



Investigation of Induced Seismicity Related to the Development of Shale Gas in Northeast British Columbia and Northwest Territories, Canada



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David Snyder (NRCan), and Scott Cairns (Geoscience Office, NT)



Natural Resources
Canada

Ressources naturelles
Canada

Canada

Outline



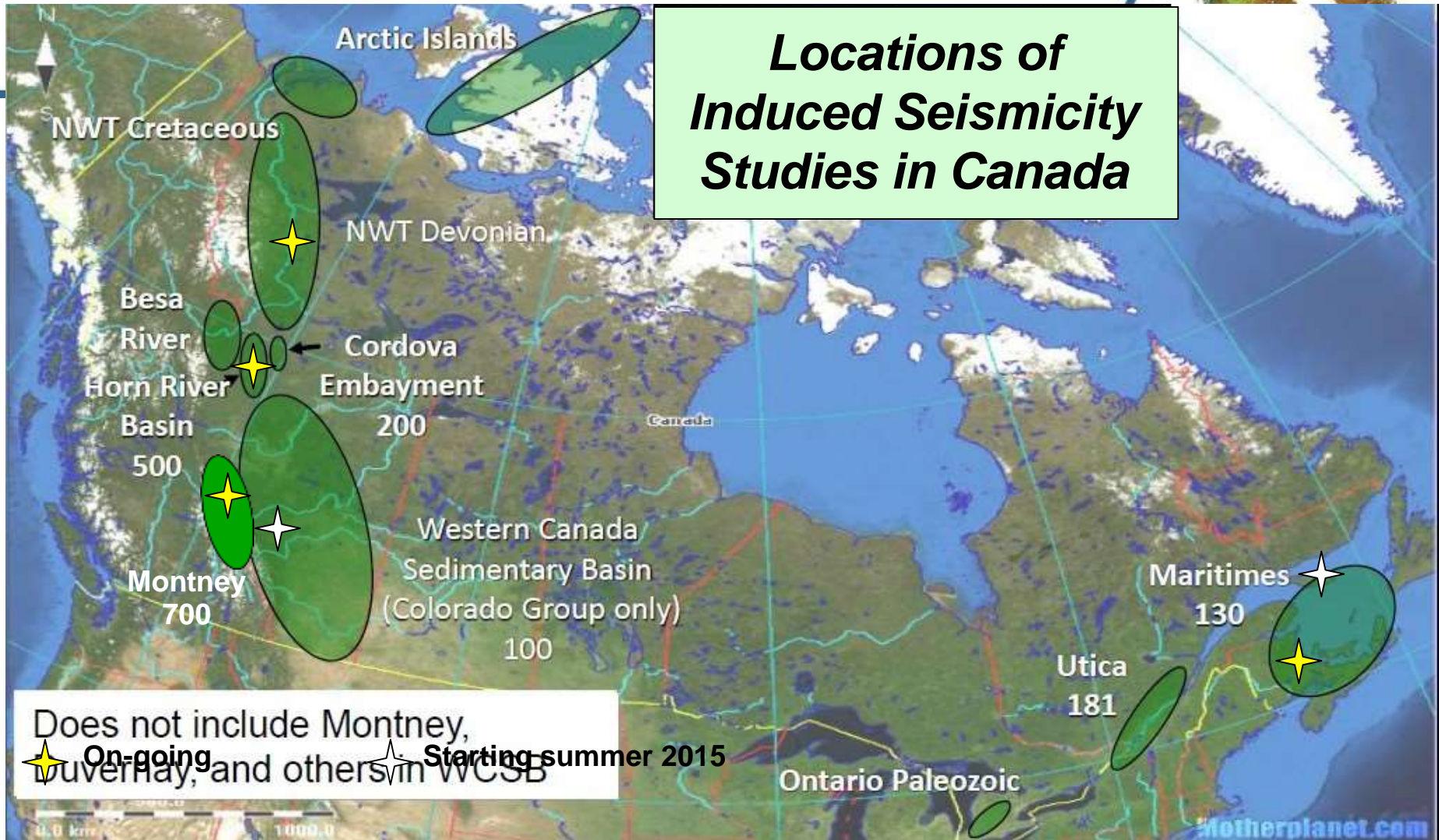
- NRCan's Induced Seismicity Research
- Northeast BC Seismic Array
- Case Study: Horn River Basin, BC
- Case Study: Norman Wells, NWT
- Implications to Shale Gas Development
- Conclusions

Project Goals and Outlines of NRCan's Induced Seismicity Research



- Initiated in 2012 with both internal and external sources of funding (ecoEII, Geoscience BC and CAPP)
- A coordinated effort involving both public and private sectors to address critical knowledge gaps in induced seismicity related to unconventional shale gas development
- Improved earthquake monitoring for areas with shale gas development potentials
- Detailed studies of background seismicity to establish pre-development reference lines
- Focused case studies to examine pre-/post-development variations

Locations of Induced Seismicity Studies in Canada

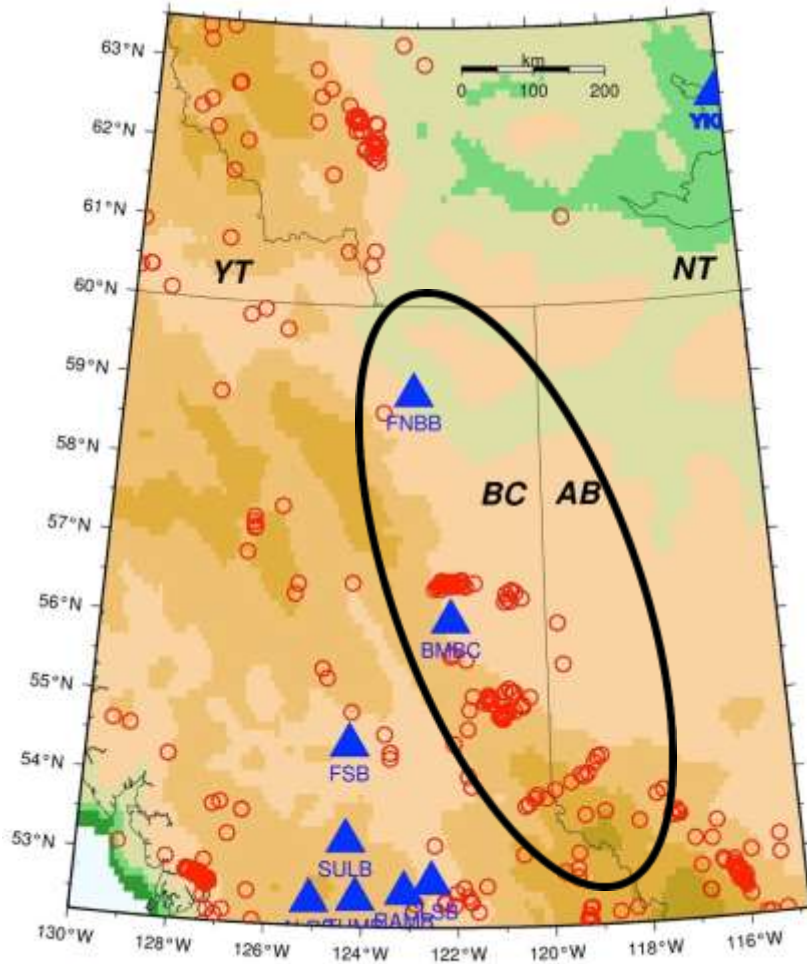


Does not include Montney, Wuverhay, and others in WCSB
★ On-going ☆ Starting summer 2015

