Lecture 1 : Introduction to earthquakes.
Keys points of today's lecture

- Earthquakes occur on « locked » faults (elastic rebound)

- Most of the magnitude scales saturate

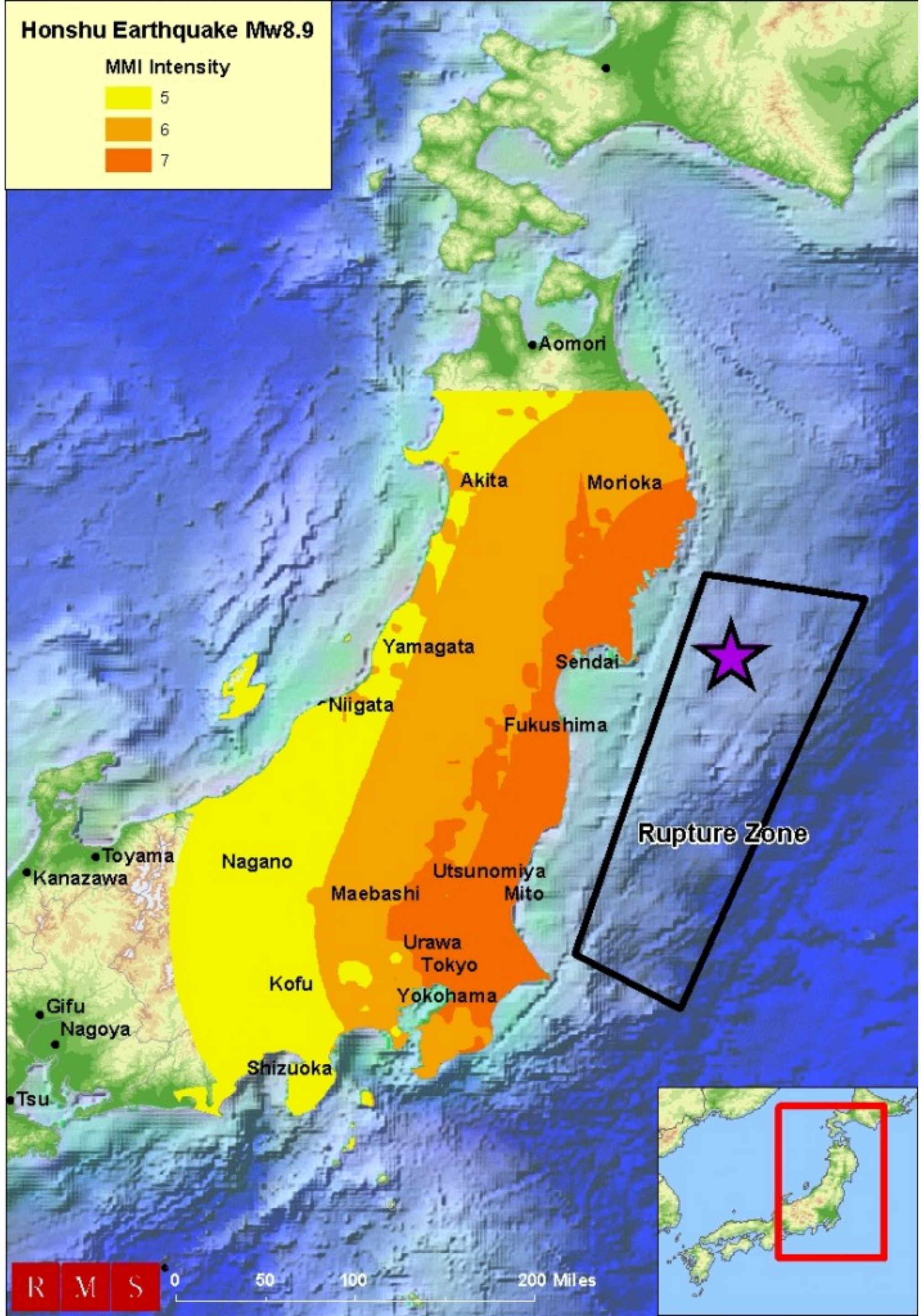
- Case studies : San Francisco 2006, Tohoku 2011

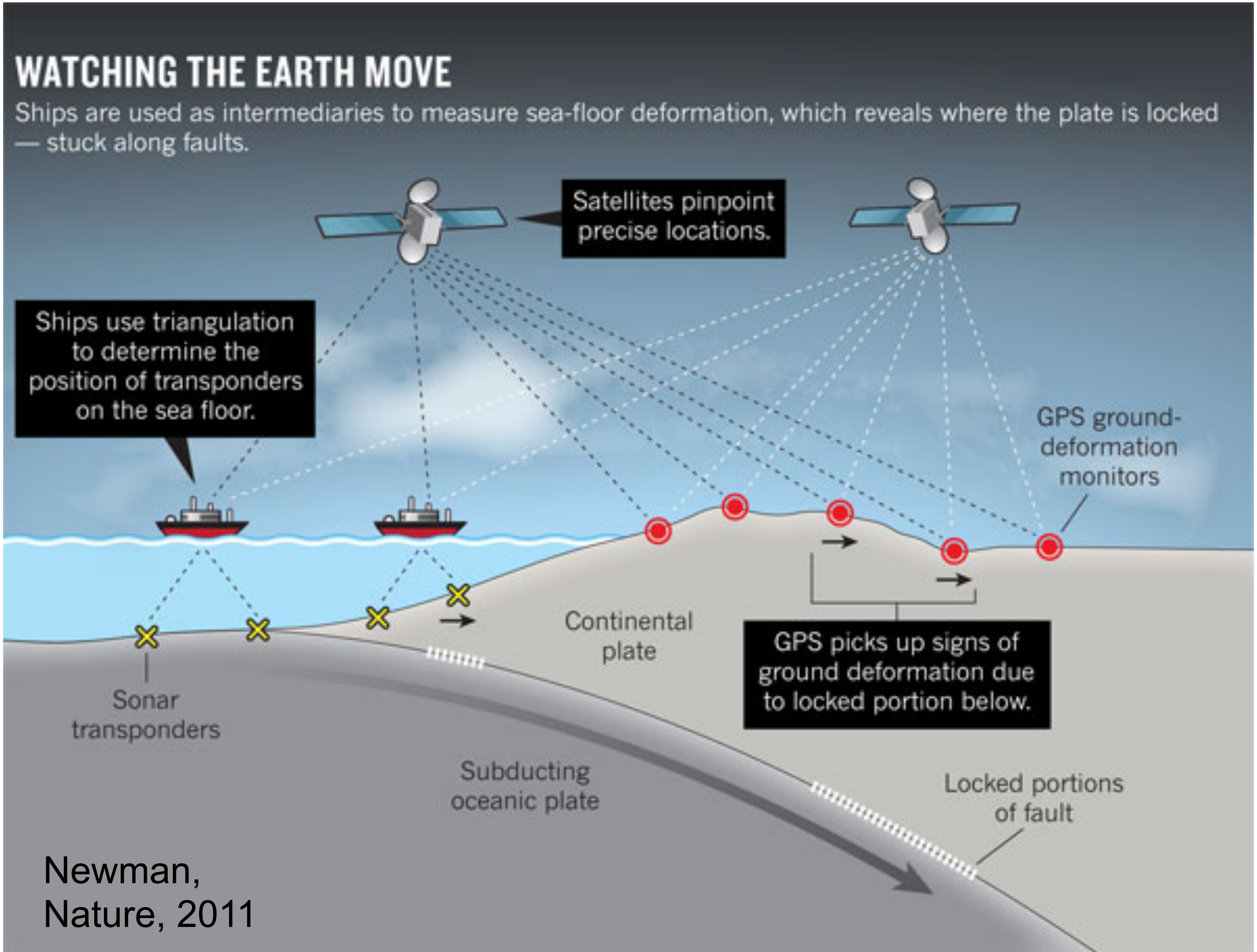
References

Stein and Wysession. 2003. Chapter 4.

Lay et Wallace. Modern Global Seismology. P 364-374

Elastic rebound

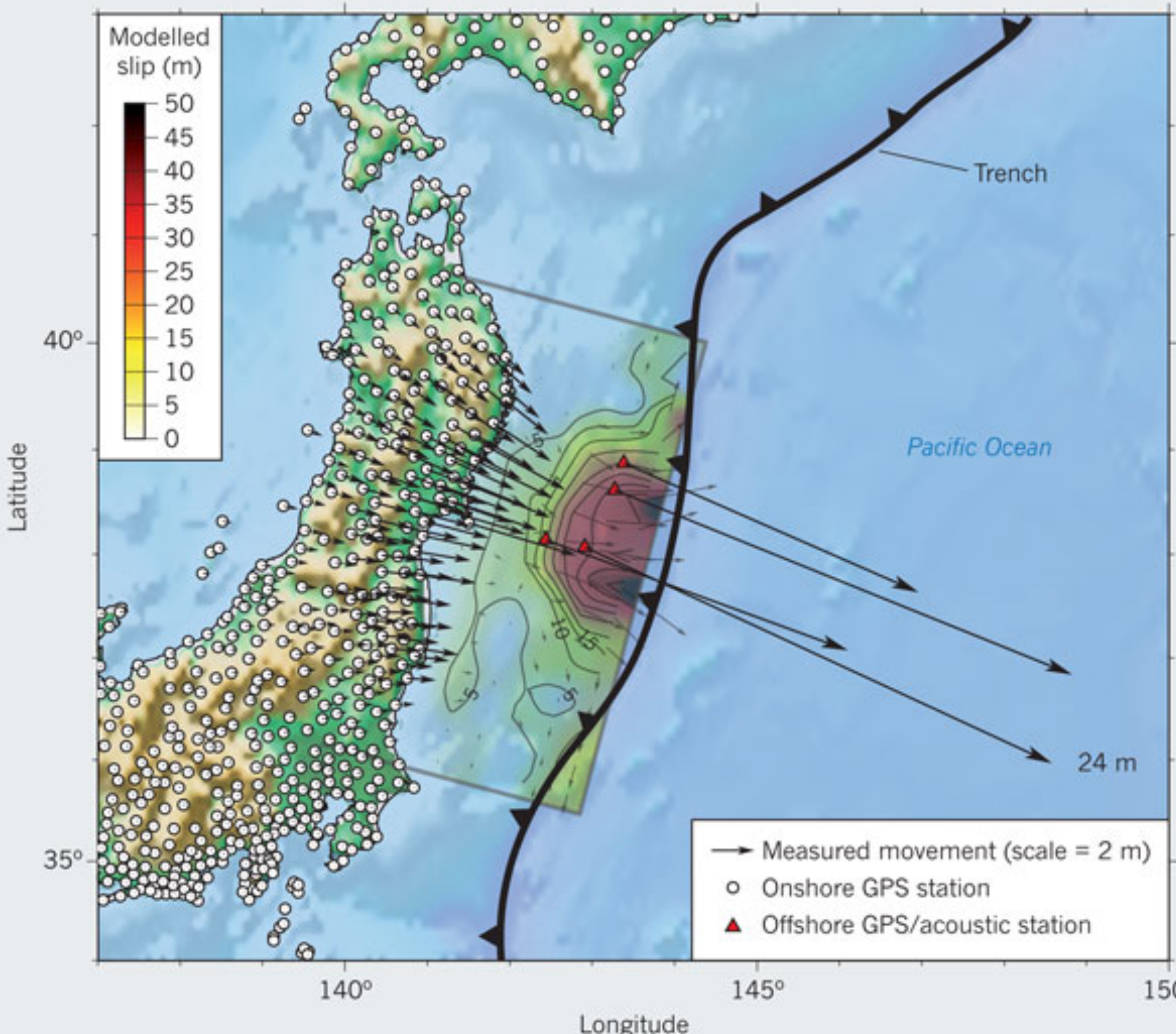

Honshu Earthquake Mw8.9
MMI Intensity
5
6
7
Aomori
Akita
Morioka
Yamagata
Sendai
Niigata
Fukushima
Rupture Zone
Toyama
Kanazawa
Nagano
Utsunomiya
Maebashi
Mito
Urawa
Tokyo
Kofu
Yokohama
Gifu
Nagoya
Shizuoka
Tsu
R M S
0
50
100
200 Miles



Newman, Nature, 2011

LOPSIDED MEASURES

Most of the action during the 11 March 2011 tsunami-forming earthquake that hit Japan was offshore, but the vast majority of ground-deformation sensors are on land.

