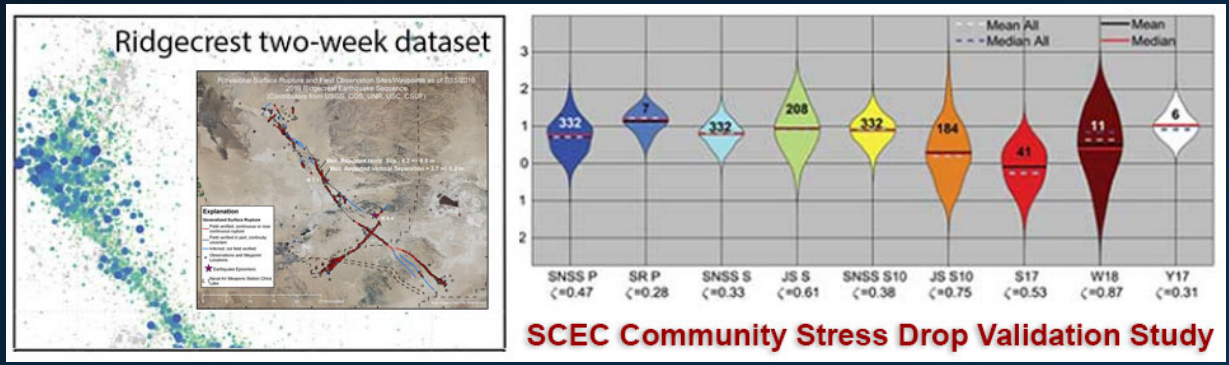
SCEC Community Stress Drop Validation Project



Annemarie Baltay (USGS)
Rachel Abercrombie (Boston University)
Shanna Chu (USGS)
Taka'aki Taira (UCB)

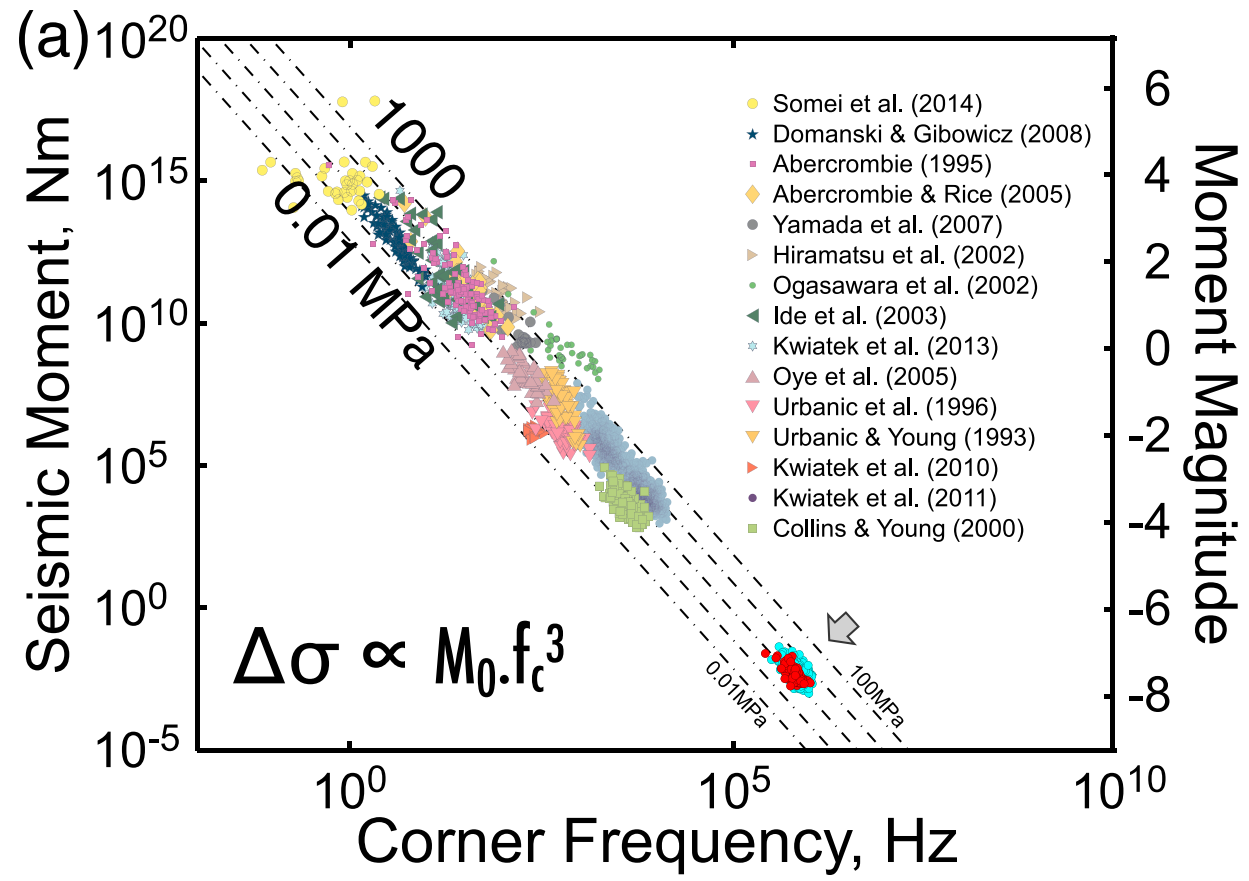
To address SCEC's research priority of understanding stress: a coordinated, **community effort to improve methods to estimate stress drop and determine its dependency on earthquake and material heterogeneities.**

Goals of SCEC TAG are to understand the nature and causes of discrepancies in earthquake stress drop, and where random and physical variability arises.

Invite community to calculate and submit estimates of stress drop for a common data set (2 weeks of 2019 Ridgecrest earthquakes)

Compare & investigate differences
Recalculate & repeat

Introduction to General Problem



e.g. Yoshimitsu *et al.*, GRL 2015

Stress drop fundamental to source physics, ground motion prediction.. But.....

Constant Stress Drop varies over 3+ Orders of Magnitude

Combination of Smaller scale studies

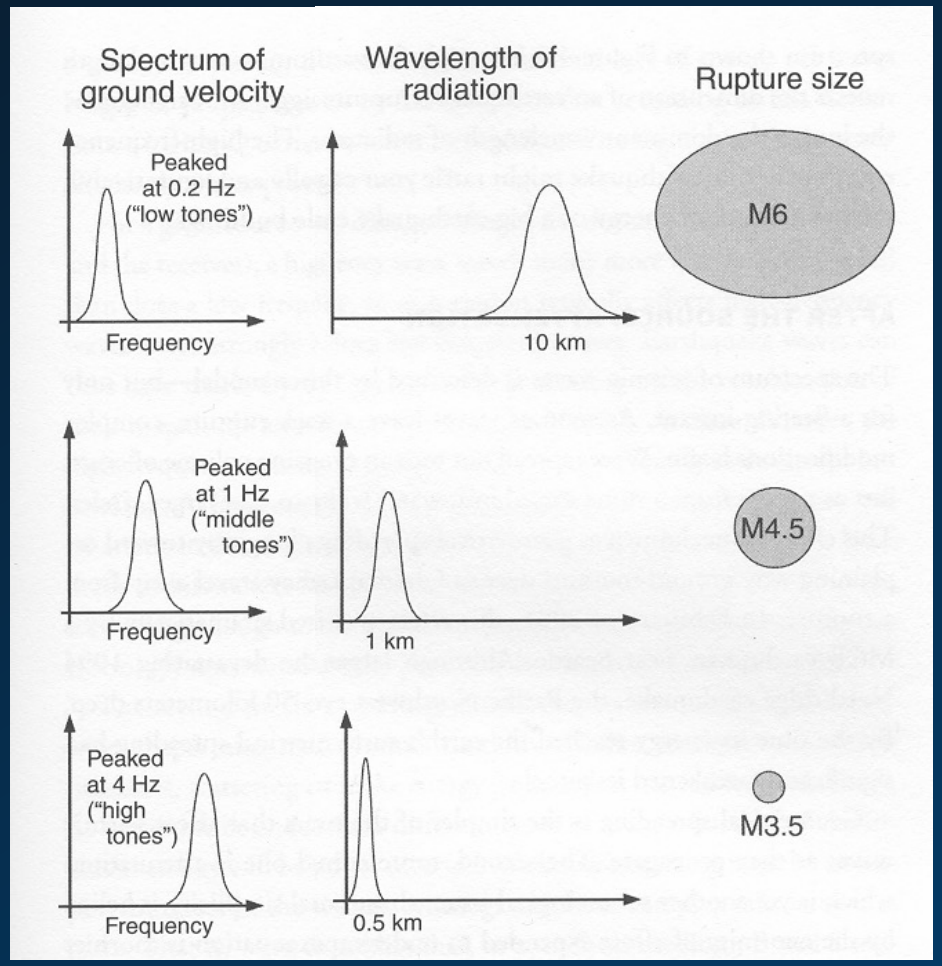
M trends within individual studies?
Spatial variability?
Depth dependence?

