Ground-motion prediction equations (GMPEs) for induced events and how they differ from those for natural events

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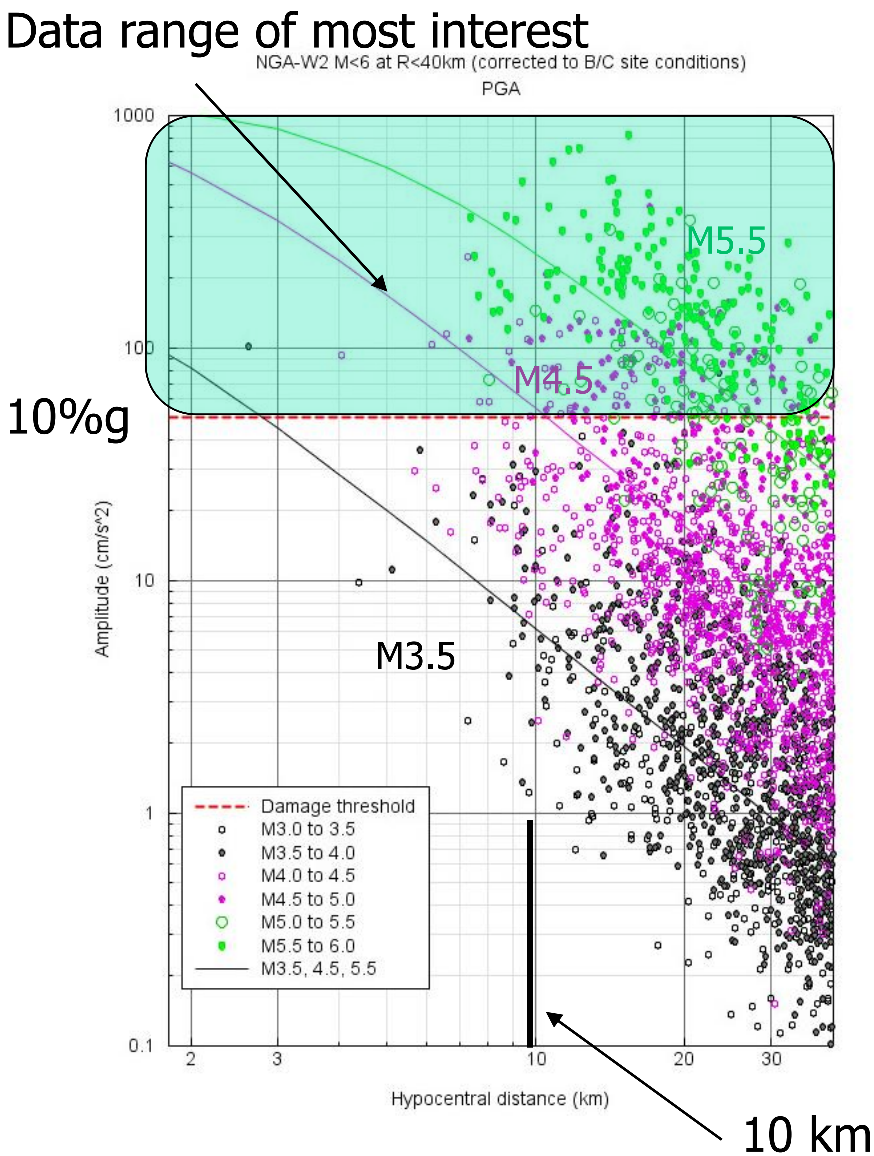
Overview

- Empirical and model-based GMPEs for induced events
- Key ground motion issues for induced-event GMPEs
- 3 GMPEs that work for induced events in CENA, and why
- Comparison of GMPEs with IS observations
- Recommended 4-GMPE suite for IS in CENA for 2017 maps



Empirical GMPEs: regress amplitudes (Y) (for each frequency) to a functional form that includes terms for source, path and site: eg. Atkinson, 2015 GMPE

What data do we want?

Ideally we want data from events of **M**>3 covering a full range of distance (2 km to >100 km)

- *each event at multiple stations/distances*
- *each station recording multiple events*

(resolve source, path, site)

Filling gaps: there are a number of seismological models that can help fill data gaps – this is crucial for induced seismicity applications in central/eastern US (CENA)

Atkinson (2015): $$\log Y_{A15} = c_0 + c_1 \mathrm{M_w} + c_2 \mathrm{M_w}^2 + c_3 log R$$

- developed for small-to-moderate events ($3<M_w<6$) at short distances (<50km), using California motions corrected to the NEHRP B/C reference site condition (V_{S30}=760m/s).

Using seismological models to fill data gaps

- Stochastic ground-motion models, based on effective point source concept, can be used to leverage empirical data
- The idea is to start with a robust seismological model that has appropriate magnitude and distance scaling built into it
- Calibrate a few essential parameters to the region or application
- Method MUST be calibrated to regional ground-motion observations to be useful

