# An overview of induced-seismicity ground motions and their implications for hazard

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# This presentation

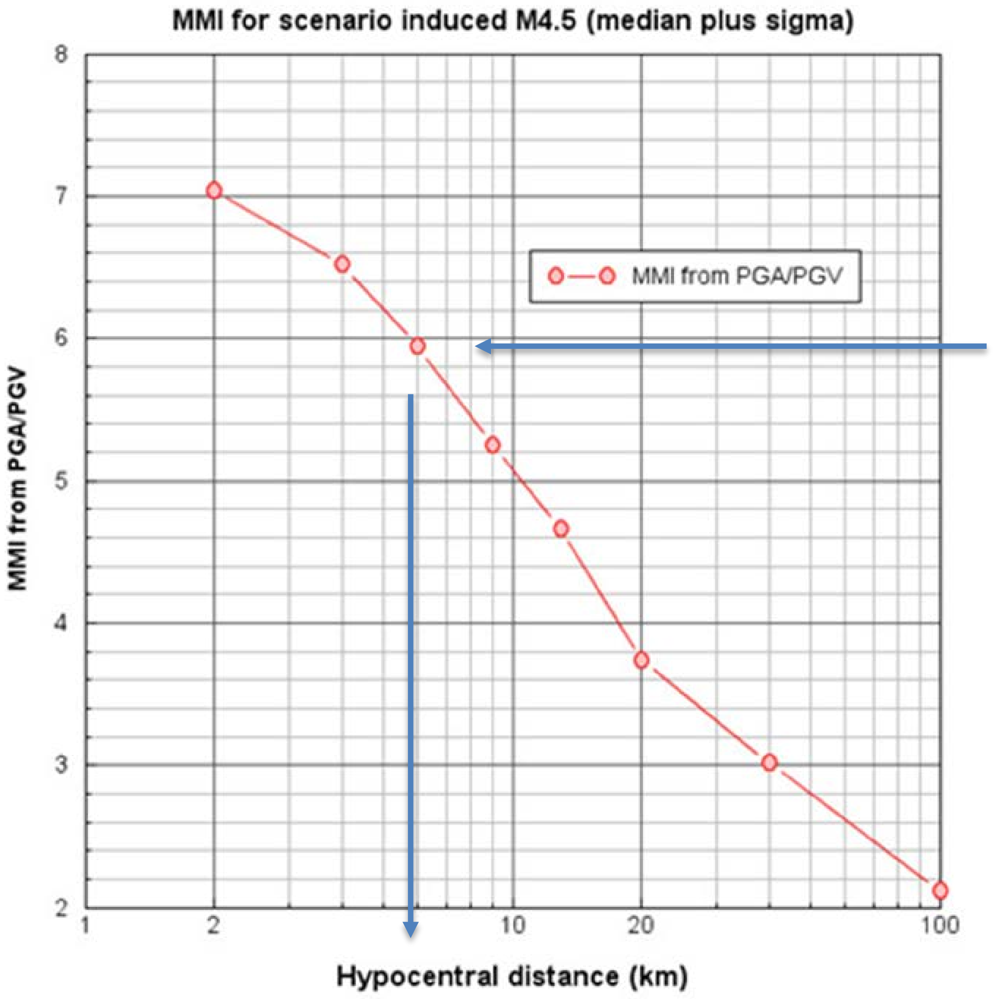
- How ground motions from induced events drive hazard
- Ground-motion models and their evolution for induced-seismicity applications
- Current data and uncertainties in ground-motion modeling for induced motions – and implications for hazard

# What drives hazard from induced events?

1. 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)
2. 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
3. Ground motions from induced events, as a function of magnitude and distance
4. Uncertainties in all of the above

# Simple deterministic explanation of how it works:

Example for Fox Creek, where odds of initiating a sequence with M>3 events is ~1/100 per horizontal hydraulic fracture well




- Based on well stats (Ghofrani and Atkinson, 2016), 1/10,000 event is ~**M**4.5
- Use ground-motion models for induced events to calculate peak ground acceleration and velocity for M4.5 (median plus 1 standard deviation)
- Convert PGA/PGV to felt intensity (MMI) (Worden et al., 2012): MMI=6 is damage threshold
- MMI of 6 for scenario 1/10,000 event will be experienced within 6 km of the hypocenter
- So keep operations ~5 km away laterally to preclude potentially-damaging motions

