The Abdus Salam
International Centre
for Theoretical Physics

2464-3

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Faults have rules: scaling, friction, stress drops

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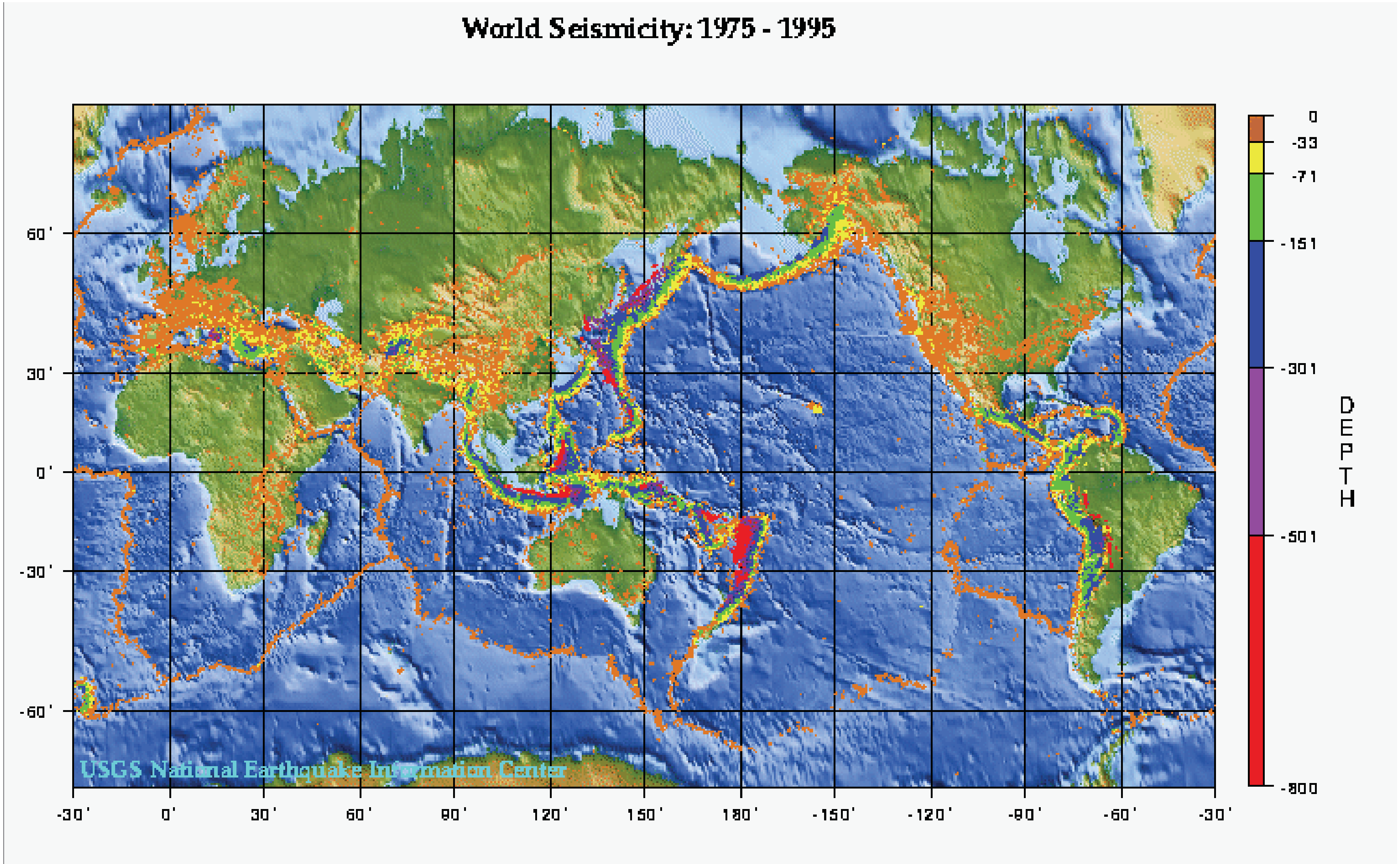
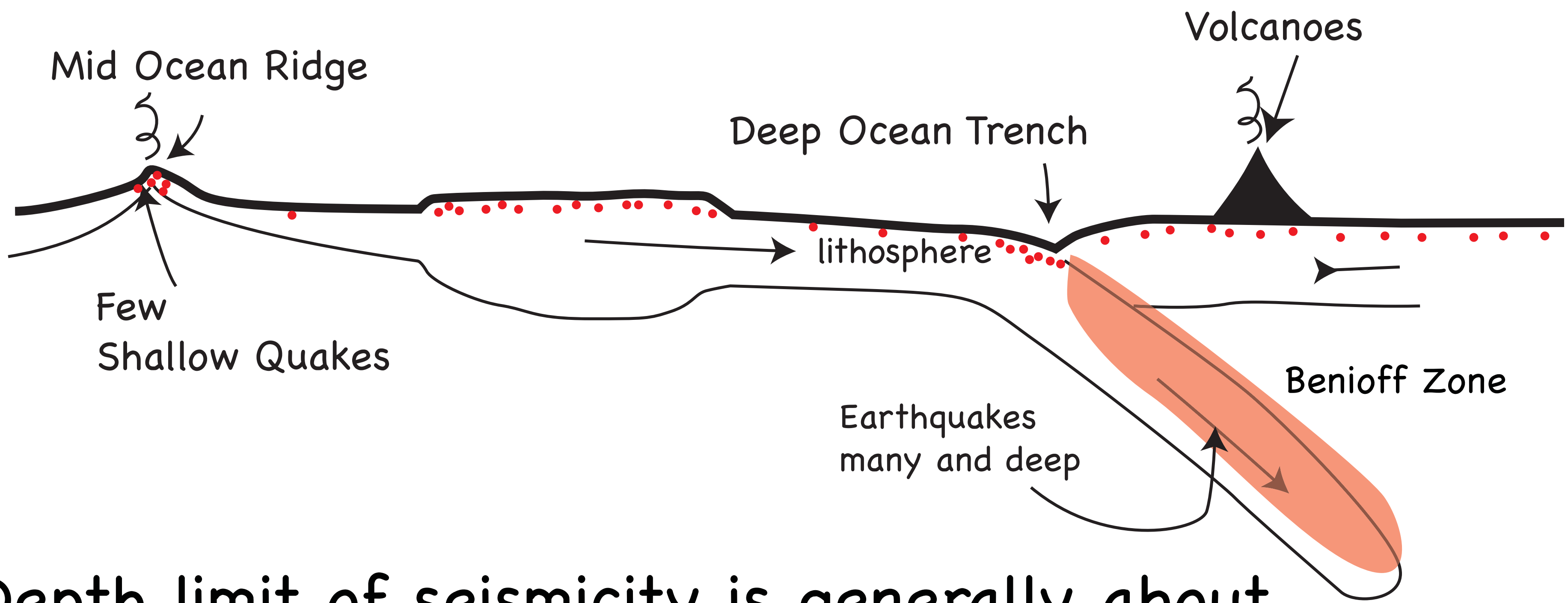
USA

Rules of the Game...

Scaling Laws....



Observation: The Depth to which Earthquakes occur in the earth is limited....

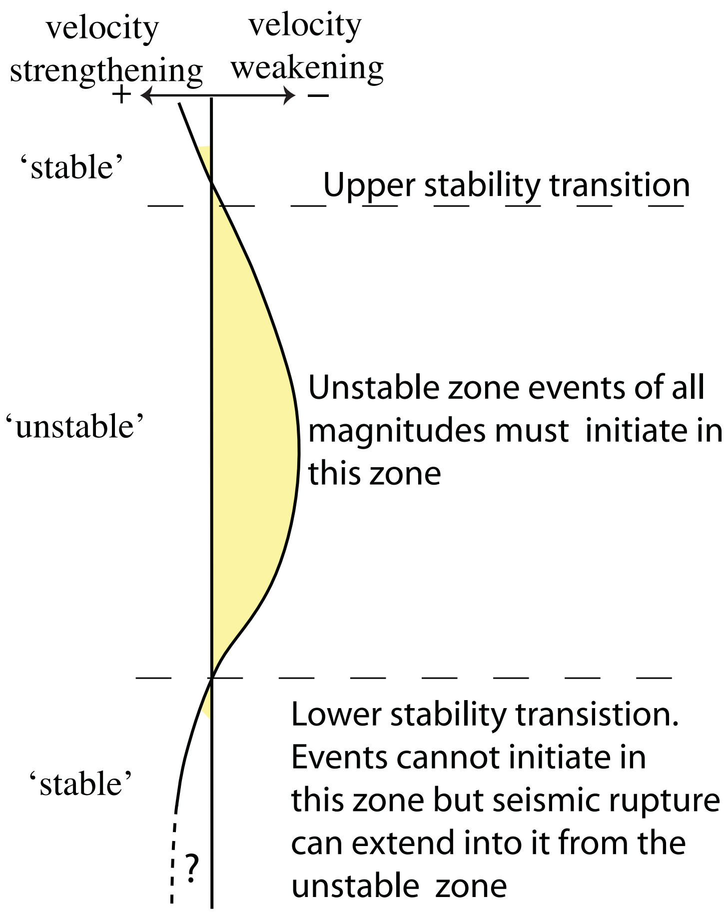


Depth limit of seismicity is generally about 10 to 20 km away from convergent plate boundaries....

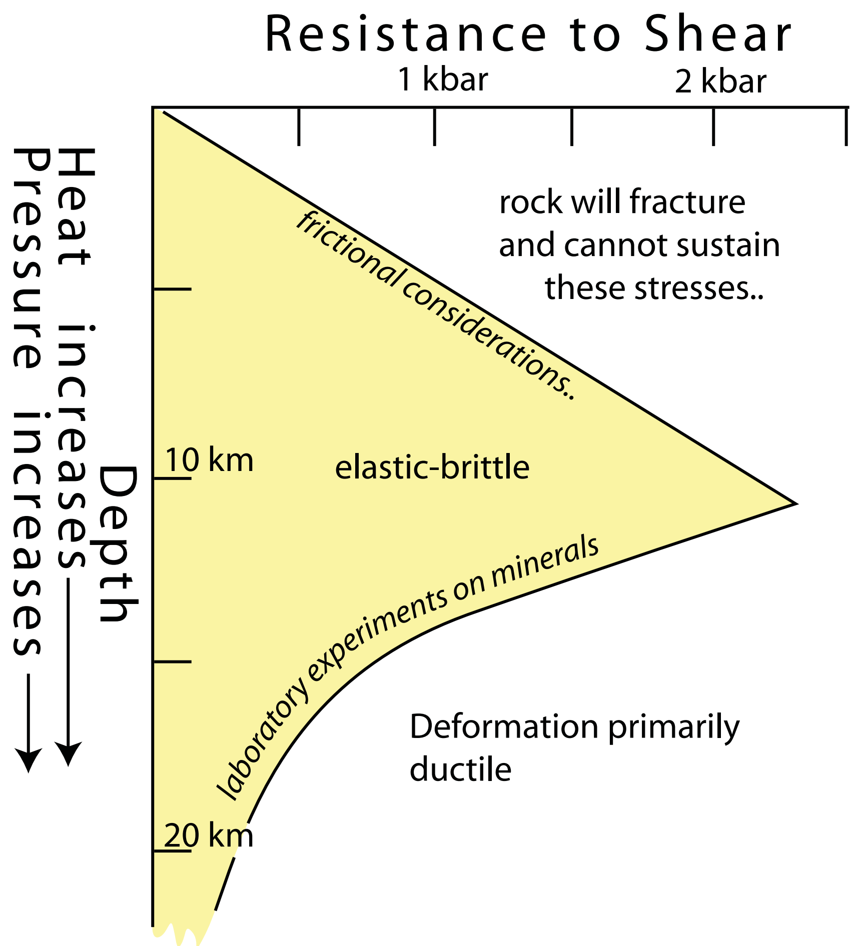
Generally attributed to heat (distribution of isotherms - presence of seismicity defining Benioff Zone is argument that old 'cool' lithosphere is being subducted)

