Alberta Energy Regulator

AGS
ALBERTA GEOLOGICAL SURVEY

Forecasting Hazard from Induced Earthquakes

Ryan Schultz

Overview

1) Probabilistic Seismic Hazard Analysis (PSHA).
    - Ground Motions Parameters
    - Earthquake Catalogues & Recurrence Relations
    - GMPEs
    - Hazard Calculation
    - Deaggregation
2) Shortcomings of PSHA for IS & workarounds.

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Chapter 1:

Probabilistic Seismic Hazard Analysis (PSHA)

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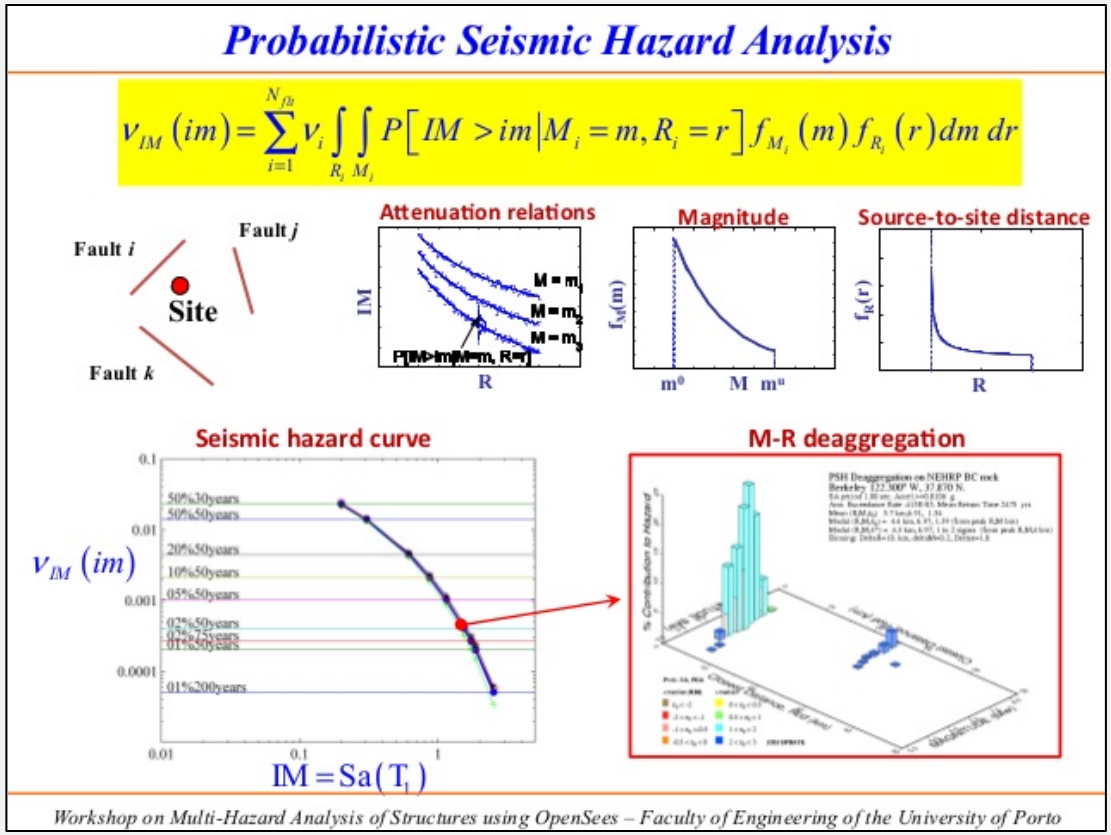
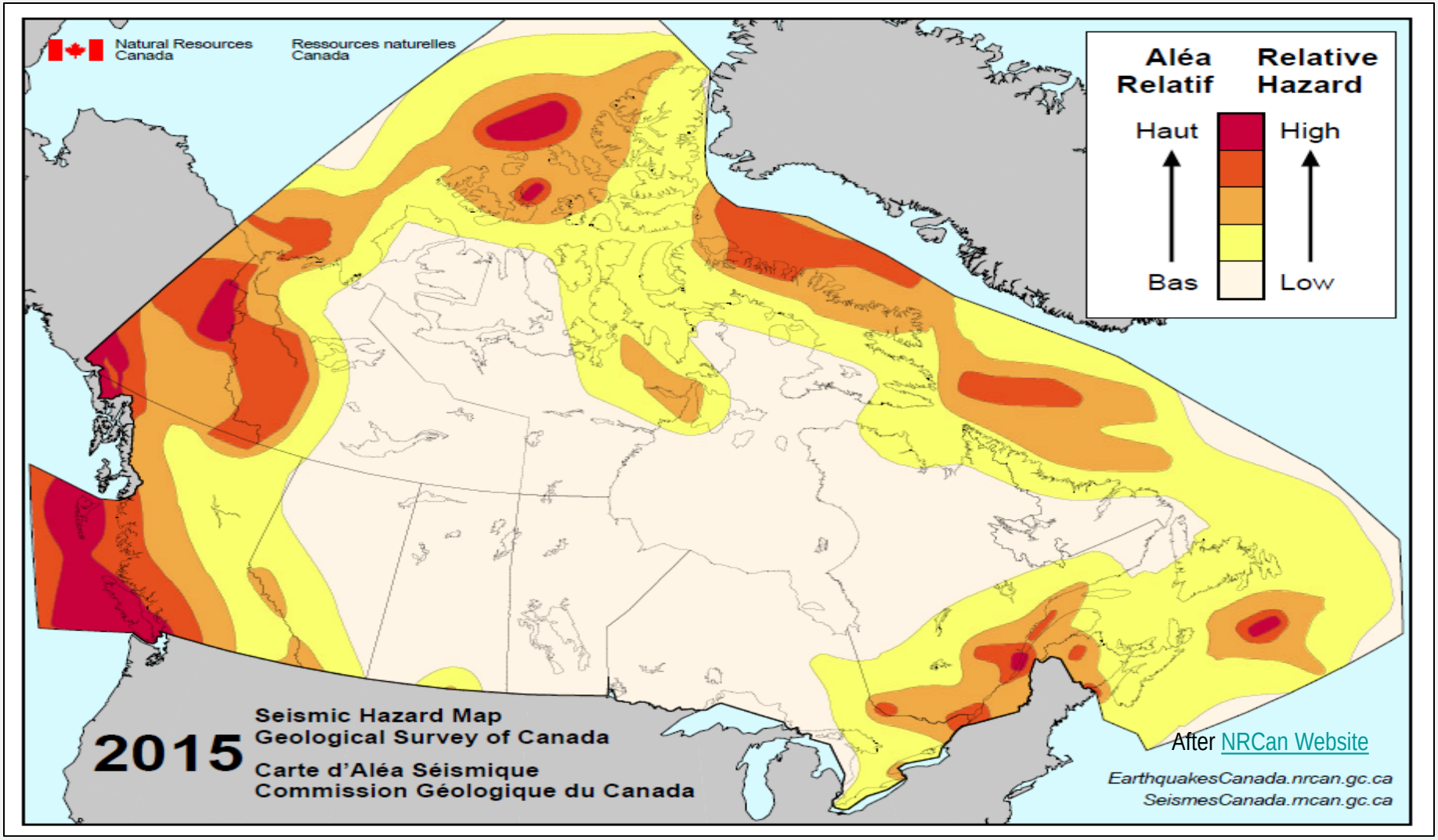
Probabilistic Seismic Hazard Analysis

- Requires much input data:
  - Ground Motion Parameters
  - Recurrence Relationships
  - Rate & Location Models
  - GMPEs
- Means to make best-guesses at the likelihood of future earthquakes & their anticipated ground motion.
- Also allows user to see what's contributing most to the hazard.