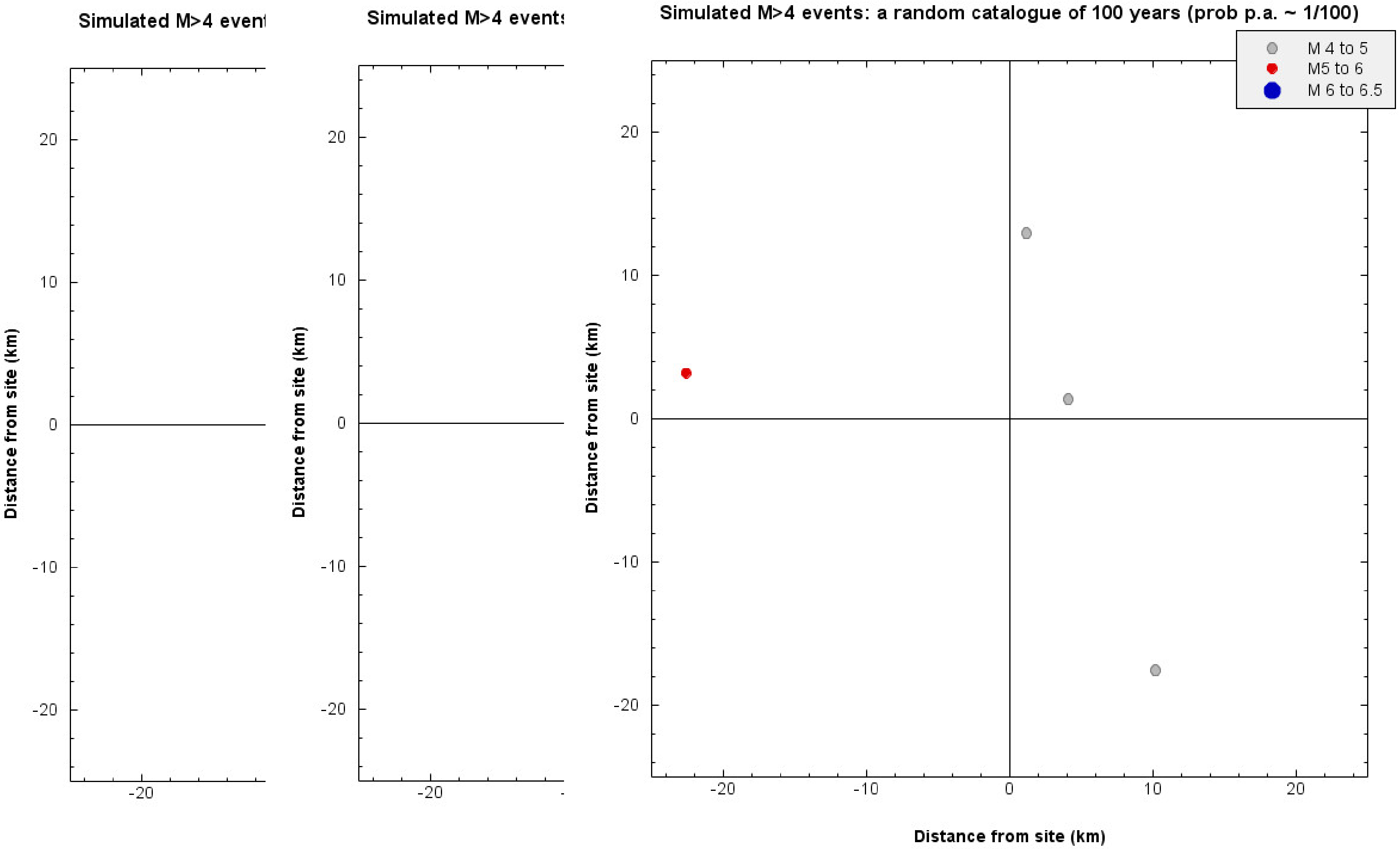
Drawbacks: Considers only one scenario; likelihood accounted for only in general way

# Probabilistic approach to induced-seismicity hazard: use probabilistic seismic hazard analysis (PSHA) to consider the range of hazard contributions and their relative likelihoods

- Consider a large box, 50 km x 50 km, with a site in the middle; operations happening at typical regional rates throughout the box
- Assume the rate parameters from Ghofrani&Atkinson, 2016 statistical study (with b-value of 1, and distribution of **M**max from 5.0 to 6.5) – similar to Fox Creek rates
- Use EQHaz (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

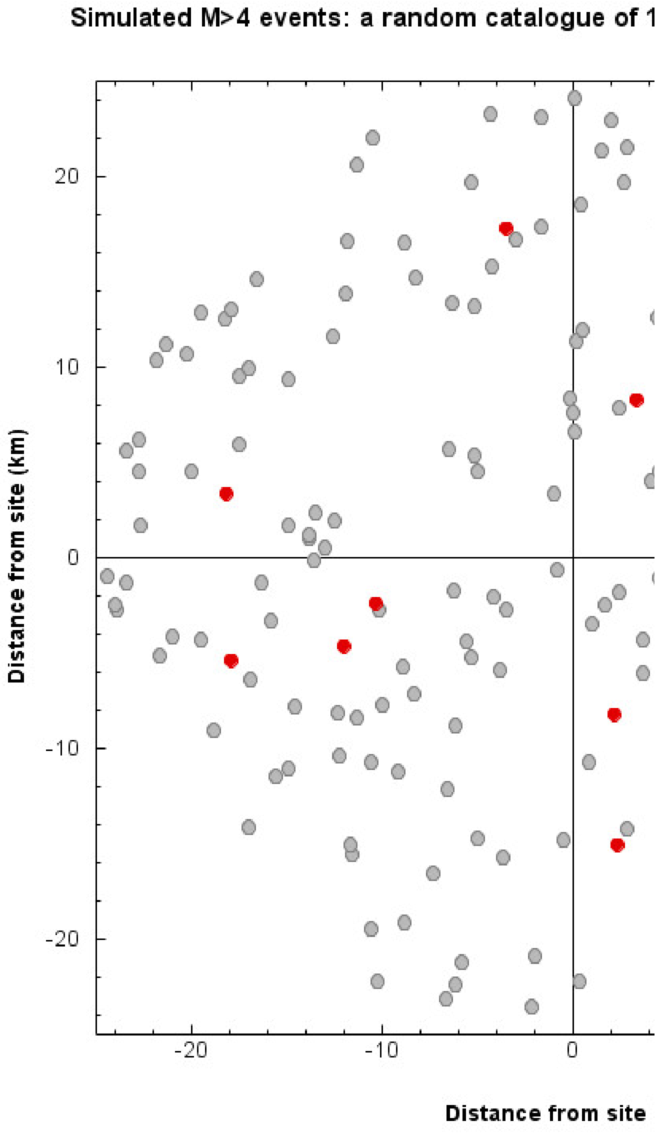
# Simulated Catalogues: random 100 year snapshots

