Ground motions from three recent events in western Alberta and northeastern B.C. and their implications for induced-seismicity hazard

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Introduction

- Significant increase in number of events in western Alberta in the last few years, at both M>2, M>3 level (especially near Crooked Lake)
- most events appear to be induced by: (i)hydraulic fracturing in horizontal wells; or (ii) disposal wells
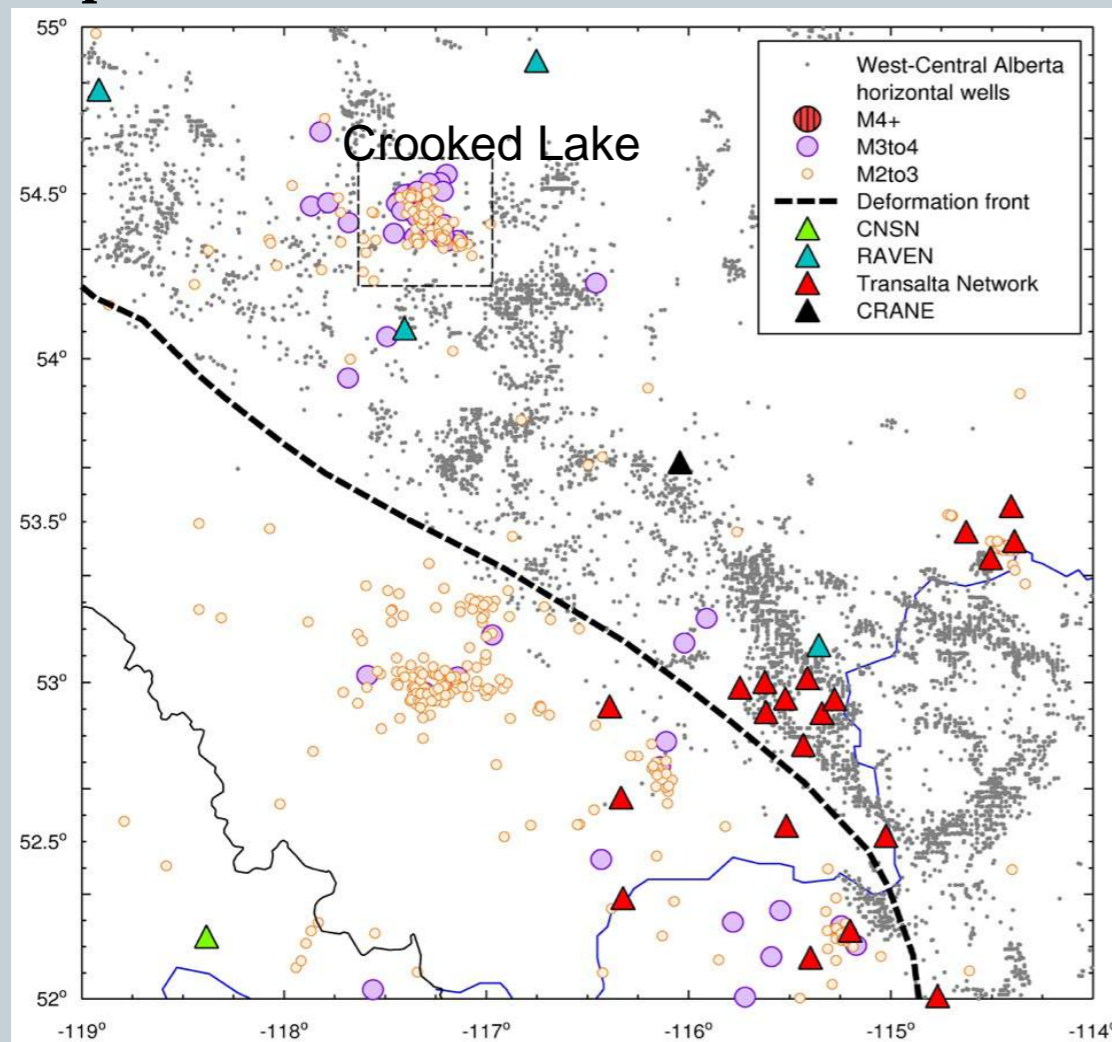
total number of events/year
(For the map area)

Year	M>2	M>3
2010	16	1
2011	2	1
2012	5	1
2013	42	13
2014	238	14
2015-toMarch	74	11

Events of M>2 since 2007; note coverage for M>2 not complete....
but M>3 should be complete

Study Events (red stars)

-events near Ft.St.John HF-related
-RockyMtnHouse ambiguous (not HF)

Date	Depth	M AGY14	M (RMT)	M_L (GSC)
30/07/ 2014 (FSJ)	2 to 5km	4.0	3.8	3.8
04/08/ 2014 (FSJ)	2 to 5km	4.2	4.2 (NMX) to 4.4 (GSC)	4.0
09/08/ 2014 (RMH)	4 to 8km	3.9	3.8 (GSC) to 3.9 (NMX)	4.3

Map of Study Earthquakes, Catalog Events **M**>3 (1985−2014), Seismographic Stations, and Cities in the Region

