Hazards from Induced Seismicity: Crooked Lake Case Study

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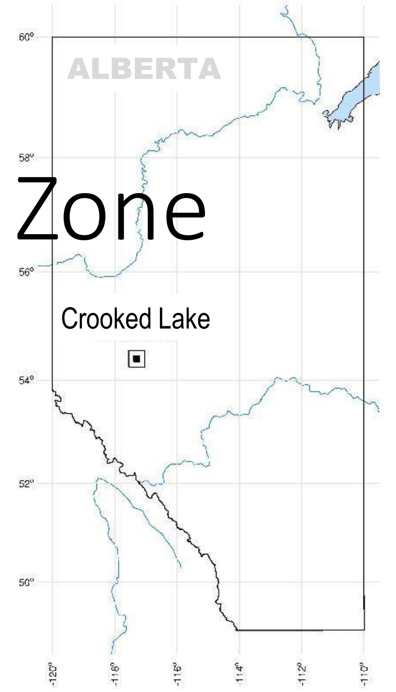
Hydraulic Fracturing in Western Canada

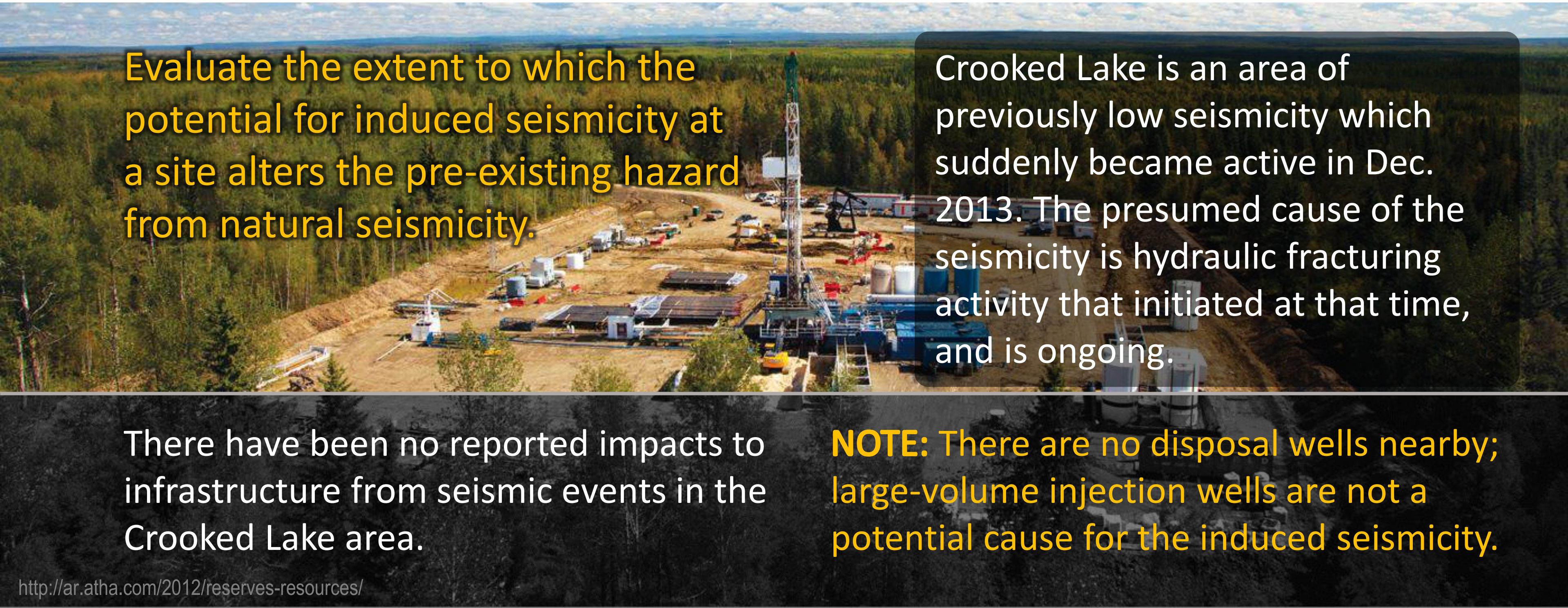
- Since about 2008, tight oil and gas reservoirs in western Canada have increasingly been developed with multi-stage hydraulic fracturing of horizontal wells.
- Hydraulic fracturing in western Canada has in some instances been associated with significant induced seismicity
- A series of earthquakes, the largest being **M**3.8, were triggered by hydraulic fracturing in the Horn River Basin of northeastern B.C. (B.C. Oil and Gas, 2012).
- In the last few years, several sequences of seismicity at the **M**>3 level have been induced by hydraulic fracturing in western Alberta and northeastern B.C. (Atkinson et al., 2015), with the largest events to date being just over **M**4.
- In December of 2013, the seismicity rate at Crooked Lake (*Fox Creek*) changed dramatically when a sequence of events of **M**>3 was apparently initiated by hydraulic fracturing.

Crooked Lake: New Seismic Source Zone

There were dozens of events of **M**>2 in 2013/2014, with several of **M**>3.

In January 2015, there were an additional 24 events of **M**≥2 in the same area, six of which had **M**>3. The largest event, which occurred Jan. 23, 2015, had an estimated **M**=3.9 (Novakovik and Atkinson, 2015; ML=4.4).





Evaluate the extent to which the potential for induced seismicity at a site alters the pre-existing hazard from natural seismicity.

Crooked Lake is an area of previously low seismicity which suddenly became active in Dec. 2013. The presumed cause of the seismicity is hydraulic fracturing activity that initiated at that time, and is ongoing.

There have been no reported impacts to infrastructure from seismic events in the Crooked Lake area.

NOTE: There are no disposal wells nearby; large-volume injection wells are not a potential cause for the induced seismicity.