Uncertainties? Resolution? Simplifying Assumptions?
Different studies do NOT agree

If you really want to know more, see review Abercrombie (2021)
Phil. Trans. Roy. Soc. http://doi.org/10.1098/rsta.2020.0131

Measurements from Frequency of Seismic Waves

1960s and 1970s Aki, Brune, Kanamori, Madariaga etc.
(pre digital recording and big computers..)
Source spectrum has simple shape:



Earthshaking Science, Sue Hough, 2002

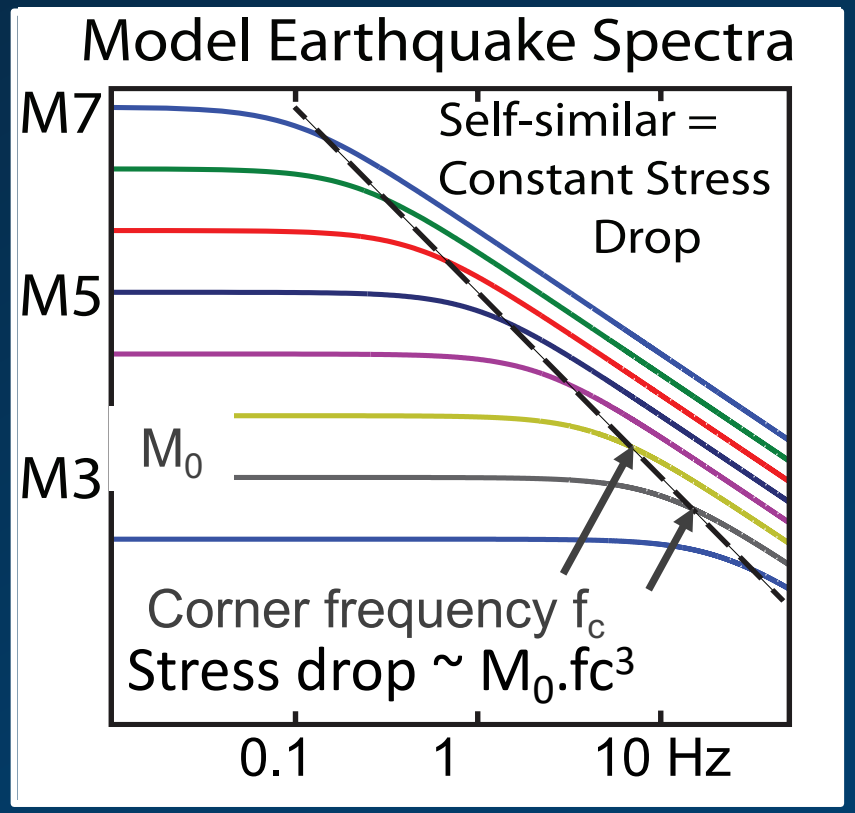
Peak in velocity spectrum

= corner frequency (fc) in displacement

~ 1/ **source dimension**

Brune Model:

n =2 $$M_0(f) = \frac{M_0}{1 + \left(\frac{f}{f_c}\right)^n}$$



Seismic Moment: M_0 = rigidity × slip × area
= Long period level

Stress Drop ~ strain ~ slip / √area

Higher stress drop implies higher seismic hazard

Consider 2 earthquakes with same M_0 and different $\Delta\sigma$

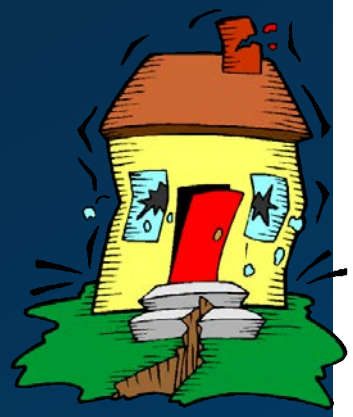
Stress drop, $\Delta\sigma$

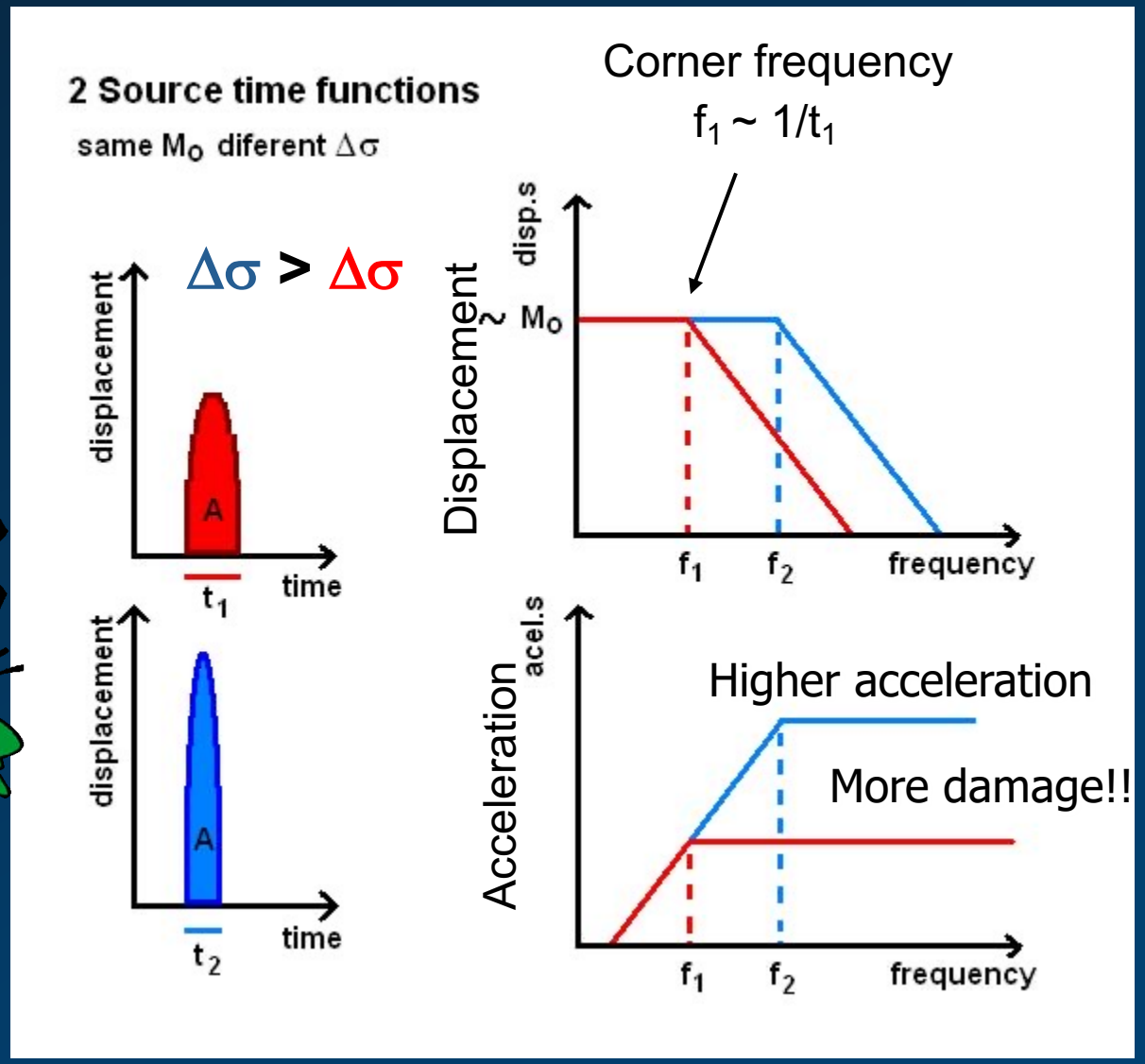
Static stress released by the rupture

$\Delta\sigma \sim$ slip/length

higher $\Delta\sigma \Rightarrow$
higher slip,
smaller length,
shorter duration

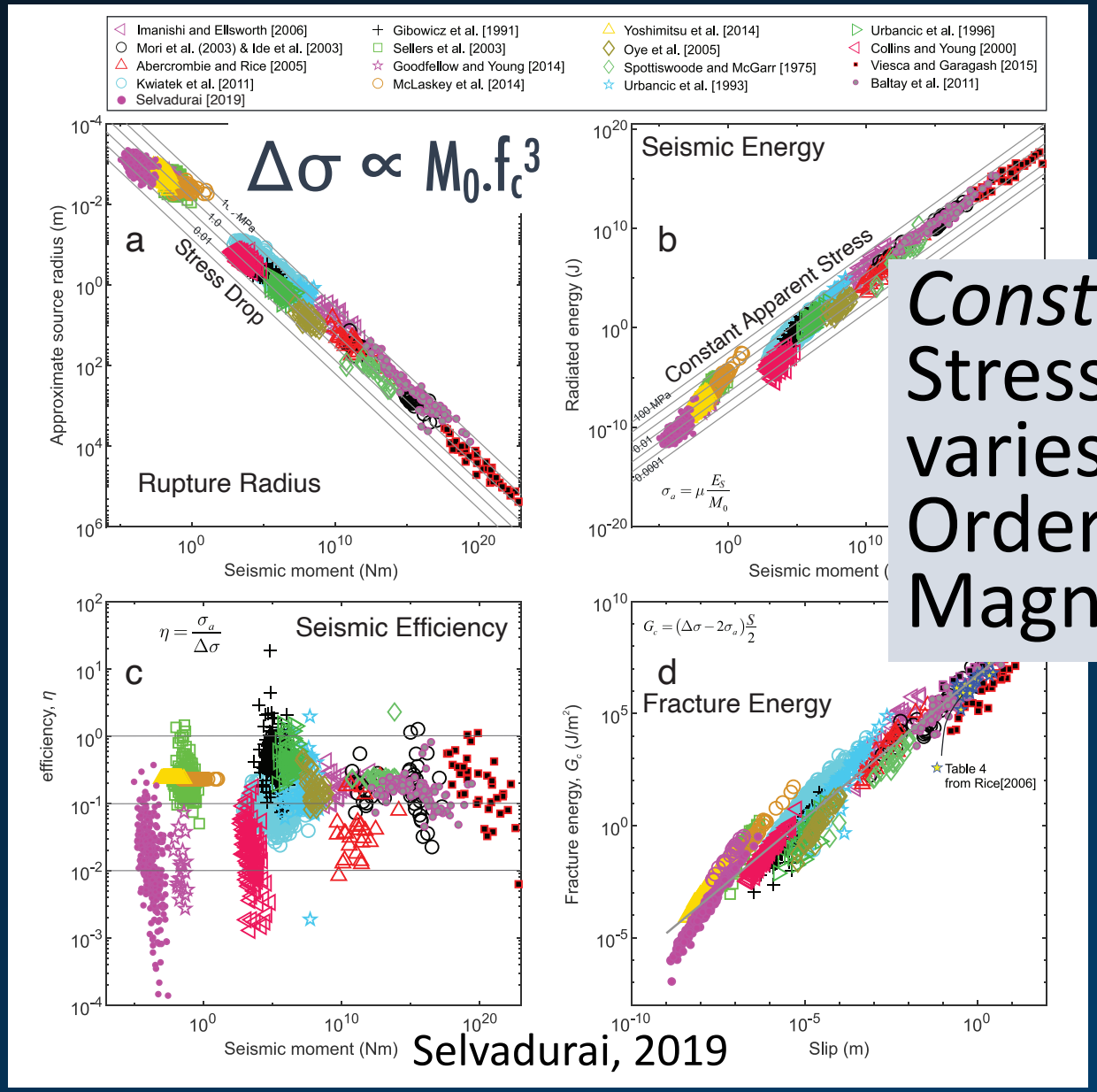
Higher Ground Accelerations





Earthquake Physics –

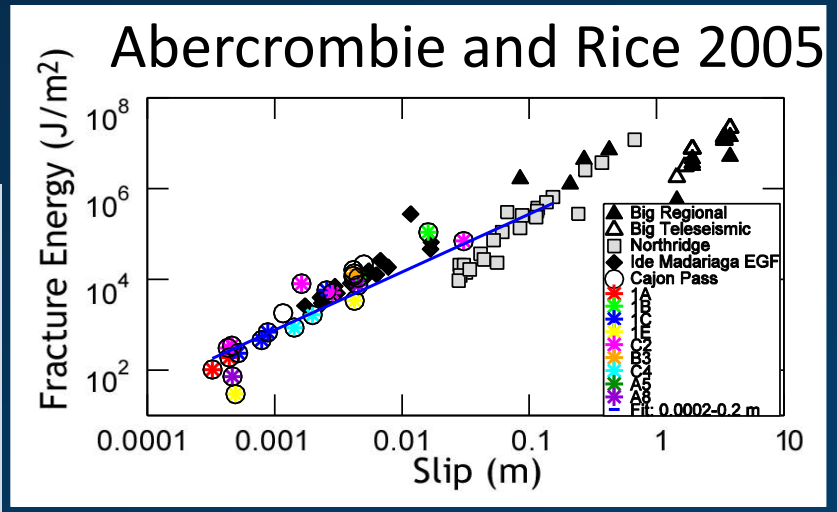
Where are measurements from? Do they really constrain models?



