# Recap for SEISMIC RISK: FAULTS, INTENSITY & MAGNITUDE

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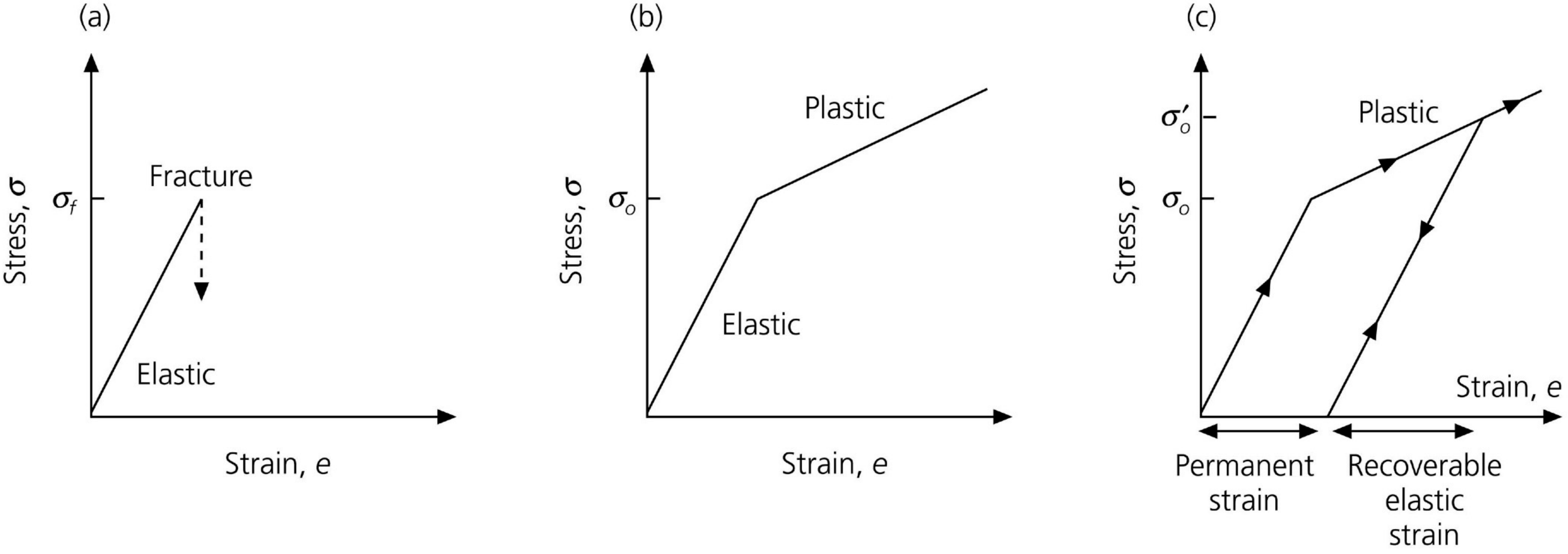
DEGLI STUDI DI TRIESTE

# Different Rheologies

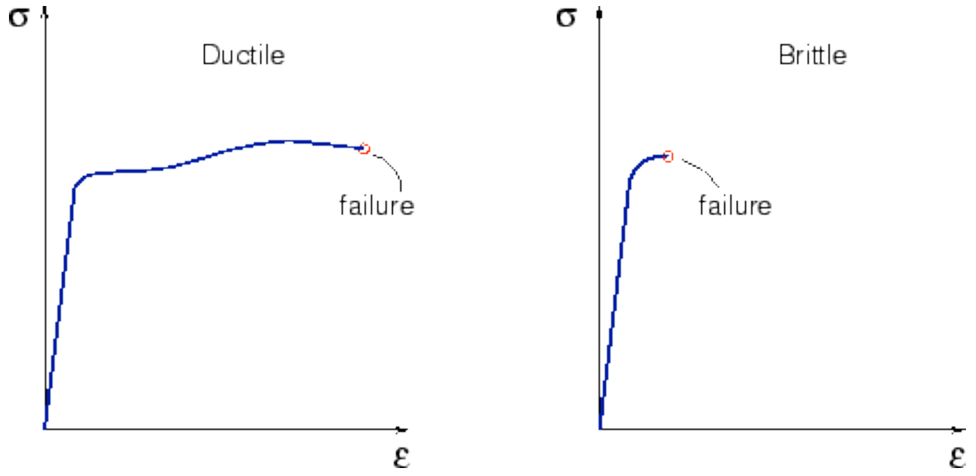
**Figure 5.7-1: Elastic and plastic rheologies.**

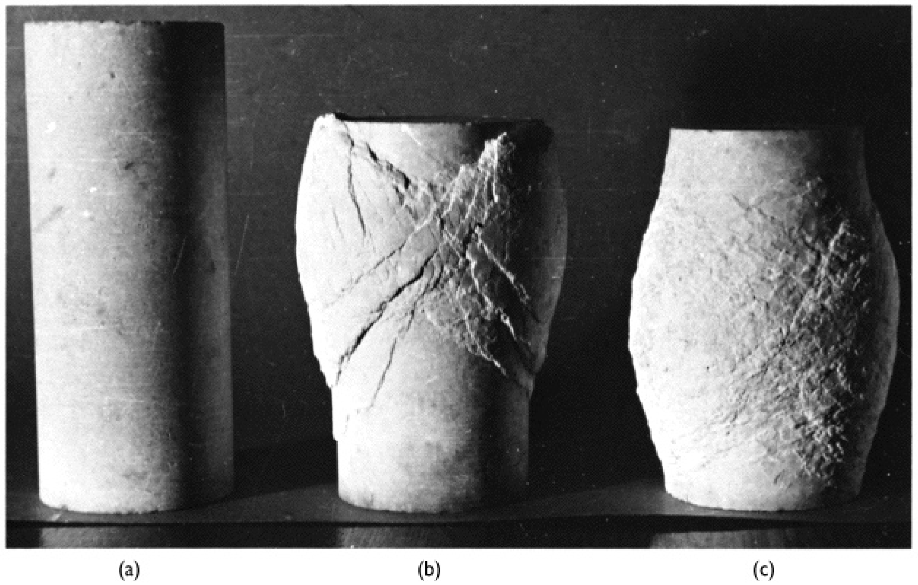


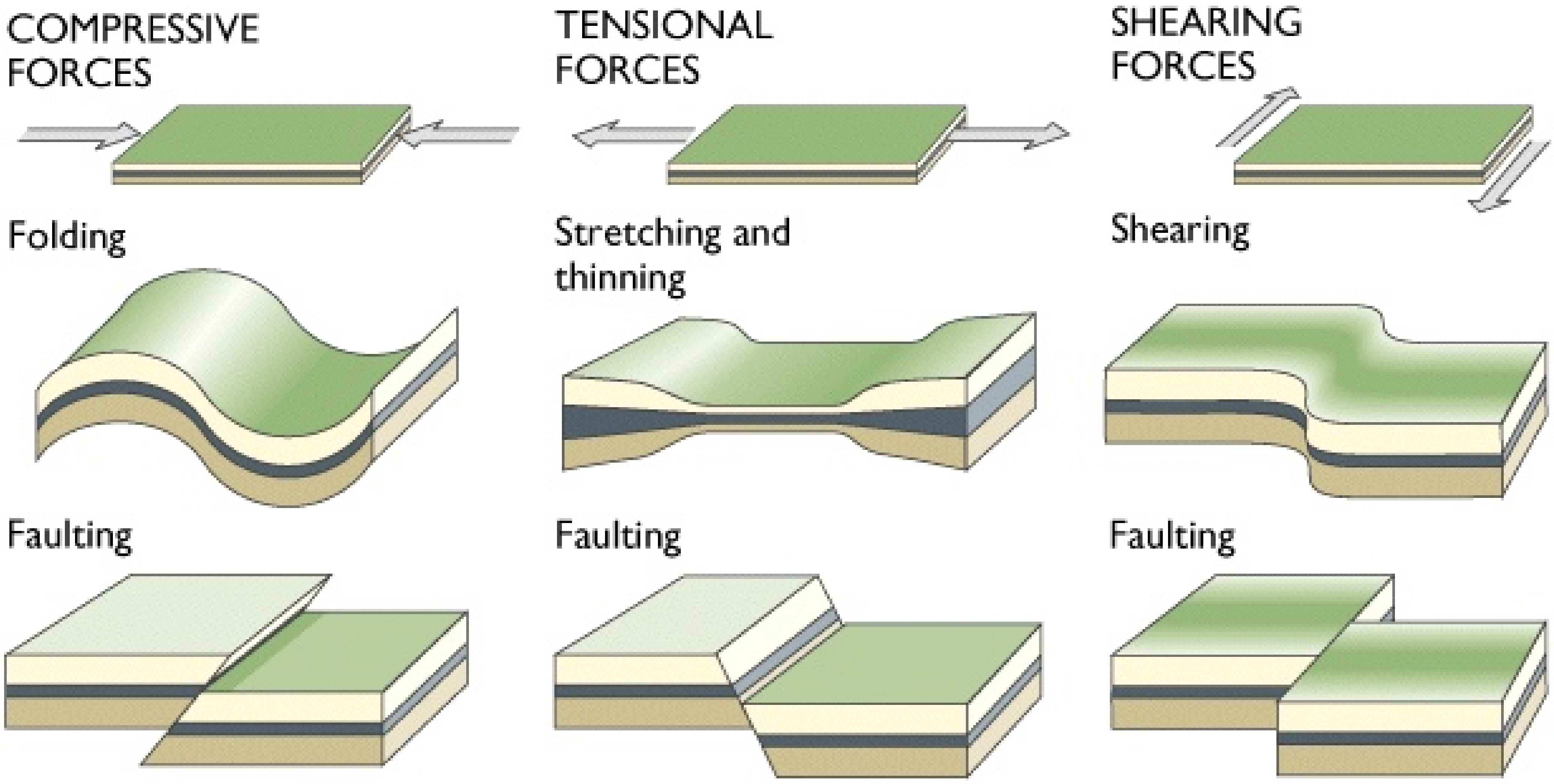
The mechanical properties of rocks deforming in the brittle regime are nearly insensitive to temperature, but very sensitive to strain-rate and **confining pressure**. Indeed, **friction** critically depends on the pressure acting across planes.

The fracture strength of rocks at the Earth's surface is the lowest and is controlled by the failure criteria only, but it increases with depth due to increasing lithostatic pressure.

