# Earthquake Stress Drops in Southern California

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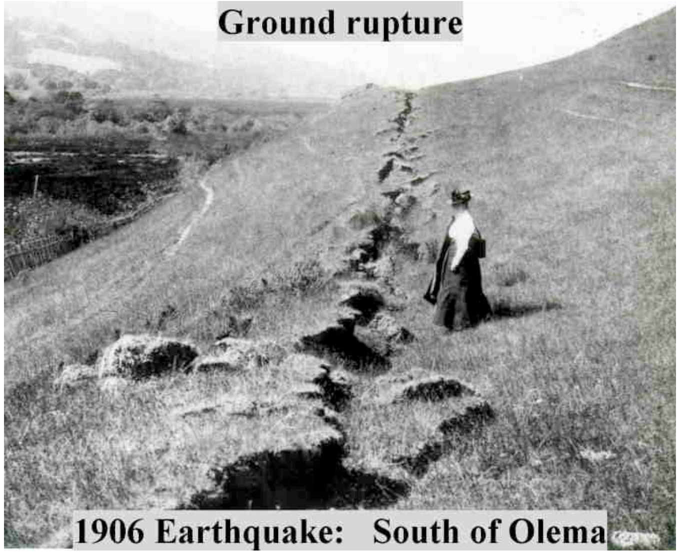
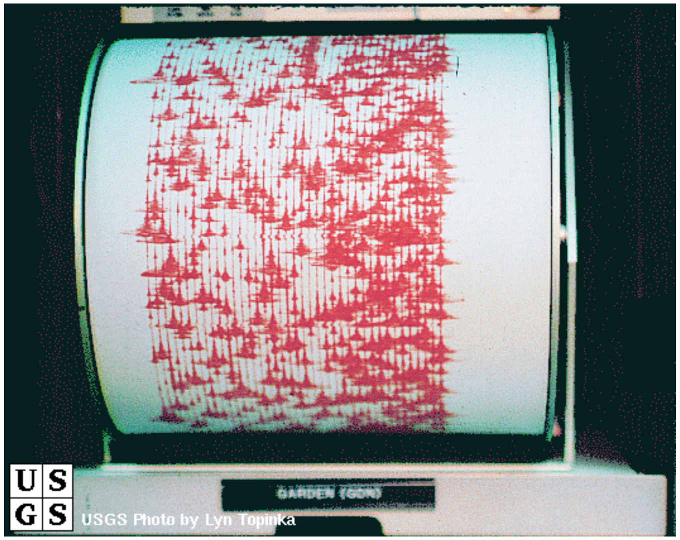
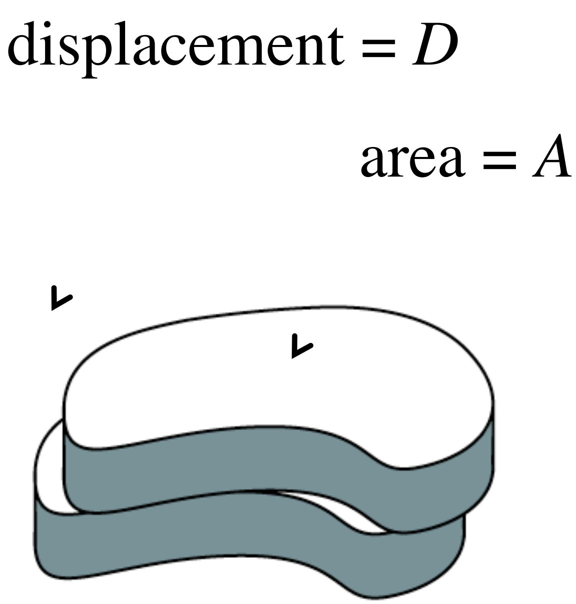



Lots of data for big earthquakes (rupture dimensions, slip history, etc.)




Small earthquakes are only observed from seismograms; no direct measurements of physical properties

# Two parameters




fault area

average displacement

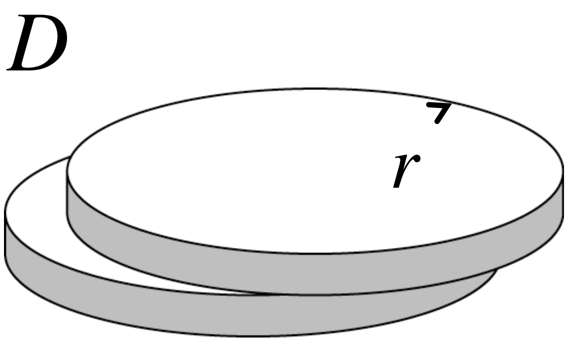
Moment $M_0 = \mu A D$

shear modulus

Stress drop $\Delta\sigma = \sigma_{\text{final}} - \sigma_{\text{initial}}$

average shear stress on fault

# Circular crack model




average displacement

$$\Delta\sigma = \frac{7\,\pi\,\mu\,D}{16\,r} = \frac{7\,M_0}{16\,r^3}$$

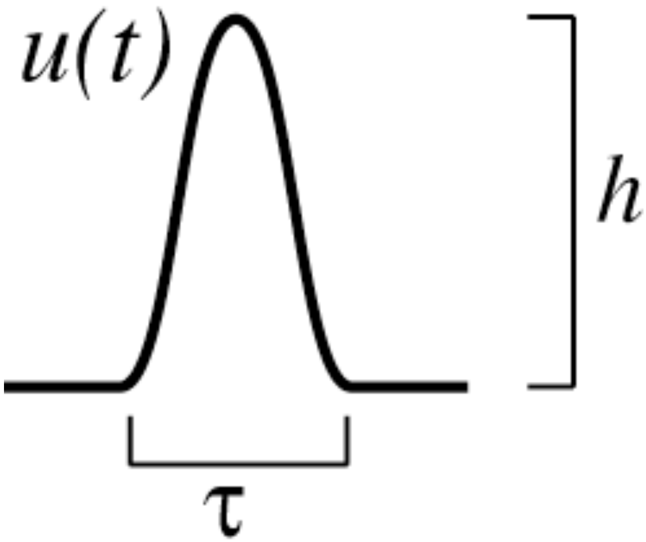
fault radius

$$M_0 = \mu A D = \mu \pi r^2 D$$

Stress drop is proportional to displacement/radius ratio

(*Eshelby*, 1957; *Brune*, 1970)

# Seismology 101



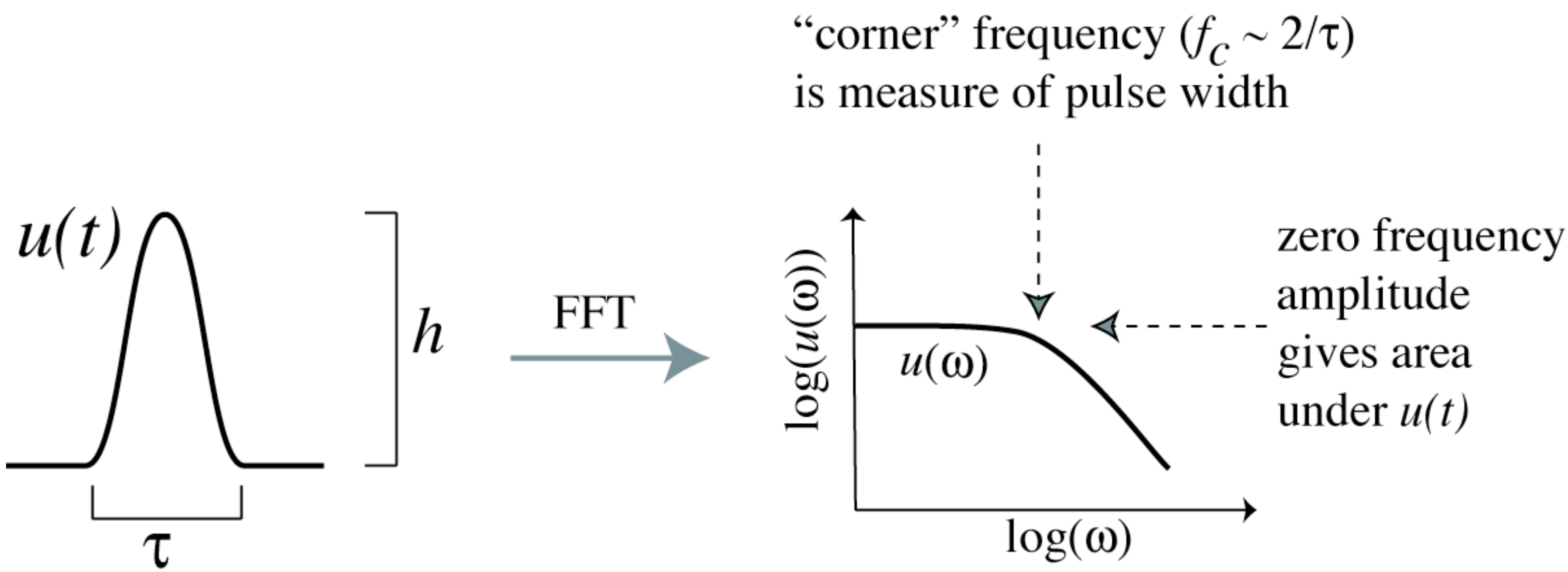

In theory, far-field seismometer will record displacement pulse from small earthquake (can be either $P$ or $S$ wave), ignoring attenuation and other path effects

Area under displacement pulse $f(h\tau)$ is related to seismic moment $M_0$ (one measure of event strength)

Pulse width $\tau$ is related to physical dimension of fault and rupture velocity

# Spectral Analysis 101

Time Series | Spectrum



# How to get Brune-type stress drop

$\log[u(f)]$

$\log(f)$

Original spectrum

Correct for attenuation

$f_c$

$\Omega_0$

$\log[u(f)]$

theoretical curve

$\log(f)$

Estimate $\Omega_0$ and $f_c$

Correct for geometrical spreading

$M_0$

$$\Delta\sigma = \frac{7\,M_0}{16\,r^3}$$

Assume circular crack model

cubed!

$r$

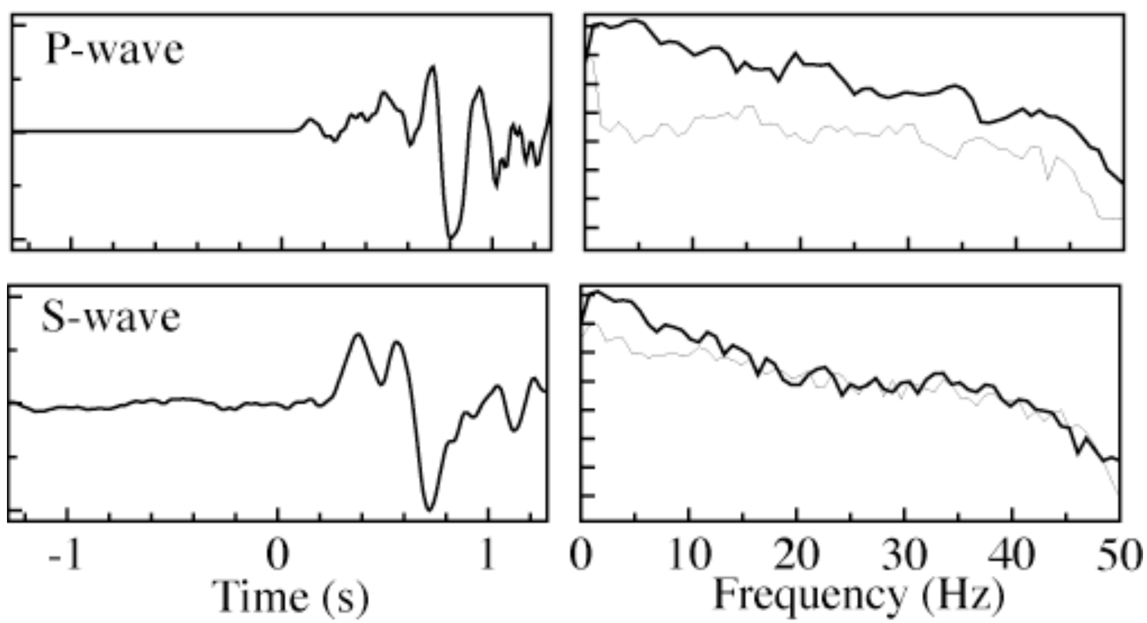
Assume rupture velocity and source model (*Brune*, *Madariaga*, *Sato* & *Hirasawa*, etc.)

# Previous $\Delta\sigma$ results and issues

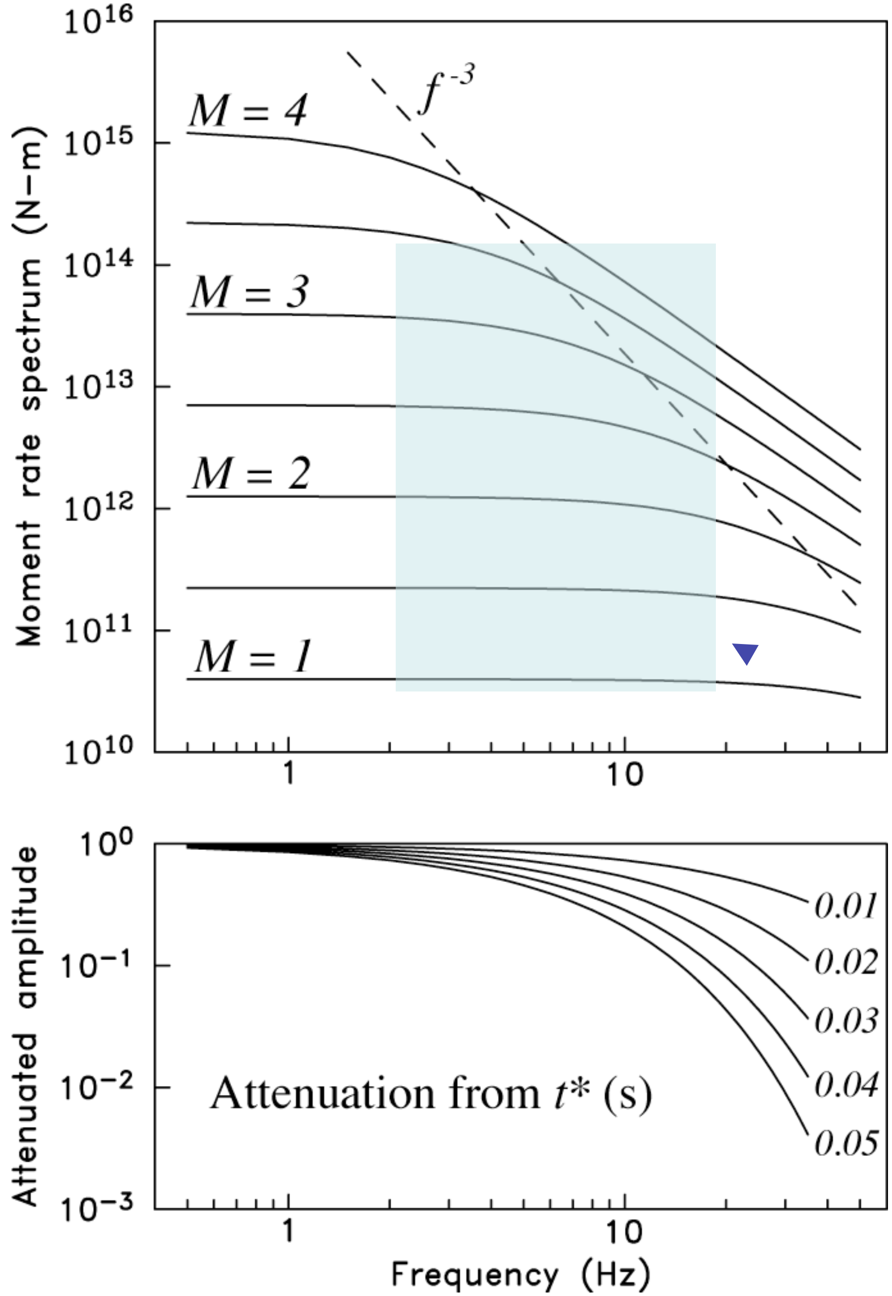
- $\Delta\sigma = 0.2$ to 20 MPa from corner frequency studies
- Much less than absolute shear stress levels predicted by Byerlee's law and rock friction experiments
- Little dependence of average $\Delta\sigma$ on $M_0$, implying self-similar scaling of earthquakes, but possibility of small increase with $M_0$ has been debated
- Some evidence that plate-boundary earthquakes have lower $\Delta\sigma$ than mid-plate earthquakes
- Hard to compare $\Delta\sigma$ results among studies because they often use different modeling assumptions and are based on small numbers of earthquakes

