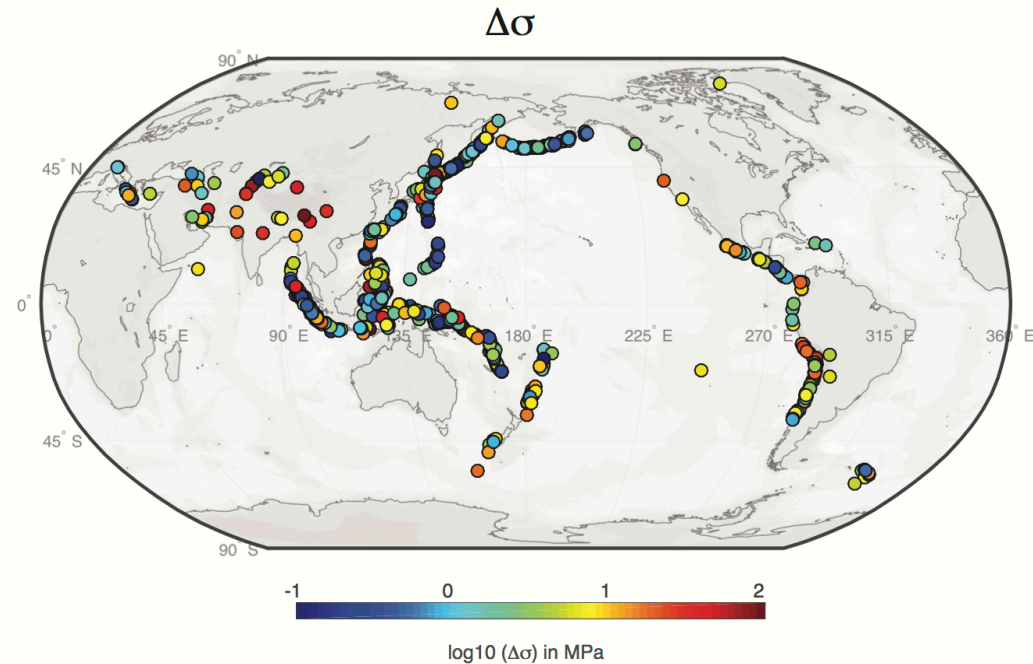
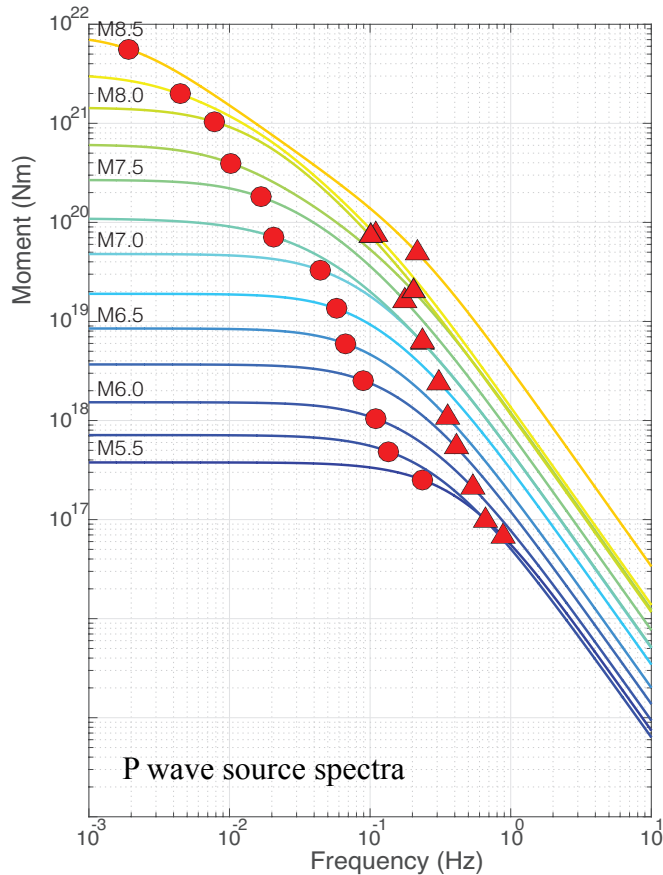


Earthquake Source Scaling

Marine Denolle

Collaborator: Peter Shearer



SCEC - September 10th 2016



Earthquake Self-Similarity

Length (L)

Width (W)

Slip on fault

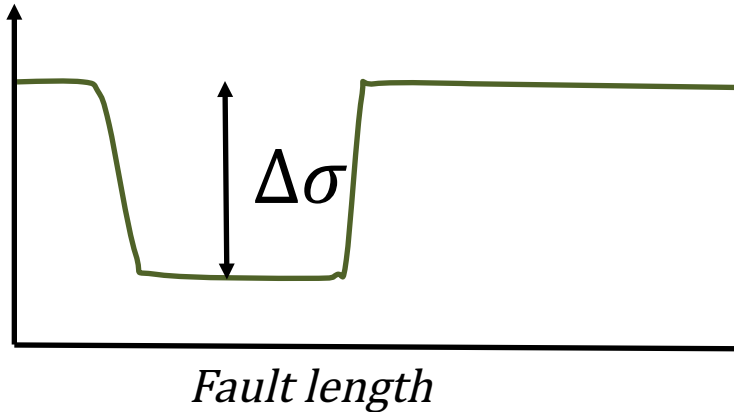


M5

Matryoshka!

Static measures of earthquakes

- Static stress drop $\Delta\sigma$ = difference between the stress on the fault before and after the earthquake.



Stress \propto strain

$$\Delta\sigma \propto \mu \frac{D}{W}$$

Geometry of the fault dictates strain

At 15 km depth, lithostatic pressure is about 400MPa.

$D = 1\text{m}$, $W = 10\text{ km}$, $\mu = 1\text{E}10\text{ Pa}$, $\Delta\sigma = 1\text{MPa}$.

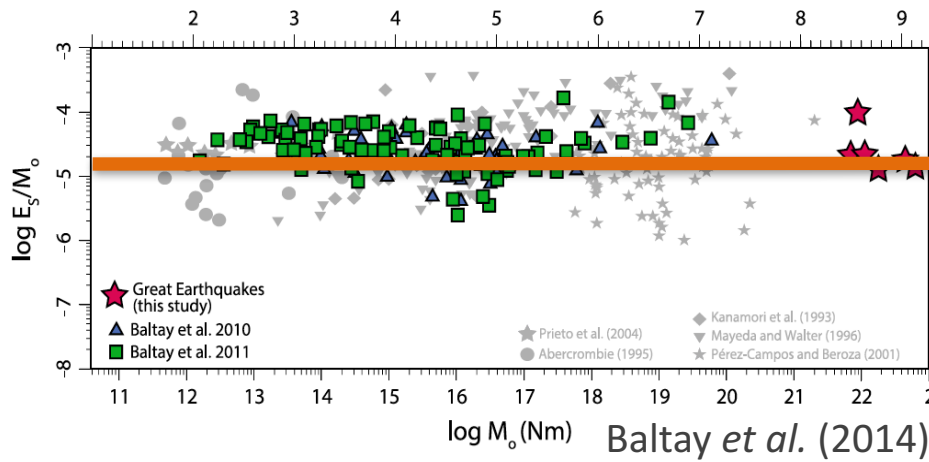
Are stress drops similar for small earthquakes and for large earthquakes?

Dynamic measures of earthquakes

- Kinetic energy carried by seismic waves $E_R = \rho c \int V^2(t) dt$ (strong ground motion)
- Fast/high stress drop earthquakes radiated more than slow/low stress drop earthquakes.
- E_R/M_0 is scaled energy

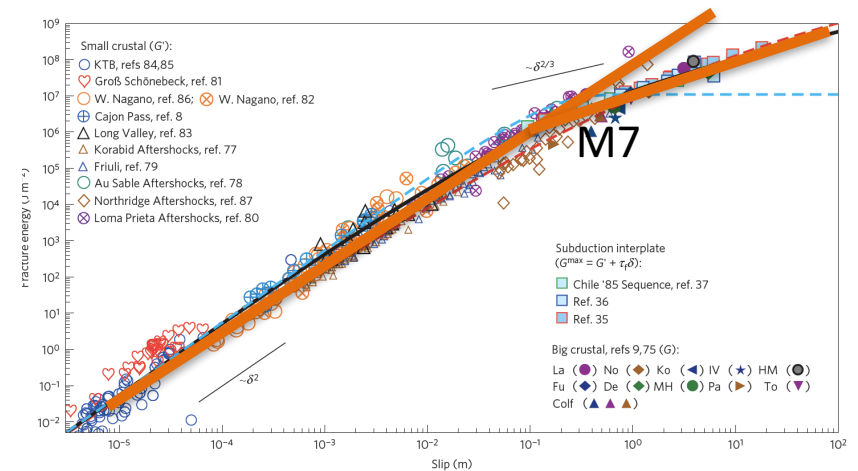
Do large earthquakes radiate, proportional to their size, more seismic waves?

Yes ?



$$E_R/M_0$$

No ?

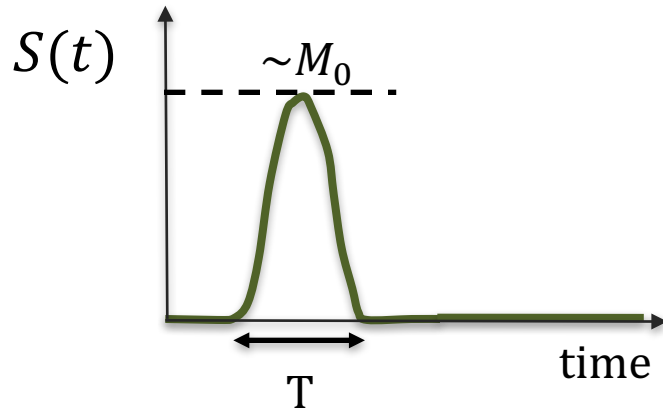


Viesca and Garagash (2015)

$$G \propto (\Delta\sigma/2 - \mu E_R/M_0) S$$

Seismic Observations

Far-field displacement seismogram



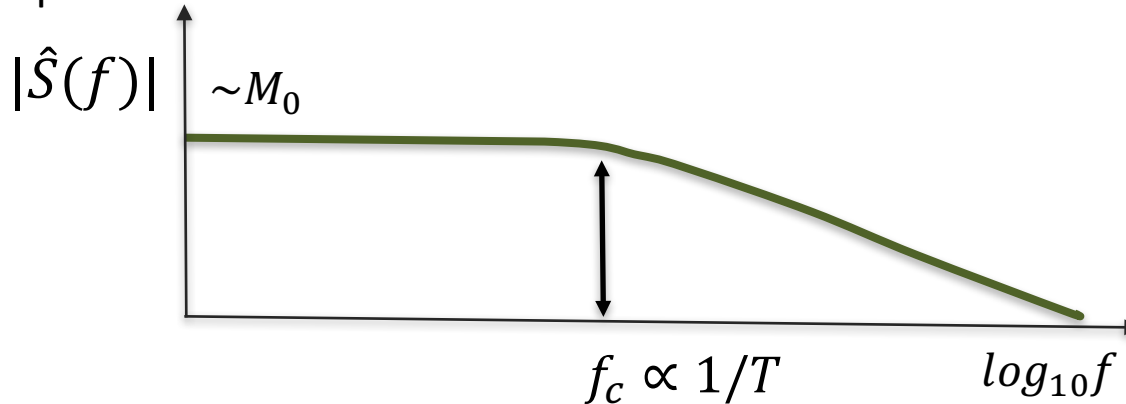
$$M_0 = \mu DA$$

μ rigidity ($\sim 10\text{GPa}$)
D displacement
A fault area (WL?)

