Induced Seismicity – Implications of non-stationary hazard

Gail Atkinson

Western University

With acknowledgment of my Induced Seismicity colleagues

Especially Hadi Ghofrani and Karen Assatourians

Western UNIVERSITY · CANADA

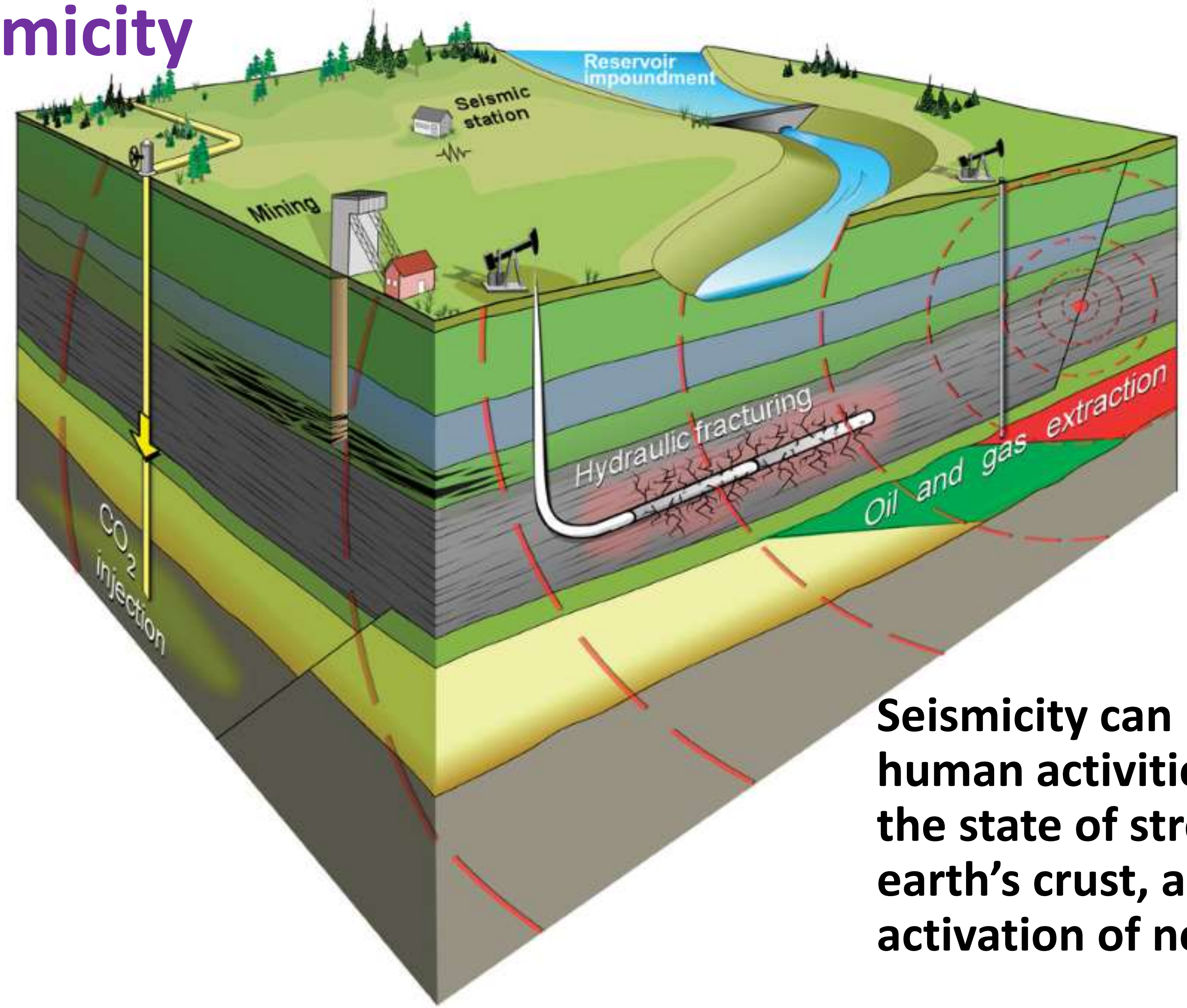
For more information: www.inducedseismicity.ca

Overview

- Induced Seismicity background
- Parameters that control induced seismicity hazard
- Induced Seismicity Hazard Assessments
  - Hindcasting versus forecasting hazard
  - Non-stationary characteristics of the hazard
- Recommendations and Conclusions

Induced Seismicity

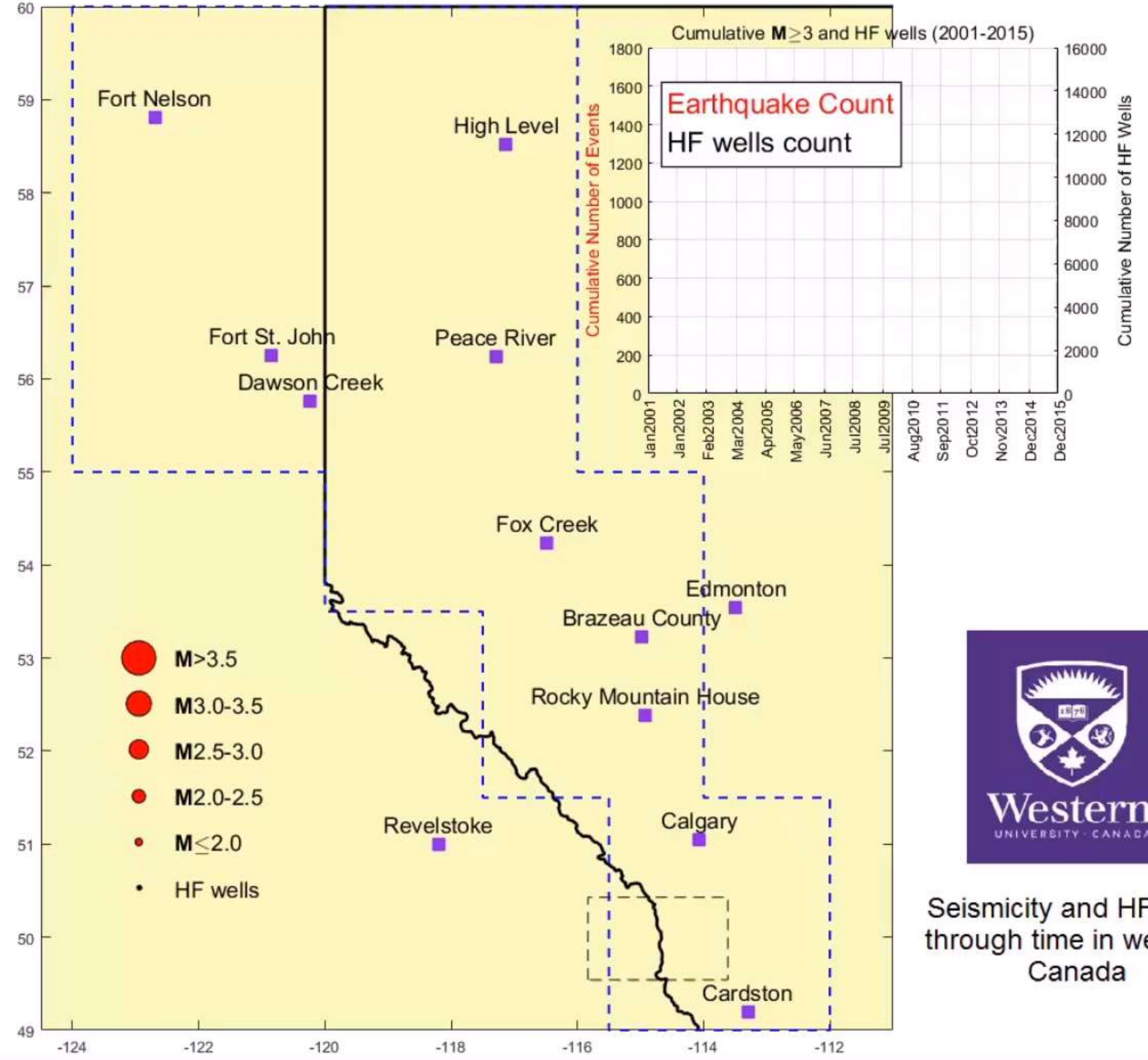
In the central US (Oklahoma), the primary driver of induced seismicity is wastewater disposal. In western Canada (western Alberta and eastern B.C.) it is hydraulic fracturing in long horizontal wellbores.



