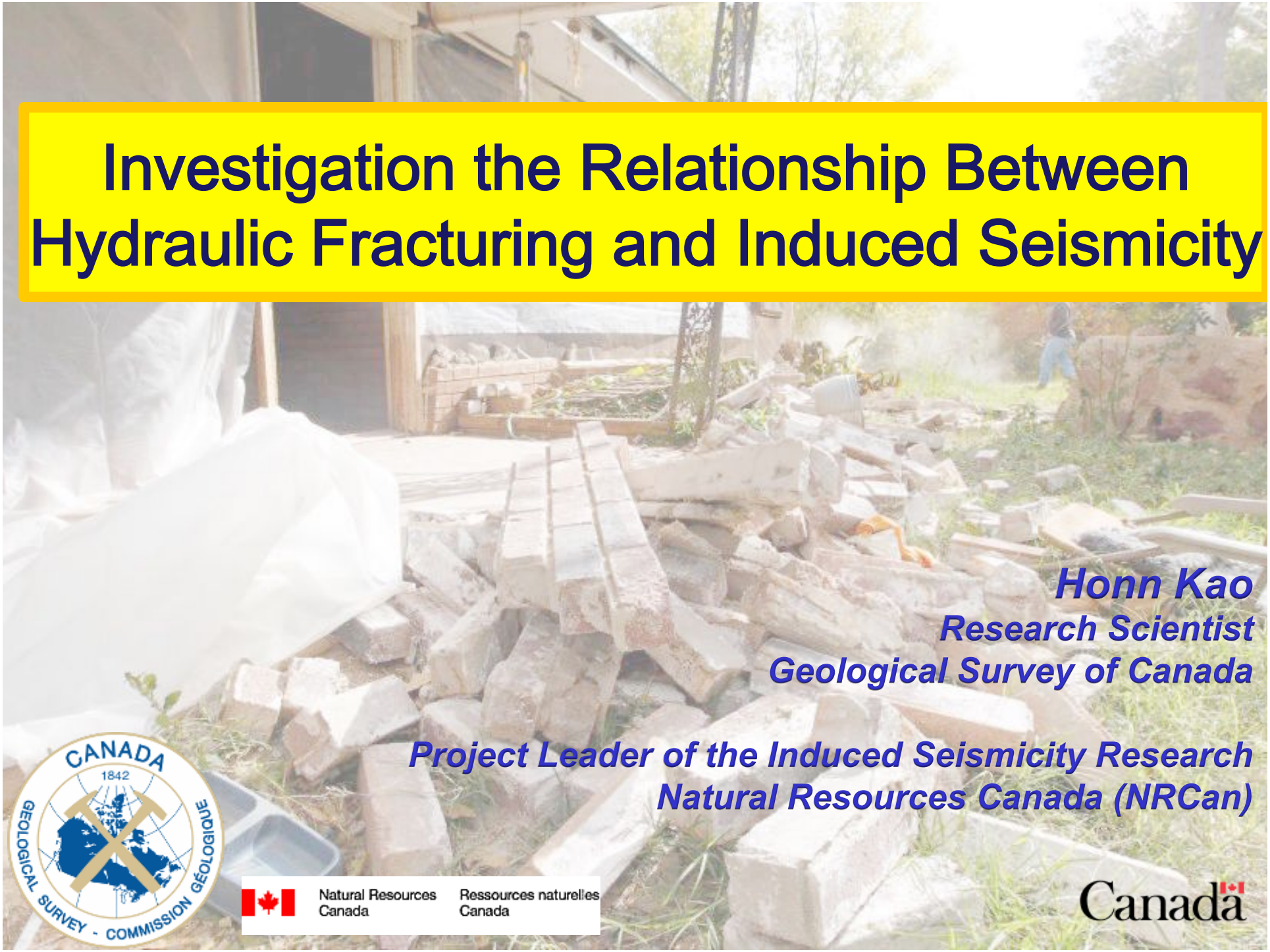
Investigation the Relationship Between Hydraulic Fracturing and Induced Seismicity



Honn Kao
Research Scientist
Geological Survey of Canada

Project Leader of the Induced Seismicity Research
Natural Resources Canada (NRCan)

CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE

Natural Resources Canada | Ressources naturelles Canada

Canada

Changing Earthquake Patterns in the USA

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Oklahoma quakes this year top tremors in California

By Marlena Baldacci and Mariano Castillo, CNN

Updated 8:21 PM ET, Thu June 19, 2014

Story highlights

So far this year, there have been more quakes in Oklahoma than California

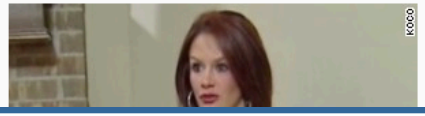
Experts: Wastewater wells appear linked to many quakes

Scientists worried about a major earthquakes

California may be known for its earthquakes, but so far this year it has been surpassed by an unlikely state: Oklahoma.

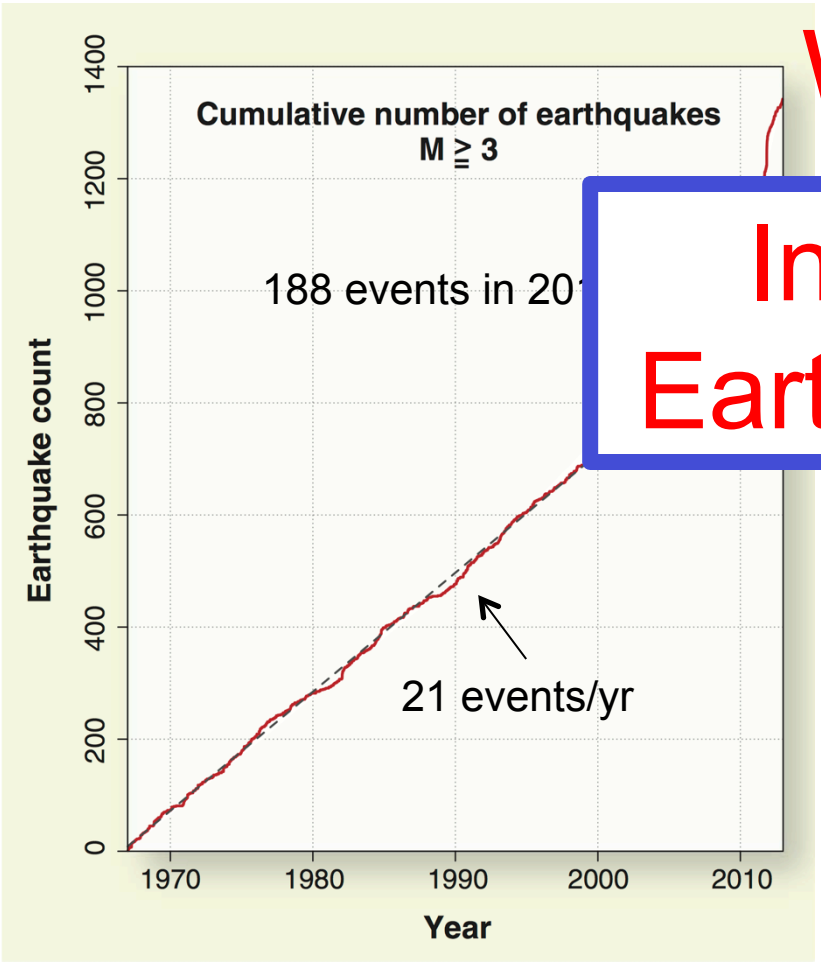
Experts say wastewater wells are likely linked to the big increase in the number of quakes recorded in Oklahoma.

Between 1978 and 2008, Oklahoma experienced an average of just two quakes of 3.0 magnitude of greater. In 2014, as of Thursday, there have been about 207 such quakes recorded in the state, according to the U.S. Geological Survey.



The upward trend started in 2009, with 20 quakes of 3.0 magnitude or greater, then 43 the following year, and jumping every year with the exception of 2012.

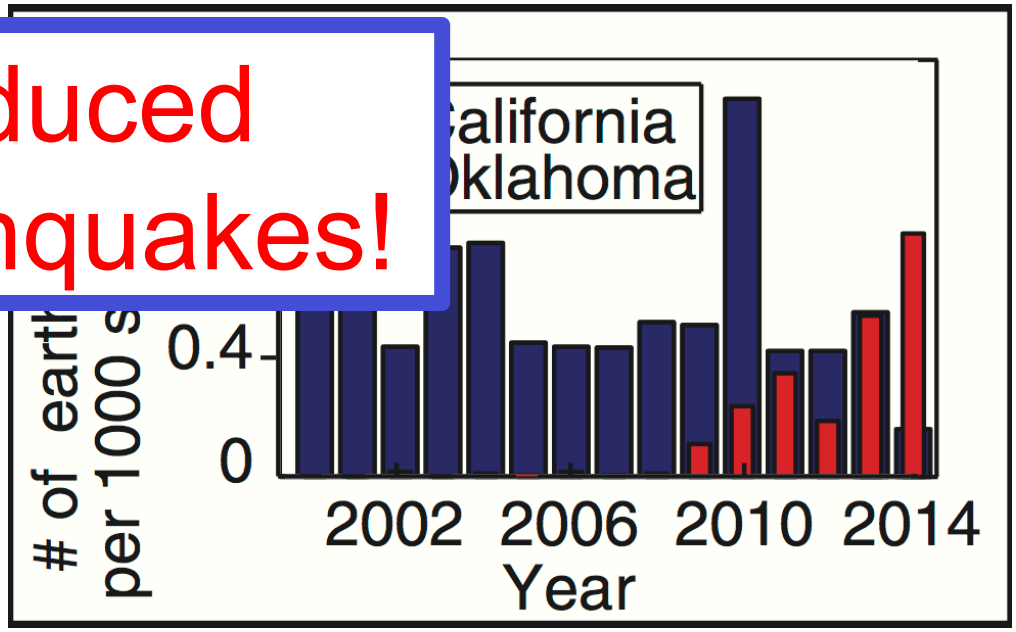
Changing Earthquake Patterns in the USA



Earthquakes in the U.S. midcontinent 1967-2012 (Ellsworth, 2013)

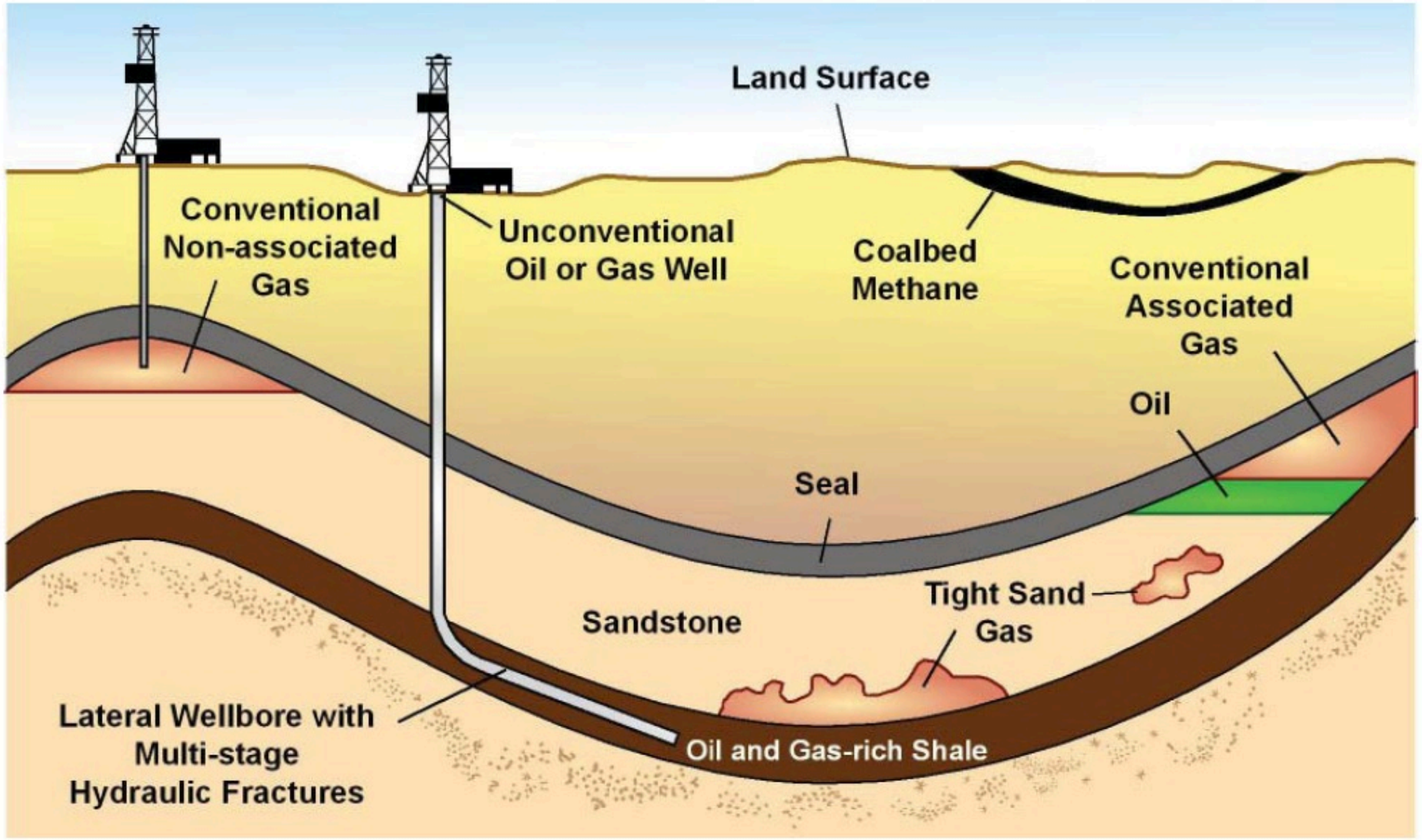
WHY?

