Distinguished Webinar Series in Earthquake Engineering and Seismology

Organized by the Canadian Association of Earthquake Engineering

Hazards to engineering structures from induced seismicity

Wednesday, April 6, 2022, 3:00 p.m. EDT

Registration Link: https://us02web.zoom.us/webinar/register/WN_RMvENWjzT6G-llmaih-cNA

Abstract

There has been a significant increase in the rate of earthquakes associated with hydraulic fracturing and wastewater disposal. The increased rate of seismicity and the potential for localized strong ground motions from very shallow events poses an increased hazard to critical infrastructure such as major dams—particularly for older high-consequence structures. I overview the factors that affect the likelihood of damaging ground motions and examine their implications for hazard assessment and mitigation. A strategy to reduce the likelihood of potentially damaging ground motions should contain elements of both mitigation and avoidance. For critical facilities, an effective strategy includes (i) an exclusion zone having a radius of ~5 km; and (ii) a monitoring-and-response protocol to track the rate of events at the M> 2 level within 25 km, with adjustment of operational practices if required. An exclusion zone provides a deterministic safety margin to ensure the integrity of those few facilities for which failure consequences are unacceptable. Real-time monitoring tied to a response protocol can be used to control the rate of significant events and thereby limit the hazard more broadly.

Gail M. Atkinson

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https://www.uwo.ca/earth/people/emeritus/atkinson.html

Short Bio: Gail M. Atkinson

Gail Atkinson is a Professor Emeritus at Western University, Canada, who conducts research at the engineering-seismology interface. She specializes in seismic hazards and ground motions, with a focus over the past decade on hazards due to induced seismicity. She has been active in the development of seismic design regulations for buildings, dams, and nuclear power plants, has been involved in hundreds of site-specific seismic hazard evaluations, and has authored over 200 research articles. Professor Atkinson has served as President of both the Seismological Society of America and the Canadian Geophysical Union, currently serves as a member of the U.S. National Earthquake Hazard Mapping Advisory Board and the U.S. Earthquake Prediction Evaluation Council and is a Fellow of the Royal Society of Canada. In 2021 she was recognized with the Harry Fielding Reid Medal of the Seismological Society of America, awarded for outstanding career contributions to seismology.

Hazards to engineering structures from induced seismicity

Gail M. Atkinson

Canadian Earthquake Engineering Association Seminar

April 6, 2022

Western
UNIVERSITY · CANADA

For information and publications:
www.inducedseismicity.ca

Overview

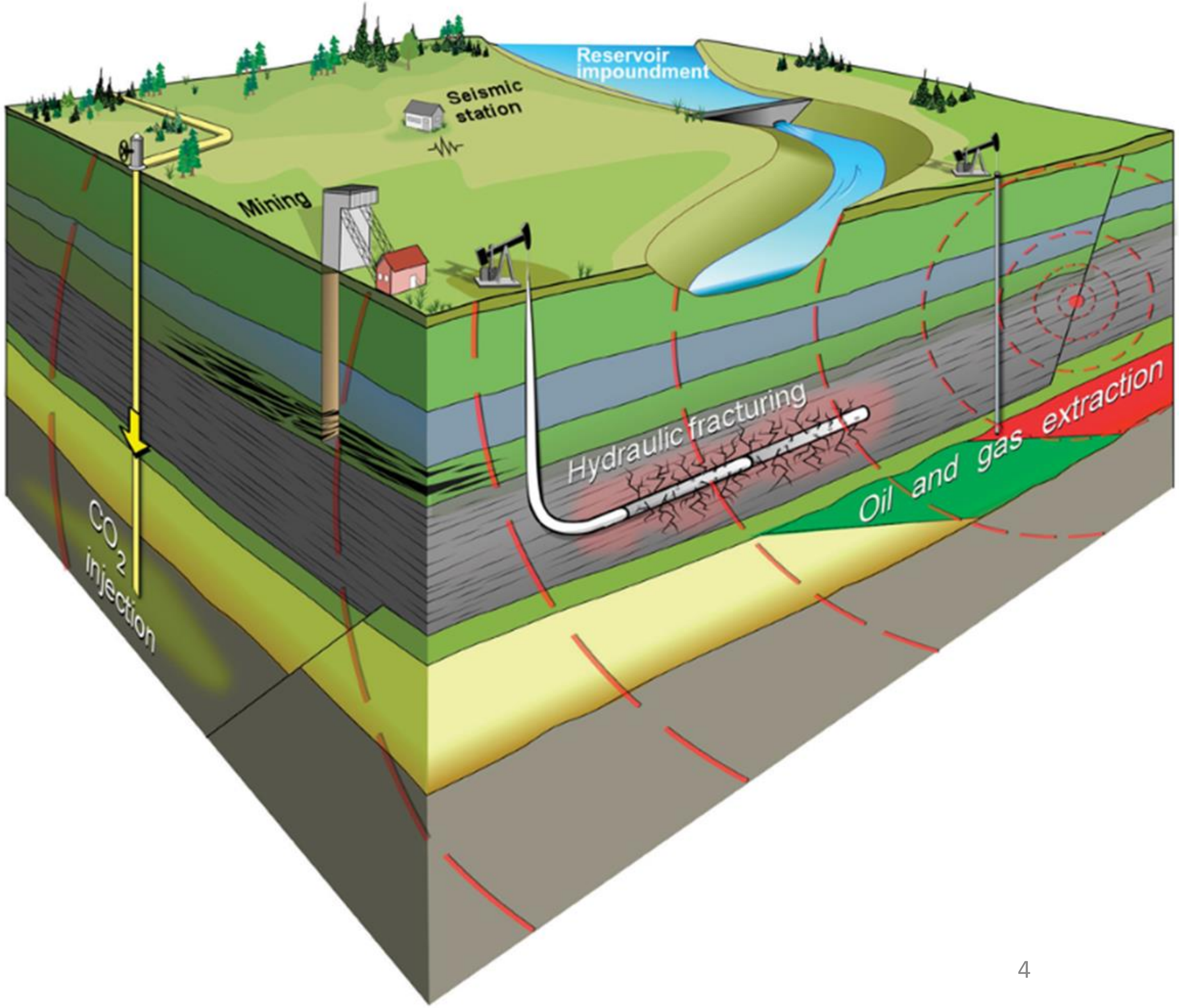
1 –Induced seismicity processes and observations

2 – Ground motions from induced events

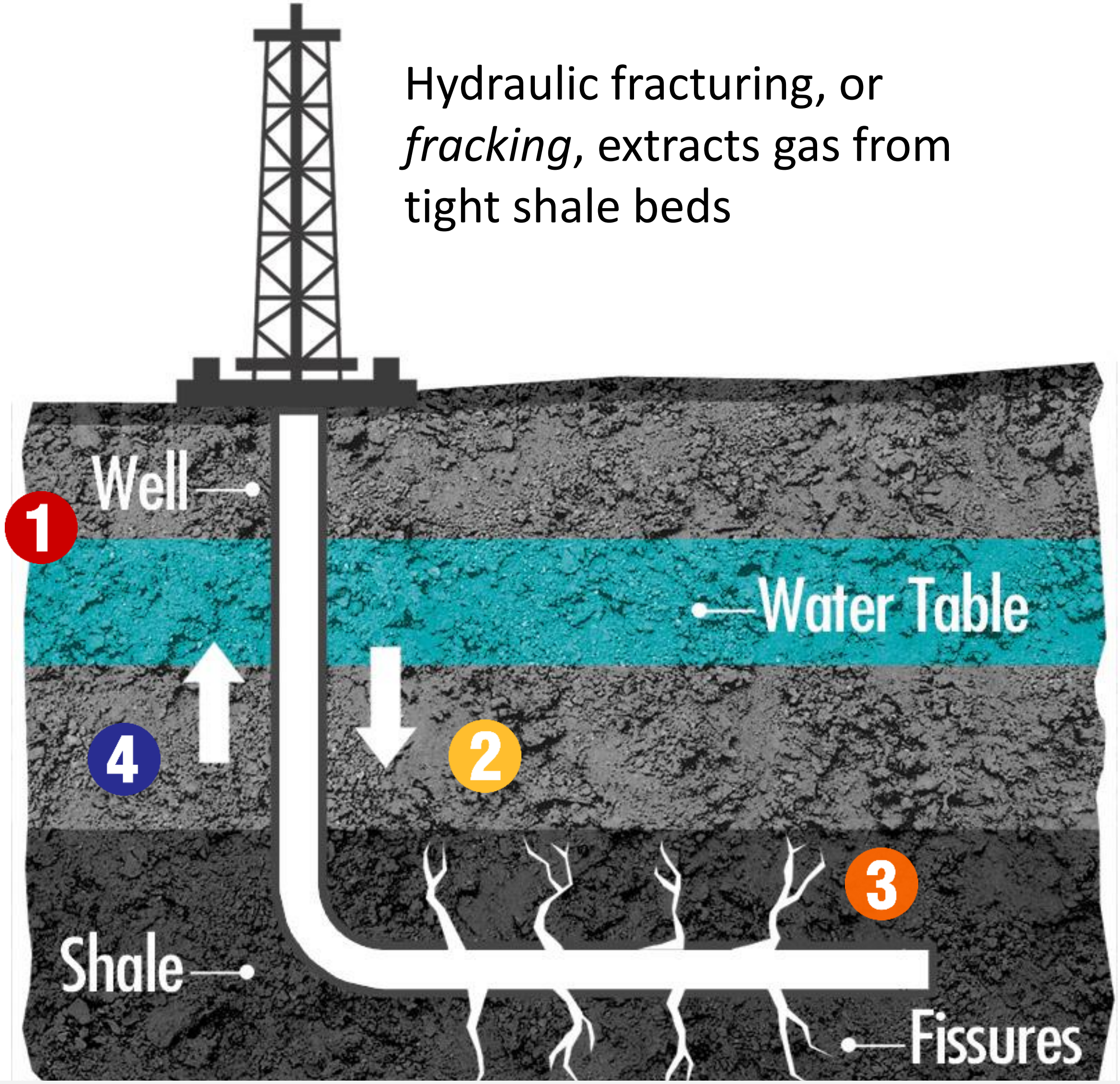
3 – Evaluation and mitigation of seismic hazard from induced events

What is induced seismicity?

- Induced seismicity: seismic events that are induced (or triggered) by man-made activities including reservoir impoundment, mining, oil and gas production, fracking, wastewater disposal, etc.
- Focus today is seismicity triggered by oil and gas activity in the western Canada sedimentary basin (WCSB), by hydraulic fracturing



Hydraulic fracturing and earthquakes



Hydraulic fracturing, or *fracking*, extracts gas from tight shale beds

2 Inject water, sand and chemicals at high pressure

3 Fracking opens small cracks (making very tiny earthquakes)

4 The sand particles hold the cracks open: gas flows up the well

Fluid pressures may find a path to pre-existing fault, triggering earthquakes; activation may also occur via stress transfer

Some examples of induced events

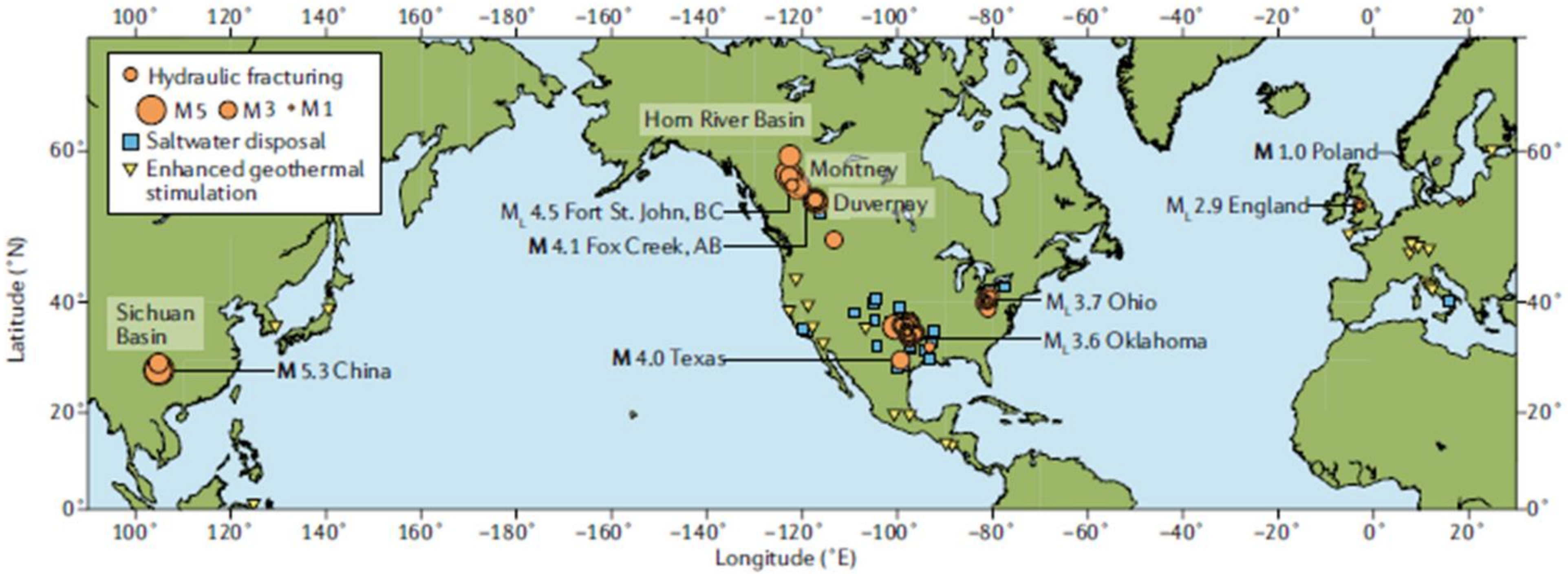


Figure: Atkinson, Eaton and Igonin, 2020

Fig. 1 | Global distribution of induced seismicity. The global distribution of hydraulic fracturing (HF), enhanced geothermal stimulation and saltwater disposal induced seismicity (data taken from REF.[158]). Documented cases of HF-induced seismicity include the USA (Oklahoma, Texas, Ohio), Canada (Alberta, BC), England, Poland and China. Note that the labels reference HF events; in some areas, there are larger saltwater disposal events in the same region that are not labelled (such as in China and Oklahoma).

- Historical: Rocky Mountain Arsenal (M5.3, 1967), fluid injection, 1962-1966; Gazli, Uzbekistan, gas recovery (M7.2), 1976-1984: Water Reservoirs: Lake Mead (M5), Koyna (M6.3), Oroville (6.1).
- Many countries: U.S., Italy, Russia, Germany, Netherlands, India, etc. Many provinces: B.C., Alberta, Ontario, Quebec.
- Oil/Gas: Rocky Mtn House Alberta, gas extraction, 1975-2000; Youngstown, Ohio (M4.0), fluid injection, 2011; Prague, Oklahoma (M5.7), fluid injection, 2011.
- Largest hydraulic-fracture induced events worldwide have been in western Canada (M4.6 Ft. St. John), Korea (M5.5) and China (M5.7)

Triggering earthquakes: necessary conditions

- a source of stress perturbation;
- a pre- existing critically stressed fault with sufficient surface area to host the event (e.g. M4to5 earthquake ~1km); and
- a coupling mechanism that directly or indirectly connects the source to the fault

So: it is good practice to avoid injection near known faults, but not all faults can be imaged in advance. Most triggered events have occurred on previously unknown faults, even in areas with good 3D seismic imaging.

Mechanisms for fault reactivation

- pore-pressure effects (reduce effective stress on fault)
- poroelastic effects (transfer stress perturbation through rock frame)
- aseismic slip (HF causes creep on frictionally stable parts of fault system that transfer stresses to unstable regions beyond)

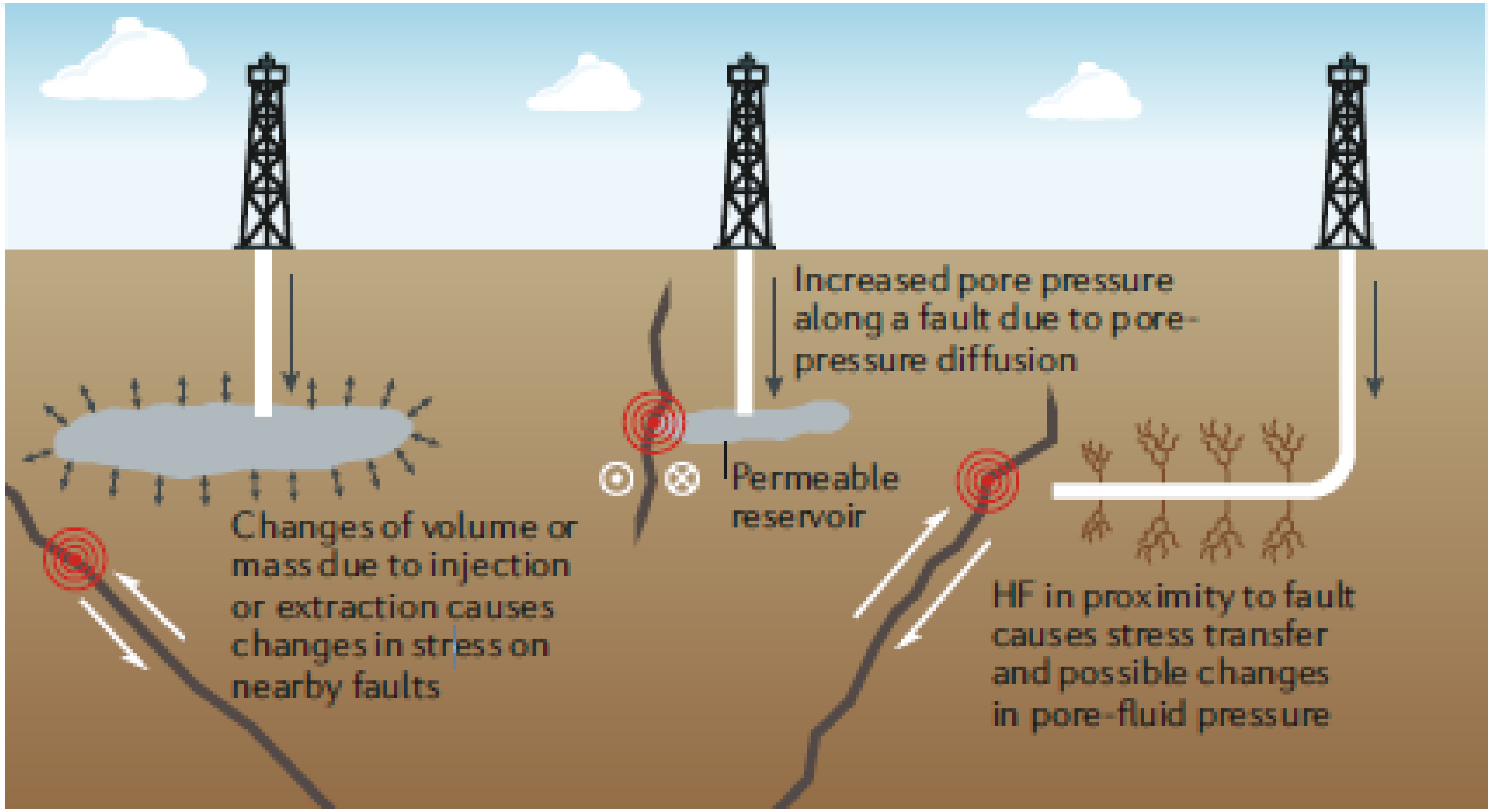


Fig. 2 | **Possible triggering mechanisms of HF-induced seismicity.** Direct and indirect pathways to connect stress perturbation to critically stressed faults and, thereby, trigger earthquakes. Pathways include large-volume disposal of fluids into a permeable zone that is in hydrological contact with faults, a change in stress due to an overlying load or hydraulic fracturing (HF) in proximity to faults. Adapted with permission from REF.[10], Cambridge University Press.

