions derived from two stations (2.1 < M_L < 2.9). (*d*) For events larger than M_L 3.0, waveforms from three stations can be used in the location process.



station toward the source based on an assumed velocity model, and the hypocenter is located at the point that satisfies the travel time difference between the identified S and P phases.

In case of relatively large events that P and S phases can be identified at more than one station, we measure the S–P time differences from all seismograms, but the back azimuth from only the closest three-component station. This is because back azimuths estimated from distant stations are often unreliable due to their low signal-to-noise ratio (SNR). Including these uncertain estimates would deteriorate the accuracy of our solutions.

The SEISAN software determines how well an incoming P wave is polarized by calculating the correlation coefficient and predicted coherence of three-component waveforms (Roberts et al. 1989; Ottemöller et al. 2012). This parameter can be used to select the optimum solution for back azimuth. For a noise-free linearly polarized signal, the correlation coefficient is equal to 1. In practice, this index should be positive and as high as possible. Results with poor correlation coefficient values are rejected. In such cases, the selected time window that contains the P arrival is shifted slightly in search for the highest correlation coefficient.

Accuracy and uncertainty tests

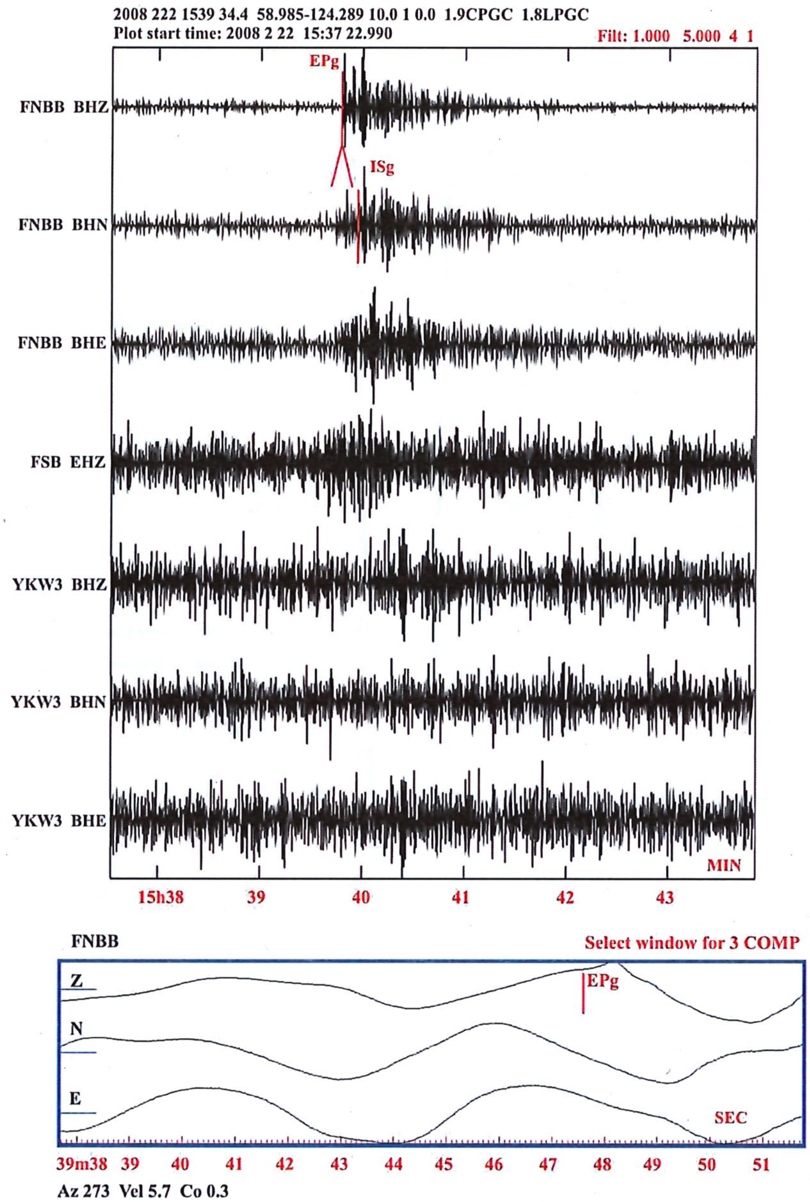
Before we systematically re-evaluate the pattern of background seismicity of the HRB with the SSL method, we conducted several experiments to carefully assess the accuracy and uncertainty of the SSL-derived results. Unlike most conventional location methods whose uncertainties are described by an ellipsoid around the best-fitting solution according to the travel time residuals observed at individual stations, the uncertainty of an SSL-derived location is described by two parameters specifying the range of back azimuth and the range of distance. The uncertainty in back azimuth is primarily from the three-component particle motions that define the ray path, whereas the uncertainty in the distance is controlled by the precision of P and S arrival times.

Our first experiment was to use waveform data from station FNBB to locate 26 local events whose hypocenters were well constrained by a temporary dense seismic array deployed during July

Table 1. Velocity model used in the location process.

Layer	Thickness (km)	V_p (km/s)	V_s (km/s)
1	0.5	5.10	2.95
2	3.5	5.90	3.41
3	5.0	6.20	3.58
4	6.0	6.60	3.81
5	17.0	7.20	4.16
6	4.0	8.20	4.73

Fig. 4. Seismograms corresponding to a small (M_L 1.8) local event that occurred on 22 February 2008. Top panel: Waveforms recorded at the three closest Canadian National Seismograph Network stations. Pg and Sg arrivals can be clearly picked only at station FNBB, while no signals can be recognized at other stations. Bottom panel: A zoom-in window of a few seconds around the picked P first arrival to calculate the corresponding back azimuth (Az), apparent velocity at the surface (Vel), and correlation coefficient (Co).