$$L \propto T, W \propto T, D \propto T$$

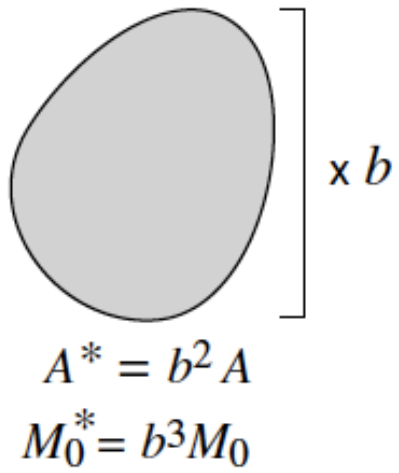
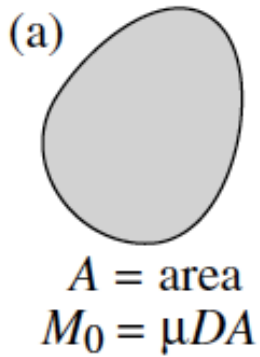
$$\rightarrow M_0 \propto T^3$$

Source spectrum

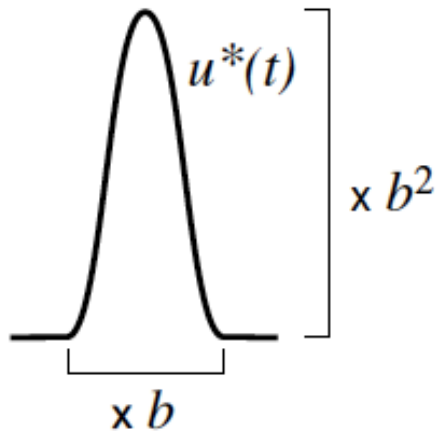
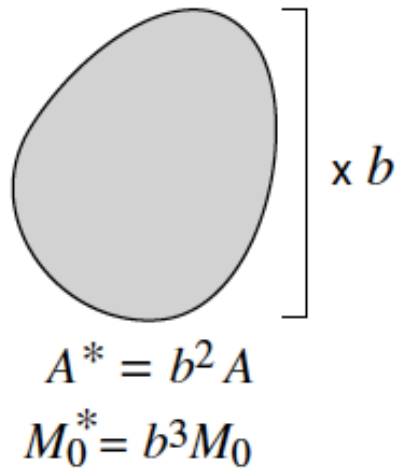
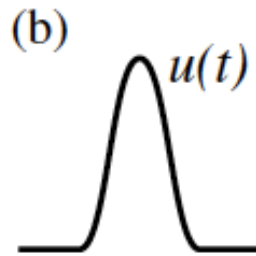
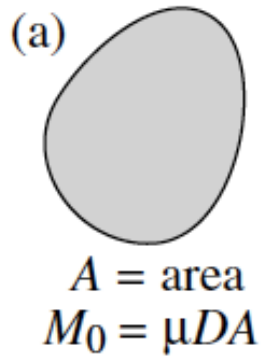


$$\rightarrow M_0 \propto f_c^{-3}$$

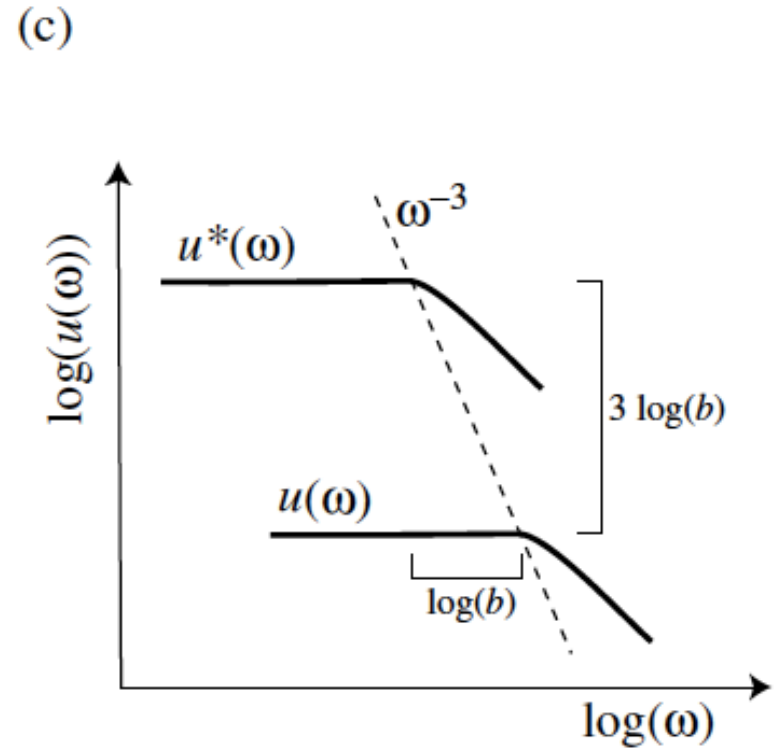
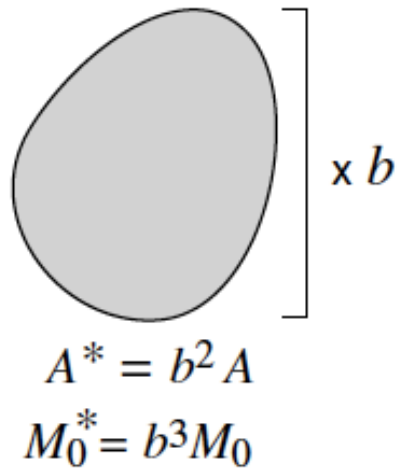
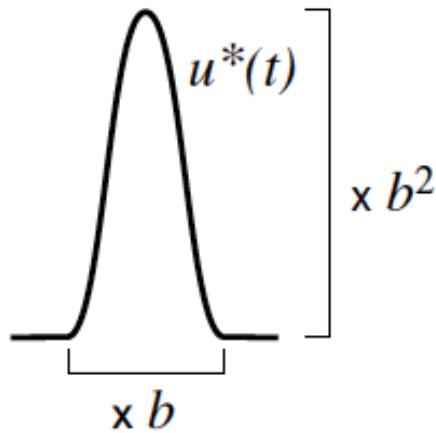
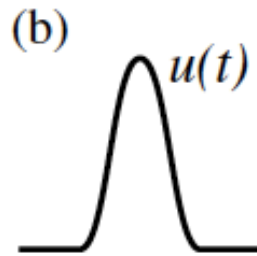
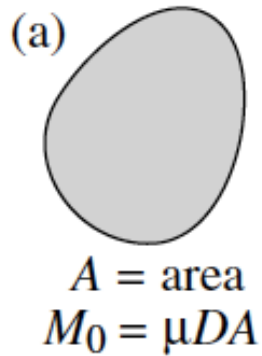
Earthquake scaling



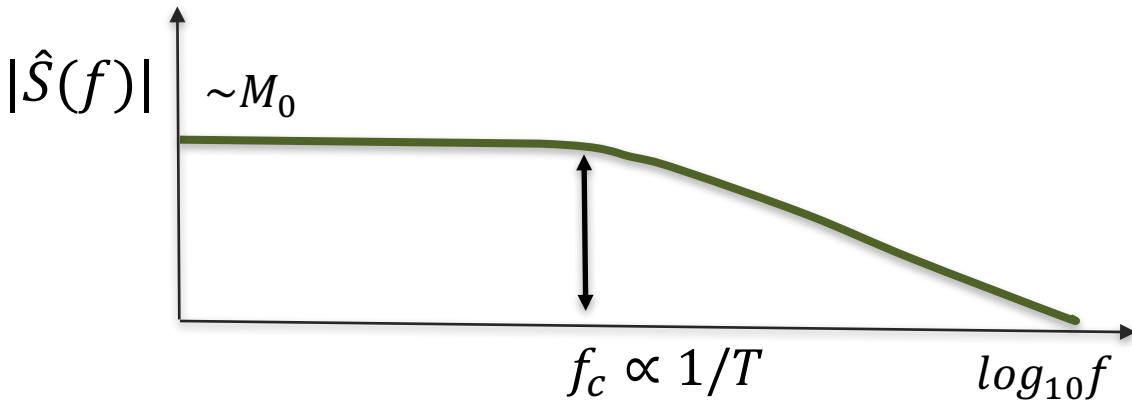
Earthquake scaling



Earthquake scaling



Measures of stress drop and radiated energy



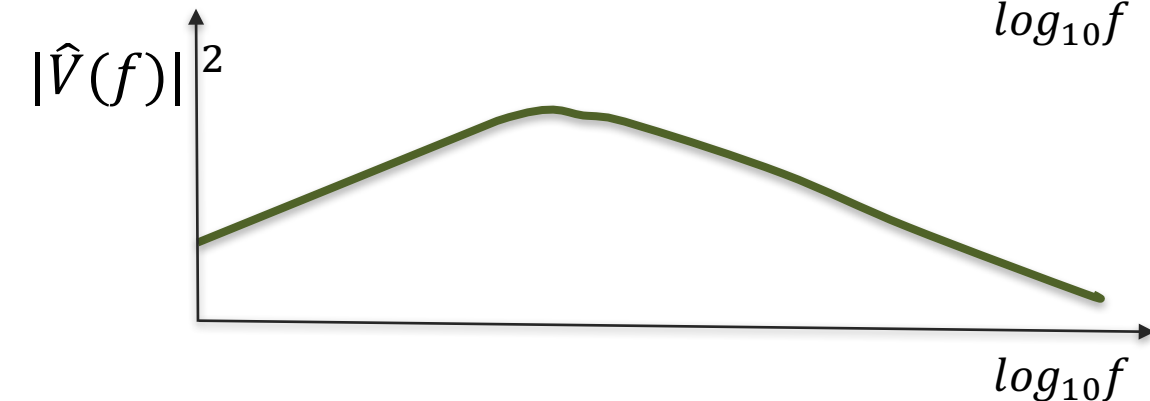
$$1) \quad L = V_r T = V_r / f_c$$

$$2) \quad M_0 = \mu D L^2$$

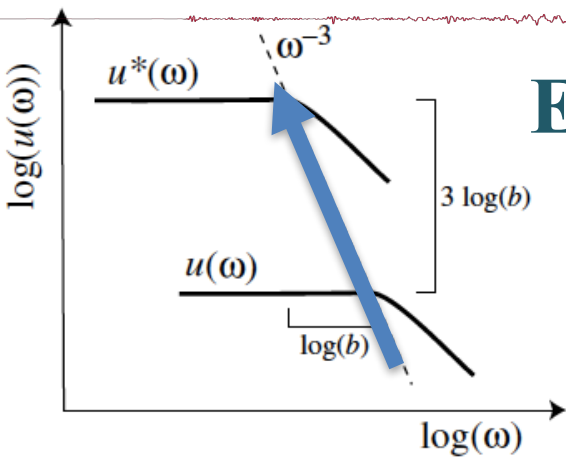
$$3) \quad \Delta\sigma = \frac{M_0}{L^3} = \frac{M_0}{V_r^3} f_c^3$$



