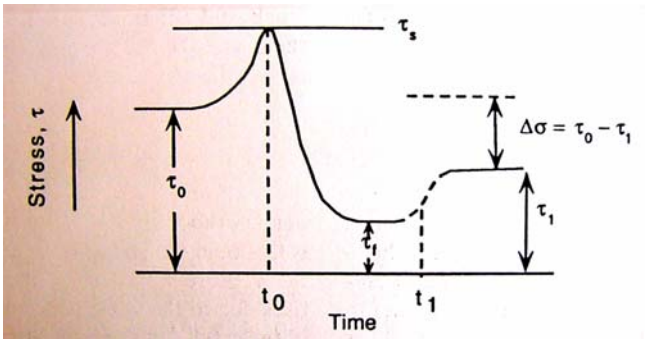
Earthquake Dynamics

Stress Behavior During Faulting



$$\Delta\sigma = \tau_0 - \tau_1 \qquad \textit{Stress Drop}$$

$$\bar{\sigma} = \frac{1}{2}(\tau_0 + \tau_1) \quad \textit{Average Stress}$$

- Only the change in stress can be observed seismically – absolute stress cannot
- Stress drop in earthquakes typically ranges from 10-100 bars (1-10 MPa)
- Lithostatic stress is at least an order of magnitude larger

$$P = \rho g h = 2.67 \cdot 981 \cdot (10 \cdot 10^5) = 2600 \; bars$$

Stress Drop

$$\Delta\sigma = C\mu\frac{\bar{u}}{L}$$

$$L = C\left(\frac{M_0}{\Delta\sigma}\right)^{1/3}$$

$$M_0 = \mu L^2 \bar{u}$$

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

$$\Delta\sigma = C\frac{M_0}{L^3}$$

Equations for Stress Drop

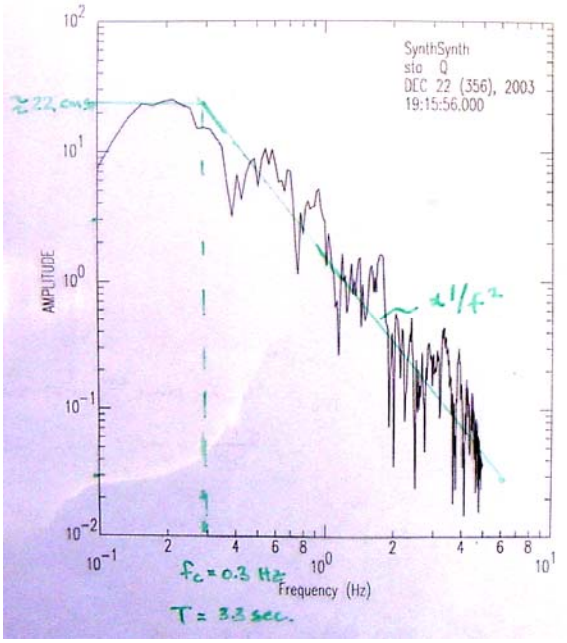
	Circular ($\lambda = \mu$)	Strike Slip	Dip Slip
Stress drop ($\Delta\sigma$)	$\frac{7\pi}{16}\mu\frac{\bar{D}}{a}$	$\frac{2}{\pi}\mu\left(\frac{\bar{D}}{w}\right)$	$\frac{4(\lambda+\mu)}{\pi(\lambda+2\mu)}\mu\left(\frac{\bar{D}}{w}\right)$
Strain energy ($\Delta W = S\sigma D$)	$\frac{16}{7\mu}a^3\Delta\sigma\bar{\sigma}$	$\frac{\pi}{2\mu}w^2L\Delta\sigma\bar{\sigma}$	$\frac{\pi(\lambda+2\mu)}{4(\lambda+\mu)\mu}w^2L\Delta\sigma\bar{\sigma}$
Moment ($M_o = \mu S\bar{D}$)	$\frac{16}{7}\Delta\sigma a^3$	$\frac{\pi}{2}\Delta\sigma w^2L$	$\frac{\pi(\lambda+2\mu)}{4(\lambda+\mu)}\Delta\sigma w^2L$

FIG. 1. Relations between stress drop, strain energy, offset, dimension, and moment for static cracks. Dimensions of the fault are a radius, L length, w width; initial stress is σ_0; final stress is σ_1; stress drop is $\Delta\sigma = \sigma_0 - \sigma_1$; average stress is $\bar{\sigma} = (\sigma_0 + \sigma_1)/2$; average dislocation is $\bar{D}$.