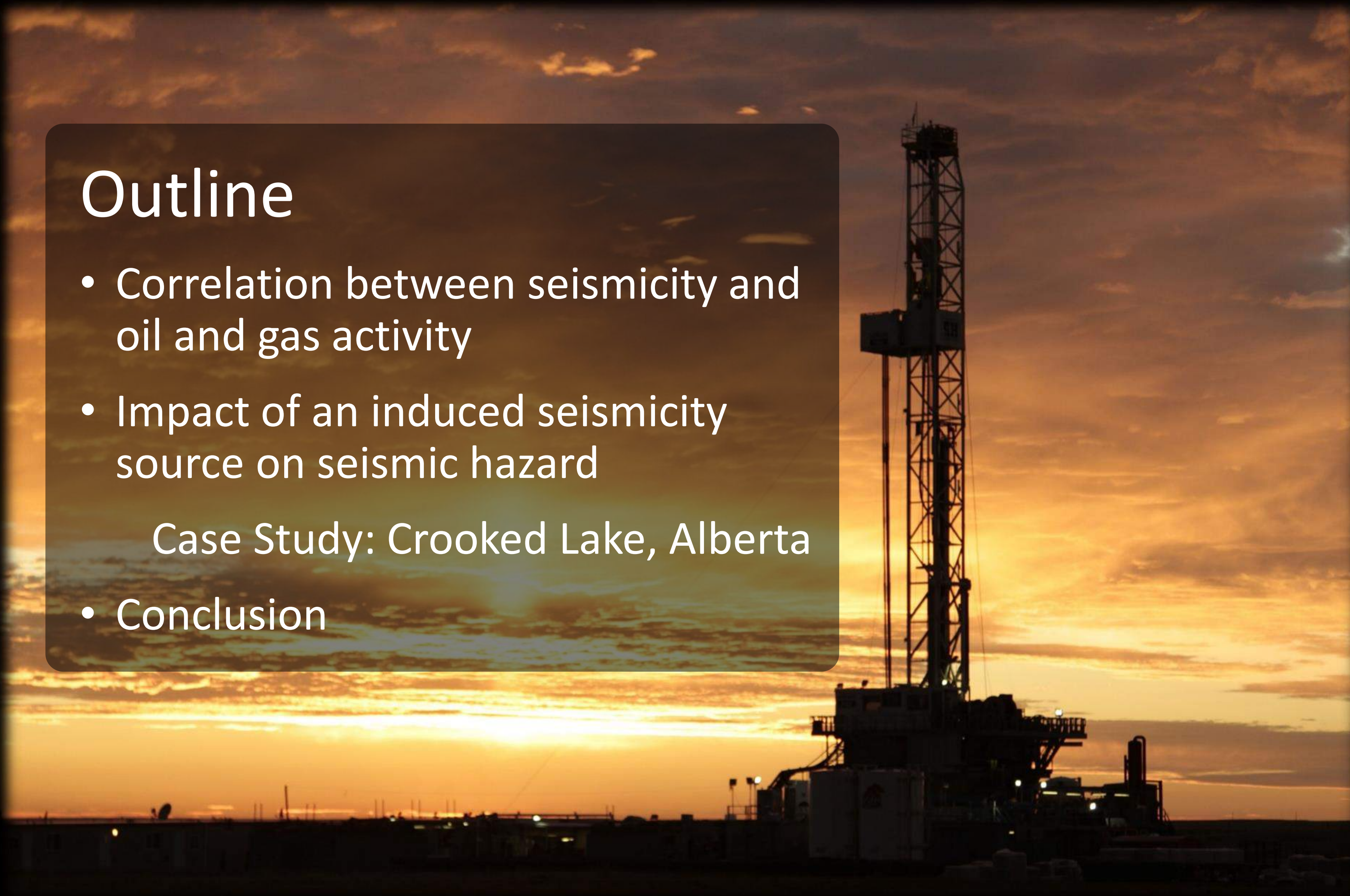
http://ar.atha.com/2012/reserves-resources/

Outline

- Correlation between seismicity and oil and gas activity
- Impact of an induced seismicity source on seismic hazard

  Case Study: Crooked Lake, Alberta

- Conclusion



Marathon Oil entered the Niobrara's Denver/Julesburg basin in 2010. The emerging Niobrara is described as having tight, layered chalk and marlstone with some natural fracturing, where hydraulic fracturing methods can be applied. Pictured is an H&P FlexRig. Photo courtesy of Bruce Kelsch, Marathon Oil