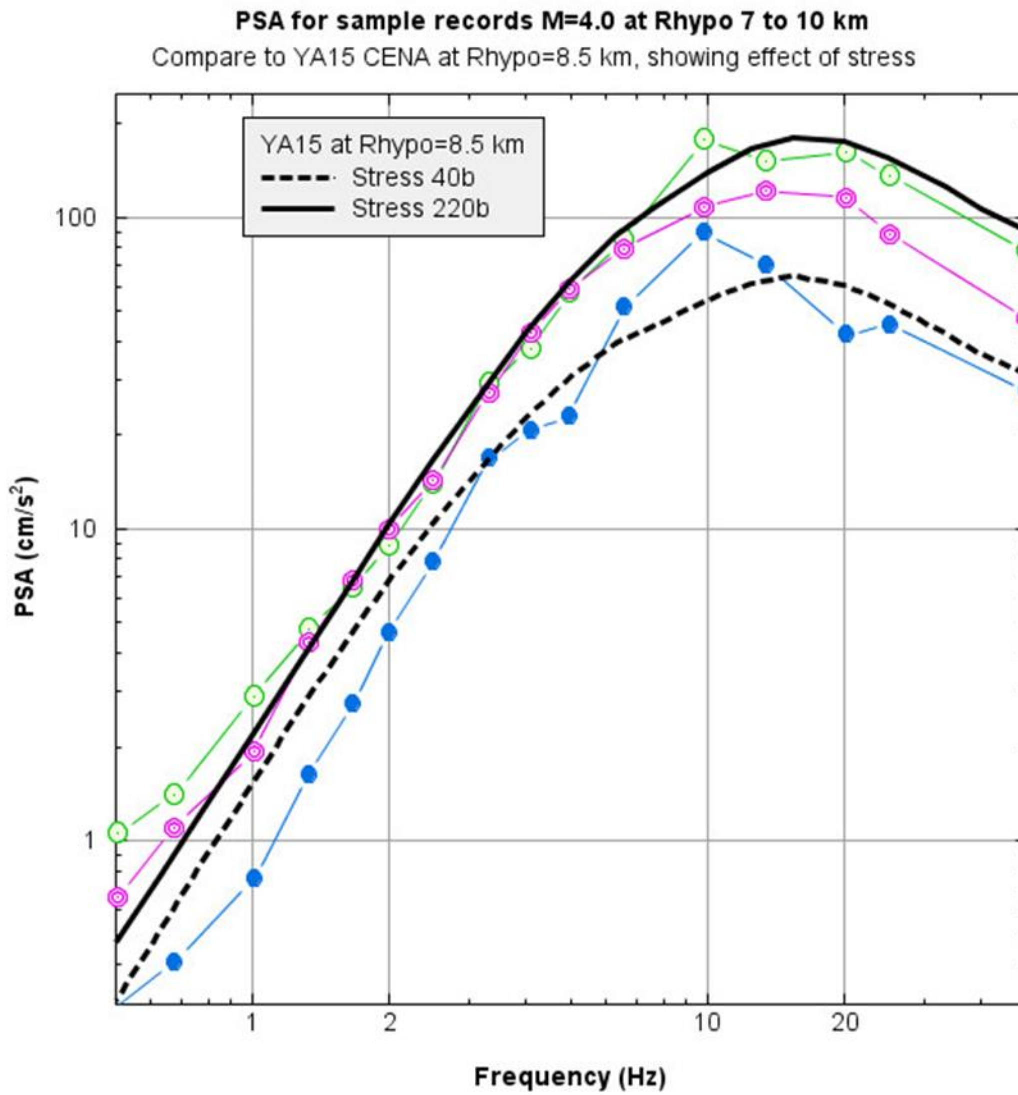
Generic GMPE model (Yenier and Atkinson, 2015, 2016)

- Encapsulated effective point-source model into a simple functional form that can be adjusted by application
- Calibrated model as a whole for California using NGA-W2 database (ensures appropriate scaling over wide magnitude/distance range)
- Adjusted model for CENA (central and eastern North America) using NGA-E database
- Showed that model can be applied to induced events in Oklahoma

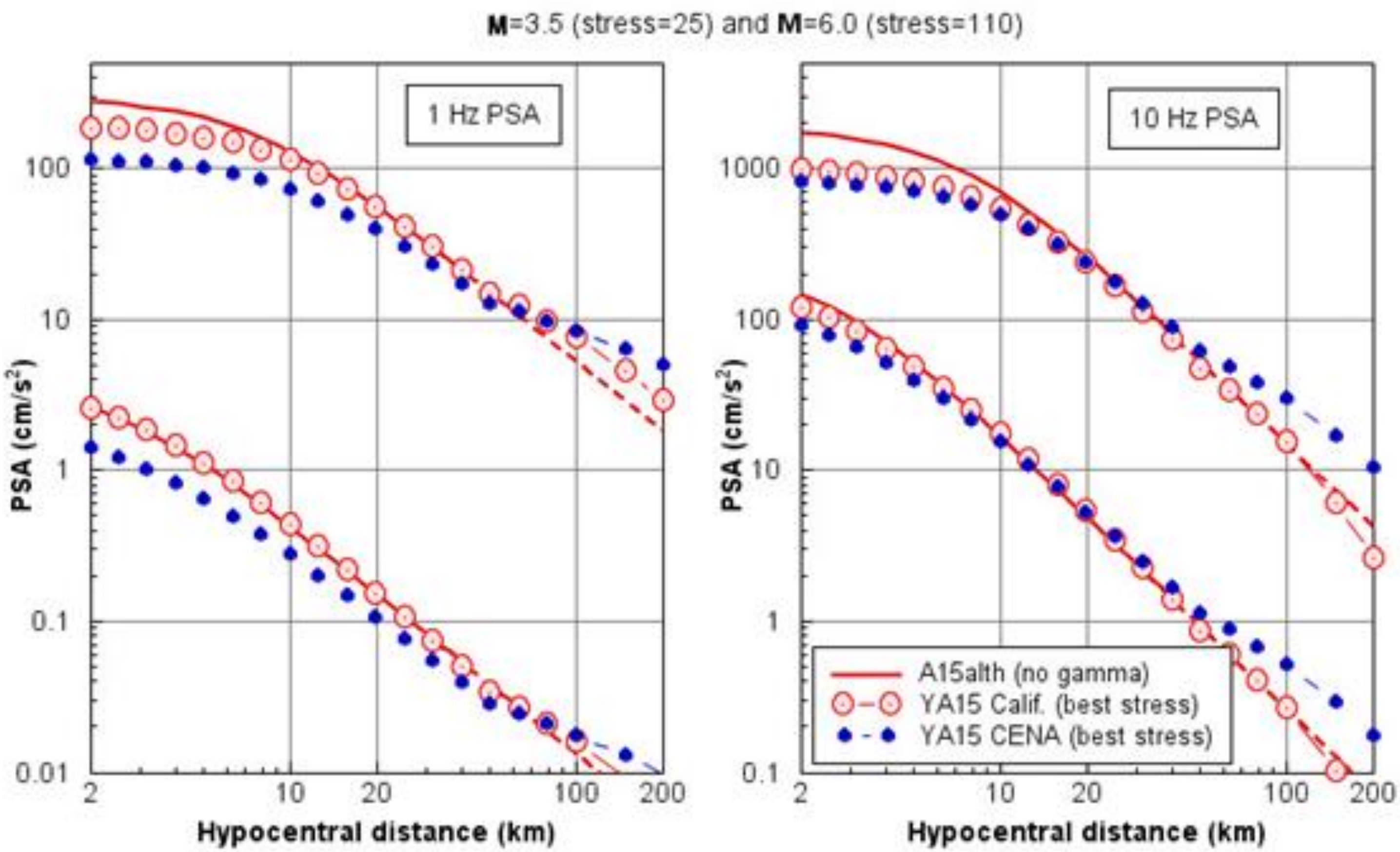
Influence of stress parameter on ground motions

There are multiple definitions of stress parameter and they cannot be readily compared across studies; what matters is spectral amplitude at high frequencies

*The effect of stress parameter on spectral shapes and amplitudes in the YA15 model. Response spectra are shown for a **M**=4 event at R_{hypo}=8.5 km for stress parameter values of 40 and 220 bars , for the YA15 CENA GMPE equations (B/C site conditions). Observed site-corrected spectra for **M**=4.0 records in Oklahoma having 7 km ≤ R_{hypo} ≤ 10 km are shown to illustrate typical comparisons of model to recorded data*



