Carol Prentice - Haiti
Mark Quigley - Darfield
(Discuss)

Introductory overview part 2

(More discussion?)

What happens at the source

↓

Magnitude scales (pp. 11-16)

Relationships between magnitude and slip, rupture length, rupture area etc.

+

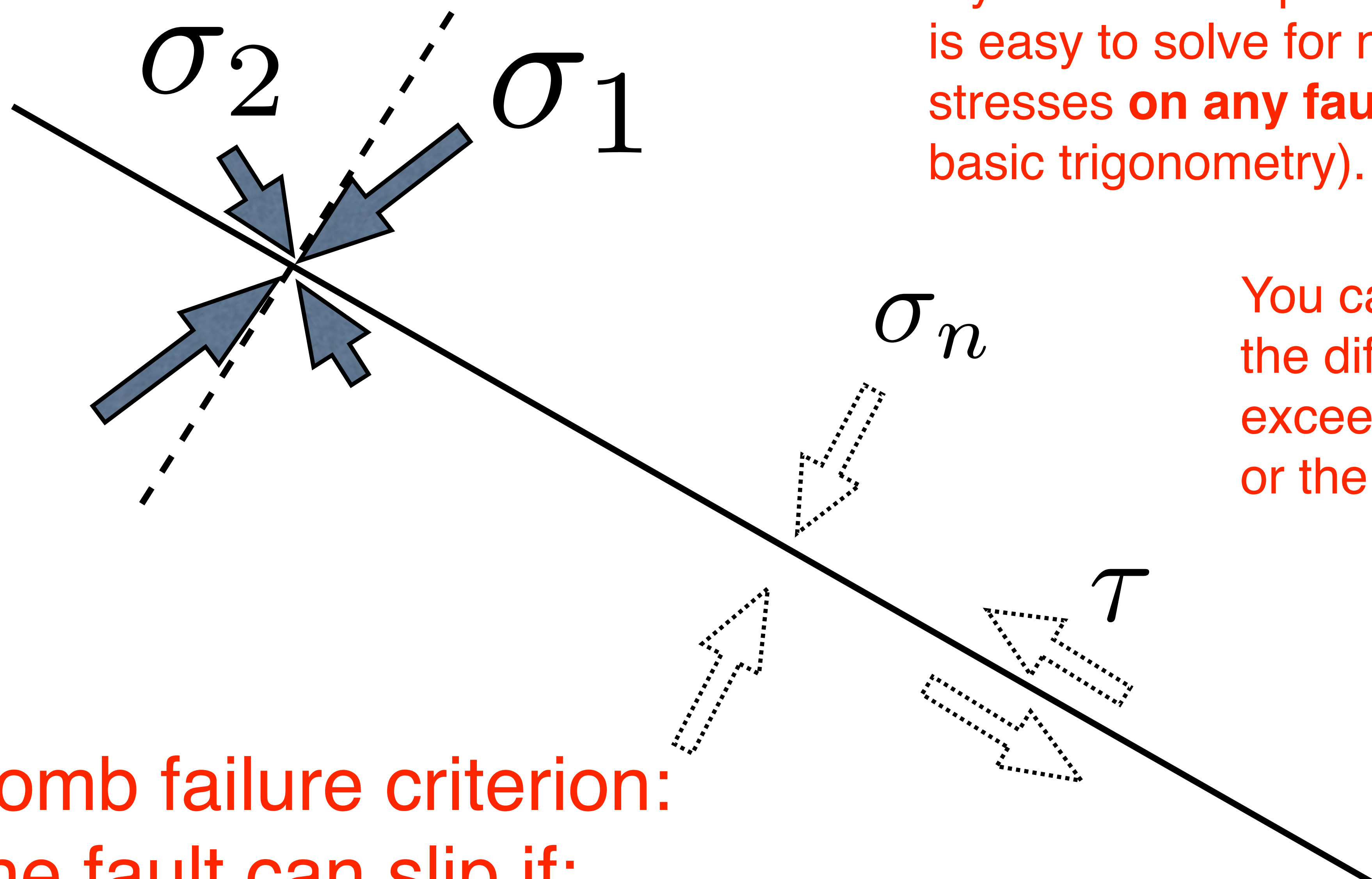
Gutenberg-Richter relationship: Magnitude-frequency

↓

Probabilities from moment accumulation rate and G-R relationship (or assumed recurrence interval) (pp. 25-33)

$$\sigma = \begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$

If you know the principal stresses it is easy to solve for normal and shear stresses **on any fault plane** (using basic trigonometry).

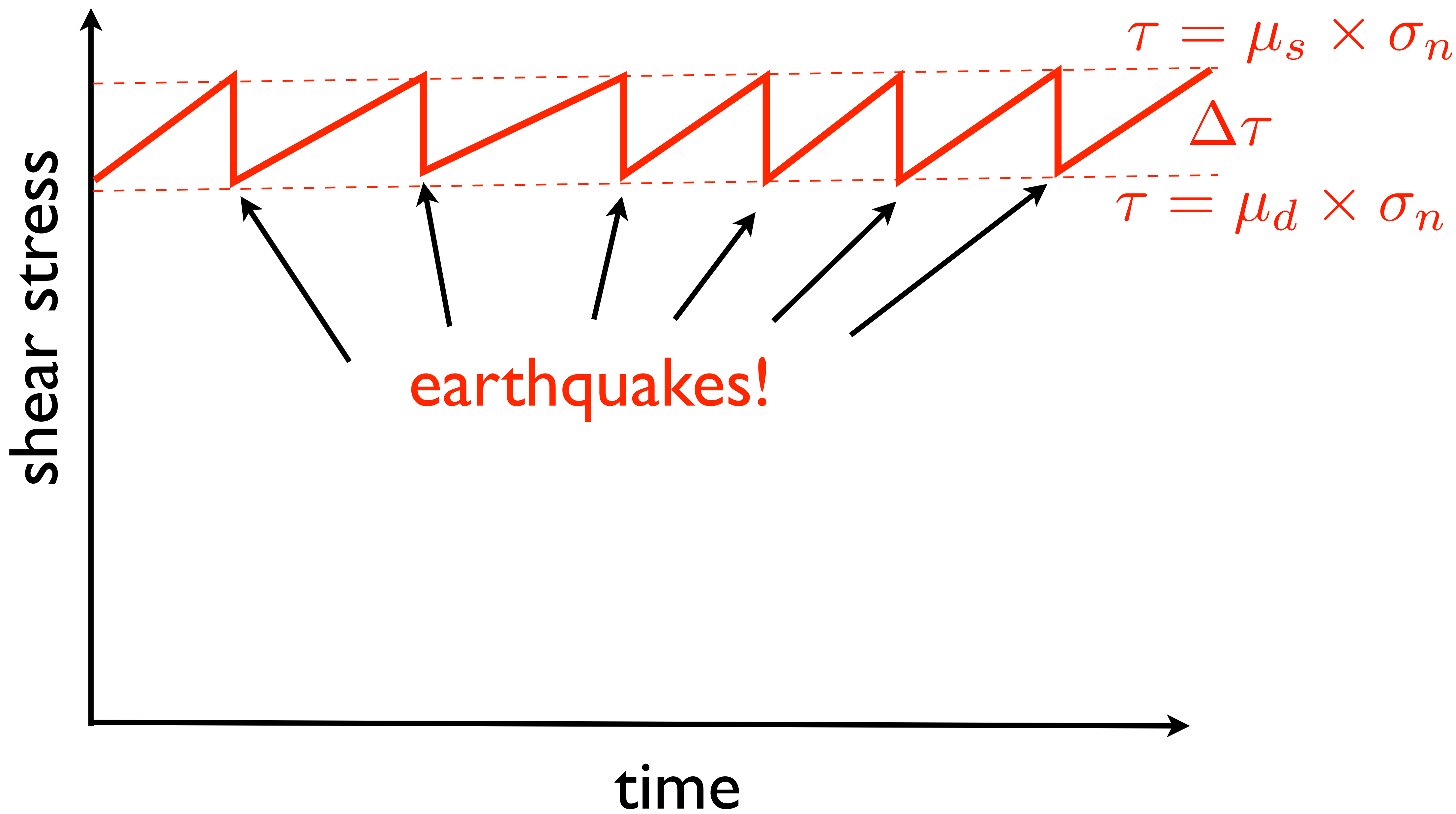


You can very easily estimate the differential stress. It can't exceed a few hundred MPa or the rock will break.

Coulomb failure criterion:
The fault can slip if:

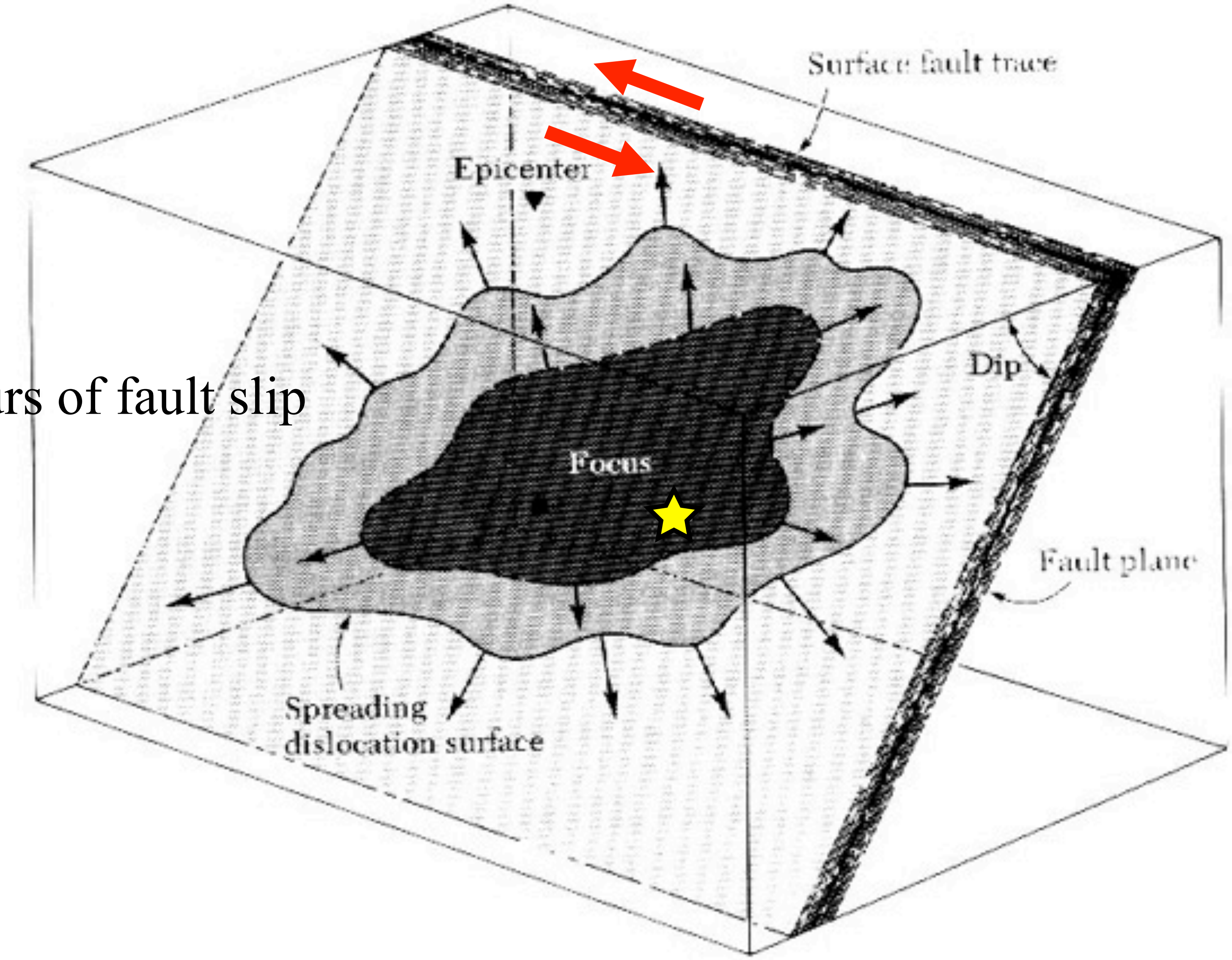
$$\tau = \mu \sigma_n$$

For many faults, earthquake shear stress drop is much smaller than "background" shear stress



Fault friction is actually more complicated than this because it depends on slip speed and the presence of water in the fault zone

What happens at the fault during an earthquake?

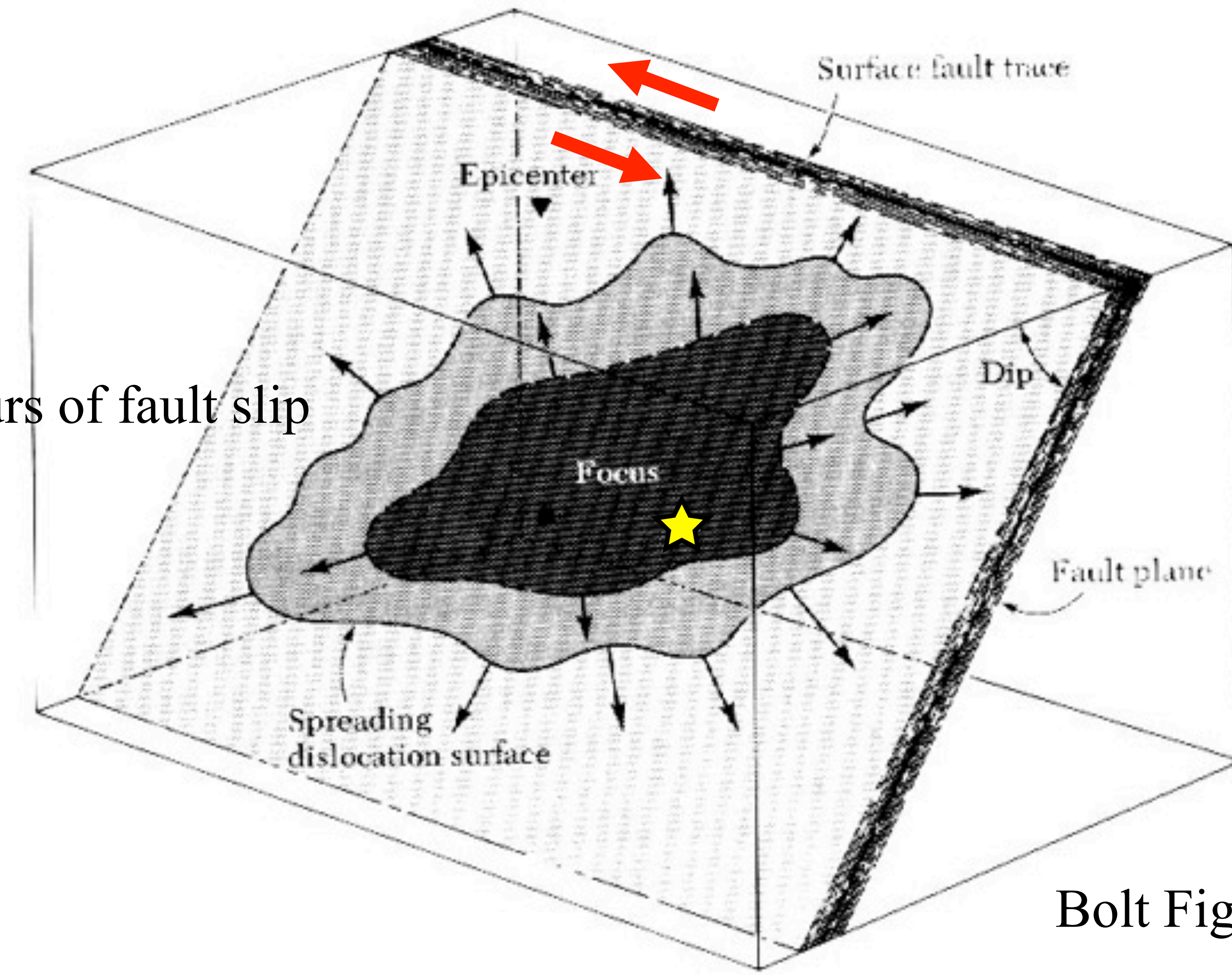


B. Bolt, Earthquakes, Figure 4.9

- Fracture starts at the hypocenter
- Fracture spreads out over some area
- Seismic waves radiate from wherever fault is slipping
  - Disturbance of rock travels far, but rock does not move far
  - Size of waves depends on how much slip happens over how large an area