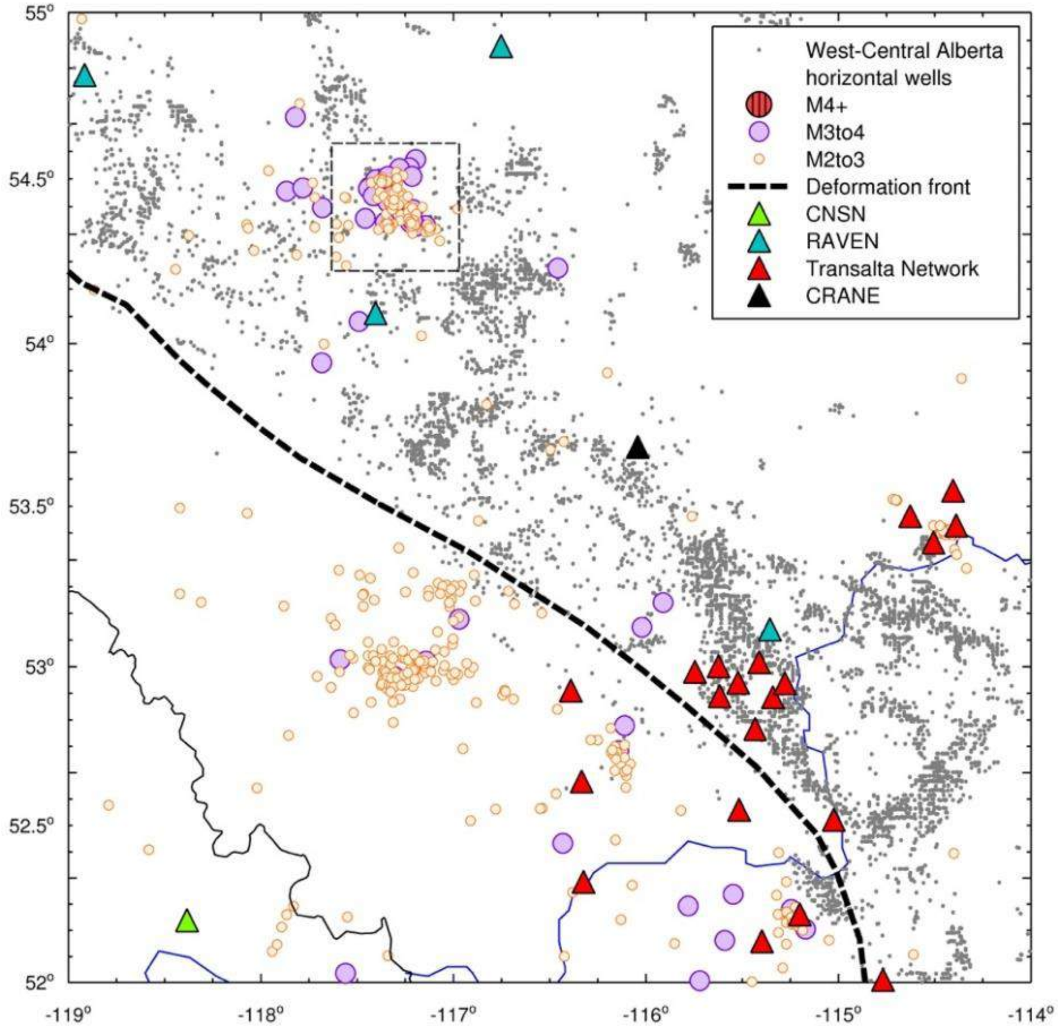
Seismicity in Alberta

- Catalogue information (**M**, location) obtained from the TransAlta/Nanometrics seismographic network, installed in 2014 in connection with the Canadian Induced Seismicity Collaboration at Western University: www.inducedseismicity.ca
- Information on HF wells comes from the public records of the *Alberta Energy Regulator* (AER)

CNSN: Canadian National Seismic Network

RAVEN: Regional Alberta Seismic Observatory for Earthquake Studies Network

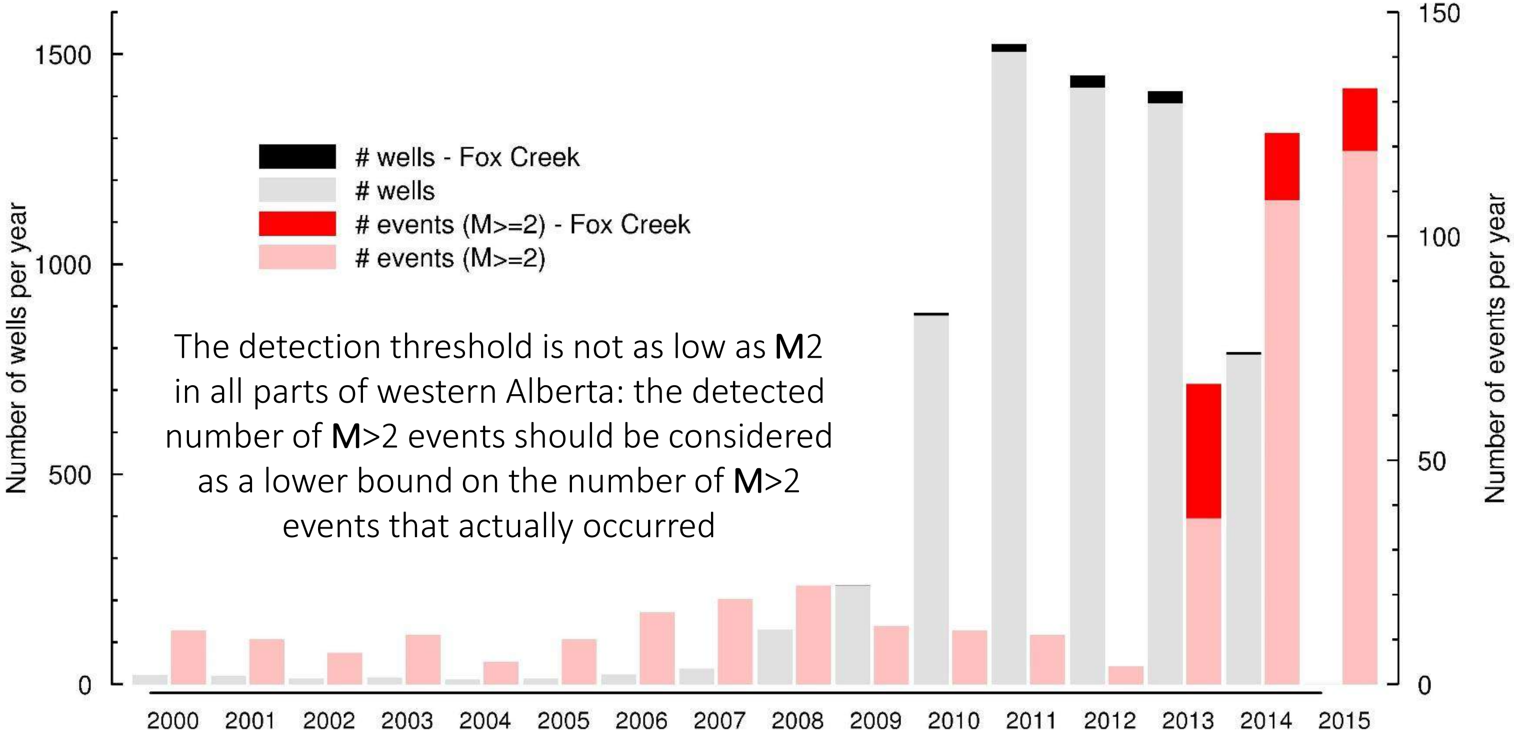
CRANE: Canadian Rockies and Alberta Network



Seismicity in Alberta of **M**>2 since 2007. Events are colour-coded based on their moment magnitude. Triangles: seismic stations from different networks. Grey dots: the location of hydraulically-fractured (HF) wells.

