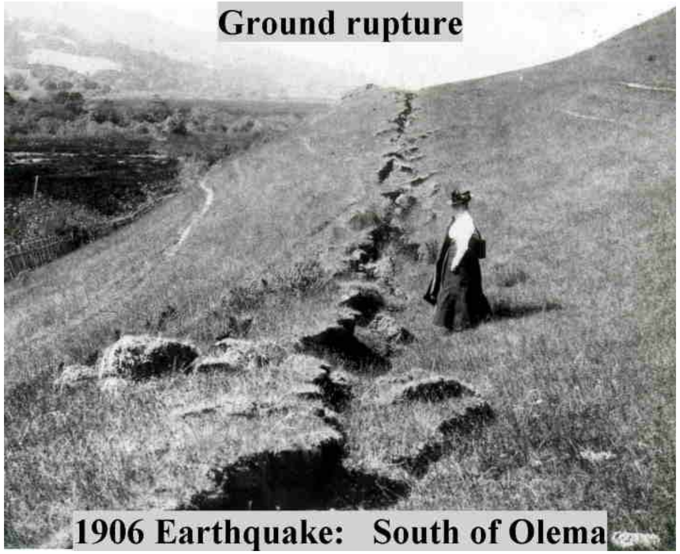
Earthquake stress drop estimates: What are they telling us?

Peter Shearer

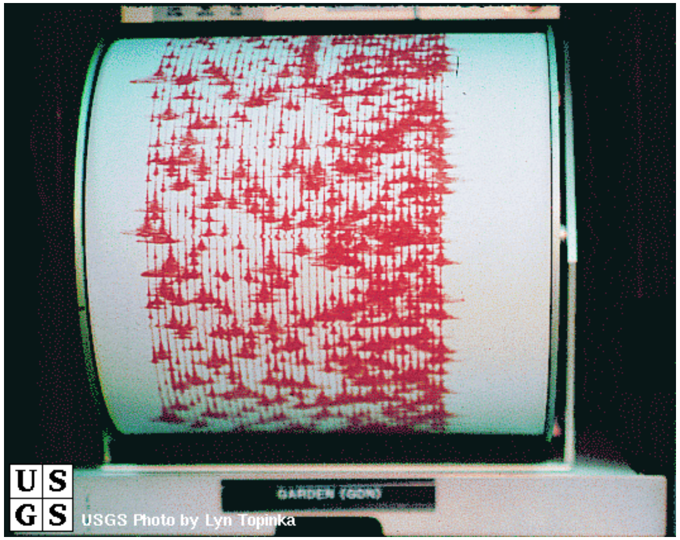
IGPP/SIO/U.C. San Diego

October 27, 2014

SCEC Community Stress Model Workshop



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

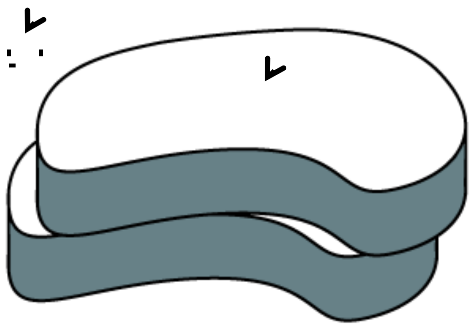


Small earthquakes are only observed from seismograms; no direct measurements of physical properties

Two parameters

displacement = D

area = A



fault area

average displacement

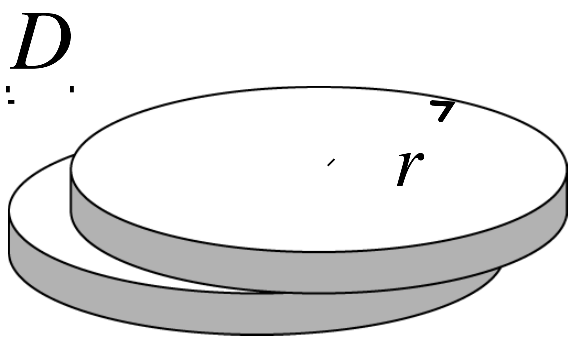
Moment $M_0 = \mu A D$

shear modulus

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

average shear stress on fault

Circular crack model



average displacement

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

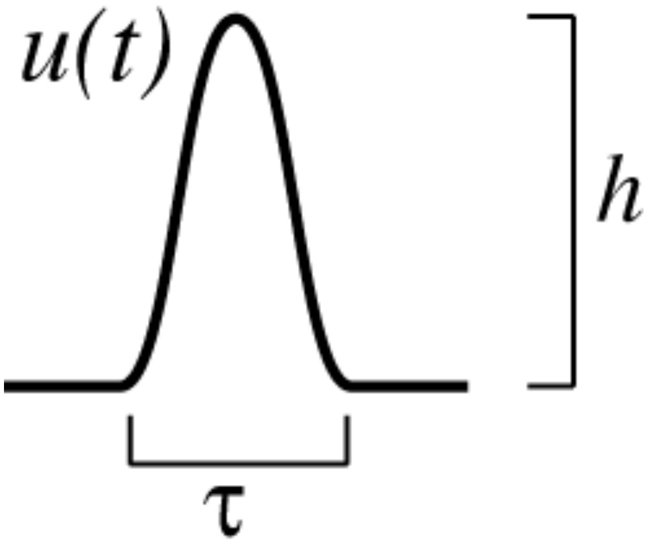
fault radius

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

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

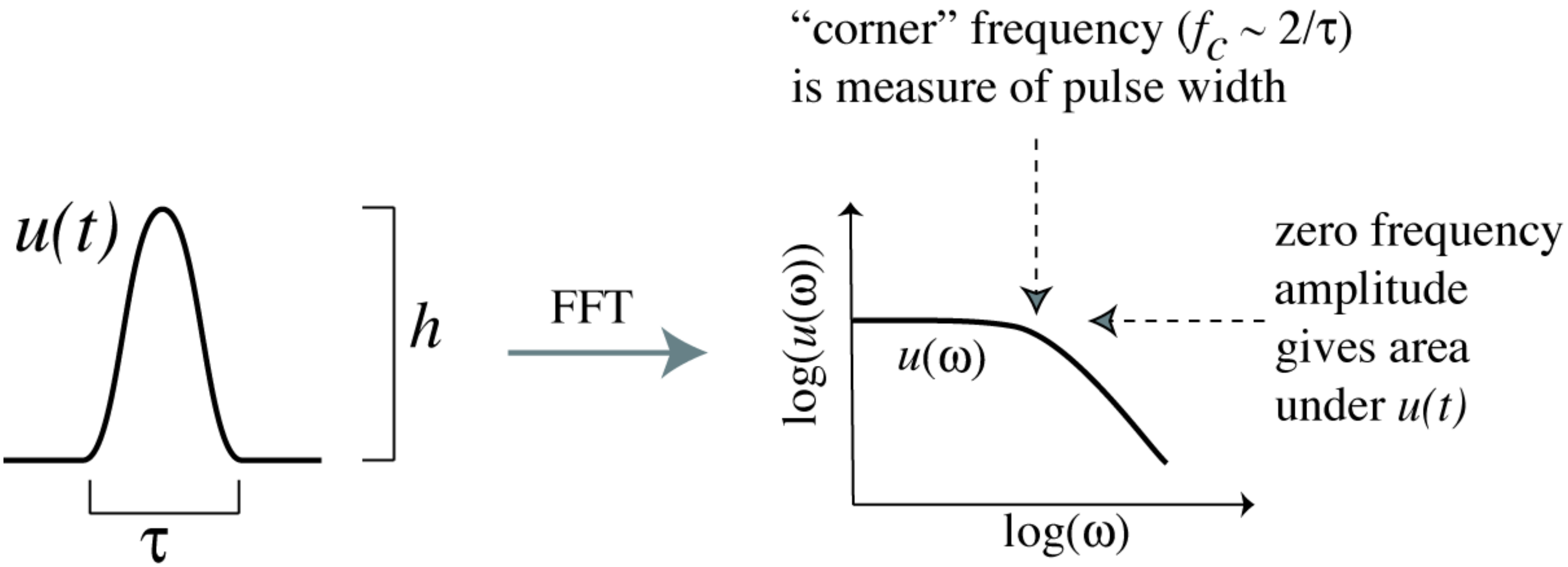
Area under displacement pulse $f(h\tau)$ is related to seismic moment M_0 (one measure of event strength)

Pulse width τ is related to physical dimension of fault, rise time, and rupture velocity

Spectral Analysis 101

Time Series

Spectrum




How to get Brune-type stress drop

f_c

Ω_0

log[$u(f)$]

log(f)

theoretical curve

Original spectrum

Correct for attenuation

Estimate Ω_0 and f_c

Correct for geometrical spreading and radiation pattern

M_0

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

Assume circular crack model

cubed!

r

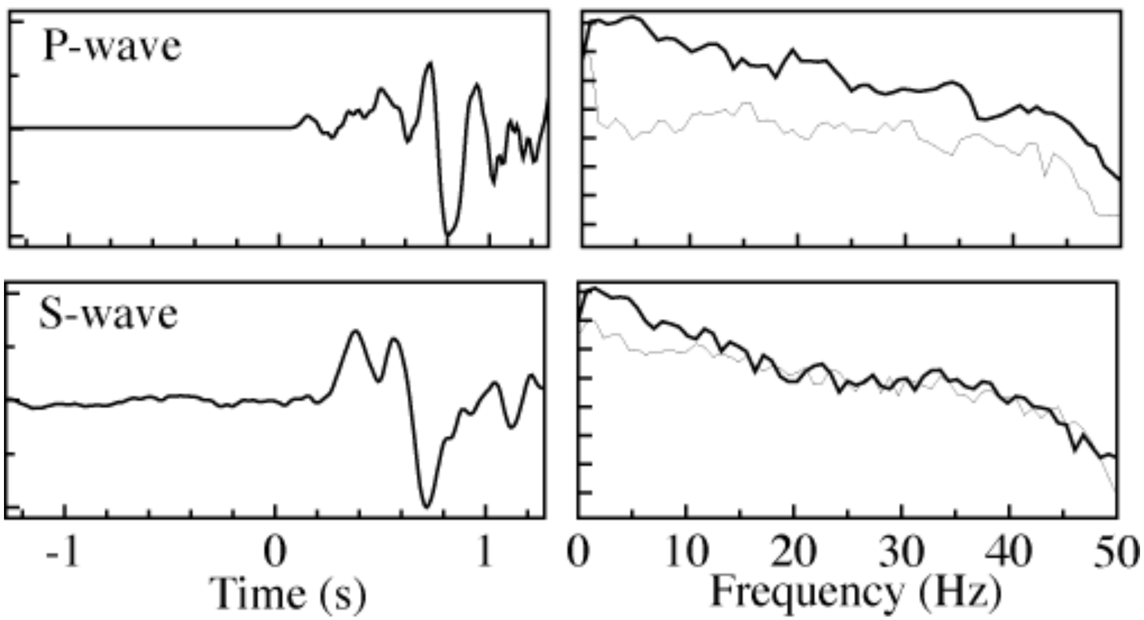
Assume rupture velocity and source model (*Brune*, *Madariaga*, *Sato & Hirasawa*, *Kaneko & Shearer*, etc.)