Rheological Explanations

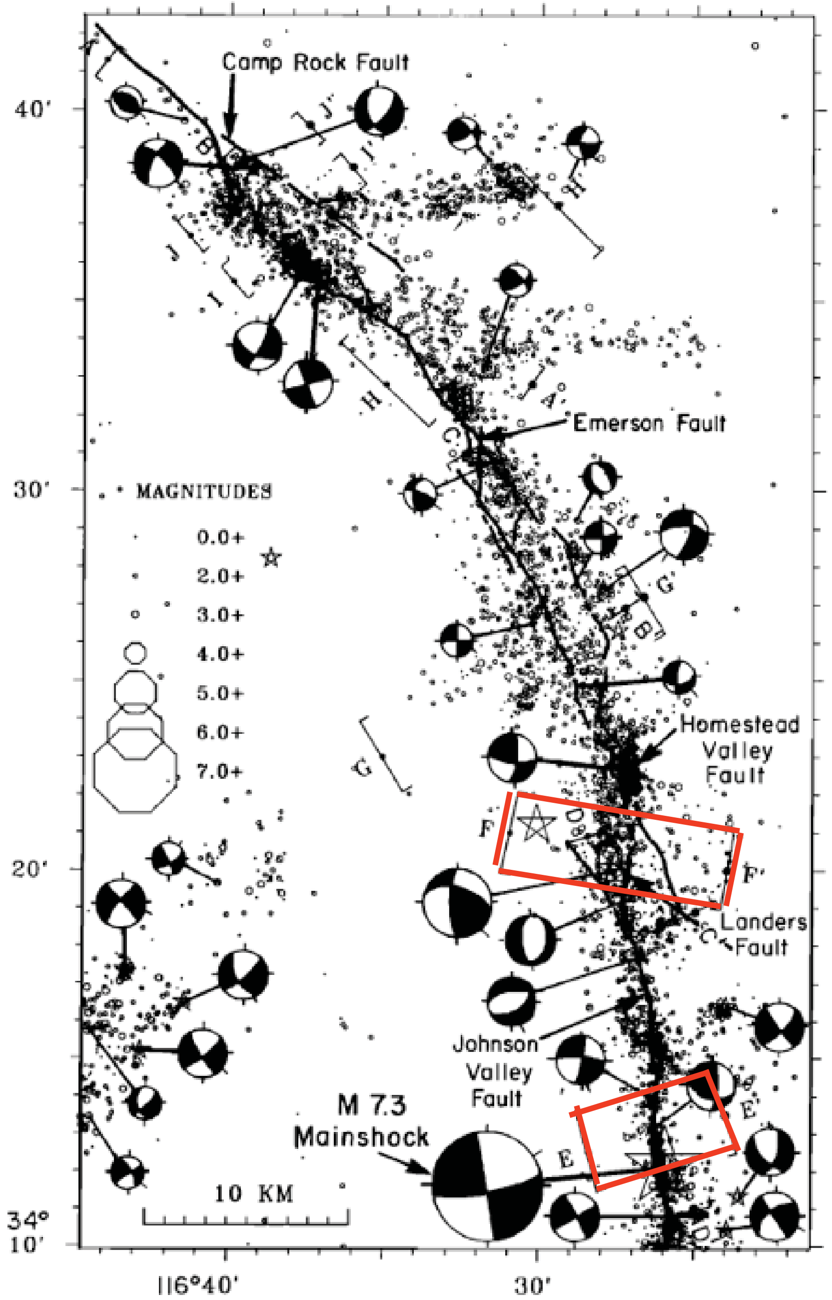
Friction rate behaviour

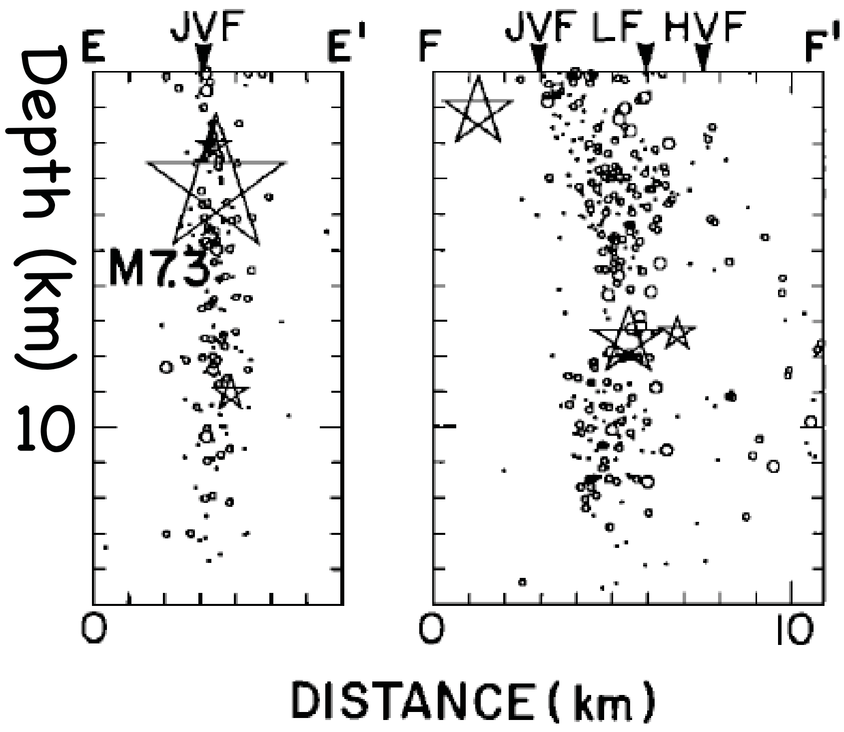


Strength Envelope




Jun 22, 1992
Landers

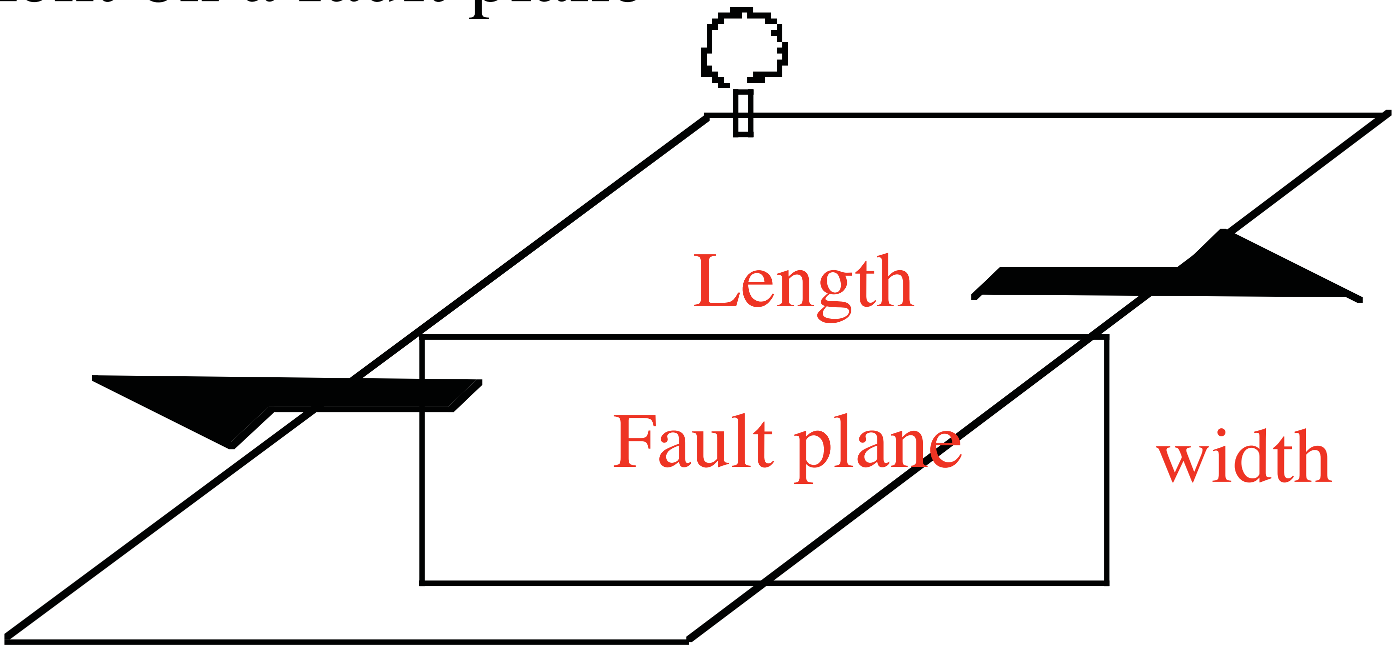




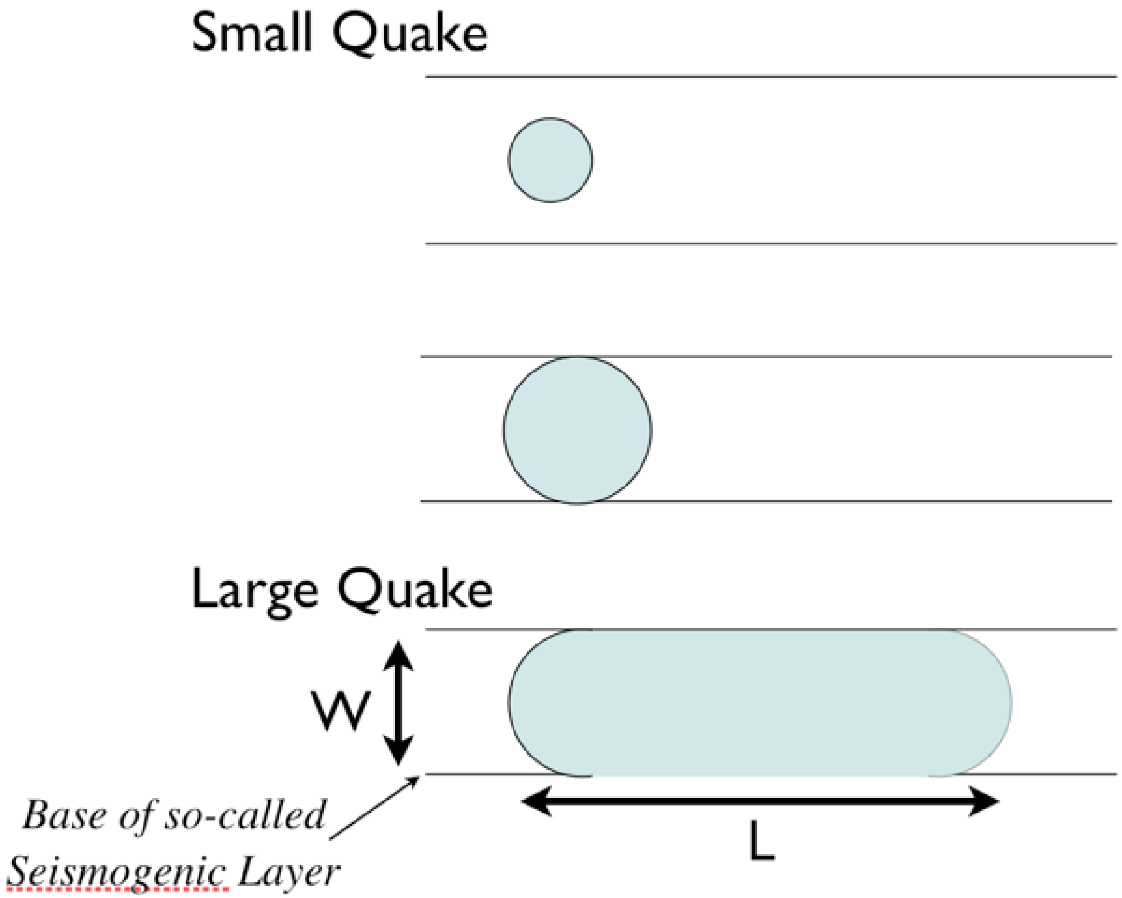
Idea of a 'Fault Plane' extending to base of seismogenic layer

Concept of a Fault Plane:
A fracture across which there has occurred a relative displacement of rock on alternate sides of the fracture.