Sidebar - A useful application of the generic GMPE model: can use it to back-calculate the equivalent stress parameter values for empirical GMPEs (calculate logY from GMPE, then find stress with YA15 eqn to match)
e.g. A15 Calif GMPE implies 25 bars for **M**=3.5, 110 bars for **M**=6.0

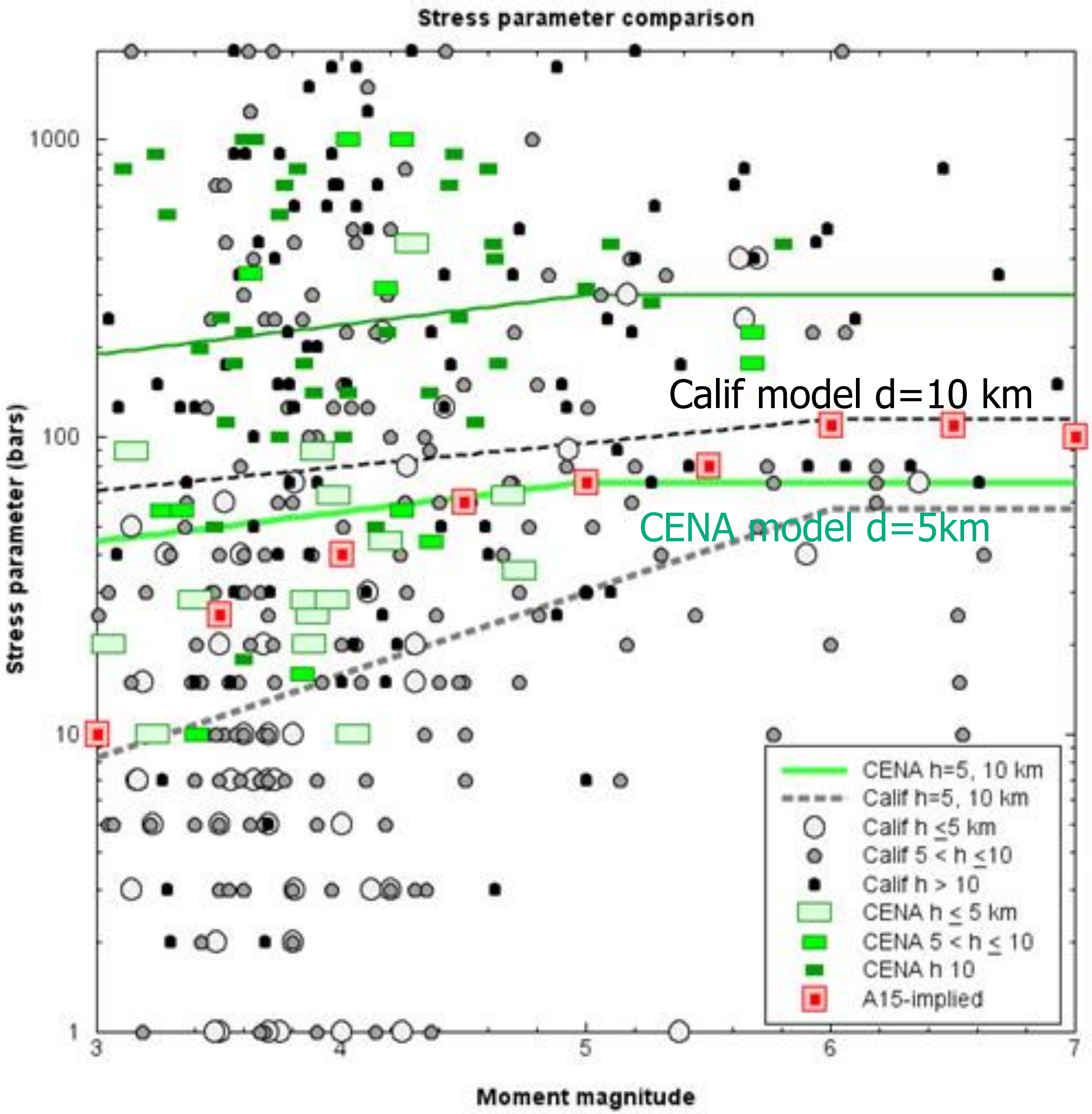


*Comparison of A15 empirical GMPE (alternative saturation) with YA15 equivalent point-source-model GMPEs for California and CENA, for **M**=3.5 and **M**=6.0, with YA15 stress value chosen to match A15 at each magnitude (25 bars for **M**=3.5, 110 bars for **M**=6.0).*

Comparing eastern (green) and western (black) stress parameter values

-back-calculated values implied by A15 (red) are also shown

Stress parameter values increase with **M** (to **M**~4 or 5) and with depth



Inferred stress parameter as a function of magnitude for A15 GMPE (squares) compared to empirical stress data (symbols) and models (lines) of YA15 for California and CENA. Circles are stress values from YA15 for events in California; rectangles are stress values from YA15 for events in CENA (both coded by focal depth). Lines show median stress model of YA15 for California (dashed) and CENA (solid) for focal depths of 5 and 10 km.

Note that A15 implied stress values (California; h~8km) similar to expected values of CENA stress for h~5 km, for **M**>3.5