General $\Delta\sigma$ 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

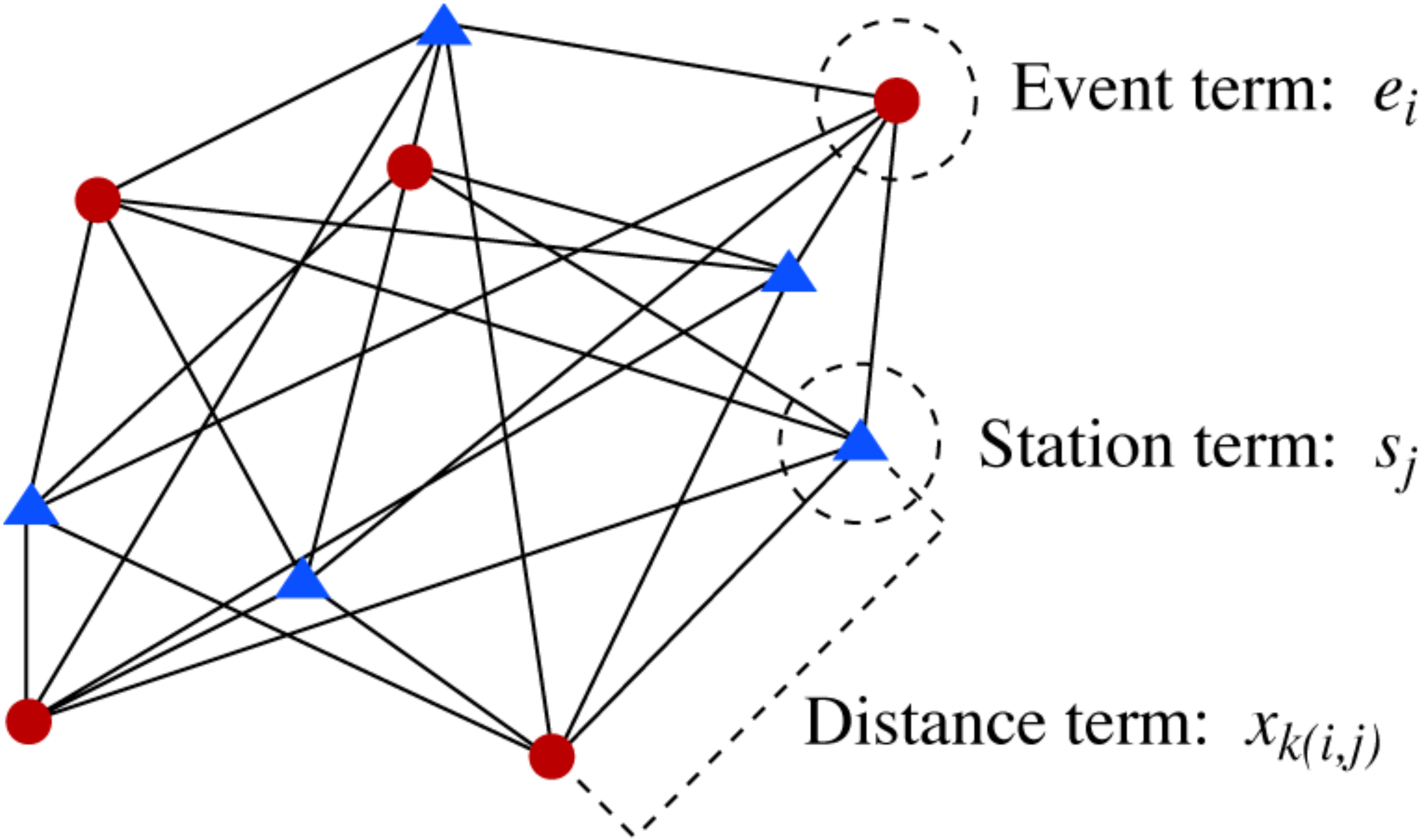
UCSD/Caltech spectral analysis

- 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

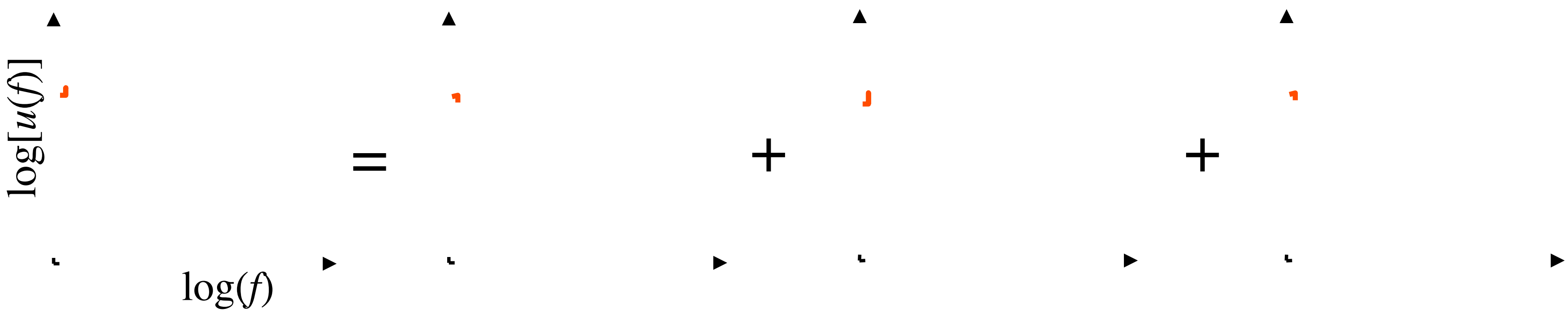
Isolating Spectral Contributions



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

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

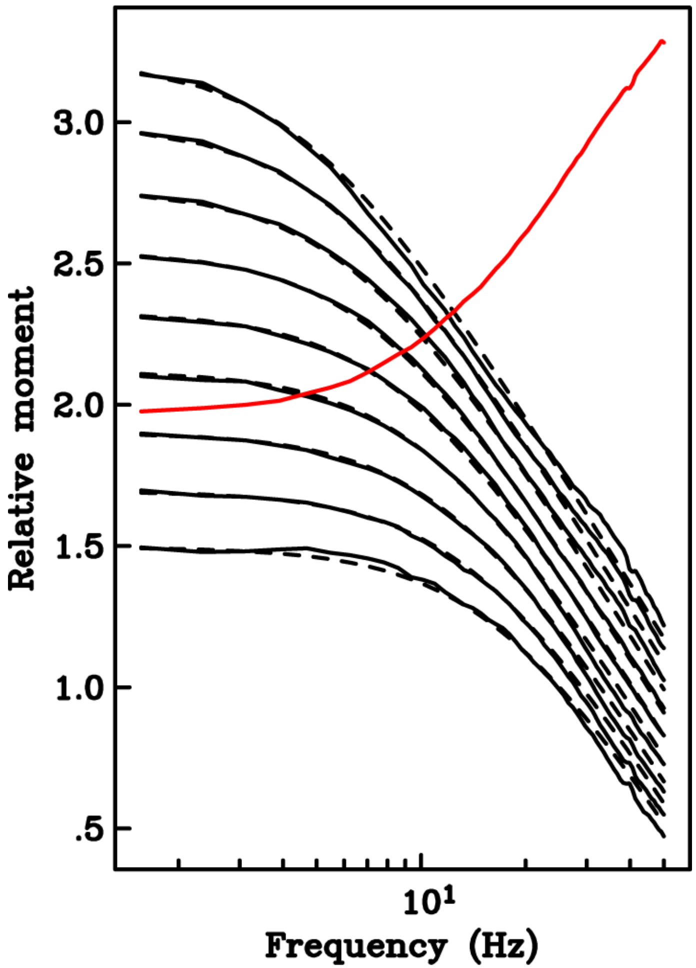
Observed spectrum	Source spectrum	Receiver response	Distance term to account for Q