# UCSD/Caltech spectral analysis

- Online database of seismograms, 1984–2003
- > 300,000 earthquakes
- *P* and *S* multi-taper spectra computed for all records
- 60 GB in special binary format




Egill Hauksson

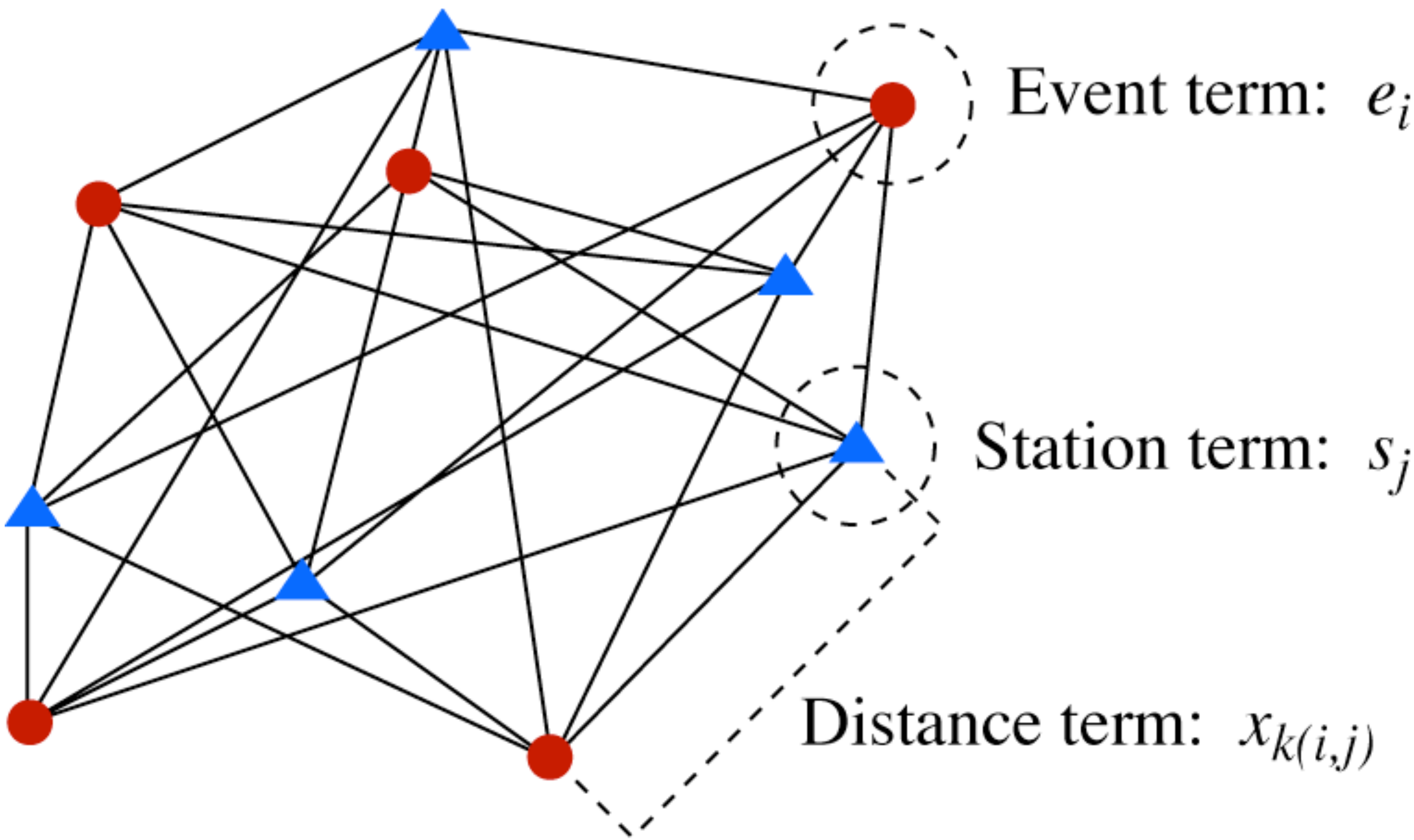



# Source and *Q* effects on spectra

- $\omega^{-2}$ model
- $\Delta\sigma = 3$ MPa

Good signal-to-noise for SCSN SP data

# Isolating Spectral Contributions




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

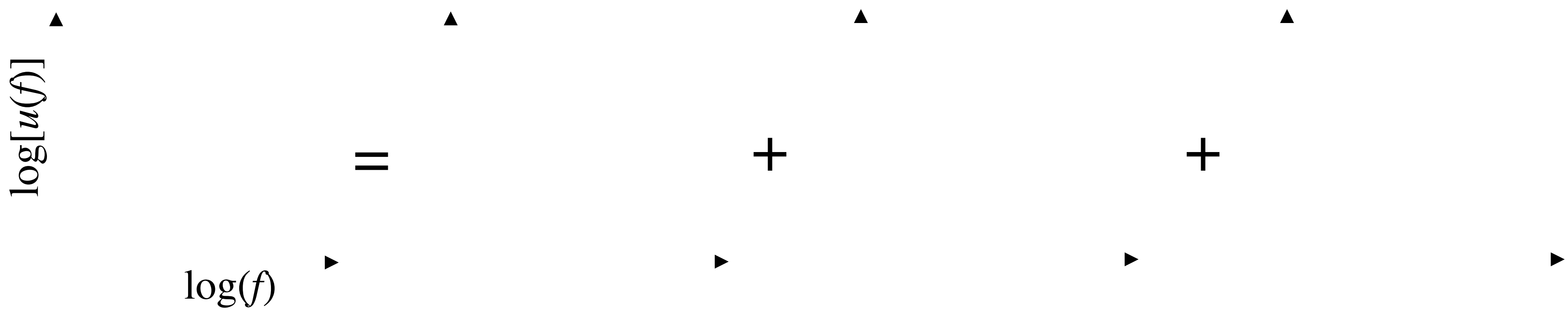
$$d_{ij} \approx e_i + s_j + x_{k(i,j)}$$

Observed spectrum

Source spectrum

Receiver response

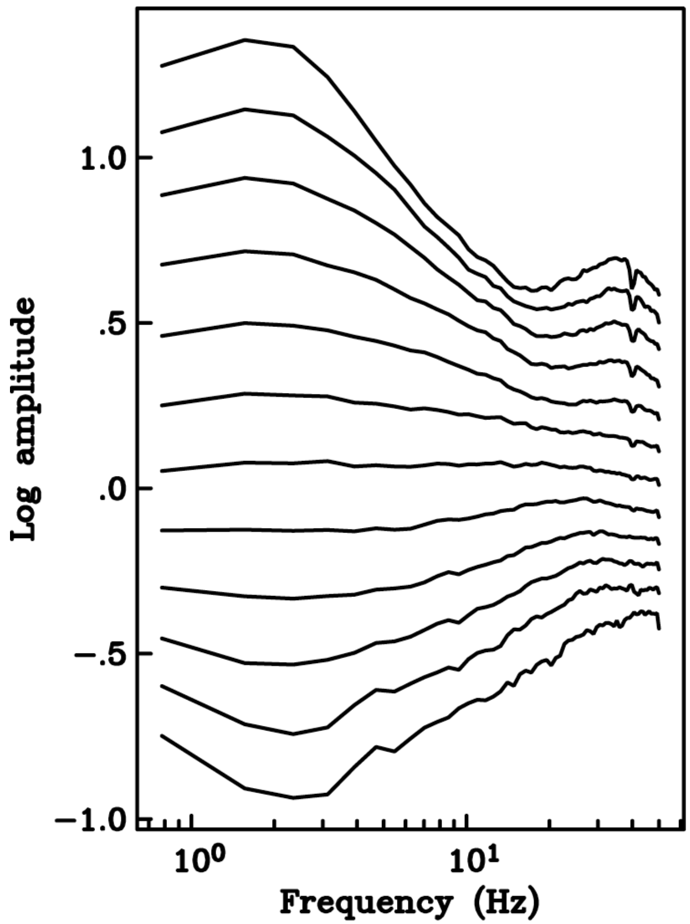
Distance term to account for $Q$




- > 60,000 earthquakes, >350 stations
- 1.38 million *P*-wave spectra (STN > 5, 5-20 Hz)
- Iterative least squares approach with outlier suppression

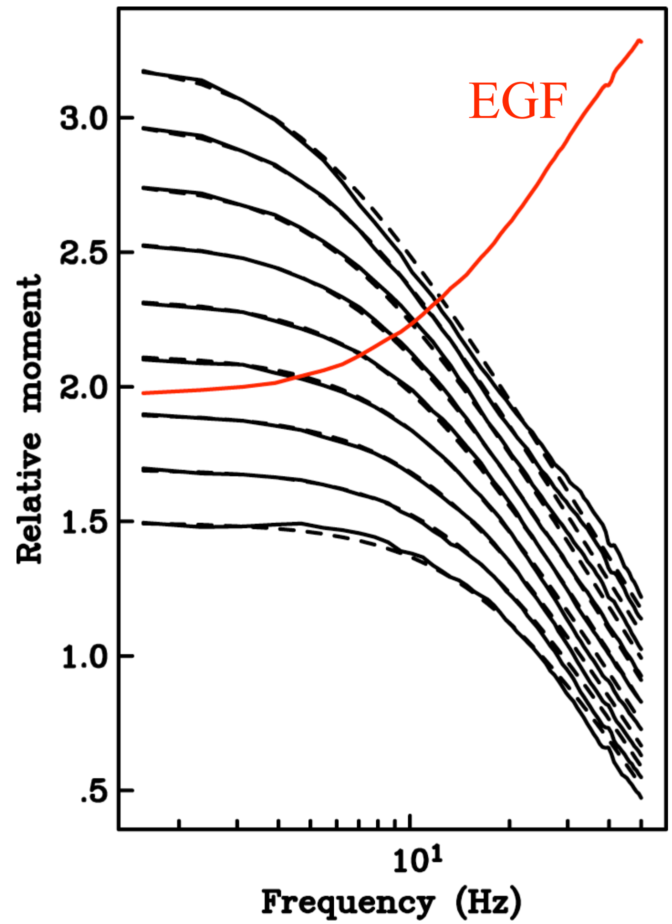
# Source spectra binned by relative moment

Raw source terms




Solve for constant $\Delta\sigma$ model and empirical Green's function (EGF)

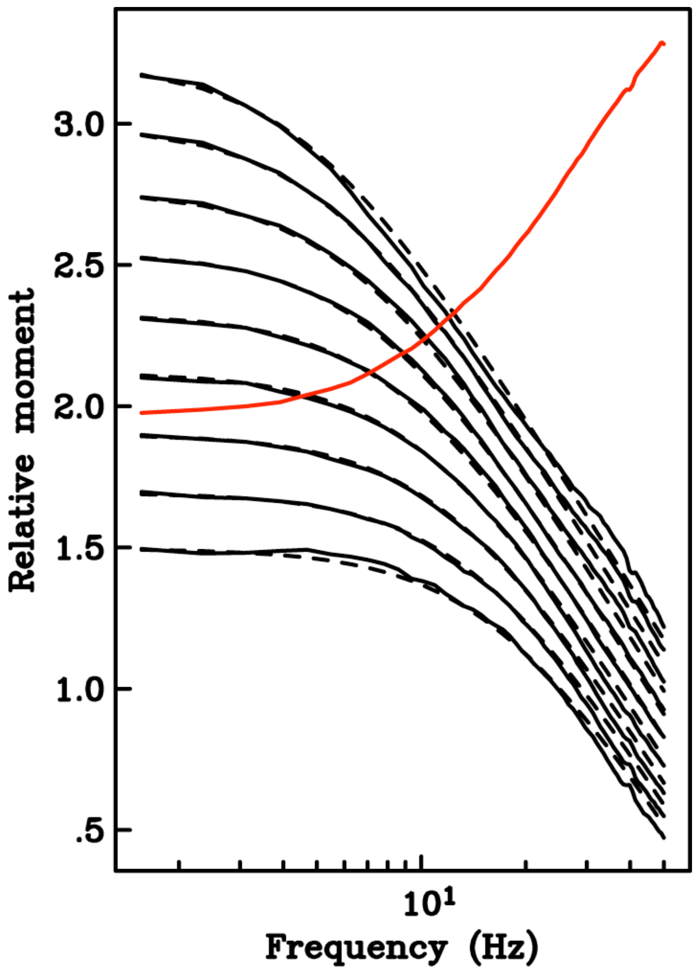
EGF corrected




Best fit obtained for $\Delta\sigma$ = 1.6 MPa, $\omega^{-2}$ model (e.g., *Abercrombie*, 1995)

# Assumed source model

- *Madariaga* (1976), *Abercrombie* (1995)




We fit data (solid lines) between 2 and 20 Hz, using:

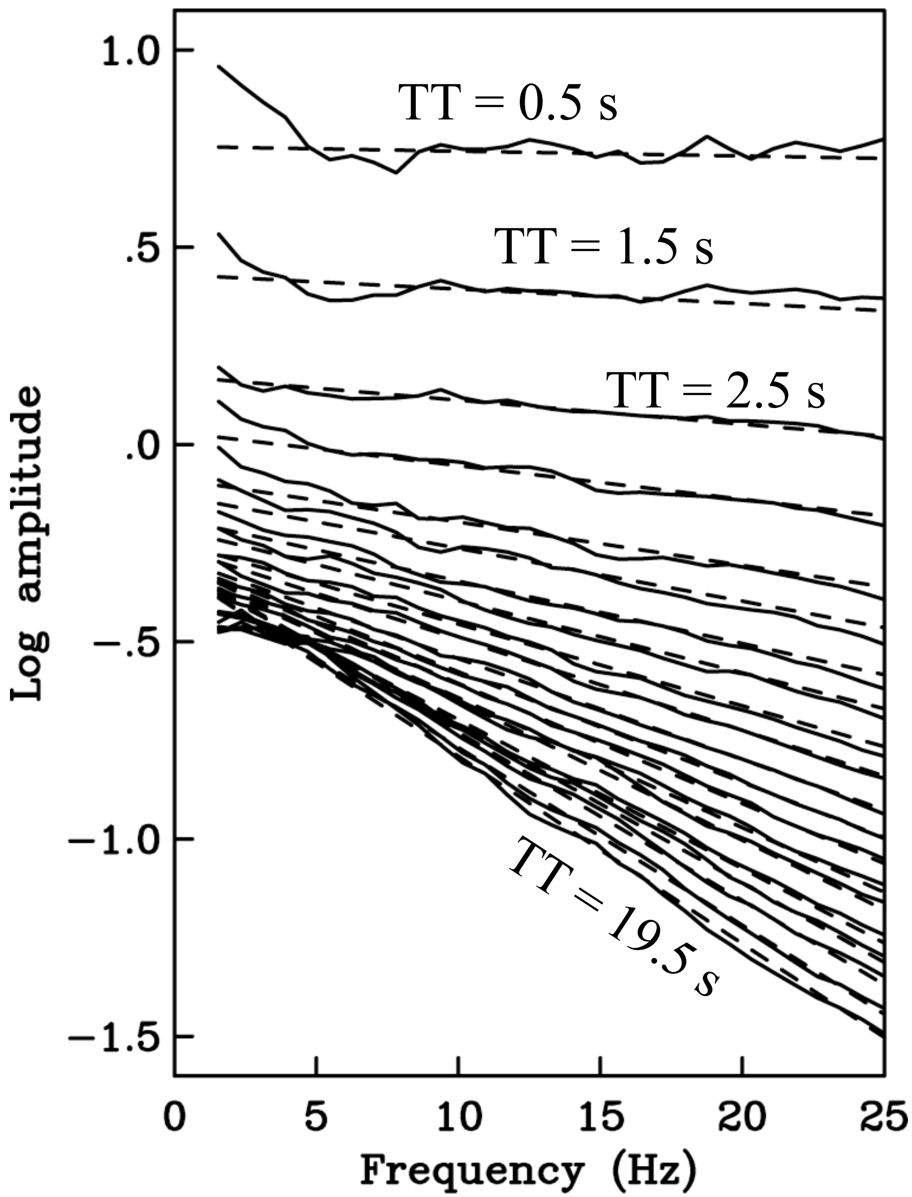
$$u(f) = \frac{\Omega_0}{1 + (f/f_c)^n}$$

$$f_c = \frac{0.42\ \beta}{(M_0/\Delta\sigma)^{1/3}}$$

(assumes rupture velocity = 0.9 β)

Model prediction (dashed lines) is for $\Delta\sigma$ = 1.60 MPA (constant)

# Travel time spectral terms (distance dependence)

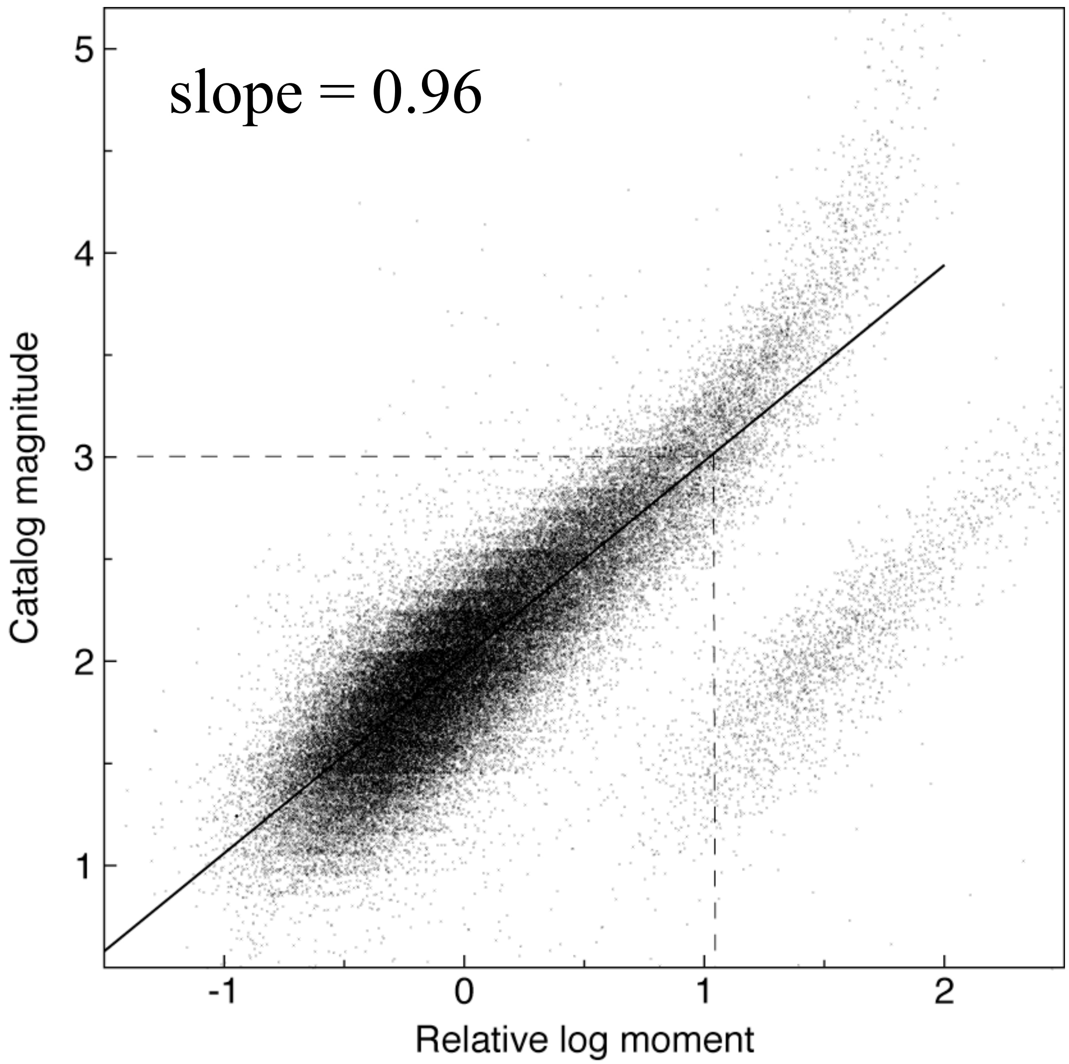



Dashed lines show fit to slopes ($t^*$) for $Q = 560$ model

Consistent with *Schlotterback & Abers* (2000) $Q$ model

Good check on method

# Calibration to absolute moment



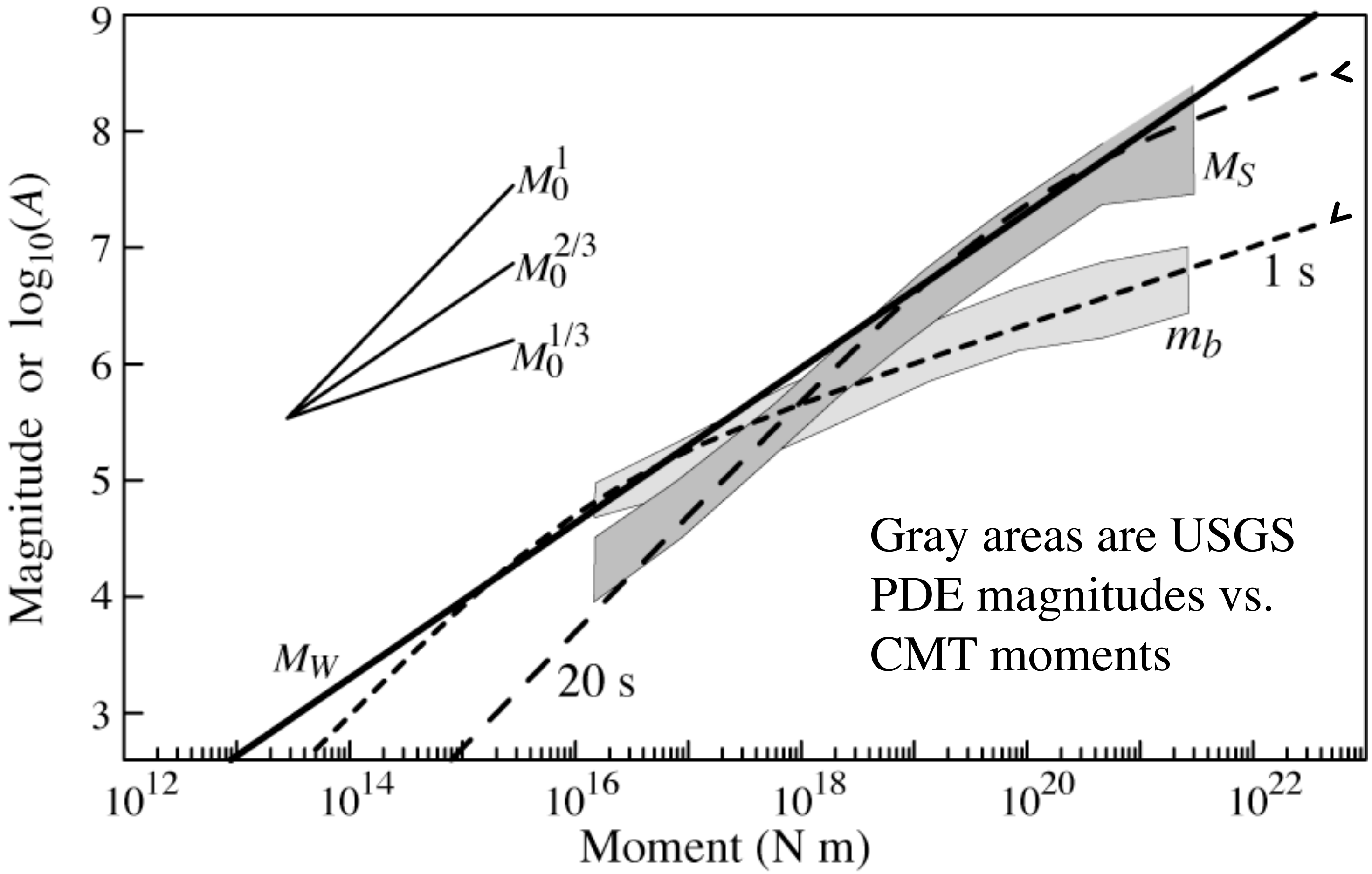

$M_W = 2/3 \log_{10} M_0 - 10.7$

(*Kanamori*, 1977)

Slope $\neq$ 2/3 so $M_L \neq M_W$ over magnitude range.

Method: Assume $M_L = M_W$ at $M = 3$. This gives $M_W$ for other size events. Implies $M_L = 2$ is actually $M_W = 2.3$

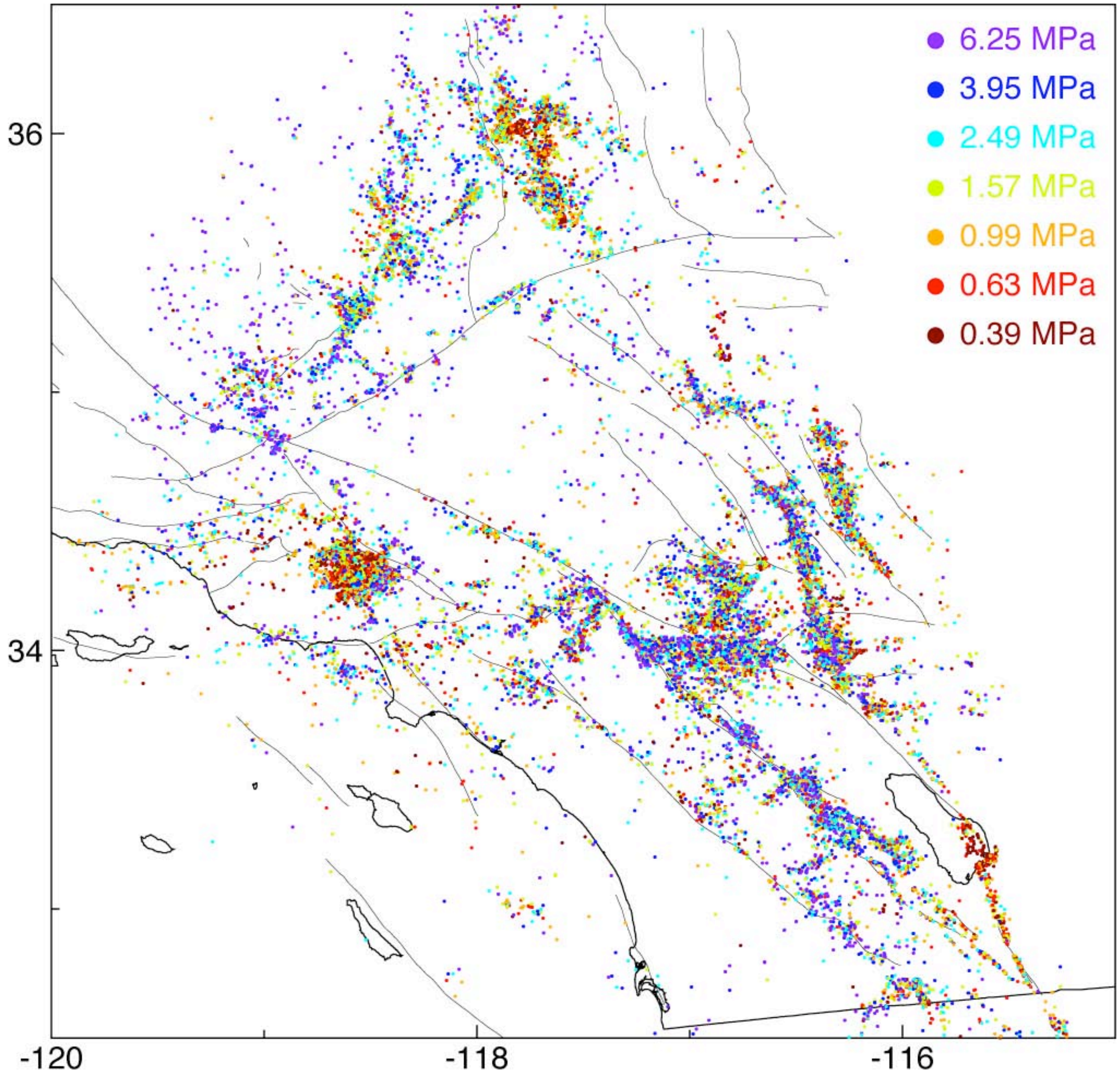
# Magnitude vs. Moment




$\omega^{-2}$ model predictions

M < 3 earthquakes will have unit $M/M_0$ slope, not 2/3

# Calculated Earthquake Stress Drops

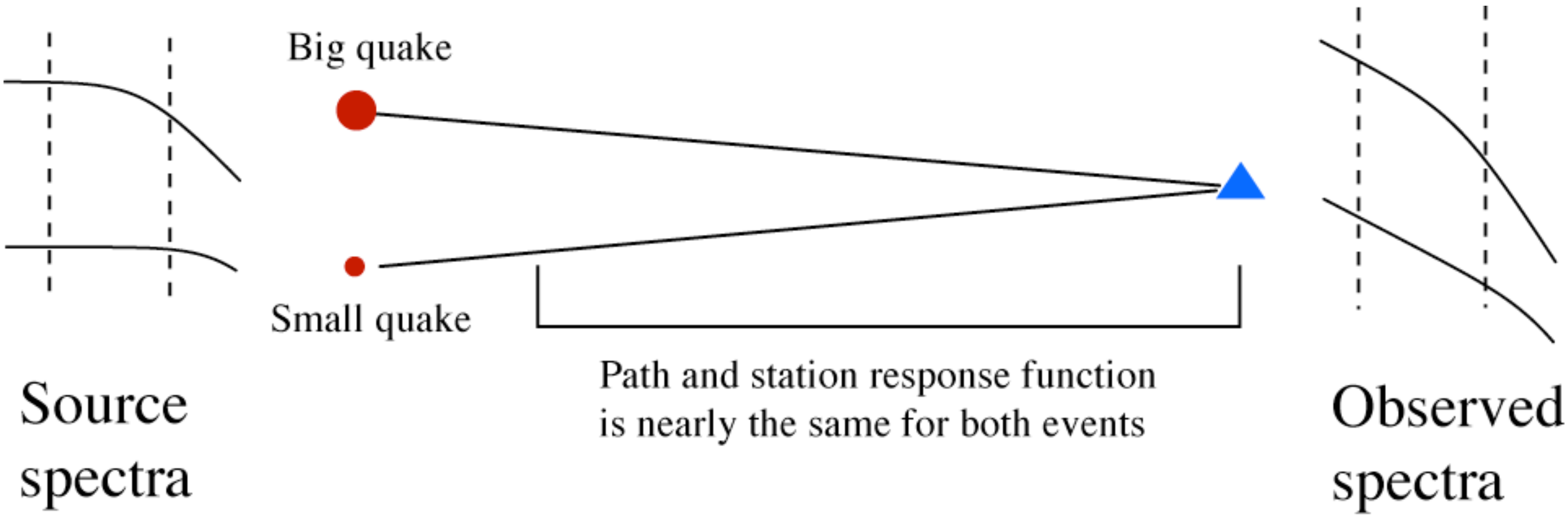



- 65,070 events
- > 300,000 spectra
- 1989–2001
- > 4 spectra/event
- 5 - 20 Hz band