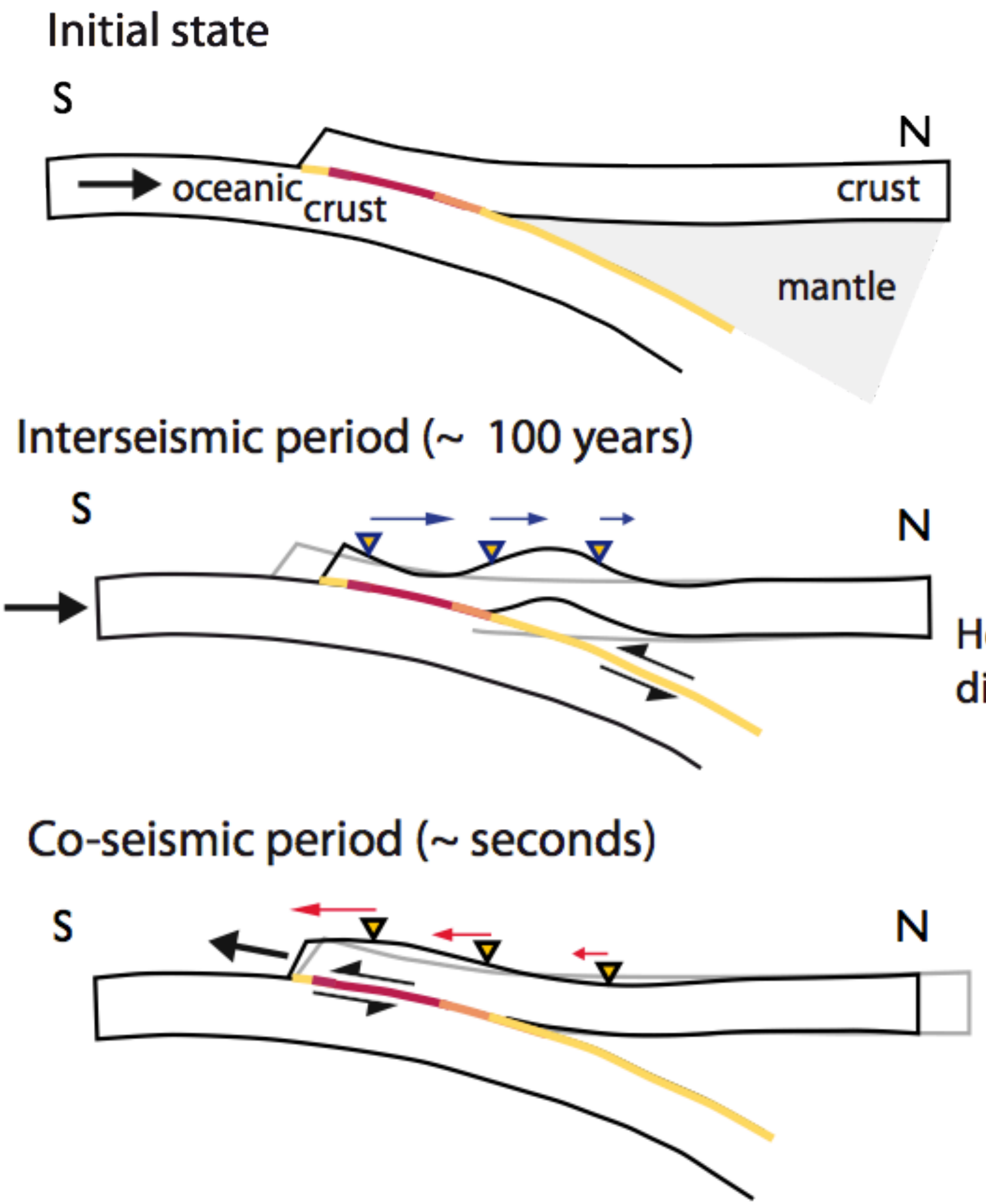


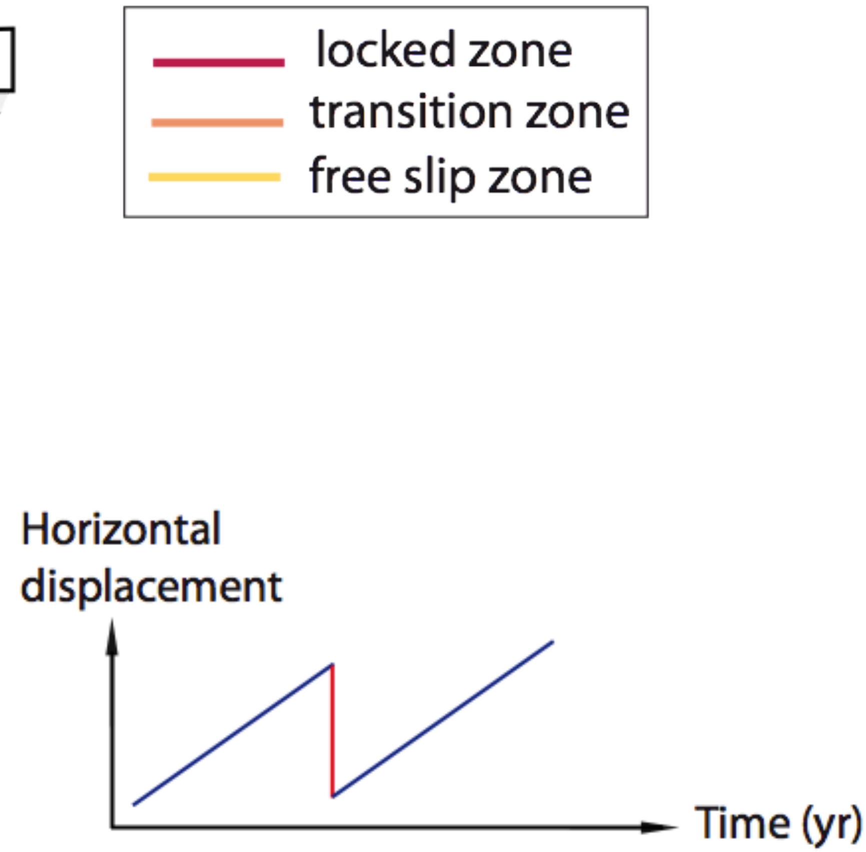
Newman, Nature, 2011

40 meters of slip

Mw=9

Seismic cycle (subduction)

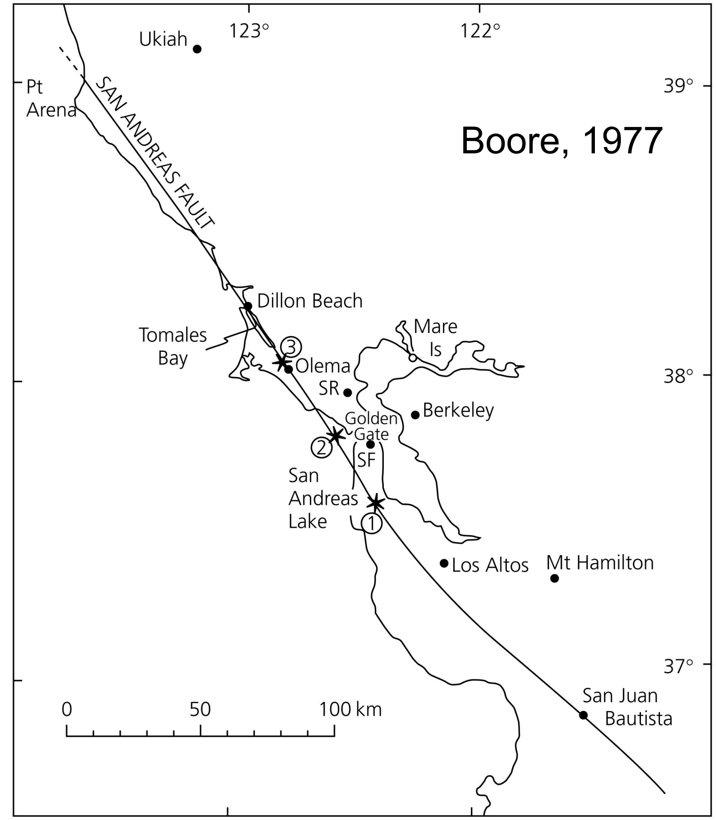


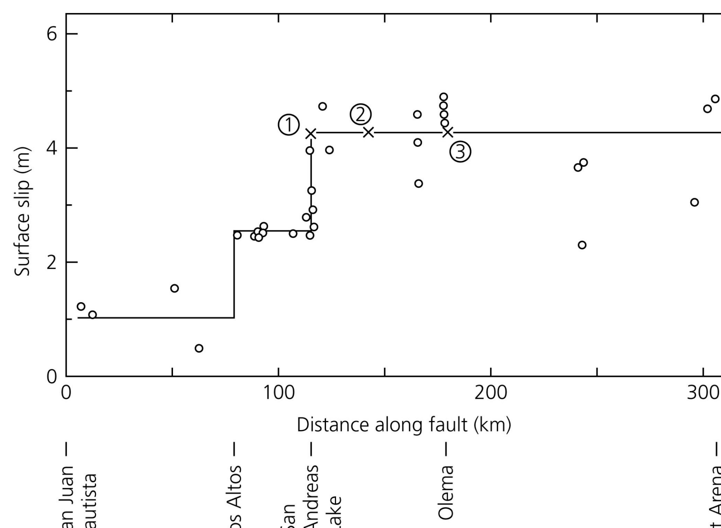


1906 SAN FRANCISCO EARTHQUAKE (magnitude 7.8)

~ 4 m of slip on 450 km of San Andreas
~2500 deaths, ~28,000 buildings destroyed (most by fire)

Catalyzed ideas about relation of earthquakes & surface faults





Source : S. Stein

SEISMIC CYCLE AND PLATE MOTION

Over time, slip in earthquakes adds up and reflects the plate motion

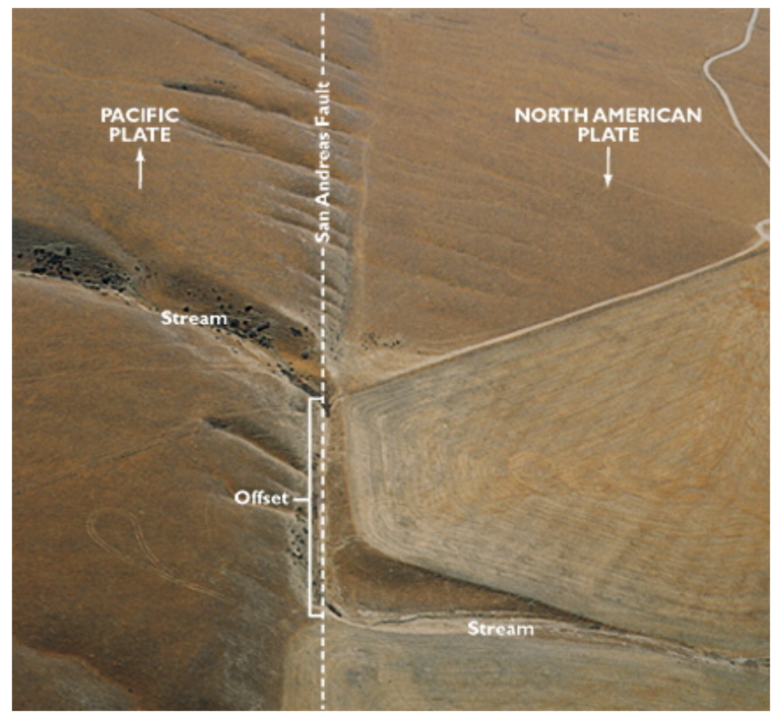
Offset fence showing 3.5 m of left-lateral strike-slip motion along San Andreas fault in 1906 San Francisco earthquake

~ 35 mm/yr motion between Pacific and North American plates along San Andreas shown by offset streams & GPS

Expect earthquakes on average every ~ (3.5 m)/ (35 mm/yr) =100 years

Turns out more like 200 yrs because not all motion is on the San Andreas

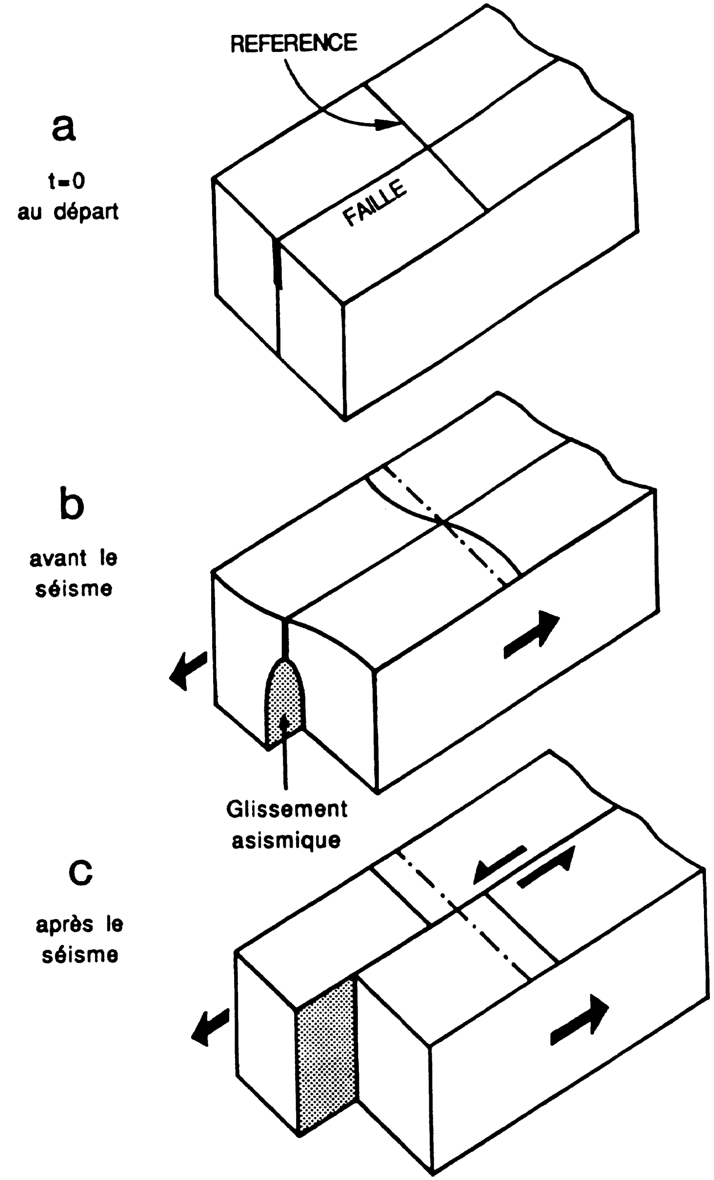
Moreover, it's irregular rather than periodic



Source : S. Stein

Elastic rebound

This fence running across the San Andreas fault in Marin County was offset 8.5 ft in the 1906 San Francisco earthquake as the land on the far side of the fault moved to the right.