Seismicity in Alberta

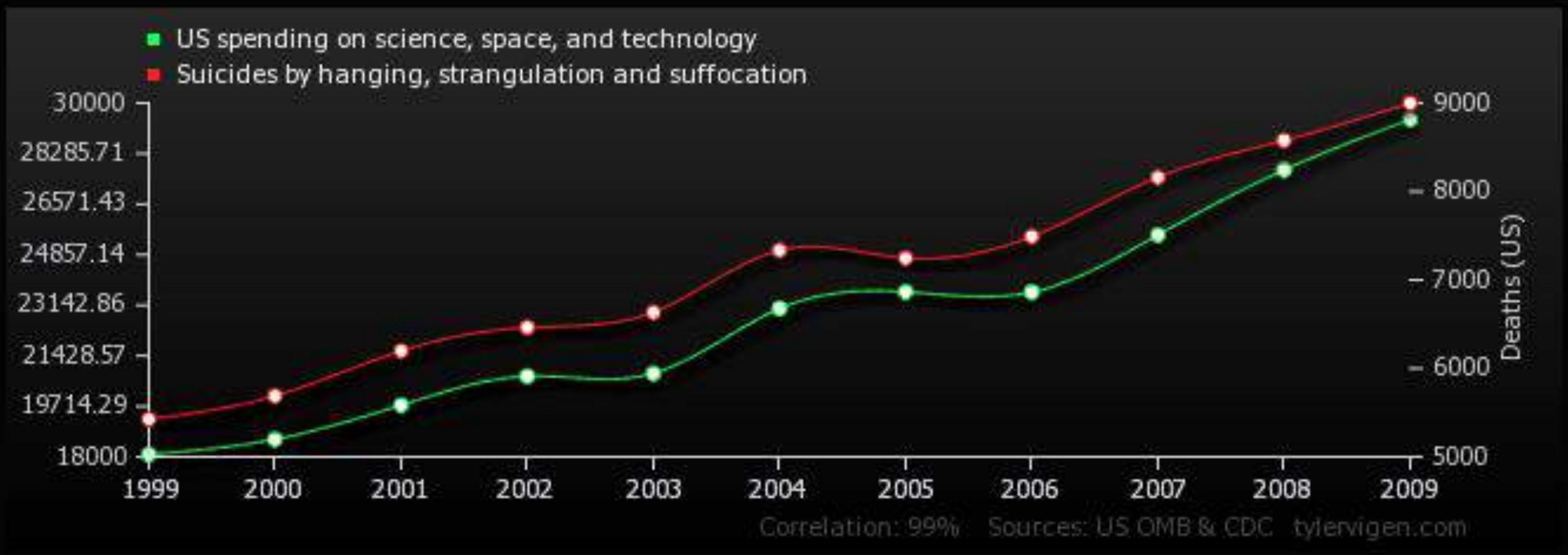
A small number of HF wells appears to be associated with a relatively large number of earthquakes



Number of seismic events of **M**>2 in comparison to the number of wells in Alberta; the Crooked Lake (Fox Creek) contributions are shown at the top of each bar.

"Correlation Isn't Causation"

- The simple fact that both the number of HF wells and the number of earthquakes are increasing in time does not suggest any causal relationship. If the HF wells are inducing earthquakes, they must precede the earthquakes in time, and be closely related in space.



OMB: Office of Management and Budget
CDC: Centers for Disease Control and Prevention

Spatial Correlation between Earthquakes and Wells

- Scanning the well database from AER: count the number of HF wells with earthquakes of **M**>2, **M**>3, and **M**>4 within a 20 km radius.
- The 20 km criterion for potential spatial correlation was chosen as an upper bound on the likely correlation distance considering a number of factors:

    i. the location uncertainty in events is typically 10 km in most areas, and sometimes larger (until very recently) as evidenced by differences in event locations quoted by different agencies (AGS, GSC) for the same events;

    ii. events might be induced at distances up to a few km from the causative well, as the fluid pressures diffuse along local faults and fractures;

    iii. the HF wells may be several km in lateral extent.

Temporal Correlation between Earthquakes and Wells

- There is a potential temporal correlation if the event occurred within a window beginning with the date drilling was completed and ending ~1 month after the "on production" date.
- Previous studies suggested that triggered earthquakes usually occur either during or hours after hydraulic fracturing begins (Holland, 2011; BCOGC, 2012) but this appears to be changing.
- In particular, in Crooked Lake some of the larger events have occurred during flowback operations after the completion of hydraulic fracturing (Schultz et al., 2015).

Rates of Induced Seismicity from Hydraulic Fracturing

- Applying the above criteria (space and time) suggests that the rate of induced events at the **M**>3 level *may* be of the order of 1/100 to 1/1000 in the region as a whole, and higher at Crooked Lake. (Note: causality not firmly established)

The count is incomplete at the **M**2 level due to the sparse station coverage.

Of the 7102 total wells, 397 wells are not considered since the "on production" dates are not reported.

Well data are not complete for 2014; may be missing some wells that are potentially correlated with seismicity in 2014.