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

Assumed source model

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



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

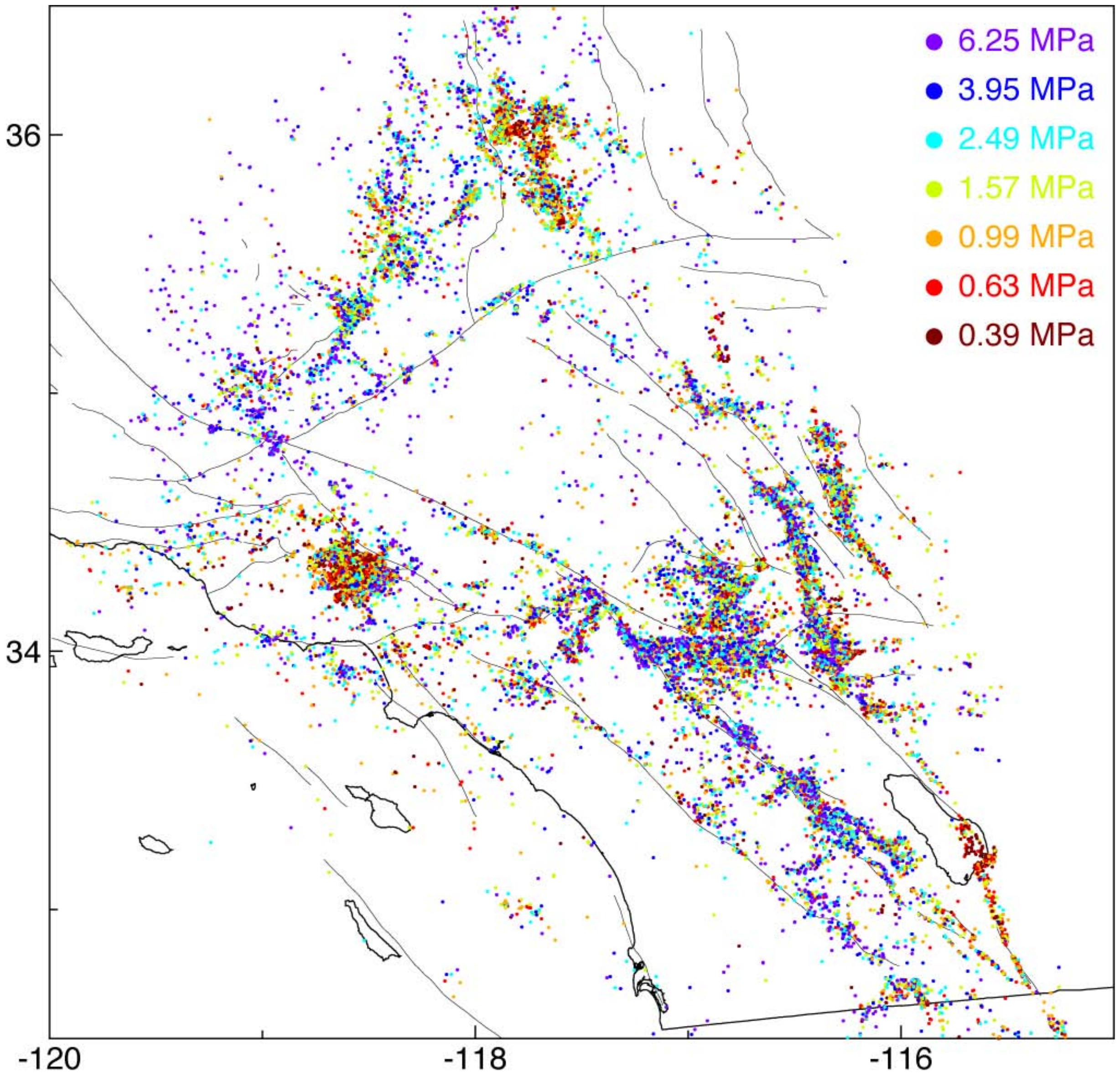
$$u(f) = \frac{\Omega_0}{1 + (f/f_c)^n}$$

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

(assumes rupture velocity = 0.9 β)

Model prediction (dashed lines) is for Δσ = 1.60 MPA (constant)

Calculated Earthquake Stress Drops

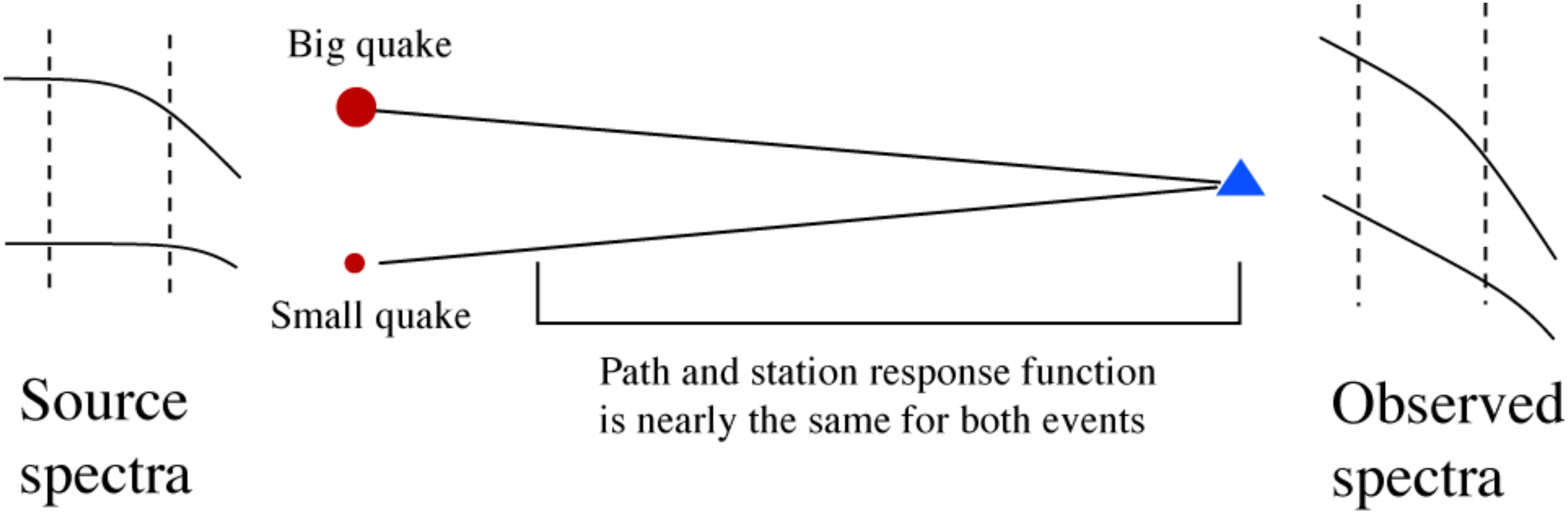


- 65,070 events
- > 300,000 spectra
- 1989–2001
- > 4 spectra/event
- 5 - 20 Hz band

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

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

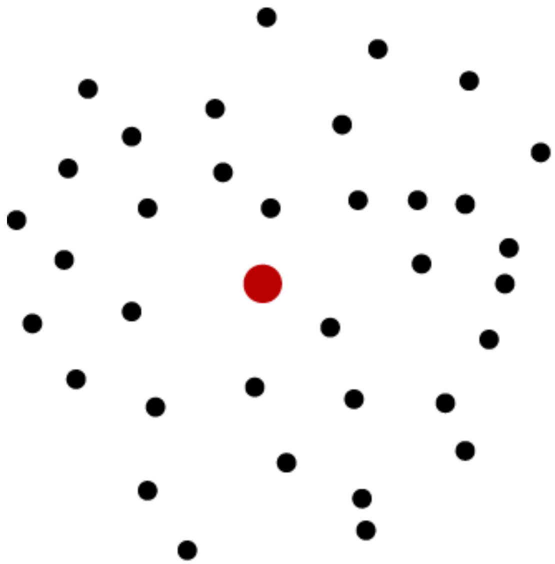
Empirical Green’s Function (EGF)



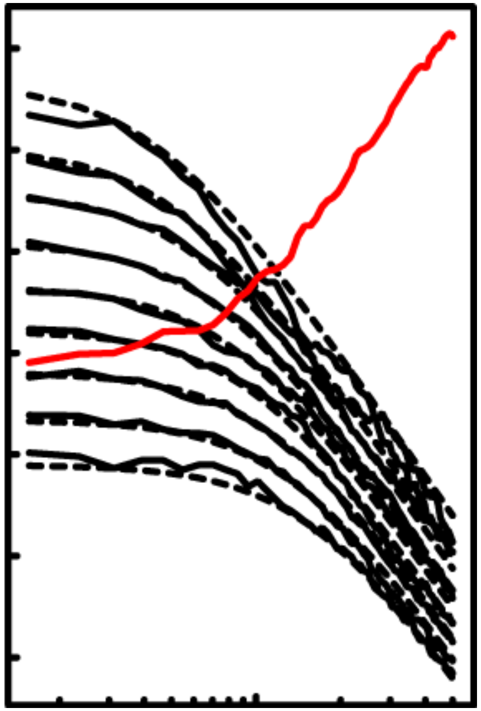
Subtract small event from big event to get estimate of true source spectrum for big event

Source-specific EGF method

For each event, find 500 neighboring events:

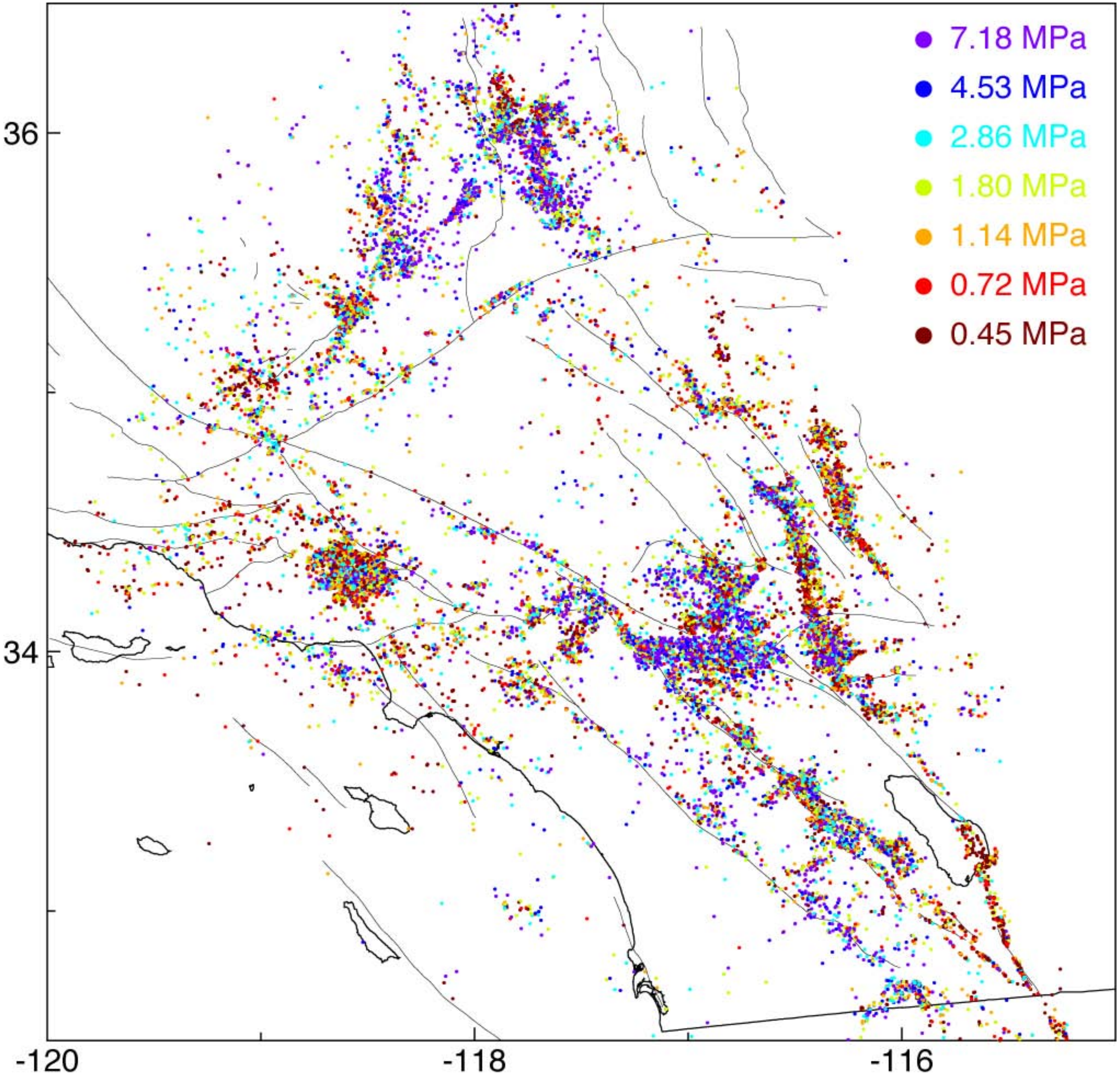


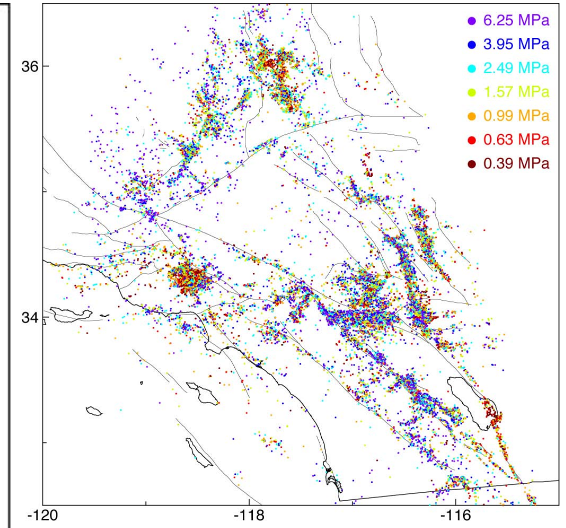
Fit moment binned spectra to $\Delta\sigma$ and EGF



Then subtract EGF from target event spectrum and compute $\Delta\sigma$ for this event

Observed source Δσ using spatially varying EGF method



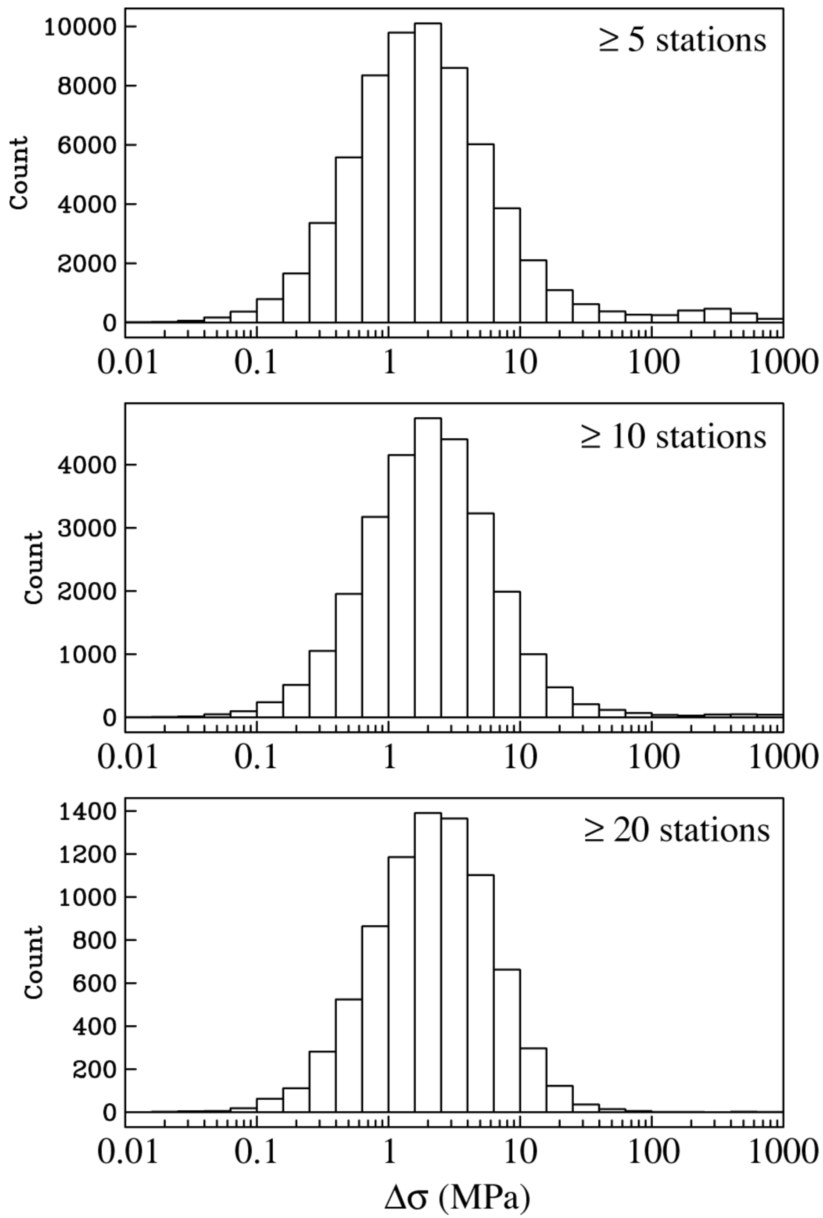


^

Previous result using constant EGF method

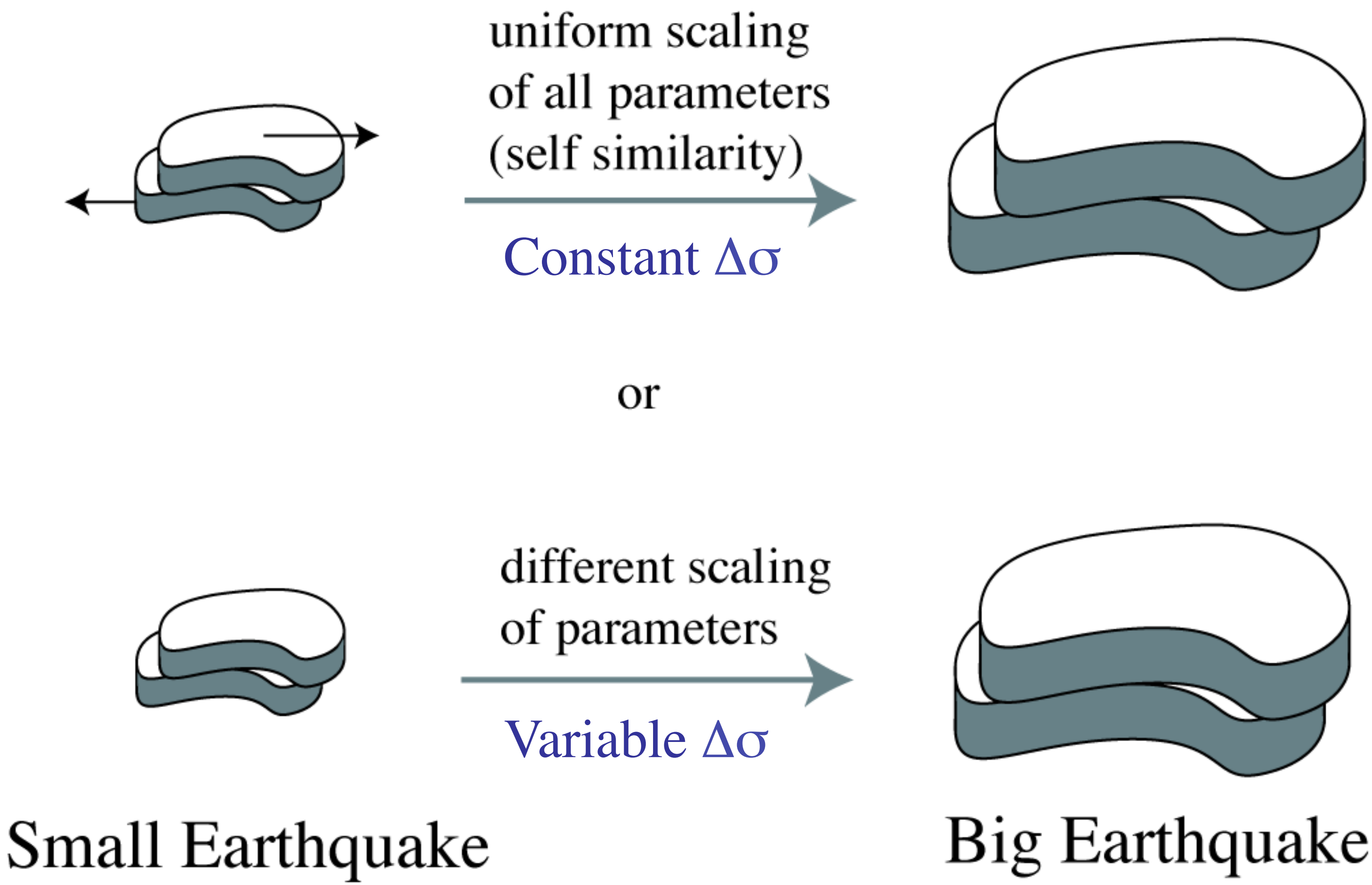
< New results

How variable are earthquake stress drops?

