The Apparent Stress Controversy: Does Earthquake Self-Similarity Hold and Who Cares?

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Presentation Outline

Background issues & controversy

Approach using scattered waves (coda)

Comparison to other source scaling studies

Ground motion validation (PSA, PGV, PGA)

Conclusions

Why do we care?

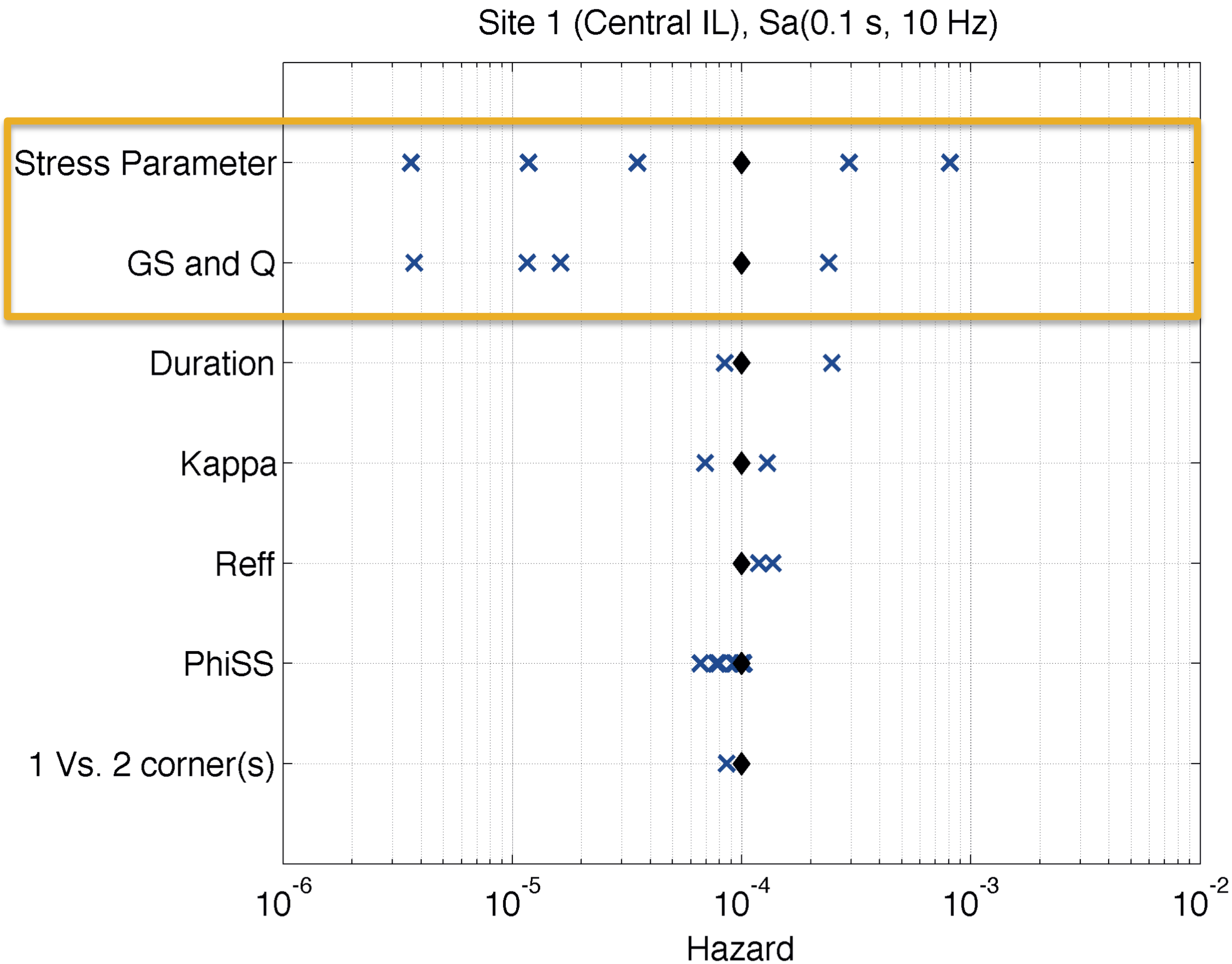
-A fundamental question exists on whether the physics of earthquake rupture is the same for small and large earthquakes (e.g., constant rupture velocity?).

- academic and practical applications
- can tell us the state of stress in a particular region

-Knowing the answer can guide forward modeling efforts for strong ground motion prediction and improve building design standards.

-Implications for getting it wrong can have “real world” consequences (*e.g.*, ground motion predictions for future damaging earthquakes could be significantly underestimated).

Strong Sensitivity in Ground Motion Prediction Equations (GMPE's)



[*Abrahamson*, 2011]

Seismic discrimination for explosion monitoring requires a change in scaling!

Issues with direct *S*-wave estimates

Radiated energy estimates from *S*-wave spectra require *significant* broadband corrections for path, site, and source radiation pattern.

Alternatively we can use spectral ratios and/or empirical Green's function deconvolution which remove common site and path effects, but large scatter remains and requires a lot of averaging.

…., and you need large and small events to be nearly co-located with same focal mechanism…, this is not always easy to find!

Source spectral ratios of two co-located events removes common path and site effects (in theory). We consider the case when scaling is non-self-similar.

$$\frac{\dot{M}_1(\omega)}{\dot{M}_2(\omega)} = \frac{M_{0_1}\left[1+\left(\omega/\omega_{c_2}\right)^2\right]^{p/2}}{M_{0_2}\left[1+\left(\omega/\omega_{c_1}\right)^2\right]^{p/2}}$$

Brune omega-square model (1970) assumes p=2

low frequency asymptote = $\frac{M_{0_1}}{M_{0_2}}$ high frequency asymptote = $\left(\frac{M_{0_1}}{M_{0_2}}\right)^{\frac{1}{3}}$