Red = fewer high frequencies, lower stress drop or high near-source attenuation

Blue = more high frequencies, higher stress drop or low near-source attenuation

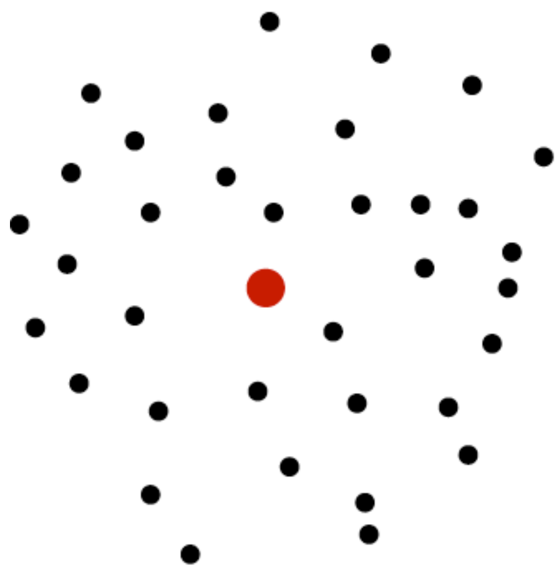
# Empirical Green's Function (EGF)



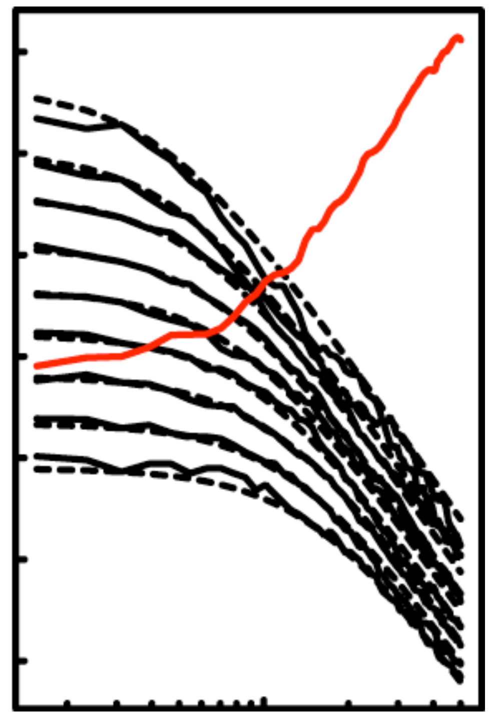

Subtract small event from big event to get estimate of true source spectrum for big event

# Source-specific EGF method

For each event, find 500 neighboring events:

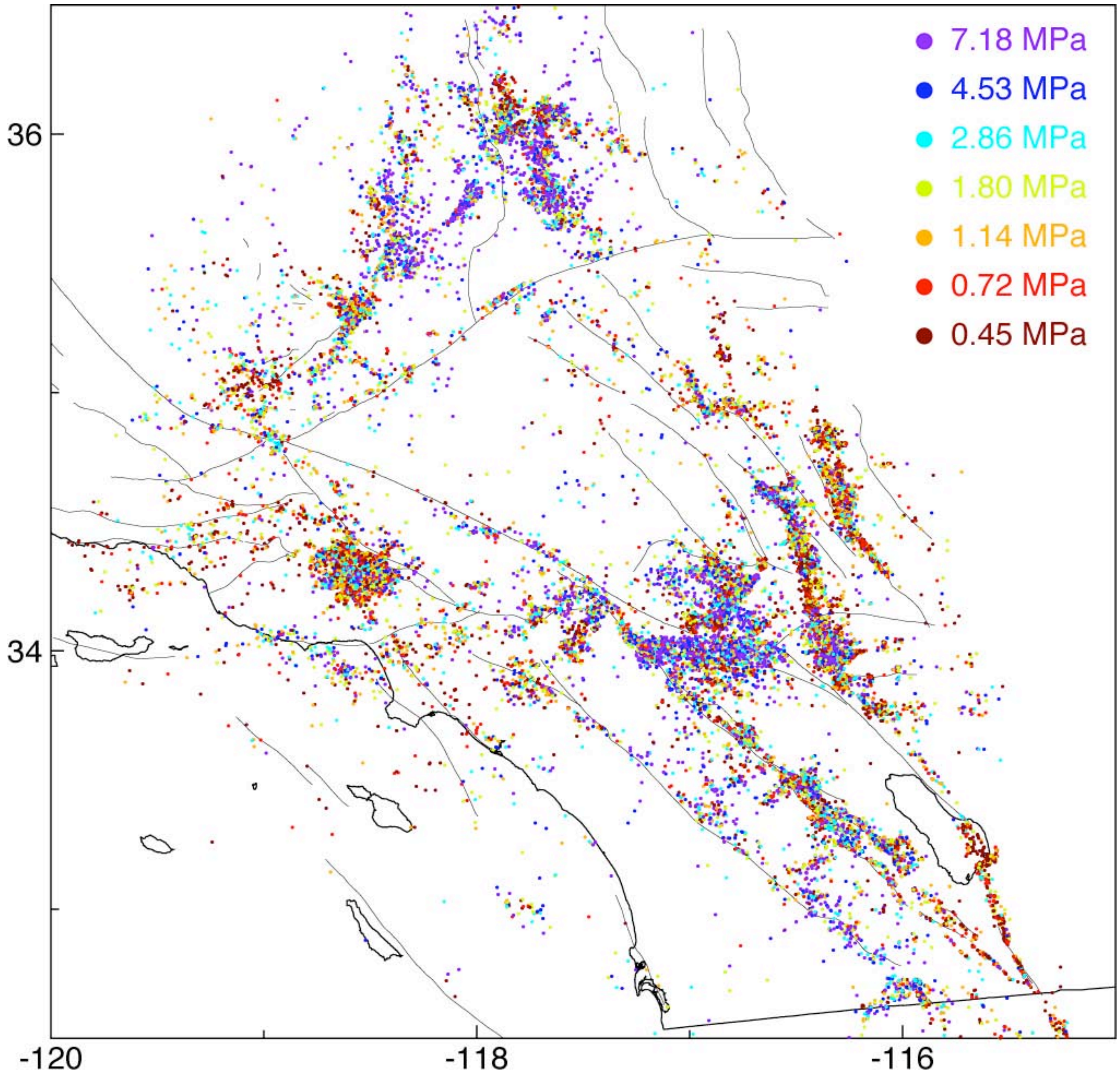


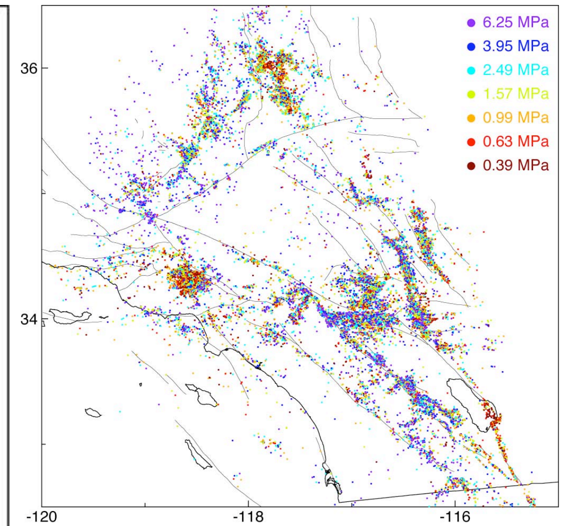
Fit moment binned spectra to Δσ and EGF



Then subtract EGF from target event spectrum and compute Δσ for this event

# Observed source Δσ using spatially varying EGF method

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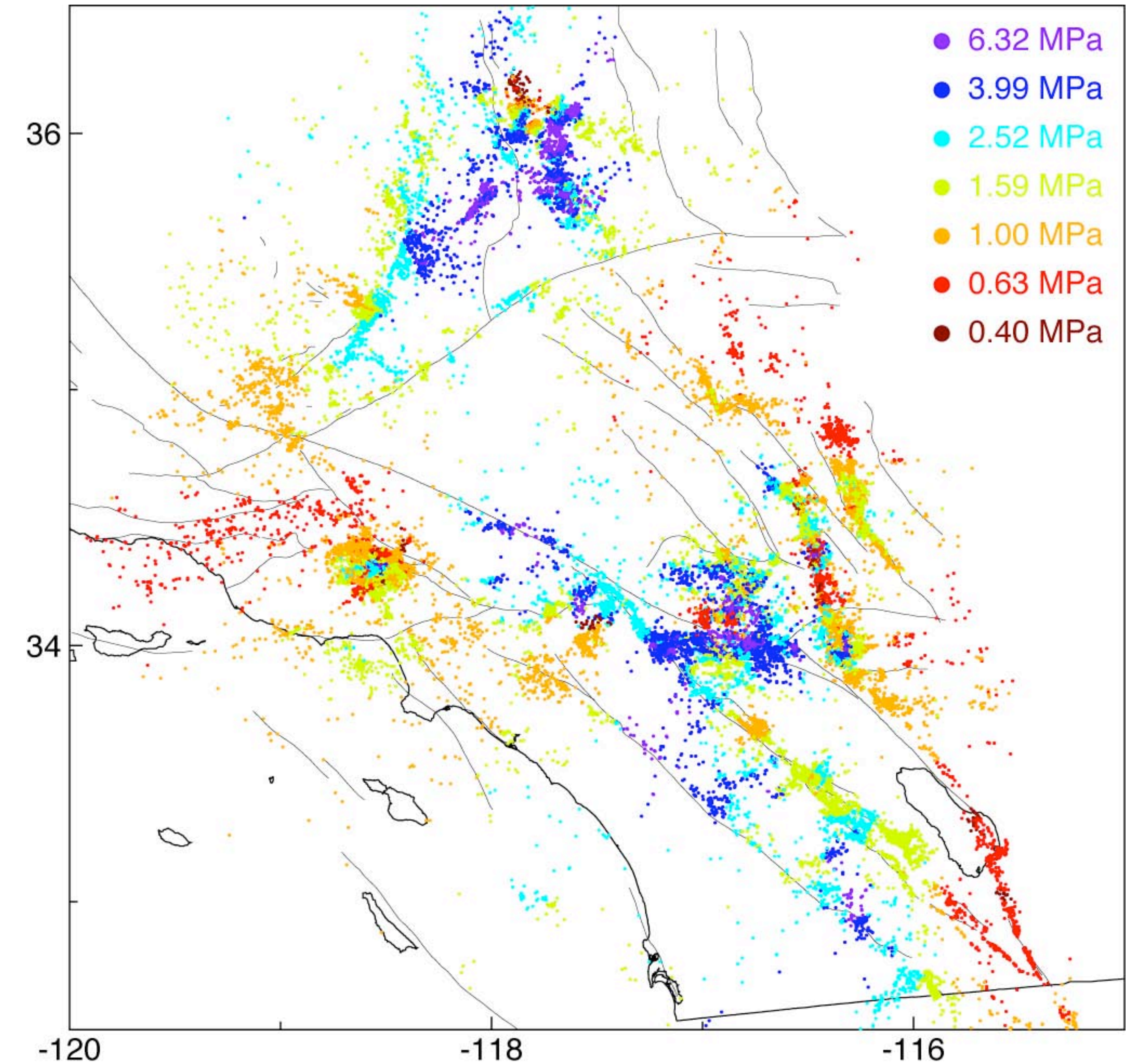
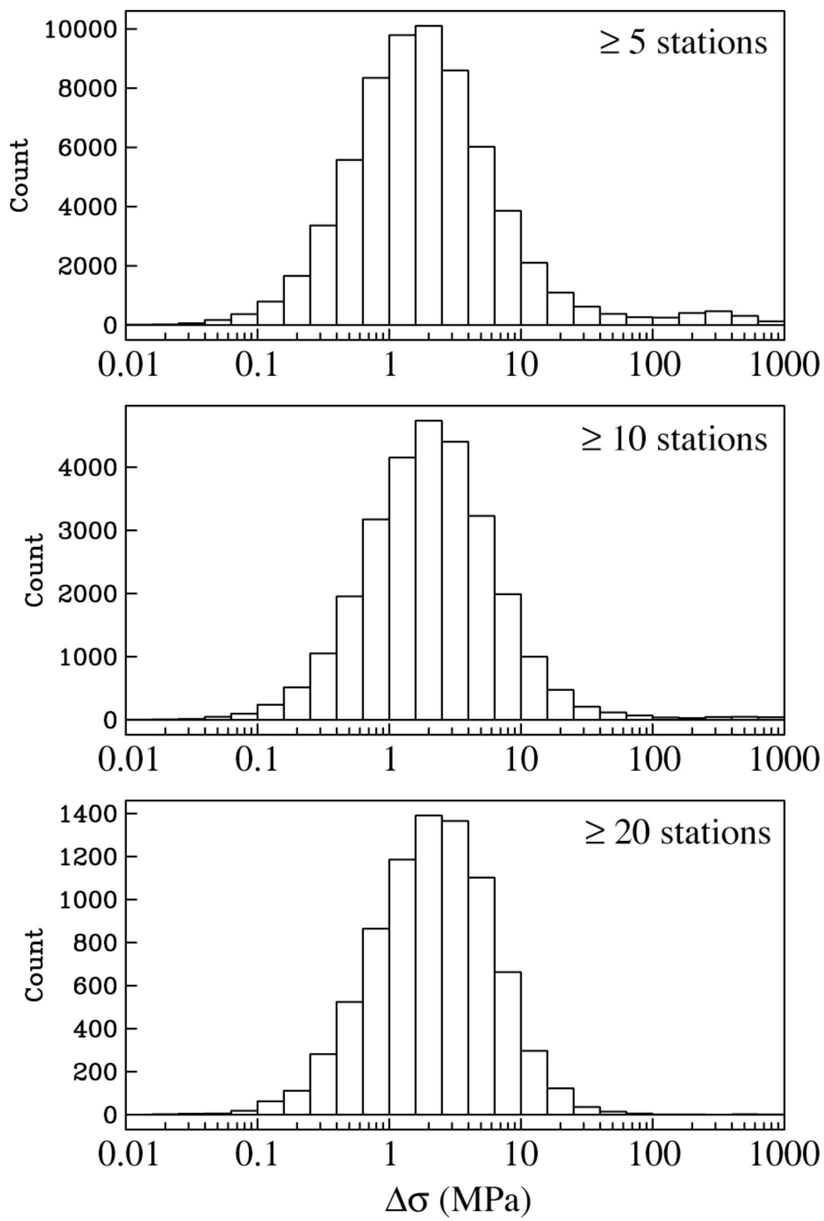
Previous result using constant EGF method

