Investigating Earthquake Scaling Using Spectral Ratios and Simple Earthquake Models

William R. Walter[1], Rengin Gok[1], Kevin Mayeda[2,3], Luca Malagnini[4], Irene Munafo[4] and Seung-Hoon Yoo[3]

LLNL[1], Weston Geophysics[2], UC Berkeley[3], INGV[4]

Lawrence Livermore National Laboratory

EGS Workshop 2012: Earthquake Source Physics on Various Scales

3 October 2012

LLNL-PRES-592872

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

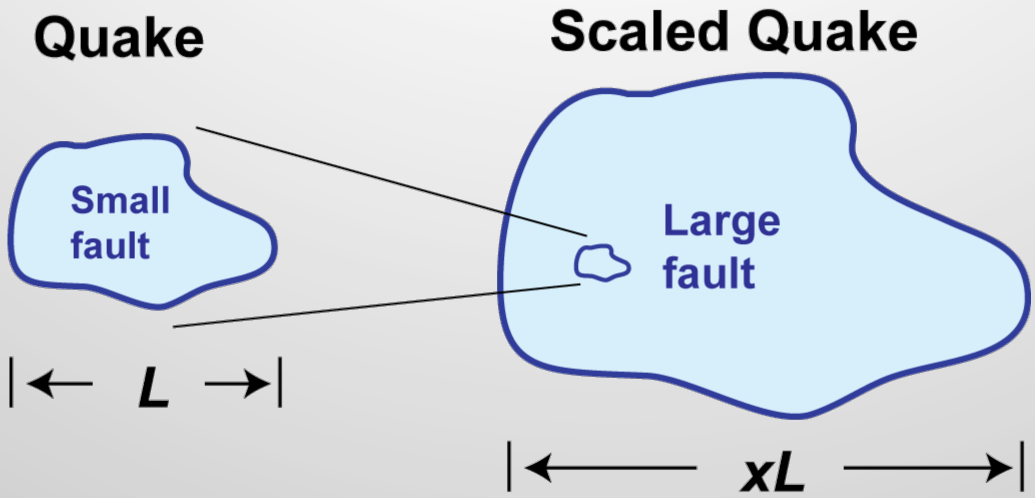
Earthquake Source Questions

- How does a small rupture grow into a large one?
  - Is there a difference at any point during the rupture between the probability of large or small event? (Scaling)
- What are the causes of observed apparent stress variance? Can we predict this variance? (Scaling)
- Can we improve our ability to forecast earthquake ground motions for practical applications? (Scaling?)
  - Given the wealth of online historic data how do we more consistently define relationships between events? (e.g. massive cross-correlation?)
  - Given our source and Earth models how well are we doing in practice?

Outline

- Overview of scaling and simple earthquake models
- A brief overview of techniques to examine scaling
- Some current observations and model interpretations
- Using earthquake scaling models for hazard prediction and explosion monitoring

How do earthquakes scale?

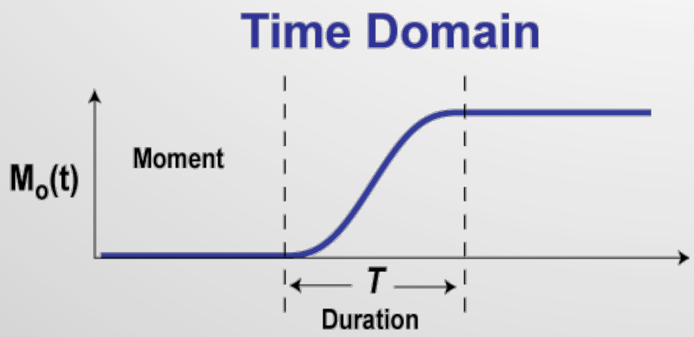


Average Stress Drop = $\Delta\sigma$
Average Media Properties = μ
Average Rupture Velocity = V
Average Scaled Energy = E/M_o = e
Average Apparent Stress = $\sigma_a = \mu e$

Are these physical parameters the same or do they change systematically? How variable are they from event to event?

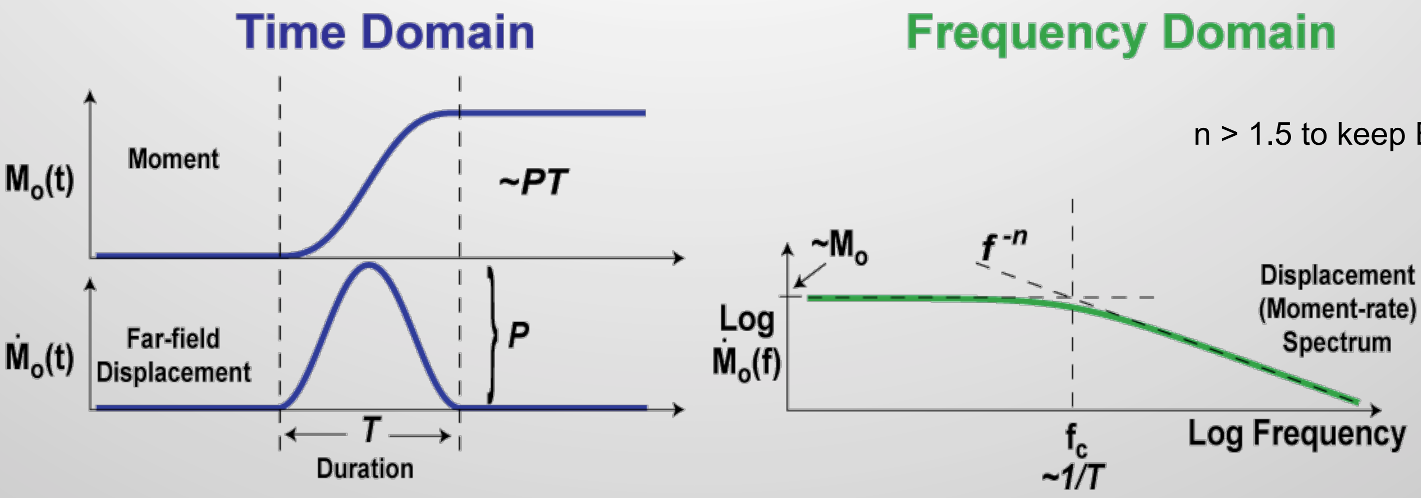
After Walter et al. (2006) AGU Monograph paper

Simple Earthquake Models and Measurements



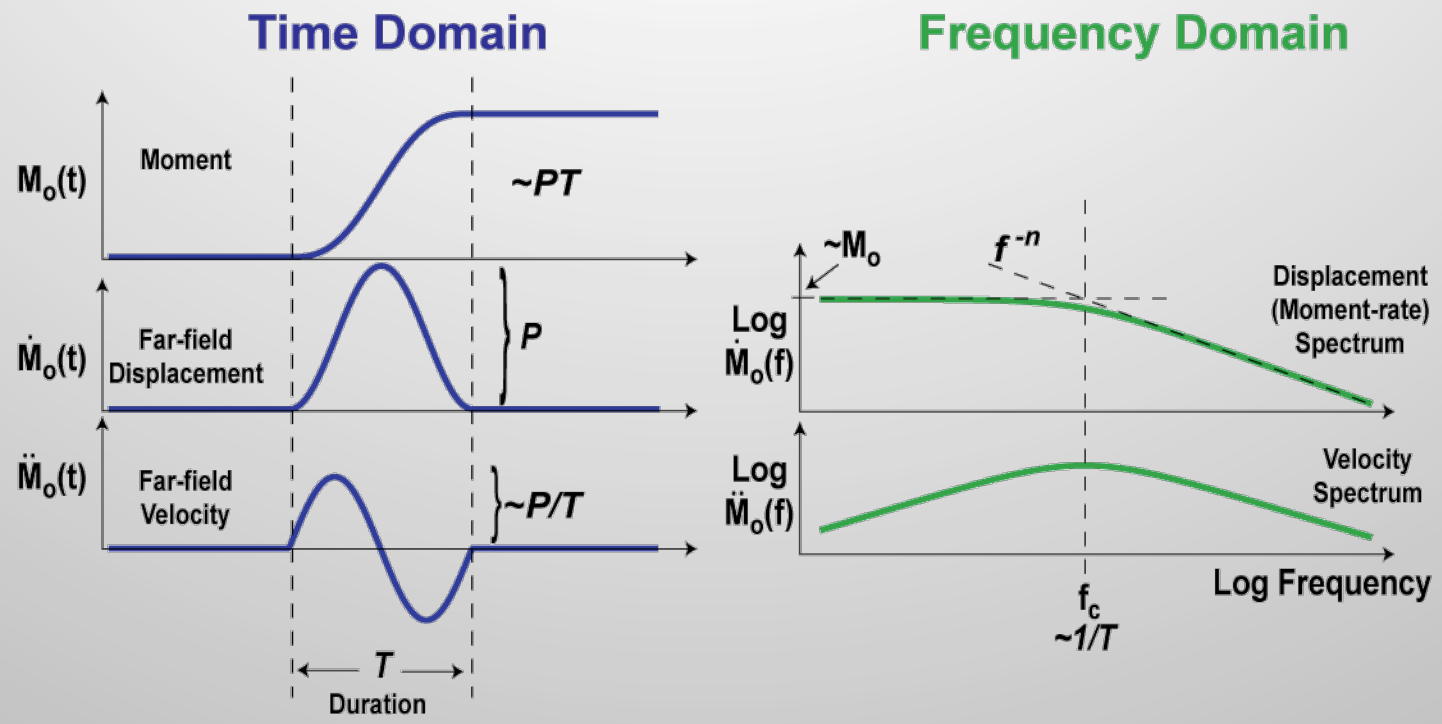
After Walter et al. (2006) AGU Monograph paper