Legend
△ Station
★ Epicenter (This study)
□ City
○ Earthquake

Magnitude
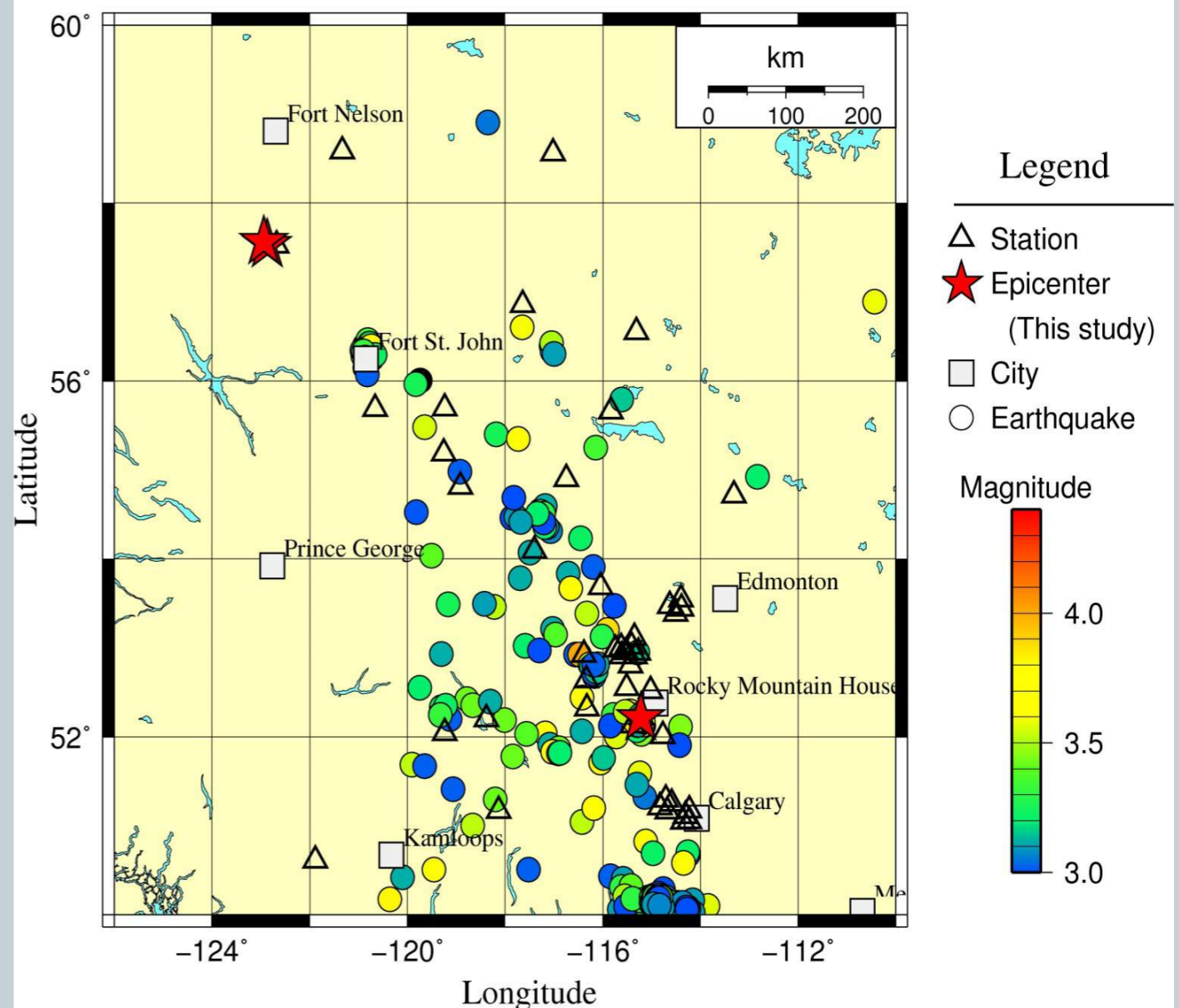
*Events of **M**>3 (1985-2014) and network stations (2014).*

Ground motion attributes of events

- 1Hz PSA (5% damped pseudo-acceleration): vert.comp. used to estimate moment M (**M**) (AGY14 algorithm, BSSA2014)
- Here, 1Hz PSA (vert) compared to AGY14, Atkinson (2015) small-M GMPE (horiz) and NGA-W2 data (similar **M**) for California
- Attenuation trend/ amplitudes similar to California