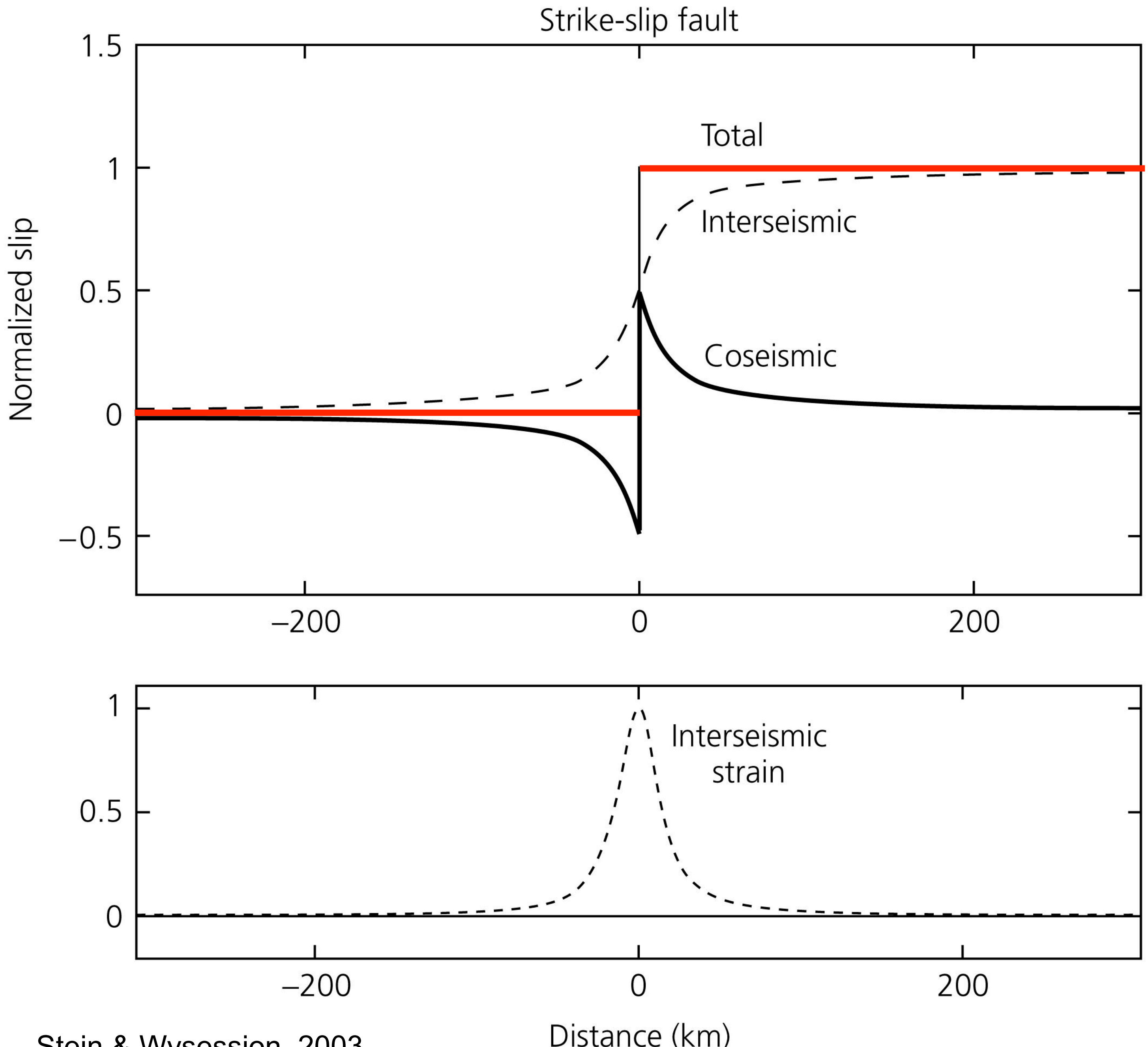
Sources : Kramer, Geotechnical Earthquake Engineering (haut, gauche)
Bolt, Earthquake and Geological Discovery, 1993 (bas, gauche)
Madariaga et Perrier, Les tremblements de terre, 1991 (droite)

Figure 4.5-12: Coseismic and interseismic slips and strains.

Large earthquakes release all strain accumulated on locked fault between earthquakes

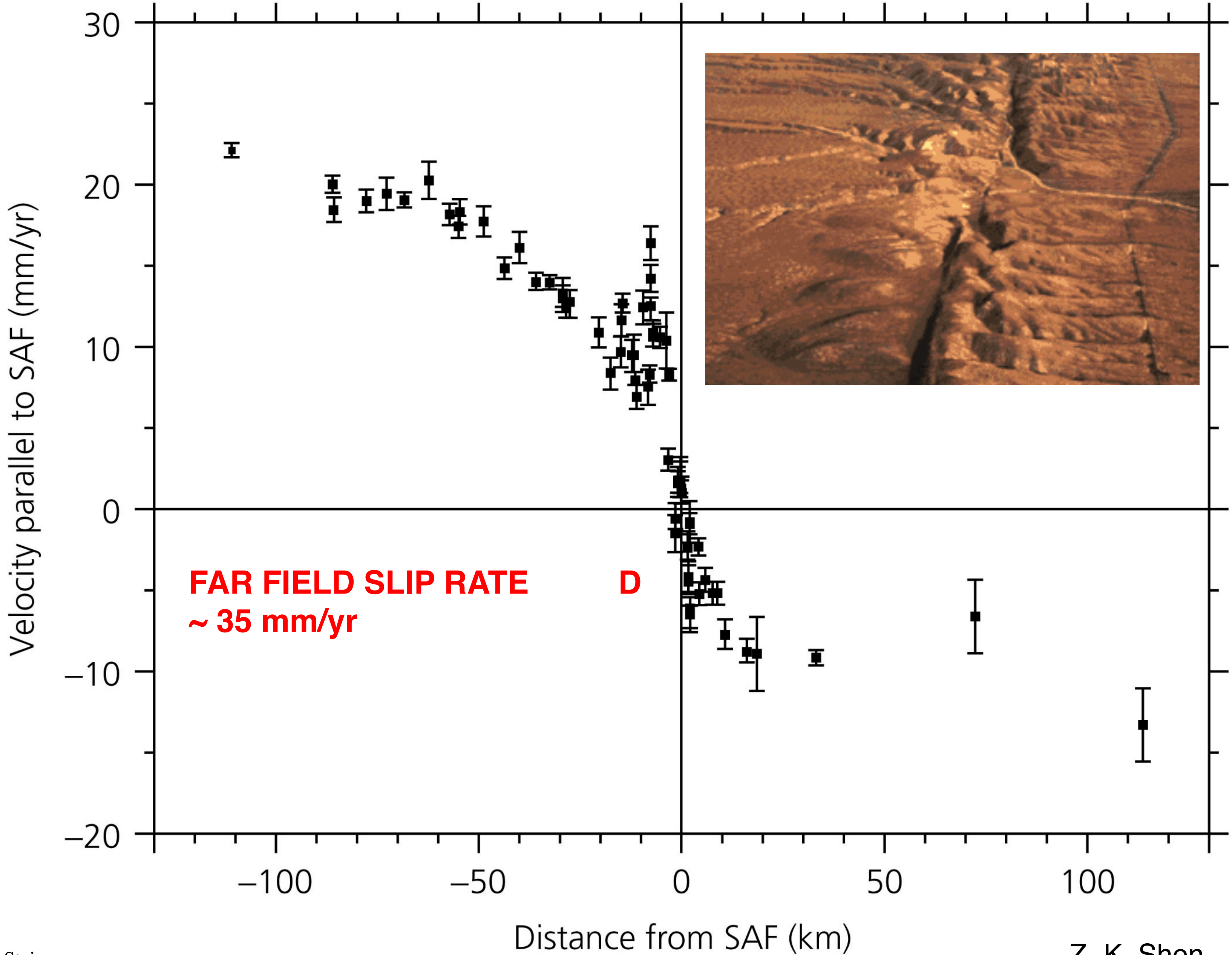
Coseismic and interseismic motion sum to plate motion

Interseismic strain accumulates near fault



Stein & Wysession, 2003

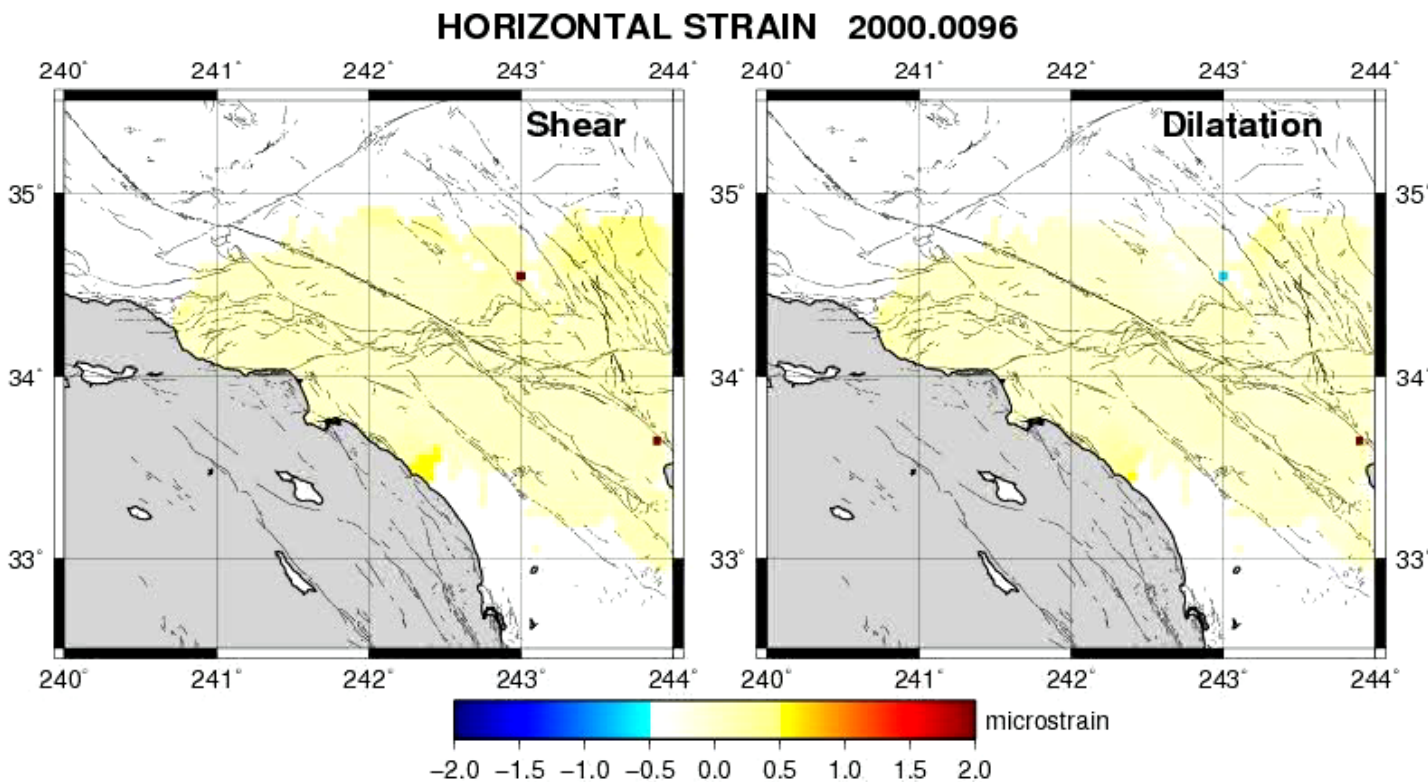
Figure 4.5-13: Fault-parallel horizontal interseismic motion across the San Andreas fault.