Seismicity can be induced by human activities that change the state of stress in the earth's crust, allowing re-activation of nearby faults

Figure 2. Potential sources of induced seismicity (reservoir impoundment, mining, oil and gas extraction, hydraulic fracturing, fluid or gas disposal or injection for enhanced oil recovery).

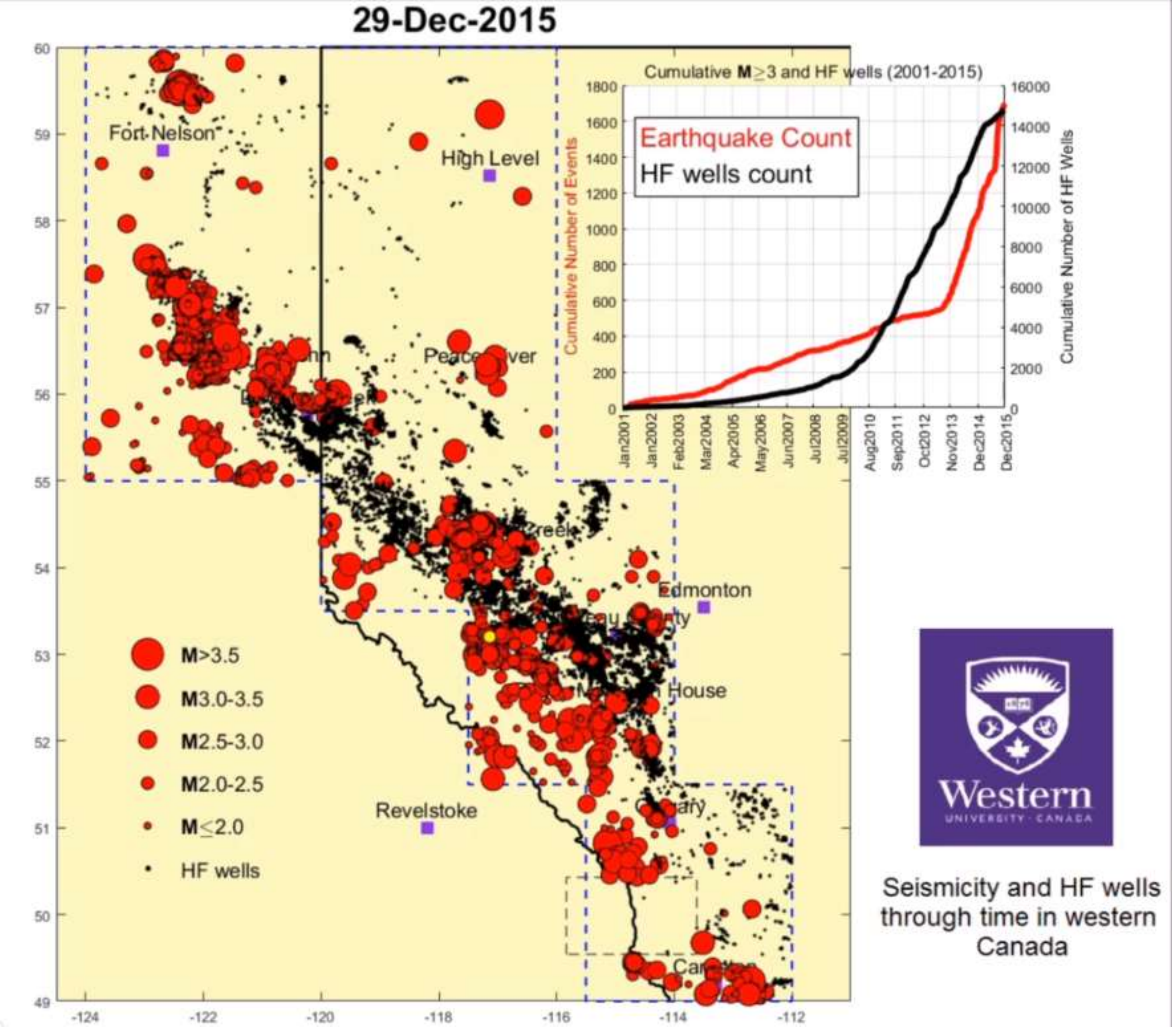
Credit: Hadi Ghofrani



Seismicity and HF wells through time in western Canada

Time-lapse video version:
www.inducedseismicity.ca/presentations/TimeLapseVideo

Credit: Hadi Ghofrani

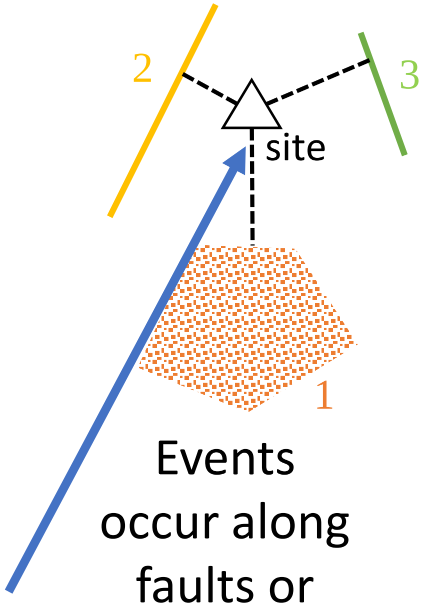


Seismicity and HF wells through time in western Canada

Assessing Earthquake Hazard
– same framework for induced and natural events

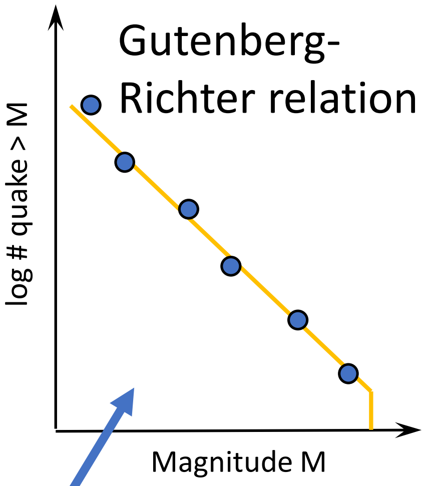
Buildings need to withstand motions that have a likelihood of 2% in 50 years.
Critical facilities (i.e. major dams) need to withstand motions that have a likelihood of less than 1/10,000 per year (1% in 100 years)