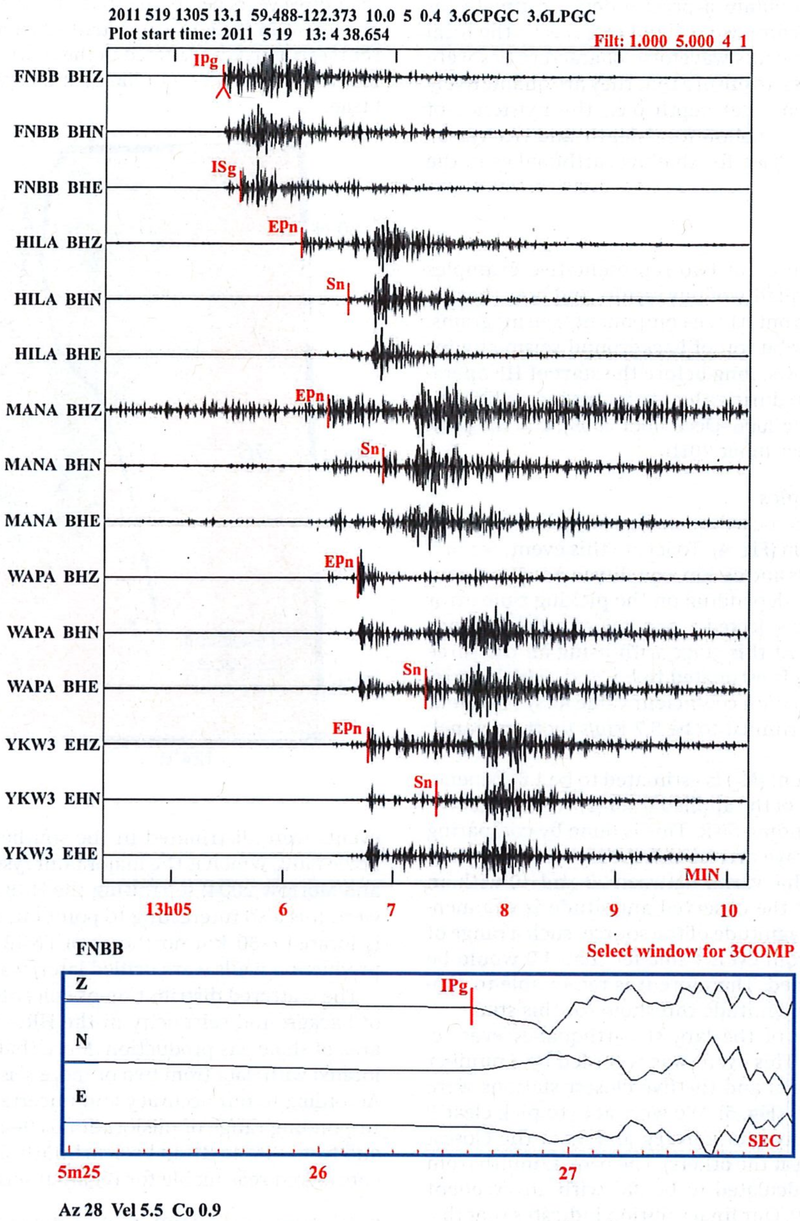


and August of 2011 in one of the HF sites. The size of these local events ranges from M_L 2.0 to 3.1 (British Columbia Oil and Gas Commission 2012). Using only one station, we were able to locate all these events. Taking the locations determined by the local dense array as the ground truth, our results show an error of 0–5 km in distance and from –18° to 39° in back azimuth (Fig. 3*a*). The means are 2 km and 11.5°, with their standard deviations being 1.4 km and 15°, respectively. If we consider the smallest events ($M_L < 2.2$) that were recorded only by the FNBB station, then the error has a range of 0–3 km in distance and from –18° to 39° in back azimuth (Fig. 3*b*). The means are 1.5 km and 11.1°, with their standard deviations being 1.5 km and 20.5°, respectively.

Our second experiment was to use waveform data from multiple stations (FNBB, BMBC, YKWN, and FSB) to locate those ground truth events. Due to the sparse distribution of seismograph stations in the region, we could only conduct this experiment for events with M_L 2.2 or larger. For the 15 events that we could identify their arrivals at two stations, the corresponding distance and back azimuth errors ranged from 0 to 4 km and from –16° to 31°, respectively (Fig. 3*c*). For the three events that we could identify their arrivals at three stations, the corresponding error in the back azimuth further reduced from –11.6° to 11.5° with a mean of –1.4° (Fig. 3*d*).

The above experiments show that the location uncertainty is strongly dependent on the number of stations used in the process. Therefore in the worst-case scenario with only one station available, the mislocation error is characterized by a relatively narrow (5 km) arc strip spanning 39° away from the true great-circle path between the epicenter and the station.

Fig. 5. Seismograms corresponding to a local event (M_L 3.6) that occurred on 19 May 2011. Idenfication of seismic phases can be made at multiple stations (Pg and Sg at FNBB and Pn and Sn at others. Layout and format are the same as that of Fig. 4.



Finally, we repeated the above experiments using a variety of velocity models. Instead of the six-layered velocity model that is used in NRCan's routine determination of earthquake locations (Table 1), we also tried the IASPEI velocity model (Kennett and Engdahl 1991) and a very simple model with one crustal layer over a mantle half-space. With the IASPEI velocity model, our results show an error of 0–6 km in distance and from −17° to 40° in back azimuth. The means are 2 km and 12°, with their standard deviations being 1.7 km and 16°, respectively. These values are statistically equivalent to the results obtained with NRCan's six-layered model, suggesting that the SSL method is tolerant to some velocity model differences. However, the corresponding error in distance increases significantly (up to 11 km) when the oversimplified model consisting of a crustal layer over a mantle half-space is used. The back azimuth error, in contrast, remains almost unchanged (−15° to 38°). This result implies that an incorrect velocity model probably affects the accuracy of distance much more than that of back azimuth.

Given the same error in back azimuth, the actual epicentral mislocation would increase with distance. To put a cap on the amount of epicentral mislocation due to the back azimuth error and for the practical purpose of monitoring seismicity in the HRB, we only locate earthquakes within 100 km from the station FNBB in this study.

In contrast to the epicenter of a local event, the estimation of focal depth is more challenging. While natural earthquakes in this region can occur in a large depth range, from near the surface to as deep as ~35 km, most HF operations are performed along horizontal wells at depths between ~2 and 5 km. Therefore, precise determination of focal depth can be a useful factor to discriminate shallow HF-induced earthquakes from deep tectonic events. Unfortunately, the SSL method is not ideal in constraining the focal depth, especially when the epicentral distance is large. The sparse station coverage in northeast British Columbia before 2013 also made it impossible to obtain a precise depth estimate for regional earthquakes. Therefore, we will not emphasize the focal depth of our results. Each event's waveform characteristics were visually verified, nonetheless, to ensure that they are qualitatively consistent with the derived focal depth (i.e., the existence of strong surface waves means a shallow focal depth, and vice versa). Default depth of 10 km was used for shallow earthquakes in the HRB.

Results

In this section, we first present two representative examples demonstrating the overall quality of our results and how the epicenters are determined from three-component seismograms. Then, we focus on the distribution of background seismicity for three separated time windows: long before the start of HF operations (July 2002–July 2003), during the initial period of light to moderate activity (December 2006–December 2009), and the peak of activity (January 2010–December 2011).

Two representative examples

The first example is a microearthquake whose seismic signals appeared on only one station (Fig. 4). To locate this event, we first picked P and S phase arrivals and assign a quality factor (emergent or impulsive) to each phase depending on the picking time error (top panel, Fig. 4). Then we selected a window of a few seconds around the P wave arrival. At this stage with using all the three components, back azimuth is estimated to be 273°, which corresponds to the highest correlation coefficient value (0.3). Apparent P wave velocity is also determined to be 5.7 km/s (bottom panel, Fig. 4).

The magnitude of this event (M_L) is estimated to be 1.8. Depending on the center frequency of the applied filter (2, 4, 8, and 12 Hz), we calculated the corresponding SNR. This is done by comparing 15 s of noise before the P wave arrival and the last 15 s of S wave coda. The observed SNR value varies between 22 and 40 with an average of 29.7. Given that the observed amplitude is exponentially proportional to the magnitude of the source, such a range of SNR implies that signals from events smaller than 1.0 would be very difficult to be recognized. Therefore it is reasonable to consider 1.0 as the minimum magnitude threshold for this study.

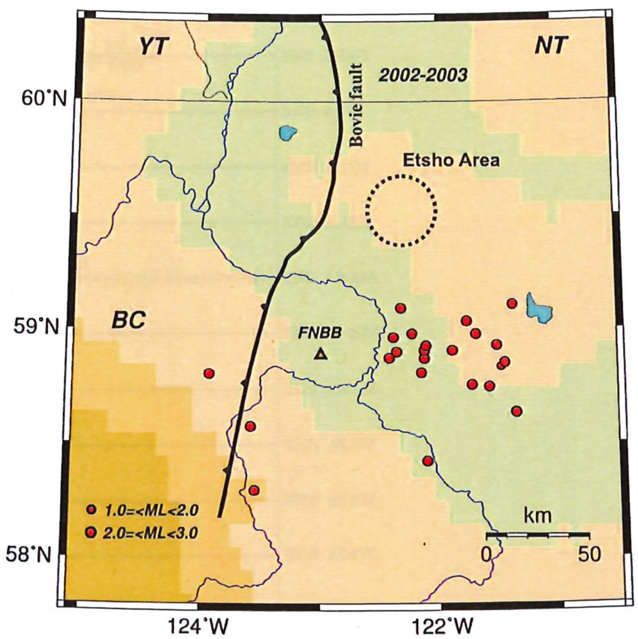
The second event is one of the largest earthquakes ever recorded in the HRB (M_L 3.6). This event was recorded by a number of stations in western Canada and the five closest stations were used in our locating process (Fig. 5). We were able to pick clear P and S phase arrivals at all five stations (Pg and Sg at the closest station FNBB, and Pn and Sn at the others). The back azimuth from FNBB to the source was calculated to be 28° with an excellent correlation coefficient of 0.9. Our final solution indicates that this event occurred 76 km north-northeast from Fort Nelson (59.488°N, 122.373°W). In comparison, the routinely determined epicenter is located at 59.489°N, 122.405°W, which is ~1.8 km from our solution.