Simple Earthquake Models and Measurements



After Walter et al. (2006) AGU Monograph paper

Simple Earthquake Models and Measurements

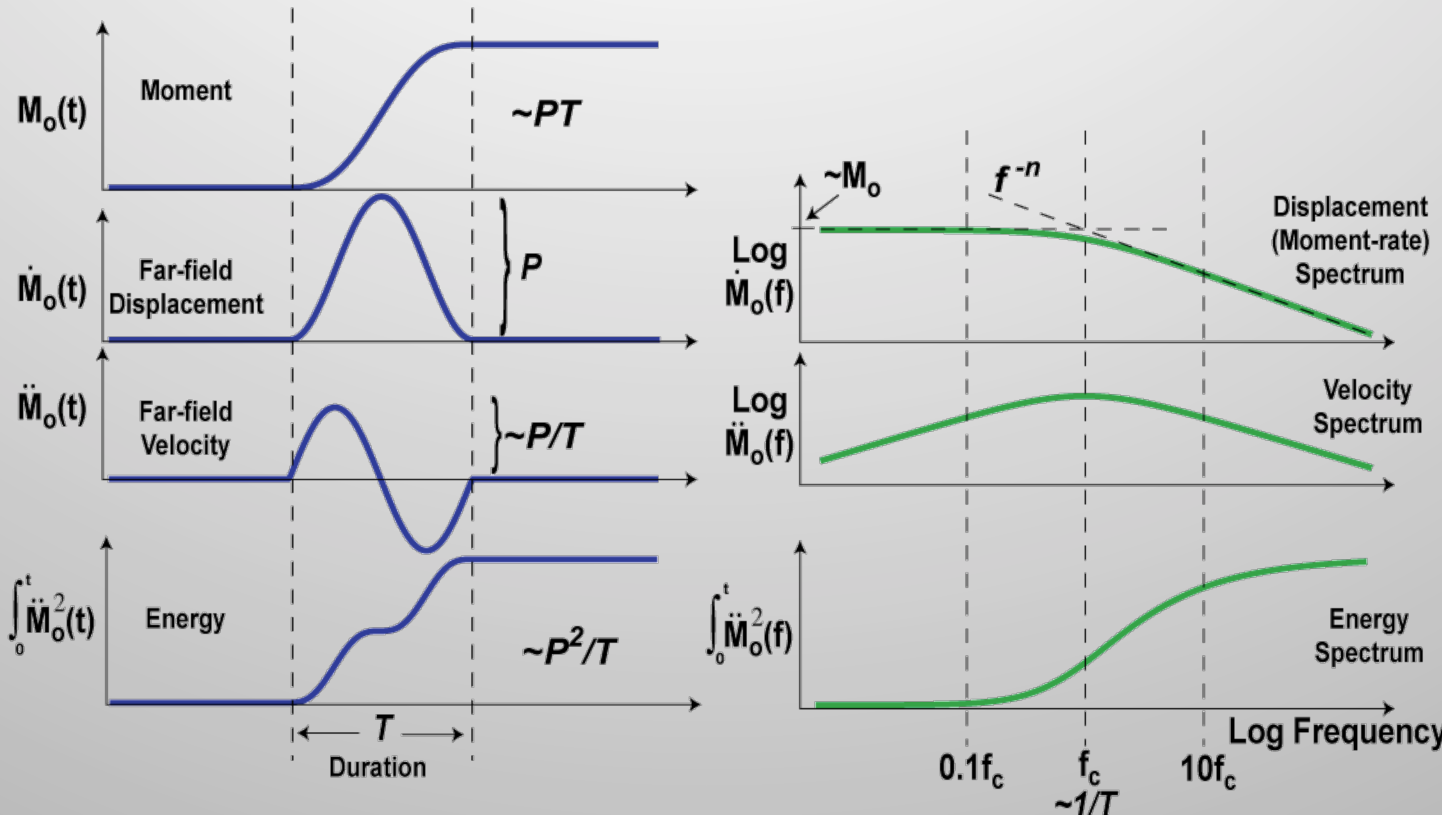


After Walter et al. (2006) AGU Monograph paper

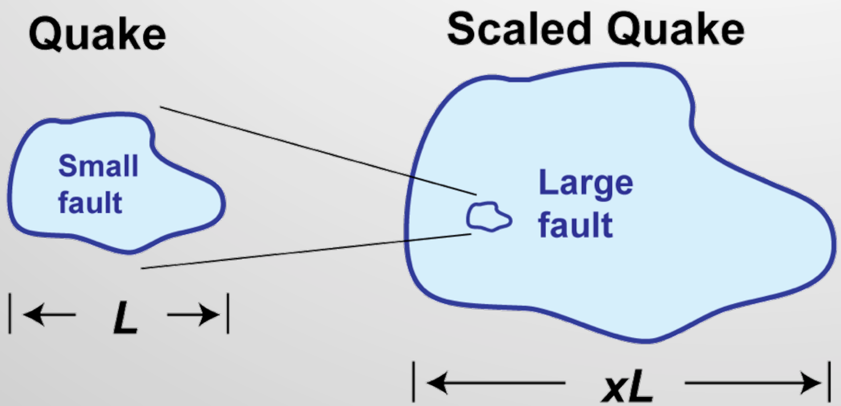
Simple Earthquake Models and Measurements

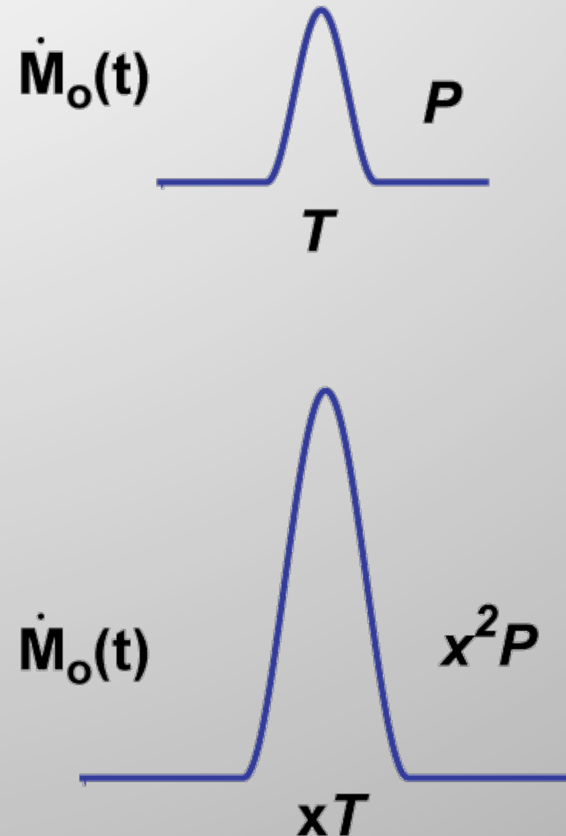
Time Domain

Frequency Domain



Self-similar earthquake scaling – time domain



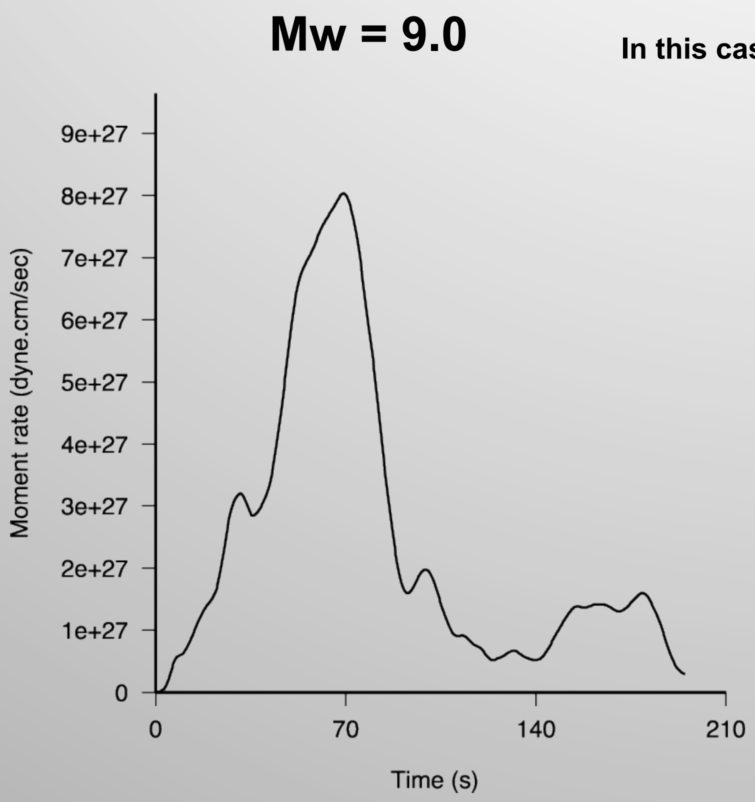


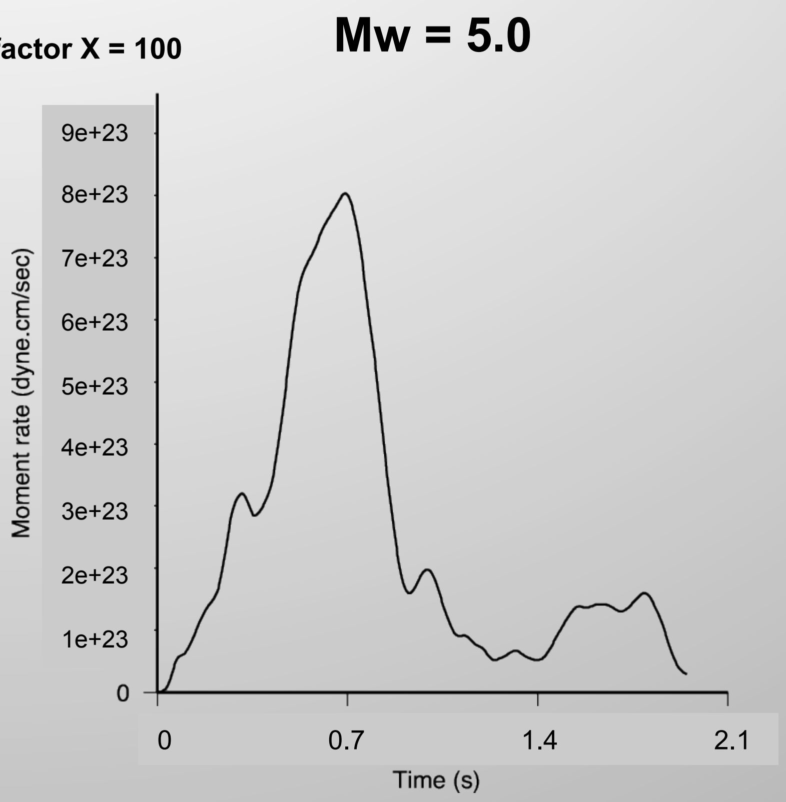
$Area = A \sim L^2$	$Area = x^2 A$
$Slip = \bar{u} \sim (\Delta\sigma/\mu)L$	$Slip = x\bar{u}$
$M_o = \mu\bar{u}A \sim \Delta\sigma L^3$	$M_o = x^3 M_o$
$Duration = T \sim \bar{u}/V \sim L$	$Duration = xT$
$Energy = E \sim P^2/T$	$Energy = x^3 E$
$Scaled\ E = E/M_o = e$	$Scaled\ E = E/M_o = e$

Implicit that $\Delta\sigma$, μ and V are the constant for all events

For example here is how the Japan Mw 9.0 Tohoku-Oki compares with a scaled hypothetical Mw 5.0 aftershock

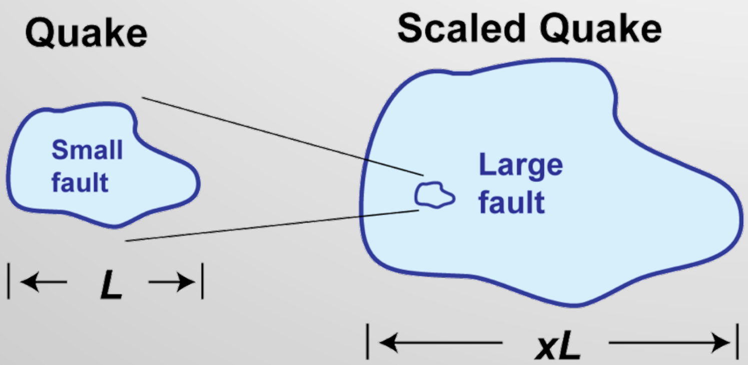
In this case scale factor X = 100





After Gavin Hayes USGS web page: http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite_fault.php

Self-similar earthquake scaling – frequency domain

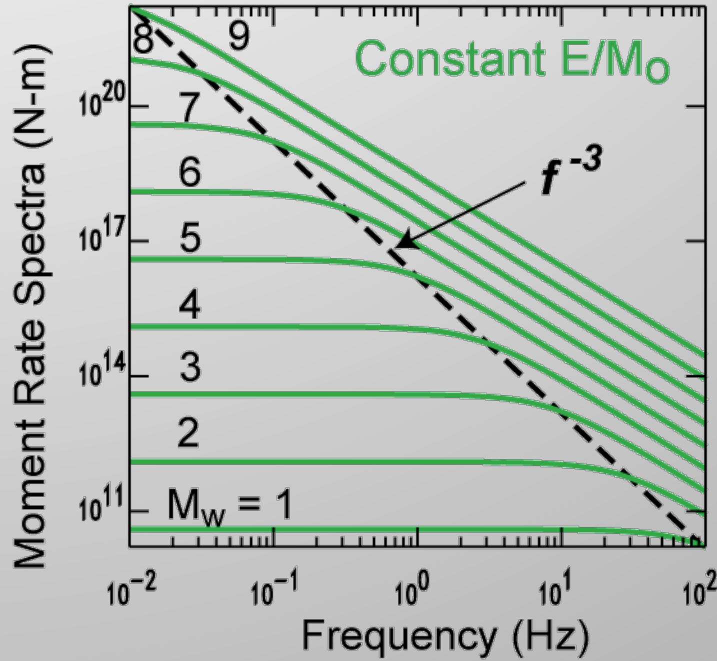


Area = A ~ L^2
Slip = $\bar{u}$ ~ $(\Delta\sigma/\mu)L$
$M_o = \mu\bar{u}A \sim \Delta\sigma L^3$
Duration = T ~ $\bar{u}/V \sim L$
Energy = E ~ P^2/T
Scaled E = E/M_o = e

Area = x^2A
Slip = $x\bar{u}$
$M_o = x^3M_o$
Duration = xT
Energy = x^3E
Scaled E = E/M_o = e

Spectra are invariant under f^{-3} scaling
(see also Prieto et al., 2004; Kanamori and Rivera, 2004)