1 Where?
(Earthquake locations)



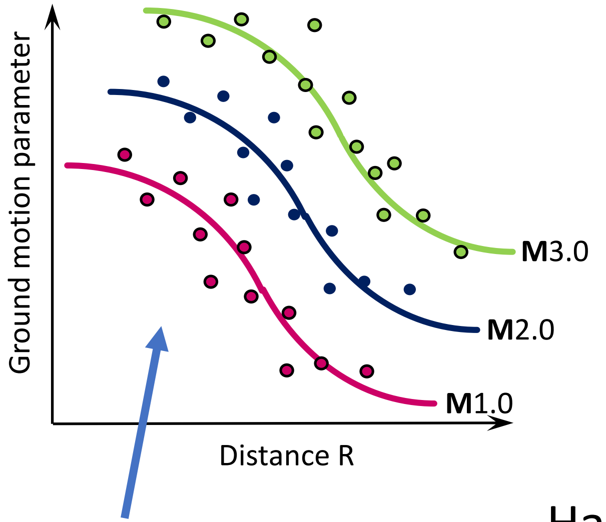
Events occur along faults or zones around a site

2 How often?
(Earthquake number, sizes, rates)



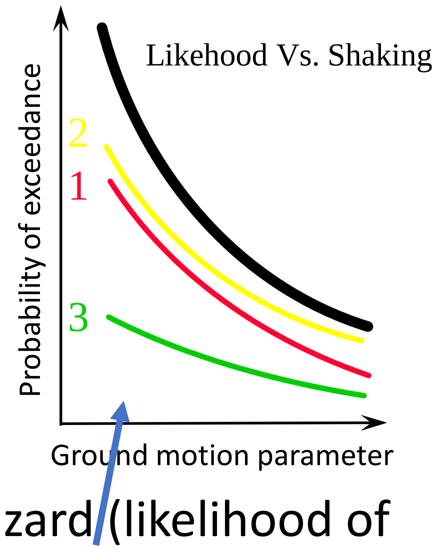
G-R relation measures earthquake size (magnitude) and rates in the zones

3 Ground motions
(Shaking vs distance relations)



Intensity of shaking depends on earthquake magnitude and distance

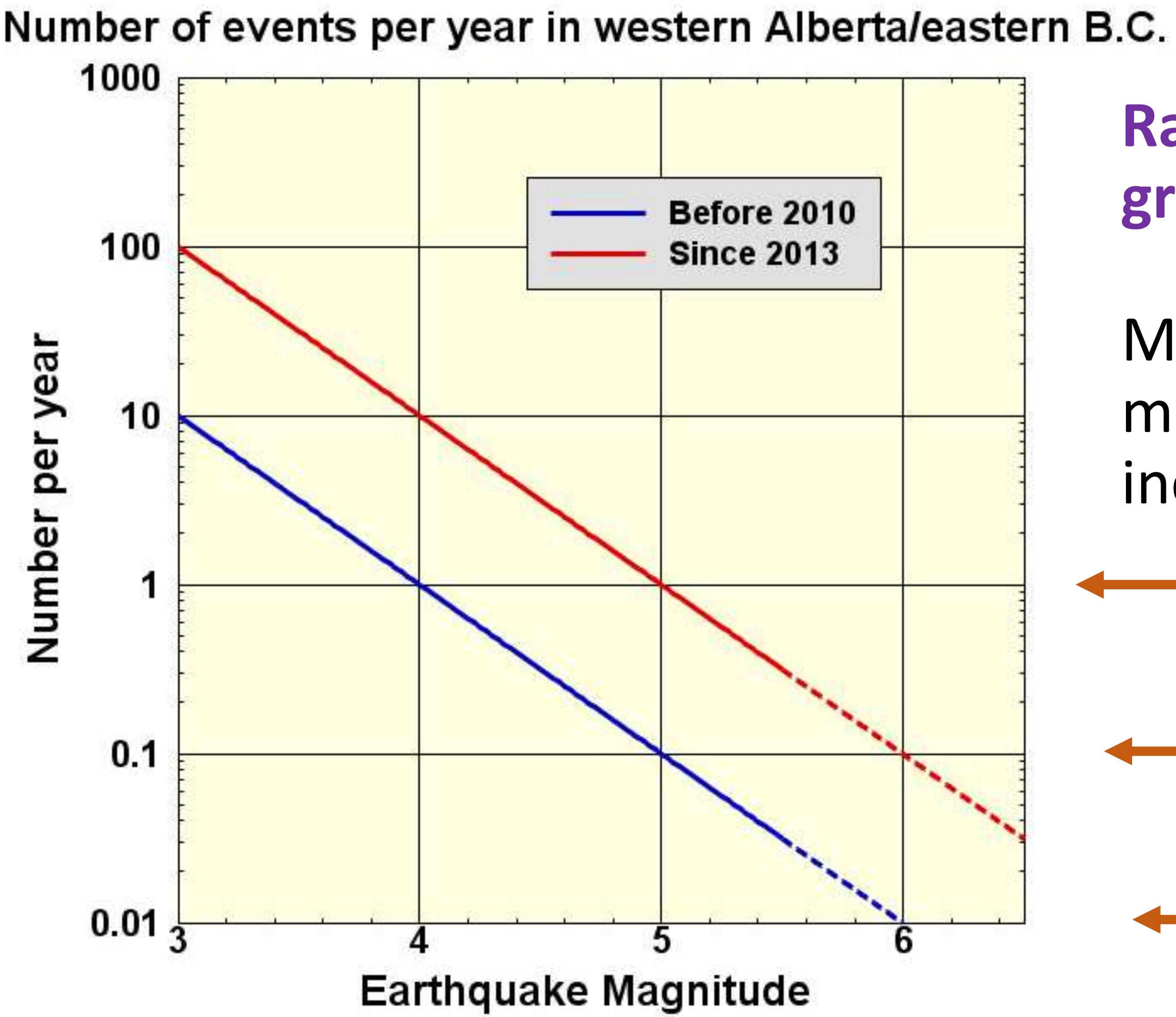
4 Hazard curve



Hazard (likelihood of strong shaking) calculated from location, size and rate of events

What parameters control the induced seismicity hazard?

