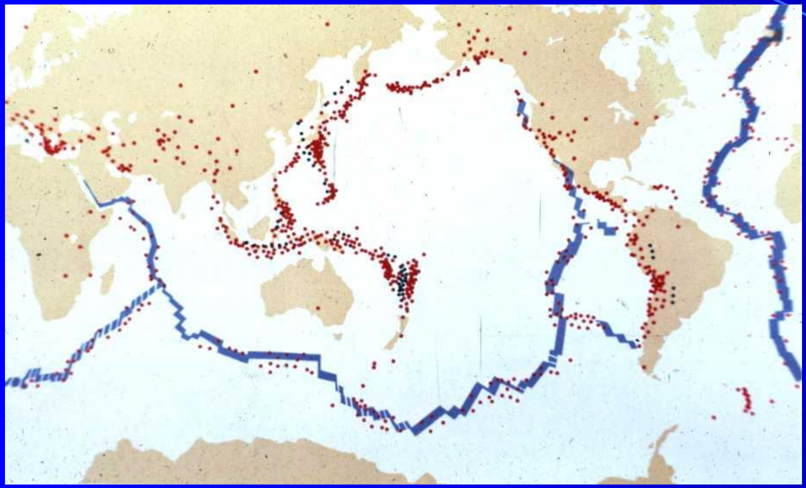
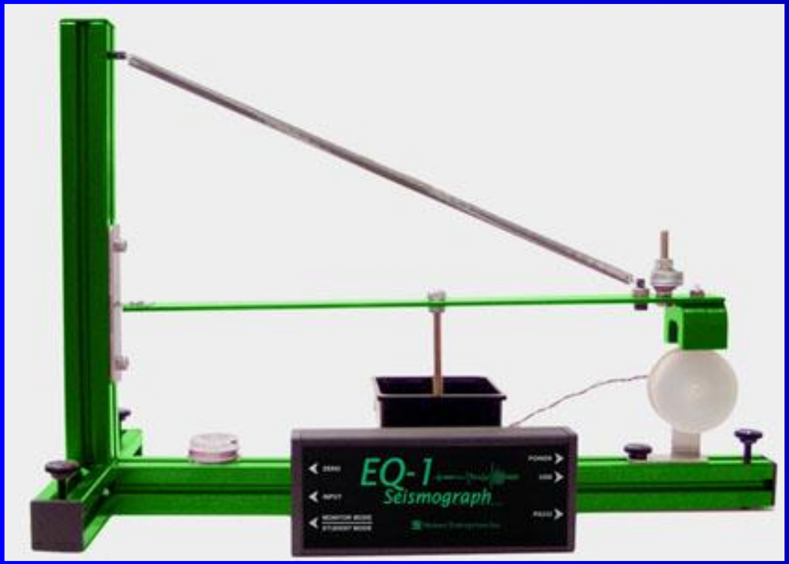
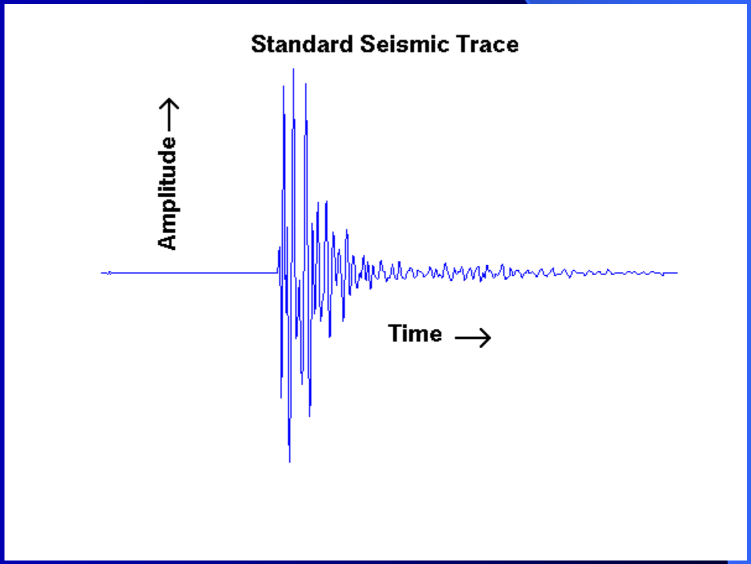
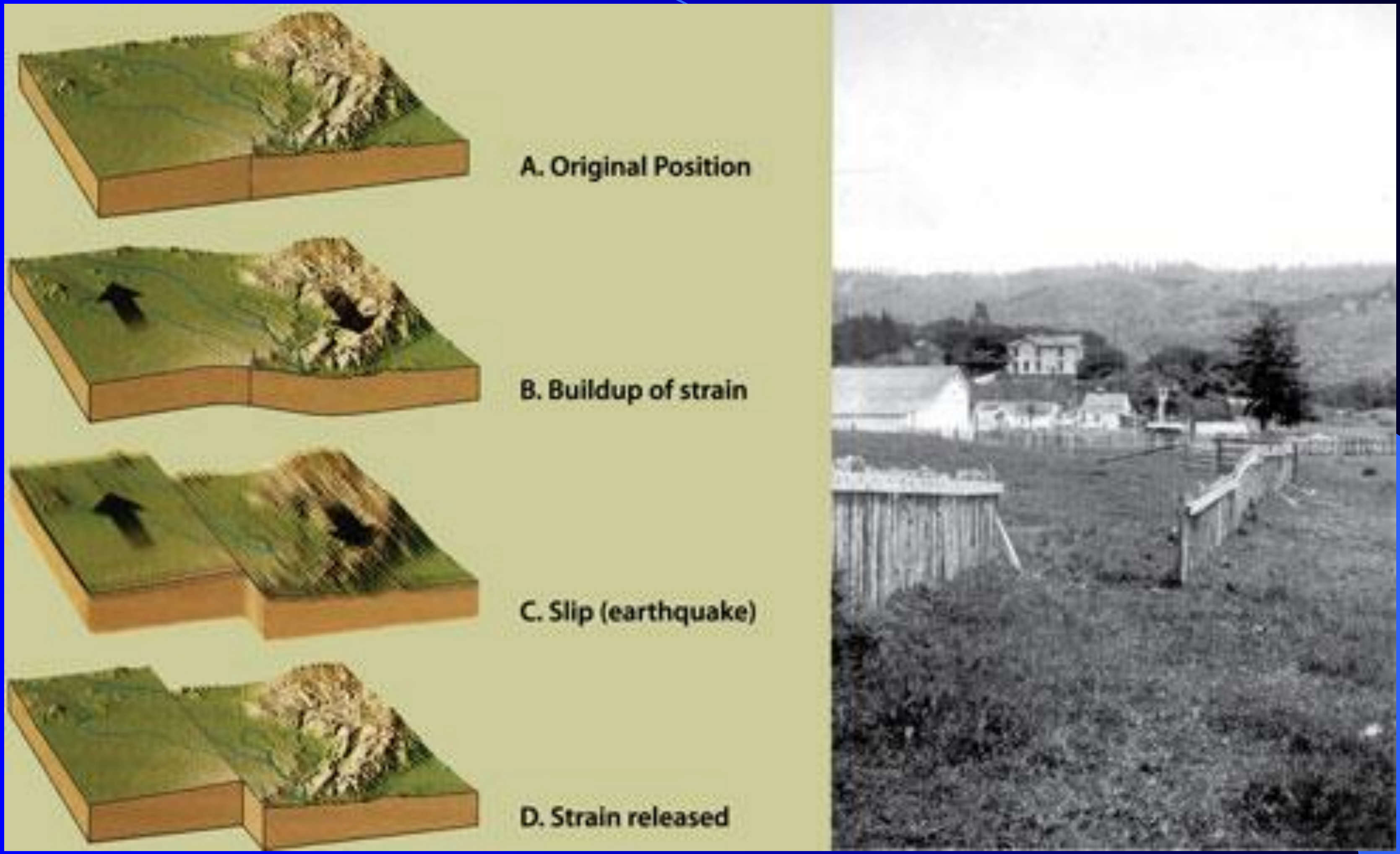
Earthquakes