Induced Earthquakes!



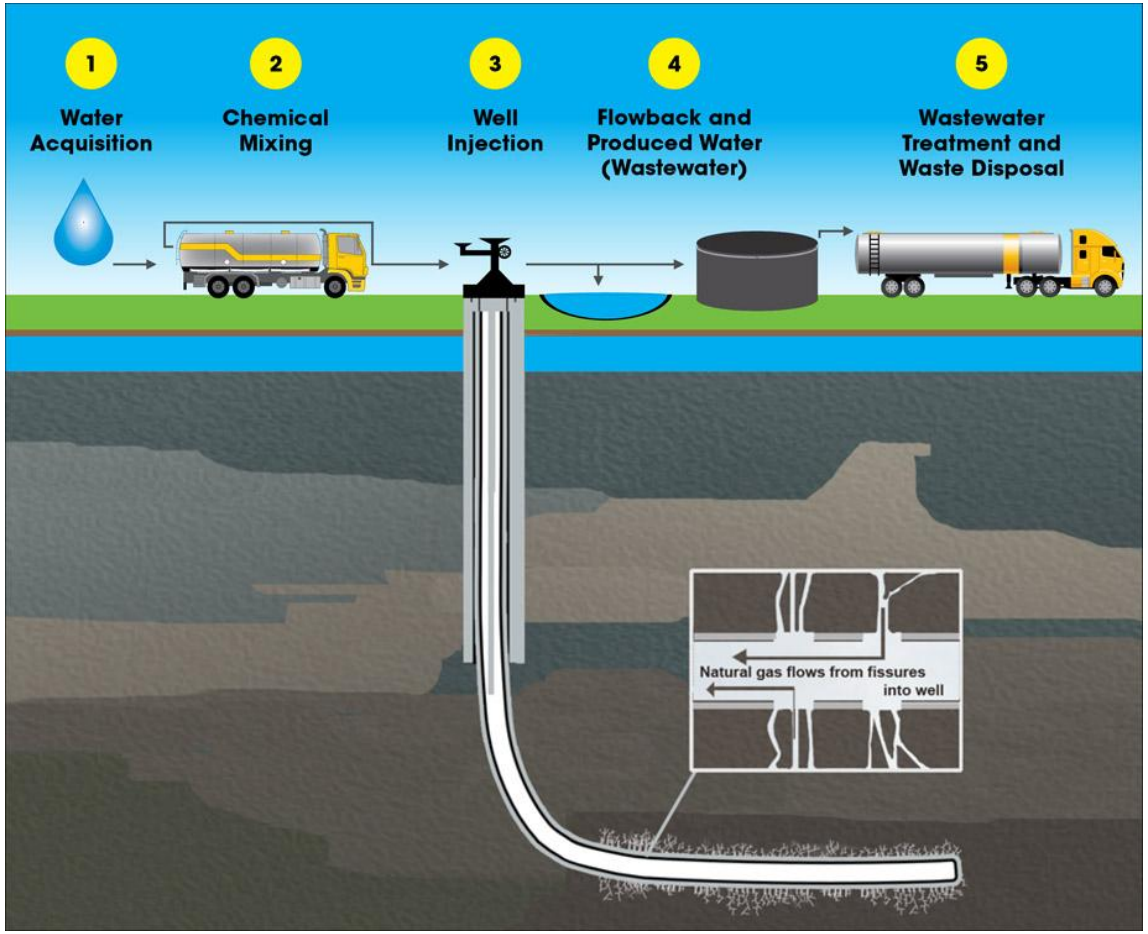
Comparison of *M* 3+ Earthquakes in California and Oklahoma 2000-2014 (Keranen et al., 2014)

The Geology of Conventional and Unconventional Oil and Gas



Source: EIA

Hydraulic Fracturing (aka Fracking/Frac'ing)

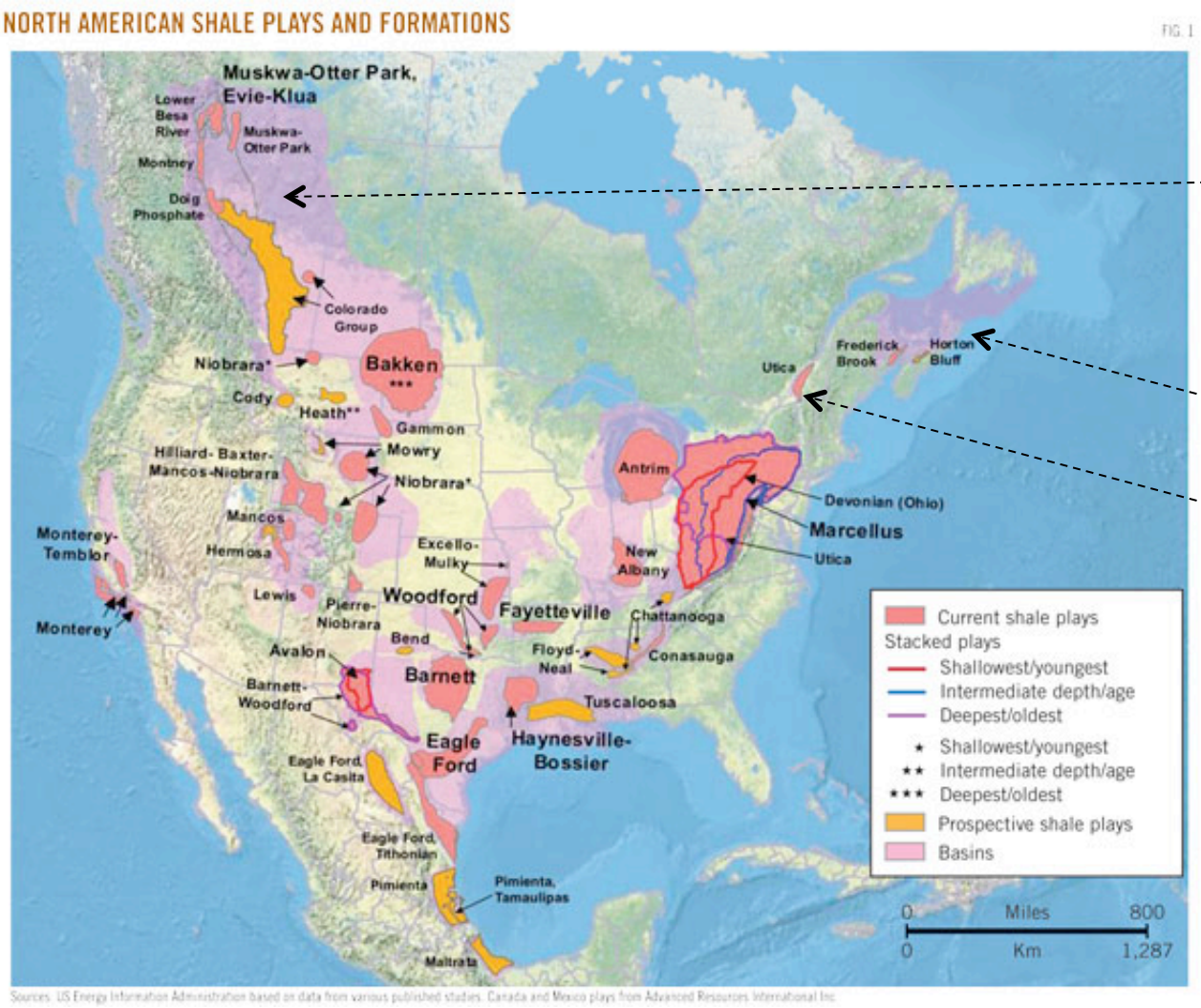


epa.gov

- Well depth 1–3 km
- Multiple (often 4–16) horizontal wells
- Multiple (5 to 20) HF stages per well
- Injection pressure ~45–65 MPa
- Each stage uses ~4,000 m^3 of water and ~200 tons of sand

✧ An Olympic swimming pool = 2,500 m^3

Unconventional Oil and Gas in North America



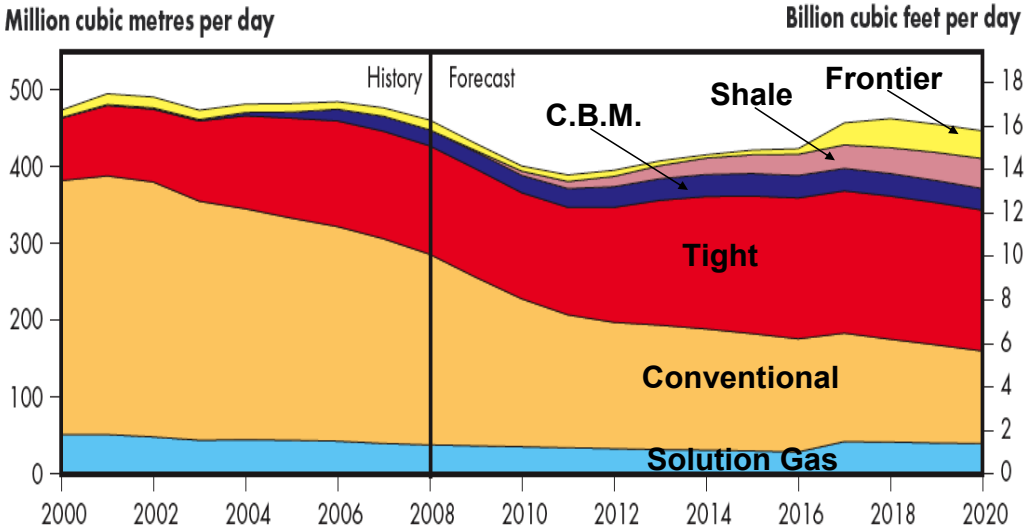
In Canada:

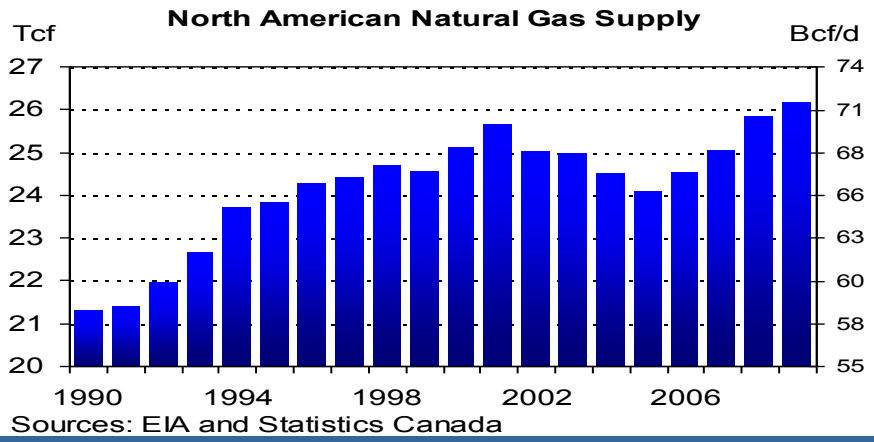
- West Canadian Sedimentary Basin
  (BC, AB, SK, NT, YT)
- Maritimes Basin
  (NB, NS)
- St. Lawrence Platform
  (QC)

US EIA (2011)

UCOG are Changing the North American Energy Market

- Shale gas increased estimates of Canada's natural gas supply to over 100 years at current production rates (Canadian Society for Unconventional Gas)
- NEB has now included shale gas in their outlook scenario
- Shale gas has reversed the declining trend of natural gas supply in the U.S.
- Shale gas is expected to have a similar impact in Canada





HF-induced Earthquakes in US and Europe

Eola Field, Garvin County, OK

- 43 earthquakes in January 2011
- *M* between 1.0 and 2.8

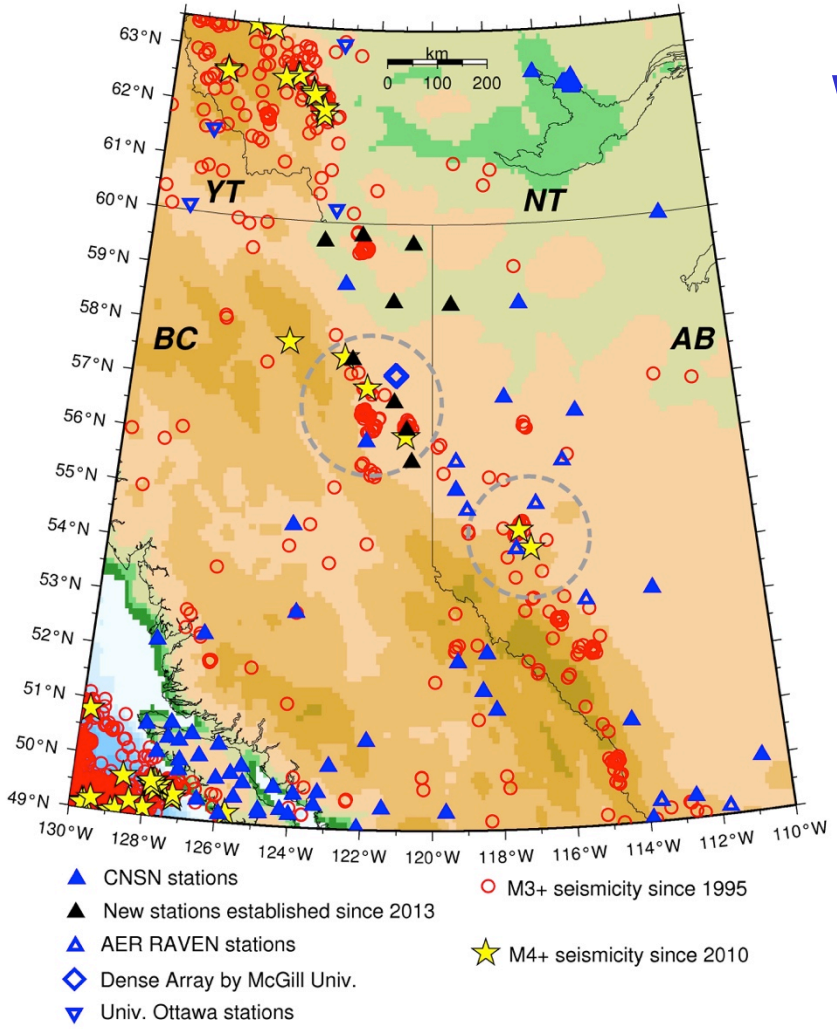
Holland (2011)

Bowland Basin, England

- 50 earthquakes in March–May 2011
- *M* up to 2.3

De Pater and Baisch (2011)

Maximum magnitude of HF-related earthquakes keeps increasing!