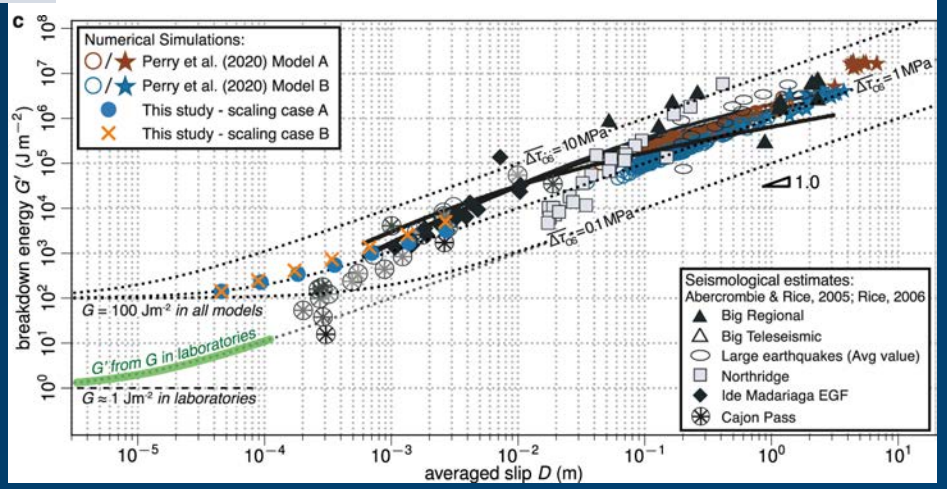
Selvadurai, 2019

Constant Stress Drop varies over 3+ Orders of Magnitude

Abercrombie and Rice 2005

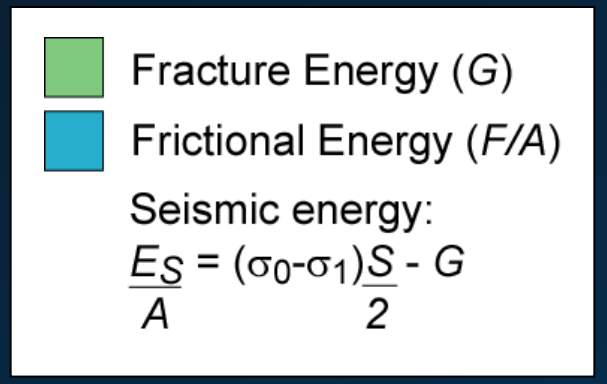


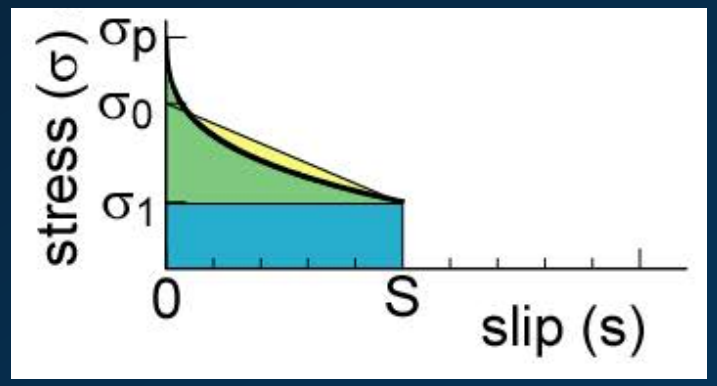
Ke, McLaskey & Kammer 2022



Fracture Energy: Seismic Estimates of G' – at each point, or an "average" point

$G' = \Delta\sigma/2 * s$ – Energy/ Area





Measure:
Stress drop $\Delta\sigma$
Slip s
Seismic radiated Energy E_S
Rupture area $A \sim r^2$

Either – use dynamic and kinematic modeling to measure spatially varying parameters in a finite fault inversion

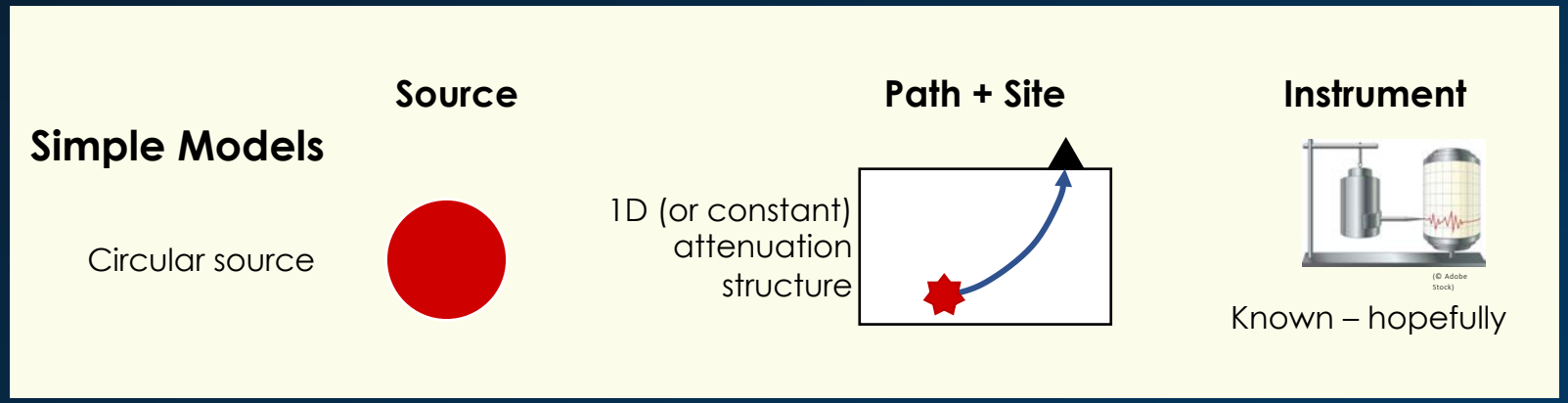
OR

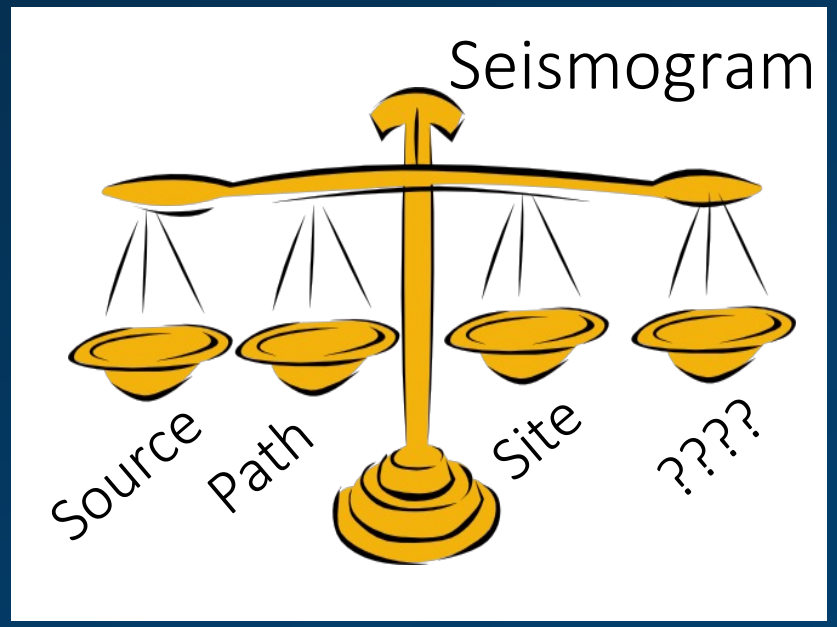
Use average values for whole rupture
Assume simple (circular) source models

Higher Quality and Quantity of data: Larger earthquakes

Lower Quality and Quantity of data: Smaller earthquakes

First Problem: how separate source and path in recorded seismograms?