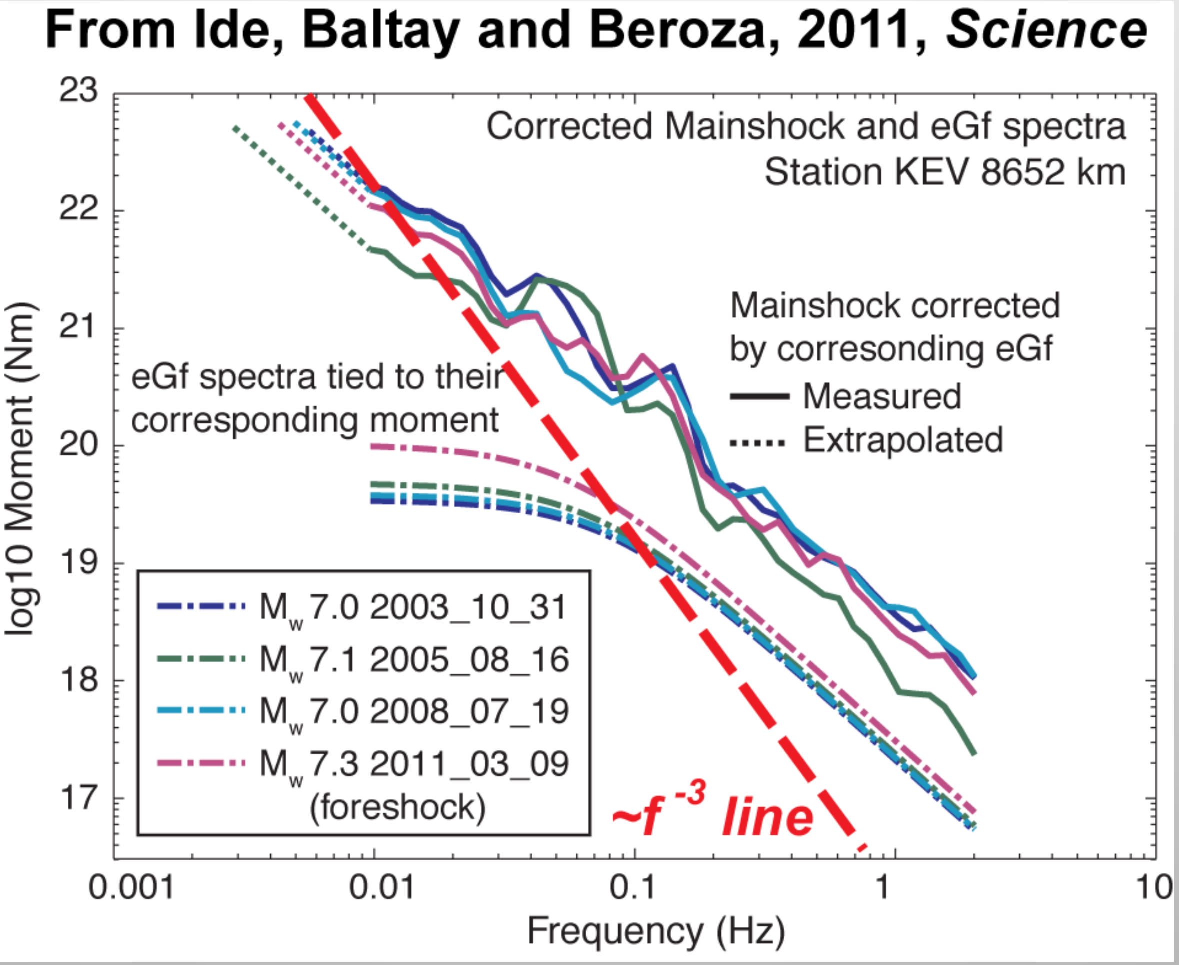
$$M_o \sim \Delta\sigma L^3 \sim \Delta\sigma V^3T^3 \sim (\Delta\sigma V^3)f_c^{-3}$$



Implicit that Δσ, μ and *V* are the constant for all events

After Walter et al. (2006) AGU Monograph paper

For example here is how the Japan Mw 9.0 Tohoku-Oki compares with Mw 7 nearby events



P-wave spectra where I have added the self-similar f^{-3} scaling line

Non-self similar scaling

1) Changes in $\Delta\sigma$ and/or V with size
(e.g. large have higher $\Delta\sigma$ and/or V than small)

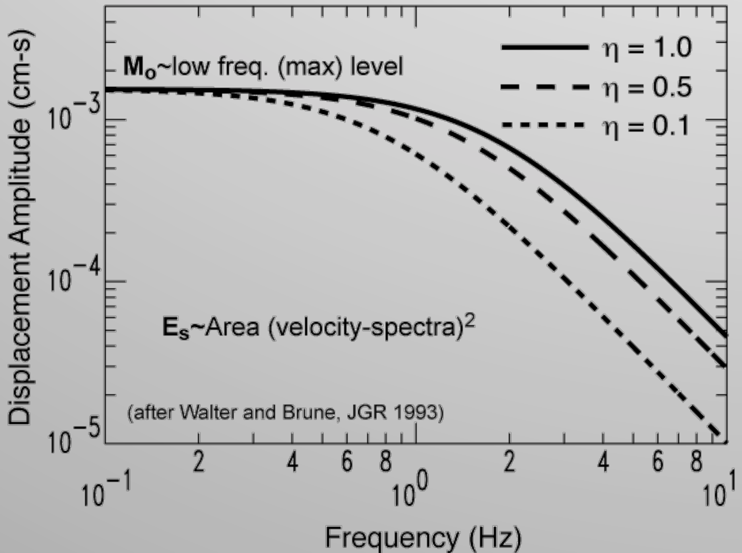
2) Changes in efficiency with size
(large more efficient than small)

Kanamori and Rivera (2004):

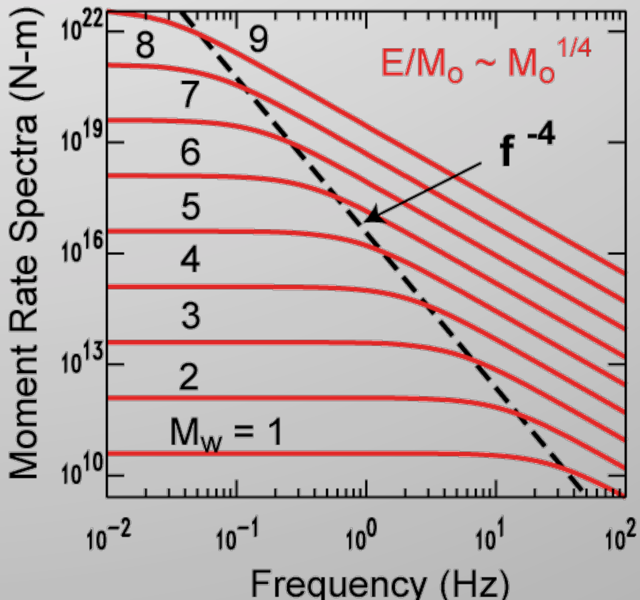
$$M_o \sim f_c^{-(3+\varepsilon)}$$

$$\tilde{e} \sim M_o^{\varepsilon/(3+\varepsilon)} \sim (\Delta\sigma V^3)$$

Constant moment shear crack spectra for different seismic efficiencies



An Example where $M_o \sim f_c^{-4}$

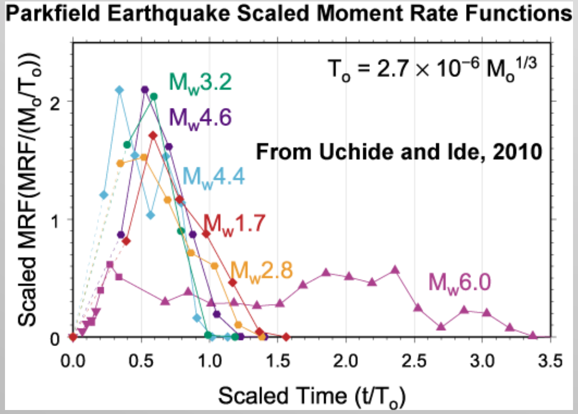


Spectral shape invariant as f^{-4}

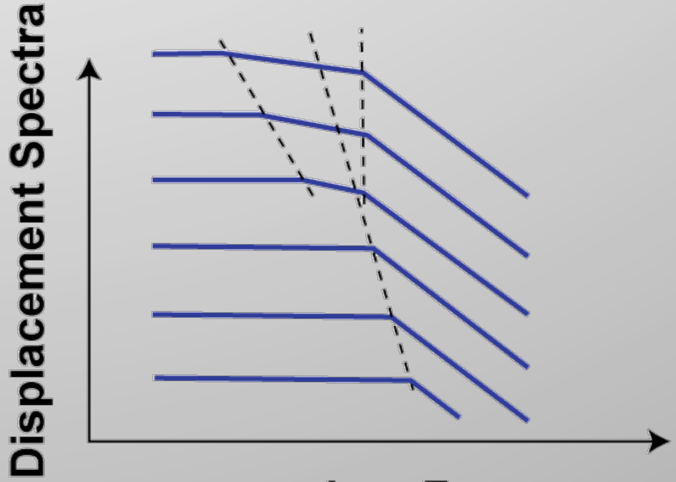
Non-self-similar scaling: source time and spectral shape change

1) Changes in fault shape with size
(e.g. equidimensional growth to unidimensional growth in response to seismogenic boundaries

Time Domain example



Frequency domain example



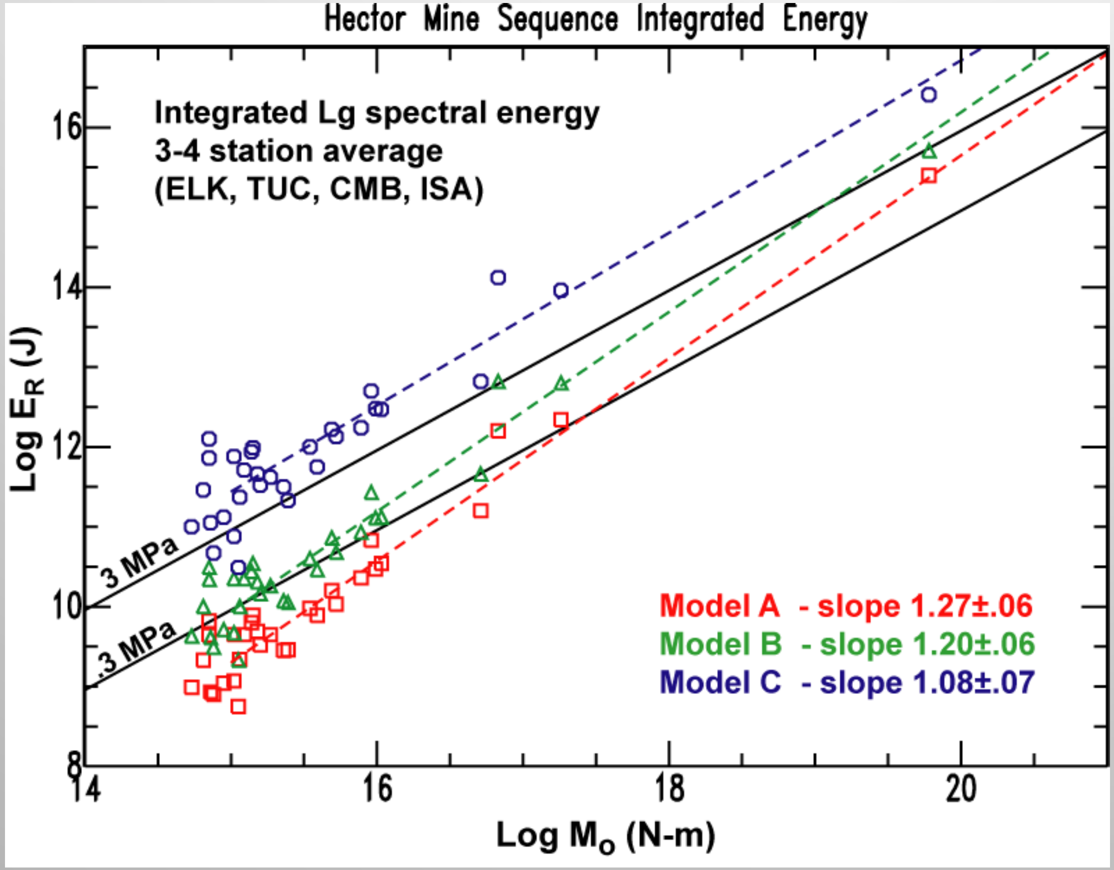
After Walter et al. (2006) AGU Monograph paper