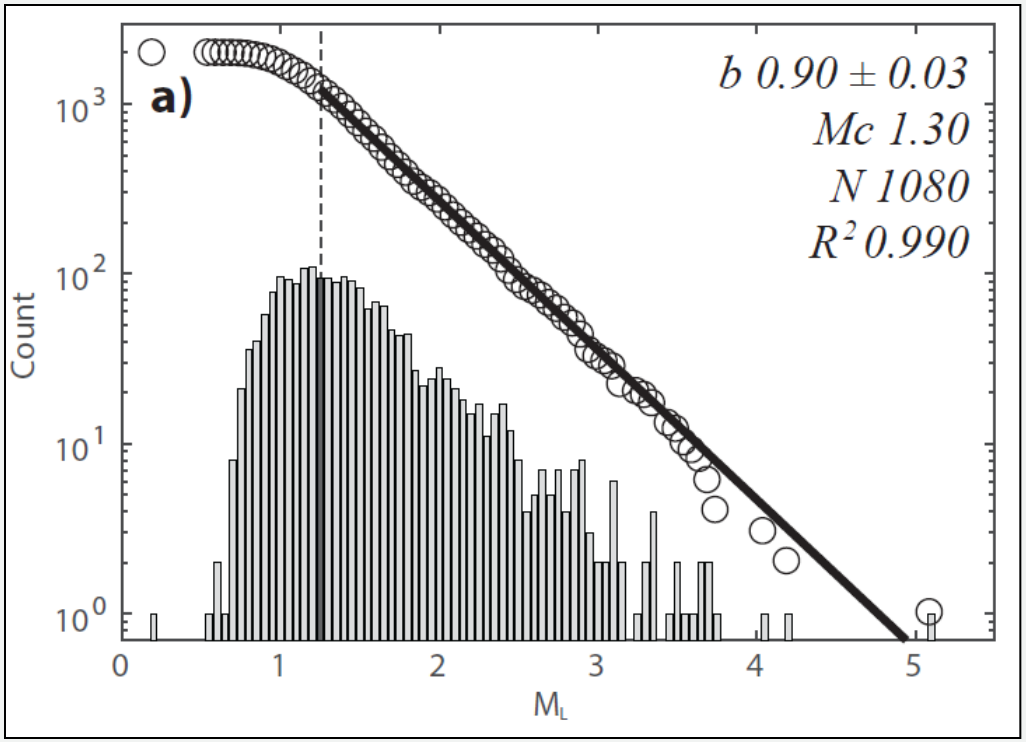
Probabilistic Seismic Hazard Analysis



Recurrence Relations & Rate/Location Models

- Examine GR-FMD, fit for *a*- and *b*-values.
- Function that describes the expectation value for the number and frequency of earthquake at a given magnitude.
- Assumes enough information for a location, and a stationary Poisson process in time.

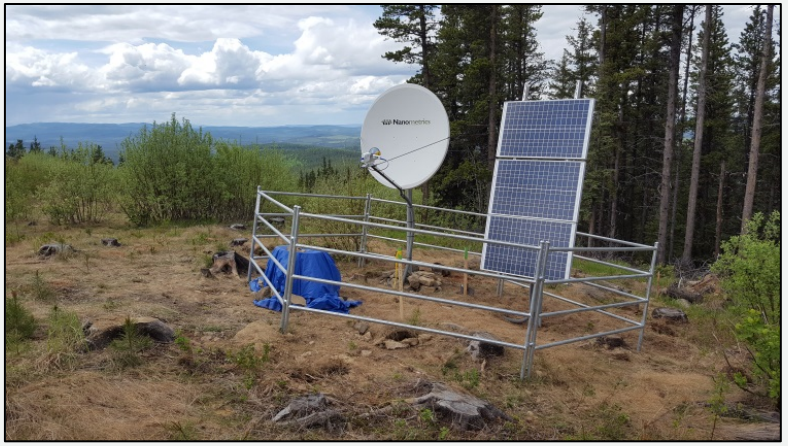
$$\nu_{IM}(im) = \sum_{i=1}^{N_{flt}} \nu_i \int_{R_j} \int_{M_j} P\left[IM > im \middle| M_i = m, R_i = r\right] f_{M_i}(m) \, f_{R_i}(r) \, dm \, dr$$



$$N_M = 10^a 10^{-bM}$$

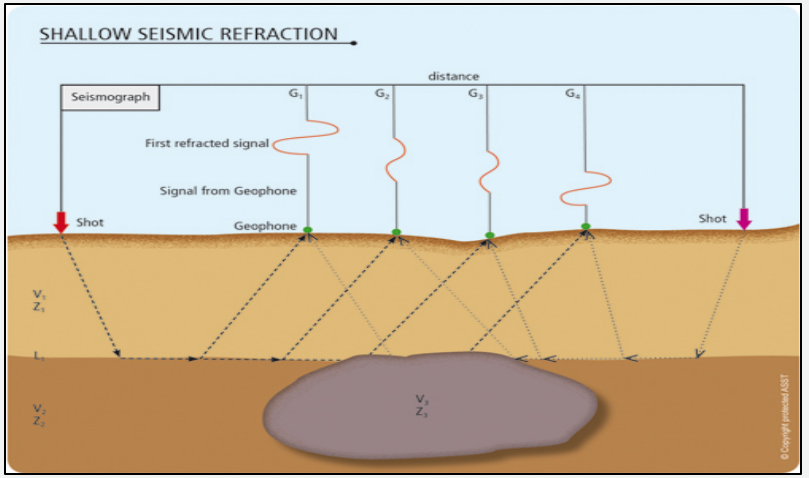
Ground Motion Parameters

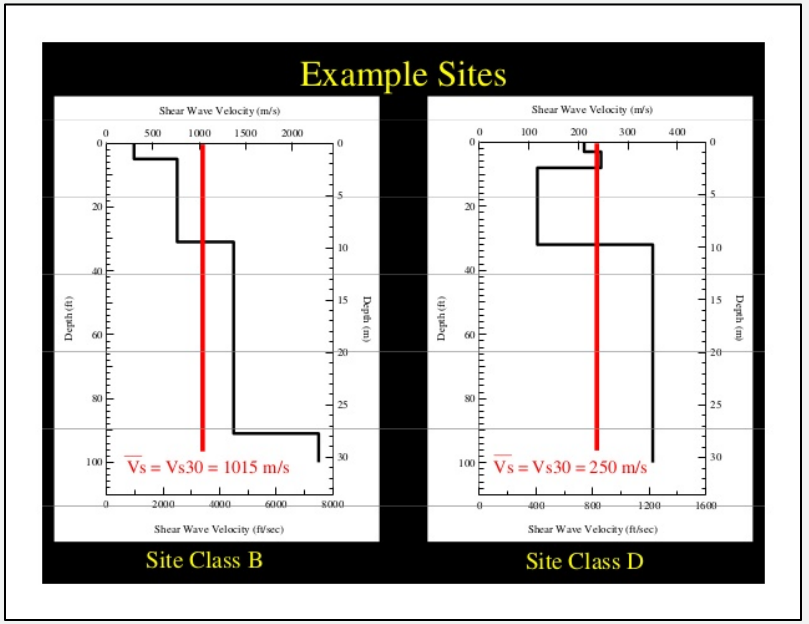
- Collected in real-time from seismic stations.
- Multiple variants & data sources:
  - PGA, PGV, PSA(f), MMI, IM, DYFI
- Ground motion results from multiple effects: source, propagation path, and site effects.



Site Amplification & Vs30

- Site conditions can affect the resultant amplitudes of ground motion.
- Near-surface soil shear-velocity conditions at seismic stations are often quantified.
- Vs30 acts as a proxy for site amplification, allowing for the removal of site-specific conditions from GM parameters.





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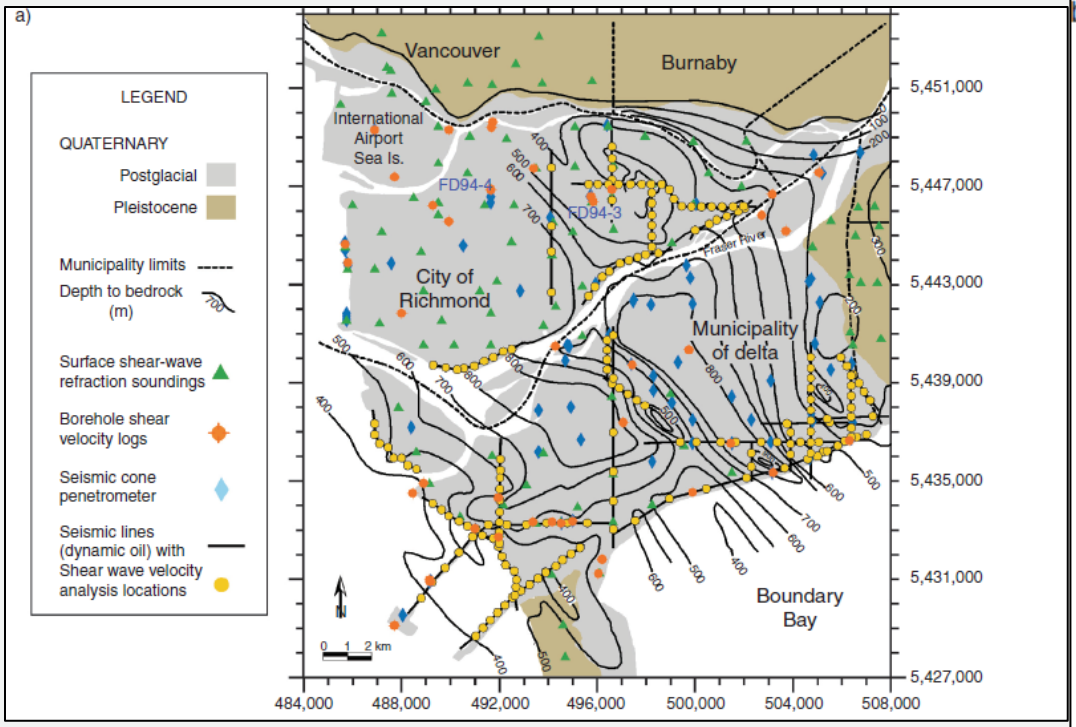
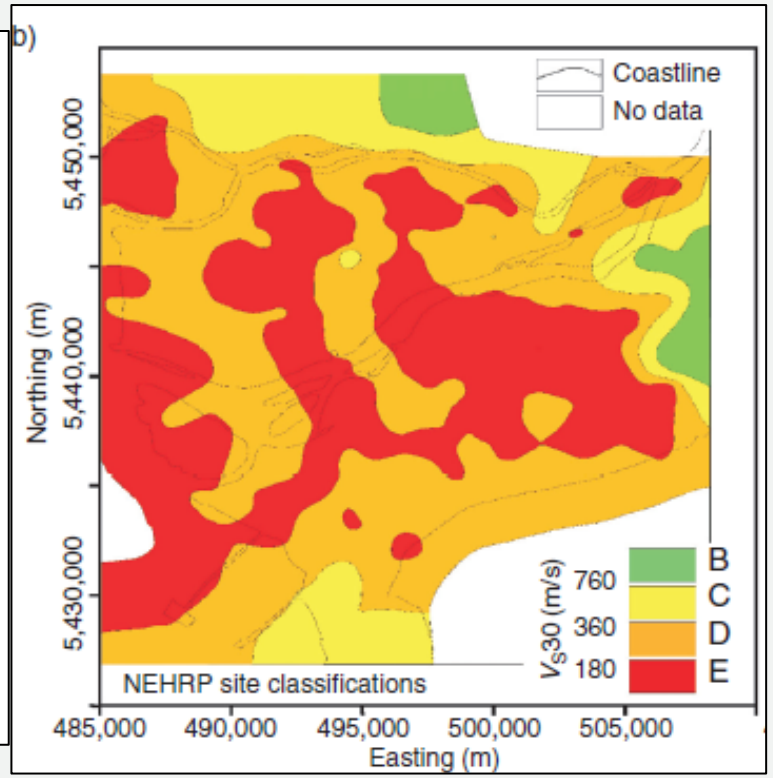
Case Study: Frasier River Delta