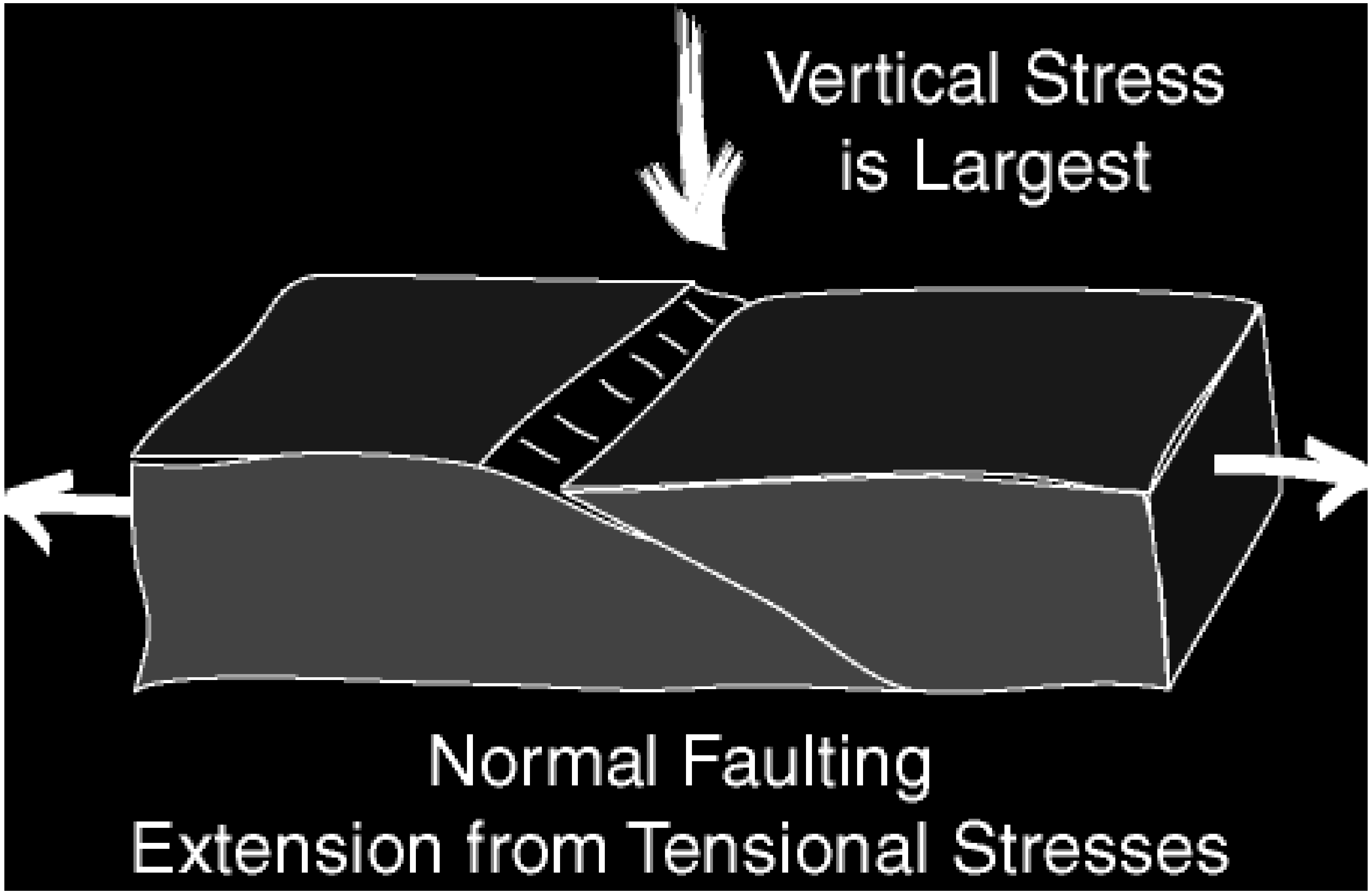
# Brittle & Ductile



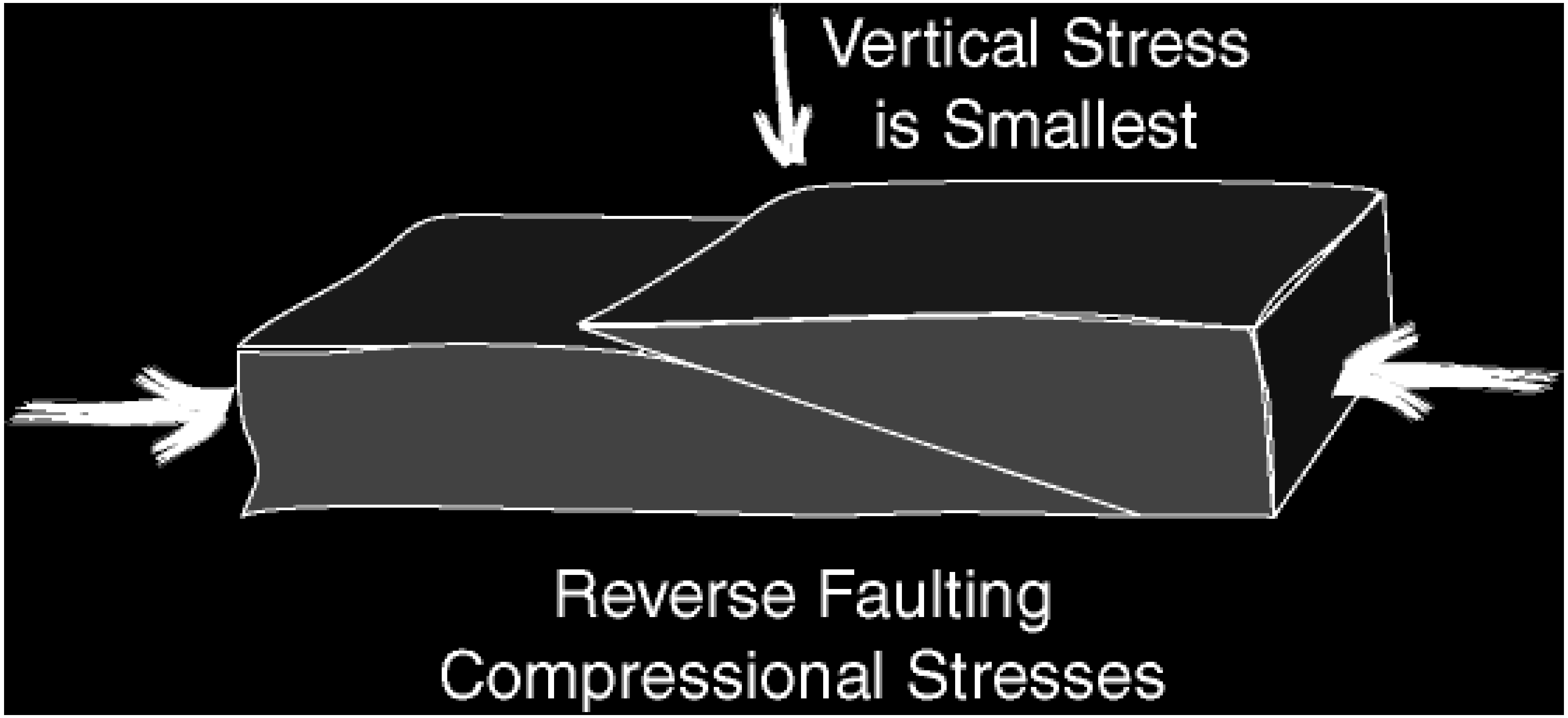




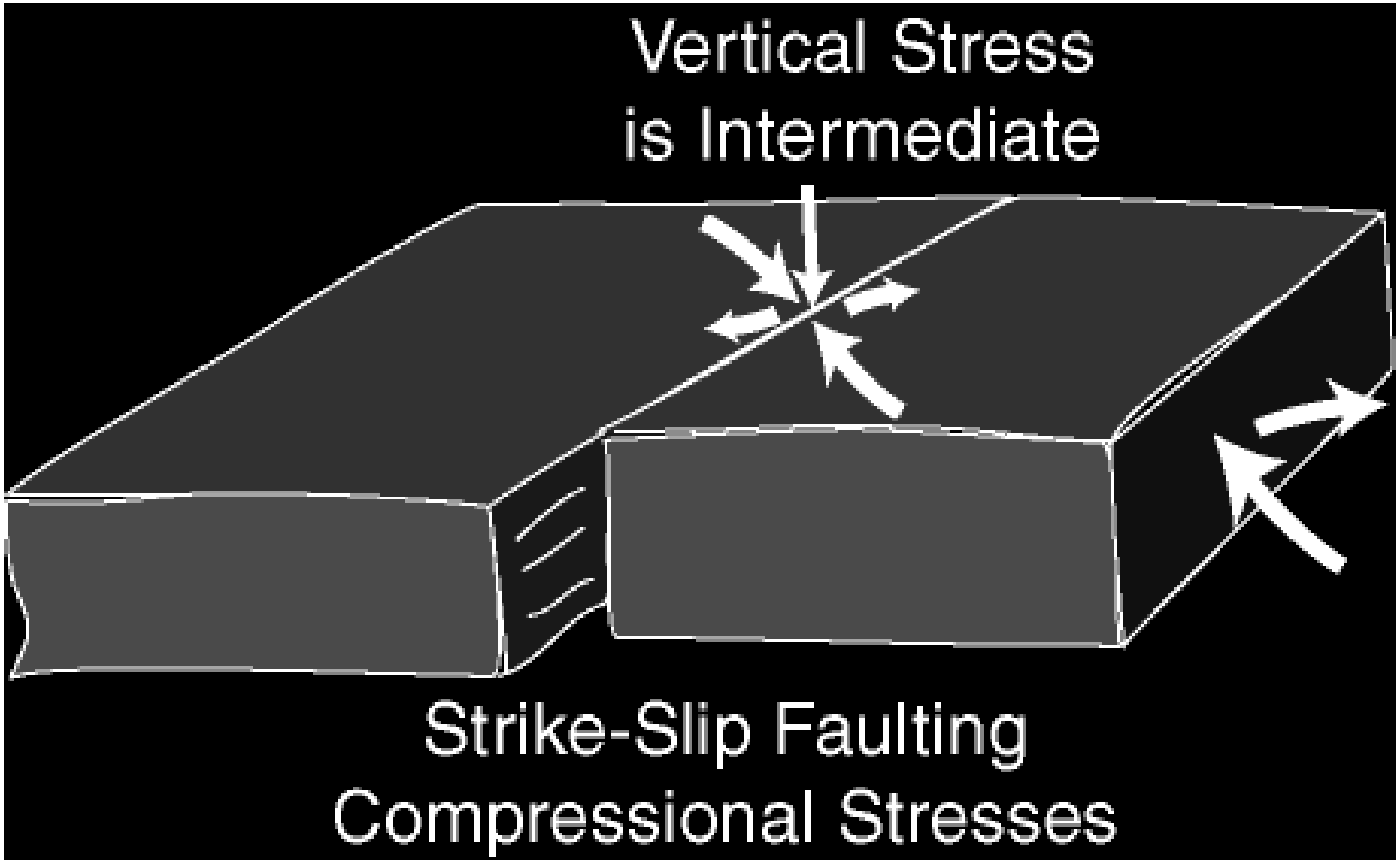
# Normal Faulting Stresses



# Reverse Faulting Stresses

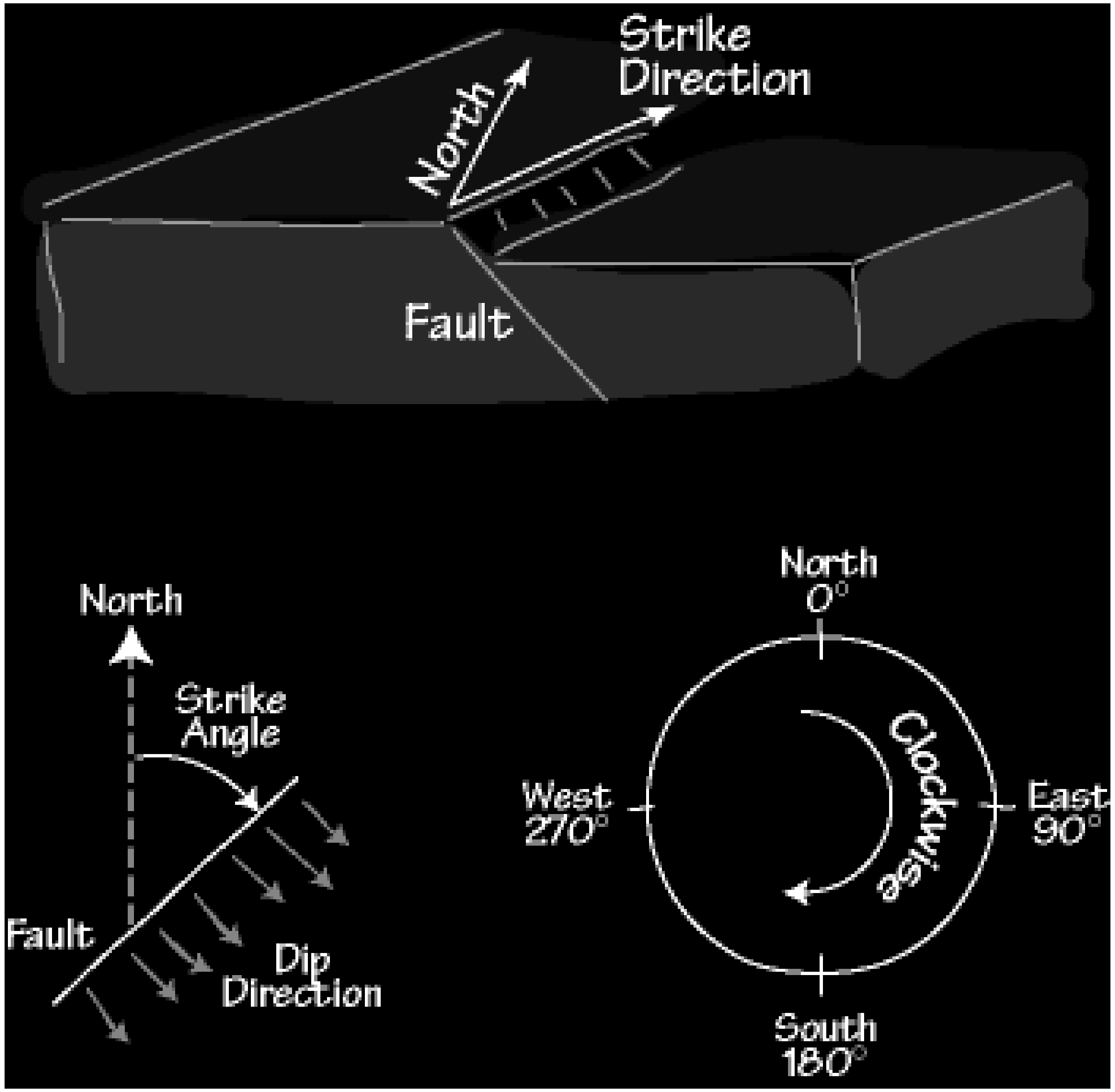


# Strike-Slip Faulting Stresses



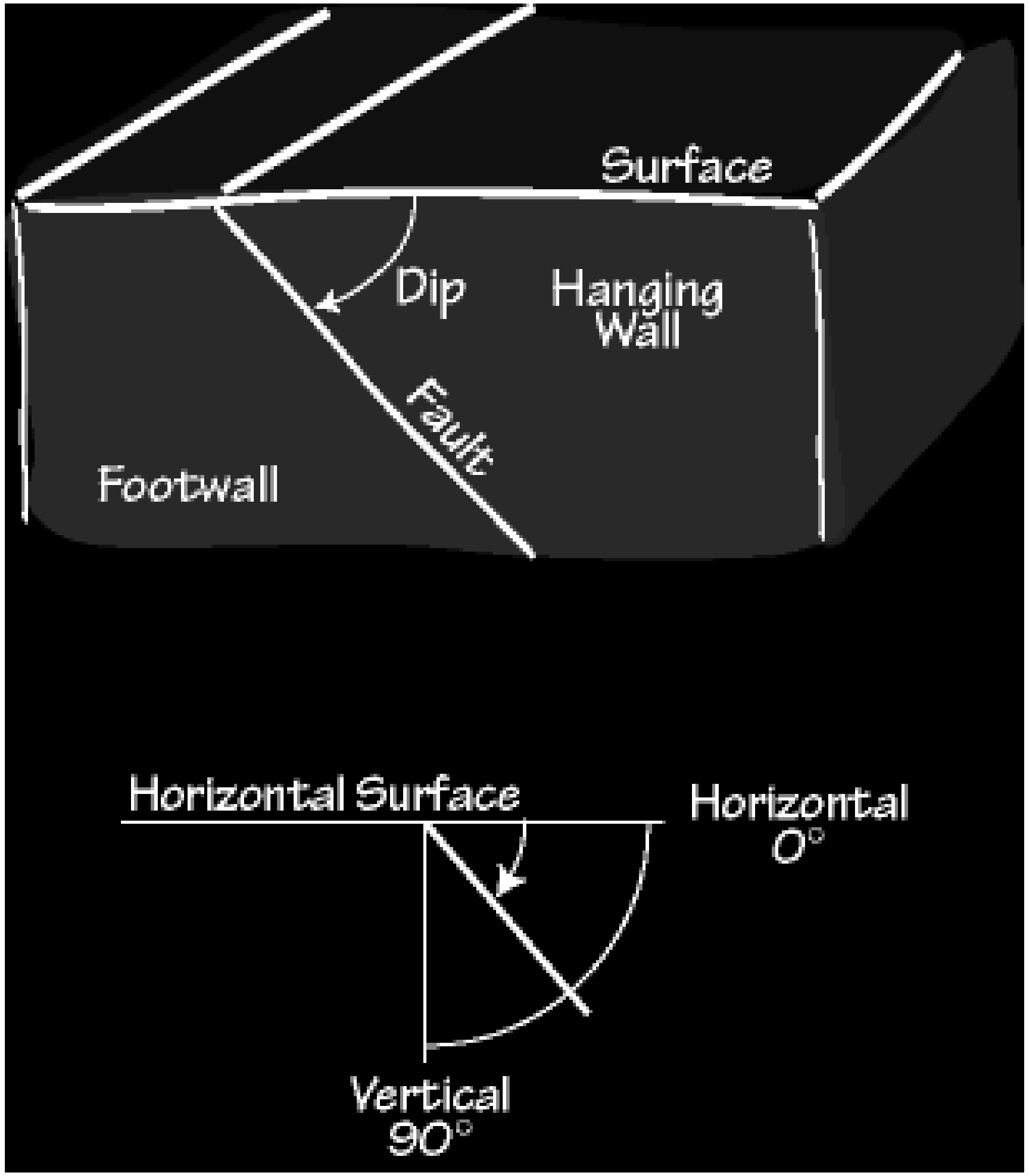
# Fault Geometry Terminology: STRIKE

Strike is an angle use to describe the orientation of the fault surface with respect to North.



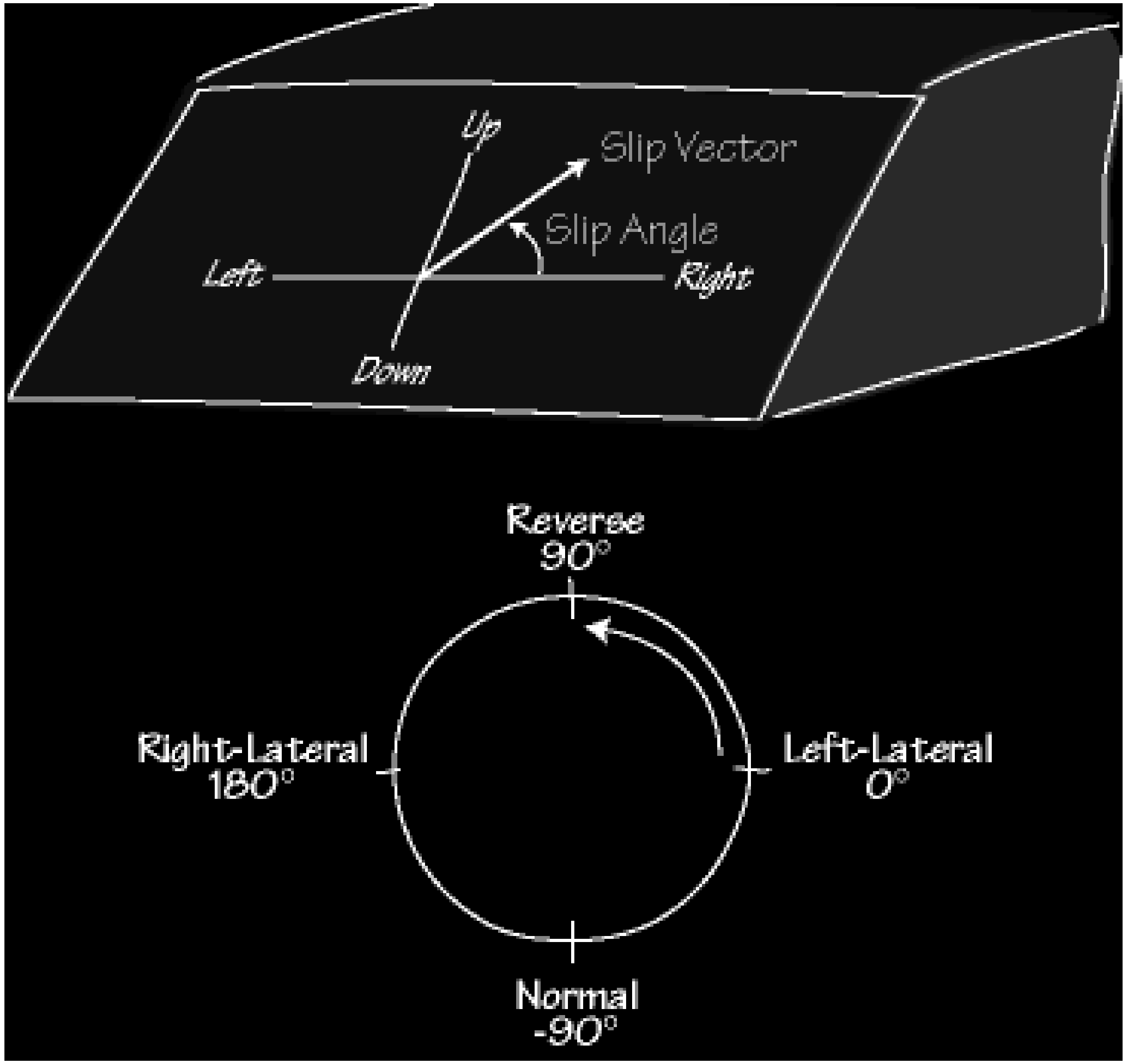
# Fault Geometry Terminology: DIP

The orientation of the fault surface with respect to Earth's surface is defined by the fault dip.



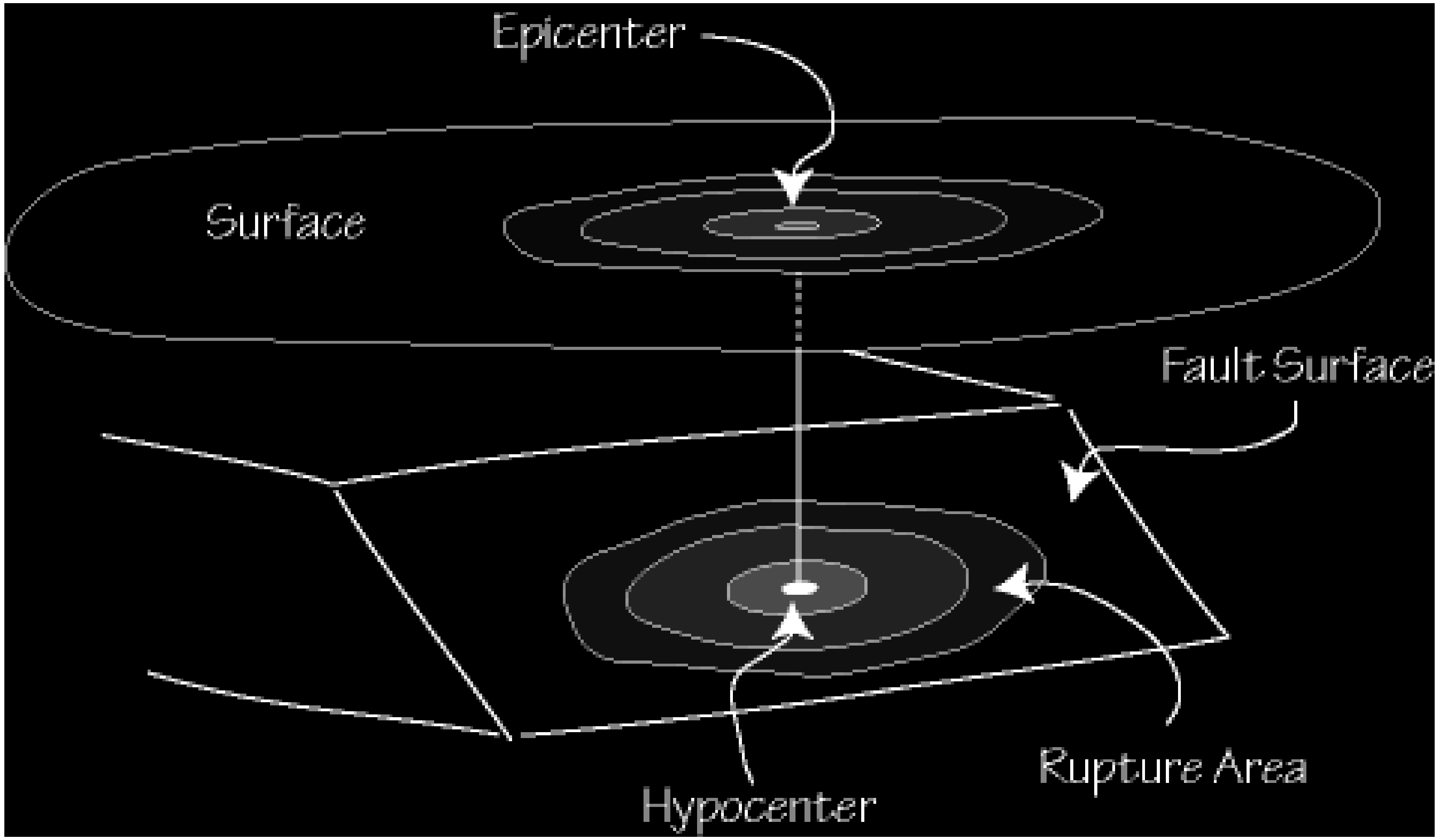
# Fault Geometry Terminology: SLIP

Slip angle is used to describe the orientation of the movement of the hanging wall relative to the foot wall.