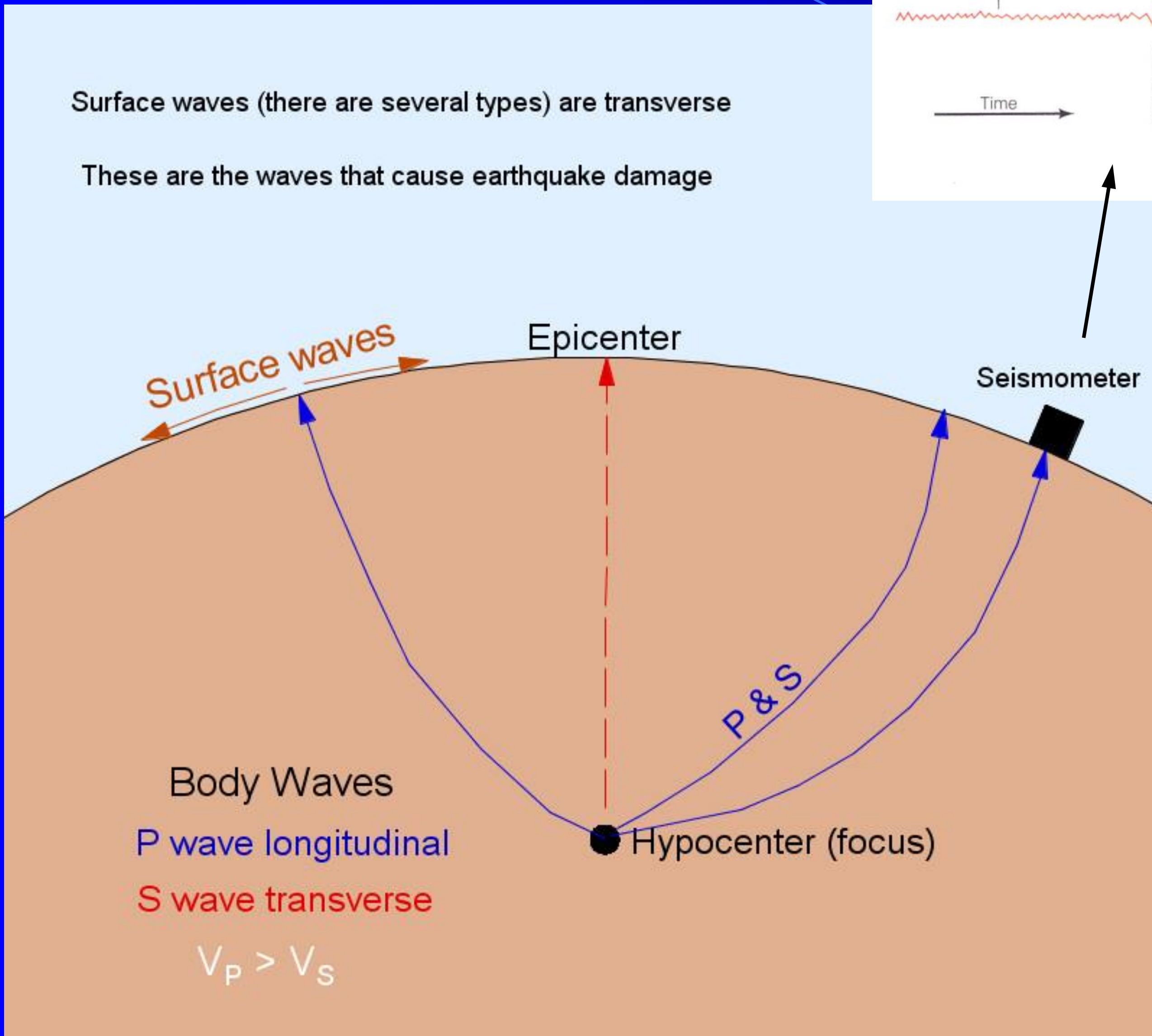


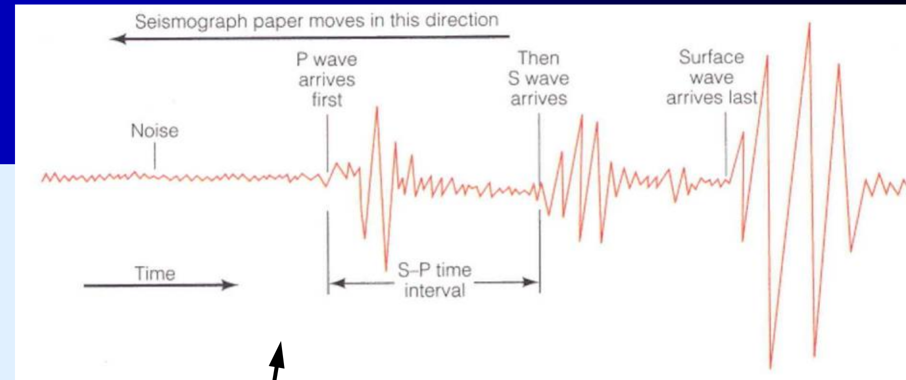


Elastic Rebound Theory



Earthquakes occur when strain exceeds the strength of the rock and the rock fractures.

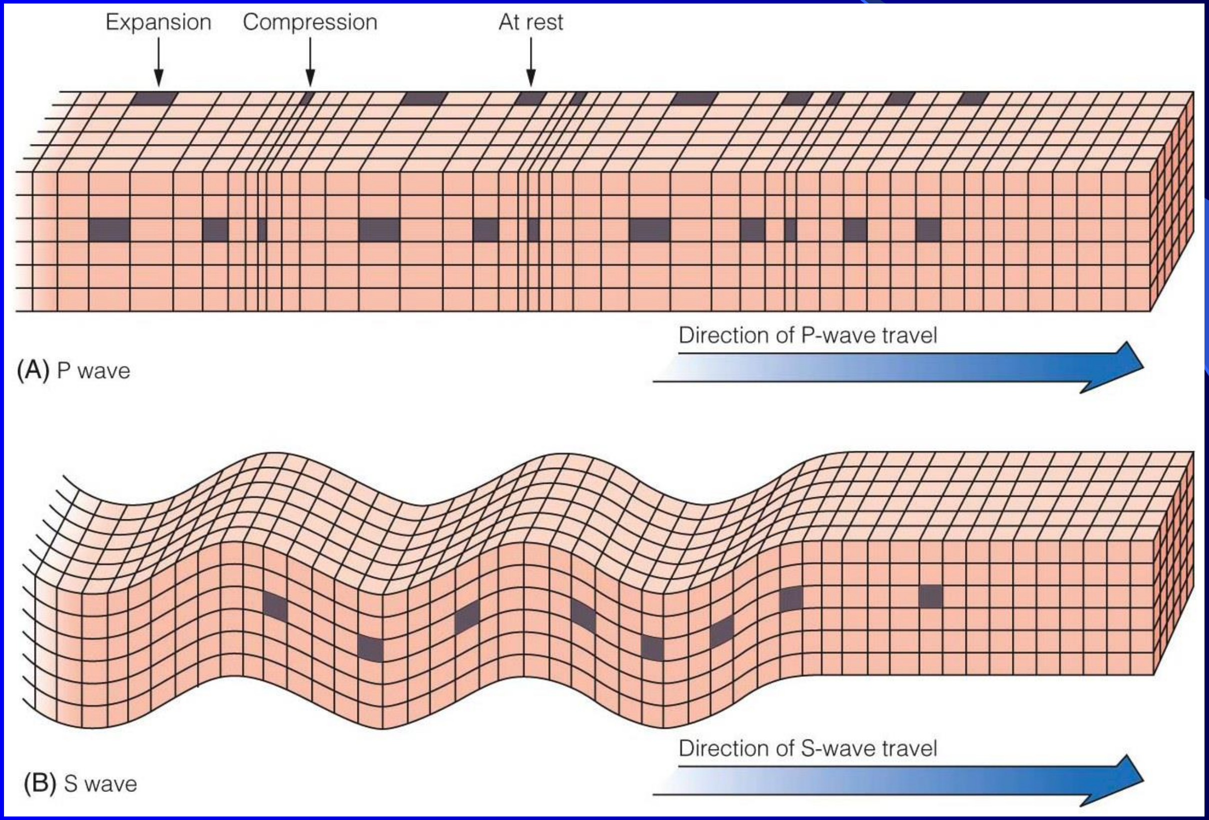




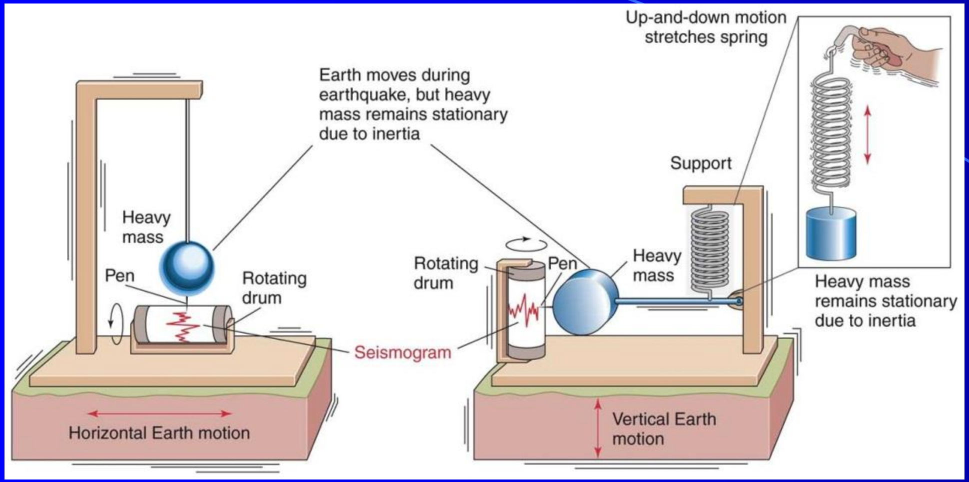
The arrival of earthquakes waves is recorded by a seismograph. The amplitude of the P-wave displacement is used to determine the Richter magnitude.