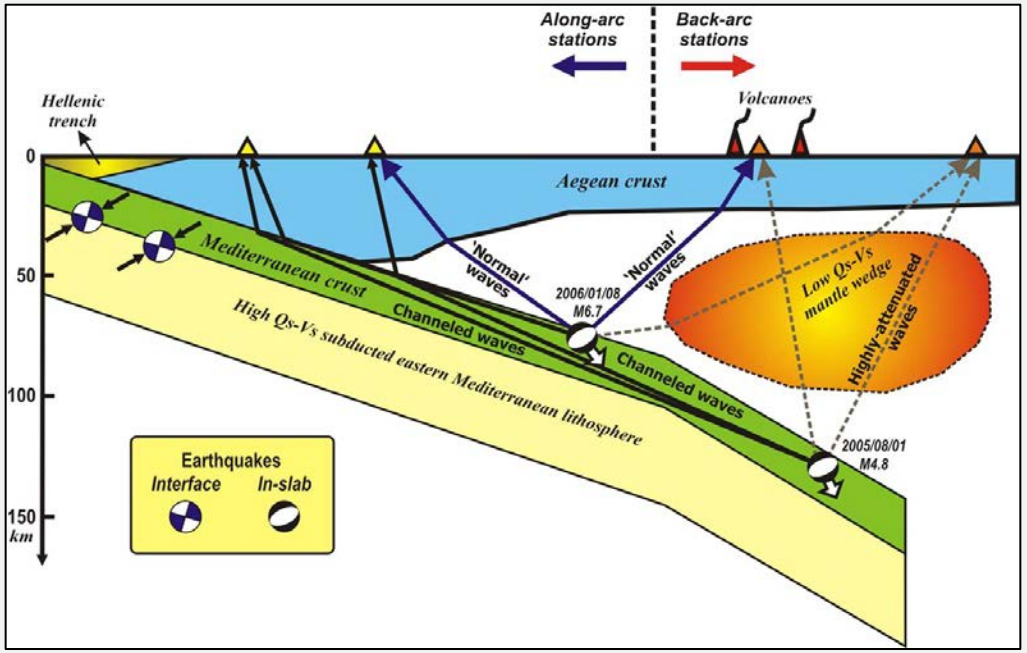


After Hunter et al., 2010

Ground Motion Predication Equations (GMPEs)

- GMPEs provide a means to interpolate ground motions to regions without sensors.
- Provide an empirical fit to the data and account for multiple factors: distance, magnitude, local soil conditions, local structure, faulting mechanism, etc..

$$\nu_{IM}(im) = \sum_{i=1}^{N_{flt}} \nu_i \int_{R_j} \int_{M_j} P\left[IM > im \middle| M_i = m, R_i = r\right] f_{M_i}(m) \; f_{R_i}(r) \; m \; dr$$



After Skarlatoudis et al., 2013

Ground Motion Predication Equations (GMPEs)

- GMPEs provide a means to interpolate ground motions to regions without sensors.
- Uncertainties in GMPEs are on a log scale. Caused by both epistemic error (systematic) caused by biased modelling, and aleatory error (random).

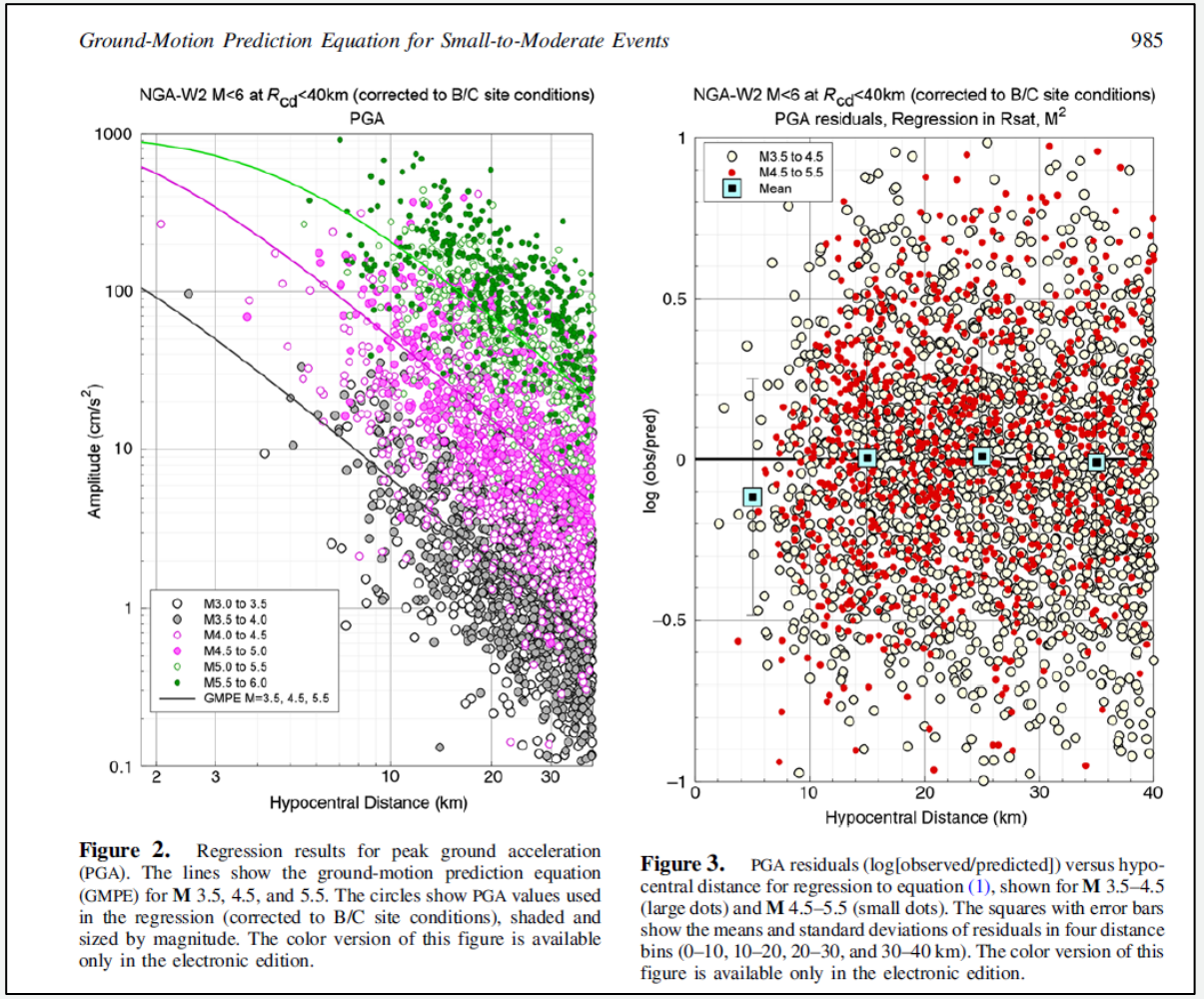
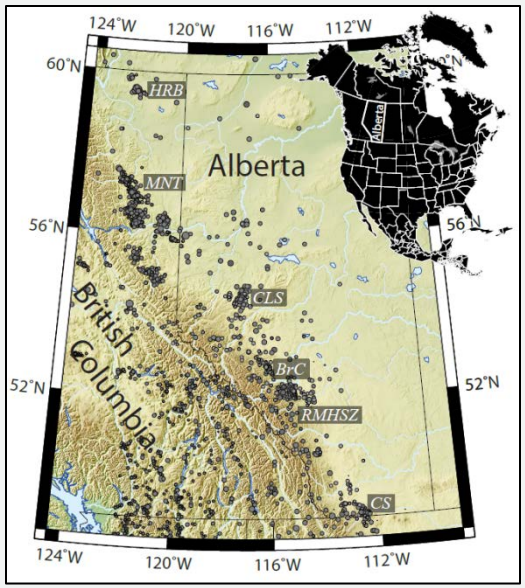


Figure 2. Regression results for peak ground acceleration (PGA). The lines show the ground-motion prediction equation (GMPE) for **M** 3.5, 4.5, and 5.5. The circles show PGA values used in the regression (corrected to B/C site conditions), shaded and sized by magnitude. The color version of this figure is available only in the electronic edition.