Seismicity of the HRB before the start of shale gas production (July 2002 – July 2003)

The NRCan earthquake catalog shows no seismicity in the HRB prior to 2004. To determine whether this lack of background seismicity is a genuine pattern or an artifact due to the sparse seismograph stations in the region, we selected the time window between July 2002 and July 2003 to conduct a systematic SSL analysis in search for any earthquake events that might not be large enough to be detected by CNSN. This time window is more than three years before the start of local HF operations, and thus any detected seismicity must be natural phenomena.

We were able to identify and locate a total of 24 earthquakes with magnitudes ranging from M_L 1.8 to 2.9 (Fig. 6). Most of these events were distributed in the southern HRB to the east of the Bovie fault, which is the major fault system in the region (Maclean and Morrow 2004) separating the HRB and the Liard Basin to the west. It is also interesting to point out that the Etsho area (which is located ~80 km northeast of FNBB, where most of shale gas production wells were drilled later) was apparently aseismic.

Fig. 6. Background seismicity within 100 km from station FNBB during the period of July 2002 – July 2003. This time window is more than three years before the start of any hydraulic fracturing operations in the Etsho area (dashed circle) of the Horn River Basin. Local earthquakes scattered in the southern part of the Horn River Basin and to the west of FNBB, but no events were detected near Etsho.



The scattered distribution of epicenters confirms the existence of background seismicity in the HRB, but not necessarily at the area of shale gas production. More than 87% of these events were located with data from two or more seismograph stations (Table 2). According to our accuracy and uncertainty test results, their corresponding range of mislocation is 0–4 km in epicentral distance and from –16° to 31° in back azimuth. Such a location precision is considered reasonable for regional seismicity.

Seismicity of the HRB during the initial period of HF operation (December 2006 – December 2009)

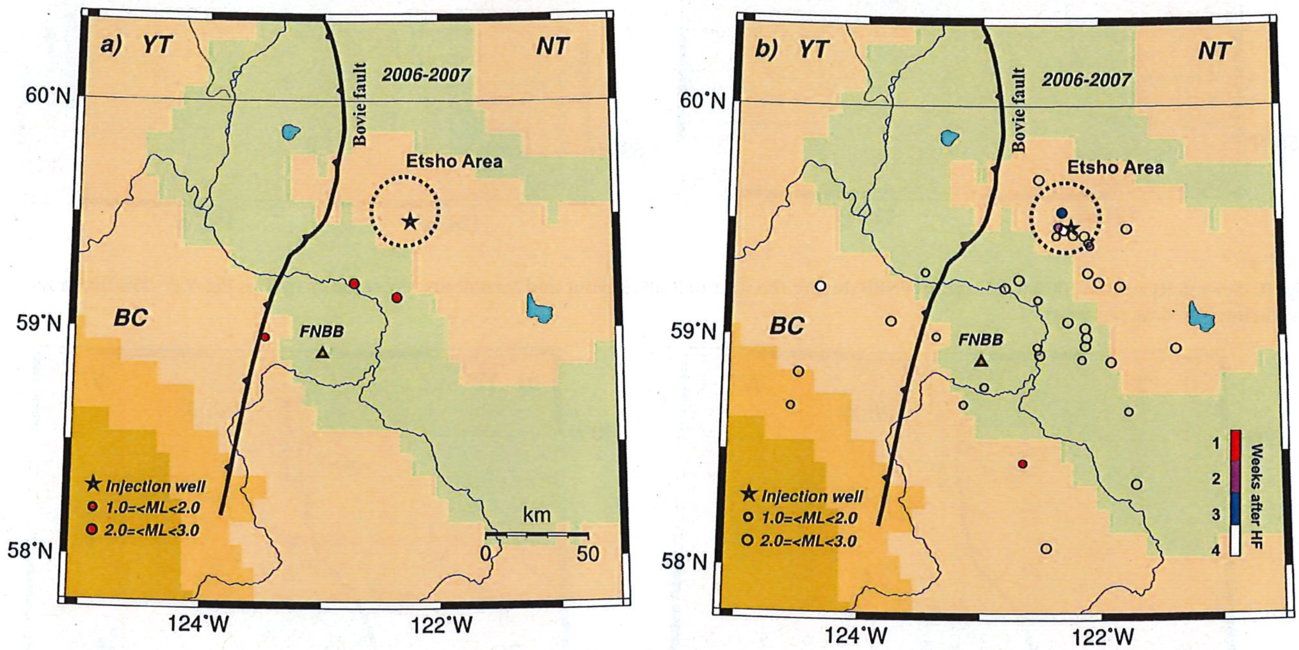
Very limited HF operations were started in the Etsho area of the HRB during the final days of November 2006. There was no trace of visible seismic activity at the FNBB station in November, but we were able to locate three local events in December 2006. HF operations resumed in 2007 for several days near the end of February and another two weeks in March. For the entire 2007, a total of 39 events were located with M_L in the range of 1.3–2.9. Three of these earthquakes occurred during the days of HF operations, but there is no spatial correlation between them and the location of HF fluid injection wells (Fig. 7).

In contrast, we located more events in 2008 (63 events) and 2009 (44 events) as the number of HF days gradually increased (Table 2). The magnitude range, however, appeared to stay effectively unchanged: between M_L 1.0 and 3.0 for events in 2008 (Fig. 8) and between M_L 1.4 and 3.1 for events in 2009 (Fig. 9). It is important to point out that more activity was observed close to injection wells

Table 2. Percentage of days per year when hydraulic fracturing (HF) operation was performed and detected local seismic events in the Horn River Basin.

Year	HF days per year (%)	Total no. of events	Total no. of events during HF	Solutions from one station (%)	Solutions from two stations (%)	Solutions from three stations or more (%)
2002–2003	0	24	0	12.5	62.5	25.0
2006	1.9	3	0	0	100	0
2007	6.8	39	3	56.4	38.5	5.1
2008	14.2	63	33	55.5	41.3	3.2
2009	15.0	44	32	29.6	56.8	13.6
2010	82.5	58	54	19.0	48.3	32.7
2011	84.9	131	119	10.7	50.4	38.9

Fig. 7. Seismicity within 100 km of station FNBB during the initial stage of shale gas development in the Horn River Basin (December 2006–December 2007; ~ 7% hydraulic fracturing (HF) days per year). Stars mark the locations of HF injection wells. (*a*) Events that occurred during the times of local HF operation. (*b*) Events that occurred during non-HF days. Epicenters are marked as solid or open circles if the time lapse between the end of previous HF operation and the origin time is within or greater than one month, respectively.



during the days of HF operations rather than in between the intervals. This is while the number of HF operation days is just a fraction (between 1.9% and 15%) of the year (Table 2). Furthermore, events that occurred during non-HF days tend to cluster around the Etsho area (Figs. 7*b* and 8*b*). Many of them happened shortly after the end of HF operation (often within a couple of weeks, Figs. 7*b* and 8*b*). The observed spatiotemporal pattern of local seismicity is unlikely to be artifacts due to epicenter mislocation because most events were located using data from two or more stations (Table 2).