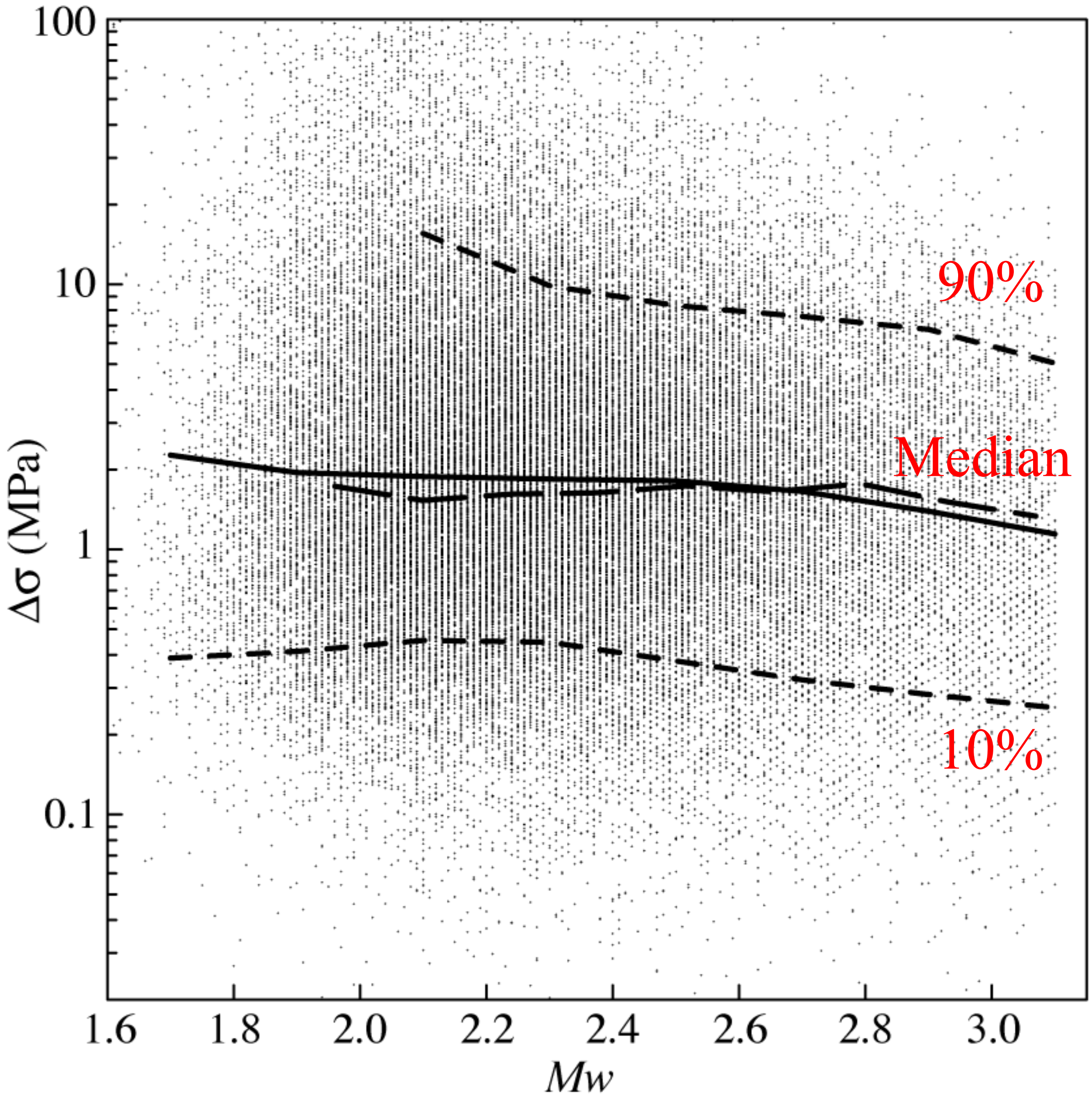


- Harder to resolve high Δσ events due to high corner frequencies
- Results are more reliable when more stations are stacked
- Δσ = 0.2 to 20 Mpa
- ~10x local scatter
- ~10x regional variations