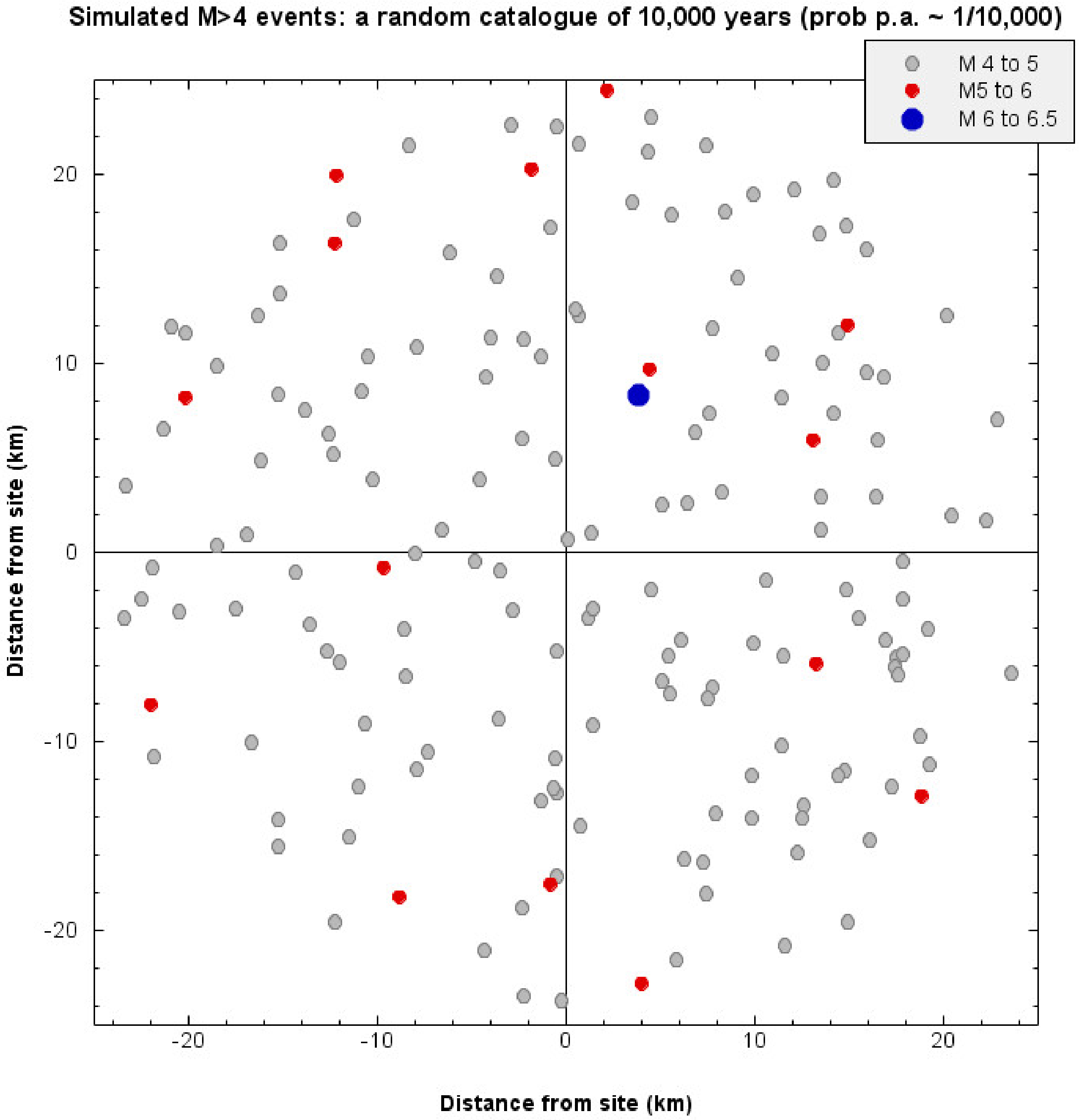
- does not look very troubling……

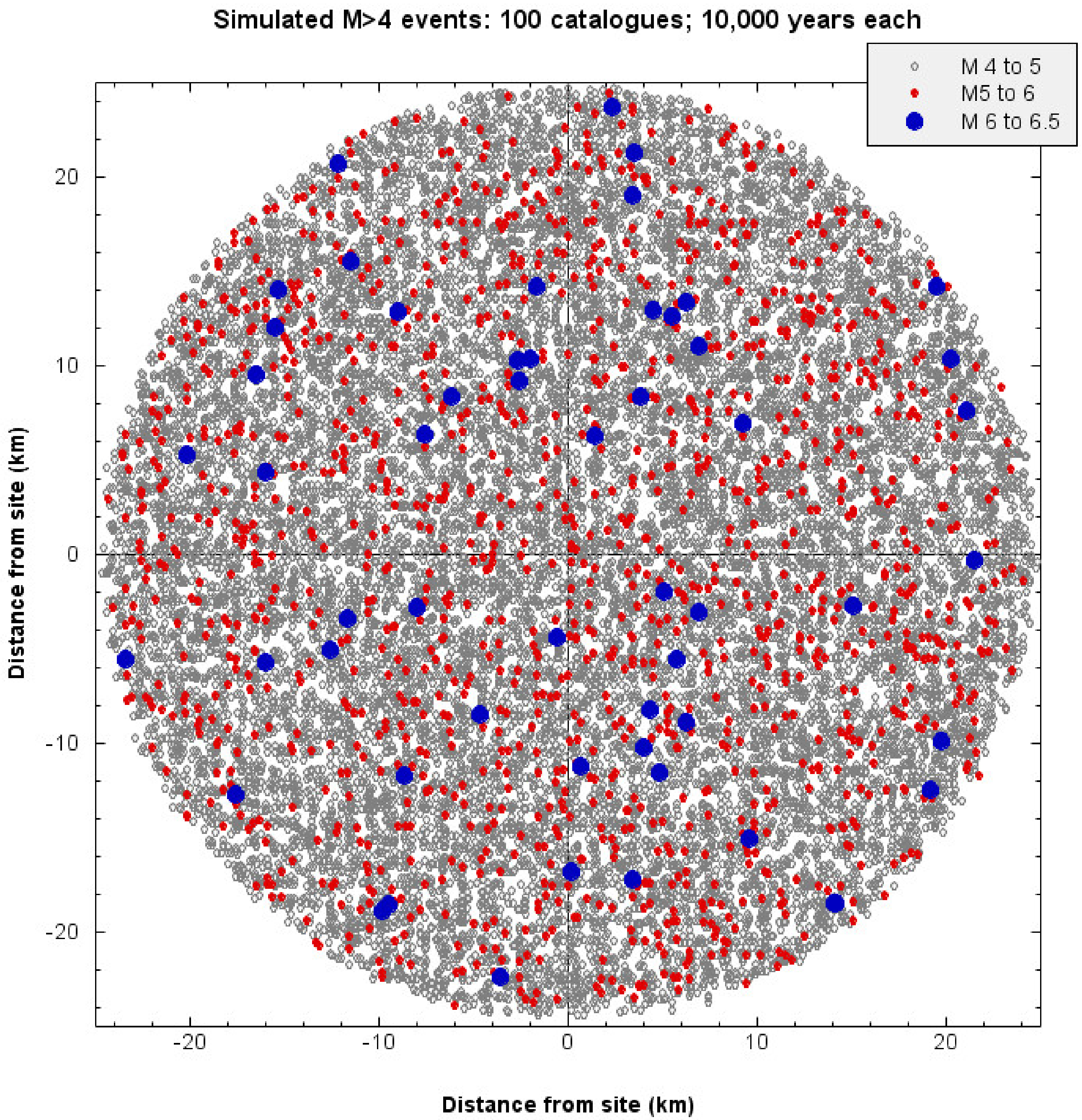


# Simulated Catalogues: random 10,000 year snapshots

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

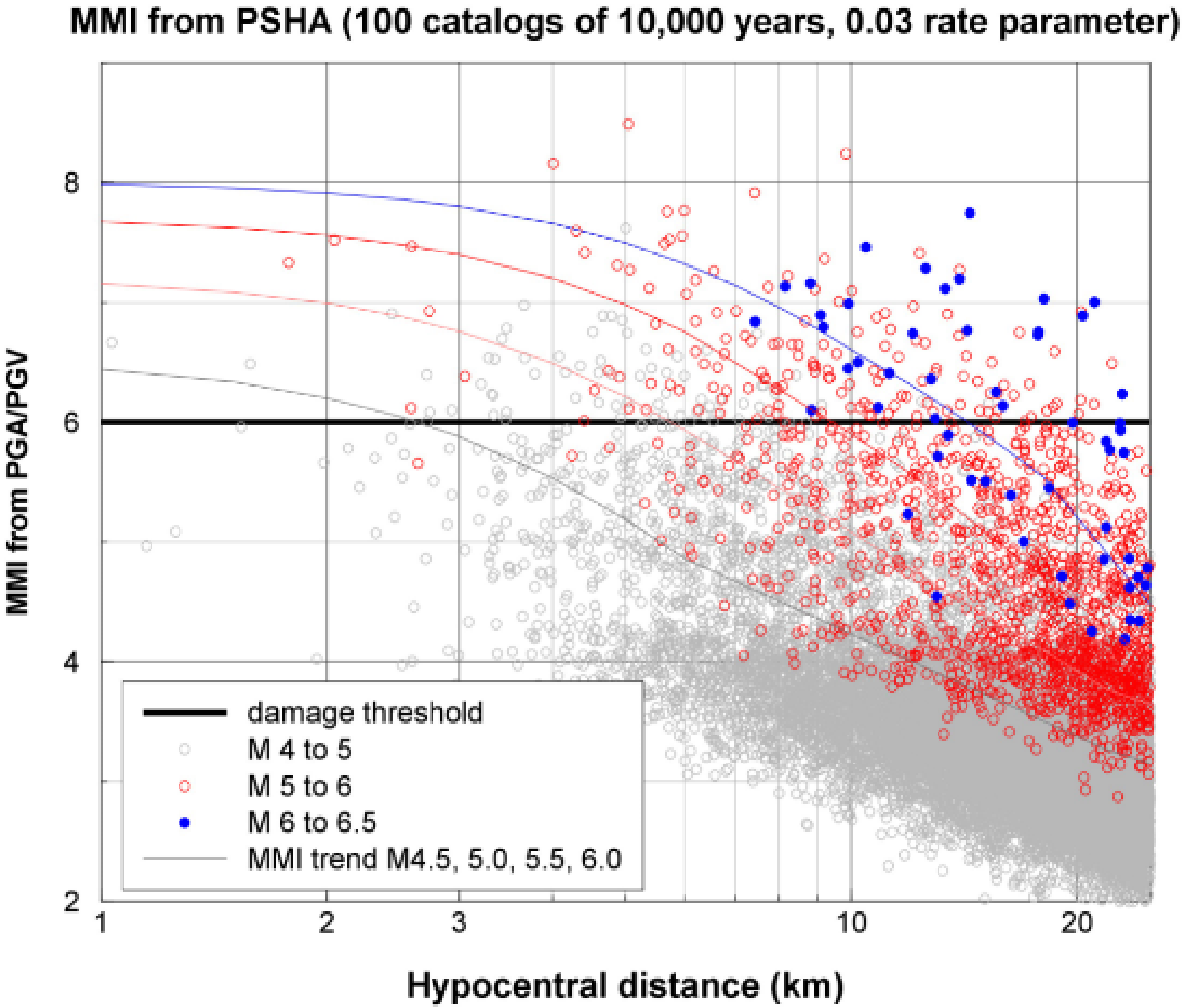





# Simulated Catalogues: 100 catalogues of 10,000 years

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