Northeast BC and Western AB

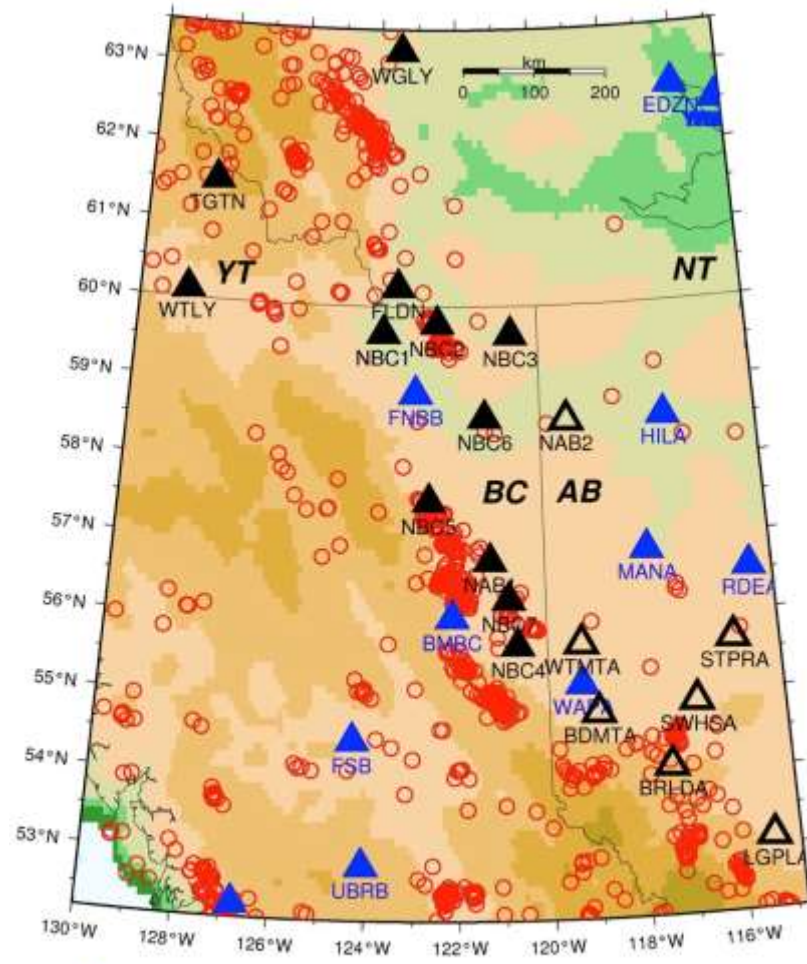


Seismic stations before 2012



▲ CNSN/POLARIS stations ○ Seismicity (ML>=2) between 2000 and 2006

Seismic stations now and future



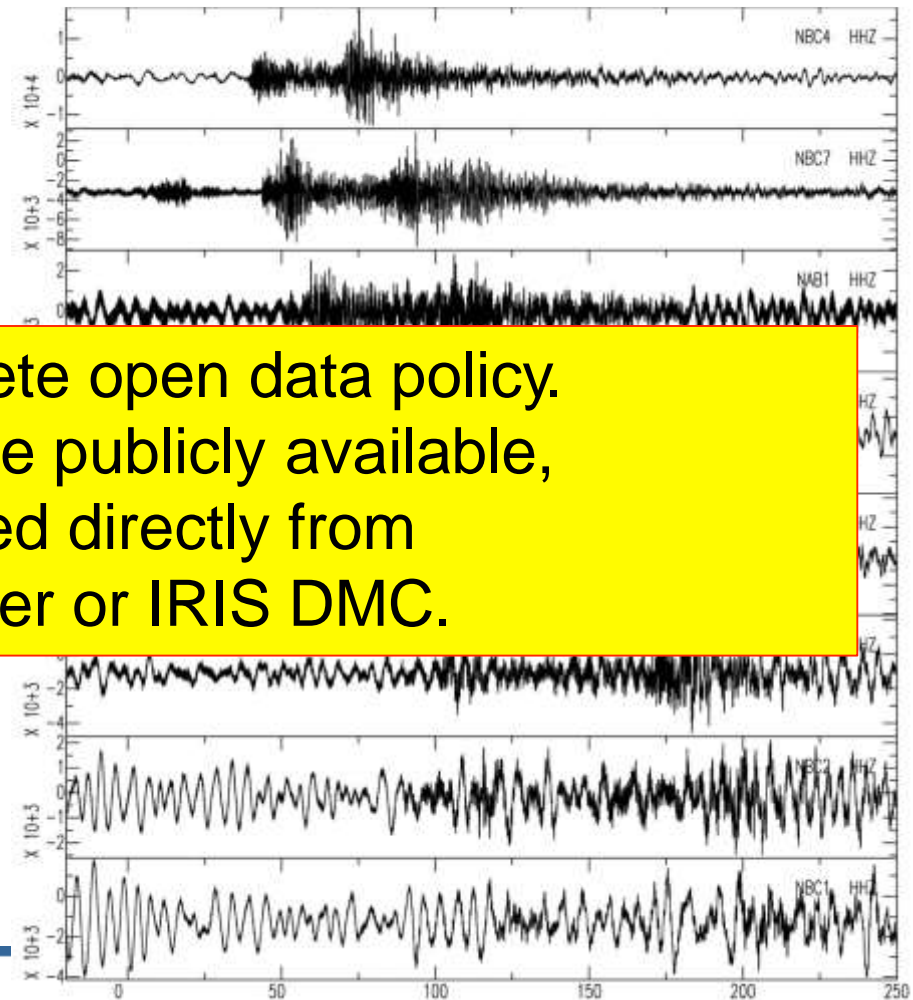
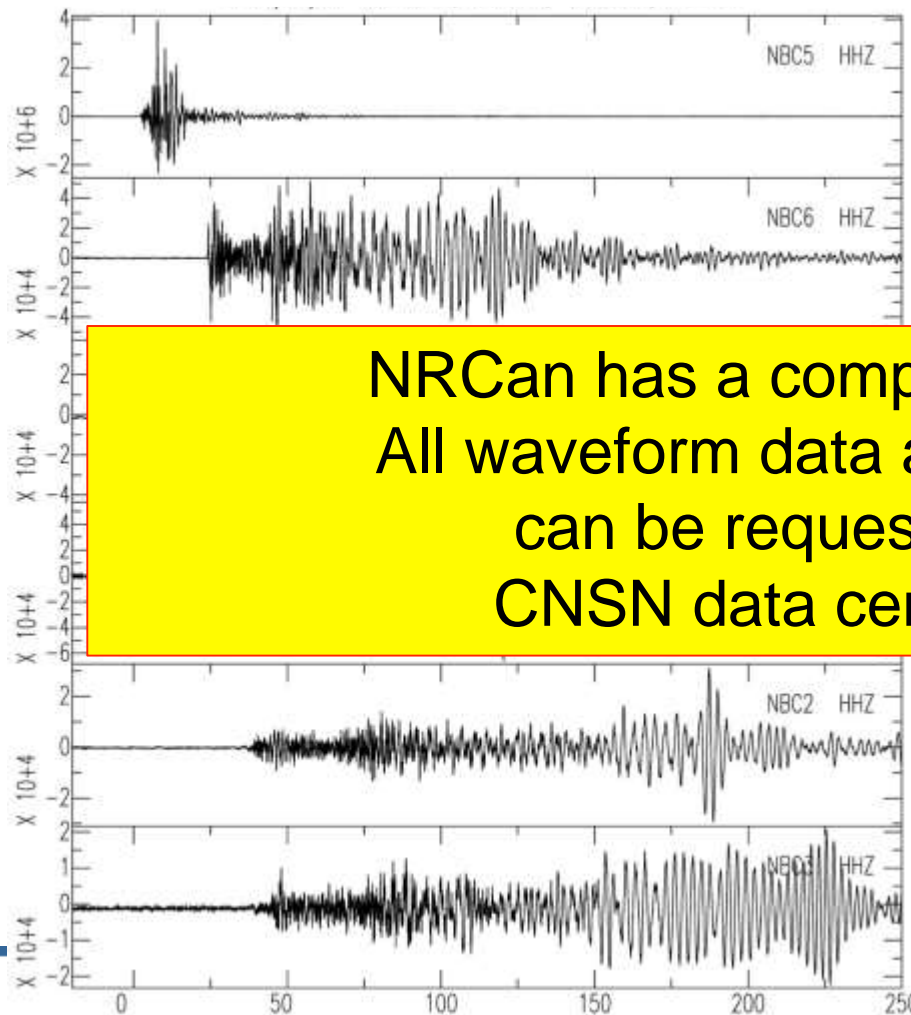
▲ CNSN/POLARIS stations ○ Seismicity (ML>=2) after 2007
 ▲ New stations established in 2012 and 2014
 △ New stations established/planned in 2015-2016

Northeast BC Seismic Array: Waveforms of the Largest HF-Induced Earthquakes



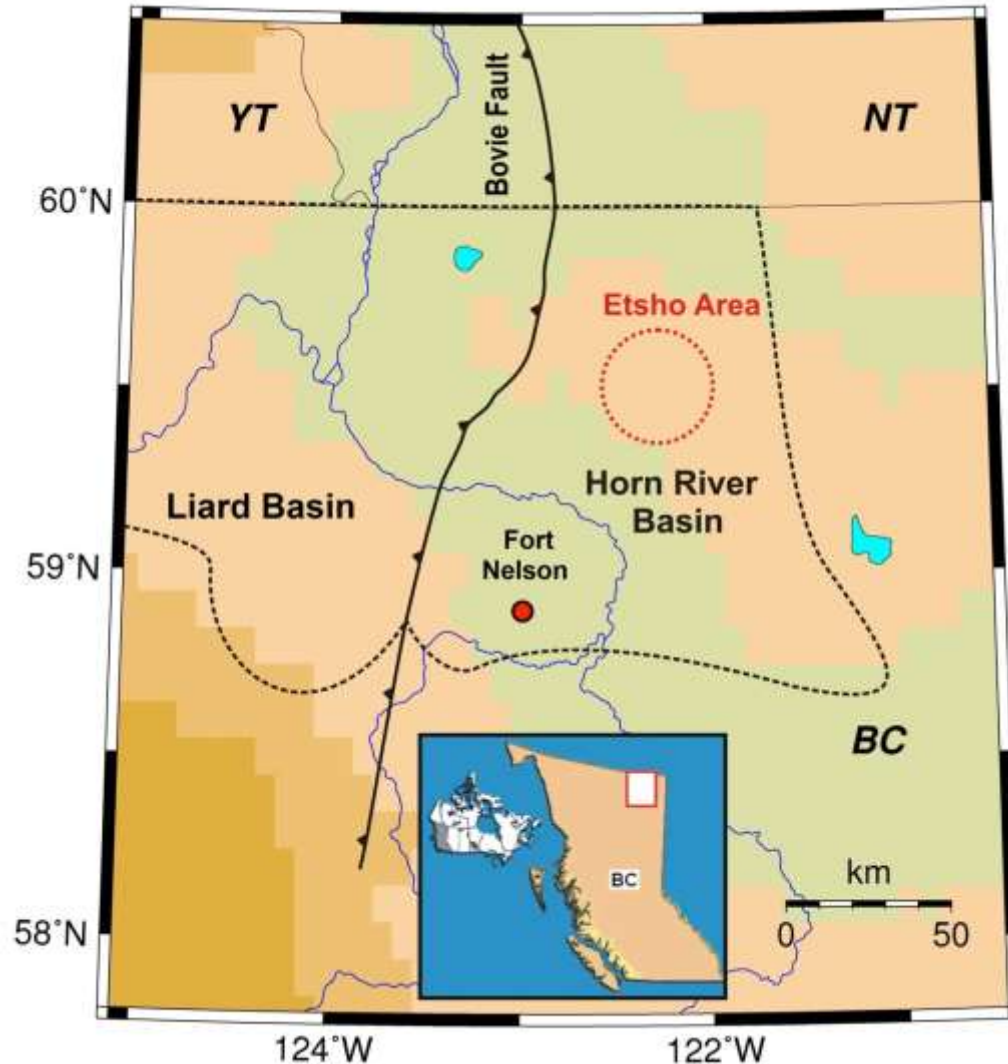
2014/08/04, Between Fort Nelson and
Fort St. John, BC, M_L 4.44