Based on the spatiotemporal distribution of the observed seismicity, it is highly likely that local HF operation in 2008 and 2009 might have disturbed the regional stress regime, which in turn resulted in some seismic events. In other words, the observed seismicity can be interpreted as fault movement in response to local variations of stress due to sudden increase of fluid volume associated with HF injection. Within the HRB, the shallow, very high permeability Mississippian Debolt zone is being used for water disposal. Therefore the possibility of induced seismicity due to waste water disposal is considered to be very low (Jeff Johnson, personal communications).

Seismicity of the HRB during the peak period of HF operation (January 2010 – December 2011)

The years of 2010 and 2011 correspond to the peak period of local HF operations. Not only was there a sharp increase in the total volume of injected fluids (5 to 10 times), but also the time windows of HF operation were significantly longer (Table 2). There were more than 300 HF days in each year in 2010 and 2011, which are in great contrast to that during 2006–2009.

We located 58 events in 2010 (Figs. 10*a* and 10*b*) and 131 earthquakes in 2011 (Figs. 10*c* and 10*d*). The observed magnitude range also clearly shifted to higher values: M_L between 1.6 and 3.6 in 2010–2011. Spatially, the concentration of observed earthquakes near the injection wells during HF operations in this two-year time period is more obvious than ever (Fig. 10). But due to mislocation errors, general trend of the located earthquakes in the Etsho area resembles an arch (Fig. 10*c*). Temporally, the occurrence of earthquakes during non-HF days is significantly fewer than HF days. However, this is probably biased due to the fact that HF operation was performed during the majority of the days in 2010 and 2011 (Table 2).

Due to the generally larger magnitudes of observed events, we were able to locate approximately one third of events (32.7% for

Fig. 8. Seismicity within 100 km of station FNBB during the year of 2008. Layout and format are the same as that in Fig. 7 (~ 14% hydraulic fracturing (HF) days per year).

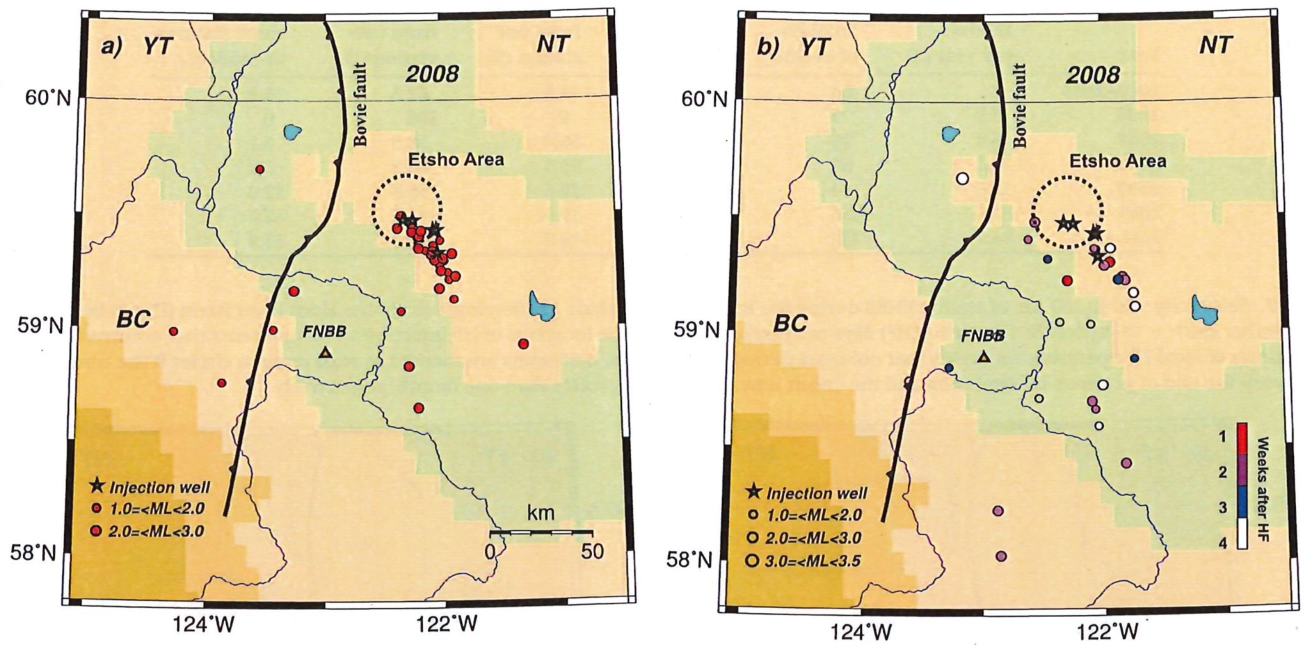
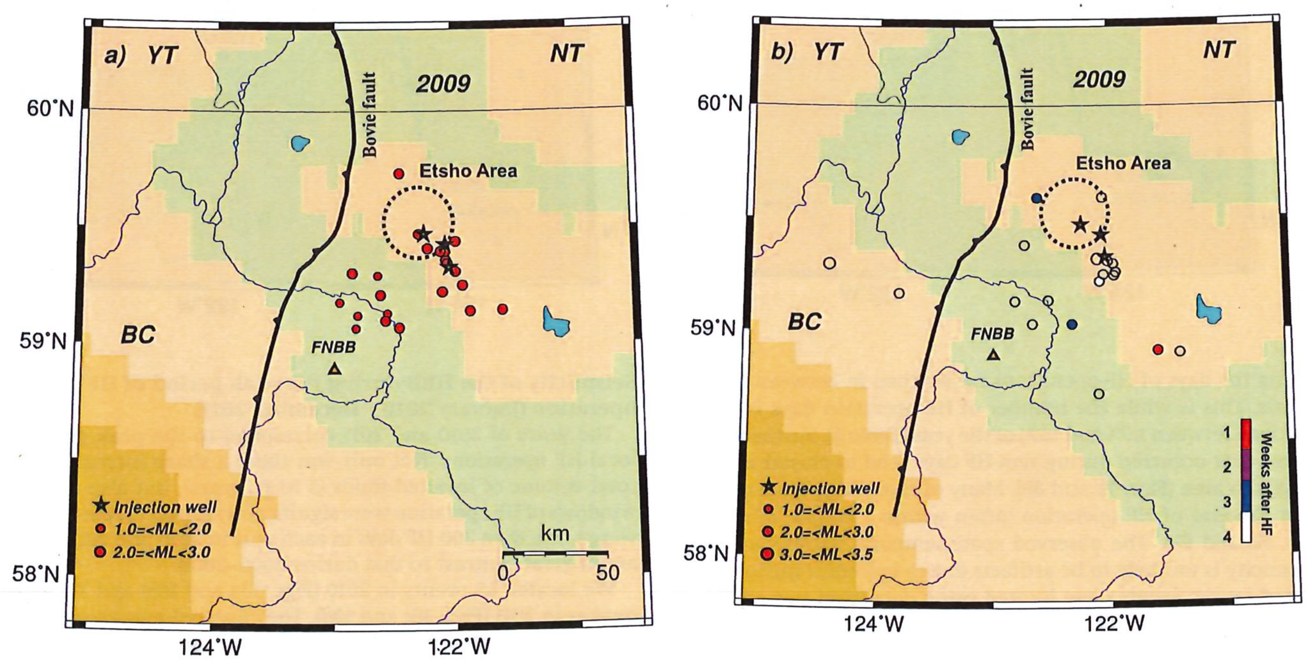


Fig. 9. Seismicity within 100 km of station FNBB during the year of 2009. Layout and format are the same as that in Fig. 7 (~ 15% hydraulic fracturing (HF) days per year).