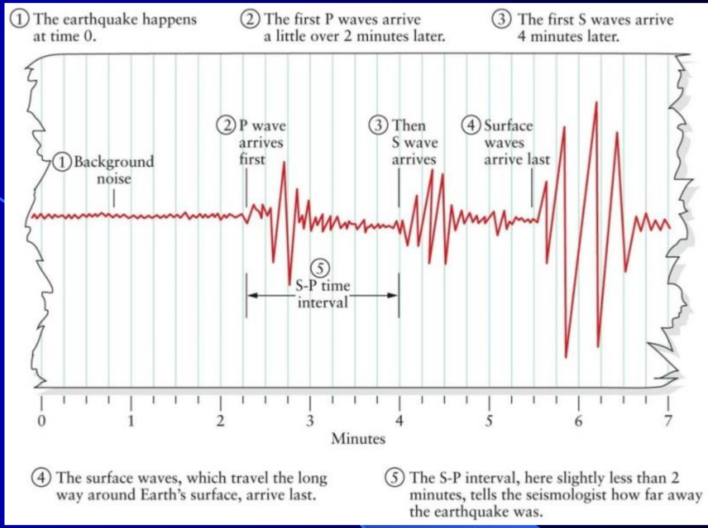
Earthquake Waves

- **Body waves** – move through the solid earth
    - P-waves - longitudinal
    - S-waves - transverse
- **Surface waves** - transverse