Concept of Earthquake: Sudden and discrete displacement on a fault plane



Small (circular) vesus Large (rectangular) earthquakes ruptures on faults...



'small'
circular- rupture growth in all directions on fault plane

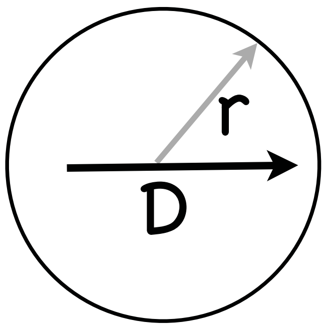
'large'
rectangular - rupture limited in vertical and grows horizontally

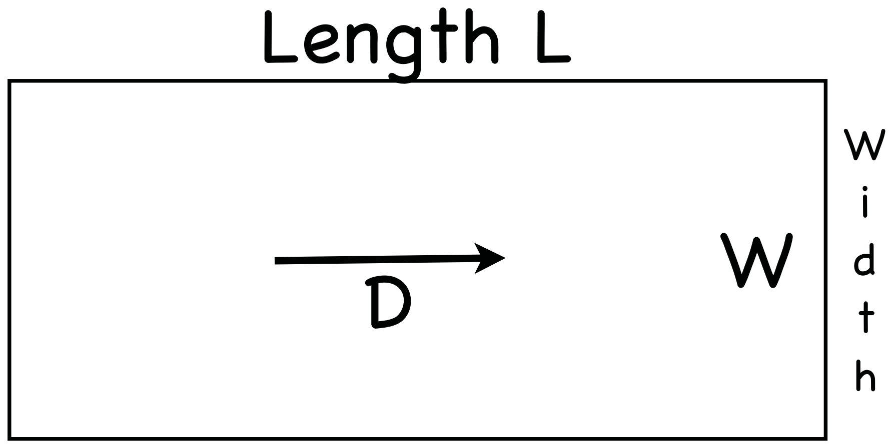
"Aspect Ratio" = L/W

seismic moment Mo

like Magnitude M can be measured directly from a seismogram....

unlike Magnitude - it can also be related directly to physical parameters that describe the earthquake source...





$$Mo = \mu \pi r^2 D \quad \text{or} \quad = \mu LWD$$

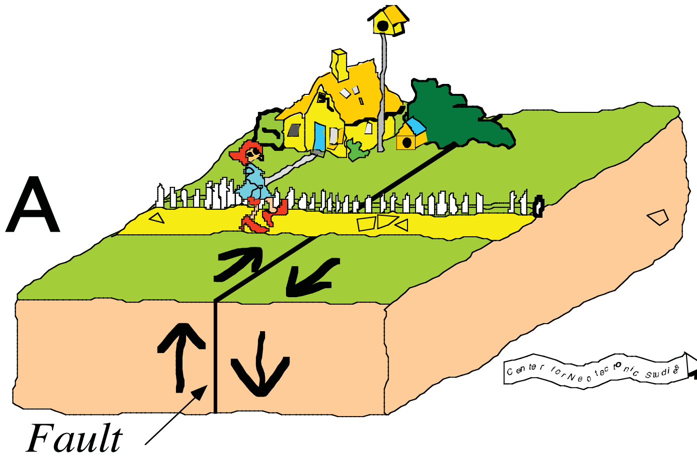
μ is crustal rigidity (proportionality constant between stress and stain)

D is slip on fault plane

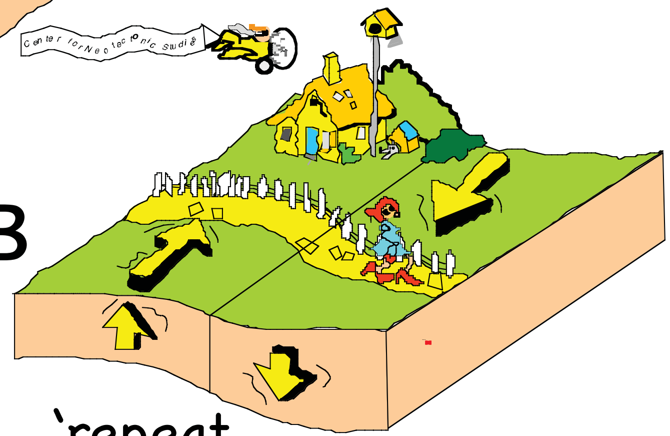
S = Area of fault plane = πr^2 for circular fault

S = Area of fault plane = LW for rectangular fault

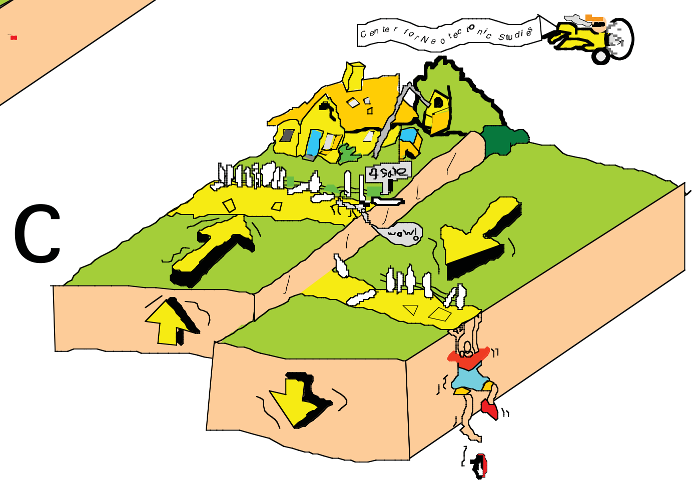
Concept of Elastic Rebound and Stress Drop...

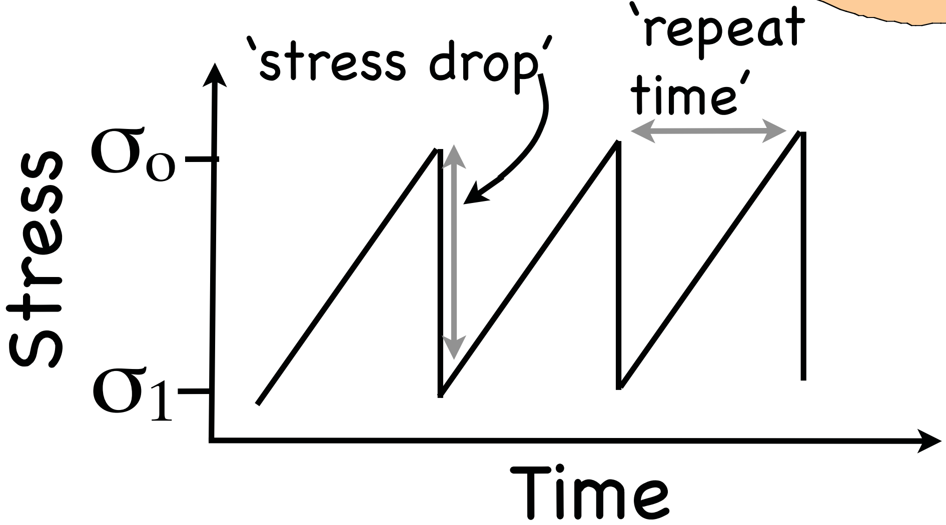


Stress accumulates in crust around fault during interseismic period..



When stress accumulates to level equivalent to fault strength – fault slips and crust experiences a ‘stress drop’





Summary: Physical Variables Used to Describe the Earthquake Fault Source

L = fault dimension (e.g., length, width, radius)

S = fault area

D = average coseismic offset

μ = material property (rigidity)

σ_o = initial stress on fault

σ_1 = final stress on fault

σ = mean stress on fault = $(\sigma_o+\sigma_1)/2$

$\Delta\sigma = \sigma_o-\sigma_1$ = stress drop on fault

$\Delta\sigma$ is proportional to strain energy released during quake = ΔW

$\eta\ \chi\ \Delta W$ = amount of strain energy released as seismic waves

Summary: Measures of Earthquake Size from Seismology

M = magnitude

Mo = seismic moment

Moment Magnitude Mw and Seismic Moment Mo

Work done during an earthquake (strain energy drop)

$$W = \bar{\sigma}\bar{D}S \qquad \left(\frac{force}{area} \times distance\ x\ area\right)$$

$$\bar{\sigma} = average\ mean\ stress$$

average mean stress in terms of stress drop

$$\Delta\sigma = 2\left(\frac{\sigma_o - \sigma_1}{2}\right) = 2\bar{\sigma} \qquad true\ if\ stress\ drop\ total$$

rewriting

$$\bar{\sigma} = \frac{\Delta\sigma}{2}$$

elastic strain energy drop/release during earthquake

$$W = W_o = \frac{1}{2}\Delta\sigma\bar{D}S$$

$$and\ because\ M_o = \mu S\bar{D} \quad because\ \mu = 3 - 6 \times 10^{11}\frac{dyn}{cm}$$

$$because\ observations\ show\ \Delta\sigma = 20 - 60\ bars = 2 - 6 \times 10^7 dyn/cm^2$$