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

$$M_0 = \mu(\pi a^2)\bar{D}$$

What do we need to measure?



$$|\dot{u}(\omega=0)| = \frac{2|\dot{M}(\omega=0)|R_{sv}}{4\pi\rho\bar{r}^3}$$

$$|\dot{M}(\omega)| = \frac{M_0 \cdot 1}{(1+\omega^2/\omega_c^2)}$$

$$|M(\omega=0)| = M_0$$

$$M_0 = \frac{2\pi\rho\bar{r}^3}{R_{sv}}|\dot{u}(\omega=0)|$$

$$= \frac{2\cdot\pi\cdot 2.67\cdot(38.5\cdot10^5)\cdot(3.5\cdot10^5)^3\cdot 22}{R_{sv}}$$

$R_{sv} \approx 1$

$M_0 \approx 6.1\cdot10^{25}$ dyne cm

$M_w = 6.5$

Estimation of Static Stress Drop & Radiated Energy for the Sen Simeon EQ.

since $\Delta\bar{\sigma} = \frac{7 M_0}{16 a^3}$ we will find the stress drop for an "equivalent" circular fault.

assuming that the radius is a function of the rupture speed and time we have...

$$a = V_r \cdot \tau \quad \text{since } V_r \approx \beta$$

$$= \beta\tau = \beta / f_c$$

then

$$\Delta\bar{\sigma} = \frac{7}{16} M_0 \left(\frac{f_c}{\beta}\right)^3$$

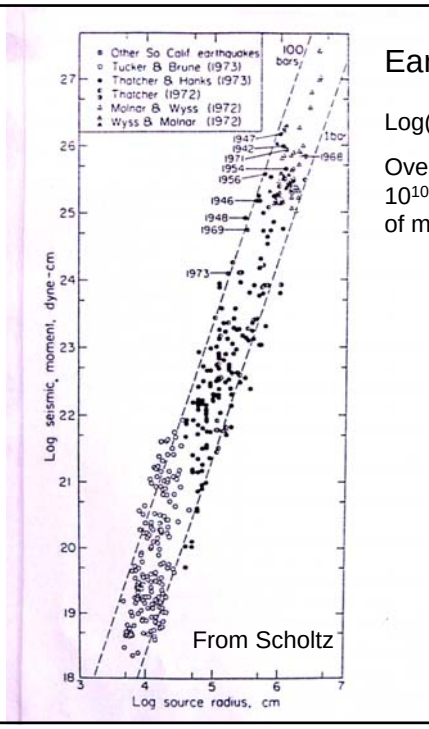
$$= \frac{7}{16}(6 \cdot 10^{25} \text{ dyne cm}) \frac{(0.3 \text{ 1/s})^3}{(3.5 \cdot 10^5 \frac{\text{cm}}{\text{s}})^3}$$

$$= 1.65 \cdot 10^7 \frac{\text{dyne}}{\text{cm}^2} = 16.5 \text{ bars}$$

$$1 \text{ bar} = 10^6 \text{ dyne/cm}^2$$

$$E_r = \frac{(16.5 \cdot 10^6)}{2 \cdot 3 \cdot 10^{11}} 6 \cdot 10^{25} = 1.65 \cdot 10^{21} \text{ dyne cm}$$

$$= 1.65 \cdot 10^{14} \text{ Joules}$$



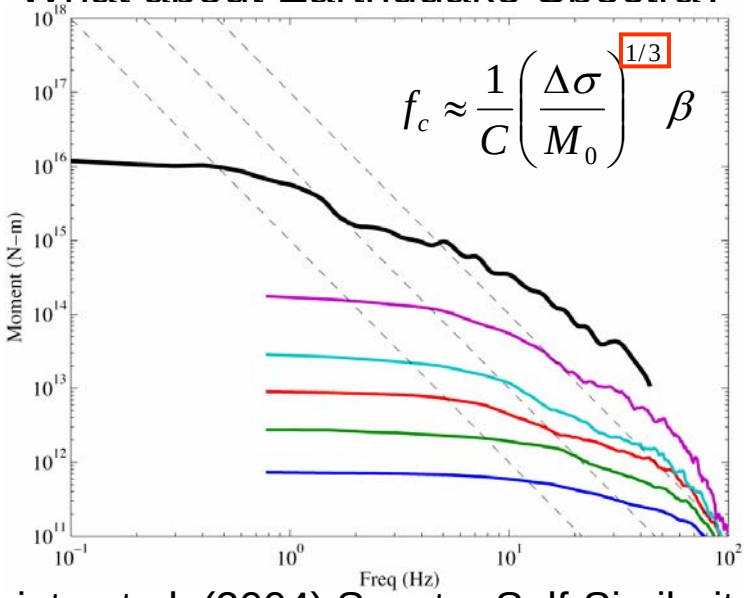
Earthquake Self Similarity

Log(moment)~3*log(radius)