2015/01/23, Crooked Lake, AB,
 M_L 4.36



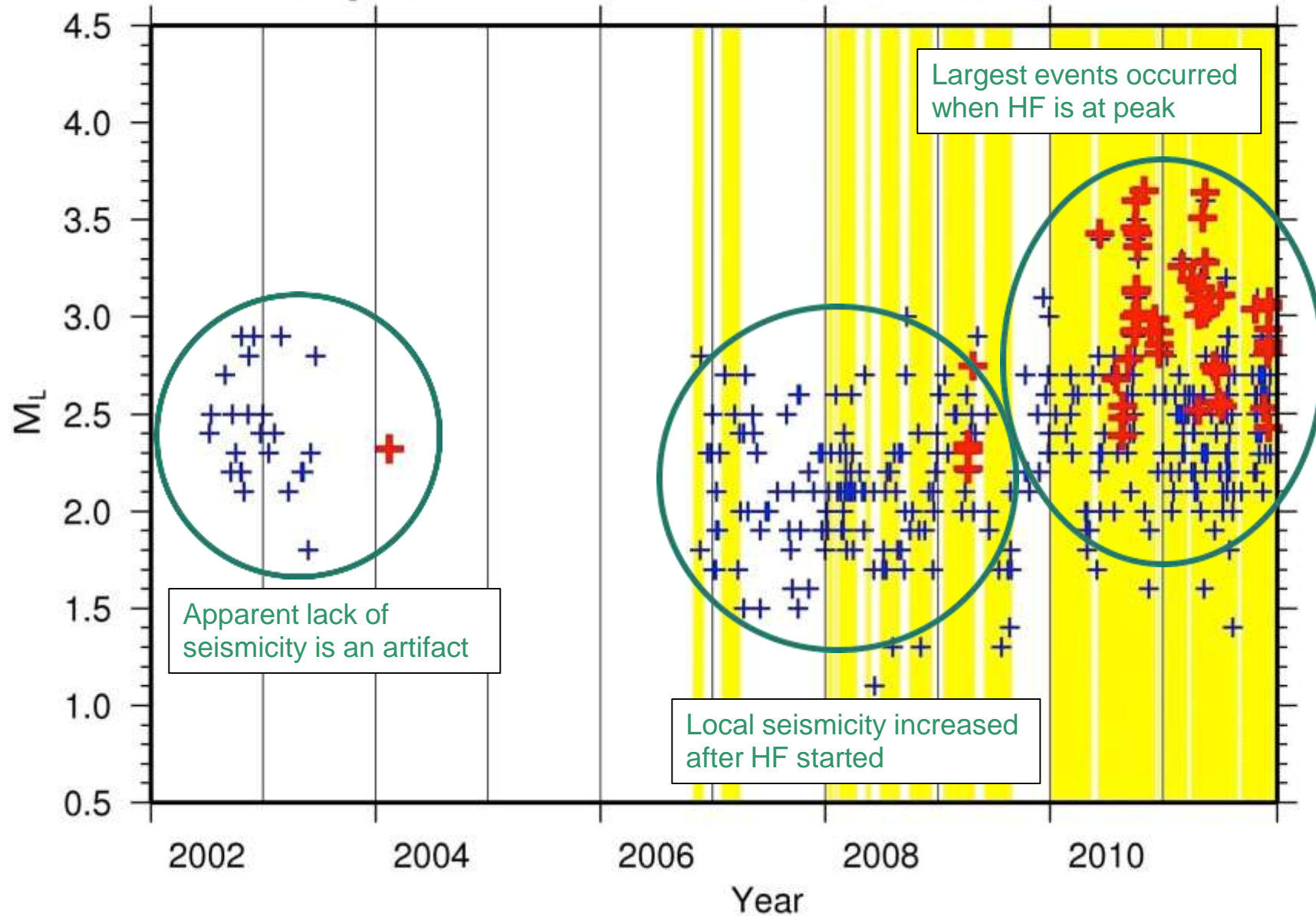
NRCAN has a complete open data policy.
All waveform data are publicly available,
can be requested directly from
CNSN data center or IRIS DMC.

Case Study: Horn River Basin, BC



- A major shale gas production area in British Columbia
- Hydraulic fracturing started in as early as late-2006
- Most HF operations in the Etsho area
- Peak shale gas production in 2010 and 2011
- Historically, this area had few earthquakes.

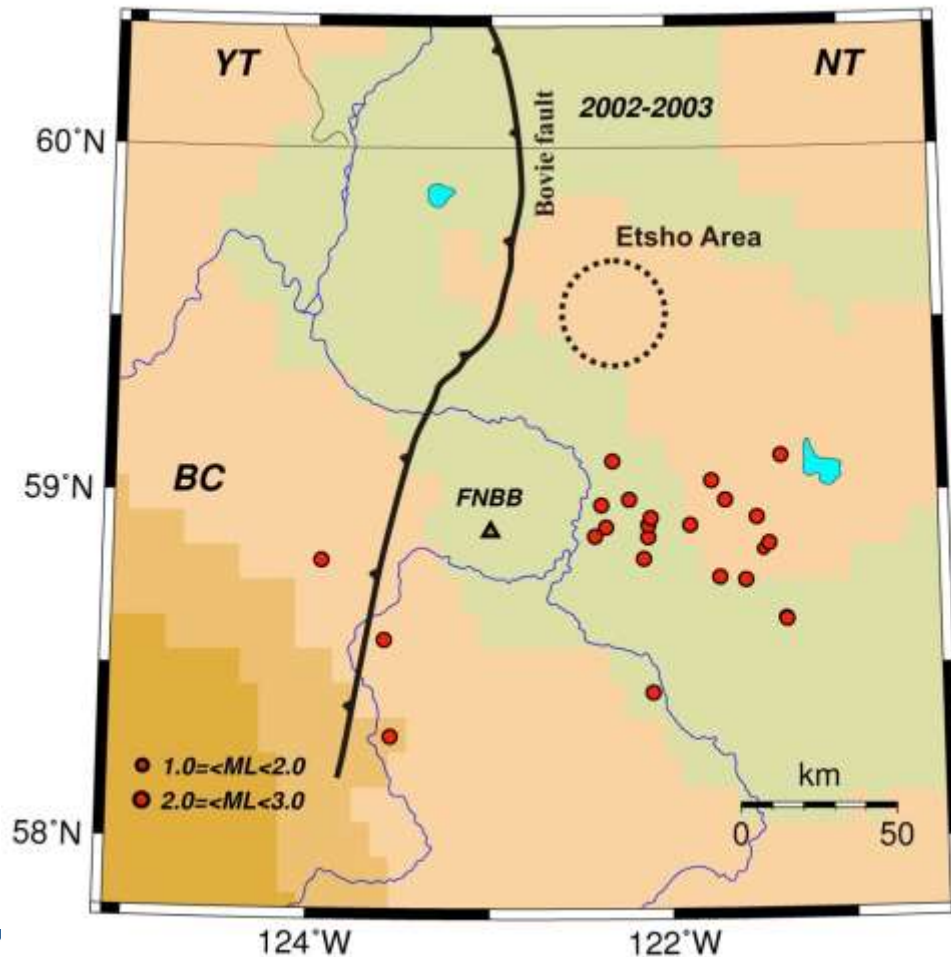
Earthquakes in the Horn River Basin, NE BC



Seismic Baseline for NE BC



Pre-HF Background Seismicity (2002-2003)