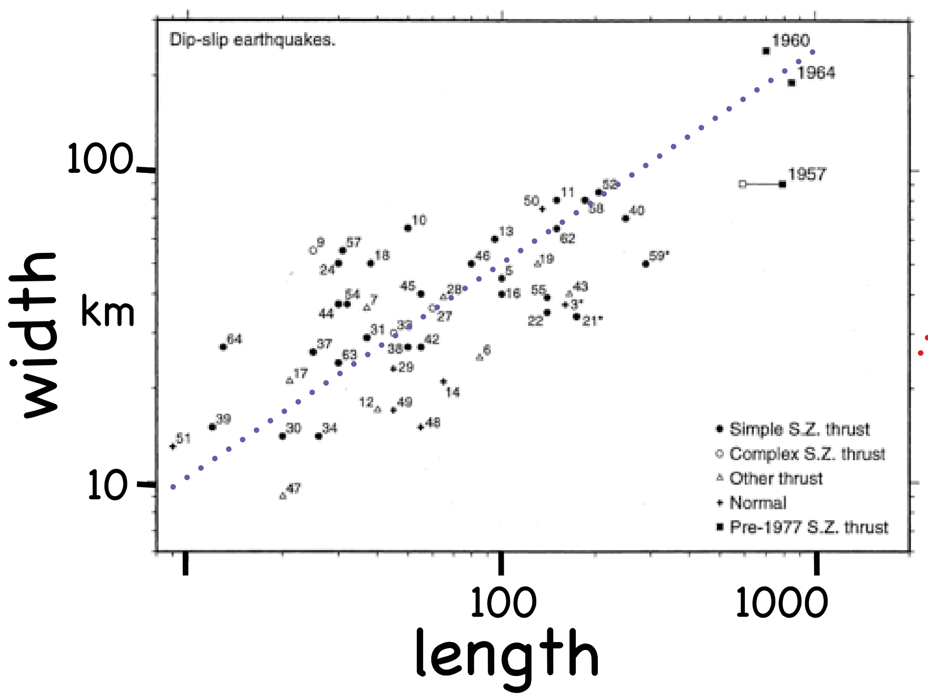
$$W = W_o = \frac{1}{2}\Delta\sigma\bar{D}S \quad = \frac{\Delta\sigma}{2\mu}M_o = \frac{Mo}{2 \times 10^4}$$

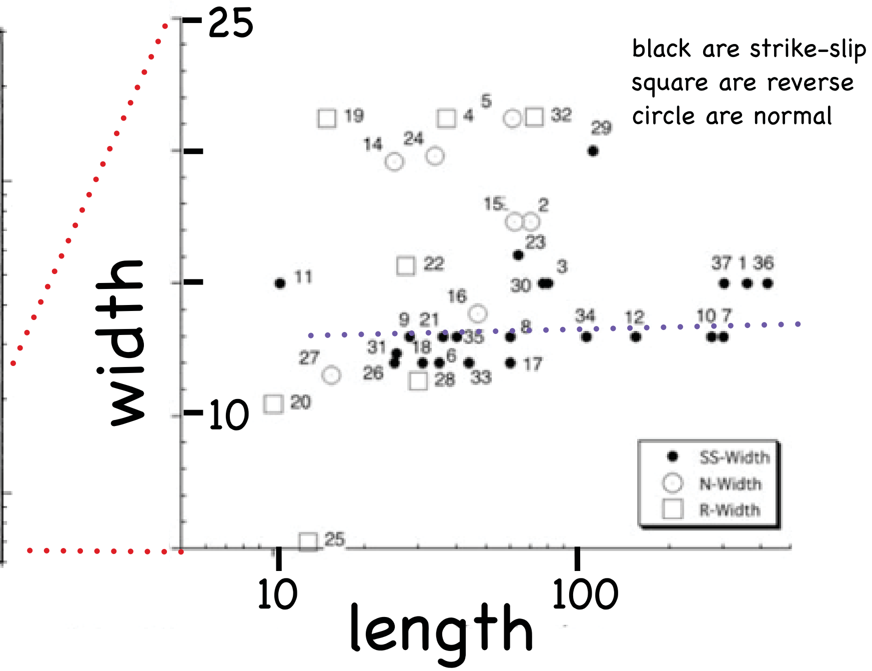
placing this expression for work/energy into Gutenberg-Richters relationship between seismic energy and magnitude.. Log Energy = 1.5 M + 11.8...

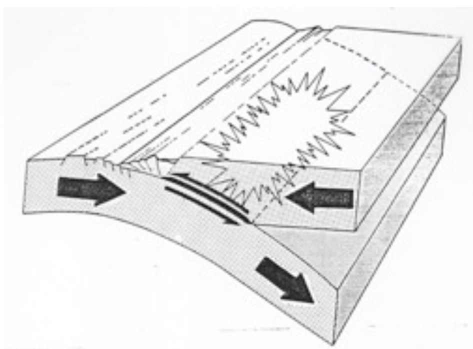
$$Log(\frac{M_o}{2 \times 10^4}) = 1.5M + 11.8$$