Figure: Atkinson, Eaton and Igonin, 2020

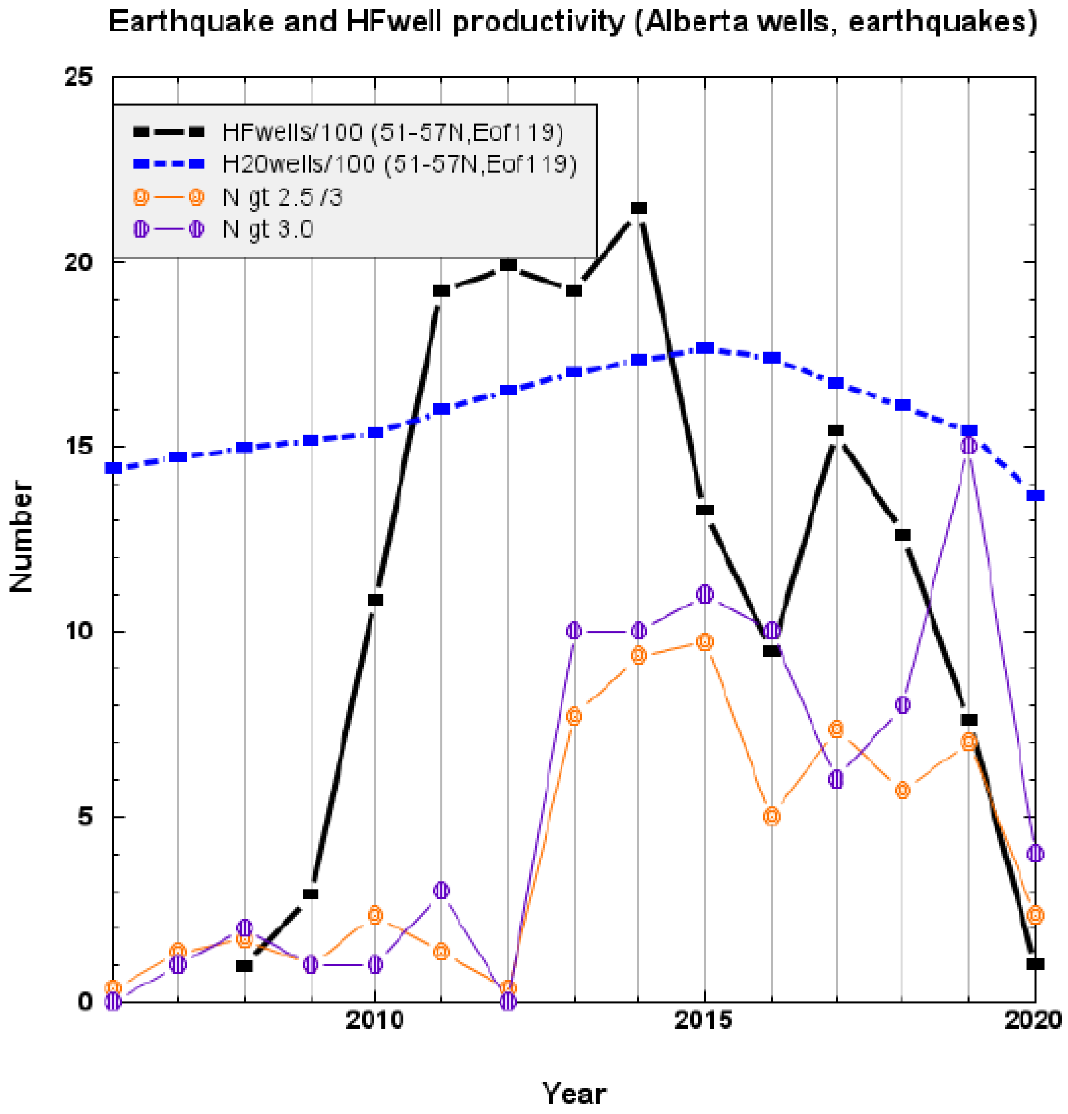
Can we predict whether induced seismicity will occur?

- Overall mechanisms reasonably well understood (change in stress, pore pressure changes, existing faults/fractures, etc.)
- Hundreds of thousands of wells, frack, injection operations
  - Only a small percentage of these have anomalous (unintended) induced seismicity (e.g. M>2)
- There is currently no validated predictive model to determine whether anomalous seismicity will be induced based on operational and geological parameters for a particular planned operation
- None of the larger induced events were predicted in advance (rather, we seek explanations after the fact)

So the short answer is No….. Though we know likelihood varies with conditions

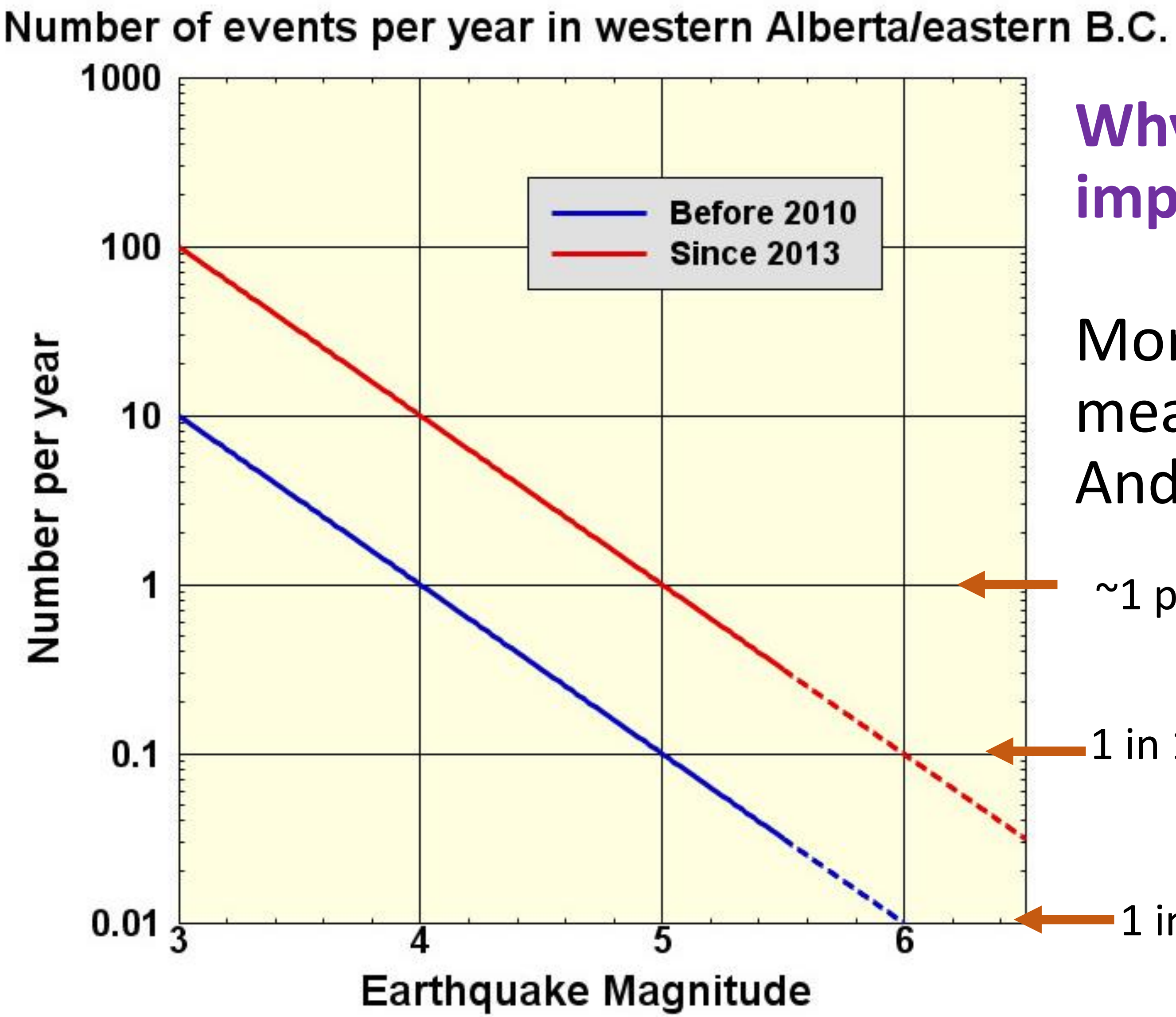
Observed rates of earthquakes of M>3

- About 60% of earthquakes in the Western Canada Sedimentary Basin since 2013 appear related to HF in time and space (Atkinson et al., 2016; Ghofrani and Atkinson, 2021); about 30% linked to wastewater injection (10% natural)
- increase in annual rate of **M**>3 in Alberta (from ~1 to 2/yr to ~10/yr) follows dramatic increase in HF wells (while # of water wells constant)
- ~1% of HF wells in Alberta, and ~15% of HF wells in northeast B.C., are associated with **M**>2 seismicity in time and space (Ghofrani and Atkinson, 2021)



Ghofrani and Atkinson, 2021

Figure 10. Yearly counts of earthquakes and HF wells in area 51-57N, east of 119W. HF well count is divided by 100. Disposal wells counts (divided by 100) in each year also shown. Count of M≥2.5 is divided by 3 (to be equivalent to rate for M≥3, for assumed Gutenberg-Richter slope of 1). HF wells database for 2020 is incomplete.



Why the ramp-up is important:

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

~1 per year

1 in 10 chance per year

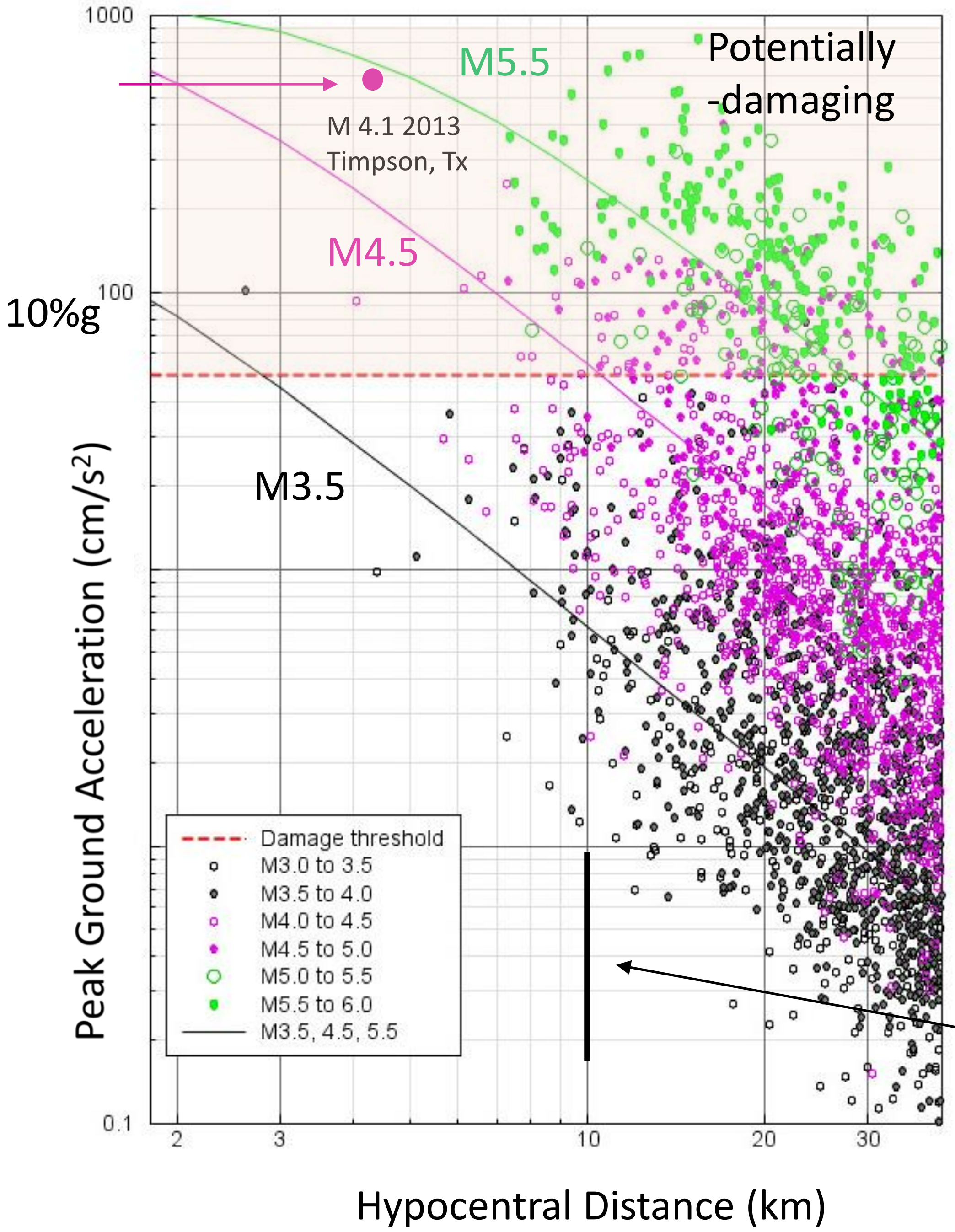
1 in 100 chance per year

The Gutenberg-Richter relation:
For every 100 M3 events, we will get ~10 M4 events, about 1 M5 event…. And so on

Ground motions from induced events

- Ground motions (all event types) are a combination of source, path and site effects
- Source effects generally characterized by moment magnitude (low frequency) and stress parameter (high frequency)
  - Induced events may have relatively low stress because they have a shallow focal depth, and many studies suggest that stress increases with increasing depth
- Path effects (geometric spreading and anelastic attenuation) similar to natural earthquakes but induced events can be observed/felt at closer distances due to shallow focus
- Site effects should be the same for natural and induced events (i.e. depend on the site, not the nature of the source or crustal path)

Ground motion models (GMMs) for induced events



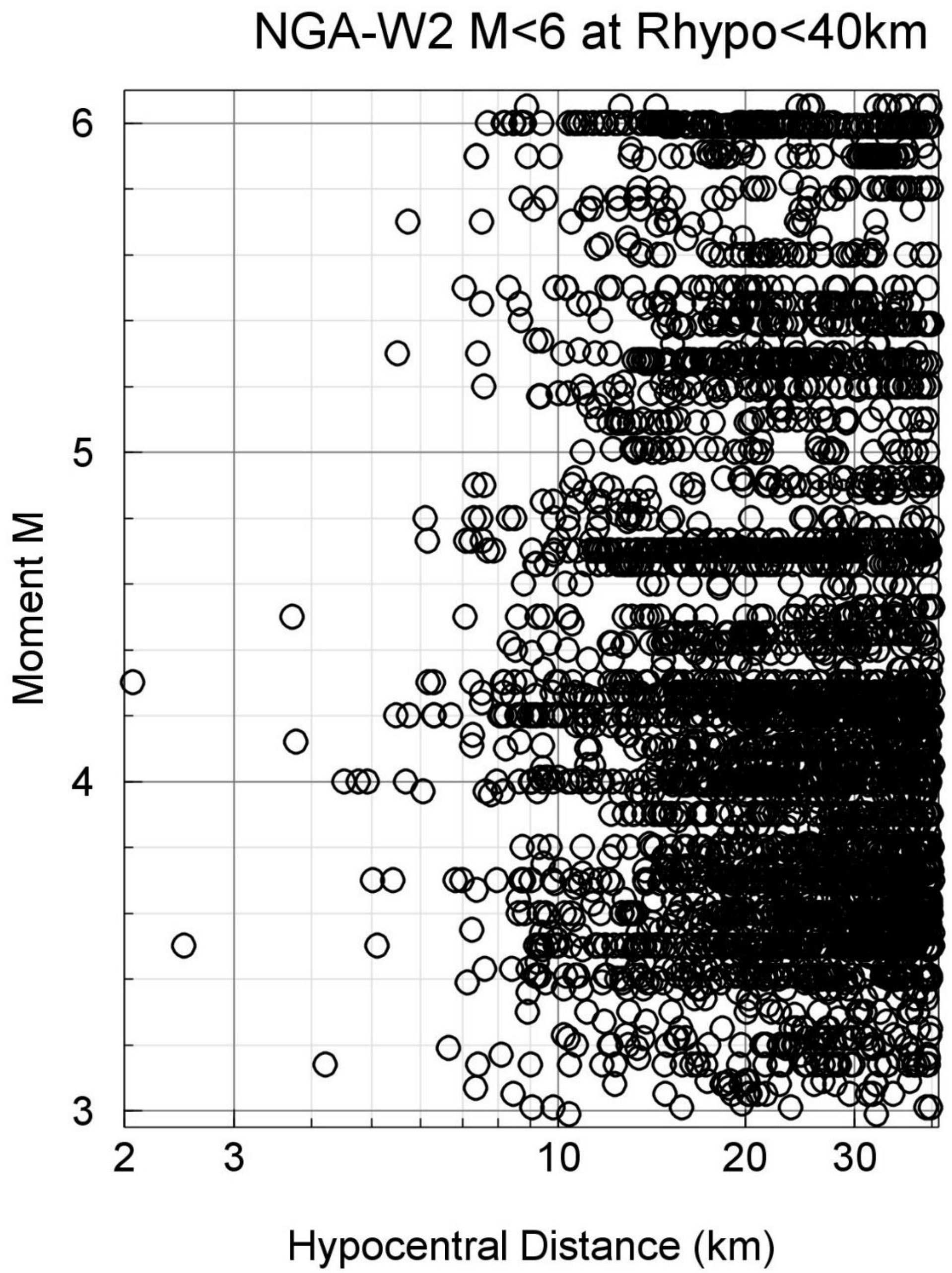
Early GMMs (e.g. Atkinson, 2015) assumed that shallow natural events are good analogues for induced events,
IFF we correctly model scaling of motions from small-to-moderate events at close distances (*note*: most NGA-W2 GMMs do not satisfy this condition; they focus on scaling for larger events)

e.g. California PGA data shown at left – note large scatter, demonstrating that sometimes moderate events cause large ground motions, especially at close distances