Seismogram (X):

$X(t) = S(t) * G(t) * I(t)$

Frequency spectrum:

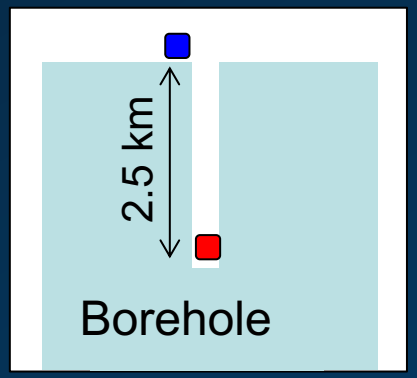
$X(f) = S(f) \times G(f) \times I(f)$

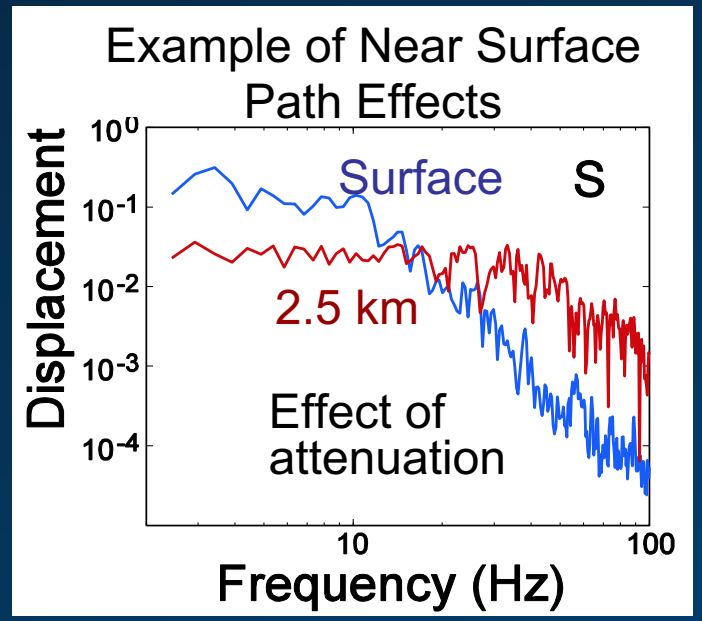
In practice: Trade-offs.

Hard to resolve with limited frequency range data - in either frequency OR time domain

Path and Site have Significant Errects

Site Effects on M~2
Abercrombie 1995





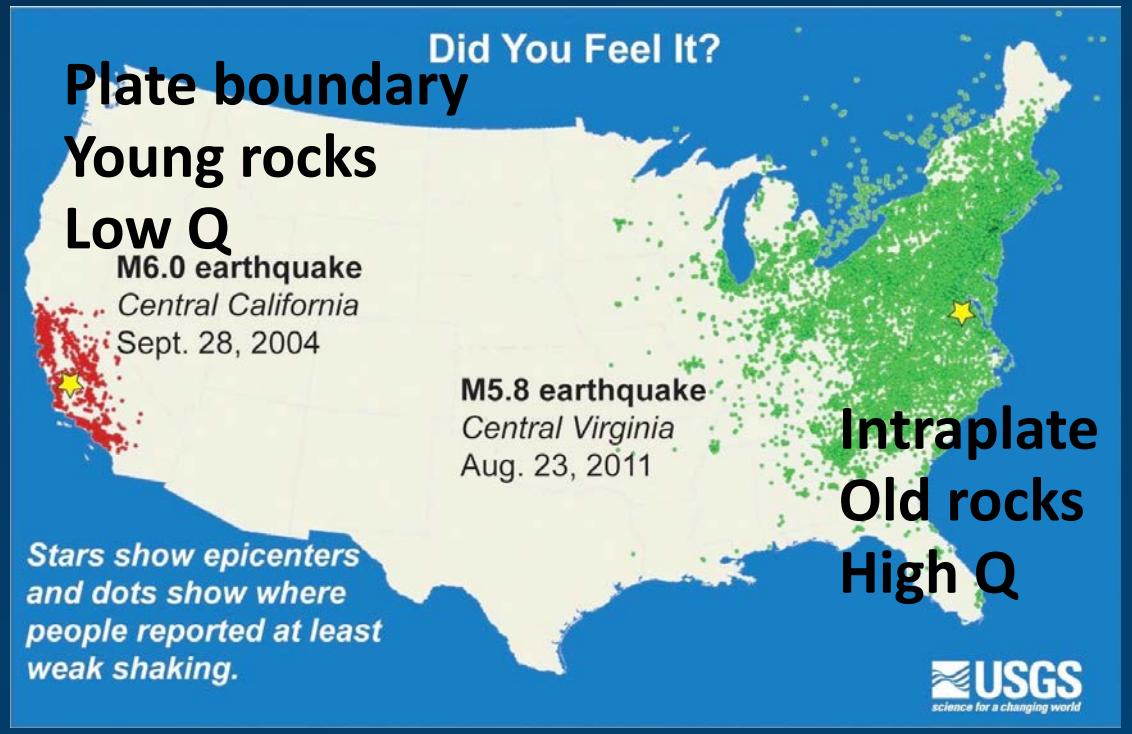
Seismic waves are attenuated as they travel through the earth (path and site effects)

Higher frequencies more attenuated so problem harder for smaller earthquakes

For example: Two M6 earthquakes were felt very differently in different parts of the USA

Because attenuation is higher in warmer, higher strain rate west.

Are the earthquake sources different too?



Introduction to Methods

Most earthquakes are small, so not well-enough recorded for detailed finite-fault modeling

Simple Individual Spectral Fitting – Separation of source and path is Ambiguous

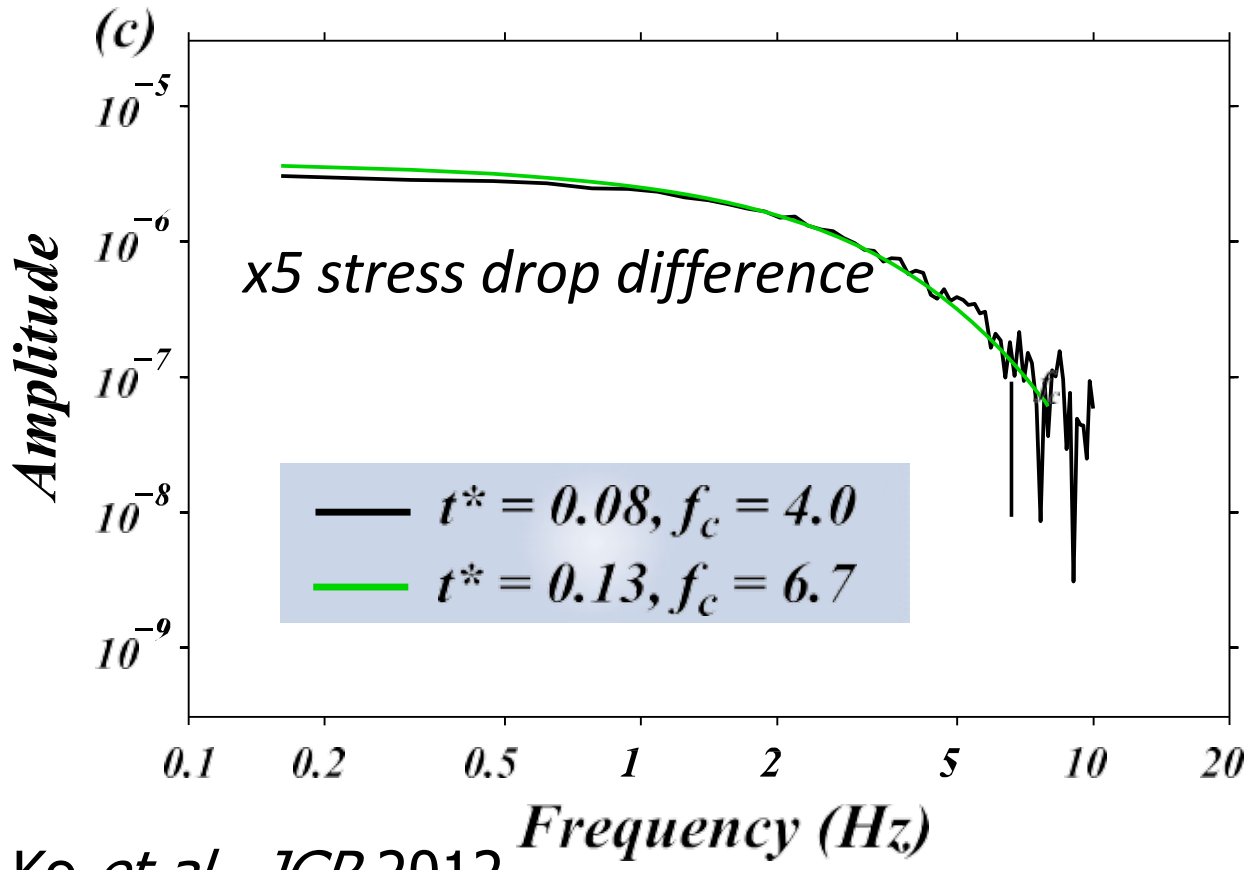
$$M_0(f) = \frac{Ce^{-\pi f t/Q}}{1+\left(\frac{f}{f_c}\right)^2}$$