Over a huge range of moment (more than 10^{10}) the stress drop varies by only 2 orders of magnitude!

$$L \approx C\left(\frac{M_0}{\Delta\sigma}\right)^{1/3}$$

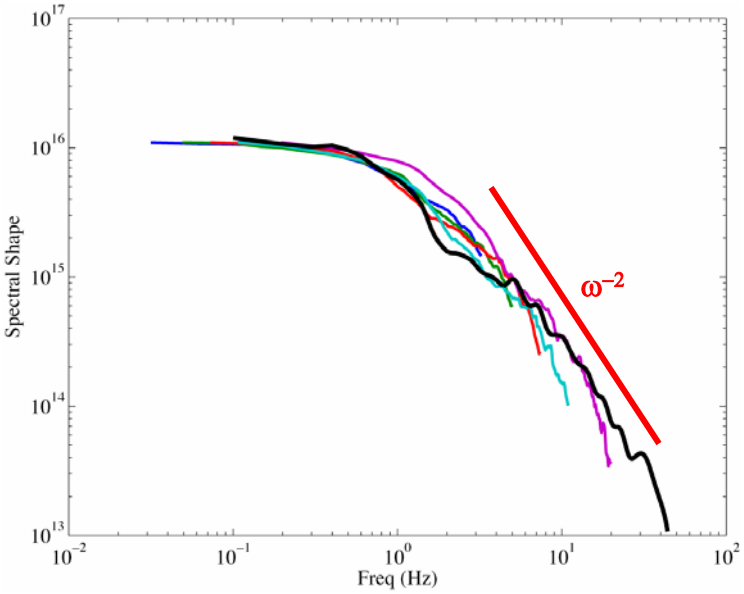
What about Earthquake Spectra?



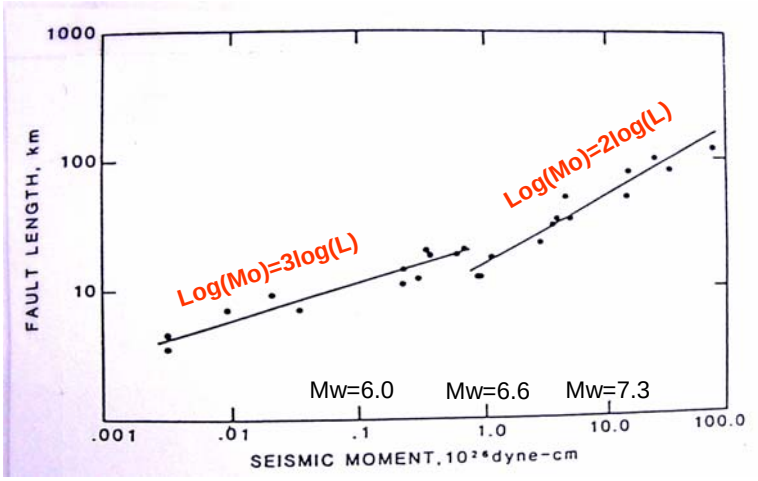
$$f_c \approx \frac{1}{C}\left(\frac{\Delta\sigma}{M_0}\right)^{1/3}\beta$$

Prieto et al. (2004) Spectra Self-Similarity

Prieto et al. (2004) Spectra Self-Similarity



A Break In Scaling



Modified from Scholtz

If L Grows Bigger than Seismogenic Thickness

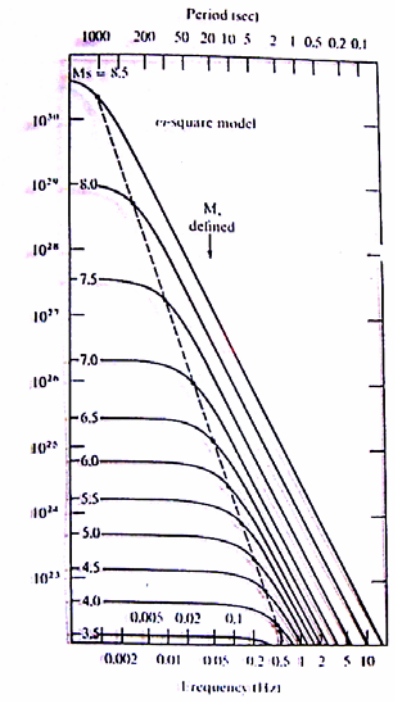
$$\Delta\sigma = C\mu\frac{\bar{u}}{L}$$