< New results

# Best fitting constant Δσ model over 500 events

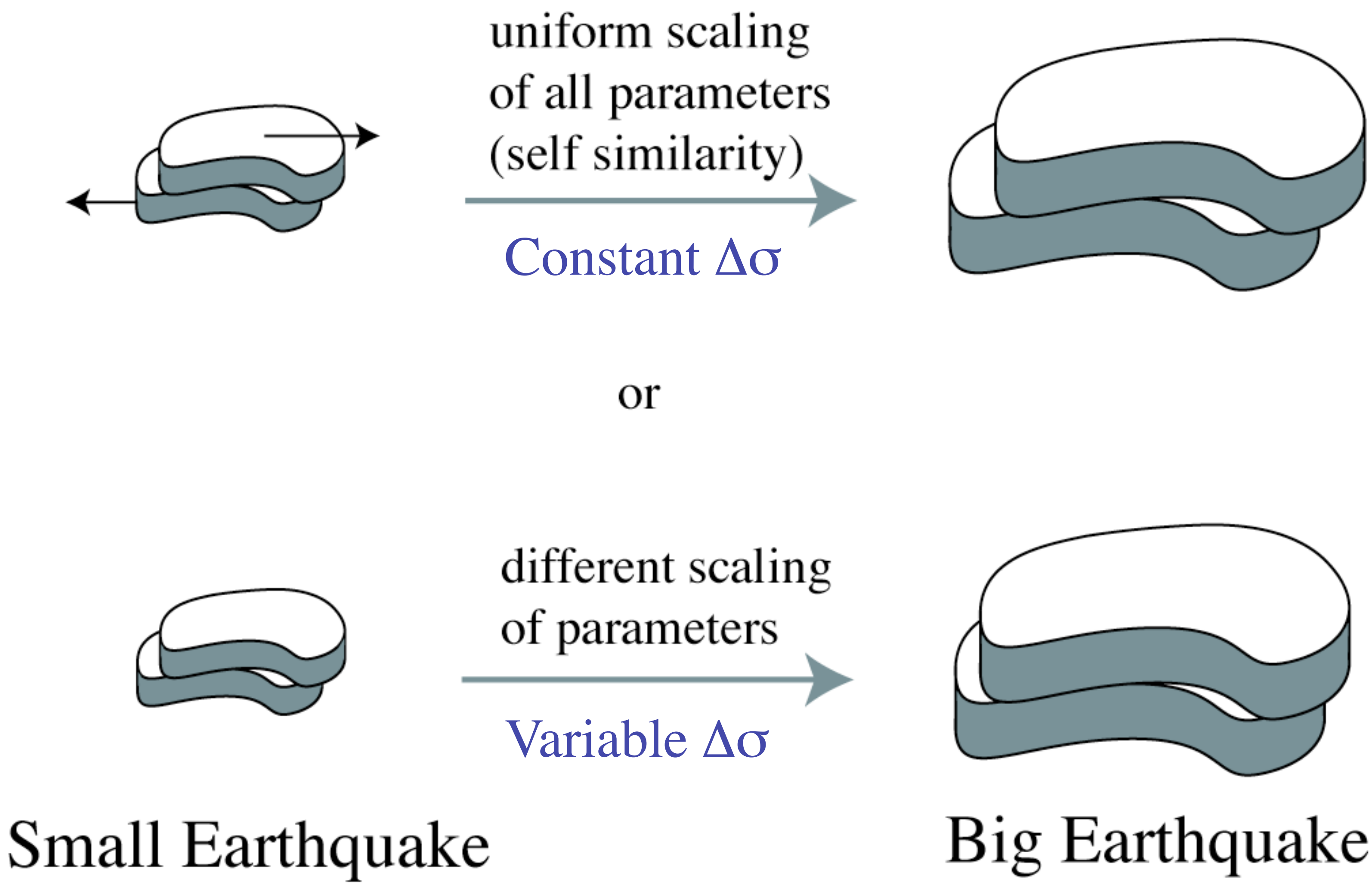


# How variable are earthquake stress drops?

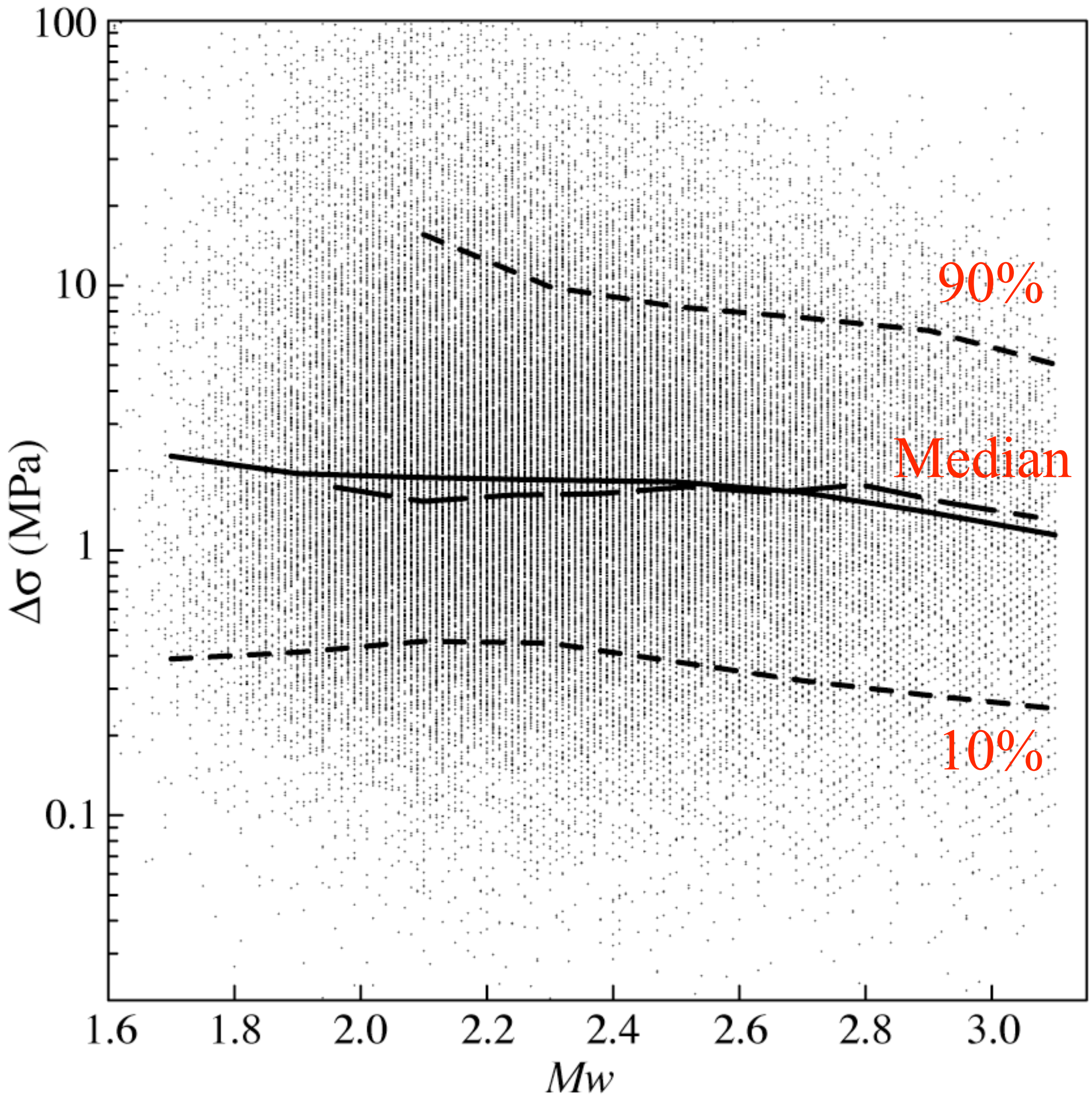



- Harder to resolve high $\Delta\sigma$ events due to high corner frequencies
- Results are more reliable when more stations are stacked
- $\Delta\sigma = 0.2$ to $20$ MPa