t*=t/Q

Large trade-offs in limited frequency range of typical data

Is a single "stress drop" the best way to characterize an earthquake?

Fit synthetic data for Q and fc



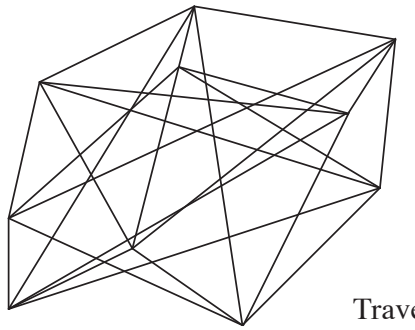
Ko *et al., JGR* 2012

Introduction to Methods

Various Alternatives Developed to Improve Resolution

Large Scale Inversion: Using multiple earthquakes recorded at multiple stations to separate source, path and site effects

Inversion for Spectral Components



Event term: e_i

Station term: s_j

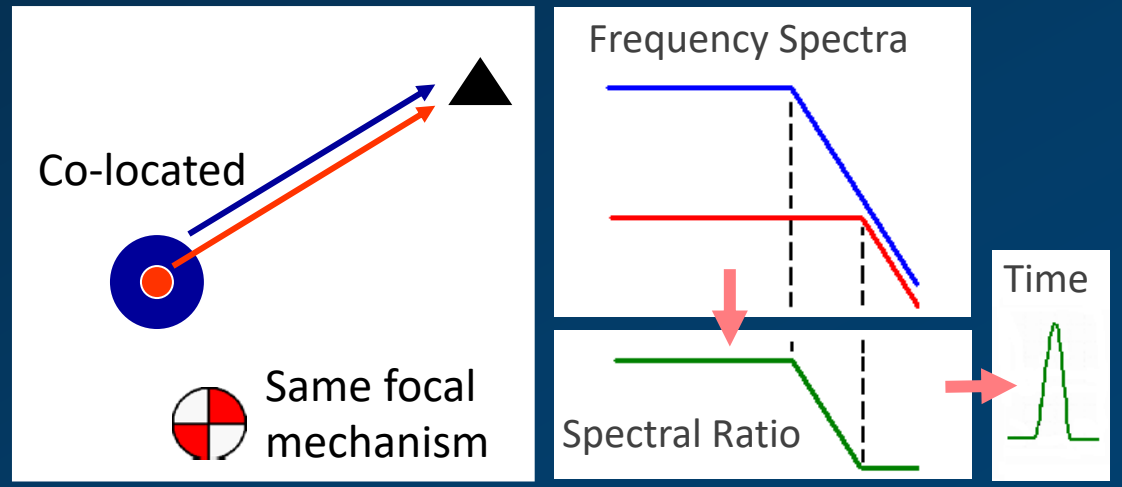
Travel time term: $t_{k(i,j)}$

$$d_{ij} \approx e_i + s_j + t_{k(i,j)} + r_{ij} \text{ (residual)}$$

Observed spectrum	Source spectrum	Receiver response	Travel-time dependent term to account for Q

Solved with iterative least-squares method with outlier supression

Empirical Green's Function (EGF) – use small, co-located earthquake to remove path and site effects

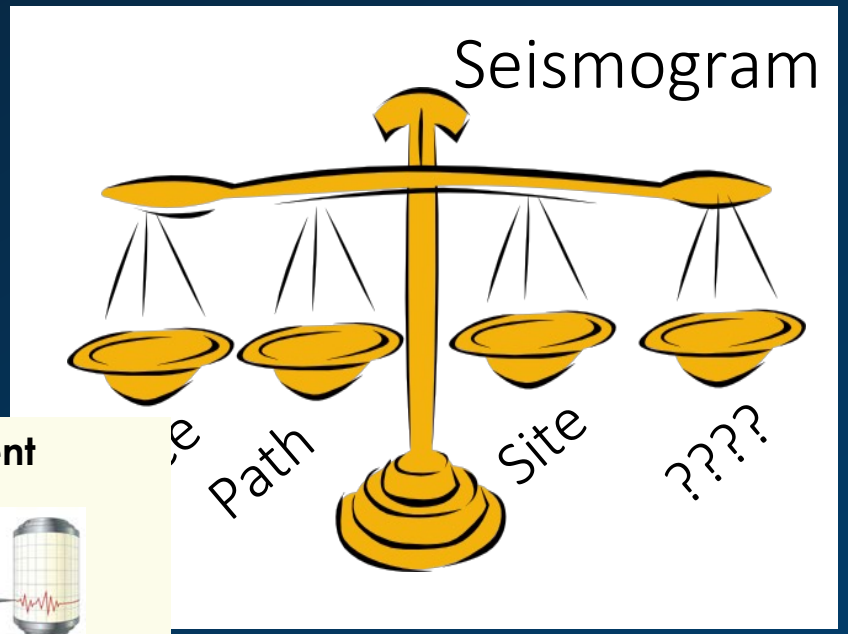


And many variations and combinations … as you will see!

Real Earth is Far More Complex

Separate source and path in recorded seismograms

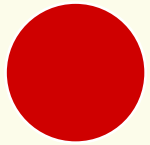
Characterise source with simple parameters/model



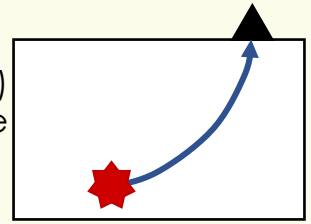
Source | **Path + Site** | **Instrument**