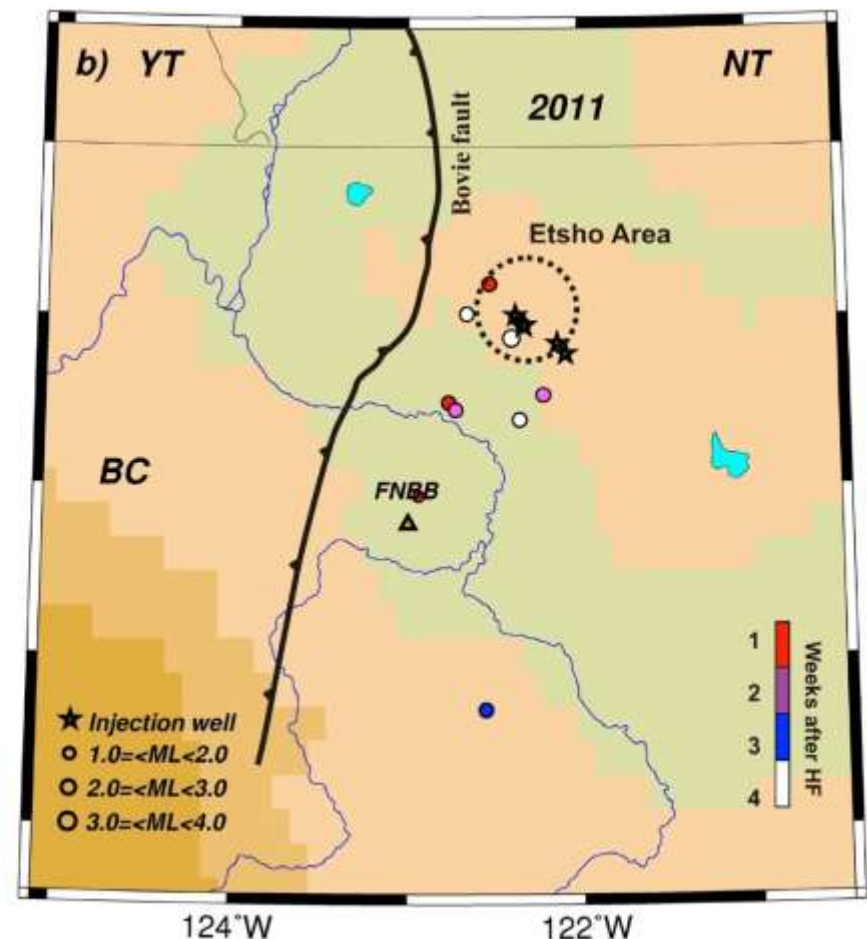
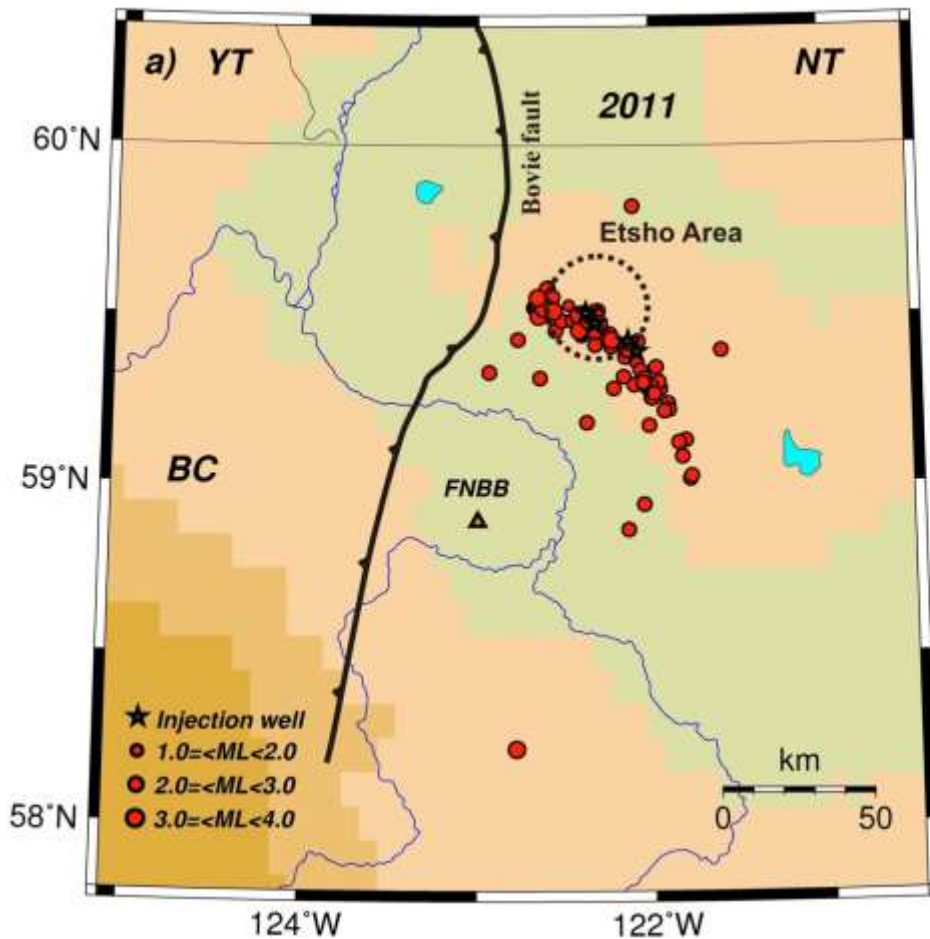
- 4 years before HF
- 24 earthquakes located
- M_L between 1.8 and 2.9, most are smaller than 2.5 (detection threshold of CNSN)
- Most occurred in the southern HRB, none was in the shale gas production area (Etsho)

Regional Seismicity During Peak HF Period



Events when HF was conducted

Events when no HF was conducted



HF days: 84.9% Seismicity: 90.8%

Non-HF days: 15.1% Seismicity: 9.2%

HF Completion Reports Filed by Operators



www.fracdatabase.com

BC Oil & Gas COMMISSION
 1000, 300-39A Victoria, BC Phone: (250) 493-8200 Fax: (250) 493-8200

COMPLETION REPORT

A signed form and a complete report must be submitted in duplicate under the act of Regulation, s.36, within thirty days of the end of each completion or workover or a matching Notice of Operations. An incomplete report will not be accepted and will be returned to the sender.

Completion Workover Cased

Well Name: **ECA HZ KM/G** U.W.I. 2006
 Bottom-hole Location: **27' offset from surface location**
 Well Permit No.: **2006B-092-L/094-O-02/00**
 Start Date: **2011-08-30** First 2011
 Intervals Worked (mKB): **2463 - 5364 71** Geol. Musk

Reason for Work: **Initial completion of a horizontal well**

Each of the following must be provided with this report:

- Chronological summary of work done
- Detailed completion/workover reports
- Downhole schematic diagram
- If a cased well abandonment, a summary of surface abandonment cement plug, weld on cap, and for abandoned wells on crown land for the location to be a candidate for an Application for Certificate of Registration

Completion Type: Open Hole Single Dual Multi Commingled Gas lift

Completion Activity: Open Hole Perforate Fracture Acidize Bridge Plug
 Cement Squeeze Remedial Other

Stimulation Type: Fracture Acid Squeeze Acid Wash

Stimulation Volume: **see attached** m³ Stimulation (For multiple stimulations, please attach a full list for each stimulation done)

Flow Summary (for each formation): **Muskwa**
 Flow Rate: **85.5** 10^{m³/day Flow Pressure: **1492**}

Any radioactive material (i.e. frac sand)? No Yes. If yes, attach on site, attach sketch of location showing burial location and indicate depth

Results of work done: **Well was completed, stimulated, and put on production.**

Status of well as a result of work done (completed, oil, gas, abandoned, etc): **Perforated and fractured HT**

CONTACT INFORMATION

Name: **Bruce Standing** Position: **Completions Engineering**
 Permit Holder: **Penn West Exploration**
 Phone: **403-539-9300** Fax: Email: **Bruce.standi**

Permit Holder: **EnCana Co**
 Phone: **403-645-3849**

BC Oil & Gas COMMISSION
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COMPLETION REPORT

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Completion Workover Cased

Well Name: **HUSKY BIVOLAC C-81-B/94-I-8** U.W.I. 2006
 Bottom-hole Location: **offset from surface location**
 Well Permit No.: **2011-09-23**
 Start Date: **2011-09-23** First 2011
 Intervals Worked (mKB): **1799.0 - 1801.0 mKB** Geol. Musk

Reason for Work: **Perforate, stimulate and evaluate the Muskwa for sweet gas production.**

Each of the following must be provided with this report:

- Chronological summary of work done
- 2011-09-24 Travel to location.
- 2011-09-25 Install total of 607 mats on site and prepare location for or
- 2011-09-26 Hold pre-job safety meeting and review all hazards. Rig in min. test. Run a Cement Bond Log. rig out
- 2011-09-27 Wait on Service Rig
- 2011-09-28 Move on rig unit and equipment test rig anchors OK
- 2011-09-30 Make up & run the 114.3mm L-80 20.09 kg/m casing - to 17 Mpa - solid hold for 10 mins.
- 2011-10-01 Install 70 Mpa Frac head-pressure test solid test; rig up sk into 114.3mm casing; release service rig; pressure test casing - held 3
- 2011-10-02 Misc operations
- 2011-10-03 Run Gamma Ray Neutron Log to correlate on depth; run in perforate Muskwa 1799.0 - 1801.0 mKB; all shots fired; monitor press
- 2011-10-04 well on weather
- 2011-10-5-7-8-9-10-11-12-13 Misc operations - spot frac tanks, ched defective tank; began heating frac water - heated to 25 °C
- 2011-10-14 Frac delayed by frac company ill 18h
- 2011-10-16 Frac Muskwa 1799.0 - 1801.0 mKB - 833ml water, 241 min shut-in 11000 kPa; flow the well on clean up - recovered 62m3 @ 4t 48/4
- 2011-10-17 continued flowback - recovered 228.54m3
- 2011-10-18 continued flowback - recovered 245.68m3; rig in Snubbing
- 2011-10-19 Snub in prod tog 60.3mm J55 EUE and tag sand @ 1804.4
- 2011-10-23 Set tubing plug at 1789.0 mKB - pressure test tubing plug
- 2011-10-25-26-27 Snub in new BHA, set packer @ 1776.7 mKB, pres
- 2011-10-28-29-30-31, 11-01-02-03-04 Continue to flow well to recover electronic recorders
- 2011-11-05 Run tubing plug, bleed off well. Circ. well over to fresh well tubing and annulus with diesel fuel as frost protection.
- 2011-11-06 Move off Grent production testlers and all other support eq
- 2011-11-07 Move off wellsite shack, sewage tank and light tower. Mon
- 2011-11-08 Finish loading out swamp mats and clean up location.
- 2011-11-09 Wrap up POs in Rainbow Lake and travel back to home by

OPERATION COMPLETE

oqc-24completionworkoverreport Rev. Jun 2, 2010

BC Oil & Gas COMMISSION
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COMPLETION / WORKOVER REPORT

A signed form and a complete report must be submitted in duplicate under the authority of the Oil and Gas Activities Act, Drilling and Production Regulations, s.36, within thirty days of the end of each completion or workover operation, to the Victoria address noted above. Attach the matching Notice of Operations. An incomplete report will not be accepted and will be returned to the sender.