• The rupture grows at about 90% of the S-wave velocity (2 to 3 km per second)

• Rock on either side of the fault moves at about 1 m/sec (and just for a few seconds in any place)



Bolt Figure 4.9

• The rupture grows at about the S-wave velocity (2 to 3 km per second)

then

• Crustal blocks on either side of the fault “realize” that they are no longer attached (because the fault is unstuck) and they begin to slide past each other

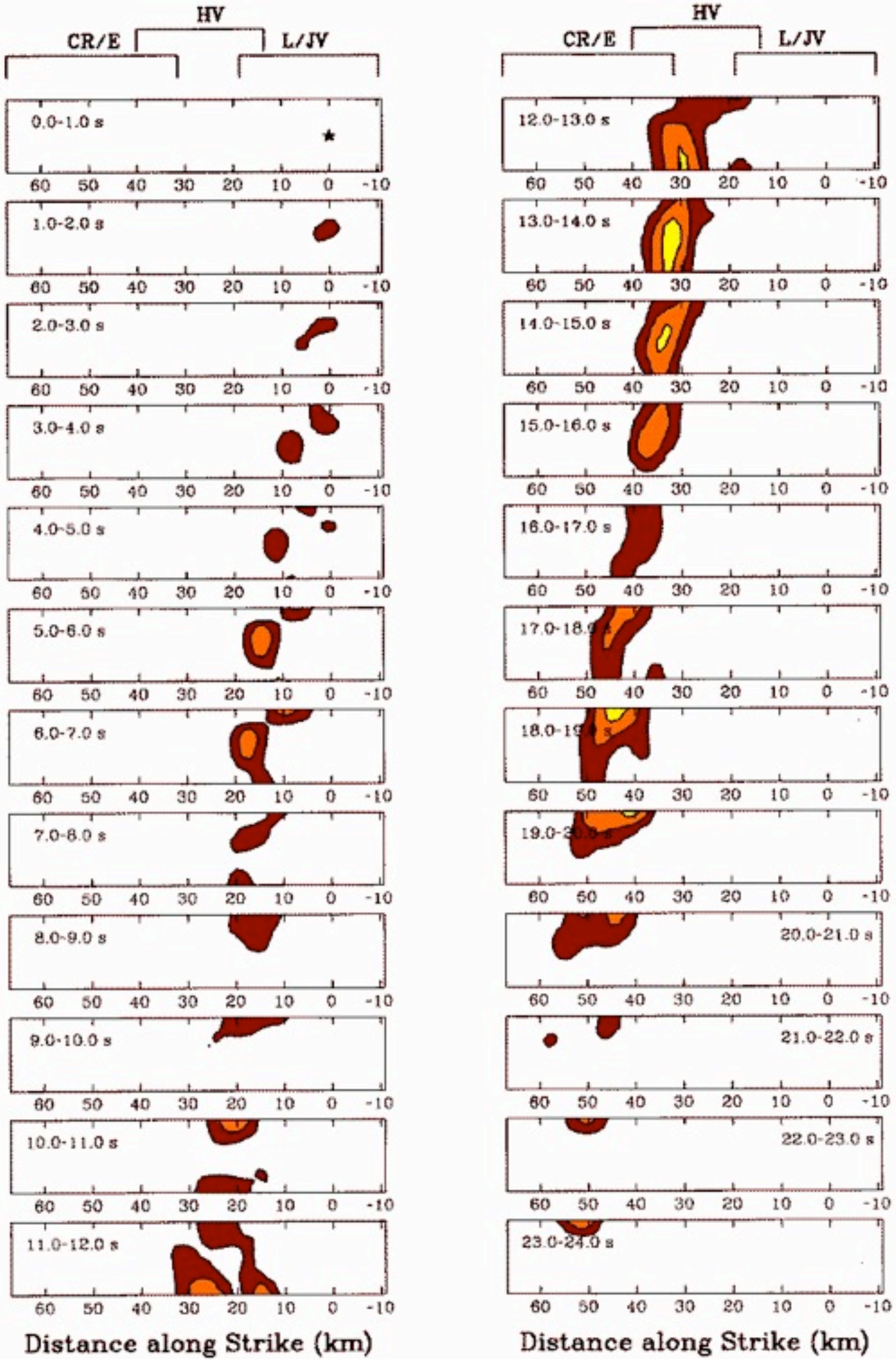
• coyote runs off cliff

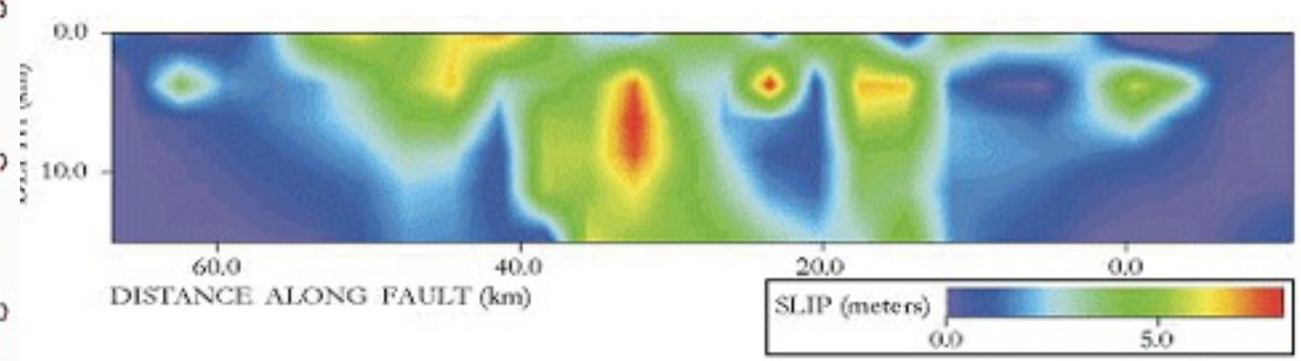
then

• coyote falls

1994 M = 7.4 Landers, California earthquake

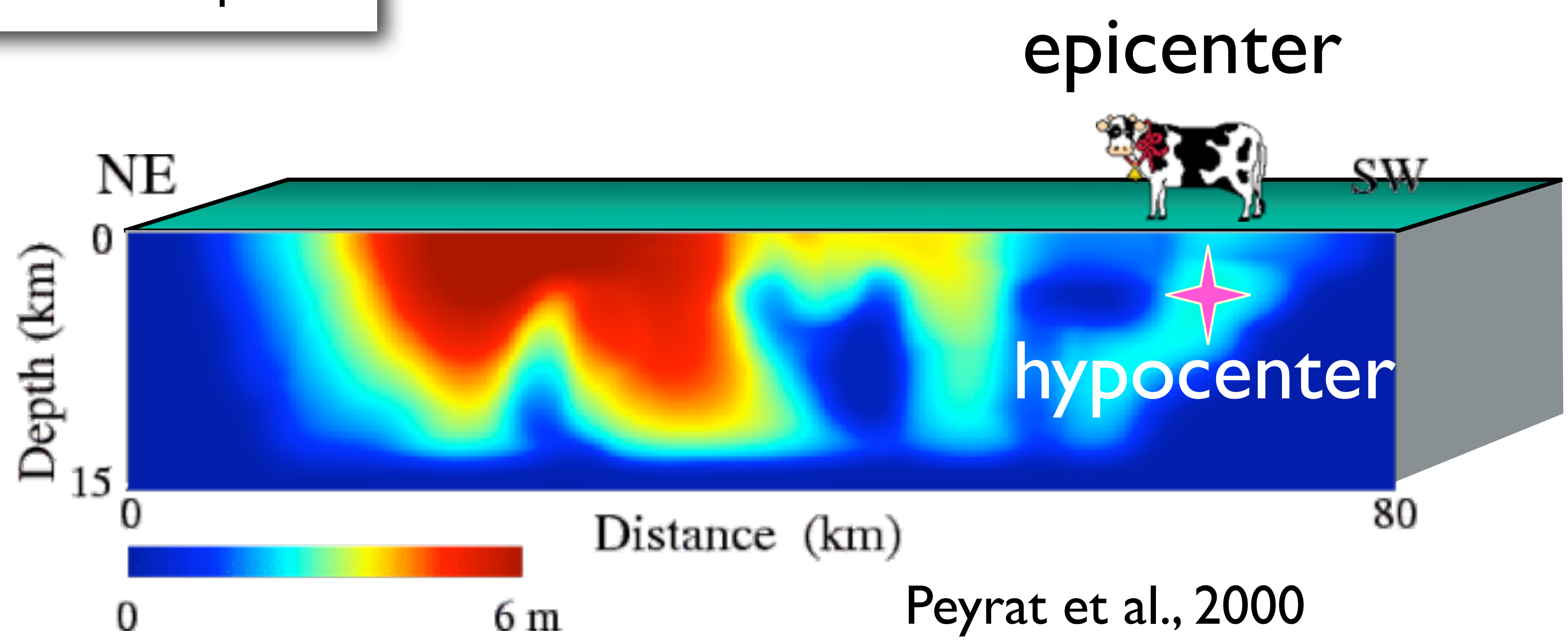
Total rupture time: 20-25 seconds. Fault is slipping only where you see the colors.


HV
CR/E
L/JV
0.0-1.0 s
1.0-2.0 s
2.0-3.0 s
3.0-4.0 s
4.0-5.0 s
5.0-6.0 s
6.0-7.0 s
7.0-8.0 s
8.0-9.0 s
9.0-10.0 s
10.0-11.0 s
11.0-12.0 s
12.0-13.0 s
13.0-14.0 s
14.0-15.0 s
15.0-16.0 s
16.0-17.0 s
20.0-21.0 s
21.0-22.0 s
22.0-23.0 s
23.0-24.0 s
60 50 40 30 20 10 0 -10
Distance along Strike (km)


0.0
10.0
60.0
40.0
20.0
0.0
DISTANCE ALONG FAULT (km)
SLIP (meters)
0.0
5.0

When it's all over... splotchy slip distribution

1994 M = 7.4 Landers, California earthquake



Peyrat et al., 2000

rupture begins at the hypocenter and travels away
("unilateral" = one-way, "bilateral" = both ways)

We can use this information to get earthquake moment magnitude...

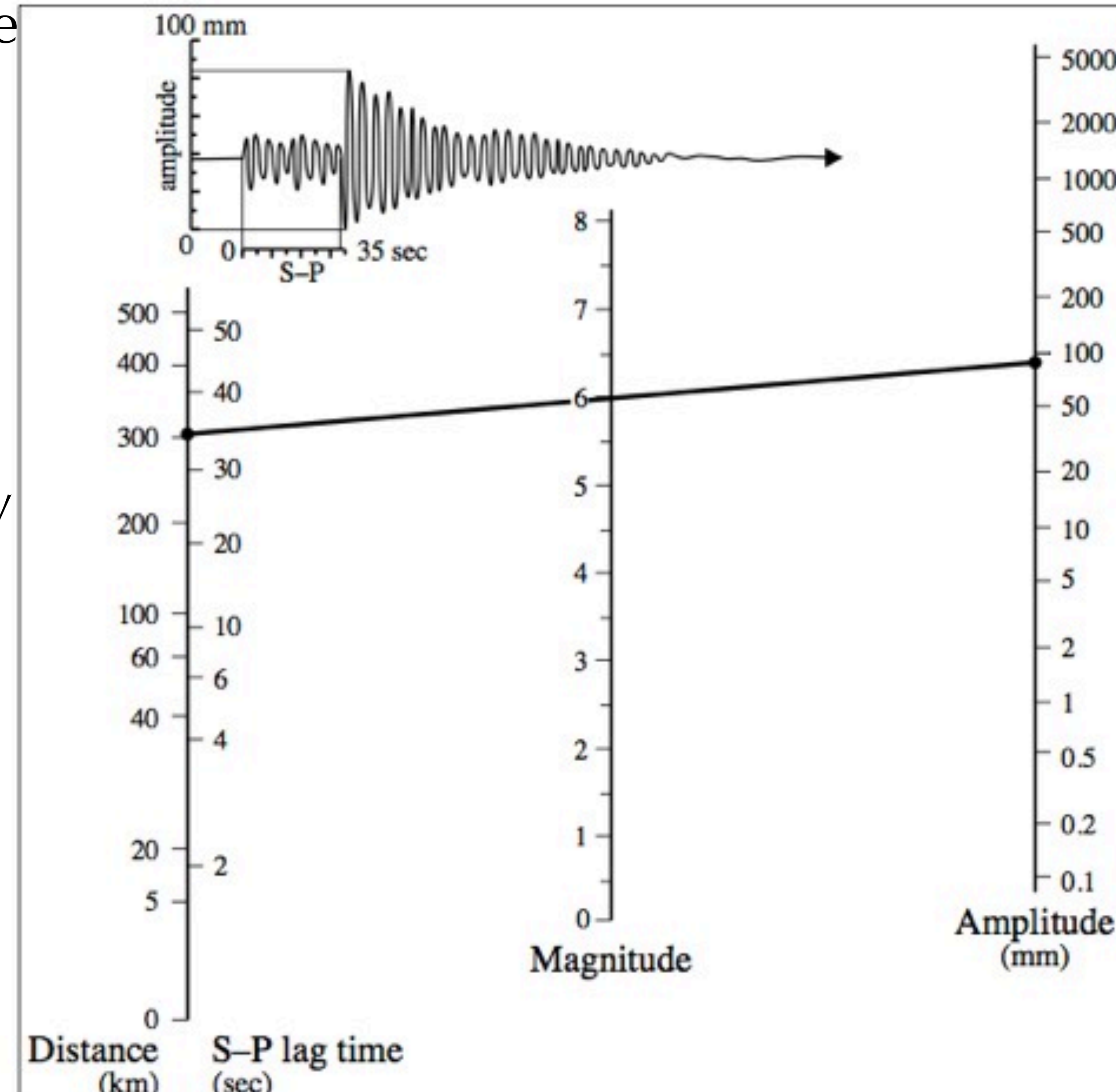
Magnitudes

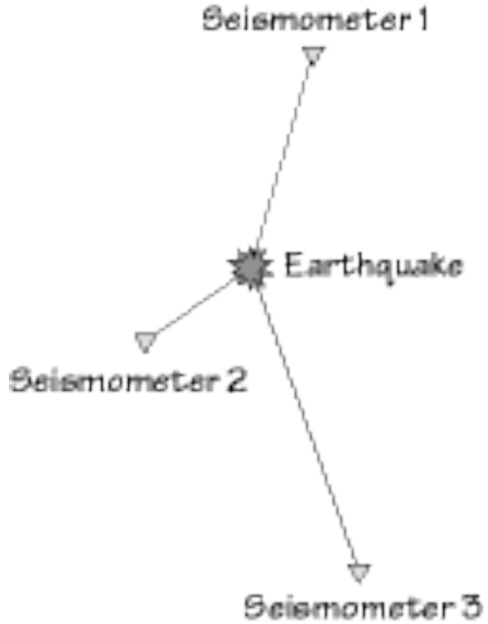
(1) Based on amplitudes of surface waves

(2) Based on energy (moment) release

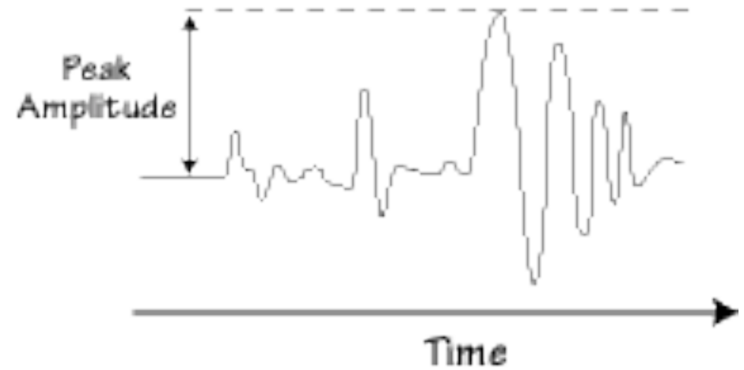
A quick method (pre electronic calculators), involved using a graphical construct (called a Nomogram) that takes care of the mathematics by constructing the axes in a particular fashion.

The Nomogram allows one to compute the magnitude by plotting the distance between the quake and observatory on the left axis, and the seismometer deflection in millimetres on the right axis. (The amplitude of the deflections in the supplied table have been adjusted so that they are what would have been recorded by a Wood- Anderson seismometer – essentially the actual ground motions have been multiplied by 2000 which is the amplification of the Wood-Anderson seismometer at these frequencies). The points on the left and right axes are connected by a straight line, and the intersection on the middle axis is the earthquake magnitude.