- Rate of earthquakes (i.e. density of seismicity)
- Maximum magnitude of events….. But current consensus is that this is the same for induced and natural earthquakes – controlled by size of nearby faults that might be re-activated
  - Largest HF event to date is **M**5.7 (China)
  - Largest wastewater event to date is **M**5.7 (Oklahoma)
- Ground motions as a function of magnitude and distance



Ramp-up in seismicity rates greatly increases hazard:

More little earthquakes means more big earthquakes! And increased hazard.

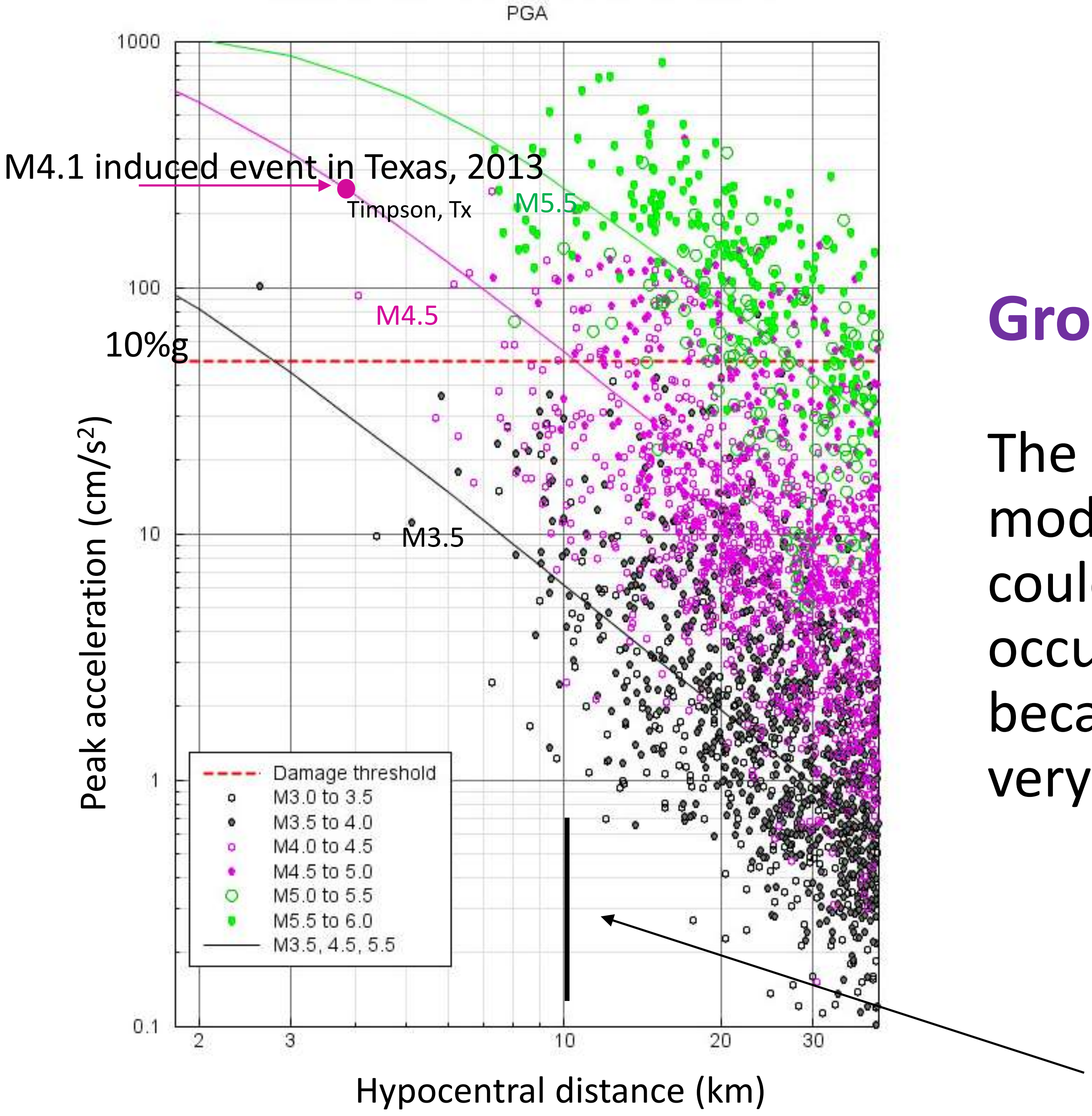
~1 per year

1 in 10 chance per year

1 in 100 chance per year

The Gutenberg-Richter relation:

For every 100 M3 events, we will get ~10 M4 events, about 1 M5 event…. And so on



Ground motions:

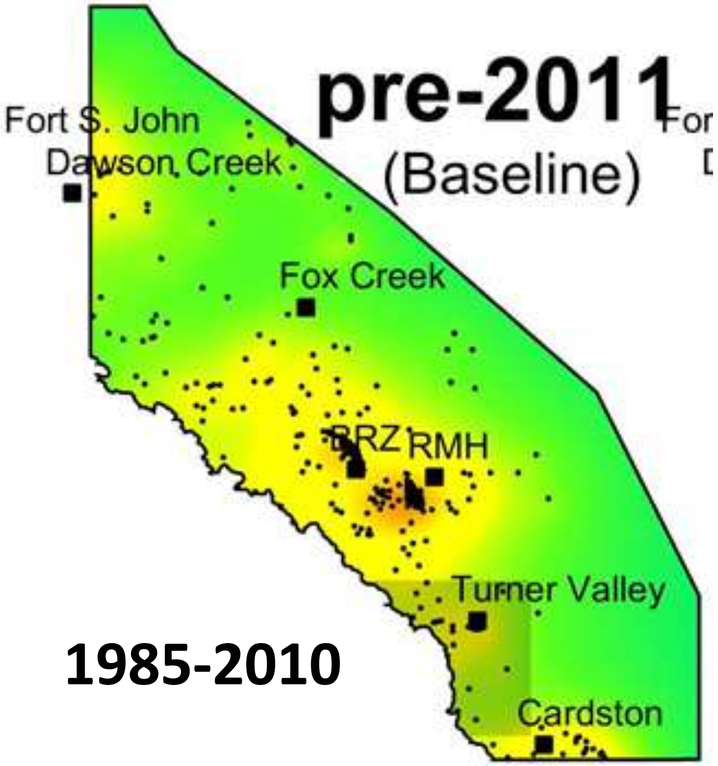
The ground motions for moderate induced events could be large if they occur very nearby… because events can be very shallow (<5 km)