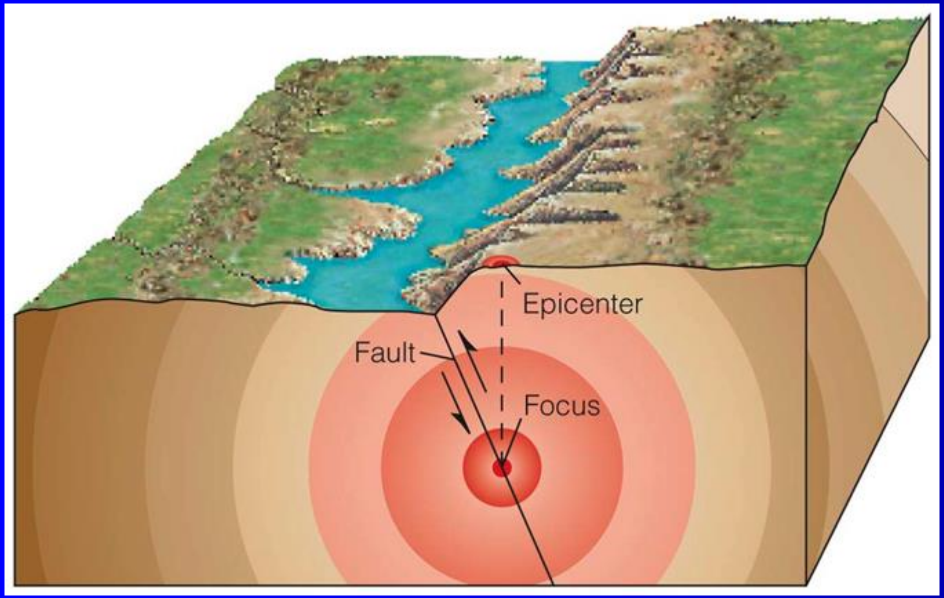


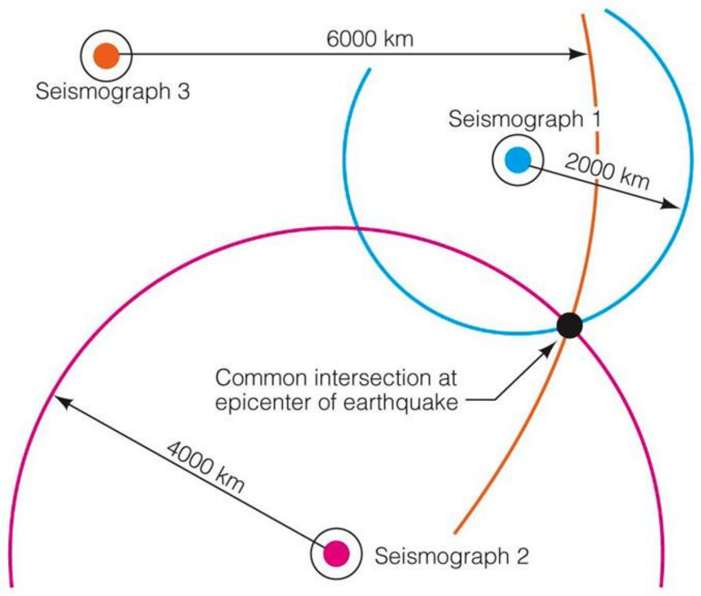
Recording Earthquakes





Locating earthquake epicenter





Earthquake magnitude – amount of energy released

Determination of Richter Magnitude for an Earthquake

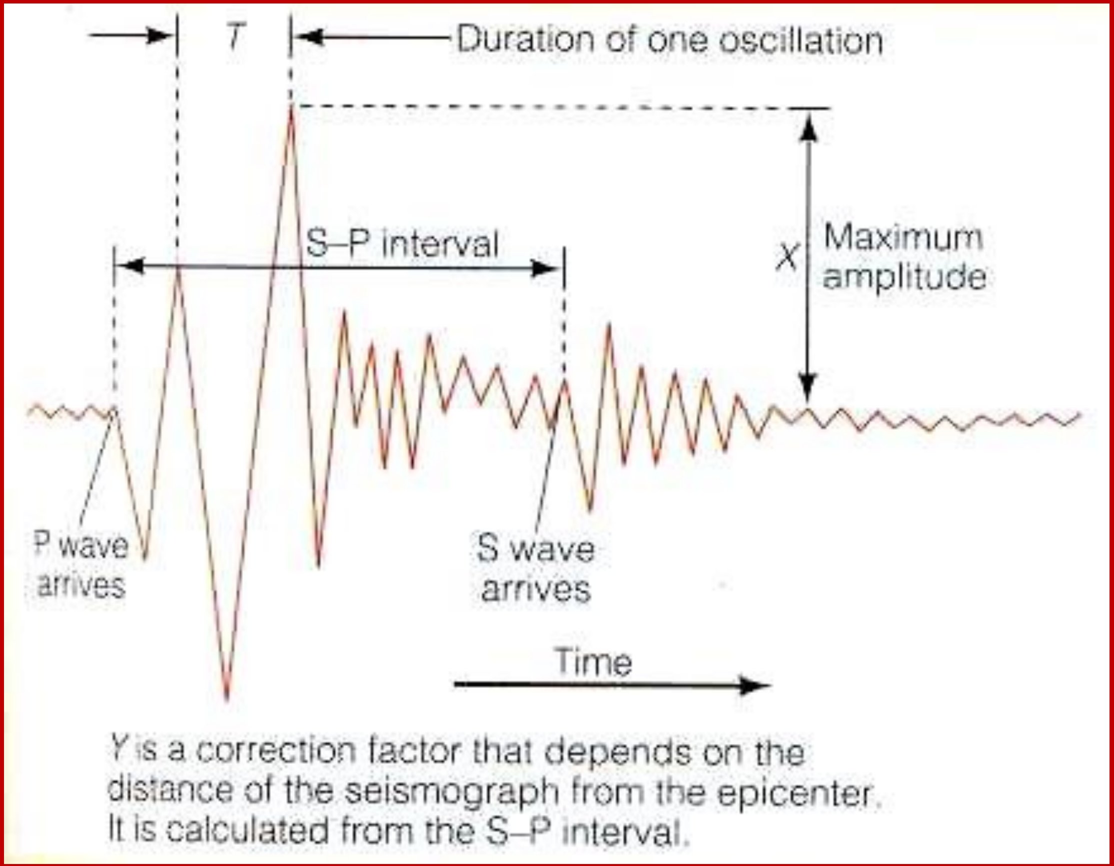
$M = \log(X/T) + Y$

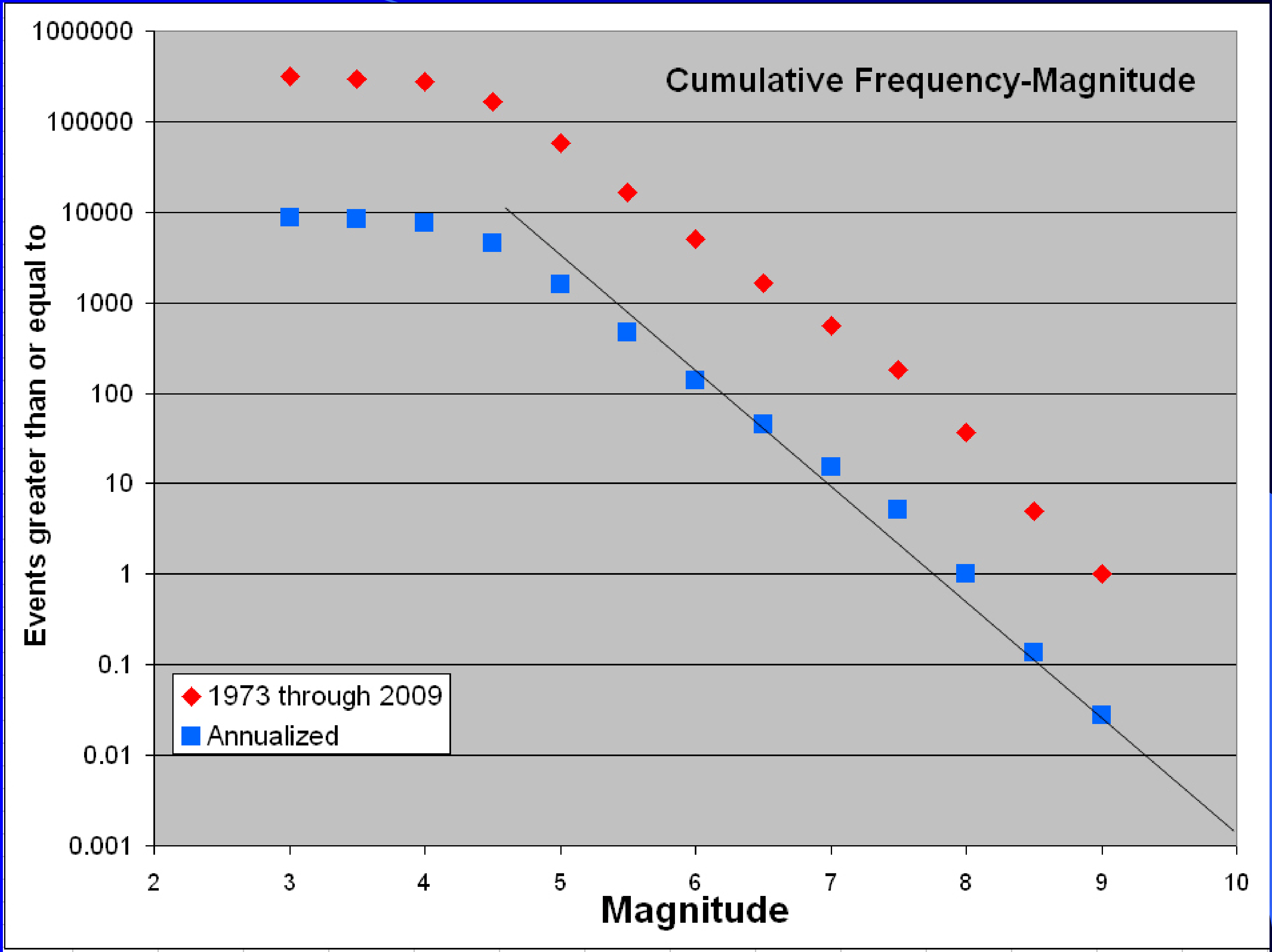
1M ~ 10X

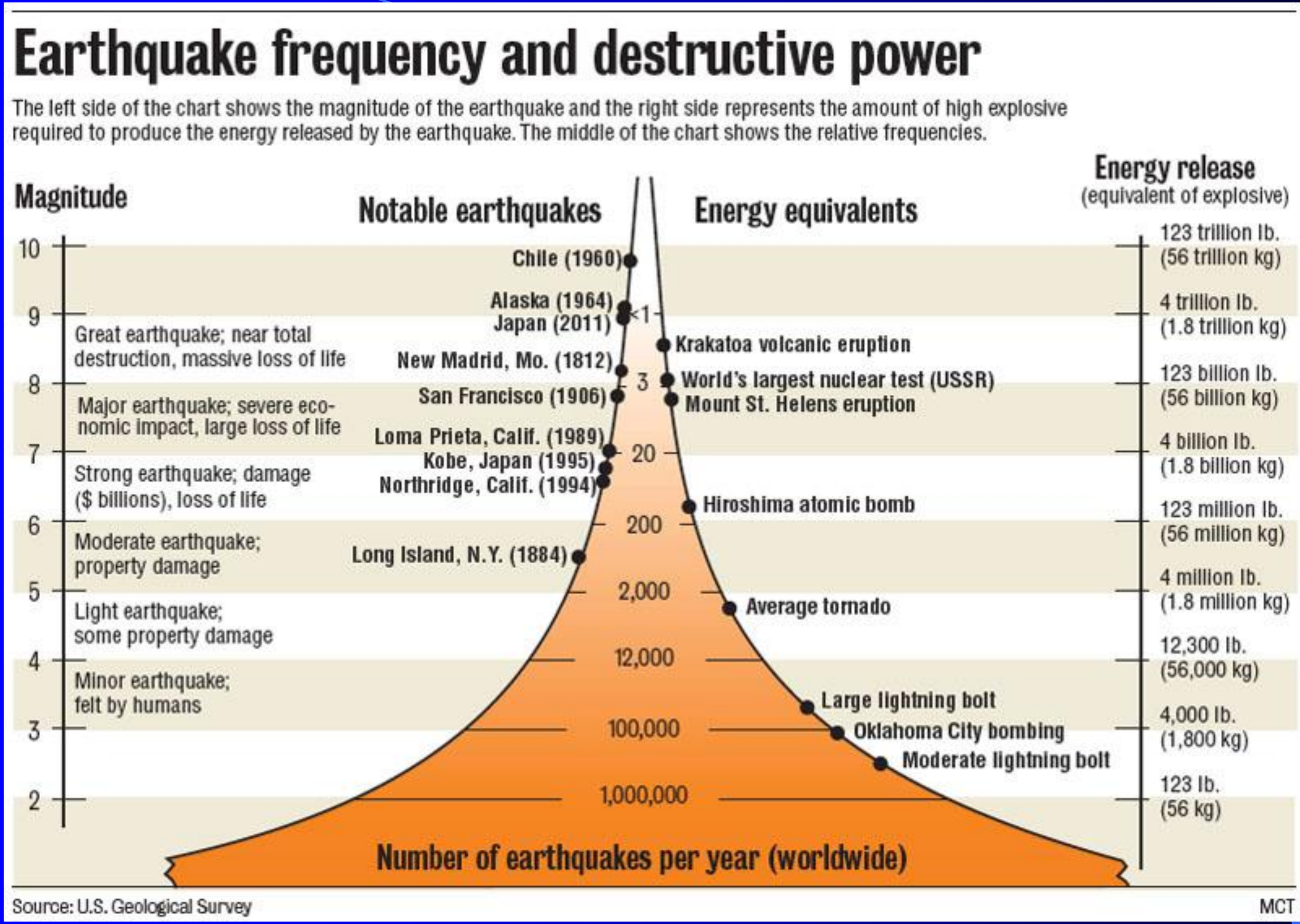
Energy ~ X^2

1M ~ 100x energy

However, energy increase when summed over the whole range of waves in a wave record is only 30x. Confusion time!




Cumulative Frequency-Magnitude
Events greater than or equal to
1000000
100000
10000
1000
100
10
1
0.1
0.01
0.001
2
3
4
5
6
7
8
9
10
Magnitude
1973 through 2009
Annualized


Earthquake frequency and destructive power
The left side of the chart shows the magnitude of the earthquake and the right side represents the amount of high explosive required to produce the energy released by the earthquake. The middle of the chart shows the relative frequencies.
Magnitude
Notable earthquakes
Energy equivalents
Energy release
(equivalent of explosive)
10
9
8
7
6
5
4
3
2
Great earthquake; near total destruction, massive loss of life
Major earthquake; severe economic impact, large loss of life
Strong earthquake; damage ($ billions), loss of life
Moderate earthquake; property damage
Light earthquake; some property damage
Minor earthquake; felt by humans
Chile (1960)
Alaska (1964)
Japan (2011)
New Madrid, Mo. (1812)
San Francisco (1906)
Loma Prieta, Calif. (1989)
Kobe, Japan (1995)
Northridge, Calif. (1994)
Long Island, N.Y. (1884)
<1
3
20
200
2,000
12,000
100,000
1,000,000
Krakatoa volcanic eruption
World's largest nuclear test (USSR)
Mount St. Helens eruption
Hiroshima atomic bomb
Average tornado
Large lightning bolt
Oklahoma City bombing
Moderate lightning bolt
123 trillion lb. (56 trillion kg)
4 trillion lb. (1.8 trillion kg)
123 billion lb. (56 billion kg)
4 billion lb. (1.8 billion kg)
123 million lb. (56 million kg)
4 million lb. (1.8 million kg)
12,300 lb. (56,000 kg)
4,000 lb. (1,800 kg)
123 lb. (56 kg)
Number of earthquakes per year (worldwide)
Source: U.S. Geological Survey
MCT

Earthquake intensity – damage caused by earthquake

- Subsurface material
- Type of construction
- May not be directly related to earthquake magnitude

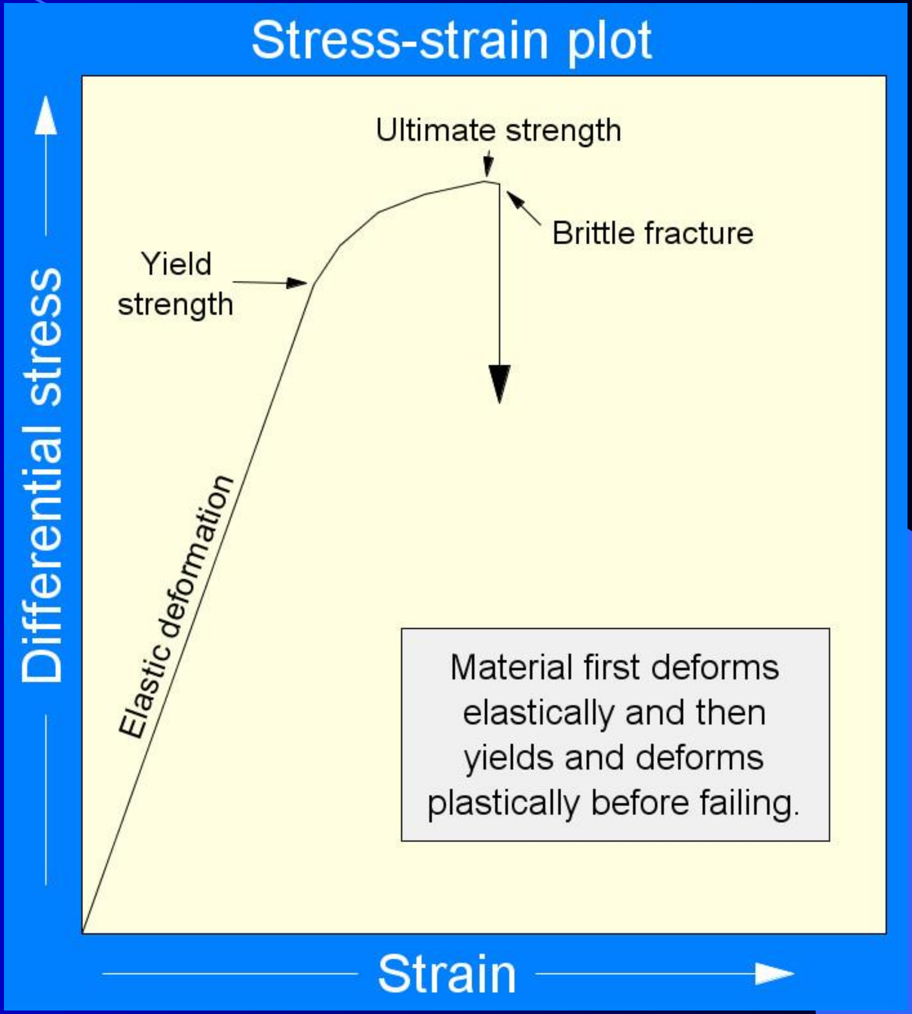
TABLE 6.1 Earthquake Magnitudes, Frequencies, and Effects