1-Hz PSA (vertical component) for three study events (circles) in comparison to Atkinson, Greig &Yenier (2014) vertical-component magnitude scaling curve (AGY14, solid line) from which moment magnitude is determined. Dashed line shows GMPE of Atkinson (2015) (horizontal component on B/C site conditions). Light plus symbols show California data from the NGA-West2 database (horizontal components, corrected to B/C site conditions) for events in same magnitude range (±0.2 units).
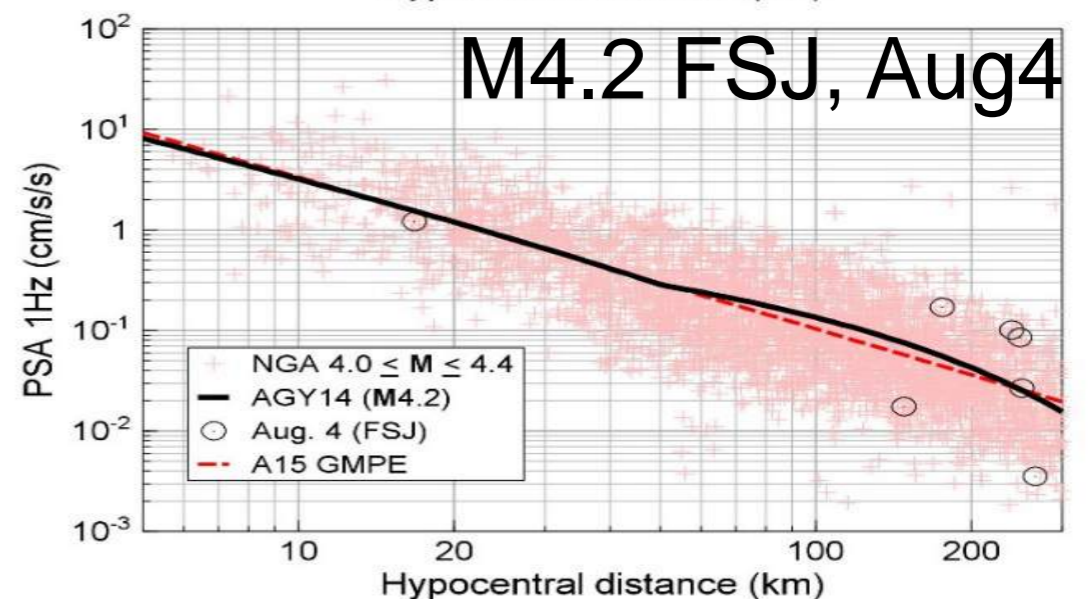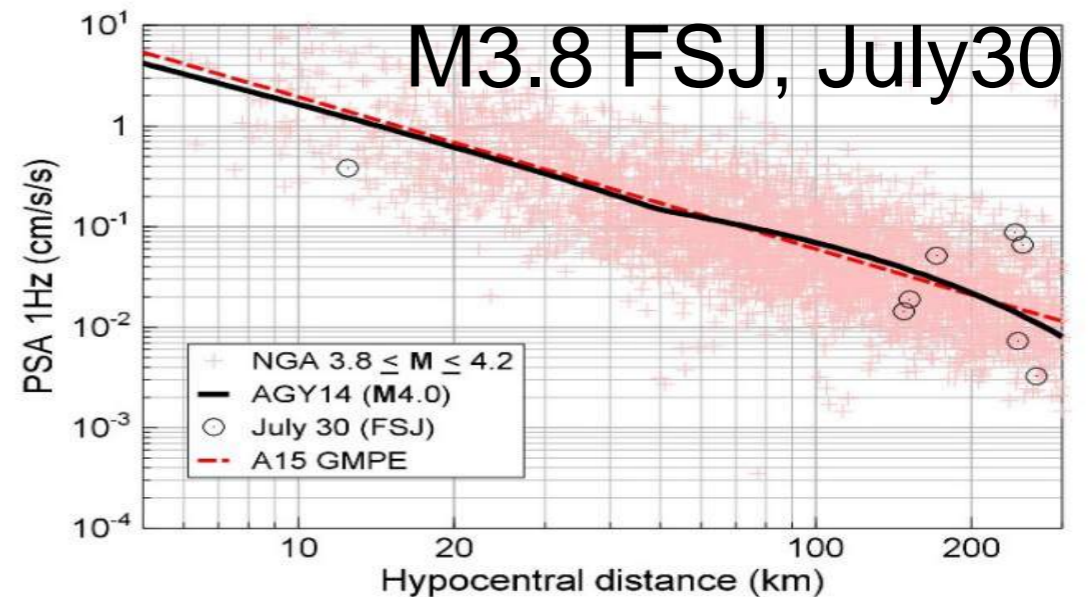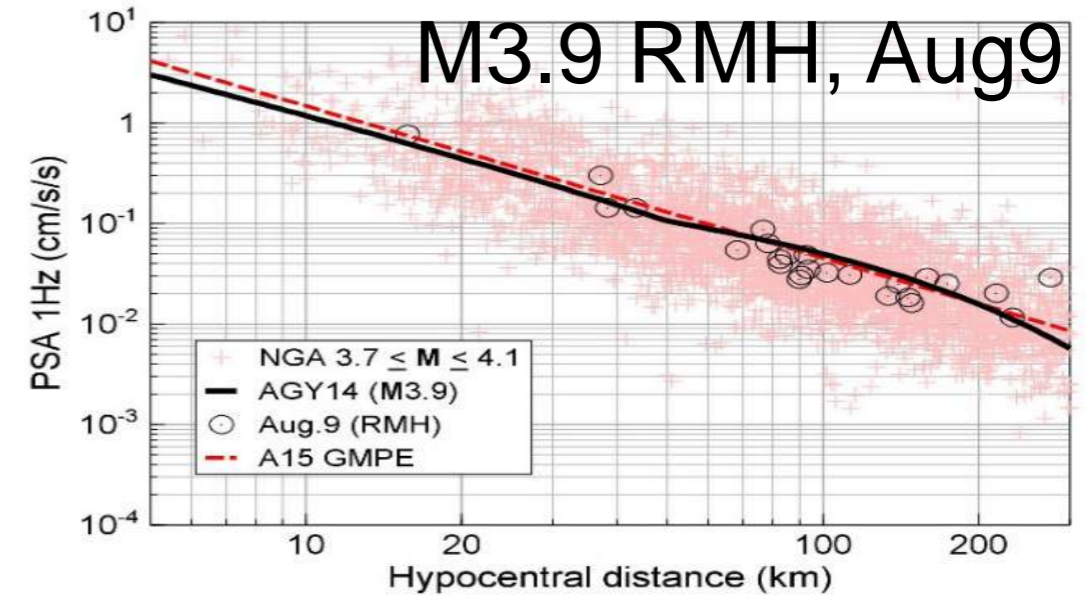
Horizontal-component PSA

- **Assume data are NEHRP D**
- **Plot Atkinson, 2015 GMPE (small-to-moderate events) for NEHRP D conditions**
- **(3 events have similar M: 3.9, 4.0, 4.2)**
- Note low amplitudes at closest stations (<20 km) at higher frequencies