$$L = C\left(\frac{M_0}{\Delta\sigma W}\right)^{1/2}$$

$$M_0 = \mu L W \bar{u}$$

$$\Delta\sigma = C\frac{M_0}{L^2 W}$$

$$f_c = \frac{1}{C}\left(\frac{\Delta\sigma W}{M_0}\right)^{1/2}\beta$$



Scaling of Source Spectra

$$\Omega(\omega) = \frac{\Omega(0)}{[1 + (\omega/\omega_0)]^2}.$$

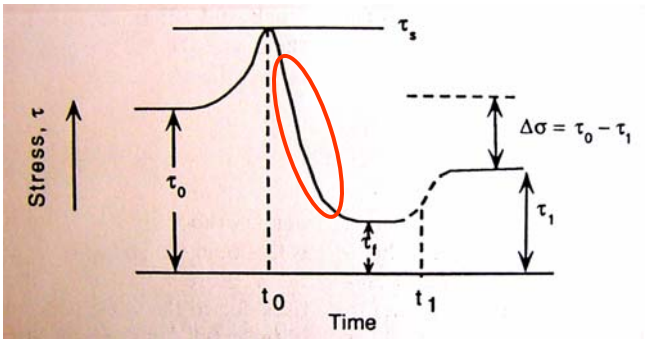
FIGURE 14.14
Same as Figure 14.13 except that the spectra share the common shape of equation (14.36). The broken line is the locus of ω_0. [From Aki, 1967; copyrighted by the American Geophysical Union.]

Scaling of Source Spectra

- How spectra change with moment

- How spectra change with stress drop

Stress Behavior During Faulting



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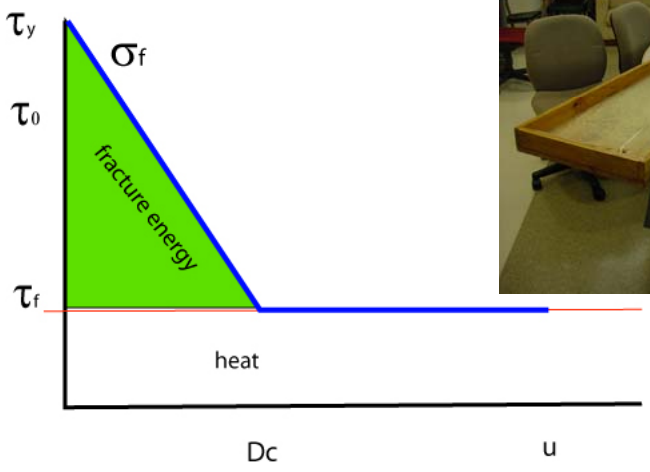
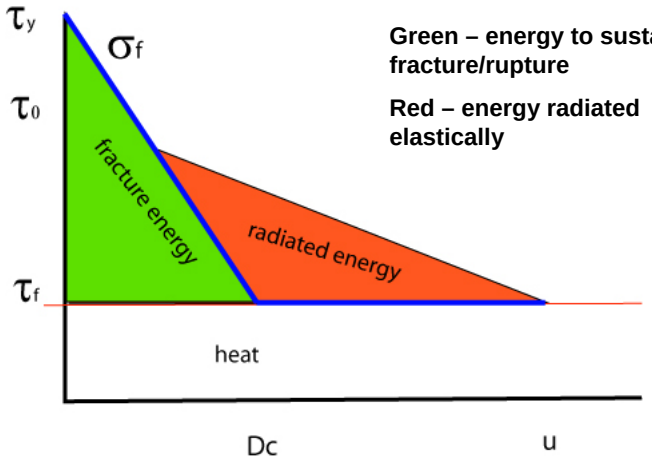
Slip Weaking Law