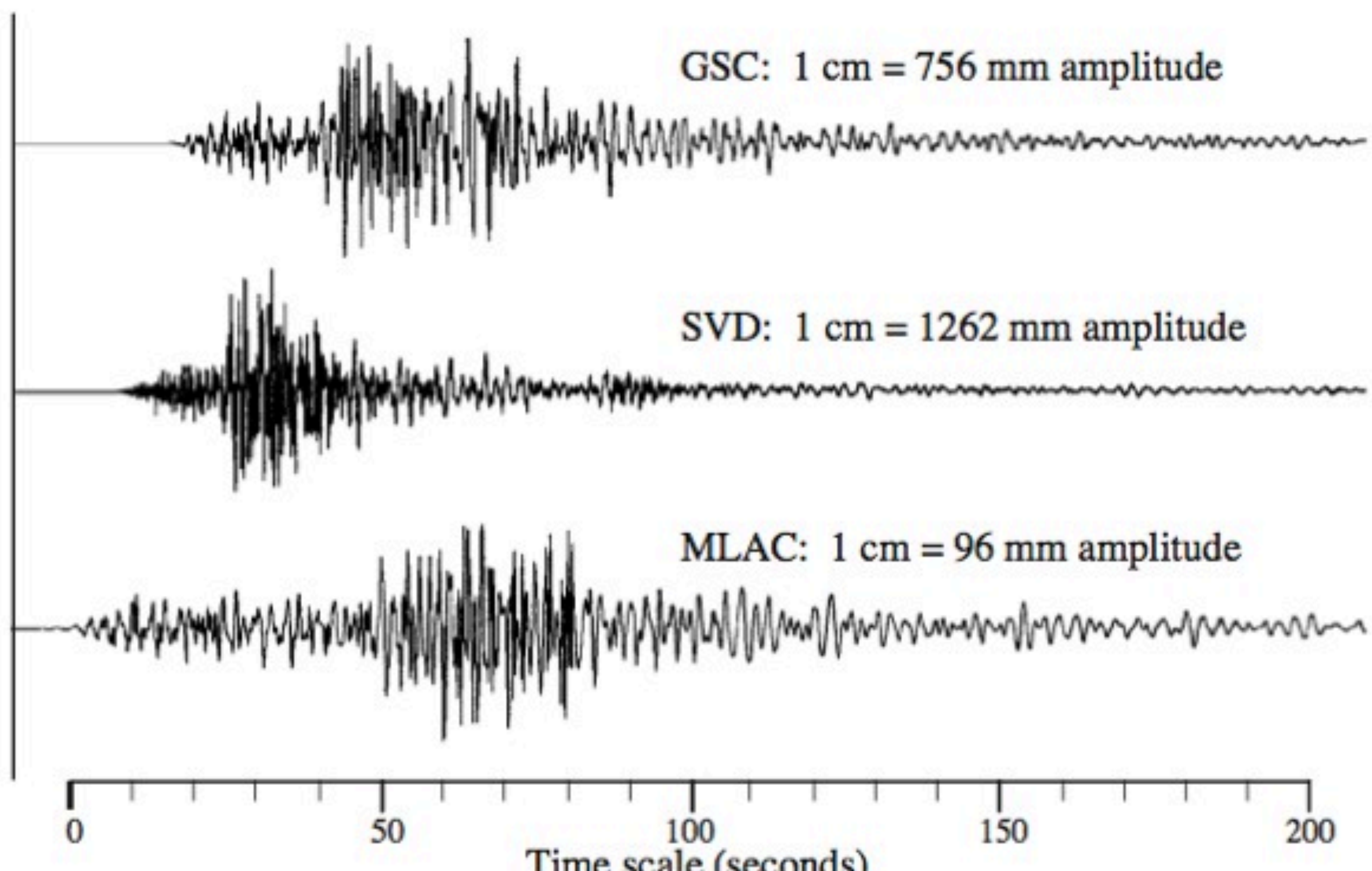




Seismometer 1
Earthquake
Seismometer 2
Seismometer 3



Peak
Amplitude
Time



GSC: 1 cm = 756 mm amplitude
SVD: 1 cm = 1262 mm amplitude
MLAC: 1 cm = 96 mm amplitude
0
50
100
150
200
Time scale (seconds)

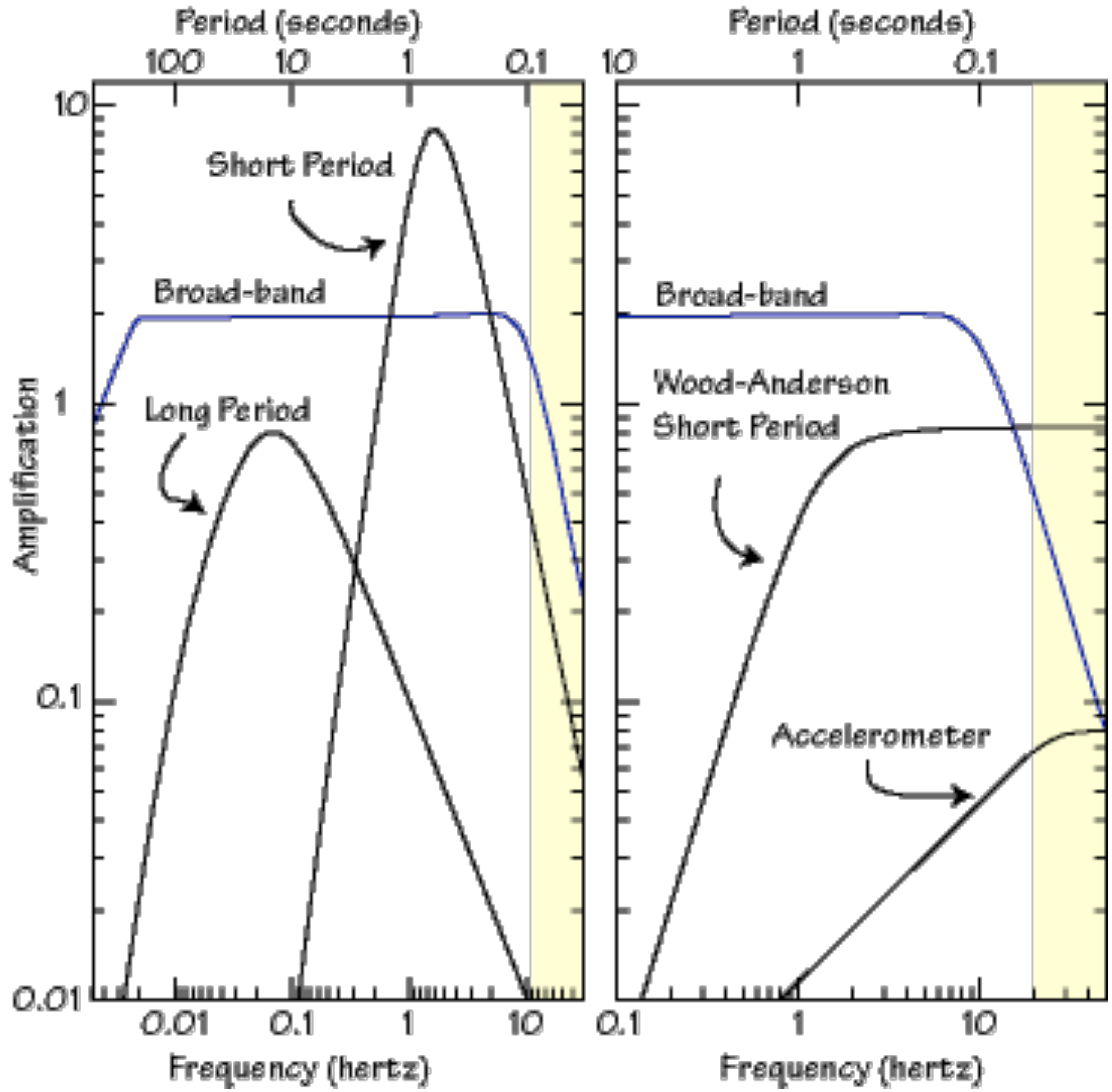
C. Ammon

Why doesn't the Richter scale work well for large earthquakes?

- It is based on Wood - Anderson seismographs from the 1920's (and their modern equivalents), which measure **high-frequency** waves well, but **not low frequency** waves.

- Most energy from big earthquakes is carried in low-frequency waves, which Wood - Anderson seismographs (and modern equivalents) cannot detect!!

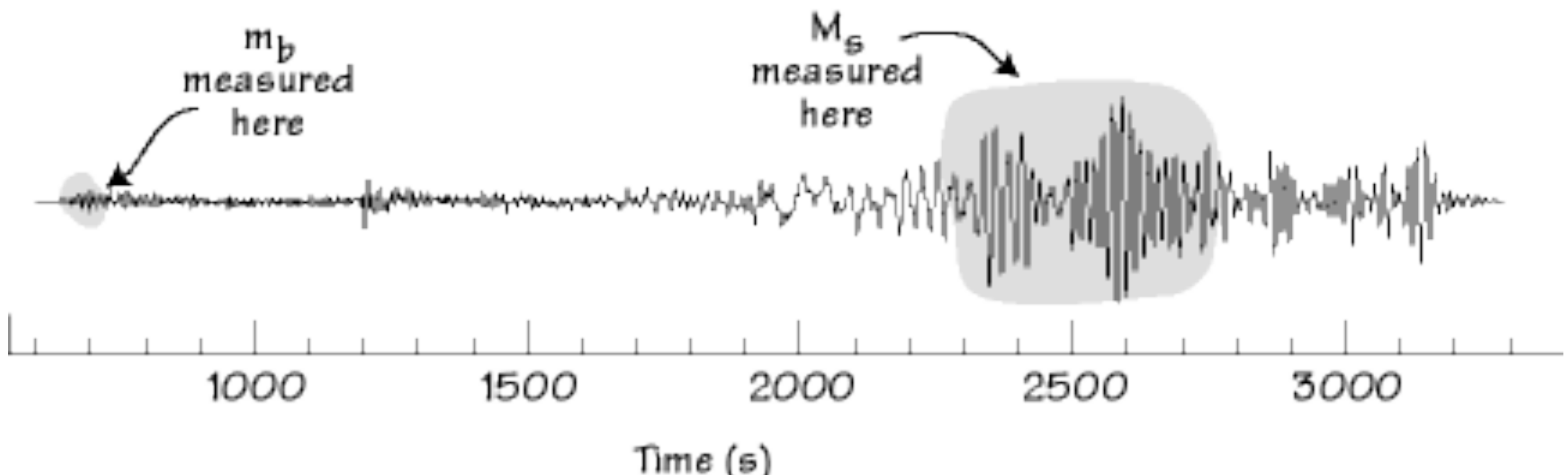
- Therefore, the Richter Magnitude for really big quakes is **too low**.



Period (seconds)
100
10
1
0.1
10
0.1
0.01
Amplification
Short Period
Broad-band
Long Period
0.01
0.1
1
10
Frequency (hertz)
Period (seconds)
10
1
0.1
Broad-band
Wood-Anderson
Short Period
Accelerometer
0.1
1
10
Frequency (hertz)

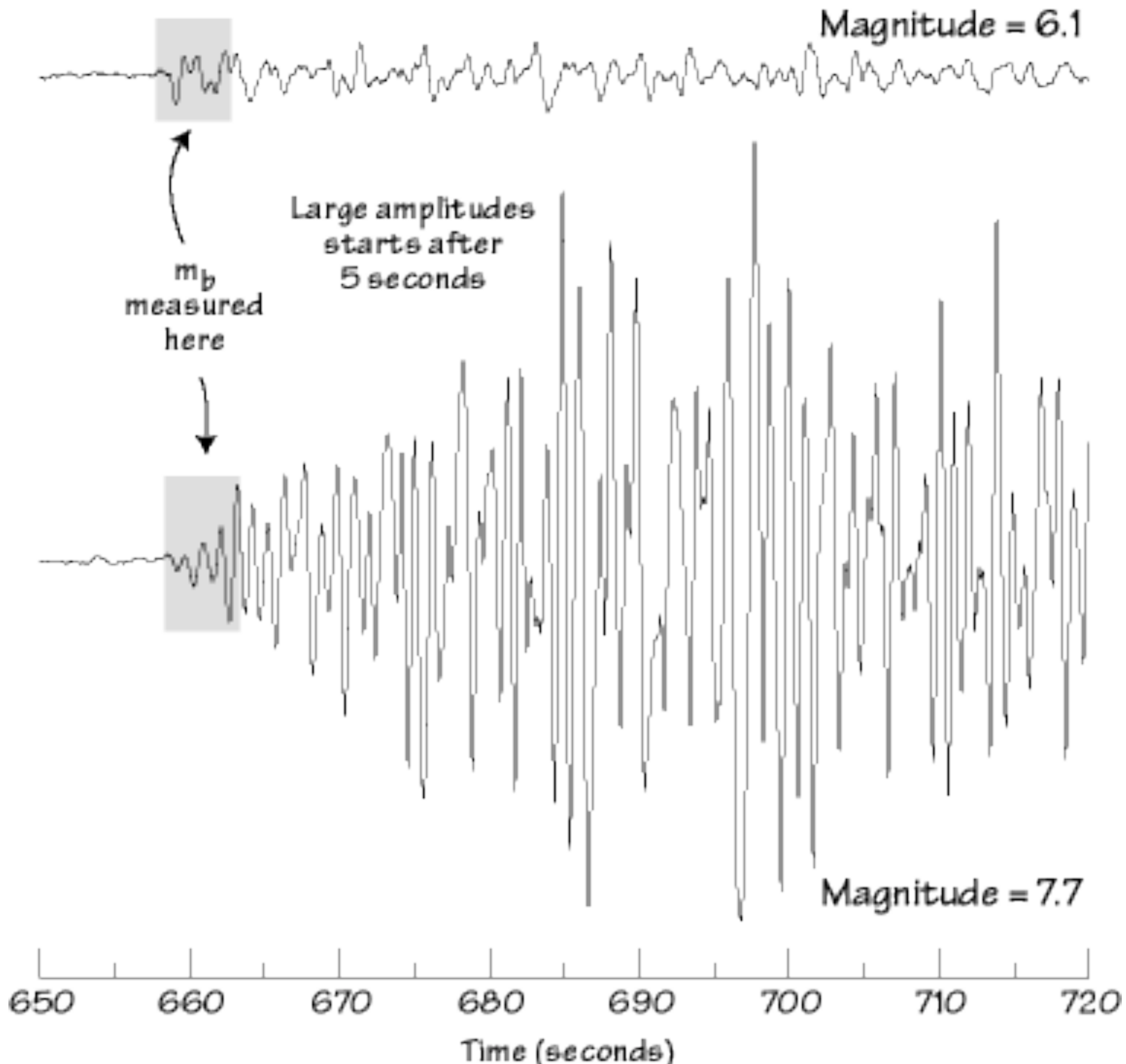
Magnitude	Symbol	Wave	Period
Local (Richter)	M_L	S or Surface Wave*	0.8 s
Body-Wave	m_b	P	1 s
Surface-Wave	M_s	Rayleigh	20 s
Moment	M_w	Rupture Area, Slip	> 100 s

*whichever's biggest at a period of 0.8s, and ALSO always using a Wood-Anderson seismograph (or converting amplitude so seismogram looks just like one from a WA seismograph)