$$E_R = \rho c \int |\hat{V}(f)|^2 df$$

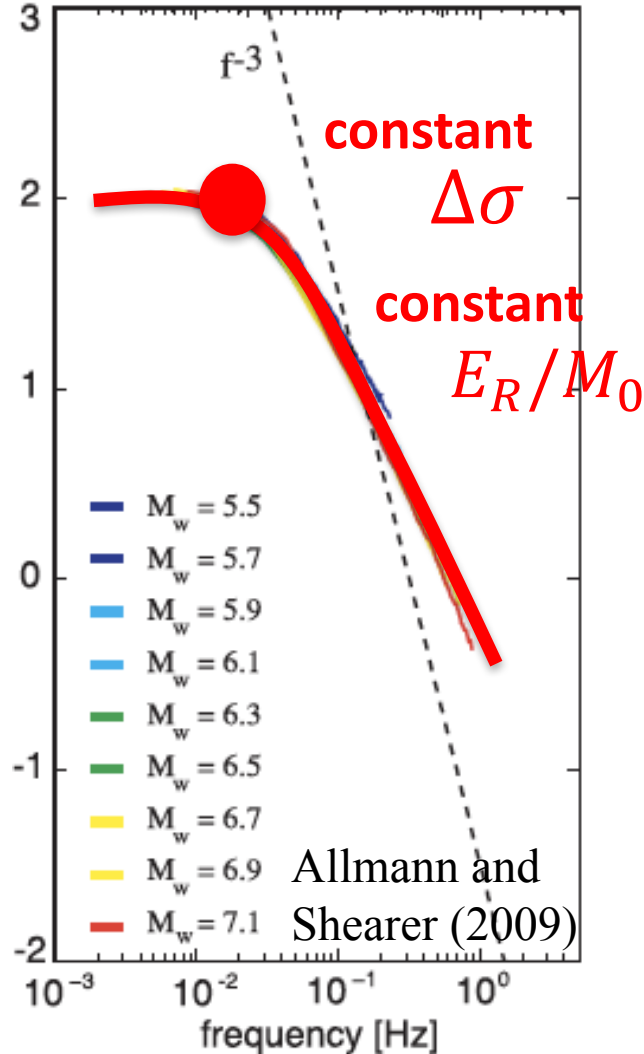


Earthquake Self-Similarity



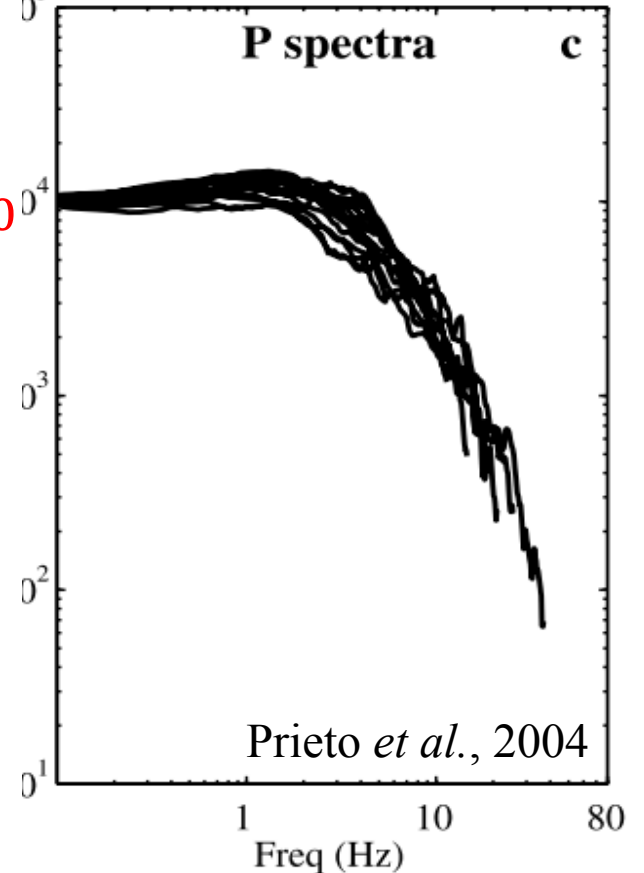
Prieto *et al.* (2004)

Global scale: M 5.5-7.1



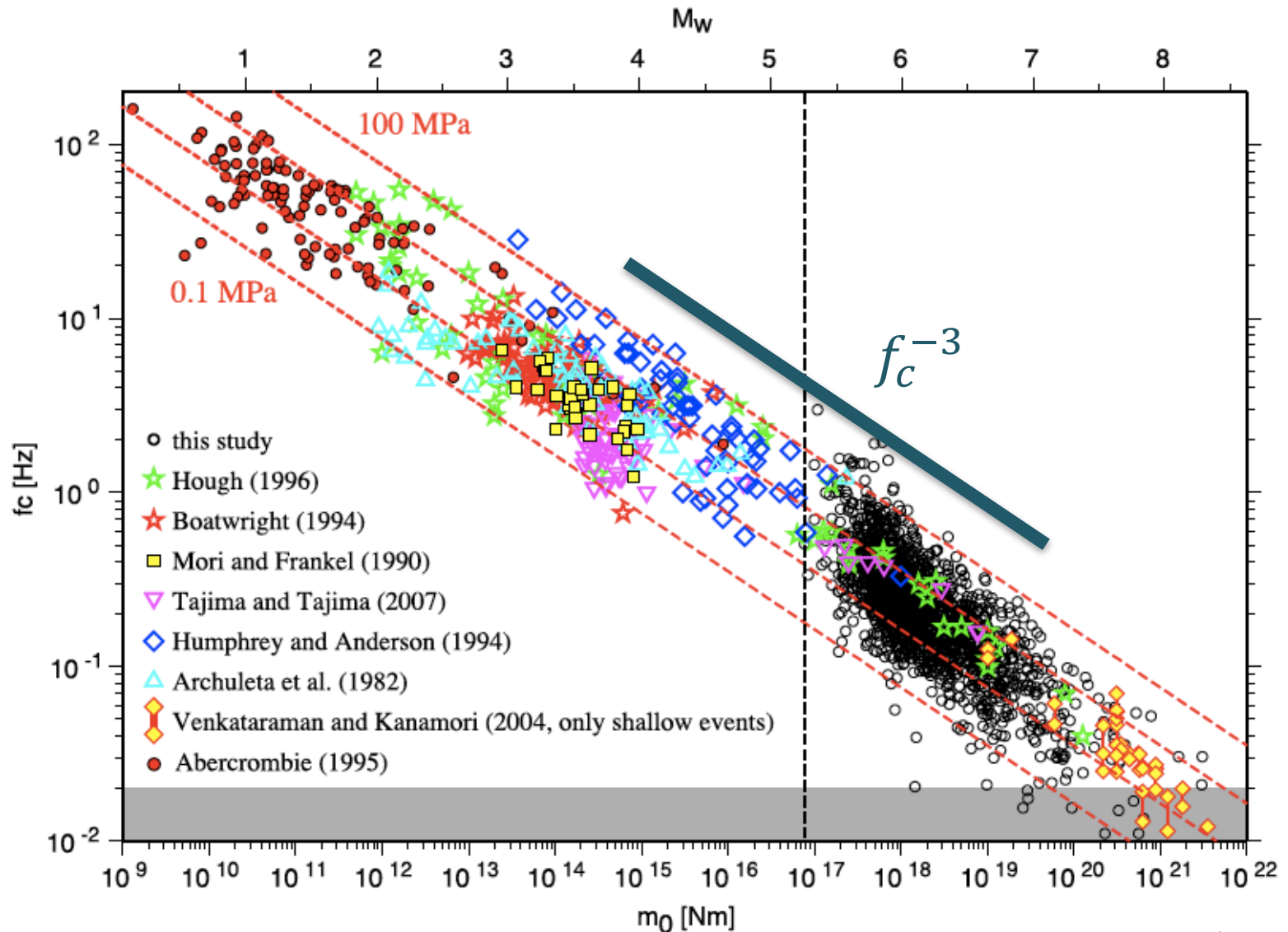
Allmann and Shearer (2009)

Local scale: M 0.5-3.4



Prieto *et al.*, 2004

Comprehensive view: independent data sets, independent methods



Allmann and Shearer (2009)



Main question: are earthquakes self-similar?

1. Source duration T follows a scaling $M_0 \sim T^3$
2. Source spectrum shape is identical (if shifted)

1. and 2.



$\Delta\sigma$ and E_R/M_0 are invariant with earthquake sizes

Conclusion for today: **NO**

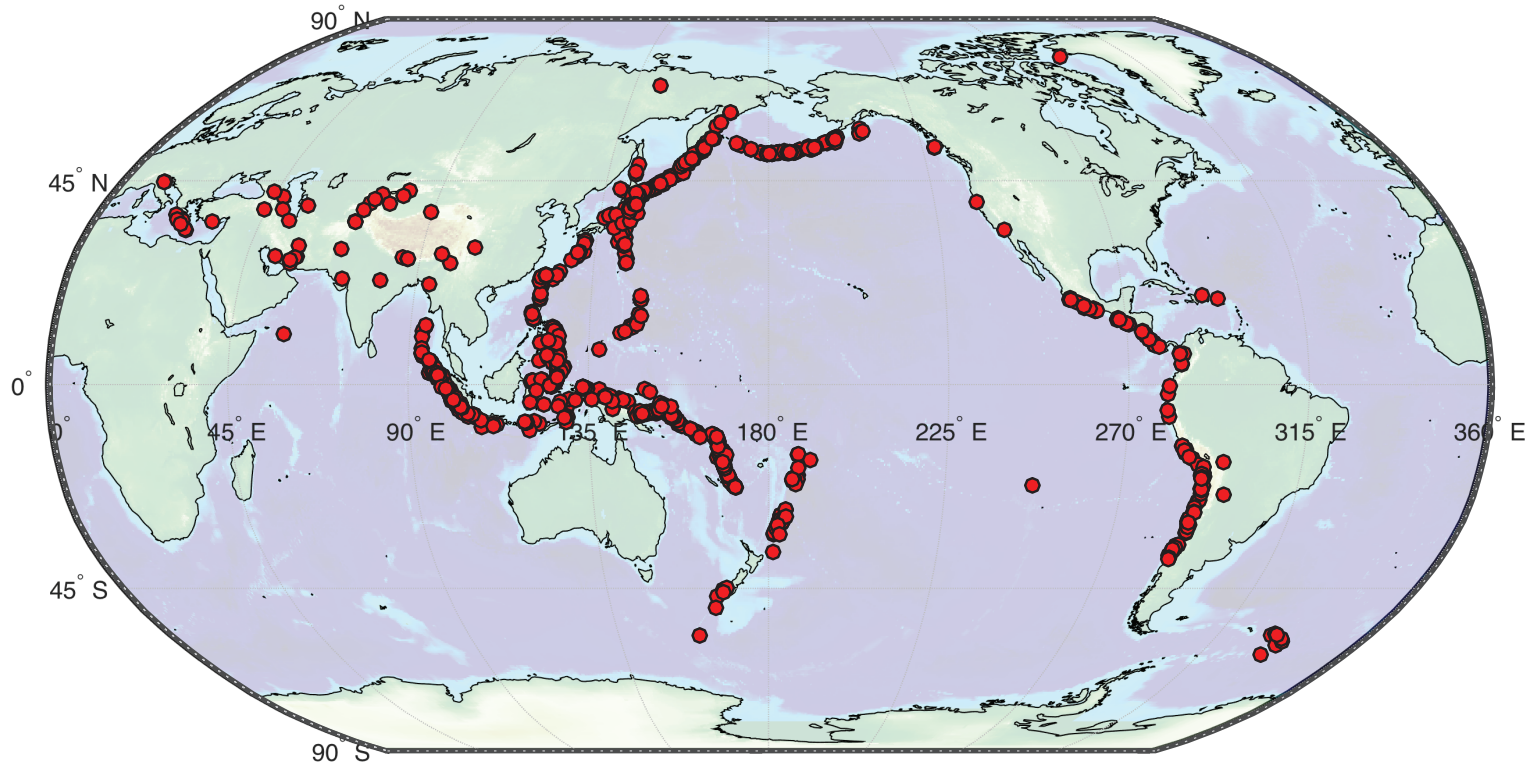
1. and 2.