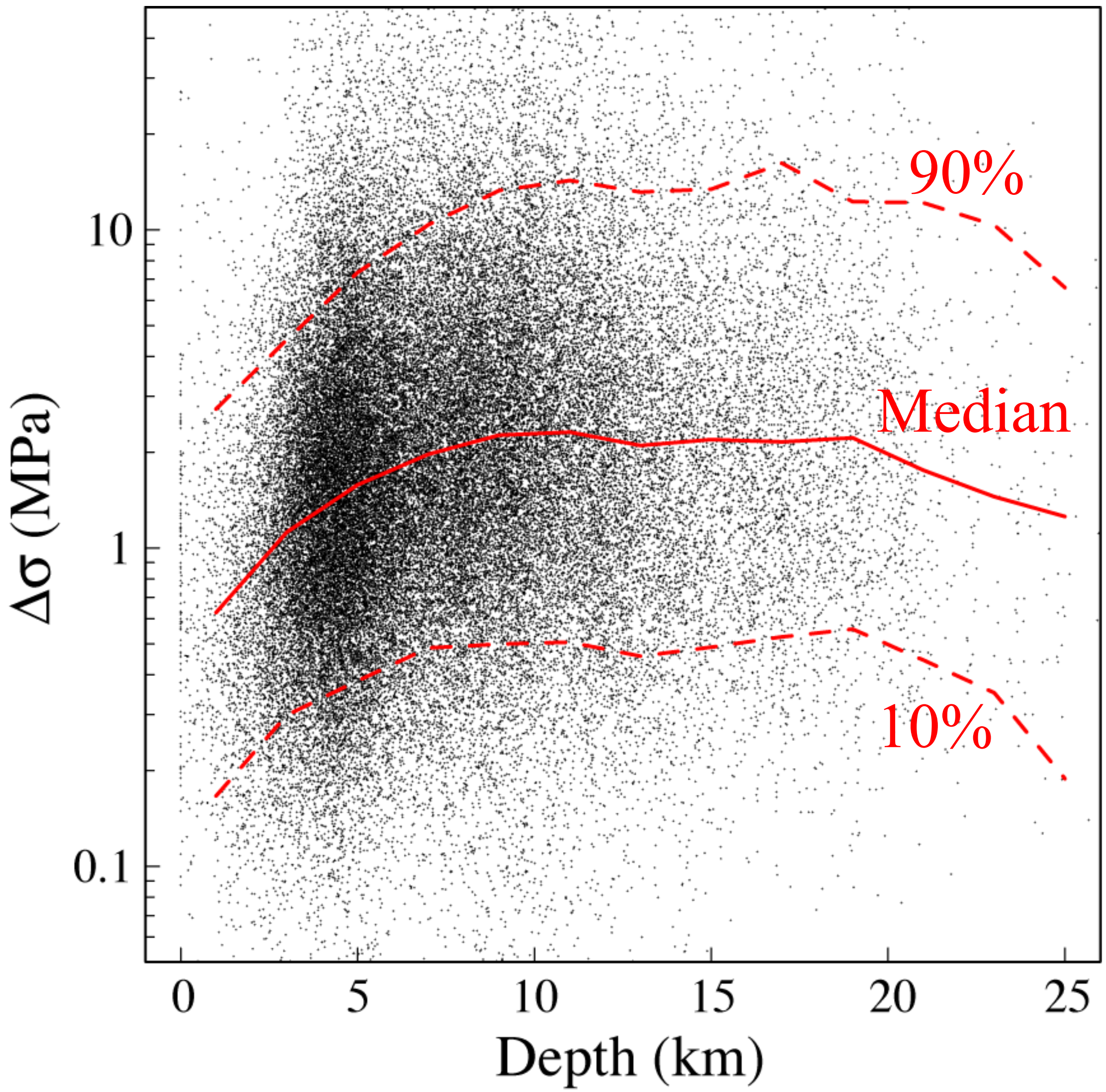
Earthquake scaling



Median stress drop does not vary with M_W



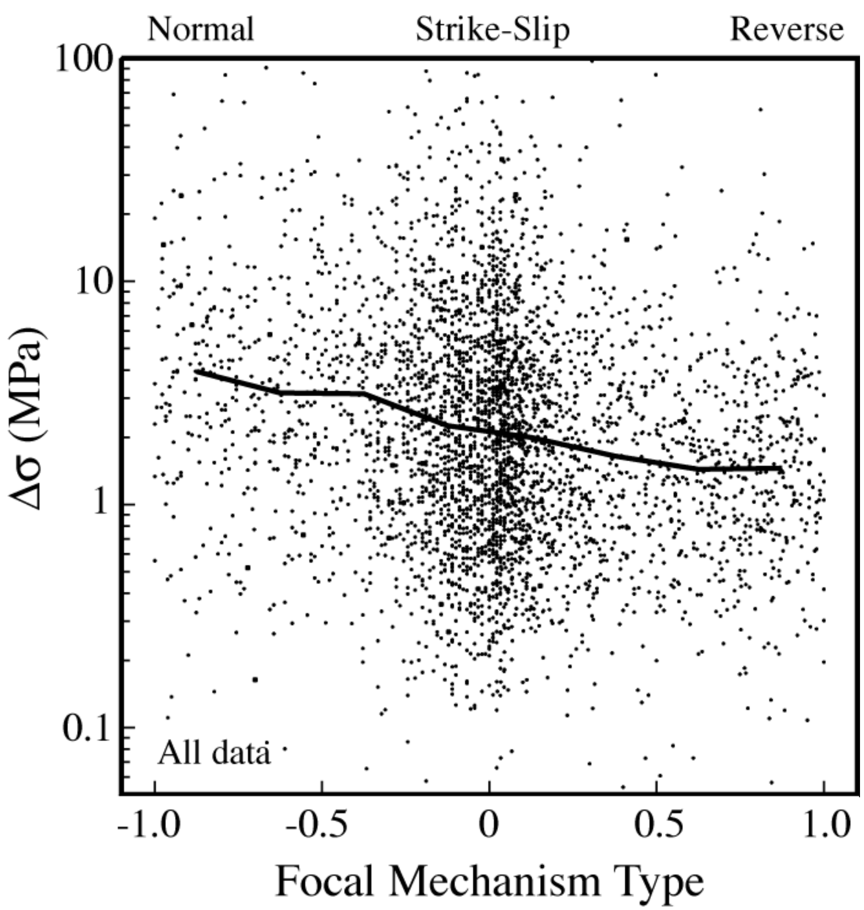
Stress drop versus depth

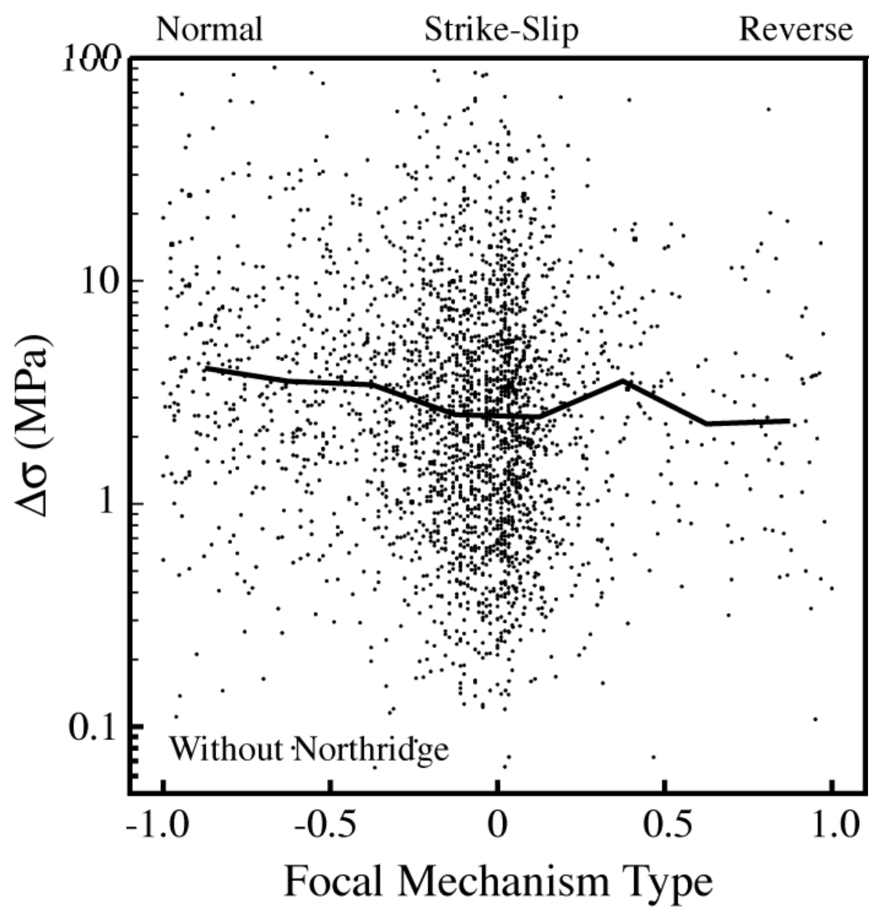


- Average Δσ increases from 0.6 to 2 MPa from 0 to 8 km
- But slower rupture velocities at shallow depths could also explain trend
- Nearly constant from 8 to 18 km
- Large scatter at all depths