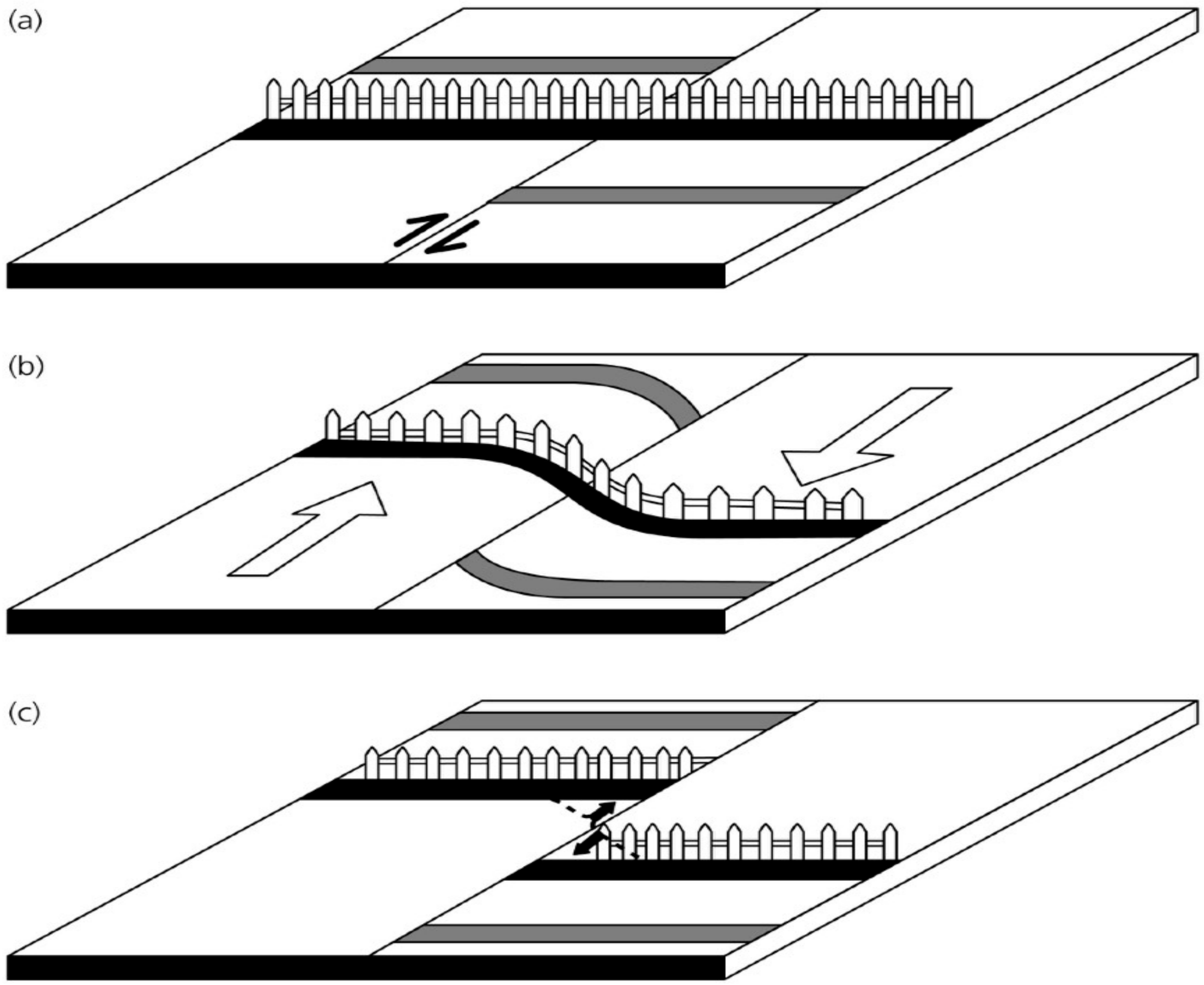


# Hypocenter and Epicenter

The hypocenter (or focus) is the place where the rupture begins, the epicenter is the place directly above the hypocenter.

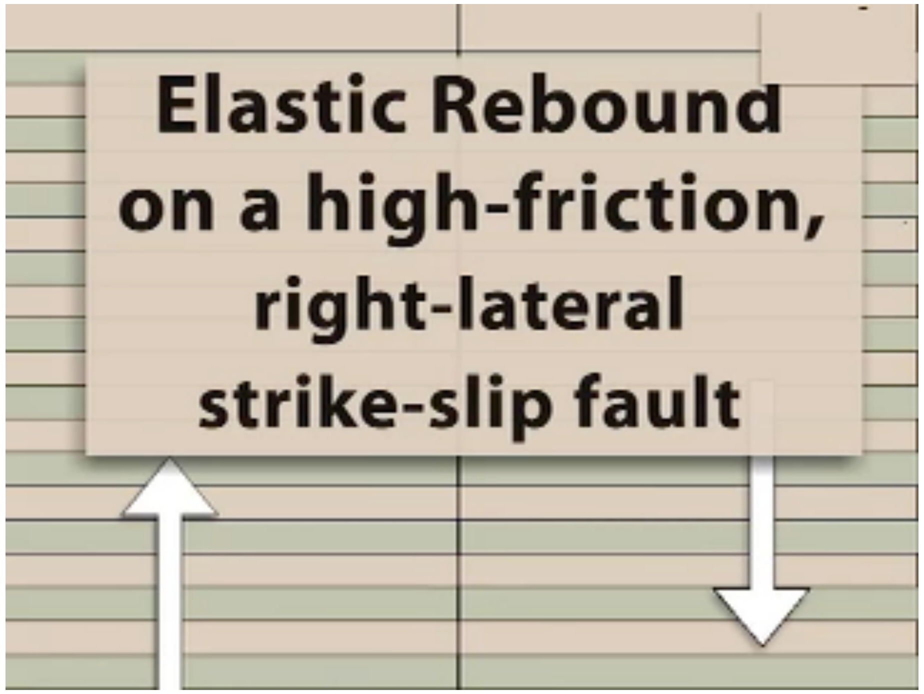


# Elastic rebound (Reid)



From an examination of the displacement of the ground surface which accompanied the 1906 San Francisco earthquake, Henry Fielding Reid, Professor of Geology at Johns Hopkins University, concluded that the earthquake must have involved an "elastic rebound" of previously stored elastic stress.

Reid, H.F., "The mechanics of the earthquake", v. 2 of "The California earthquake of April 18, 1906". Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington Publication 87, 1910.



http://www.iris.edu/hq/programs/education_and_outreach/aotm/4

# Earthquake rupture

Can be described by: a) formation and b) propagation of a crack.

The crack tip acts as a stress concentrator and if the stress exceeds some critical value then sudden slip occurs, and it drops to the dynamic frictional value; when the slip has stopped the stress reaches a final level

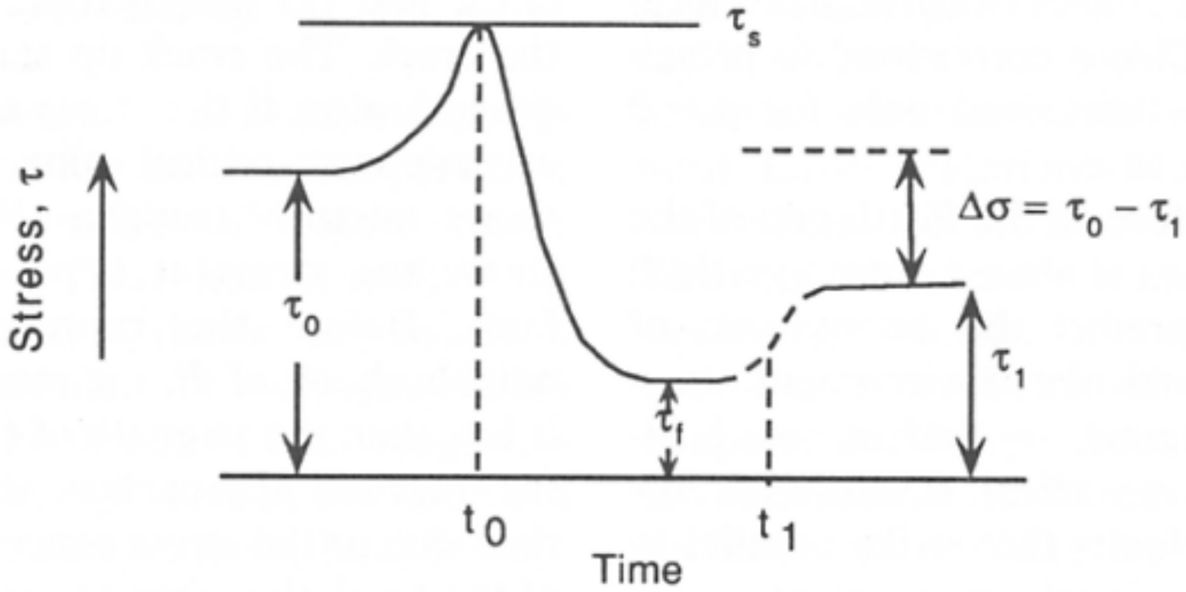
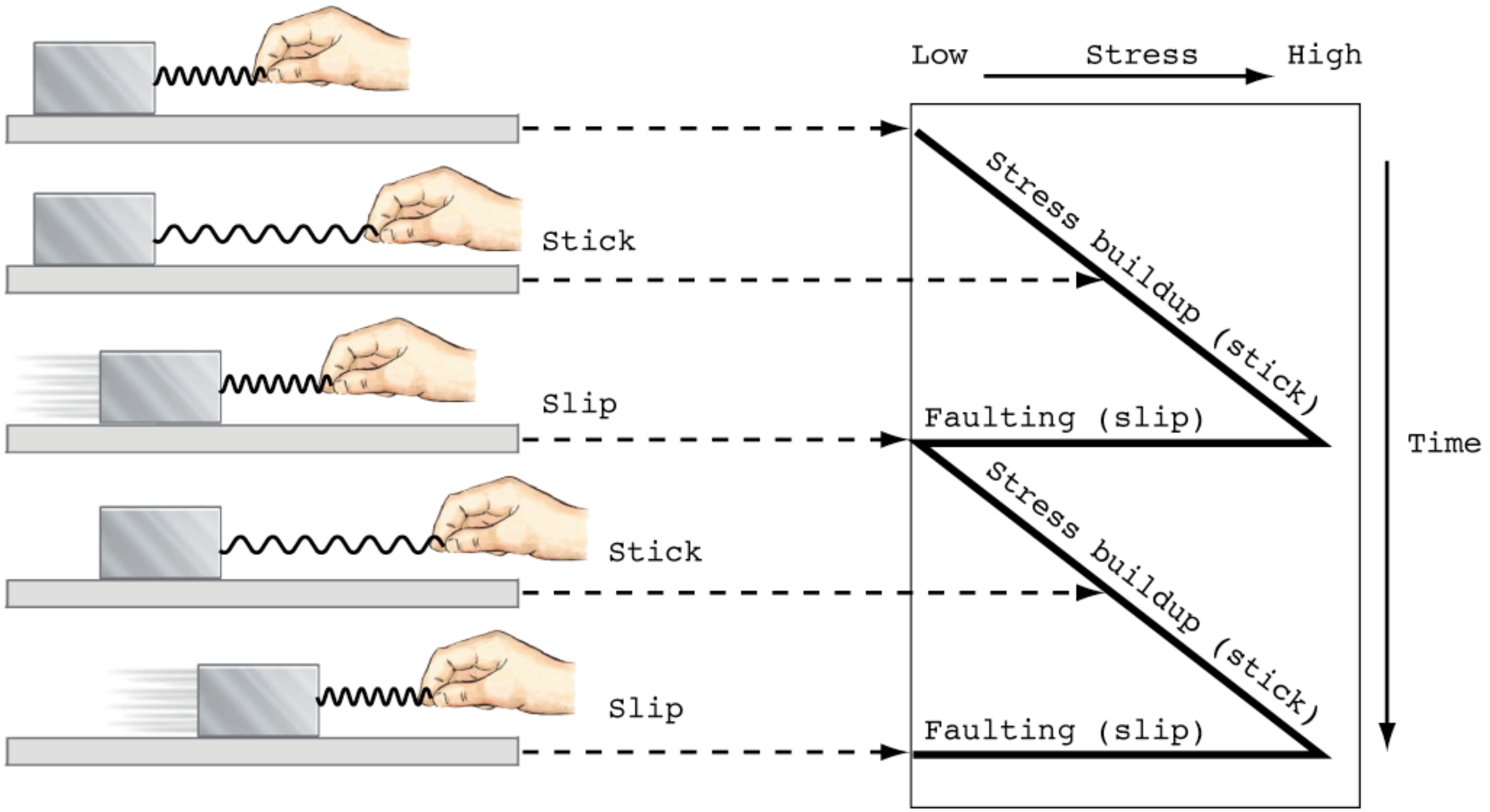


**FIGURE 9.2** Stress at a point on a fault surface. As the rupture front approaches the point, stress increases to a value of $\tau_s$, after which failure occurs at the point. The point slips to a displacement $D$, and stress is reduced to some value $\tau_f$. The difference between the initial stress and the final stress, $\Delta\sigma$, is defined as the stress drop. (After Yamashita, 1976.)

# Stick-slip

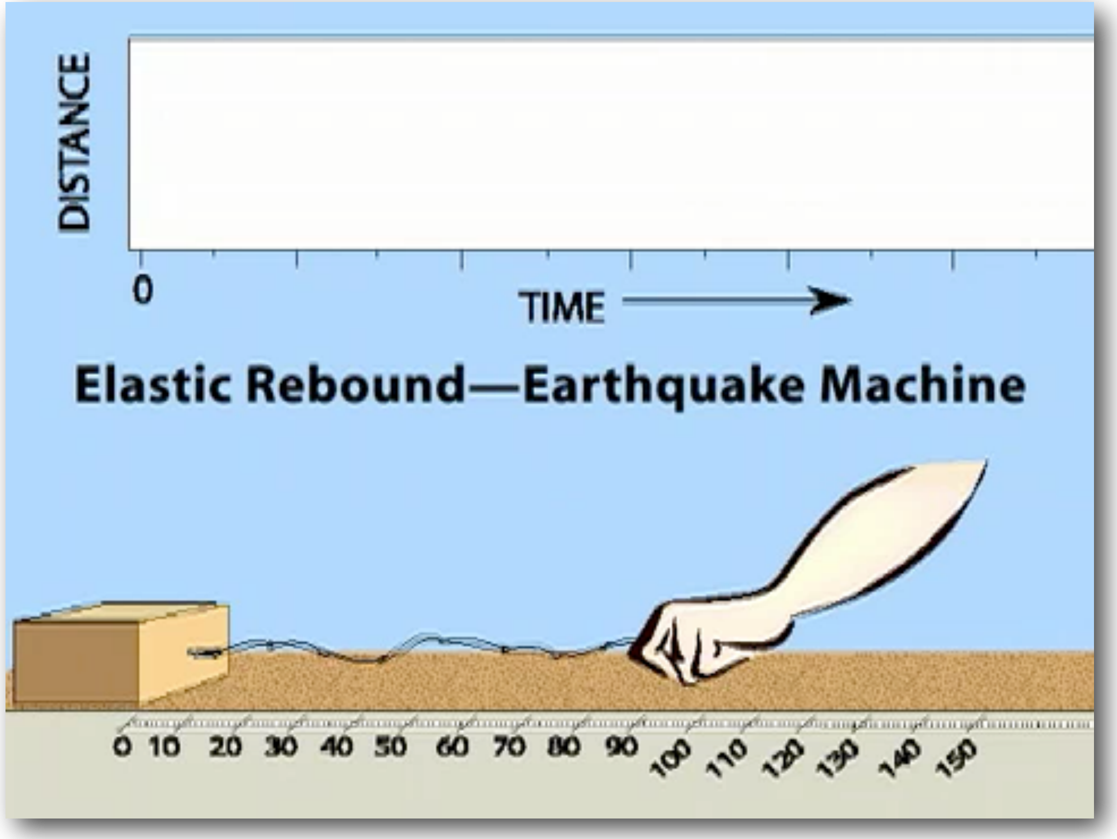


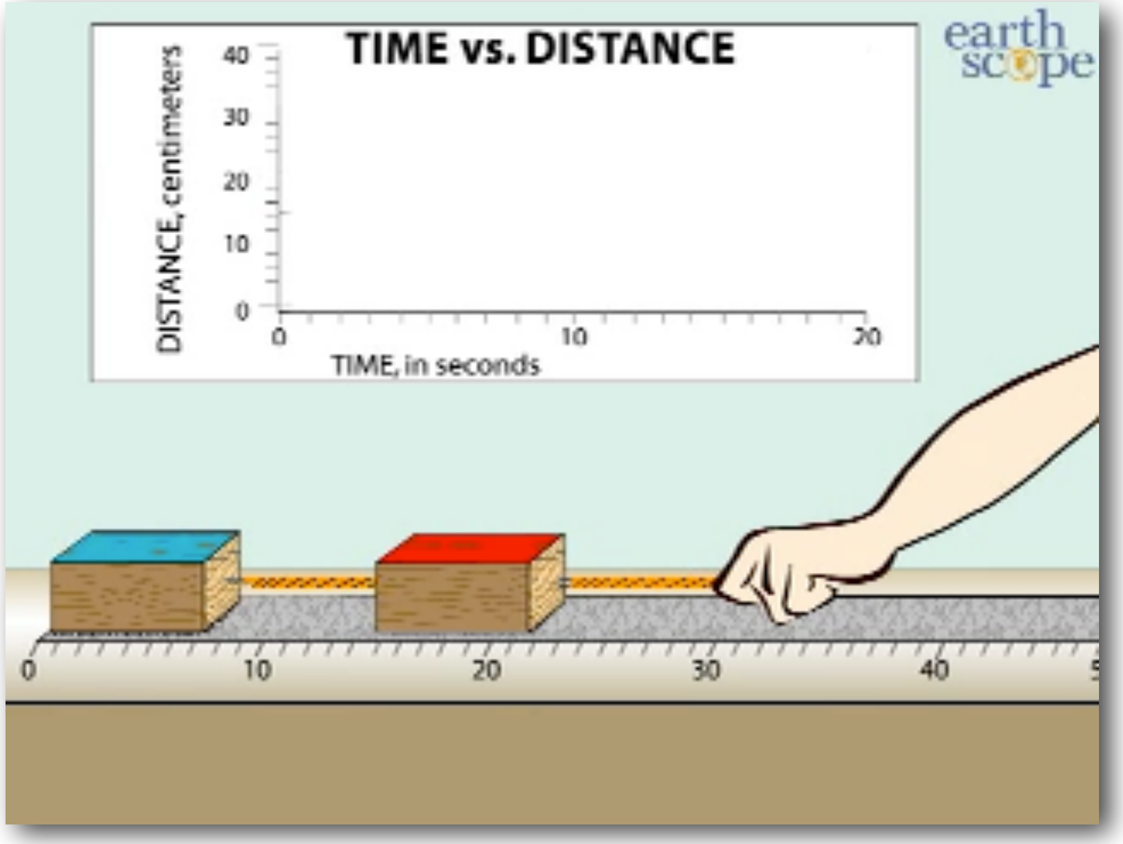
Earth, S. Marshak, W.W. Norton

Elastic strain accumulates during the interseismic period and is released during an earthquake. The elastic strain causes the earthquake –in the sense that the elastic energy stored around the fault drives earthquake rupture.
There are three basic stages in Reid's hypothesis.