Figure 3. PGA residuals (log[observed/predicted]) versus hypocentral distance for regression to equation (1), shown for **M** 3.5–4.5 (large dots) and **M** 4.5–5.5 (small dots). The squares with error bars show the means and standard deviations of residuals in four distance bins (0–10, 10–20, 20–30, and 30–40 km). The color version of this figure is available only in the electronic edition.

After Atkinson et al., 2015

Seismic Hazard Curve



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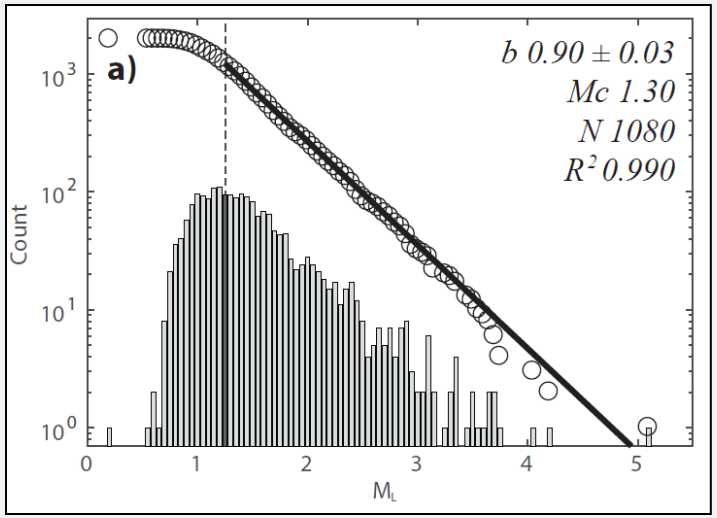