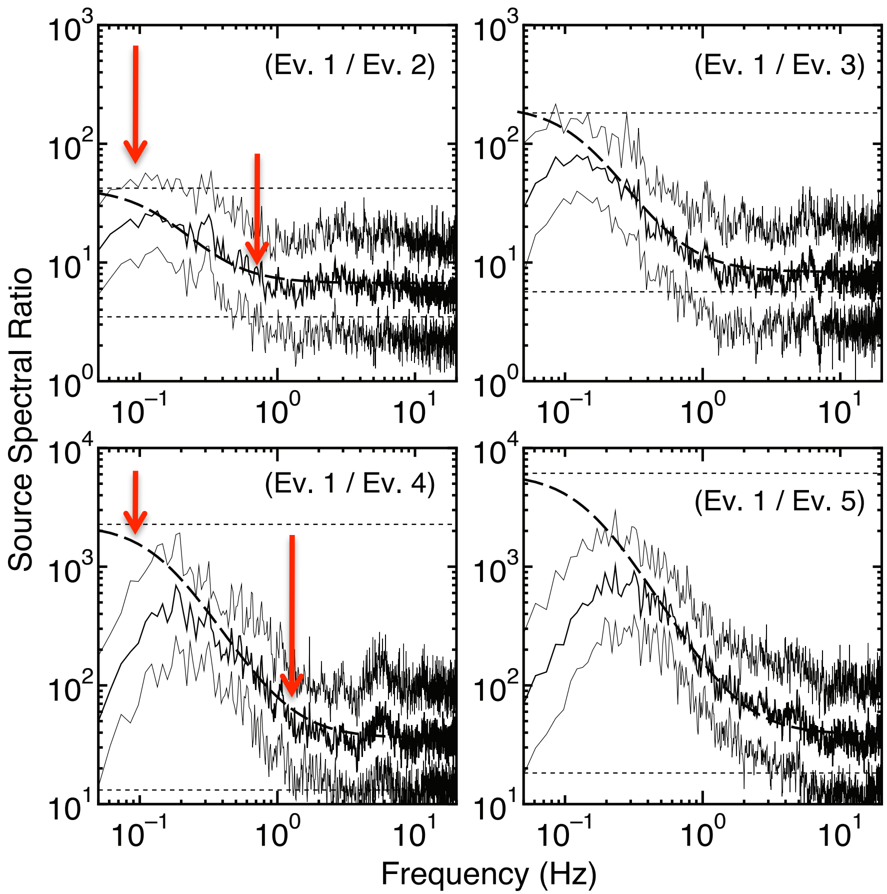
If scaling is non-self-similar, then

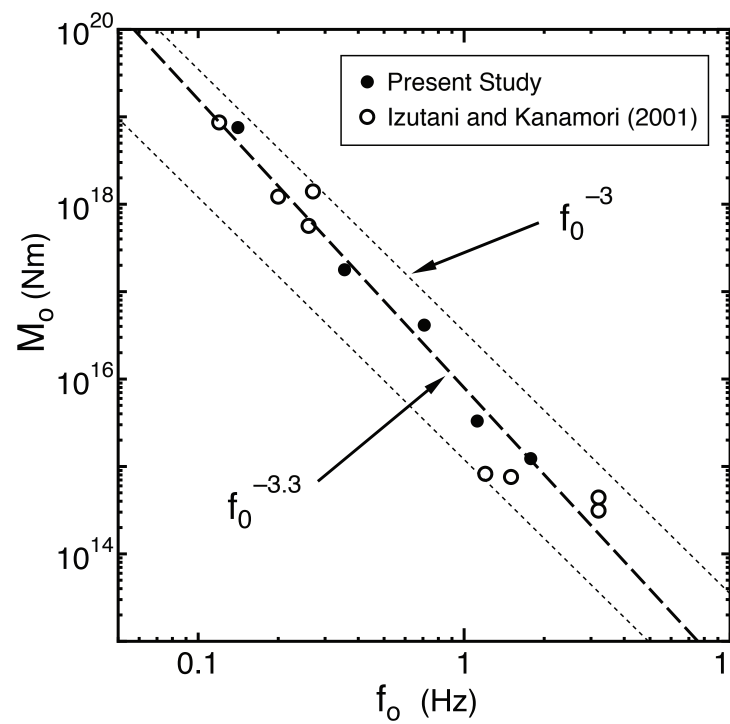
$$\omega_{c_i} = 2\pi f_{c_i} = \left(\frac{k_i\sigma_{a_i}}{M_{0_i}}\right)^{1/3} \qquad \sigma_{a_i} = \sigma'_a\left(\frac{M_{0_i}}{M'_0}\right)^{\psi} \qquad \psi = \frac{\varepsilon}{\varepsilon+3} \qquad M_0 \propto f_c^{-(3+\varepsilon)}$$

(Kanamori and Rivera, 2004)

However…

Source spectral ratios from local *S*-waves from the 2004 mid Niigata, Japan sequence exhibit large data variance and makes source parameter interpretations very questionable.





No error estimates shown!

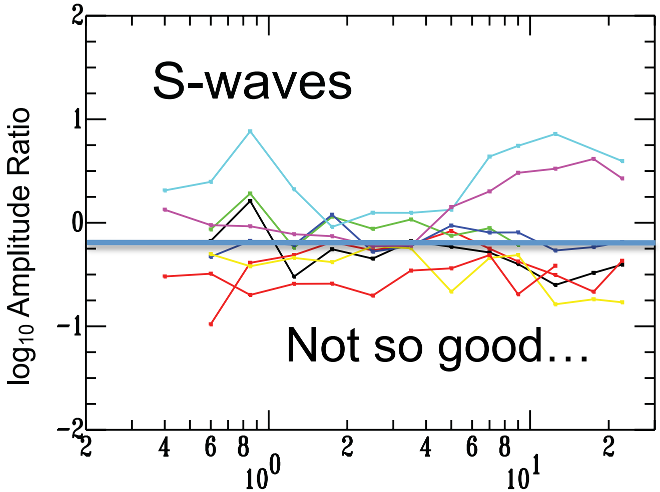
Note: Averaging was done using ~35 stations at a range of azimuths.

from Izutani, 2005, GRL

A different approach…

A new approach using spectral ratios improves upon EGF methods by dramatically reducing variance and increasing number of events.

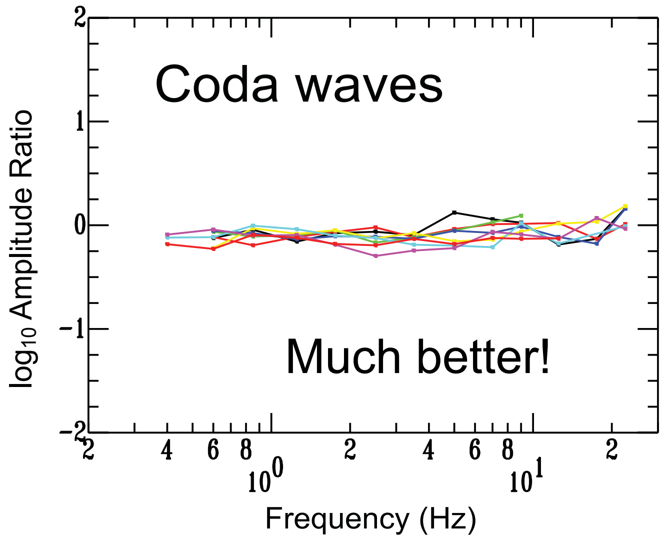
Traditional approaches using direct *P* or *S*-waves exhibit large amplitude scatter.



Example (top) shows *S*-wave derived source ratios of two nearby earthquakes (M_w3.6). Colored lines are from the 8 local stations used.

Large scatter is due to source heterogeneity and subtle, yet significant path variations.

The scattered wavefield (coda) averages over path and source complexity making it ideal for sparse station deployments in complicated or poorly known/ calibrated regions.

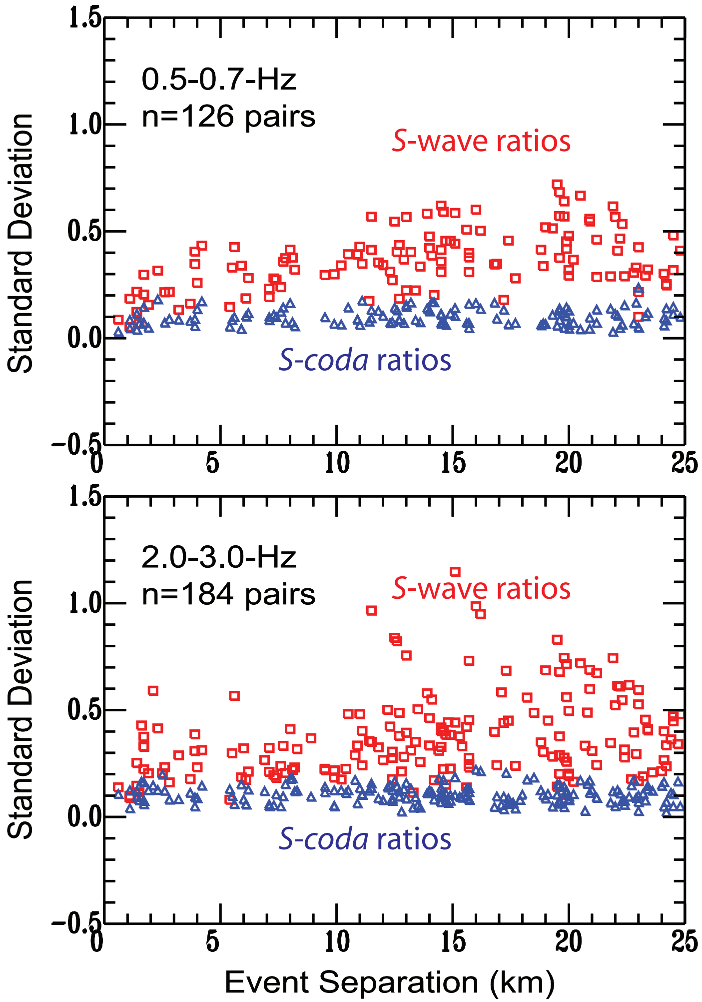


Coda ratios (bottom) are free of these effects and are roughly 4-to-5 times less variable.

from Mayeda et al., 2007, GRL

More events can be used…

Coda ratios are not as sensitive to event separation so more events can be used in spectral ratio studies.