1) Stress accumulation (e.g., due to plate tectonic motion)
2) Stress reaches or exceeds the (frictional) failure strength
3) Failure, seismic energy release (elastic waves), and fault rupture propagation

# Stick-slip





http://www.iris.edu/hq/programs/education_and_outreach/aotm/1

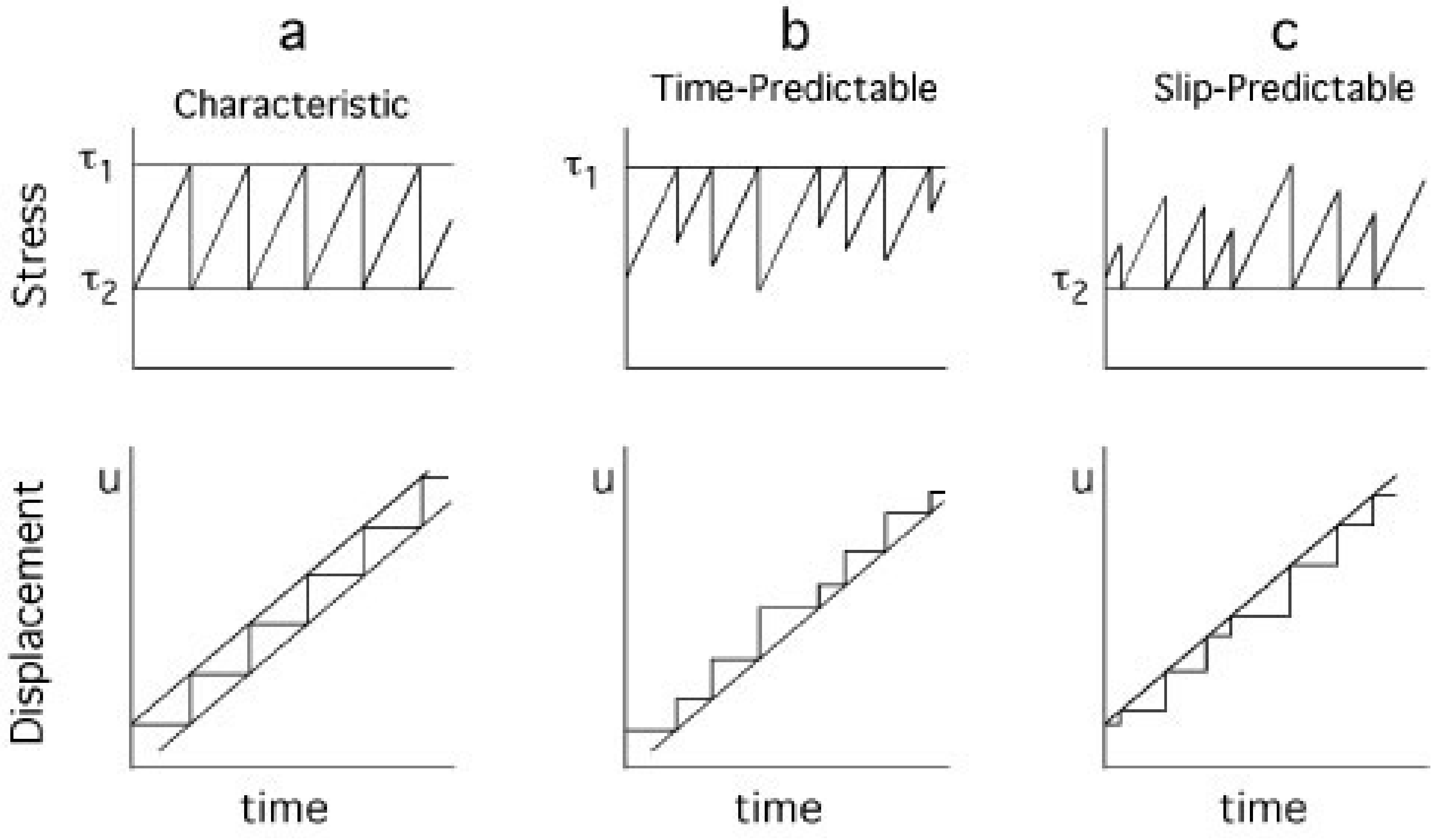
# Stress cycle: prediction models

$\tau_1$ is the shear stress at initiation of slip and reflects fault strength. $\tau_2$ is the shear stress at which slip ceases and reflects fault friction.

(a) **Characteristic model** of stick-slip faulting. Each earthquake is identical in stress history, recurrence interval and slip.

(b) **Time-predictable model**. If slip is proportional to stress drop, and plate motions are steady, we can predict the time of the next earthquake based on the amount of slip during the previous earthquake.

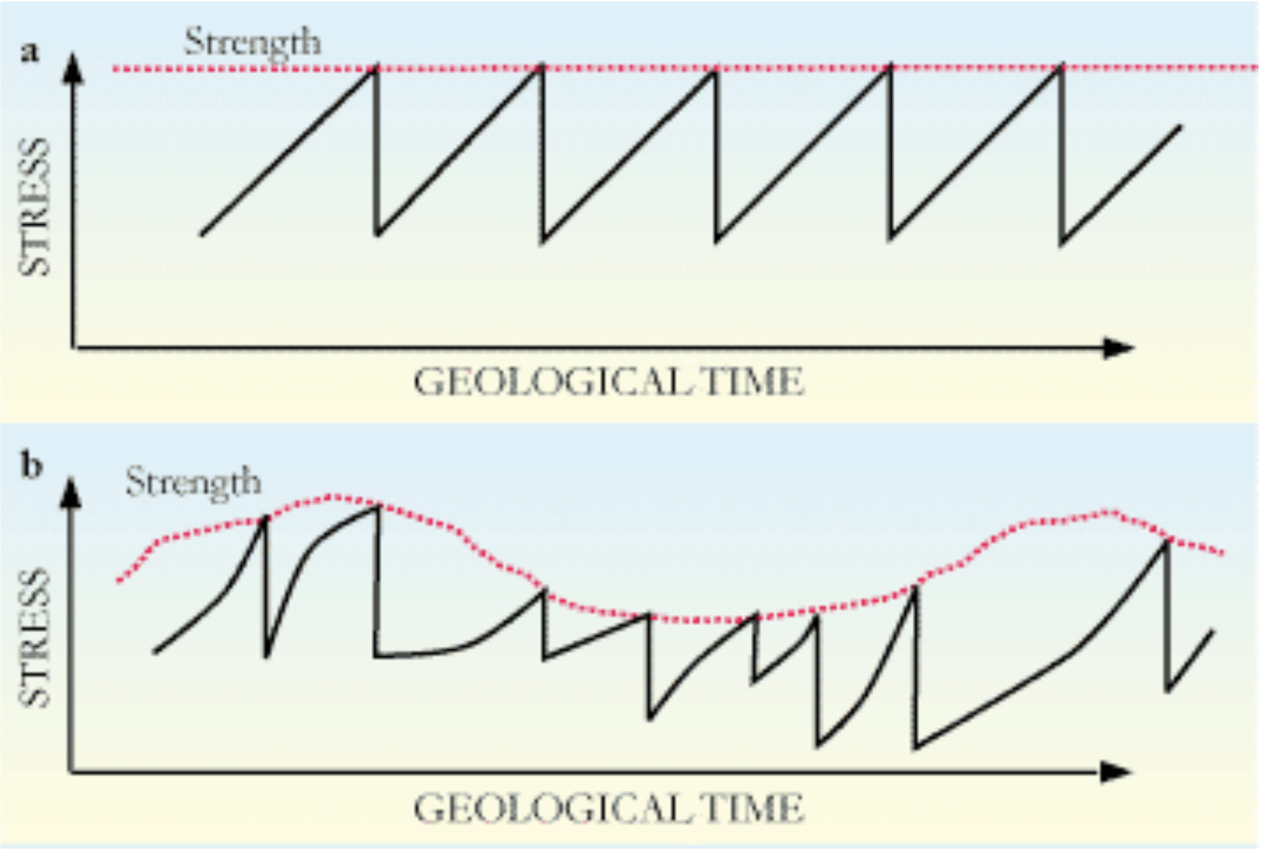
(c) **Slip-predictable model**. Knowing the time of the last earthquake and assuming steady plate motion, we can predict the size of an earthquake expected at a particular time.



# Stress cycle

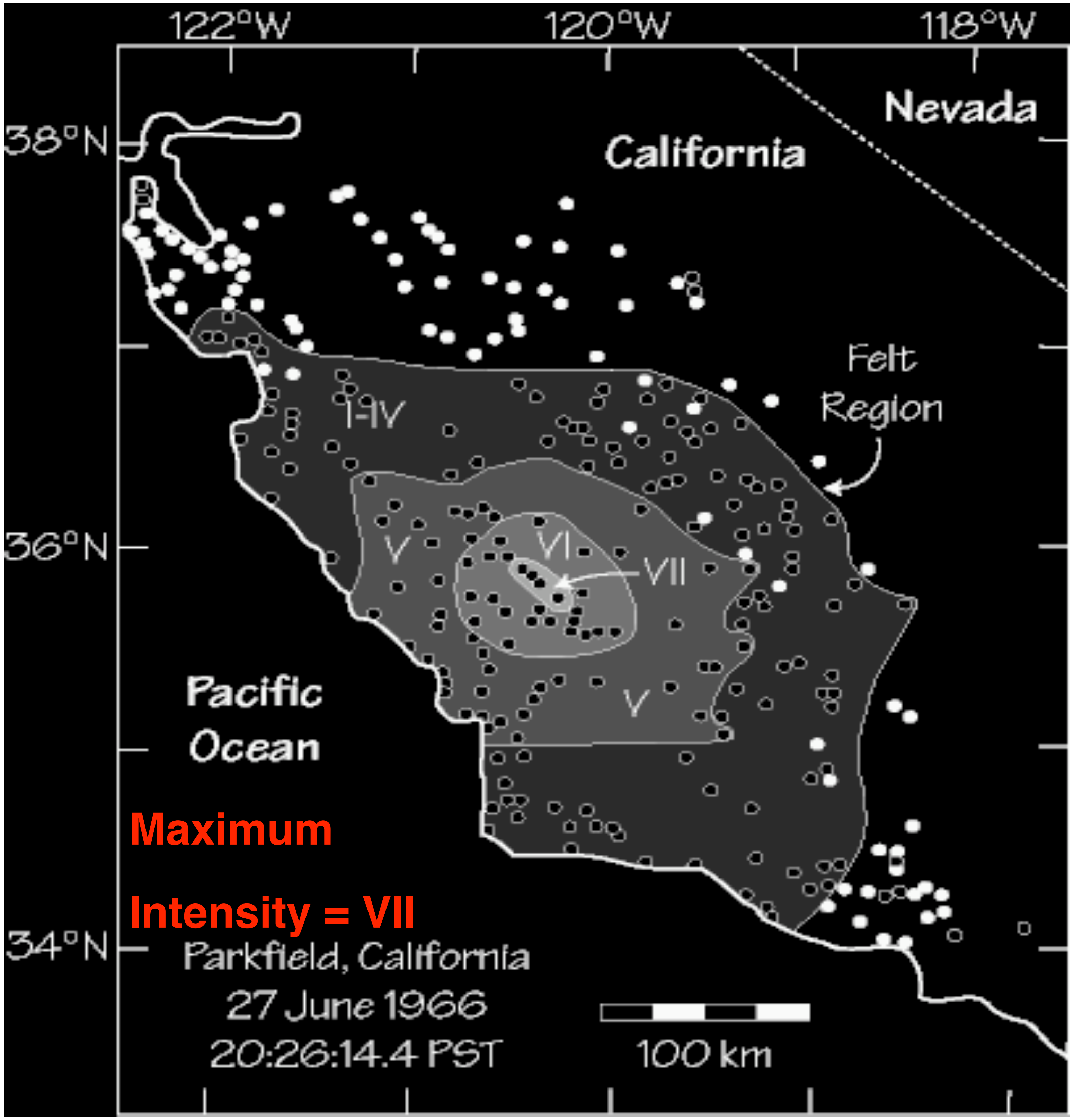
The stress drop causes a time interval during which the stress builds up again to critical value. This type of frictional behaviour is known as **stick-slip**, or unstable sliding (as opposed to continue slip on smooth surfaces: stable sliding).

Earthquakes are generally thought to be **recurring slip episodes on preexisting faults**: the importance is no more on the strength of the rock but on the stress-stability cycle.



# Maximum Intensity

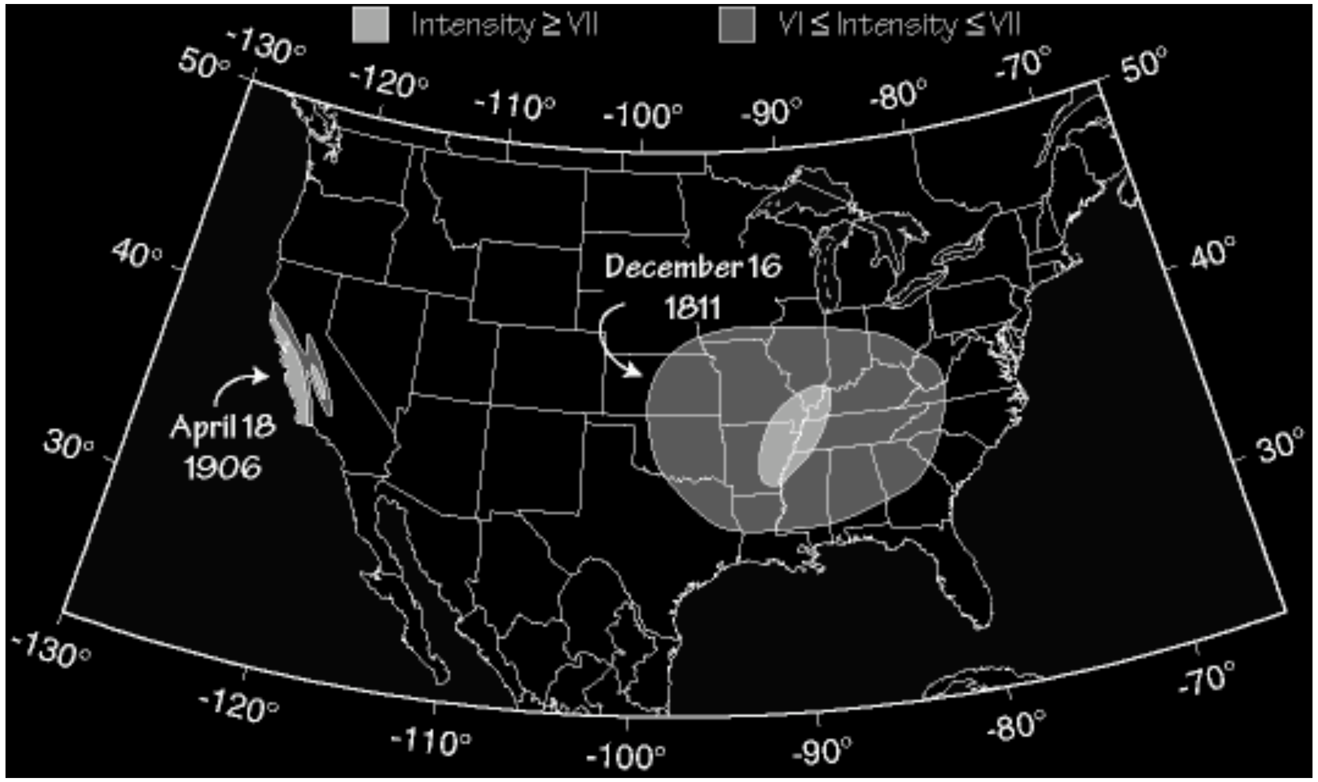
Maximum Intensity is used to estimate the size of historical earthquakes, but suffers from dependence on depth, population, construction practices, site effects, regional geology, etc.