$\Delta\sigma$ and E_R/M_0 are invariant with earthquake sizes



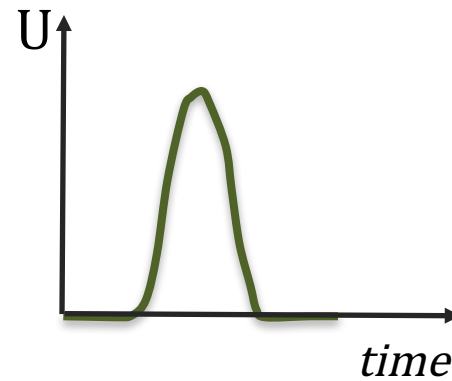
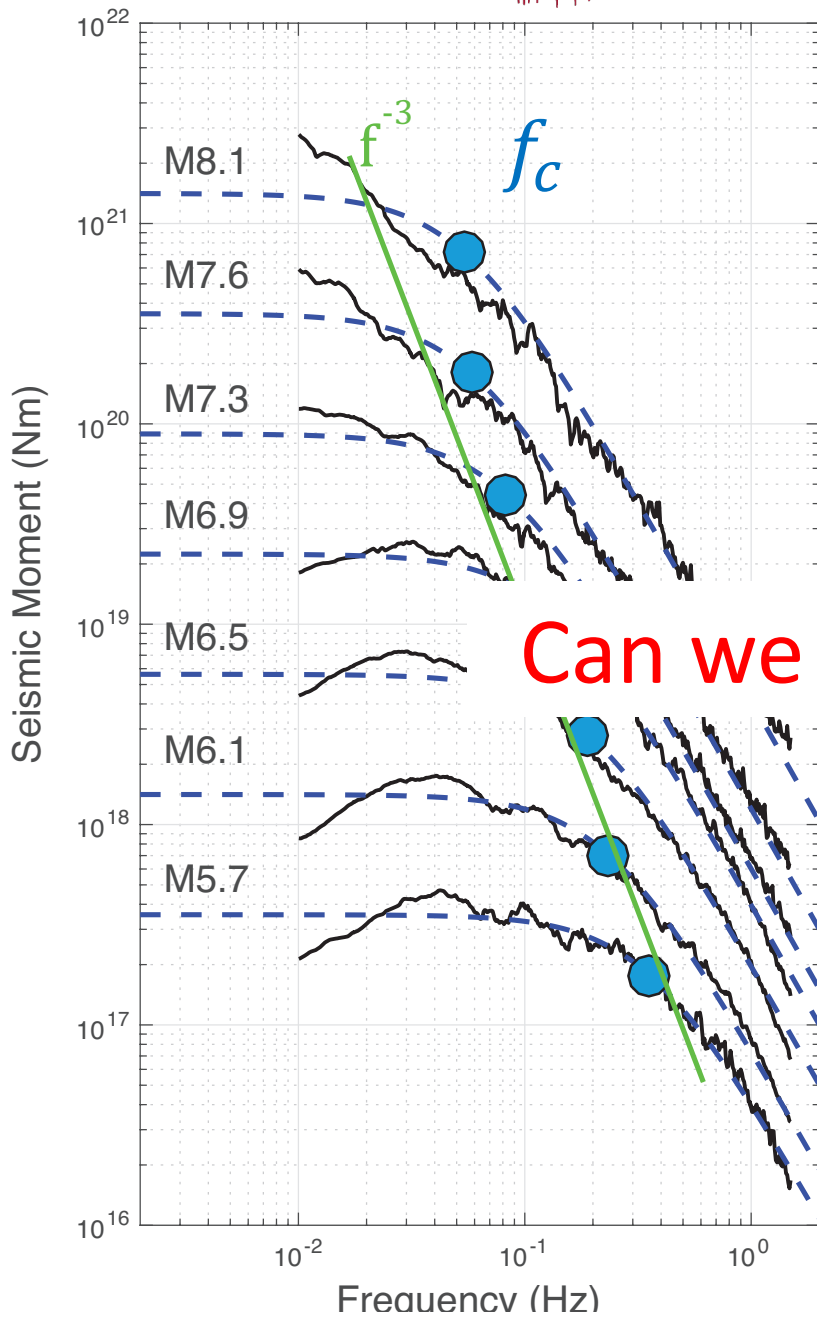
Global catalog of M5.5+ since 1990



800+ $M < 7$

126 $M > 7$

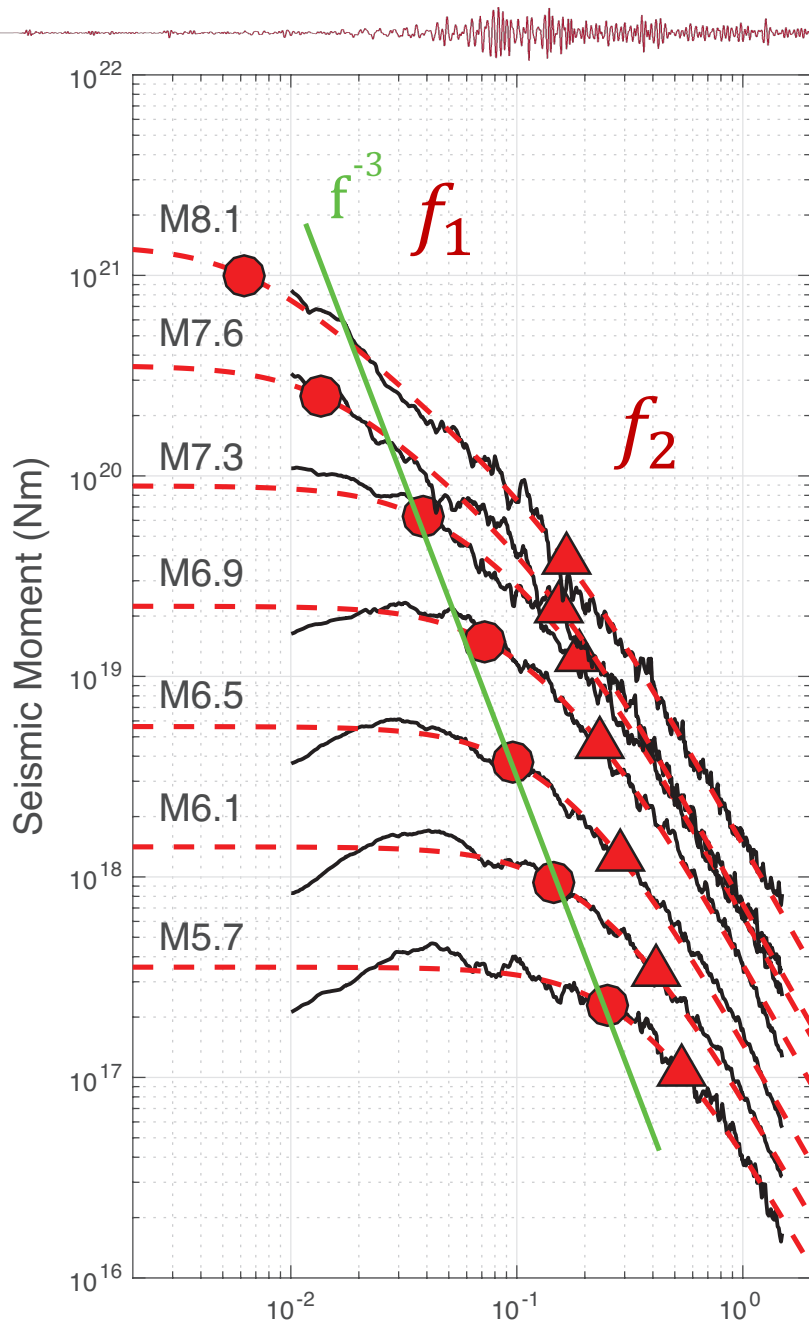
15 $M > 8$



Can we do better?

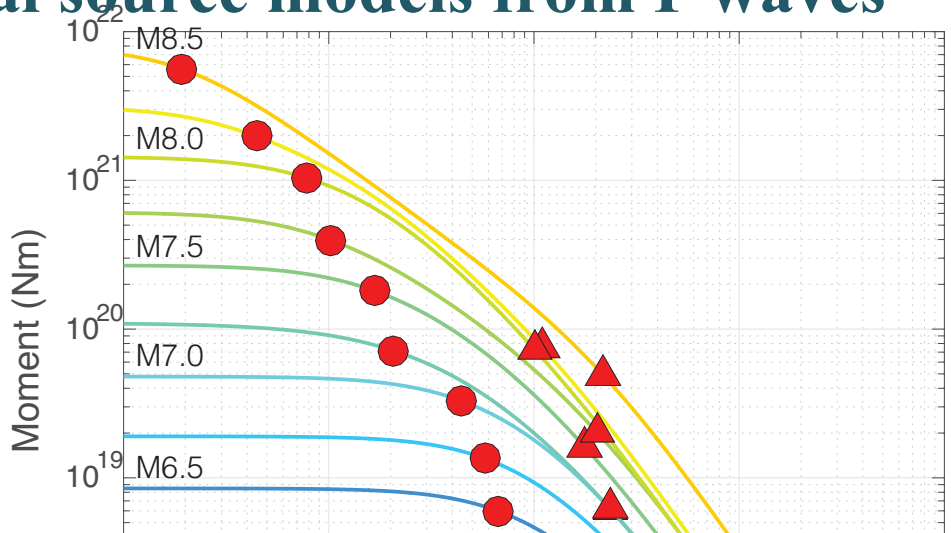
M_c

(f_c)

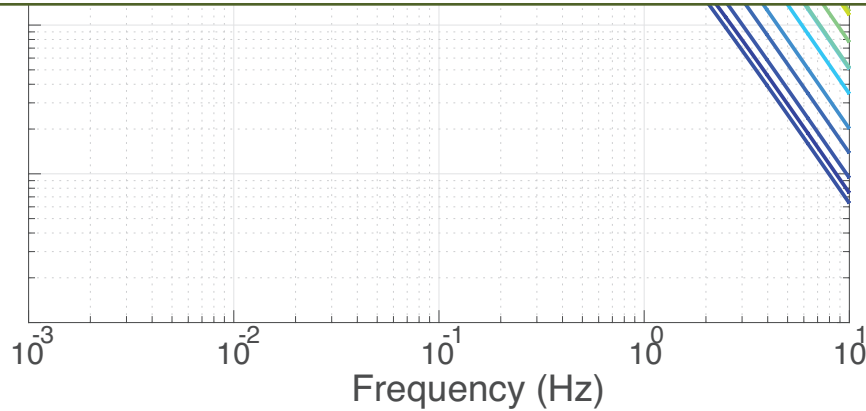


$$S(f) = \frac{M_0}{\sqrt{1 + \left(\frac{f}{f_1}\right)^2} \sqrt{1 + \left(\frac{f}{f_2}\right)^2}}$$