Source : S. Stein

Z.-K. Shen

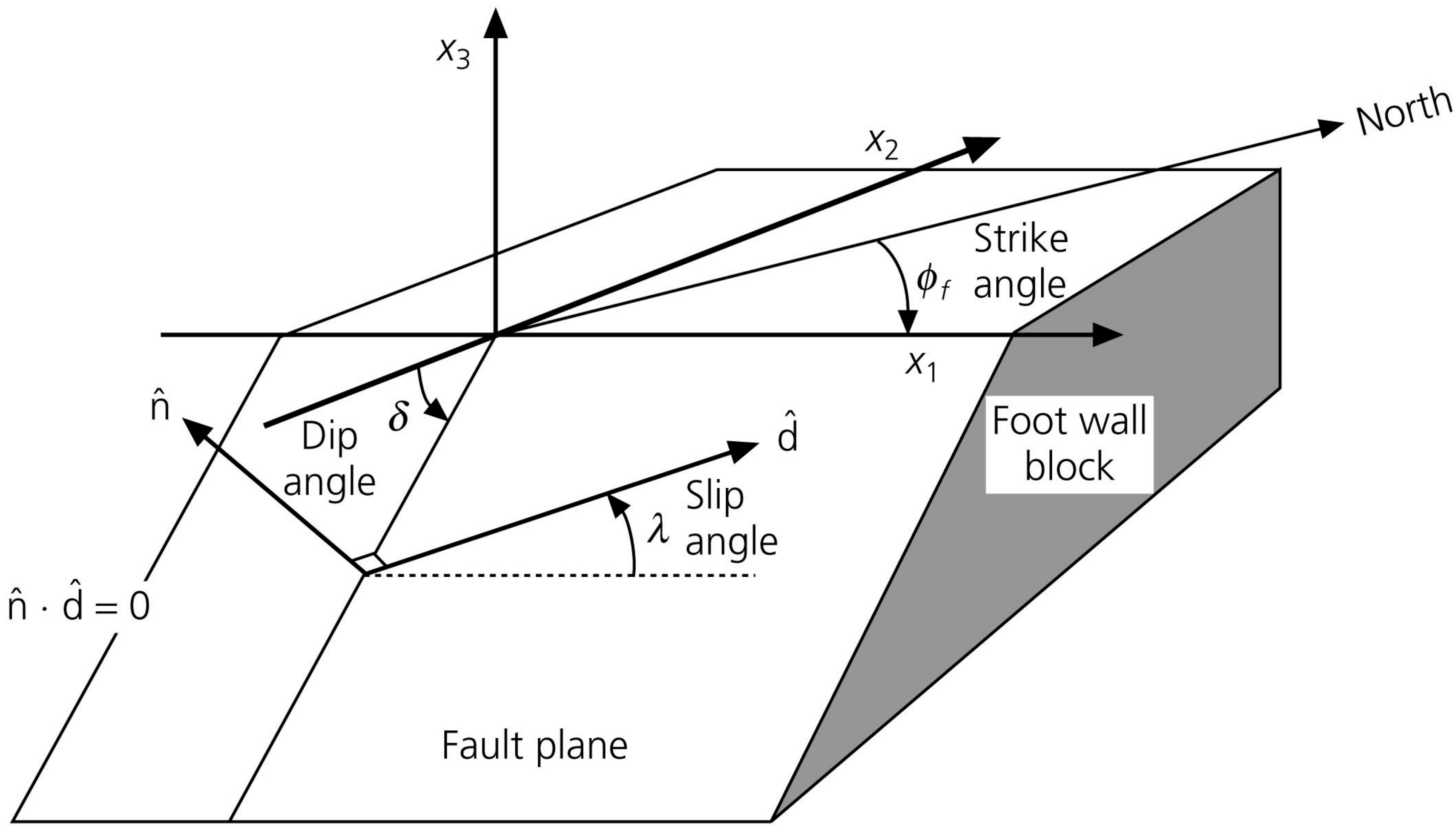
Deformation from GPS



Fault movement and fault geometry

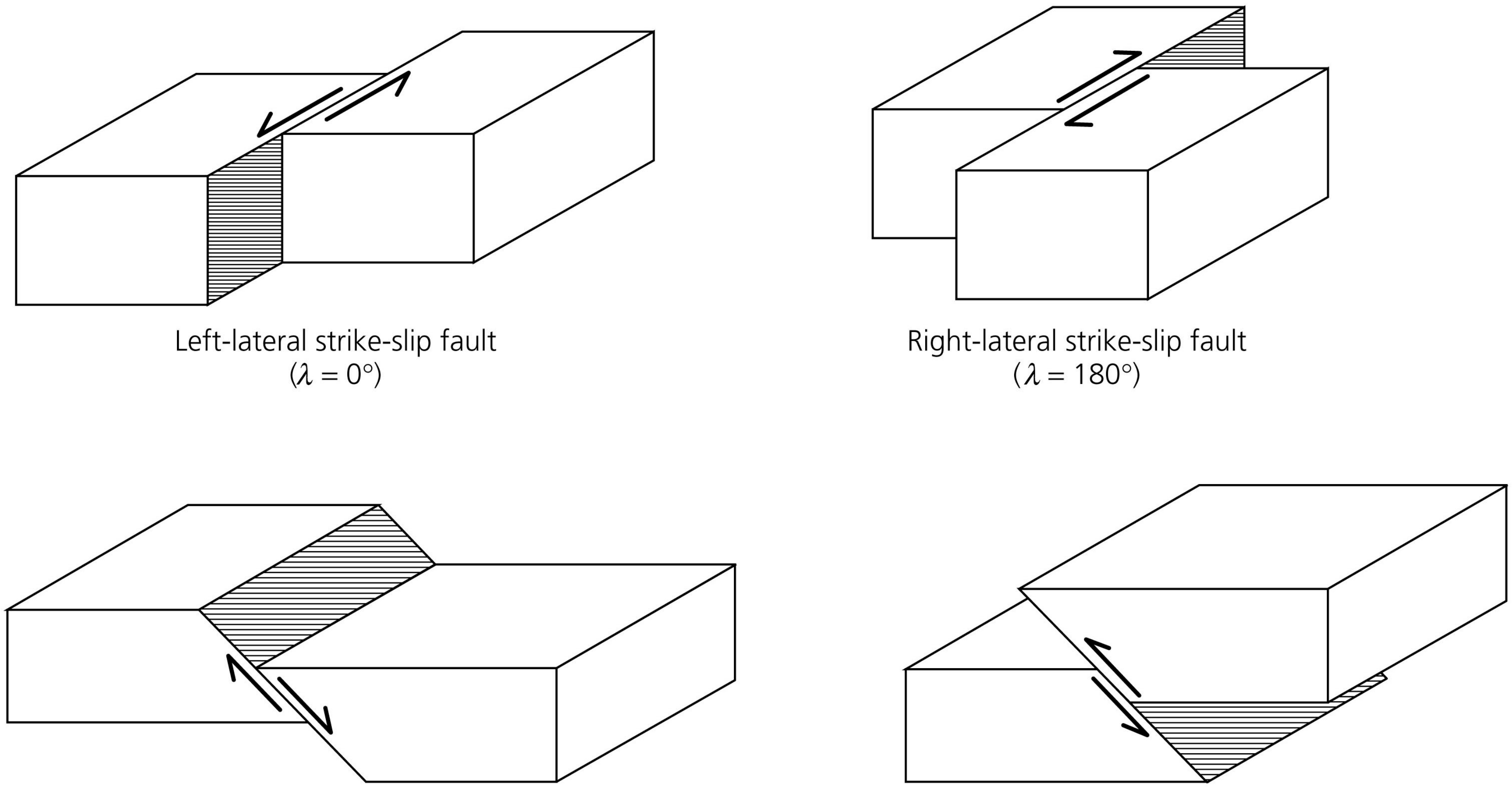
- The slip vector indicates the direction in which the upper side of the fault (hanging wall block) moved with respect to the lower side (the footwall block)

Figure 4.2-2: Fault geometry used in earthquake studies.



Sources: Stein et Wysession

Figure 4.2-3: Basic types of faulting.



Left-lateral strike-slip fault
($\lambda = 0°$)

Right-lateral strike-slip fault
($\lambda = 180°$)

Normal dip-slip fault
($\lambda = -90°$)

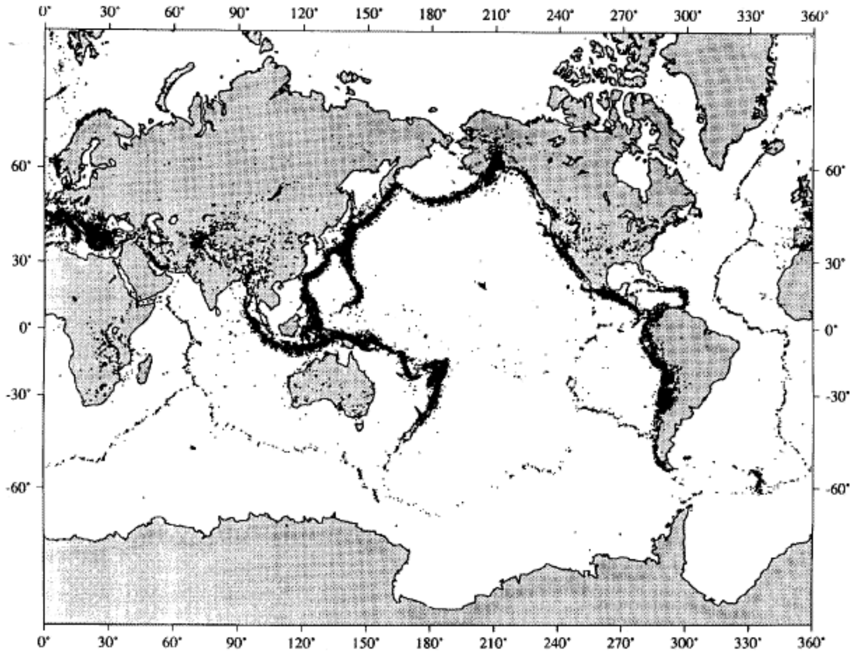
Reverse dip-slip fault
($\lambda = 90°$)

Sources: Stein et Wysession

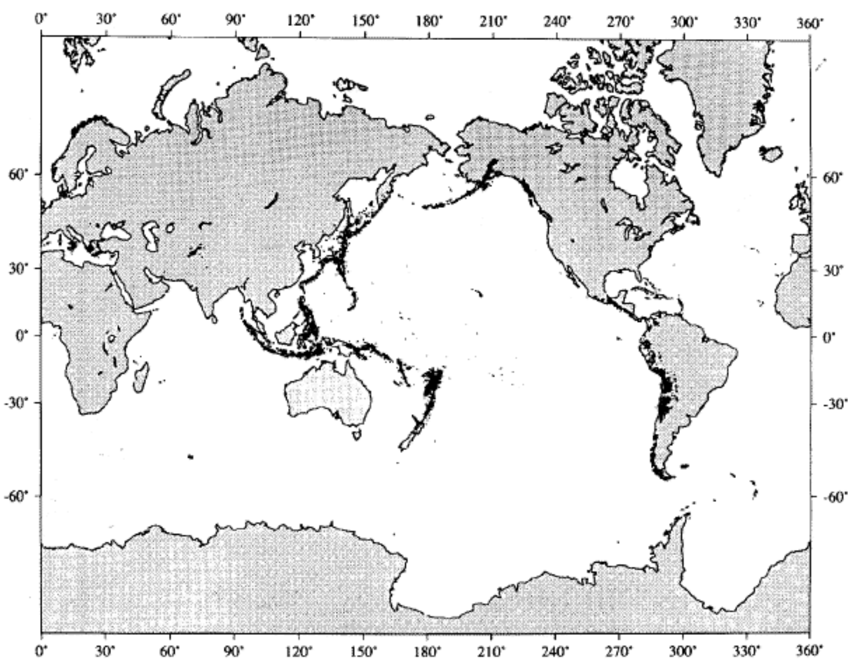
Earthquake localization

- Monitoring of current activity
- Hazard assessment
- Spatial distribution: focal mechanisms, earth´s structure

Global earthquake distribution 1970 – 1980



Source depth < 100 km



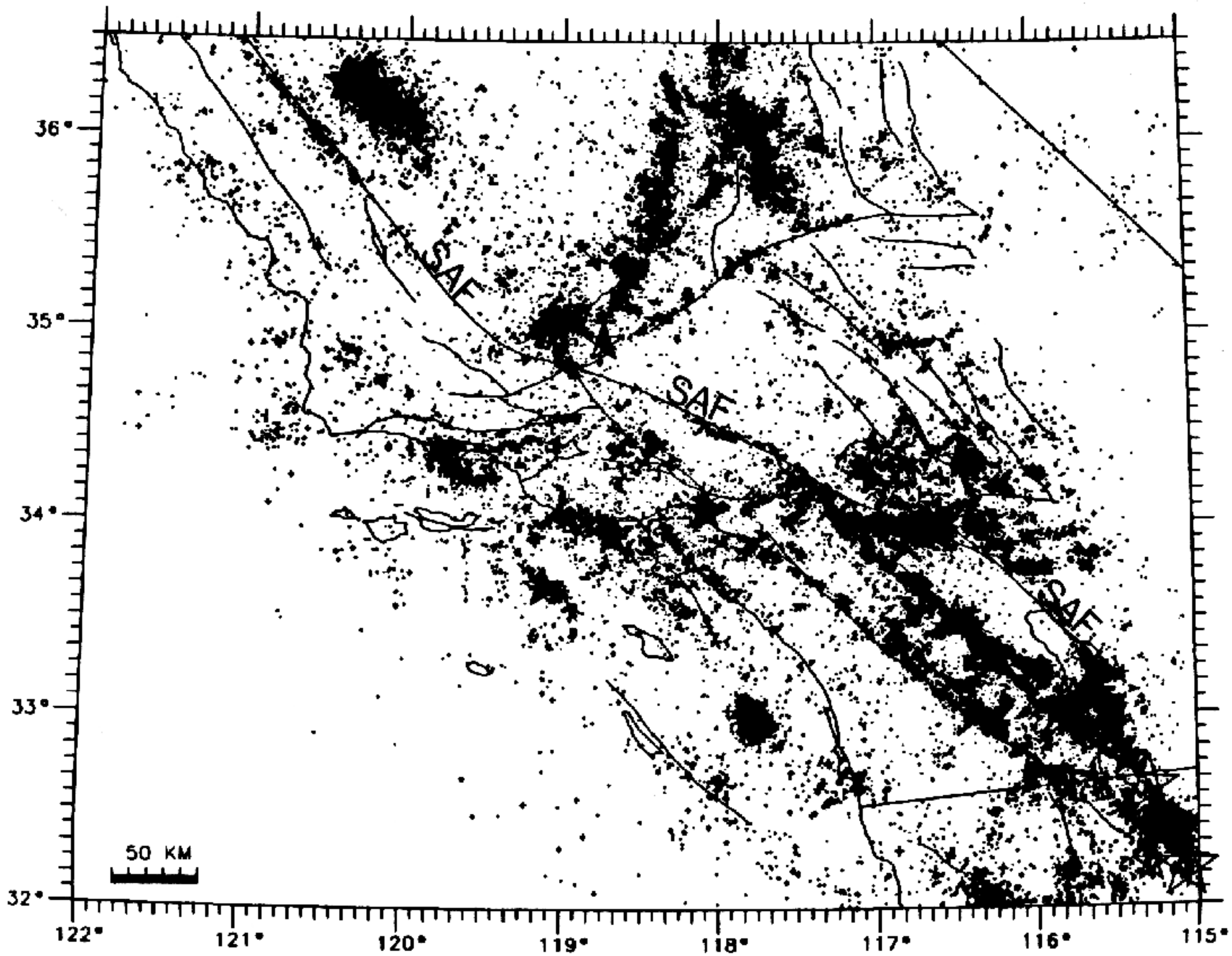
Source depth from 100 to 700 km

Courtesy of F. Scherbaum's lecture notes

→ Earthquakes mark plate boundaries

→ Deep earthquakes only at subduction zones

⇒ Earthquake distribution greatly contributed to development of plate tectonics



Regional scale: earthquake locations in Southern California 1978 – 1988 & active faults