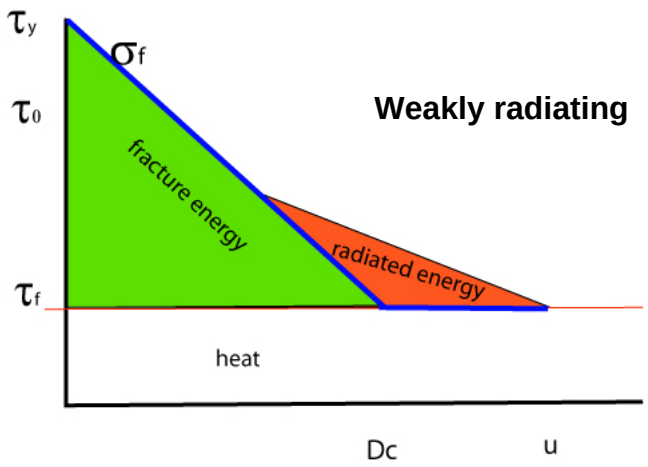




Green – energy to sustain fracture/rupture

Red – energy radiated elastically

Energy Budget



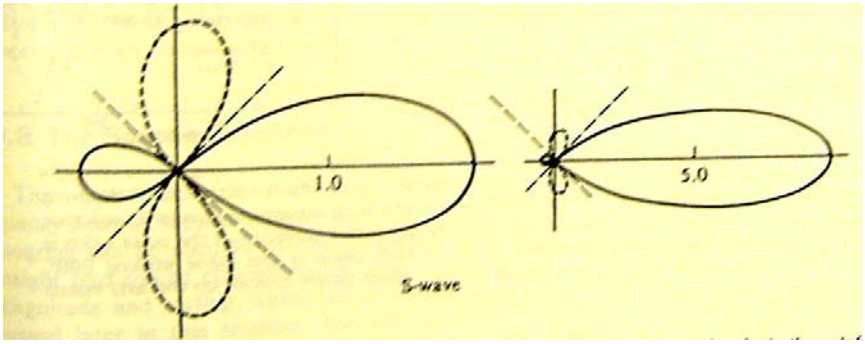
Radiated Energy

$$E_R = \bar{\sigma} u A = \frac{\bar{\sigma} M_0}{\mu} = \frac{\Delta\sigma M_0}{2\mu}$$

$$\log(E_R) = 1.5M + 11.8 \quad \textit{Gutenberg}$$

$$E_R = c\int \dot{u}^2(t)dt = c\int \dot{u}^2(\omega)d\omega$$

Directivity & Radiation Patterns



Vr/β=0.5

Vr/β=0.9

then

$$\Delta\sigma = \frac{7}{16} M_0 \left(\frac{f_c}{\beta}\right)^3$$

$$= \frac{7}{16}(6\cdot 10^{25}\ \text{dyne cm}) \frac{(0.3\ 1/s)^3}{(3.5\cdot 10^5 \frac{cm}{s})^3}$$

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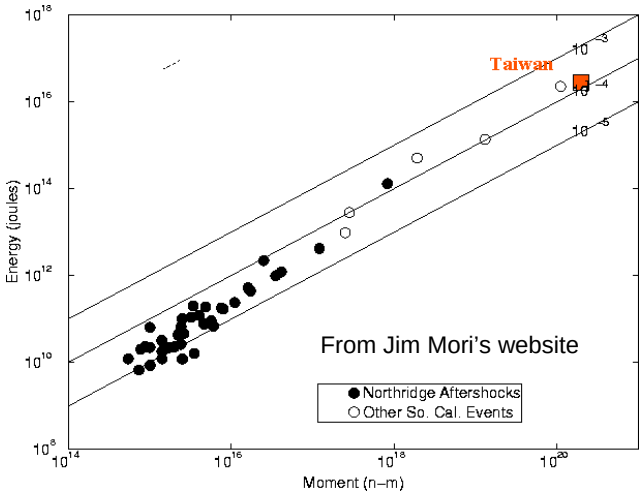
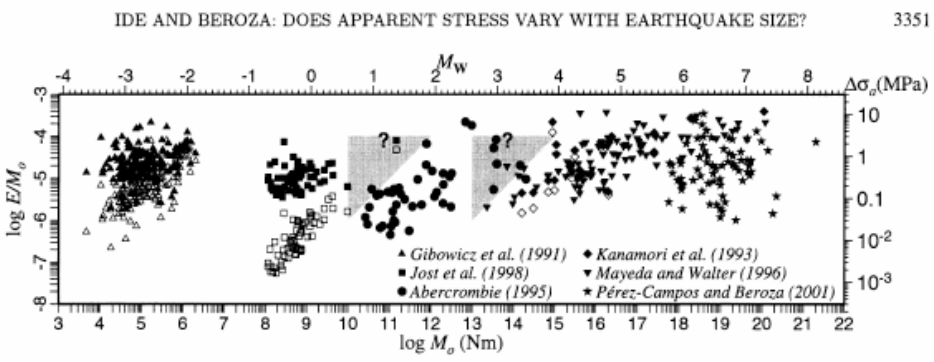
Scaling of Radiated Energy?



An increasing rate of radiated energy to seismic moment suggests different frictional properties of large earthquakes. Melting, thermal pressurization, and other lubrication mechanisms can reduce friction and thereby increase the ratio of energy to moment with increasing moment.

Scaling of Radiated Energy?



Accounting for limited recording bandwidth, and attenuations in published studies suggests a nearly constant ratio of radiated energy to moment (Ide and Beroza (2001).

The scaling of energy to moment is an active, passionately debated current research area.