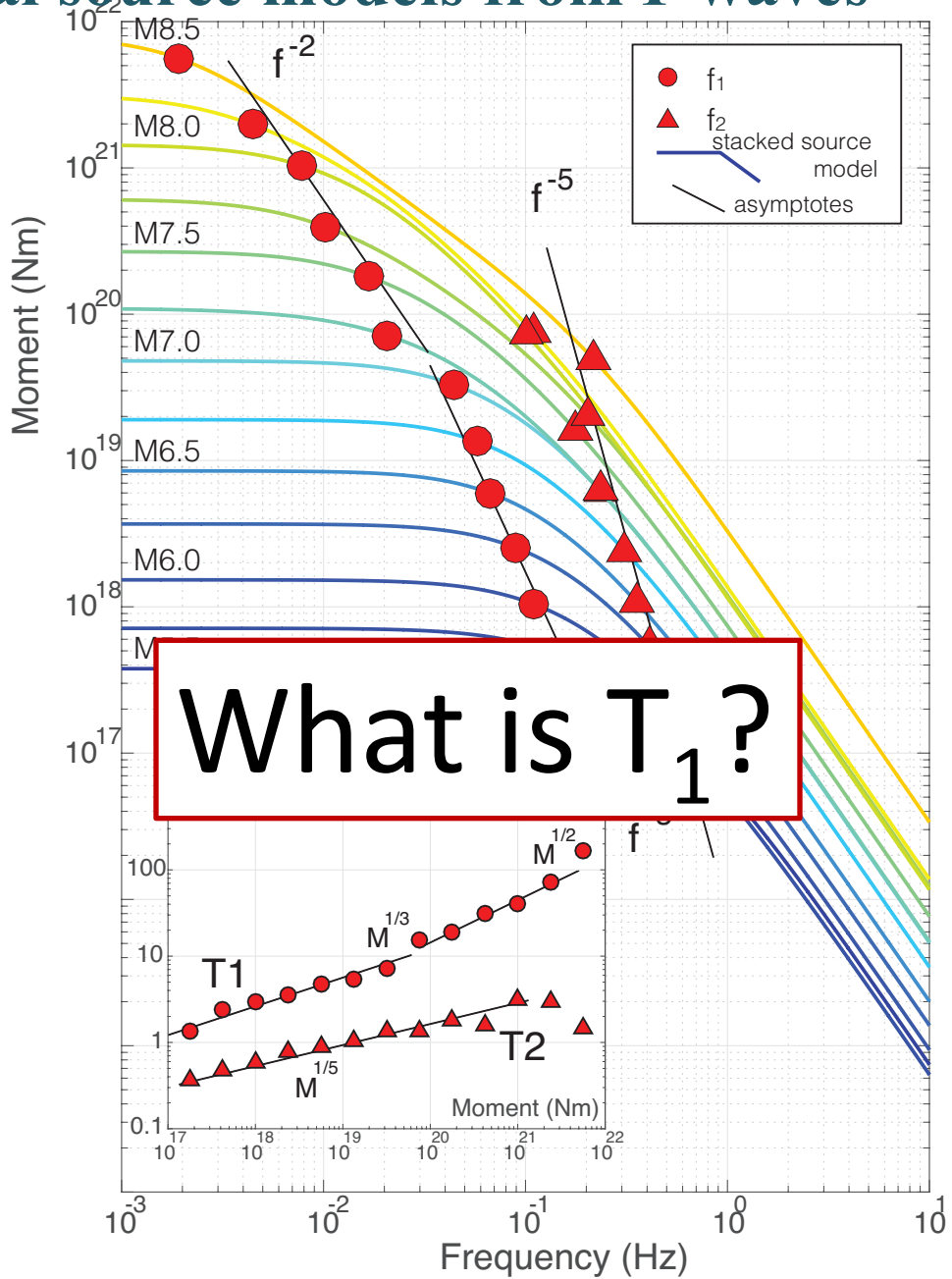
Best-fit global source models from P waves



Variable spectral shapes breaks self-similarity

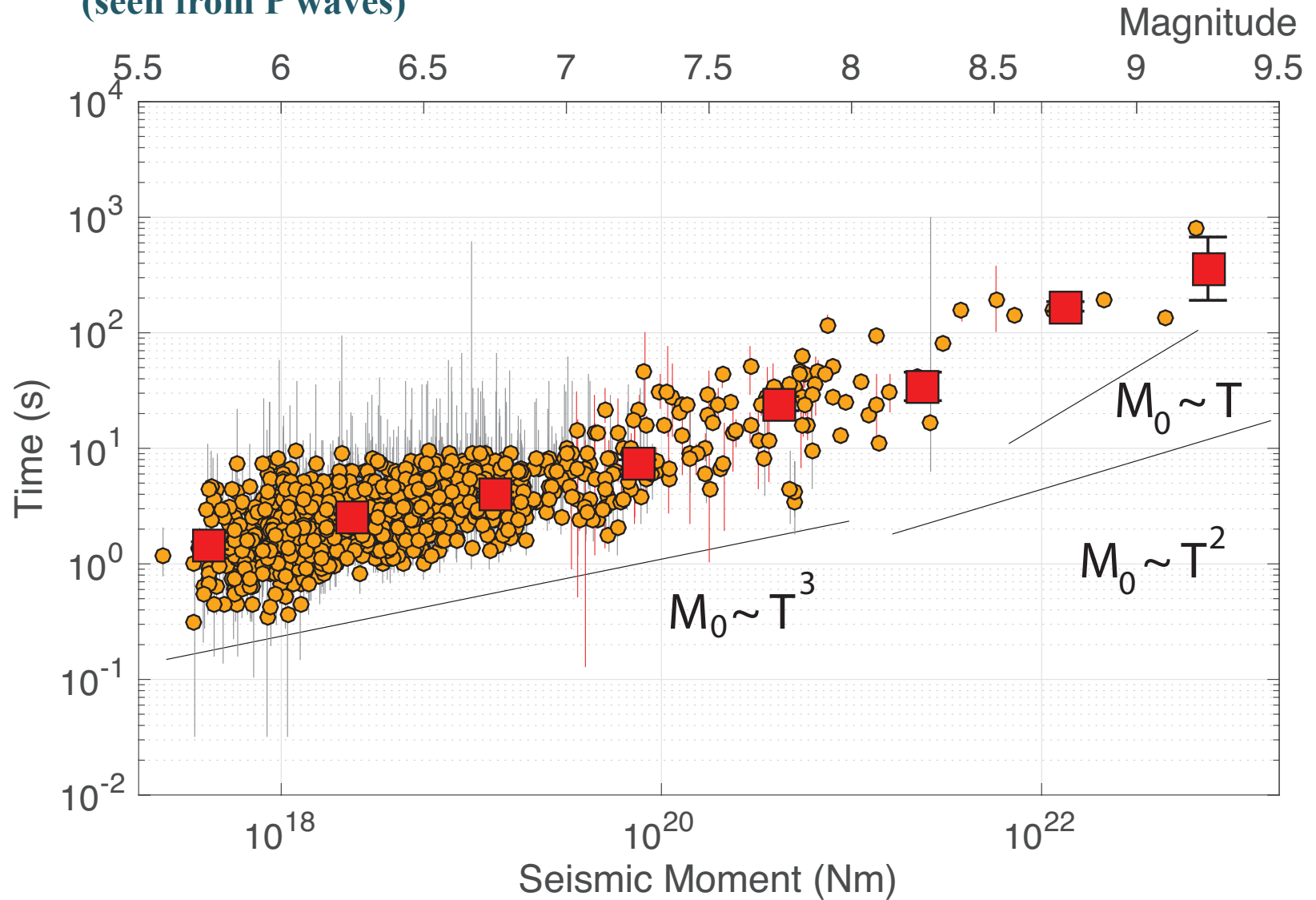


Best-fit global source models from P waves



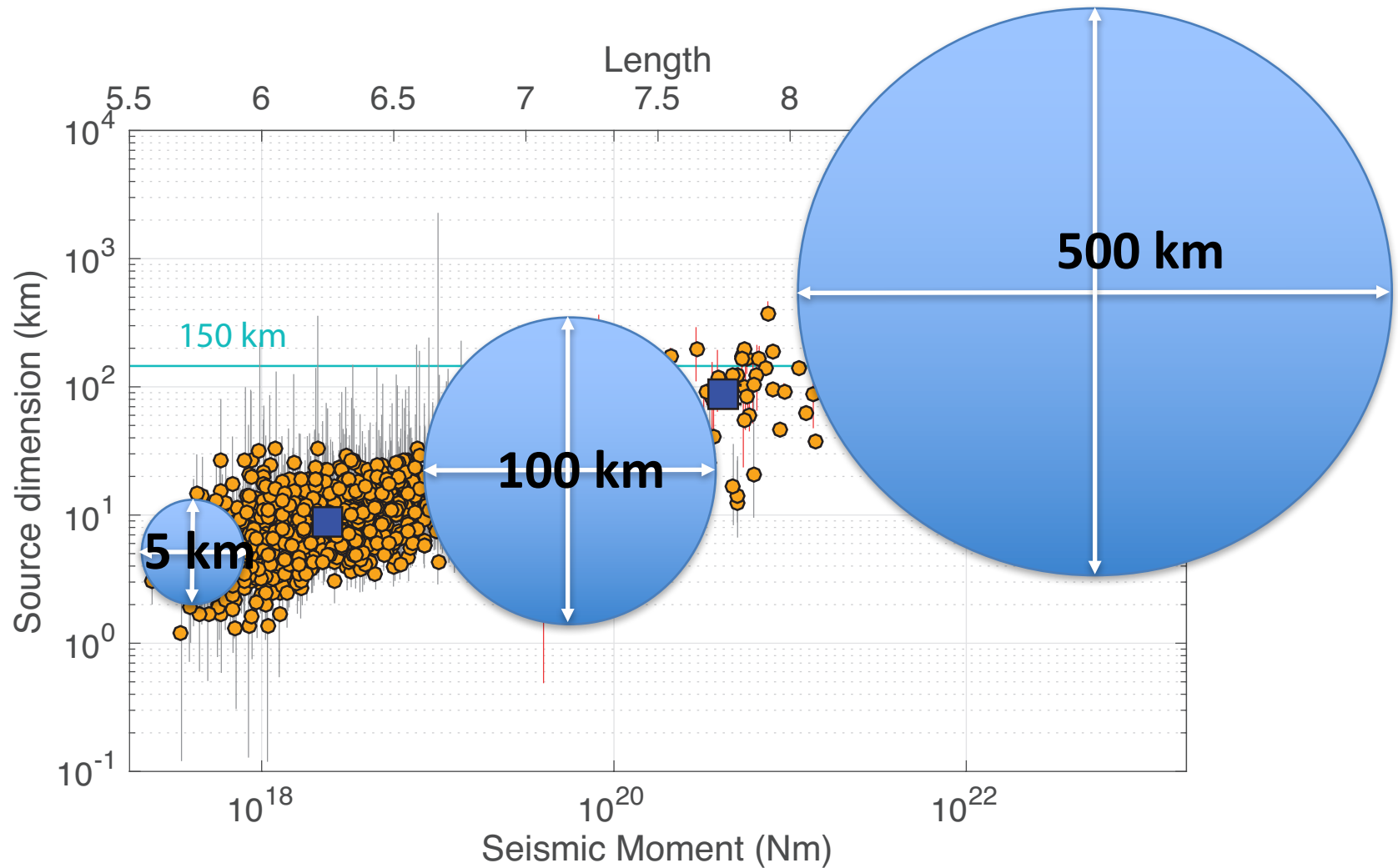
T₁ source duration

(seen from P waves)