Horizontal-component PSA for frequencies of 0.5 Hz (top), 3.3 Hz (middle) and 10 Hz (bottom) for the three study events (M4.0 and M4.2 near FSJ, M3.9 near RHM), in comparison to A15 GMPE (D site conditions) for the corresponding magnitudes. Assumed site amplification factors for the A15 GMPE, to convert from B/C to D site conditions, are 3.1, 2.2 and 1.6 for frequencies 0.5, 3.3 and 10 Hz, respectively.
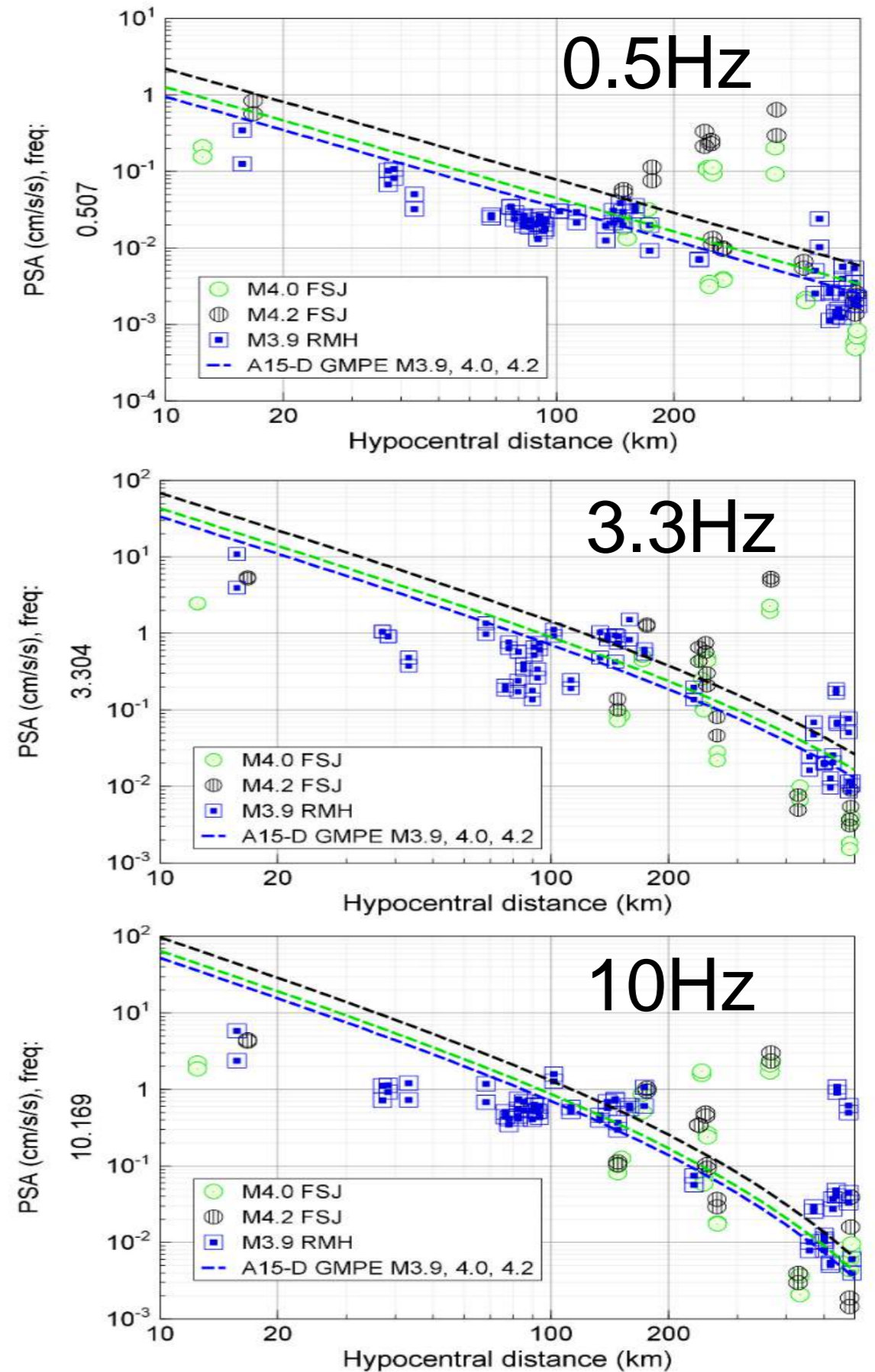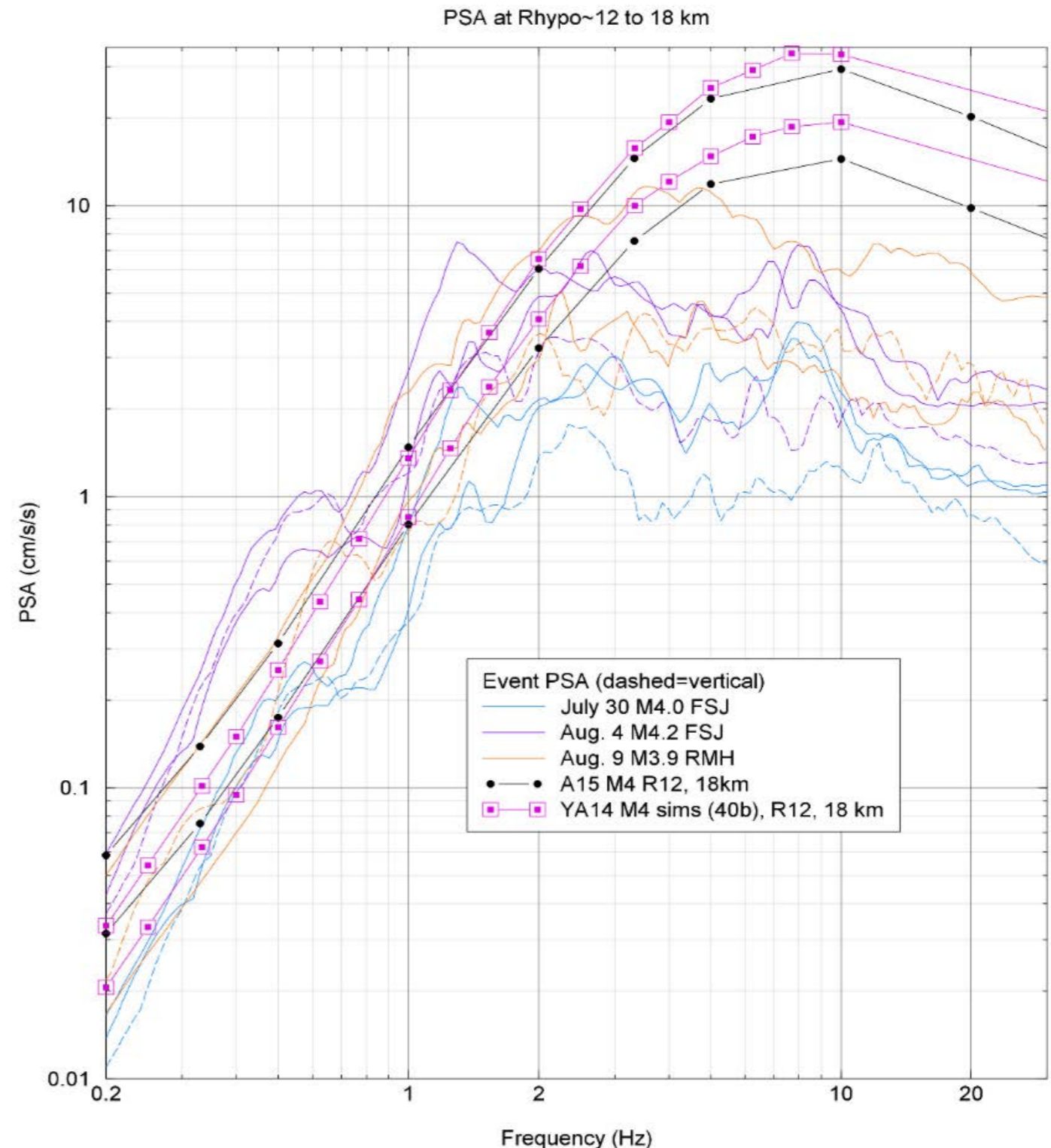
- Spectra from closest stations (<20 km) are low at high frequencies, relative to Brune-model with 40bar stress (i.e. lower than avg for natural **M**4 events in Calif)
- Also low relative to A15 empirical model for California
- Could imply low stress (i.e. For shallow **M**4, YA15 suggest 10bars), but……