2) Changes in fault physics with size
(e.g. dynamic friction changes with size)

Outline

- Overview of scaling and simple earthquake models
- A brief overview of techniques to examine scaling
- Some current observations and model interpretations
- Using earthquake scaling models for hazard prediction and explosion monitoring

Estimating scaling in a sequence: direct energy calculations



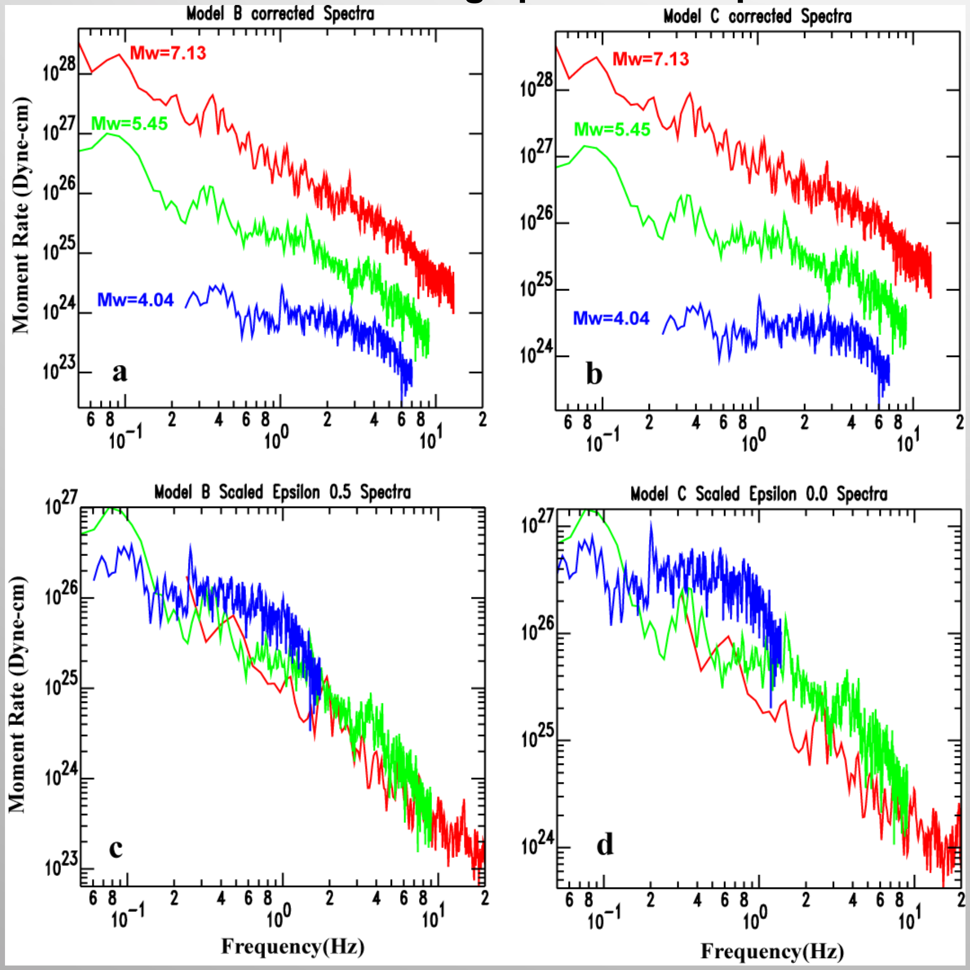
Direct energy measures depend strongly on the path corrections used:

Model A – High Q
Model B – Medium Q
Model C – Low Q

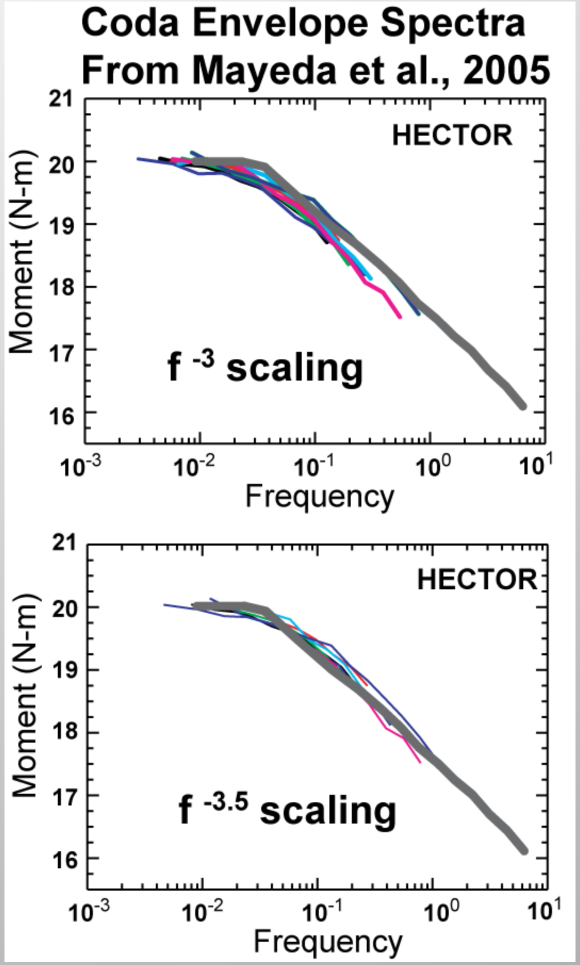
After Walter et al. (2006) AGU Monograph paper

Estimating scaling in a sequence: spectral scaling – also depends upon path corrections

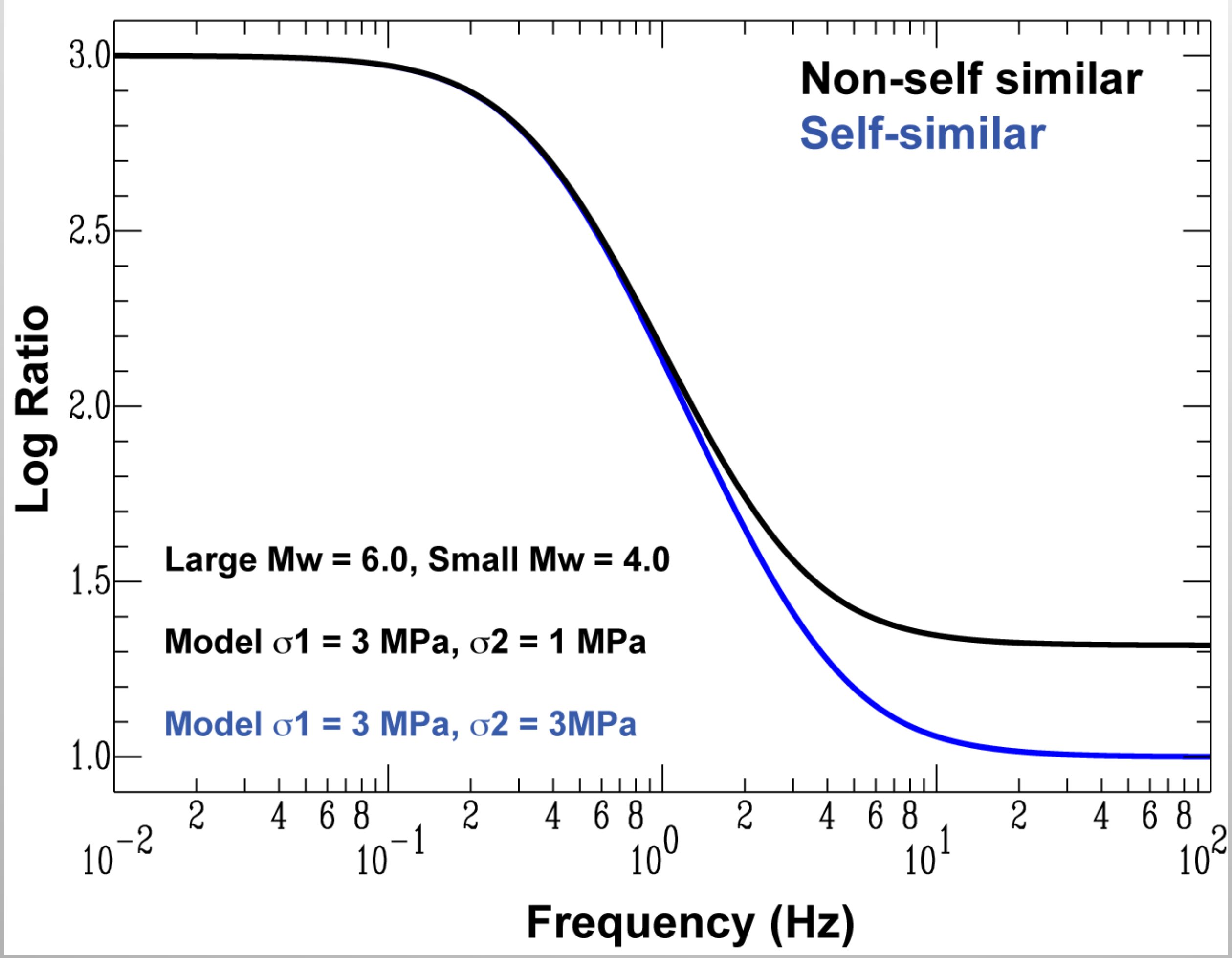
Hector Mine Lg spectra example



After Walter et al. (2006) AGU Monograph paper



EGF ratio methods are attractive because the path cancels but a source model is needed to interpret them

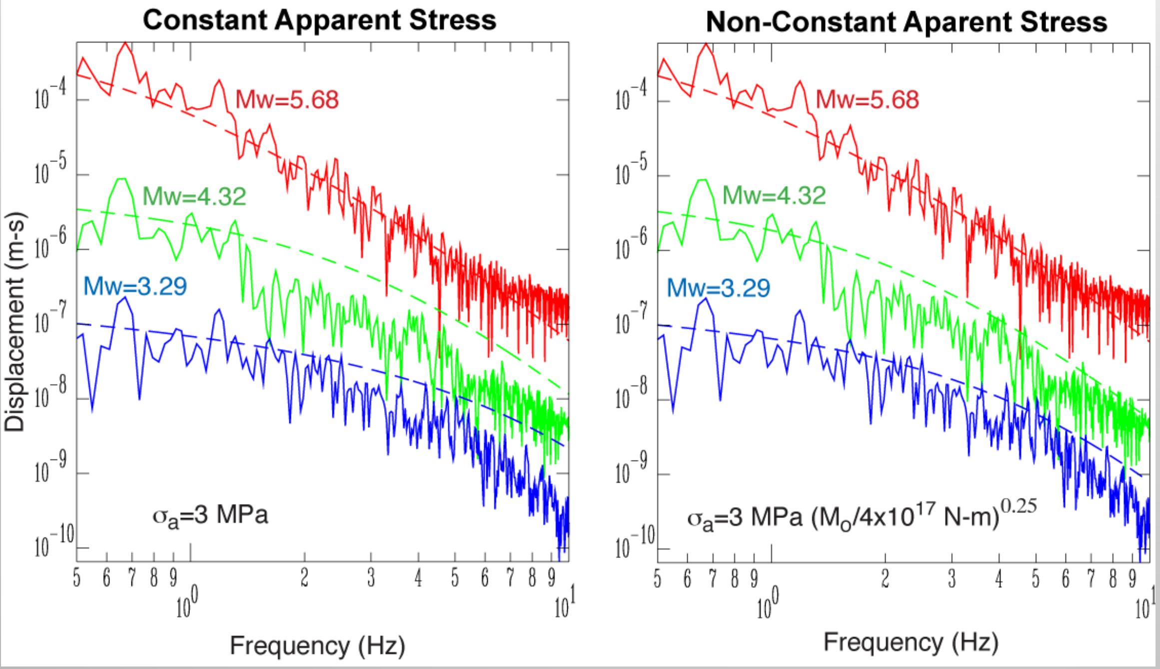


Need a brief segue back to models

The model is then used to generate these curves

We developed a generalized point-source azimuthally-averaged single-corner-frequency analytical model

An example of MDAC2 fits to Lg spectra from the 1992 Little Skull Mountain sequence at the Nevada Test Site: Mainshock and two aftershocks.