source dimension

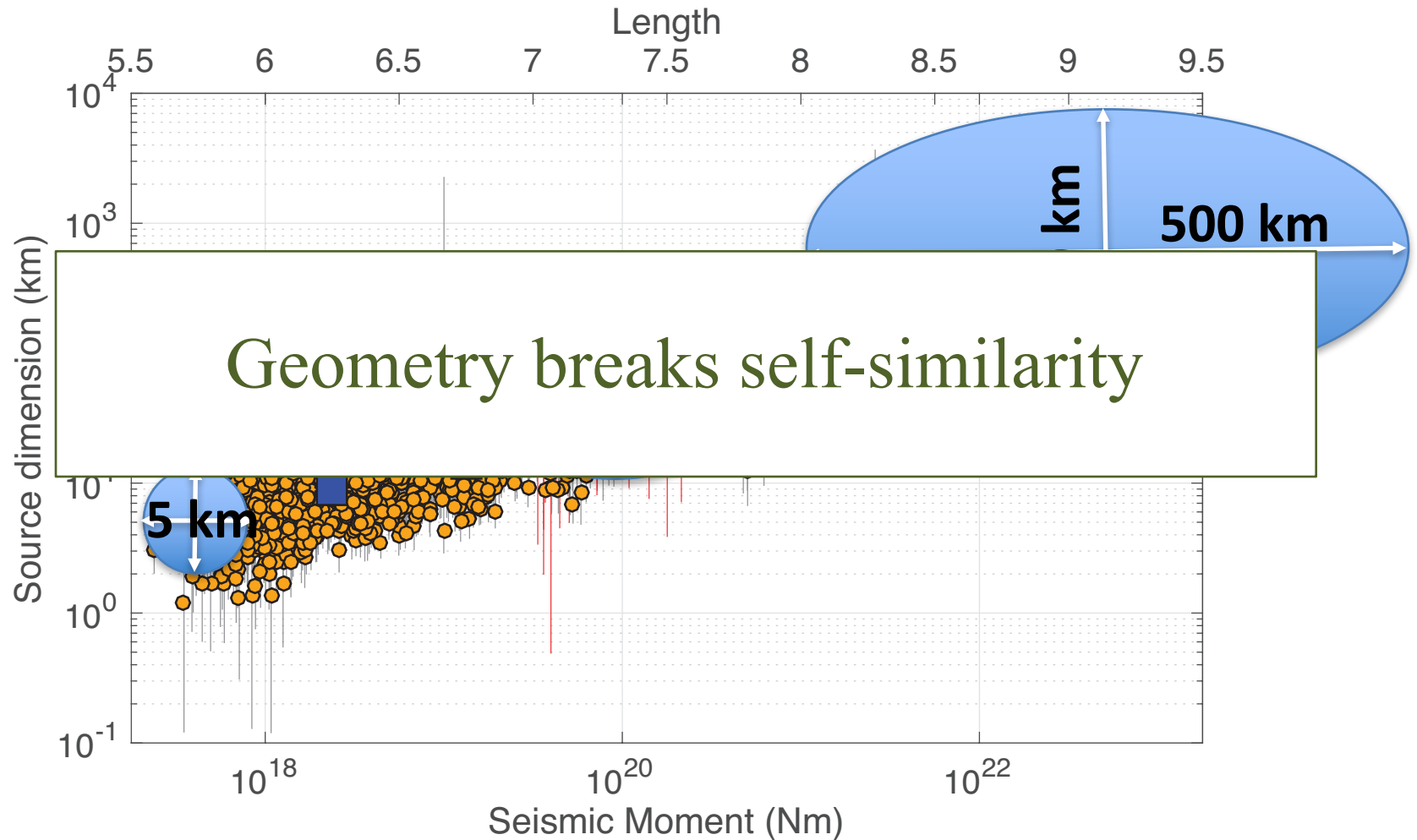
Fault dimension $L \propto T$



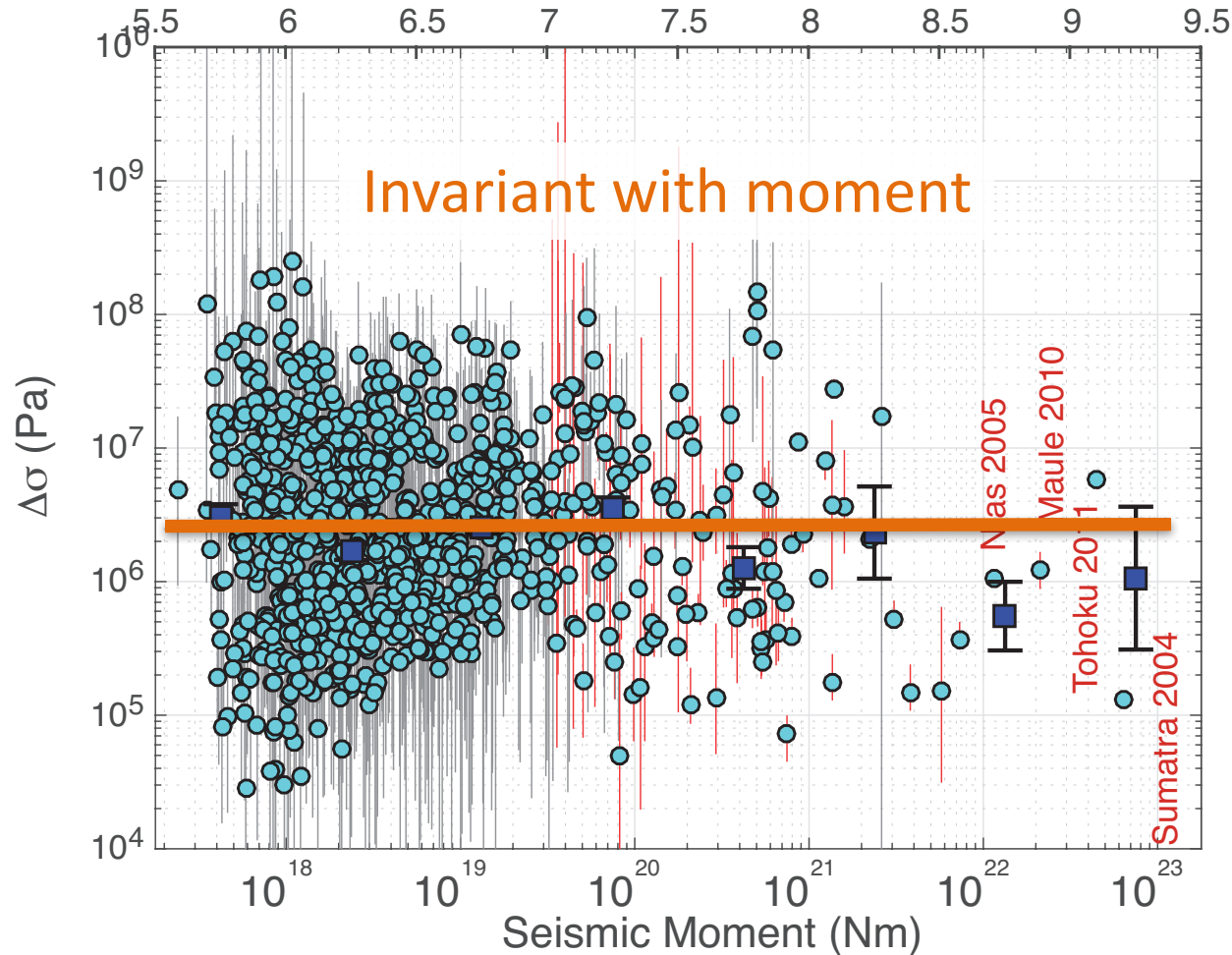
source dimension

Width dimension $W \sim L^{2/3}$ (Leonard, 2010)

Fault dimension $L \propto T$



Stress drop with moment

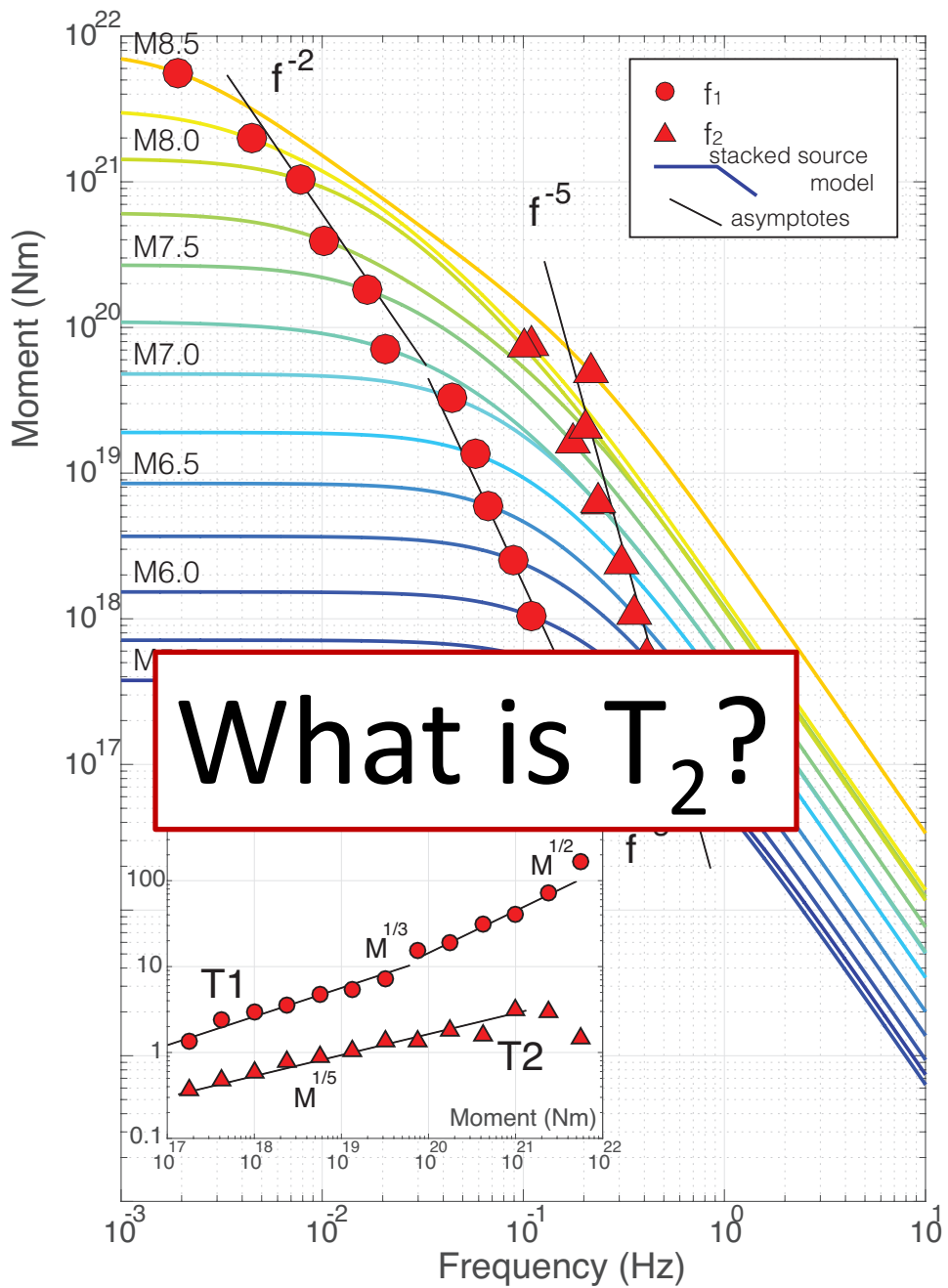


Median is 1.9MPa.