**Ground motions generated from all 100 catalogues of 10,000 years (including variability):** (for specified GMPE model)

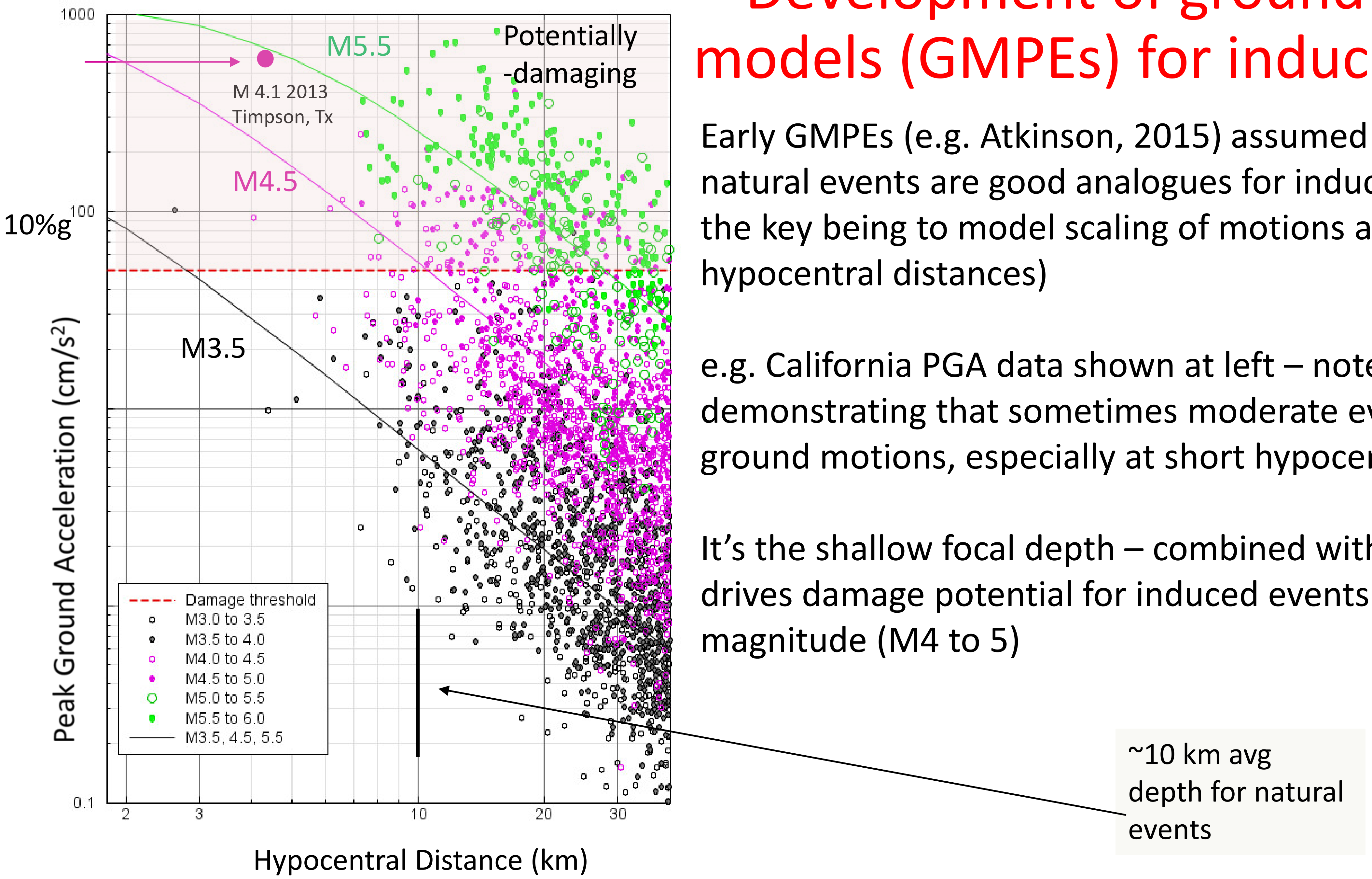
- if our goal is to have no greater than 1/10,000 p.a. chance of exceeding damage threshold (MMI=VI), we need to have no more than 100 exceedences of black line… in our 100 x 10,000yr catalogues

**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 response if rate of M>2 within 25 km rises to >2 events/year

Ground motion prediction equations (GMPEs) – explaining how motion intensity scales with magnitude and distance – have a strong influence on evaluating mitigations that will achieve goals

# Development of ground motion models (GMPEs) for induced events

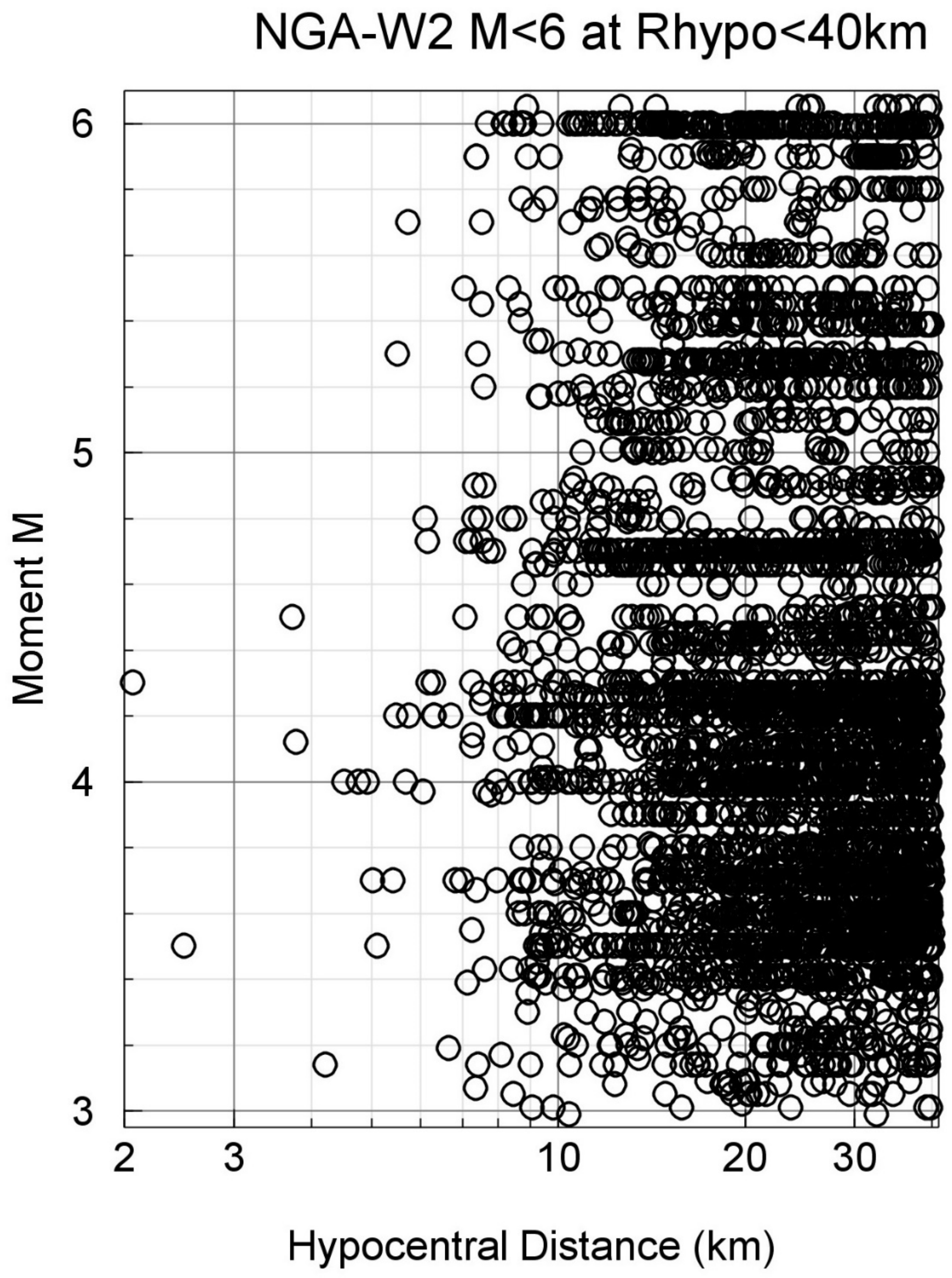



Early GMPEs (e.g. Atkinson, 2015) assumed that shallow natural events are good analogues for induced events – with the key being to model scaling of motions at short hypocentral distances)