Generalized Source Spectrum (e.g. Walter and Brune 1993):

$$\dot{M}(\omega) = \frac{M_o}{\left(1+\left(\frac{\omega}{\omega_c}\right)^2\right)^{p/2}}$$

Walter and Taylor (2001), conserves energy, specifies P and S-waves, allows apparent stress scaling:

$$\omega_{cp} = \zeta\omega_{cS}$$

$$\omega_{cS} = \left(\frac{K\sigma_a}{M_o}\right)^{1/3} \quad \text{where} \quad K = \frac{16\pi}{\beta_s^2\left(\frac{R_{\theta\phi P}^{\;2}\zeta^3}{\alpha_s^5}+\frac{R_{\theta\phi S}^{\;2}}{\beta_s^5}\right)}$$

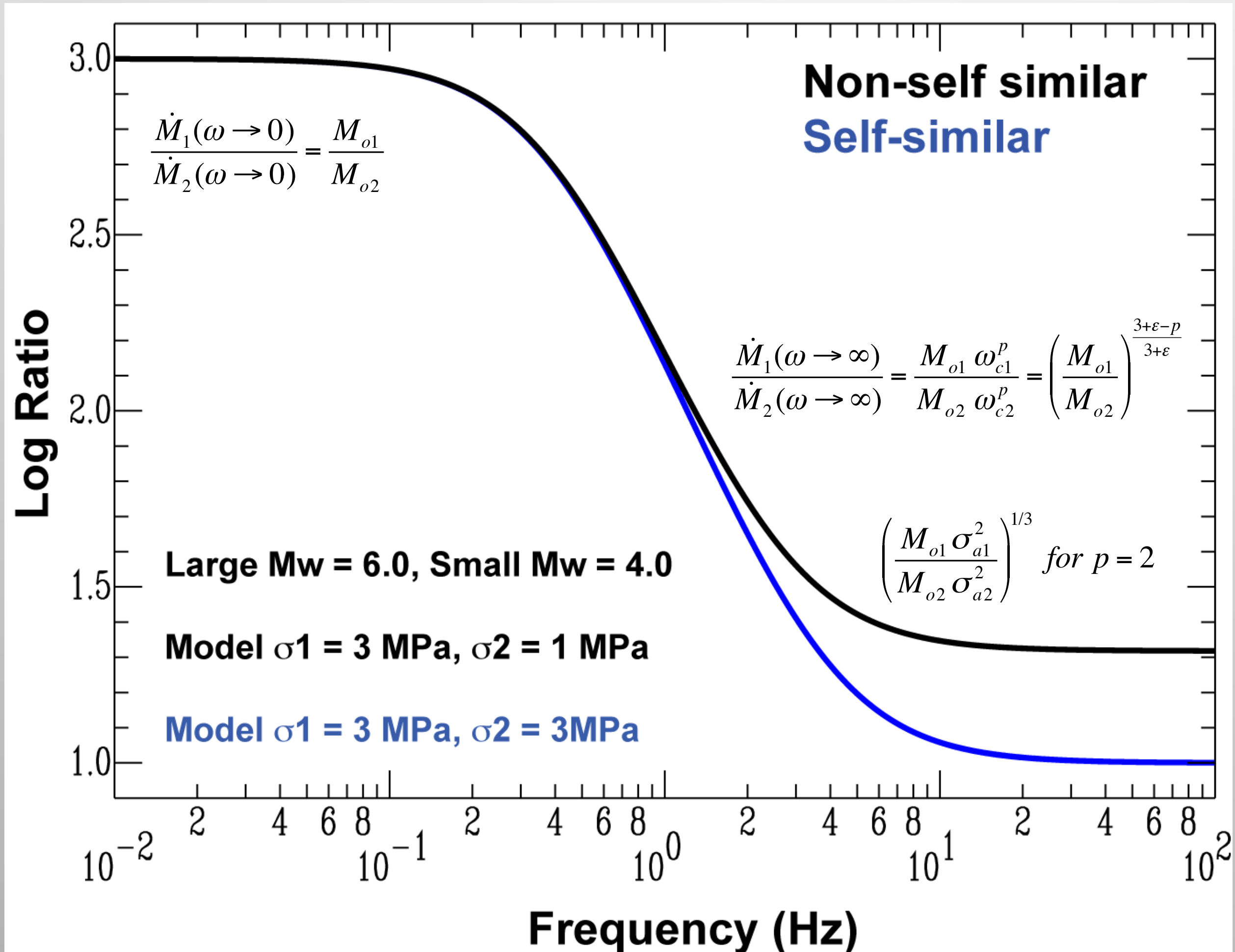
$$\sigma_a = \sigma_a'\left(\frac{M_o}{M_o'}\right)^{\psi}$$

Described in an LLNL Technical report on MDAC:
http://www.llnl.gov/tid/lof/documents/pdf/240563.pdf
Fuller write up as a journal paper in progress

Can tie to Kanamori and Rivera (2004):

$$M_o \sim \omega_c^{-(3+\varepsilon)} \qquad \psi = \frac{\varepsilon}{\varepsilon+3}$$

Apparent stress differences are clearest in the EGF ratio in the high frequency asymptote



Generalized Source Spectrum:

$$\dot M(\omega) = \frac{M_o}{\left(1+\left(\frac{\omega}{\omega_c}\right)^2\right)^{p/2}}$$

Walter and Taylor (2001):

$$\omega_c = \left(\frac{k\sigma_a}{M_0}\right)^{1/3} \quad \text{and} \quad \sigma_a = \sigma'_a\left(\frac{M_0}{M'_0}\right)^{\psi}$$

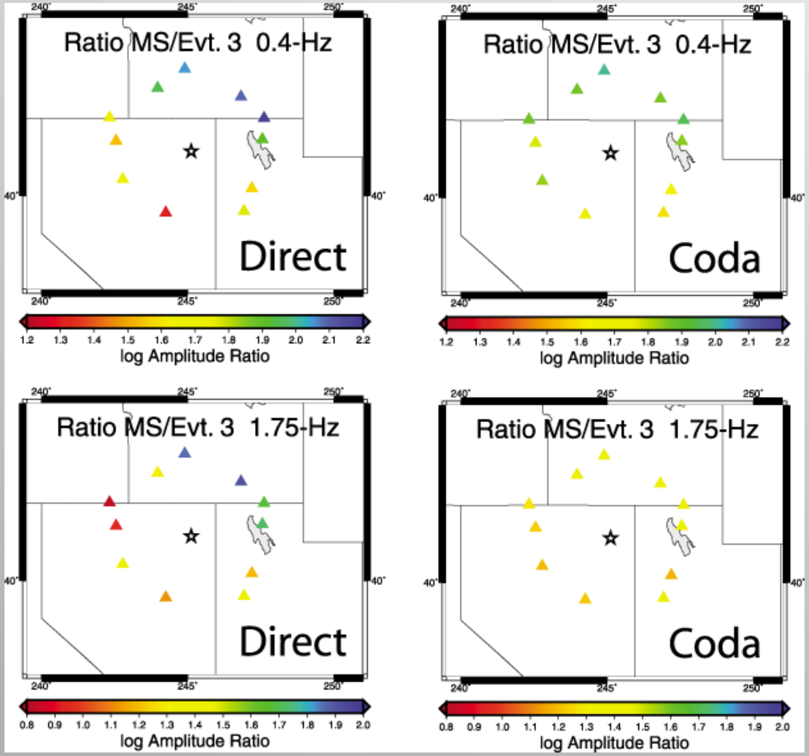
Kanamori and Rivera (2004):

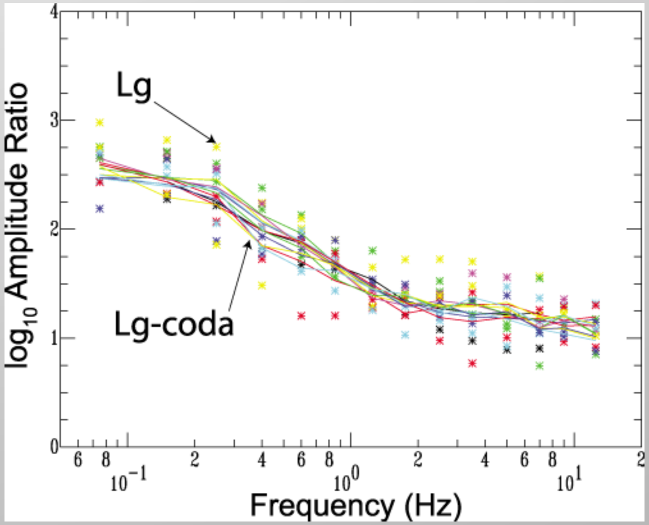
$$M_o \sim \omega_c^{-(3+\varepsilon)}$$

$$\psi = \frac{\varepsilon}{\varepsilon+3}$$

The coda spectral ratio technique offers a number of advantages to EGF investigations

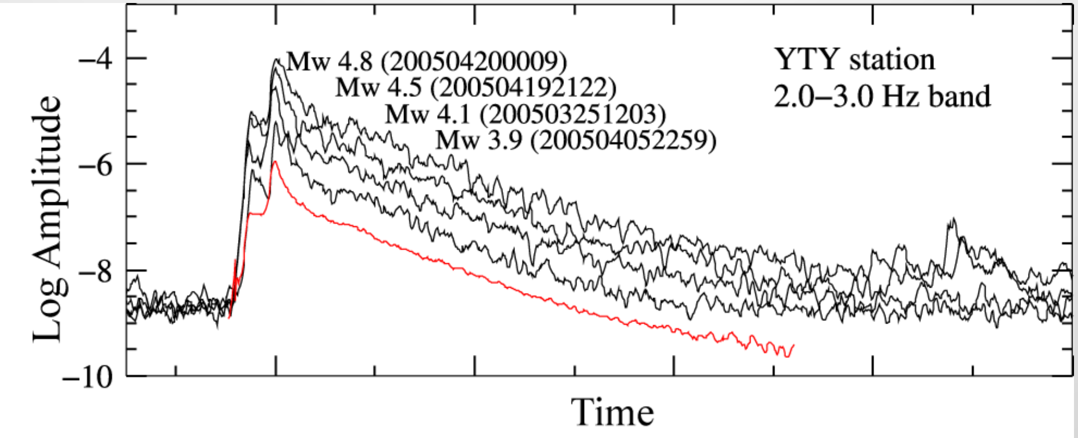
Mayeda, Malagnini and Walter (2007) method:
1) Coda averages over directivity and radiation patterns
2) Coda matches direct wave but with much less variance
3) Can use a wider range of events as EGF

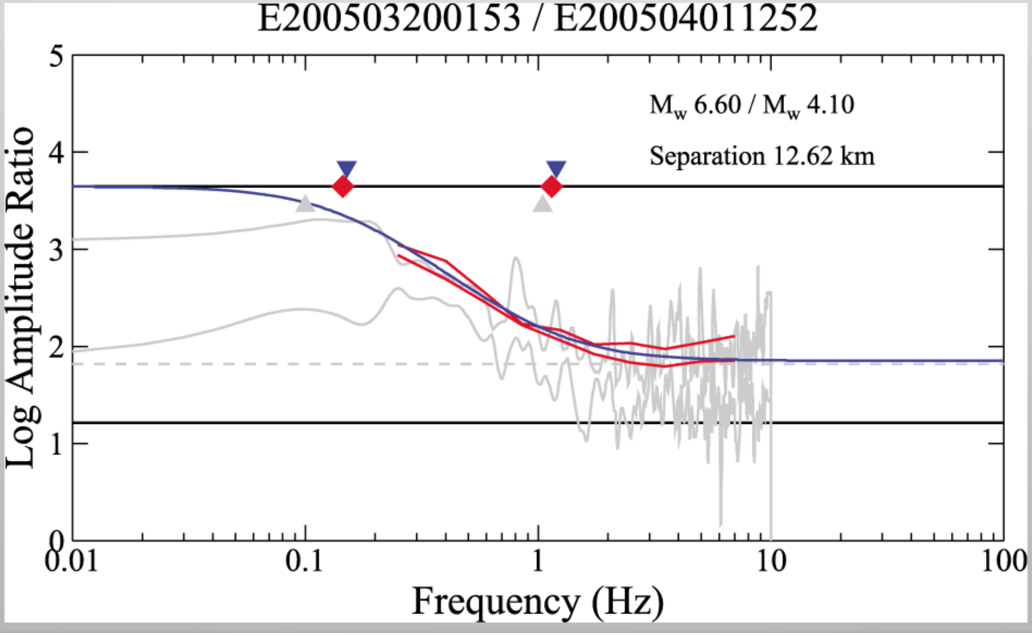




After Mayeda and Malagnini (2009)