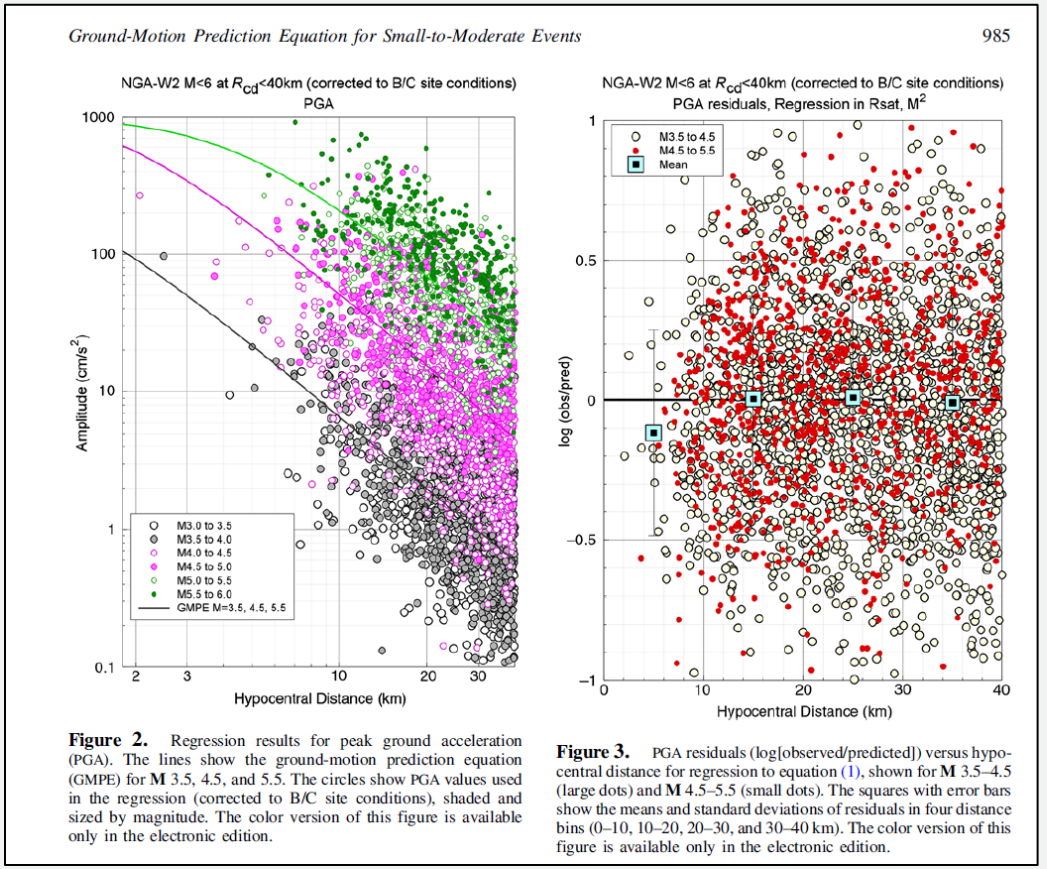

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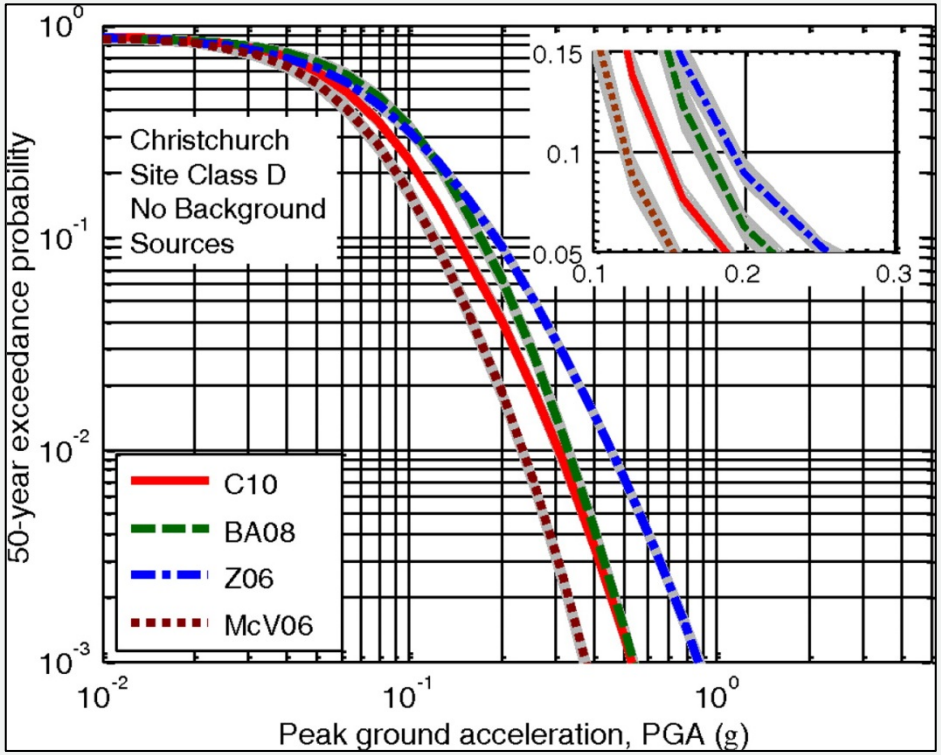
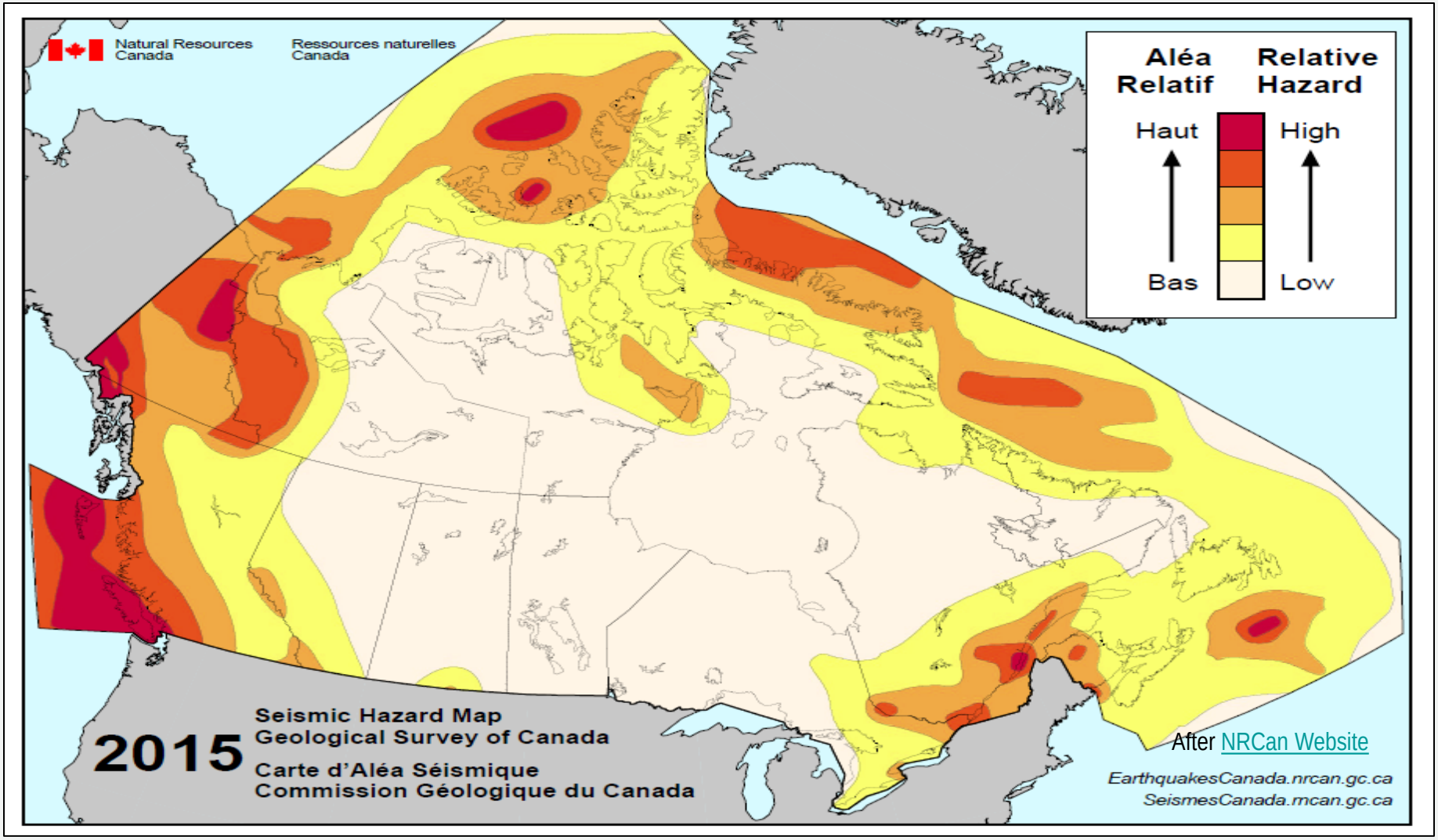
Seismic Hazard Curve

- Translation of multiple factors related to earthquakes into a simple relationship between probability (over a time interval) and ground motion (PGA, PGV, PSA, MMI, etc.).
- Variability from models and uncertainties can be propagated into hazard curve.
- Structural engineering and building codes based off of expected tolerances.
- See also USGS website.



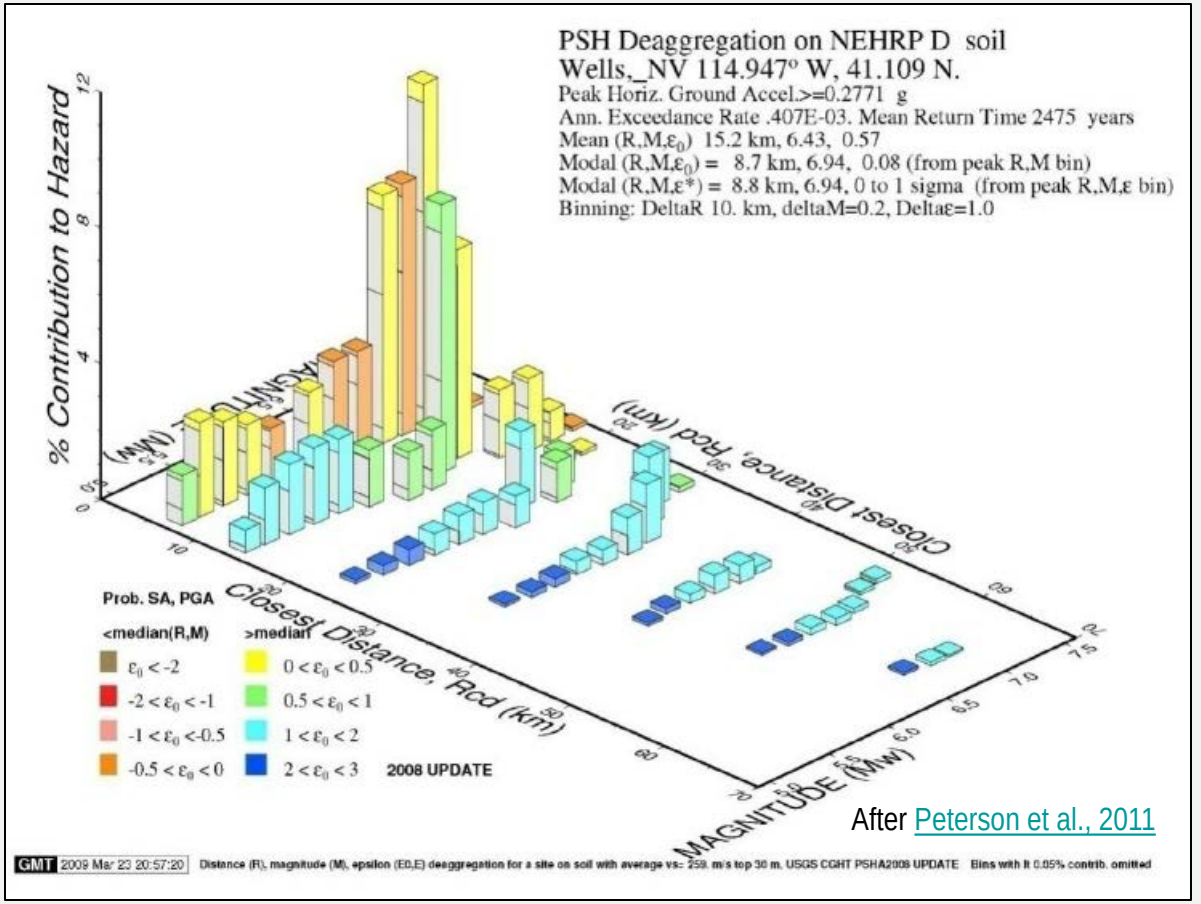
After Bradley et al., 2012

Final Product!



Deaggregation

- Deaggregation is a method to separate individual components contributing to hazard.
- Allows for the quantification of contribution to hazard for each variable, to see which affects the resultant hazard curves the most.



After [Peterson et al., 2011]

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Chapter 2:

Complications for PSHA with Induced Earthquakes

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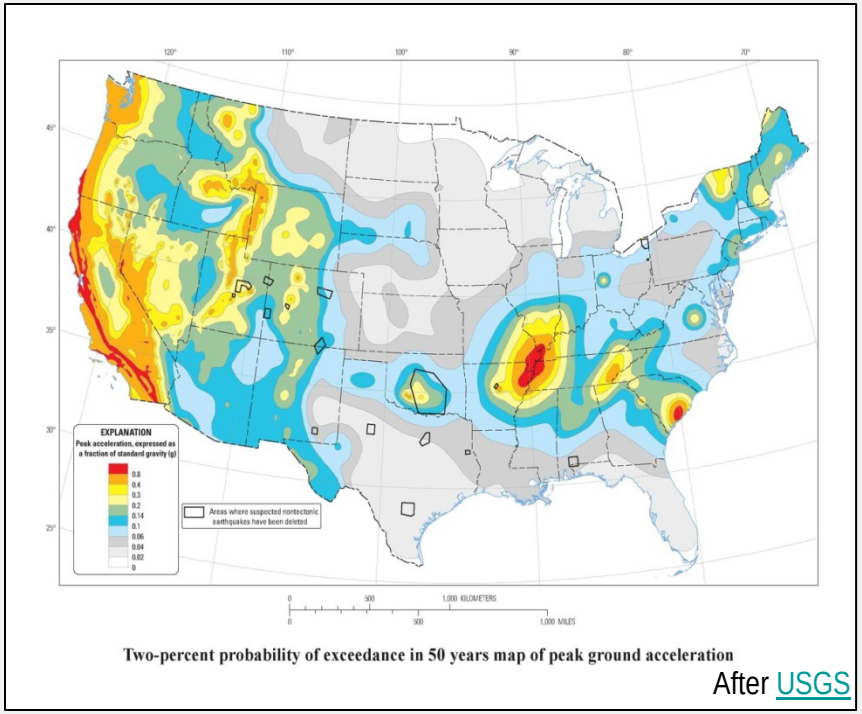
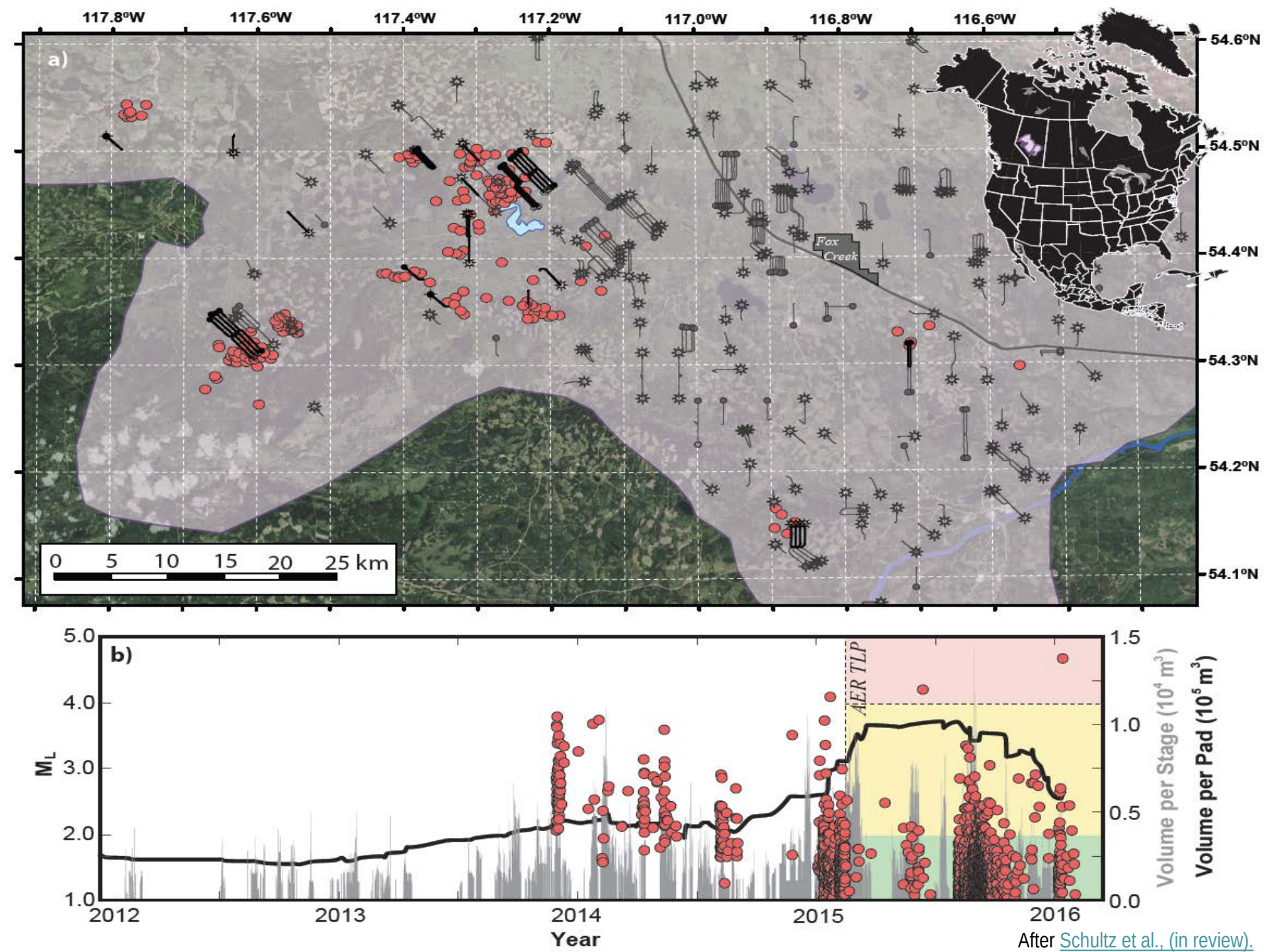
Problems for IS-PSHA?

- Rate models: PSHA assumes stationary Poisson process in time, IS rates are variable with time.
- Location models: PSHA needs to characterize locations, IS pops up unexpectedly.
- Maximum magnitude: PSHA uses tectonic caps to magnitudes, does IS have operational-related maximums?
- USGS workaround is to use smaller time scales and assume conditions still hold.



Two-percent probability of exceedance in 50 years map of peak ground acceleration

After USGS

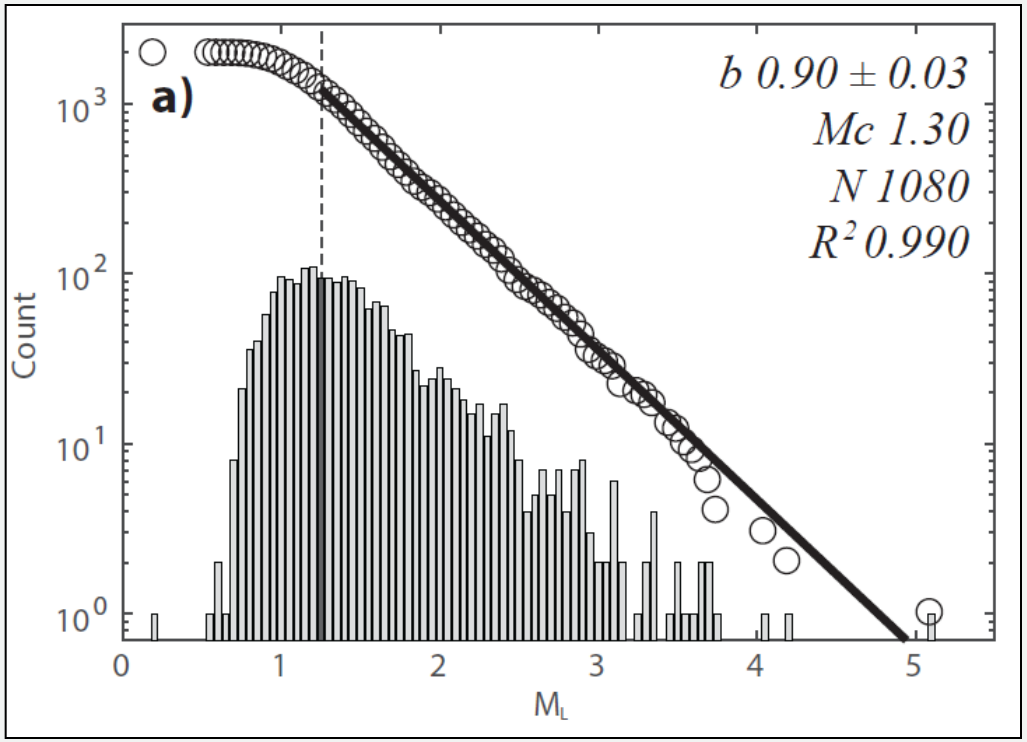


After Schultz et al., (in review).

The Rate Problem

- Examine GR-FMD, missing time dependence of induced seismicity.

$$N_M = 10^a 10^{-bM}$$



- Modifications to a value suggested based on solutions to pore-pressure diffusion equation [Shapiro et al., 2010].

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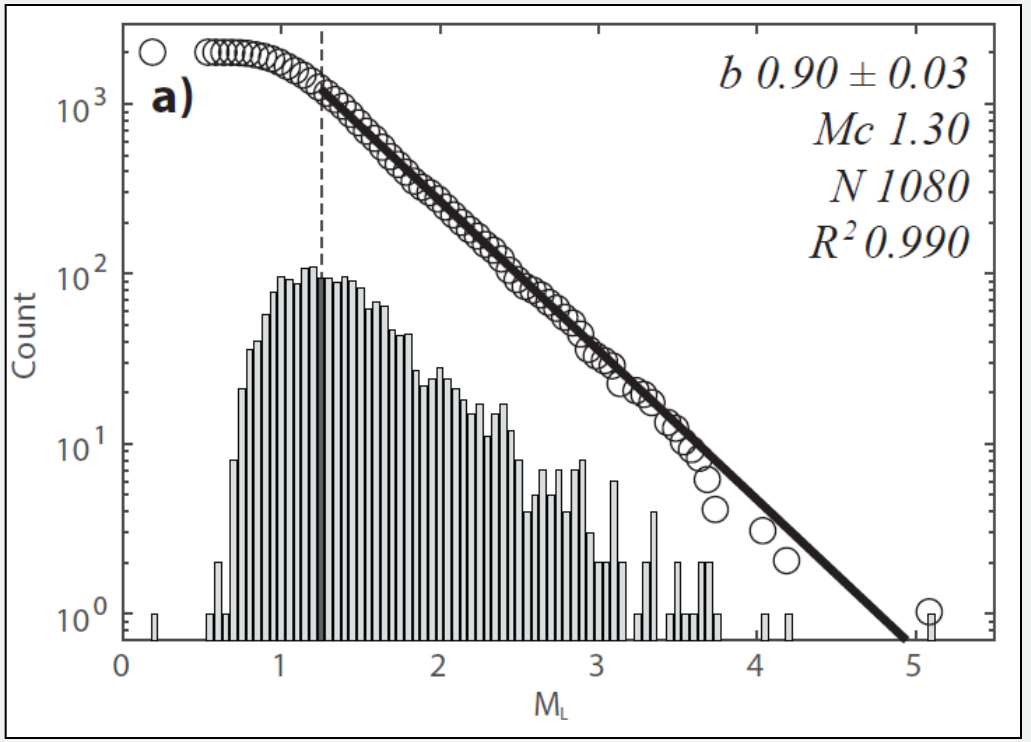


- Modifications to a value suggested based on solutions to pore-pressure diffusion equation [Shapiro et al., 2010].