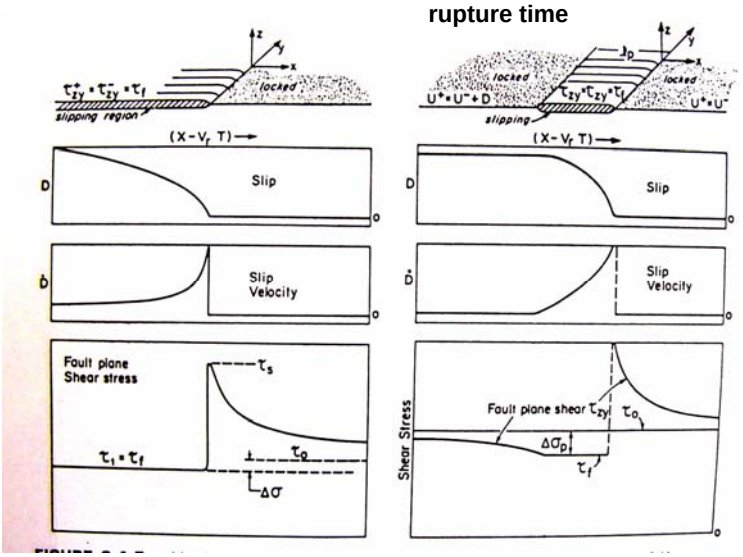
Crack-like rupture

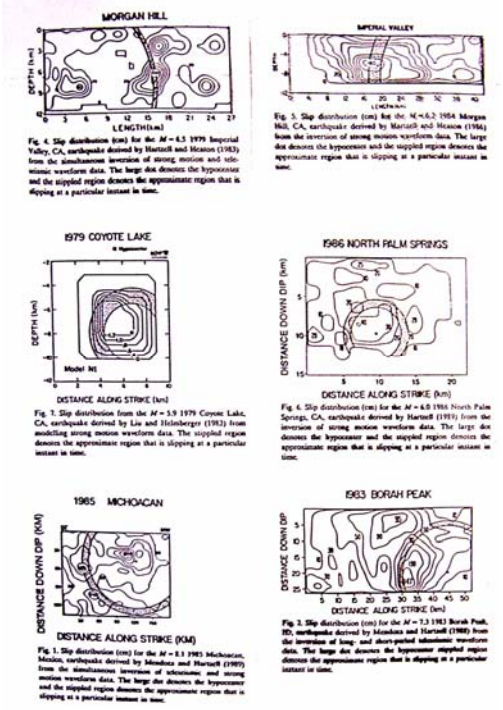
Slip rise time equivalent to total rupture time

Pulse-like rupture

Velocity dependent friction

Slip rise time much less than total rupture time





Heaton and Heaton's (1990) analysis of kinematic rupture models indicates that only a small fraction of the fault is rupturing in a given instant.

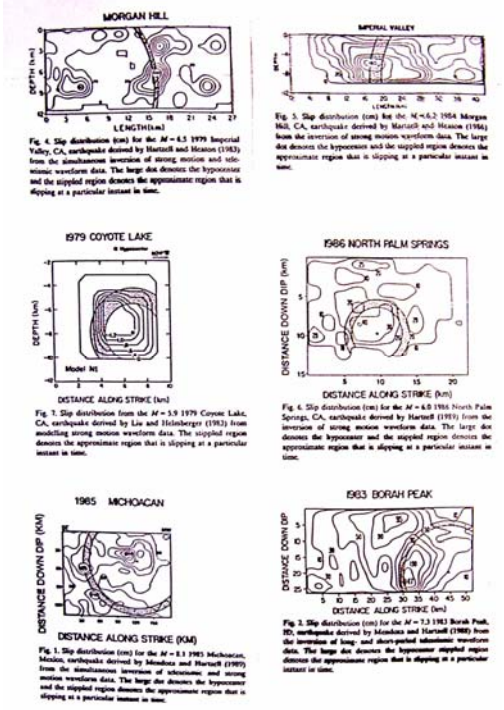
The rise time from kinematic models represents a maximum value

Average Slip Velocity

$$\Delta\sigma \approx C\mu\frac{\bar{u}}{L}$$

$$\bar{u} \approx \frac{\Delta\sigma}{C\mu}L = \frac{\Delta\sigma}{C\mu}\beta t$$

$$\dot{\bar{u}} \approx \frac{\Delta\sigma}{C\mu}\beta \approx \frac{60\cdot 10^6}{3.5\cdot 10^{11}} * 3.5\cdot 10^5 \approx 60\frac{cm}{s}$$