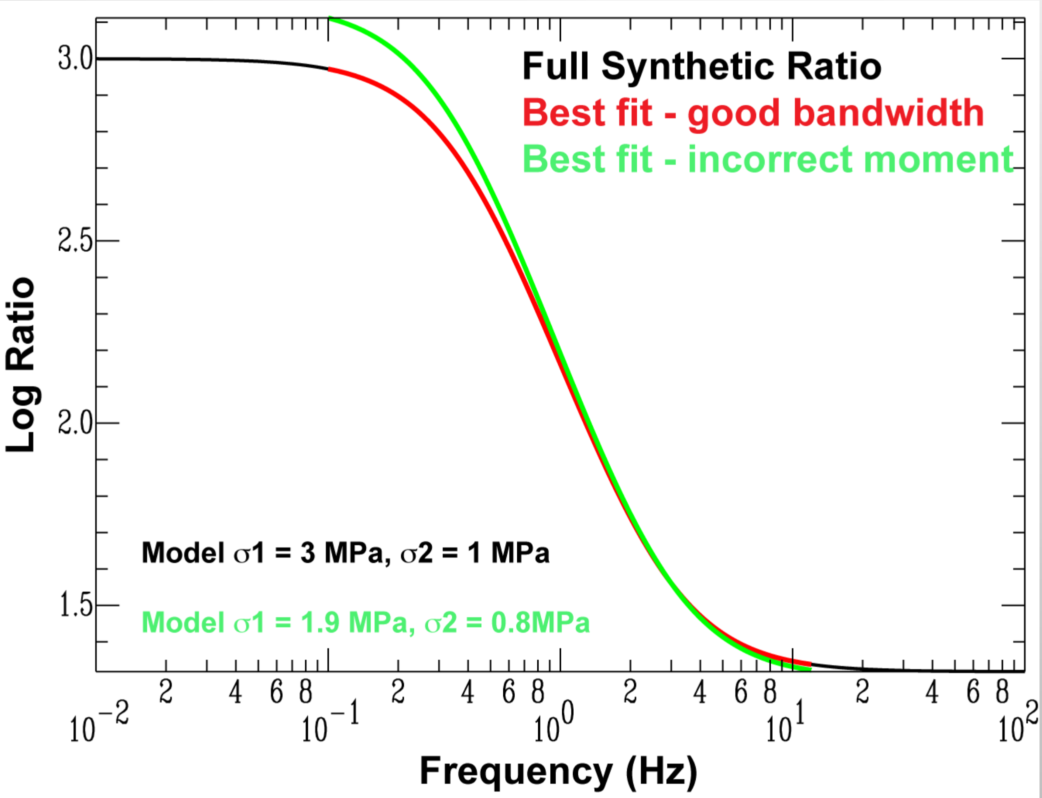
The coda spectral ratio technique is easy to use and you do not need to know much about coda

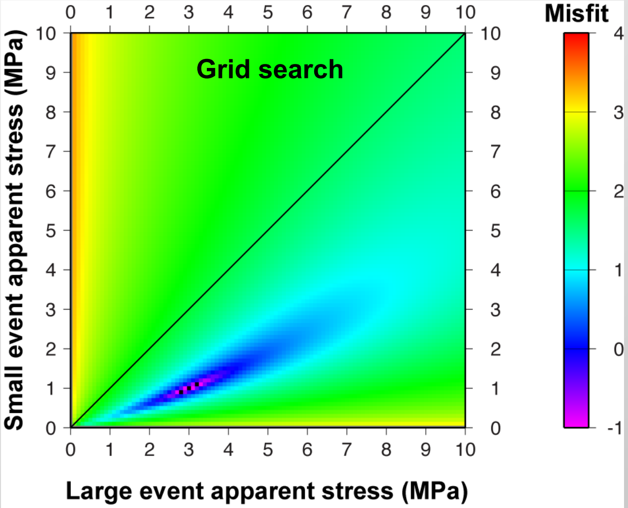


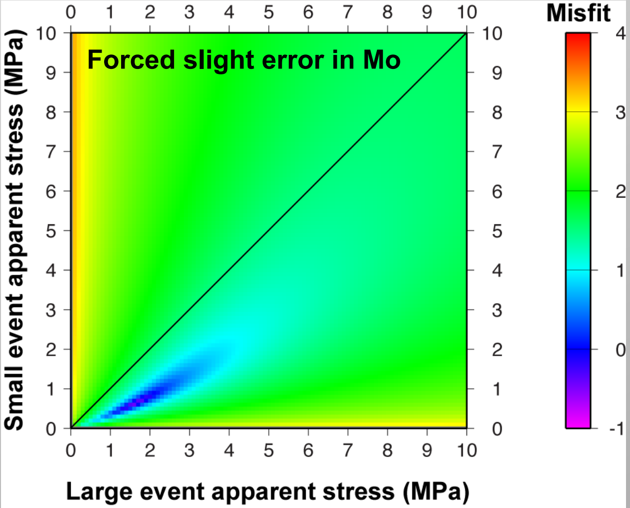


After Yoo et al. (2010)

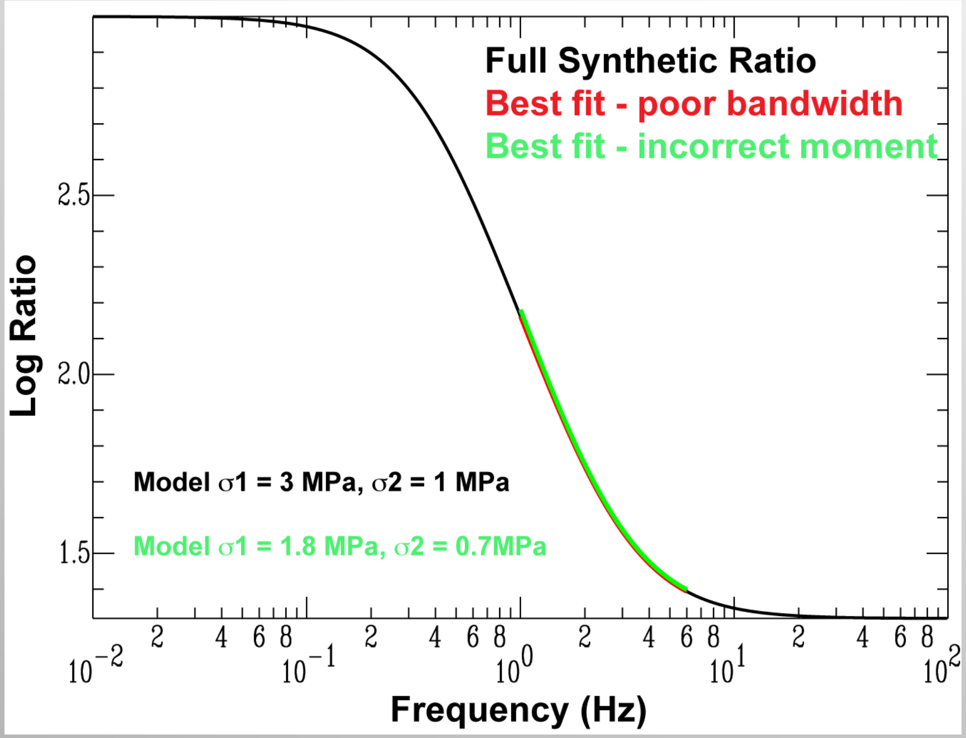
With good bandwidth different apparent stress values can be resolved

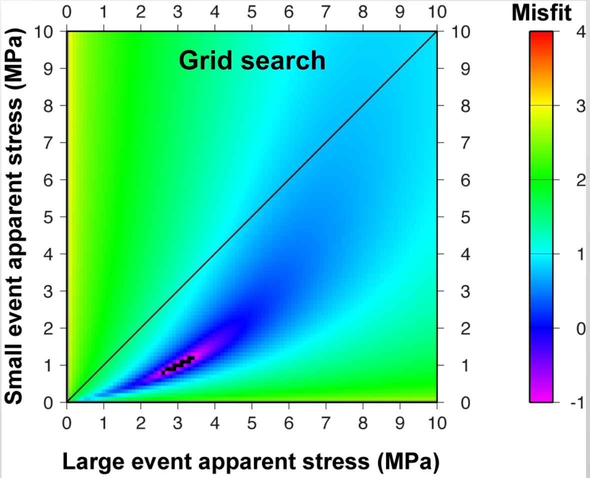


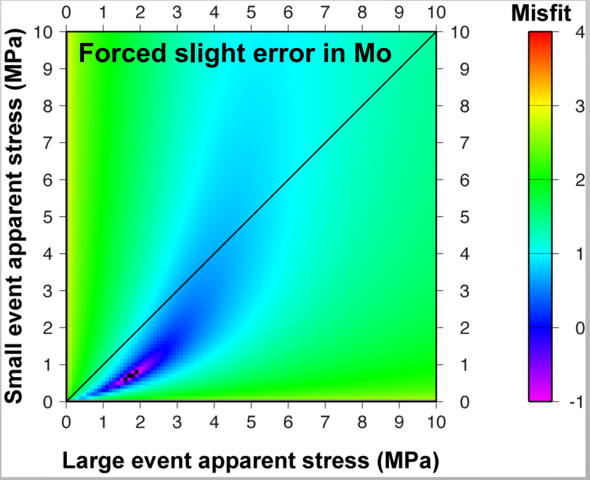




When bandwidth is poor the resolution of apparent stress values is poor



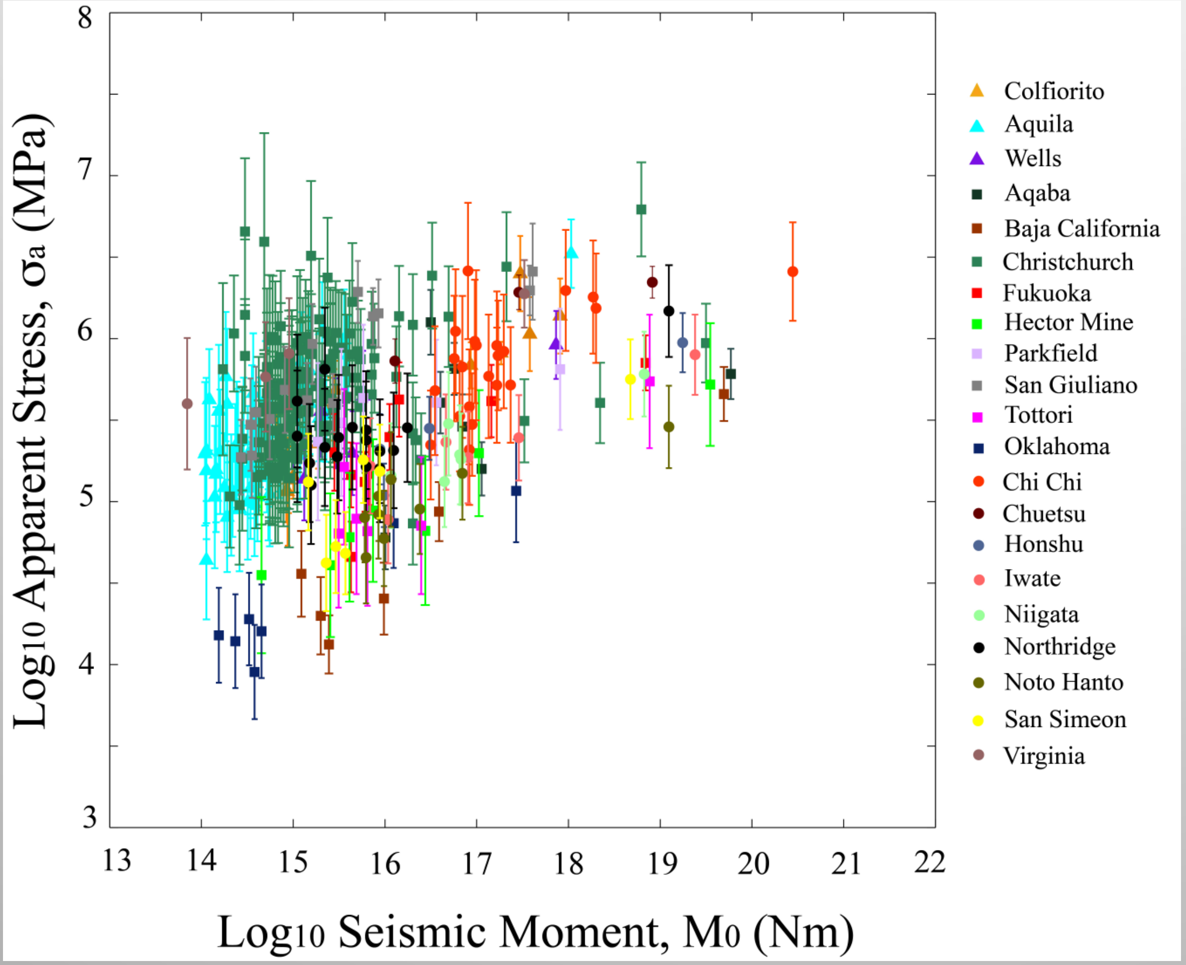




Outline

- Overview of scaling and simple earthquake models
- A brief overview of techniques to examine scaling
- Some current observations and model interpretations
- Using earthquake scaling models for hazard prediction and explosion monitoring