PSA (5% damped; solid lines horizontal component, dashed lines vertical component) at closest station to each of the three events (Rhypo 12 to 18 km), in comparison to A15 spectrum for M4 at 12 to 18 km, and Yenier and Atkinson (2014) WNA simulation model for M4 at 12 to 18 km.
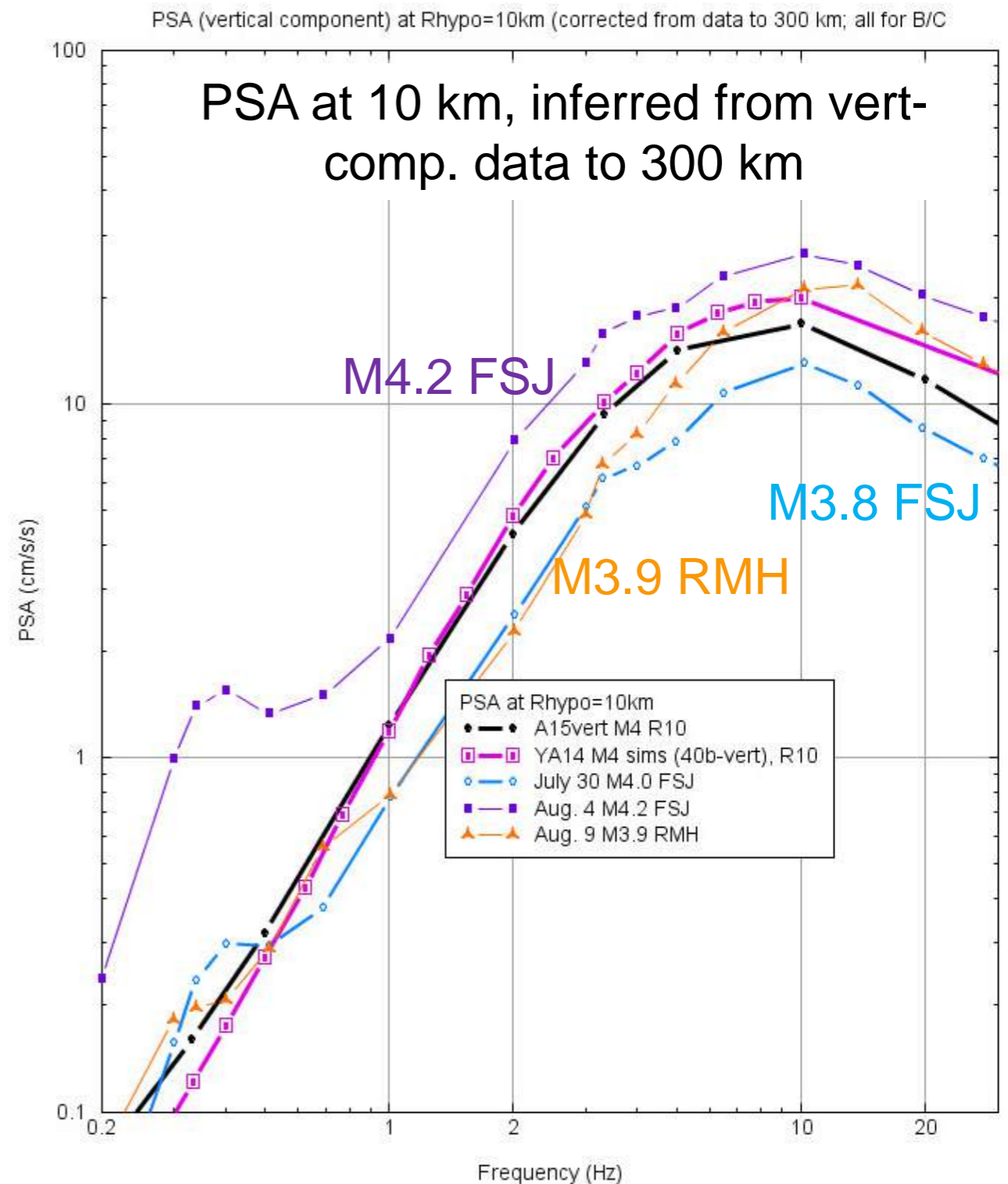

PSA at Rhypo~12 to 18 km

Event PSA (dashed=vertical)
- July 30 M4.0 FSJ
- Aug. 4 M4.2 FSJ
- Aug. 9 M3.9 RMH
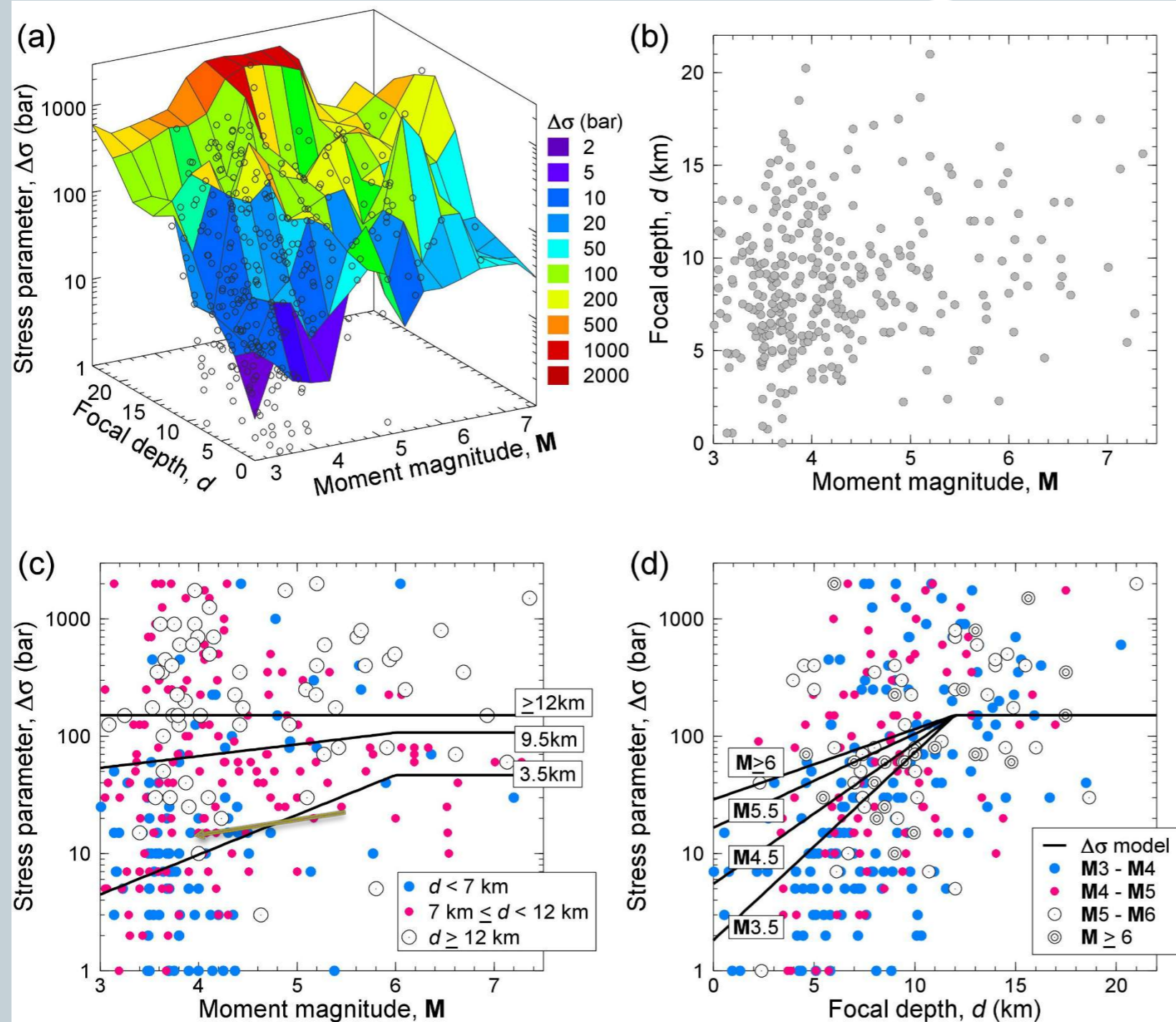- A15 M4 R12, 18km
- YA14 M4 sims (40b), R12, 18 km