M9 2011 Tohoku $\Delta\sigma \sim 8\text{MPa}$ (similar to Brown *et al.*, 2015)

M9 2004 Sumatra $\Delta\sigma \sim 0.1\text{MPa}$

M8.5 2010 Maule, M8.7 2005 Nias $\Delta\sigma \sim 1\text{MPa}$



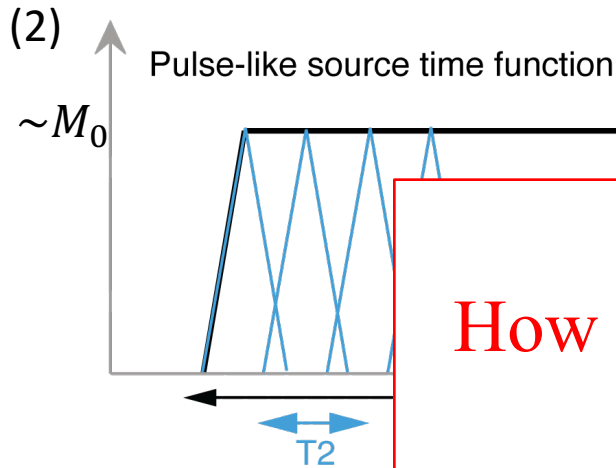
What is the other time scale, T_2 ?

(1) T_2 varies between 0.5s and 5s

$T_2 \propto W$? \rightarrow too short

what we know

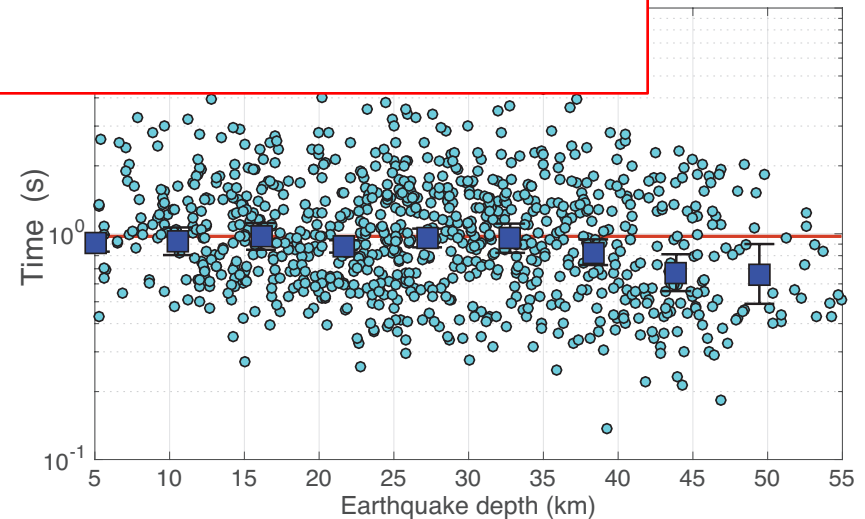
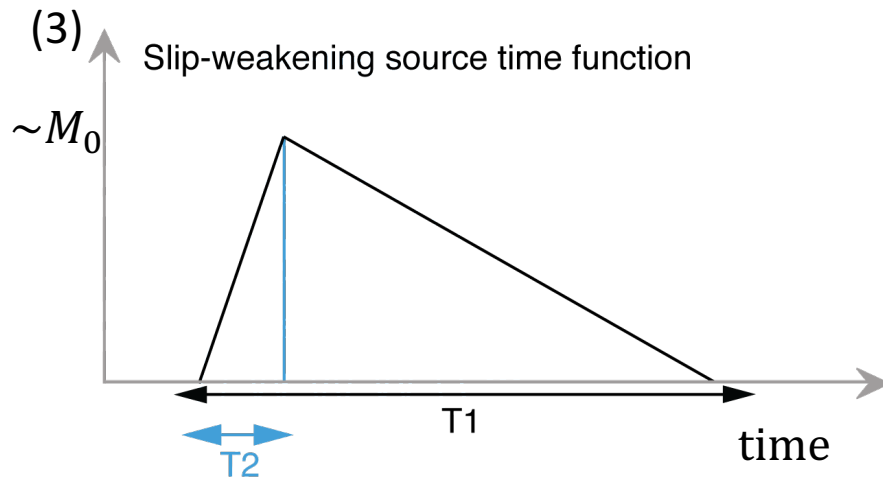
1. T_2 varies with moment.



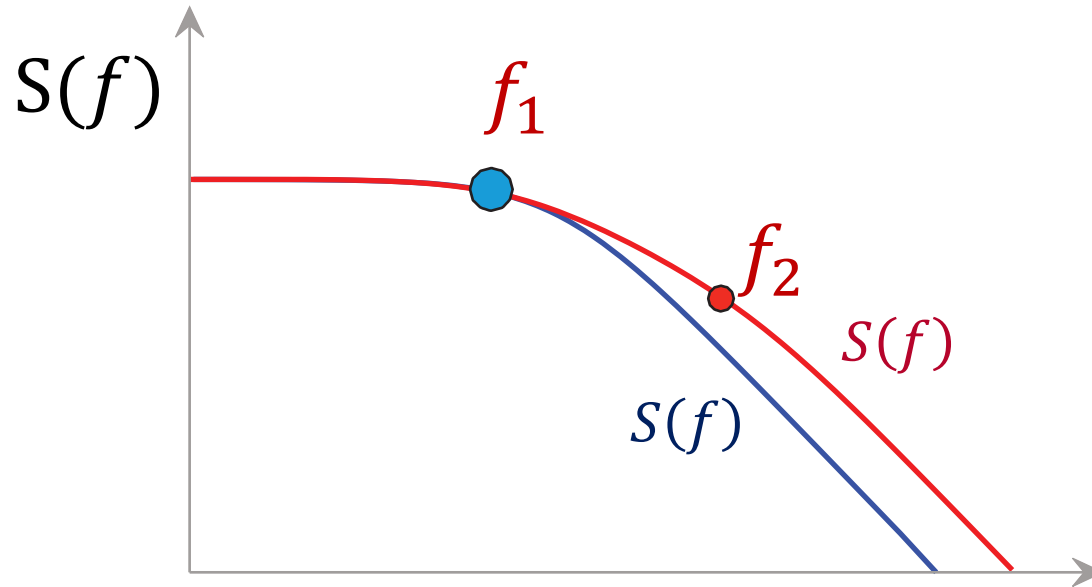
$$T_2 \propto M^{1/5}$$

How does T_2 affects radiated energy?

depth.