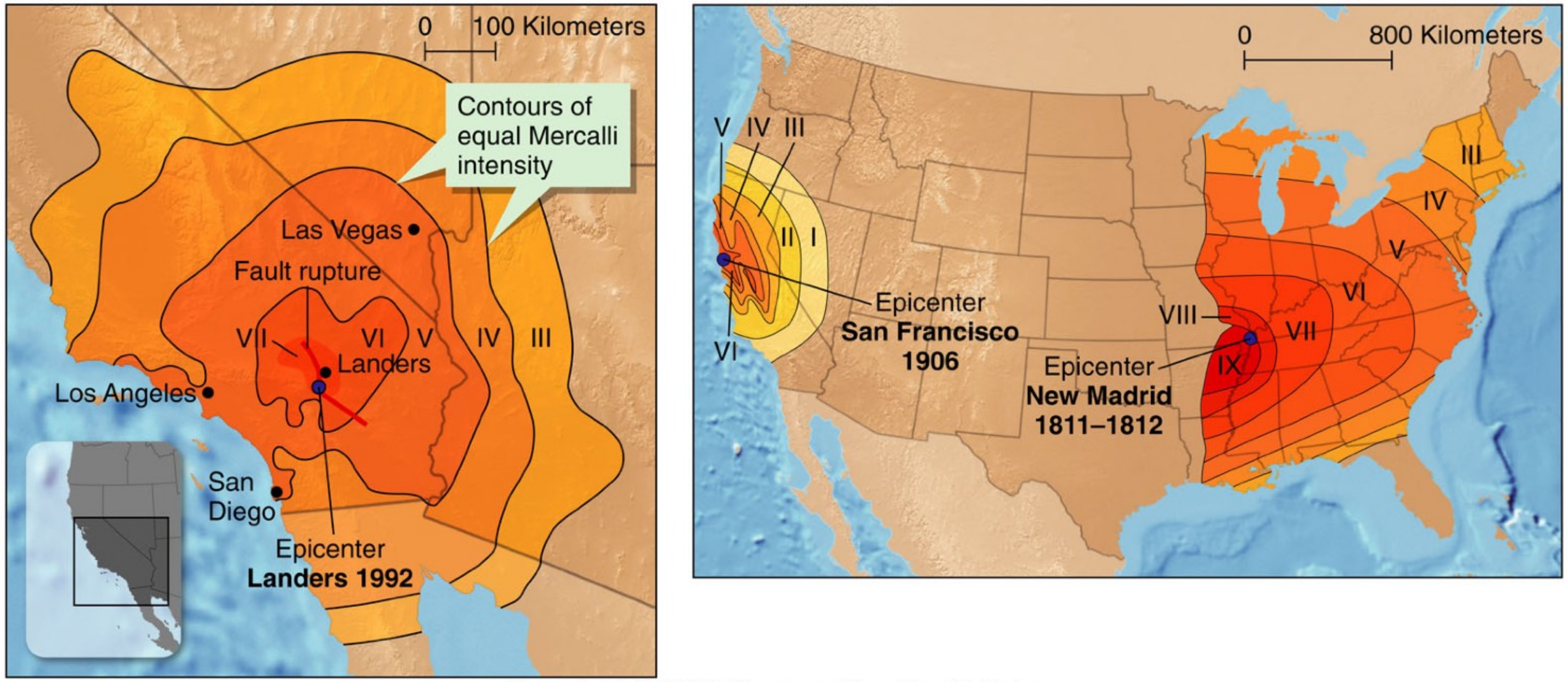
**Maximum Intensity = VII**

Parkfield, California
27 June 1966
20:26:14.4 PST

# 1906 SF and 1811-12 New Madrid



These earthquakes were roughly the same size, but the intensity patterns in the east are broader than in the west (wait for Q...)



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# Mercalli Intensity and Richter Magnitude

| Magnitude | Intensity | Description |
|---|---|---|
| 1.0-3.0<br>Micro | I | **I.** Not felt except by a very few under especially favorable conditions. |
| 3.0 - 3.9<br>Minor | II - III | **II.** Felt only by a few persons at rest, especially on upper floors of buildings.<br>**III.** Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated. |
| 4.0 - 4.9<br>Light | IV - V | **IV.** Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.<br>**V.** Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop. |
| 5.0 - 5.9<br>Moderate | VI - VII | **VI.** Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.<br>**VII.** Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. |
| 6.0 - 6.9<br>Strong | VII - IX | **VIII**. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.<br>**IX.** Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. |
| 7.0 and higher<br>Major great | VIII or higher | **X.** Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.<br>**XI.** Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.<br>**XII.** Damage total. Lines of sight and level are distorted. Objects thrown into the air. |

# Intensity scales

<table>
<tr><th>MM</th><th>RF</th><th>JMA</th><th>MCS</th><th>MSK</th></tr>
<tr><td rowspan="2">I</td><td rowspan="3">I</td><td></td><td rowspan="2">II</td><td rowspan="2">I</td></tr>
<tr><td rowspan="4">I</td></tr>
<tr><td rowspan="2">II</td><td rowspan="2">III</td><td>II</td></tr>
<tr><td>II</td><td rowspan="2">III</td></tr>
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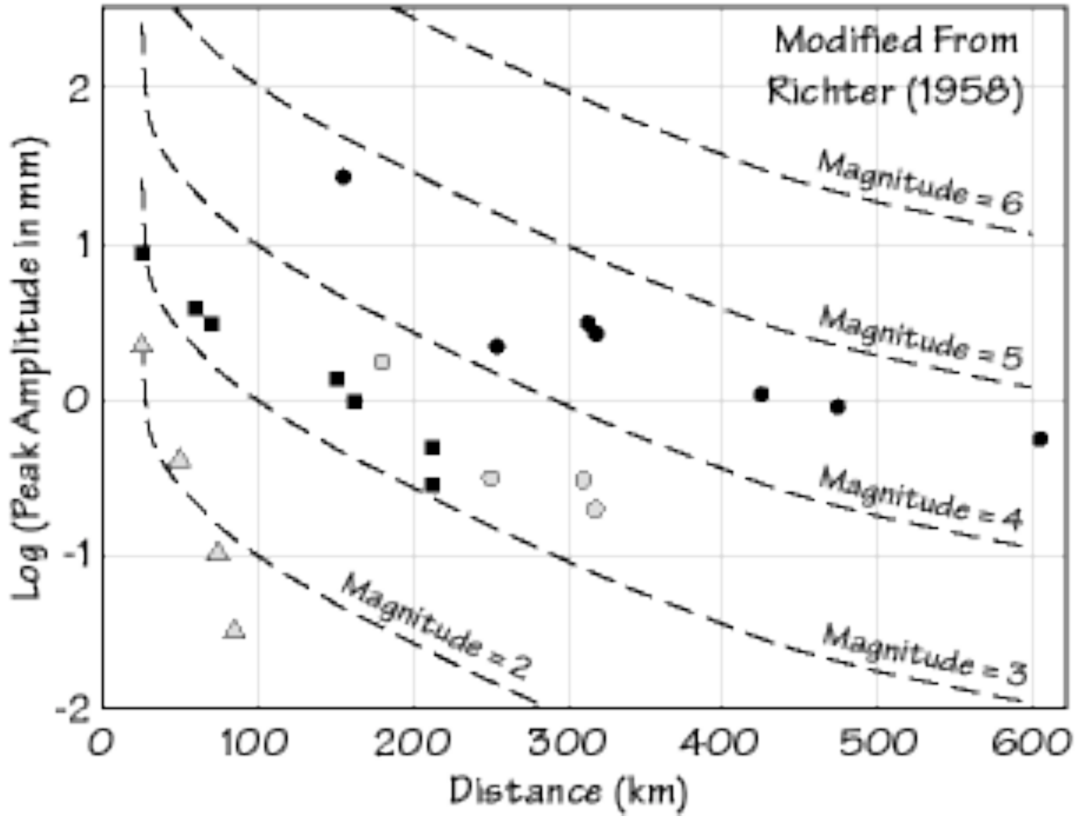
<tr><td>XII</td></tr>
<tr><td>XI</td><td rowspan="2">VII</td><td rowspan="2"></td><td>XI</td></tr>
<tr><td>XII</td><td>XII</td></tr>
</table>

MM – Modified Mercalli; RF – Rossi-Forel; JMA – Japanese Meteorological Agency;
MCS – Mercalli-Cancani-Sieberg; MSK – Medvedev-Sponheuer-Karnik

# Magnitude Scales - Richter

The concept of magnitude was introduced by Richter (1935) to provide an objective instrumental measure of the size of earthquakes. Contrary to seismic intensity, I, which is based on the assessment and classification of shaking damage and human perceptions of shaking, the magnitude M uses instrumental measurements of earth ground motion adjusted for epicentral distance and source depth.



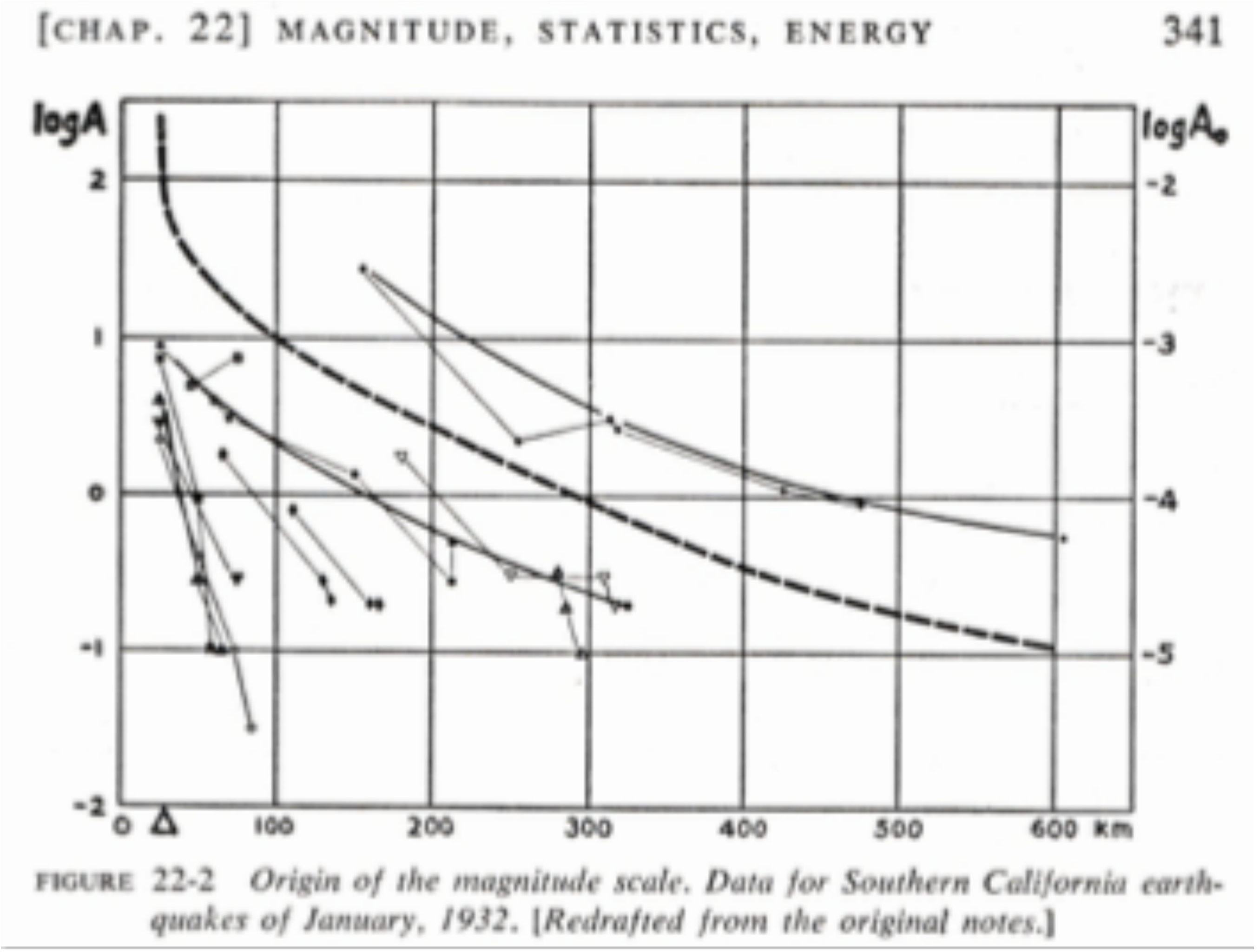
The original Richter scale was based on the observation that the amplitude of seismic waves systematically decreases with epicentral distance.

Data from local earthquakes in California

The relative size of events is calculated by comparison to a reference event, with $M_L=0$, such that $A_0$ was 1 μm at an epicentral distance, Δ, of 100 km with a Wood-Anderson instrument:

$$\mathbf{M_L=\log(A/A_0)=\log A-2.48+2.76\Delta.}$$

# Magnitude Scales - Richter

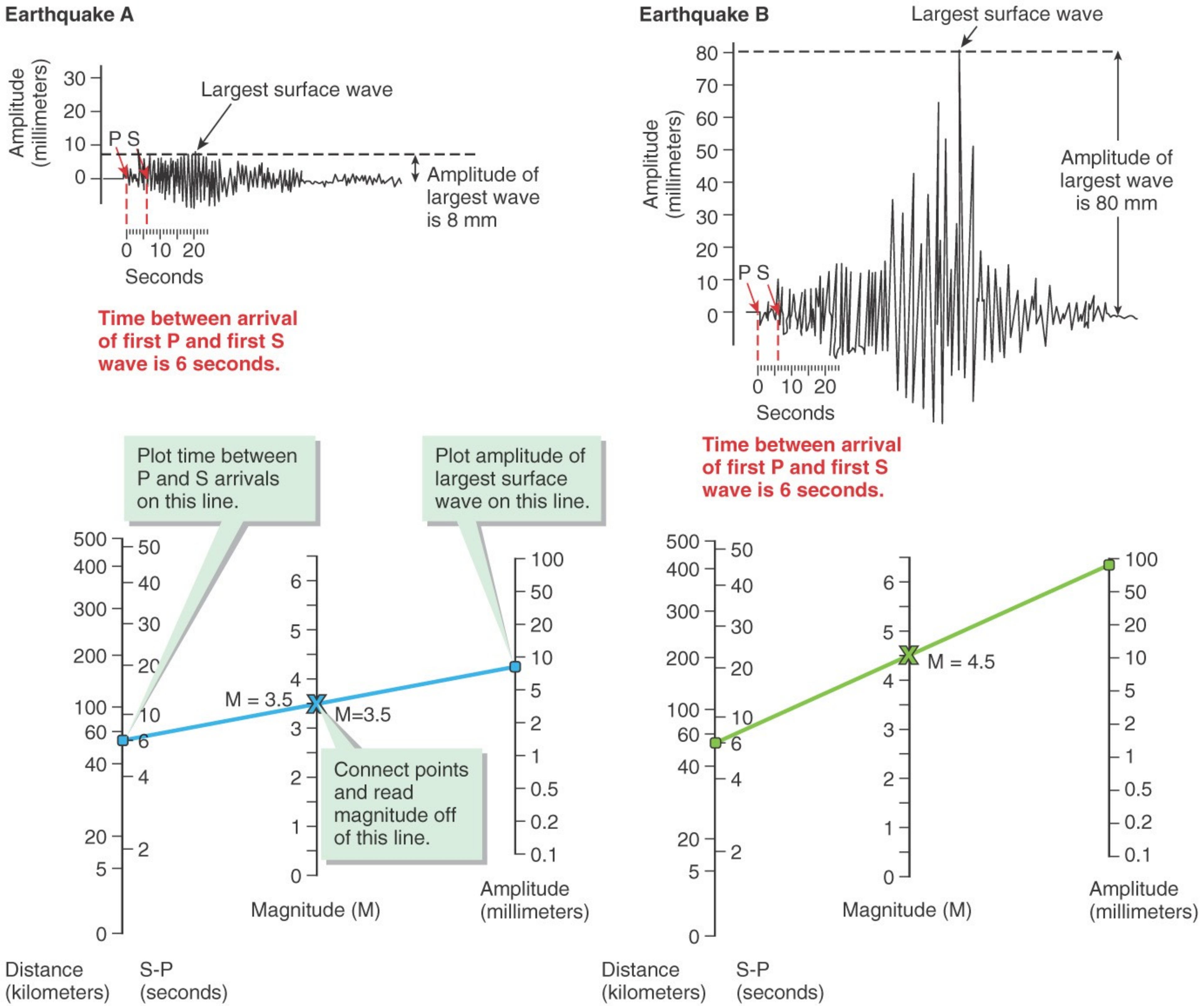


[CHAP. 22] MAGNITUDE, STATISTICS, ENERGY 341

FIGURE 22-2 *Origin of the magnitude scale. Data for Southern California earthquakes of January, 1932. [Redrafted from the original notes.]*

“I found a paper by Professor K. Wadati of Japan in which he compared large earthquakes by plotting the maximum ground motion against distance to the epicenter. I tried a similar procedure for our stations, but the range between the largest and smallest magnitudes seemed unmanageably large. Dr. Beno Gutenberg then made the natural suggestion to plot the amplitudes logarithmically. I was lucky because **logarithmic plots are a device of the devil**. I saw that I could now rank the earthquakes one above the other. Also, quite unexpectedly the attenuation curves were roughly parallel on the plot. By moving them vertically, a representative mean curve could be formed, and individual events were then characterized by individual logarithmic differences from the standard curve. This set of logarithmic differences thus became the numbers on a new instrumental scale. Very perceptively, Mr. Wood insisted that this new quantity should be given a distinctive name to contrast it with the intensity scale. My amateur interest in astronomy brought out the term "magnitude," which is used for the brightness of a star.”

Charles F. Richter - An Interview by Henry Spall, Earthquake Information Bulletin. Vol. 12, No. 1, January - February, 1980



**Time between arrival of first P and first S wave is 6 seconds.**

Plot time between P and S arrivals on this line.