Coda spectral ratio observations on 21 sequences show significant variability in apparent stress values



Mayeda et al. 2007

Malagnini et al., 2008

Malagnini and Mayeda, 2008;

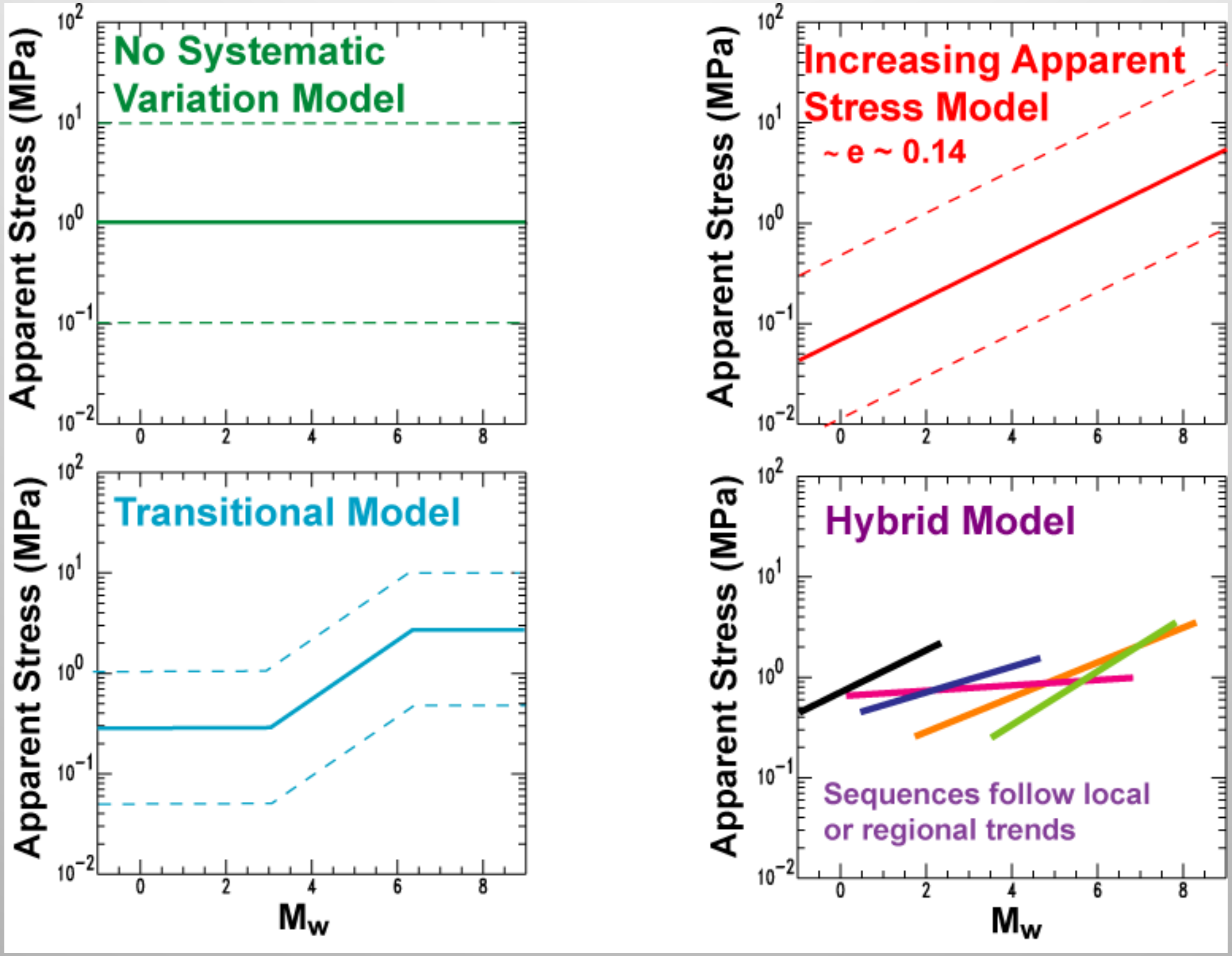
Mayeda and Malagnini, 2009;

Mayeda and Malagnini, 2010

Malagnini et al., 2011

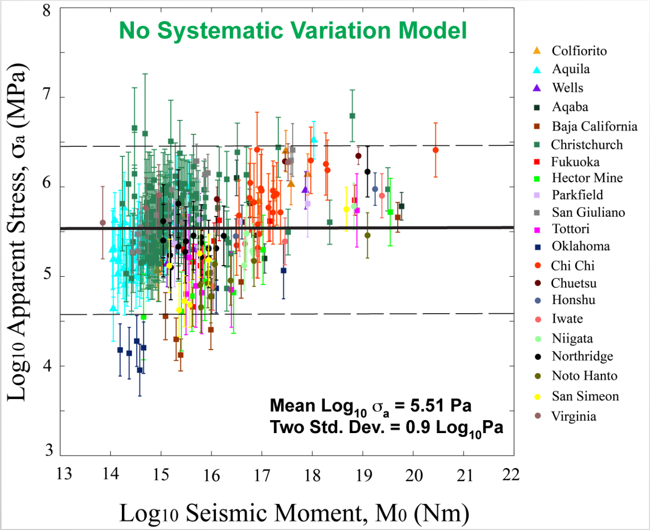
And a number of sequences that are not yet published data

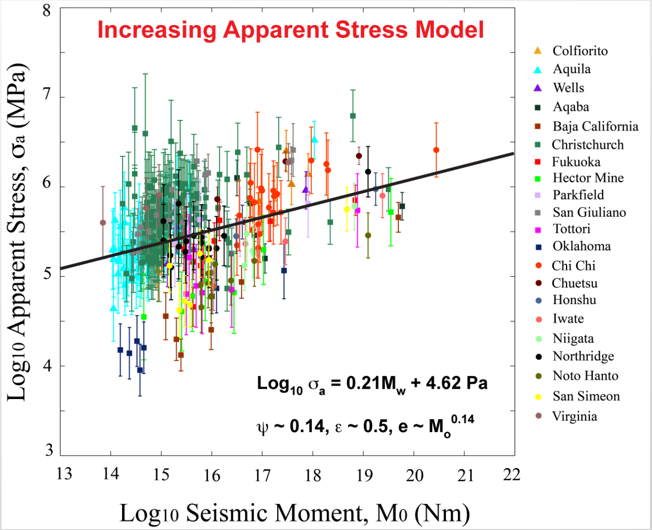
Can we use the observed data to distinguish between some of the hypothesized general models?

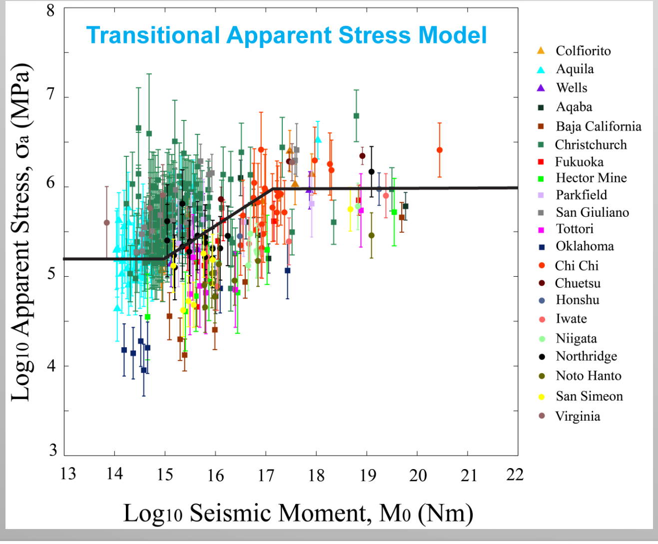


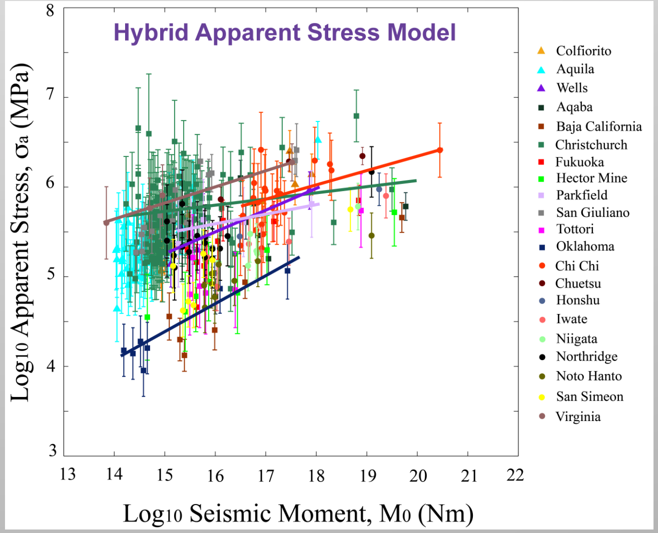
After Walter et al. (2006) AGU Monograph paper

When compared to global models there are indications that local conditions are important