It's the shallow focal depth – combined with variability - that drives damage potential for induced events of relatively low magnitude (M4 to 5)

~10 km avg depth for natural events

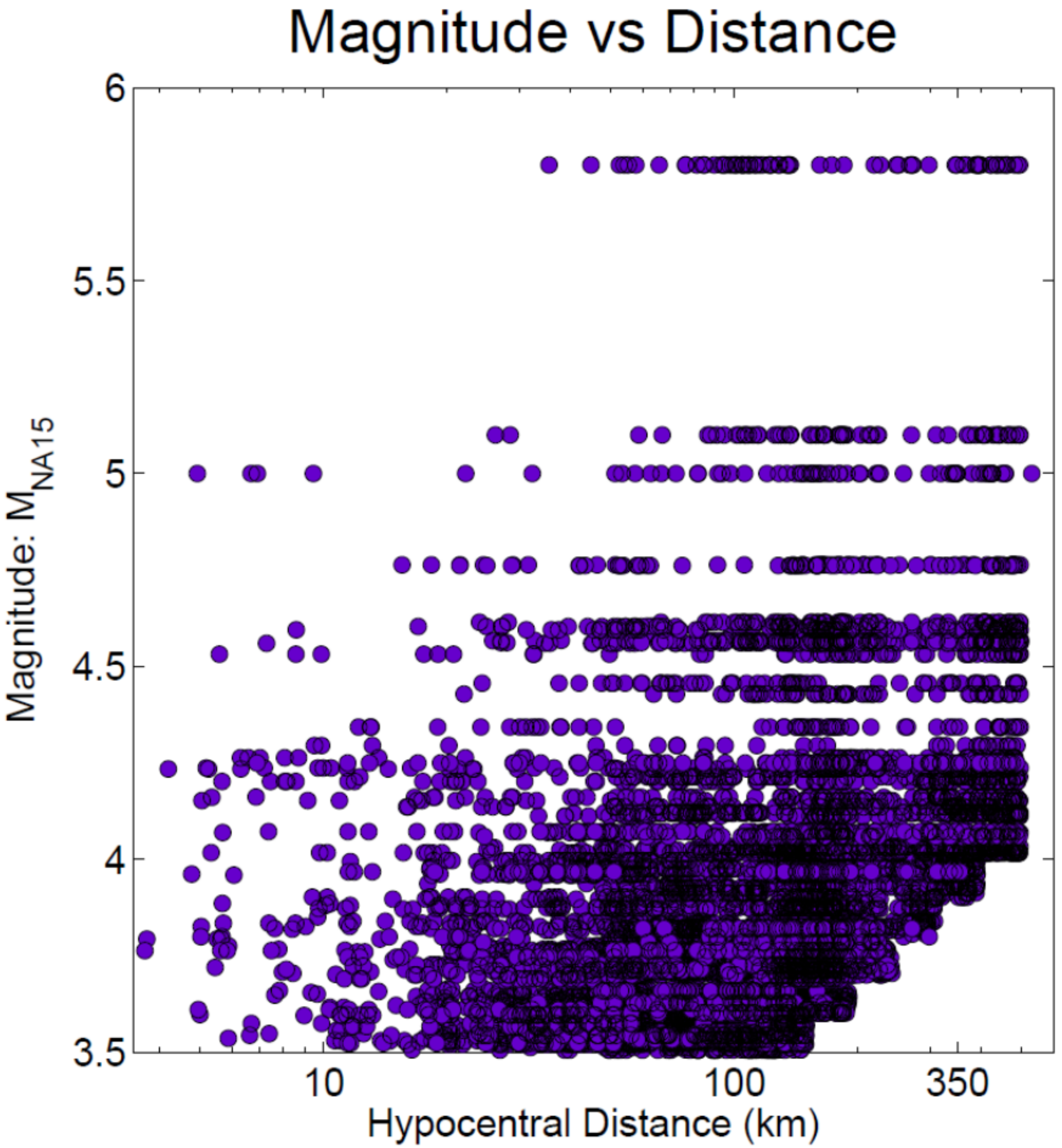
Evolution of GM models: Data distribution in magnitude-distance



- **Natural events (California) used as analogues (Atkinson, 2015)**
- Induced events Oklahoma (lots)
- Induced events western Canada (WCSB) – sparse at close distances

e.g. Atkinson, 2015: Moderate natural events in California at short hypocentral distances used as analogues for induced events in central/eastern North America

Evolution of GM models: Data distribution in magnitude-distance



Natural events (California)

Induced events Oklahoma (lots)

Induced events western Canada (WCSB) – sparse at close distances

e.g. Novakovic et al., 2018: Oklahoma
7278 records from 194 earthquakes (**M** 3.5 – 5.8) recorded on 101 seismograph stations. Consider records within a cut-off distance that increases from 120 km for **M** = 3.5 to 500 km for **M** ≥ 4.0 events.

Evolution of GM models: Data distribution in magnitude-distance

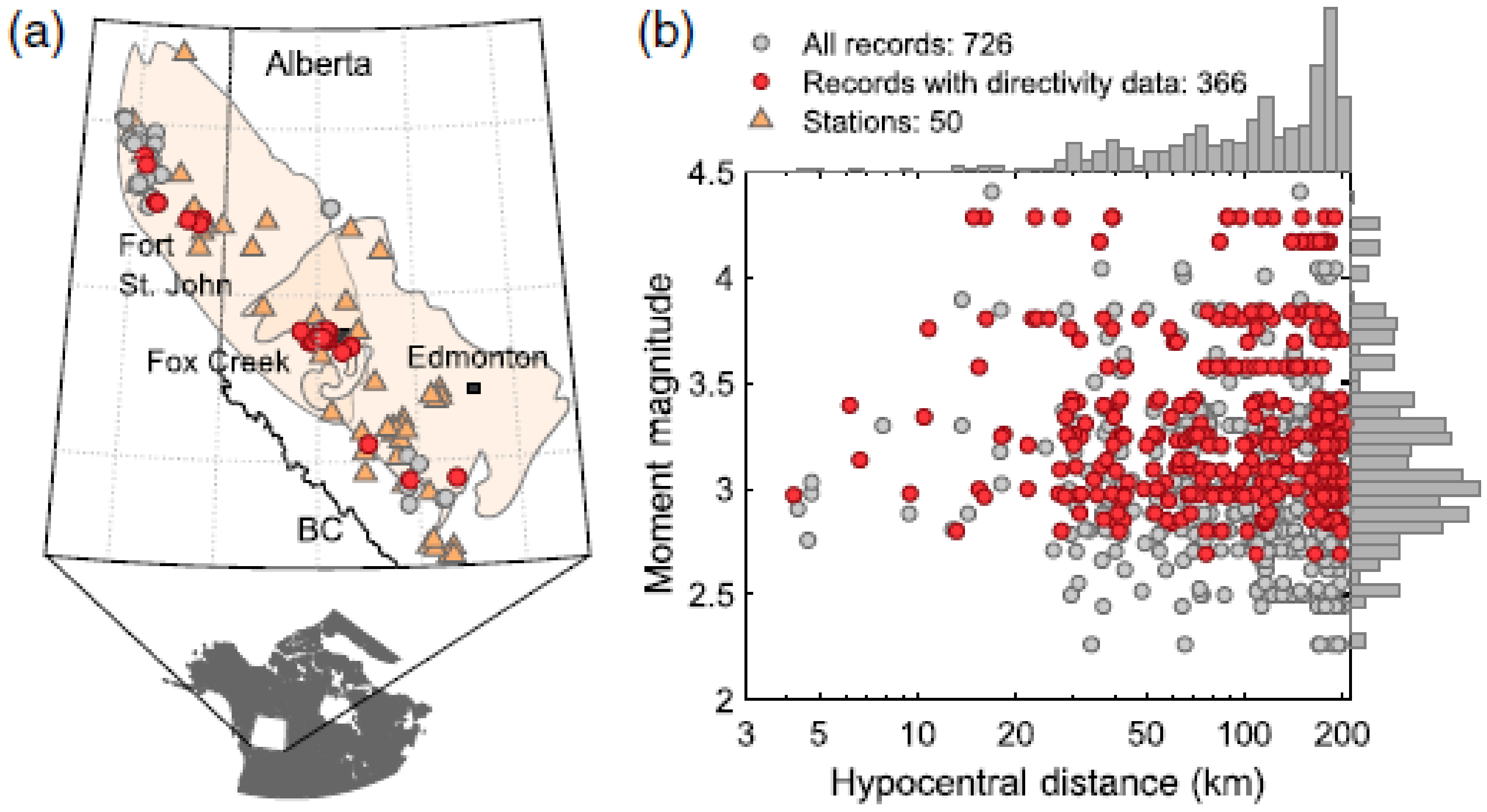


Figure 1. Database of study earthquakes and records. (a) Map of stations (triangles) and study earthquakes (light circles); those with resolvable directivity are shown as dark circles. Shaded region is the western Canada sedimentary basin (WCSB). (b) Record distribution by moment magnitude and distance. The color version of this figure is available only in the electronic edition.

- Natural events (California)
- Induced events Oklahoma (lots)
- **Induced events western Canada sedimentary basin (WCSB) – sparse at close distances (but private operators have many more data!)**

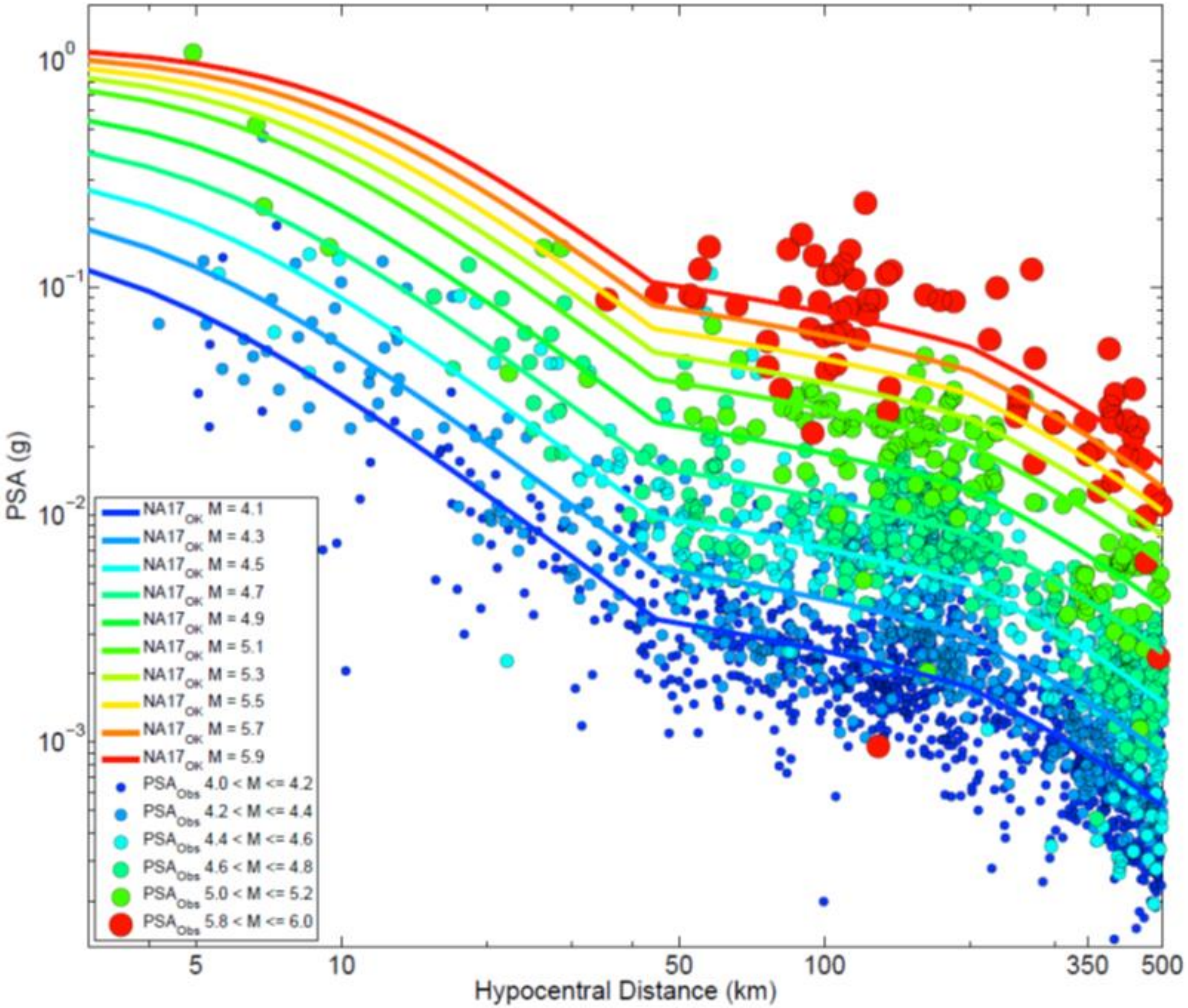
e.g. Holmgren et al., 2020: Alberta
726 records from 92 earthquakes (**M** ~2.5 – 4.5) recorded on 50 seismograph stations.

Ground-motion models for induced events

- Due to data limitations for large M and/or close distances (especially for public data in western Canada), models that have scaling constrained need to be used (to ensure realistic amplitudes)
- Some approaches have used empirical constraints
  - Atkinson, 2015 (and update by Atkinson and Addo, 2018, 2019 for events in B.C.); Abrahamson and Addo (2018) (update of ASK14 NGA-W2 using induced data)
- Other approaches constrained using seismological model, but calibrated with data:
  - Yenier and Atkinson, 2015; Novakovic et al., 2018; Holmgren et al., 2020
- Seismological model approaches follow the generic GMM of Yenier and Atkinson (2015)
  - Main event parameters are Mw (controls long period) and stress drop (controls short-period)
  - Attenuation, site effects and overall calibration factor determined by data
  - Approach validated and calibrated extensively with California NGA-W2 database (Yenier and Atkinson, 2015)

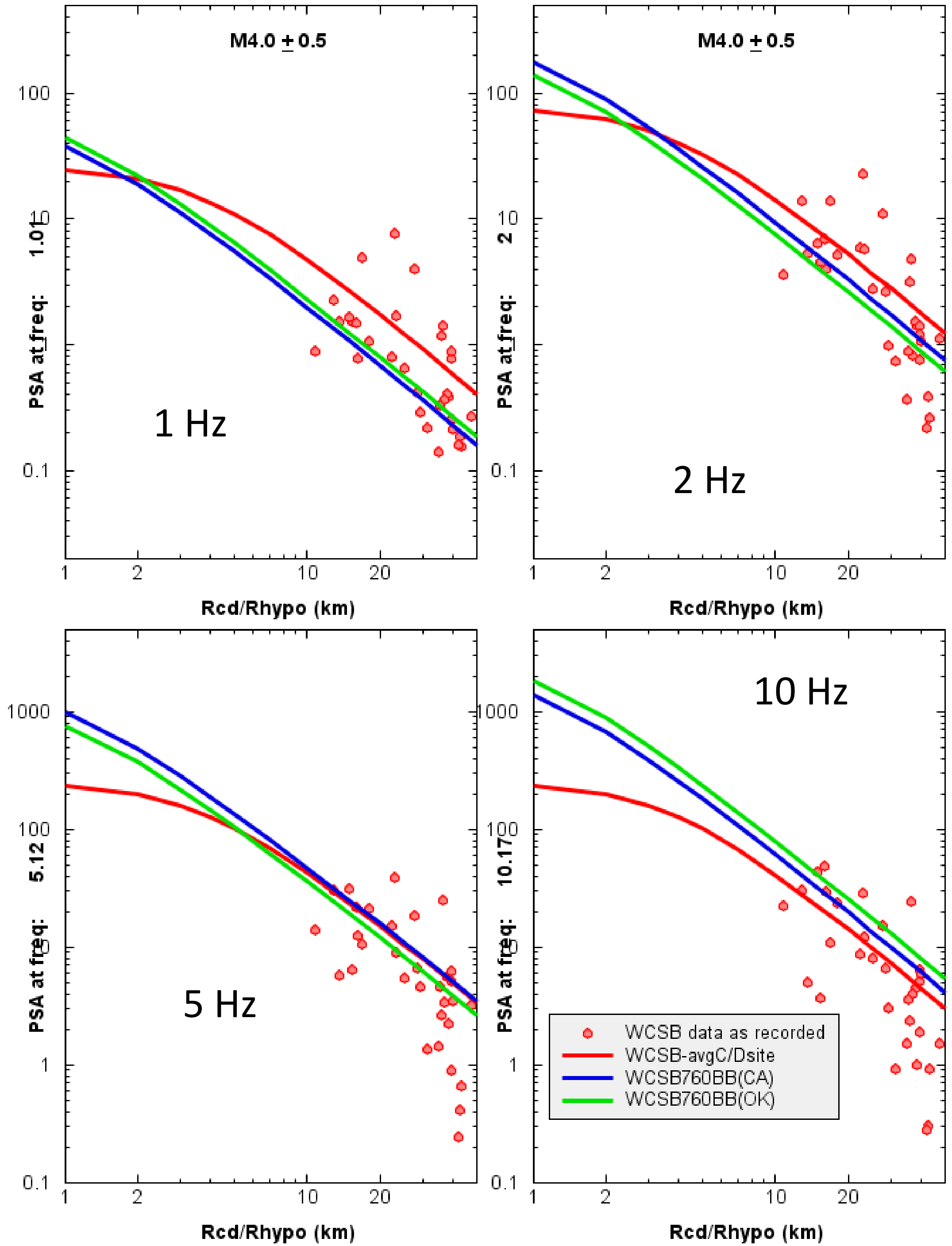
Example of generic GMM for induced events (Oklahoma): Novakovic et al., 2018