West Canadian Sedimentary Basin

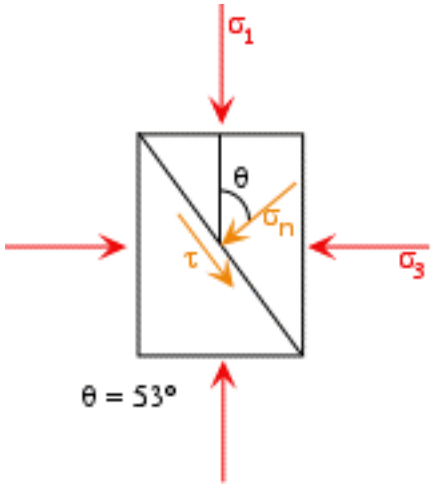
2010-10-05, HRB, BC, M_L 3.6
2011-05-19, HRB, BC, M_w 3.6
2013-05-28, Montney, BC, M_L 4.2
2014-08-04, Montney, BC, M_w 4.4
2015-01-23, Fox Creek, AB, M_w 4.4
2015-06-13, Fox Creek, AB, M_w 4.4
2015-08-17, Montney, BC, M_w 4.6*

* New world record for HF-induced earthquakes

Farahbod et al. (2014, 2015a, 2015b); Schultz et al. (2015)

Basic Physics of Induced Earthquake

Earthquake = Shear Failure Along a Geological Fault



$$\tau = \tau_0 + \mu\,\sigma_n$$

τ : Shear Strength

τ_0 : Internal Cohesion

μ : Coefficient of Friction

σ_n : Normal Stress

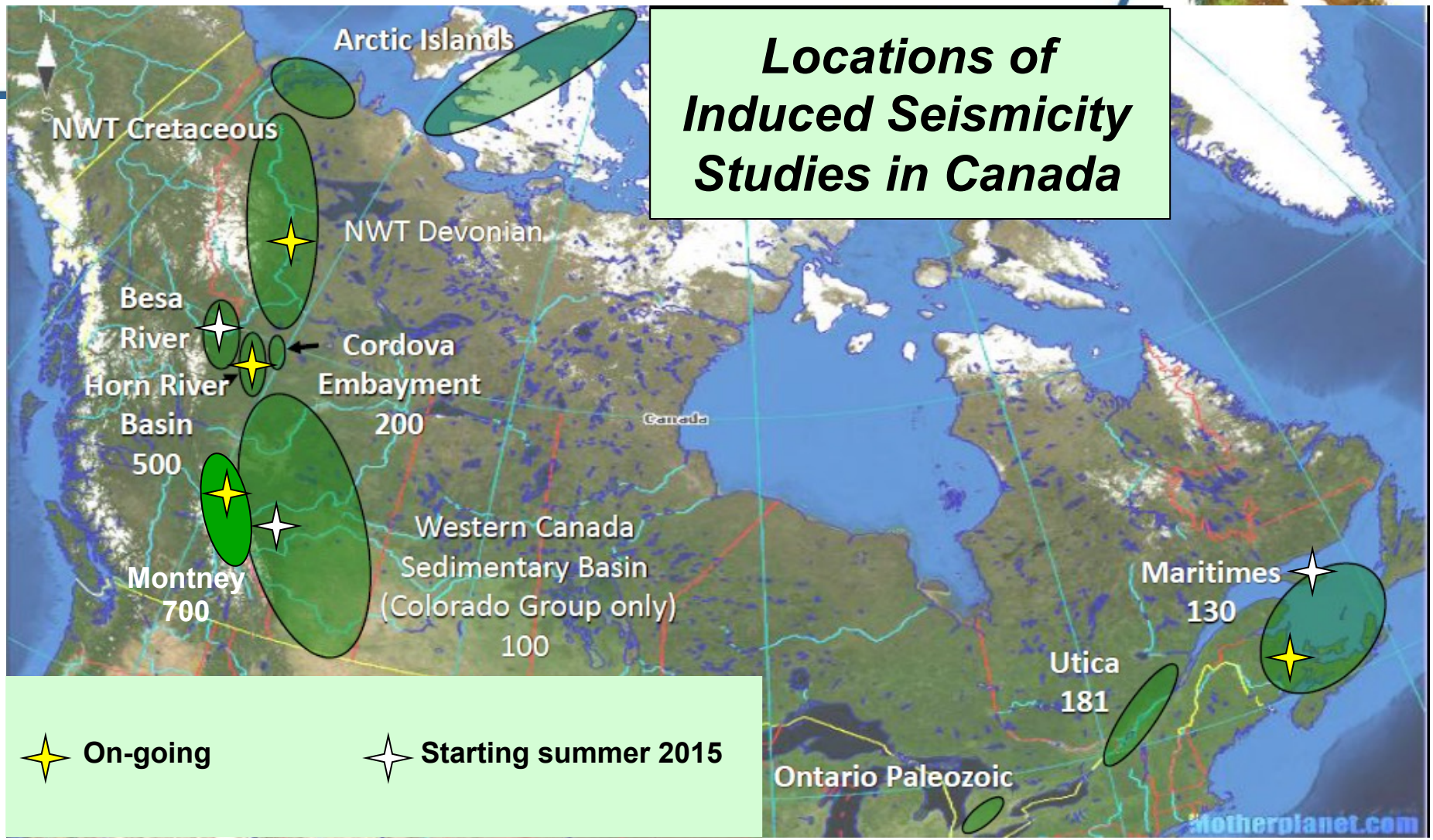
After fluid is injected, pore pressure (p) increases and the "effective" normal stress becomes less

$$\sigma_n' = \sigma_n - p$$

Scholz (1990)

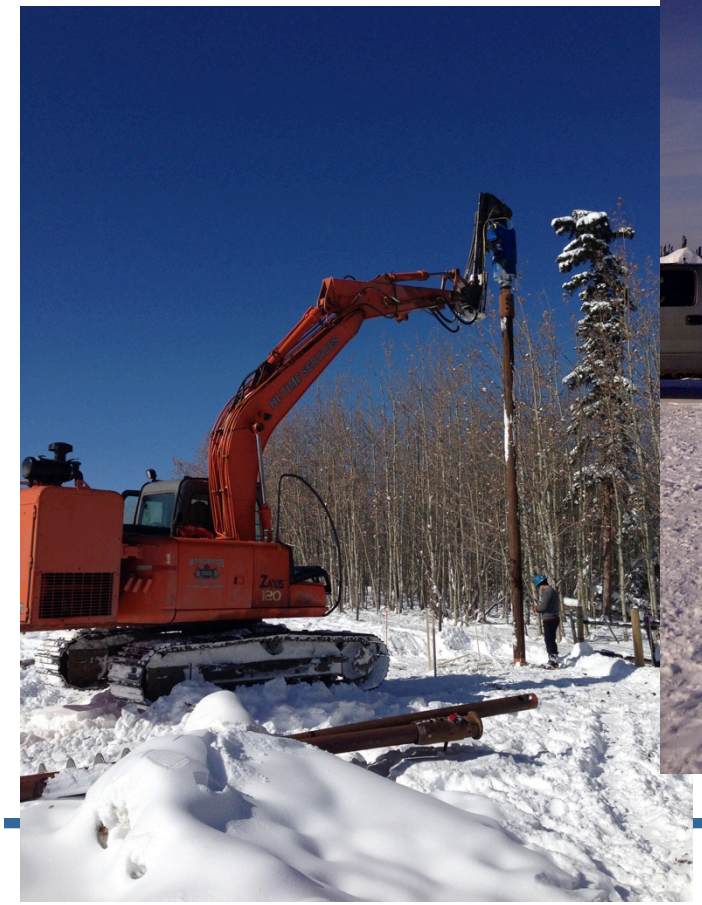
NRCan's Induced Seismicity Research

- Initiated in 2012 as part of the Shale Gas Research Project, Environmental Geoscience Program
- A coordinated effort involving both public and private sectors to address critical knowledge gaps in induced seismicity related to unconventional gas and oil development
  - ✓ Improved earthquake monitoring for areas with development potentials
  - ✓ Detailed studies of background seismicity to establish pre-development reference lines
  - ✓ Focused case studies to understand the relationship between seismogenesis and man-made operations


Locations of Induced Seismicity Studies in Canada
Arctic Islands
NWT Cretaceous
NWT Devonian
Besa River
Cordova Embayment
200
Horn River Basin
500
Montney
700
Western Canada Sedimentary Basin
(Colorado Group only)
100
Maritimes
130
Utica
181
Ontario Paleozoic
On-going
Starting summer 2015
Canada
Motherplanet.com

Install New Stations in NE BC

Screw piling through the muskeg layer

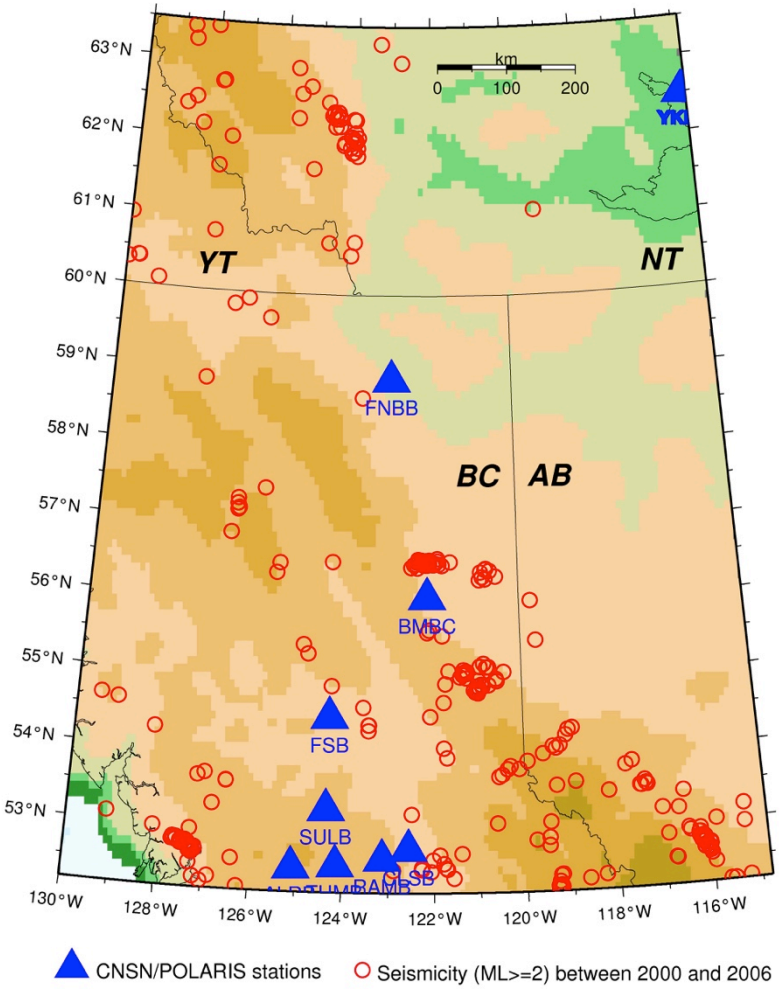


Extra solar panels and battery capacity

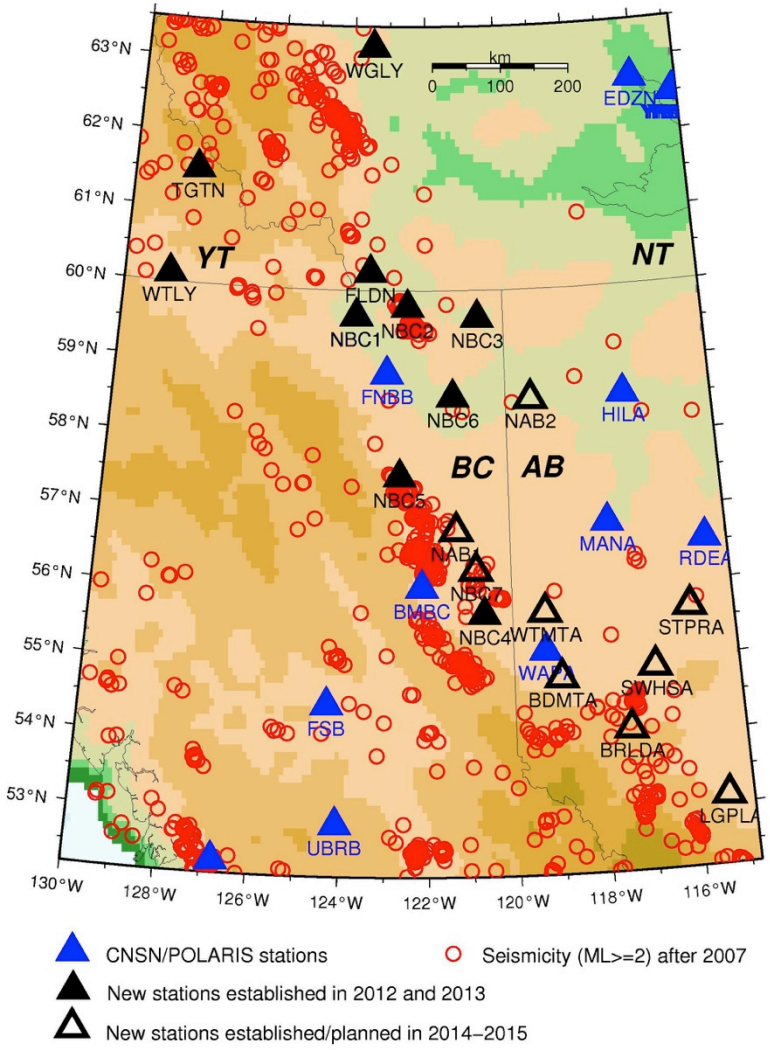
Posthole installation to reduce noise level

