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

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

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)

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:

Peak in velocity spectrum
= corner frequency (fc) in displacement
~ 1/ source dimension

Earthshaking Science, Sue Hough, 2002
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

$\Delta\sigma \sim \text{slip/length}$

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

*Higher Ground Accelerations*
Earthquake Physics – Constant Stress Drop

Where are measurements from? Do they really constrain models?

**Constant Stress Drop varies over 3+ Orders of Magnitude**

Selvadurai, 2019

Ke, McLaskey & Kammer 2022
Fracture Energy: Seismic Estimates of $G'$ – at each point, or an “average” point

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

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

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

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?

Simple Models

- Circular source
- 1D (or constant) attenuation structure
- Known – hopefully

Seismogram (X):
\[ X(t) = S(t) \times G(t) \times I(t) \]

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 Effects

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?

Plate boundary
Young rocks
Low Q
M6.0 earthquake
Central California
Sept. 28, 2004

Intraplate
Old rocks
High Q
M5.8 earthquake
Central Virginia
Aug. 23, 2011

Effect of attenuation

Example of Near Surface Path Effects

Borehole

Displacement

10

100

2.5 km

10^{-2}

10^{-3}

10^{-4}

Example of Near Surface Path Effects
Introduction to Methods

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

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

\[ t^* = t/Q \]

Large trade-offs in limited frequency range of typical data

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

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

Fit synthetic data for Q and fc

Ko et al., JGR 2012

- x5 stress drop difference
- \( t^* = 0.08, f_c = 4.0 \)
- \( t^* = 0.13, f_c = 6.7 \)
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

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

Simple Models

Source

Path + Site

Instrument

Real Earth is far more complex

Circular source

1D (or constant) attenuation structure

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Known – hopefully
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?
11 independent groups submitted preliminary results.

Some outliers - (preliminary, not full QC)

Variation in \( f_c, M_w, \Delta \sigma \) and dependence on ML

spectral ratio assumes \( M_0 \) from ML=M\(_w\), or KK spectral fitting.
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

Submitted fc and Uncertainties, 55 Earthquakes