$$\boxed{Log(M_o) = 1.5M_w + 16.1}$$

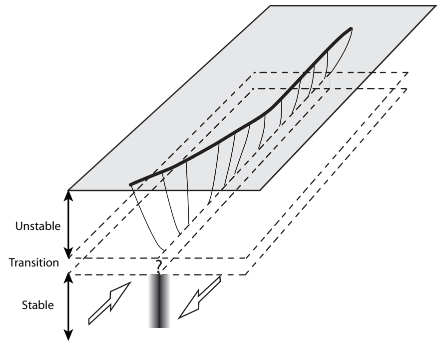
Rupture Length versus Width





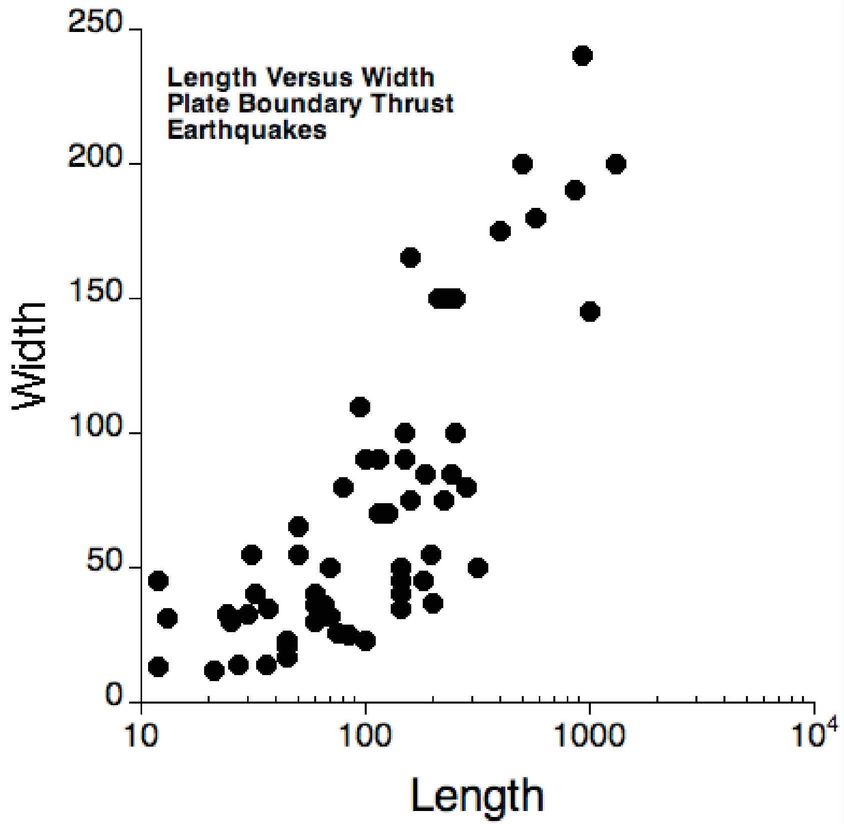


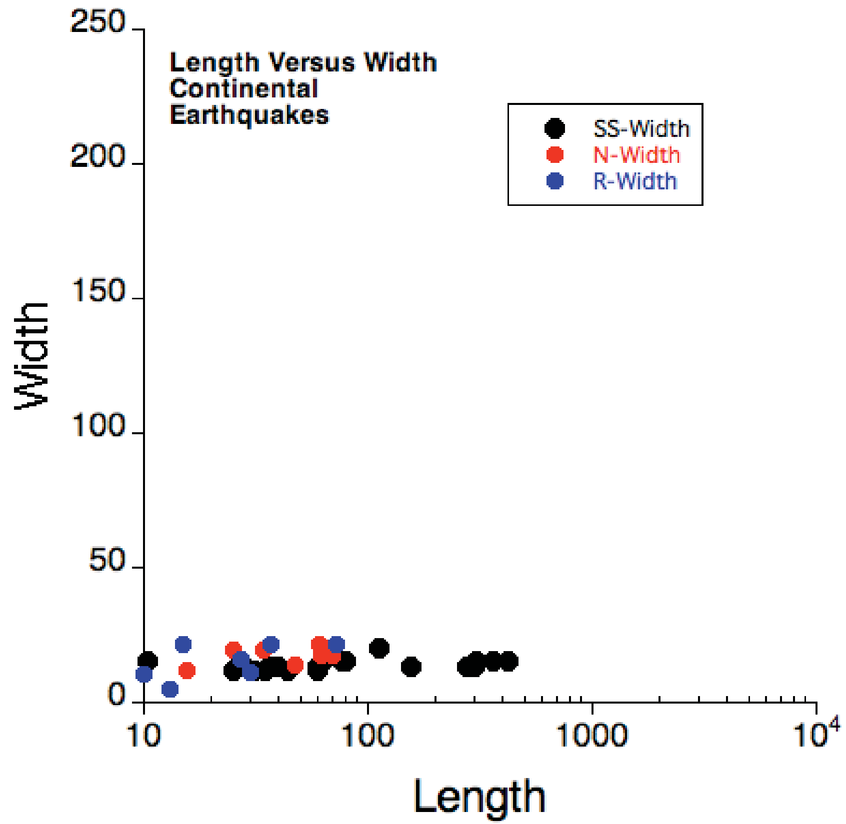
Subduction

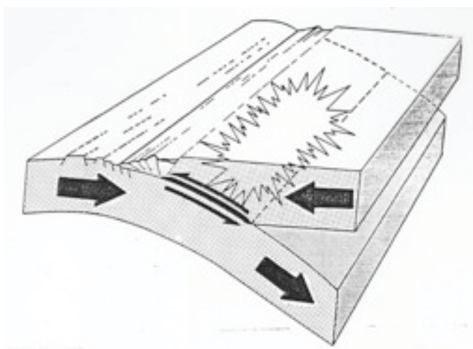


Continental

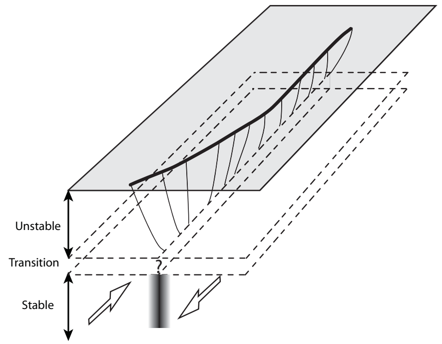
Rupture Length versus Width





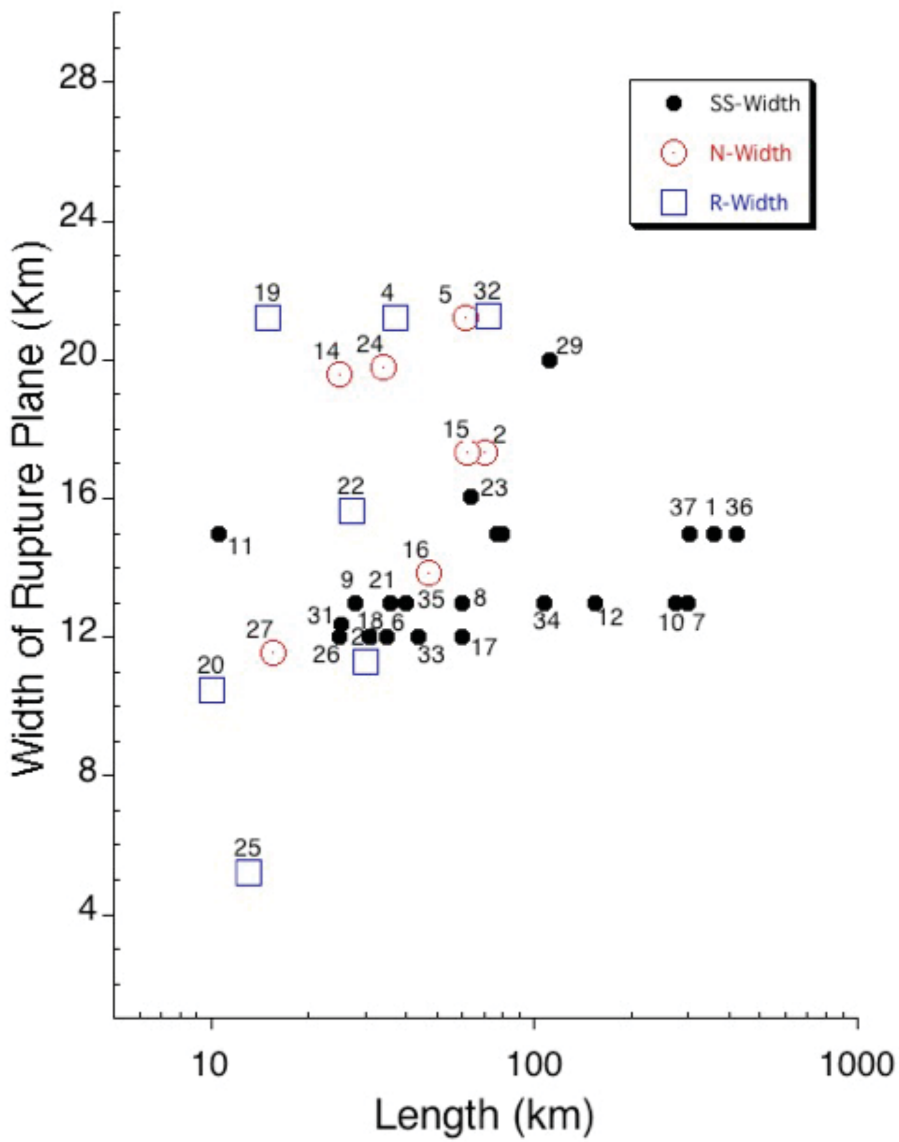


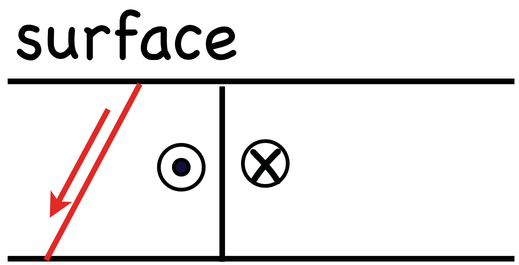
Subduction



Continental

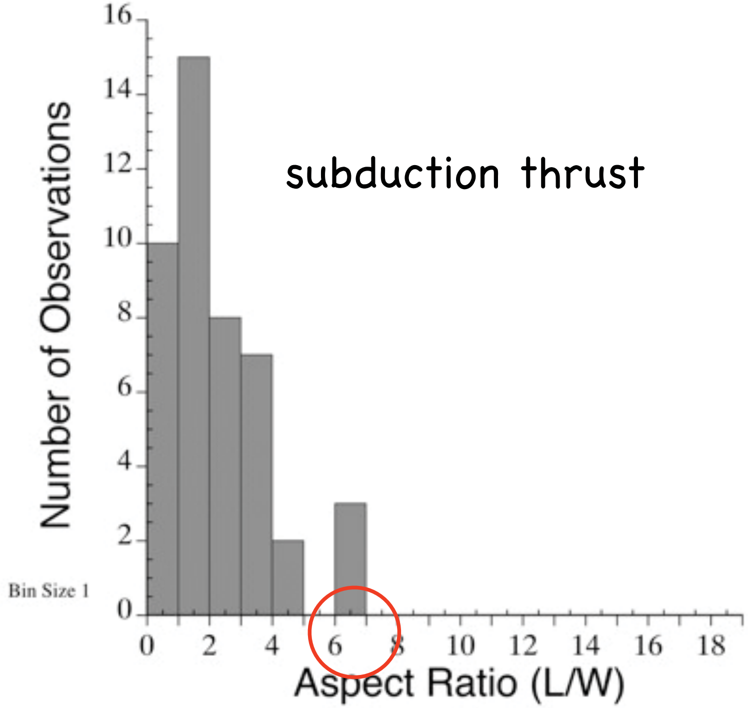
Length vs Width Continental Earthquakes...

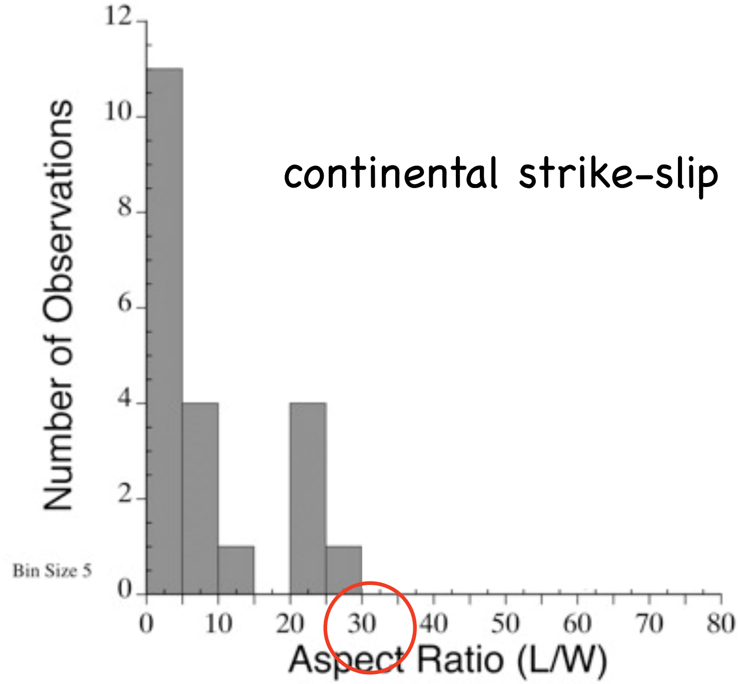


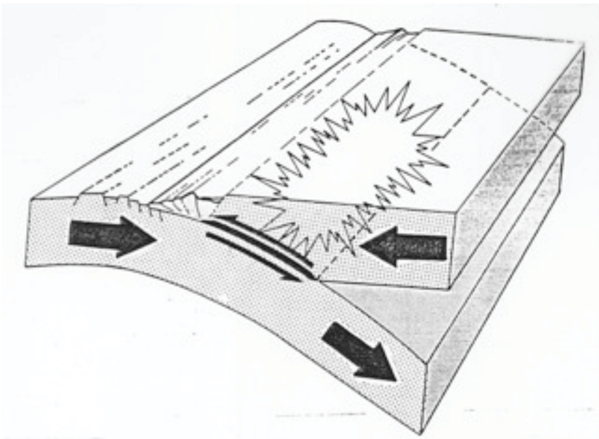


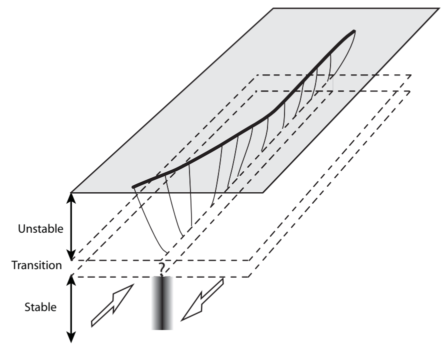
Aspect Ratio: Rupture Length L / Rupture Width W

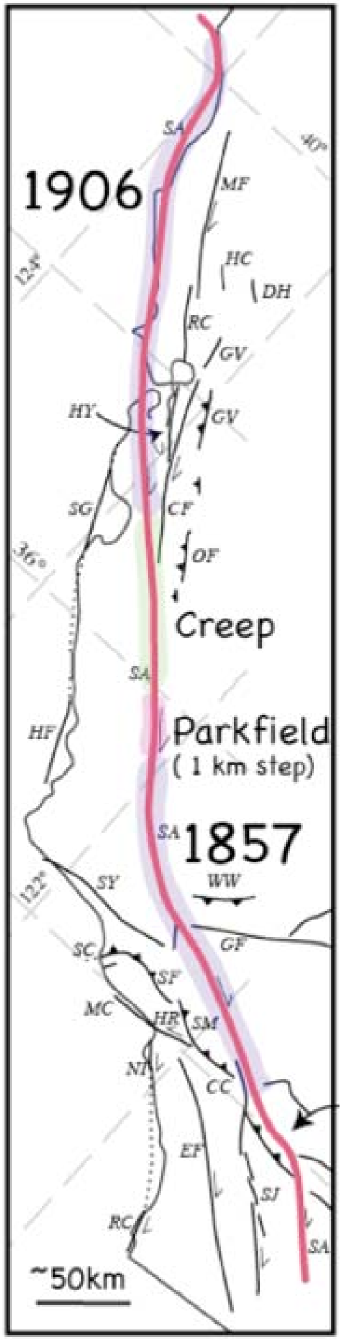
histograms of total number quakes with given aspect ratio...