N. Pinter

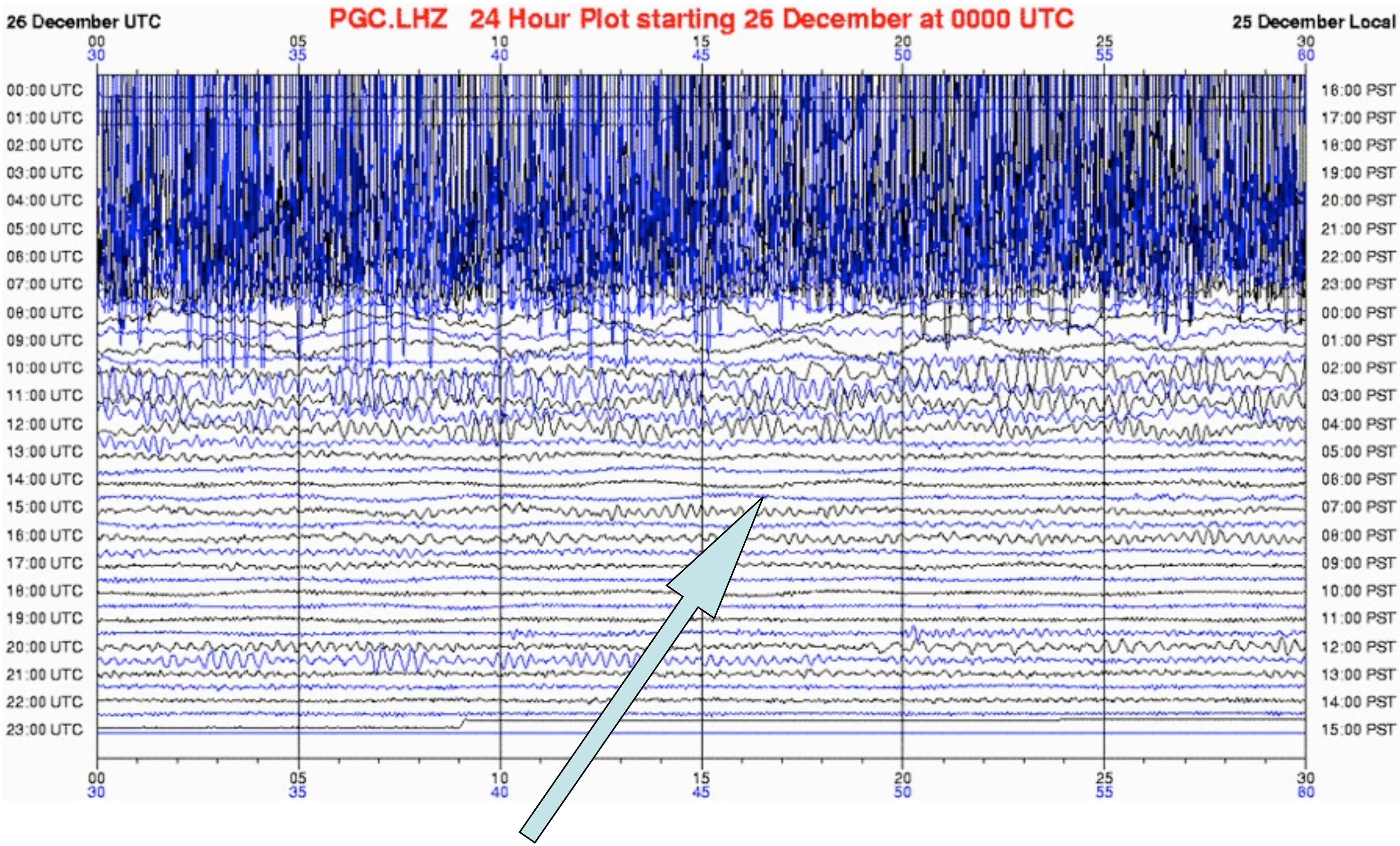
M_b and M_L are inadequate for large earthquakes



N. Pinter

Sumatra Earthquake: 26 December 2004

measured in Victoria BC



These low-frequency waves 16 hours later are still from the same earthquake. Higher sensitivity instruments show that the Earth rang like a gong for days, really long period (low-frequency) waves!

Earthquake magnitude scales

Magnitude	Symbol	Wave	Period
Local (Richter)	M_L	S or Surface Wave*	0.8 s
Body-Wave	m_b	P	1 s
Surface-Wave	M_s	Rayleigh	20 s
Moment	M_w	Rupture Area, Slip	> 100 s

C. Ammon

Mw is calculated from the **earthquake energy release**, which can be done with **many** different kinds of data, such as very long-period wave recordings from special ("broad band") seismometers and even GPS measurements of permanent ground displacement

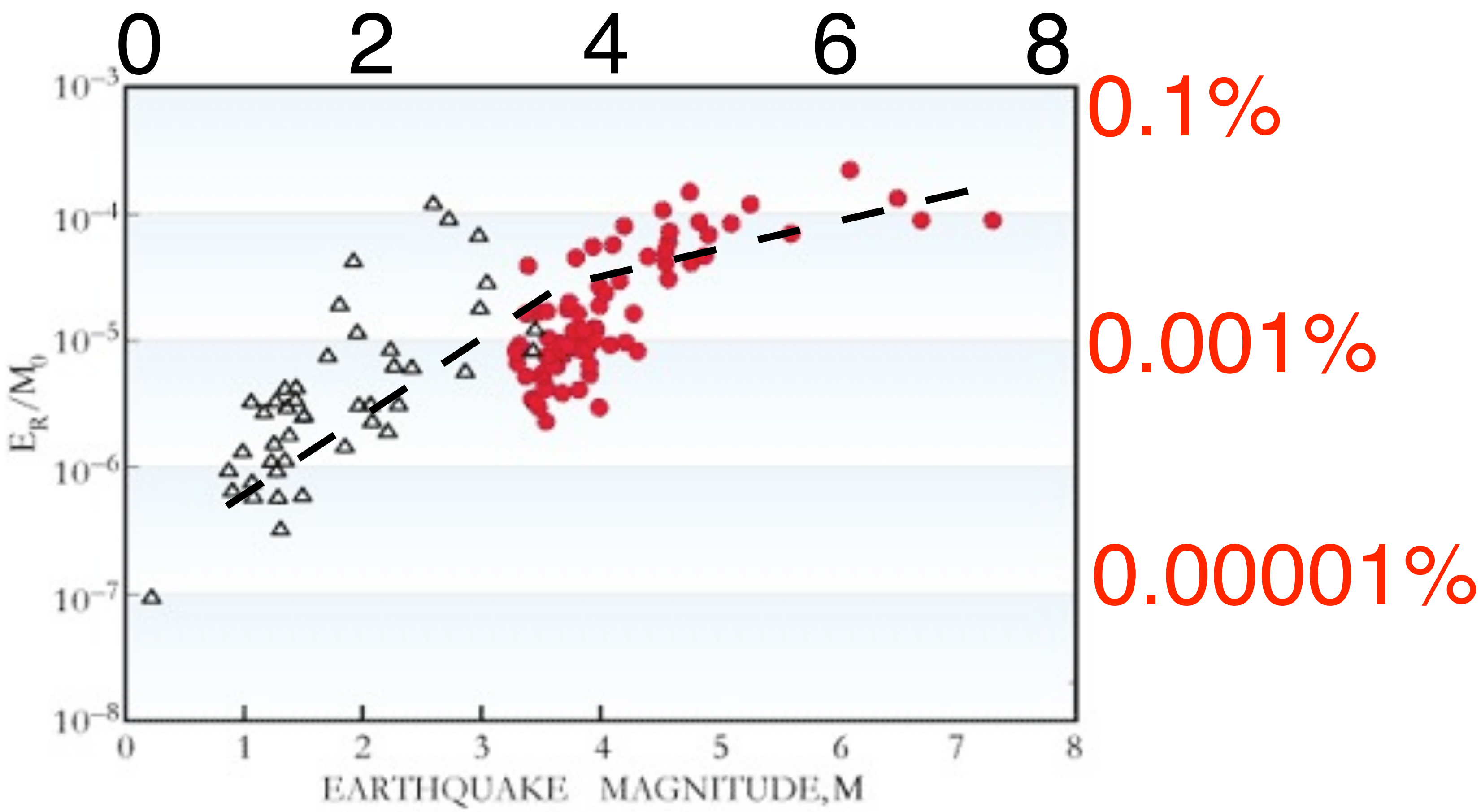
M_W is best for large earthquakes

Seismic moment M_o = rupture area x slip x G

(slip varies with position so $M_o = \int_A Gs\ dA$)

- units: s (m) x A (m^2) x G (N/m^2) = N m
- moment is defined in physics as force x distance
- values are **big**. 2.3 x 10^{20} N m for the 1999 Izmit M 7.4 earthquake
- we have recipes to convert M_o to something that looks like the Richter magnitude (log scale, up to 10)

Energy devoted to seismic shaking is just a tiny % of the total energy of the earthquake (seismic moment)



In a large earthquake, proportionally more energy goes to shaking (and the energy is spent on shaking at lower frequencies).

Magnitude as a function of slip, rupture size, and stress drop

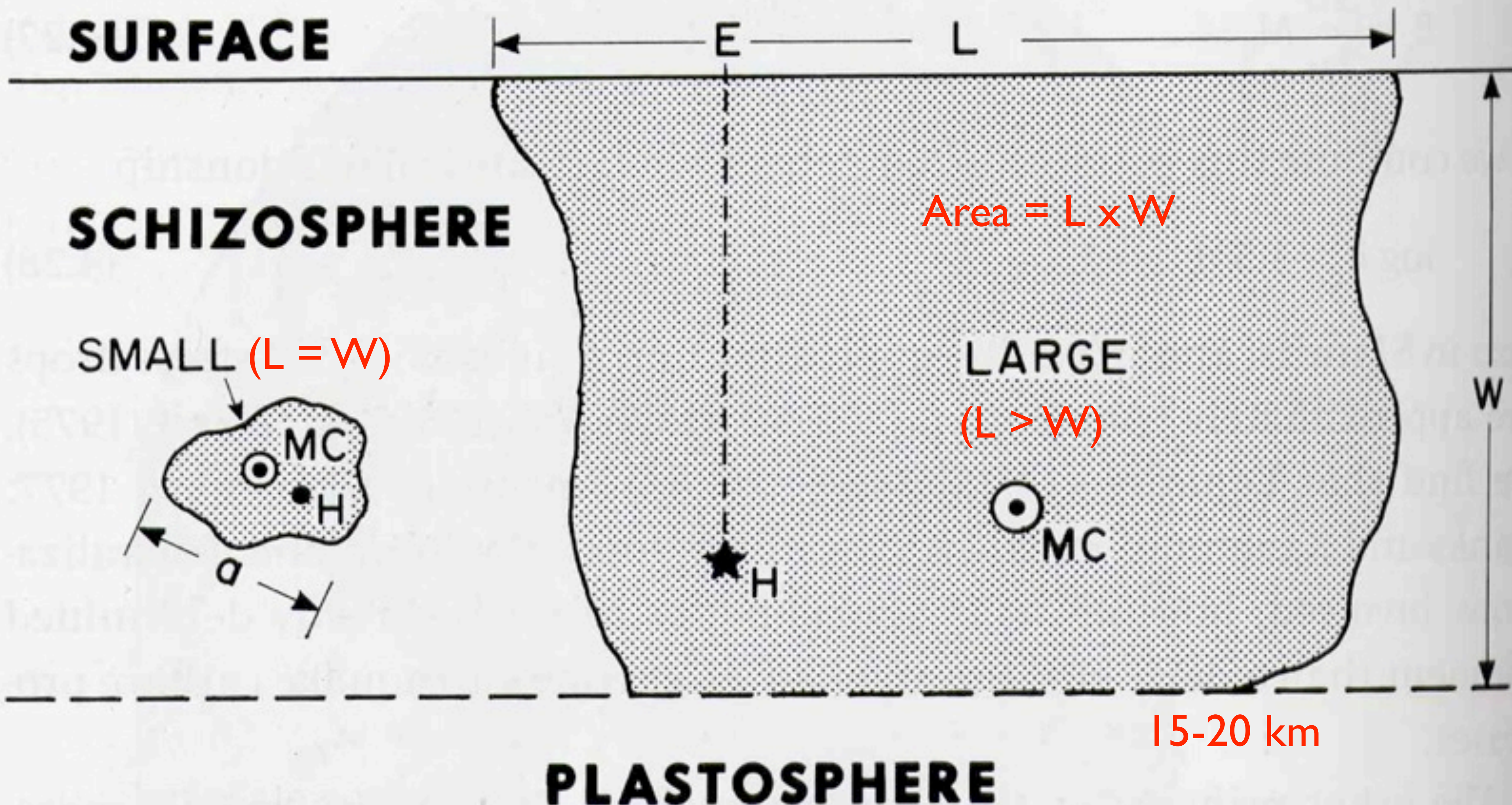
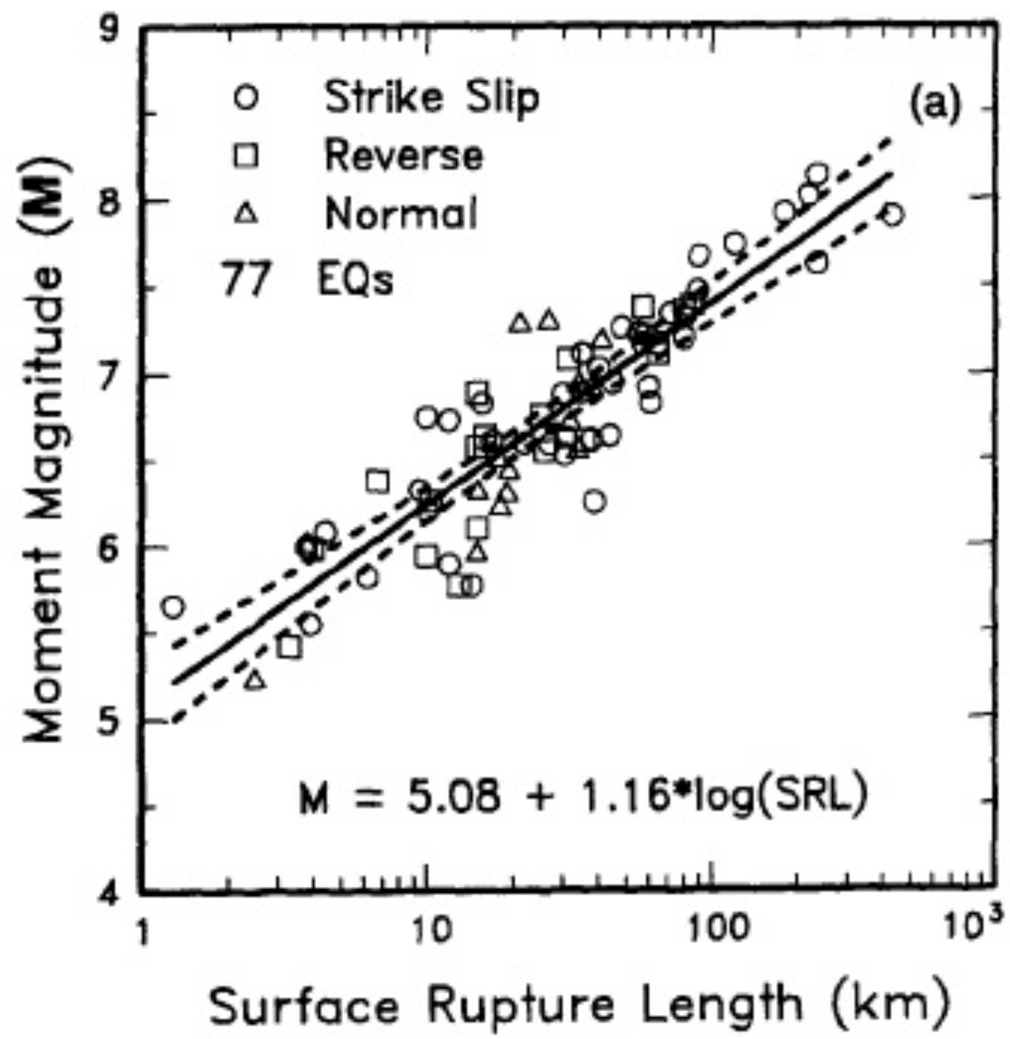