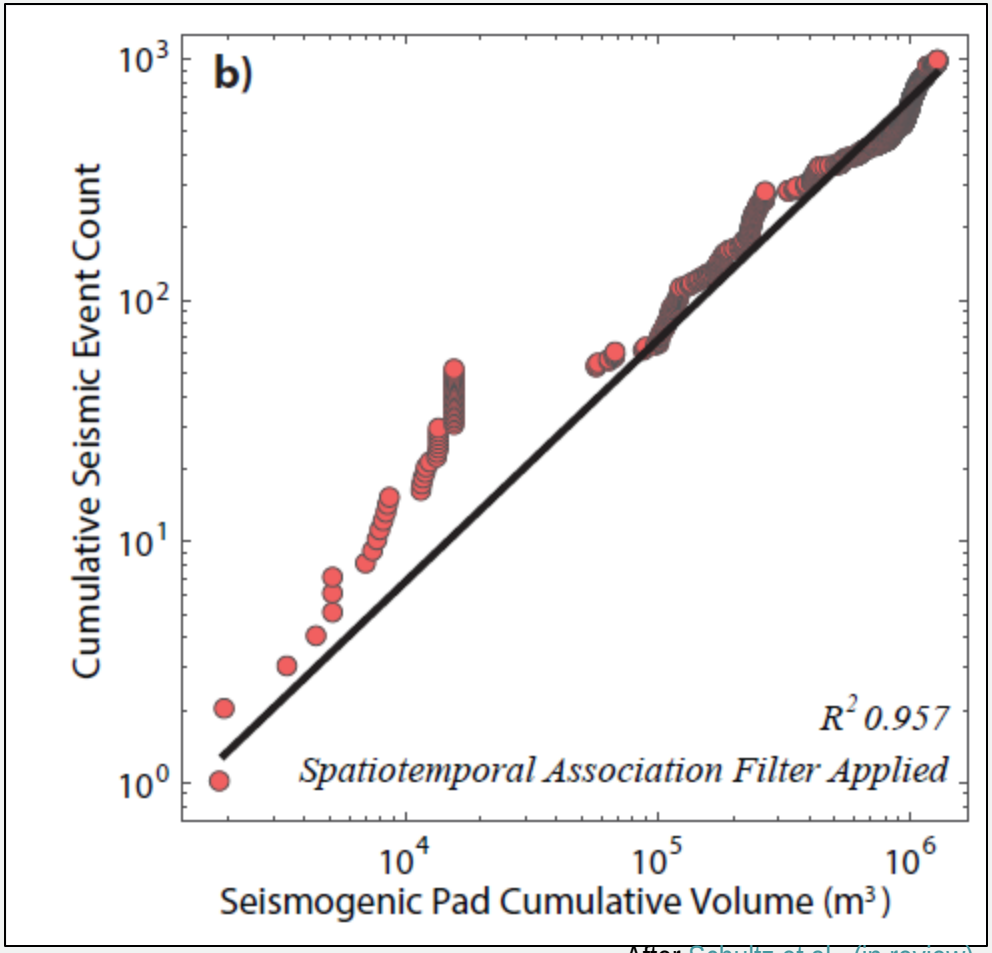
- Seismogenic Index: $a = \Sigma + \log_{10}(V(t))$

$$N_M = V(t) \cdot 10^{\Sigma} 10^{-bM}$$

Rate via HF Stimulation Volume?

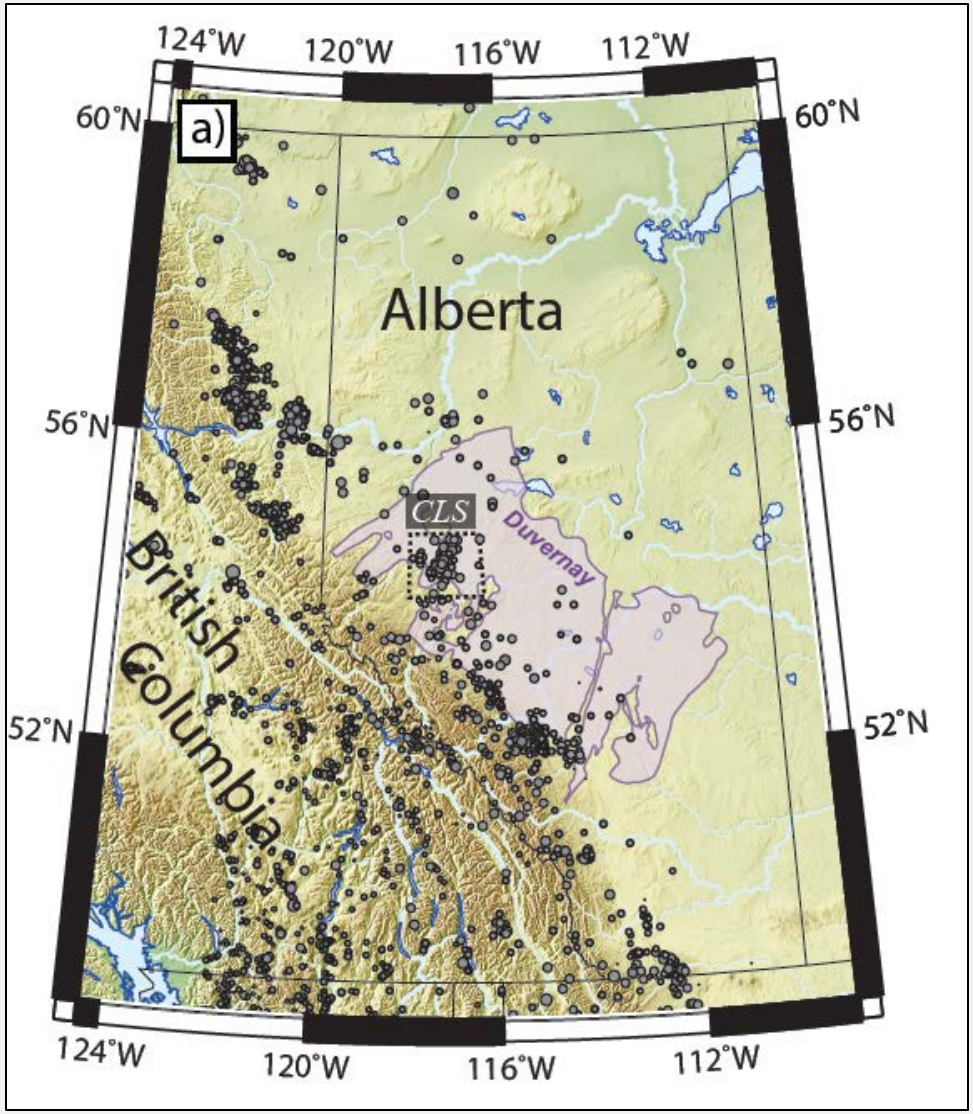
- Examine GR-FMD, missing time dependence of induced seismicity.
- Modifications to a value suggested based on solutions to pore-pressure diffusion equation [Shapiro et al., 2010].
- Seismogenic Index: a $= \Sigma + \log_{10}(V(t))$