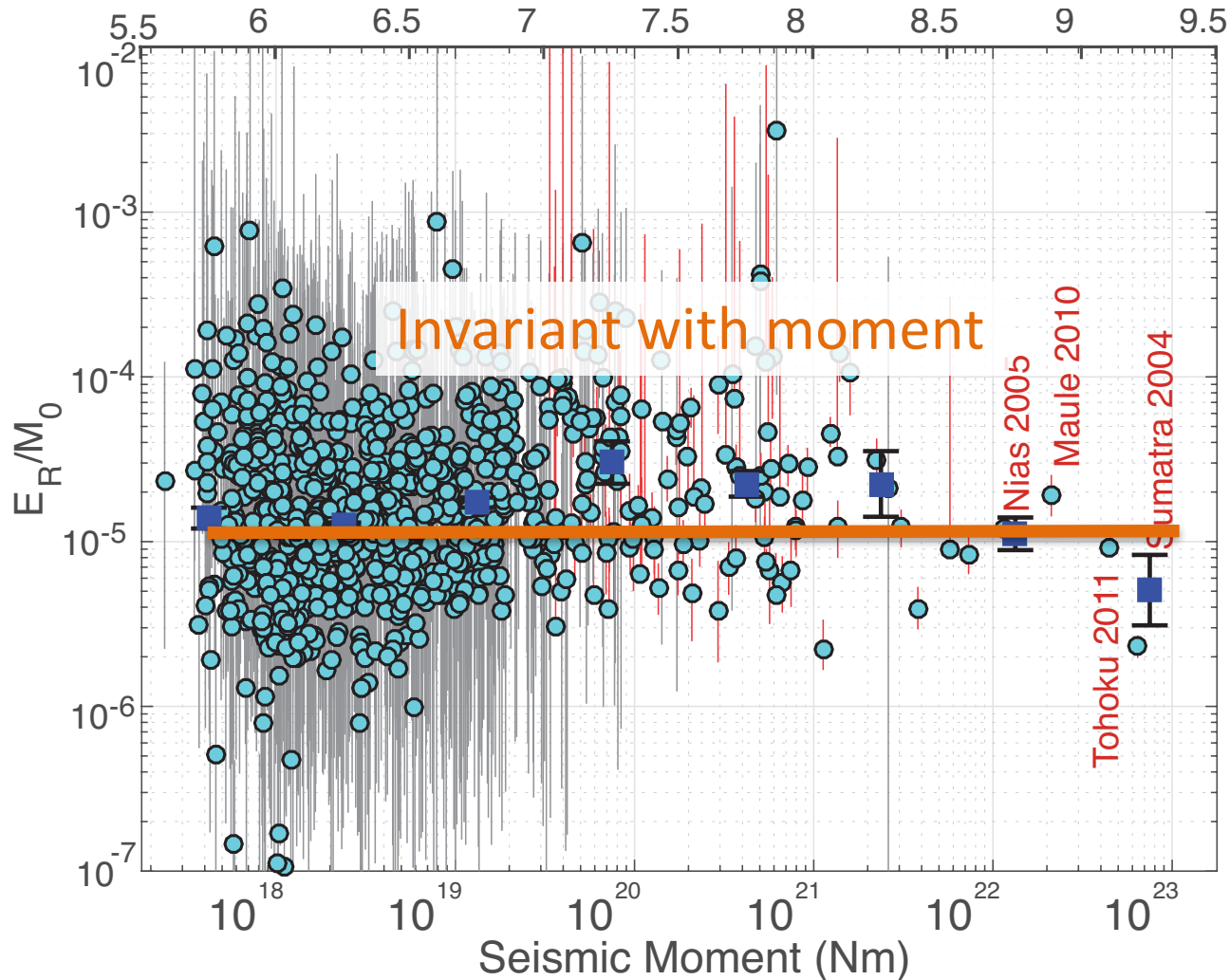
Radiated energy



$$E_R = \int |f S(f)|^2 df$$

$$E_R > E_R$$

Radiated energy with moment



Median is
 $\frac{E_R}{M_0} = 1.5E-5 \text{ J/N/m.}$

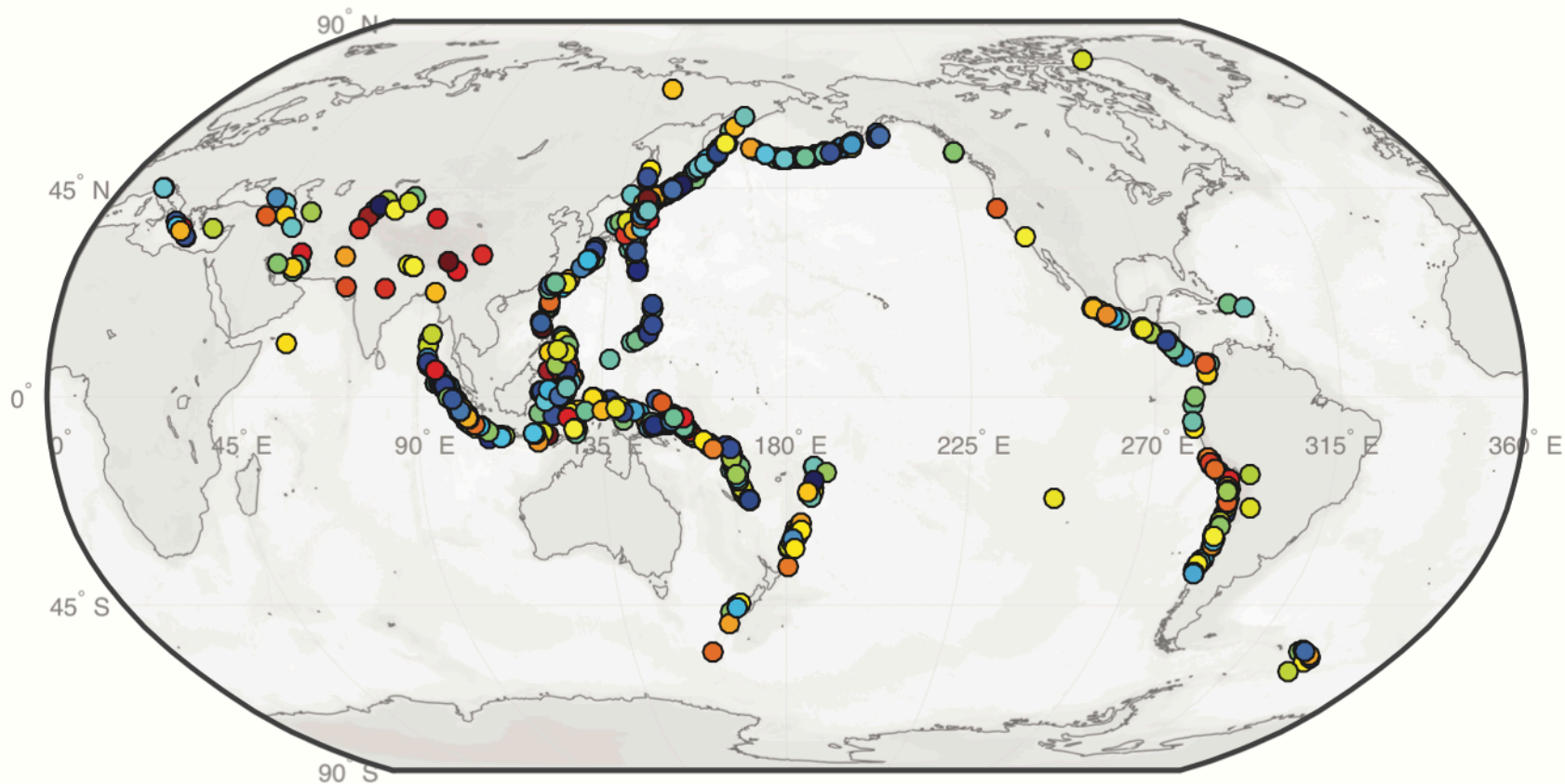
$$\tau_a = \mu \frac{E_R}{M_0}$$

$$\mu = 39 \text{ GPa}$$

Median is
 $\tau_a = 0.6 \text{ MPa}$



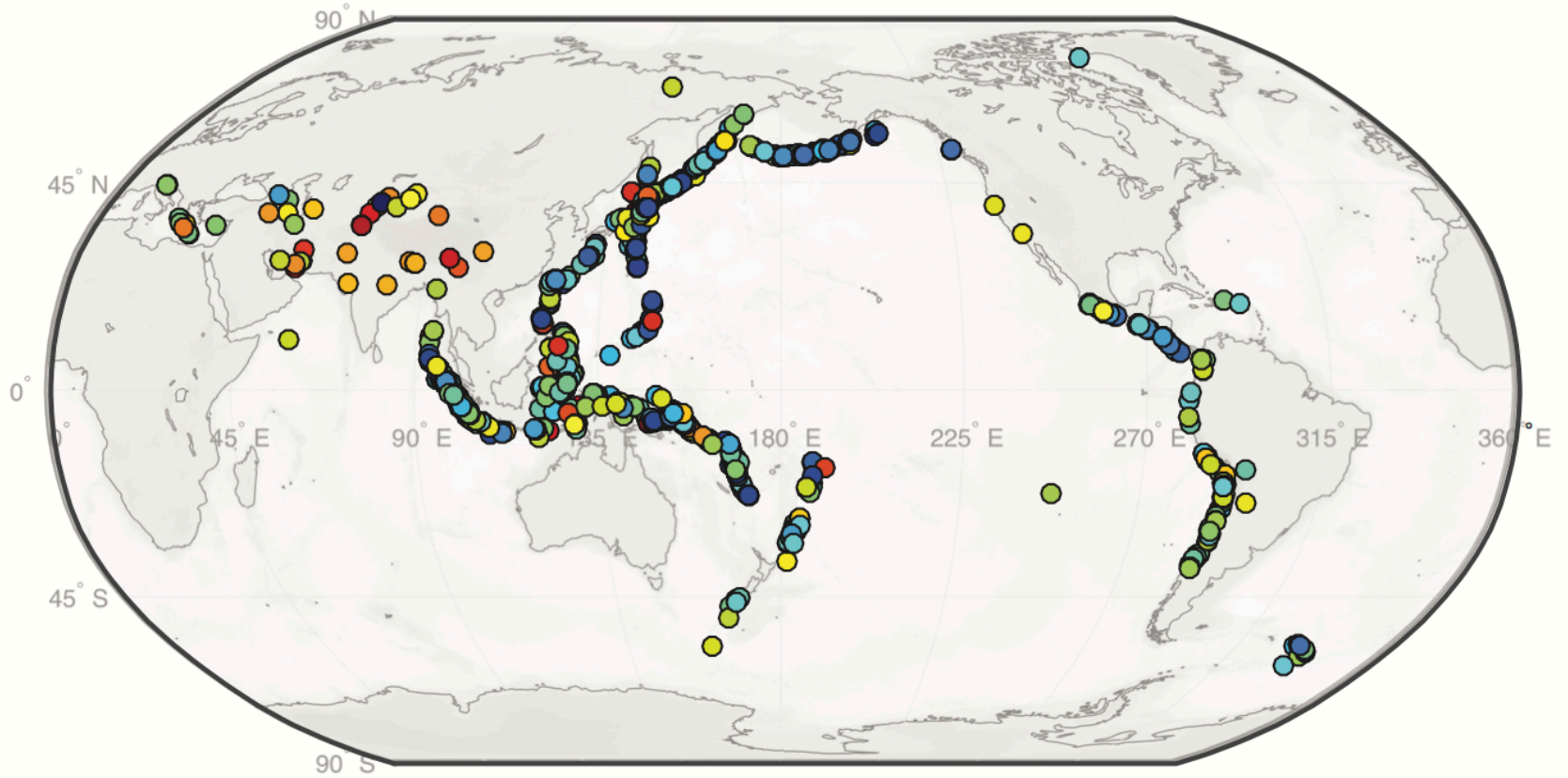
$\Delta\sigma$



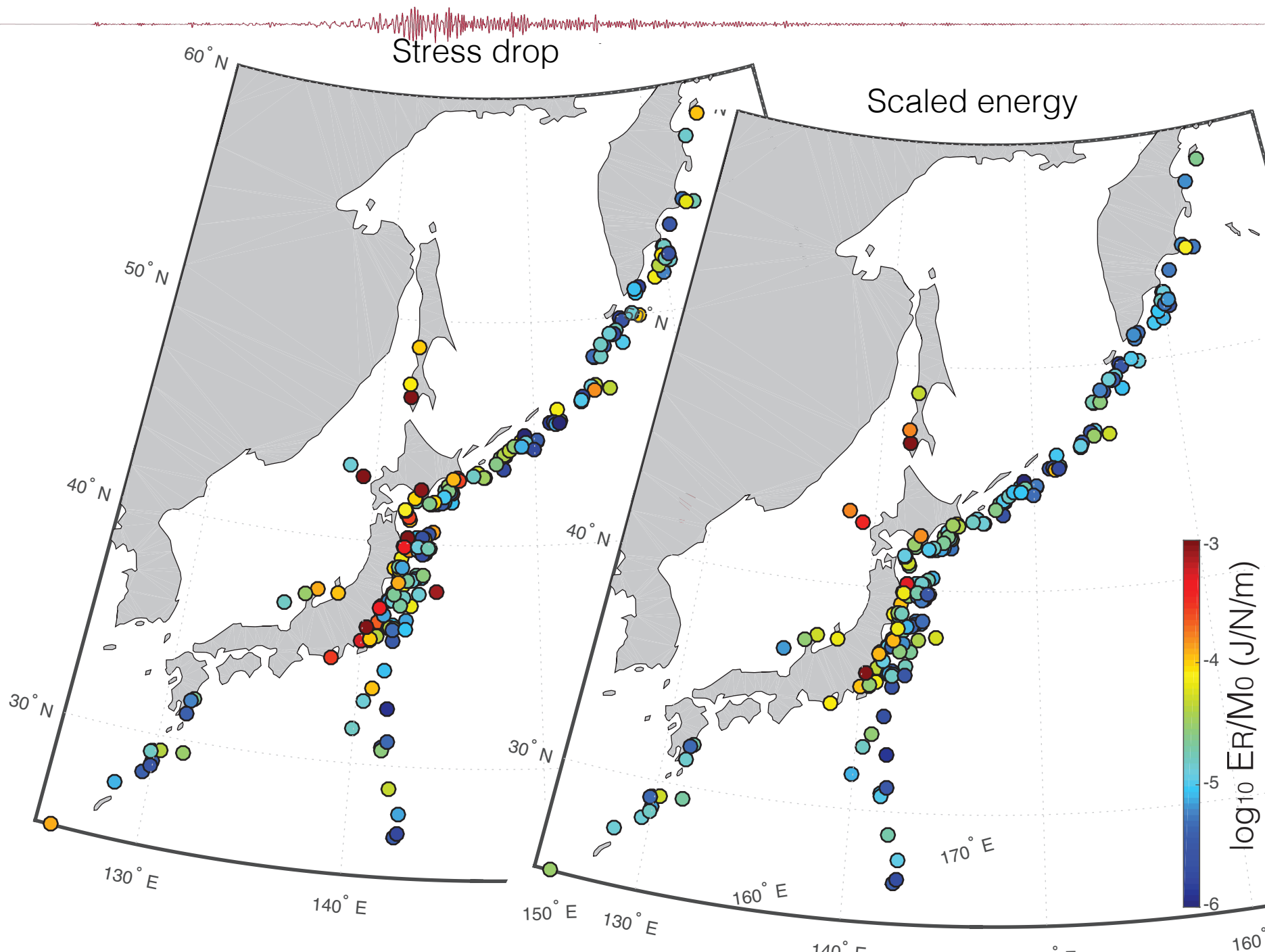
$\log_{10}(\Delta\sigma)$ in MPa



ER/M₀



$\log_{10} (ER/M_0) \text{ (J/m/N)}$





Earthquake Self-Similarity

1. Source duration T follows a scaling $M_0 \sim T^3$ until the fault reaches a natural boundary (free surface – brittle-ductile transition zone)
2. Source spectrum shape is NOT identical (if shifted). It has an intermediate slope that increases radiation

Conclusion for today

$\Delta\sigma$ and E_R/M_0 are invariant (or weakly variant) with earthquake size

BUT

This does not imply self-similarity

Outstanding questions

1. What is T_2 ? Pulse-like ruptures or dynamic weakening?
2. Do strike slip and normal faults exhibit similar spectral shape?