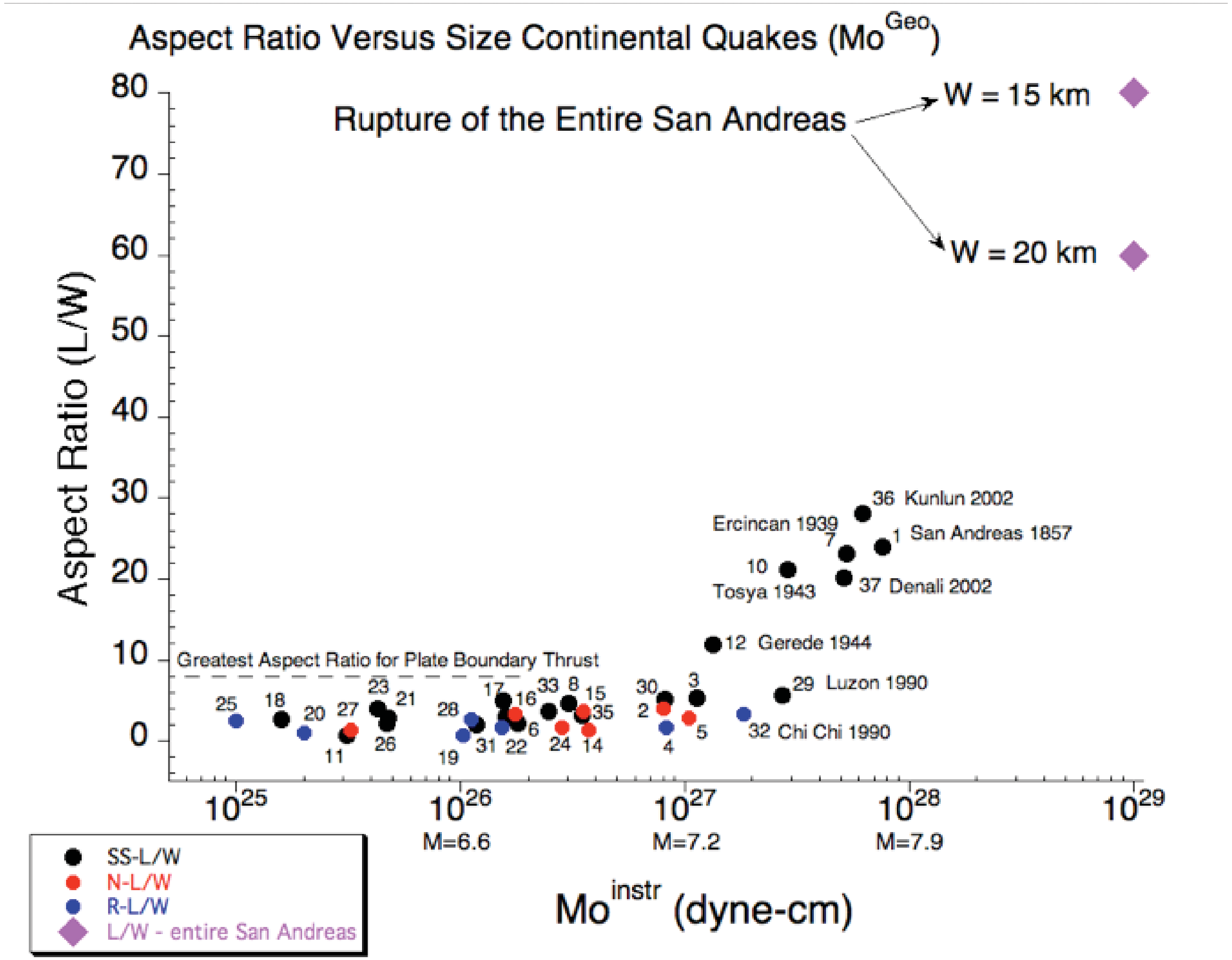


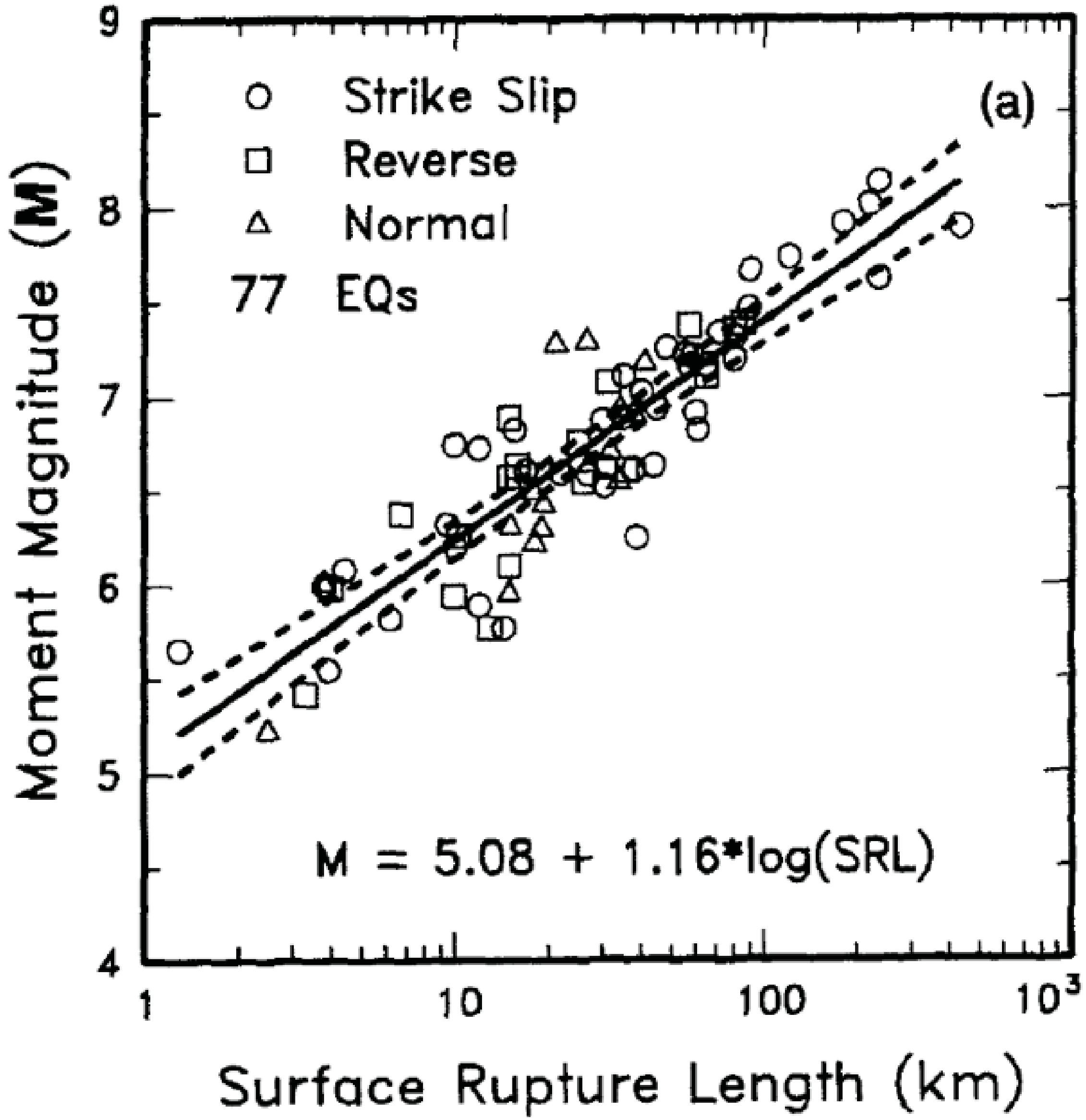






Can/will entire 1200 km length of San Andreas rupture in single M8.6 quake?



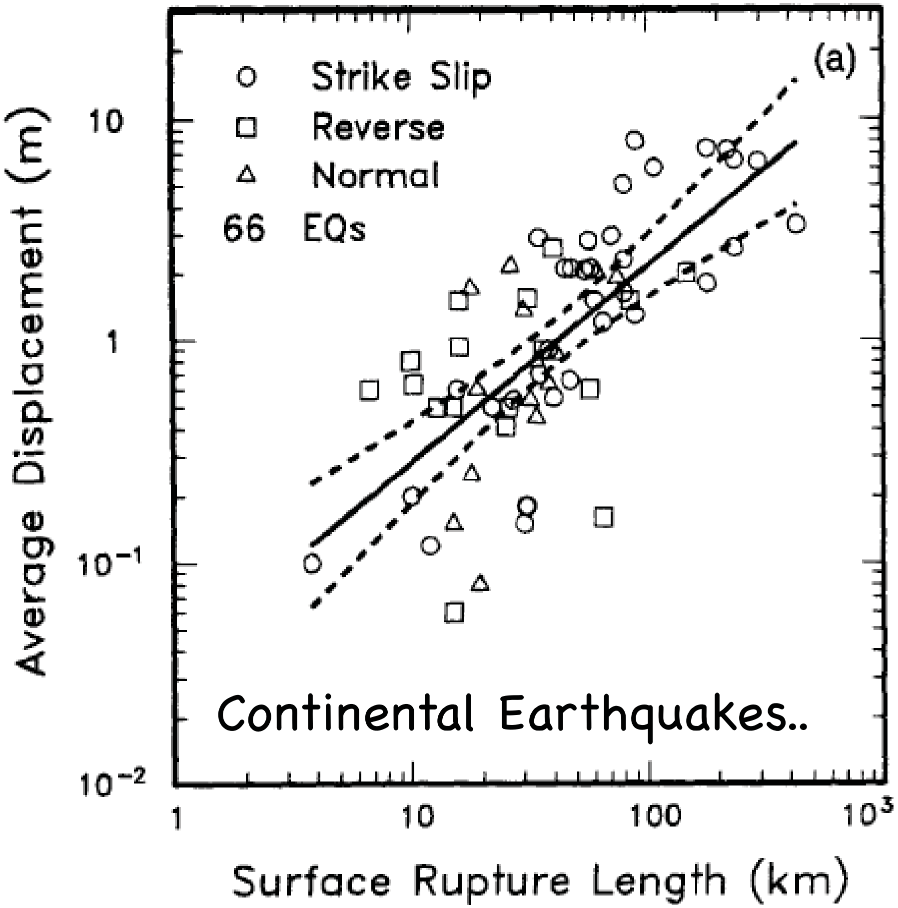


Empirical Scaling Law for Magnitude vs Rupture Length

of practical importance to seismic hazard

Wells & Coppersmith, 1994

Empirical Scaling Law for Displacement vs Rupture Length



Wells & Coppersmith 1994

all events

Log (D) = -1.43 + 0.88*Log(L)

just strike-slip

Log (D) = -1.70 + 1.04*Log(L)

Log (D) = Constant + ~1.0*Log(L)

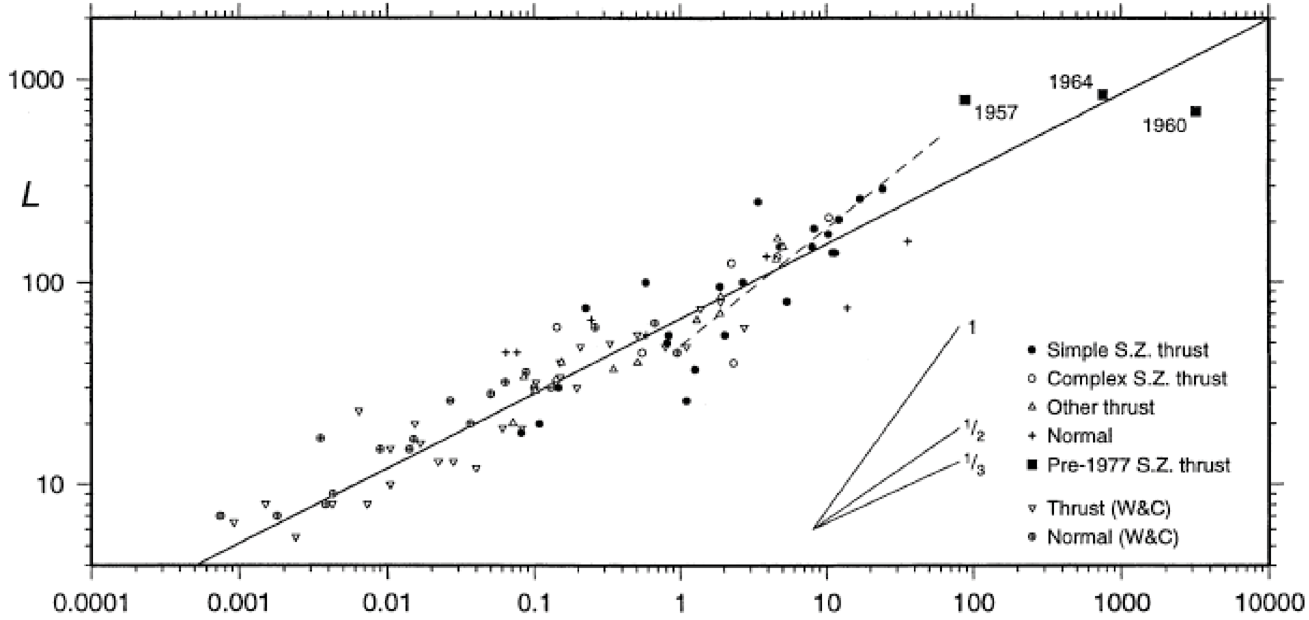
$D = \text{Constant} * L^1$

Slip Proportional to Rupture Length

$Mo = \mu LWD = \mu L(\propto L) \propto \mu L^2$

Subduction Zone Thrusts...