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

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

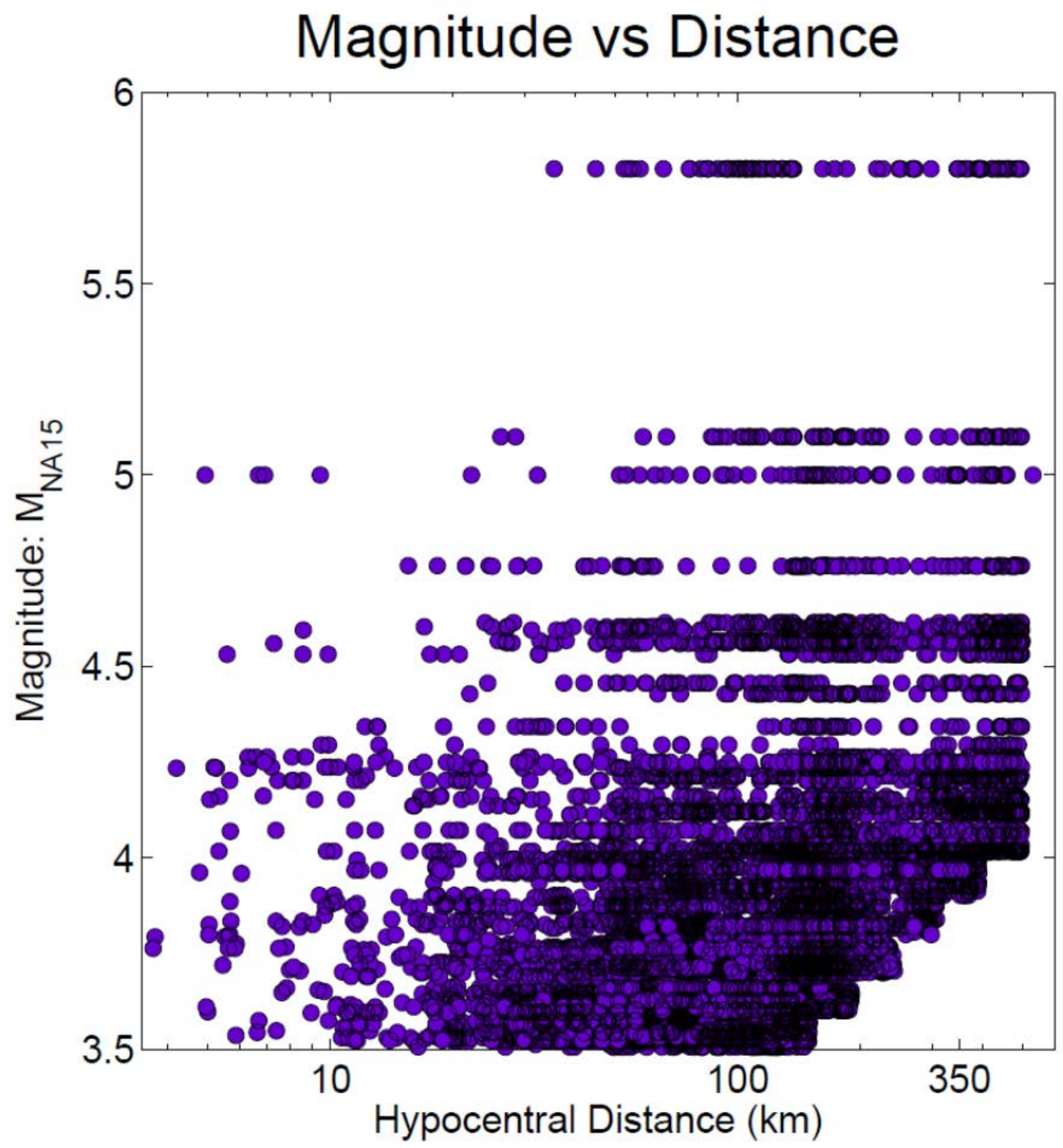
# Evolution of GMPE models: Data distribution in magnitude-distance




- **Natural events (California) used as analogues**
- 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 GMPE models: Data distribution in magnitude-distance




Natural events (California)