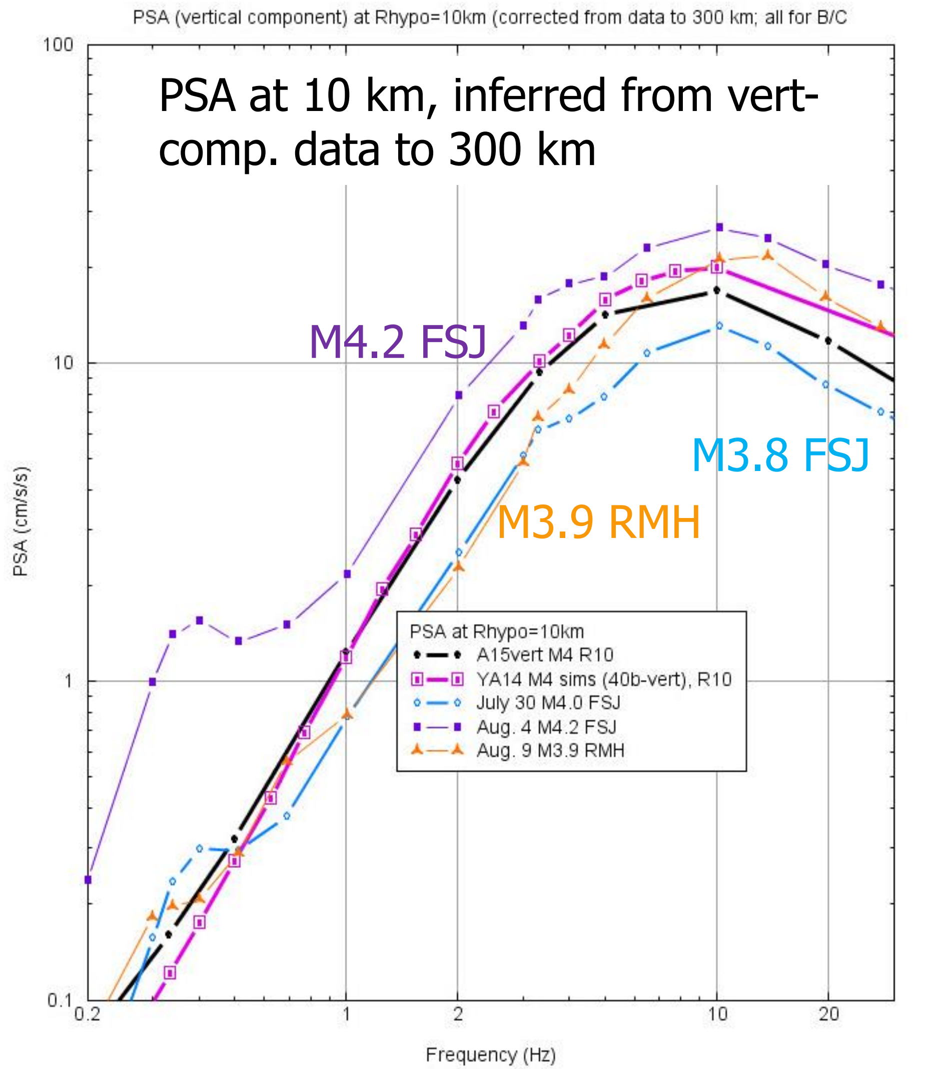
- This is why it works!

Key ground-motion issues for induced seismicity (important for ground-motion modeling; needed to extend empirical data)

- Stress parameter and its dependence on focal depth and tectonic region
- Potential differences between natural and induced-event stress parameter?
- Mainshock versus aftershock stress values (big difference seen in Prague, 2011 sequence)
- Near-source distance scaling (attenuation rate)
- CENA site response

The effects of tectonic region (east vs. west) counteracts the effect of focal depth: M4 events for shallow events in CENA have similar spectra to those for deeper events in California (stress parameter effects nearly cancel out)

- Inferred spectra at 10 km for 3 induced events of **M**~4 in Alberta/NE BC are compared to A15 empirical model from NGA-W2 data (black line) and to stochastic simulation model prediction assuming 40 bars (pink line) (from Atkinson et al., 2014 SRL)



*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.*

Attenuation Effects: For both natural and induced events, there is a **near-distance saturation effect** (often modeled with an effective depth term (h_{eff})). It needs to be magnitude-dependent, because saturation effects stronger for large events

Overall attenuation depends on the combination of near-distance saturation and the geometric spreading rate

Overall attenuation rate for small events (M~4) **MUCH steeper than 1/R.** Assuming 1/R from 20 km in to 5 km will greatly underestimate motions.