Station Densification in NE BC

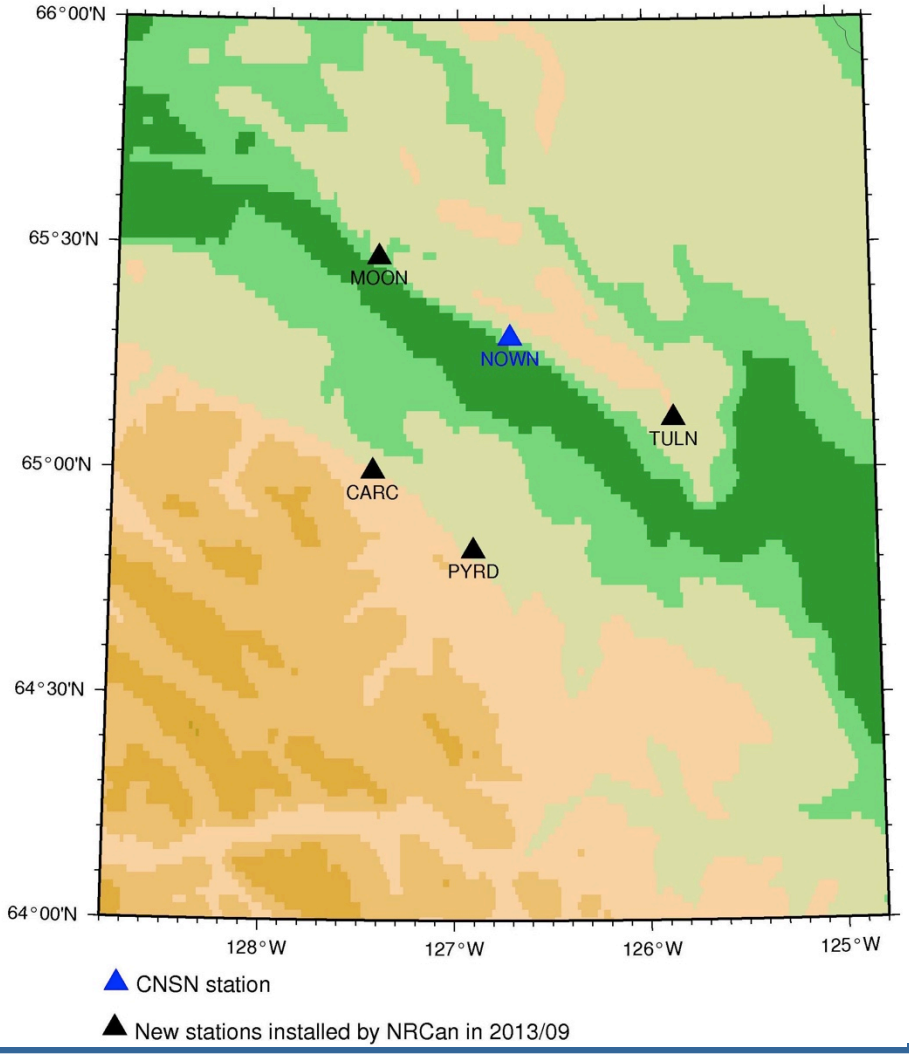
Station Distribution Before 2013

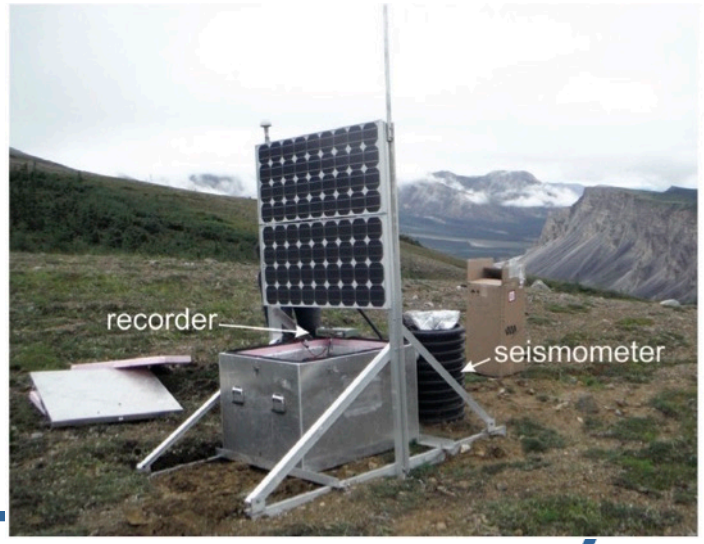


Station Distribution as of Sep 2015



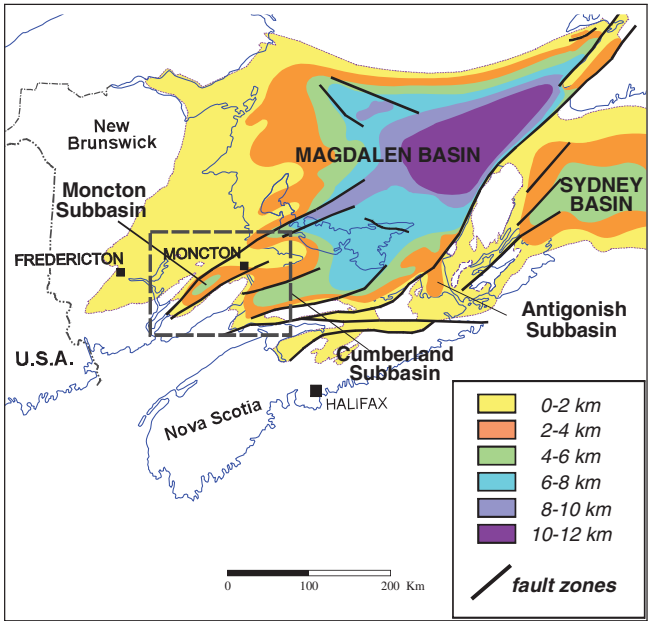
Norman Wells Local Array, Northwest Territories

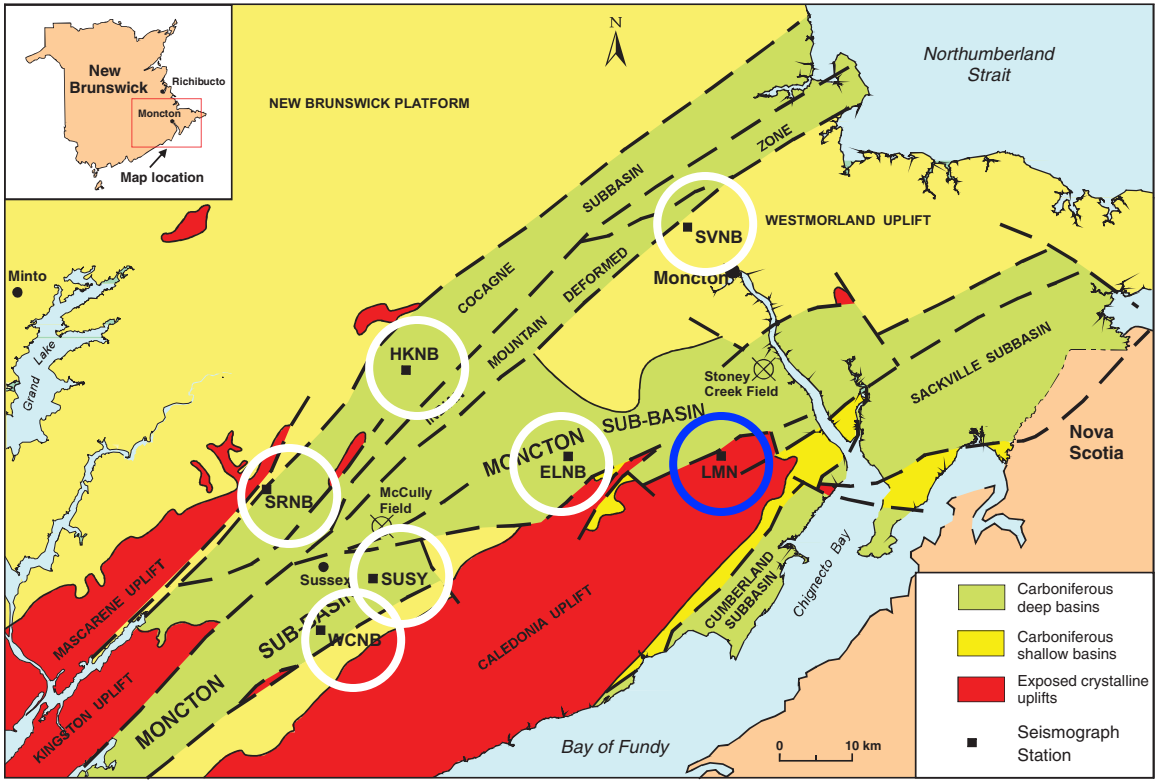




Cairns et al. (2014)