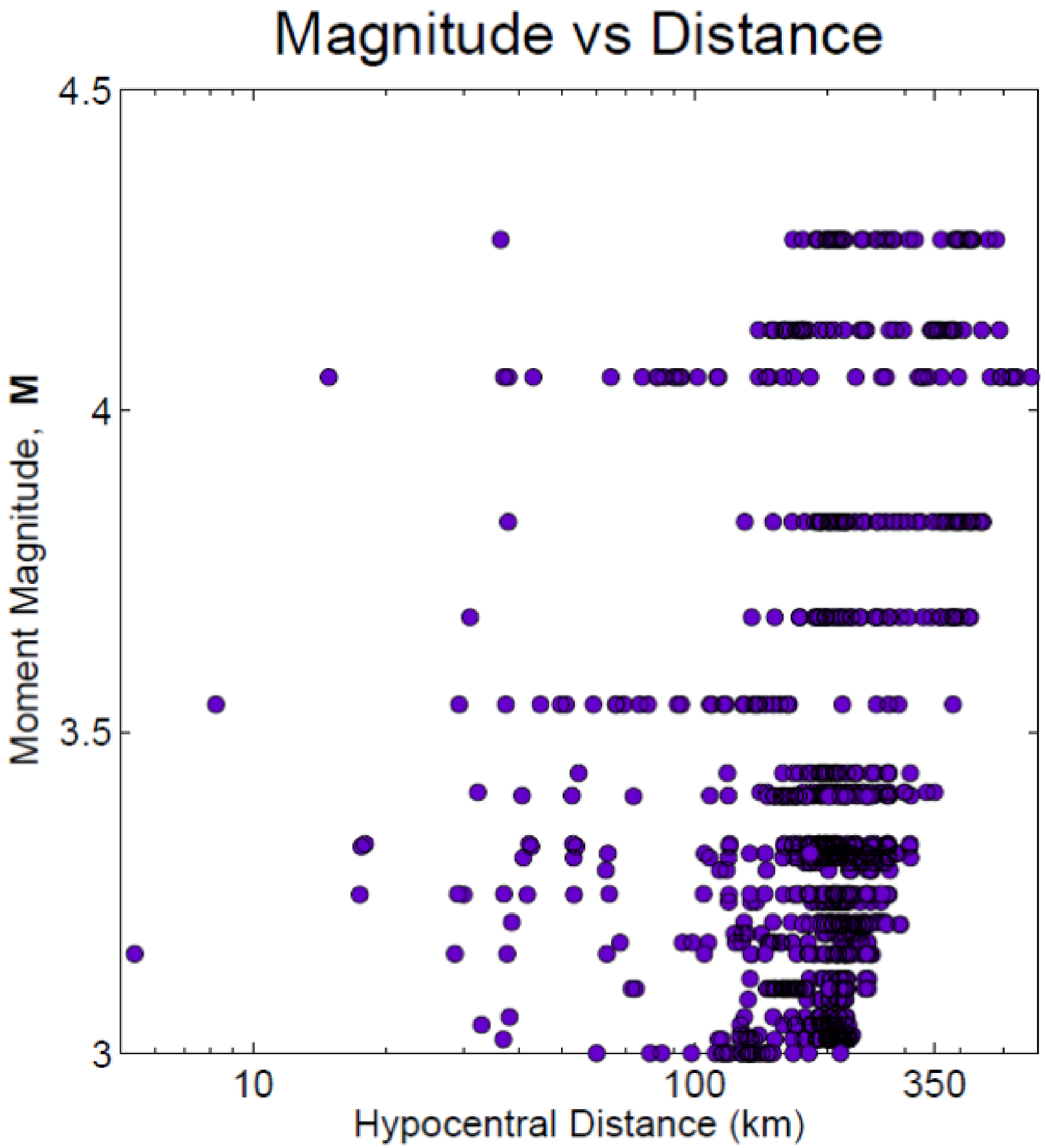
**Induced events Oklahoma (lots)**

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 GMPE models: Data distribution in magnitude-distance



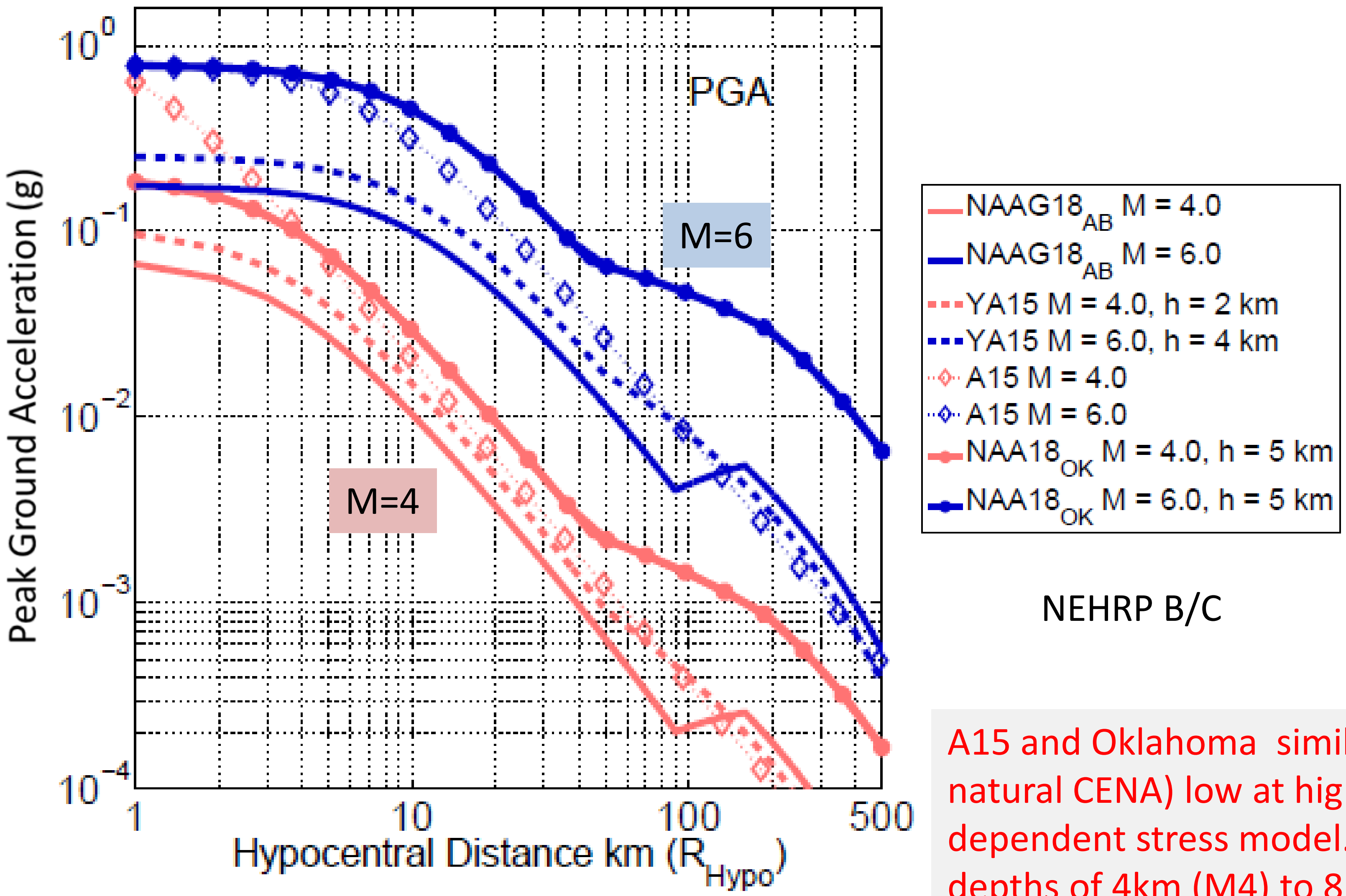

- Natural events (California)
- Induced events Oklahoma (lots)
- **Induced events western Canada (WCSB) – sparse at close distances**

**e.g. Novakovic et al., 2019: Alberta**
884 records from 37 earthquakes (**M** 3.0 – 4.3) recorded on 75 seismograph stations. Consider records within a cut-off distance that increases from 200 km for **M** = 3.0 to 600 km for **M** ≥ 4.0 events.