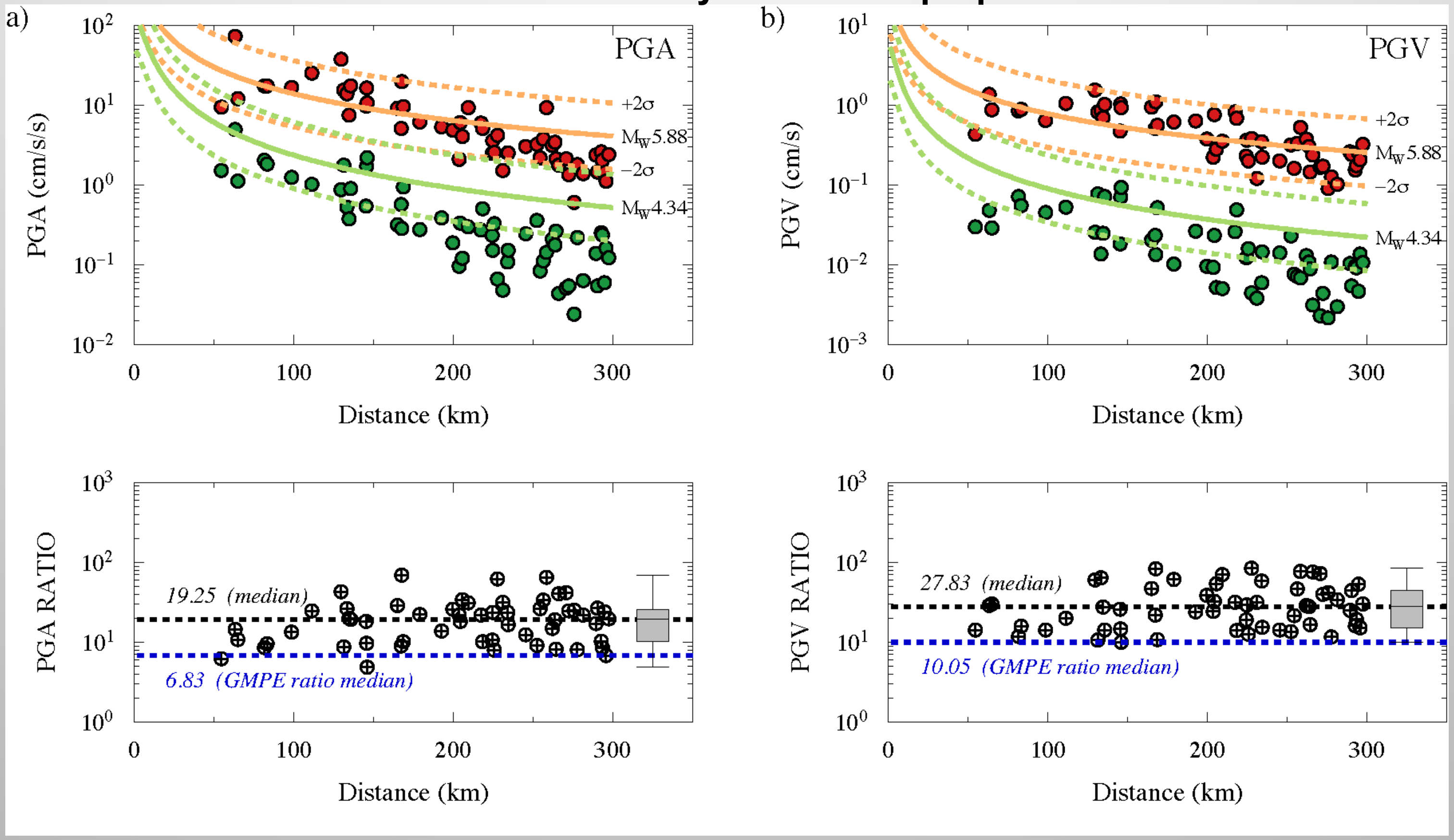


Outline

- Overview of scaling and simple earthquake models
- A brief overview of techniques to examine scaling
- Some current observations and model interpretations
- Using earthquake scaling models for hazard prediction and explosion monitoring

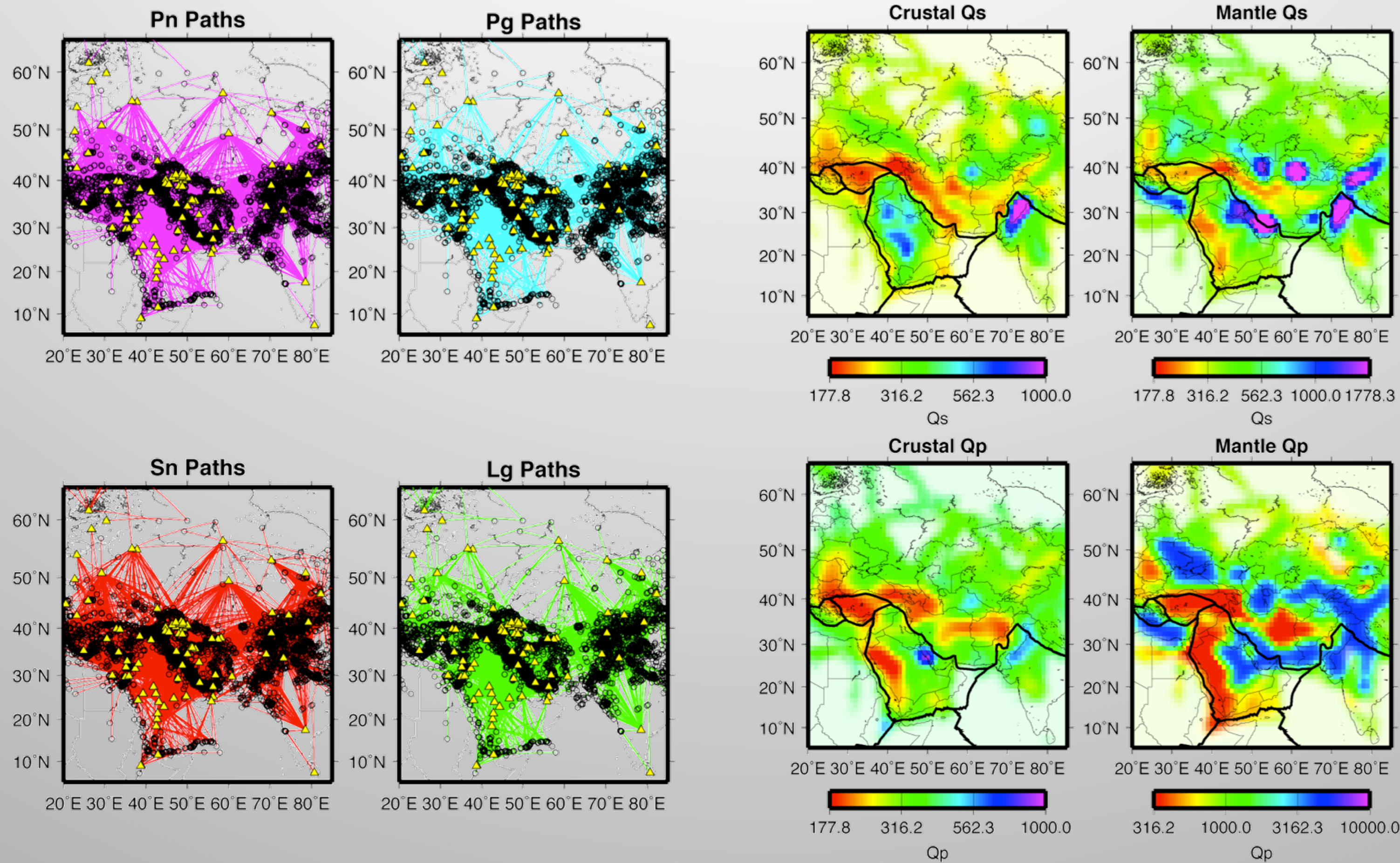
An example of deviations from ground motion prediction equations that can be explained by apparent stress scaling

From Yoo and Mayeda 2012 in prep.



Over-estimation of GMPE's for the Wells NV aftershocks can be explained by their lower apparent stress than the mainshock

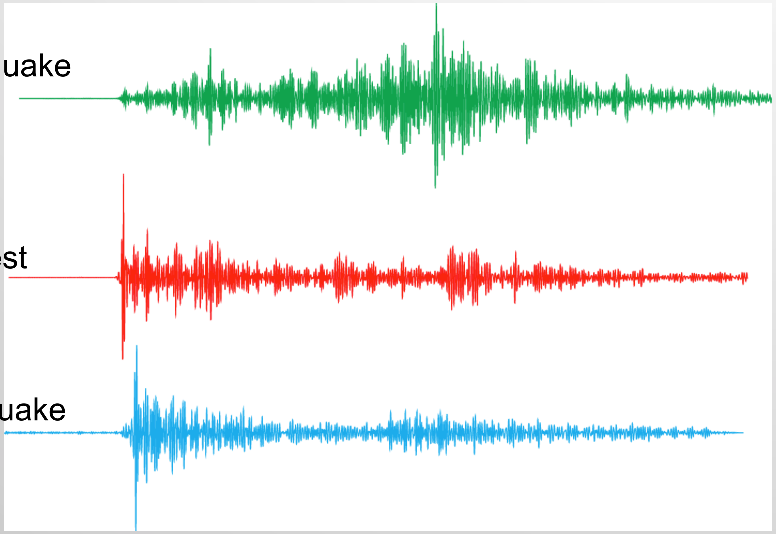
We use our source model with apparent stress scaling to derive attenuation maps over broad regions

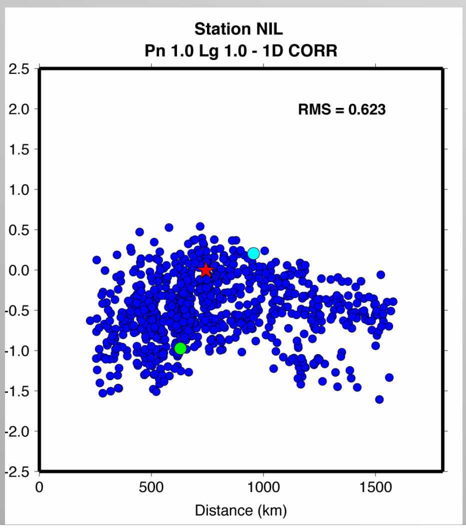


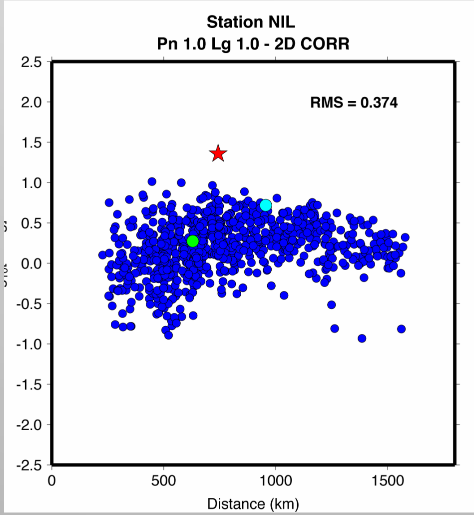
Observed Amp. = Source * Geometric-Spreading * 2-D Attenuation * Site

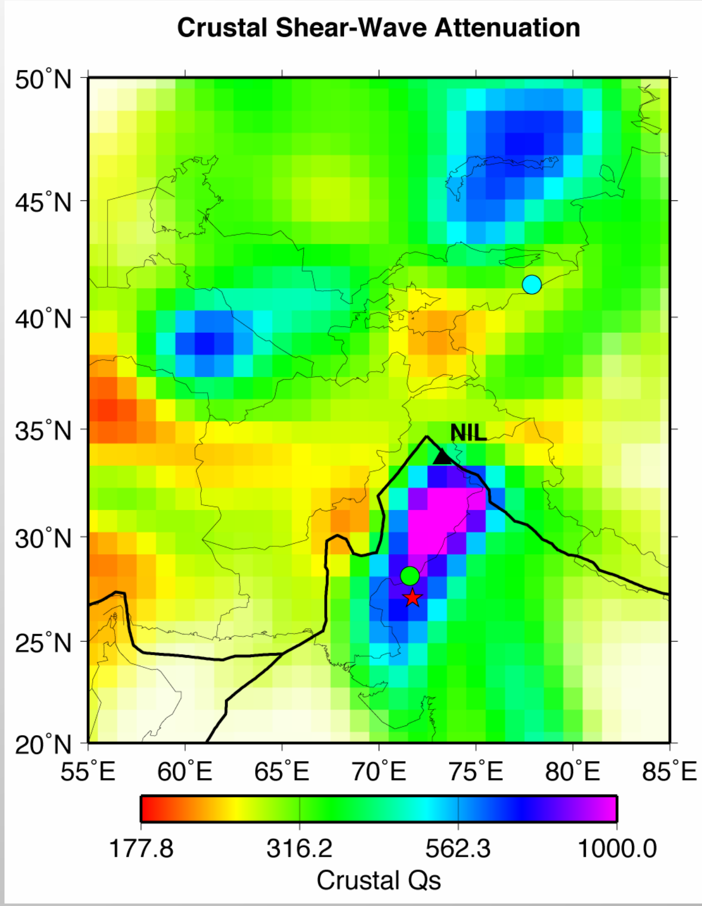
Pasyanos, M.E., W. R. Walter, and E. M. Matzel (BSSA, 2009).

Using earthquake-based amplitude tomographic path corrections allows broad area discrimination









Pasyanos, M.E., and W. R. Walter, (GRL, 2009).

Summary

- The scaling behavior of earthquakes remains under active investigation
- Nearly all studies show significant variance in apparent stress values that is incompletely explained and affects forecasting
- Forecasting ground motion is possible with a variety of different but self-consistent models. Allowing source scaling seems to help
- Need consistent techniques applied to a wide variety of data
  - Coda amplitude ratio techniques offers a number of advantages to study scaling
  - Massive cross-correlation using different scaling models also has appeal