- ….. If we consider the near-distance spectrum inferred from regional data we reach a different conclusion
- Here the spectra (vert.comp.) inferred at Rhypo=10 km agree with expectations for 40-bar Brune model
- (so source spectra ambiguous)

*Inferred near-source spectra at Rhypo=10 km, computed from vertical-component PSA at <300 km corrected to 10 km with A15 attenuation model. Also shown are California simulation model spectrum at 10 km for **M**=4, 40bars (Yenier and Atkinson, 2015) (inset squares) and empirical GMPE spectrum model of Atkinson (2015) for **M**4 at 10 km (solid black circles); model spectra converted to equivalent vertical spectra assuming H/V model for B/C site conditions as given in Atkinson and Boore (2006). Inferred source spectra for the 3 events also corrected to B/C.*

PSA (vertical component) at Rhypo=10km (corrected from data to 300 km; all for B/C)

PSA at 10 km, inferred from vert-comp. data to 300 km

M4.2 FSJ

M3.8 FSJ

M3.9 RMH

PSA (cm/s/s)

PSA at Rhypo=10km
- A15vert M4 R10
- YA14 M4 sims (40b-vert), R10
- July 30 M4.0 FSJ
- Aug. 4 M4.2 FSJ
- Aug. 9 M3.9 RMH

Frequency (Hz)
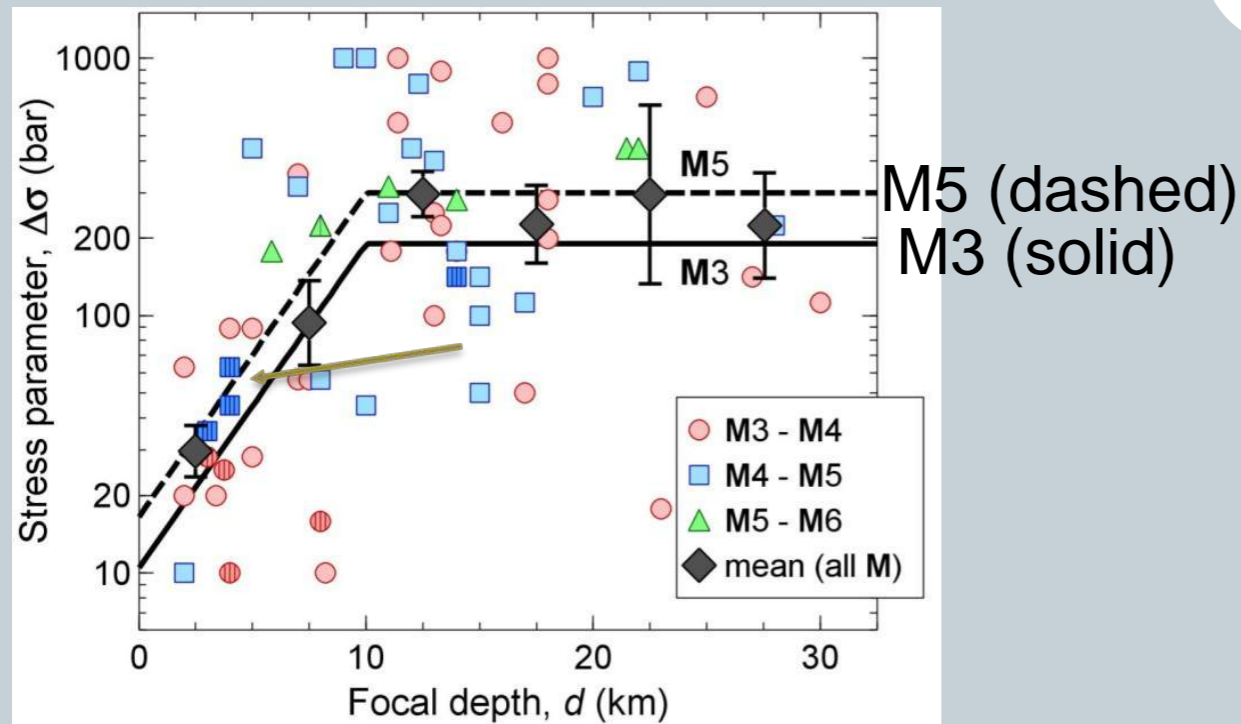
- California stress parameter depends on **M** and depth (NGAW2 dbase)