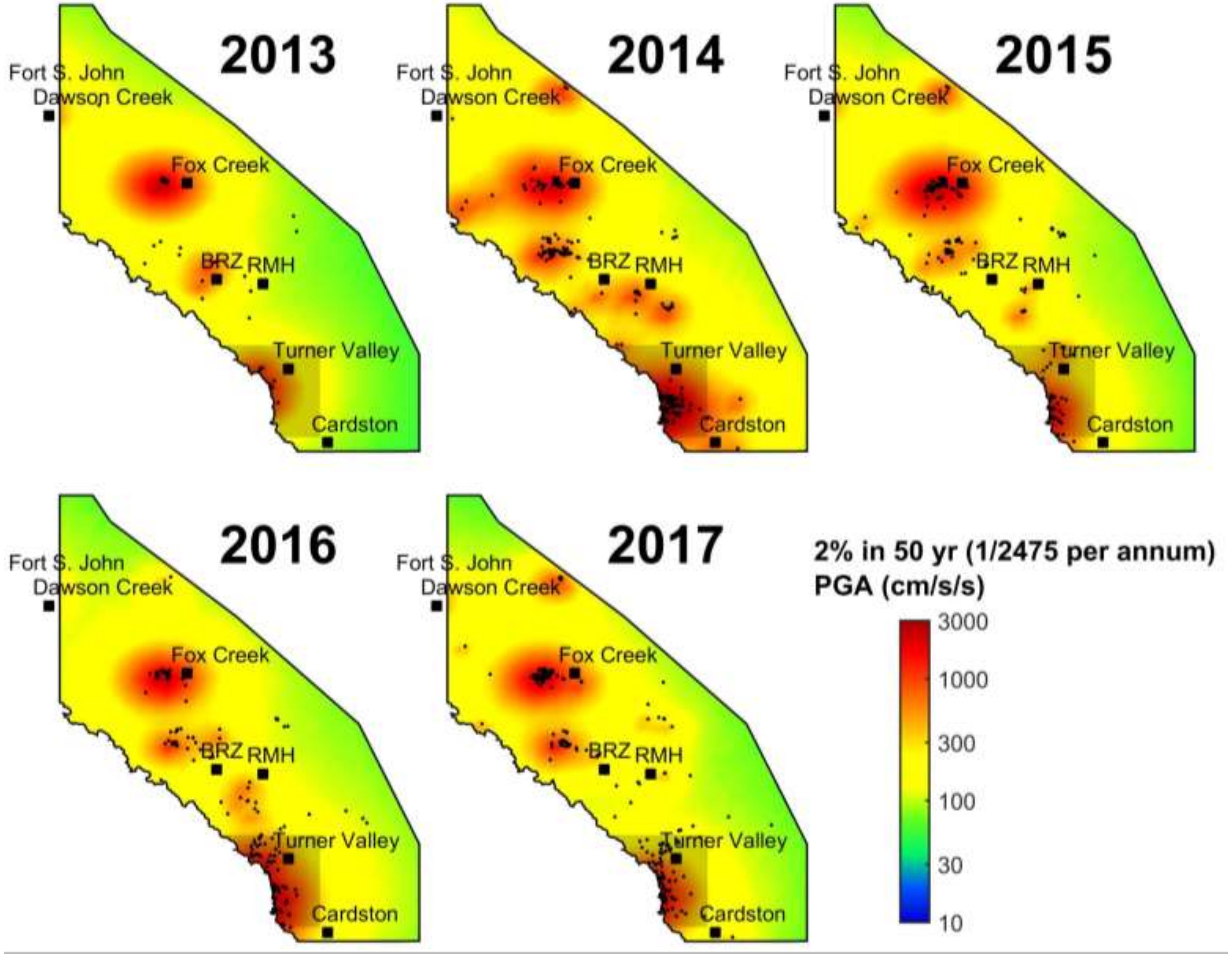
Induced seismicity hazard assessments: Hindcasting versus forecasting

- A hindcast uses past seismicity rates to calculate the hazard, assuming that the past seismicity rates continue (within the time period of interest)
    - The rate and locations of earthquakes are calculated from an observed catalogue for a past time period
- A forecast aims to assess the hazard if operations that might trigger induced seismicity are initiated near a site
    - The rate and locations of earthquakes are calculated from an assumed likelihood of activation and earthquake distribution

Example of hindcast model for Alberta

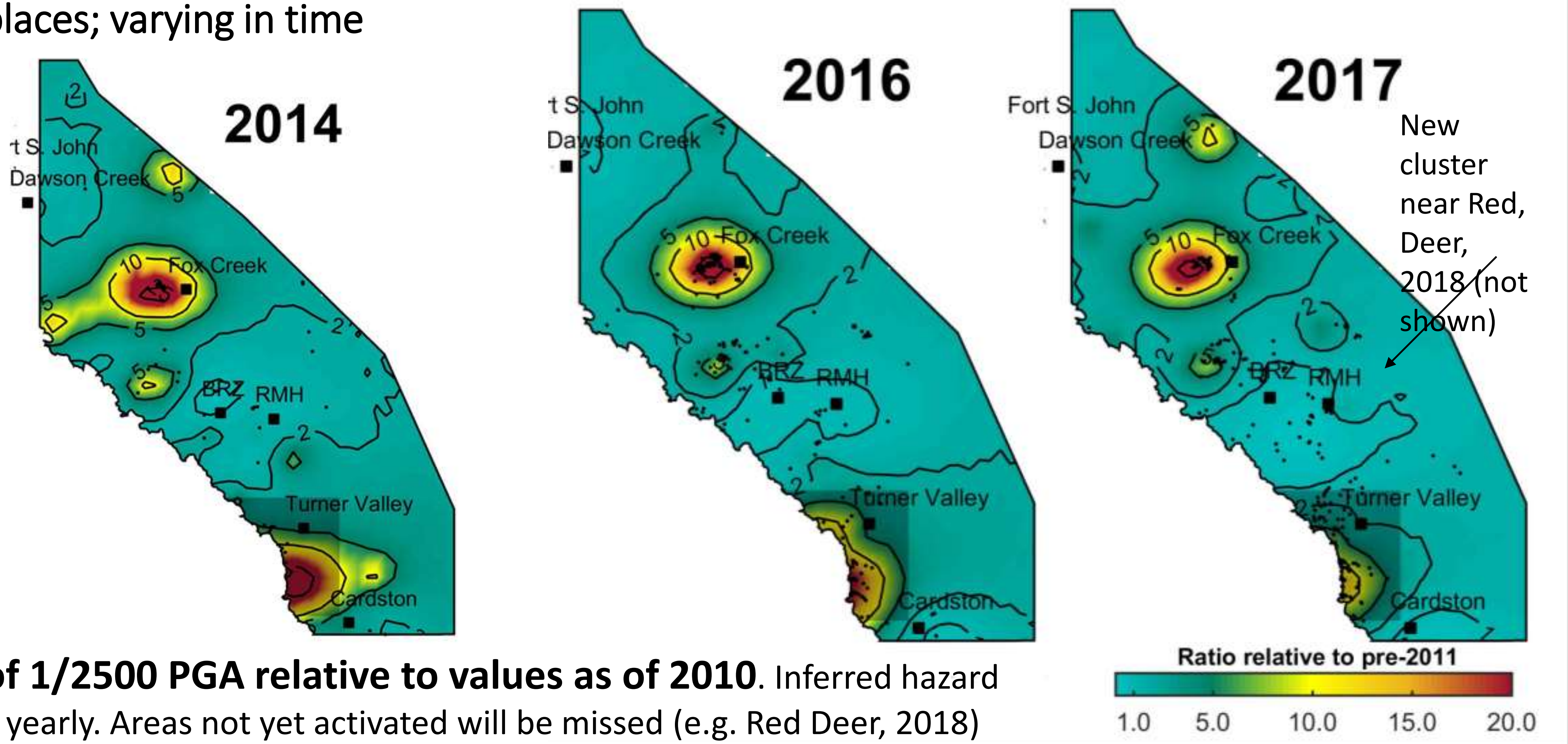
(Ghofrani et al., 2019 SRL)