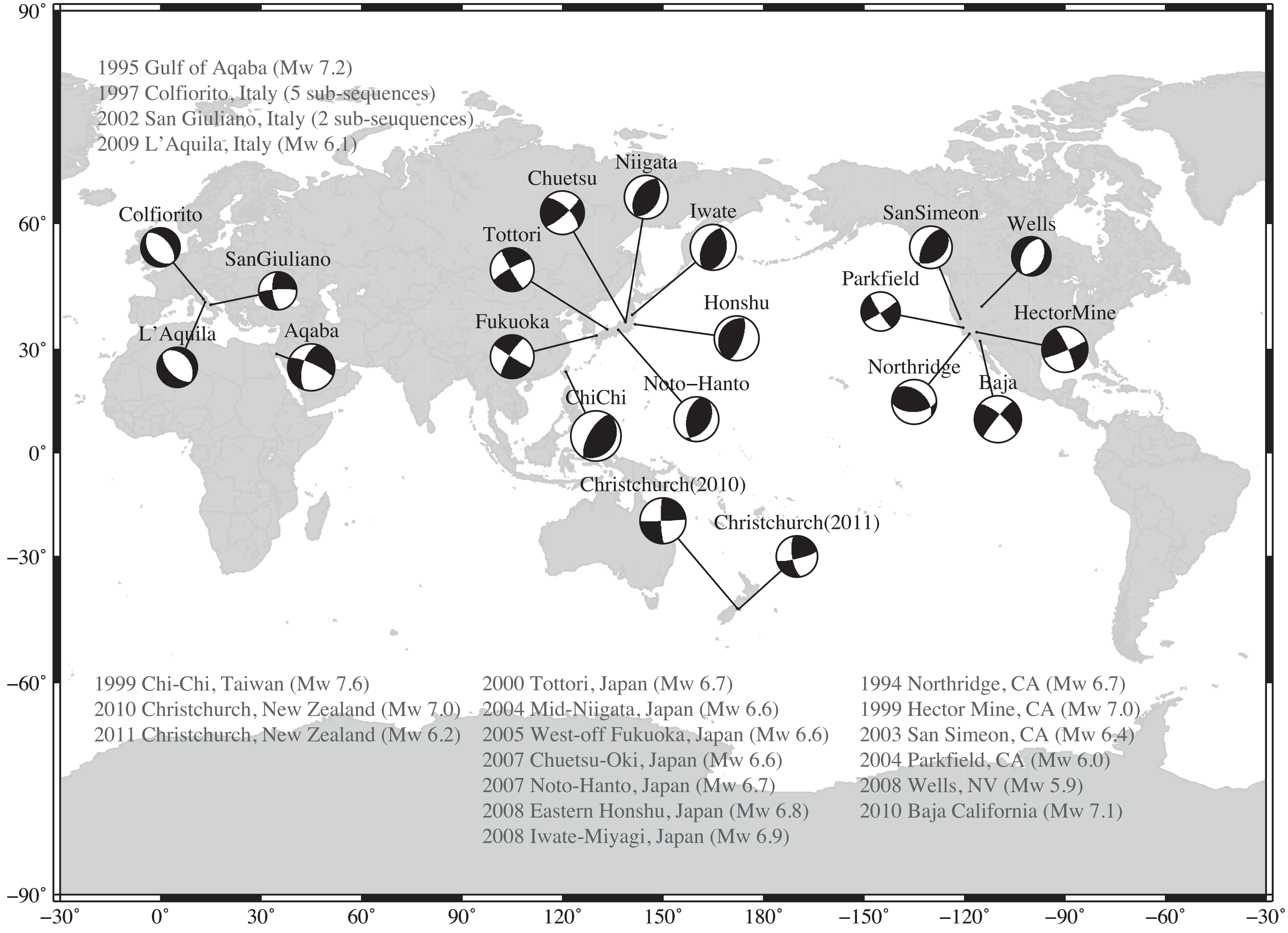
- **Coda spectra ratios are a factor of 2 to 3 times smaller in data scatter than direct waves.**
- **Averaging nature of coda reduces path and source radiation heterogeneity.**
- **Results mean that event pairs don't have to be co-located as with *S*-waves!**
- **This ratio method is not dependent upon path and site correction assumptions.**

from Mayeda et al., 2007, GRL

Summary of Advantages:

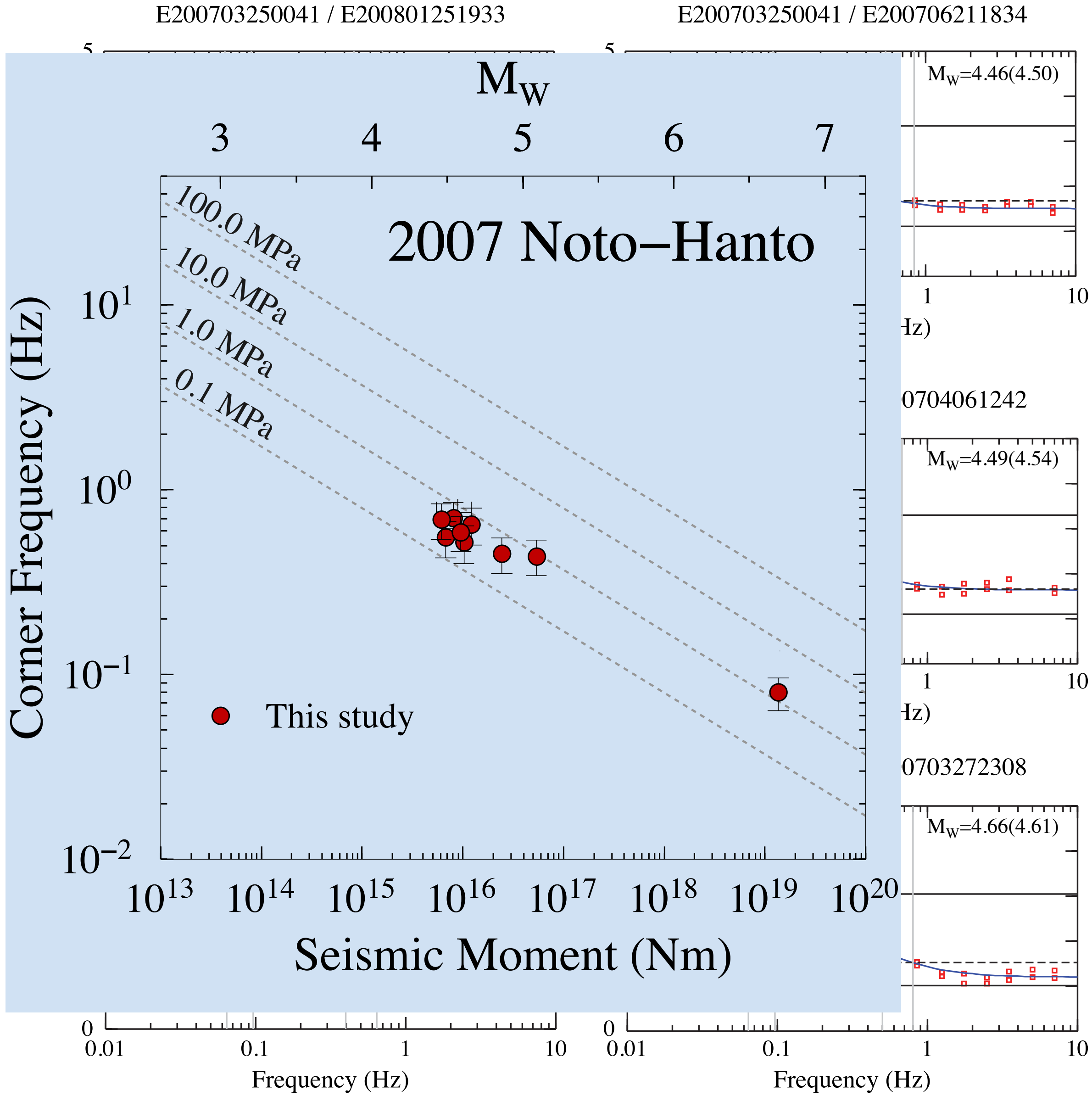
- Scattered waves (coda) average over the heterogeneous crust.
- Coda is not very sensitive to radiation pattern or source directivity.
- Coda envelope amplitude represents a convolution of the entire source process.
- More events can be used as Green's functions.
- The method provides a stable, average radiated source spectrum.