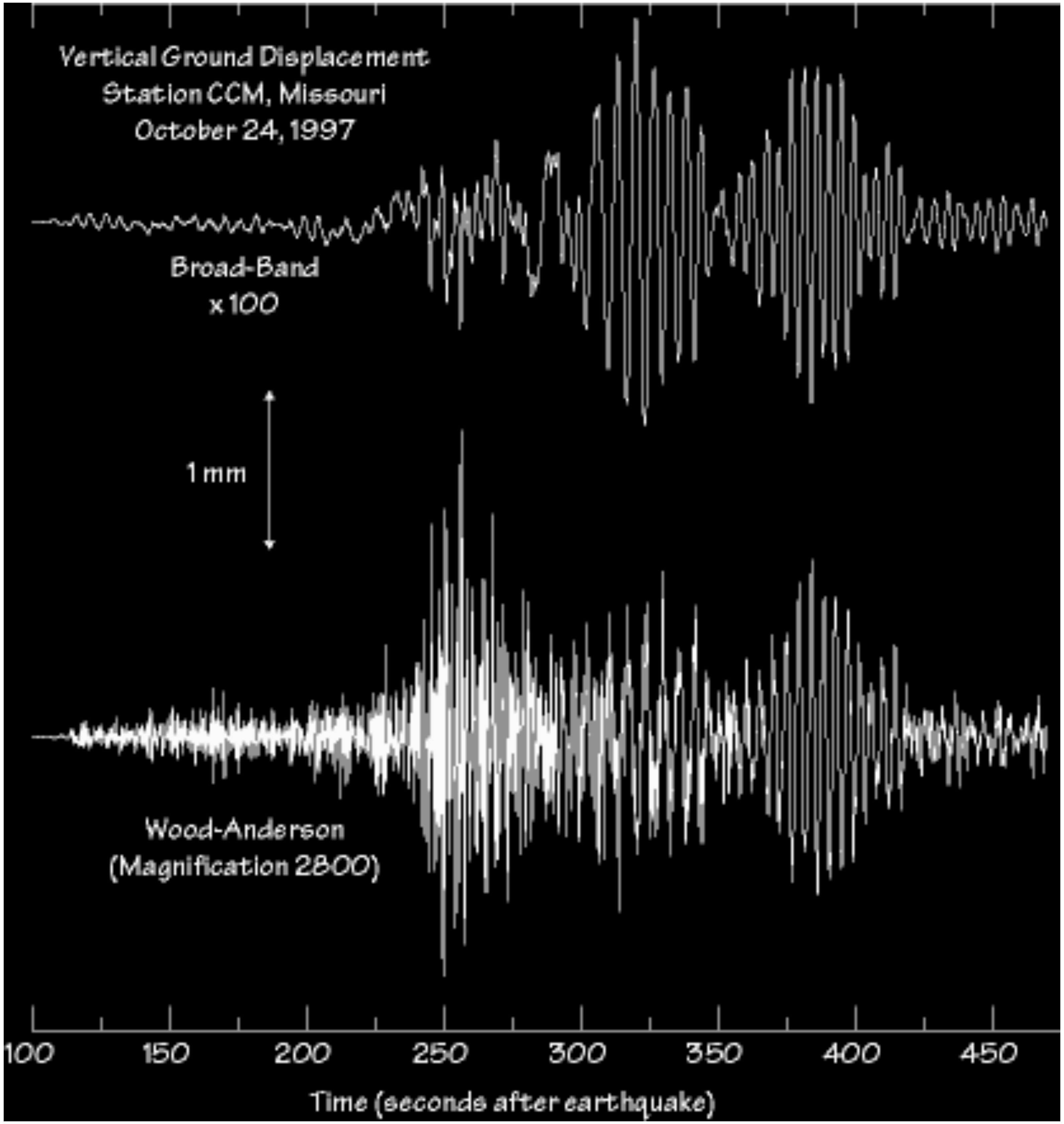
Plot amplitude of largest surface wave on this line.

Connect points and read magnitude off of this line.

**Time between arrival of first P and first S wave is 6 seconds.**

# Wood-Anderson Seismometer

Richter also tied his formula to a specific seismic instrument.



# Magnitude Scales

The original $M_L$ is suitable for the classification of local shocks in Southern California only since it used data from the standardized short-period Wood-Anderson seismometer network. The magnitude concept has then been extended so as to be applicable also to ground motion measurements from medium- and long-period seismographic recordings of both surface waves ($M_s$) and different types of body waves ($m_b$) in the teleseismic distance range.

The general form of all magnitude scales based on measurements of ground displacement amplitudes A and periods T is:

$$M = \log\left(\frac{A}{T}\right) + f(\Delta, h) + C_r + C_s$$

M seismic magnitude
A amplitude
T period
f correction for distance and depth
$C_s$ correction for site
$C_r$ correction for source region

$M_L$ **Local magnitude**

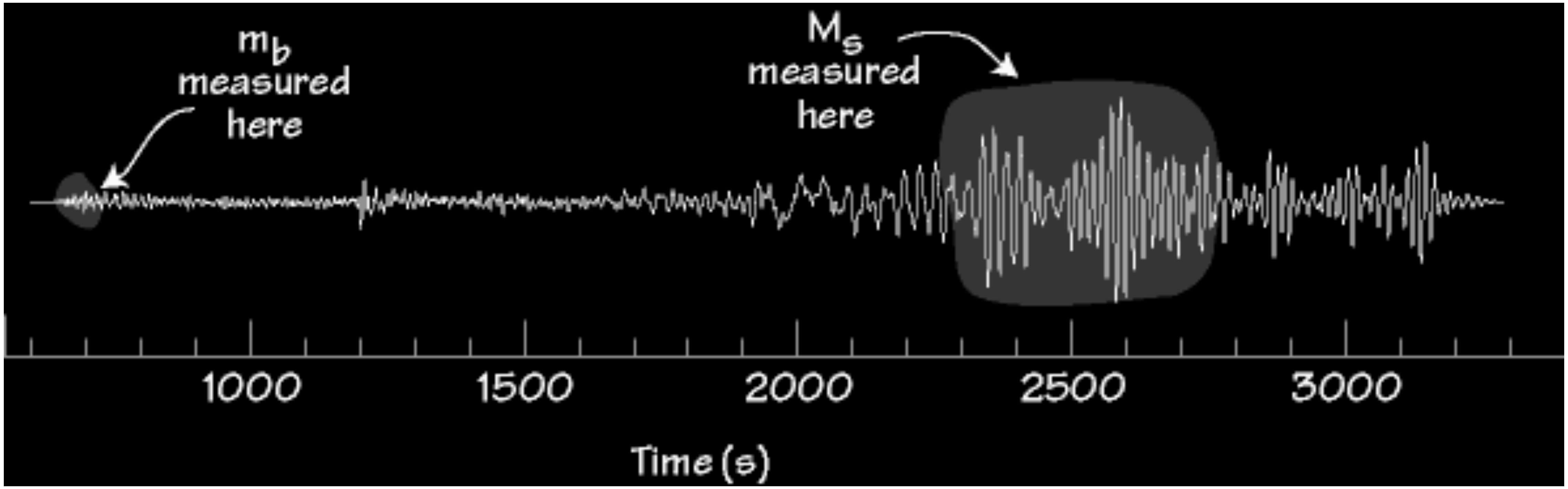
$m_b$ **body-wave magnitude** (1s)

$M_s$ **surface wave magnitude** (20s)

# Teleseismic $M_S$ and mb

The two most common modern magnitude scales are:

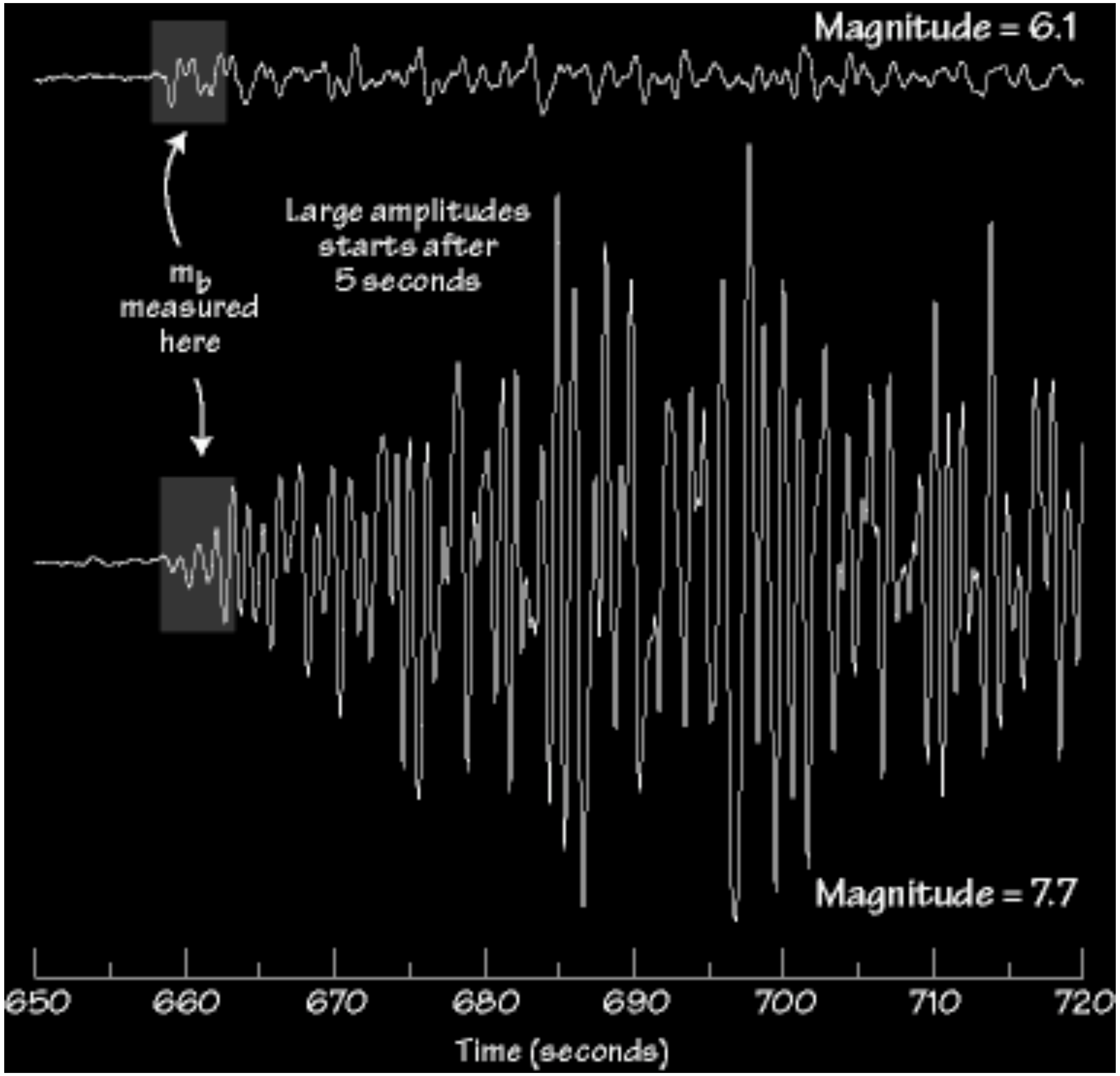
- $M_S$, Surface-wave magnitude (Rayleigh Wave, 20s)
- $m_b$, Body-wave magnitude (P-wave)



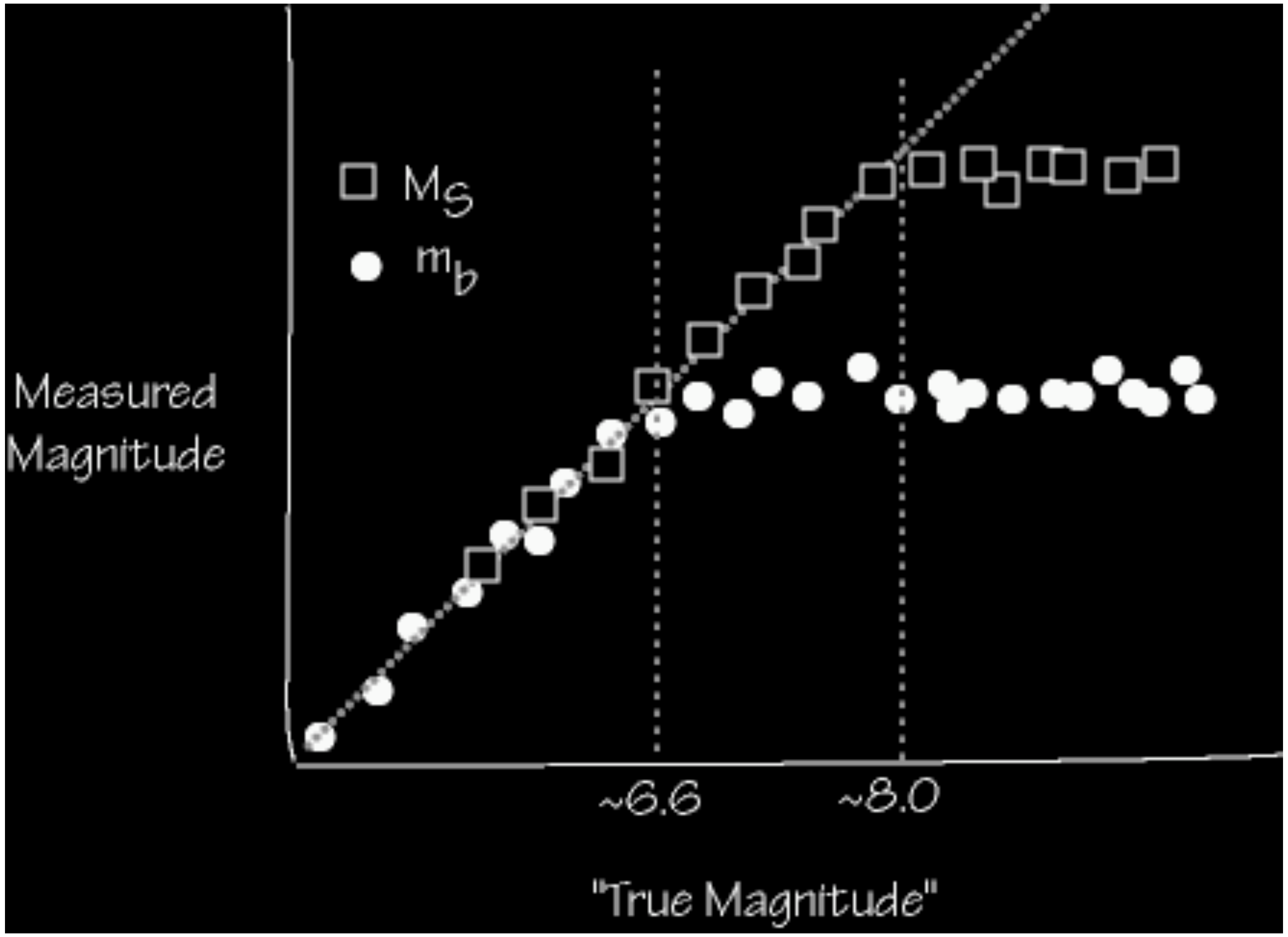
# Example: $m_b$ "Saturation"

$m_b$ seldom gives values above 6.7 - it "saturates".

$m_b$ must be measured in the first 5 seconds - that's the rule.