Expected value of 1/2500 PGA (cm/s^2), obtained from observed earthquakes (black dots) in the time period.
Shaded regions (Turner Valley) are areas where the catalog is contaminated by undistinguished blasts.

Impact of changing seismicity rates: hindcast model (Ghofrani et al., 2019 SRL): increases in 1/2500 ground motion by factor>10 in some places; varying in time

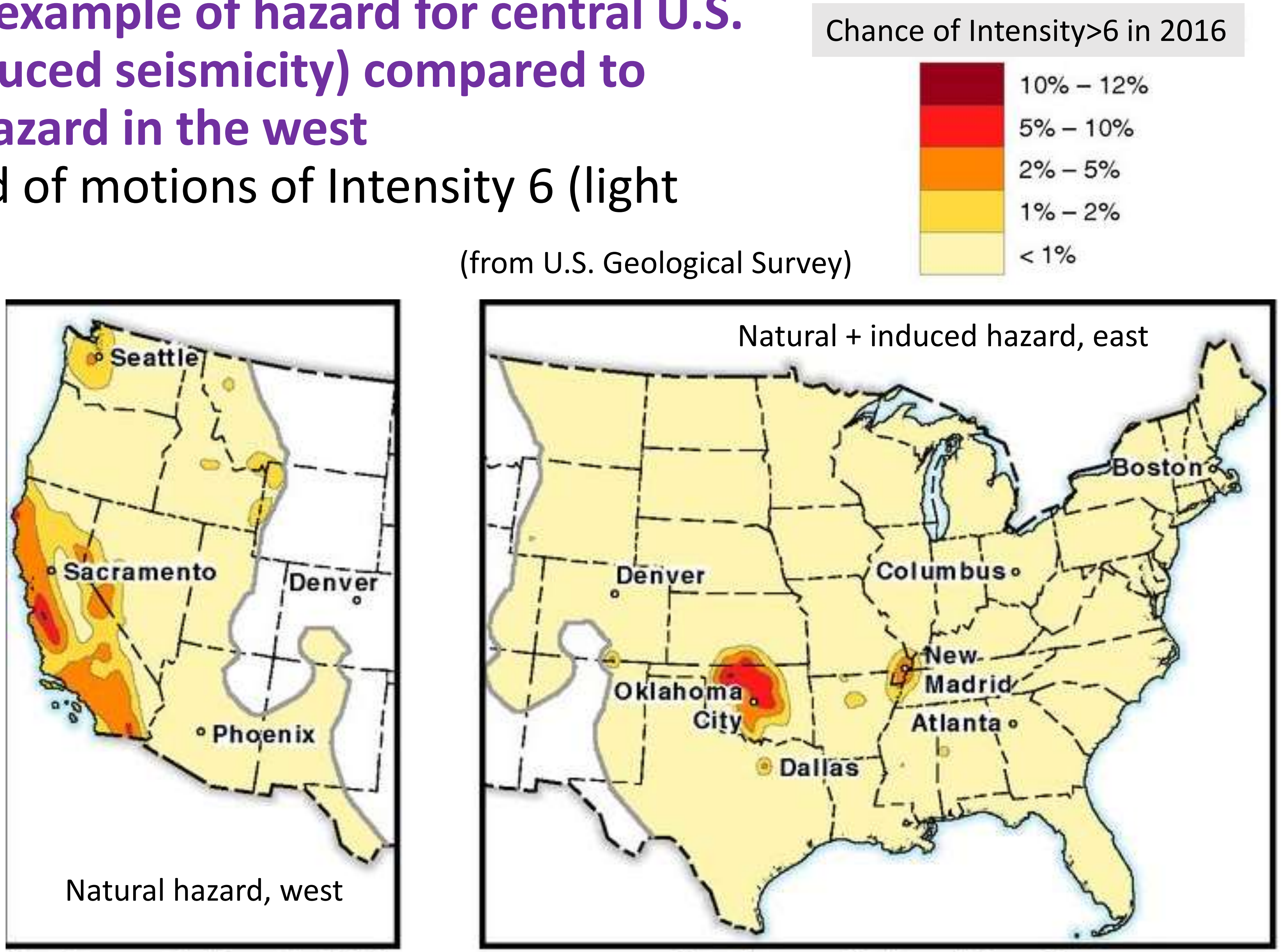


Ratio of 1/2500 PGA relative to values as of 2010. Inferred hazard changes yearly. Areas not yet activated will be missed (e.g. Red Deer, 2018)

Hindcast example of hazard for central U.S. (from induced seismicity) compared to natural hazard in the west

Likelihood of motions of Intensity 6 (light damage)

(from U.S. Geological Survey)