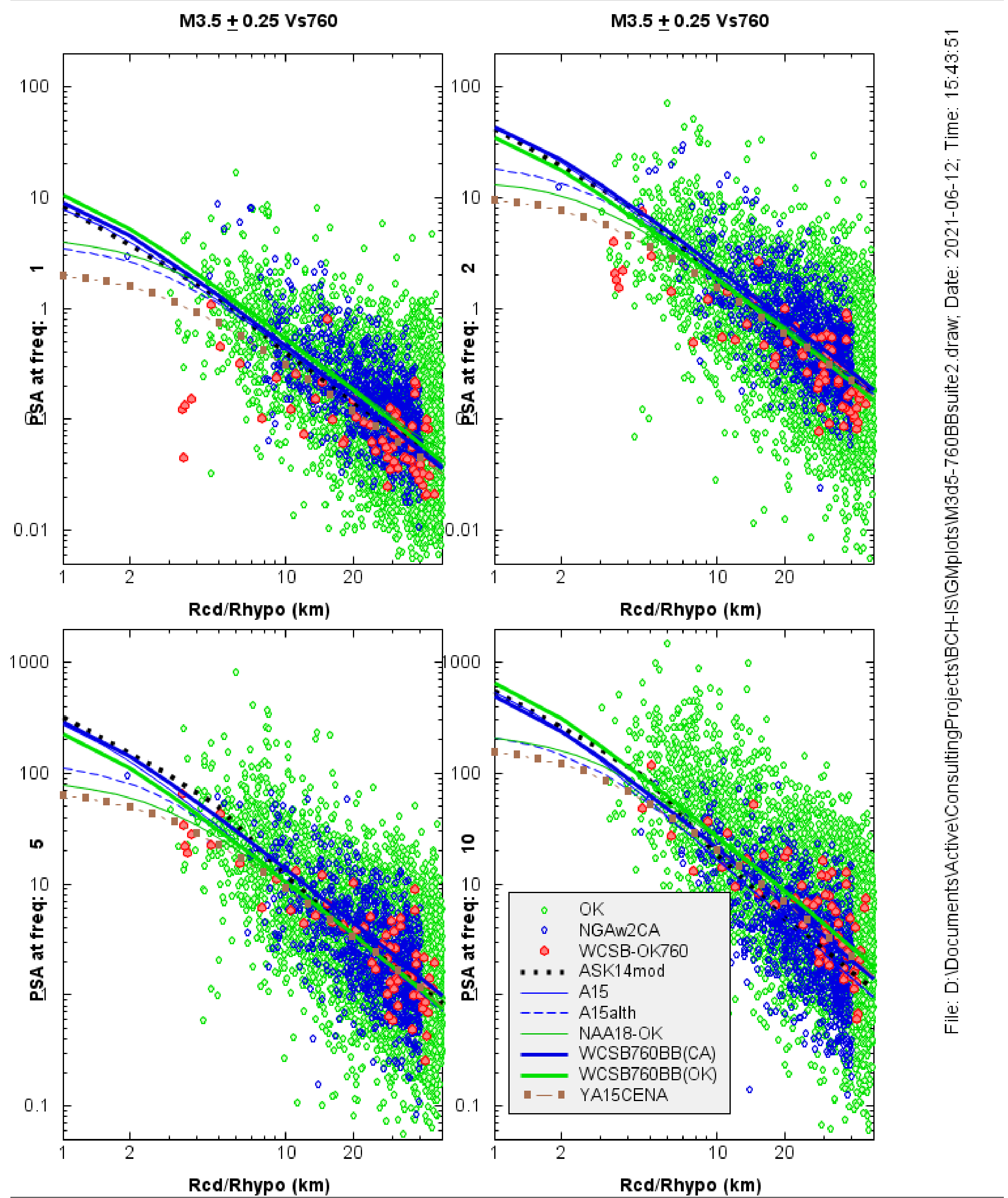
- Plot shows 5Hz PSA observations (colour-coded by M) compared to derived GMPE (observations corrected for site terms to 760 m/s)
- Scaling in magnitude/distance constrained by generic GMM approach (Yenier and Atkinson, 2015) with regional adjustments for attenuation shape and stress parameter scaling



GMM for induced events in WCSB (Holmgren et al., 2020)

- Generic GMM calibrated to regional data (i.e. as in YA15); M range of data from 2.5 to 4.5
- Regional geometric spreading and anelastic attenuation match that for natural earthquakes in central and eastern North America
- Unknown site conditions, considered C/D on average; posthole seismometer influence
- Significant directivity effects enhance ground motions in some azimuths and lead to large variability
- Comparison plot shows WCSB GMM of Holmgren et al. for M4 with WCSB data (red)
- other lines show how correction of WCSB GMM to 760m/s may affect amplitude
- Also shows how alternative near-source scaling assumption could affect amplitudes at <5 km

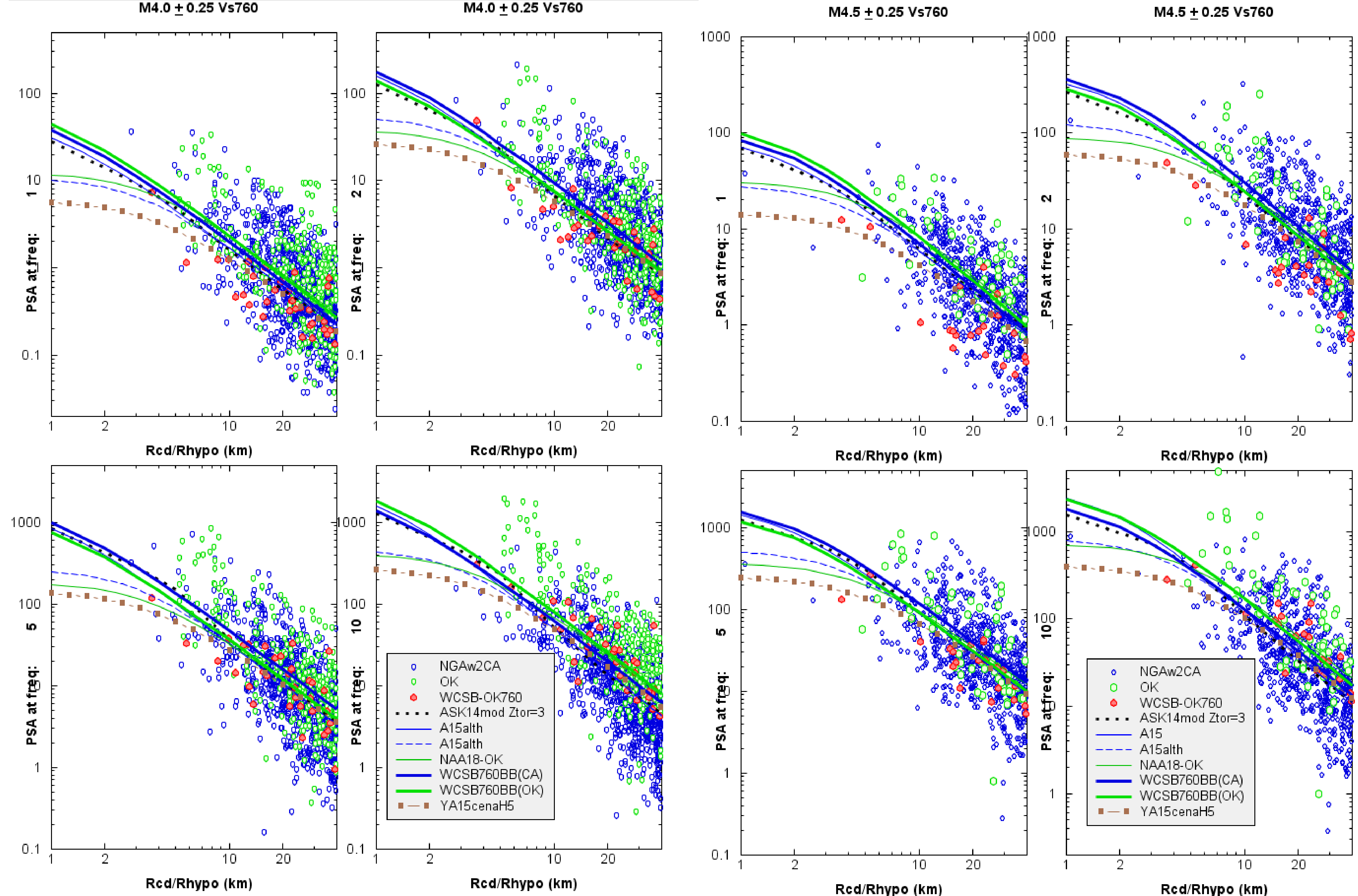




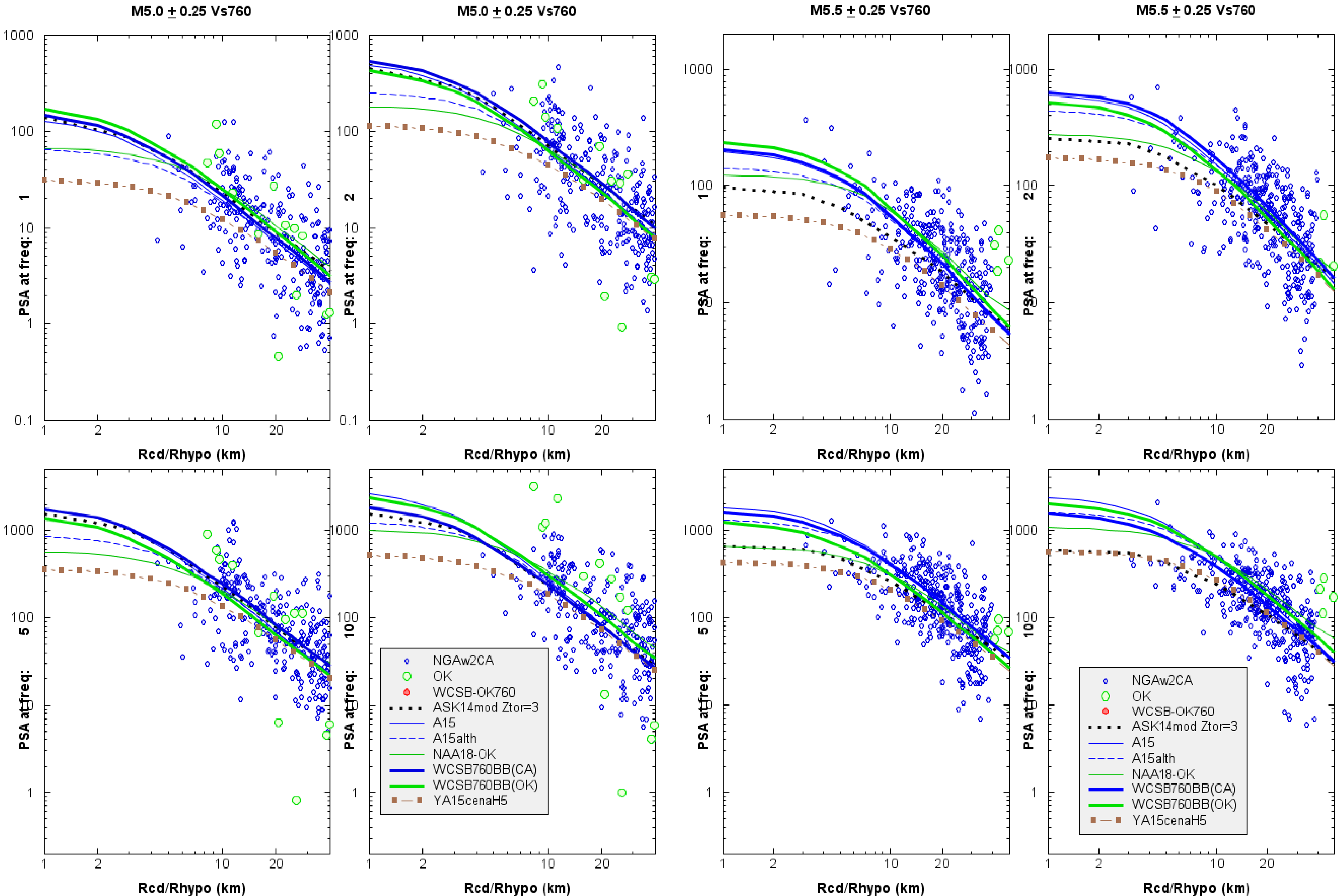
Example comparisons of GMMs and data for 760 m/s

- M3.5 (with data +/- 0.25 units; all data scaled to 760m/s)
- Lines are GMMs for 760 m/s
- Green symbols OK
- Blue symbols CA shallow events
- Red symbols WCSB (corrected to OK 760m/s reference)

For same site condition, there is reasonable agreement between all 3 datasets (OK, CA, WCSB)



M4.0 (left)
M4.5 (right)



M5.0 (left)
M5.5 (right)

Note sparseness of data for M>5; limited to NGA-W2 set

Chief limitations of GMMs for induced events

- Database limitations preclude examination of scaling of motions over a broad range of M and depth (and limit ability to distinguish characteristics that may differ between natural and induced events)
  - Common assumption is that induced and natural events would produce similar motions, on average, for same magnitude and focal depth (but average focal depth is shallower for induced events)
- Large epistemic uncertainty (model uncertainty due to database limitations), and large aleatory uncertainty (random scatter)
- More research required on how to characterize and handle the large aleatory and epistemic uncertainty, especially in site response
  - this is important for PSHA applications; site response calculations require knowledge of site conditions for both project site and seismographic reference sites

Damage potential of induced event ground motions (Atkinson, 2020)

- Can be inferred from instrumental ground motions (quantitative, but indirect)
- Can be directly observed from Modified Mercalli Intensity (MMI) observations (semi-quantitative, but direct)
- **Here we compare instrumental PGA/PGV data to felt threshold for PGA or minor cosmetic damage for PGV (dotted orange) and overall damage threshold (MMI=6) (solid orange)**
- **Damage and felt thresholds are based on typical relations between MMI and PGA/PGV in the literature**

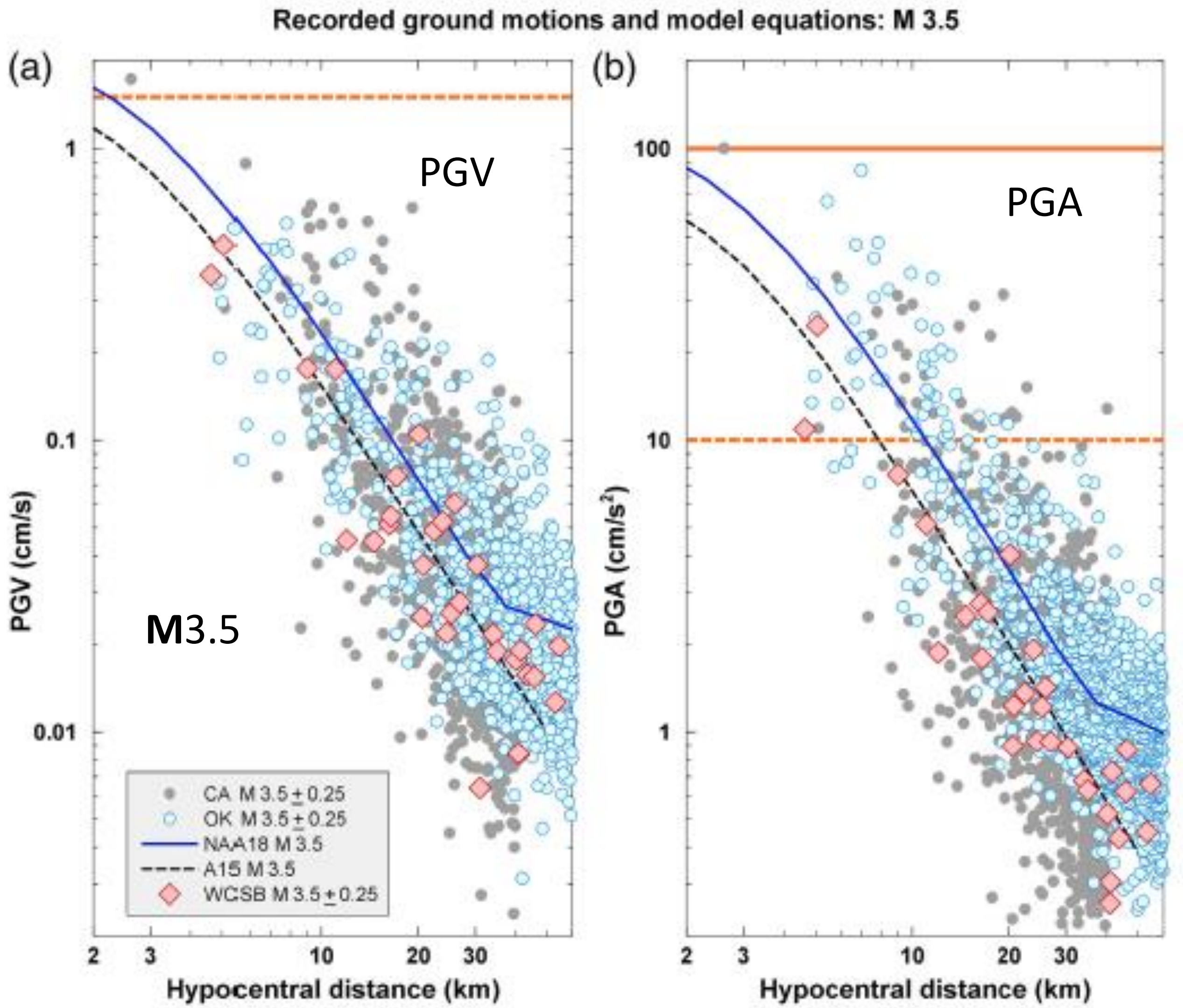


Figure 2. Recorded motions, (a) PGV and (b) PGA, of **M** 3.5 ± 0.25 for California (solid dark circles), Oklahoma (light filled circles), and the western Canada sedimentary basin (WCSB) (diamonds). California and Oklahoma motions are corrected to B/C site condition. California data were used in development of the Atkinson (2015; hereafter, A15) ground-motion model (GMM) (dashed line). Oklahoma data were used in the development of the Novakovic *et al.* (2018; hereafter, NAA18) GMM (solid line). Solid horizontal line shows typical damage thresholds, dashed horizontal line shows felt threshold for PGA, threshold for minor cosmetic damage for PGV. The color version of this figure is available only in the electronic edition.