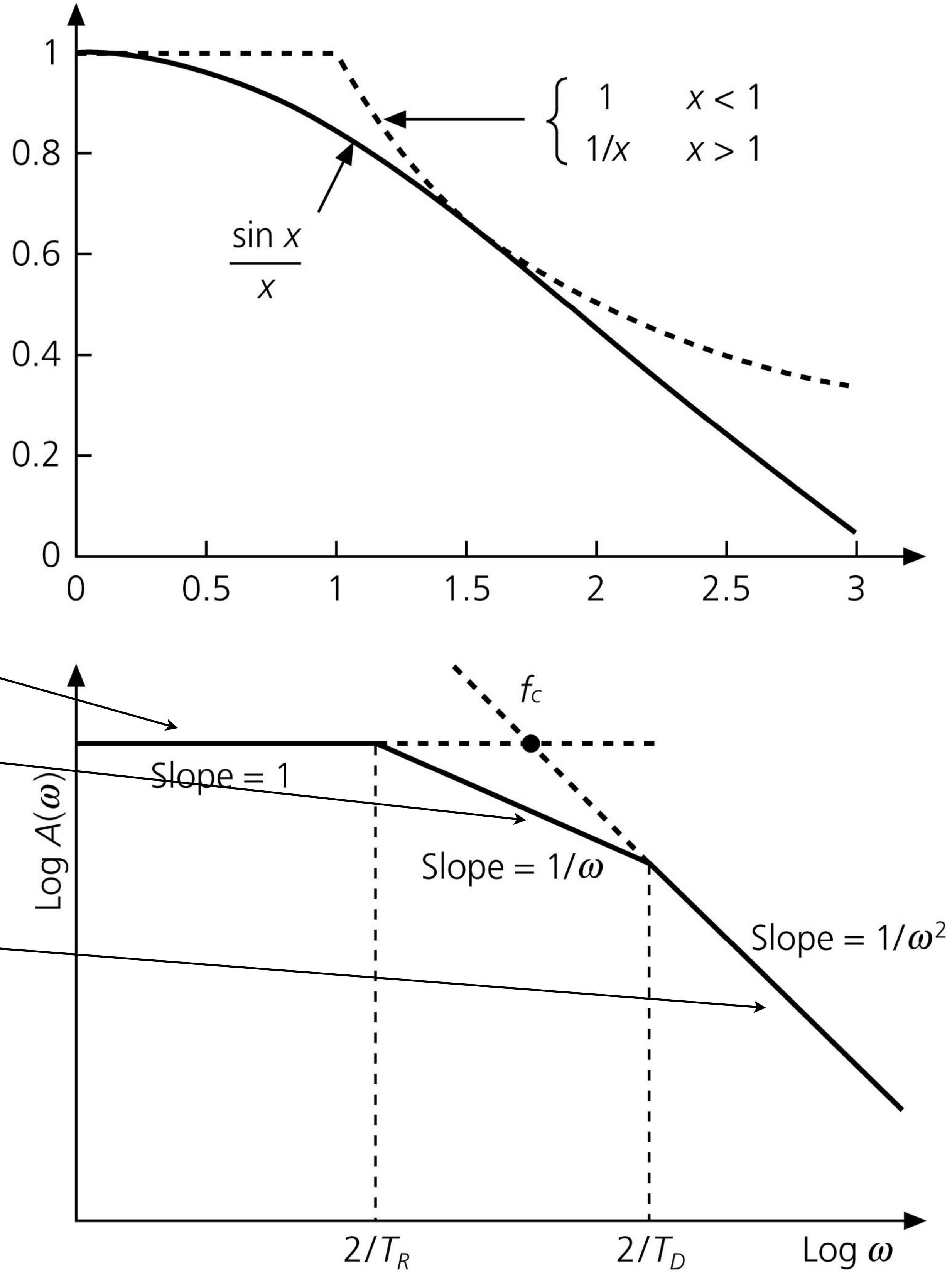
# Saturation



# Source spectrum

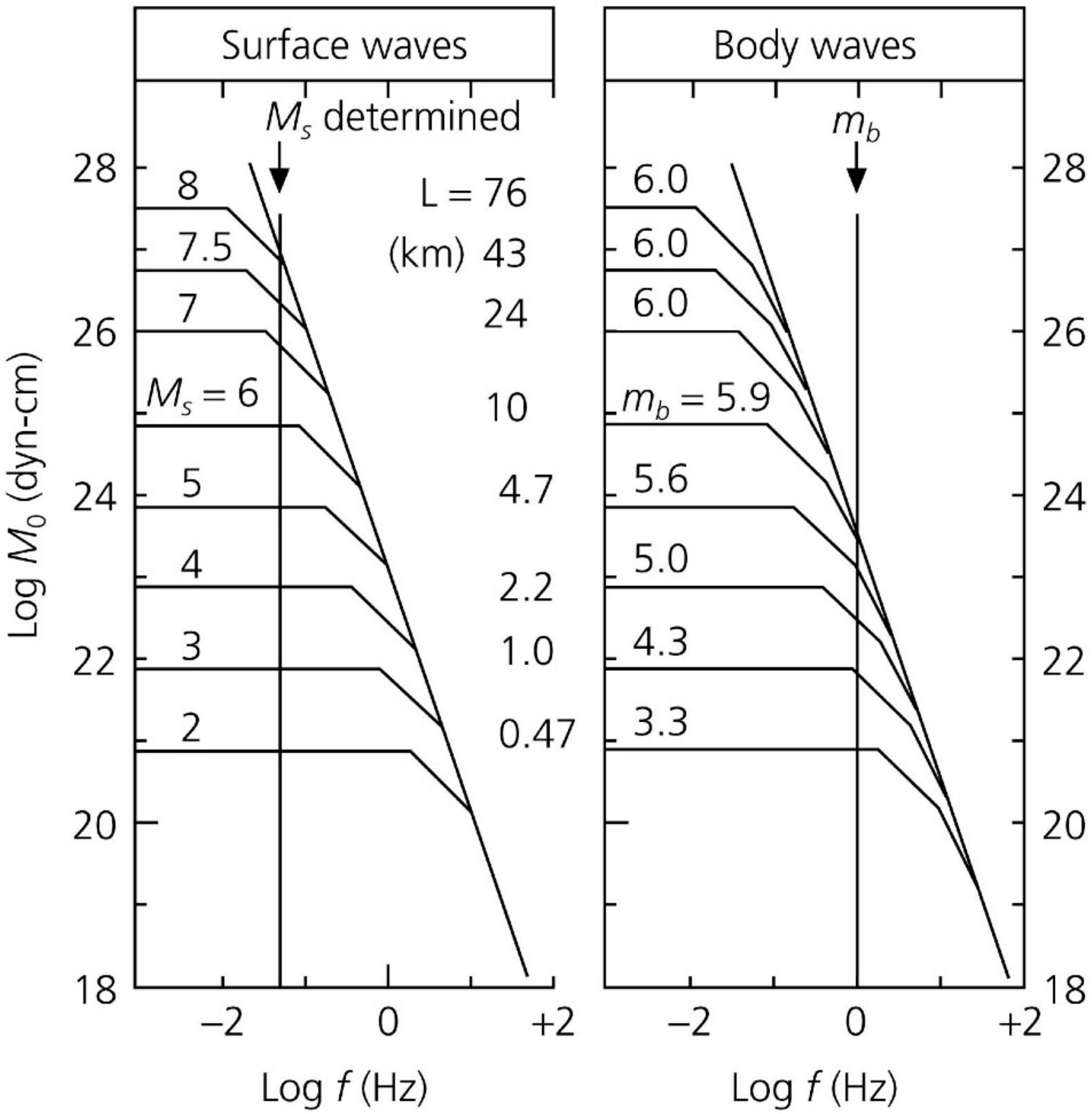
$$U(\omega) \approx \begin{cases} \boxed{M_0} & \omega < \dfrac{2}{T_r} \\[2ex] \boxed{\dfrac{2M_0}{\omega T_R}} & \dfrac{2}{T_r} < \omega < \dfrac{2}{\tau} \\[2ex] \boxed{\dfrac{4M_0}{\omega^2 \tau T_R}} & \omega > \dfrac{2}{\tau} \end{cases}$$

**Figure 4.6-4: Approximation of the (sin *x*)/*x* function, and derivation of corner frequencies.**



# Magnitude saturation

Nature limits the maximum size of tectonic earthquakes which is controlled by the maximum size of a brittle fracture in the lithosphere. A simple seismic shear source with linear rupture propagation has a typical "source spectrum".



$M_s$ is not linearly scaled with $M_0$ for $M_s > 6$ due to the beginning of the so-called saturation effect for spectral amplitudes with frequencies $f > f_c$. This saturation occurs already much earlier for $m_b$ which are determined from amplitude measurements around 1 Hz.

# Moment magnitude

Empirical studies (Gutenberg & Richter, 1956; Kanamori & Anderson, 1975) lead to a formula for the released seismic energy (in Joule), and for moment, with magnitude:

$$\log E = 4.8 + 1.5 M_s \quad \log M_0 = 9.1 + 1.5 M_s$$

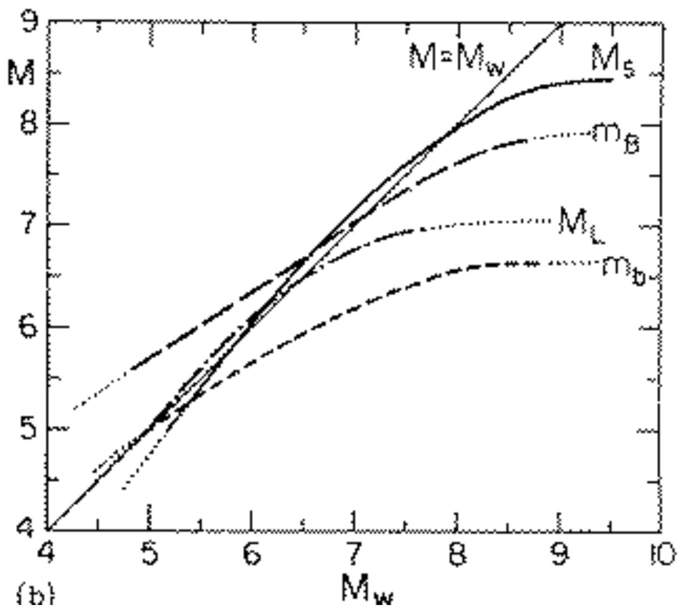
resulting in

$$M_w = 2/3 \log M_0 - 6.07$$

when the Moment is measured in N·m (otherwise the intercept becomes 10.73); it is related to the final static displacement after an earthquake and consequently to the tectonic effects of an earthauake.

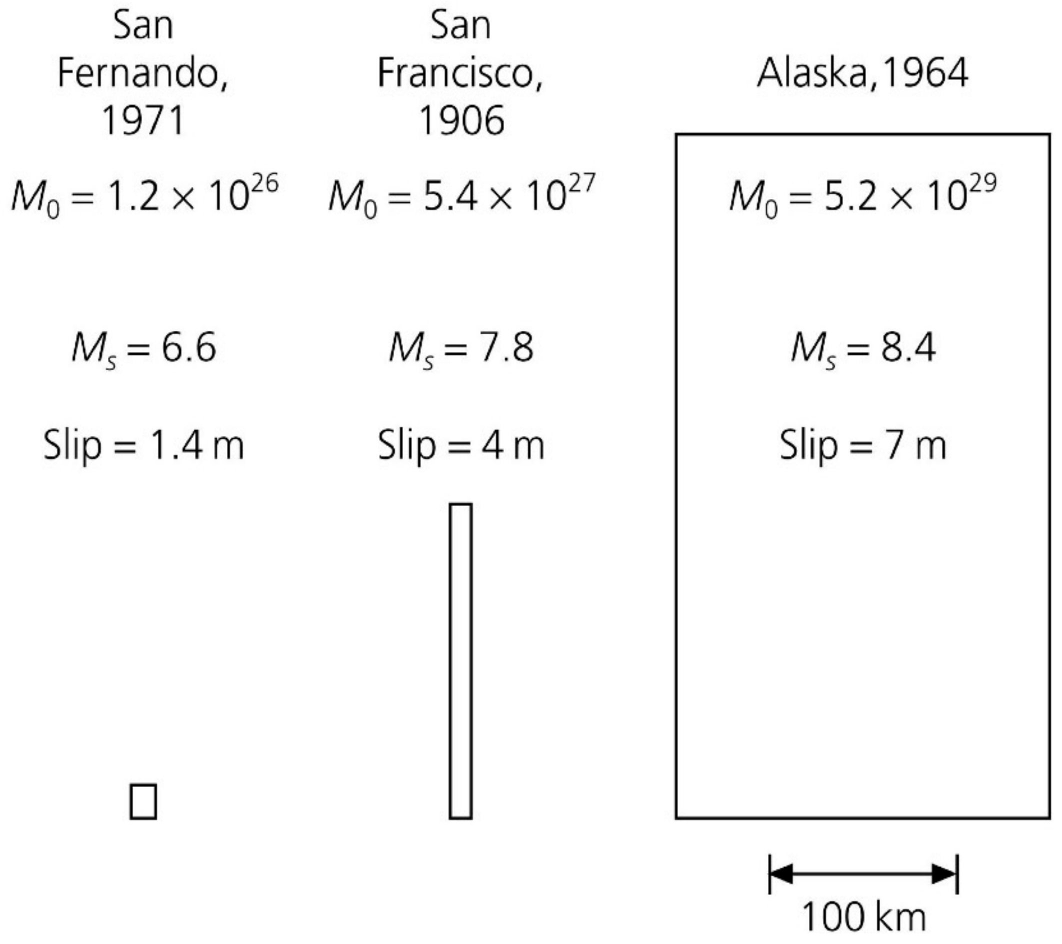
$$u(x,t) = A\cos\left(\frac{2\pi t}{T}\right) \Rightarrow v(x,t) \propto \frac{A}{T}u$$

$$\Rightarrow e \propto v^2 \propto \left(\frac{A}{T}\right)^2 \Rightarrow \log E = C + 2\log\left(\frac{A}{T}\right)$$



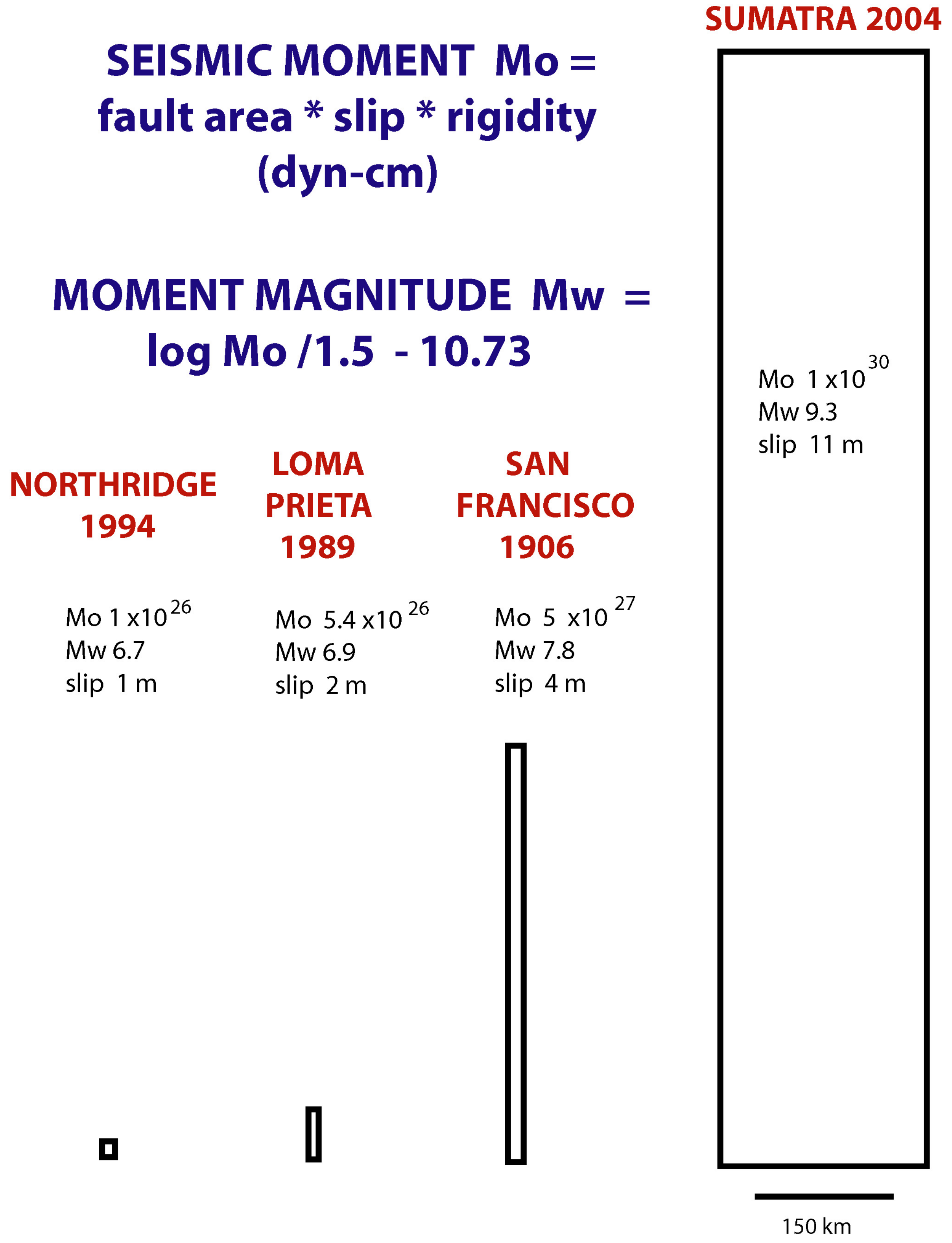
| Earthquake | Body wave magnitude $m_b$ | Surface wave magnitude $M_s$ | Fault area (km$^2$) length × width | Average dislocation (m) | Moment (dyn-cm) $M_0$ | Moment magnitude $M_w$ |
|---|---|---|---|---|---|---|
| Truckee, 1966 | 5.4 | 5.9 | 10 × 10 | 0.3 | $8.3 \times 10^{24}$ | 5.8 |
| San Fernando, 1971 | 6.2 | 6.6 | 20 × 14 | 1.4 | $1.2 \times 10^{26}$ | 6.7 |
| Loma Prieta, 1989 | 6.2 | 7.1 | 40 × 15 | 1.7 | $3.0 \times 10^{26}$ | 6.9 |
| San Francisco, 1906 | | 8.2 | 320 × 15 | 4 | $6.0 \times 10^{27}$ | 7.8 |
| Alaska, 1964 | 6.2 | 8.4 | 500 × 300 | 7 | $5.2 \times 10^{29}$ | 9.1 |
| Chile, 1960 | | 8.3 | 800 × 200 | 21 | $2.4 \times 10^{30}$ | 9.5 |