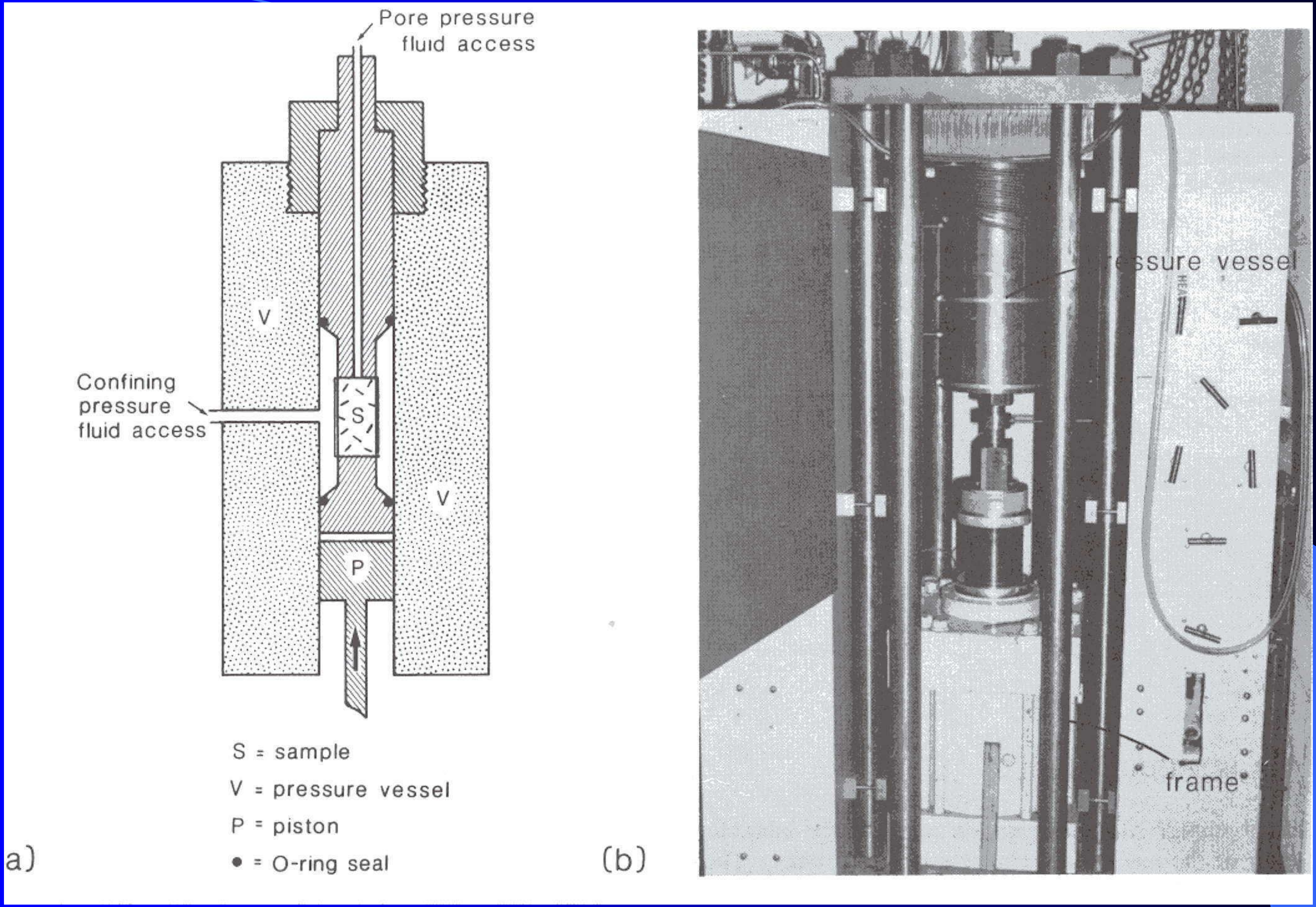
Richter and Moment Magnitude*	Number per year	Modified Mercalli Intensity Scale*	Characteristic Effects in Populated Areas
<3.4	800,000	I	Recorded only by seismographs
3.5–4.2	30,000	II–III	Felt by some people who are indoors
4.3–4.8	4,800	IV	Felt by many people; windows rattle
4.9–5.4	1,400	V	Felt by everyone; dishes break, doors swing
5.5–6.1	500	VI–VII	Slight building damage; plaster cracks, bricks fall
6.2–6.9	100	VIII–IX	Much building damage; chimneys fall; houses move on foundations
7.0–7.3	15	X	Serious damage, bridges twisted, walls fractured; many masonry buildings collapse
7.4–7.9	4	XI	Great damage; most buildings collapse
>8.0	<1	XII	Total damage; waves seen on ground surface, objects thrown in the air

*The correspondence between Richter and moment magnitudes and the Mercalli intensity is not exact because they are calculated on the basis of very different parameters.

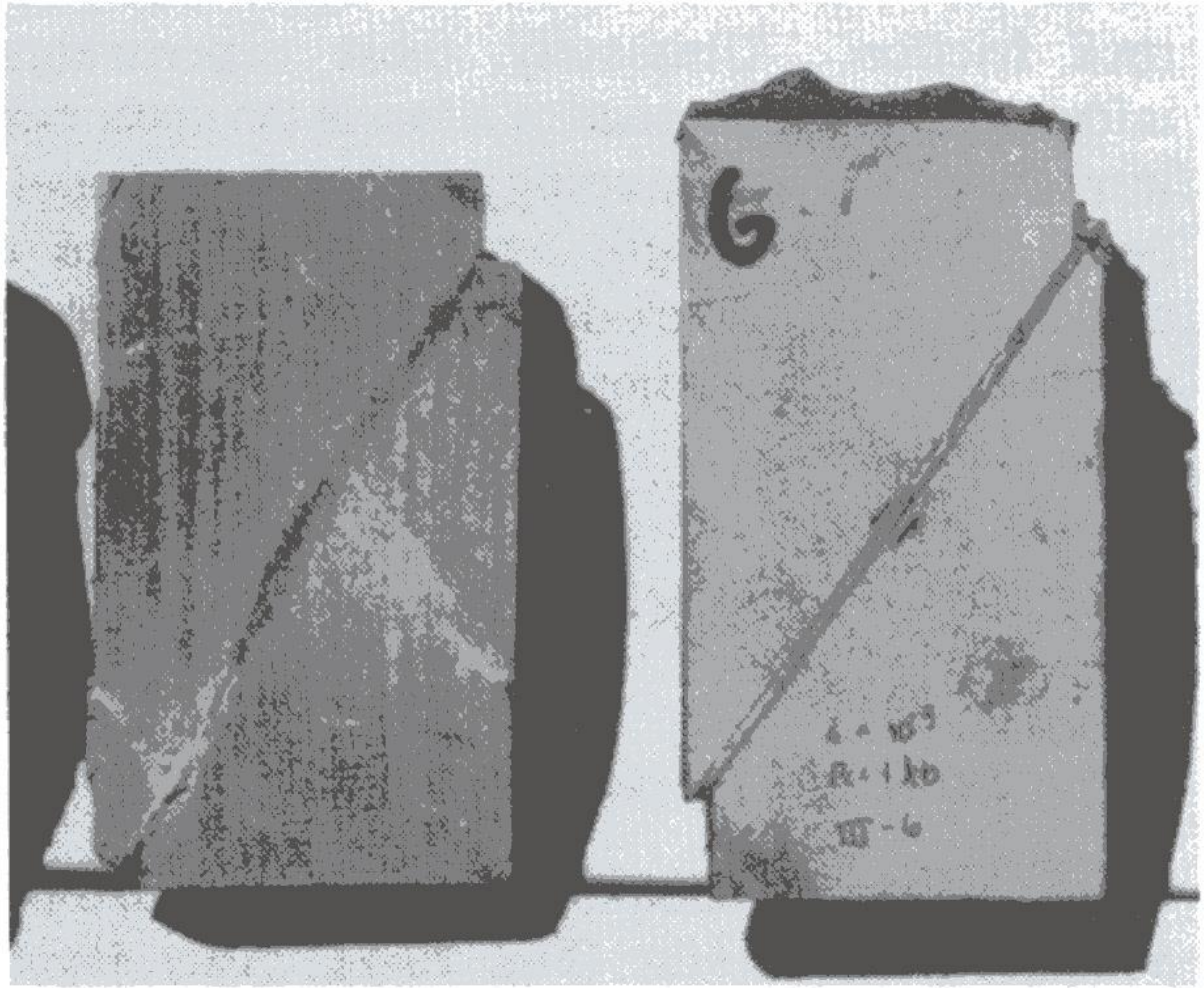
Let's break some rocks!

Rock mechanics experiments





Triaxial load machine. a) cross-sectional sketch showing the pressure vessel, sample, and piston; b) photograph of machine.