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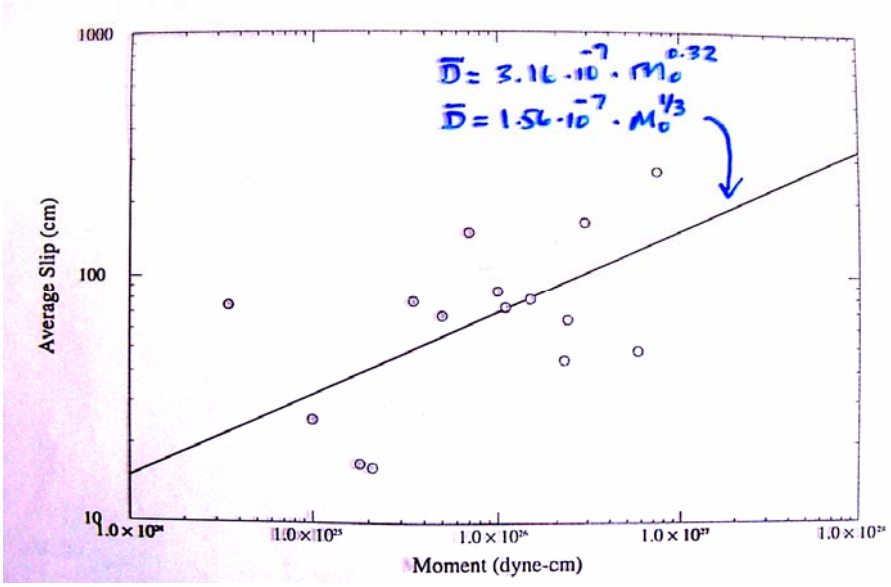
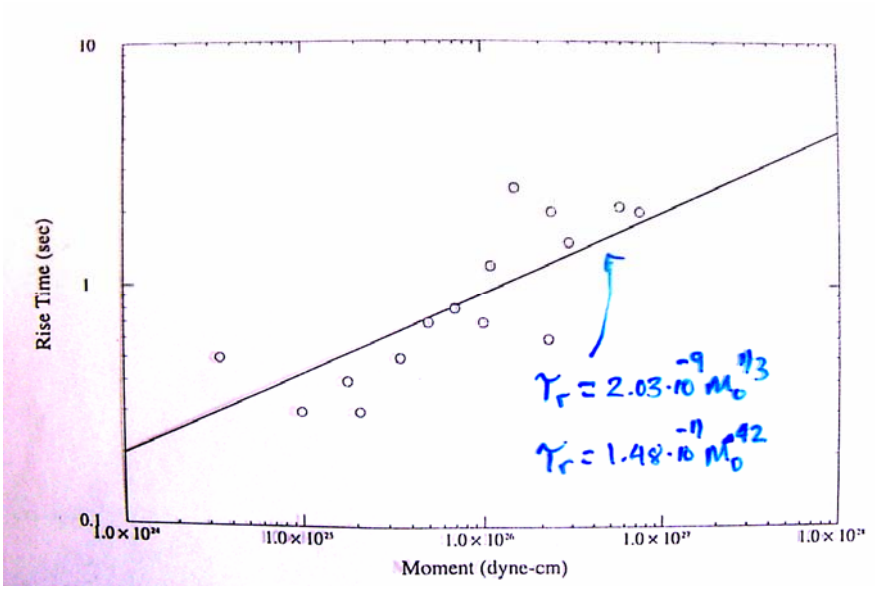