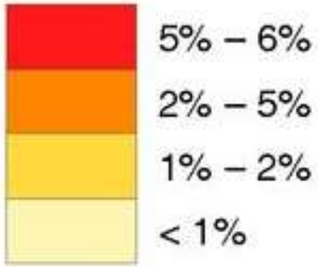


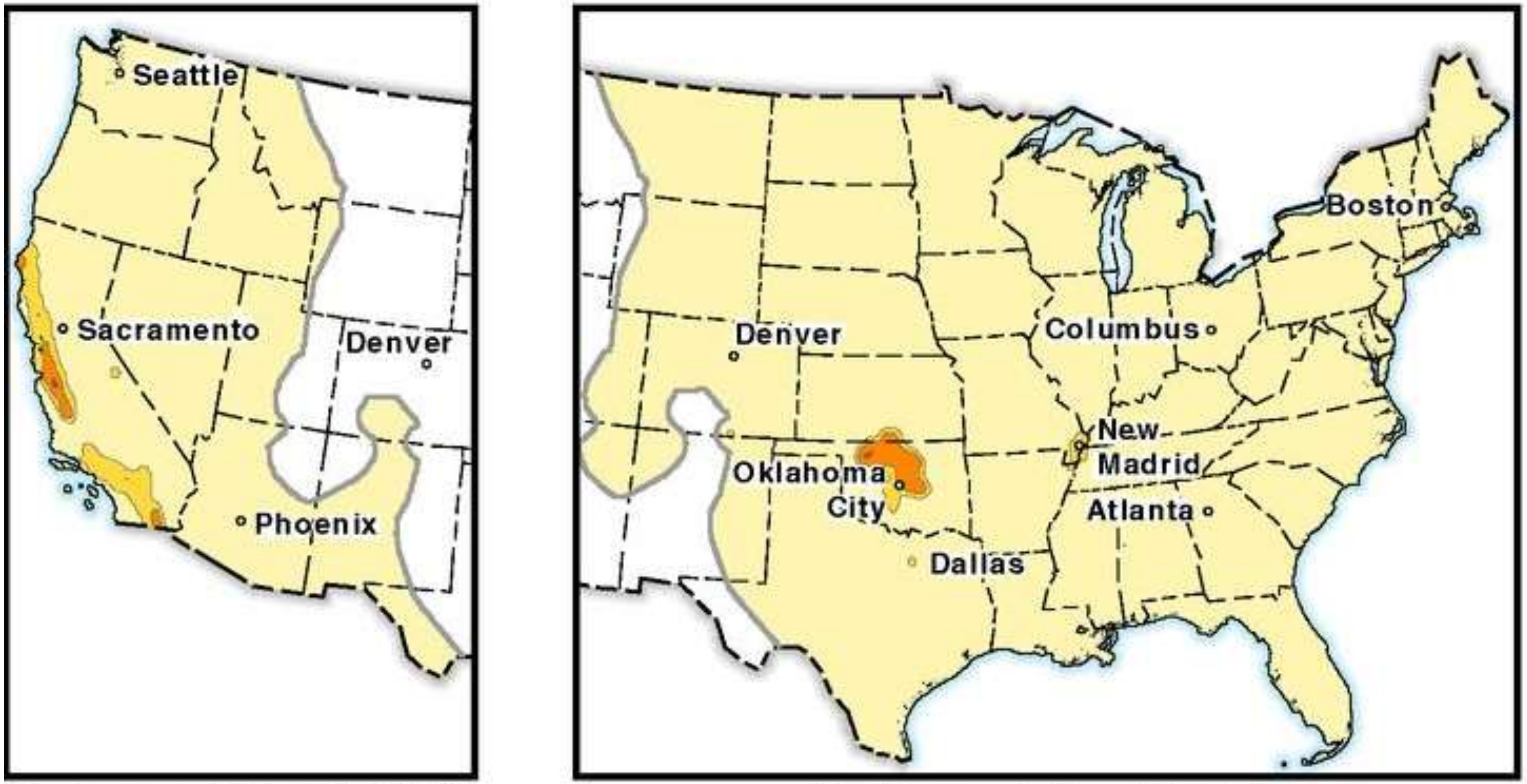
Hindcast example of hazard for central U.S. (from induced seismicity) compared to natural hazard in the west

Likelihood of Intensity 7 (moderate damage)

(from U.S. Geological Survey)

Chance of Intensity>7 in 2016





Pawnee, Oklahoma. M5.7 event, Sept. 2016. Intensity 7 shaking at distance ~20 km

Photos: Tulsa World

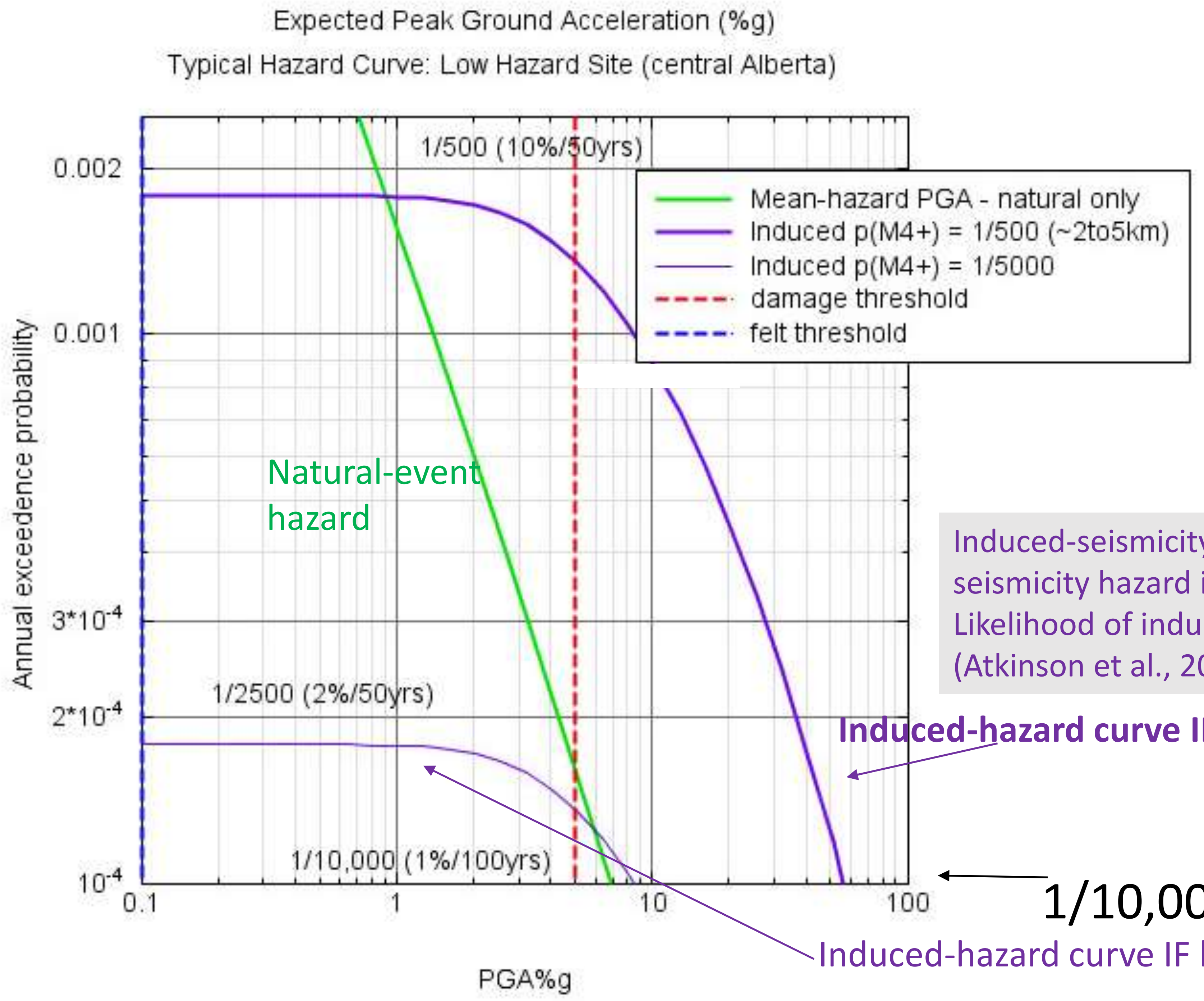
Lorca, Spain Earthquake, 2011, M5.1, Intensity=7

- **M**5.1 earthquake: 9 dead, 400 injured
- Serious damage due to shallow depth, causing large ground motions on the surface
- Human-induced stress changes related to groundwater extraction probably triggered the Lorca earthquake and caused its shallow depth (González et al., *Nature*).