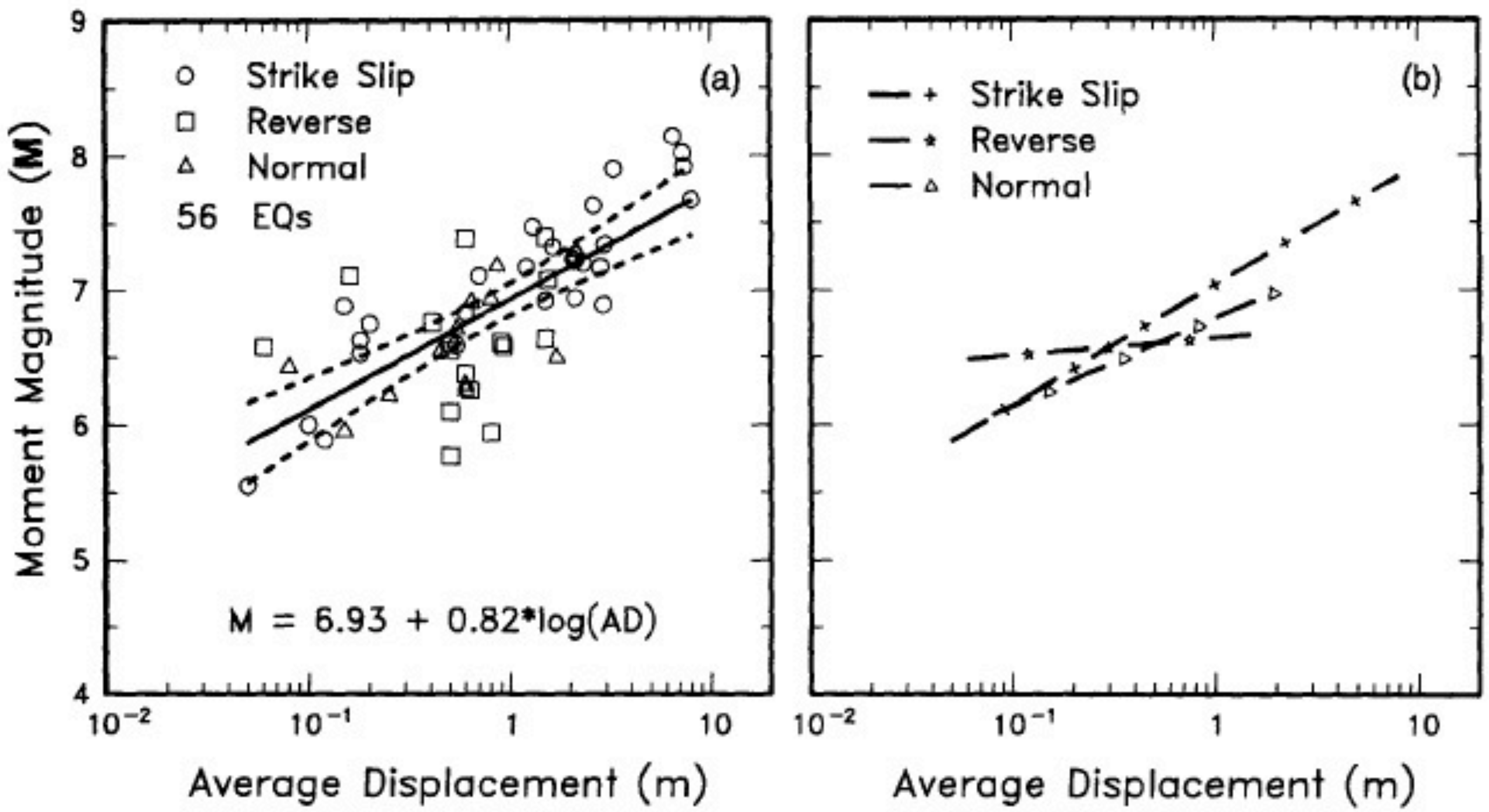
Fig. 4.9. Diagram illustrating the definitions of small and large earthquakes, showing hypocenter (H), epicenter (E), moment centroid (MC), and the dimensions of rupture (*a*, *L*, and *W*).

Moment magnitude versus rupture length



Wells and Coppersmith, 1994

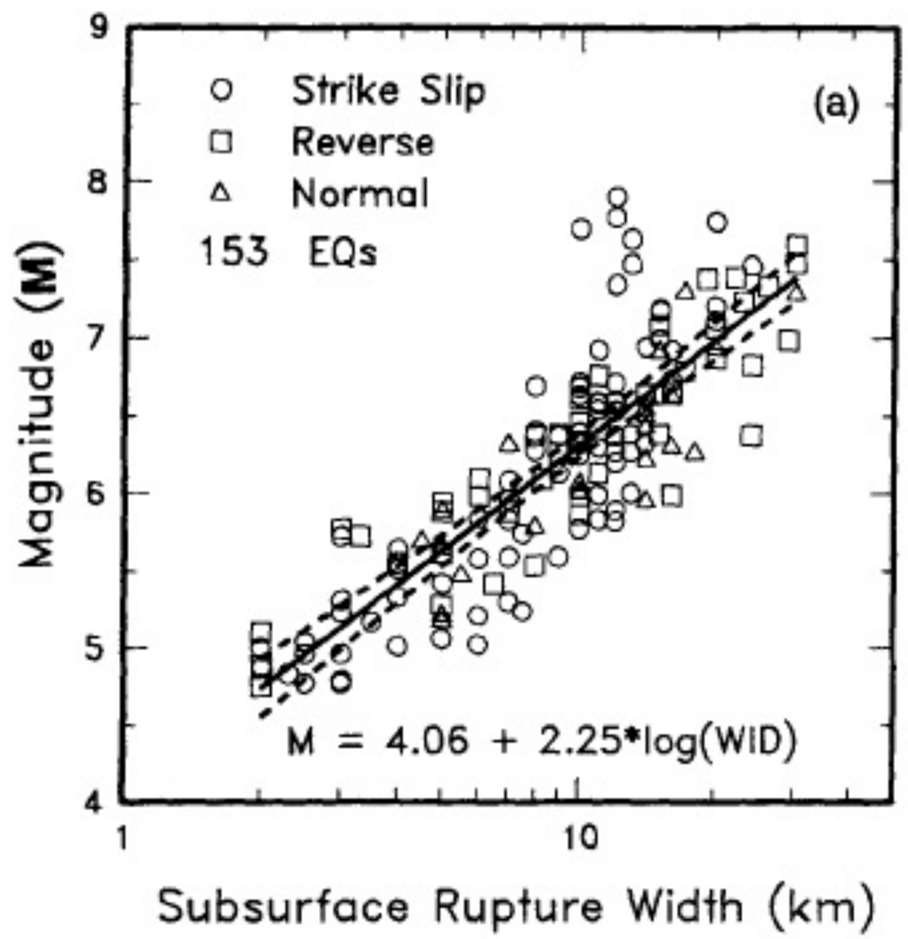
Moment magnitude versus slip



Wells and Coppersmith, 1994

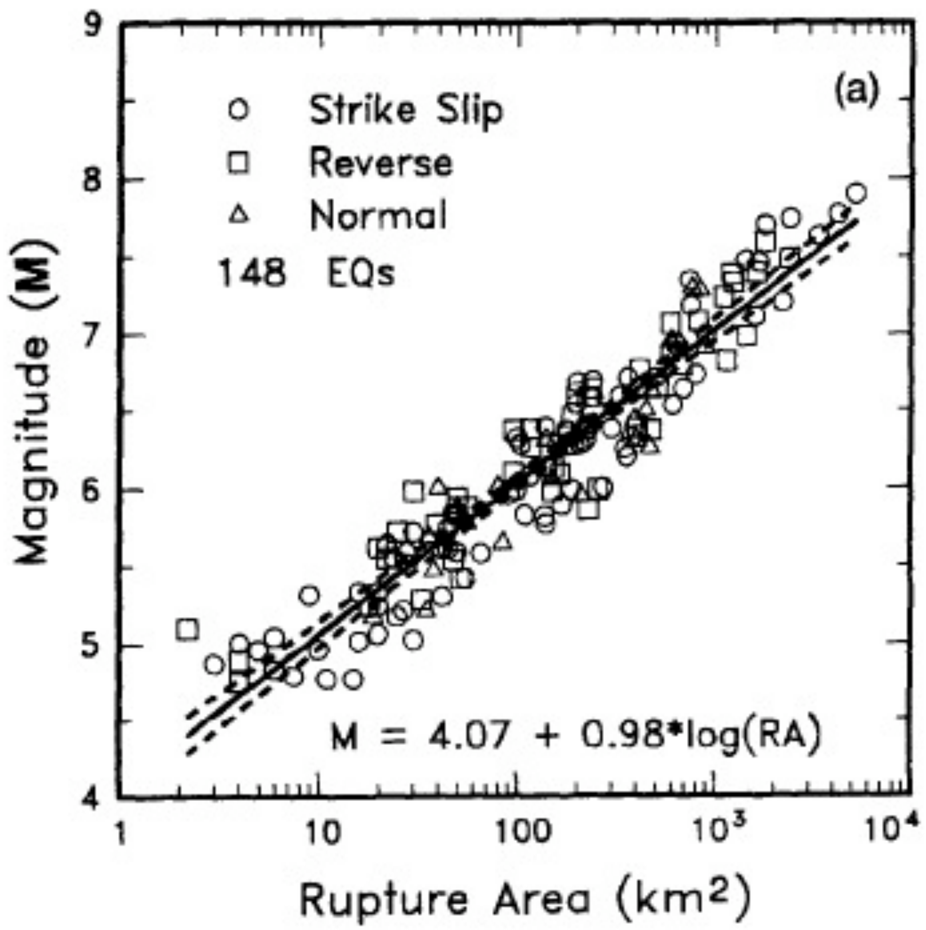
This means that slip scales with rupture length too…
which is good news for paleoseismologists

Moment magnitude versus rupture width



Wells and Coppersmith, 1994

Moment magnitude versus rupture area



Wells and Coppersmith, 1994

Slip (s) scales with rupture length too, and $M_o = GsA$. Therefore M_o is proportional to L^3 (for small quakes) or L^2W (bigger ones)

Conversion to M_w: Hanks and Kanamori, 1979 (100% empirical)

$$\log M_o = 1.5(M_w + 6.0333)$$

$$M_w = \log M_o/1.5 - 6.0333$$

$$M_o = AsG$$

M_w	Moment M_o	Length	Slip	Area
4	10^{15} N m	1000 m	2 cm	1 km^2
5	3.0×10^{16} N m	3000 m	10 cm	9 km^2
6	1.1×10^{18} N m			
7	3.5×10^{19} N m			
8	1.1×10^{21} N m			
9	3.5×10^{22} N m	1000 km	20 m	10^5 km^2

In-Class Activity: Moment magnitude and scaling relationships

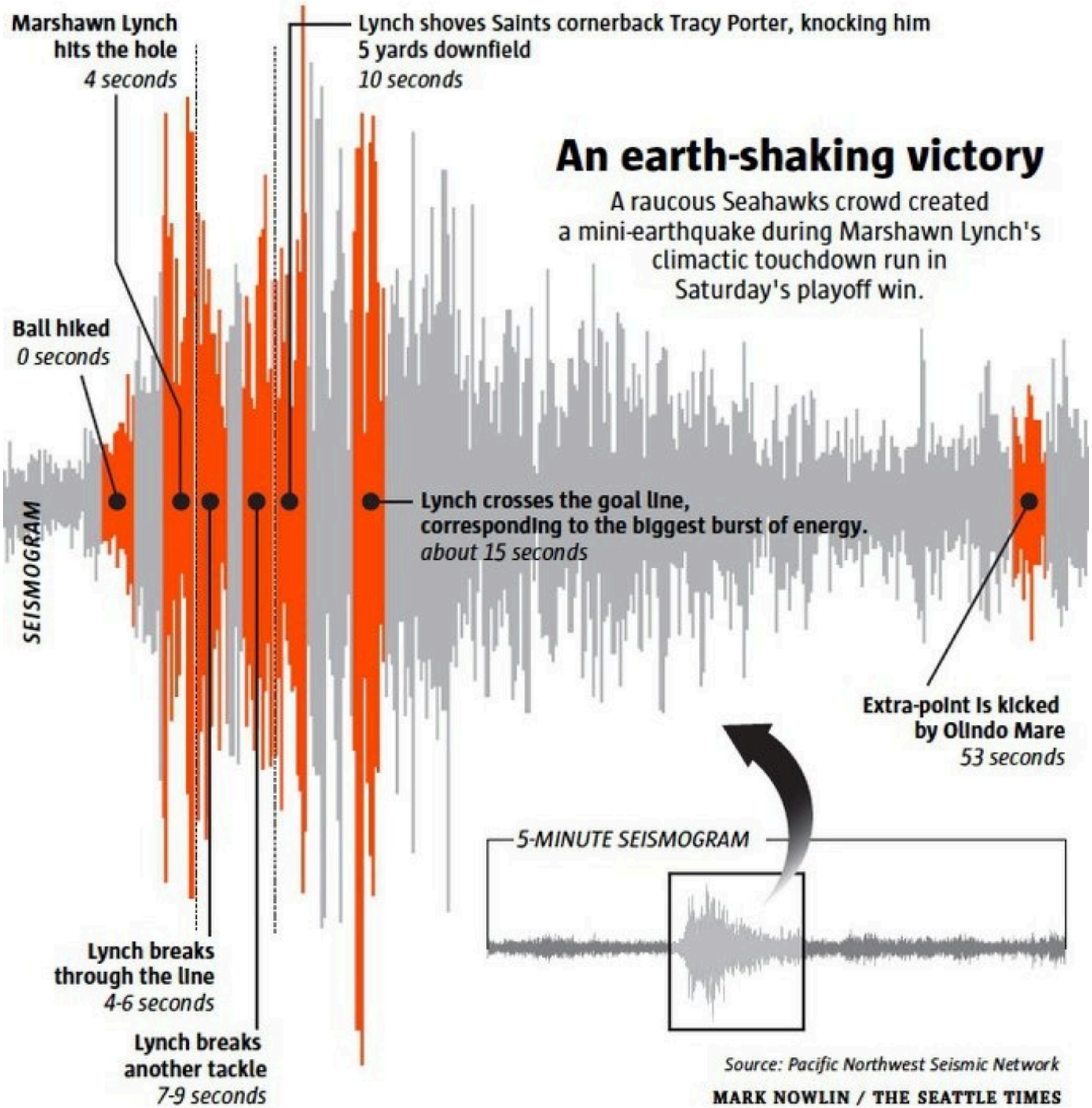
(1) Fill in the blanks in the table below, using the data from Wells and Coppersmith (1994). (Mo was calculated from Mw using the second equation below.)
(2) Moment release of an earthquake with magnitude N+1 is ___ times as great as for an earthquake with moment N, and ____ times as great as for an earthquake with magnitude N-1.
(3) Calculate the moment for one example from the table, using Mo = AsG. If it does not agree, what might be the cause of the error? Assume G = 3 x 10^10 Pa.