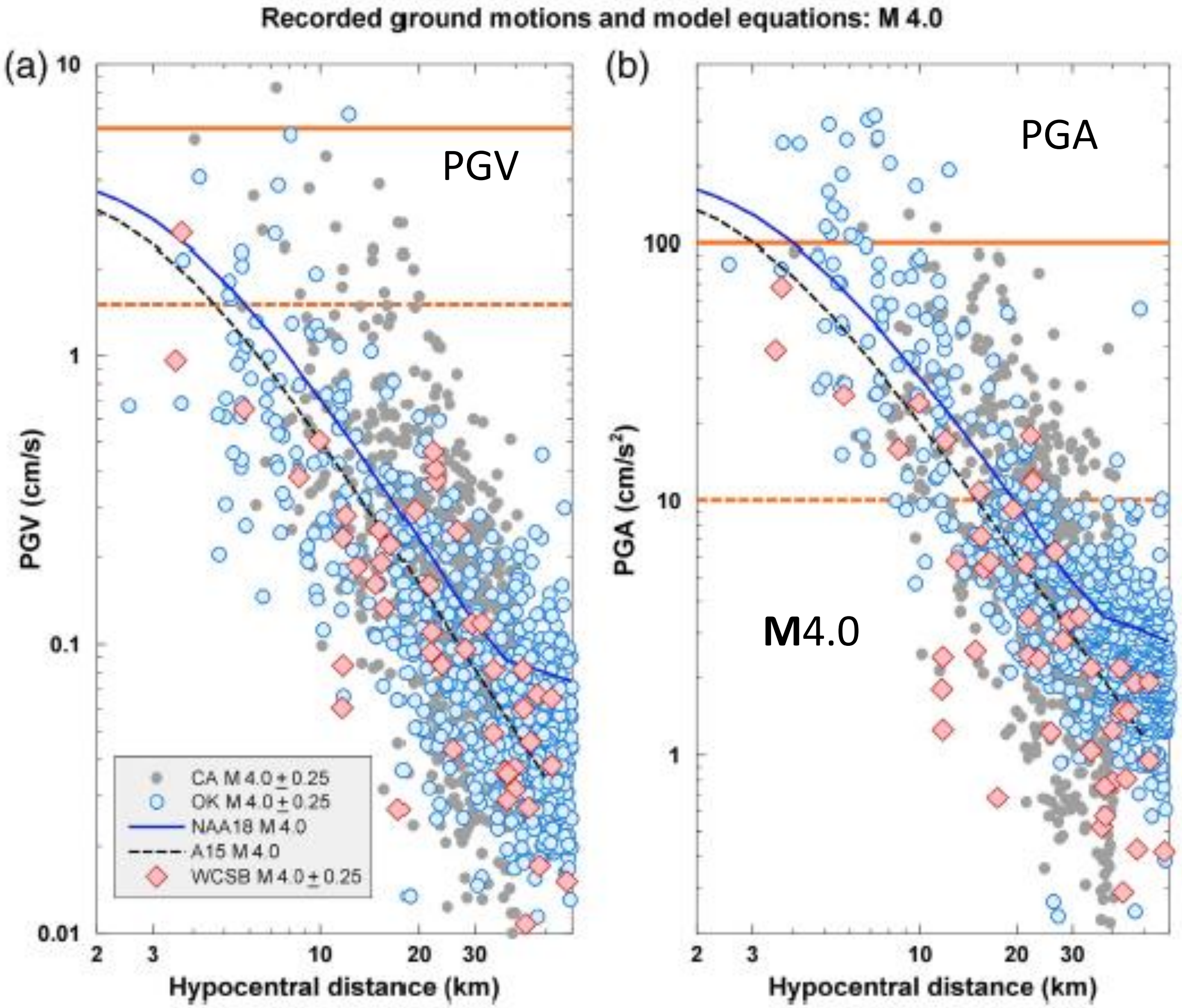
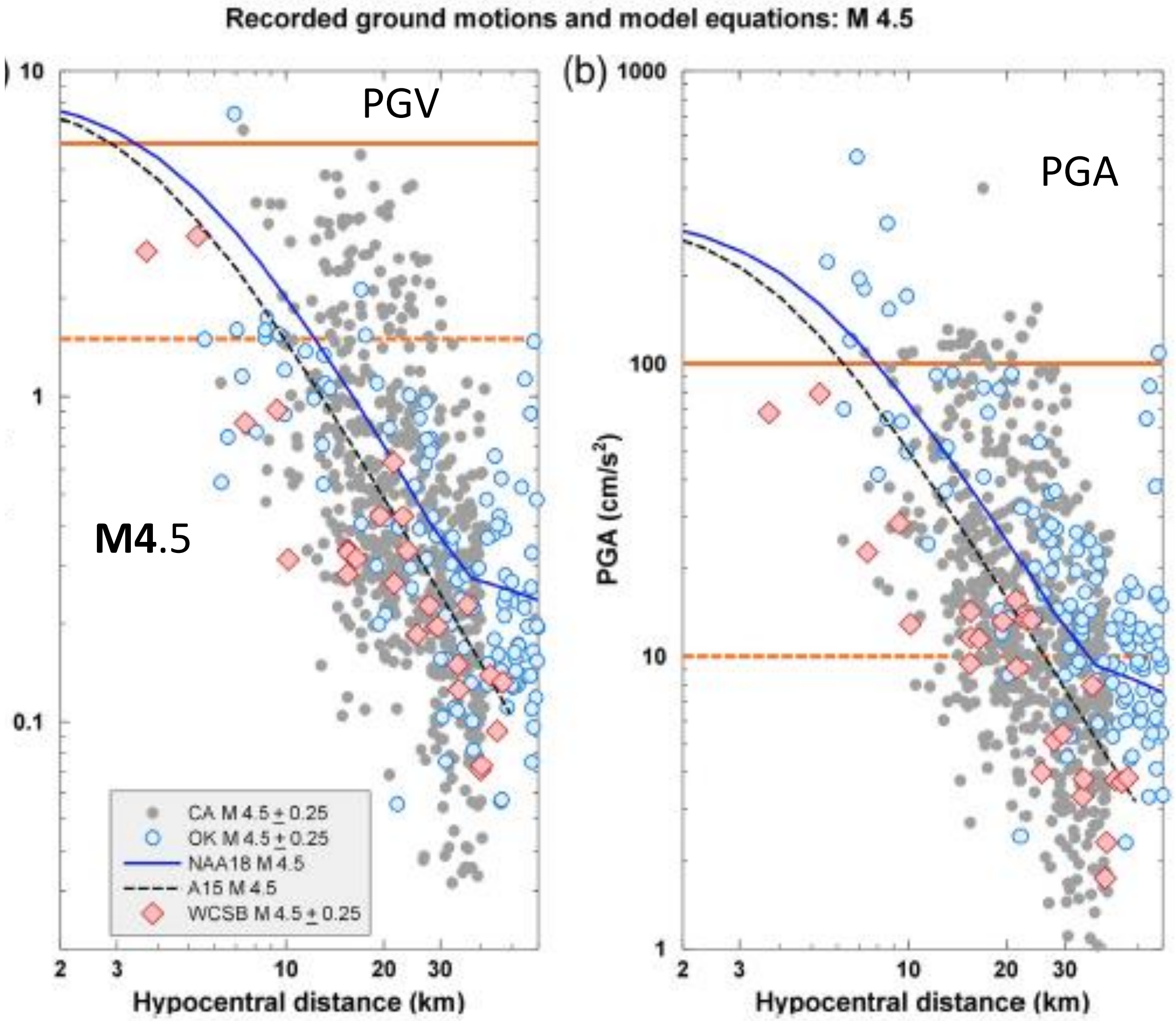


Figure 3. Recorded motions, (a) PGV and (b) PGA, of **M** 4.0 ± 0.25 for California (solid dark circles), Oklahoma (light filled circles), and the WCSB (diamonds). California and Oklahoma motions are corrected to B/C site condition. California data were used in development of the A15 GMM (dashed line). Oklahoma data were used in the development of the NAA18 GMM (solid line). Solid horizontal line shows typical damage thresholds, dashed horizontal line shows felt threshold for PGA, threshold for minor cosmetic damage for PGV. The color version of this figure is available only in the electronic edition.



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Damage potential inferred from MMI M3.6, M4.0

- Pink symbols show median, std.dev. MMI
- Lines show inferred median MMI levels for soft rock to soft soil (based on GMMs)

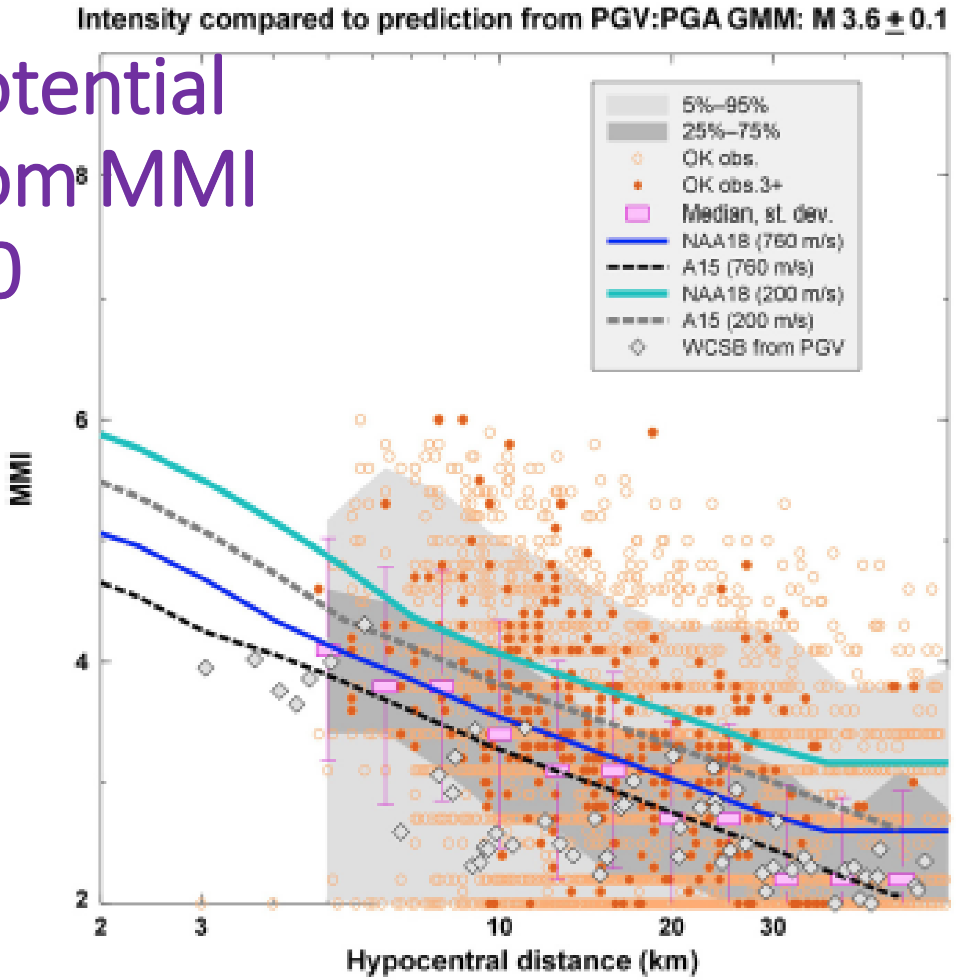


Figure 8. Modified Mercalli intensity (MMI) observations (in 1 km geocoded cells) for Oklahoma events of **M** 3.5–3.7 (circles); site conditions of MMI observations are variable. Darker symbols highlight the cells that are more reliable, having a community decimal intensity (CDI) that is based on at least three respondents. Squares with error bars show median and standard deviation, including all cells in the distance bin; no median is plotted if there are fewer than three CDI values in the distance bin. Shading shows 5th to 95th (light) and 25th to 75th (dark) percentiles of the observations (all cells). Prediction based on PGV:PGA from GMMs of NAA18 (solid line) and A15

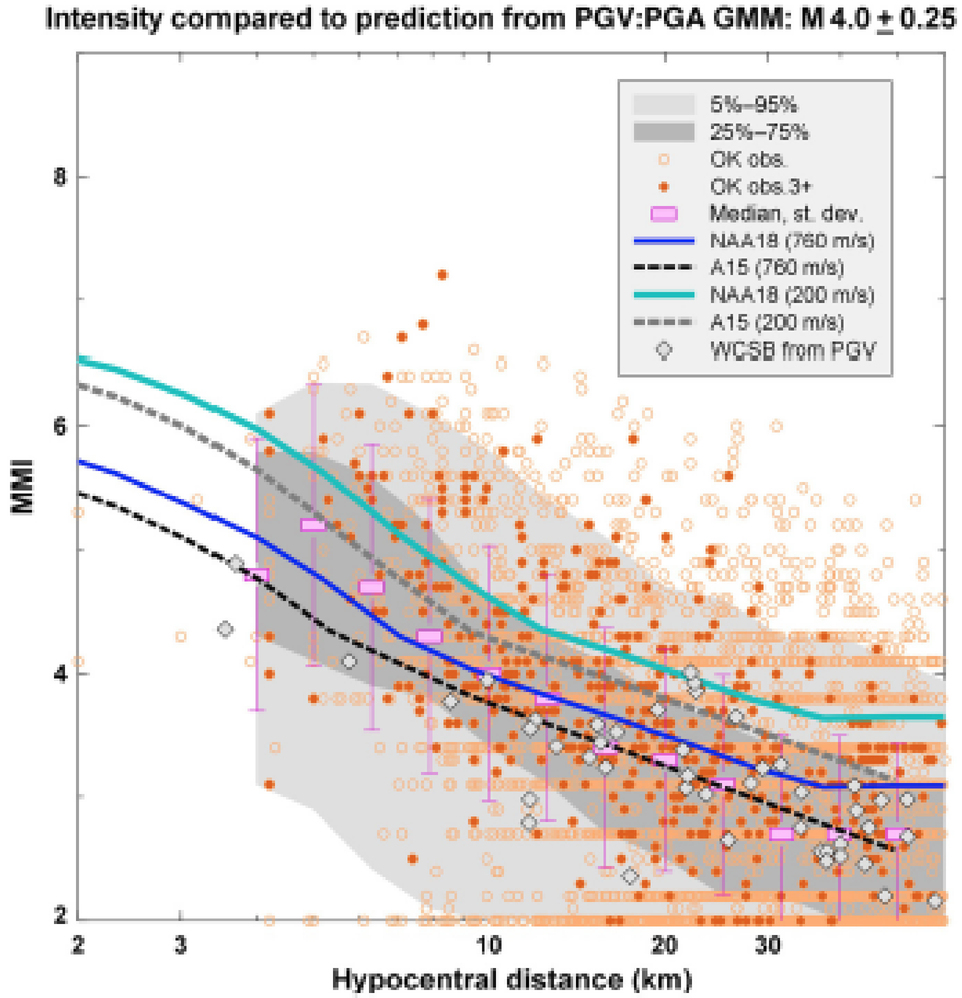
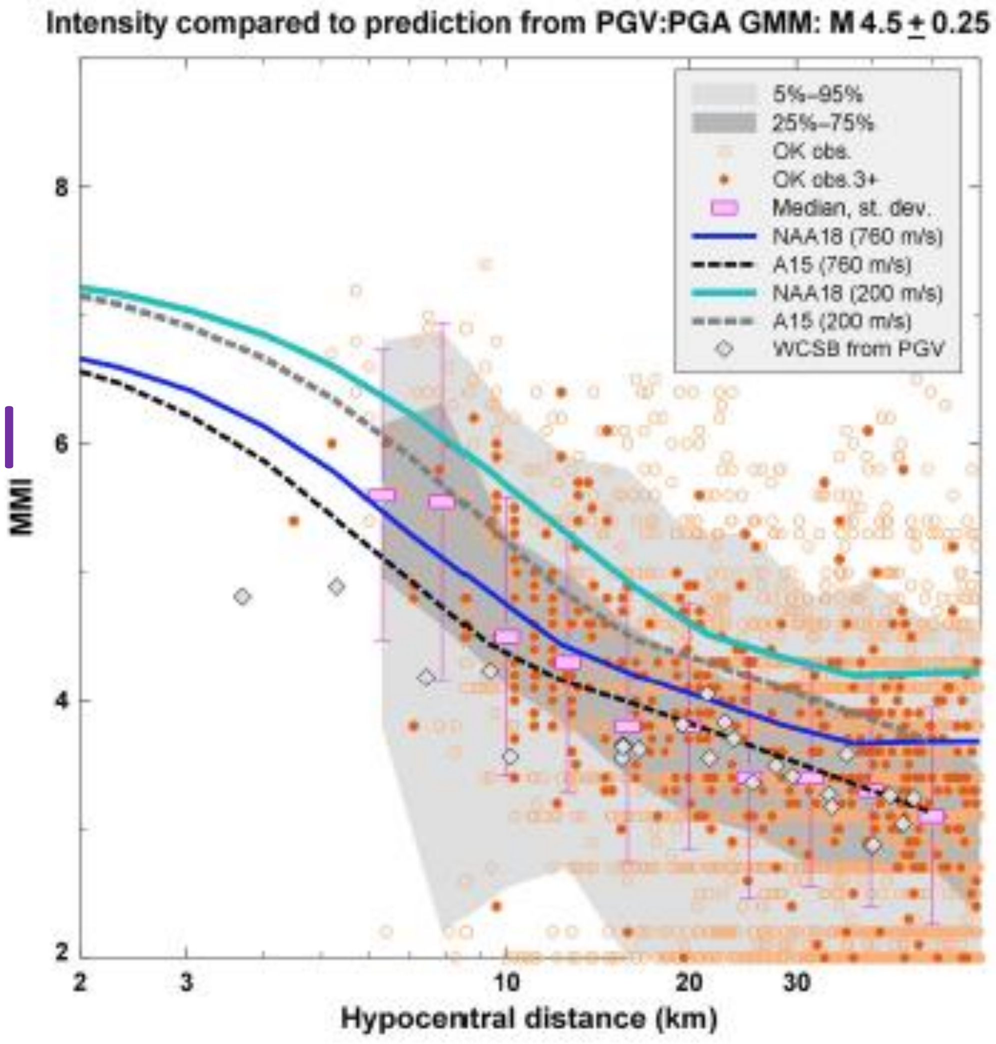