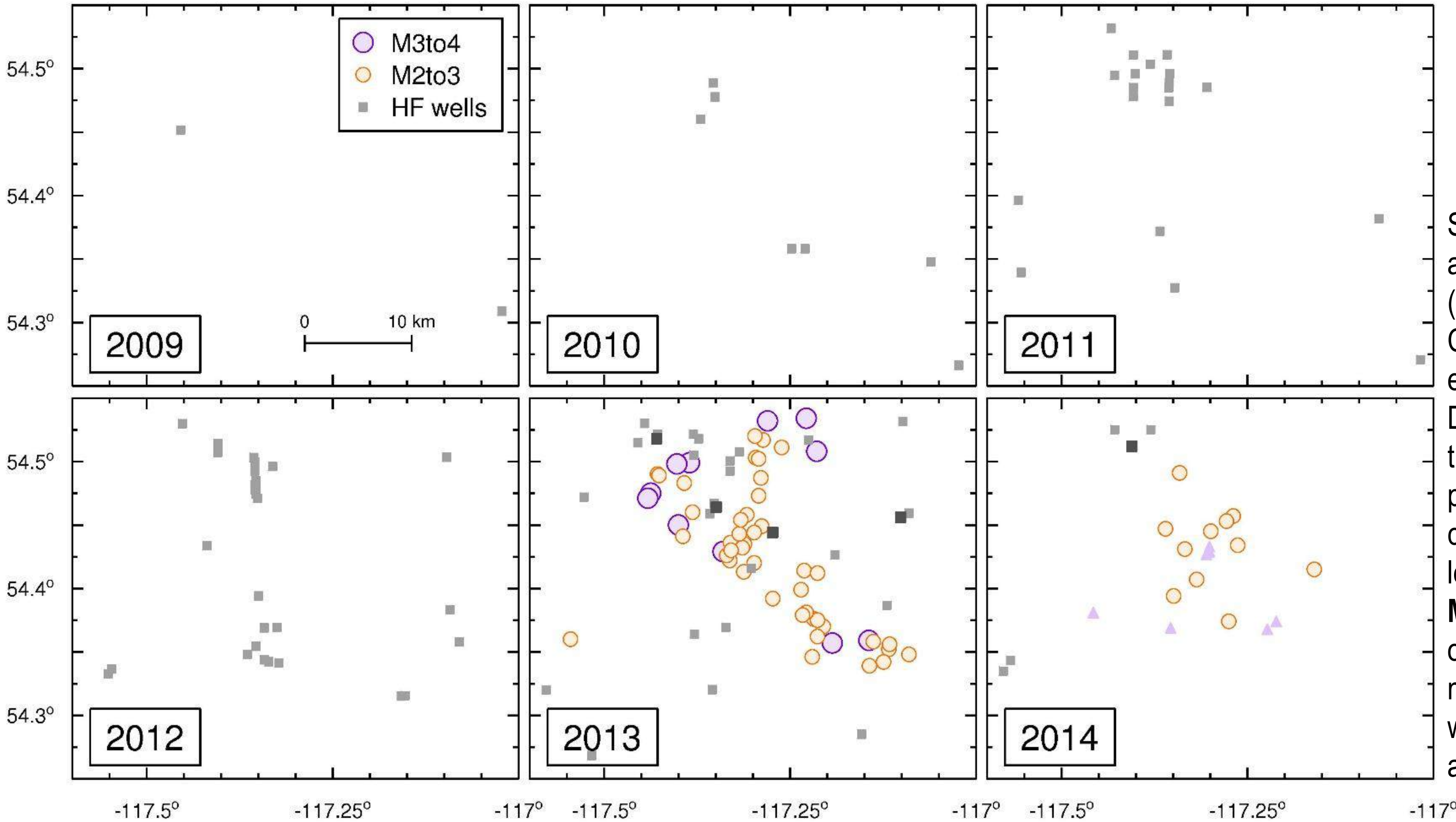
The number of wells that meet both the spatial and temporal correlation criteria, at each magnitude level

Year	M>=2	M>=3	M>=4	Whole region # wells fracked/yr	M>=2	M>=3	M>=4	Crooked Lake # wells fracked/yr
2006	0	0	0	25	0	0	0	0
2007	1	0	0	39	0	0	0	0
2008	1	0	0	131	0	0	0	0
2009	3	1	0	237	0	0	0	2
2010	6	1	0	903	0	0	0	7
2011	8	2	0	1526	0	0	0	19
2012	6	3	0	1436	0	0	0	29
2013	82	16	0	1402	4	3	0	28
2014	73	3	0	797	1	0	0	5

NOTE: There are no disposal wells or other suspected sources of induced seismicity in this area.

Rates of Induced Seismicity from Hydraulic Fracturing – Crooked Lake

- Before 2012, no detected seismic events in the area. From 2009 to 2012, over 100 wells were hydraulically fractured with no associated seismicity. In 2013 there was an abrupt acceleration of induced events. About 1/10 to 1/100 wells in this area appears to trigger significant seismicity. In western Alberta as a whole this rate appears to be an order of magnitude lower.



Seismicity (circles) and HF wells (squares) in the Crooked Lake area in each year since 2009. Darker squares: wells that satisfy the potential correlation criteria at the **M**>2 level. The triangles: **M**>3 events that have occurred in the first 3 months of 2015 (no well information yet available for 2015).

Seismic Hazard Analysis Methodology

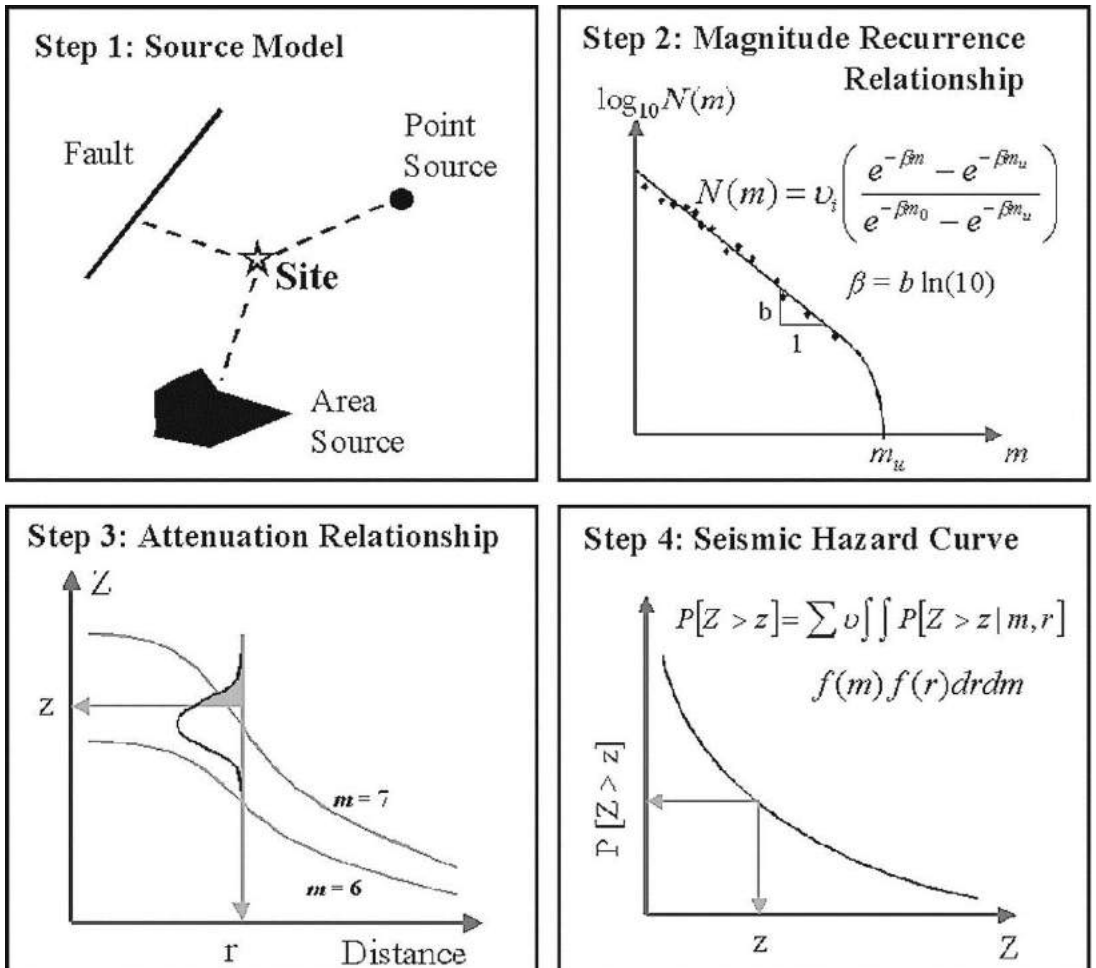
Using a classic PSHA, with the EQHAZ software (Assatourians and Atkinson, 2013)