Applied same method to 22 crustal sequences…

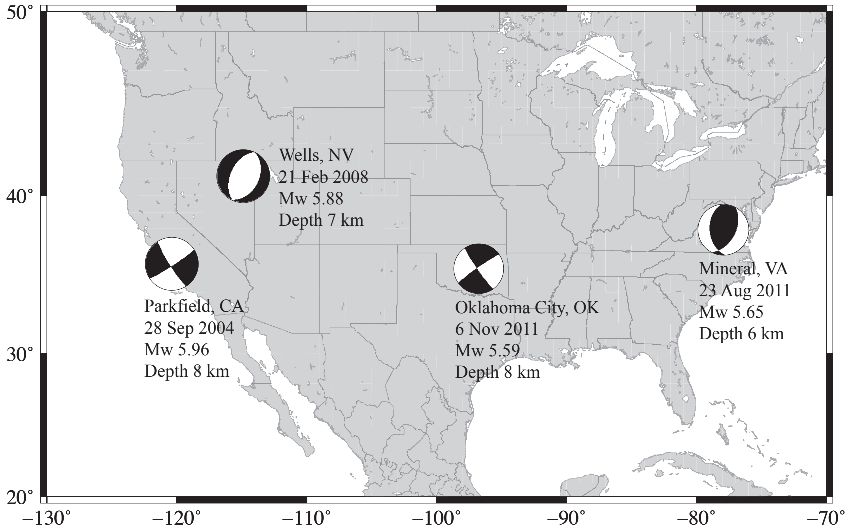


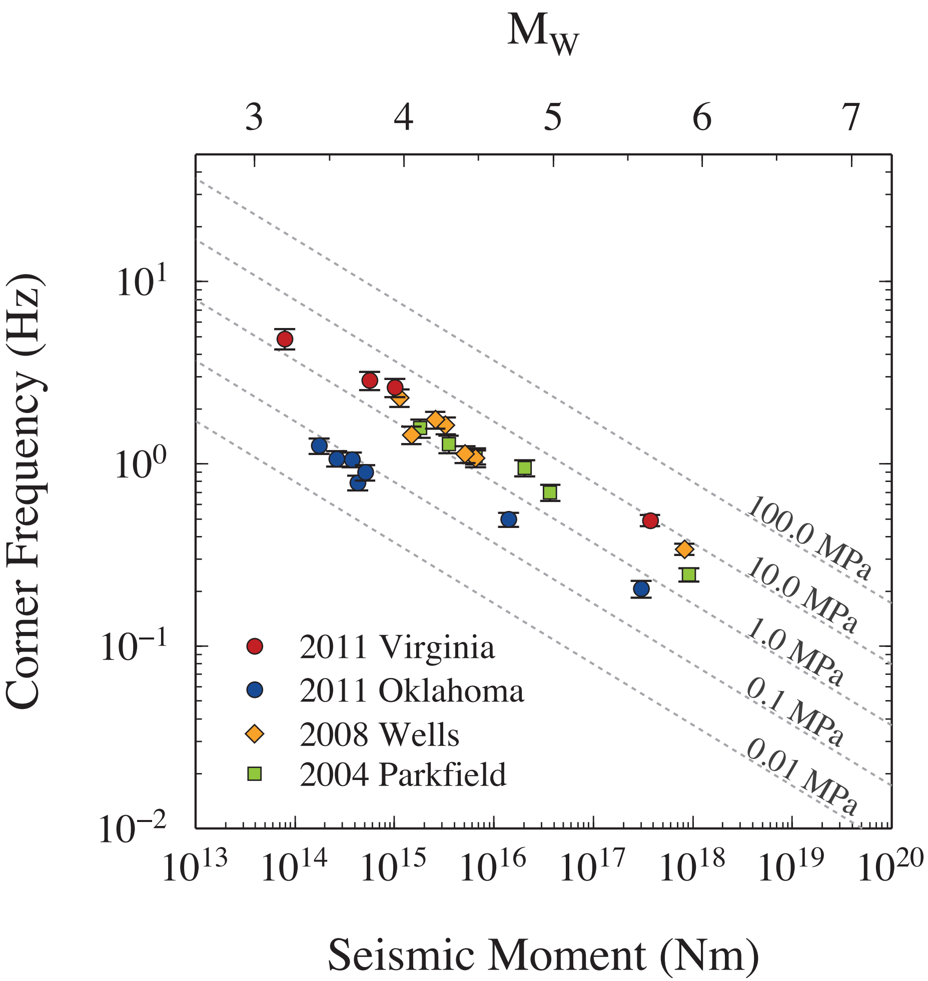
An example sequence…

Example of coda spectral ratios for the M_w 6.7 Noto-Hanto, 2007 mainshock and 6 aftershocks. Notice that the source ratios show little scatter and in nearly all cases, the high frequency asymptote for self-similarity is never reached.