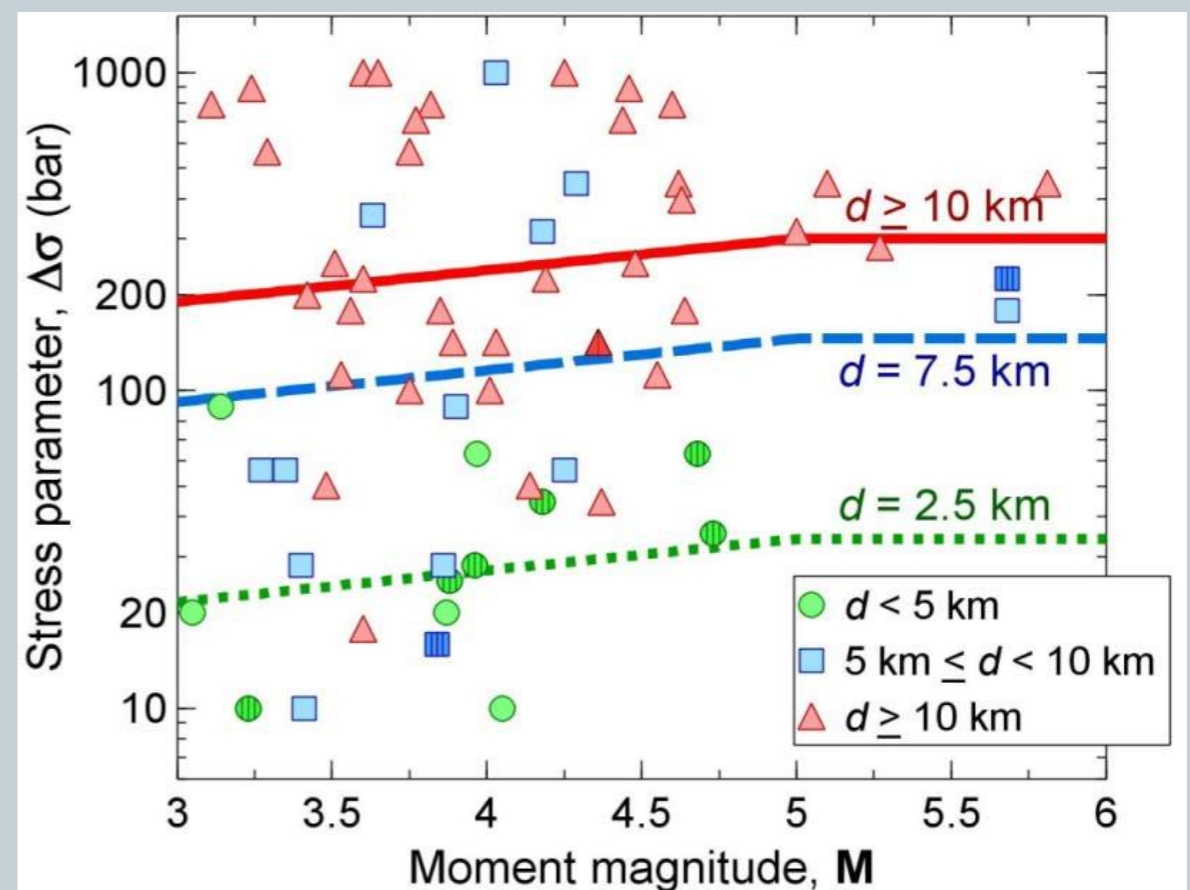- For M4 at 4km depth, stress ~ 15 bars

- (Yenier and Atkinson, 2015a)

M5 (dashed)
M3 (solid)

- ENA stress model is also depth-dependent (NGAE dbase)- with values about 3x higher than WNA

- insufficient data to resolve both **M** and depth as clearly as in California

- **M**4 at 4km depth ~50b

- (Yenier and Atkinson, 2015b)

So source parameters could be dependent on....

- Magnitude
- Focal depth
- Eastern vs. western setting
- Induced vs natural

At present there is large uncertainty over expected average source parameters for induced events in this region (about an order of magnitude uncertainty in average stress parameter)

This uncertainty has important implication for hazard estimates, as median ground motions are also very uncertain at higher frequencies.

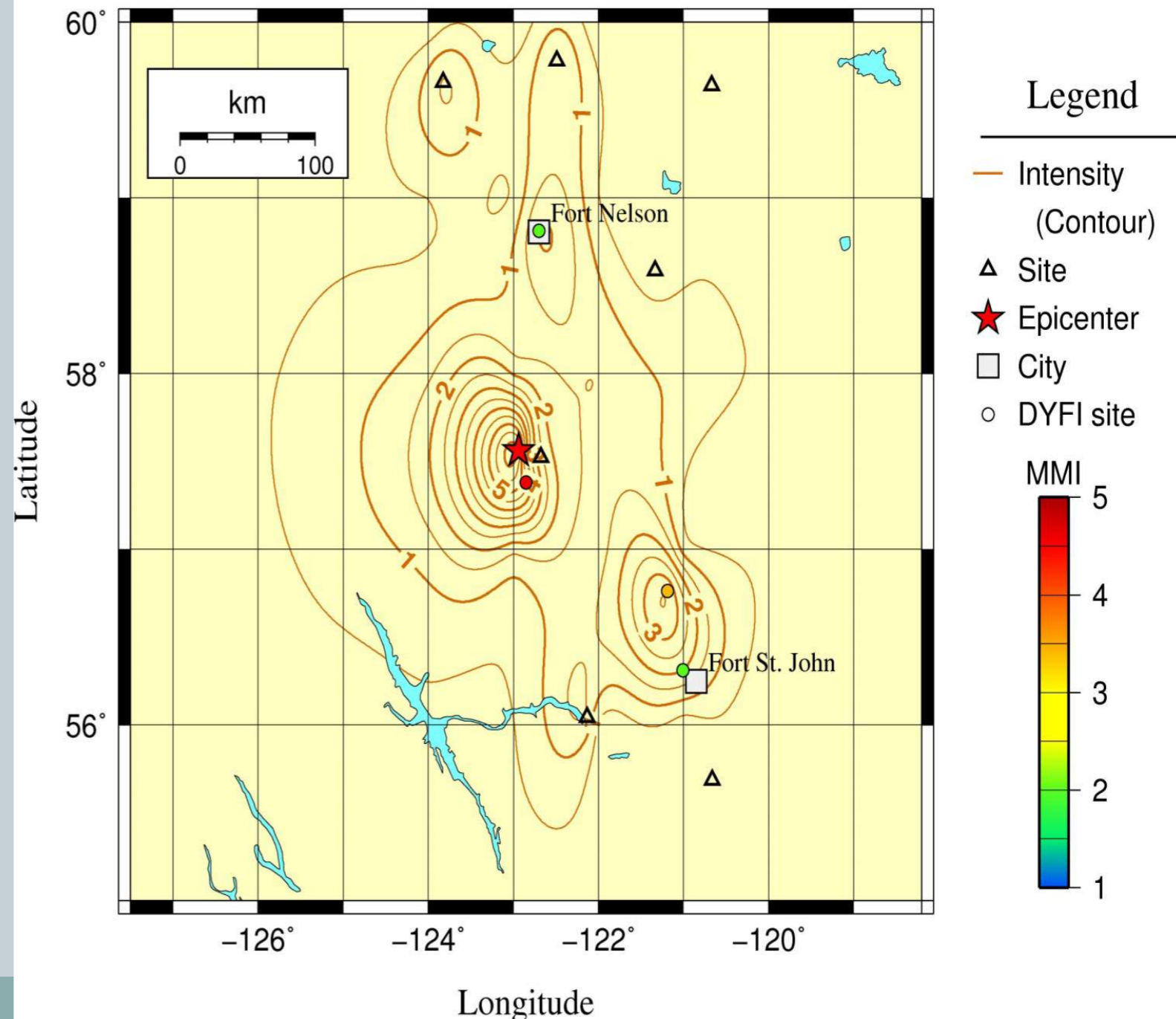It is also possible that aleatory variability (random scatter) is also high.