1. Identify the potential sources of future earthquakes (seismic source zones).

2. Calculate the frequency of earthquakes of different magnitude occur within each source.

3. Define ground-motion prediction equations: amplitude as a function of magnitude, distance, ….

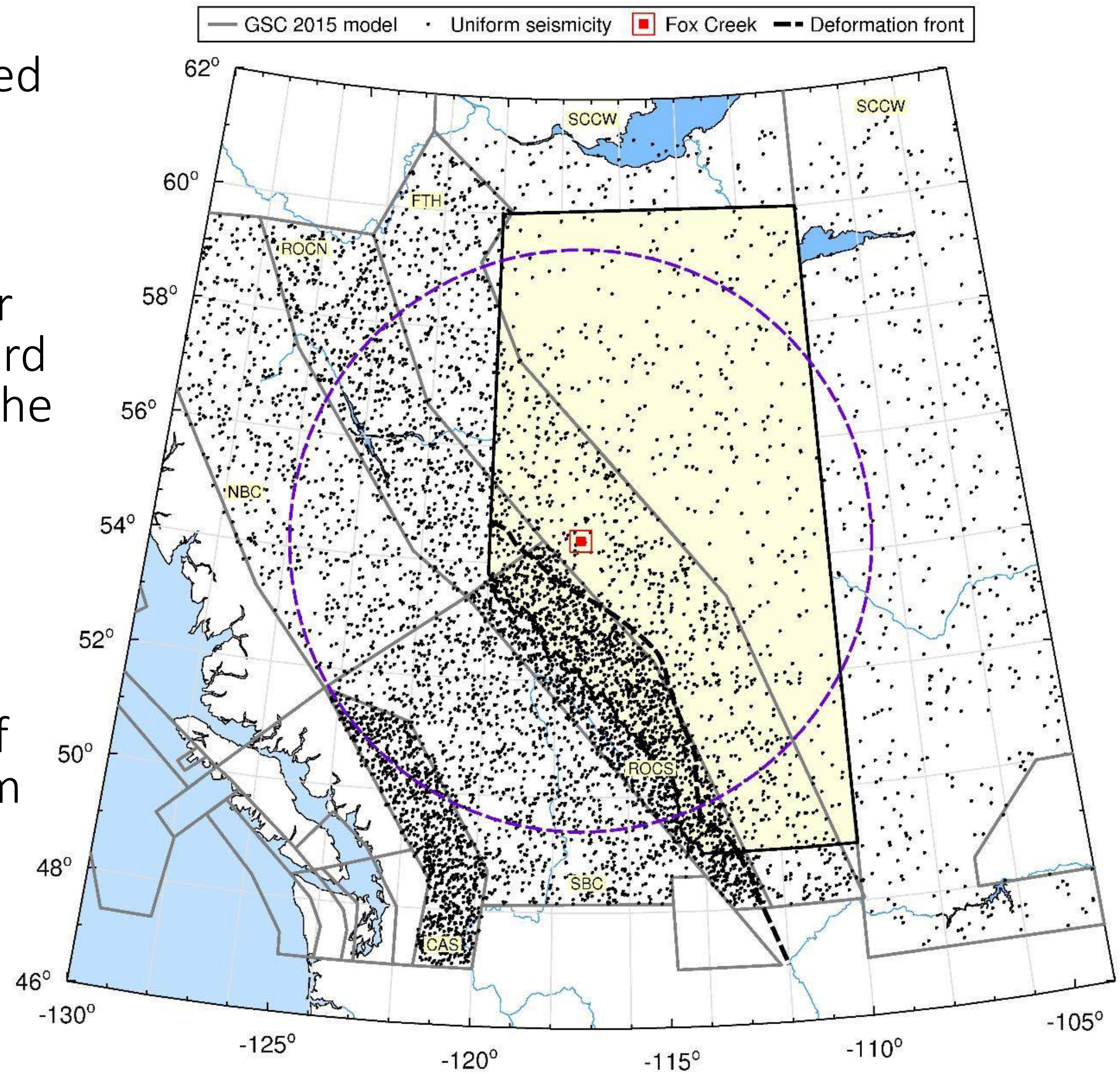
4. Calculated the hazard by integration.



Steps involved in the conventional Cornell-McGuire probabilistic seismic hazard assessment (PSHA) (after Reiter, 1990).