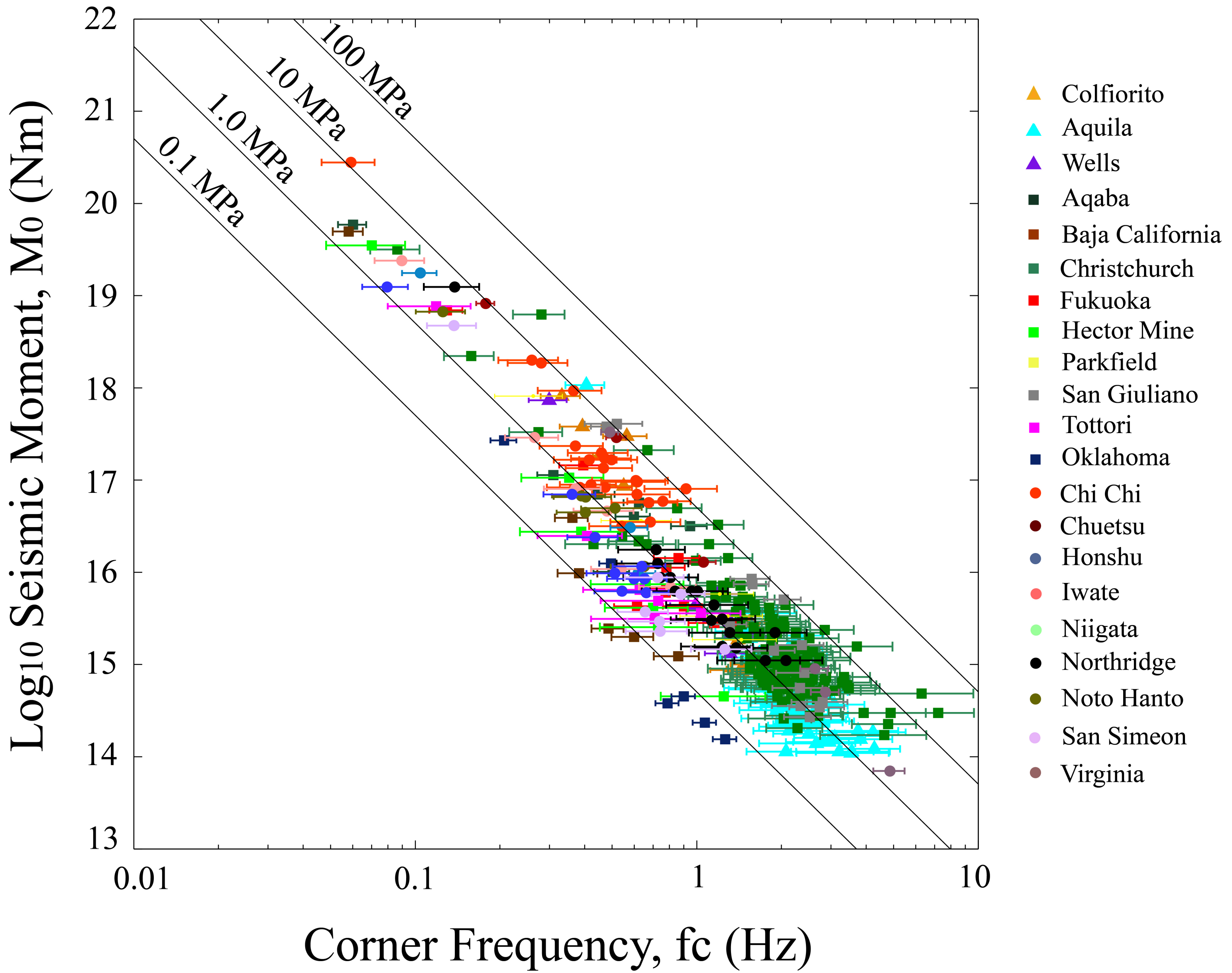


Comparison of 4 U.S. earthquakes with varying absolute stress drop but all show magnitude dependence:

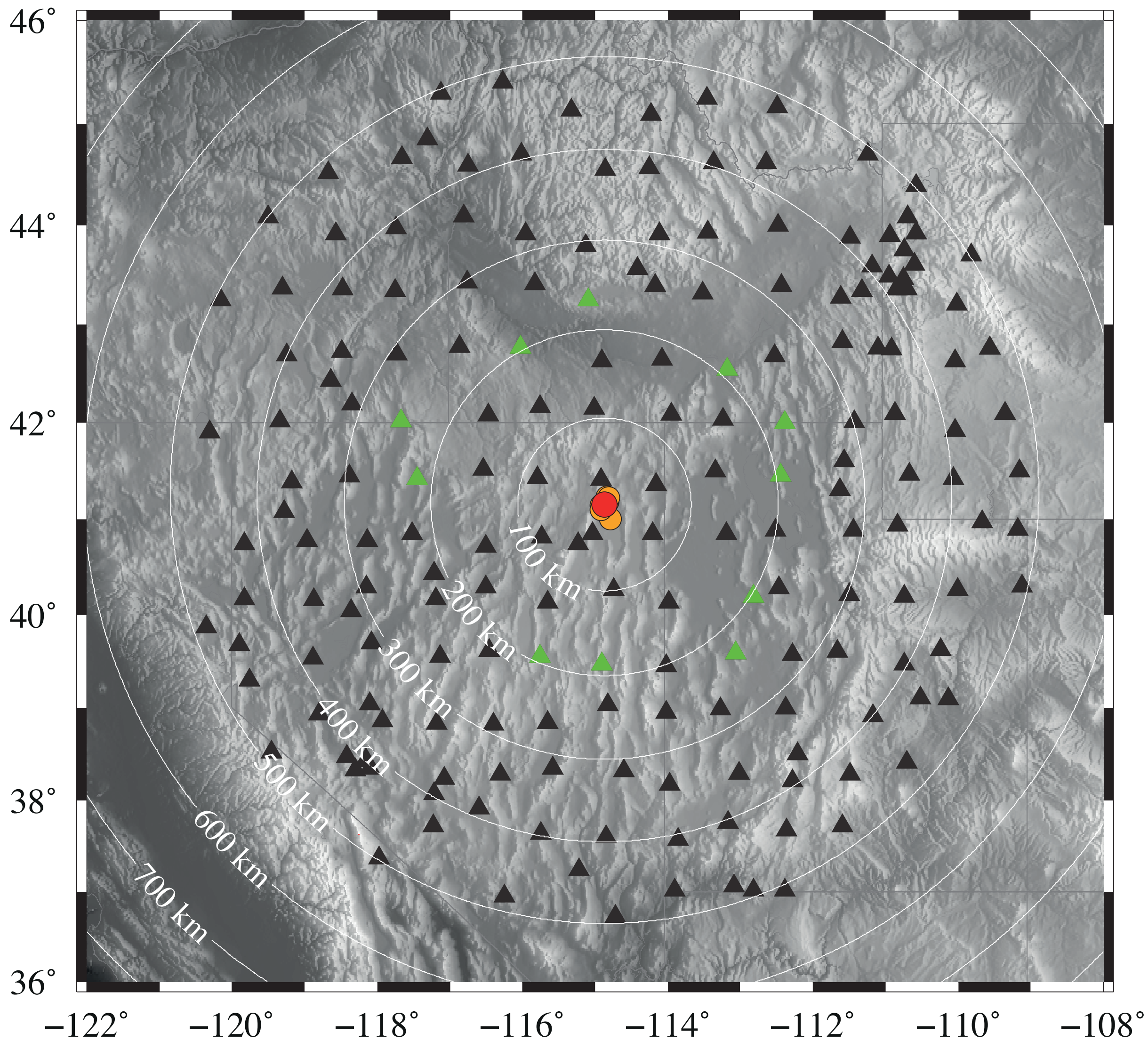




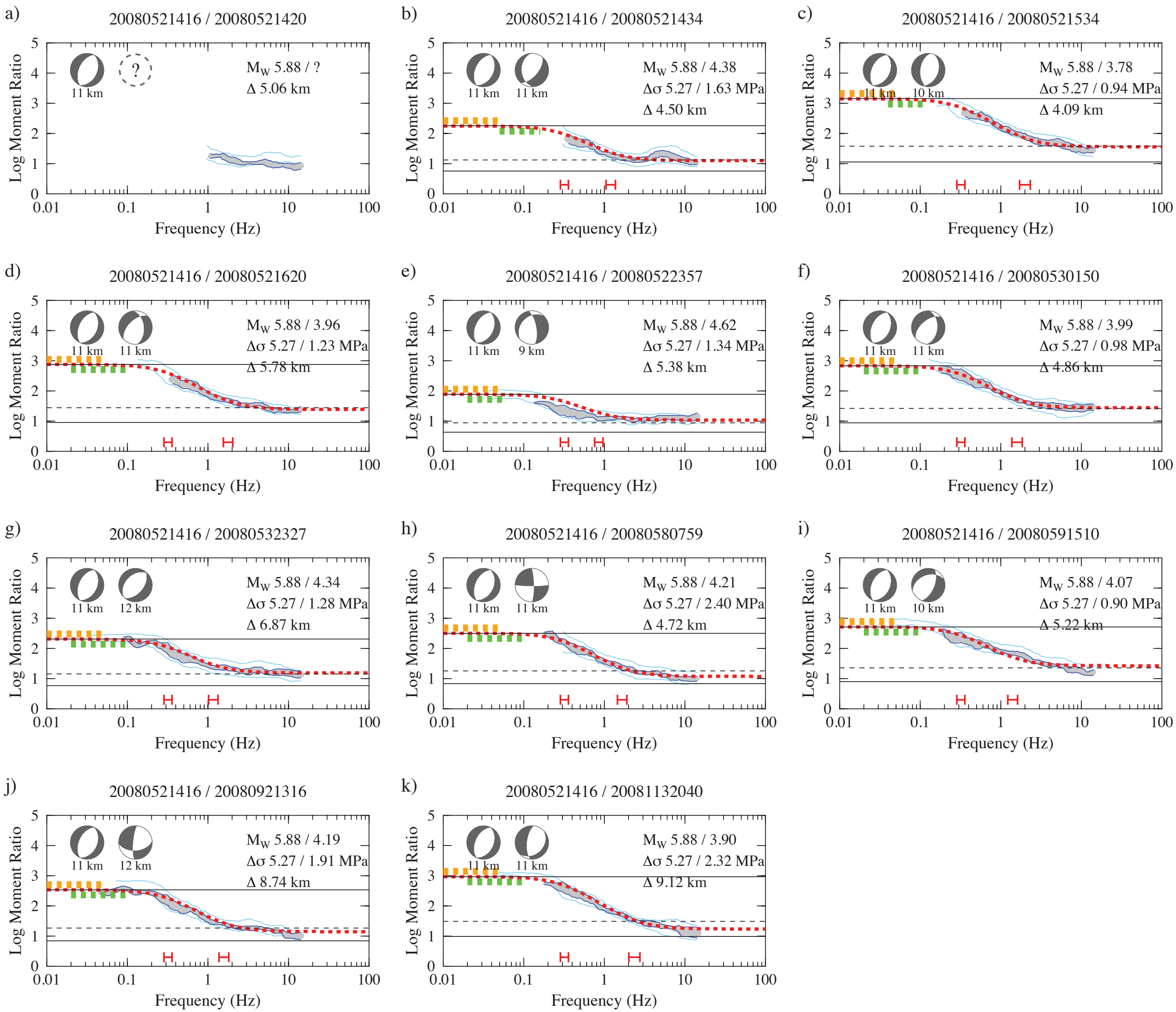
Global comparison of 21 sequences using the same methodology…