Somerville et al., 1999



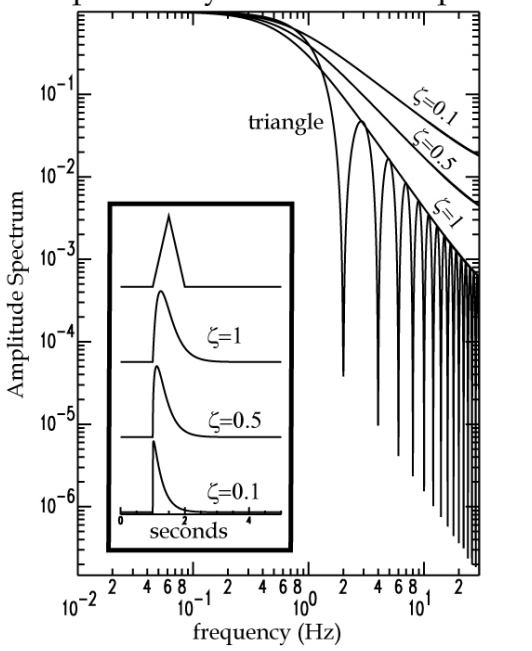
Somerville et al., 1999

Average Slip Velocity from Kinematic Models

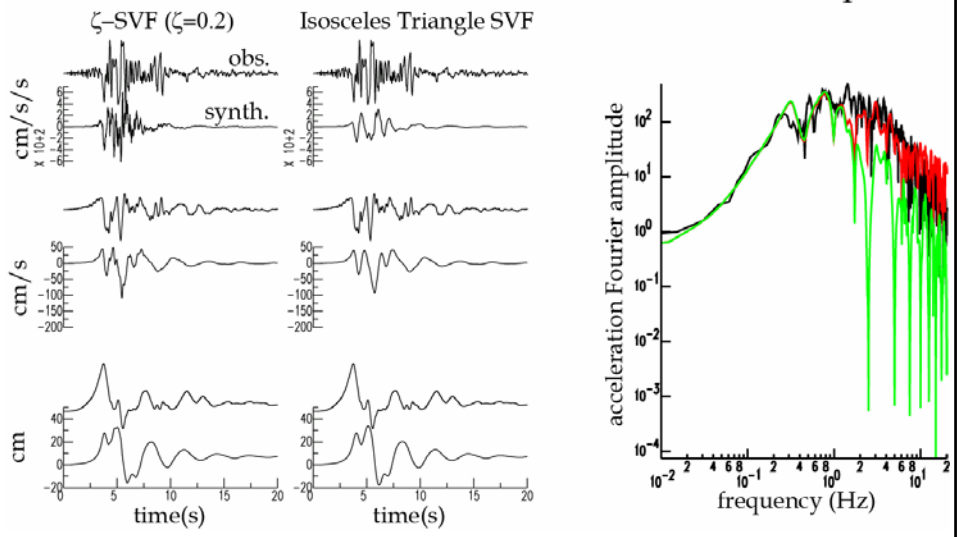
$$\dot{\bar{u}} = \frac{\overline{D}}{\tau_R} = \frac{1.56 \cdot 10^{-7}}{2.03 \cdot 10^{-9}} \frac{M_0^{1/3}}{M_0^{1/3}} \approx 77 \frac{cm}{s}$$

Based on Somerville et al., 1999

Slip Velocity Functions & Spectra



Observed and Simulated Time Histories and Spectra

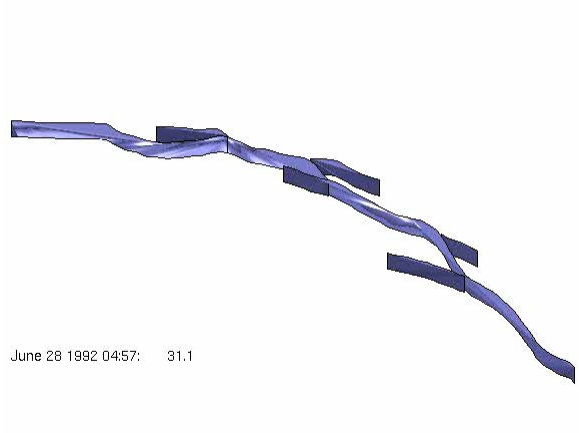


Dynamic Rupture Model for the Landers Earthquake – courtesy of Kim Olsen (SDSU)

Rupture is governed by initial and yield stress distribution, and a constitutive slip weakening friction law.

Heterogeneous slip and slip velocity are calculated.

Another View – Pwaves (green), Swaves (magenta)



TerraShake Simulation

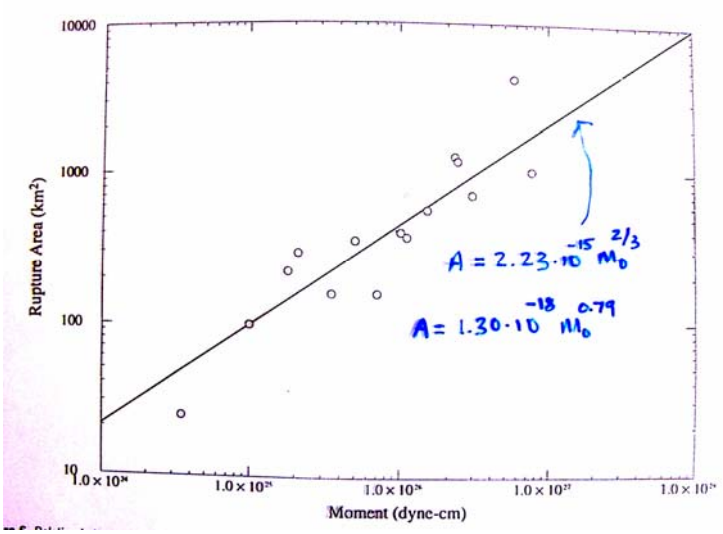
Quick time

Check out:

http://ucsdnews.ucsd.edu/newsrel/general/terrashake.asp

http://visservices.sdsc.edu/projects/scec/terashake/2.1/

Rupture Area Scaling



Somerville et al., 1999

Summary of Scaling

- As earthquakes grow larger the following increase:
  - Fault length, width, and area
  - Seismic moment & Radiated Energy
  - Rupture duration & average slip
- & the following stay the same:
  - Average stress drop
  - Average slip velocity
  - Rupture velocity
  - Ratio of Radiated Energy to Seismic Moment