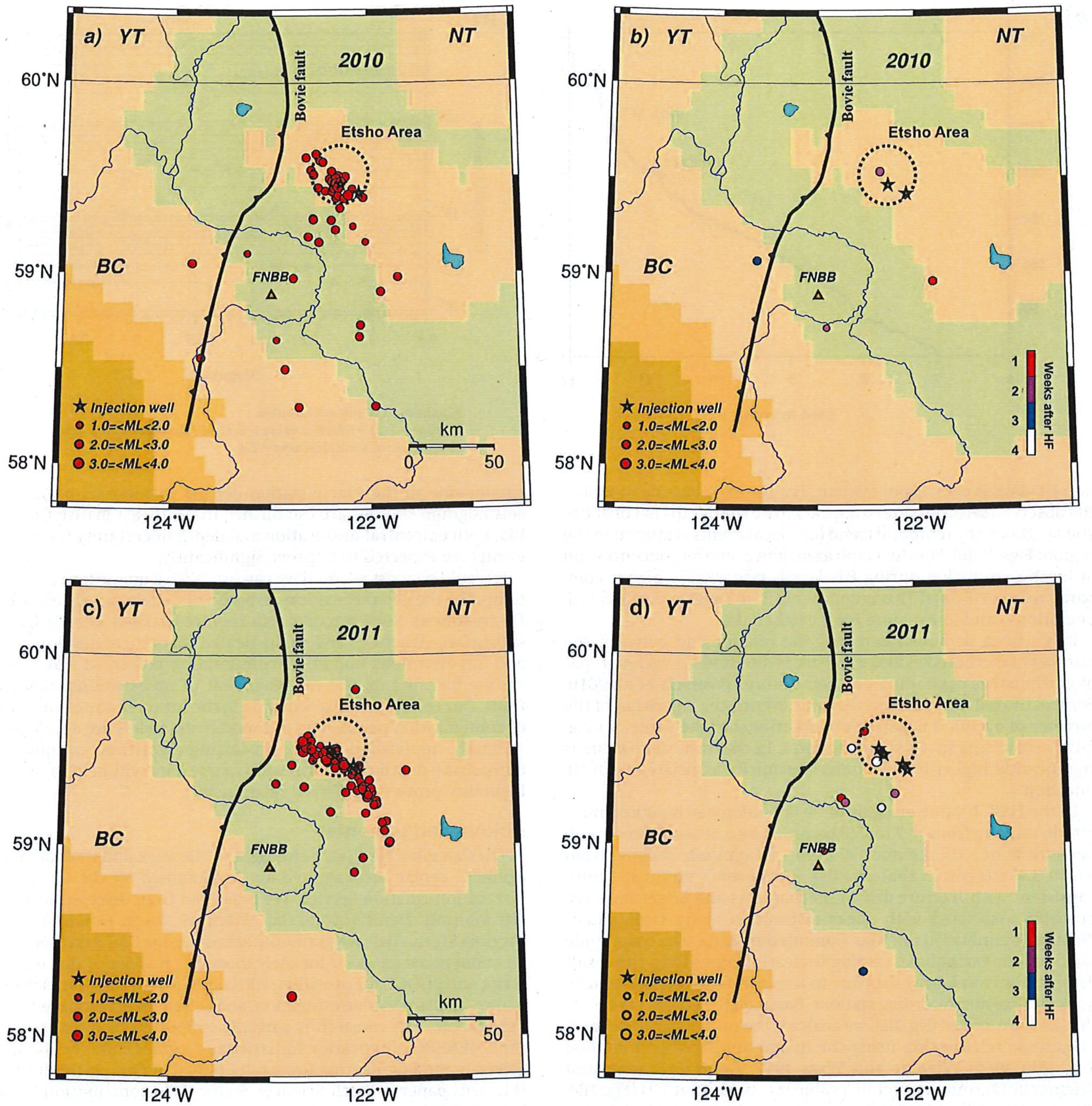


2010 and 38.9% for 2011) with arrival times from three stations or more. With the vast majority of events being better constrained by multiple stations, this time period is expected to have the greatest location precision.

Discussion and conclusions

It is important to point out that establishing positive correlation between earthquake source locations and HF operations in both time and space is only a necessary condition to infer the link between the two phenomena. Our re-analysis of historical seismograms confirms the existence of background seismicity in the HRB (in 2002–2003) before the start of HF. Scattered seismic events were detected in the region throughout the study periods of 2002–2003 and 2006–2011. Within 100 km of the FNBB station and specifically in the Etsho area where most local HF operations were performed, we observe an increasing trend of earthquake activities in both quantity and magnitude. The number of events was increased from 24 in 2002–2003 to 131 in 2011, and the maximum

Fig. 10. Seismicity within 100 km of station FNBB during (*a*) and (*b*) the year of 2010 (~82% hydraulic fracturing (HF) days per year), and (*c*) and (*d*) the year of 2011 (~85% HF days per year). Layout and format are the same as that in Fig. 7. Notice that the spatiotemporal distribution of local seismicity in this period appears to highly correlate with the local HF operations. Moreover, both the number and the maximum size of seismic events have increased with respect to those of previous years.

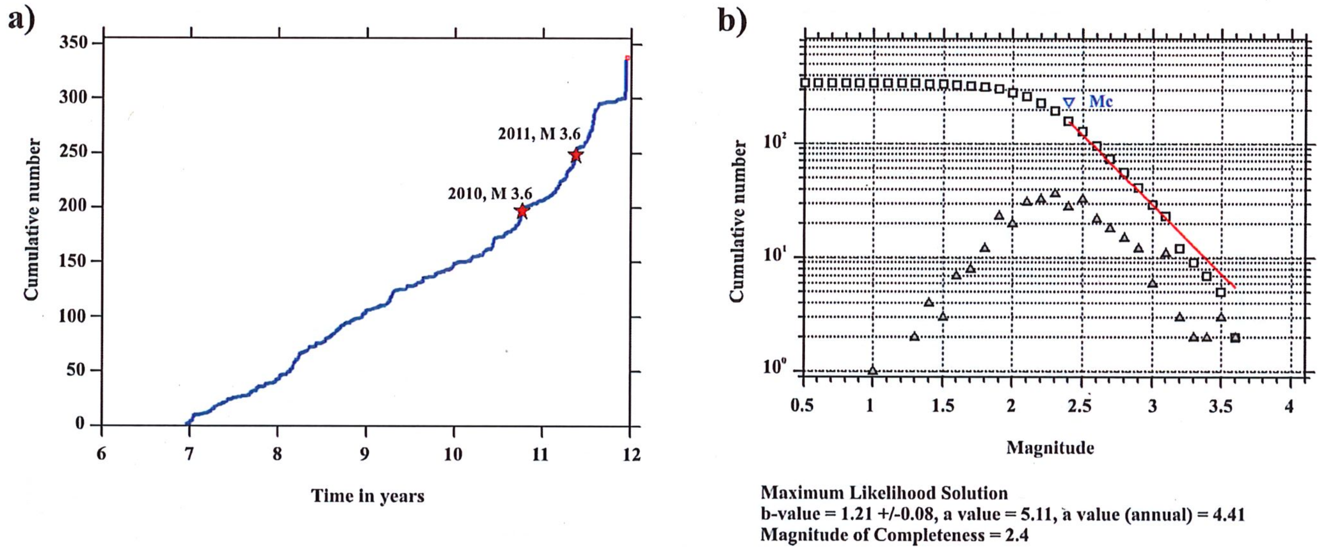


observed magnitude of earthquakes was shifted from M_L 2.9 in 2006–2007 to M_L 3.6 in 2010–2011 as the scale of HF operation expanded over the years.