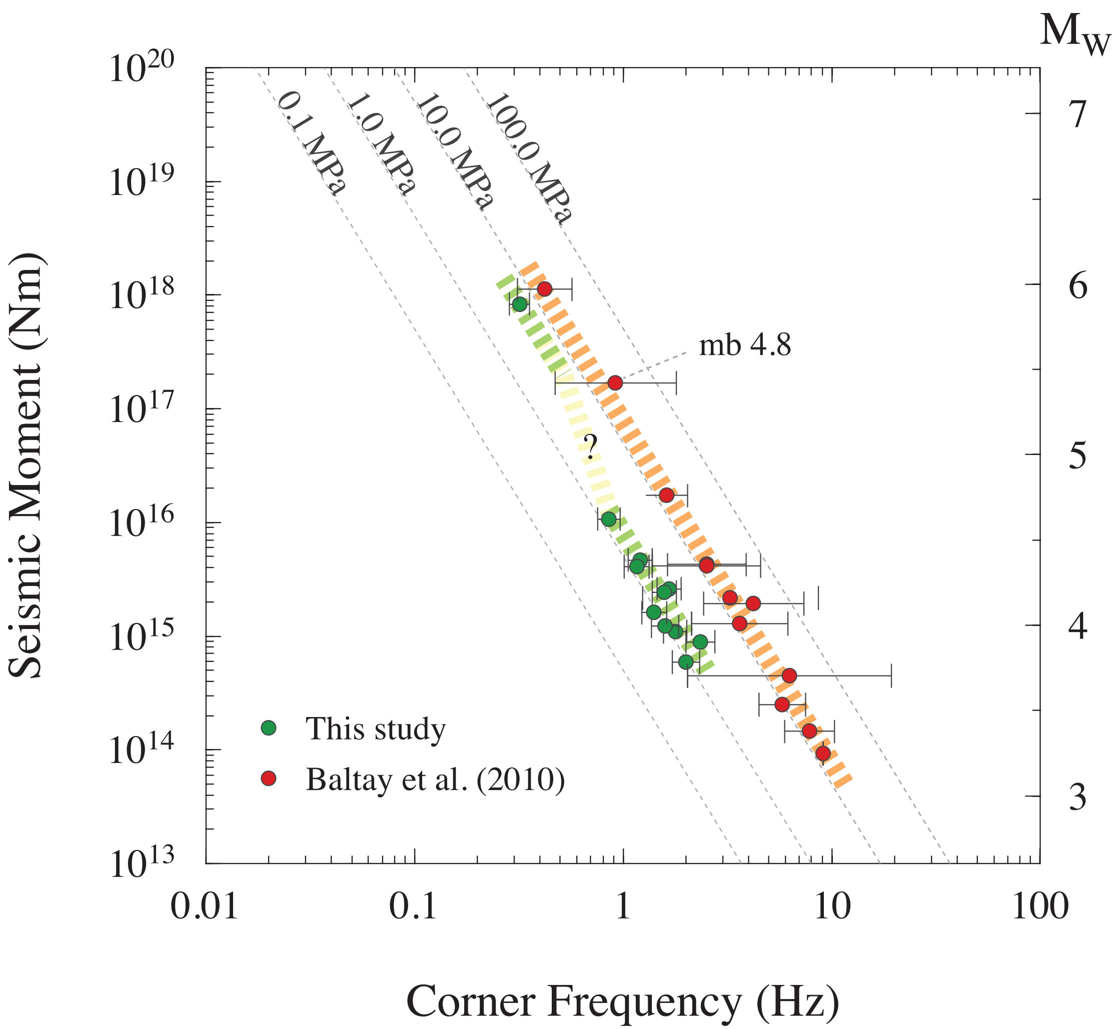
Station and event distribution for the Wells, NV sequence.



Spectral ratios are very stable and constrained by waveform M_w's



We compare other scaling results for the M_w 5.9 Wells, NV sequence and find large differences…, how to differentiate?

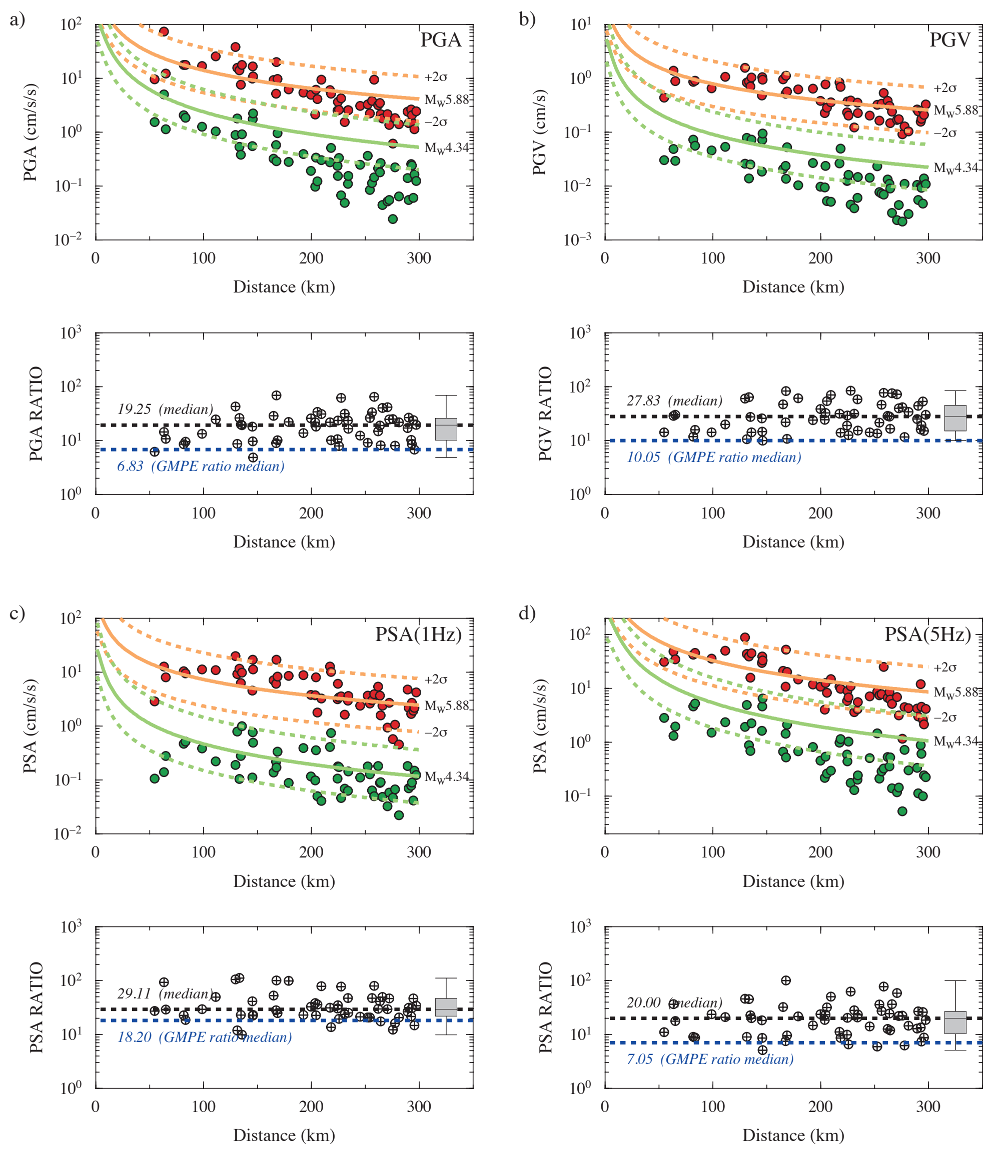


Are there independent observations that can help us validate our results?