Completion Workover Cased Well Abandonment Other

Well Name: **Apache La Jolla C-85-F / 94-O-12** Well Permit No.: **25818**
 Bottom-hole Location: **offset from surface location** U.W.I.: **2006C-086-F/084-O-1202** **JEDZ**
 Start Date: **2011-09-05** Finish Date: **2011-10-22**
 Intervals Worked (mKB): **4412 - 4425 mKB** Geological Formation: **Lower Besa River Shale**

Reason for Work: **Initial Completion**

Each of the following must be provided with this report:

- Chronological summary of work done
- Detailed completion / workover reports
- Downhole schematic diagram
- If a cased well abandonment, a summary of surface abandonment steps (cut casing 1m below ground level, place top 3m cement plug, weld on cap, and for abandoned wells on crown land weld on grave marker signpost) is to be included in order for the location to be a candidate for an Application for Certificate of Registration

Completion Type: Open Hole Single Dual Multi Commingled Gas lift

Completion Activity: Open Hole Perforate Fracture Acidize Bridge Plug
 Cement Squeeze Remedial Other

Stimulation Type: Fracture Acid Squeeze Acid Wash

Stimulation Volume: **6,035 m³** Stimulation Pressure: **Avg. pressure 80 MPa**
 Average rate 14 m³/min, 110 l / 70/140 sand, 44 l 40/80 CarboHydro/Top (OSP), 41 l 30/50 St. Goren HSP (Bauste & 120 l 30/80 CarboHSP Bauste. Total sand 315 l. Max pressure 95.8 MPa with average pressure of 80 MPa.

(For multiple stimulations, please attach a full list for each stimulation done.)

Flow Summary (for each formation): **Final flow rate up casing prior to shutting in and preparing to run production tubing**
 Flow Rate: **279 10^{m³/day}** Flow Pressure: **14,067 kPa** Flow Date: **2011-09-25, 2011**

Any radioactive material (i.e. frac sand)? No Yes. If yes, attach documentation explaining the method of disposal or, if buried on site, attach sketch of location showing burial location and indicate depth of burial and volume of material.

Results of work done: **Well capable of production after performing aforementioned work and is currently being tied in.**

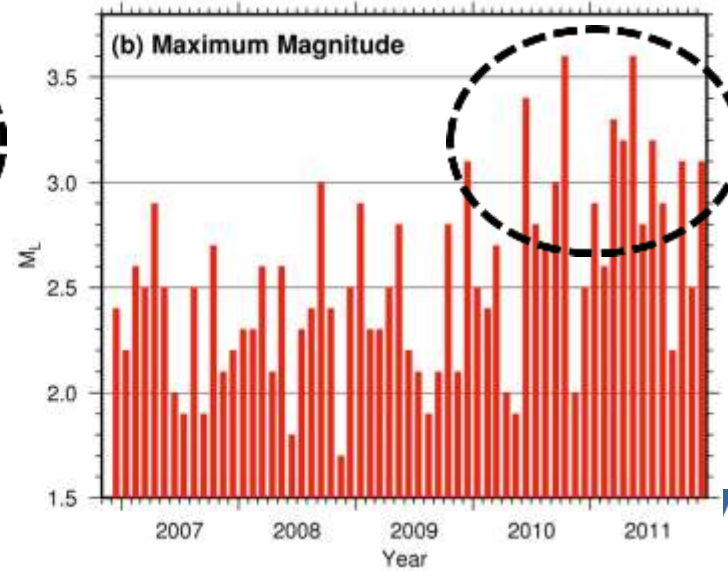
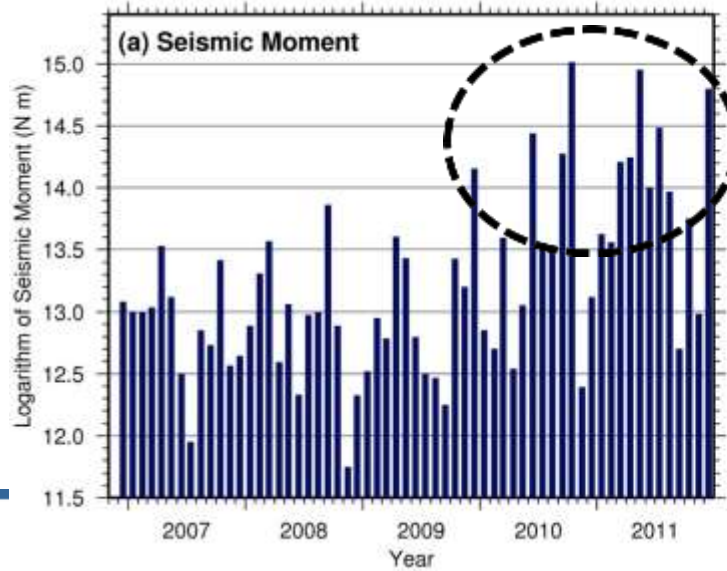
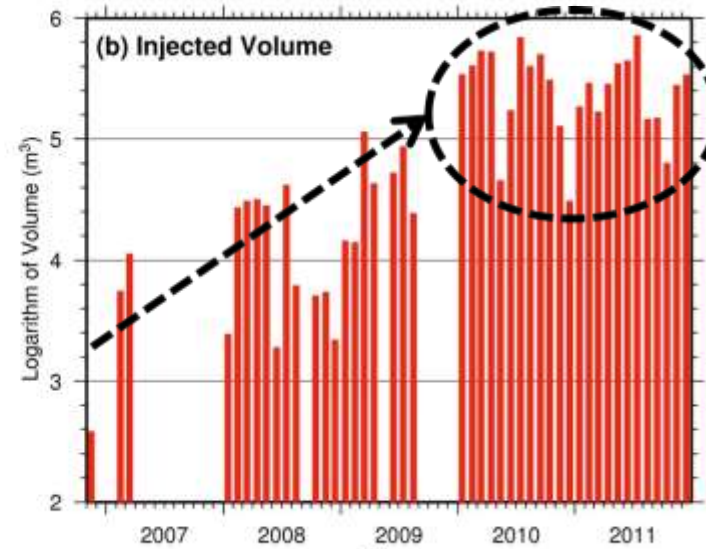
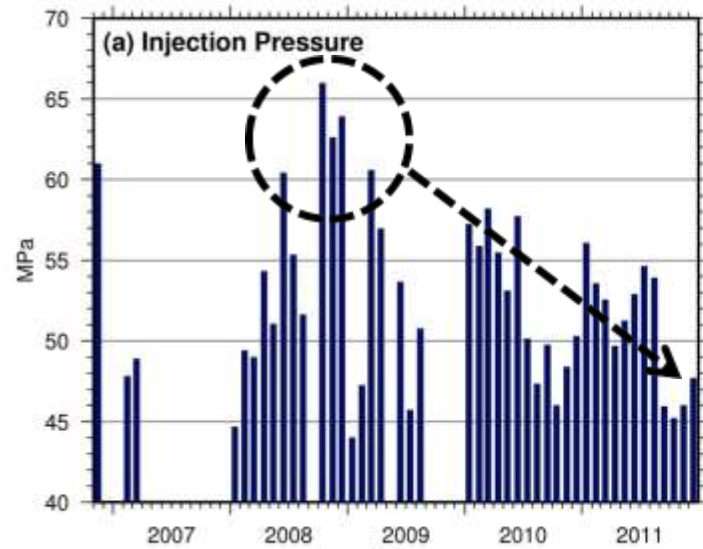
Status of well as a result of work done (completed, oil, gas, abandoned, suspended, etc): **Completed**

CONTACT INFORMATION

Name: **Kean Zemlak** Position: **Sr Staff Completion Engineer** Signature: **Kean Zemlak**
 Permit Holder: **Apache Canada Ltd.** Technical Lead: **HPHT / Sour** Date: **2011-11-22**
 Phone: **(403) 697-4729** Fax: **(403) 770-8950** Email: **kean.zemlak@apachecorp.com**

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HF Operations and Seismicity