M_w	Moment M_o	Length	Slip	Area	Duration *of slip?*
4	10^{15} N m	1000 m	2 cm	1 km^2	
5	3.0×10^{16} N m	3000 m	10 cm	9 km^2	
6	1.1×10^{18} N m				
7	3.5×10^{19} N m				
8	1.1×10^{21} N m				
9	3.5×10^{22} N m	1000 km	20 m	10^5 km^2	

$$\log M_o = 1.5(M_w + 6.0333)$$

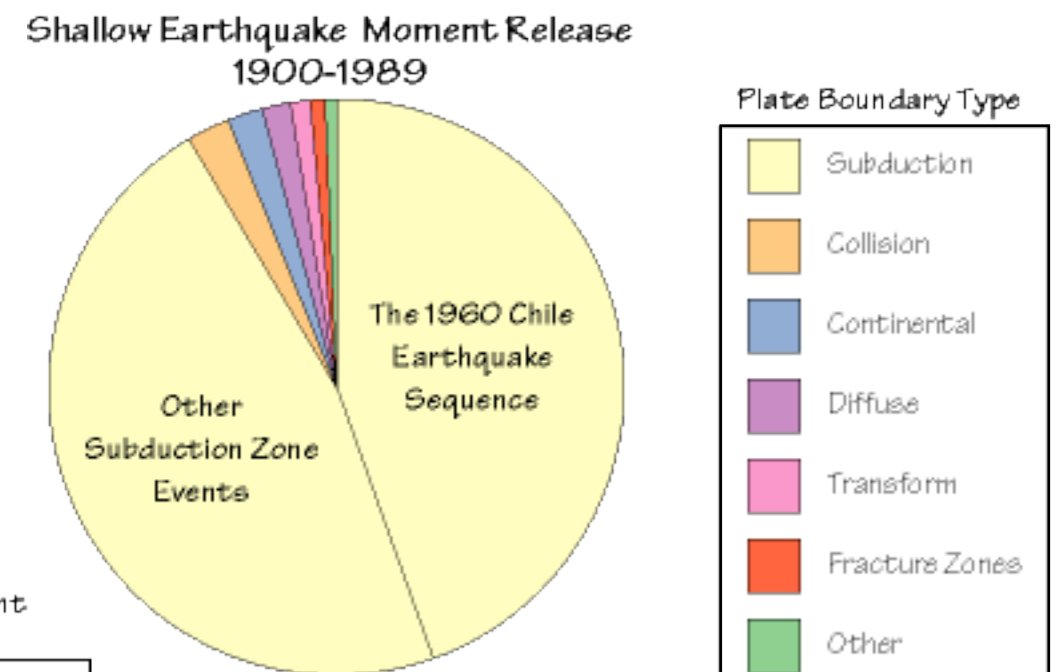
$$M_w = \log M_o/1.5 - 6.0333$$

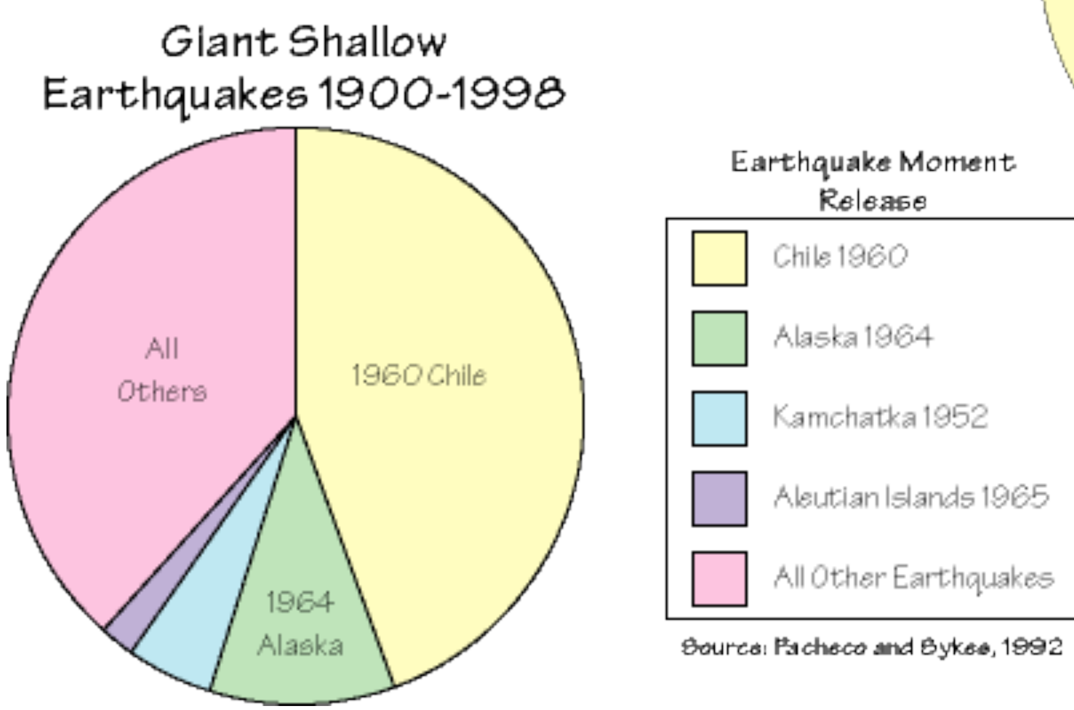
$$M_o = AsG$$



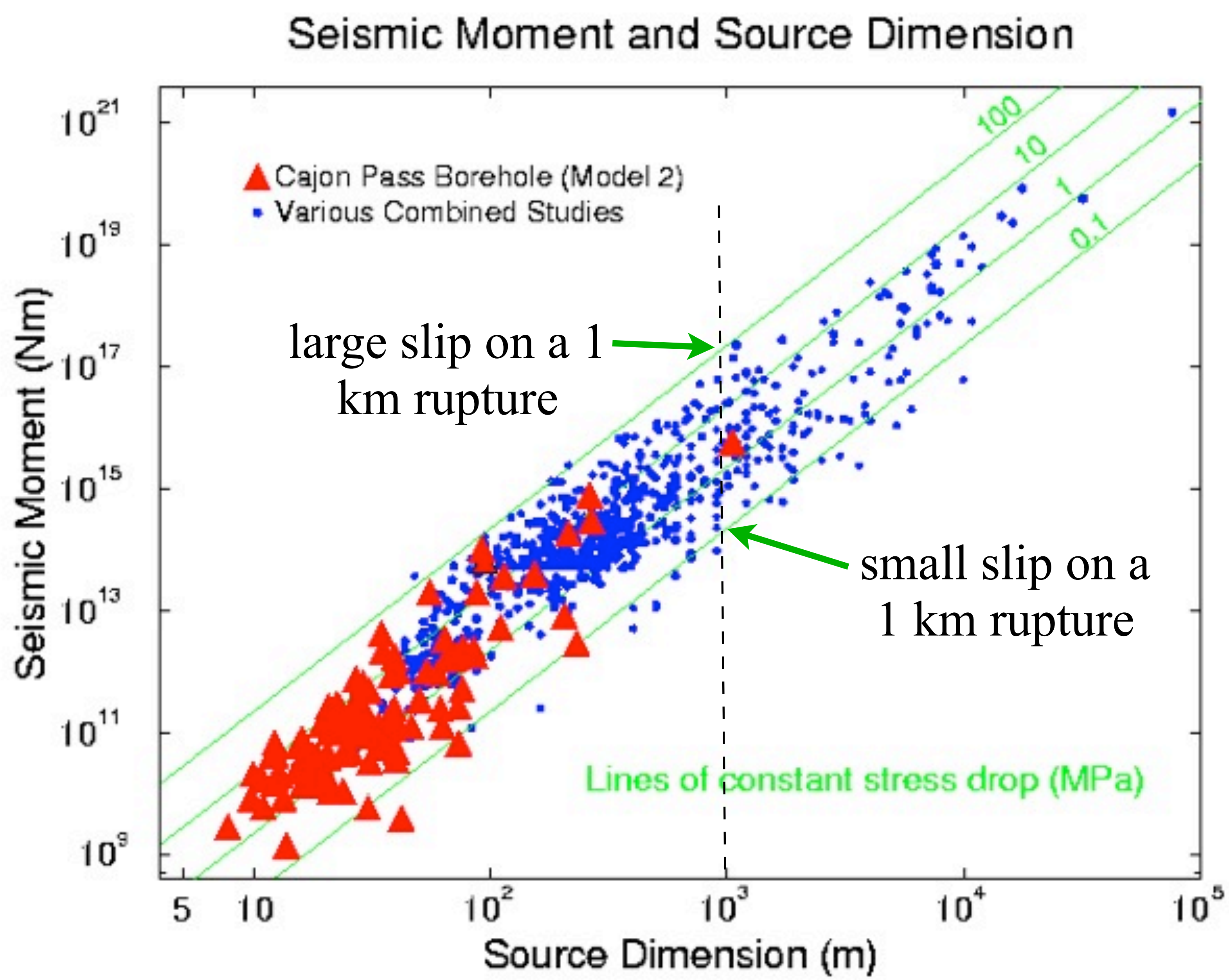
John Vidale, UW

Subduction zone earthquakes release most of the Earth’s elastic strain energy





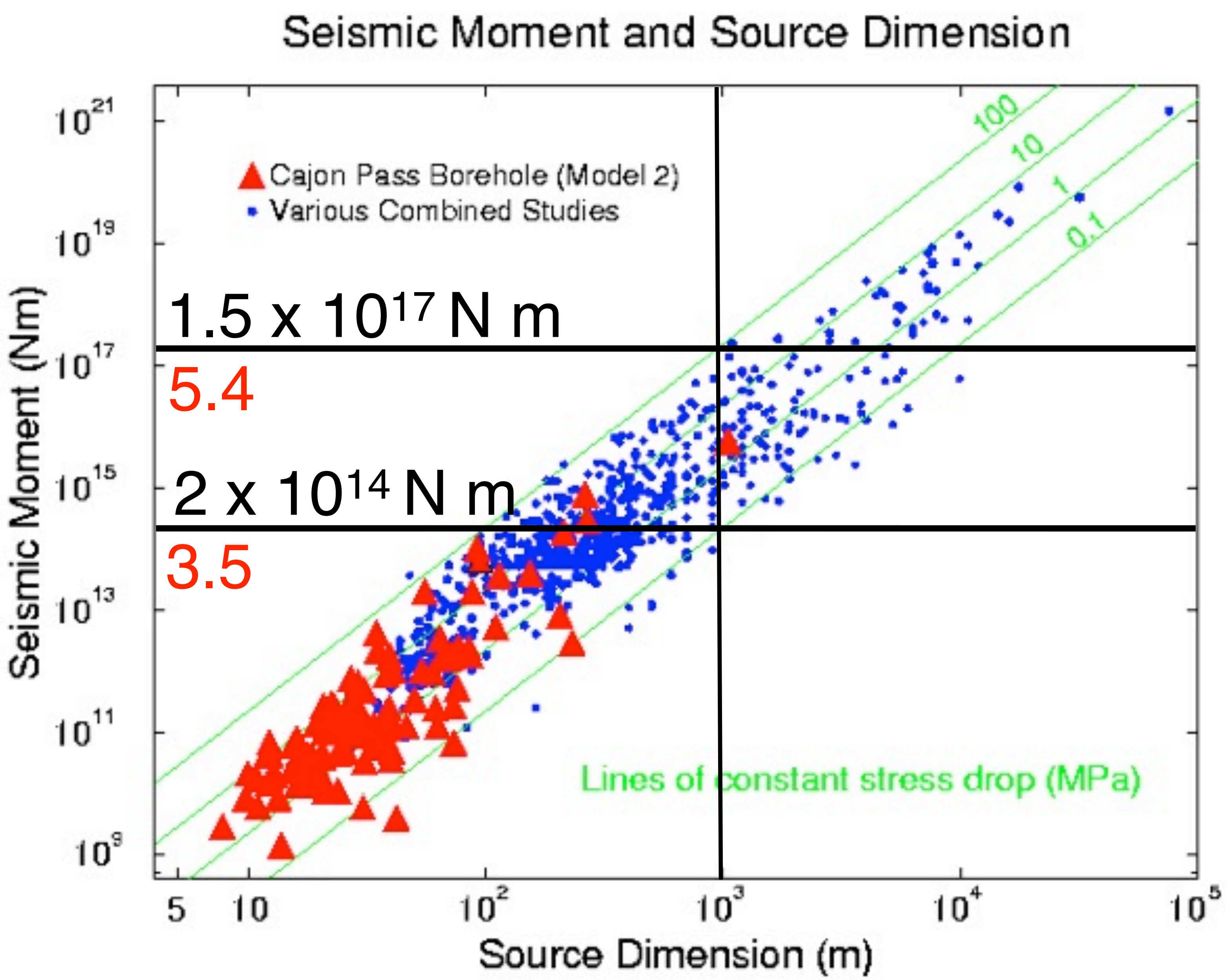
Shear stress drop $\Delta\tau$ seems insensitive to magnitude



typical $\Delta\tau$ is 1 to 10 MPa

$\Delta\tau$ is proportional to slip/L

A range of magnitudes are possible for a given rupture size



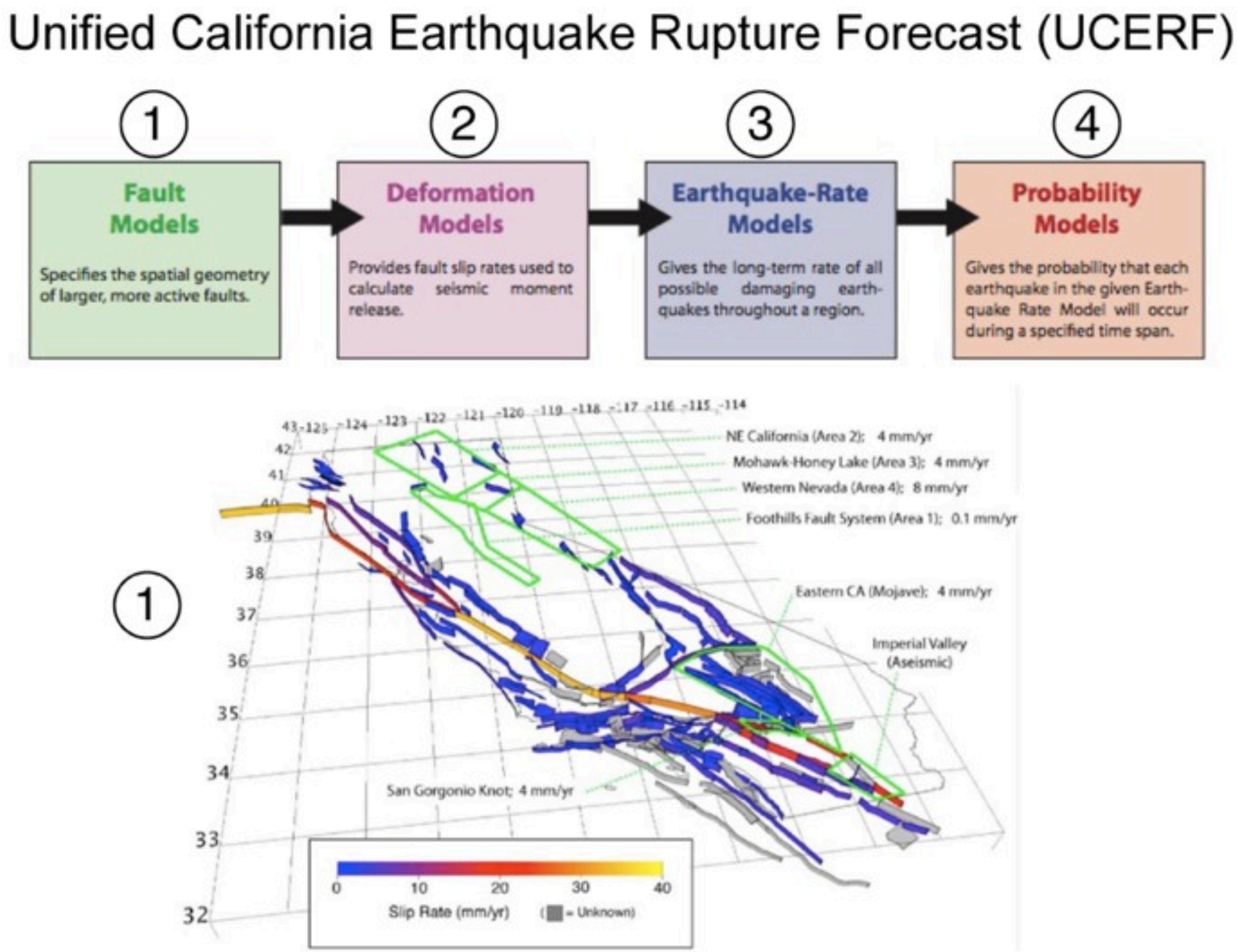
what is the range magnitudes for an earthquake rupture that is about 1 km long?

$$\log M_o = 1.5(M_w + 6.0333)$$

$$M_w = \log M_o/1.5 - 6.0333$$

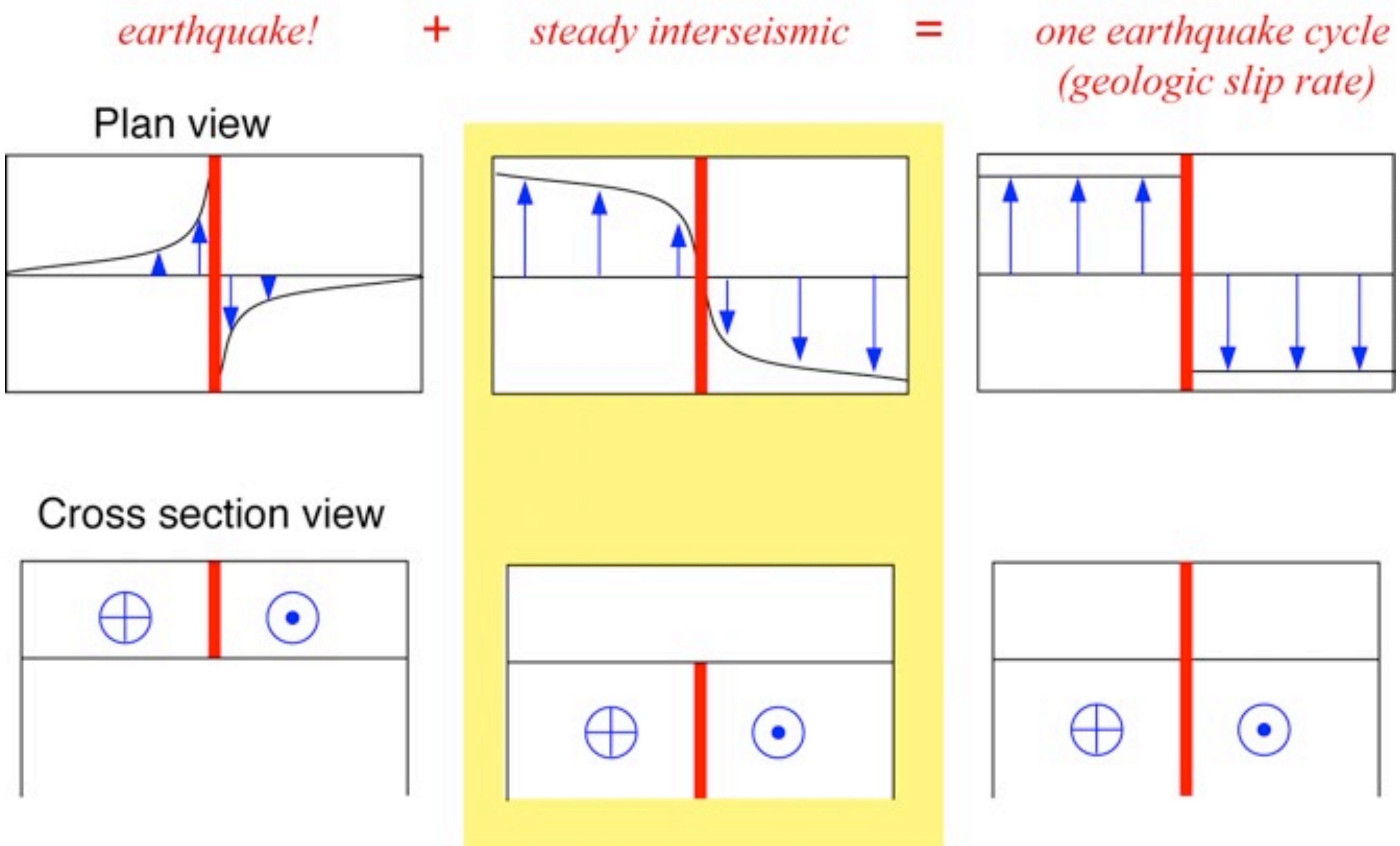
$$M_o = AsG$$

Slip rate, recurrence interval, and moment accumulation (p. 25-33)



slip rate, area of the fault, G ⟶ moment accumulation rate

Locking depth model: stick-slip in upper crust, aseismic slip at a constant rate below it



slip rate, locking depth, length of the fault → moment accumulation rate

(moment accumulation rate) x (recurrence interval) → expected moment release (size of earthquake)

Probability depends on coefficient of variation - how regular are the quakes?