Figure 9. MMI observations (in 1 km geocoded cells) for Oklahoma events of **M** 4.0 ± 0.25 (circles); site conditions of MMI observations are variable. Darker symbols highlight the cells that are more reliable, having a CDI that is based on at least three respondents. Squares with error bars show median and standard deviation, including all cells in the distance bin; no median is plotted, if there are fewer than three CDI values in the distance bin. Shading shows 5th to 95th (light) and 25th to 75th (dark) percentiles of the observations (all cells). Prediction based on PGV:PGA from GMMs of NAA18

Damage potential inferred from MMI M4.5, M5.0



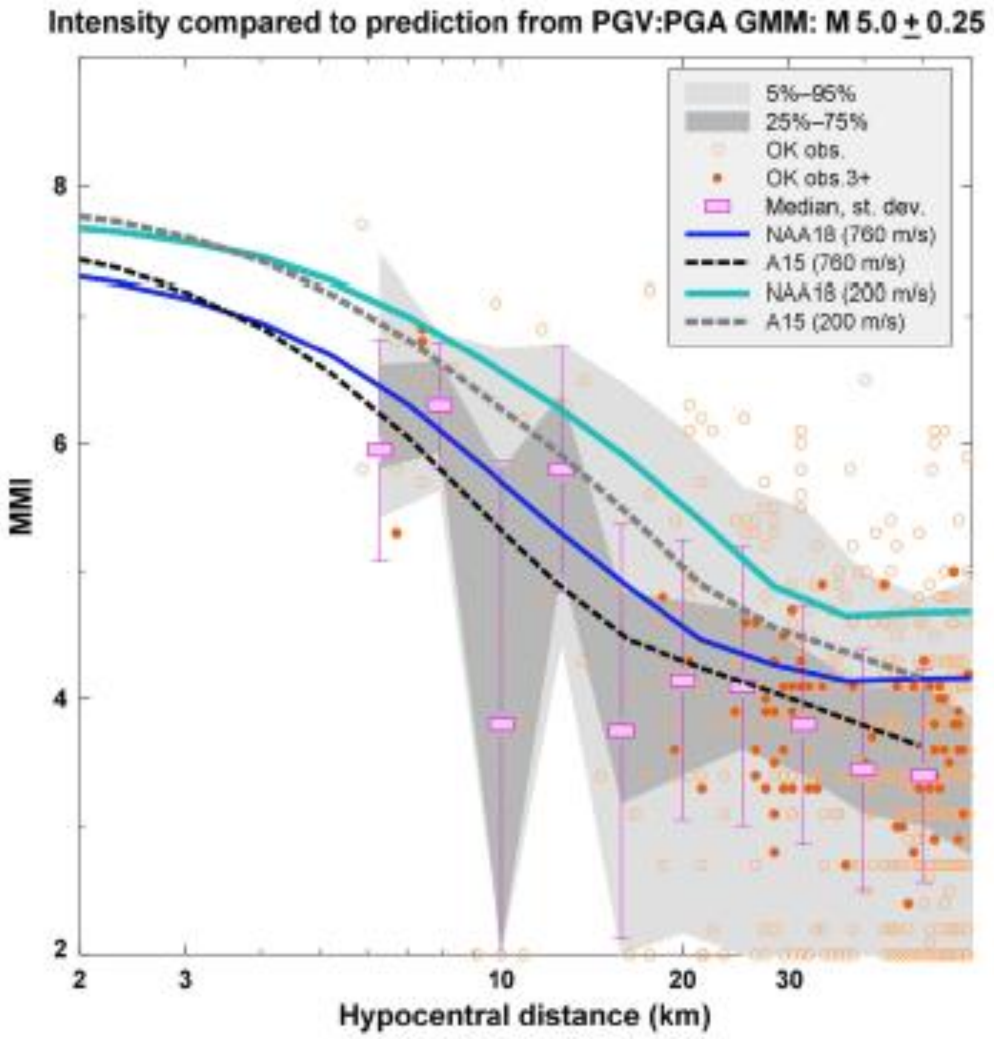


Figure 10. MMI observations (in 1 km geocoded cells) for Oklahoma events of **M** 4.5 ± 0.25 (circles); site conditions of MMI observations are variable. Darker symbols highlight the cells that are more reliable, having a CDI that is based on at least three respondents. Squares with error bars show median and standard deviation, including all cells in the distance bin; no median is plotted, if there are fewer than three CDI values in the distance bin. Shading shows 5th to 95th (light) and 25th to 75th (dark) percentiles of the

Figure 11. MMI observations (in 1 km geocoded cells) for Oklahoma events of **M** 5.0 ± 0.25 (small solid circles); site conditions of MMI observations are variable. Darker symbols highlight the cells that are more reliable, having a CDI that is based on at least three respondents. Squares with error bars show median and standard deviation, including all cells in the distance bin; no median is plotted if there are fewer than three CDI values in the distance bin. Shading shows 5th to 95th (light) and 25th to 75th (dark) percentiles of

Damage potential inferred from MMI for M5.5

- Very limited information (based on Oklahoma)
- significant damage (and some deaths) from HF induced events of M5 to 5.5 in China and Korea (but no available ground motion or MMI data)
- Overall conclusion is that MMI 7 to 8 not unusual for **M**>4.5 at <5 km

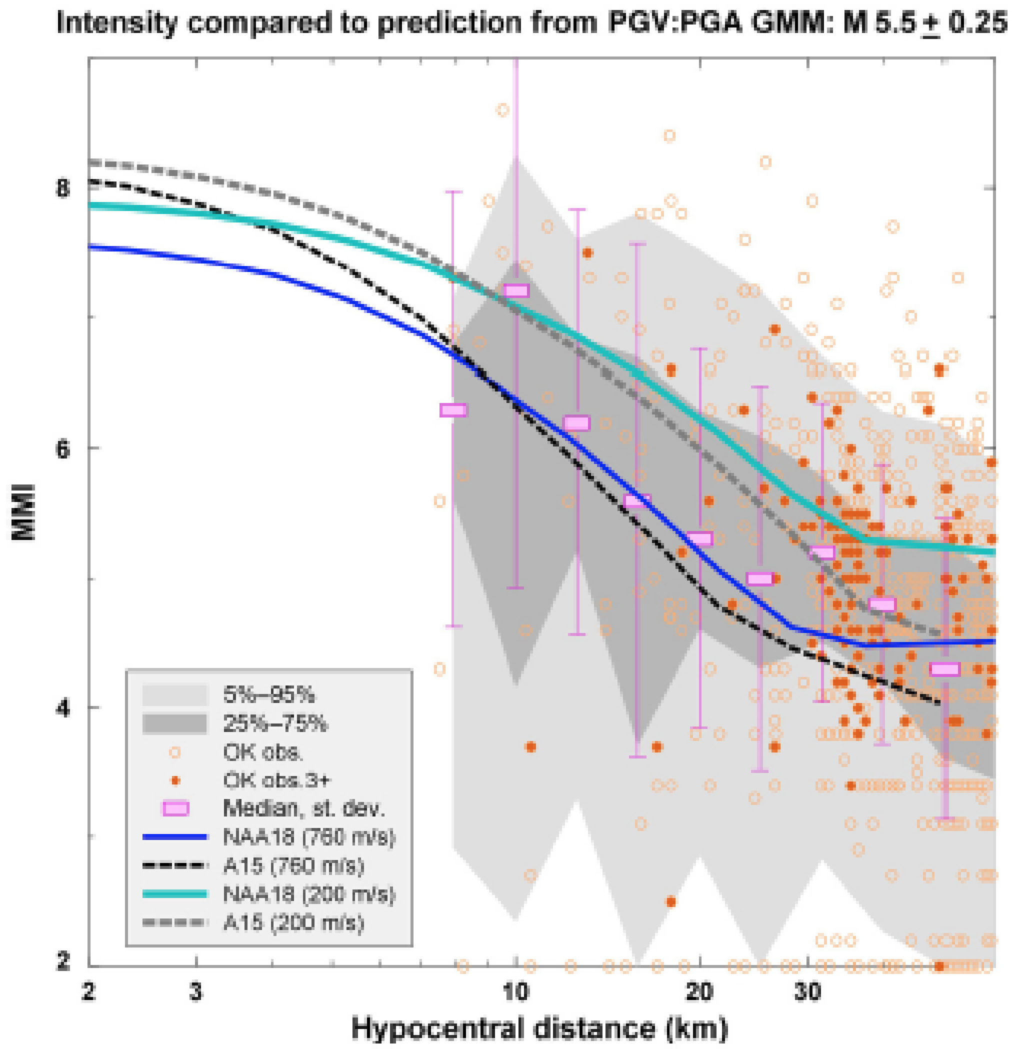


Figure 12. MMI observations (in 1 km geocoded cells) for Oklahoma events of **M** 5.5 ± 0.25 (small solid circles); site conditions of MMI observations are variable. Darker symbols highlight the cells that are more reliable, having a CDI that is based on at least three respondents. Squares with error bars show median and standard deviation, including all cells in the distance bin; no median is plotted if there are fewer than three CDI values in the distance bin. Shading shows 5th to 95th (light) and 25th to 75th (dark) percentiles of

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)

Hazard Assessment: Deterministic

- For induced earthquakes, the locations and timing are relatively well-constrained, relative to the case for natural events
  - HF-triggered events <5 km from wells, usually (but not always) within a few weeks of HF activities
  - Wastewater disposal may affect a larger area over a longer time
- The constraints on location make deterministic analysis of hazard at least somewhat feasible for induced seismicity (unlike the case for natural events in most regions)
- The challenge is that magnitude is not well constrained
  - Do we assume Mmax is based on the largest events known to be induced to date? In what region? (e.g. M~4.5 in WCSB, M~5.5 globally for HF, M>5.5 in U.S. for wastewater)
  - Do we assume Mmax from natural seismicity? (e.g. M>7)

Maximum magnitudes:

Two competing hypotheses:

- Maximum magnitude scales with injected volume (McGarr)
- Maximum magnitude same as for tectonic earthquakes, dependent only on fault size (van der Elst)

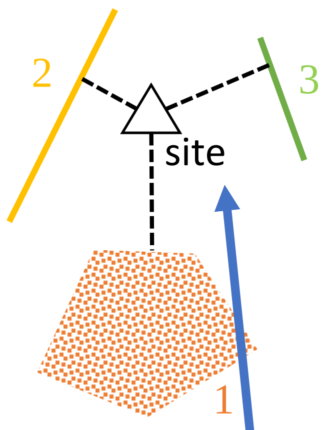
Consensus emerging that productivity (rate) scales with injected volume, but maximum possible magnitude does not.

So large events less likely for low injection volumes, but not impossible.

Assessing Earthquake Hazard Probabilistically: PSHA (Probabilistic Seismic Hazard Analysis) for induced events follows same framework as PSHA for natural events

1 Where?

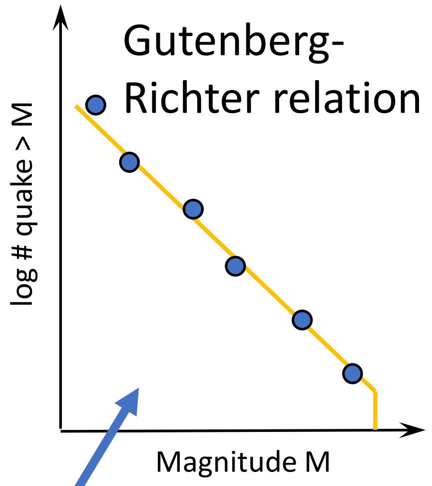
(Earthquake locations)



Events occur along faults or zones around a site

2 How often?

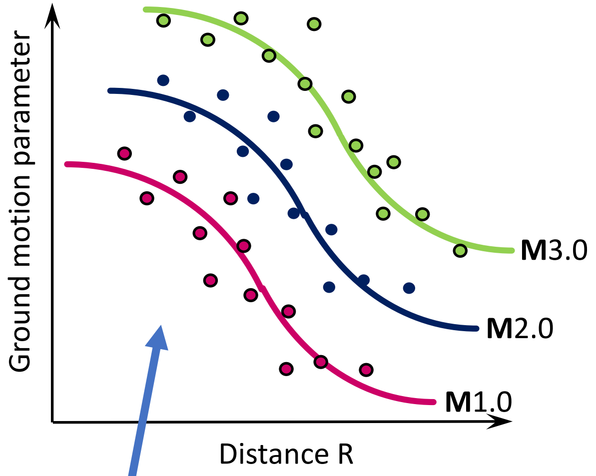
(Earthquake number, sizes, rates)



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

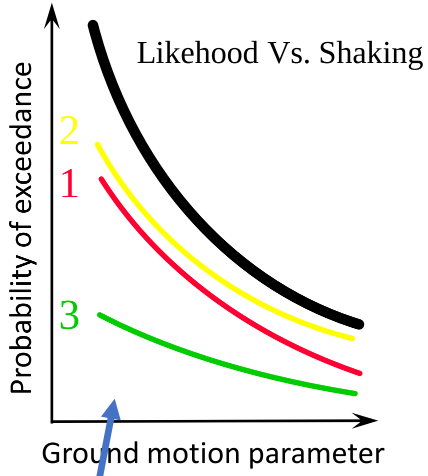
3 Ground motions

(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

Induced seismicity PSHA: Forecasting versus Hindcasting

- A forecast PSHA aims to assess the hazard if operations that might trigger induced seismicity are initiated near a site (e.g. Atkinson, 2017 FACETS PSHA)
  - The rate and locations of earthquakes are calculated from a postulated likelihood of activation and earthquake distribution for future operations that have not yet happened
- A hindcast PSHA uses past seismicity rates to calculate the hazard, assuming that the past seismicity rates continue at the same rates and in the same locations (over some time period) (e.g. Petersen et al., 2017; Ghofrani et al., 2019)
  - The rate and locations of earthquakes are calculated from an observed catalogue for a past time period, using a traditional PSHA (with smoothed seismicity approach)

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
  - Induced events, if they occur, will be within a few km of planned operations
  - The rate and locations of earthquakes are calculated from an assumed likelihood of activation and earthquake distribution
  - Likelihood of activation varies regionally, is highly uncertain, and is contingent on the planned operations

PSHA forecast: what drives hazard?

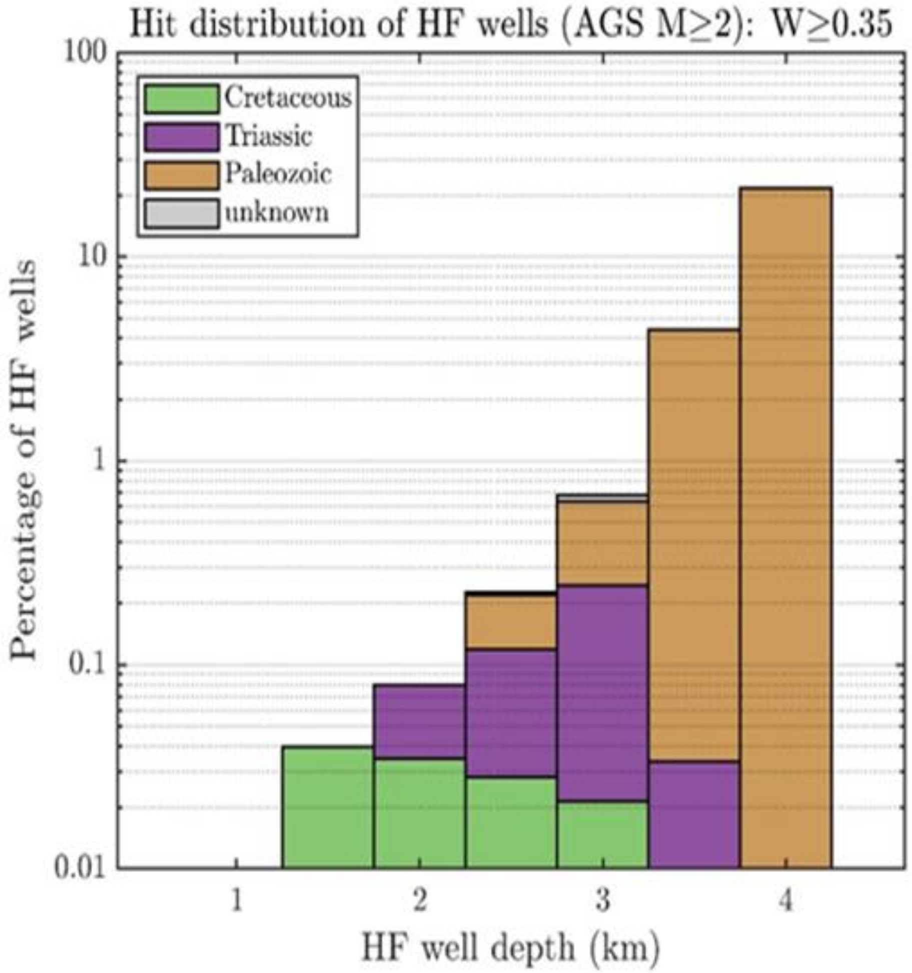
- Likelihood of initiating a sequence (of **M**>3); even if its low (<1 in 100) it is highly consequential for critical infrastructure having low acceptable failure risk (e.g. 1/10,000 per annum) – especially in low seismicity regions
- Productivity parameters for sequences
    - More productive sequences will have higher likelihood of a potentially damaging event (Gutenberg-Richter relation: 100 M3+, 10 M4+, 1 M5+)
- Maximum and minimum magnitude
- Ground motions from induced events, as a function of magnitude and distance
- Uncertainties in all of the above

Example forecast PSHA in WCSB (Atkinson, 2017 FACETS)

- Consider a large box, 50 km x 50 km, with a site in the middle; operations happening at typical regional rates throughout the box