# Types of ground-motion models for induced events (central and eastern North America)

- Due to data limitations for large M and/or close distances, models that have scaling controlled (either empirically or by seismological model) need to be used
- Empirical examples, using California data: Atkinson, 2015 (and update by Atkinson and Addo, 2018, 2019 for events in B.C.); Abrahamson and Addo (2018)
- Seismological model examples, calibrated with data (Yenier and Atkinson, 2015; Hassani and Atkinson, 2018; Novakovic et al., 2018, 2019)

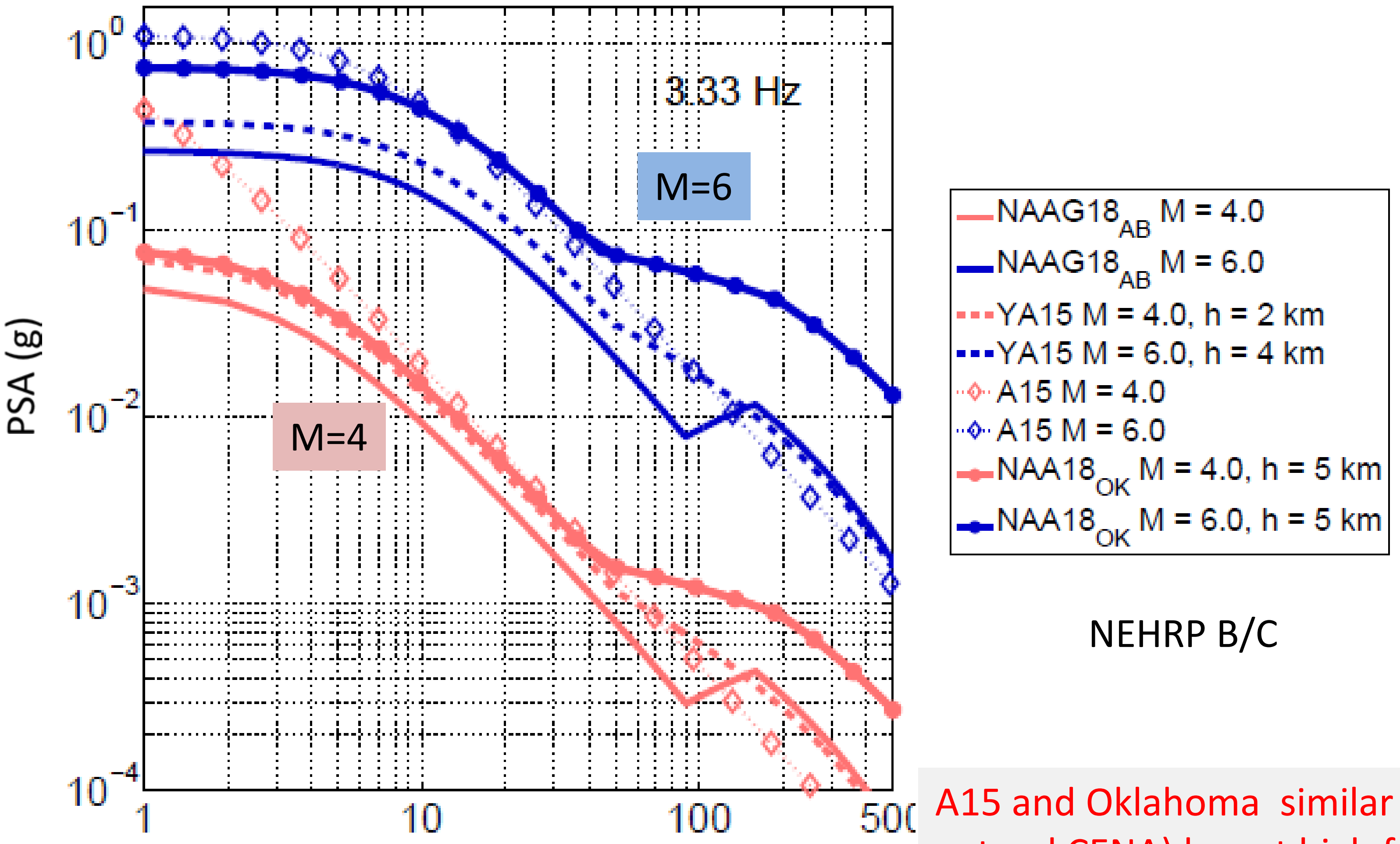
# Induced-seismicity GMPE models: PGA for M=4, 6




GMPE for Alberta as determined by Novakovic et al. (NAAG18, solid lines) in comparison to Novakovic et al. (NAA18, solid lines with circles) GMPE for Oklahoma. Yenier and Atkinson GMPE for natural events in CENA (YA15 for shallow events, dashed lines). The GMPE of Atkinson (2015, A15), as determined from moderate California earthquakes is also indicated (dotted lines).

A15 and Oklahoma similar (<50 km) (high). Alberta (and YA15 natural CENA) low at high frequencies (above corner) due to depth-dependent stress model. YA15 CENA matches A15 and Oklahoma **if** depths of 4km (M4) to 8 km (M6) are used in YA15.

# Induced-seismicity GMPE models: PSA 3.33 Hz for M=4, 6

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# Current Uncertainties and Questions

- Do high-frequency ground motions (stress parameter) really scale strongly with focal depth? And if so, what are the hazard implications?
- Are there regional differences in induced ground motions?
- Are there differences in ground motions between natural and induced events? (for the same region/focal depth)
- What is the hazard potential of small to moderate (M3.5 to 5.5) very shallow events? Is there a minimum magnitude for damage? Is there a minimum duration for damage?
- How do we decide what is an acceptable increased ground-motion hazard for critical infrastructure, and what mitigation is reasonable? Who decides? What if we/they get it wrong?