The correlation between the increasing number of local earthquakes and HF operations can be further demonstrated by the change of average earthquake occurrence rate. For the year of 2002–2003 when all earthquakes were considered natural, the average earthquake occurrence rate is ~2 events per month. Such a rate is very close to the rates derived from the numbers of earthquakes during non-HF days in the first few years (between ~1 and ~3 for 2007–2009, Table 2). In contrast, the number of local earthquakes per month during HF days jumps by almost an order (between ~4 and ~19) for the same time period. In 2011 when the HF operation reached its peak, not only the monthly occurrence rate during HF days increased by a factor of ~6 but also the rate during non-HF days jumped more than three times as well. The dramatic variation in earthquake occurrence rate seems to suggest a link to local HF operations.

Furthermore, if we compare the local earthquake patterns inside and outside of the Etsho area, the difference between HF and

Fig. 11. (*a*) Cumulative number of located earthquakes as a function of time and (*b*) relationship between number and magnitude of local earthquakes in the Horn River Basin based on the catalog determined in this study. Triangles mark the numbers of events per individual magnitude bins, whereas squares correspond to the cumulative number of events. The corresponding *b* value (i.e., the negative slope of the line) is 1.21 with an estimated magnitude of completeness (Mc) of 2.4. All parameters are listed at the bottom.



non-HF days is even more evident. For the area outside of Etsho, the observed seismic pattern appears to be similar to that of 2002–2003 without any temporal trend (i.e., local events scattered in the region; Figs. 7–10). For the Etsho area, however, the concentration of local earthquakes during HF days is remarkably higher compared to non-HF days. This is another hint to suggest that local HF operations can induce more local earthquakes.

It has been demonstrated that the relationship between the number of earthquakes and their size is different for various types of earthquakes depending on their natures (Wessels et al. 2011). For reactivated tectonic microseismic events, the logarithm of the number of events is negatively proportional to the value of magnitude, resulting in a *b* value around 1. In contrast, the *b* value is significantly higher (~2) for microseismicity associated with HF injection.

In the HRB, *b* value analysis of 70 000 microearthquakes (magnitude ranging from –1.7 to 0.5) recorded by a dense seismograph network at one HF site and 135 events (magnitude ranging from 0.6 to 3.2) suggested that smaller local events might be more consistent with fracture-driven mechanisms and larger ones are probably associated with shear dislocation along fault planes (British Columbia Oil and Gas Commission 2012). The magnitude range of our earthquake catalog is clearly higher than the result derived from local array data due to larger distance between earthquake source and recording stations. Based on the entire 338 events that we have located (Fig. 11*a*), we analyzed the earthquake frequency–magnitude relationship using the maximum likelihood method (e.g., Aki 1965; Wiemer and Wyss 1997; Goertz-Allmann and Wiemer 2013), and the overall *b* value is estimated at 1.21 (Fig. 11*b*). The corresponding completeness of our catalog is M_L 2.4. Our derived *b* value is higher than the average of tectonic/natural earthquakes, but lower than the value of typical HF-induced events, perhaps also implying that at least some of the observed events are related to local HF operation.

Precise determination of earthquake focal depths could also be a key in distinguishing induced seismicity from tectonic/natural earthquakes. In general, source depth is much more difficult to constrain than epicentral location because the travel time residuals become less sensitive to depth variation once the source-station distance is significantly greater than source depth. Unfortunately, this was exactly the scenario for the vast majority of events in our catalog due to the sparse station density in the region. As new seismograph stations are established in northeast British Columbia, both epicentral mislocation and depth uncertainty for future events are expected to improve significantly.

It would be most useful if we can establish a quantitative model to predict the geo-mechanical response of a shale gas system after HF treatment. Such a model will require detailed knowledge of subsurface structures and sophisticated theoretical development and (or) enormous numerical computation power. At this stage, we are focusing on the establishment of observational foundations. Our results could be valuable in the future in the calibration of configuration parameters as theoretical models are developed.

Finally, application of new processing algorithms to improve earthquake depth resolution with sparse data will help to unambiguously prove the inferred relationship.

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Collaborative Studies of Regional Seismicity in Northeast British Columbia

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This article documents a recently-initiated, collaborative study of seismicity in northeast British Columbia. Induced seismicity is a topic of increasing, and global interest, in particular with respect to shale-gas extraction activities. There are many important questions regarding linkages between induced seismicity and hydraulic fracturing (HF) activities. Addressing these questions requires robust datasets, including earthquake catalogues and three-component broadband seismic waveforms. Here, we describe the historical datasets available for understanding the background seismicity of northeast BC (NEBC), the deployment of new seismic stations in the area, and the resulting improvements in earthquake monitoring capability.

Our preliminary investigations show an increase in both the number of small earthquakes, and a slight increase in the average magnitude of earthquakes in regions of NEBC experiencing HF activities. Deployment of additional seismic stations in mid-2013 has substantially enhanced the monitoring capability, lowering the earthquake detection threshold from ~ M 2.5 to ~ M 1.5. This has resulted in a ten-fold increase in the number of M< 2.5 earthquakes recorded, from 14 for the 4-year period of 2009-2013 to 186 for the one-year period between August 2013 and August 2014. As additional seismic stations are deployed in the neighboring regions (Northwest Territories and Alberta) and additional data are collected, much better constraints on precise earthquake locations and depths will become available, and will help to answer the numerous key questions related to HF and related seismicity.

Introduction

There is significant global interest in induced seismicity associated with HF activities (e.g., Green and Styles, 2012; Hayes, 2012). There are many outstanding questions, including: Are induced earthquakes associated with the HF process, or with the injection of waste water into deep disposal wells? How large can these induced earthquakes be? Is the rate of seismicity (and magnitude) related to the injection pressures or the volume of injected fluids? What is the role of local faults, fluids, and the local stress regime? Answers to these questions will provide the sound science required by regulators, decision-makers, and industry to help guide this new resource.

Of all the shale gas basins in Canada (US Department of Energy

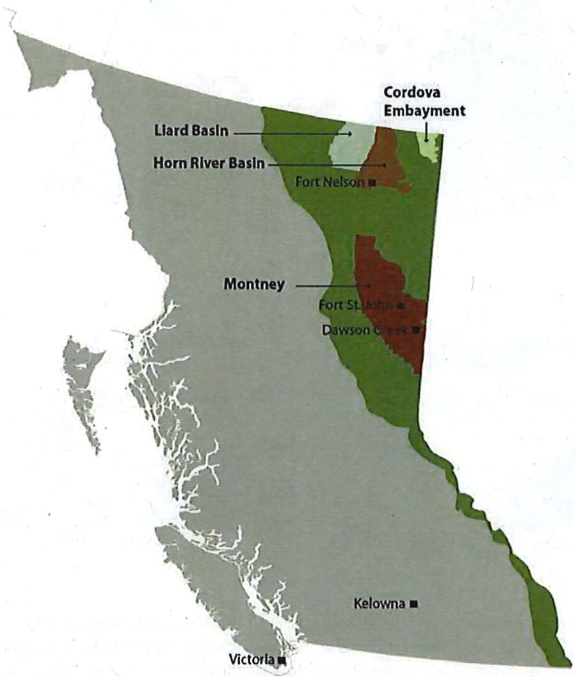

Figure 1. A map showing the location of the major shale gas basins in British Columbia, including the Horn River Basin and Montney trend in northeast BC (BCOGC report, 2012).