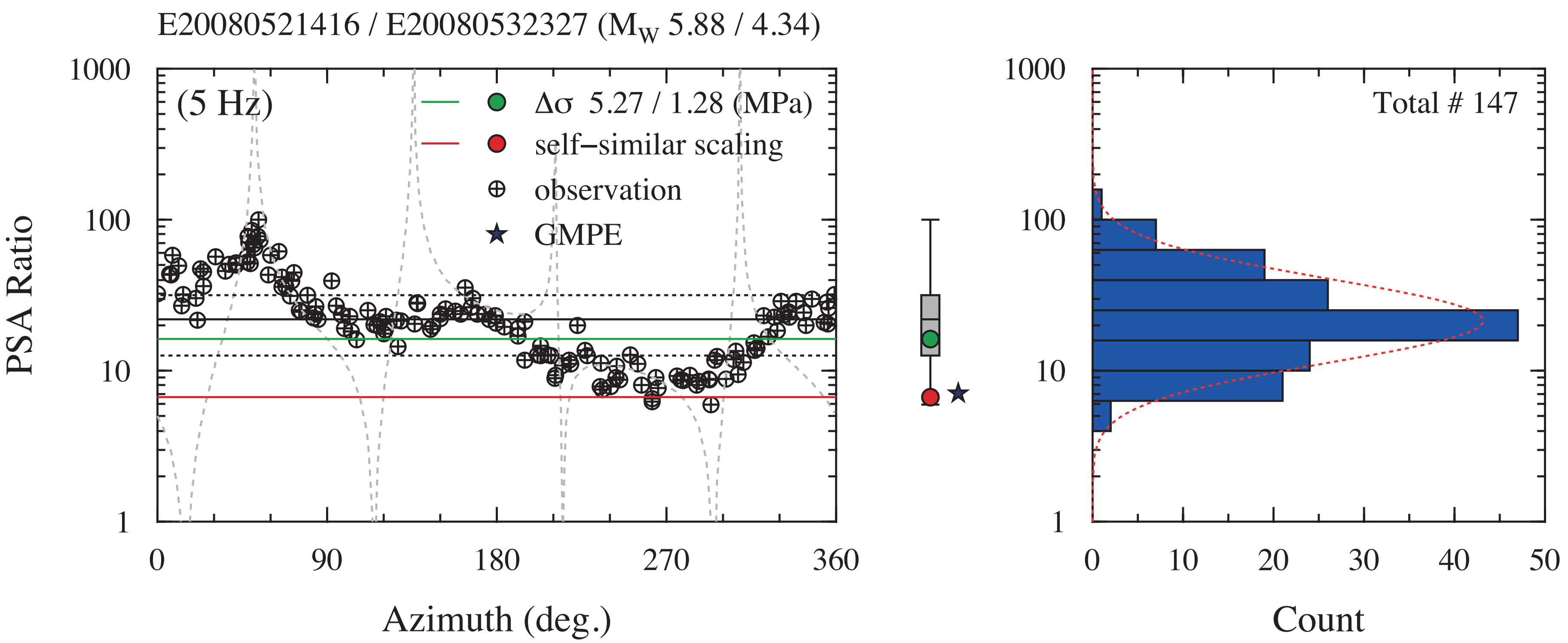
We compare our results with recent findings from Peterson et al. (2011) who tried to fit GMPEs to the Wells events.

We turn to Psuedo Spectral Acceleration (PSA) ratios derived from the Wells, NV sequence and then compare with those predicted from self-similar and non-self-similar models.

Strong and weak ground motion for the 2008 Wells, NV earthquake do not match NGA equations…., what's wrong?

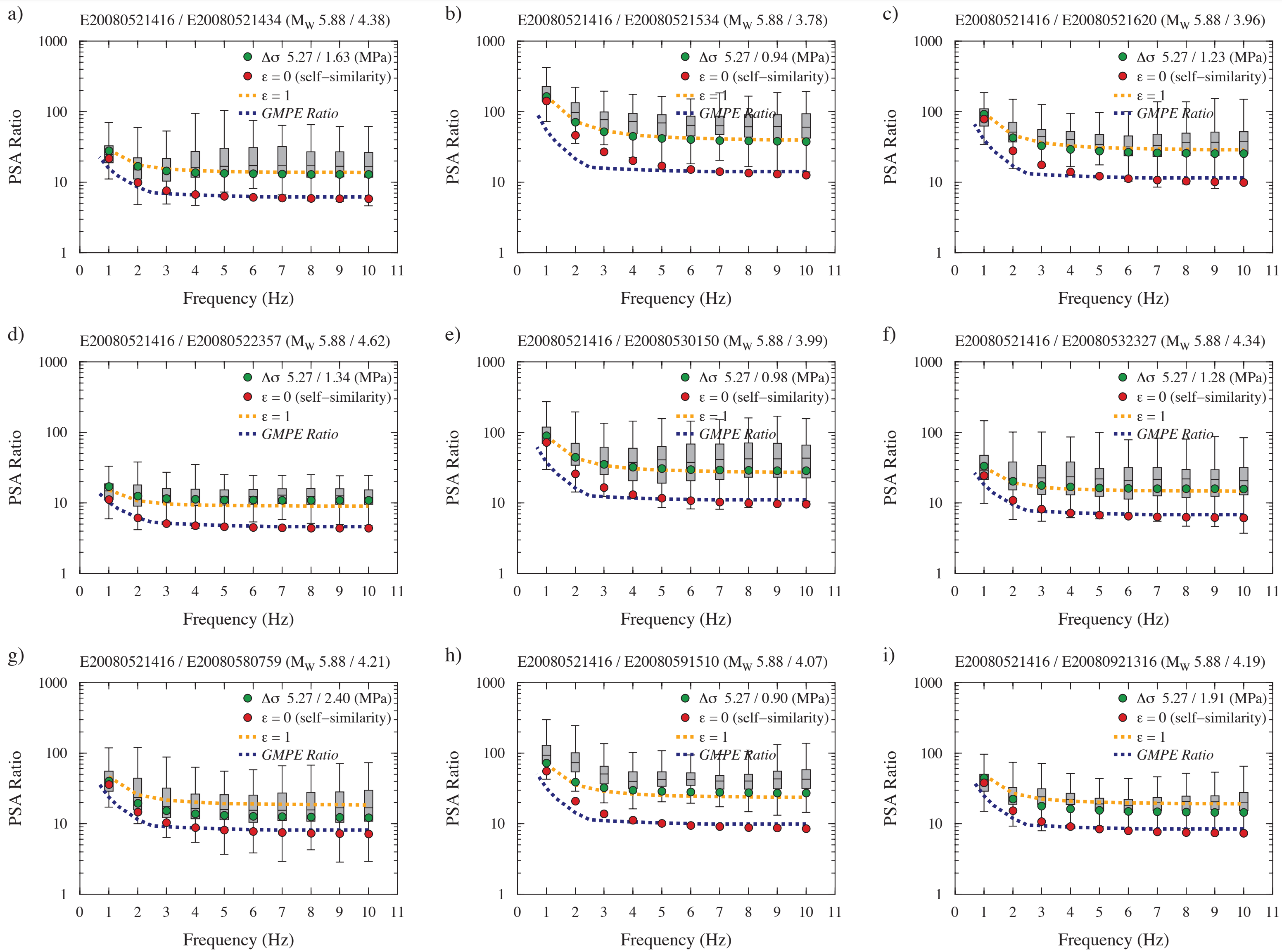


Strong and Weak Ground Motion in 2008 Wells, NV



Next we apply to all pairs for frequencies between 1-10 Hz.