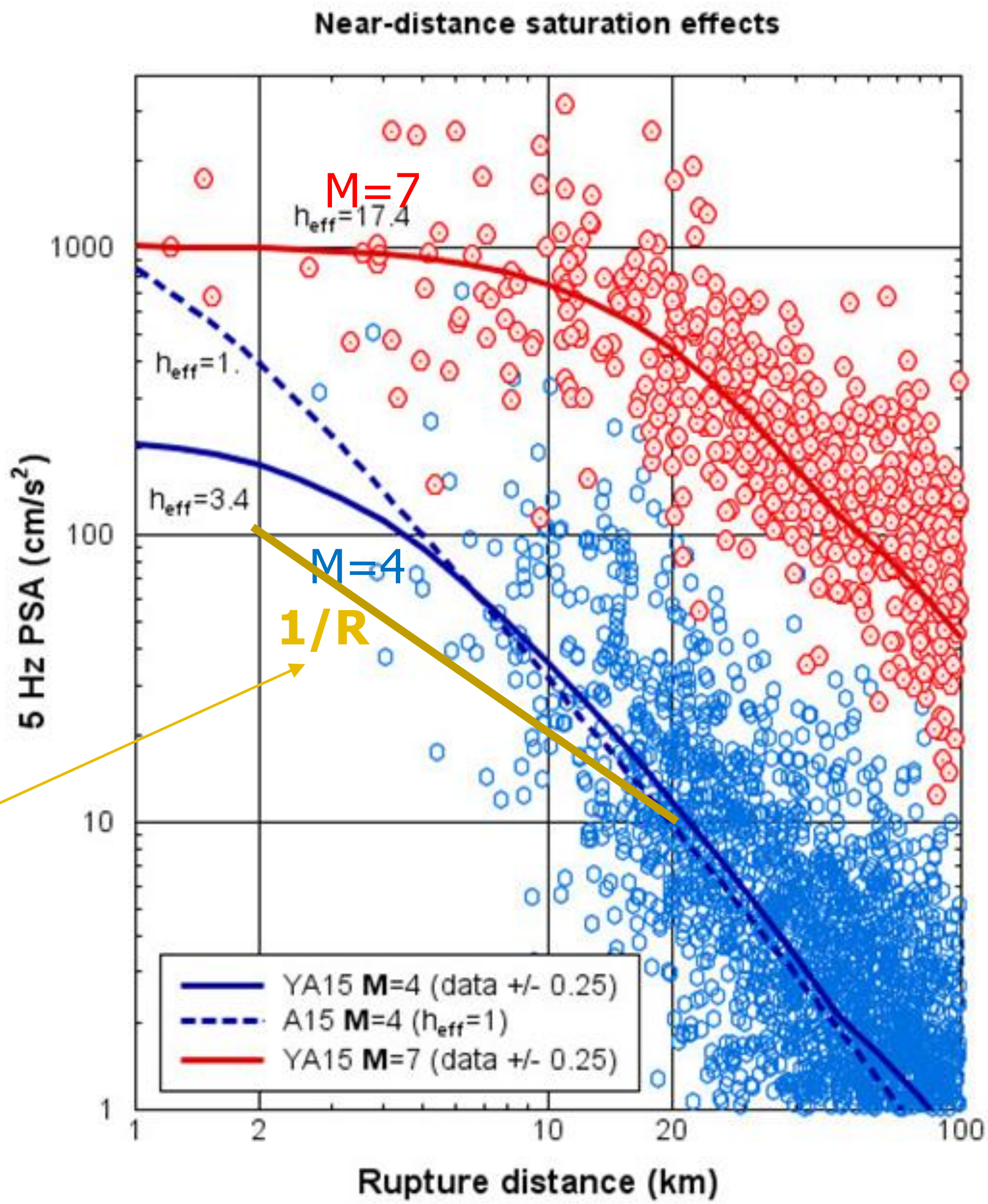


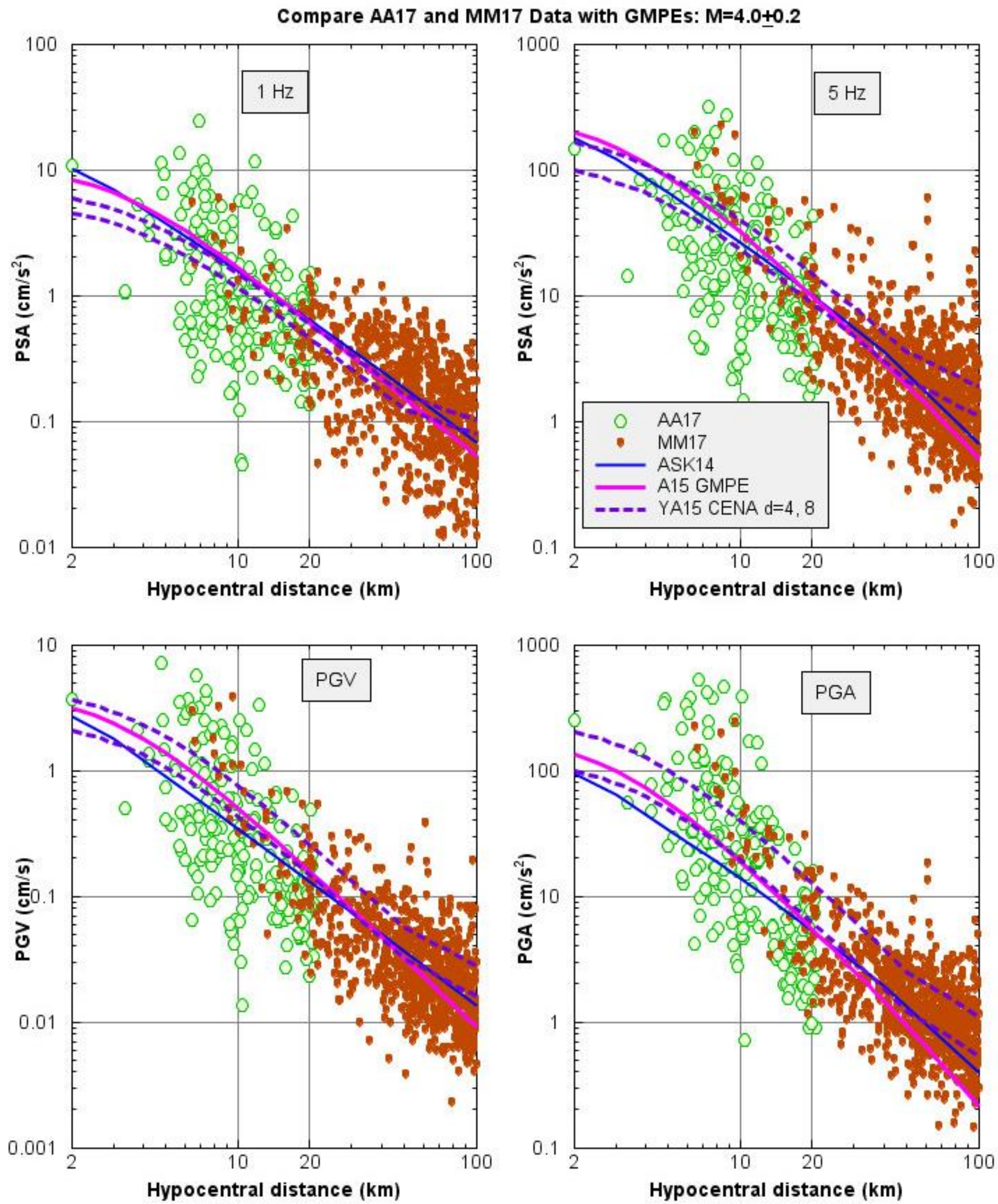
Figure: California data from NGA-W2, corrected to B/C, compared to Yenier and Atkinson (2015) point-source stochastic-model GMPE for California for **M**=4 and **M**=7 (solid lines; similar to "alternative-h_{eff}" model of Atkinson, 2015)
Atkinson (2015) small-M GMPE for **M**=4 with the steeper saturation model is also shown (dashed, h_{eff}=1km at **M**=4)

Some preliminary conclusions on GMPEs for induced events, considering stress drop and near-distance scaling issues (Atkinson and Assatourians, 2017, SRL)

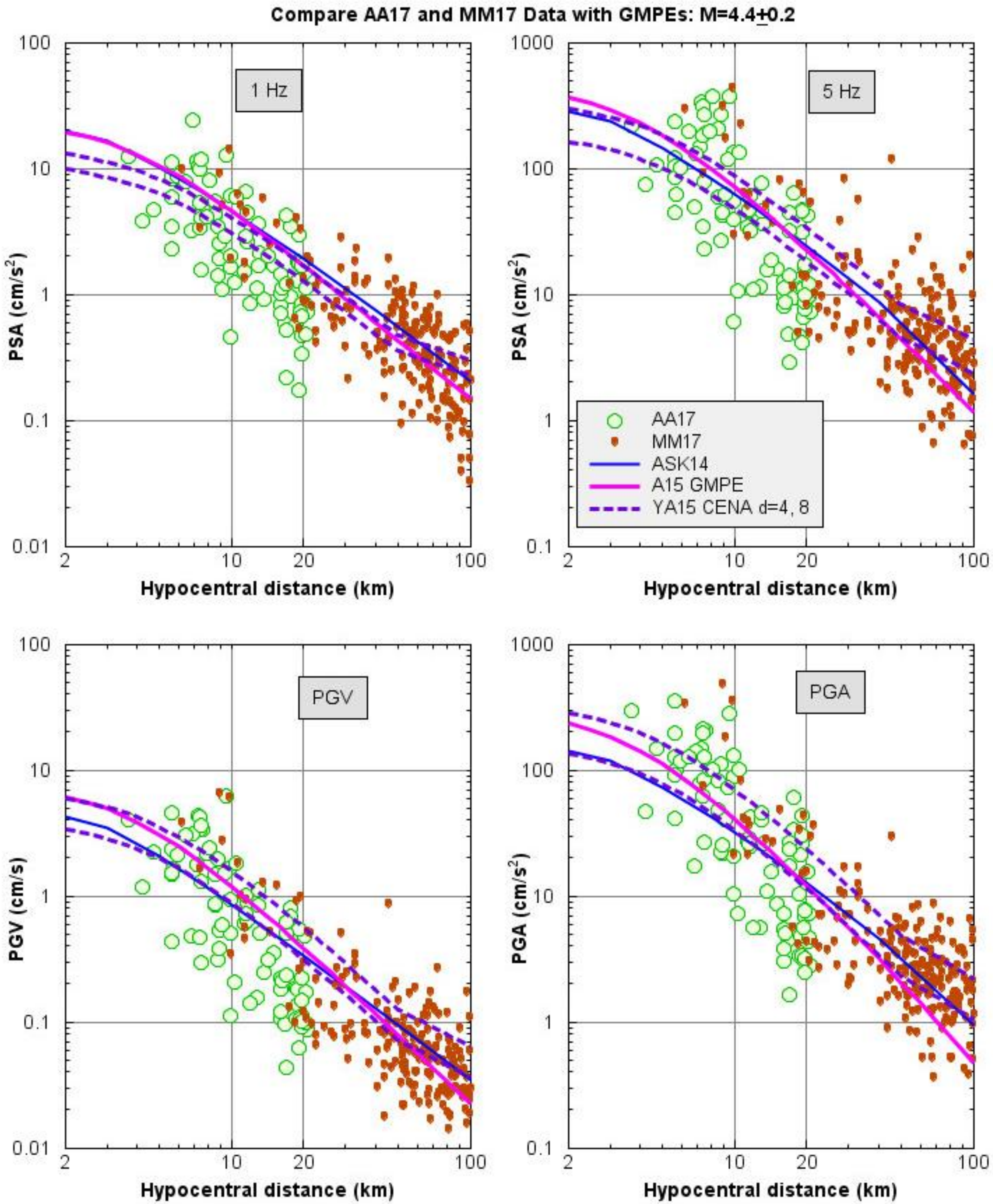
- 3 published GMPEs are (roughly) suitable for induced-event hazard analyses
  - Yenier and Atkinson, 2015 (from eastern North America, natural + induced) (YA15) (we can use a range of focal depths to sample a range of stress values)
  - Atkinson, 2015 (from shallow California, NGA-W2 data with scaling attributes appropriate for induced events) (A15)
  - Abrahamson et al., 2014 (from shallow California, NGAW2 – works if implemented with "unspecified" depth to top of rupture, which forces average depths) (ASK14)
- A15 and ASK14 work because shallow CENA events have stress similar to deeper California events: both have appropriate point-source attenuation for small M