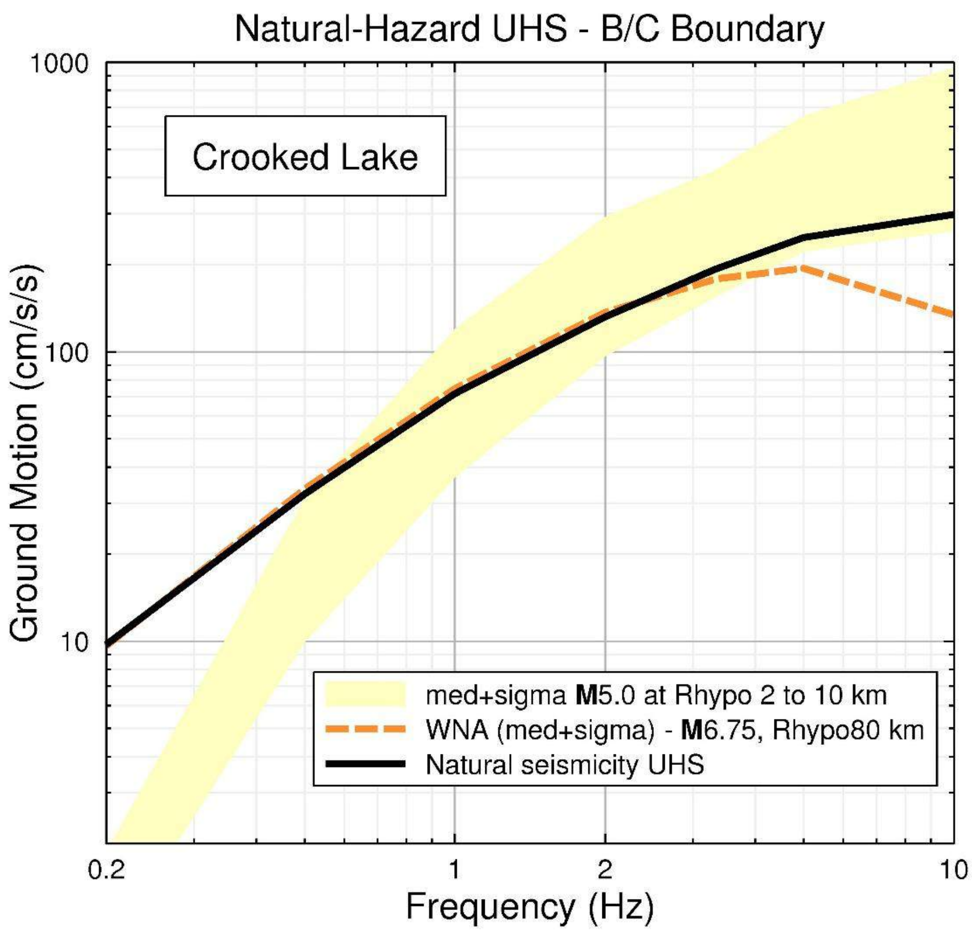
Seismic Hazard at Crooked Lake from Natural Sources

- Consider a site near Crooked Lake
- First calculate natural seismicity hazard to 2013, according to GSC model for 2015 national seismic hazard maps; the benchmark for the hazard prior to the commencement of the induced seismicity near Crooked Lake
- The baseline model from GSC does not reflect any of the induced seismicity from 2013 to the present



Natural-Hazard Uniform Hazard Spectrum (UHS)

- The UHS plots the mean-hazard values of the response spectrum (5% damped pseudo-spectral acceleration, horizontal component, on B/C site conditions) for a probability of exceedance of 1/10,000 per annum (p.a.).
- The 1/10,000 motions from the natural-seismicity hazard are similar to those expected from events of **M**~6.75 at distances ~80 km. By comparison, moderate events (**M**~5) at close distances may cause stronger motions than these scenarios at high frequencies, but much weaker motions at low frequencies (<1 Hz).



The UHS for Crooked Lake at 1/10,000 p.a. as of 2013 due to natural seismicity. Expected motions (medium GMPE plus sigma) for several scenario events are shown for comparison: **M**6.75 at 80 km (hypocentral distance), and **M**5.0 at 2 to 10 km.

Effect of induced seismicity from hydraulic fracture treatments beneath or immediately adjacent to site

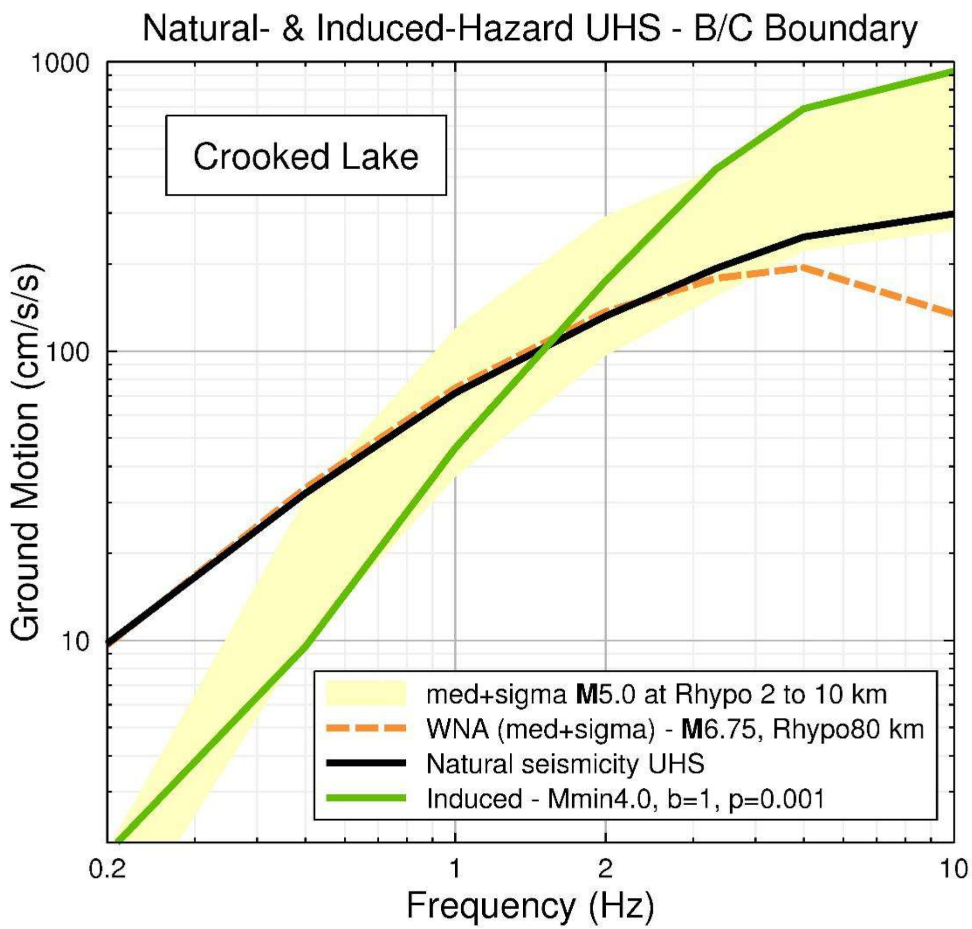
- Add small new seismic source (about 10km x 10km) having the seismicity parameters observed for the Crooked Lake sequence;
- Assume about 10 events of **M**>3 per annum;
- Uncertain *b*-value and maximum magnitude;
- Ground motion prediction equations according to Atkinson, 2015 small-**M** model, with significant uncertainty in median GMPE.