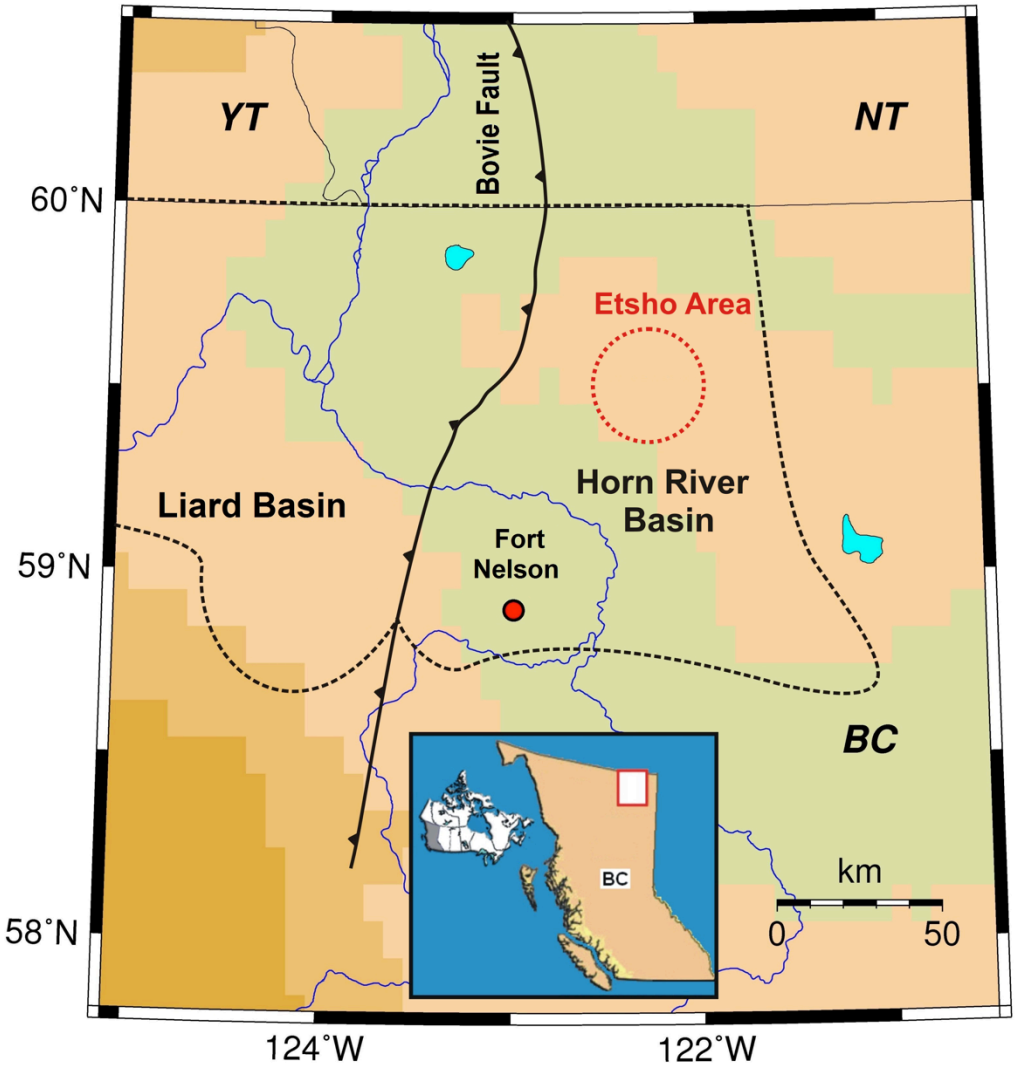
Station Densification in New Brunswick





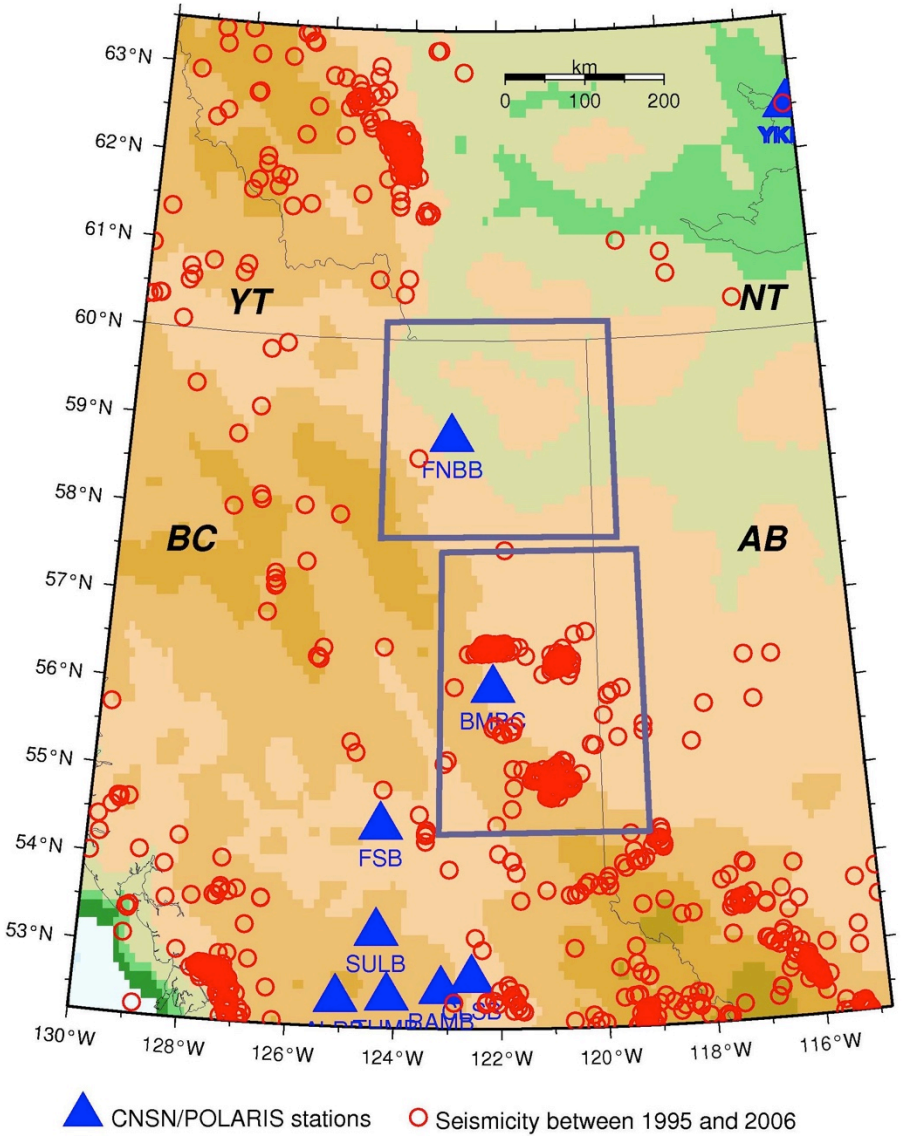
- Western part of the Maritimes Basin
- Complex relationships between the Devonian-Permian succession and the crystalline basement.
- In addition to station LMN, 6 new real-time broadband seismic stations were installed since 2013.

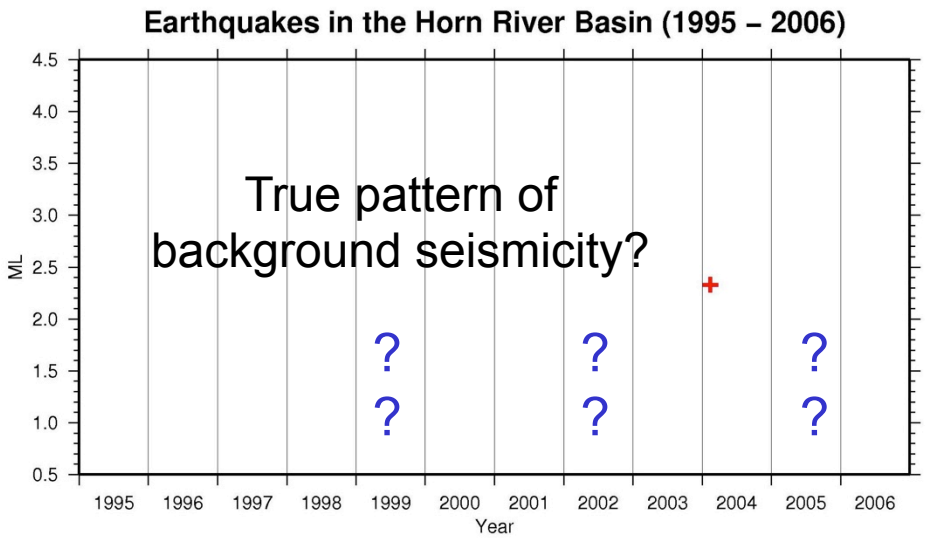
Case Study: Horn River Basin, BC

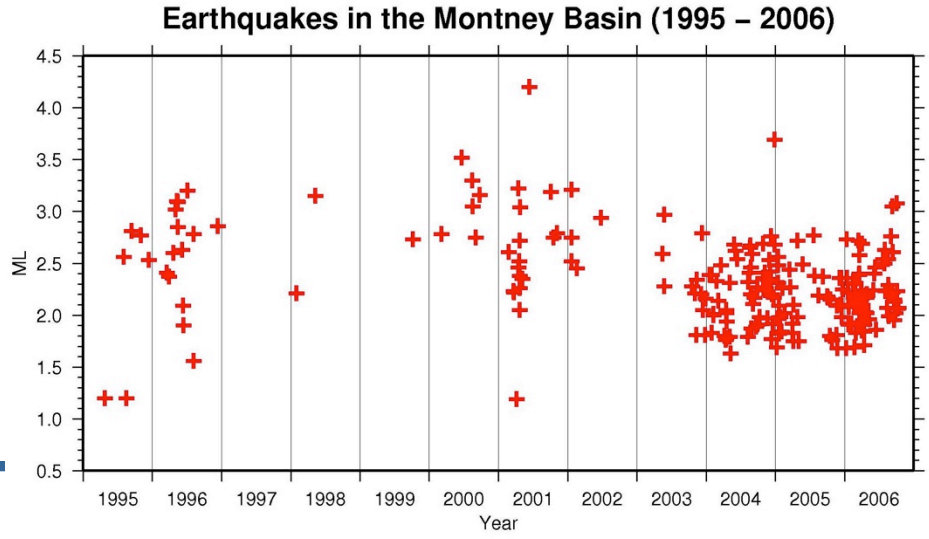


- A major shale gas production area in British Columbia
- Hydraulic fracturing started as early as late-2006
- Most HF operations in the Etsho area
- Peak shale gas production in 2010 and 2011
- Historically, this area had few earthquakes.

Seismicity in NE BC Before December 2006





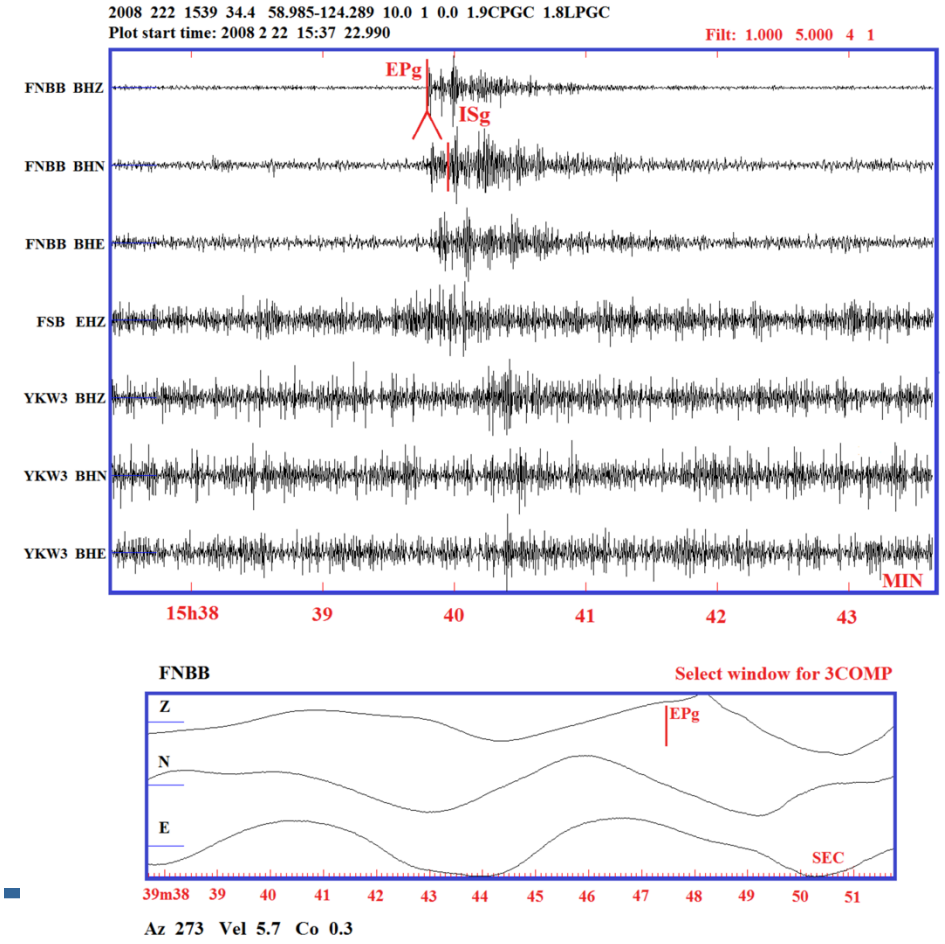


Re-analysis of Background Seismicity in the HRB

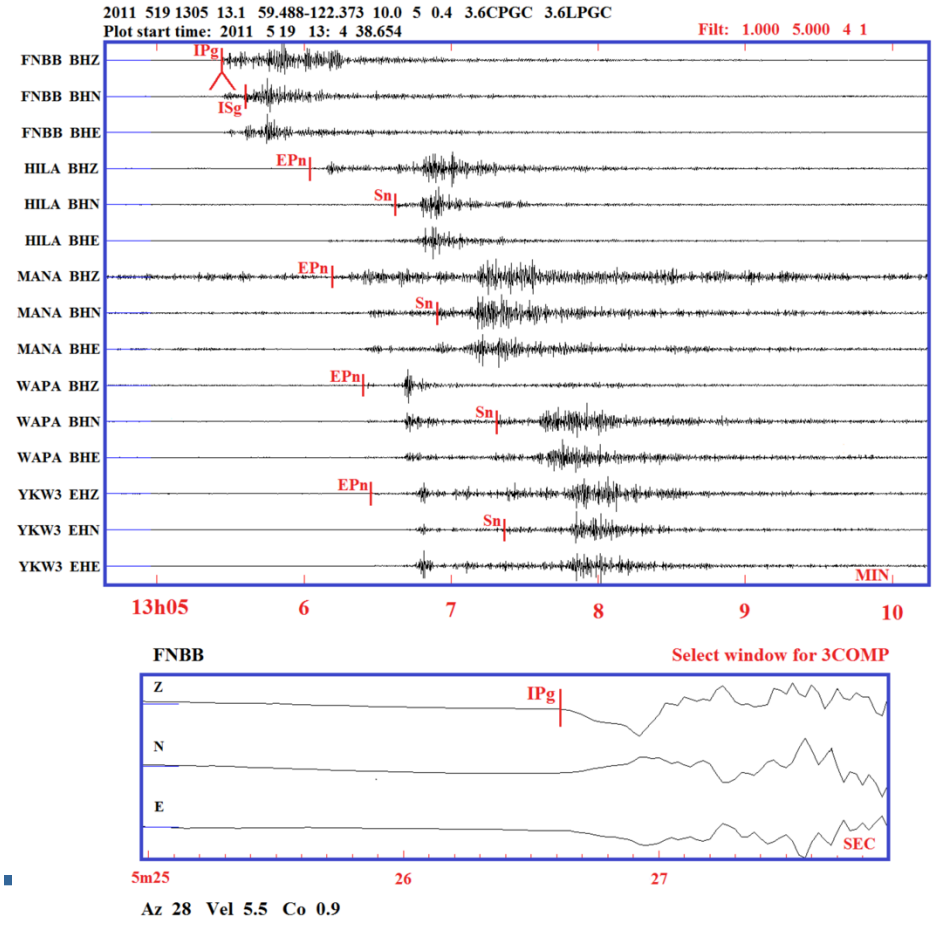
- Very difficult because there was only ONE seismograph station (FNBB; three-component, broadband)
- Must use the Single-Station Location Method (*Roberts et al.*, 1989)
  - Convert *S-P* travel time difference to epicentral distance
  - Estimate the back-azimuth from waveform cross-correlations of vertical and two horizontal components
- Include measurements from multiple stations whenever possible
- Choose a 12-month time window long before the beginning of HF (2002–2003) to exclude any HF effect.