Compare GMPEs (A15, ASK14, YA15 d=4, 8) to compiled databases: M=4.0 +/- 0.2 Assatourians and Atkinson (2017) and Morgan Moschetti (2017)

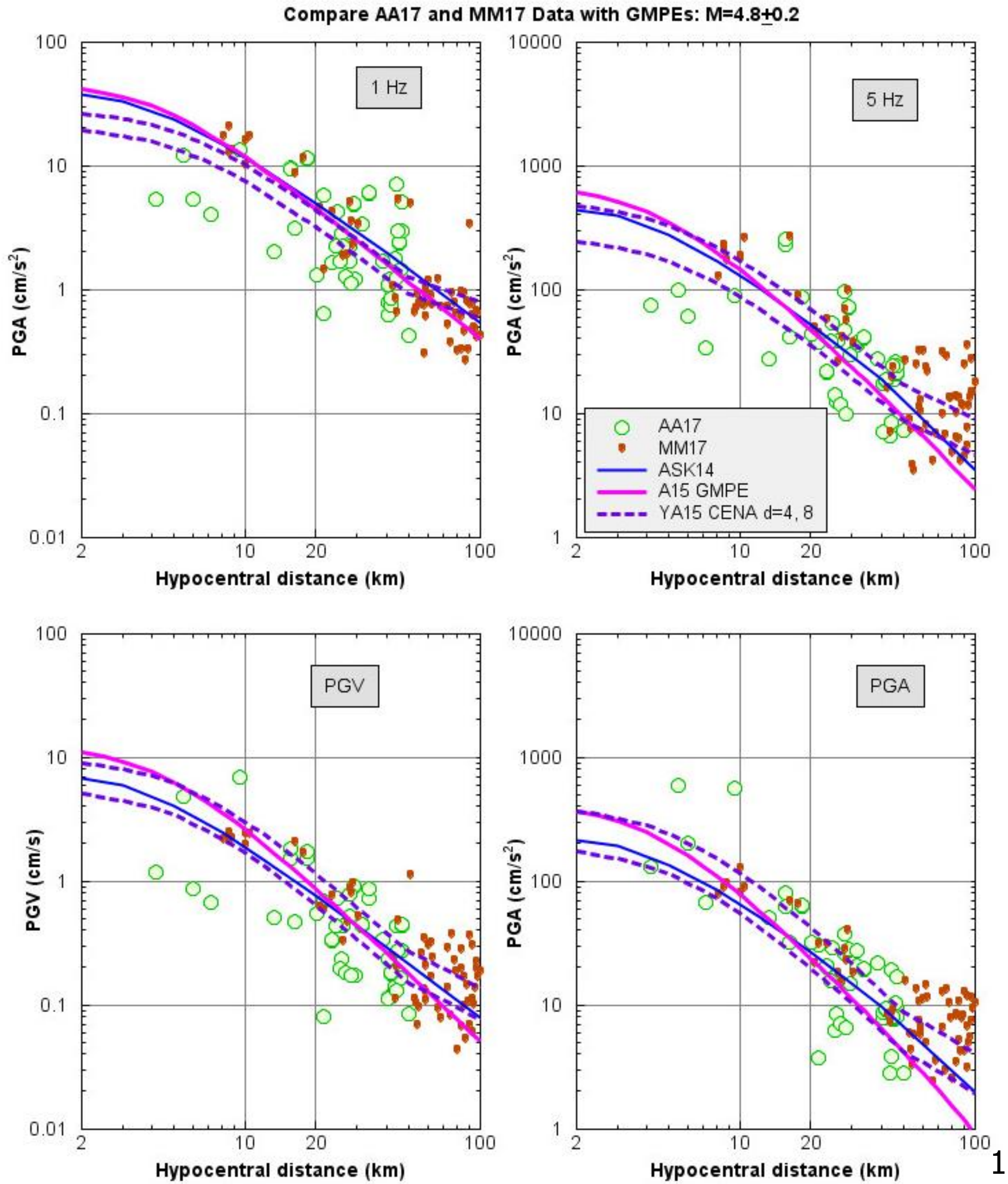
Note: All data corrected to B/C assuming Class C, with Seyhan and Stewart, 2014 corrections



Compare GMPEs (A15, ASK14, YA15 d=4, 8) to compiled databases: M=4.4 +/- 0.2 Assatourians and Atkinson (2017) and Morgan Moschetti (2017)