Courtesy of F. Scherbaum's lecture notes

→ Complicated fault pattern

→ Identification partly only through weak earthquakes

⇒ **Localization = first step of any earthquake analysis**

Courtesy of F. Scherbaum's lecture notes

Starting point: onset times of seismic waves

Time from source to station: traveltime

Localization method depends on station number and distribution:

1) Single station
2) Station network
3) Station array

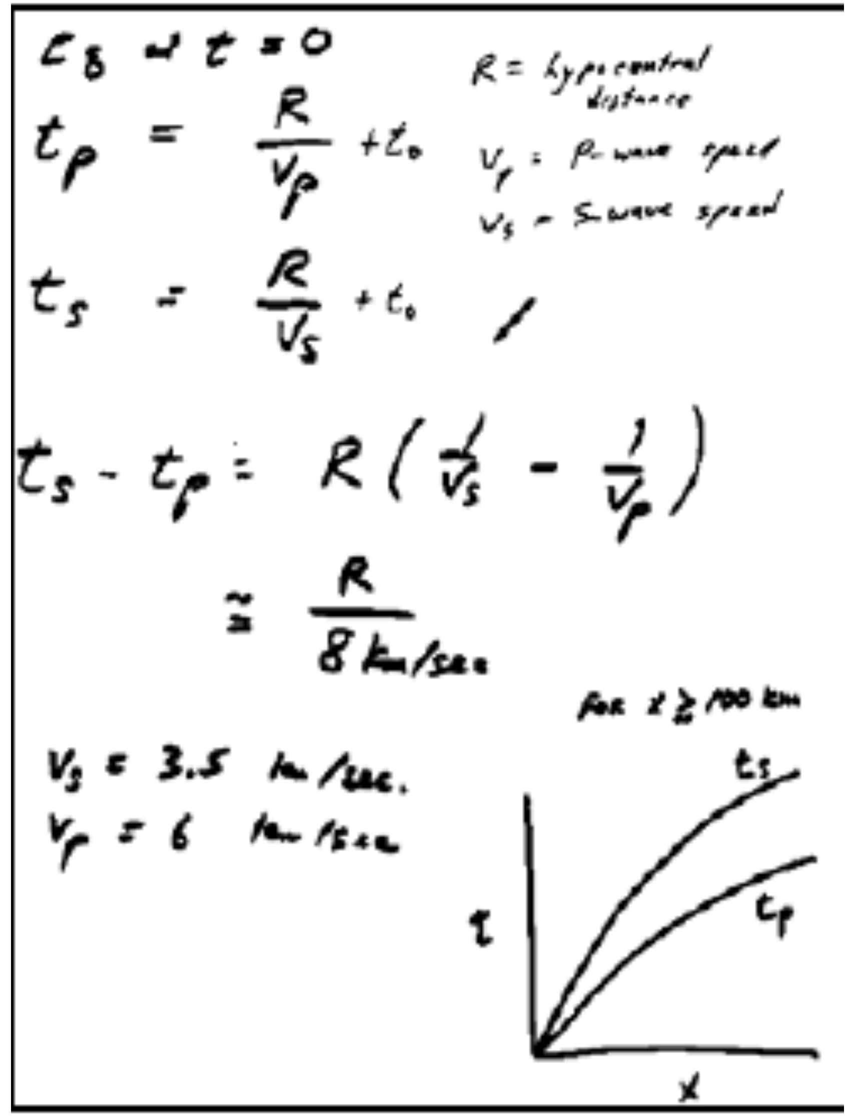
Dissertation topic…

How to estimate the distance?

Use the relative speed of the P- and the S-waves.

The Figure shows the simple math behind the process.

This is the origin of the rule of thumb used by seismologists for local earthquakes: multiply the s-p time (in sec) by 8 km/s, to get the approximate distance from the station to the epicenter.



Quantification of earthquake strength

Different approaches:

- Based on effects: **Intensity**
- Based on focal strength : **Magnitude**

Courtesy of F. Scherbaum's lecture notes

Principle of intensity measure

- Low: Human effects
- Intermediate: Building effects
- High: Change in landscape

Intensity

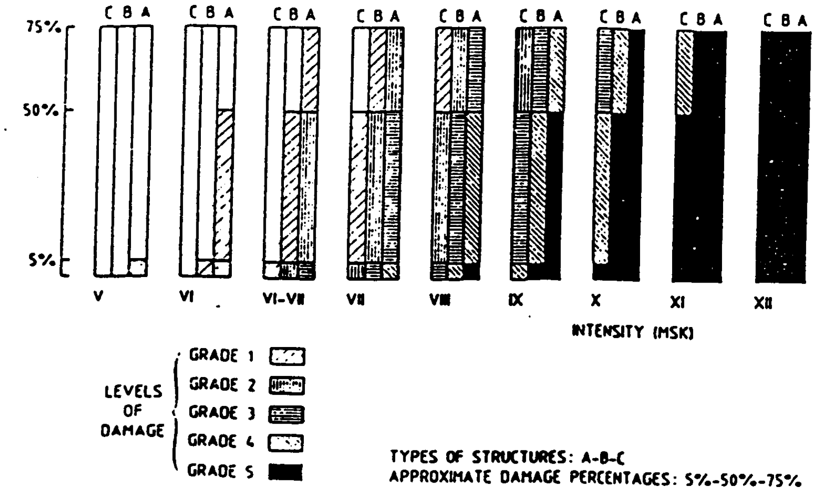


Fig.2. Progression of damage to buildings in the MSK intensity scale.

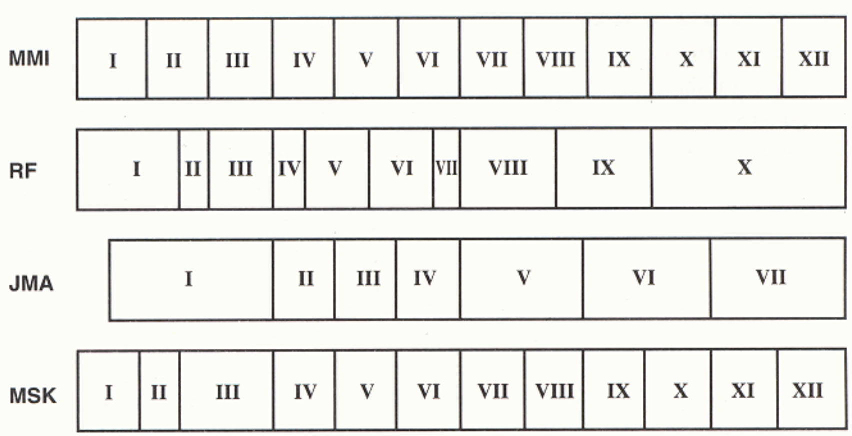


Figure 2.27 Comparison of intensity values from modified Mercalli (MMI), Rossi–Forel (RF), Japanese Meteorological Agency (JMA), and Medvedev–Spoonheuer–Karnik (MSK) scales. (After Richter (1958) and Murphy and O'Brien (1977).)

Kramer, Geotechnical Earthquake Engineering, 1997

Modified Mercalli Intensity Scale

I. People do not feel any Earth movement.

II. A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.

III. Many people indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.

IV. Most people indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement. Parked cars rock.

V. Almost everyone feels movement. Sleeping people are awakened. Doors swing open or close. Dishes are broken. Pictures on the wall move. Small objects move or are turned over. Trees might shake. Liquids might spill out of open containers.

VI. Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. No structural damage.

VII. People have difficulty standing. Drivers feel their cars shaking. Some furniture breaks. Loose bricks fall from buildings. Damage is slight to moderate in well-built buildings; considerable in poorly built buildings.

VIII. Drivers have trouble steering. Houses that are not bolted down might shift on their foundations. Tall structures such as towers and chimneys might twist and fall. Well-built buildings suffer slight damage. Poorly built structures suffer severe damage. Tree branches break. Hillsides might crack if the ground is wet. Water levels in wells might change.

IX. Well-built buildings suffer considerable damage. Houses that are not bolted down move off their foundations. Some underground pipes are broken. The ground cracks. Reservoirs suffer serious damage.

X. Most buildings and their foundations are destroyed. Some bridges are destroyed. Dams are seriously damaged. Large landslides occur. Water is thrown on the banks of canals, rivers, lakes. The ground cracks in large areas. Railroad tracks are bent slightly.

XI. Most buildings collapse. Some bridges are destroyed. Large cracks appear in the ground. Underground pipelines are destroyed. Railroad tracks are badly bent.

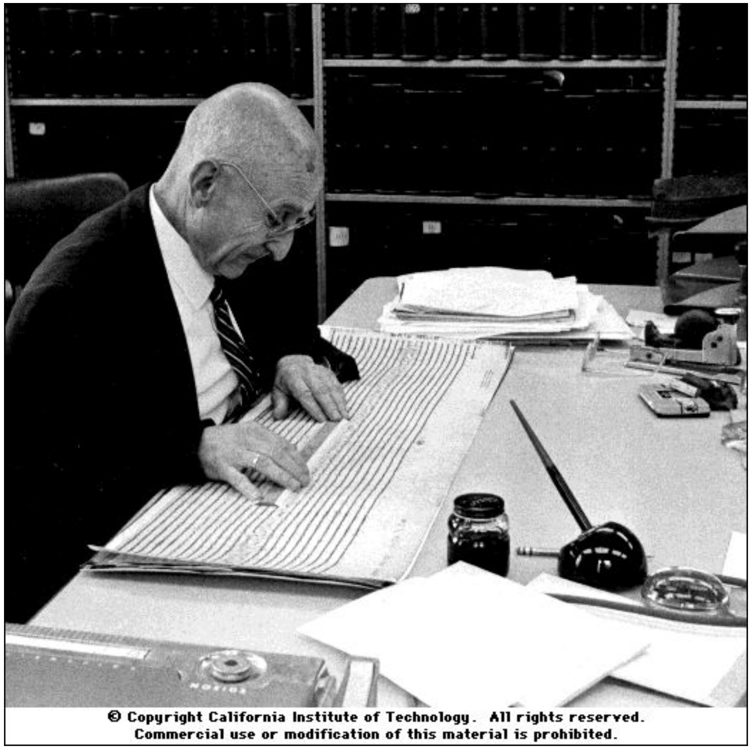
XII. Almost everything is destroyed. Objects are thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.