Two Local Earthquakes in HRB, BC

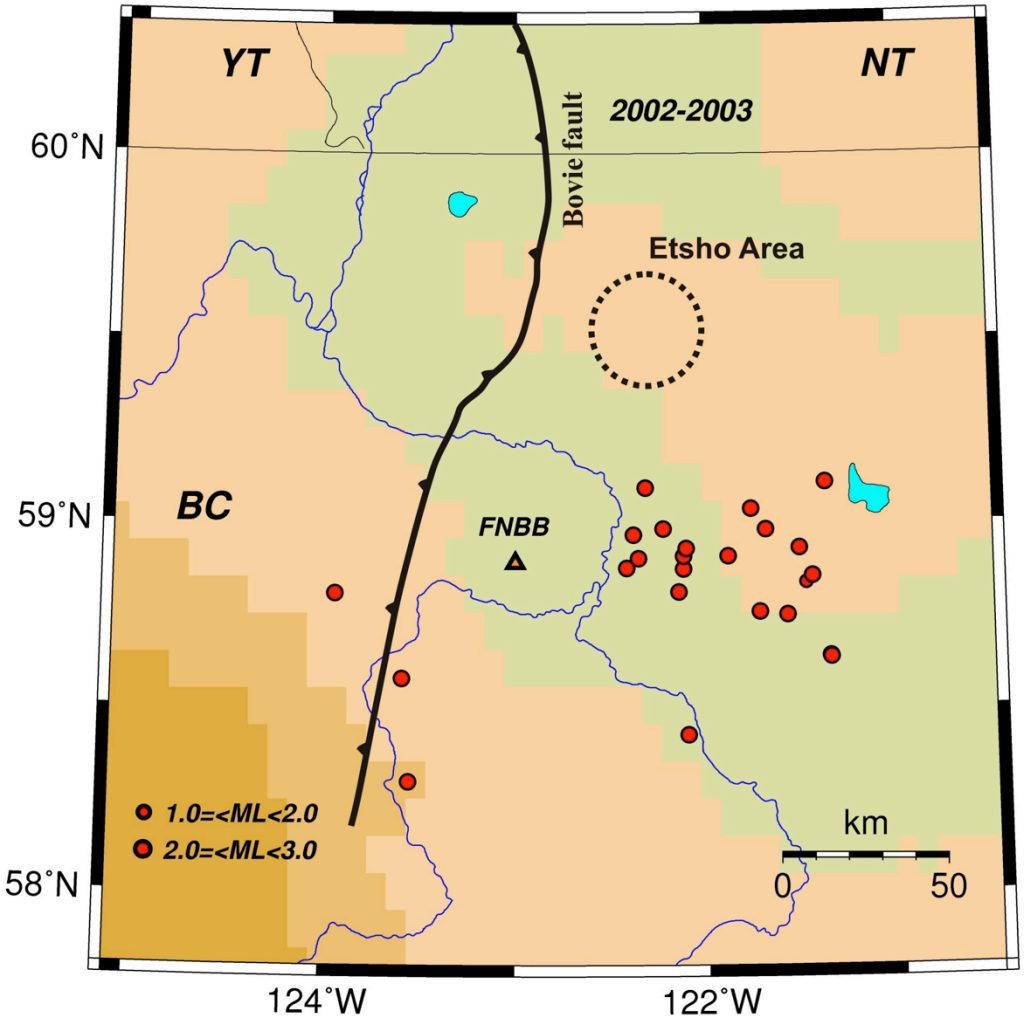
A small earthquake (M_L 1.8)
Signals seen at only one station



A larger earthquake (M_L 3.6)
Signals seen at 5 stations



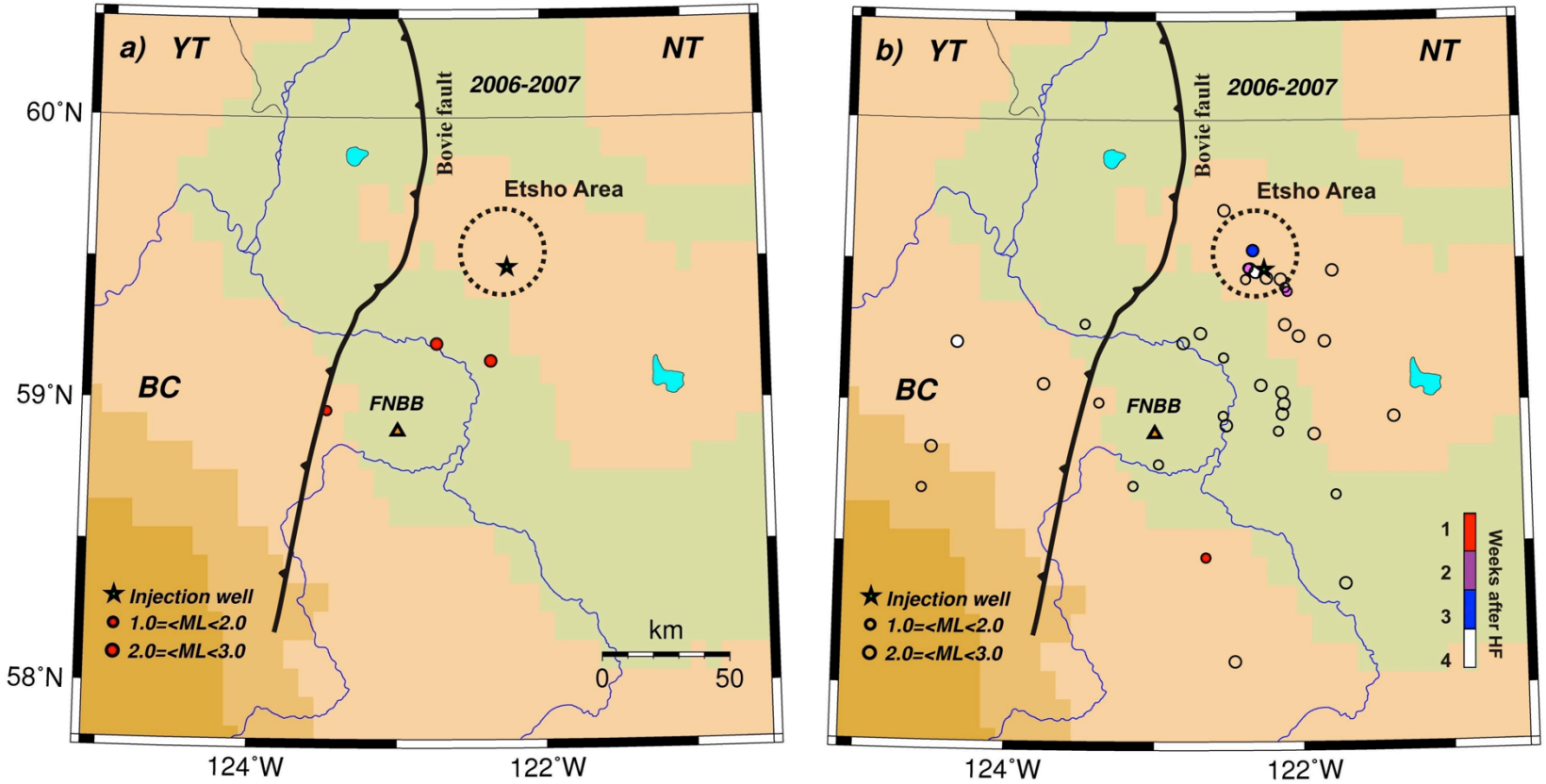
Seismicity Before Shale Gas Development



- July 2002 – July 2003, 4 years before HG in the HRB
- 24 events detected
- Most were in the southern HRB
- Some to the west and south
- M_L between 1.8 and 2.9
- Most are smaller than M_L 2.5, which was the detection threshold of CNSN for the HRB.
- There was **NO** event in the **Etsho** area.

Seismicity After Shale Gas Development

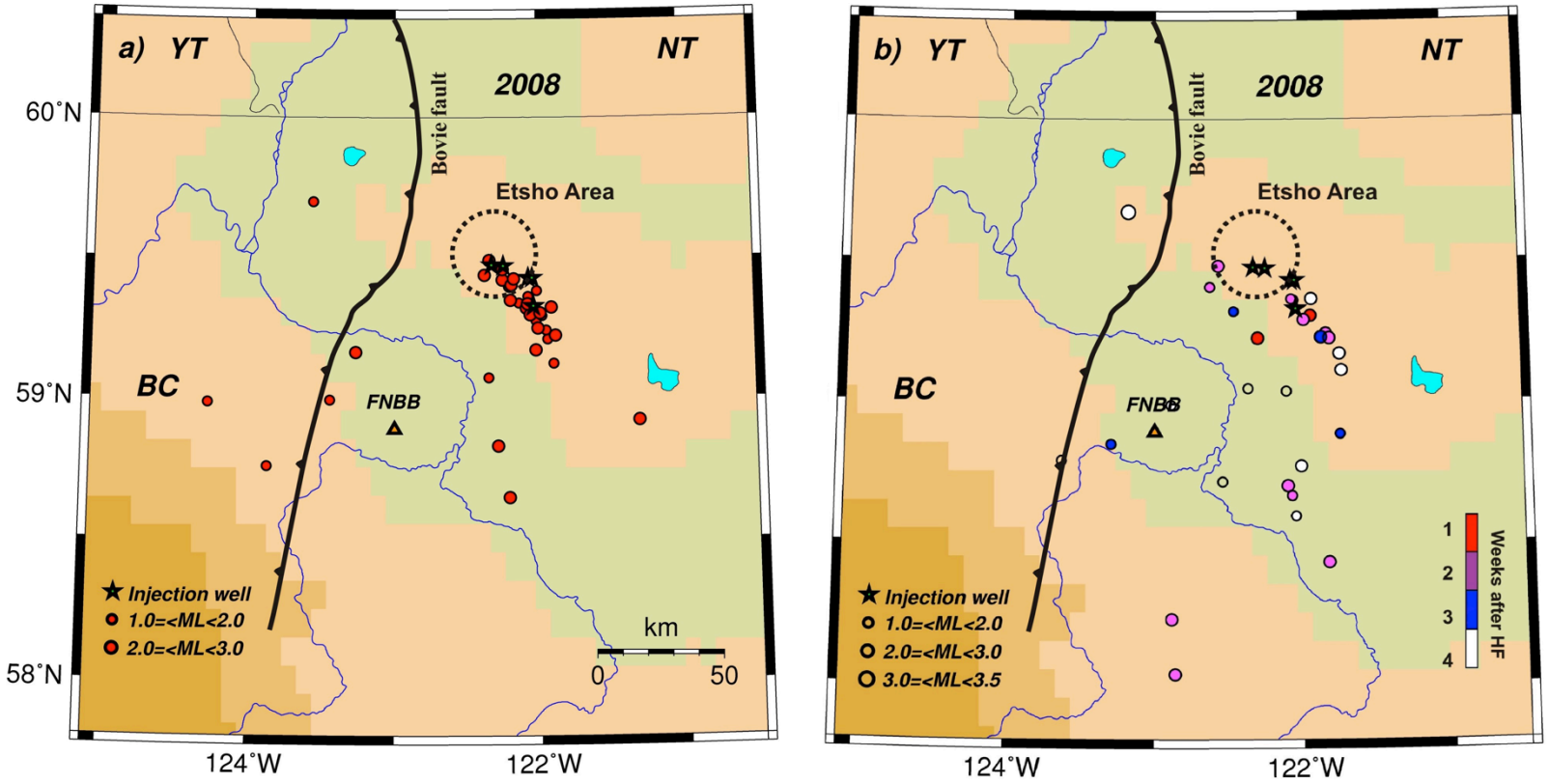
Initial Period (December 2006 – December 2007)



- 42 events with M_L in 1.3 – 2.9
- 3 events during 32 HF days, but none close to the HF wells.
- 36 during non-HF days, some were in the immediate vicinity of HF wells.
- Most non-HF events occurred after one month of the last HF operation.