Injected Volume vs. Seismicity

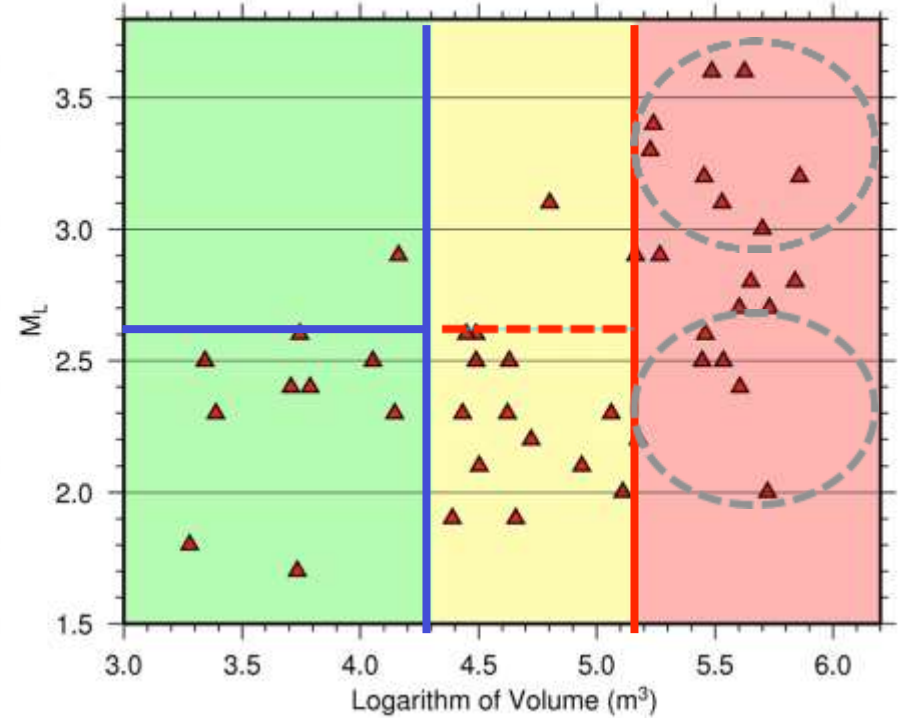
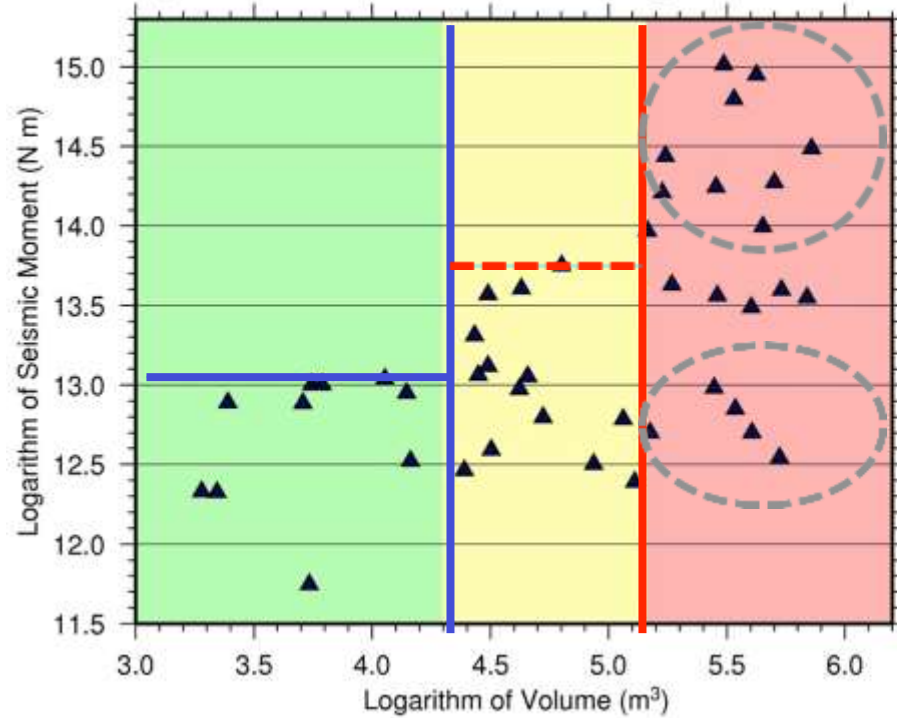


~150K m³/month

~150K m³/month

(a) Seismic Moment vs. Monthly Injected Volume

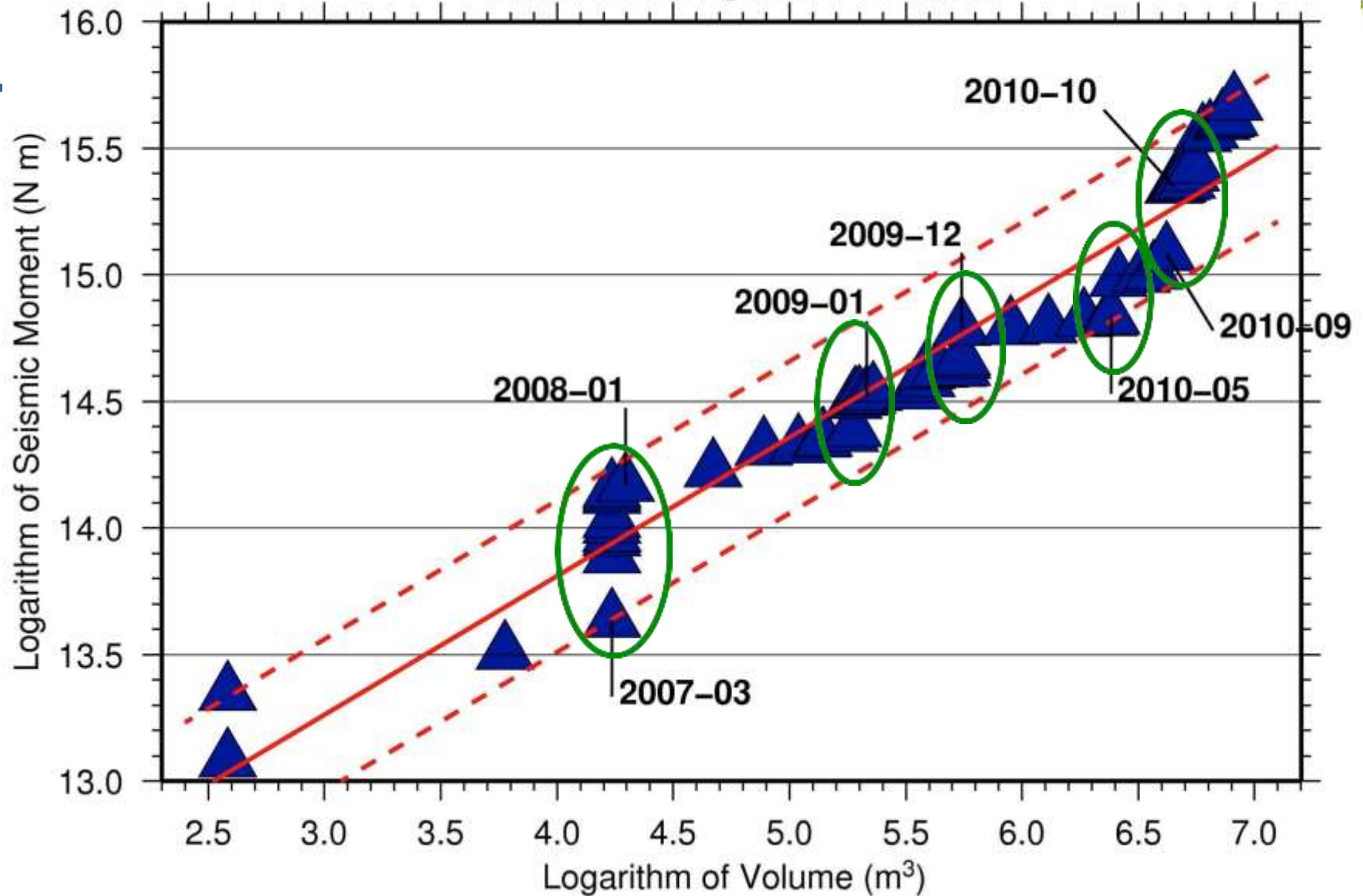
(b) Max. Magnitude vs. Monthly Injected Volume



~20K m³/month

~20K m³/month

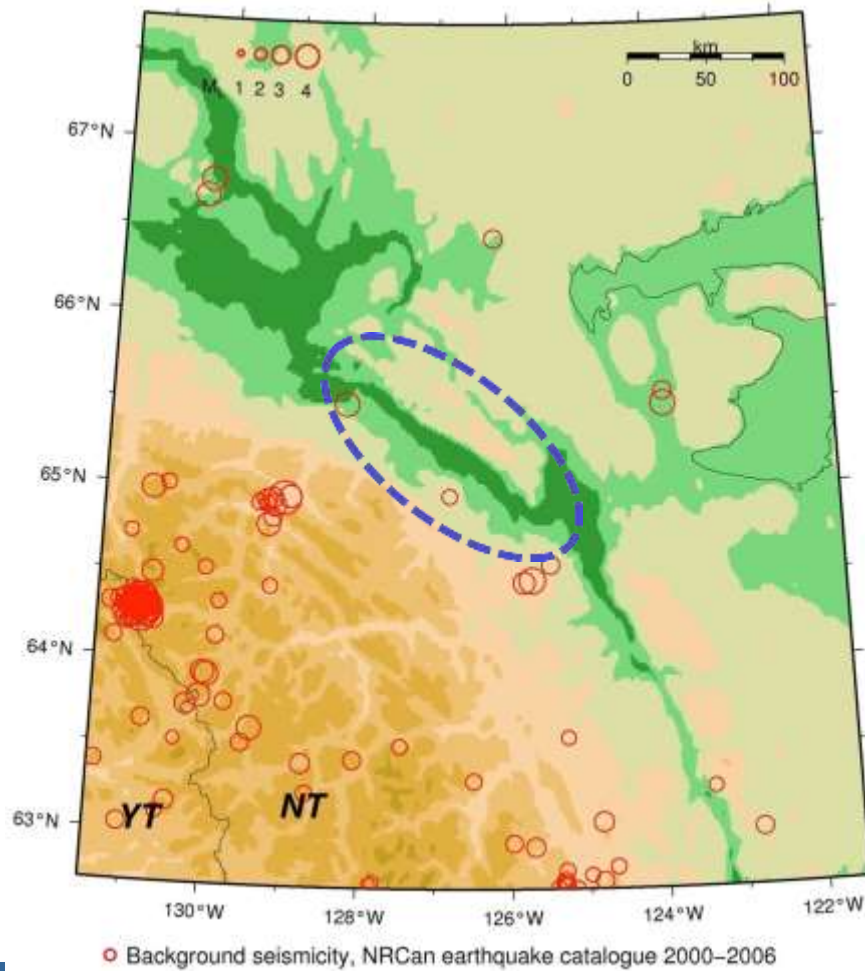
Cumulative Seismic Moment vs. Cumulative Injected Volume