Problems:

- Many influences: focal strength, distance, attenuation, direction to focus, site effects
- Damages are sometimes secundary effects
- Significant only in densely populated areas

Strength classification **in the focus : Magnitude**

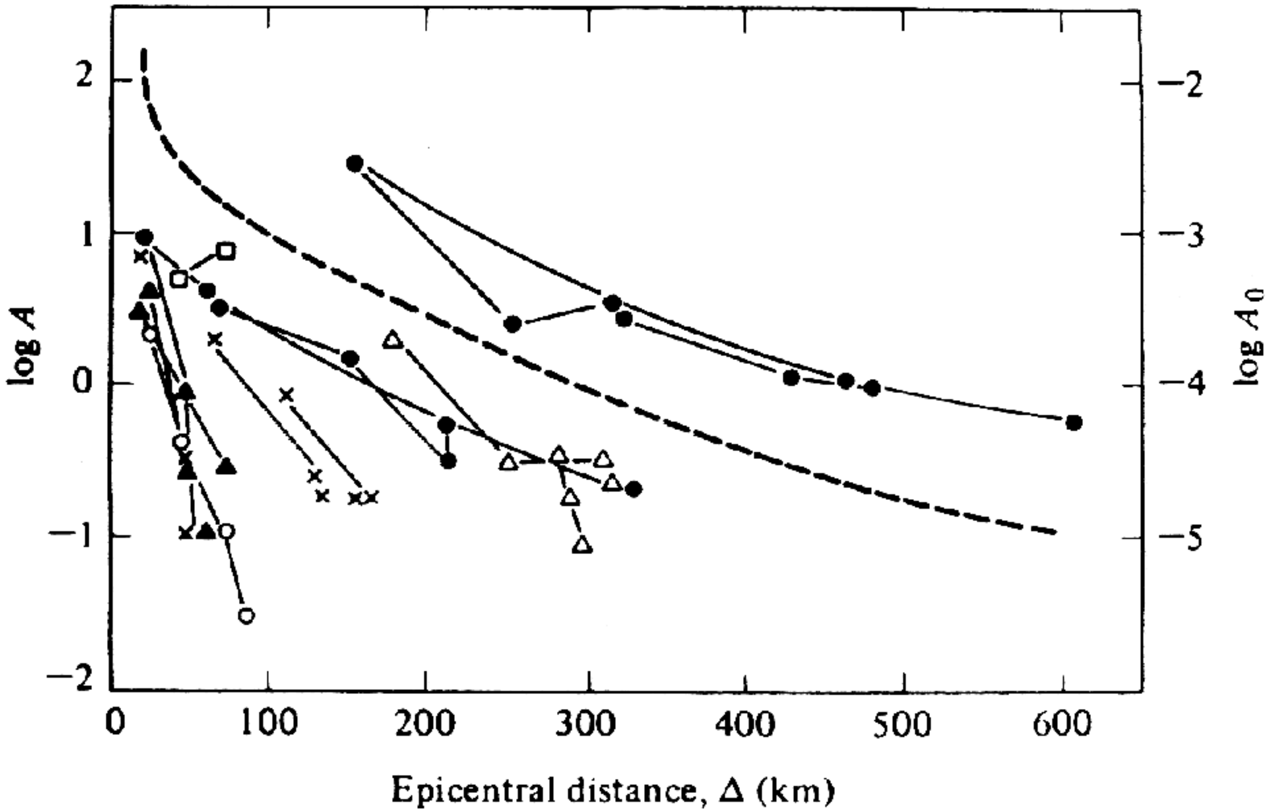
The fathers of magnitudes



B. Gutenberg C. F. Richter

Courtesy of F. Scherbaum's lecture notes

Richter (1935)



Amplitude - distance relations for Southern California earthquakes

- Amplitude ratios widely independent of measurement site

= basis of local magnitude scale

Magnitude M_L

- C. F. Richter was the first person to define the magnitude of an earthquake.
- The magnitude was defined from measurements taken using a Wood Anderson seismogram.
- All subsequent magnitude scales are defined using the same principle.

Local magnitude

$$M_L = \log\left[\frac{\text{Amplitude of this earthquake}}{\text{Amplitude of reference earthquake}}\right]$$

$$M_L = \log\left[\frac{A}{A_0(R)}\right] = \log A - \log A_0(R)$$

Both amplitudes are measured peak amplitudes in mm from a standard Wood-Anderson seismogram.

The amplitude of the reference earthquake is taken at the same distance.

The **reference earthquake:** ML=3.0, A= 1.0 mm at R= 100 km**.**

$$M_L = \log\left(\frac{A}{A_o}\right)$$

$$A = A_o 10^{M_L}$$

Magnitude de Richter

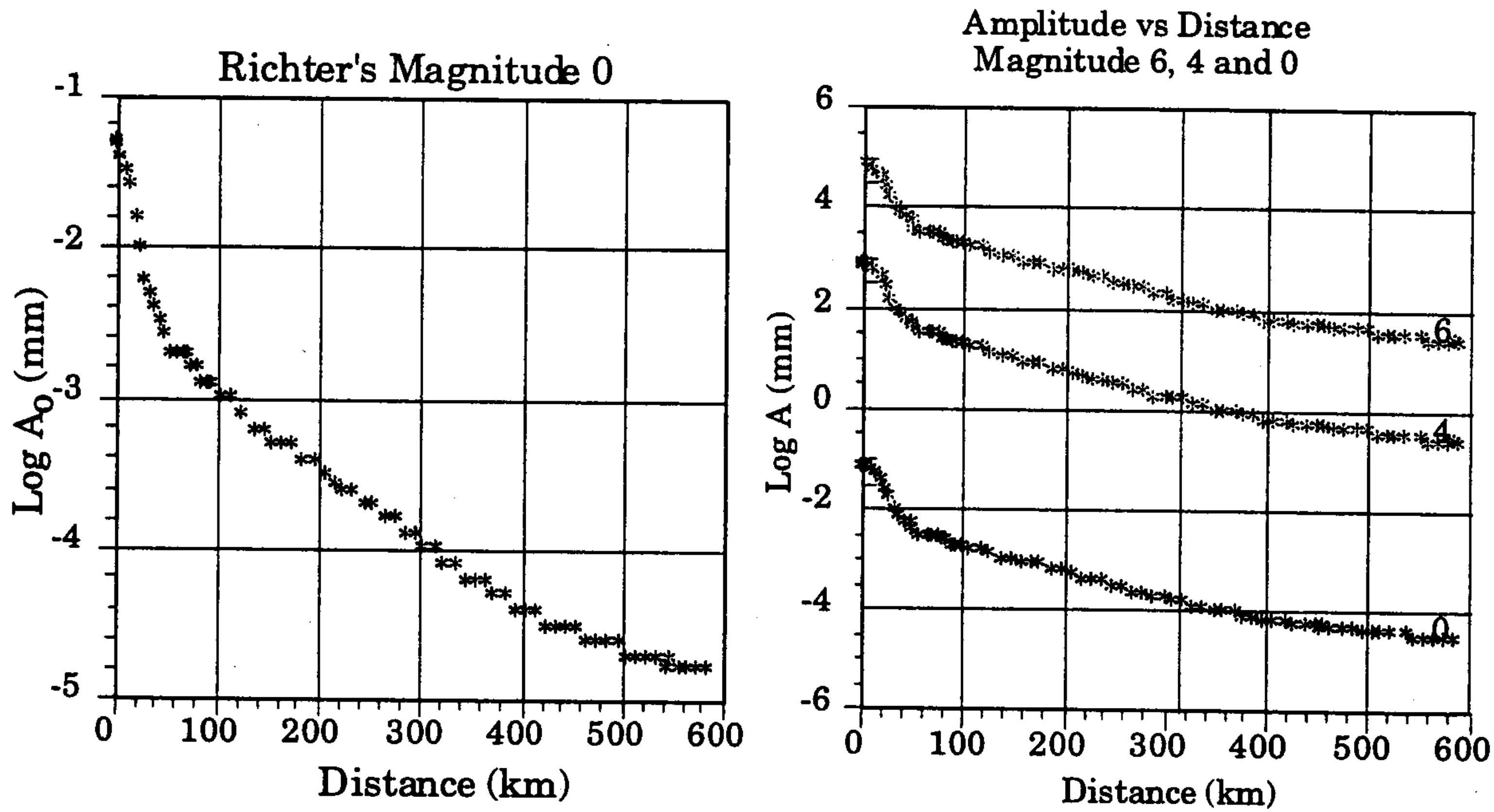


Figure 2-12. Amplitude versus distance for a M_L 0 earthquake (left) and for M_L 0, 4 and 6 earthquakes on the right. Note that magnitude is given on a logarithmic scale. A change in magnitude is simply a shift of the M_L 0 curve.

Source : Archuleta et al., 1997

EARTHQUAKE MAGNITUDE

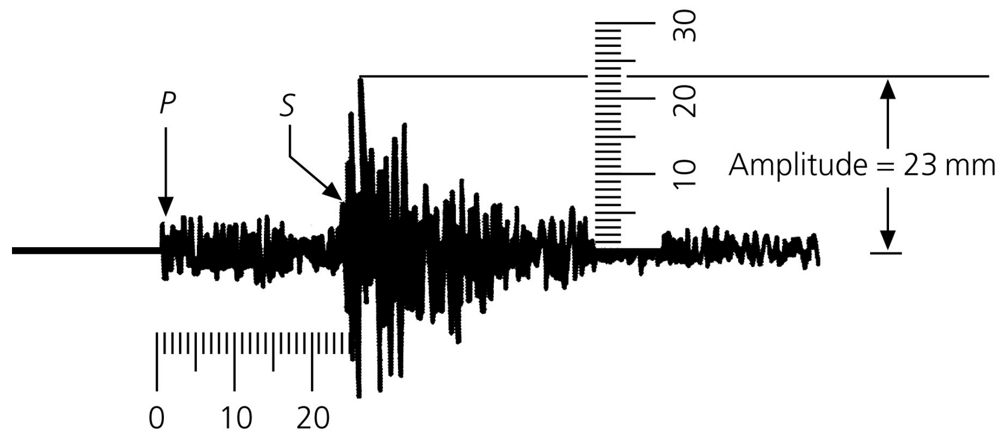
Earliest measure of earthquake size

Dimensionless number measured various ways, including

M_L local magnitude
m_b body wave magnitude
M_s surface wave magnitude
M_w moment magnitude

Easy to measure

Empirical - except for M_w, no direct tie to physics of faulting



General form of Magnitude scales:

$$M = \log(A/T) + F(h, \Delta) + C$$

A is the amplitude of the signal

T is its dominant period

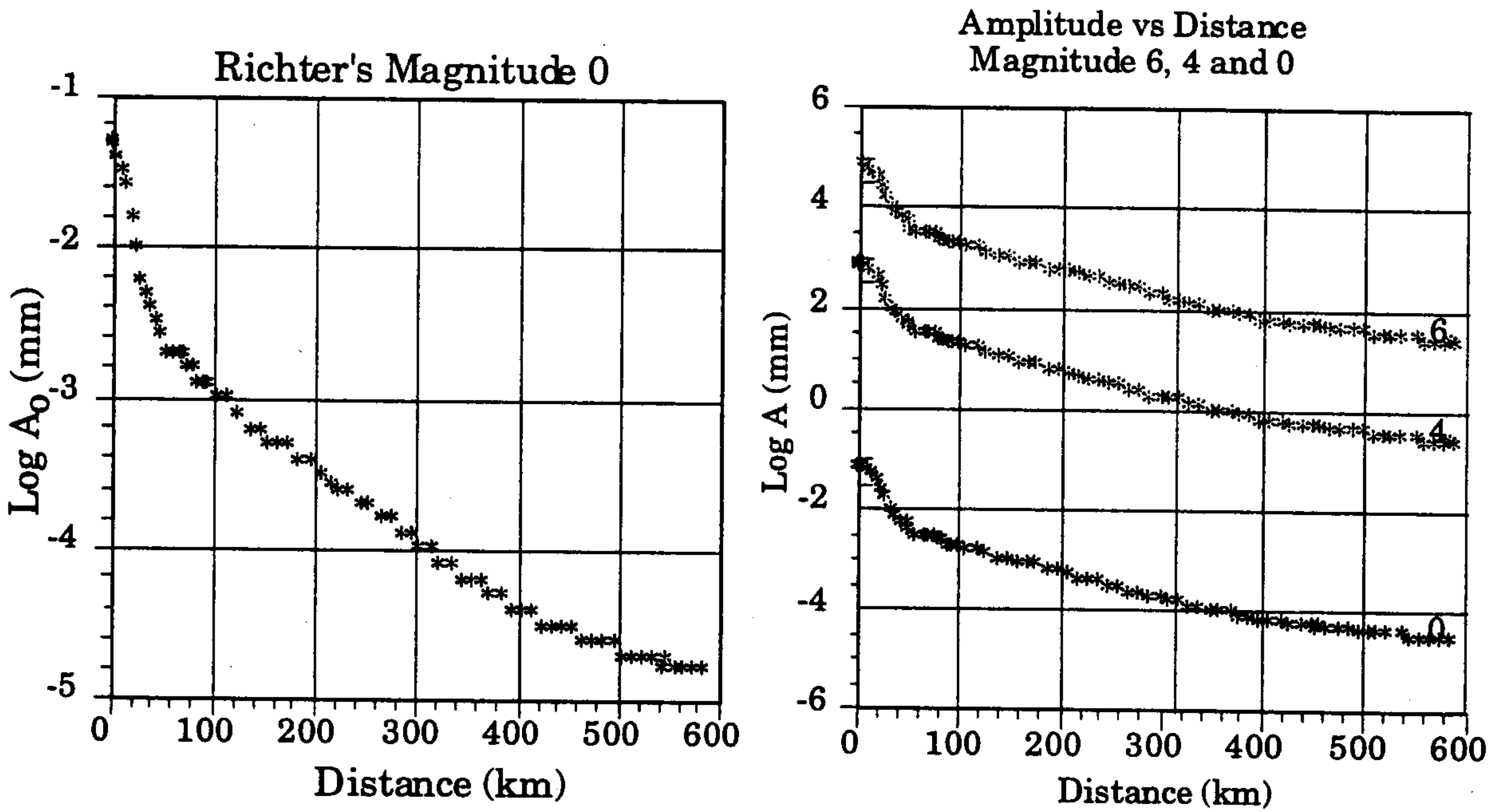
F is a correction for the variation of amplitude with the earthquake's depth h and distance Δ from the seismometer