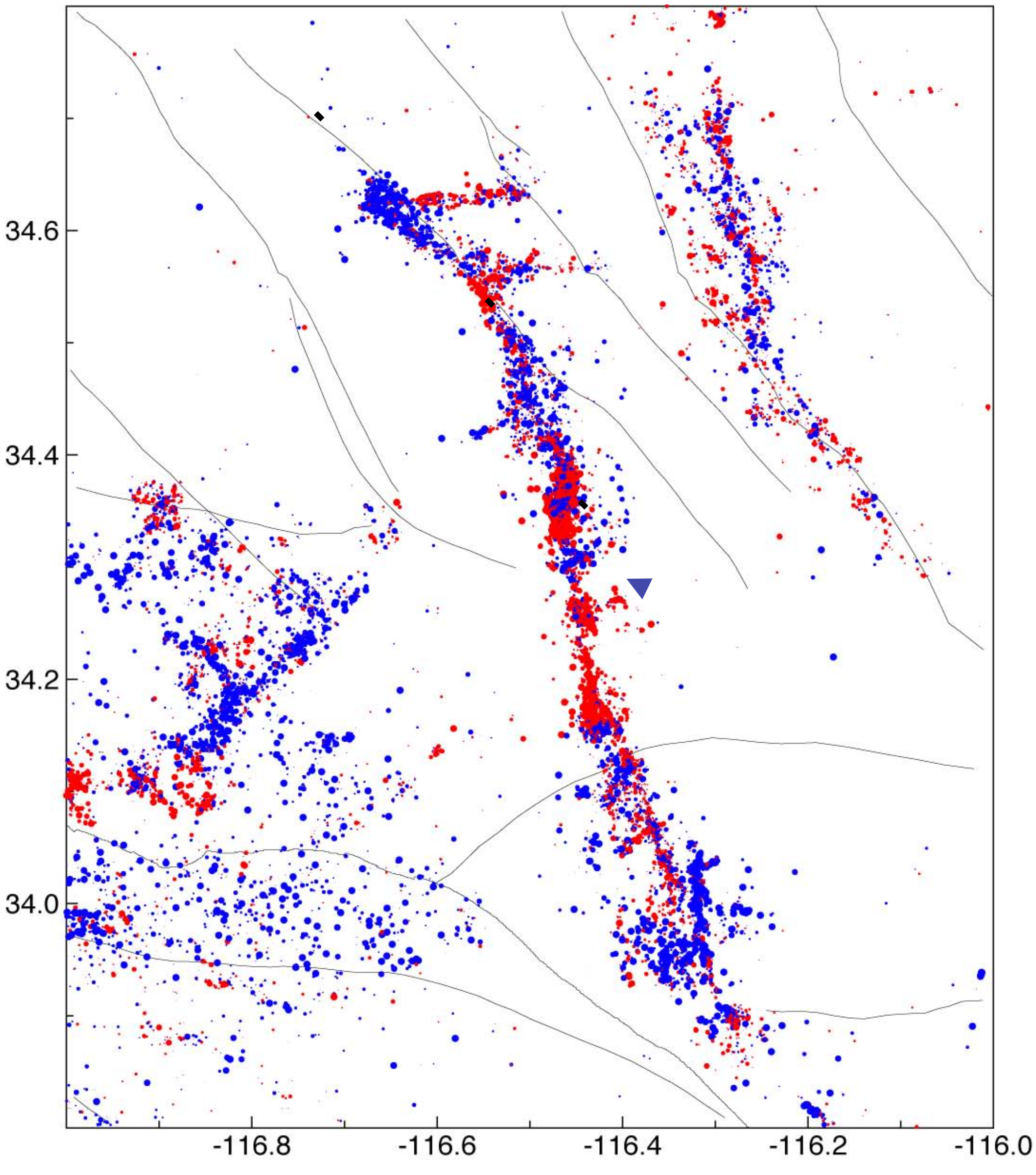
Stress drop versus type of faulting

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





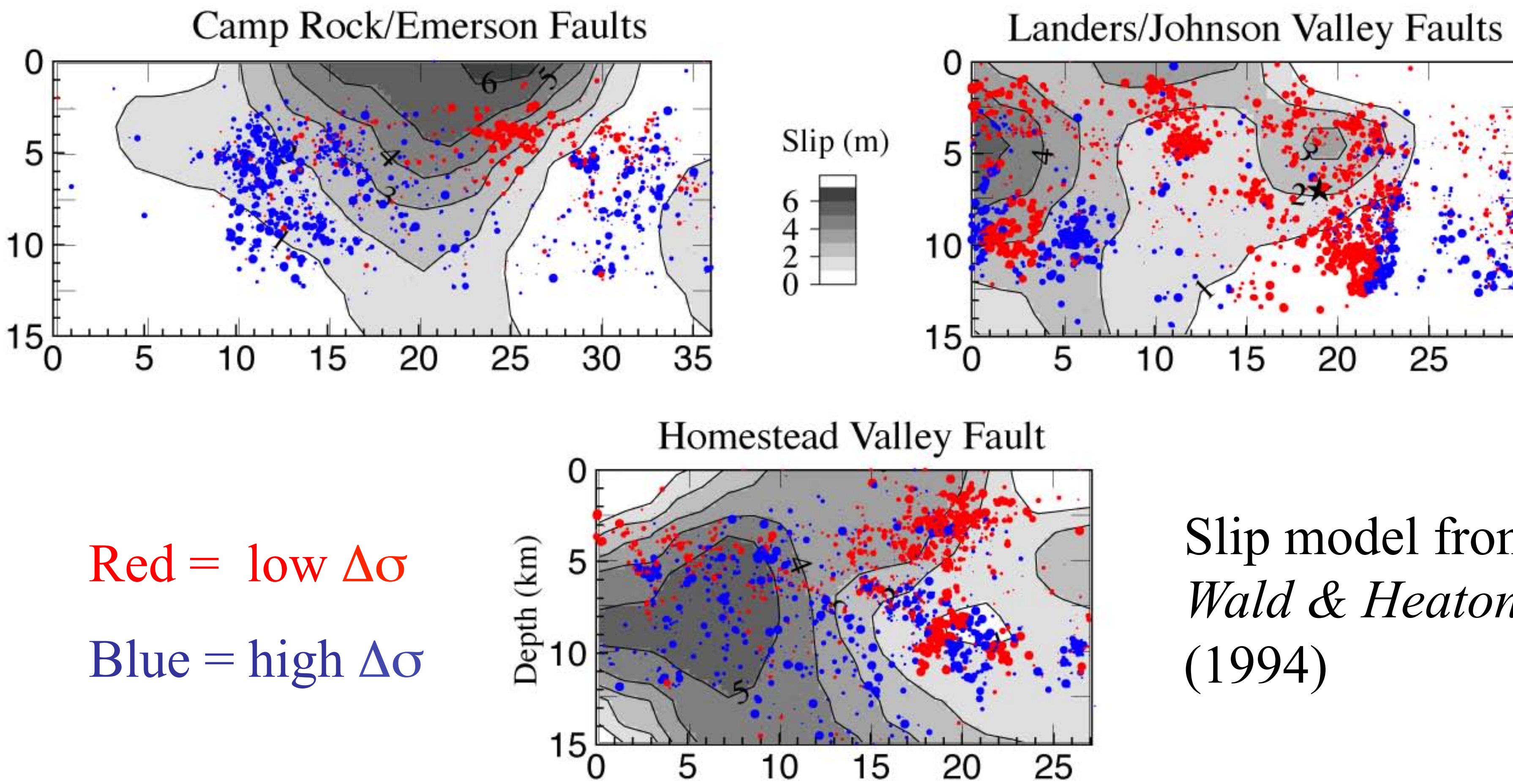
Landers Aftershocks



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

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

Comparison to Landers Slip Model



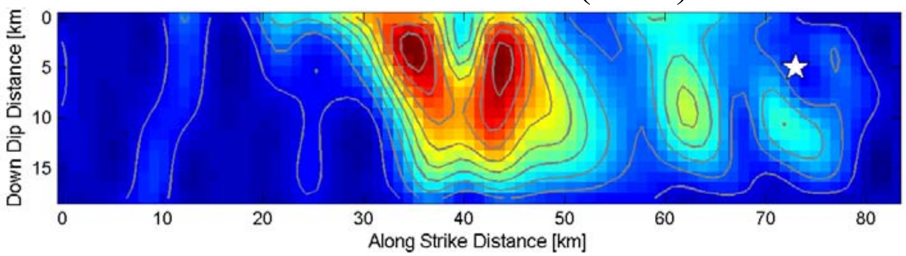
Red = low Δσ

Blue = high Δσ

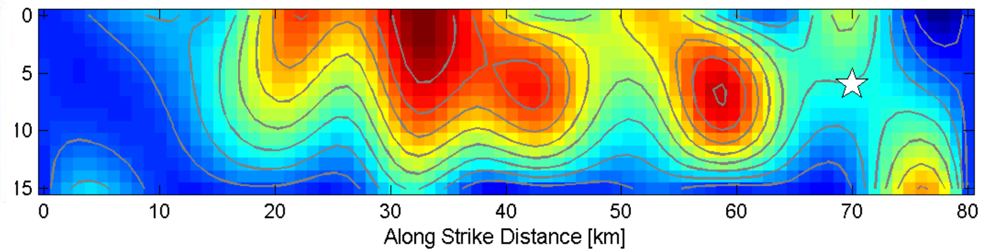
Slip model from *Wald & Heaton* (1994)

Landers Slip Models

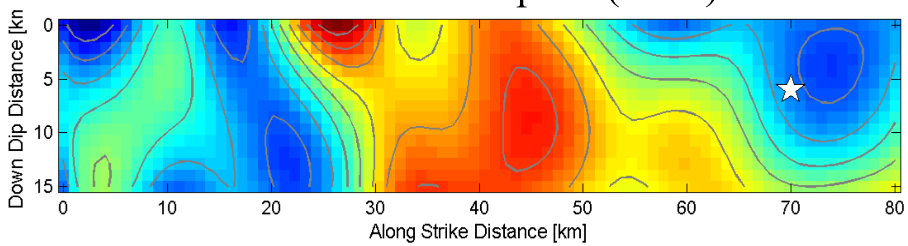
Cohee & Beroza (1991)



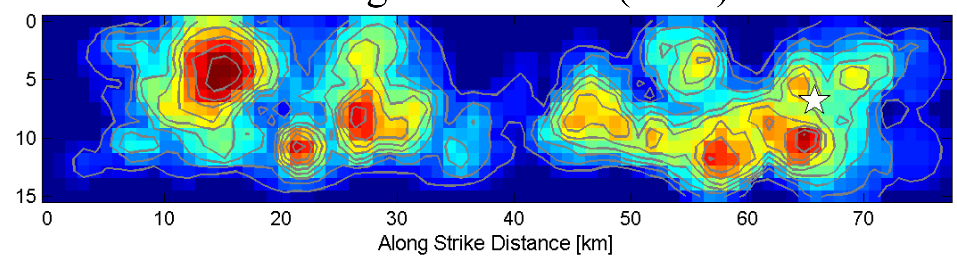
Hernandez (1999)



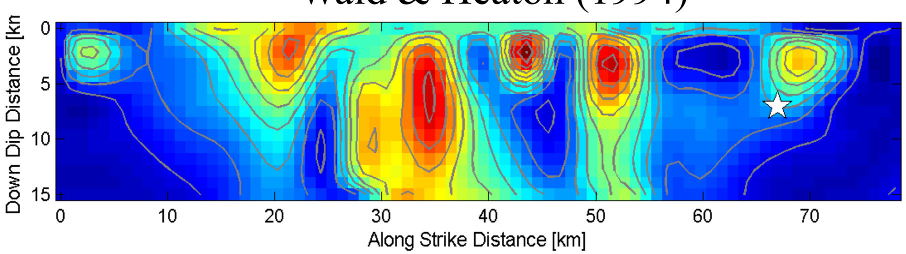
Cotton & Campillo (1991)



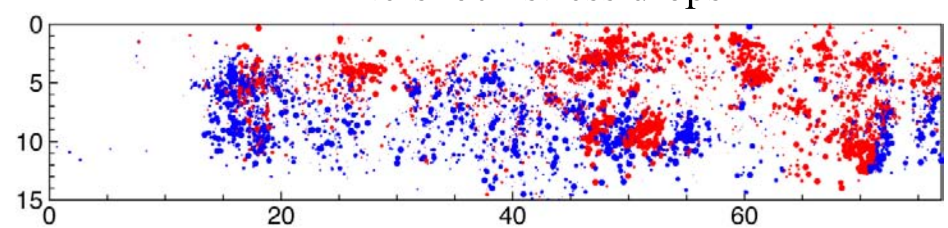
Zeng & Anderson (1999)



Wald & Heaton (1994)

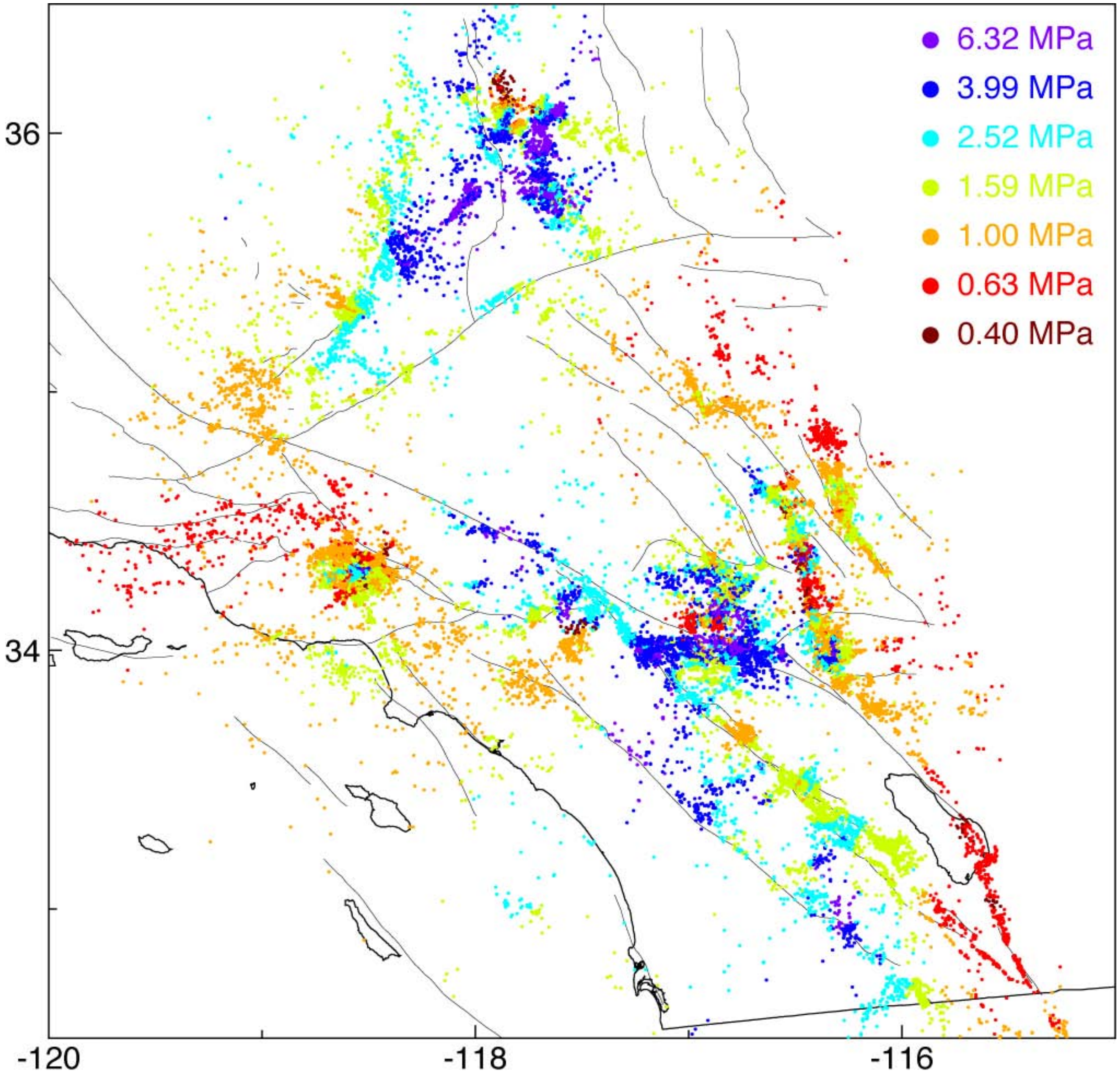


Aftershock stress drops



from www.seismo.ethz.ch/srcmod/

Average Δσ (smoothed over 500 events)