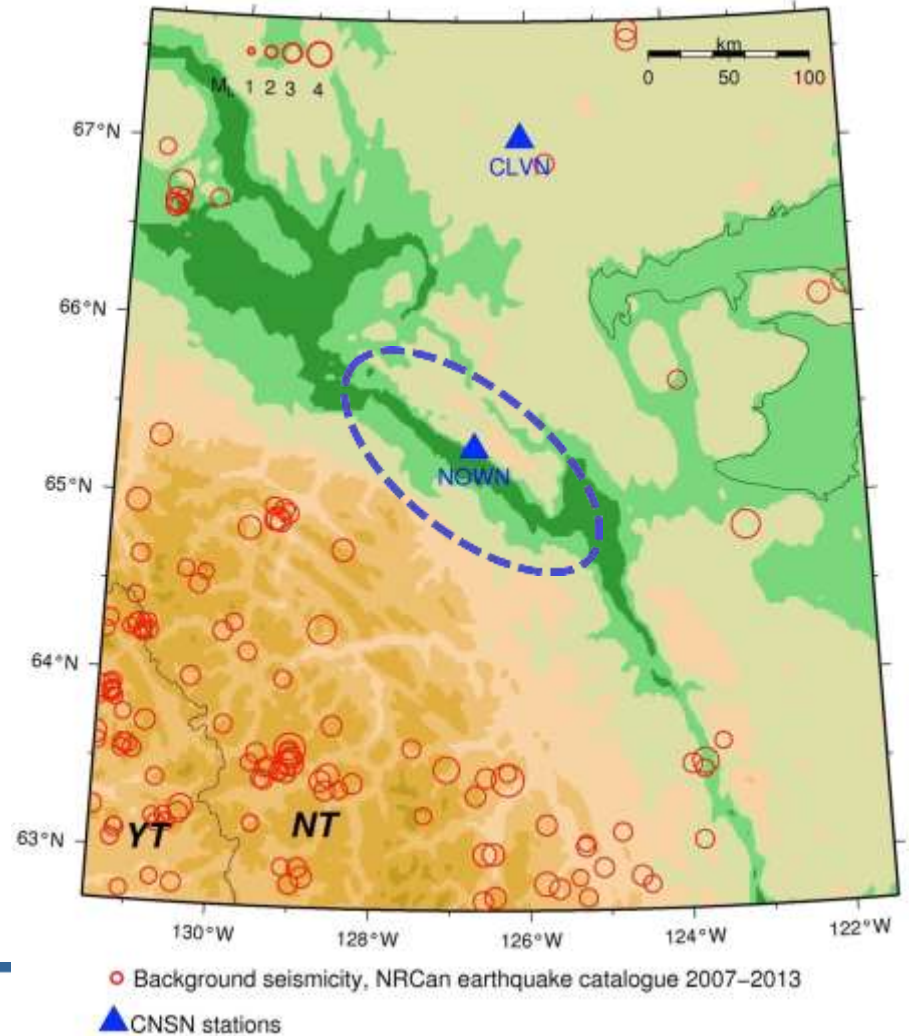
Case Study: Norman Wells, NWT



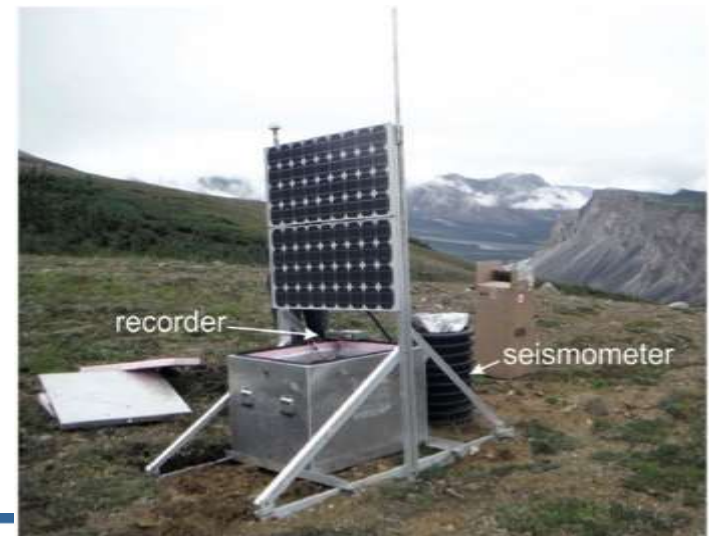
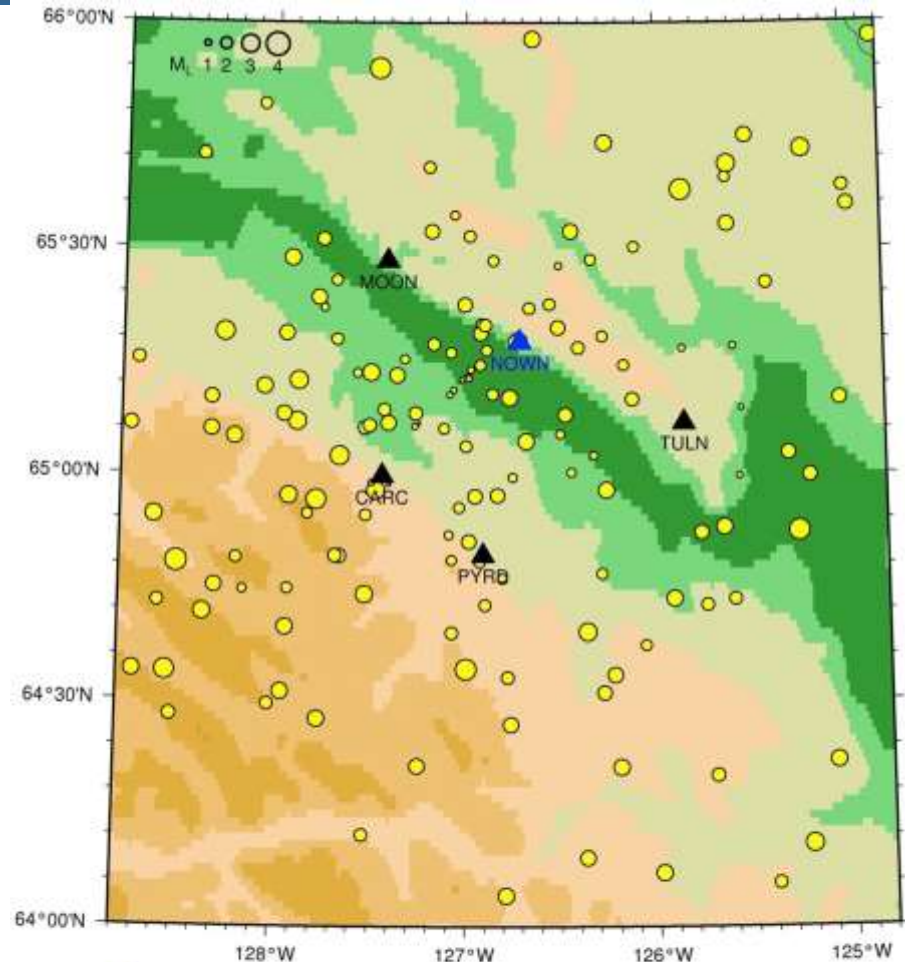
Background Seismicity 2000-2006