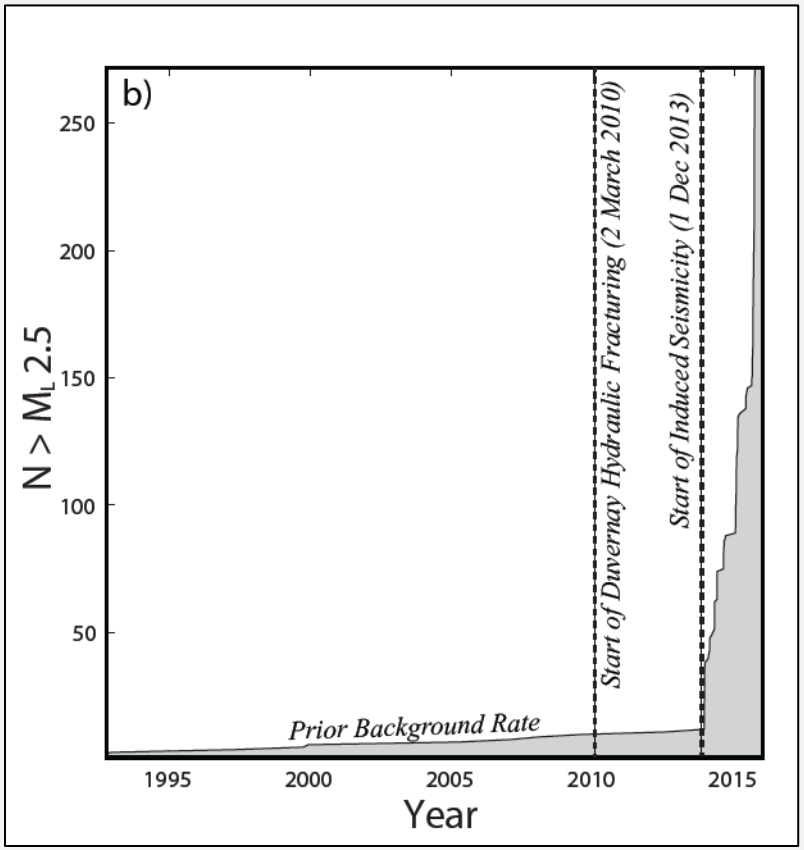
$$N_M = V(t) \cdot 10^{\Sigma} 10^{-bM}$$



After Schultz et al., (in review).

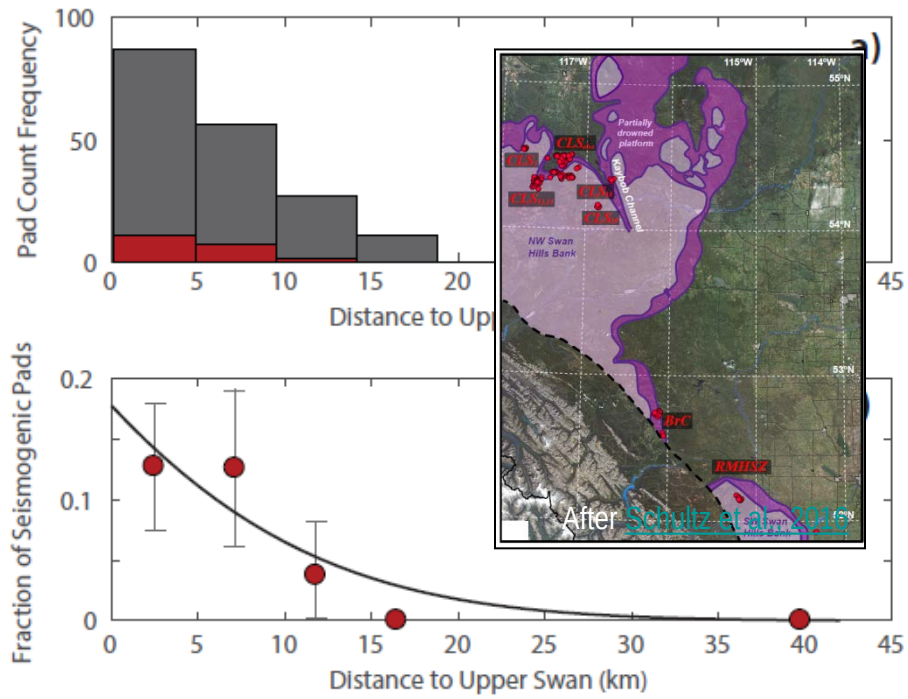
The Location Problem

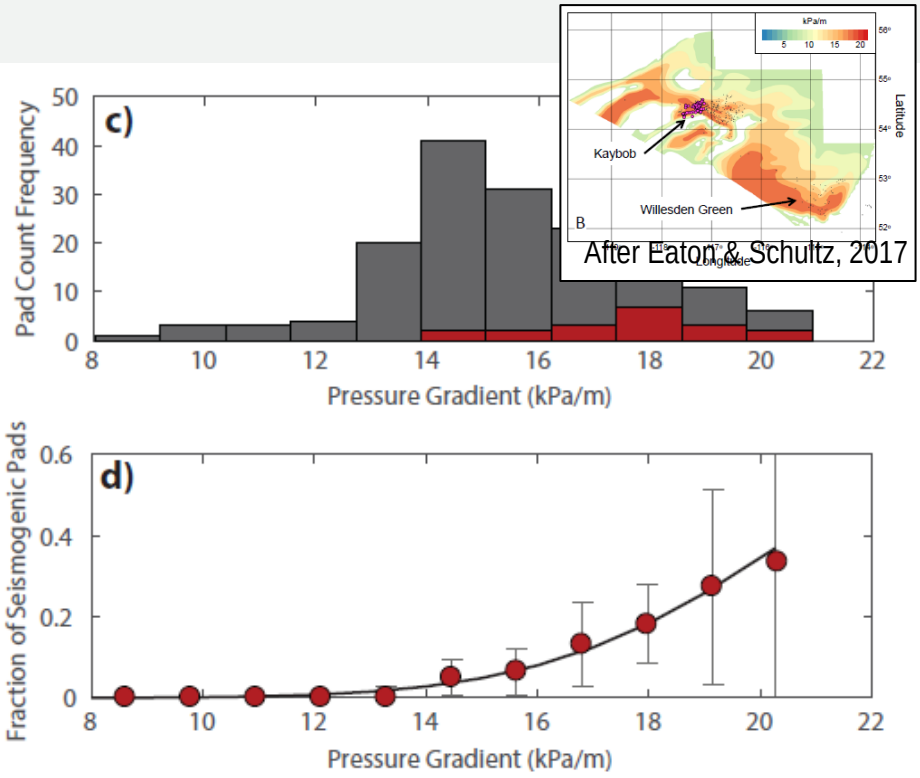




Location Models: Geological Susceptibility

- Induced earthquakes locations in central Alberta have shown a spatial correspondence with carbonate reef margins.
- Induced earthquake locations have shown a spatial correspondence with relatively higher Duvernay formation overpressure.

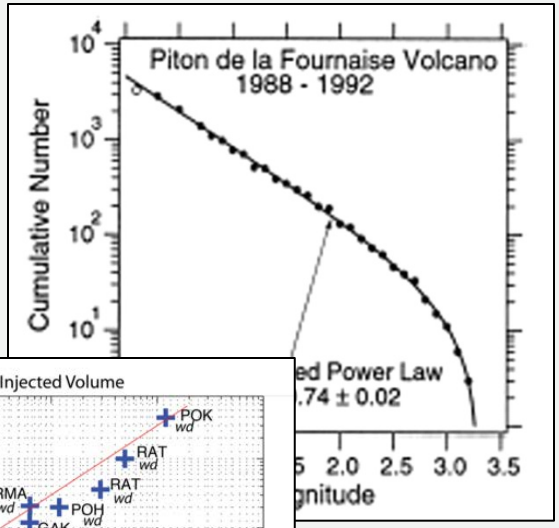


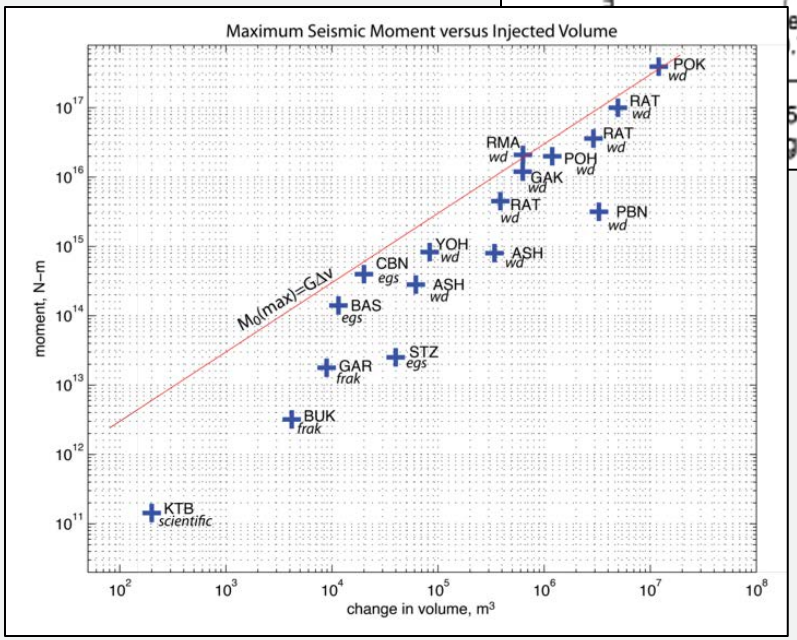


Maximum Magnitude?

- PSHA incorporates maximum magnitudes based on tectonic considerations: e.g., length of longest known faults.

- It may be possible that IS maximum magnitudes could be capped due to the total amount of fluid injected.





Questions

- **Send your questions or comments to:**

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(780) 644 5530

Ryan.Schultz@aer.ca

Thank you