L(km)



Mo / 10^{20}Nm

all events

$\text{Log}(L) = -5.58 + 0.4 * \text{Log}(Mo)$

$L = \text{Constant} * Mo^{0.4}$ --> $0.4 \approx 0.5$ --> $= \text{Constant} * Mo^{0.5}$

$L^2 \propto Mo$ -----> Seismic Moment proportional to rupture length squared

Seismic Moment Versus Rupture Area...

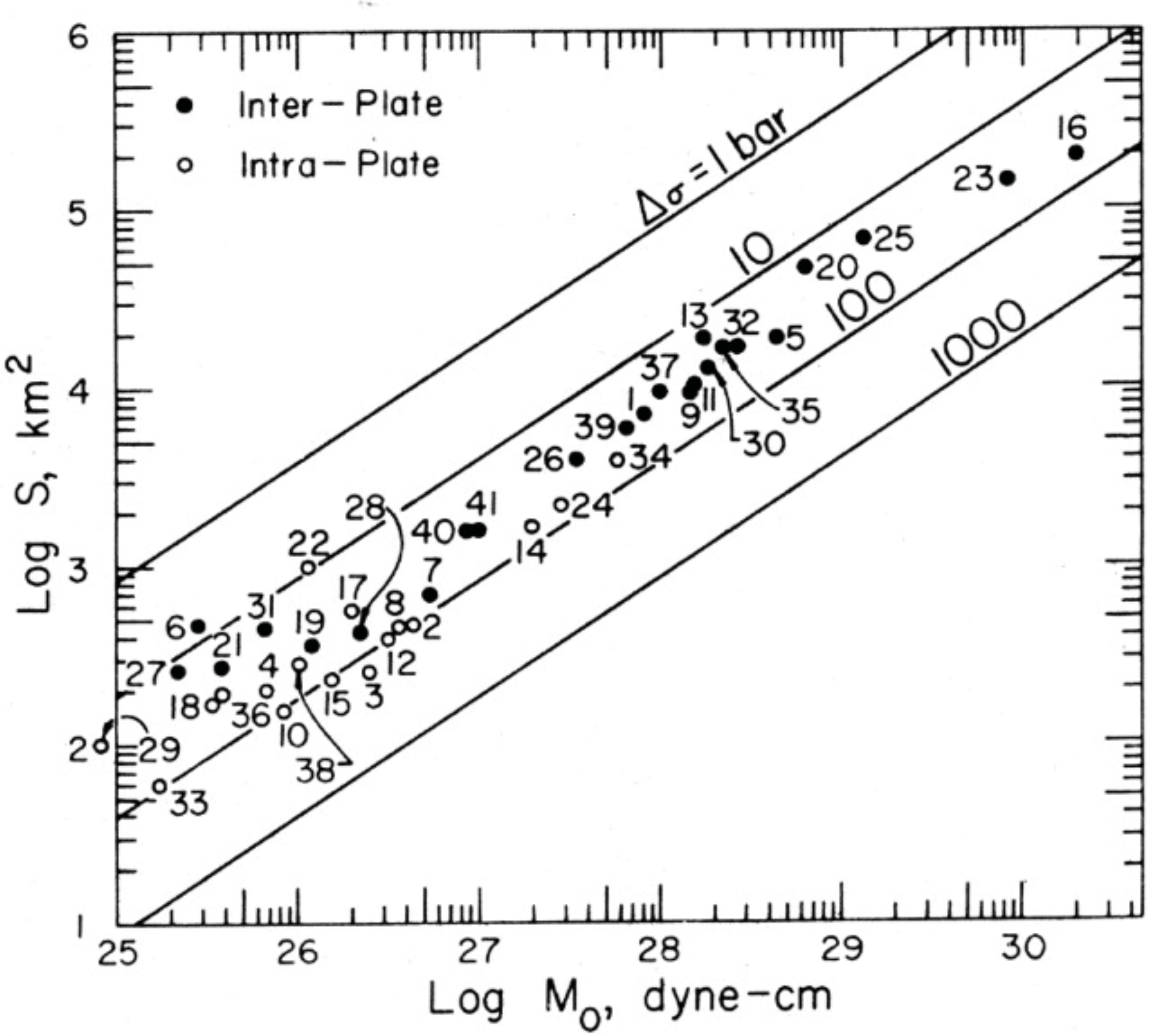


FIG. 2. Relation between S (fault surface area) and M_o (seismic moment). The straight lines give the relations for circular cracks with constant $\Delta\sigma$ (stress drop). The numbers attached to each event correspond to those in Table 1.

General Expression for stress drop

$$\Delta\sigma = C\mu\frac{\bar{D}}{\hat{a}}$$

$$\bar{D} = ave\ slip\ on\ fault\ plane$$

$$\hat{a} = Length\ Dimension\ (smallest)$$

$$C = shape\ factor \text{ (circular, rectangular, etc.)}$$

$$= \frac{7\pi}{16},\ for\ circular\ fault$$

rearranging

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

Seismic Moment in terms of Stress Drop and Fault Area

$$Mo = \mu S\bar{D} = \mu S\frac{\hat{a}}{C\mu}\Delta\sigma$$

$$Mo = \mu S\bar{D} = \mu S\frac{\hat{a}}{C\mu}\Delta\sigma$$

$$recognizing\ S\ for\ circular fault = \pi\hat{a}^2$$

$$recalling\ C\ for\ circular\ fault\ = \frac{7\pi}{16}$$

$$Mo = \mu S\bar{D} = \mu S\frac{\hat{a}}{C\mu}\Delta\sigma = \mu\frac{\pi\hat{a}^3 16}{7\pi\mu}\Delta\sigma$$

$$to\ make\ convenient\ expression\ between\ Mo,\ StressDrop,\ and\ Fault\ area$$

$$note\ a^3 = \frac{(\pi a^2)^{3/2}}{\pi^{3/2}} = \frac{S^{3/2}}{\pi^{3/2}}$$

$$Mo = \frac{16}{7\pi^{3/2}}\Delta\sigma S^{3/2}$$

$$take\ log\ of\ each\ side$$

$$Log\ Mo = (3/2)LogS + Log\frac{16\Delta\sigma}{7\pi^{3/2}}$$

$$Log\ Mo = (3/2) Log S + Log \frac{16\Delta\sigma}{7\pi^{3/2}}$$

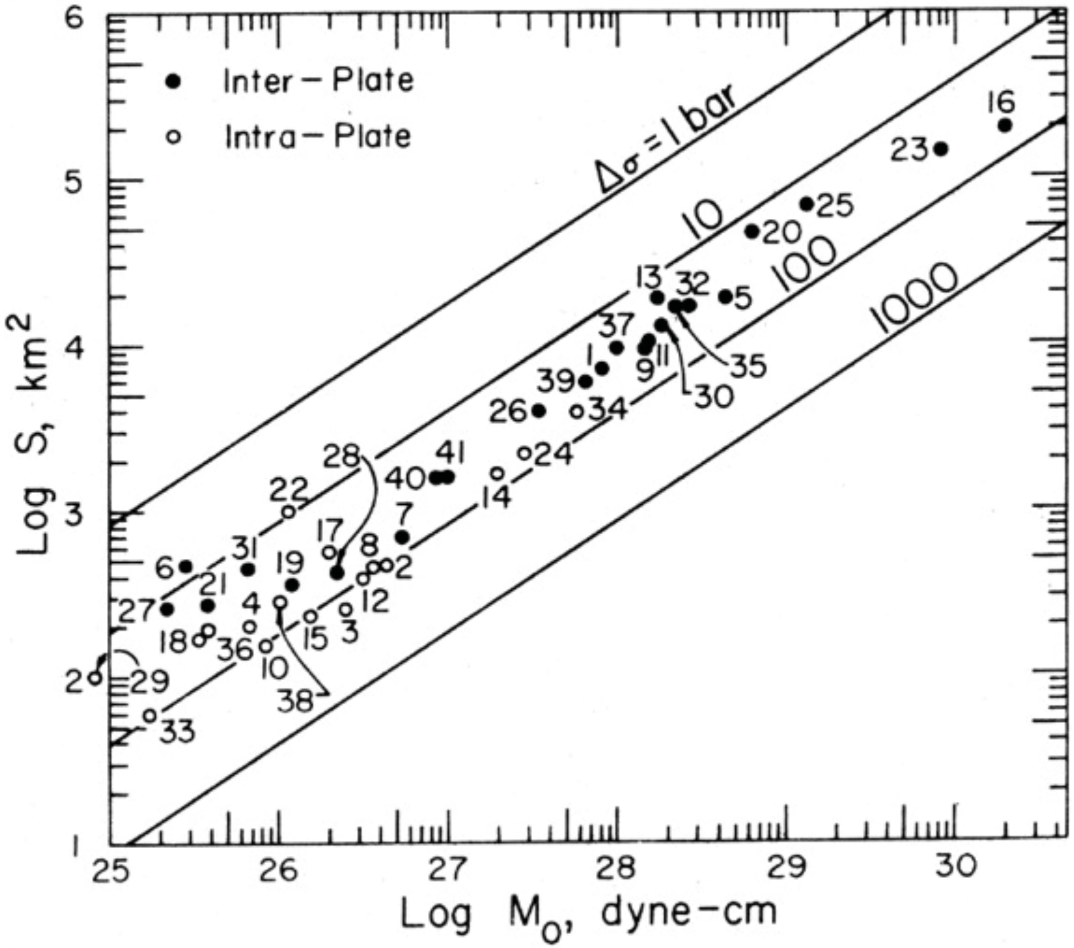


FIG. 2. Relation between S (fault surface area) and M_o (seismic moment). The straight lines give the relations for circular cracks with constant $\Delta\sigma$ (stress drop). The numbers attached to each event correspond to those in Table 1.

Relationships (scaling) between fault parameters can vary between tectonic environments...