Discussion assumes a "characteristic earthquake" model, but this is debated

Discussion also assumes that we know the rupture area before the quake happens: but many quakes are multi-segment ruptures

Wesnousky et al. (1983)

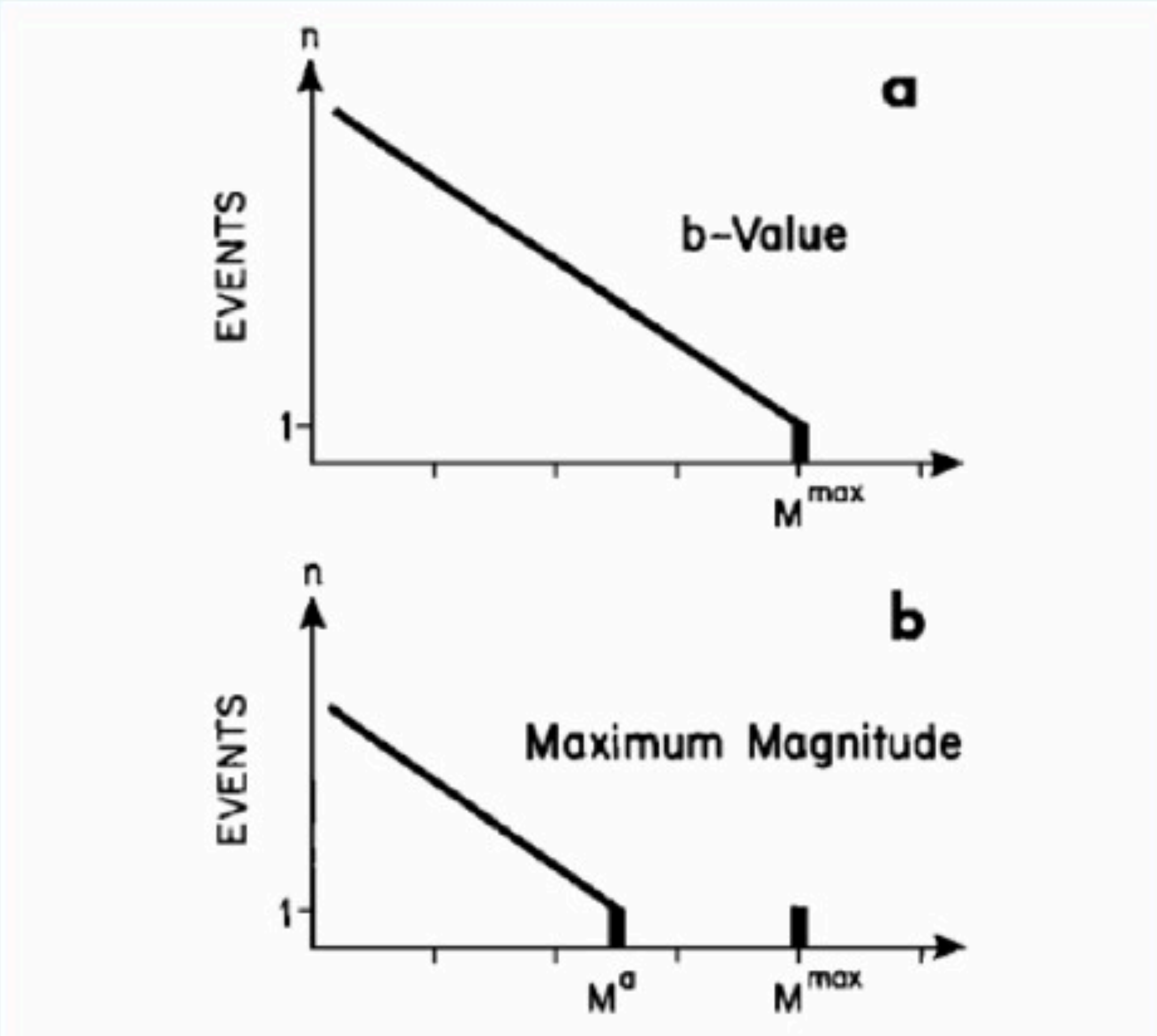
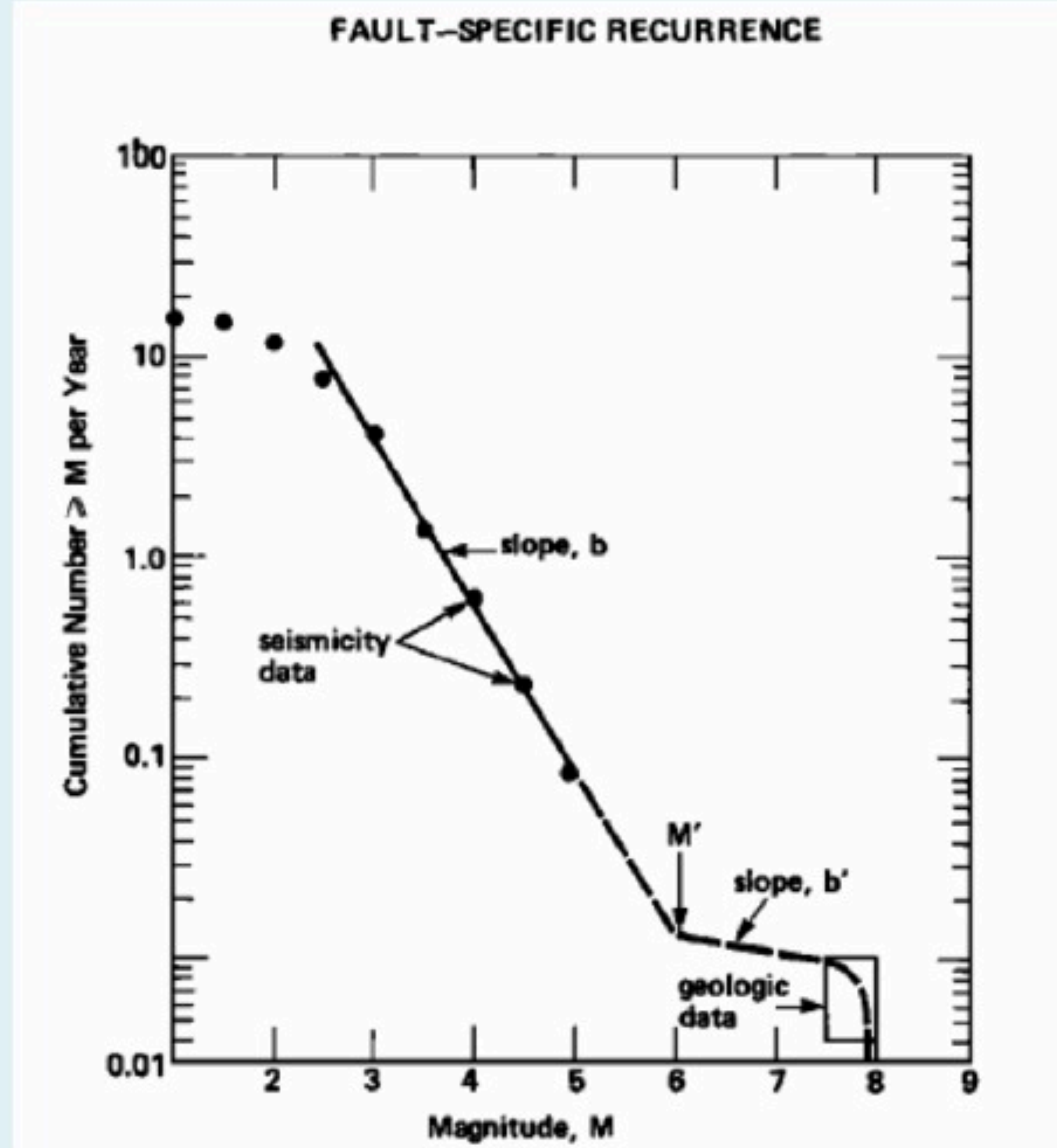


Fig. 1. Expected number of events versus magnitude on a fault during the repeat time of one M^{max} event, predicted by the (a) b value and (b) maximum magnitude models of fault behavior.

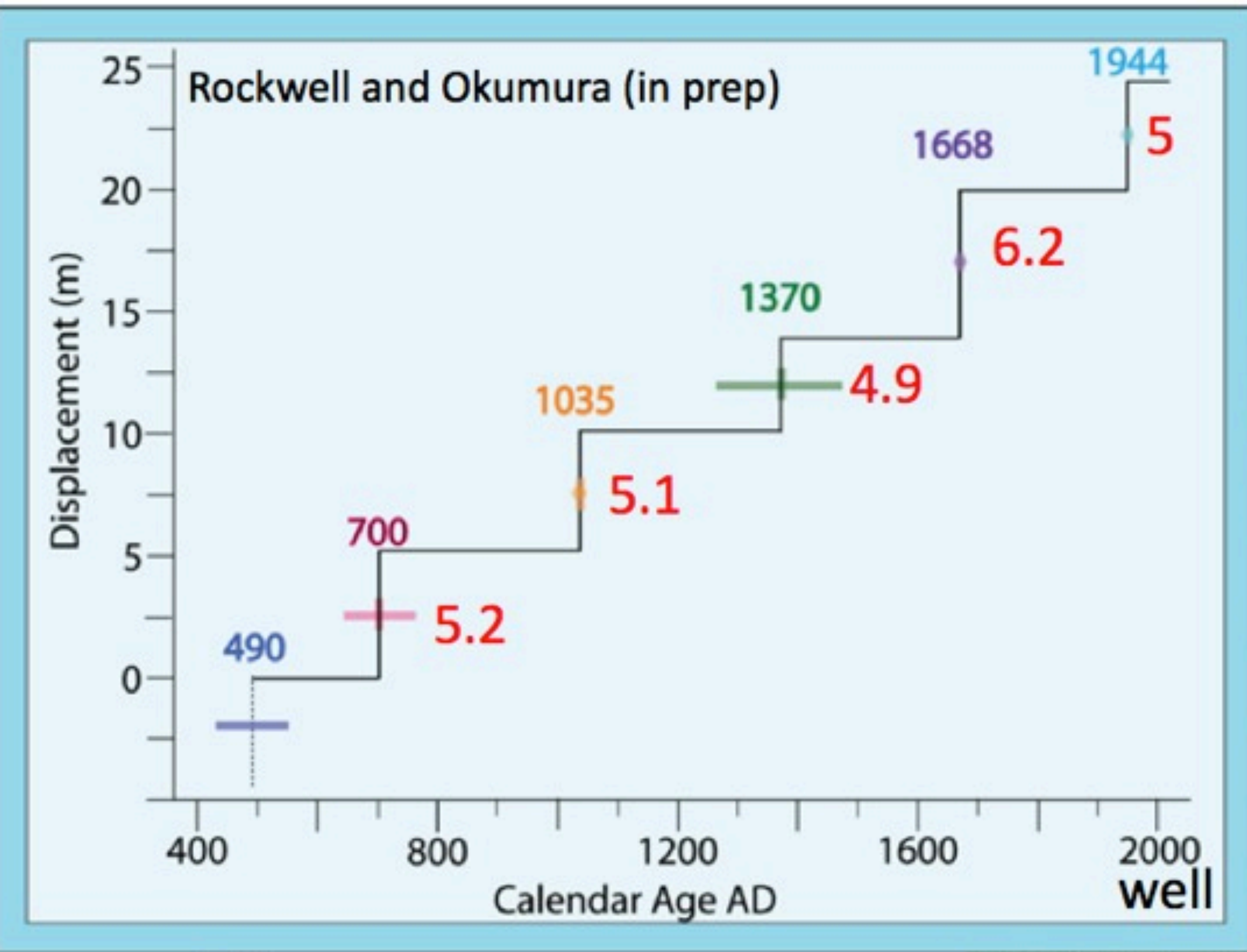
Comparison of b-value (GR) vs maximum magnitude (CE) models based on slip rates/fault lengths in Japan. Concluded observations favor maximum magnitude model.