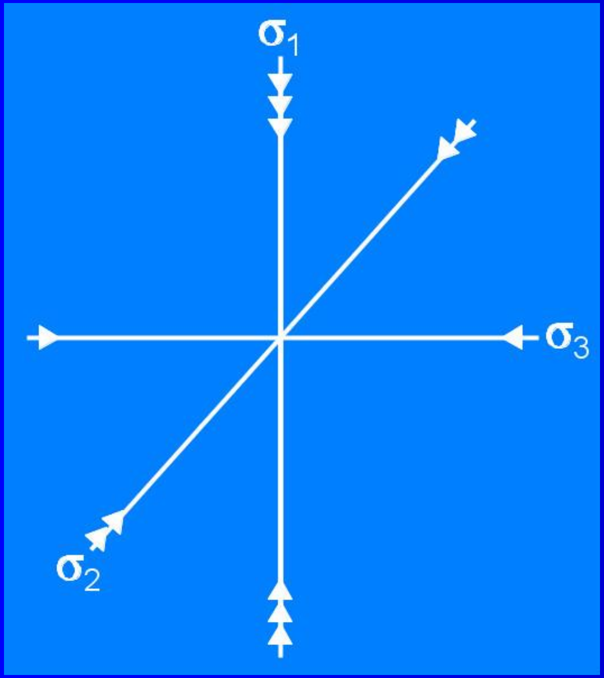
(c)

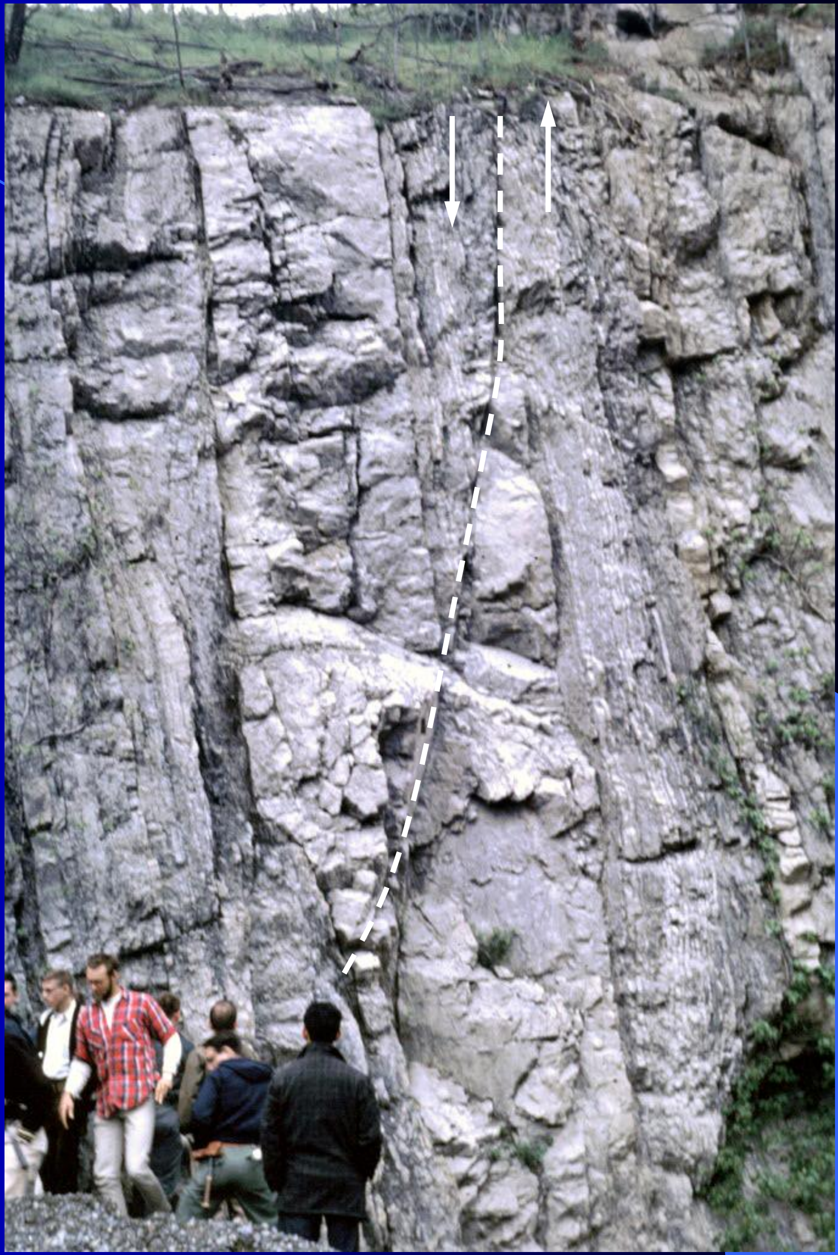
Two deformed samples. L) induced fracture; R) saw-cut for friction experiments. There is a 5 mm-thick layer of gouge along the cut. Samples are 3.5" long and 2" in diameter.

Types of Faults

Normal fault. Left side moved down relative to right side.

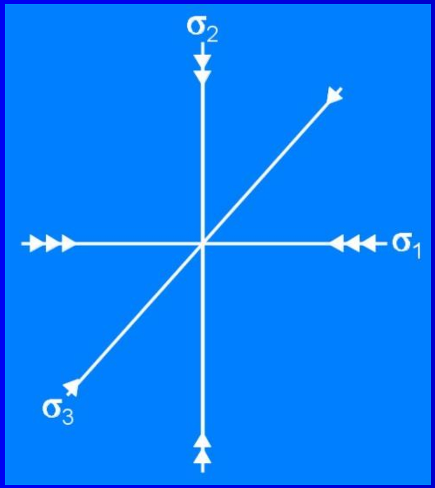
Principal stress orientations





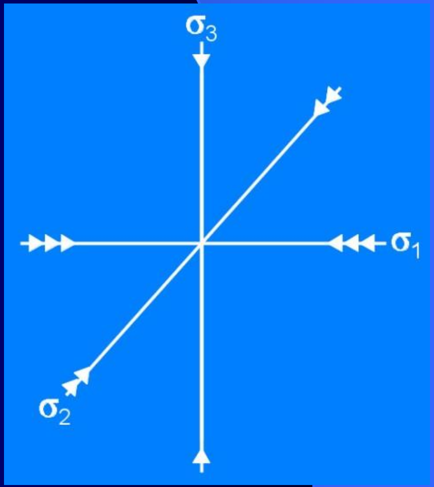
Right lateral **strike-slip fault**.

Principle stress orientations



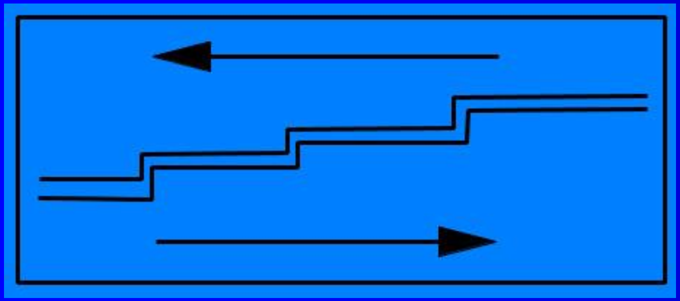
Thrust fault. Block on left thrust up and over the block on the right.

Principal stress orientations



Slickenslides show sense and direction of movement on a fault plane.

Direction of movement



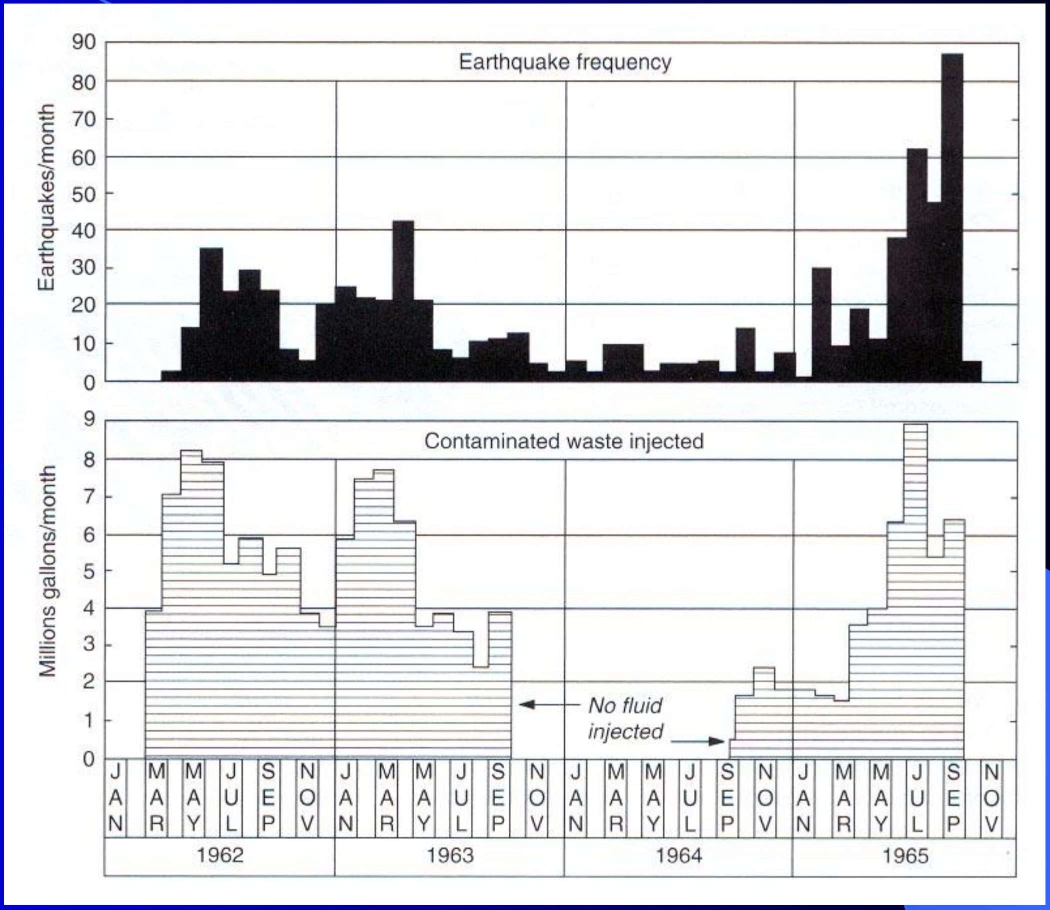
Fluids and earthquakes

If water, or another fluid, occurs in a fault zone

$$\tau = \mu(\sigma_n - P_w) = \mu S$$

where P_w = fluid pressure and $(\sigma_n - P_w)$ = effective normal stress S.

The famous beer can experiment – an interesting way to spend an evening doing science.



Rocky Mount Arsenal deep waste-disposal well and Denver earthquakes.