Background Seismicity 2007-2013



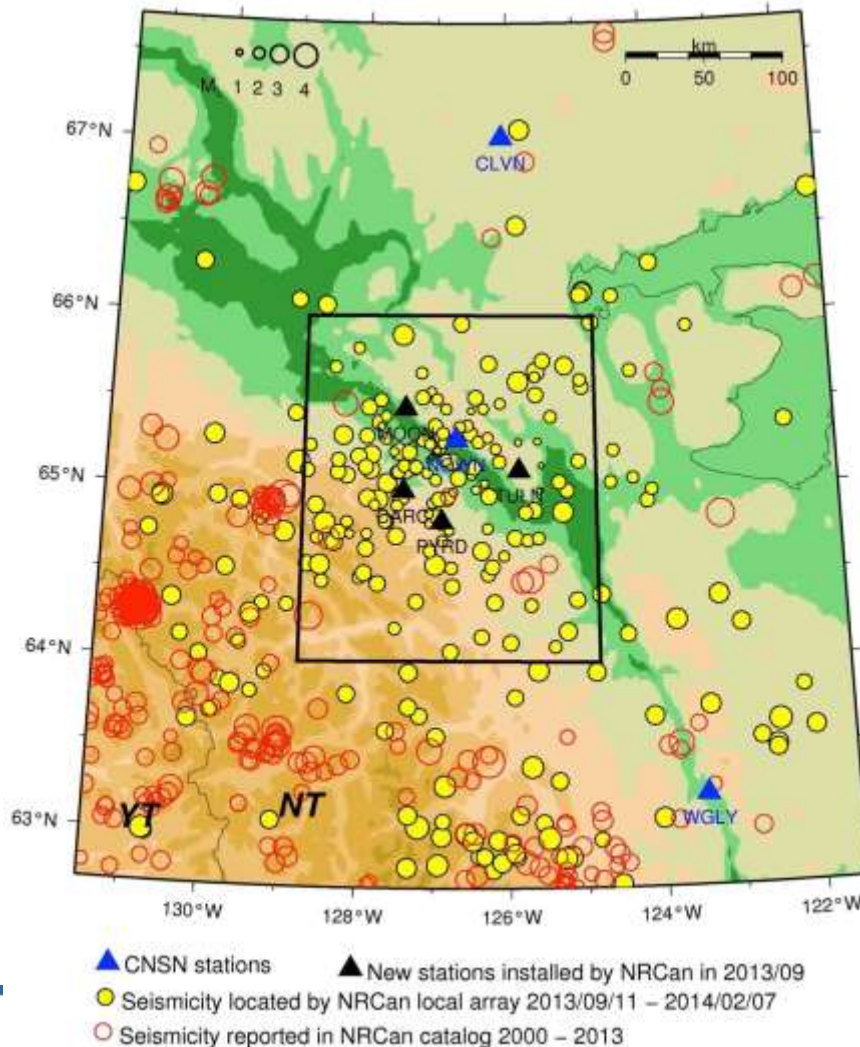
Norman Wells Local Array



Pre-HF Seismic Reference Line



CNSN Catalog + Events Recorded by NWLA



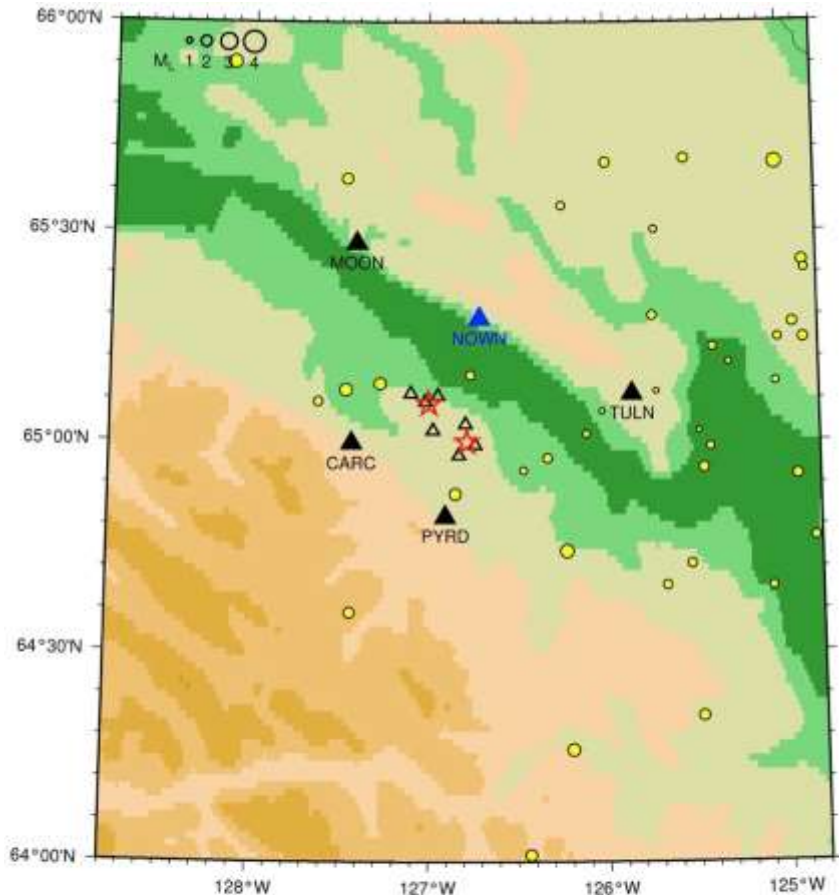
For the Norman Wells area:

- 156 events between 2013/9/11 and 2014/2/7
- On average, ~30 events per month
- Max. $M_L = 3.6$
- Min. $M_L = 0.4$
- Total seismic moment = 2.5×10^{16} N m
- Average monthly moment release = 5.04×10^{15} N m.
- Equivalent to one Mw 4.4 earthquake each month

During and Post-HF Periods

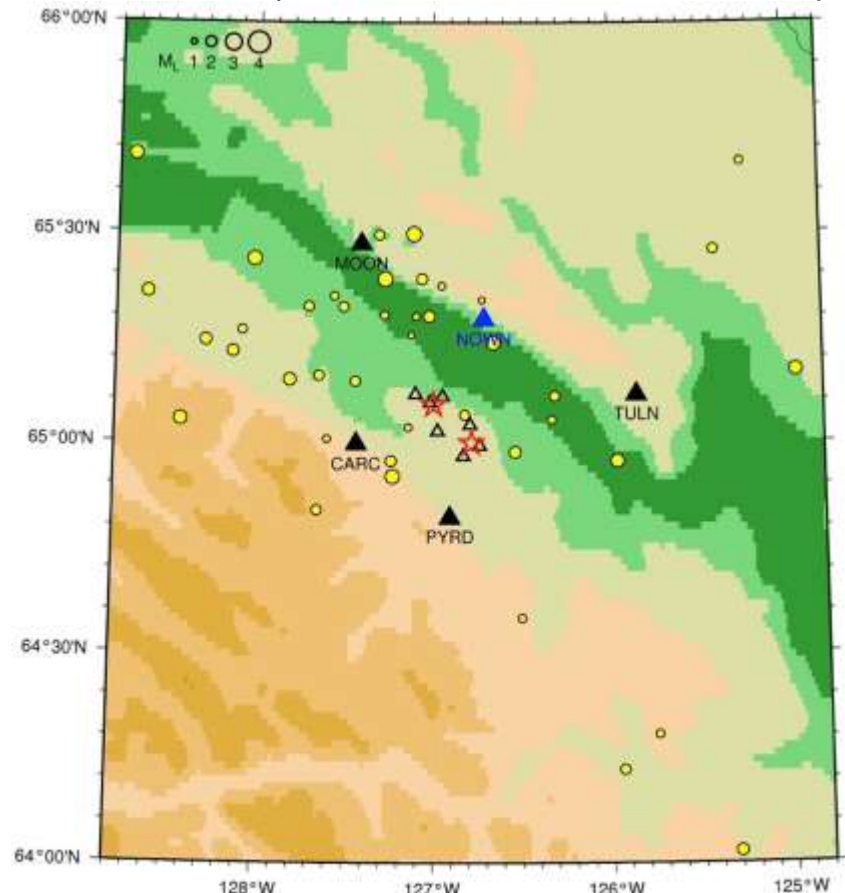


During HF (2015/2/08 – 2015/3/24)



- ▲ CNSN station
- ▲ Dense Array installed by ConocoPhillips in 2014/02
- ▲ New stations installed by NRCan in 2013/09
- Seismicity located by NRCan local array between 2014/02/08 and 2014/03/24
- Seismicity reported in NRCan catalog
- ★ Hydraulic fracturing sites 2014/02/08 – 2014/03/14

Post-HF (2015/3/25 – 2015/4/30)



- ▲ CNSN station
- ▲ Dense Array installed by ConocoPhillips in 2014/02
- ▲ New stations installed by NRCan in 2013/09
- Seismicity located by NRCan local array between 2014/03/25 and 2014/04/30
- Seismicity reported in NRCan catalog
- ★ Hydraulic fracturing sites 2014/02/08 – 2014/03/14

Comparison of pre- and post-HF Seismic Patterns in Norman Wells



Pre-HF Period:

- 156 events between 2013/9/11 and 2014/2/7
- On average, ~30 events per month
- Max. $M_L = 3.6$
- Min. $M_L = 0.4$
- Total seismic moment = 2.5×10^{16} N m
- Average monthly moment release = 5.04×10^{15} N m.
- Equivalent to one Mw 4.4 earthquake each month

During and Post-HF Period:

- 81 events between 2014/2/8 and 2014/4/30
- On average, ~29 events per month
- Max. $M_L = 2.8$
- Min. $M_L = 1.0$
- Total seismic moment = 2.1×10^{15} N m
- Average monthly moment release = 7.51×10^{14} N m.
- Equivalent to one Mw 3.8 earthquake each month
- **Injected Volume: 6.3K m³ (Feb 2014)**
7.7K m³ (Mar 2014)

There was no clear increase in the frequency and magnitude of local seismicity due to HF in the Norman Wells region!

Implication to Shale Gas Production: Sustainable Development



1. We must know the overall background seismic level before development (i.e., **each region's baseline**).
2. For each region, we need to determine the tolerance level of the geological system against HF (i.e., **up to increased frequency of local earthquakes but not increased maximum magnitude**).
 - **empirical approach (this study), or**
 - **theoretical modeling**
3. Based on each region's acceptable risk level (which depends on population density and community consensus), regulators can set the level of development and production that is sustainable in the long run (i.e., **theoretical max. magnitude and/or injected volume**).

Conclusions



- To confidently recognize any variation in regional/local seismicity that are possibly related to shale gas development, it is critical to **establish a reliable reference line for the pre-HF era**.
- Taking the HRB as a whole, **injected volume** appears to be a more important factor than the injection pressure.
- The **initial effect** of an increased injected volume is **an increase in earthquake frequency** but not magnitude.
- Relatively **large seismic moment release** ($>10^{14}$ N m) occurred only when the **monthly injected volume exceeded $\sim 150,000$ m³**, but **large monthly injected volume \neq large monthly seismic moment**.
- **Variable time lags**, from days to up to 4 months, are observed between intense HF and the occurrence of a significant local earthquake.
- Preliminary result in Norman Wells is consistent with the HRB result.
- We emphasize the **concept of sustainable development**.

External Collaborators



BC Oil and Gas Commission

Alberta Energy Regulator

Northwest Territories Geoscience Office

New Brunswick Department of Energy and Mines

Ministère des Ressources Naturelles du Québec

Geoscience BC

Energy Institute of New Brunswick

Canadian Association of Petroleum Producers

University of Calgary, University of Alberta

University of Western Ontario, McGill University



Thank You