C is a regional scale factor

$$M_L = \log\left(\frac{A}{A_o}\right)$$

$$A = A_o\,10^{M_L}$$

Magnitude de Richter



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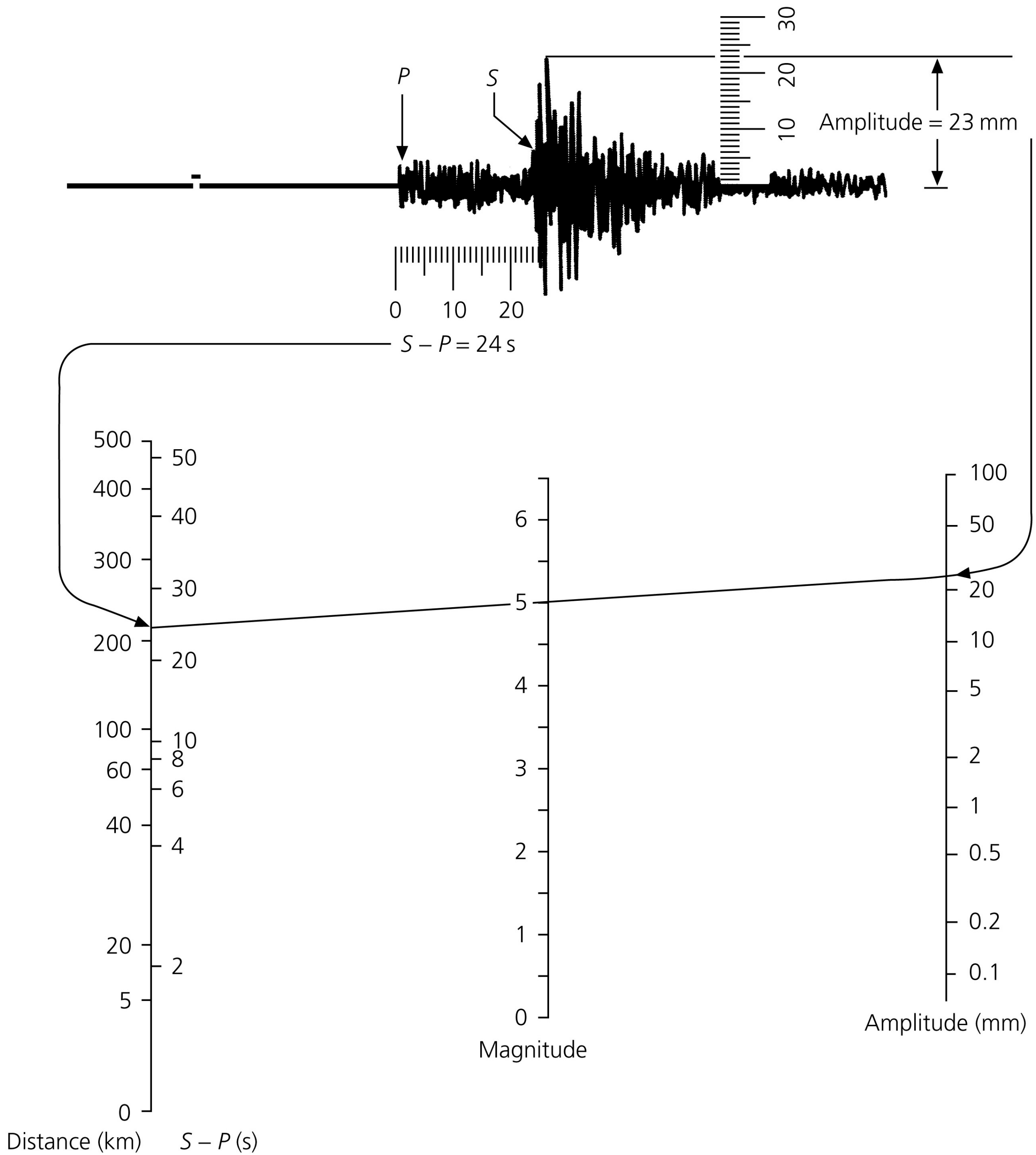
Source : Archuleta et al., 1997

Figure 4.6-1: Example of the determination of the Richter scale.



$$A(x,t) = A_o e^{-\pi f R / v_s Q(f)}$$

Anelastic attenuation

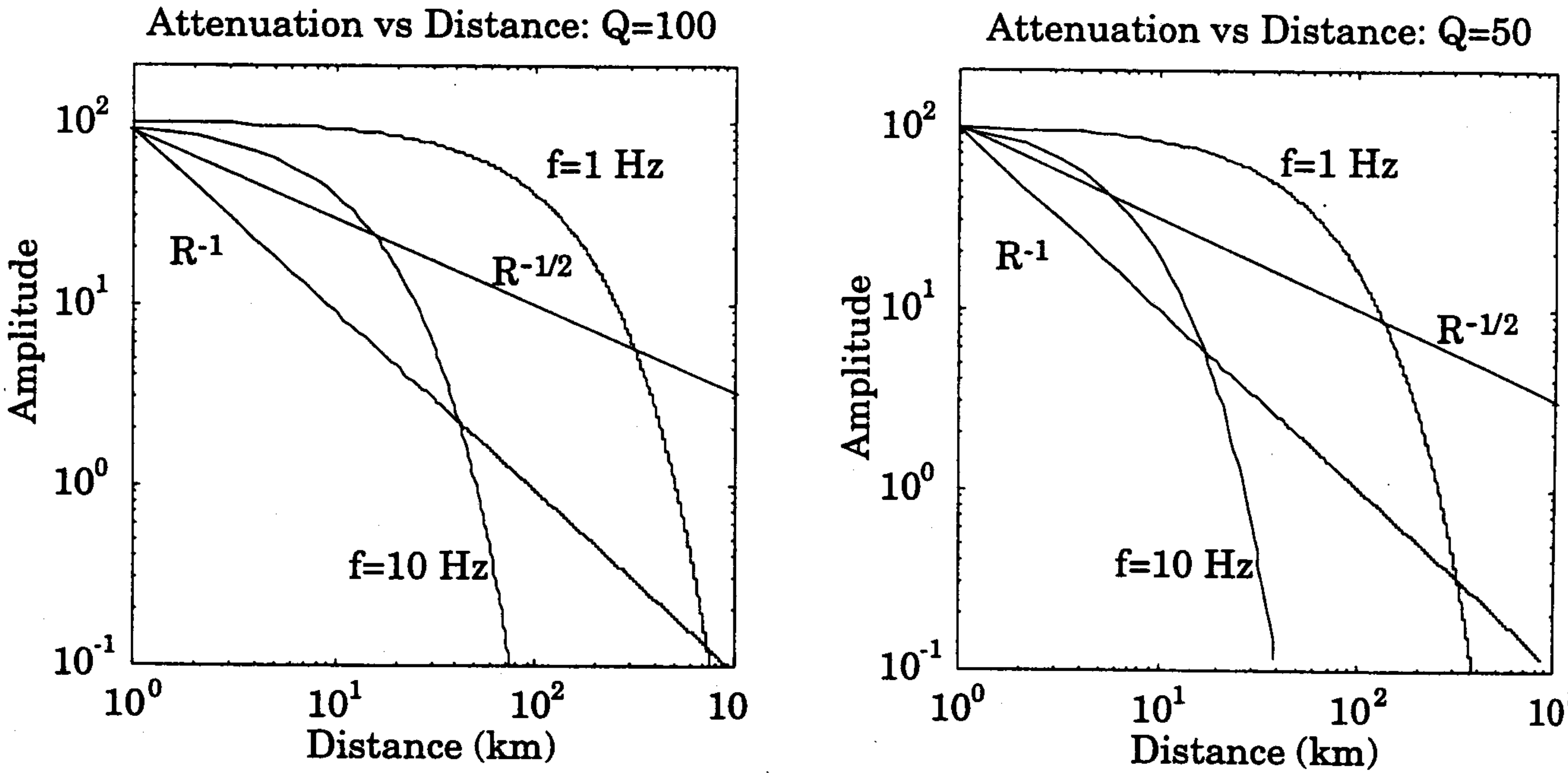


Figure 2-26. Attenuation due to geometrical spreading and intrinsic attenuation for two frequencies and for two values of Q. Geometrical attenuation is dominant for distances less than 10 km for moderate values of Q. Attenuation is strongly frequency dependent.

Source : Archuleta et al., 1997

Definitions

Teleseismic - “distant seismic” - >30^o

Regional - 500 km (5^o) to 30^o

Local - Closer than 500 km.

Body wave magnitude:

$$m_b = \log(A/T) + Q(h, \Delta)$$

A is the ground motion amplitude in microns after the effects of the seismometer are removed

T is the wave period in seconds

Q is an empirical term depending on the distance and focal depth.

Surface wave magnitude (measured using the largest amplitude, zero to peak, of the surface waves):

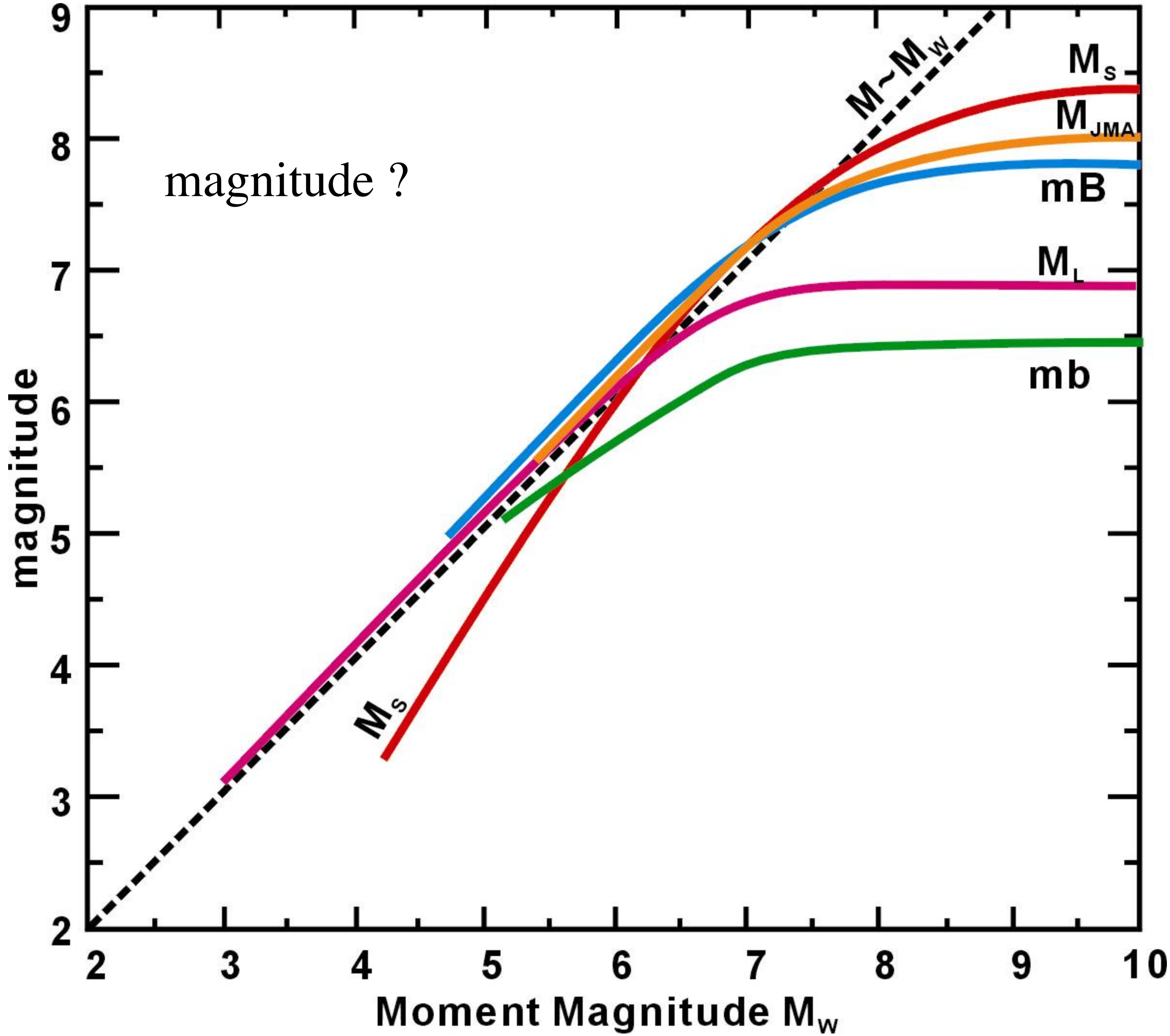
$$M_s = \log(A/T) + 1.66 \log \Delta + 3.3 \qquad \text{(general form)}$$

$$M_s = \log A_{20} + 1.66 \log \Delta + 2.0 \qquad \text{(for 20 second period Rayleigh waves)}$$

(Δ is in degrees)

Sources: Stein et Wysession

magnitude ?