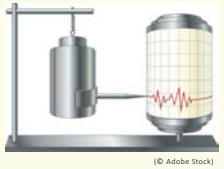
Simple Models

Circular source



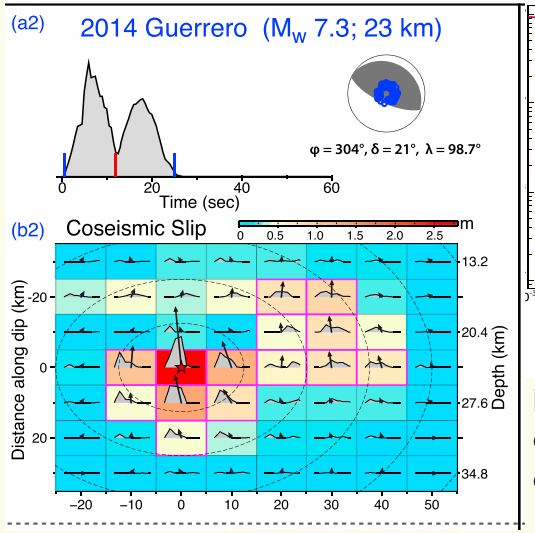
1D (or constant) attenuation structure

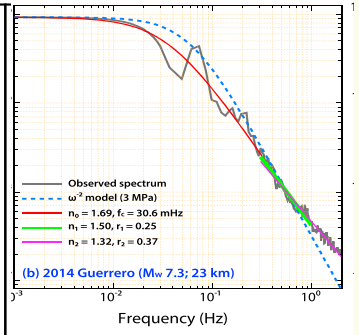




Known – hopefully

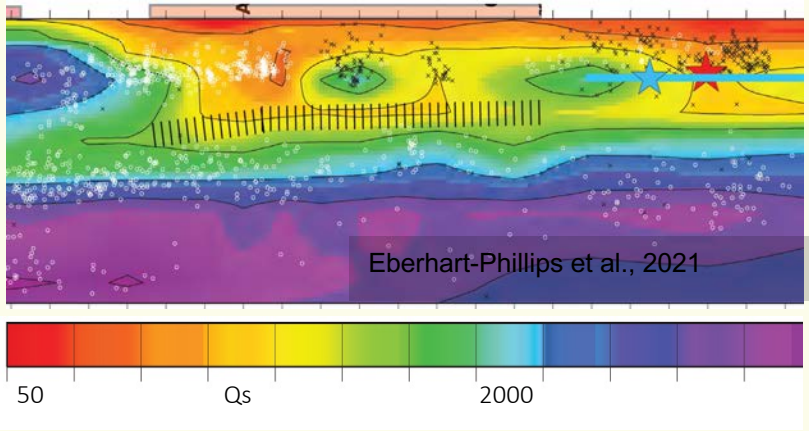
Real Earth is far more complex





Ye *et al.*, 2016

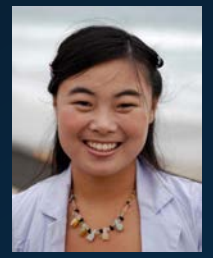
Large and Small earthquakes are complex when data are good enough to observe



Attenuation heterogeneity

Prague, OK, Earthquake sequence: Stress Drop Multi-Method Comparison

Colin Pennington



Xiaowei Chen

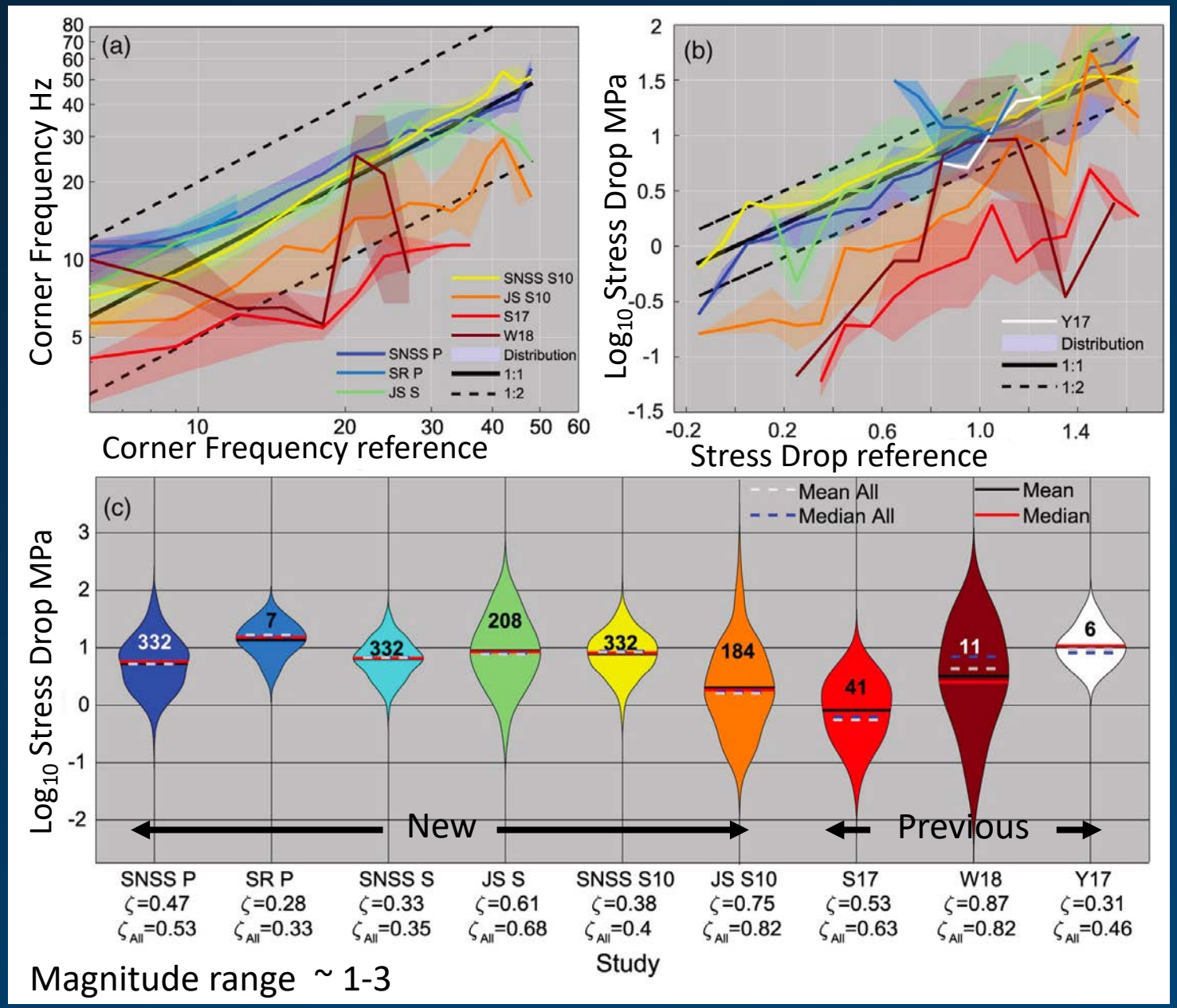
Pennington *et al.*, 2021 *JGR*

A LOT of Scatter BUT Some Real Source Signal

-RELATIVE values agree better than ABSOLUTE

-Some consistent spatial patterns

Beyond the scope of any one group….