Report, 2011), those in NEBC – e.g., the Horn River Basin and the Montney trend (Figure 1), are the most active in Canada in terms of shale gas production. This makes NEBC the ideal region in Canada to examine potential linkages between HF processes and induced seismicity. Furthermore, HF began relatively recently (2006), and in some areas has increased rapidly, and in other areas has slowed down (British Columbia Oil and gas Commission Report, 2012), thus allowing for temporal and spatial changes in seismicity as related to temporally-varying HF activities.

One of the challenges in NEBC (as in many regions of the world) is the limited monitoring of earthquakes due to relatively few seismic stations (Figure 2). Distinguishing background tectonic seismicity from induced seismicity (e.g., Horner et al., 1994; Deichmann and Giardini, 2009; Frohlich et al., 2011; Holland, 2011; Avouac, 2012; Frohlich, 2012; Ellsworth, 2013; Frohlich and Brunt, 2013; Maxwell, 2013) is often a challenge. In addition, a lack of nearby seismic stations makes seismicity depth constraints exceedingly challenging, thus limiting the

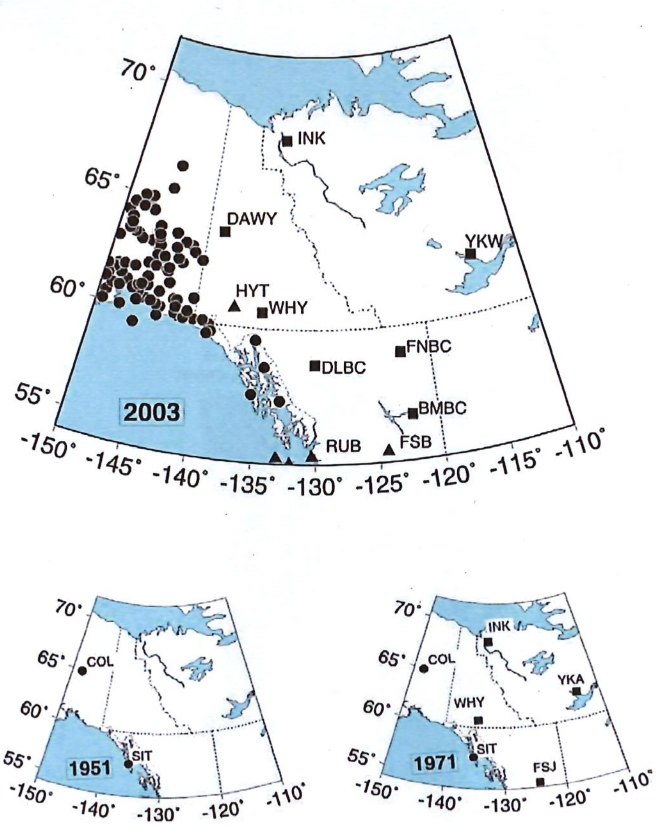

Figure 2. Maps of seismic station (triangles) distribution in northwest Canada from 1951until 2003. Additional stations were not added in the NEBC region until 2013.Squares represent 3-component broadband instruments, triangles are short-period vertical seismographs, and circles are Alaska stations.

ability to link seismicity with specific human activities.

In this article we describe a collaborative study to examine seismicity in NEBC, the determination of background tectonic seismicity, and some preliminary results between low-level seismic activity and HF activities.

Data and Analysis

This research began in 2012 as a partnership between the BC Oil and Gas Commission (BCOGC) and Natural Resources Canada (NRCan), Geological Survey of Canada – Pacific, to examine potential linkages between HF activities in NEBC and seismicity. Initially, the key data to be analyzed were the seismic waveforms recorded by stations of the Canadian National Seismic Network (CNSN) and the national earthquake database maintained by NRCan. However, it was clear that to make substantial advances in the science and understanding of induced earthquakes, additional seismic stations were required to improve location accuracy and reduce detection threshold. Geoscience BC (GBC) and the Canadian Association of Petroleum Producers (CAPP) jointly provided more than $1M in funding to deploy 6 additional state-of-the-art seismic stations in NEBC (NBC1–6). At the same time, NRCan funded two additional stations in the region (NAB1 and NAB2), and BCOGC funded the establishment of one additional station at Fort St. John (NBC7). Through an agreement of collaboration with the University of Ottawa, seismic data from new stations in the southernmost part of Yukon and Northwest Territories are also transmitted back to our data center in real-time. Installation of these stations (Figure 3) was started in 2013 in very challenging environments (e.g., see Figure 4). All broadband seismic data (e.g., see Figure 5) from these seismic stations are freely available to the global community in near-real-time.

History of Seismic Monitoring in Northeast British Columbia

For details on the history of seismic monitoring in NEBC, we refer readers to a paper by Cassidy et al. (2005). Prior to 1999, when the Fort Nelson, BC (FNBB) seismic station was deployed, there were no seismographs in this region. From 1971 until 1999, the closest instruments were operating at Whitehorse (WHY), YT, Yellowknife (YKW), NT, and Fort St. James (FSB), BC (Figure 2). These stations were more than 350 km distant from the Horn River and Montney Basins, and the earthquake catalogue was limited to earthquakes of M 3 or greater.

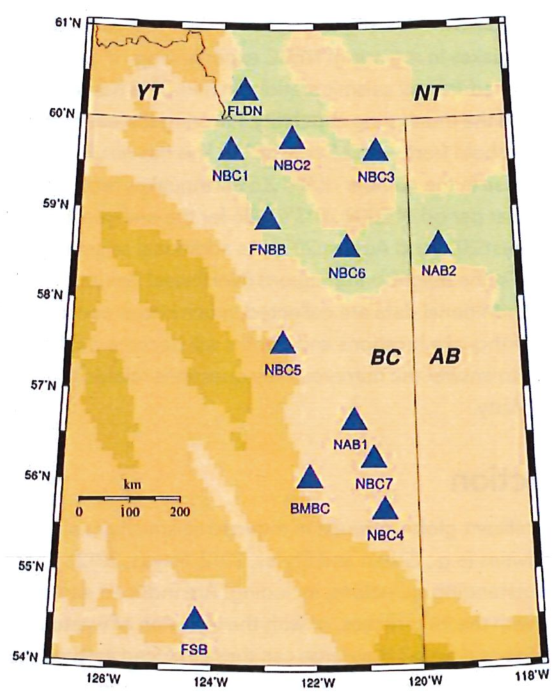

Figure 3. Map of seismic stations in the northeast BC region as of 2014 showing the 6 modern seismic stations (NBC1–NBC6) funded by Geoscience BC and CAPP; one (NBC7) by B.C. Oil and Gas Commission; two (NAB1 and NAB2) by Natural Resources Canada. Stations in the southernmost part of Yukon and Northwest Territories were established by the University of Ottawa.

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Figure 4. Photo of the new seismic station NBC1, showing the satellite dish, solar panels to power the system, and electronics – all built on a platform, and the borehole seismometer (left).

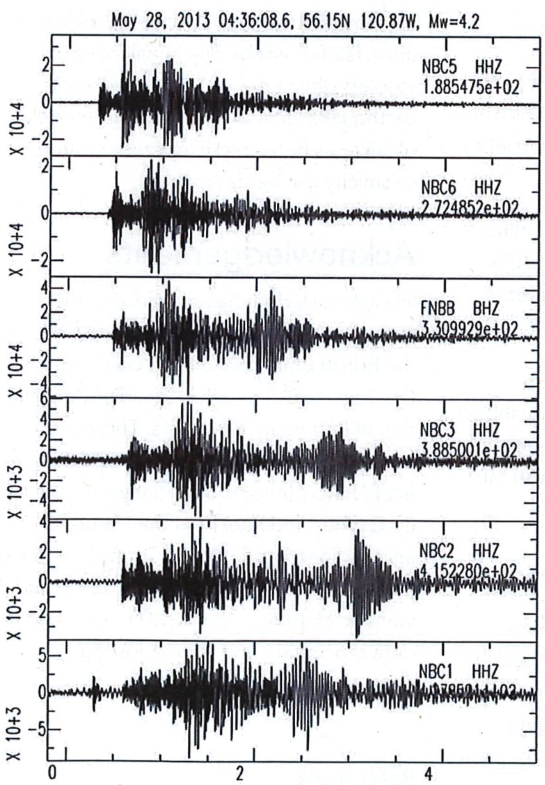

Figure 5. Example of the high-quality waveforms provided by these new seismic stations. This is the recording of a M 4.2 earthquake (May 28, 2013) in northeast BC.