- **Inferred intensity (MMI) from PGV and from felt reports (dots)**
- **PGV from A15 GMPE and observations**
- **(PGV to MMI using Worden et al., 2012)**

Instrumental intensity distribution for Aug. 4 M4.2 event near Fort St. John.

Maximum predicted instrumental intensity at the epicenter is >6; the felt distance is ~200 km.

Intensity Map of August 4, 2014 M4.2 Earthquake
(From GMPE, Station Data, DYFI)

Felt effects: Aug. 9 2014 M3.9, Rocky Mountain House

- **Inferred intensity (MMI) from PGV and from felt reports (dots)**
- **PGV from A15 GMPE and observations**
- **(PGV to MMI using Worden et al., 2012)**

Instrumental intensity distribution for Aug. 9 M3.9 event near Rocky Mountain House.
Maximum reported intensities were 4 to 5. The felt distance is >100 km.

Intensity Map of August 9, 2014 **M**3.9 Earthquake
(From GMPE, Station Data, DYFI)
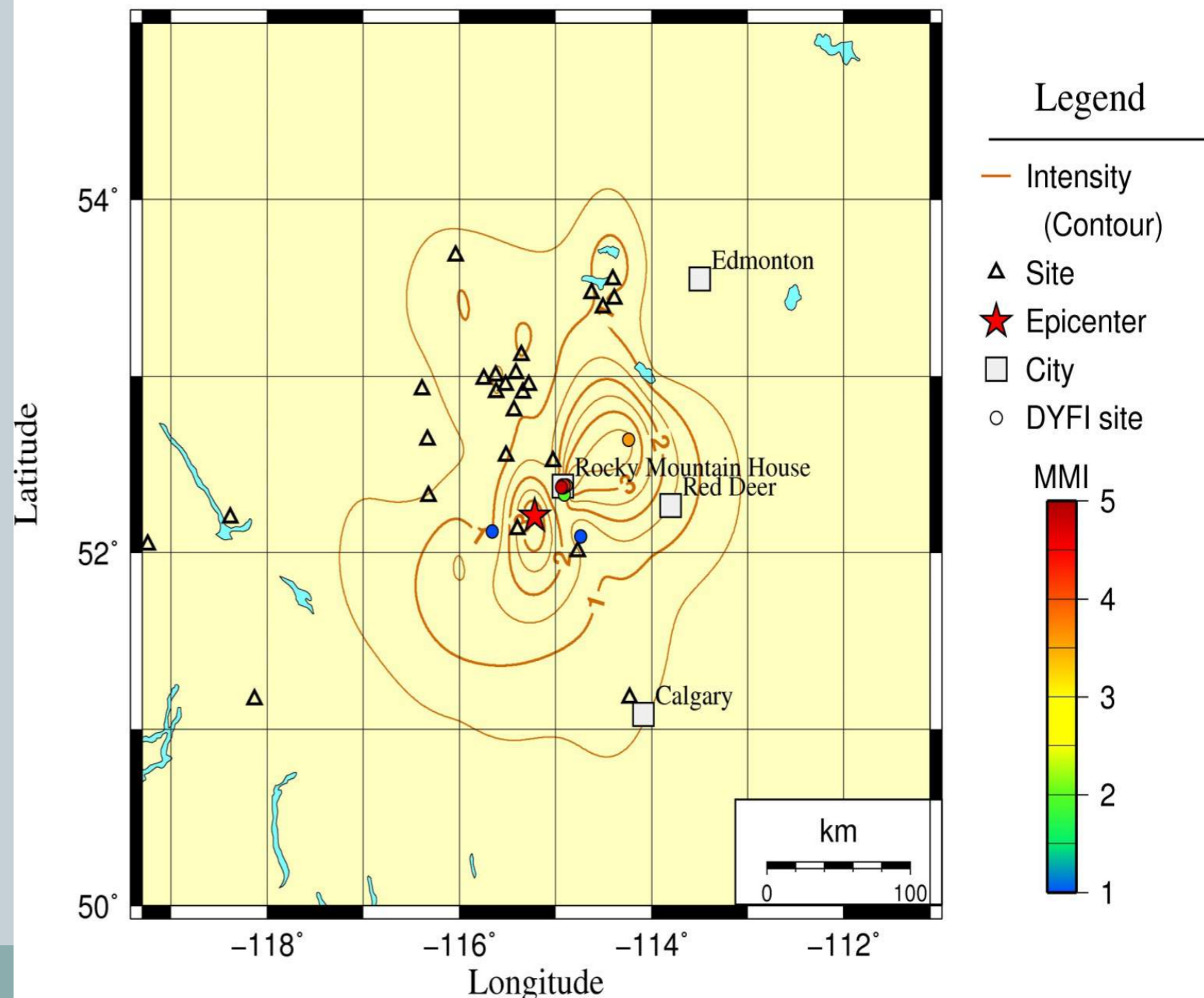
Conclusions: 3 **M**4 events of 2014

- Events near Fort St. John related to hydraulic fracturing

- Event near Rocky Mountain House likely induced but origin ambiguous (we suspect fluid injection)

- All 3 events were widely felt; the smallest caused a power outage, while the largest appears to have had damage potential

- Event attenuation and amplitudes consistent with that expected for similar events in California

- Uncertainty in source parameters and their dependence on focal depth, magnitude, and setting