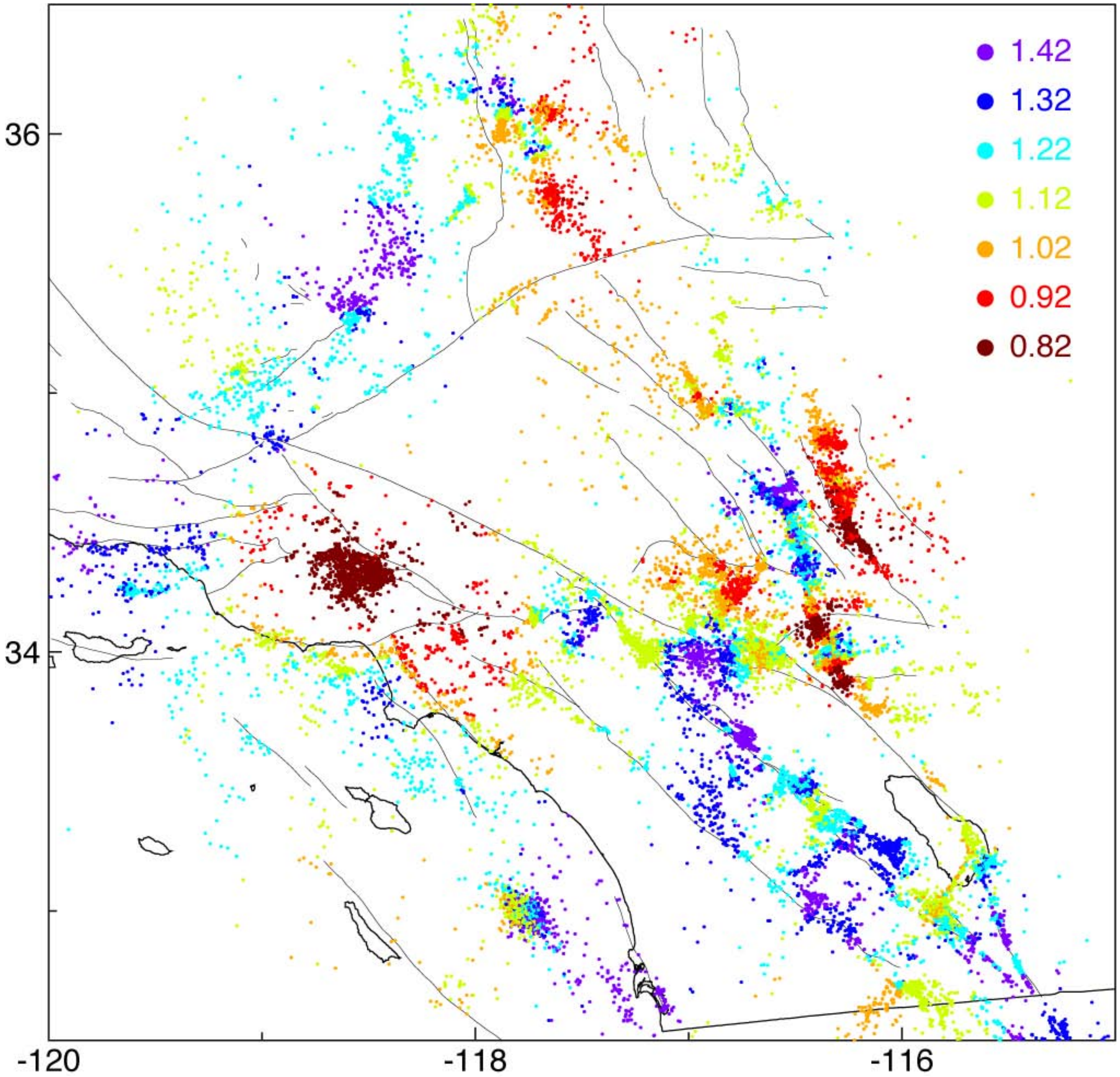


- 0.5 to 5 MPa
- Coherent patterns
- What does it mean?
- Does this say anything about absolute stress?

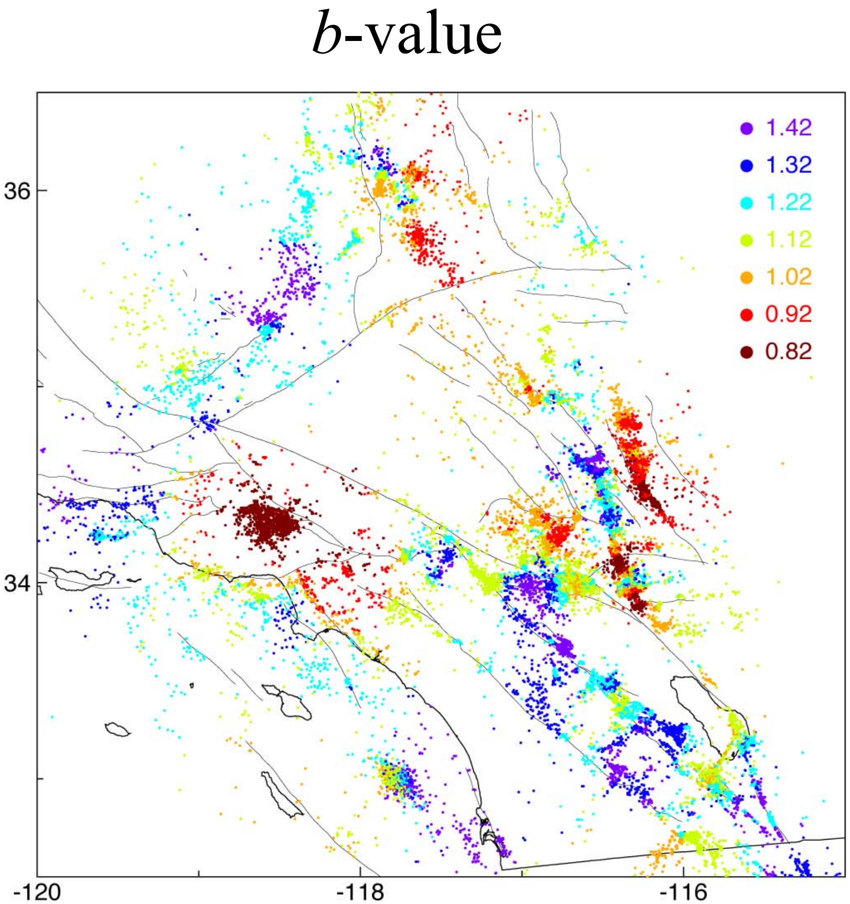
Conclusions for Southern California

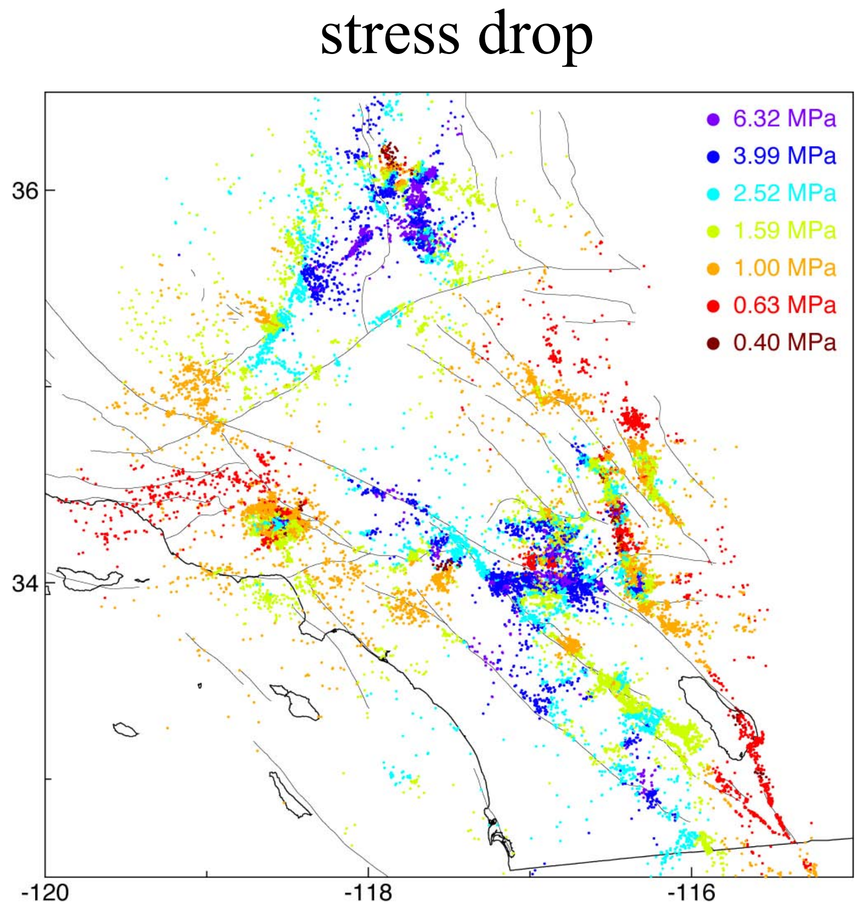
- Stress drops range from 0.2 to 20 MPa for M_L = 1 to 3.4 earthquakes, with no dependence on moment.
- Spatially coherent patterns in average stress drop (0.5 to 5 MPa), no consistent decrease near active faults.
- Shallow earthquakes radiate less high frequencies than deeper events, implying slower 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.

1989-2001 *b*-values



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





not much correlation!