Orientation of present-day US principal stresses

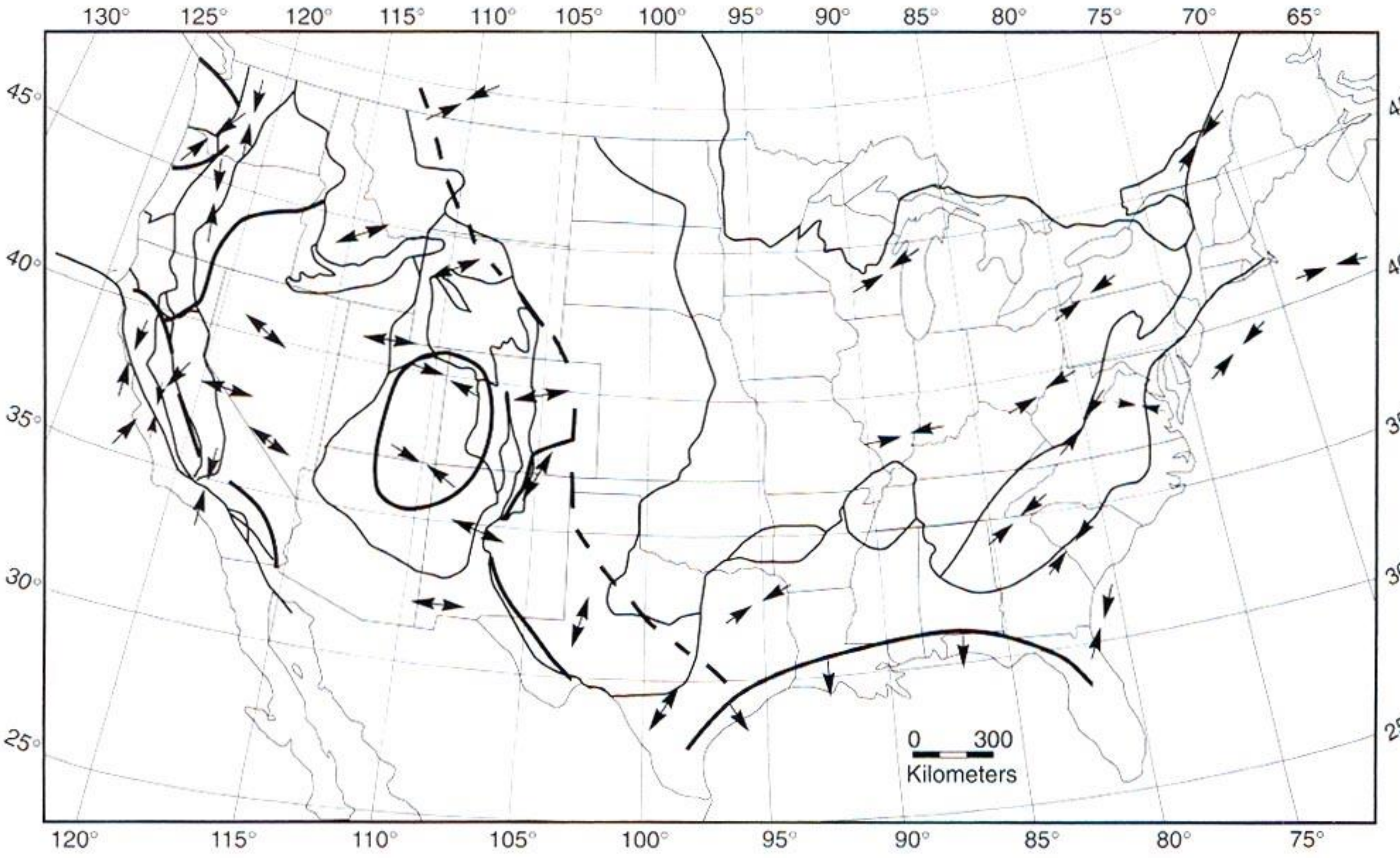
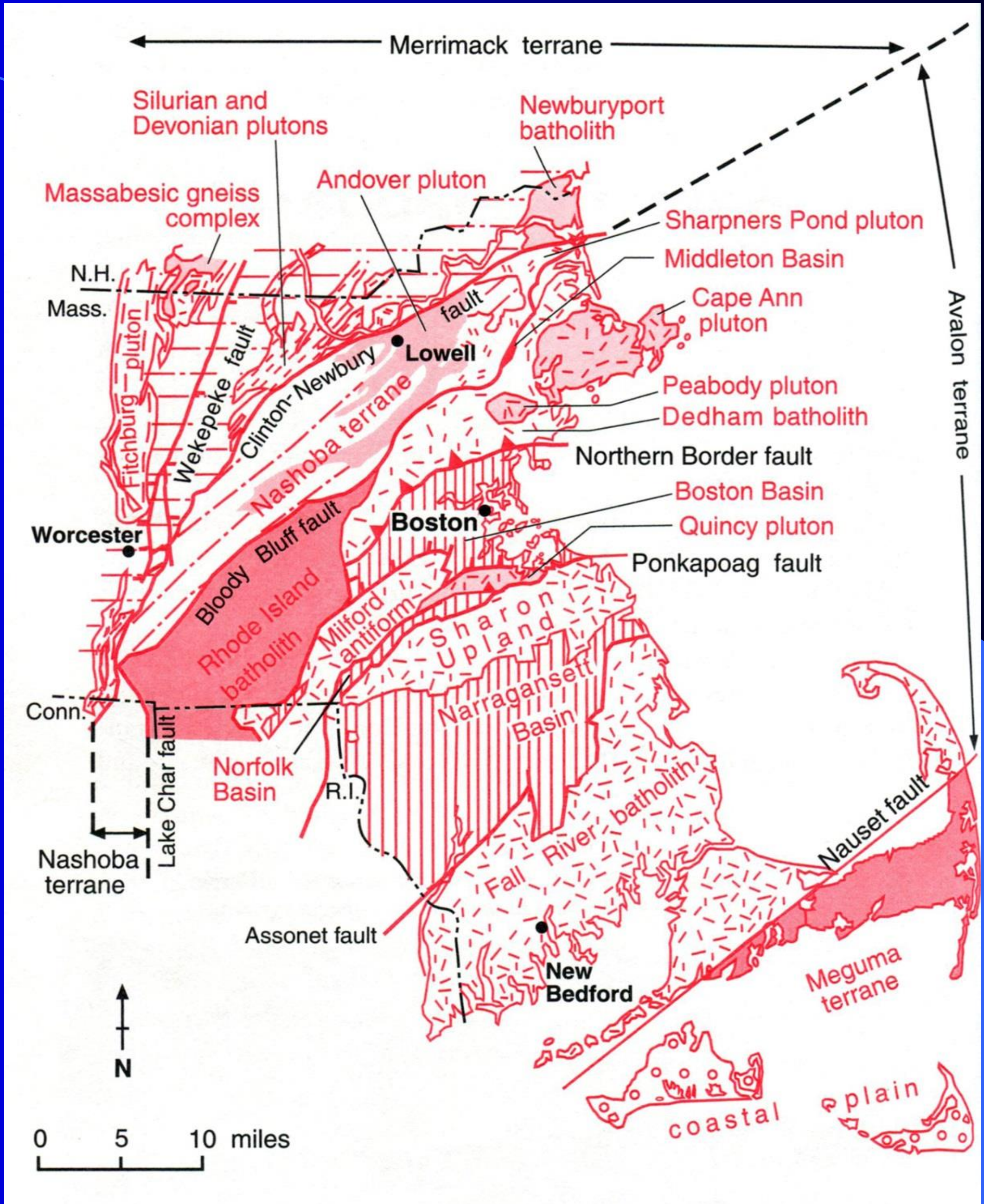


FIGURE 3E–3

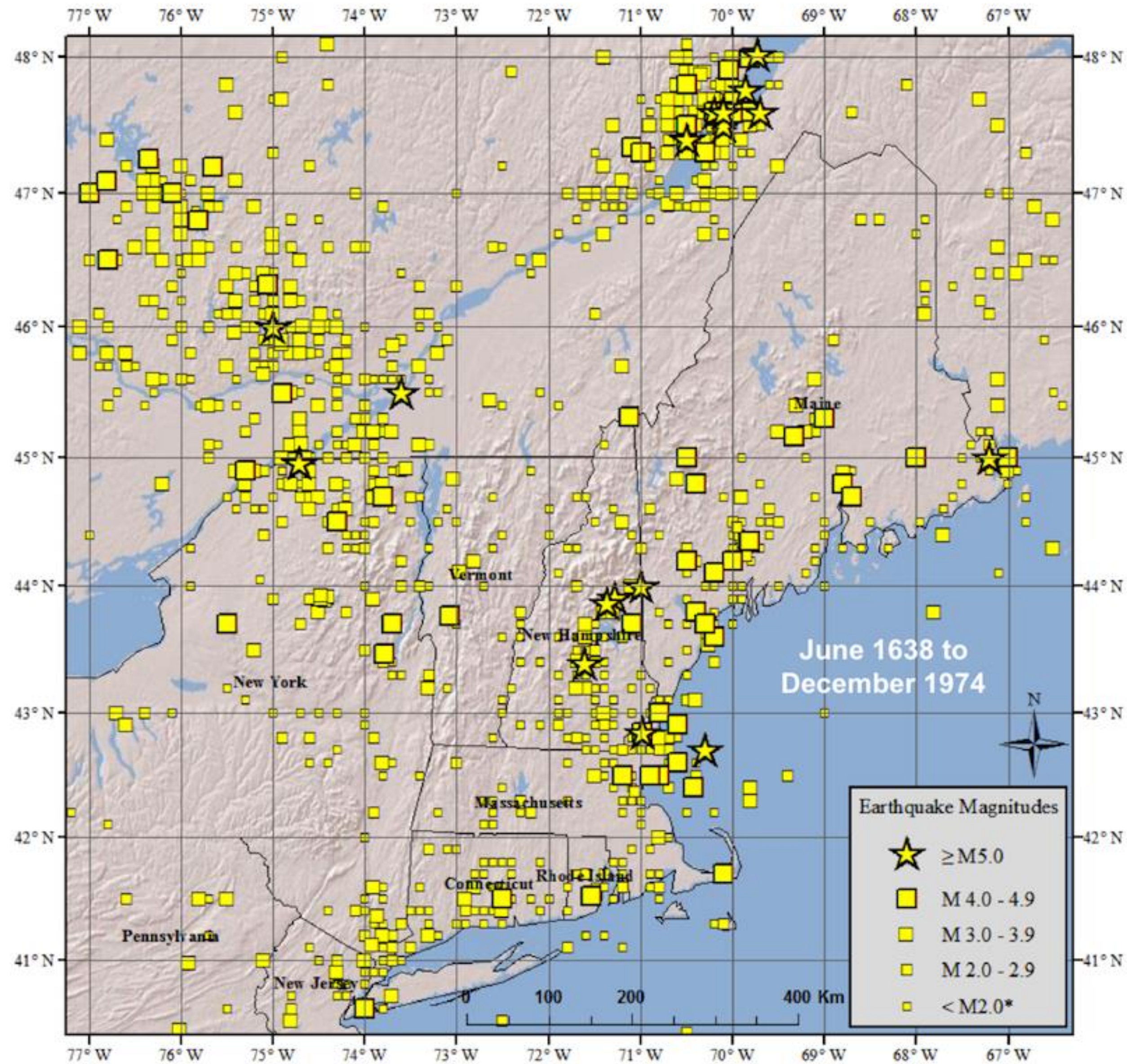
Domains of common orientation of present-day maximum (compressional) and minimum (extensional) principal stress in the United States. Arrowheads indicate whether stress is extensional or compressional. (From M. L. Zoback and M. D. Zoback, 1989, Geological Society of America *Memoir 172*.)