The relationship between magnitude and rupture length varies if data are separated according to how frequently the particular earthquakes are expected to occur (on the respective sections of the faults on which they occurred)

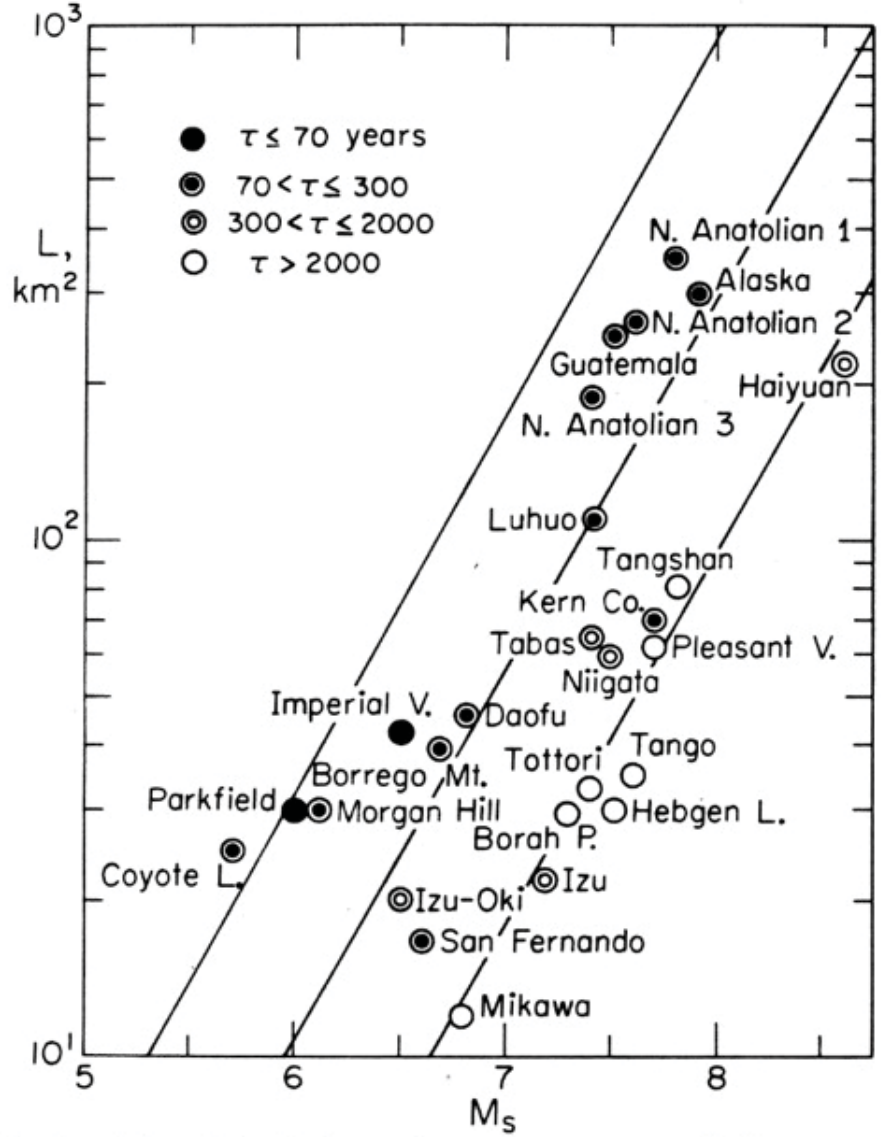


Fig. 1. The relation between the surface-wave magnitude, M_S, and the fault length, L. The solid lines indicate the trend for a constant stress drop.

Relationships (scaling) between fault parameters can vary between tectonic environments...

to start, define average stress drop as ratio

$$\bar{\Delta\sigma} = \frac{\int_S \Delta\sigma ds}{\int_S D ds}$$

$$rewrite\ by\ recalling \quad W = \frac{1}{2}\Delta\sigma\bar{D}S \quad so \quad \Delta\sigma\bar{D}S = 2W\ (E_s)$$

$$and\ M_o = \mu S\bar{D} \quad so \quad D = \frac{M_o}{\mu S}$$

$$\bar{\Delta\sigma} = \frac{2\mu E_s}{M_o} = \frac{2E_s}{S\bar{D}} = \frac{2 \times 10^{1.5Ms+11.8}}{LWD}$$

a relationship between stress drop, magnitude, fault dimensions, and offset

$$\bar{\Delta}\sigma = \frac{2 \times 10^{1.5Ms+11.8}}{LWD}$$

Assume like suggested in earlier observations that

width W is constant and $D \propto L$

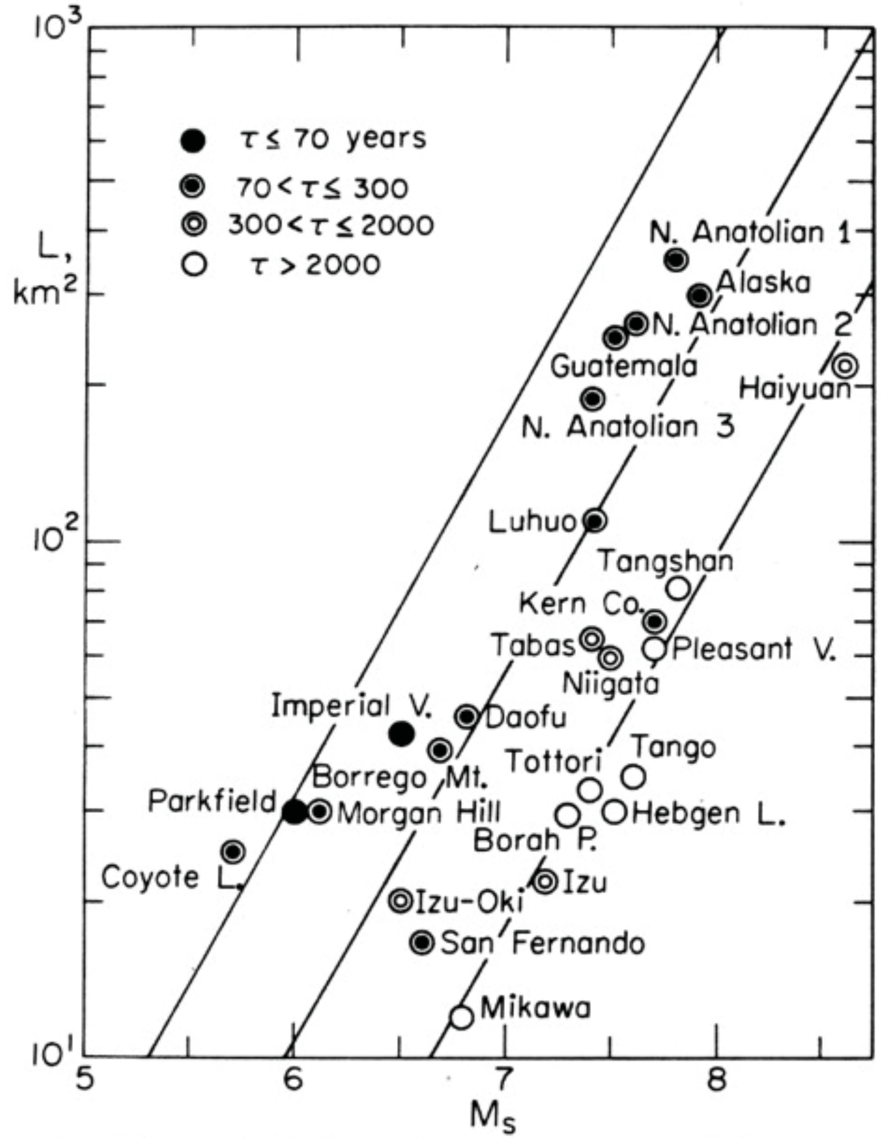
$$L^2 D \propto \frac{2 \times 10^{1.5Ms+11.8}}{\Delta\sigma}$$

taking Log of both sides...

$$LogL \propto \frac{1.5}{2} M_s - \frac{1}{2} Log\Delta\sigma$$

a relationship between rupture length, magnitude, and stress drop

$$LogL \propto \frac{1.5}{2} M_s - \frac{1}{2} Log\Delta\sigma$$



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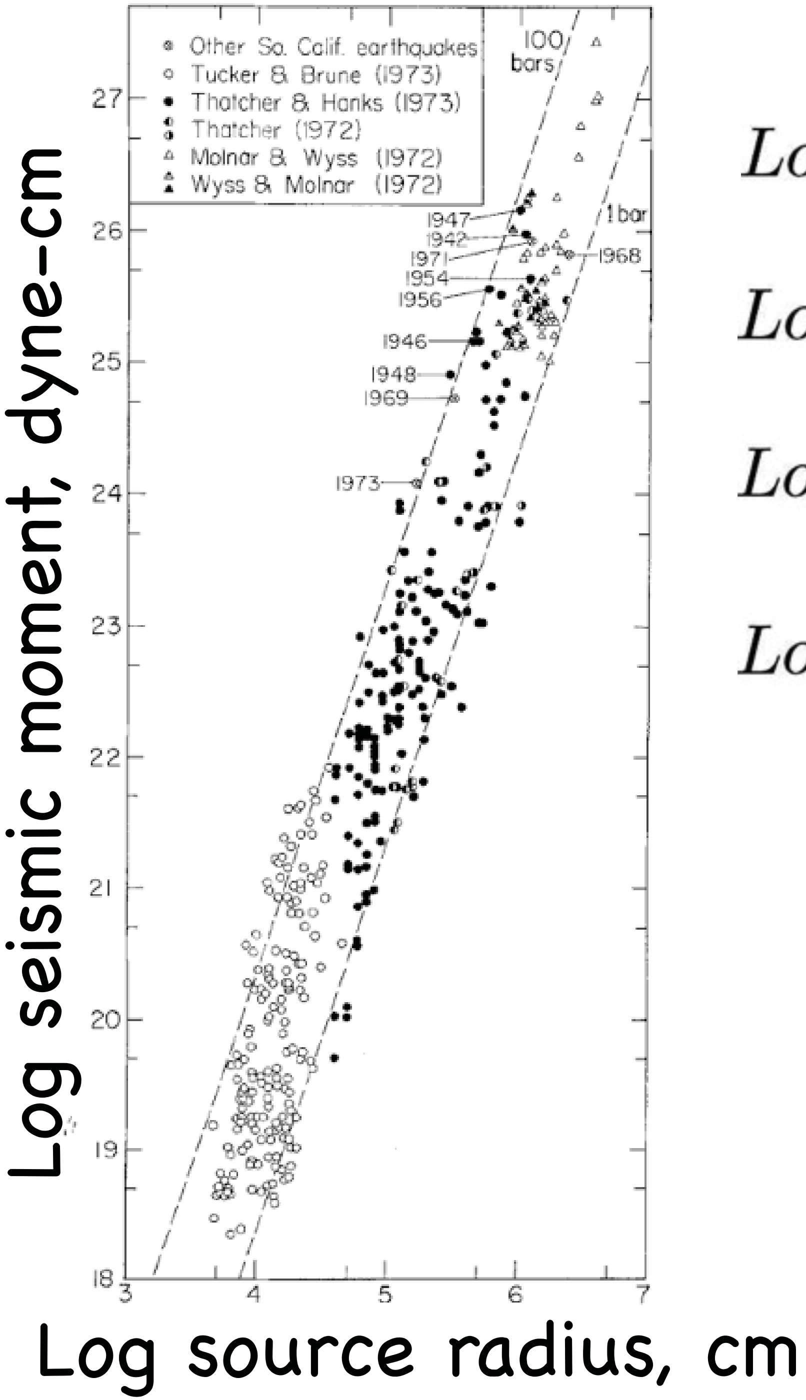

$$Log\ Mo = (3/2)LogS + Log\frac{16\Delta\sigma}{7\pi^{3/2}}$$

$$Log\ Mo \propto (3/2)Log\pi\hat{a}^2$$

$$Log\ Mo \propto Log\pi\hat{a}^3$$

$$Log\ Mo \propto Log\pi\hat{a}^3 = 3Log\pi a$$

Hanks 1977