IMPORTANT

The results will apply only to sites in very close proximity (within a few km) to such operations

Induced-Hazard Uniform Hazard Spectrum

- The UHS that results from the potential induced seismicity from hydraulic fracturing.
- Moderate events (**M**~5) at close distances may cause stronger motions than The 1/10,000 motions from the natural-seismicity hazard at high frequencies, but much weaker motions at low frequencies (<1 Hz); these are the type of motions expected from potential induced seismicity sources.



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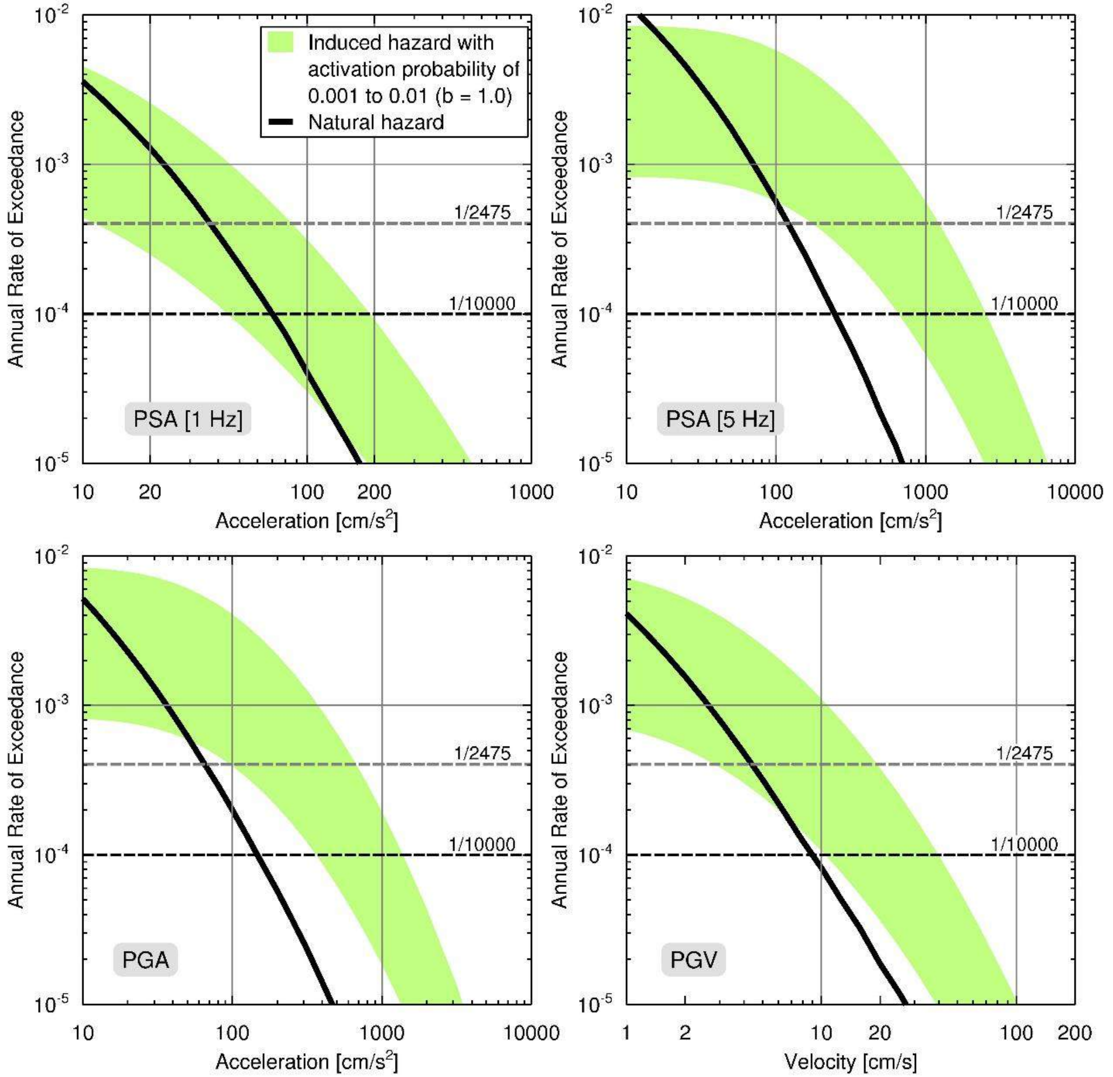
Induced- vs Natural-Seismicity Hazards

- The assumed rate of **M**≥3 events is effectively 0.01 to 0.1 on a per well basis (the product of the rate and the activation probability).
- The ground motions attributable to the induced-seismicity hazard clearly EXCEED those from the natural-seismicity hazard at all probability levels of interest.

CAUTION

This statement is heavily conditioned upon the fact that this region has a *low background level of natural seismicity*.



Induced-seismicity hazard curves at Crooked Lake showing effect of activation probability in the range from 0.01 to 0.001 p.a., for an assumed rate of 10 **M**>3 p.a. with a *b*-value of 1. (Mmin=4.0, Mmax is a distribution from 4.5 to 6.5).

Conclusions

- For a reasonable range of input parameters to a PSHA, the seismic hazard from an induced-seismicity source representing hydraulic fracturing at close proximity can greatly exceed the hazard from natural seismicity, in settings where the natural hazard is low.
  - The induced seismicity source presents the potential for significant events at very close distances, which can cause large ground motions. This issue is particularly important for critical infrastructure, for which the target reliability levels are high.
- Further research is required to understand the parameters that control the hazard, and to develop approaches for hazard mitigation.