INPUT PARAMETERS

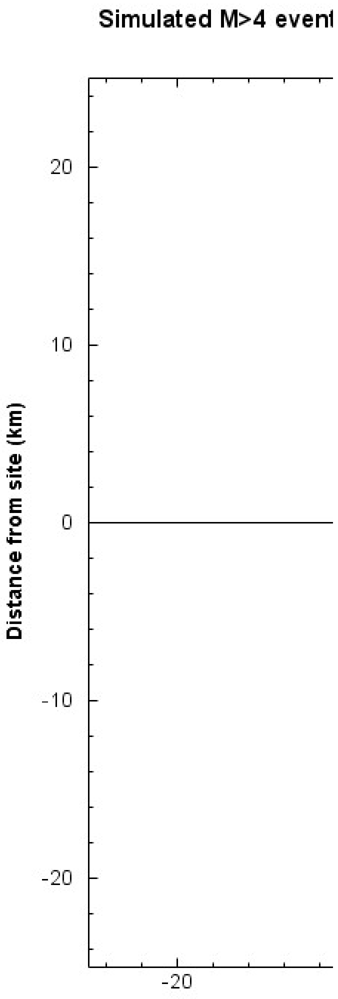
- Assume rate parameters from Ghofrani&Atkinson, 2016 statistical study (N3=0.24, with b-value of 1)
- Assume **M**min=4.0
- Use distribution of **M**max from 5.0 to 6.5
- Use EQHaz PSHA software (Assatourians and Atkinson, 2013) to simulate earthquake catalogues that could be realized over many trials (Monte Carlo)
- Two alternative ground-motion models that appear to be applicable to induced events (A15 and a lower-branch variant based on other GMMs)

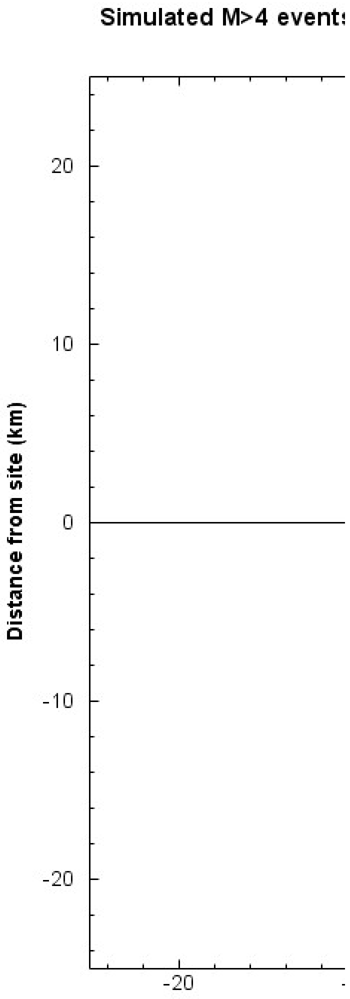


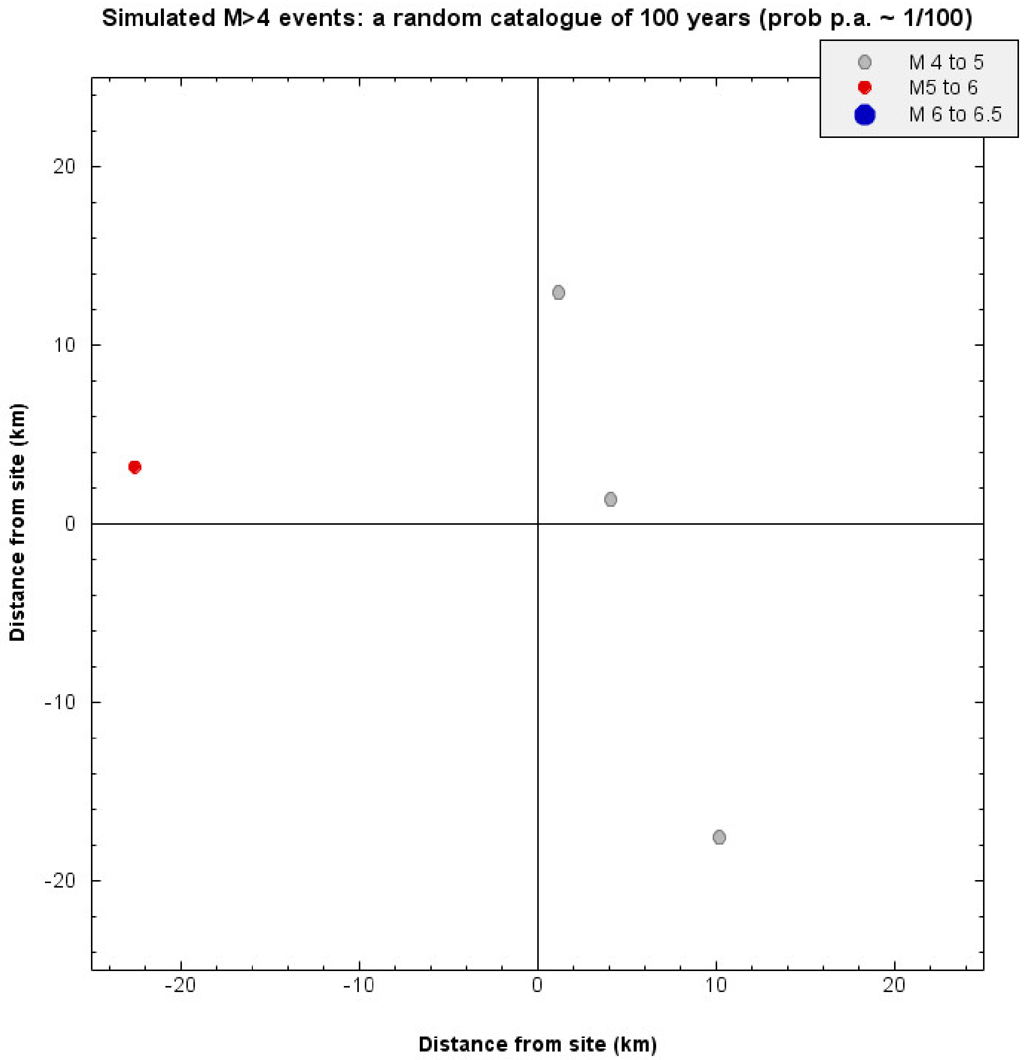
Percentage of HF wells associated with M≥2 seismicity as a function of HF well depth for Alberta. Shading shows formation age (Paleozoic, Triassic, Cretaceous). (Ghofrani and Atkinson, 2021)

Simulated Catalogues: random 100 year snapshots

- does not look very troubling……

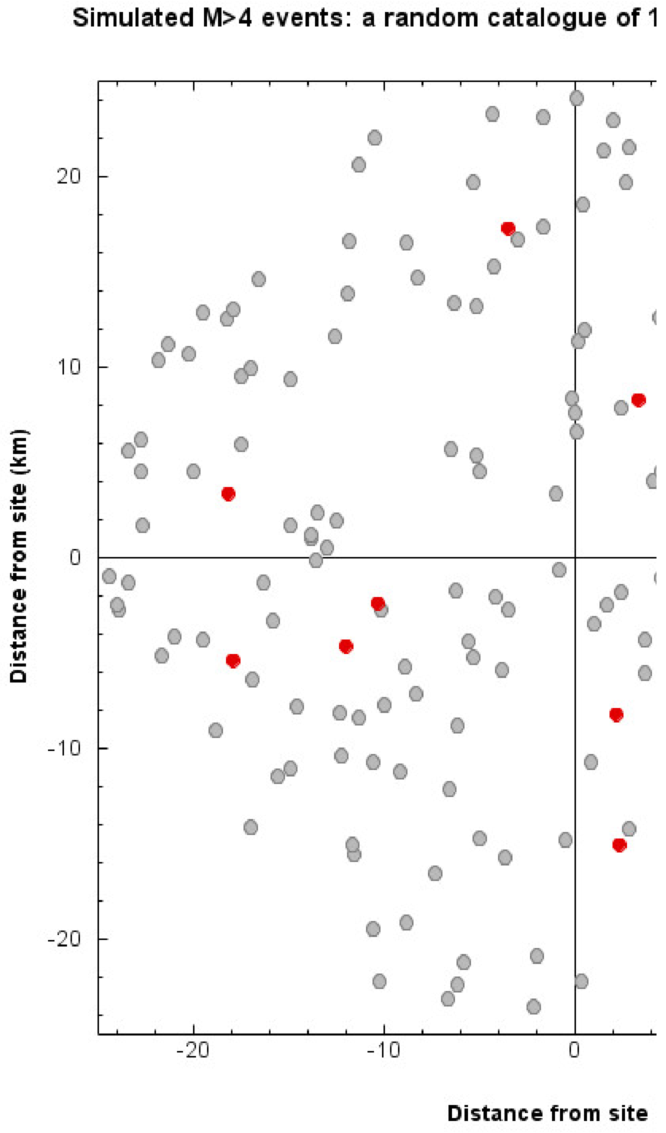


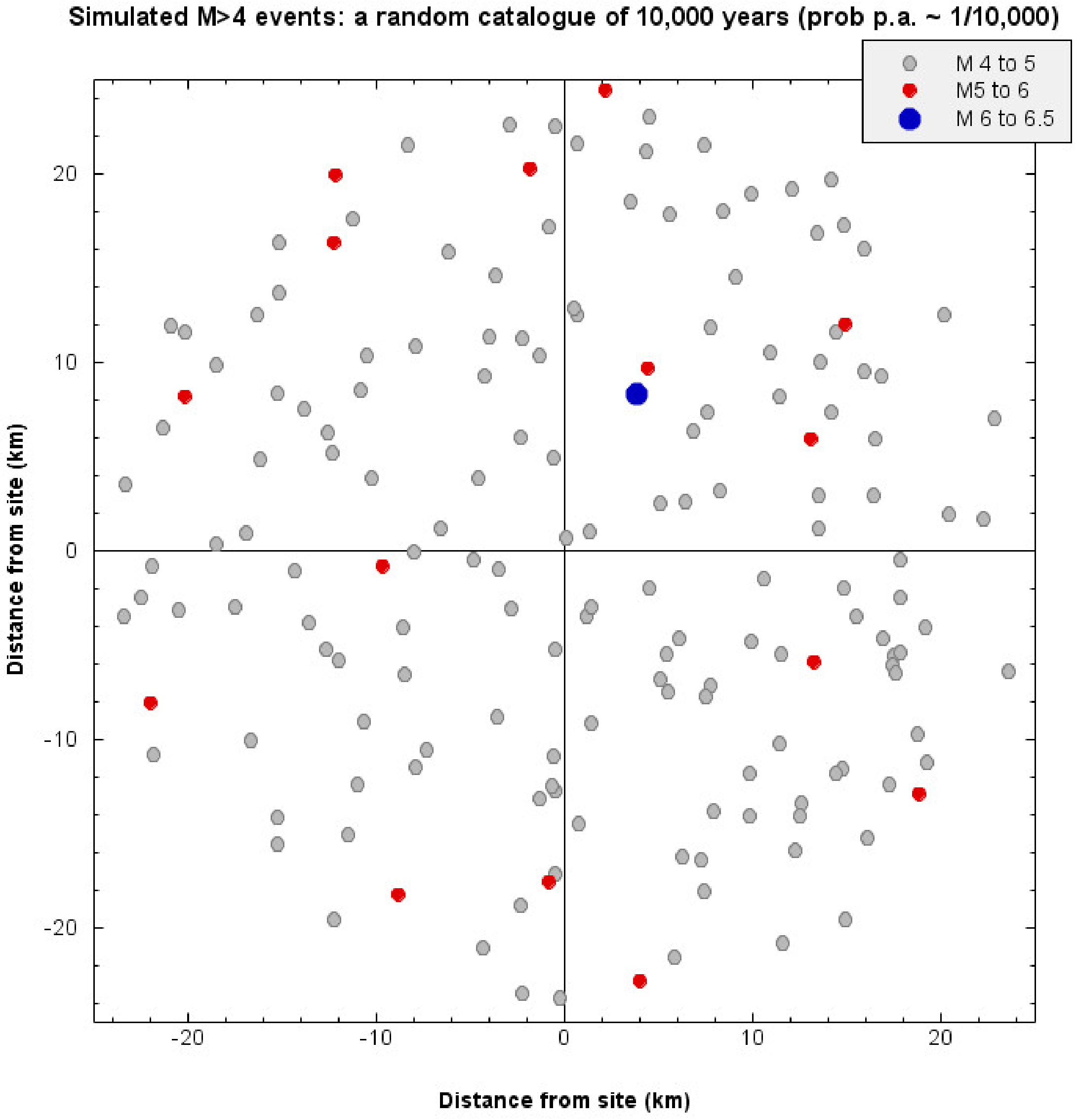


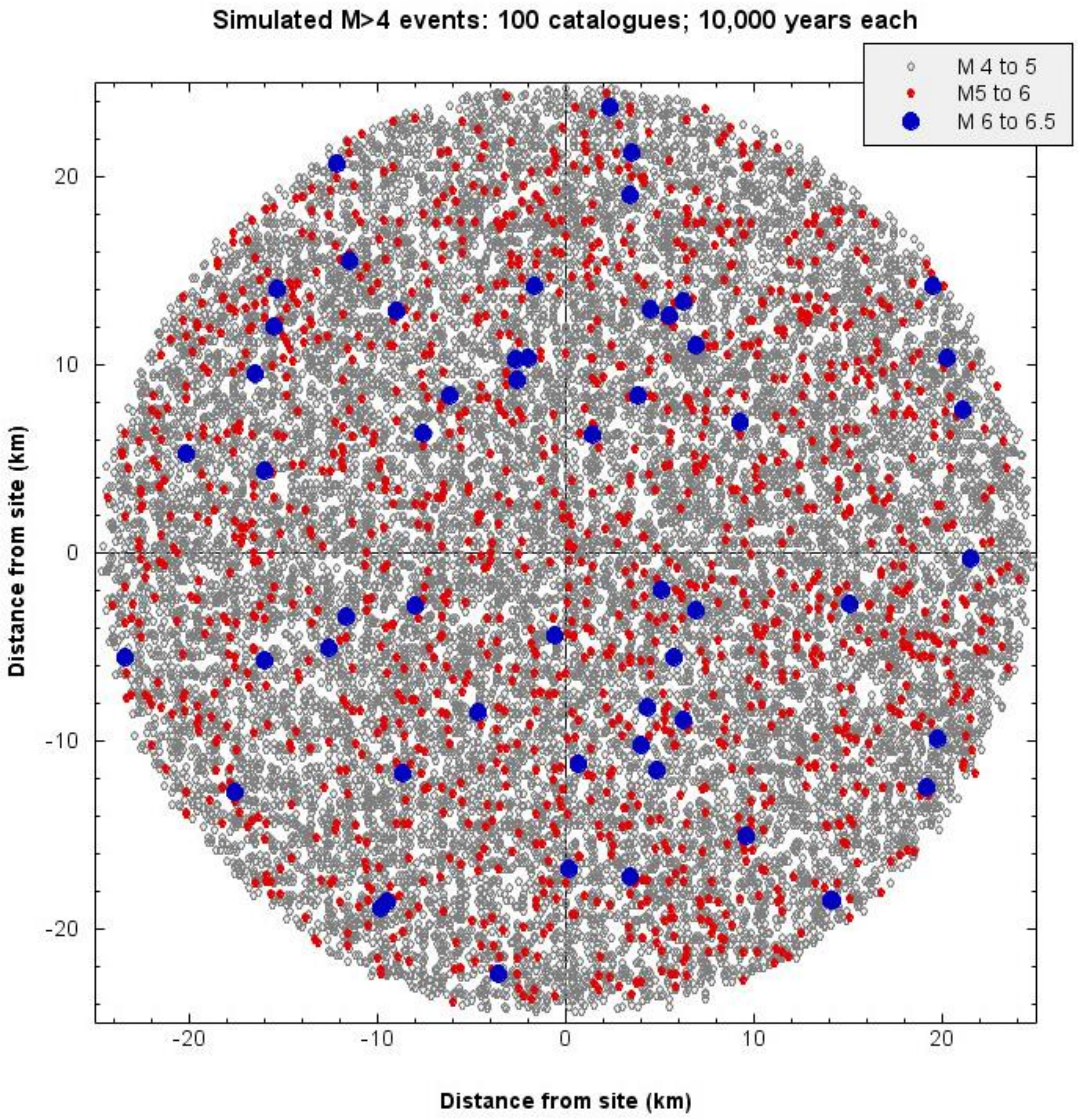


Simulated Catalogues: random 10,000 year snapshots: Mmin=4.0

-for 1/10,000 p.a., we need to withstand the largest ground motion from among these