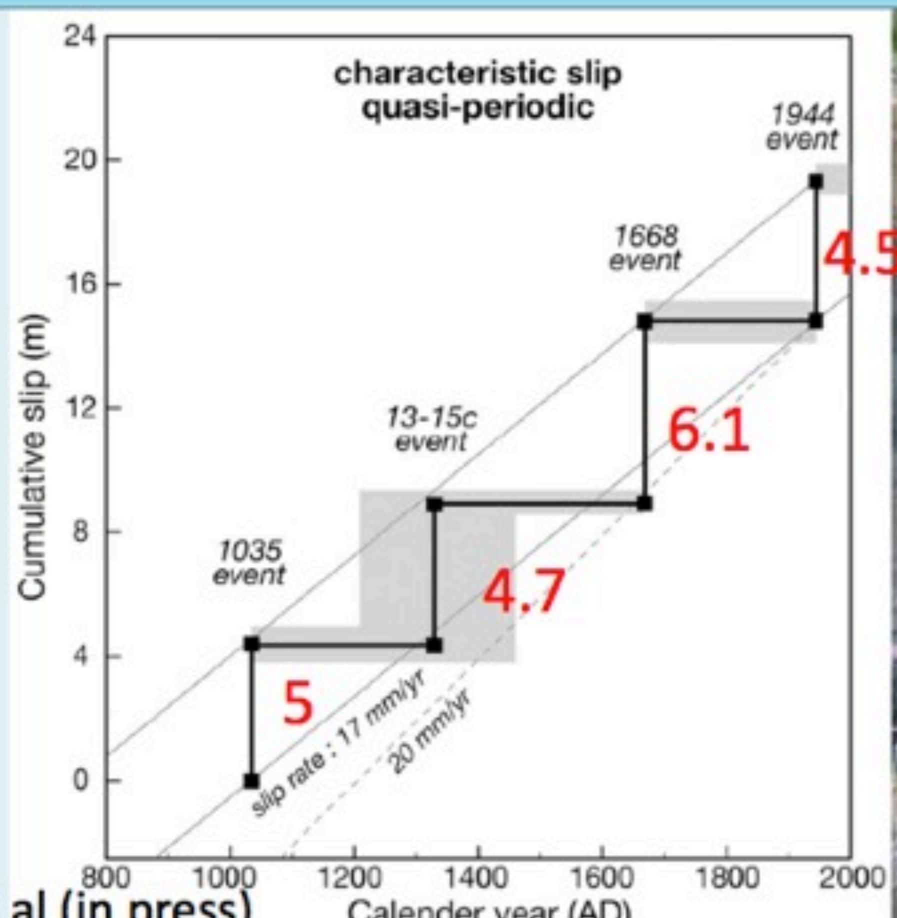
Schwartz and Coppersmith (1984)



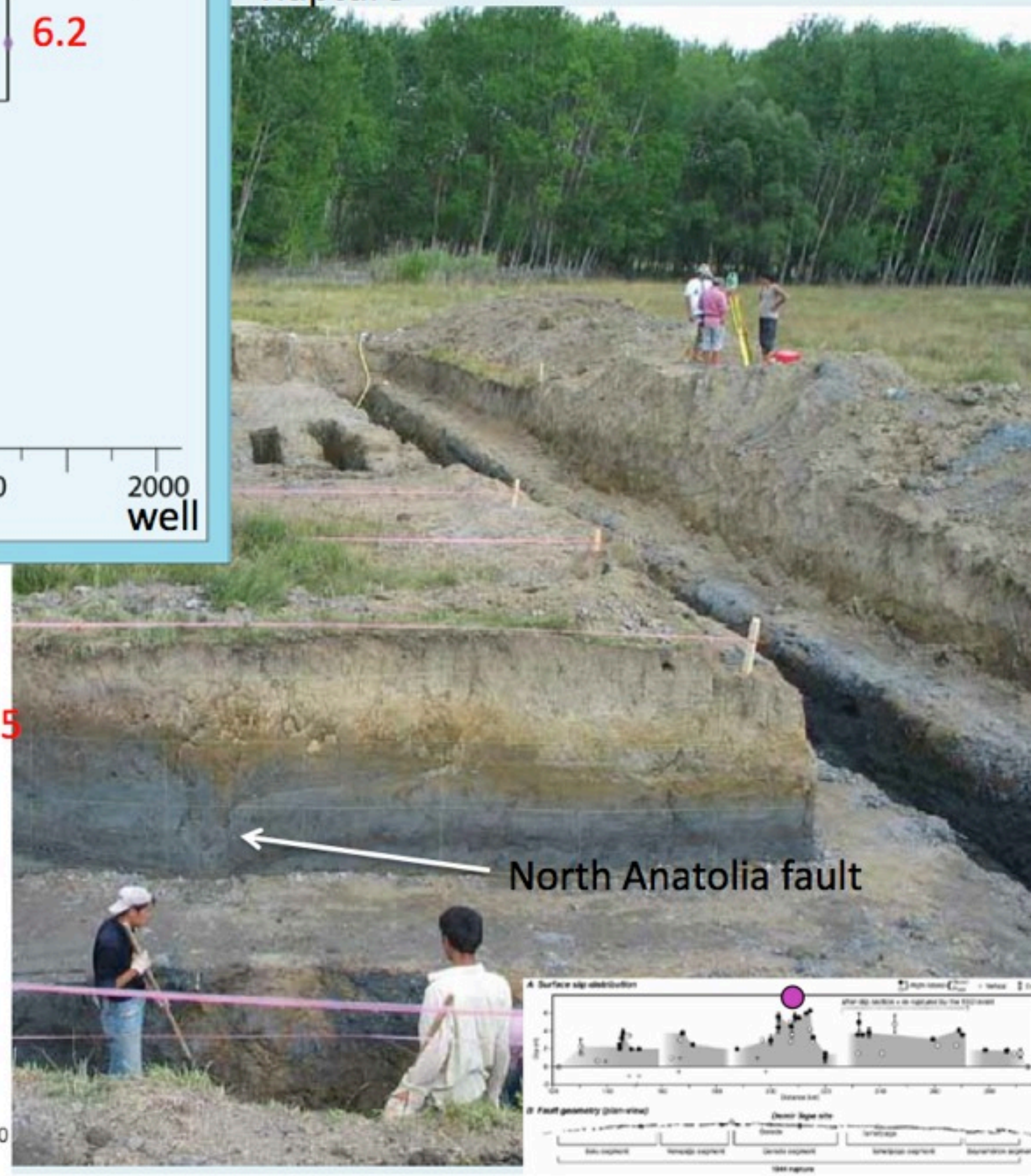
Paleoseismic recurrence, historical/instrumental seismicity for Wasatch fault (20/10km) and 1857 San Andreas rupture (±10 km). Size of repeated ruptures similar. Seismicity underestimates geological recurrence.

Repeated Offsets: North Anatolia Fault-Gerede 3D and Demir Tepe Sites on 1944 Rupture



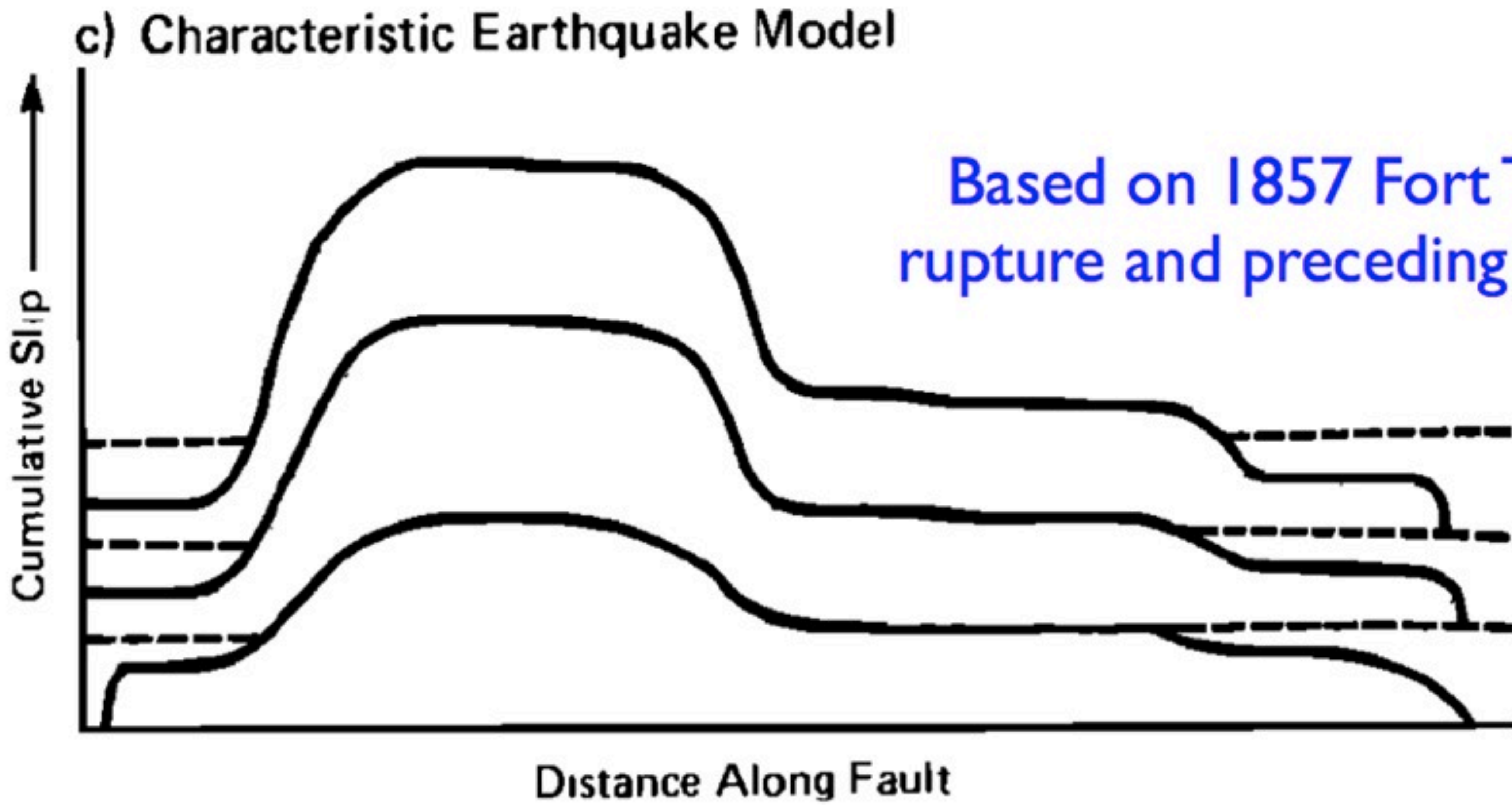


Kondo et al (in press)



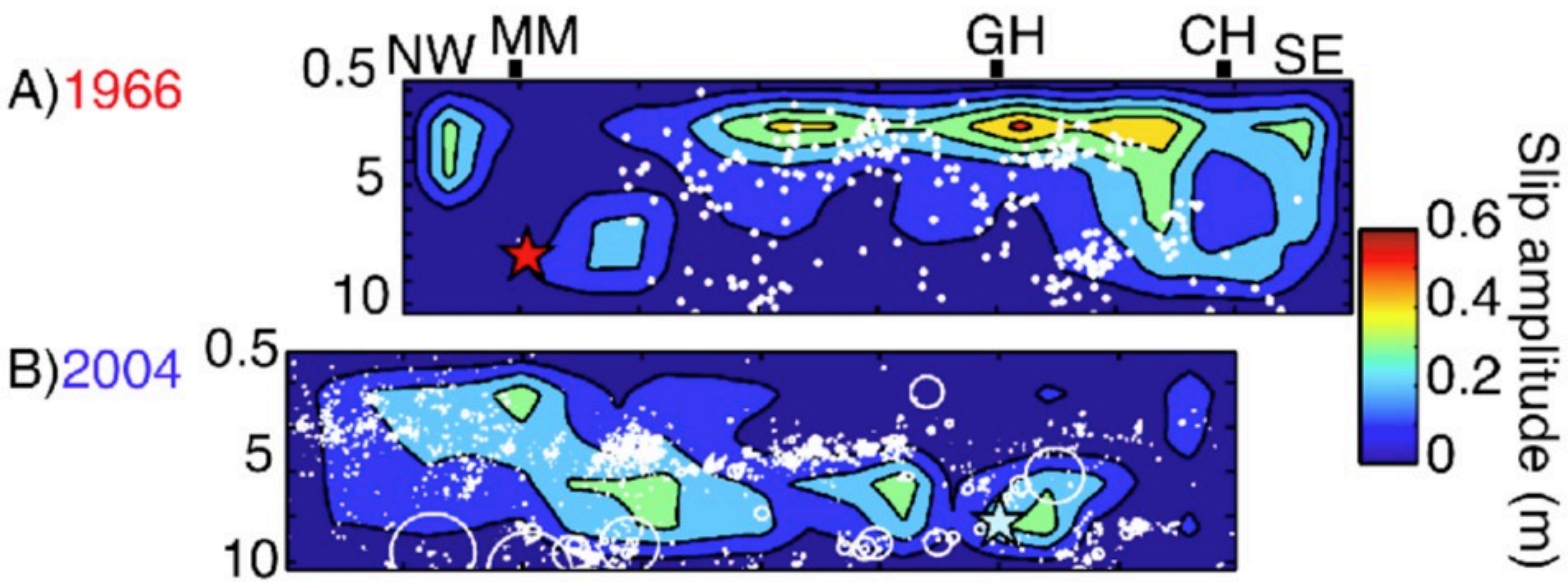
Characteristic Earthquakes hypothesized to have:

- Similar slip distributions
- More slip in regions of high slip rate

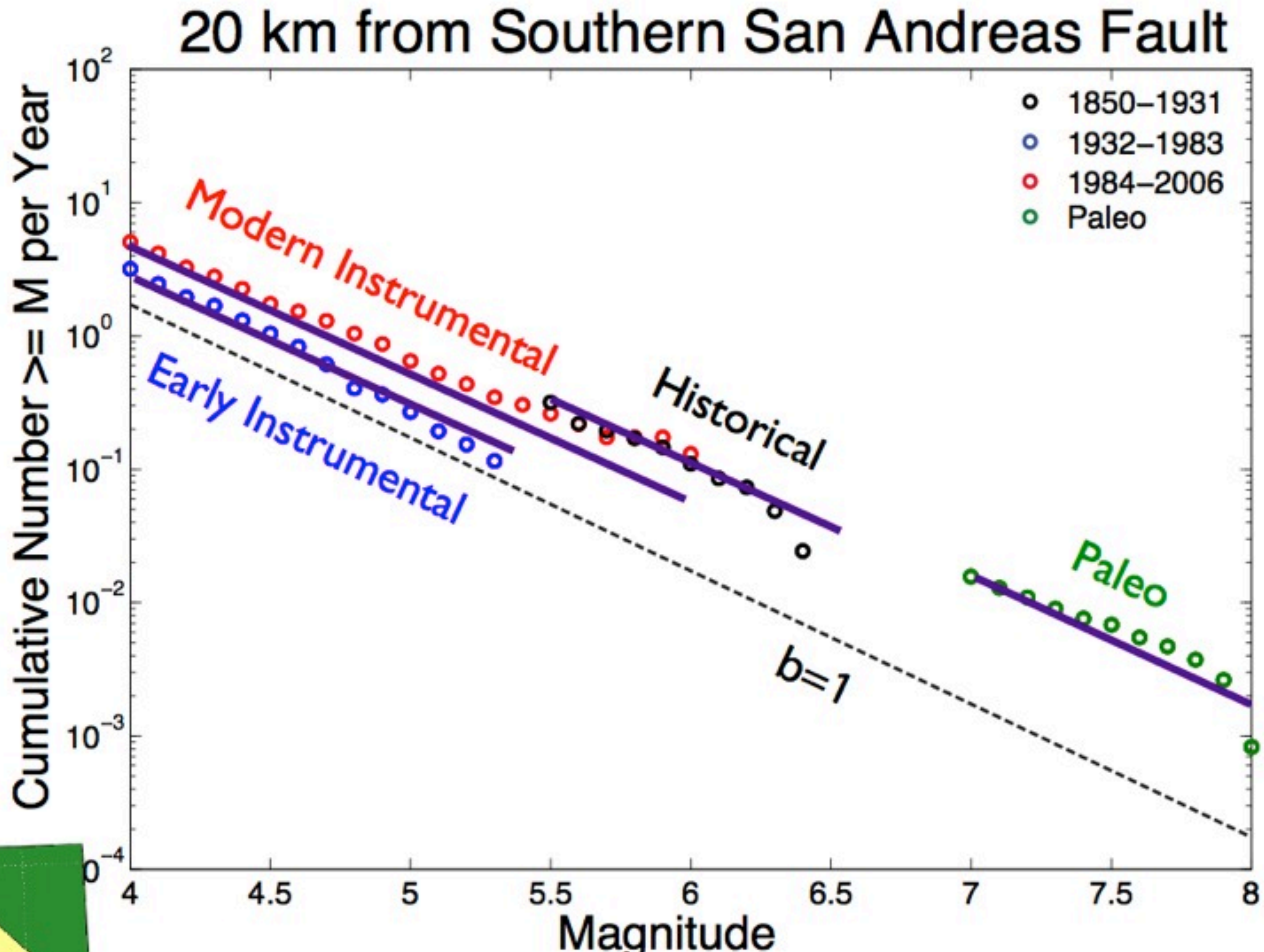


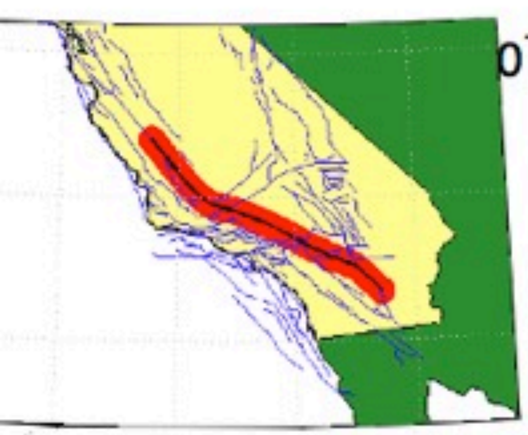
Based on 1857 Fort Tejon rupture and preceding events

Parkfield Earthquakes: Complementary, not Characteristic Slip Distributions



Every catalog, by itself, is G-R...





Paleo catalog is G-R!

... although the rates (a-values) do vary!