# Moment, Magnitude and area



**SEISMIC MOMENT Mo = fault area * slip * rigidity (dyn-cm)**

**MOMENT MAGNITUDE Mw = log Mo /1.5 - 10.73**



**SUMATRA 2004**

Mo 1 x10$^{30}$
Mw 9.3
slip 11 m

**NORTHRIDGE 1994**

Mo 1 x10$^{26}$
Mw 6.7
slip 1 m

**LOMA PRIETA 1989**

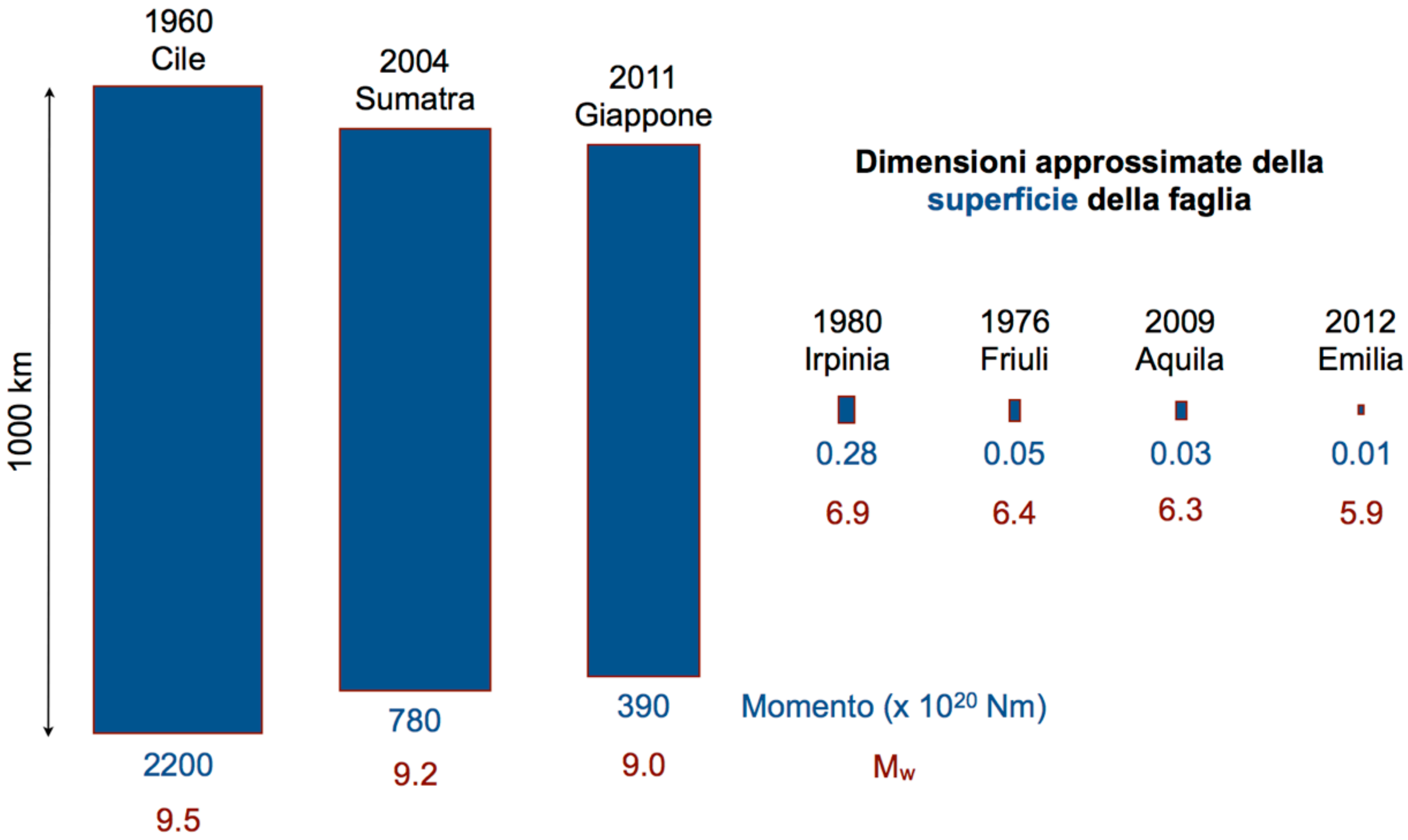
Mo 5.4 x10$^{26}$
Mw 6.9
slip 2 m

**SAN FRANCISCO 1906**

Mo 5 x10$^{27}$
Mw 7.8
slip 4 m

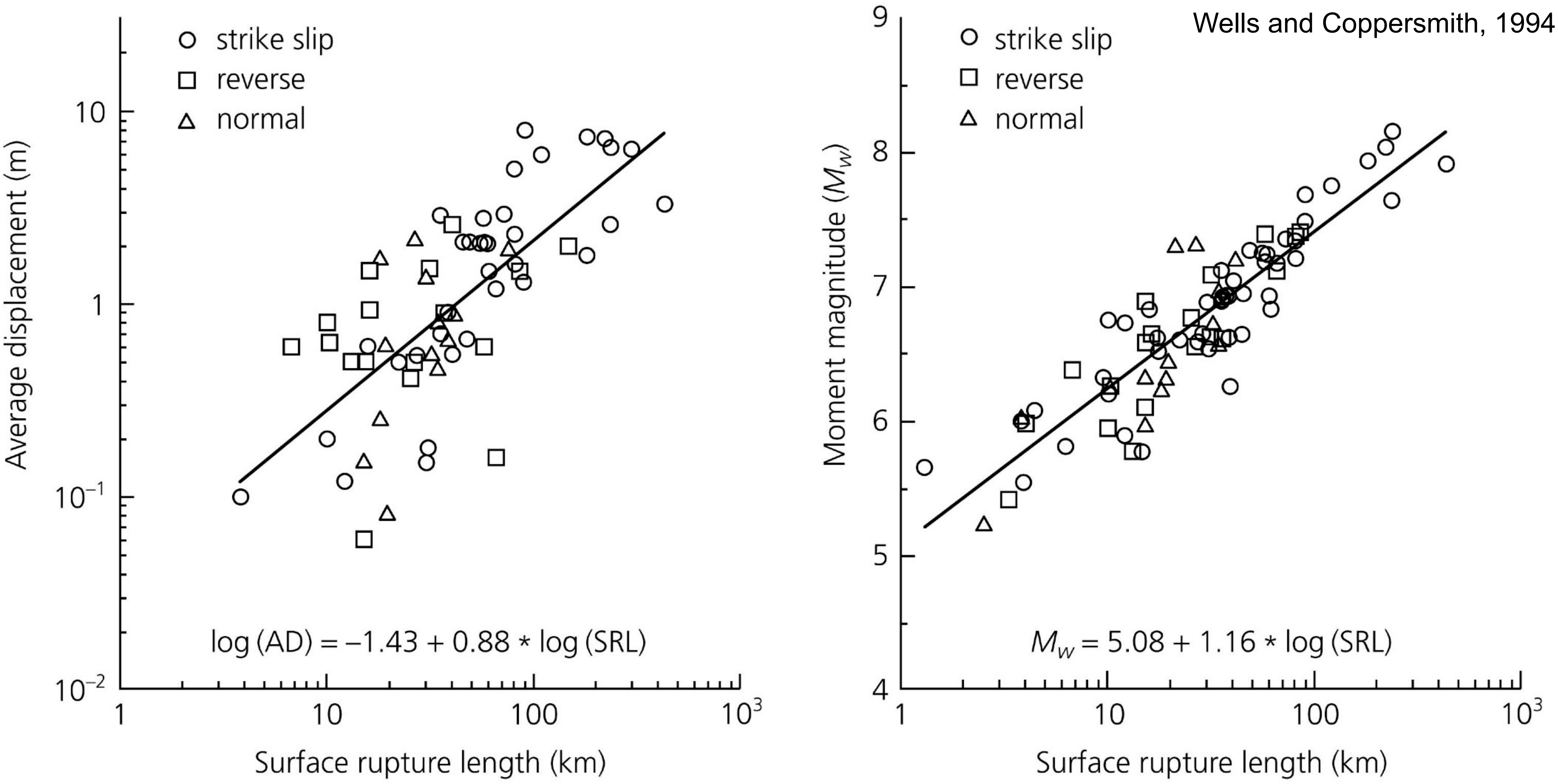
150 km

# Energia (magnitudo)



# Slip, length and moment

**Figure 4.6-7: Empirical relations between slip, fault length, and moment.**



Wells and Coppersmith, 1994

M7, ~ 100 km long, 1 m slip; M6, ~ 10 km long, ~ 20 cm slip

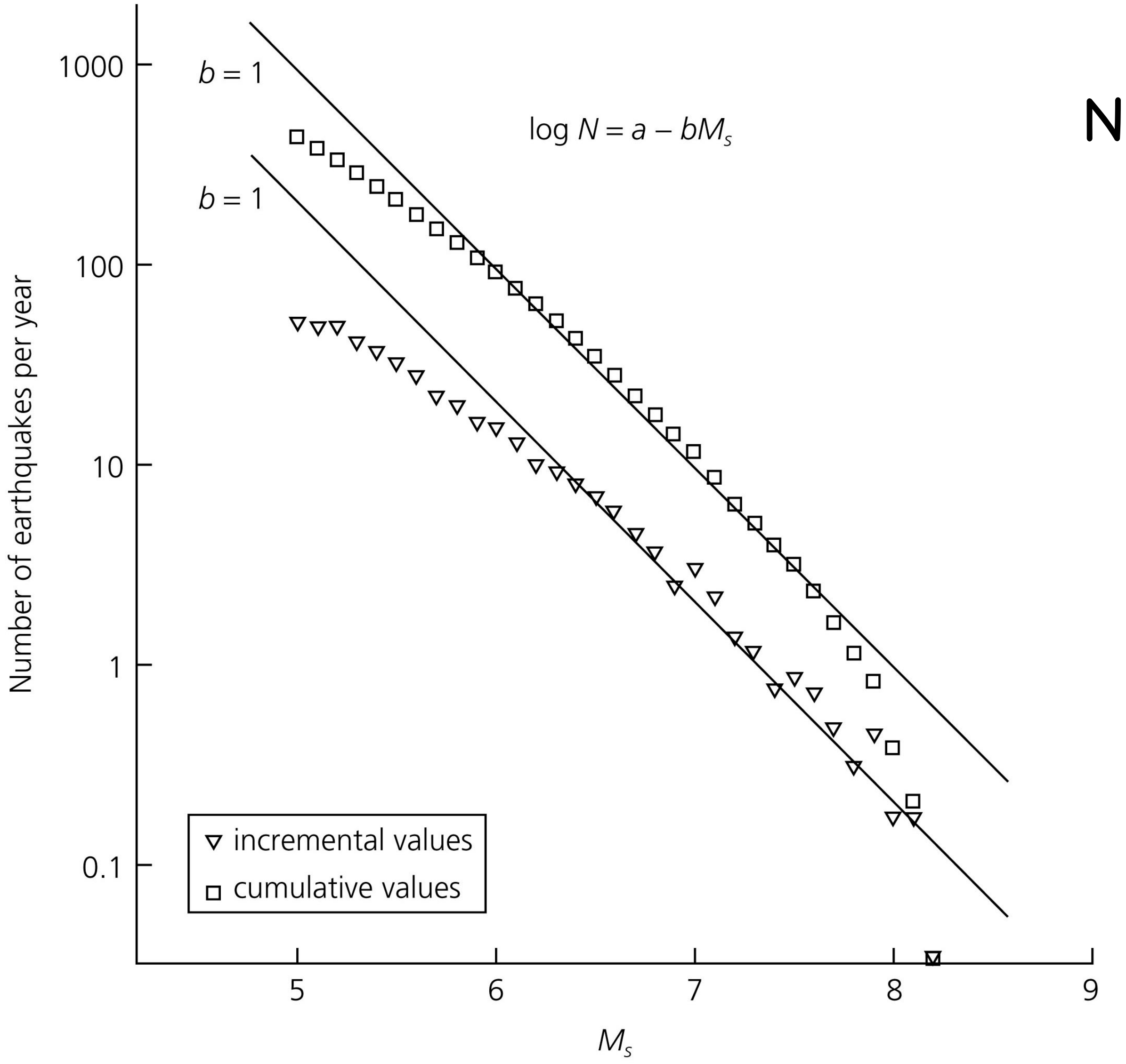
Important for tectonics, earthquake source physics, hazard estimation

**Wells** D.L. e **Coppersmith** K.J.; **1994**: New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull. Seism. Soc. Am., **84**, 974-1002.

# Gutenberg-Richter law

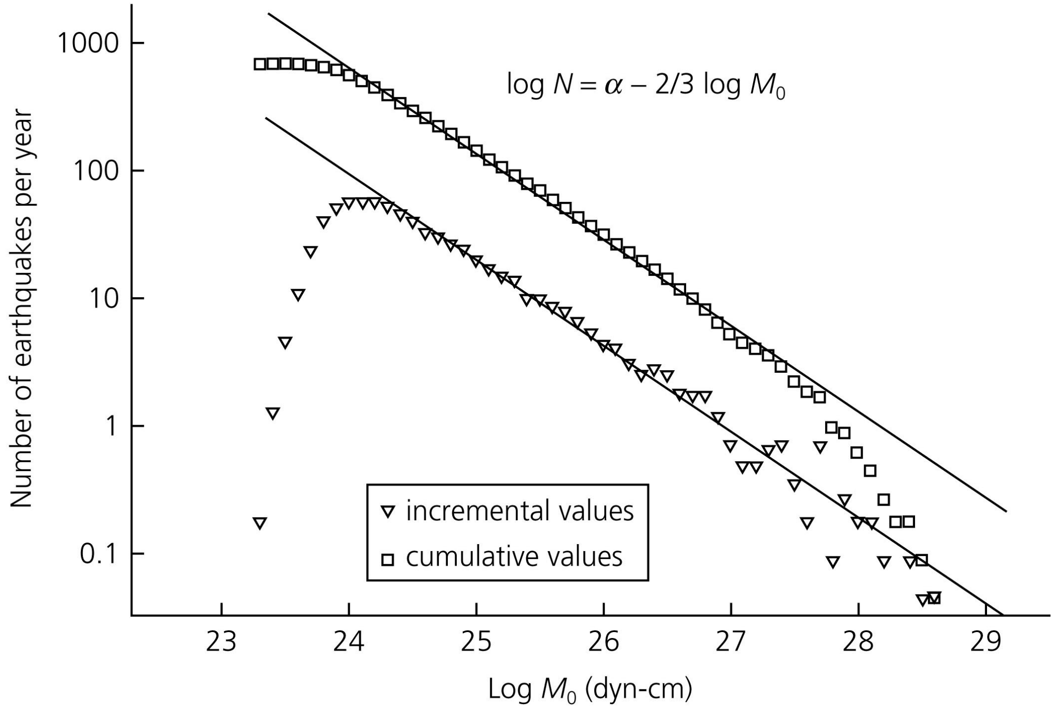
They proposed that in a given region and for a given period of time, the frequency of occurrence can be represented by: **$\log N = A - bM_s$**, where N is the number of earthquakes with magnitudes in a fixed range around $M_s$. It can be written also as a power-law for moment, distribution that arises from the self-similarity of earthquakes. While the a-value is a measure of earthquake productivity, the b-value is indicative of the ratio between large and small quakes. Both a and b are, therefore, important parameters in hazard analysis. Usually b is close to a unity.

**Figure 4.7-1: Frequency-magnitude plot for earthquakes during 1968-1997.**



$$N = \frac{10^A}{\left(10^{M_s}\right)^b} = \frac{C}{\left(M_0\right)^{2b/3}} = CM_0^{-2b/3} \approx CM_0^{-2/3}$$

**Figure 4.7-2: Frequency-moment plot for earthquakes during 1976-1998.**

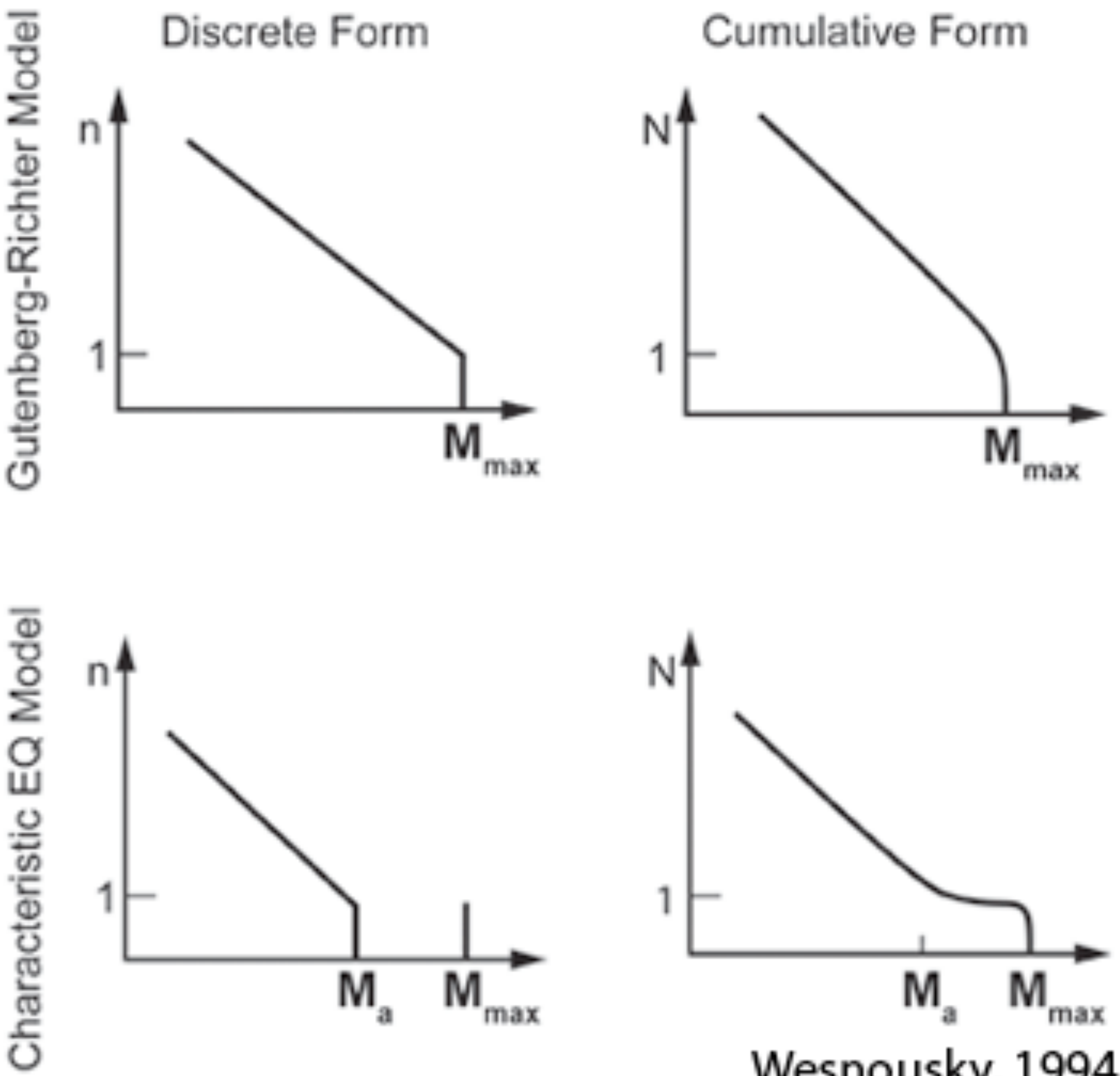


# GR & Characteristic

Two end-member models can explain the G-R statistics:

- Each fault exhibits its own G-R distribution of earthquakes.

- There is a power-law distribution of fault lengths, with each fault exhibiting a characteristic distribution.



Wesnousky, 1994

- For a statistically meaningful population of faults, the distribution is often consistent with the G-R relation.

- For a single fault, on the other hand, the size distribution is often characteristic.

- Note that the extrapolation of the b-value inferred for small earthquakes may result in under-estimation of the actual hazard, if earthquake size-distribution is characteristic rather than power-law.