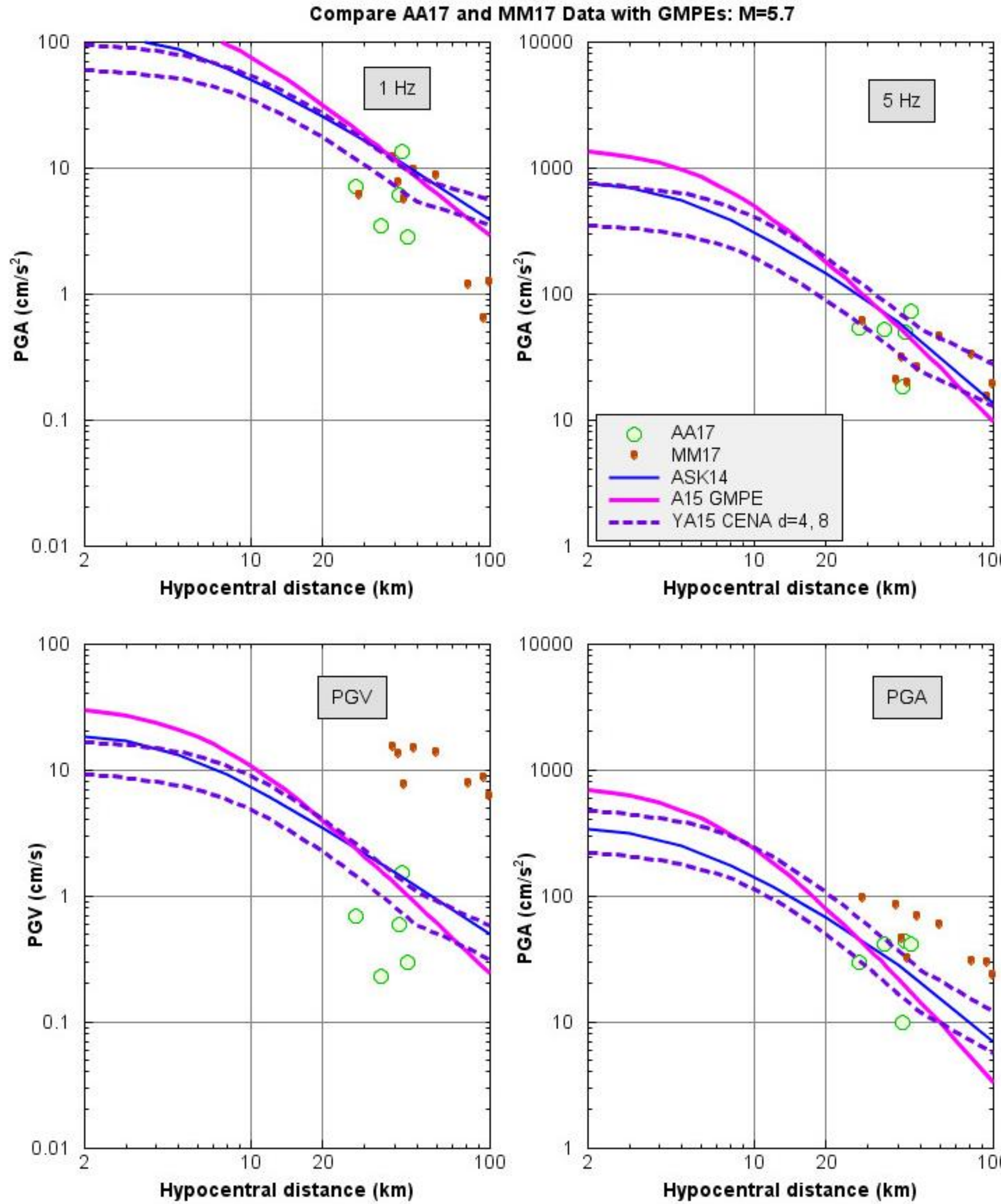


Compare GMPEs (A15, ASK14, YA15 d=4, 8) to compiled databases: M=4.8 +/- 0.2 Assatourians and Atkinson (2017) and Morgan Moschetti (2017)



Compare GMPEs (A15, ASK14, YA15 d=4, 8) to compiled databases: M=5.7 Assatourians and Atkinson (2017) and Morgan Moschetti (2017)

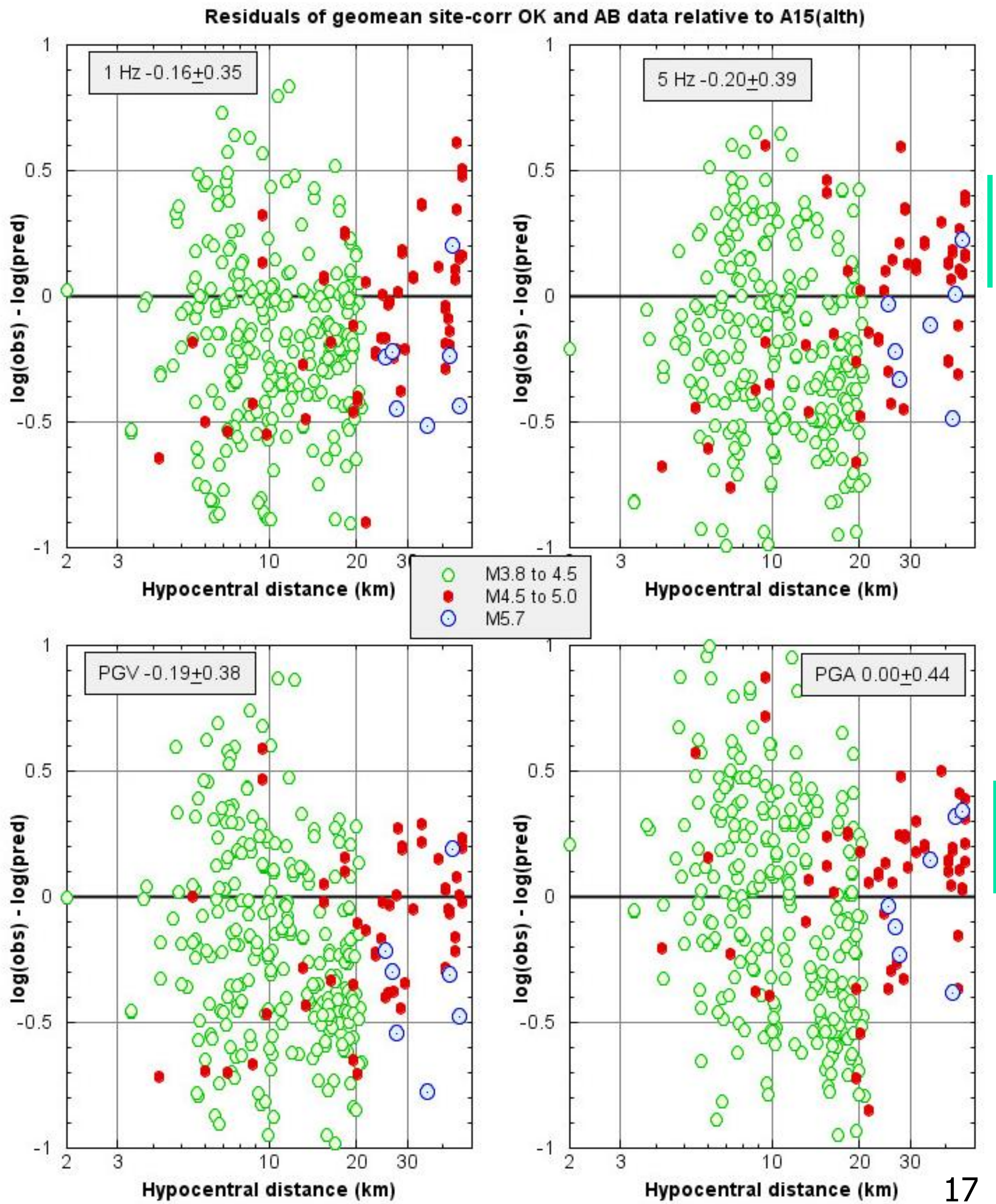
Note: the Moschetti PGV values for M5.7 are in error; new processing appears to have fixed problem