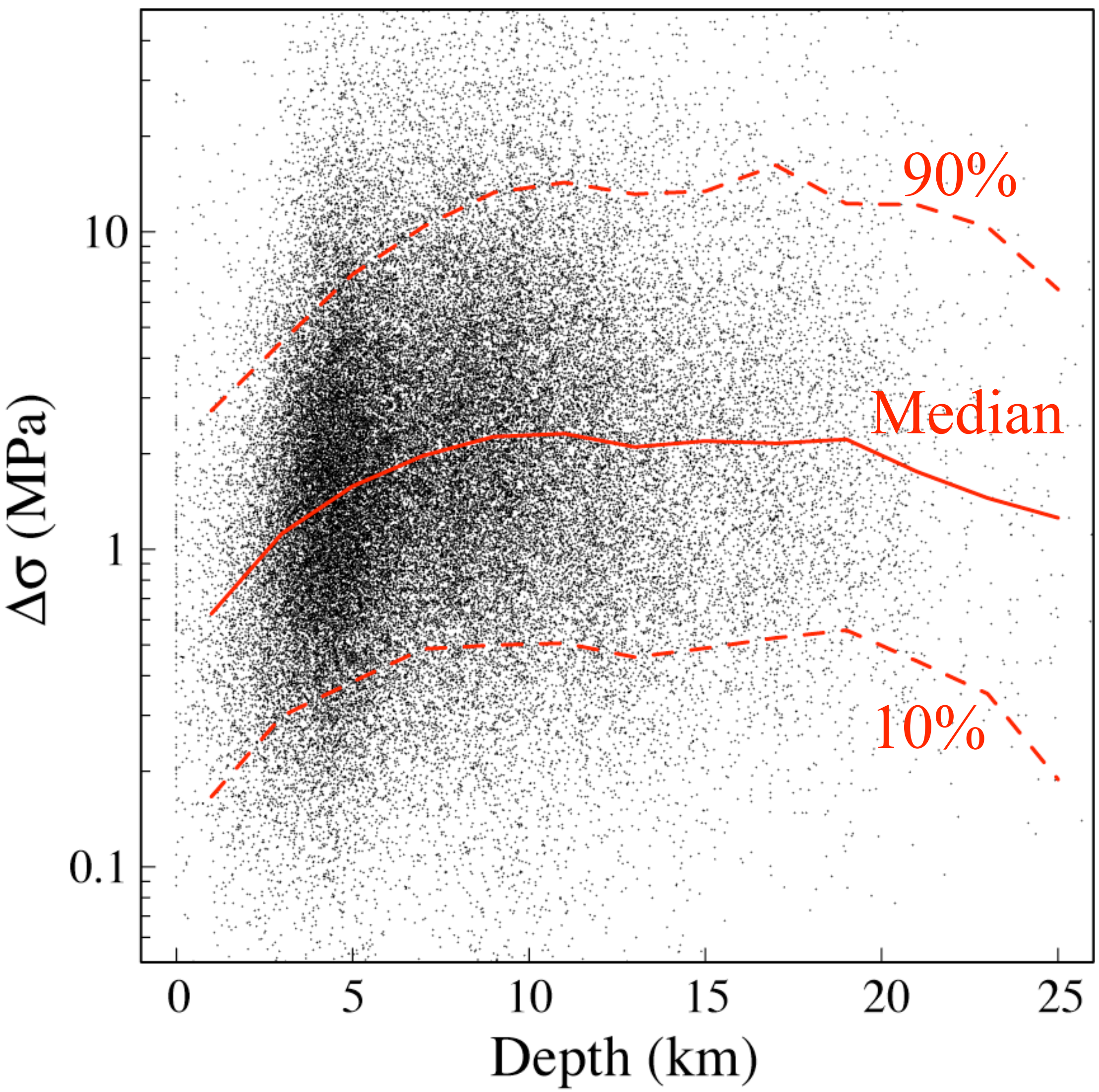
# Earthquake scaling



# Median stress drop does not vary with $M_W$



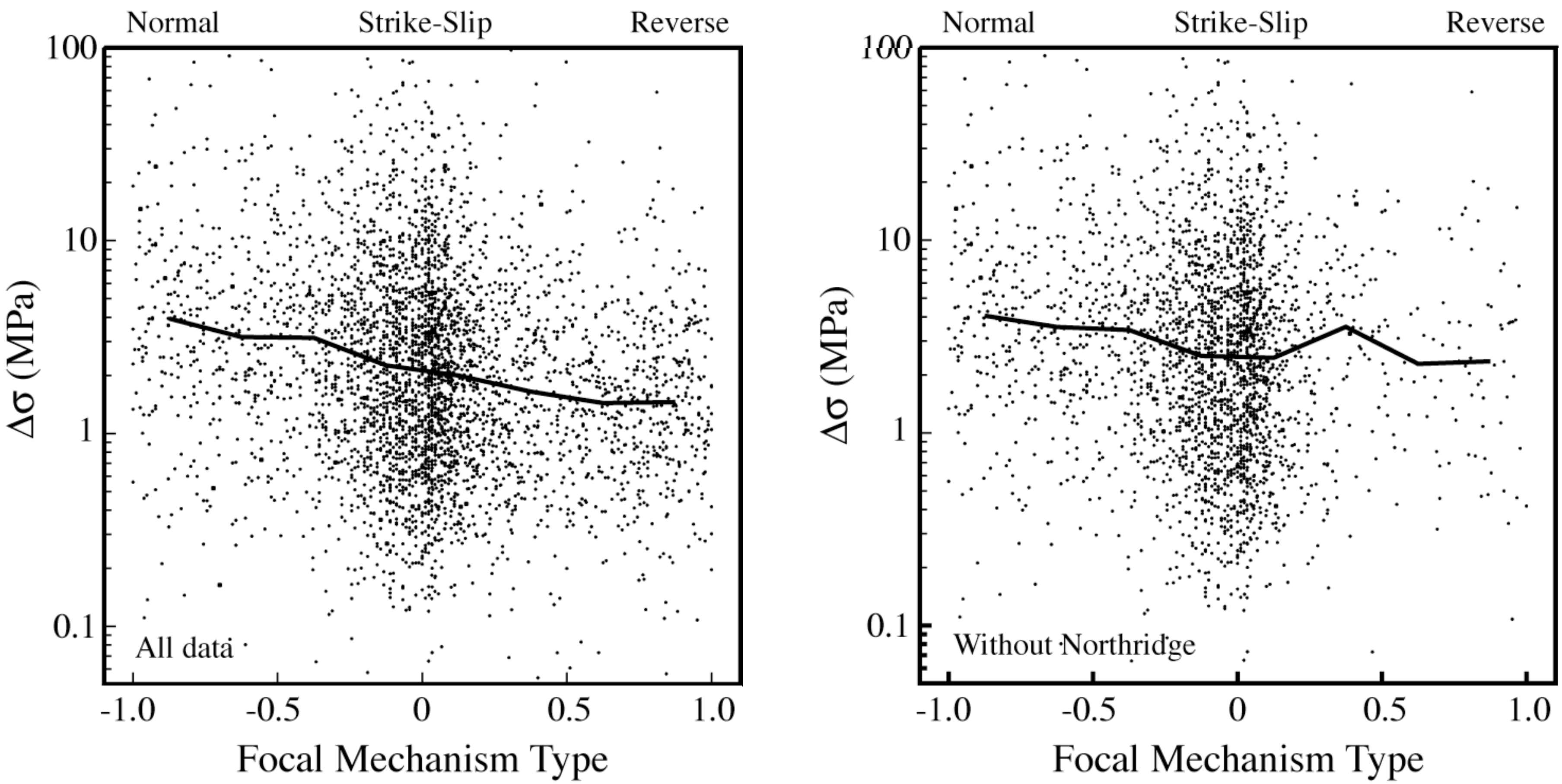
# Stress drop versus depth



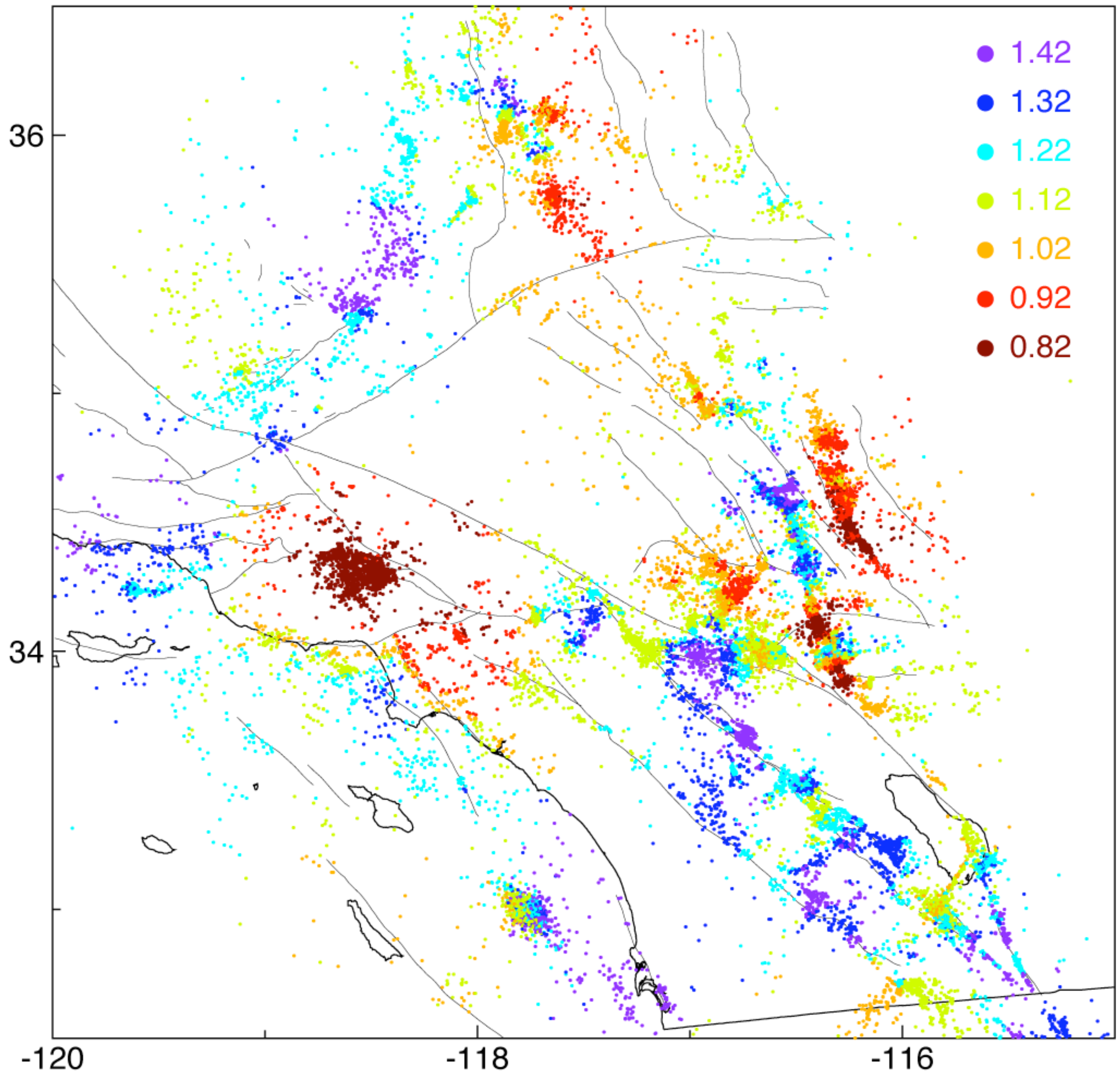

- Average Δσ increases from 0.6 to 2 MPa from 0 to 8 km
- But slower rupture velocities at shallow depths could also explain trend
- Nearly constant from 8 to 18 km
- Large scatter at all depths

# Stress drop versus type of faulting

3895 high-quality focal mechanisms from J. Hardebeck (2005)

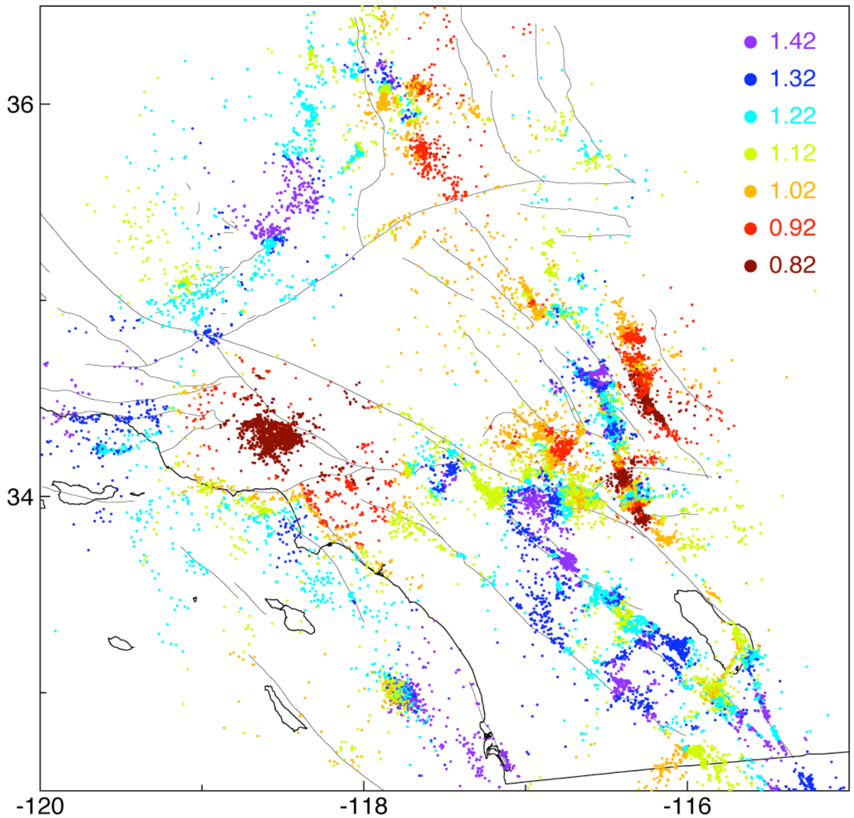


# 1989-2001 *b*-values

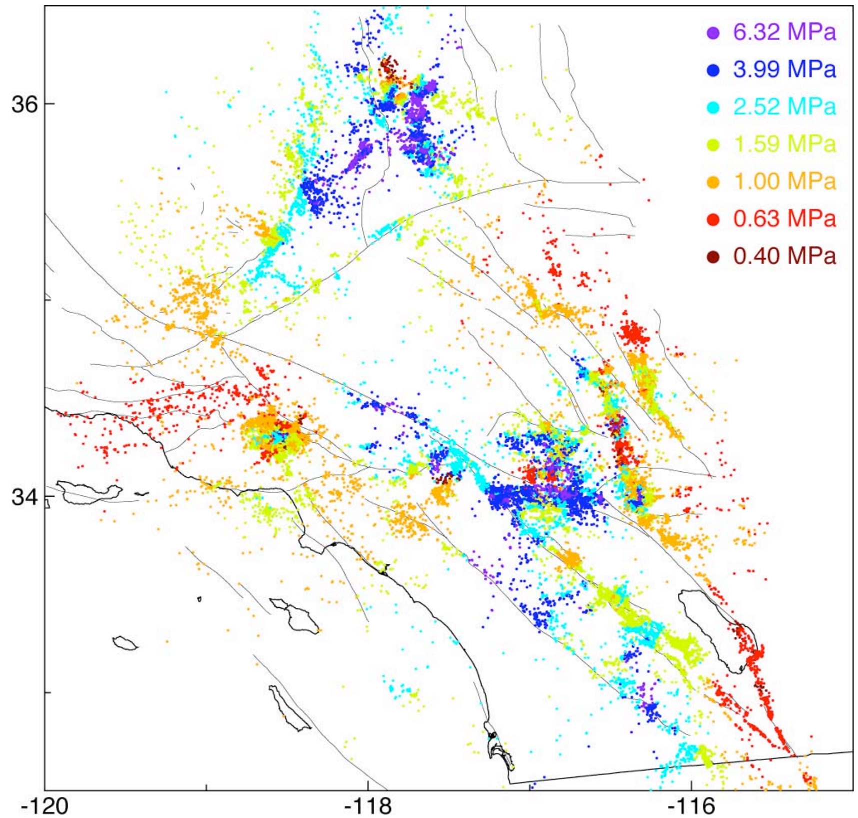



- Computed for each event and 500 nearest neighbors
- $M = 2$ to $4$
- median $b = 1.12$

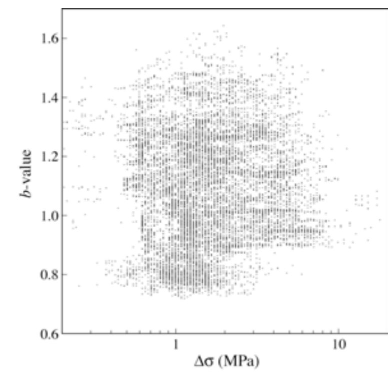
*b*-value



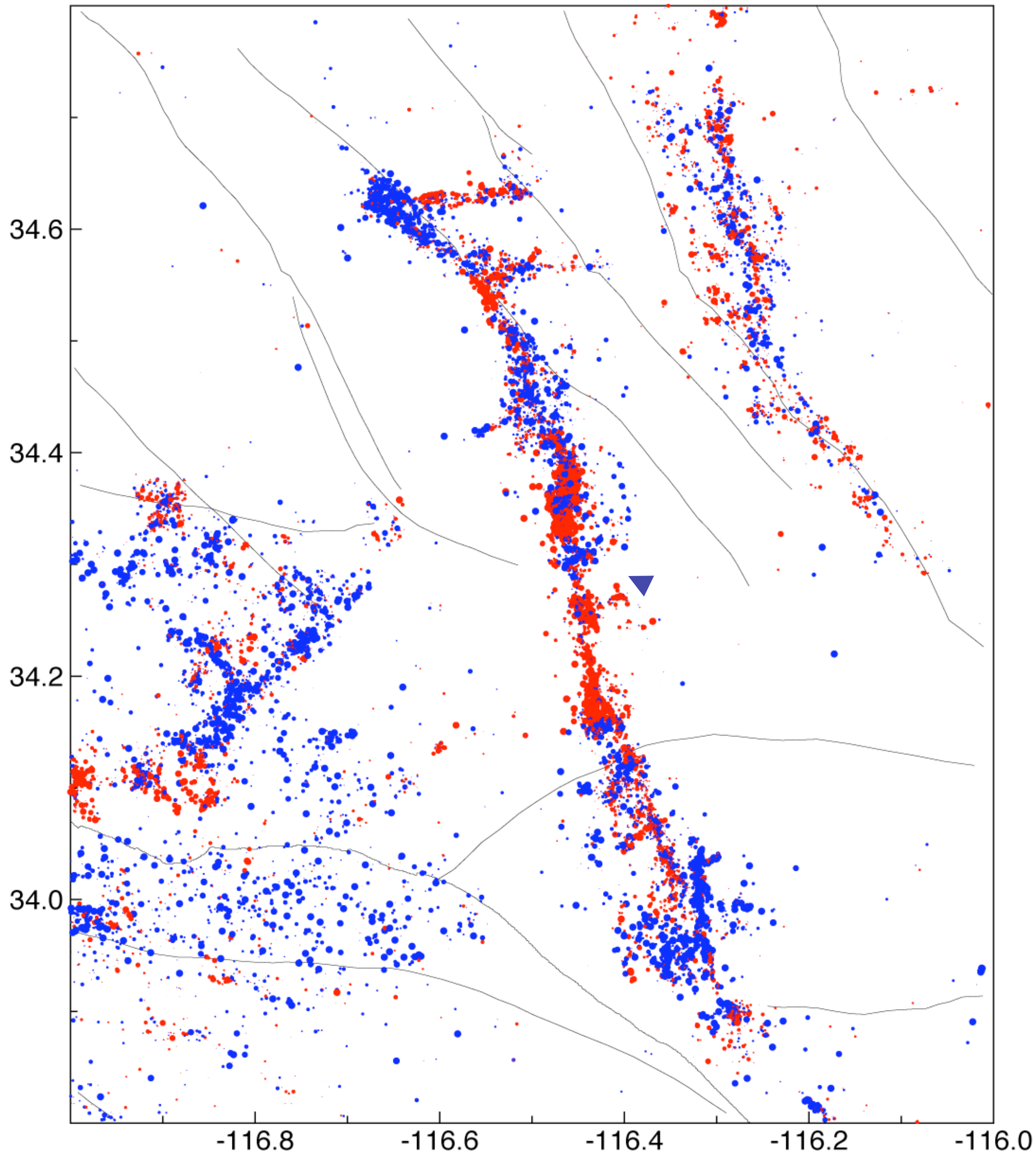

stress drop




not much correlation! ►



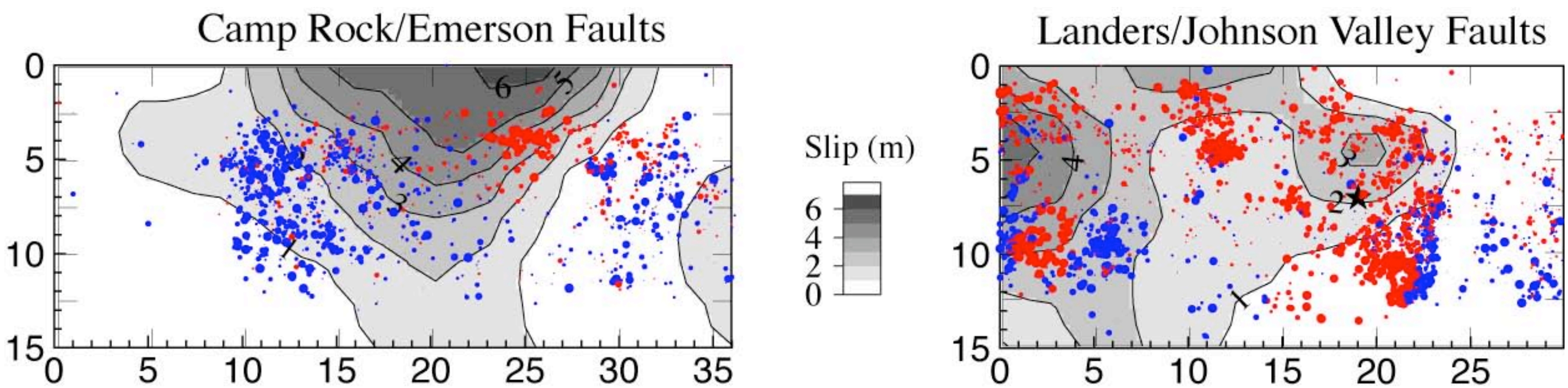
# Landers Aftershocks

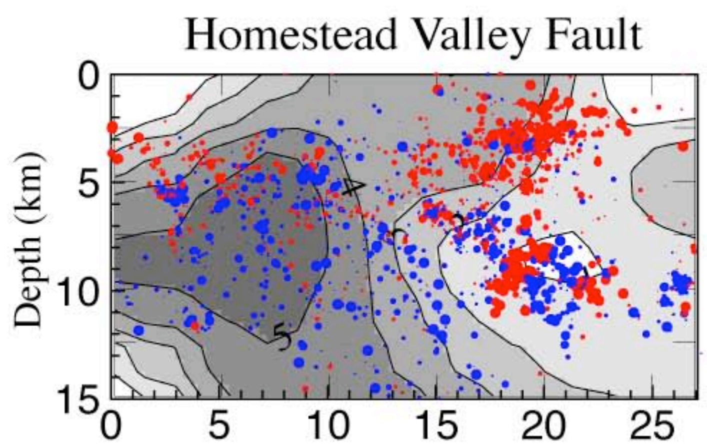



- Along-strike changes in $\Delta\sigma$
- Related to mainshock slip?