Seismicity After Shale Gas Development

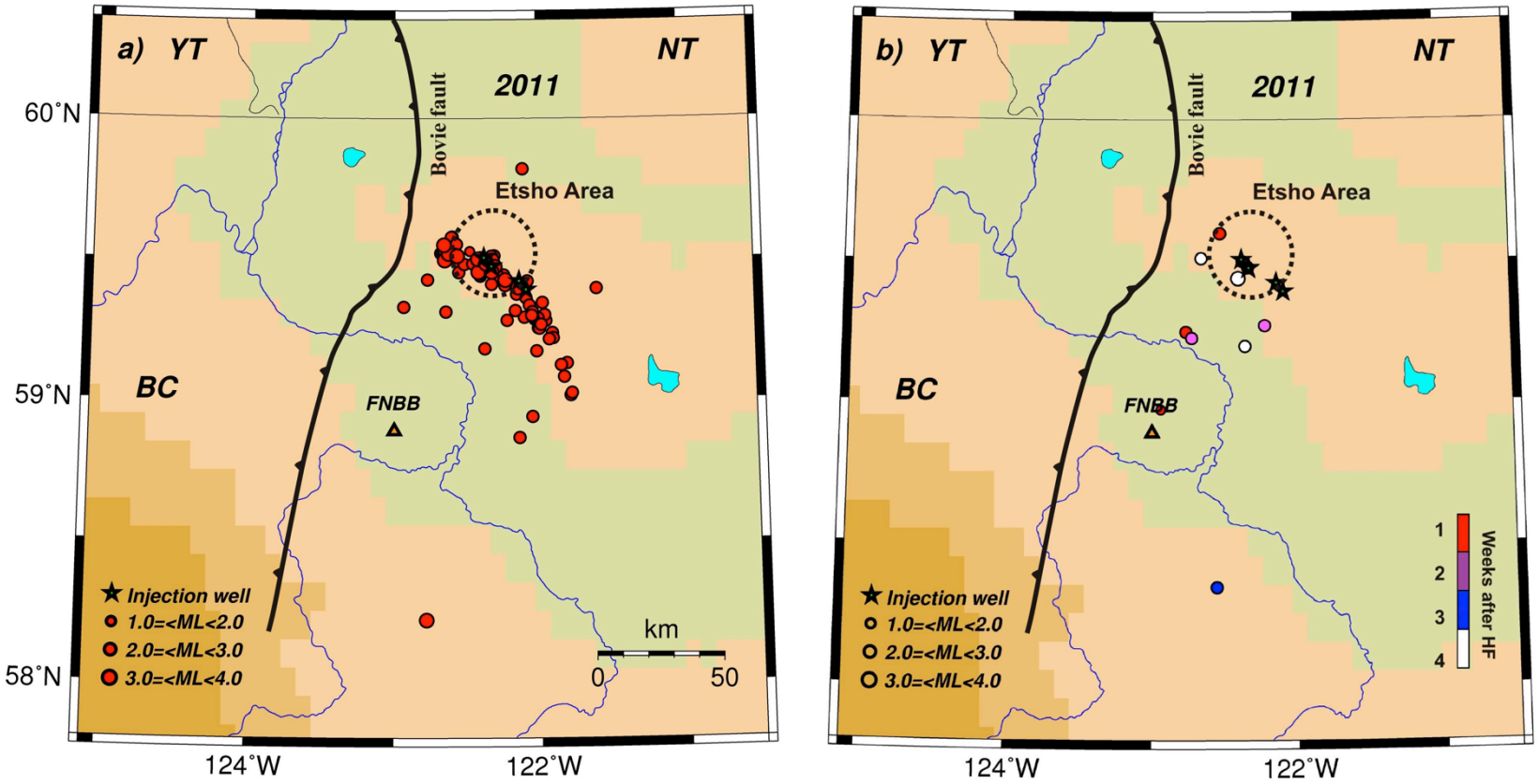
Limited HF (2008)



- 63 events with M_L in 1.0 – 3.0
- 33 events during 52 HF days, vast majority close to the HF wells.
- 30 during non-HF days, some close to the HF wells.
- Most non-HF events occurred within 4 weeks of the last HF operation.

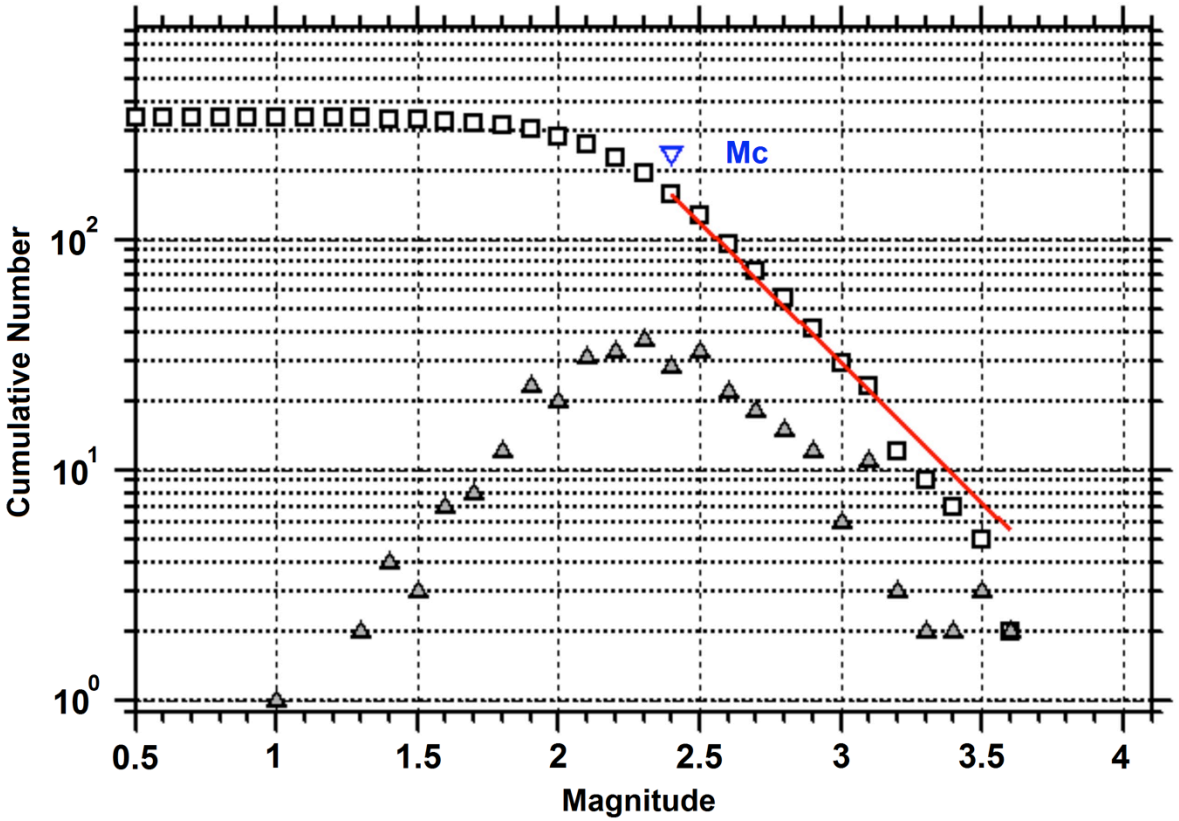
Seismicity After Shale Gas Development

Peak HF (2011)



- 131 events with M_L in 1.4 – 3.6
- 119 events during 310 HF days, majority close to the HF wells.
- 12 during non-HF days, 7 within 50 km from the HF wells.

Frequency – Magnitude Relationship for Earthquakes in the HRB, NE BC

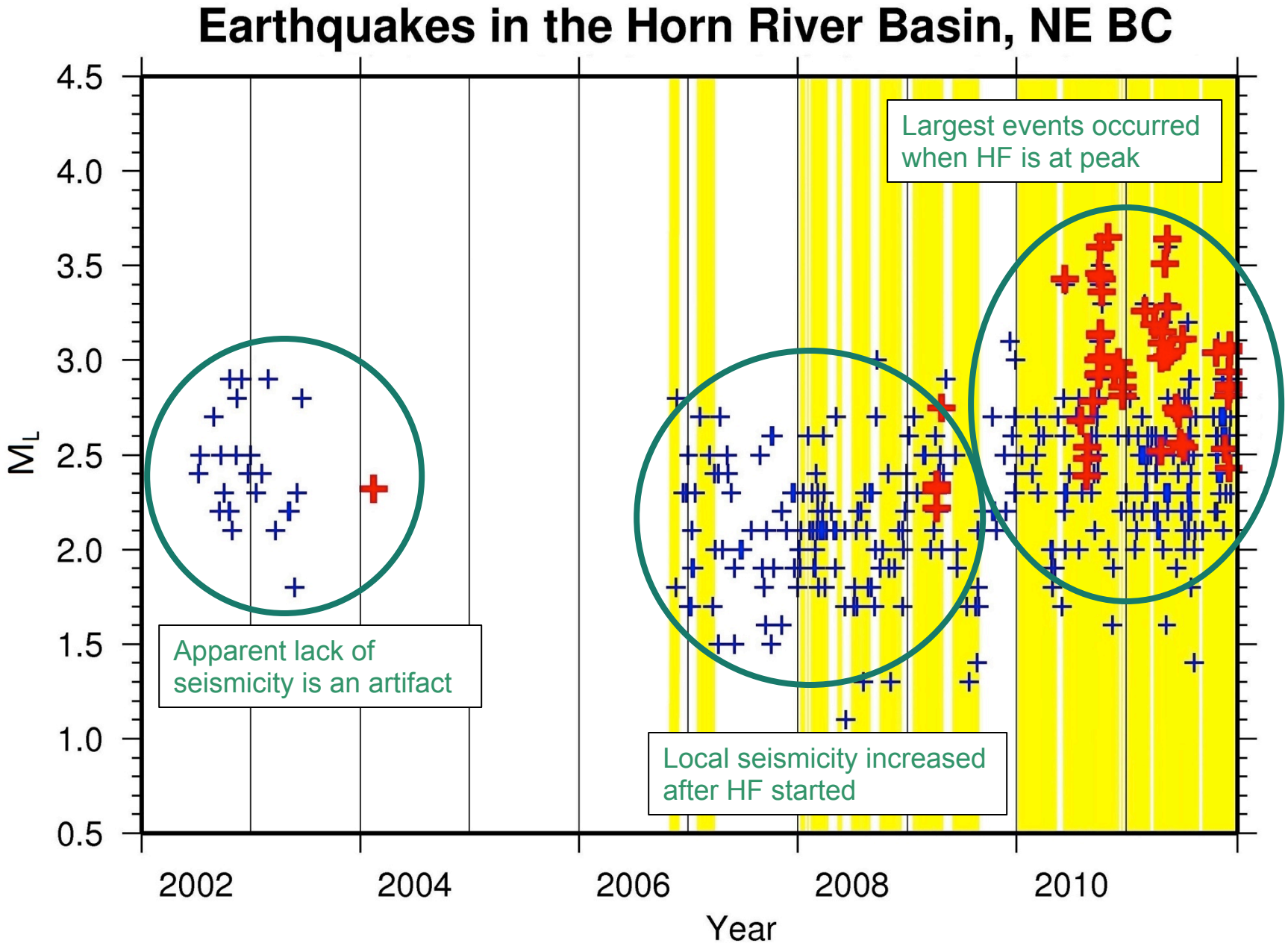


Maximum Likelihood Solution

b-value = 1.21 +/- 0.08, a value = 5.11, a value (annual) = 4.41

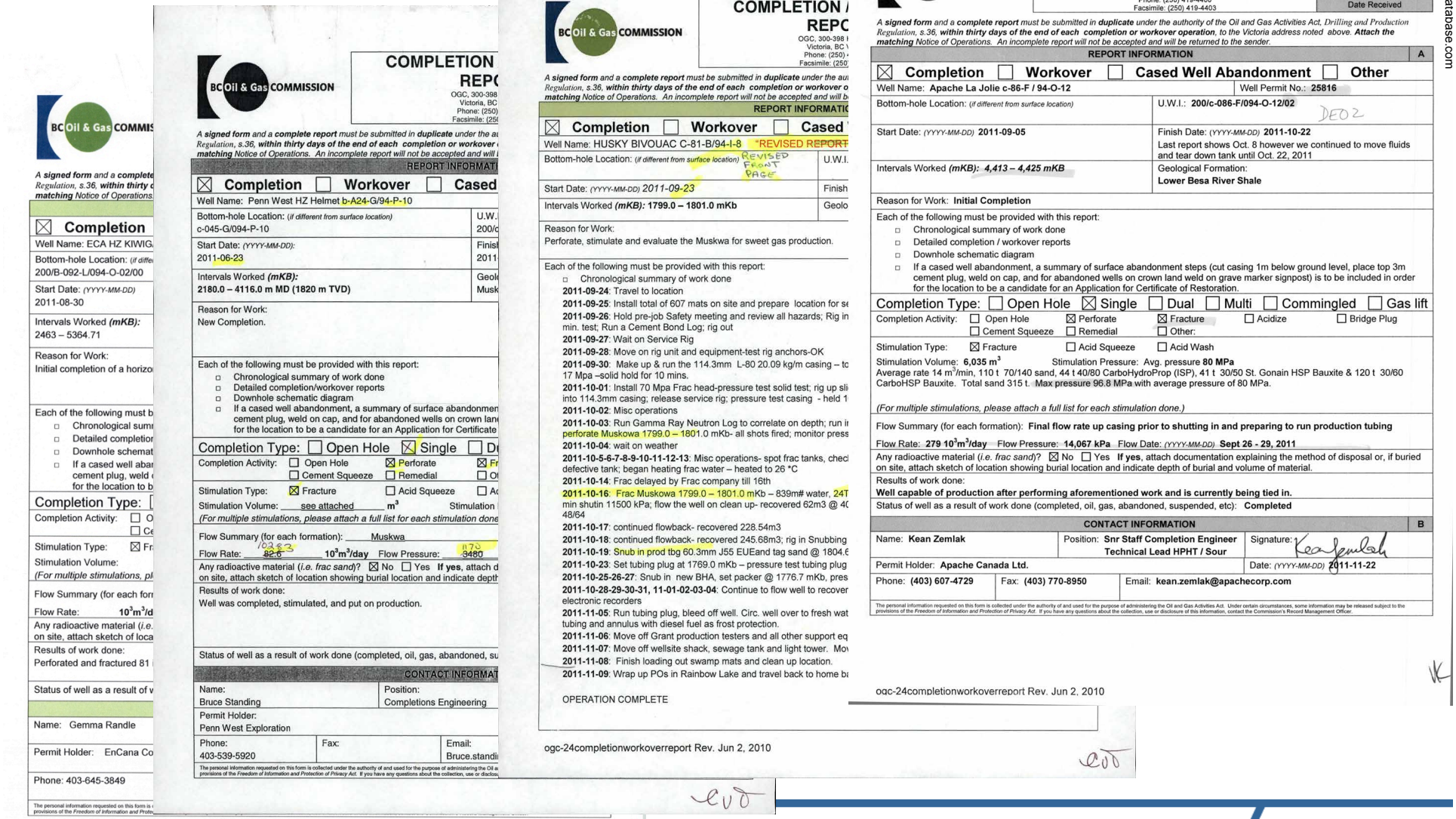
Magnitude of Completeness = 2.4

- Based on our catalog of 367 local events
- Higher than the average value of tectonic/natural earthquakes (~1)
- But lower than the typical value of HF-induced events (~2)
- Suggest that at least some of the observed events are related to local HF operations