Residuals for OK data relative to A15 - our database

*Residuals **(log10 units)** for horizontal-component PSA at 1 and 5 Hz, peak ground velocity and peak ground acceleration for induced events in Oklahoma and Alberta, relative to the A15(alternative h) GMPE. Events of **M**3.8 to 4.5 are compiled to 20 km; **M**≥4.5 events are compiled to 50 km (from Atkinson and Assatourians, 2017).*

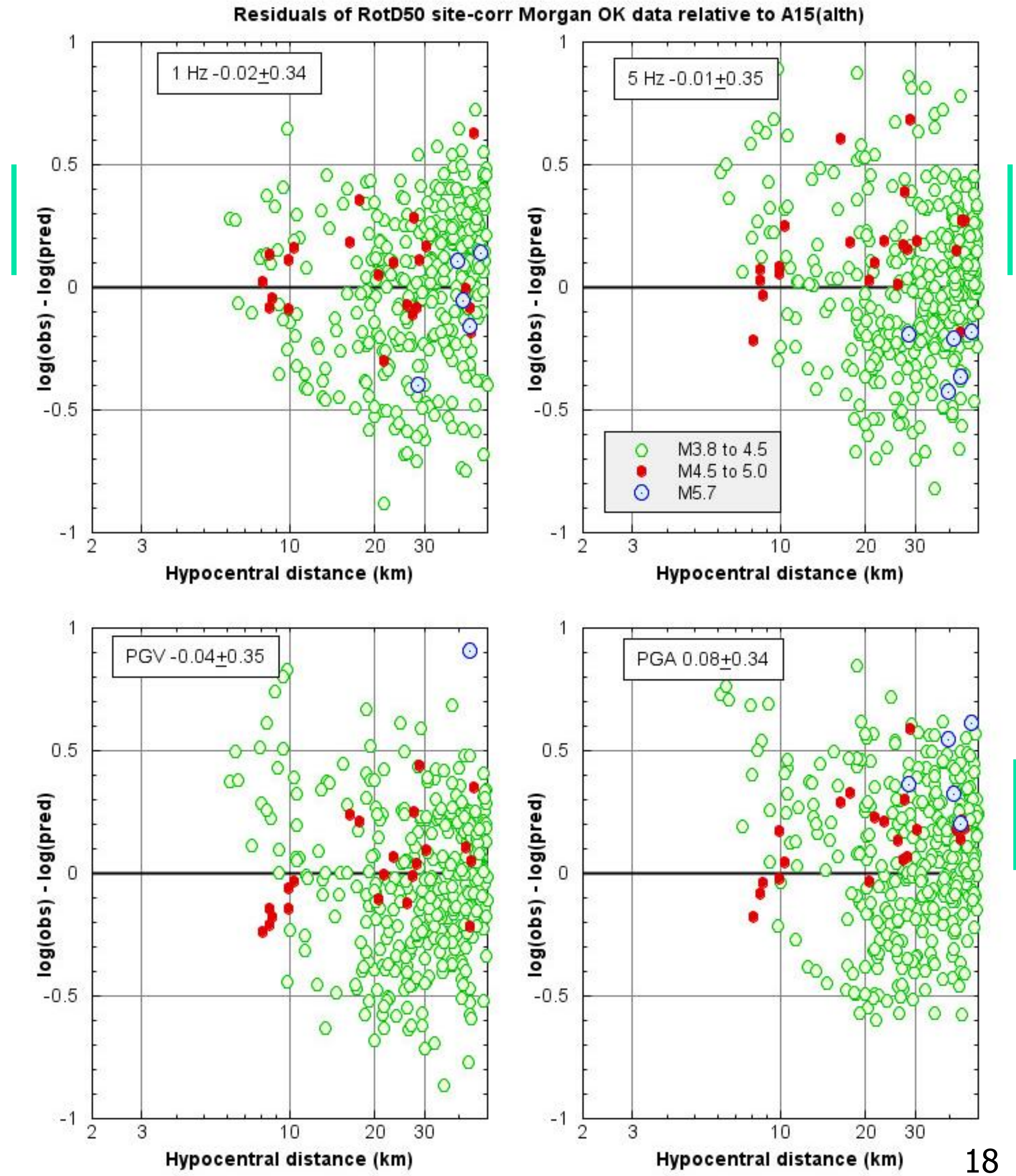
(Vert bar shows 1 ln unit)



Residuals for OK data relative to A15 – Morgan's database

*Residuals **(log10 units)** for horizontal-component PSA at 1 and 5 Hz, peak ground velocity and peak ground acceleration for induced events in Oklahoma from Morgan's database, relative to the A15(alternative h) GMPE.*

(Vert bar shows 1 ln unit)



Summary/Recommendations

- Ground-motions for induced events, at close distance, are key to hazard
- Critical ground-motion issues for induced seismicity are:
  - High-frequency level: scaling of stress parameter with magnitude, depth, tectonic region, mainshock vs. aftershock
  - near-distance attenuation
- Due to fortuitous trade-offs, 3 existing published GMPEs are roughly appropriate for induced-event hazard in CENA (with some caveats: YA15; A15; ASK14. Use YA15 with depth=4km and depth=8km to sample stress parameter range. Use unspecified depth to rupture for ASK14. **This gives 4 GMPEs that can be used for 2017 maps (YA15, d=4; YA15, d=8; ASK14; A15).**
- New induced event GMPEs for CENA are currently under development, with large databases; challenge is to unravel a complex set of source, path and site effects

Compare AA17 and MM17 events for database (for last 3 years)