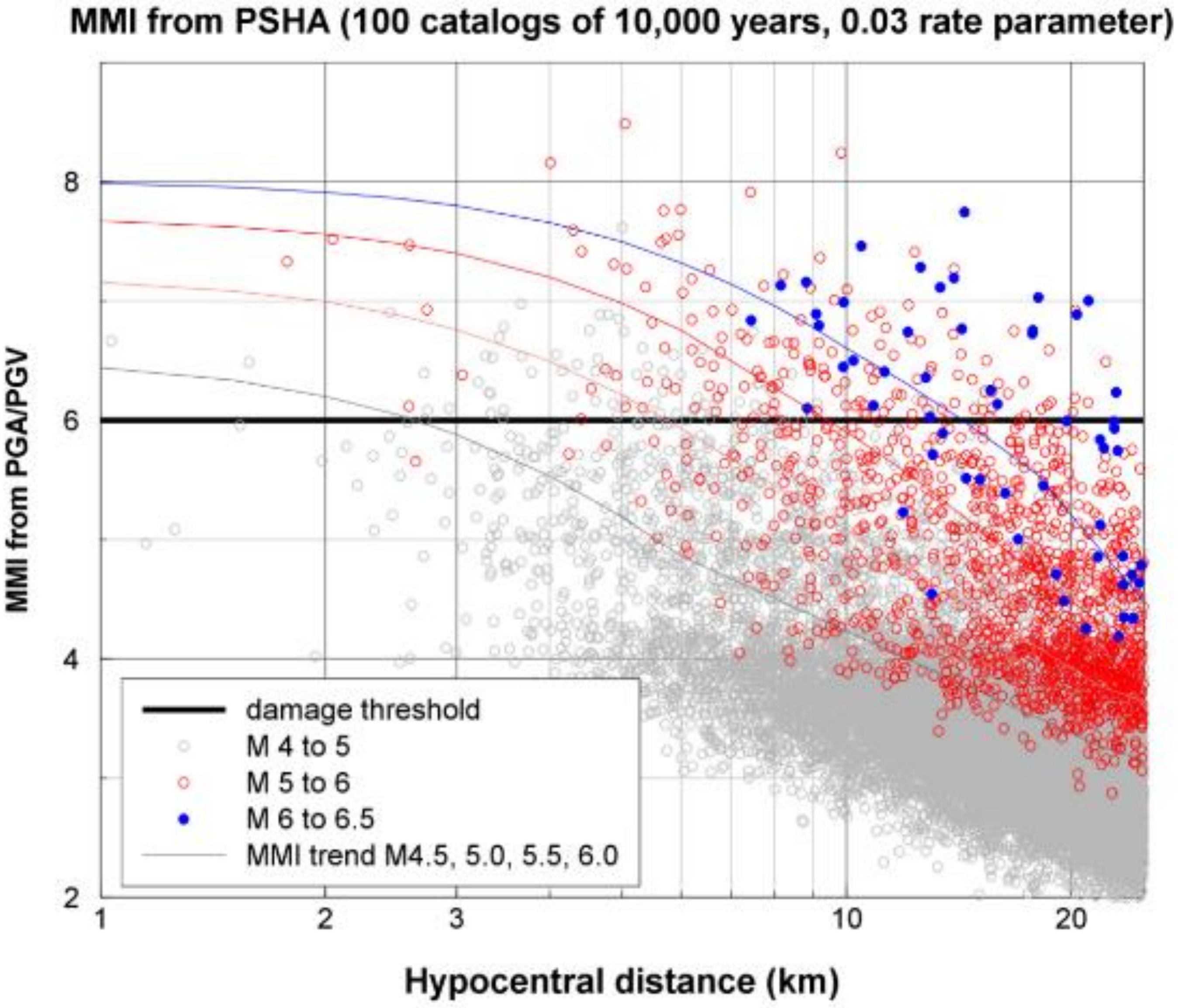






Simulated Catalogues: 100 catalogues of 10,000 years

-for 1/10,000 p.a. we need to withstand the 100th largest ground motion



Ground motions generated from all 100 catalogues of 10,000 years (including variability): (used PGA/PGV to express as MMI)

- if our goal is to have no greater than 1/10,000 p.a. chance of exceeding damage threshold (MMI=VI), we need to have no more than 100 exceedences of black line… in our 100 x 10,000yr catalogues

Achieving the Goal (<1/10,000 p.a. of MMI>VI):

- Exclusion zone of 5 km to prevent events (mostly M4 to 5) at very close distances
- Maintain broader real-time monitoring zone, out to 25 km, to track rates of **M**>2 events
  - Consider mitigation if rate of **M**>2 within 25 km rises to >2 events/year

Conclusion based on hazard forecasting

(Atkinson, 2017, FACETS)

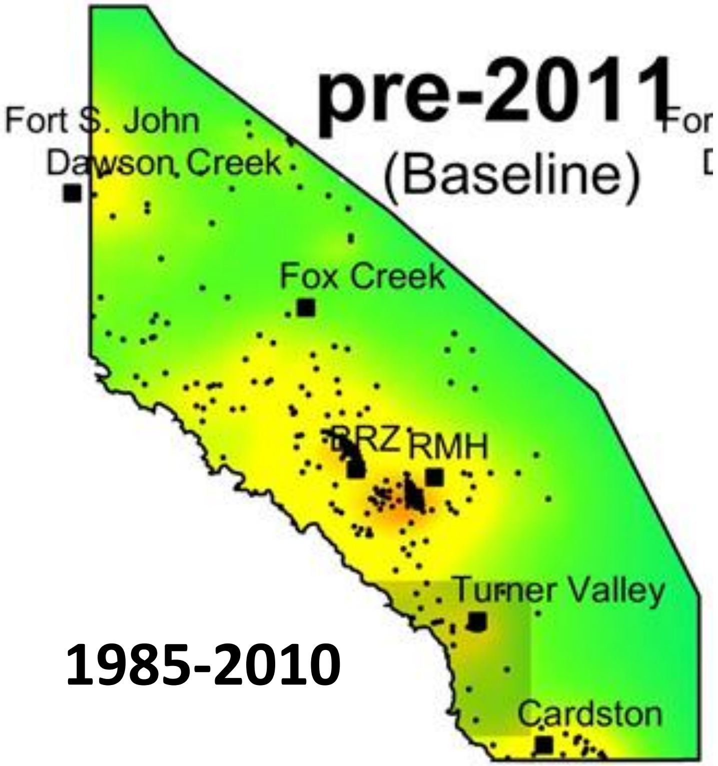
- A 5-km exclusion zone for HF operations around critical infrastructure would preclude events at very close distances (i.e. prevent scenarios in which small-to-moderate event could cross damage threshold)
- Exclusion zones alone may not provide sufficiently-low hazard, because contributions from operations beyond that zone are significant (i.e. moderate-to-large events at >5 km)
  - Regional monitoring in the 5km to 25 km radius could be used to determine regional rate parameters and determine hazard contributions (i.e. potential to reduce operations if rates become too high)

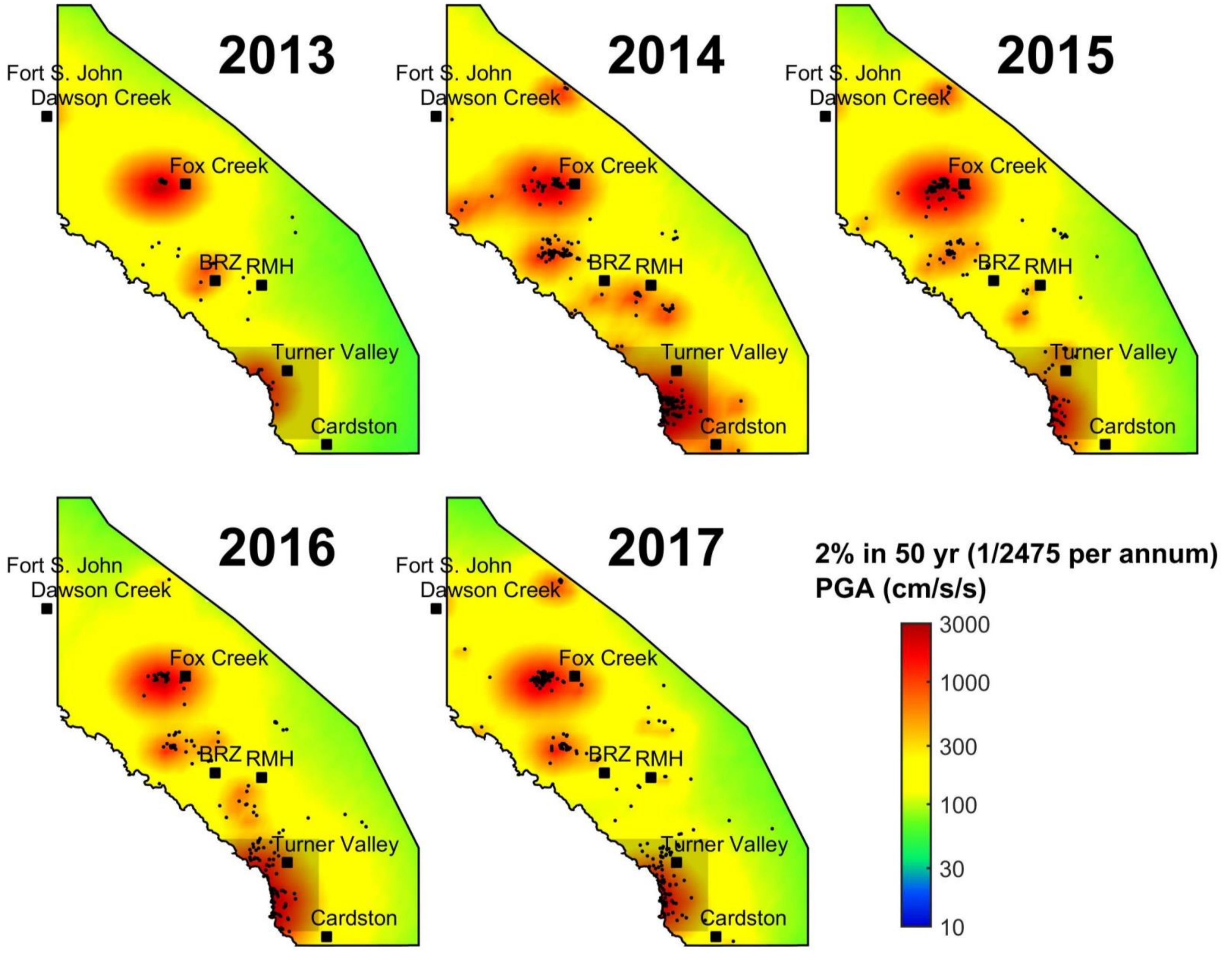
Induced seismicity hazard assessments: Hindcasting

- A hindcast uses past seismicity rates to calculate the hazard, assuming that the past seismicity rates continue at the same rates and in the same locations (over some time period)
  - The rate and locations of earthquakes are calculated from an observed catalogue for a past time period, using a traditional PSHA (with smoothed seismicity approach)
  - Perform PSHA as a hindcast using the catalogue for the year that just happened (e.g. Ghofrani et al., 2019; Petersen et al., 2017-2019)
- Hindcasts do not provide the hazard for future operations, but help us understand the regional hazard setting and how it is changing in time and space

Example of hindcast model for Alberta

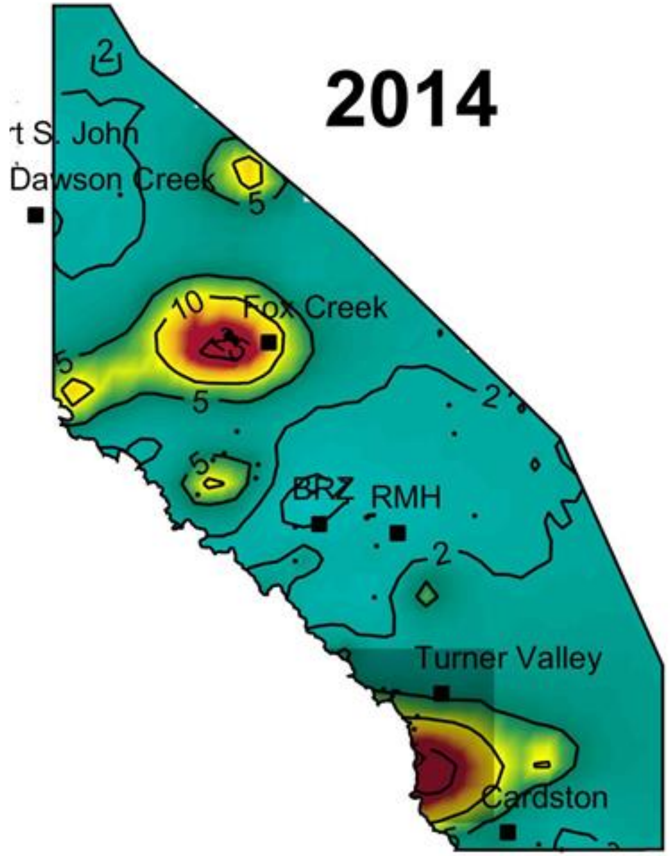
(Ghofrani et al., 2019 SRL)

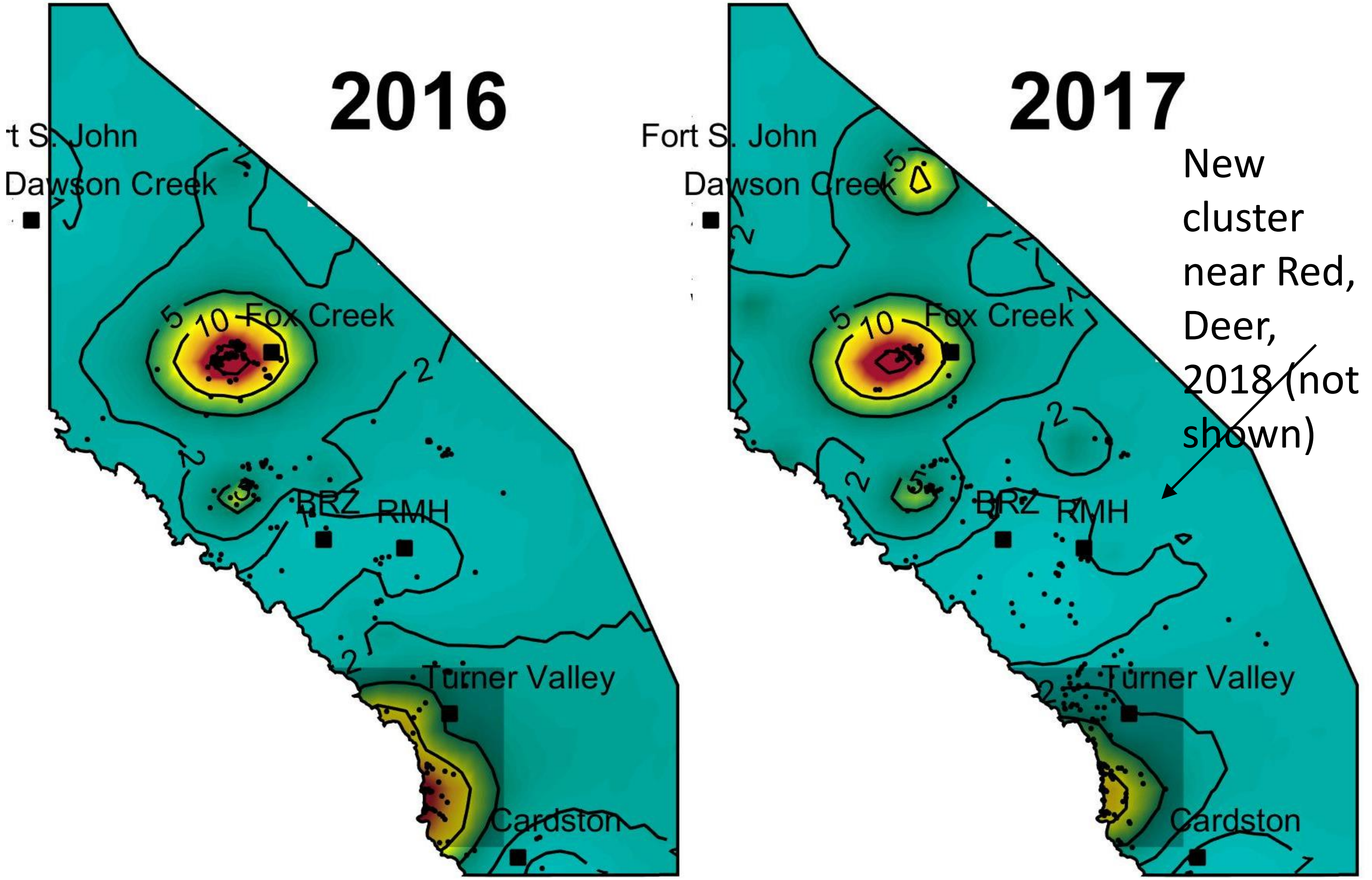




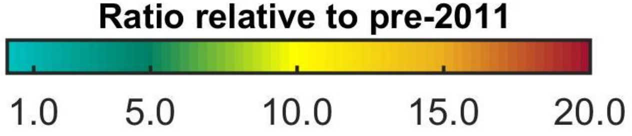
Expected value of 1/2500 PGA (cm/s^2), obtained from observed earthquakes (black dots) in the time period. Shaded regions (Turner Valley) are areas where the catalog is contaminated by undistinguished blasts.

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



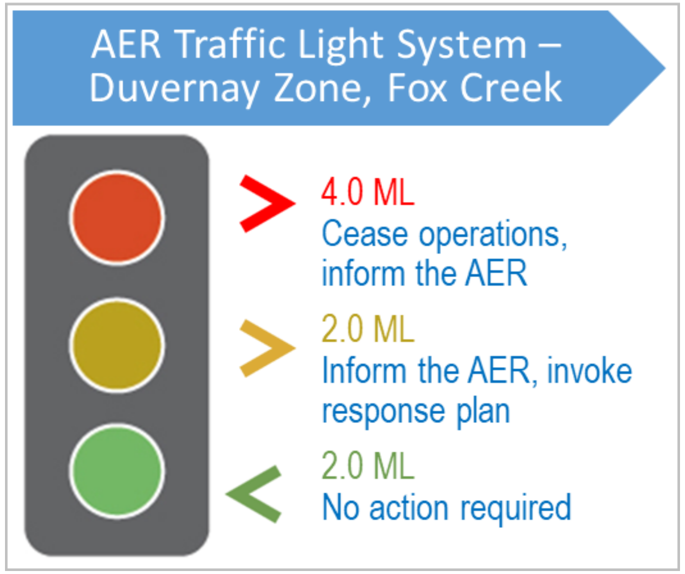


Ratio of 1/2500 PGA relative to values as of 2010. Inferred hazard changes yearly. Areas not yet activated will be missed (e.g. Red Deer, 2018) – that is why we also need forecasts!



Some considerations for monitoring and response

- Most govt monitoring/response are based on limited, retrospective traffic lights (ie. Stop HF AFTER initiating potentially-damaging sequence)
- Proactive monitoring needs to detect and accurately locate events within ~25 km of the critical infrastructure, in near-real-time
  - Instrumentation needs to be dense/sensitive enough to record low level seismicity, so we can track any changes in low-level seismicity rates (M>~1 to 2)
  - Locations need to be accurate enough to allow correlation with specific operations or geologic structures
    - And we need timely information on operations!
  - Develop appropriate response strategy if rates rise above acceptable level



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)
- Likelihood of strong ground motion near critical facilities can be kept to low levels through:
  - 1- exclusion zone of ~5 km so that moderate events are not induced at close range
  - 2- monitoring and response protocol to limit rate of events beyond the exclusion zone; this would have broad benefits on a regional level
- Development of real-time hazard assessment and response strategies will require more widely-available seismographic data with real-time analysis – and the development of protocols to use the data effectively


Questions?