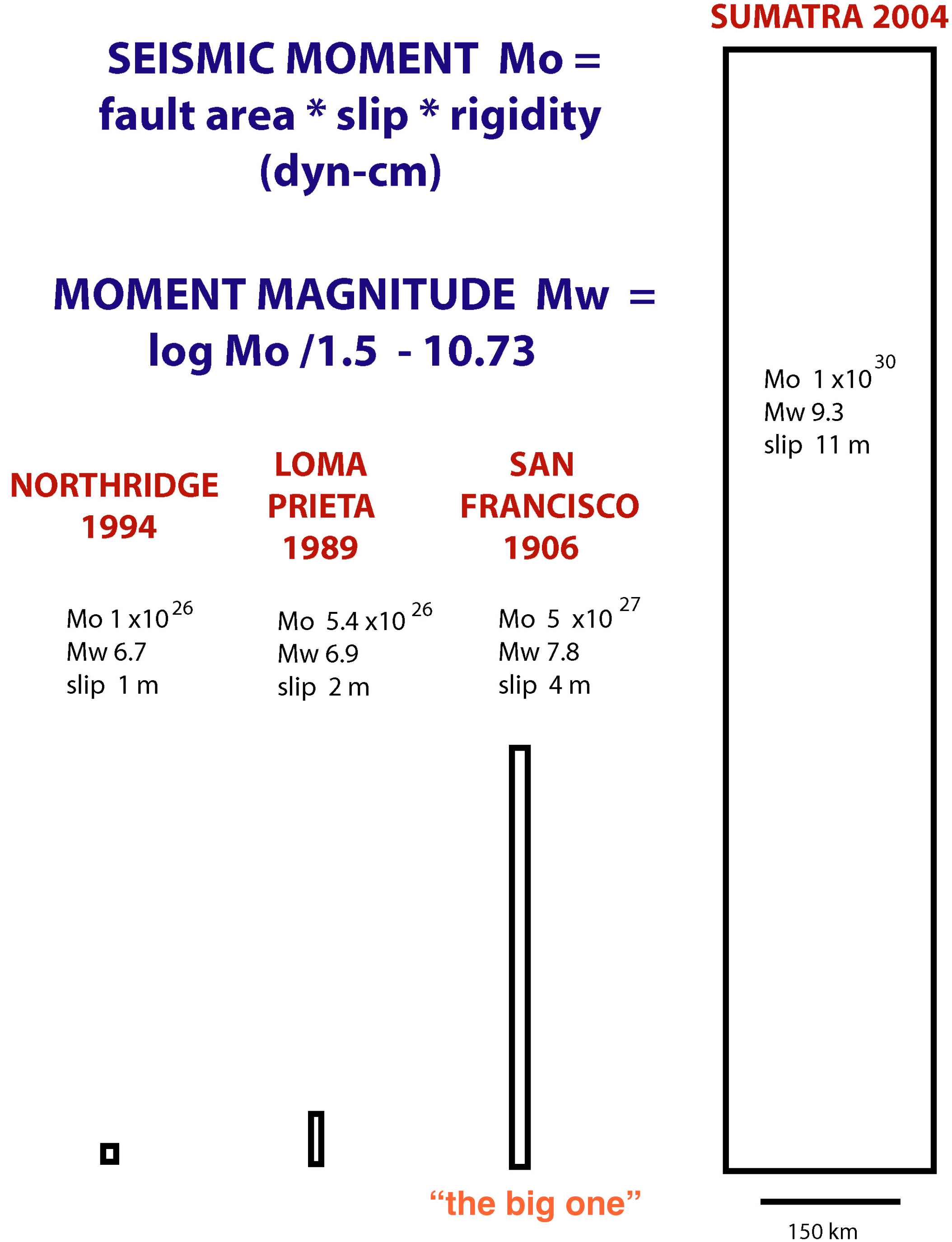
M~M_W
M_S
M_JMA
mB
M_L
mb
M_S
magnitude
Moment Magnitude M_W
2
3
4
5
6
7
8
9
10

EARTHQUAKE SOURCE PARAMETERS

Magnitude, fault area, fault slip, stress drop, energy release

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

MOMENT MAGNITUDE Mw = log Mo /1.5 - 10.73

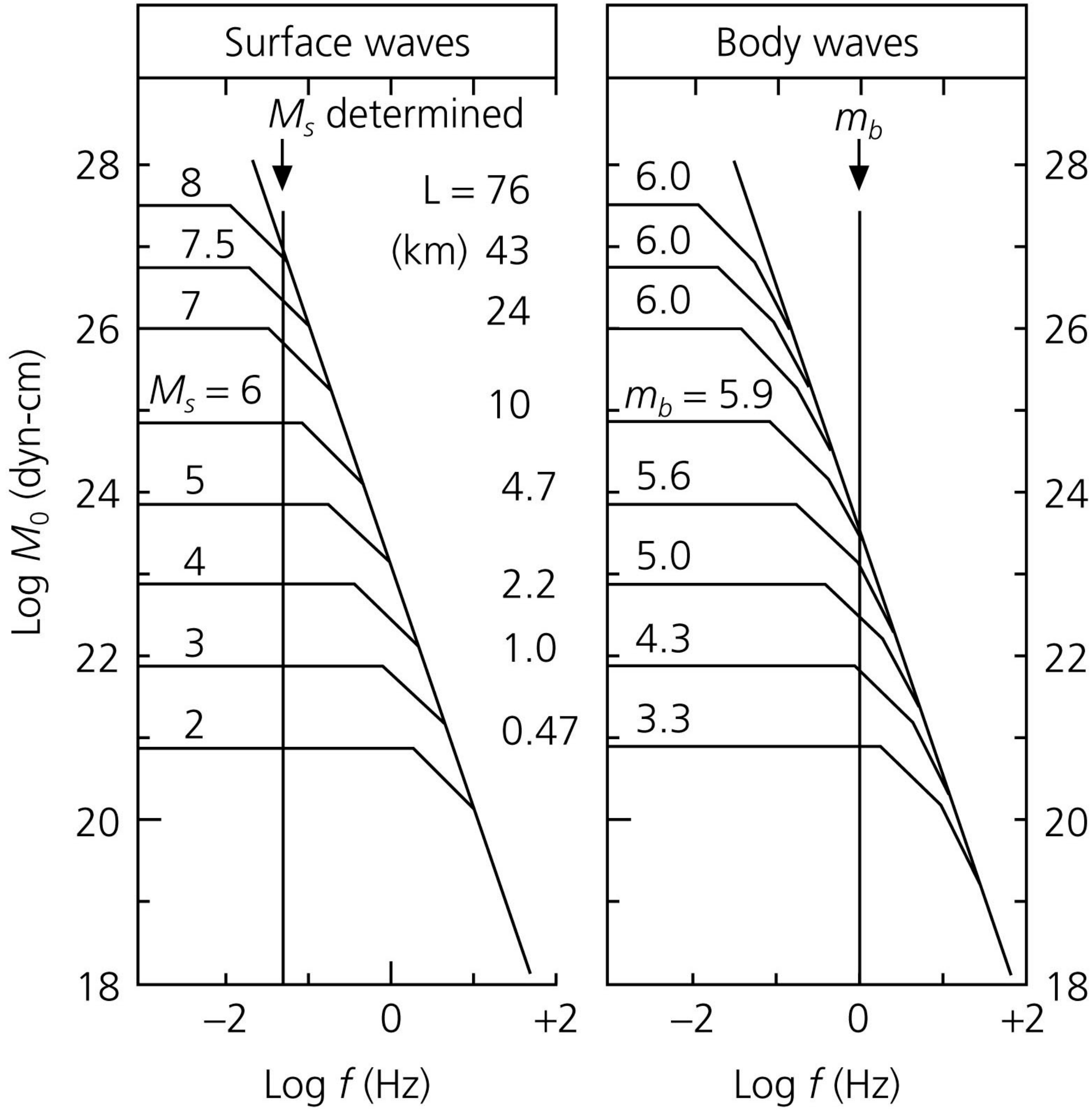


DIFFERENT MAGNITUDES REFLECT ENERGY RELEASE AT DIFFERENT PERIODS

1 s - Body wave magnitude m_b

20 s - Surface wave magnitude M_s

Long period - moment magnitude M_w derived from moment M_0

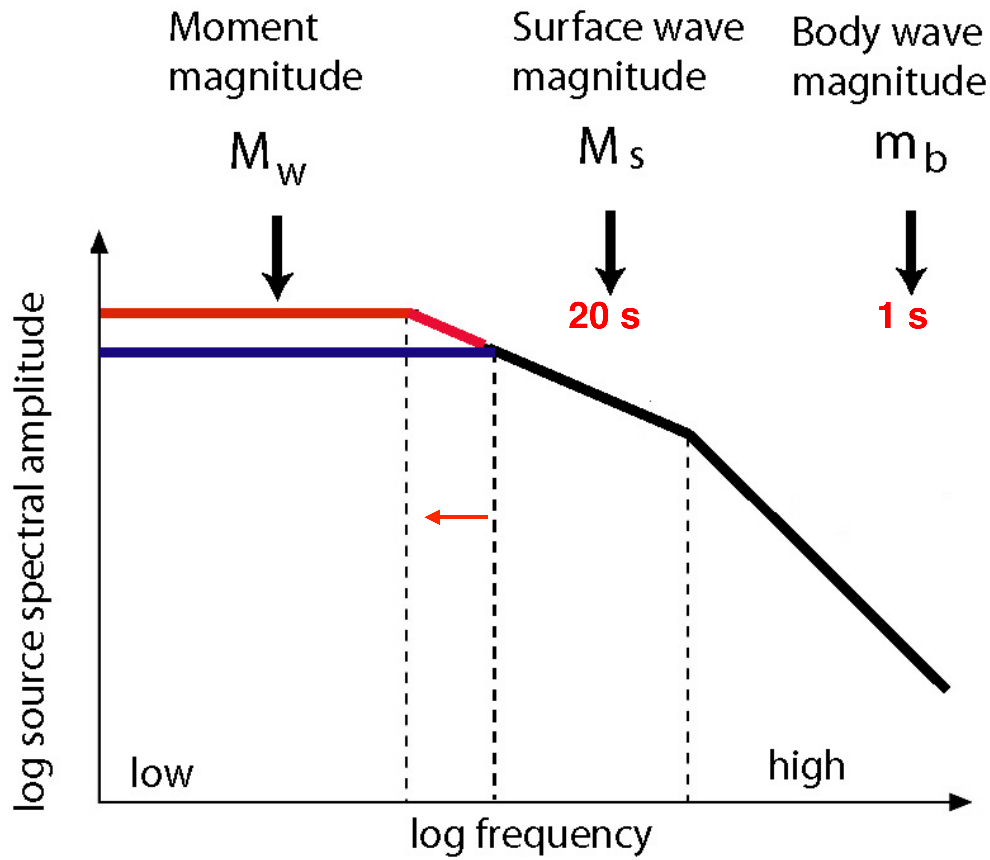


DIFFERENT MAGNITUDE SCALES REFLECT AMPLITUDE AT DIFFERENT PERIODS

Body & surface wave magnitudes saturate - remain constant once earthquake exceeds a certain size - because added energy release in very large earthquakes is at periods > 20 s

No matter how big an earthquake is, body and surface wave magnitudes do not exceed ~ 6.5 and 8.4, respectively.

For very large earthquakes only low period moment magnitude reflects earthquake's size.



This issue is crucial for tsunami warning because long periods excite tsunami, but are harder to study in real time

Moment magnitude:

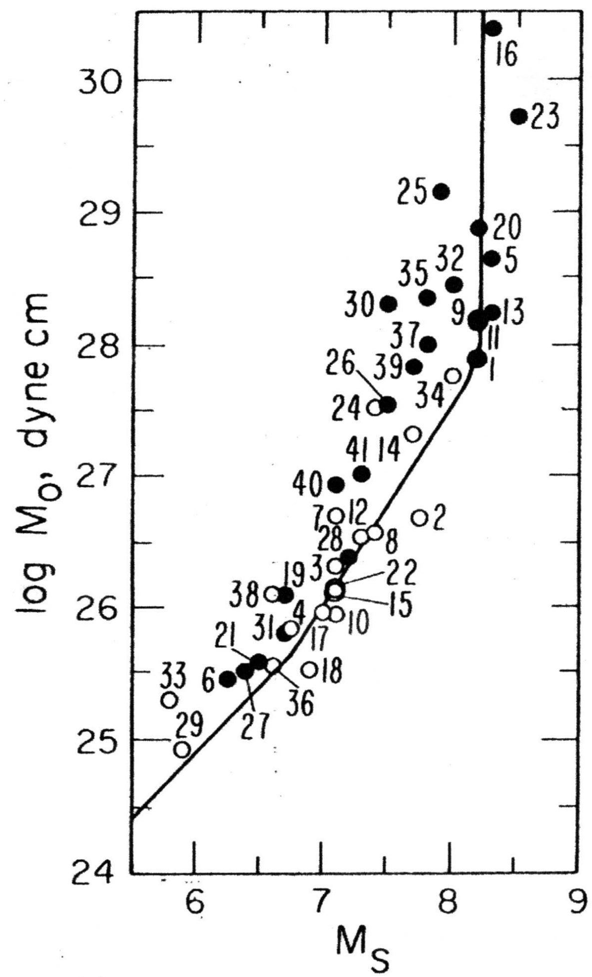
$$M_w = \frac{\log M_0}{1.5} - 10.73$$

(with M_0 in dyn-cm)

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	8.3×10^{24}	5.8
San Fernando, 1971	6.2	6.6	20 × 14	1.4	1.2×10^{26}	6.7
Loma Prieta, 1989	6.2	7.1	40 × 15	1.7	3.0×10^{26}	6.9
San Francisco, 1906		8.2	320 × 15	4	6.0×10^{27}	7.8
Alaska, 1964	6.2	8.4	500 × 300	7	5.2×10^{29}	9.1
Chile, 1960		8.3	800 × 200	21	2.4×10^{30}	9.5

TSUNAMI WARNING: THE CHALLENGE

- Upon detection of a teleseismic earthquake, assess in real-time its tsunami potential.
- *HINT:* Tsunami being low frequency is generated by longest periods in seismic source ("static moment M_0").
- *PROBLEM:* Most popular measure of seismic source size, surface wave magnitude M_s , saturates for large earthquakes.



FAR-FIELD TSUNAMI DANGER

EXTREME

PROBABLE

LOW

NIL

[*Geller,* 1976]