The Lorca Earthquake caused widespread damage, and destroyed the St. James church, pictured here. (Photo: Creative Commons)

Forecast model of induced seismicity hazard

- A forecast aims to assess the hazard *if* operations that might trigger induced seismicity are initiated near a site
  - The rate and locations of earthquakes are calculated from an assumed likelihood of activation and earthquake distribution
  - Likelihood of activation varies regionally and is highly uncertain
  - Induced events, if they occur will be within ~5km of a planned operation



Example of hazard forecast for a site in central Alberta

-PGA (central Alberta, HF operations at 2 to 5 km, with assumed likelihood of ~1/500 to 1/5000 for inducing a cluster that produces **M**>3.

Induced-seismicity hazard may greatly exceed natural-seismicity hazard in low-hazard area.
Likelihood of inducing anomalous activity is critical.
(Atkinson et al., 2015, SRL)

Induced-hazard curve IF likelihood is 1/500

1/10,000 p.a. safety target for dams

Induced-hazard curve IF likelihood is 1/5000

Hazard Mitigation Recommendations

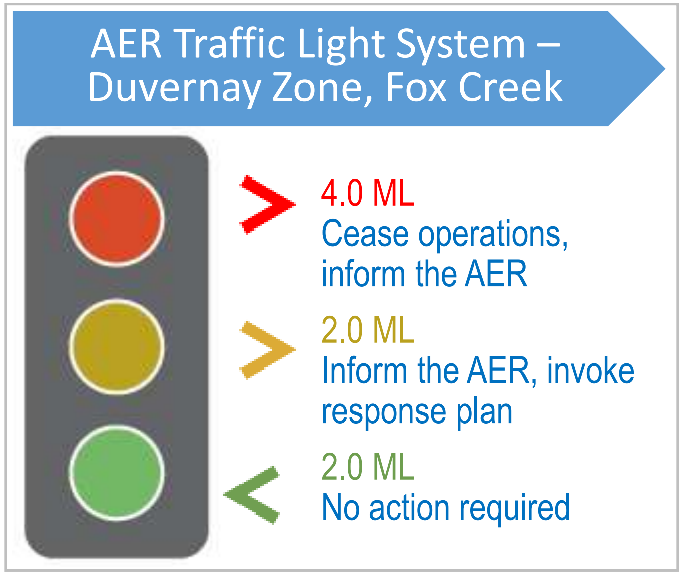
(Atkinson, 2018, FACETS)

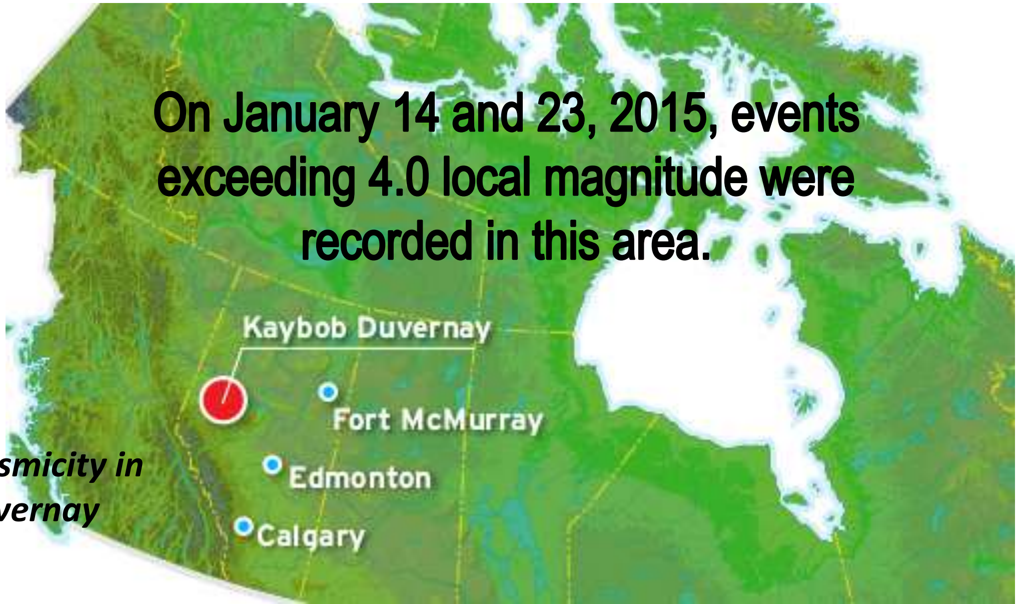
- A 5-km exclusion zone for critical infrastructure should be applied to prevent events at very close distances, because the uncertainty in estimating activation probability is unmanageable
- Exclusion zones alone may not provide sufficiently-low hazard, because contributions from operations beyond that zone are significant
- Regional monitoring in the 5km to 25 km radius is needed to determine regional rate parameters and fine-tune mitigation strategies
- Develop an appropriate response protocol (i.e. if the annual rate of induced **M**>2 in the zone from 5 to 25 km exceeds a specified rate, adjust operations to obtain a reduced activity rate)
- This protocol should be adjusted depending on the specific situation (infrastructure robustness/failure consequences)

Govt policies to date very limited, mostly retrospective:

AER Bulletin 2015-07 (Feb. 2015)

- In the Fox Creek area of Alberta (red dot), operators must report to AER if M>2 induced; must cease operations if M>4
- few data are released beyond the regulators office
- B.C. has a similar policy





Subsurface Order No. 2: Monitoring and Reporting of Seismicity in the Vicinity of Hydraulic Fracturing Operations in the Duvernay Zone, Fox Creek, Alberta

Conclusions

- Induced seismicity hazard is non-stationary in space and time
- Induced seismicity causes dramatic (but non-stationary) increase in seismic hazard to nearby facilities, in regions of low-to-moderate seismicity, unless the probability of activation is very small (i.e. <<1/1000)
- Activation probability varies greatly in space and its assessment is subject to very high uncertainty (at present, we don’t really know what it is)
- For critical facilities the best mitigation practice is a combination of hazard avoidance (though exclusion zones) and mitigation (pro-active response to changes in seismicity rate)
- How to handle induced seismicity in hazard maps and practices for building codes is an open question