Profiles for slip model of *Wald & Heaton* (1994)

# Comparison to Landers Slip Model



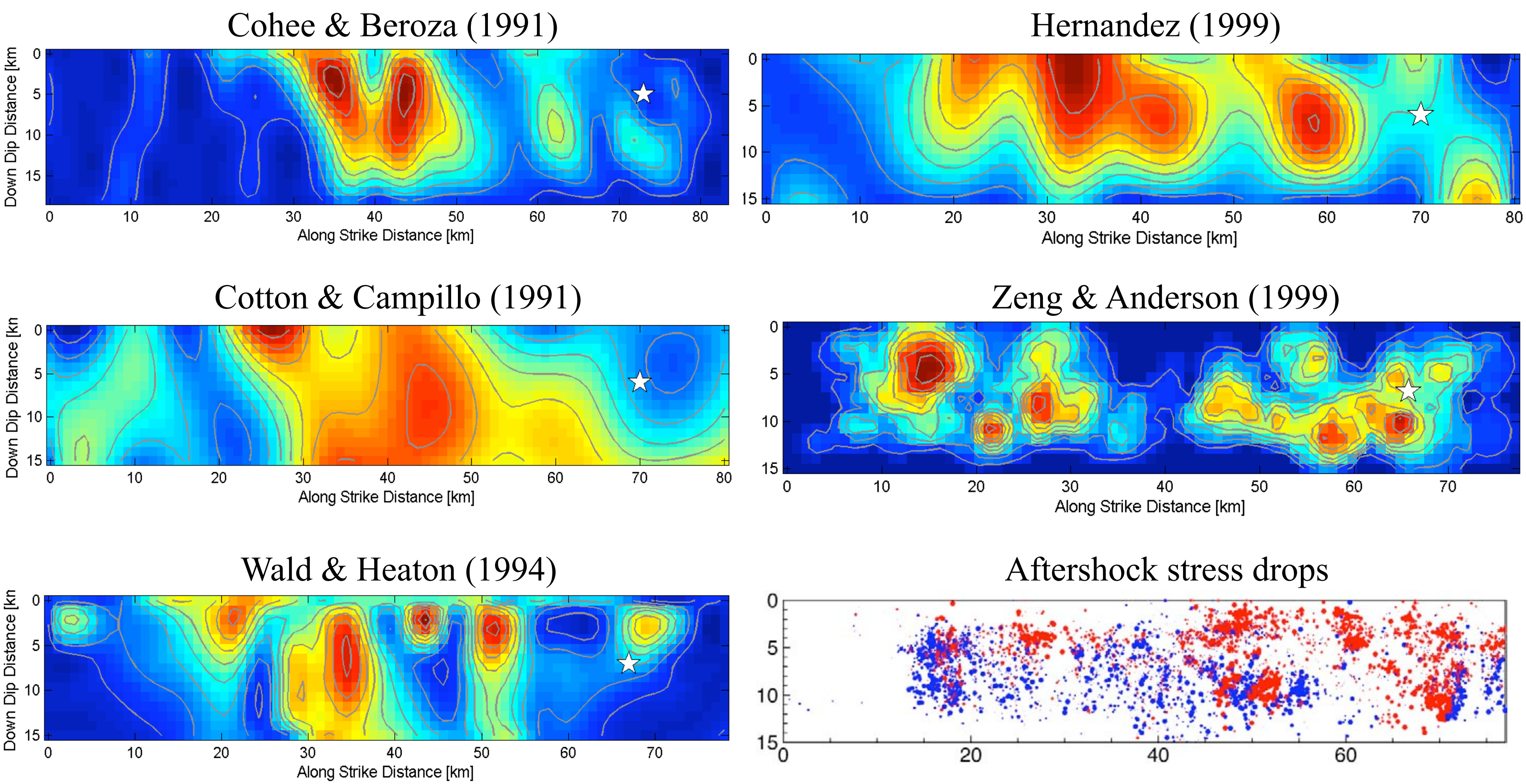




Red = low $\Delta\sigma$

Blue = high $\Delta\sigma$

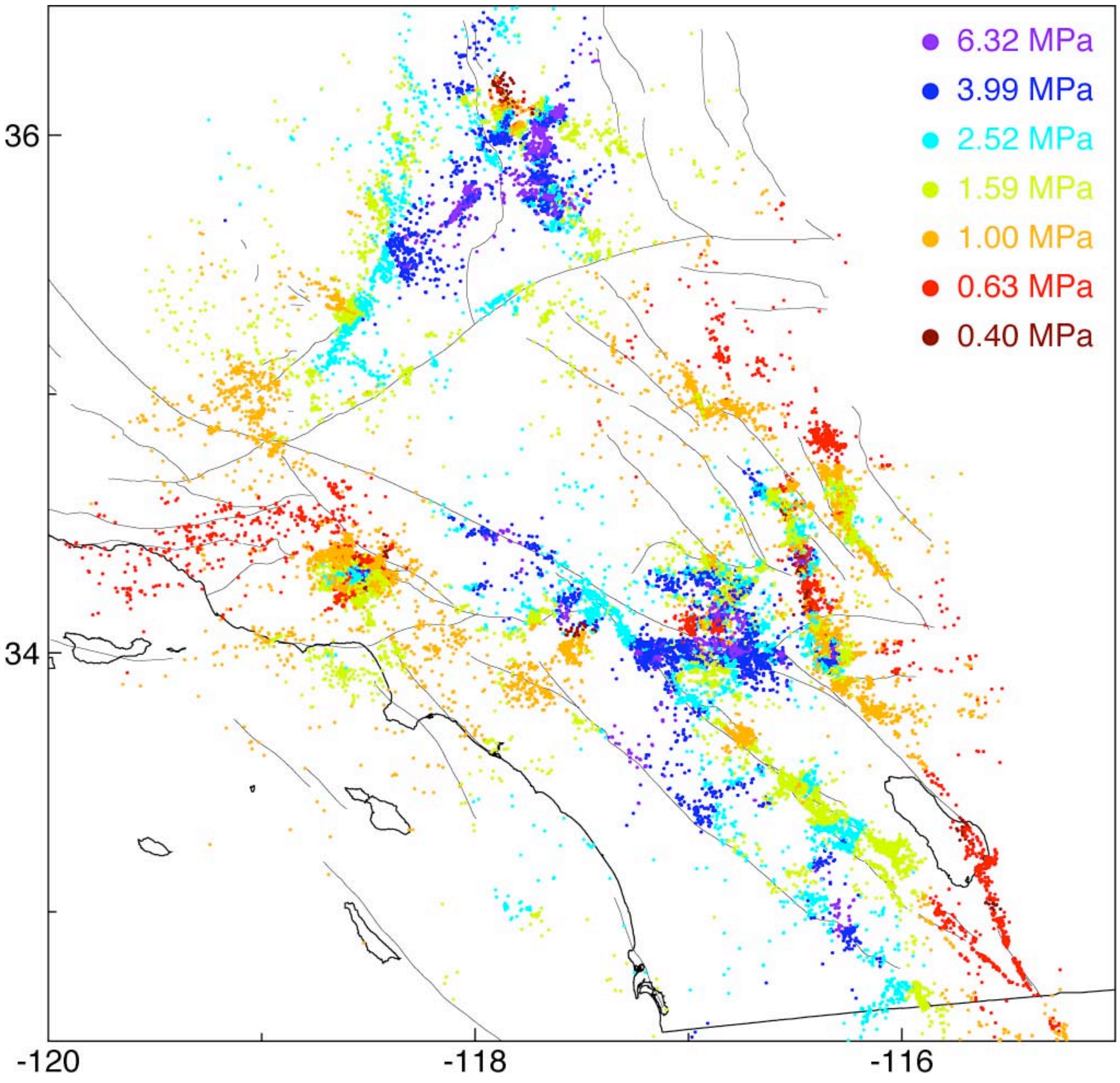
Slip model from *Wald & Heaton* (1994)

# Landers Slip Models




from www.seismo.ethz.ch/srcmod/

# Average $\Delta\sigma$ (smoothed over 500 events)

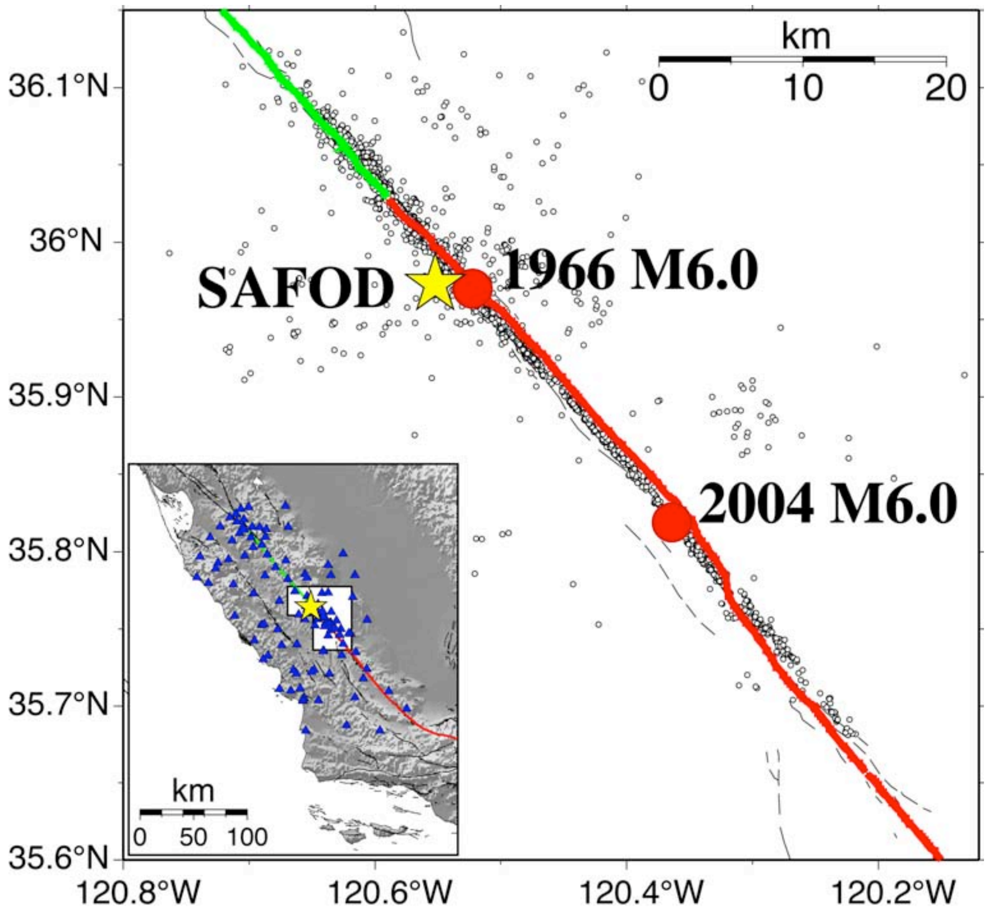



- 0.5 to 5 MPa
- Coherent patterns
- What does it mean?
- Does this say anything about absolute stress?

# Conclusions for Southern California

- Stress drops range from 0.2 to 20 MPa for $M_L = 1$ to 3.4 earthquakes, with no dependence on moment.
- Spatially coherent patterns in average stress drop (0.5 to 5 MPa), no consistent decrease near active faults.
- Shallow earthquakes radiate less high frequencies than deeper events, implying slower rupture velocities or lower stress drops.
- Landers aftershocks have strong along-strike variations in stress drop with possible correlation to slip models.
- Hard to resolve any temporal changes.

# Parkfield stress drop study




➔ Prime candidate to test for lateral and temporal $\Delta\sigma$ variations

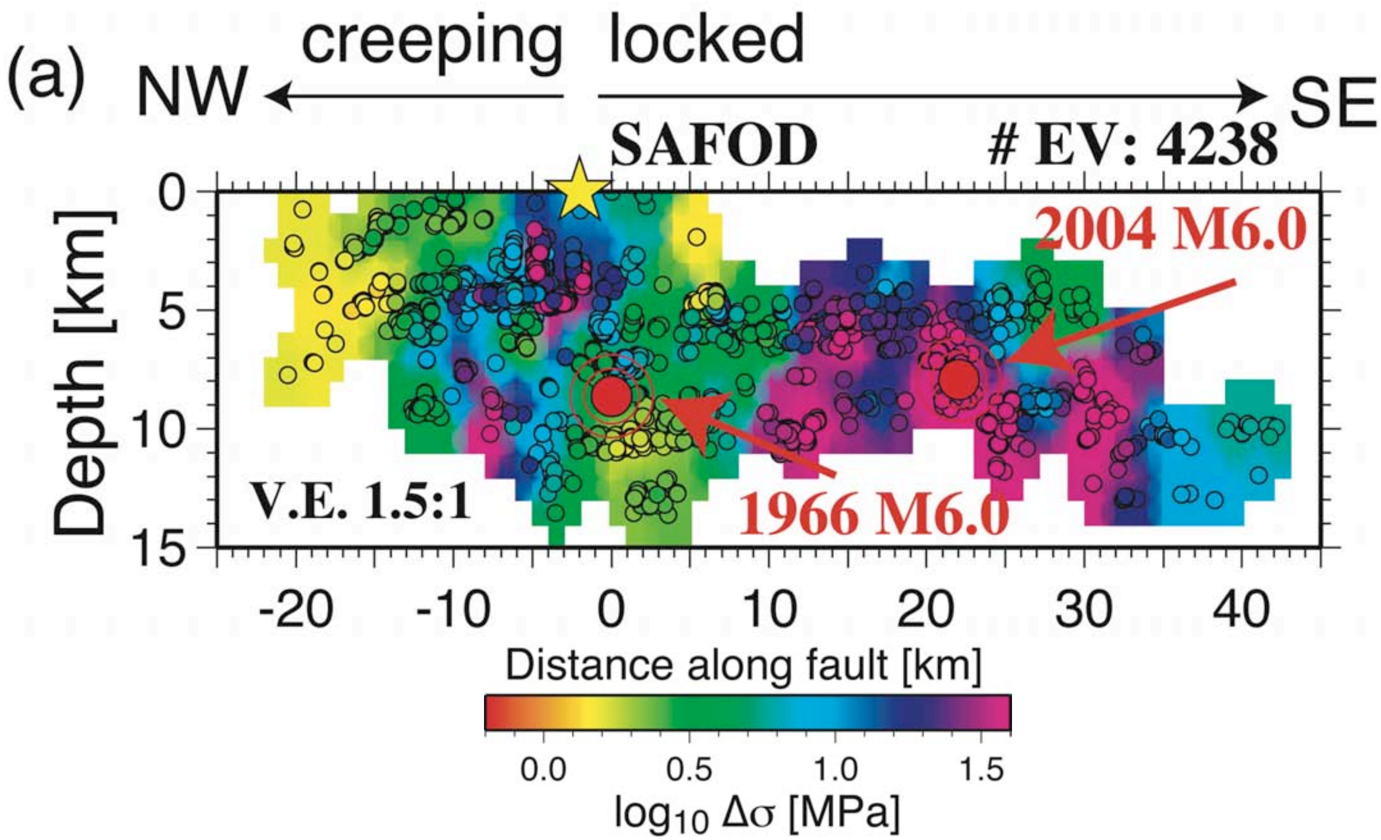
## The study area:

- Intensively studied fault
- Transition from creeping to locked
- Thousands of small earthquakes
- Repeating M~6 events
- M6.0 2004 mainshock

## The data:

- ~ 10,000 events
- 1984 to June 2005
- NCSN stations

# Lateral stress-drop variations

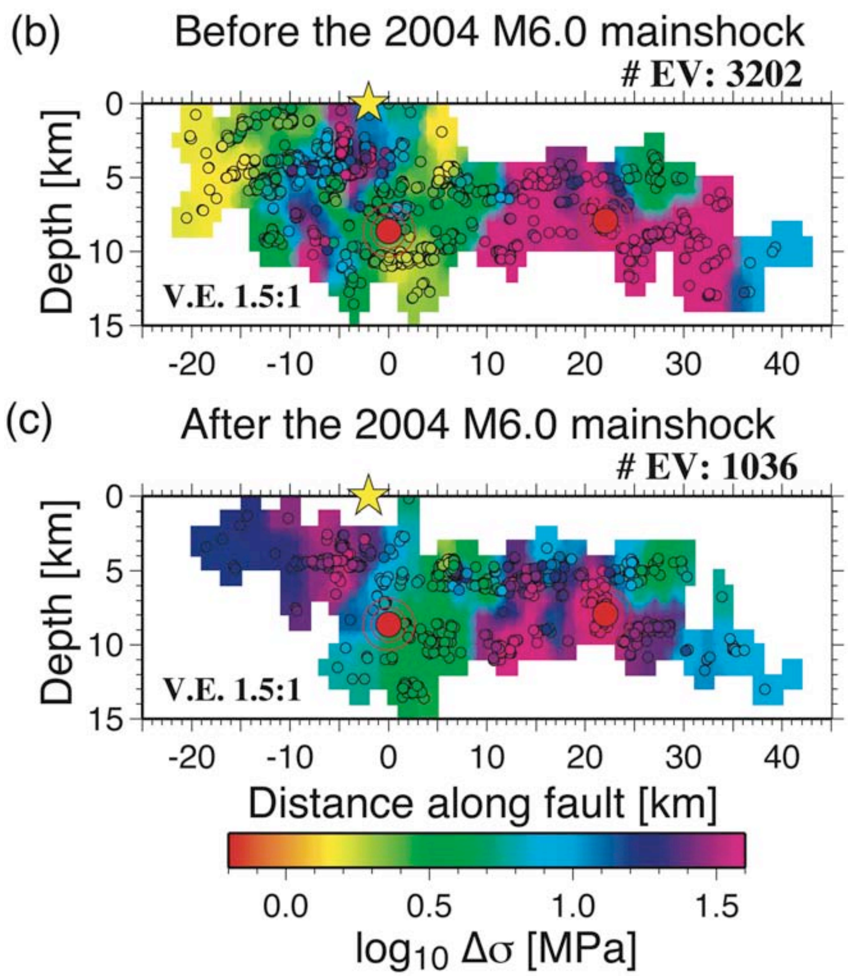


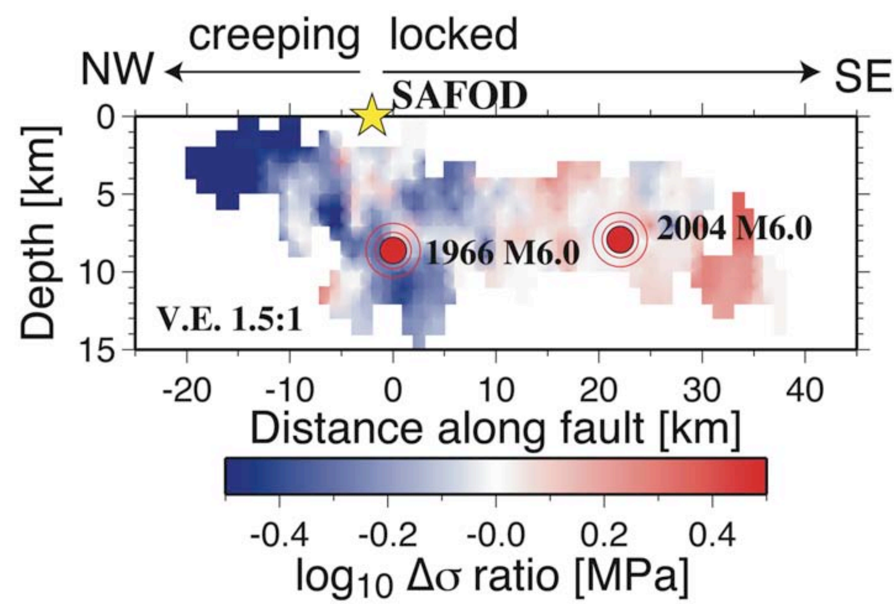

High Δσ around the *M6* 2004 event

Low Δσ in the Middle Mountain asperity

Low Δσ values along the creeping section

# Temporal stress-drop variations



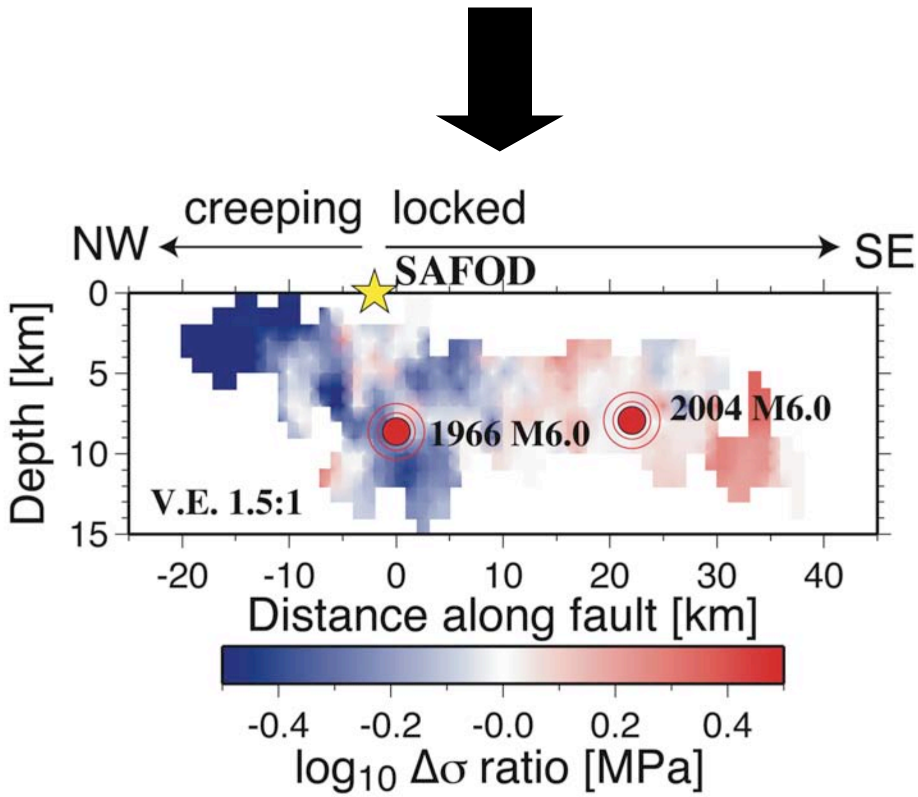



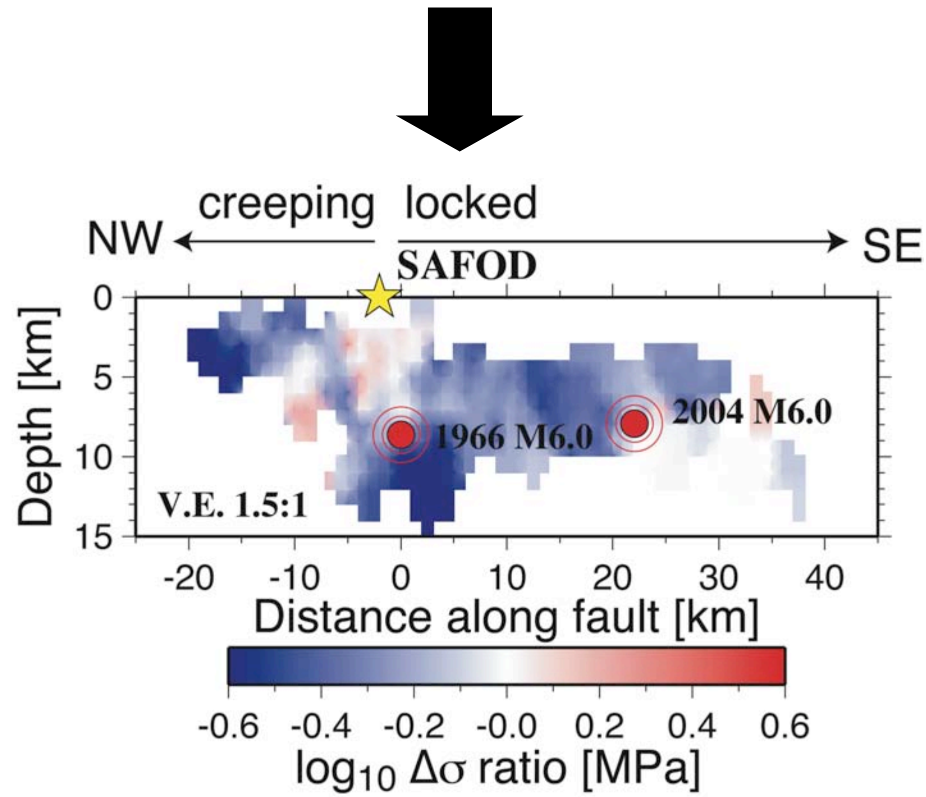

- Overall stress-drop pattern does not change
- Slight decrease in $\Delta\sigma$ around the 2004 mainshock
- Increased $\Delta\sigma$ around Middle Mountain
- Increased $\Delta\sigma$ along the creeping section

# Possible attenuation changes?

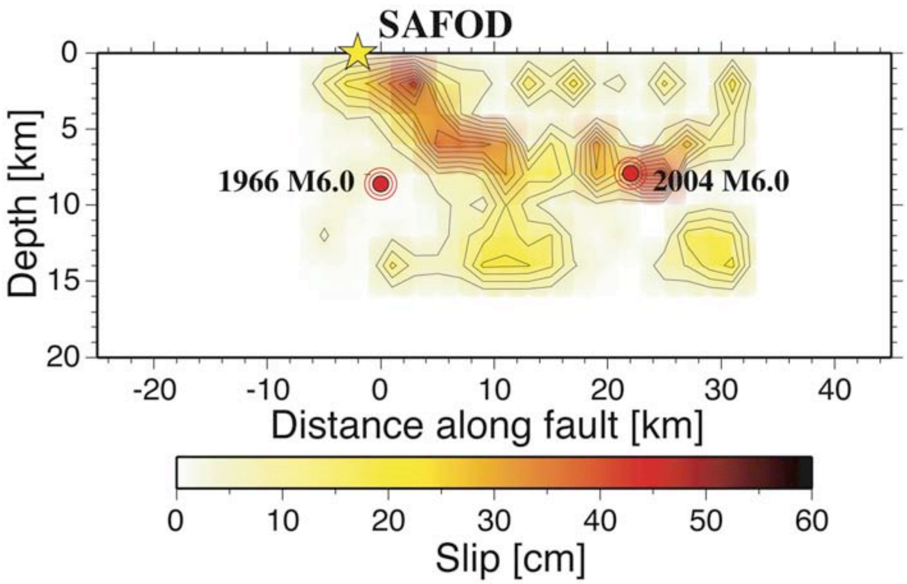
No medium changes

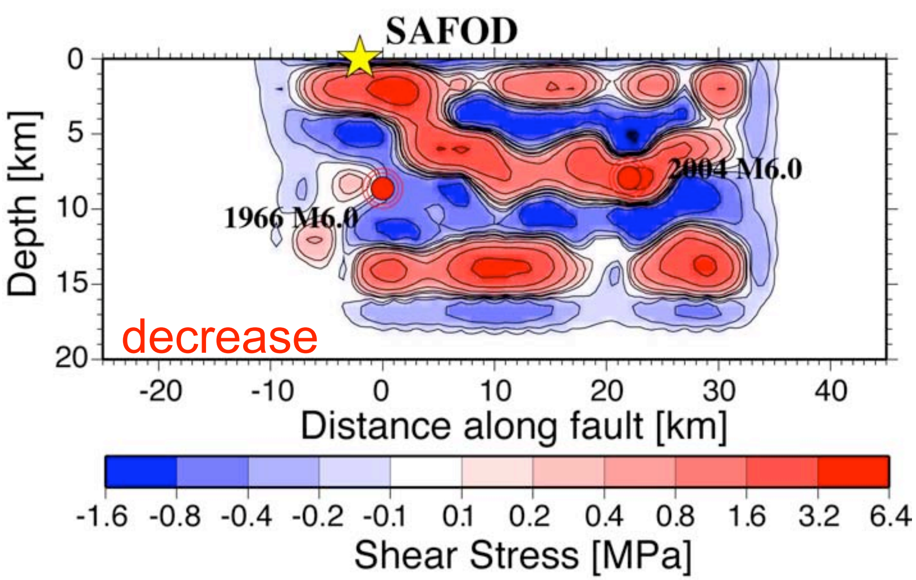
Medium changes allowed



# Mainshock shear-stress changes




🡐 Slip model of *Liu et al.* *(2005)*

- Use *Okada (1992)* to compute shear-stress changes
- Shear stress decreases in slipped areas
- $\Delta\sigma$ changes are of the same order of magnitude
- No simple relation between small earthquake $\Delta\sigma$ and mainshock shear-stress changes

# Conclusions for Parkfield

- Median stress drop is ~7 MPa for $M_L = 0.5$ to 3 earthquakes, with no dependence on moment.
- Large scatter in $\Delta\sigma$ for single events, but spatial averages show coherent patterns of high and low stress drop regions along the fault, which are largely unchanged by the 2004 *M* 6 mainshock.
- Some areas on fault have:
  - Resolvable increase in average $\Delta\sigma$ following the mainshock.
  - Increase in attenuation immediately following the mainshock.
- Mainshock shear stress changes are same order of magnitude as observed small earthquake stress drops but there is no simple relation between them.