PSA ratios do not follow self-similarity.



PSA ratios (green) w/scaling are in excellent agree with observed PSA ratios (gray) derived from 100+ stations whereas self-similar assumption (red) and GMPEs are not.

Conclusions

1. Source spectral ratios using coda envelope amplitudes give the most stable estimates of average earthquake source parameters by a factor of 3-4.

2. We find that the use of independent seismic moments is critical for accurate and unbiased estimates of corner frequency, stress drop, and apparent stress.

3. A change in source scaling (*i.e.*, break in self-similarity) explains observed PSA ground motion for Wells, Nevada events whereas GMPEs, which assume self-similar scaling, cannot simultaneously fit the mainshock and the aftershocks.

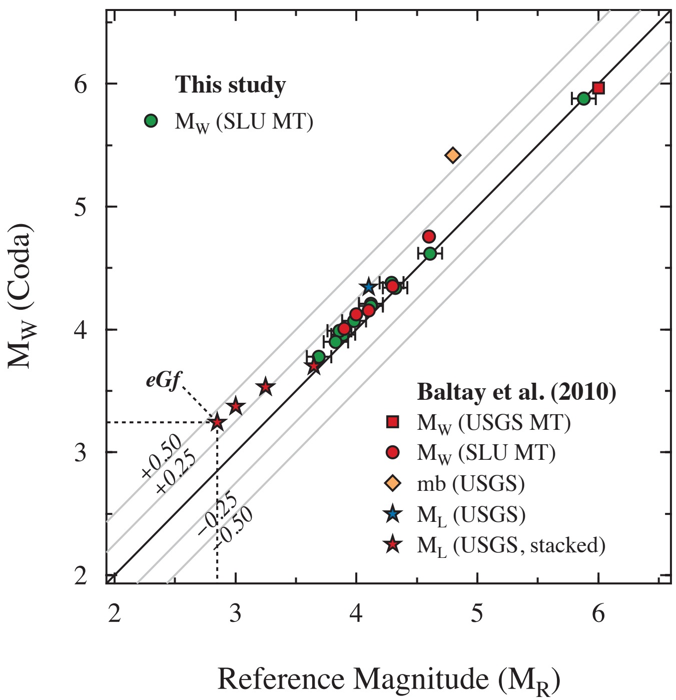
4. This is consistent with recent findings from Atkinson and Boore (2011) who found a systematic bias in GMPEs for small to moderate earthquakes in North America.

5. A more in-depth study is shown in Poster #5…, please stop by!

Wells Comparison

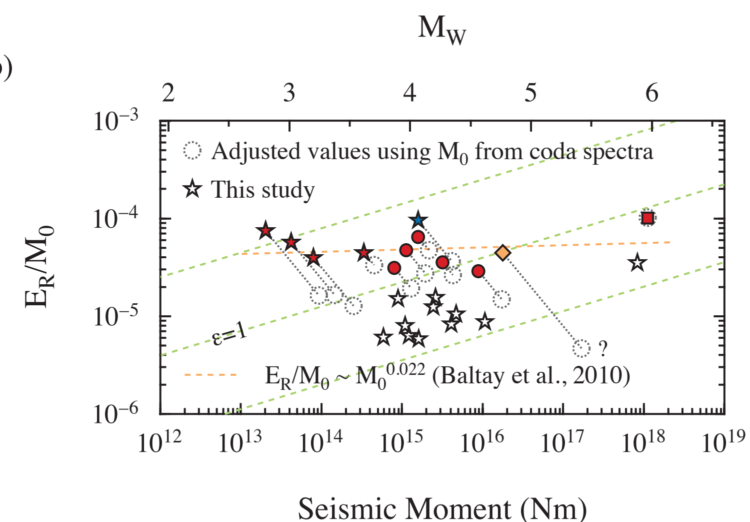
After calibration, the M2.85 eGf event shows a factor 5 larger seismic moment and stress drop increases from 3MPa to 13.1 Mpa. This biases all larger events' spectral shapes.

a)



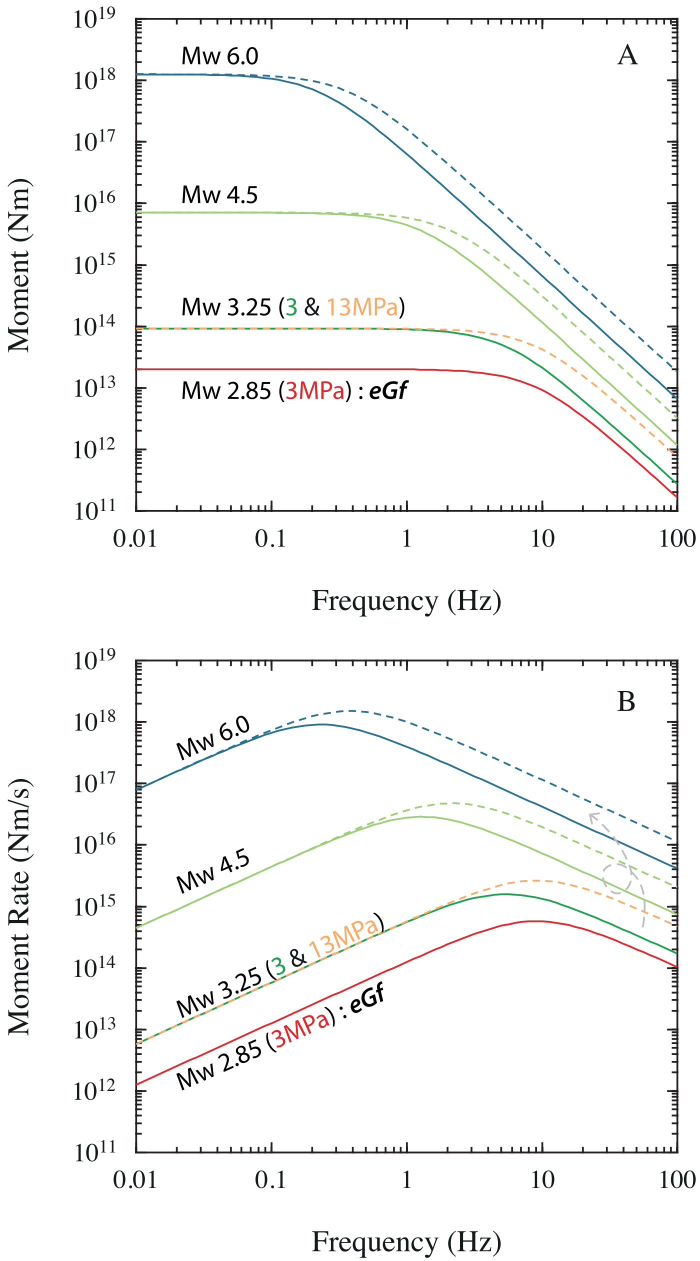
Radiated seismic energy was estimated using coda-derived spectra, but moments were derived from NEIC mags. Circles show results if the coda-derived moments were used. Yellow diamond is contaminated and should be removed.

b)



eGf Corrections introduced large biases

Because there was a significant amount of corrections applied to their source spectra, (e.g., roughly a factor of 5 in seismic moment), the smallest stacked event, their so-called empirical Green's function event, has a much higher Brune stress drop than the original assumption of 3 MPa, and is actually 13.02 MPa even though its corner frequency is still 9.08-Hz based upon the assumption of 3 MPa stress drop for an M 2.85 event. In simple terms, this is equivalent to assuming a 13.02 MPa stress drop for an Mw 3.25 eGf event. We suspect that this 13.02 MPa stress drop assumption resulted in erroneously high stress drops for all subsequent larger earthquakes during the course of their coda-derived source spectral calibration.



The intraplate Virginia M_w 5.65 sequence and local and regional stations