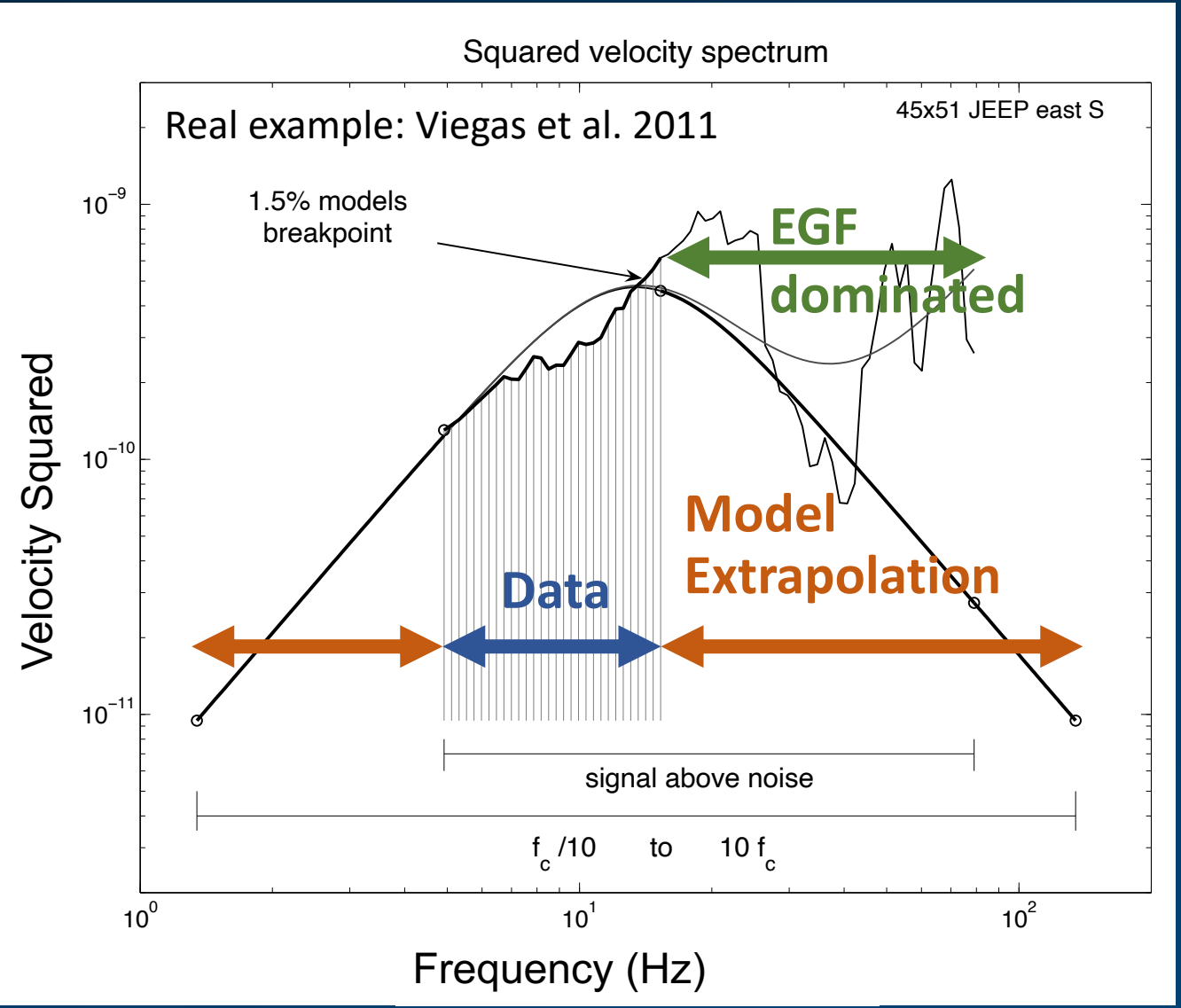
Why not Estimate Seismic Energy Instead (or as well) – integrate velocity squared

Should be Independent of Source Model Assumption..

BUT – high frequency, wide bandwidth measurement so very sensitive to attenuation and limited data

Attenuation Correction from omega-square & corner-frequency type source modeling.

How big are uncertainties?
How "model independent" is it really?

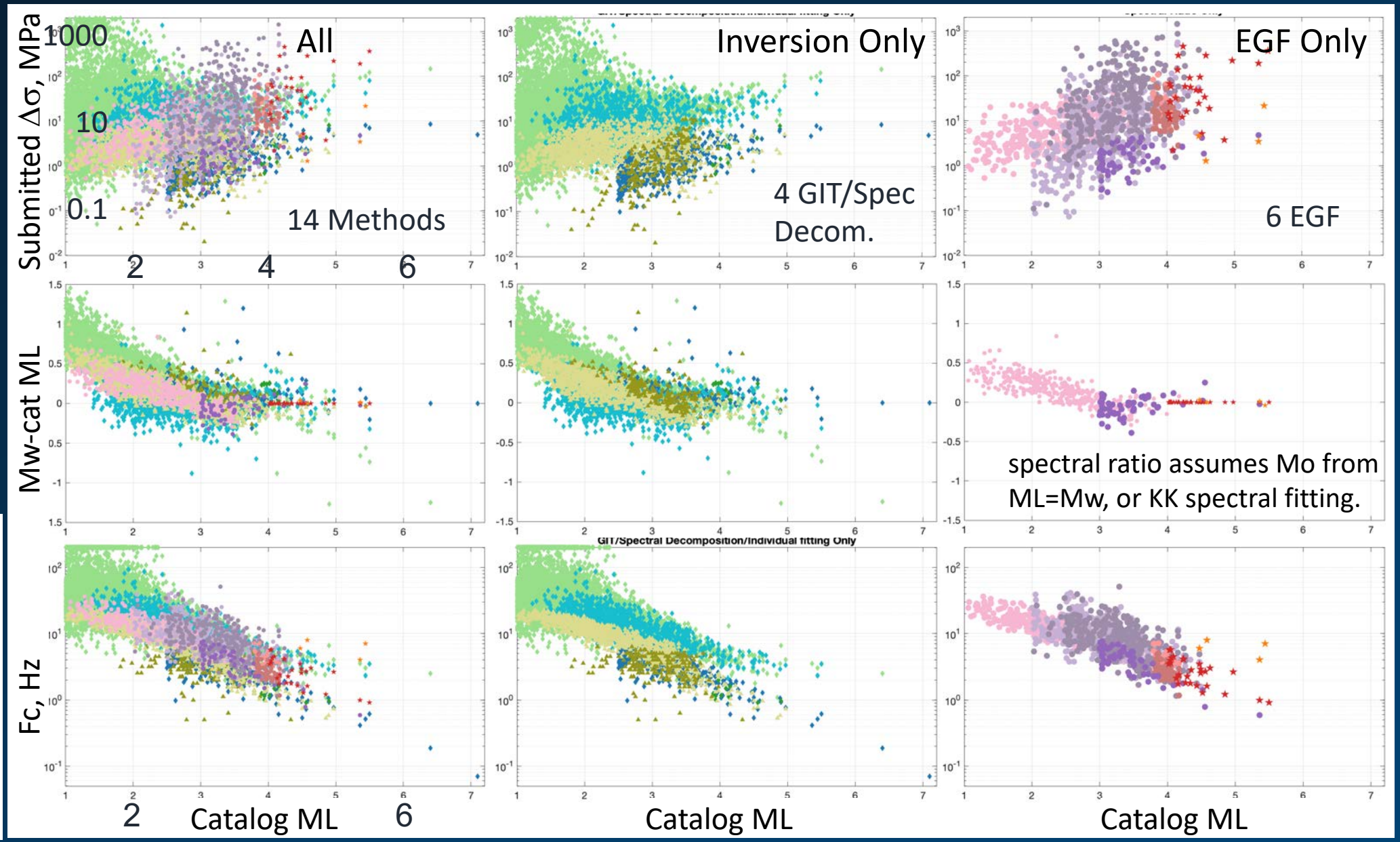


SCEC Workshop 1: 4 Nov. 2021 Preliminary Results

11 independent groups submitted preliminary results.

Some outliers - (preliminary, not full QC)

Variation in fc, Mw, $\Delta\sigma$ and dependence on ML



- GIT/SD: Vandevert et al.
- GIT/SD: Bindi et al
- GIT/SD: Chen
- GIT/SD: Devin et al.
- Filtered Amp: Ellsworth
- Spec fitting: Kemna et al.
- EGF Spec Ratio: Kemna et al.
- EGF Spec Ratio P: Liu et al.
- EGF Spec Ratio S: Liu et al.
- EGF Spec Ratio P: Ruhl et al.
- EGF Spec Ratio S: Ruhl et al.
- EGF Spec Ratio: Boyd
- EGF Finite fault: Meng et al.
- EGF Finite fault: Dreger et al.

What about Error Bars?

Most error bars do not overlap.
Only Uncertainties incorporating fc-Q tradeoff are large enough to include inter-study variation
Supino, et al, 2019 GJI
2019,, https://doi.org/10.1093/gji/ggz206