With the deployment of FNBB in 1999, the earthquake threshold was reduced to about M 2.5, but focal depths and accurate locations were still a significant challenge.

In mid-2013, with the deployment of 6 additional broadband seismic stations funded by GBC and CAPP, earthquakes detection threshold was further reduced to about 1.5 in NEBC. This increase in detection capability results in an approximately 10-fold increase in the number of recorded earthquakes from 14 for the 4-year period of 2009-2013, to 186 for the one-year period between August 2013 and August 2014 (ML < 2.5, Figure 6). This new network (Figure 3) also provides more opportunities for depth determination (for those earthquakes within ~5 km of the new seismic stations).

The primary data which is used for seismic monitoring and research in this area consists of seismograms from both the CNSN and the new NEBC seismic network (and new stations in Alberta and the Northwest Territories). The improved earthquake catalogue resulting from the lowering of the earthquake detection threshold provides an order of magnitude increase in detectable seismic events. It should be noted that these datasets are freely available to the global community via the websites:

www.earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php (earthquake catalogue); and

www.earthquakescanada.nrcan.gc.ca/stndon/NWFA-ANFO/index-eng.php (for seismic waveform data).

Preliminary Results and Ongoing Studies

Initial studies have focused on the question: do regions of HF activities in NEBC experience an increase in seismicity during the HF process? Hydraulic fracturing began in NEBC in 2006, and to understand if HF operations change the rate of seismicity, one must first have a robust estimate of natural background seismicity.

In order to better constrain the historical "background" seismicity of the Horn River Basin, a "single station technique" was tested (see Farahbod et al., 2014) to both lower the earthquake detection threshold to ~M 1 and to obtain earthquake locations using seismic data from the station FNBB. The results of Farahbod et al. (2014) clearly show that NEBC is not aseismic, but rather exhibits ongoing (pre-HF activities) background seismicity. Thus, the apparent lack of historical background seismicity in the region is an artifact due to the poor detection threshold of the CNSN.

To examine possible changes in seismicity rates associated with HF activities, Farahbod et al. (2014) considered three distinct time windows: (1) July 2002 – July 2003 – prior to the start of HF operations;

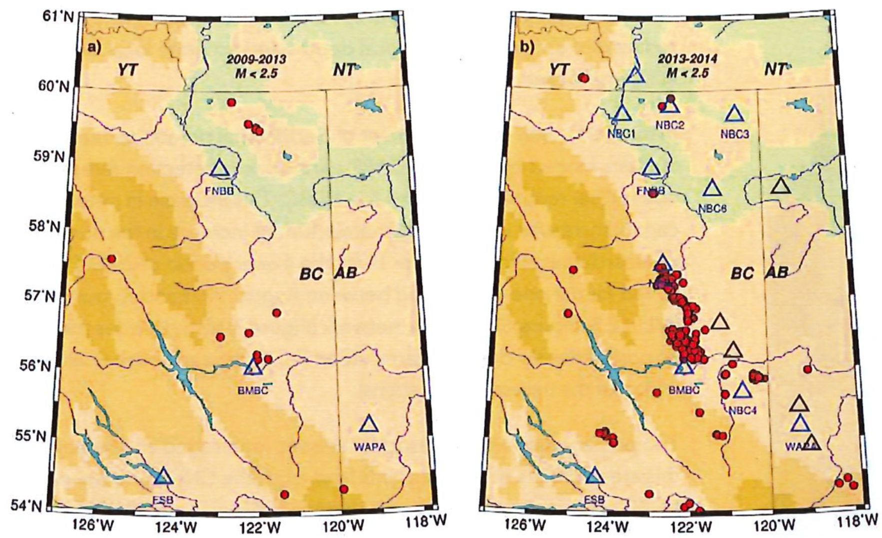

Figure 6. Seismicity (red circles) of northeastern BC a) between 2009 and 2013 and b) between August 2013 and August 2014 for events with M < 2.5. Triangles are seismic stations (black triangles are new stations established after mid-2014). This map clearly shows the enhanced ability to detect small earthquakes after the deployment of the new seismic stations in northeast BC in mid-2013.

(2) December 2006 – December 2009 – during the initial period of light/moderate HF activity; and (3) January 2010 – December 2011 – the peak of HF activity in the Horn River Basin.

The results for time window (1) – pre-HF activities, revealed 24 earthquakes of M 1.8 to M 2.9. Most of these events were located to the east of FNBB station in the southern HRB. The Etsho area (located ~80 km NE of FNBB, where most of shale gas production wells were drilled later) appears aseismic during this period.

For time period (2) – limited HF activities in the Etsho area of the HRB– and increase of minor earthquake activity was detected. During 2007, 39 events (ML 1.3 – 2.9) were located in 2008, 63 events (ML 1.0-3.0) were located, and during 2009, 44 events (ML 1.4 – 3.1) were located (Farahbod et al., 2014).

For time period (3) – peak HF operations during 2010-2011 in the HRB, there was a sharp increase in both the volume of injected fluids and the duration of HF operations (see Farahbod et al., 2014 for details). During 2010, 58 earthquakes were located, and in 2011 this increased substantially to 131 earthquakes. The magnitude range also shifted to higher values, with ML between 1.6 and 3.6.

Summary and Future Research Activities

Testing of a single-station-location technique for NEBC reveals that the apparent aseismic nature of this region is largely an artifact of a lack of seismic monitoring stations. Farahbod et al. (2014) clearly show low-levels of seismicity scattered through the Horn River Basin region of NEBC. Deployment of 6 state-of-the-art seismic stations in mid-2013 in the challenging environment of NE BC has substantially enhanced the monitoring capability, lowering the earthquake threshold from ~ M 2.5 to ~ M 1.5. This results in an increase of ten-fold in the number of earthquakes being recorded from 14 for the 4-year period of 2009-2013 to 186 for the one-year period between August 2013 and August 2014 (ML < 2.5, Figure 6).

Initial studies of regional seismicity in NEBC suggest a linkage with HF activities. Specifically, Farahbod et al. (2014) find that increasing levels of HF activities appears to result in a greater number of small earthquakes, and an increase in the maximum magnitude. It is noteworthy that only one of these earthquakes has been felt, and that the largest earthquake recorded (ML 3.6) is well below the size of earthquake that would be associated with structural damage. We acknowledge that two more felt earthquakes occurred in NEBC in late July and early August 2014 with ML of 3.8 and 4.4. Investigation is currently under way to determine if they were induced.

Future studies will take advantage of this new broadband network, as well as additional stations being deployed in the adjoining areas of AB, YT, and NT. Determination of earthquake depth, and reduction of location uncertainties will be one initial focus of those studies. Ultimately, with more and better earthquake locations and depths, models of linkages between HF operations and seismicity can be determined.

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Continued on Page 44

Continued from Page 43

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Biography can be viewed on page 39.

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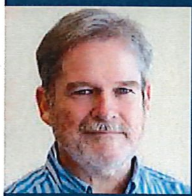
Biography can be viewed on page 37.



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