Farahbod et al. (2014, 2015a)

HF Completion Reports Filed by Operators



BC Oil & Gas COMMISSION

COMPLETION / WORKOVER REPORT

OGC, 300-398 Harbour Rd
Victoria, BC V9A 0B7
Phone: (250) 419-4400
Facsimile: (250) 419-4403

Date Received

*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 Regulation, 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.*

REPORT INFORMATION — A

☒ Completion ☐ Workover ☐ Cased Well Abandonment ☐ Other

Well Name: **Apache La Jolie c-86-F / 94-O-12** | Well Permit No.: **25816**

Bottom-hole Location: *(if different from surface location)* | U.W.I.: **200/c-086-F/094-O-12/02**

Start Date: *(YYYY-MM-DD)* **2011-09-05** | Finish Date: *(YYYY-MM-DD)* **2011-10-22**
Last report shows Oct. 8 however we continued to move fluids and tear down tank until Oct. 22, 2011

Intervals Worked ***(mKB): 4,413 – 4,425 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 Restoration.

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 t 70/140 sand, 44 t 40/80 CarboHydroProp (ISP), 41 t 30/50 St. Gonain HSP Bauxite & 120 t 30/60 CarboHSP Bauxite. Total sand 315 t. Max pressure 96.8 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 10³m³/day** Flow Pressure: **14,067 kPa** Flow Date: *(YYYY-MM-DD)* **Sept 26 - 29, 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 — B

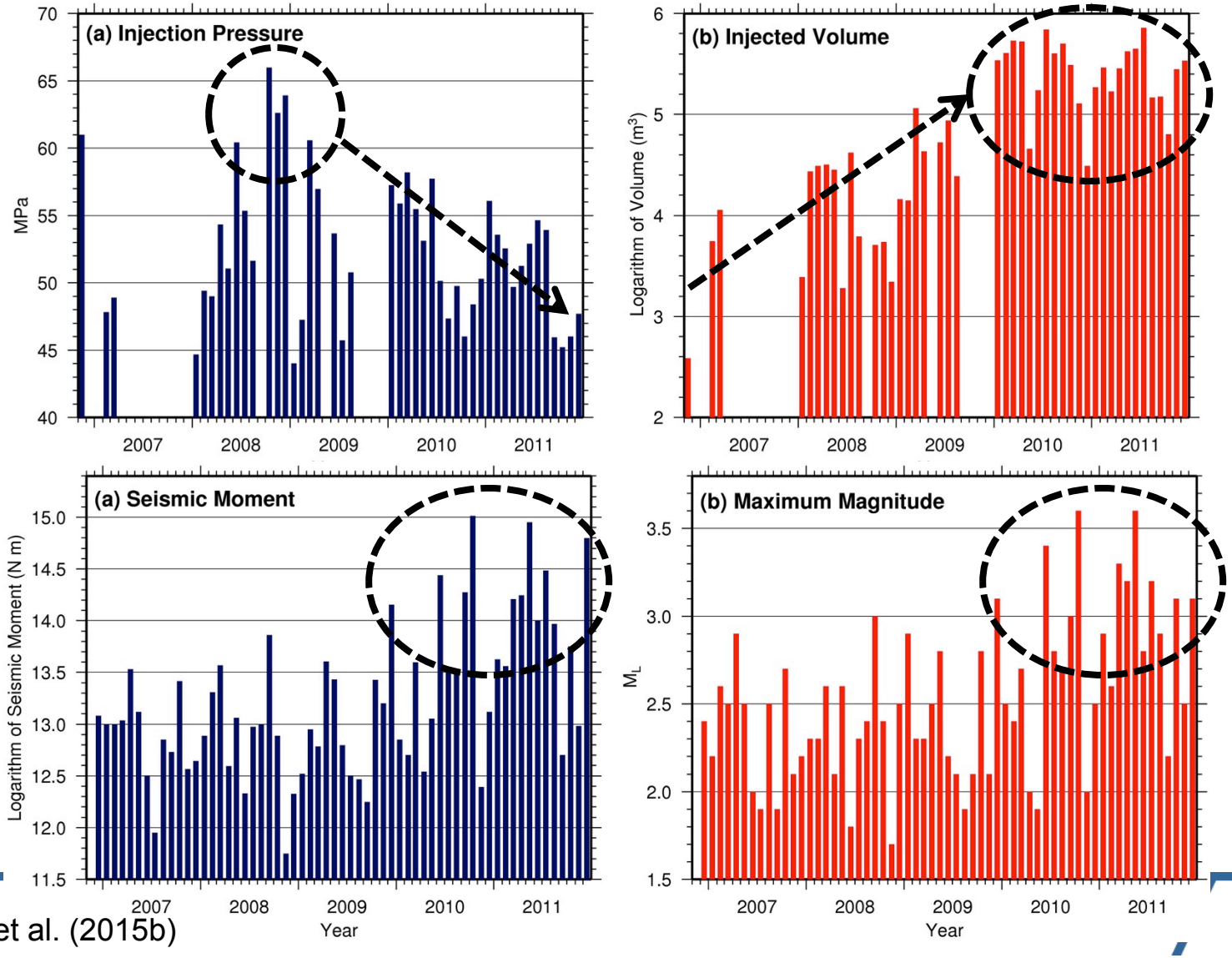
Name: **Kean Zemlak**	Position: **Snr Staff Completion Engineer / Technical Lead HPHT / Sour**	Signature: Kean Zemlak
Permit Holder: **Apache Canada Ltd.**		Date: *(YYYY-MM-DD)* **2011-11-22**
Phone: **(403) 607-4729**	Fax: **(403) 770-8950**	Email: **kean.zemlak@apachecorp.com**

The personal information requested on this form is collected under the authority of and used for the purpose of administering the Oil and Gas Activities Act. Under certain circumstances, some information may be released subject to the provisions of the *Freedom of Information and Protection of Privacy Act*. If you have any questions about the collection, use or disclosure of this information, contact the Commission's Record Management Officer.

ogc-24completionworkoverreport Rev. Jun 2, 2010

www.fracdatabase.com

HF Operations and Seismicity

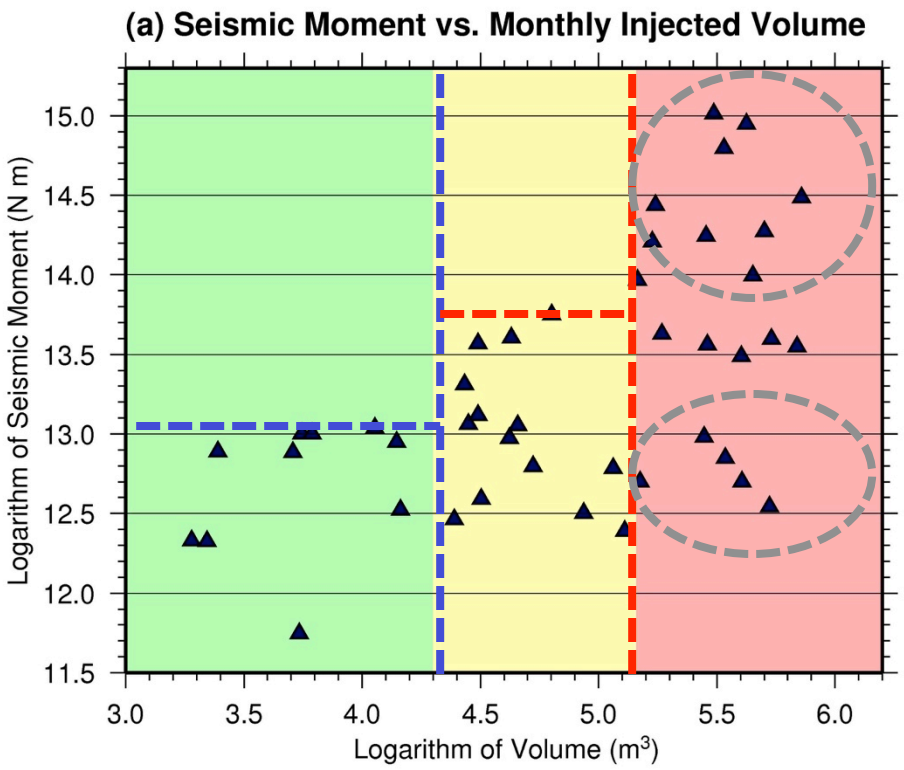


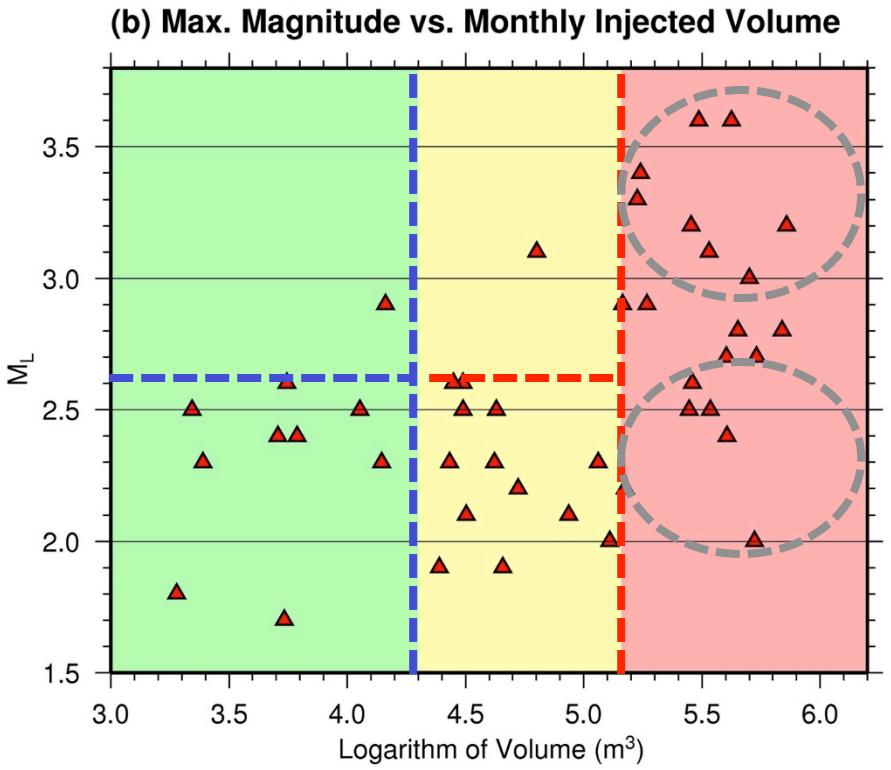
Farahbod et al. (2015b)

Injected Volume vs. Seismicity

~150K m^3/month

~150K m^3/month





~20K m^3/month

~20K m^3/month

Farahbod et al. (2015b)

Implications to Unconventional Gas and Oil Production in Canada

Roughly only 1% of wastewater disposal wells and 0.5% of HF wells in WCSB are associated with *M* 3+ induced earthquakes

Responsible Development

with a balanced approach
between maximizing economic benefit
and
protection of environment and public safety

Toward a Responsible Development

(from the perspective of induced seismicity)

1. Know the overall background seismic level before development (i.e., each region's baseline).

2. For a given region, determine the tolerance level of the geological system (i.e., up to increased number 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 sustainable production (i.e., theoretical max. magnitude of induced events and/or injected volume).

Implication to Shale Gas Production:
Region-dependent Regulations

1. Different regions have different “tolerance” levels.

2. For regions with little tolerance, development should be closely monitored and regulated. Installation of seismometers on site should be mandatory.

3. For regions with high tolerance, a larger scale of development could be allowed. But it must be monitored by regional seismograph network.

Major Collaborators

Internal:

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BC Oil and Gas Commission

Alberta Energy Regulator

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