Geology and Earthquakes in Eastern Massachusetts and New England

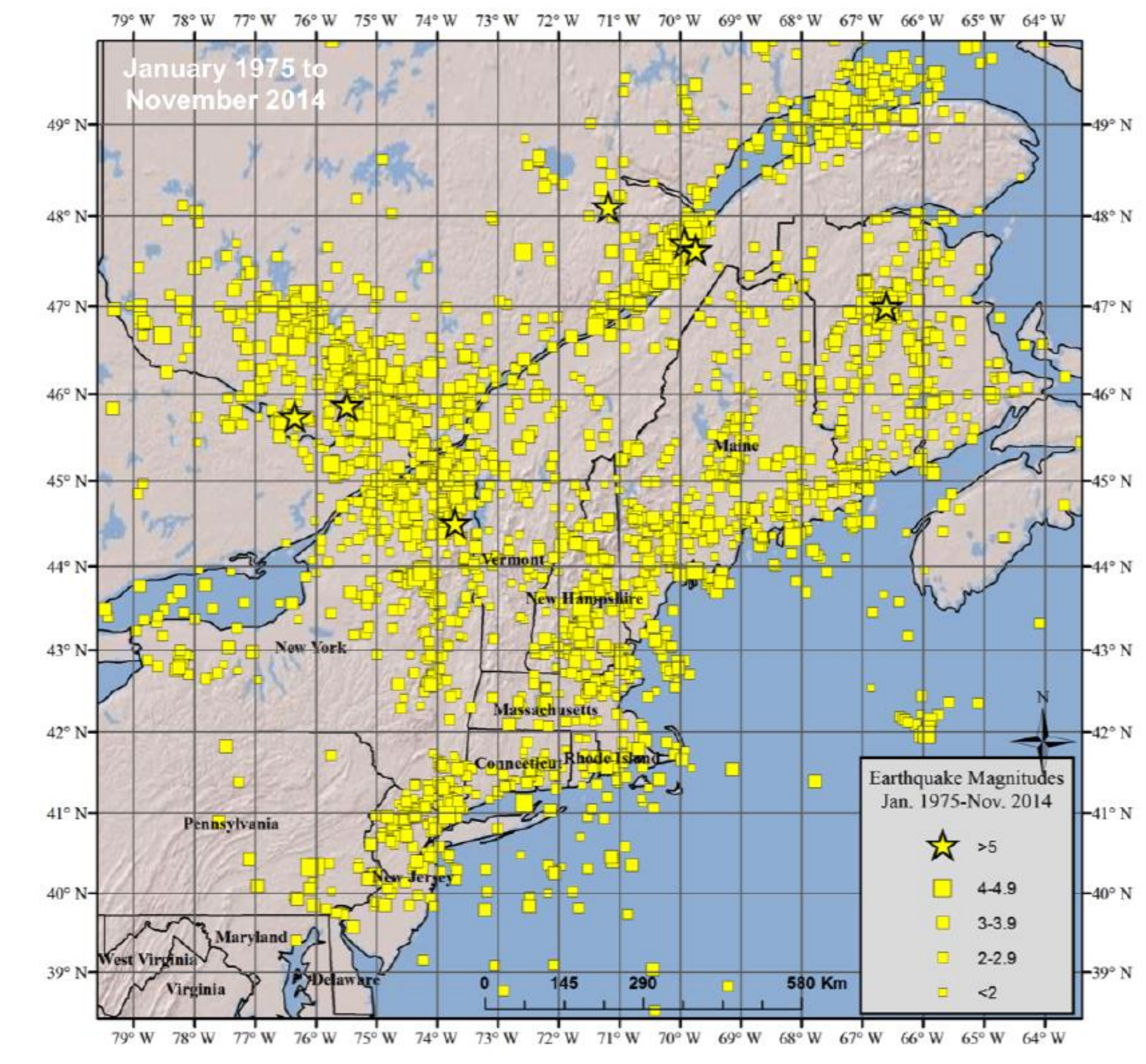


Geology of eastern Massachusetts. —Modified from Zen and others, 1983

Weston Observatory Historical Seismicity

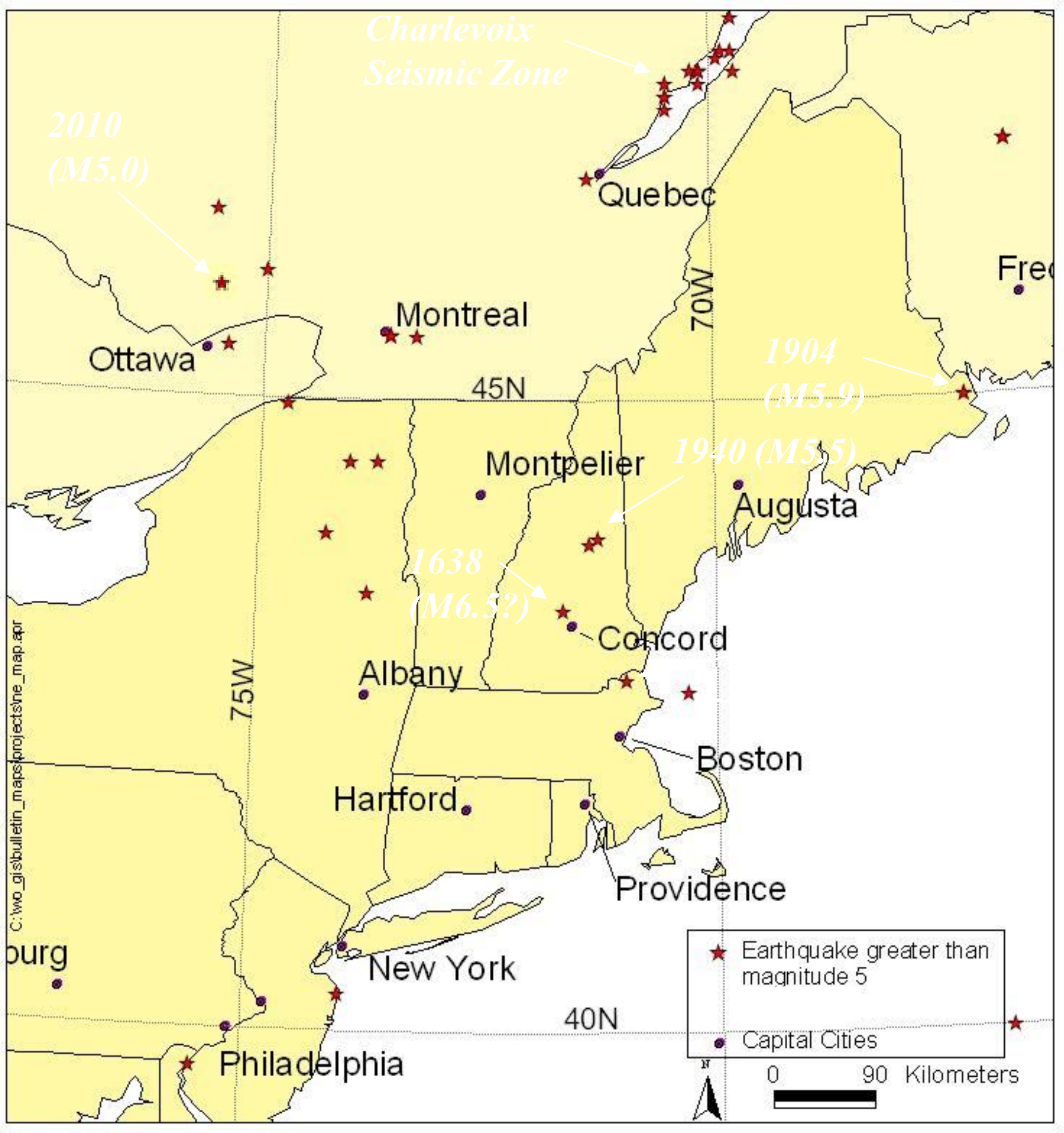


Weston Observatory Network Seismicity



Large Earthquakes 1638-2012

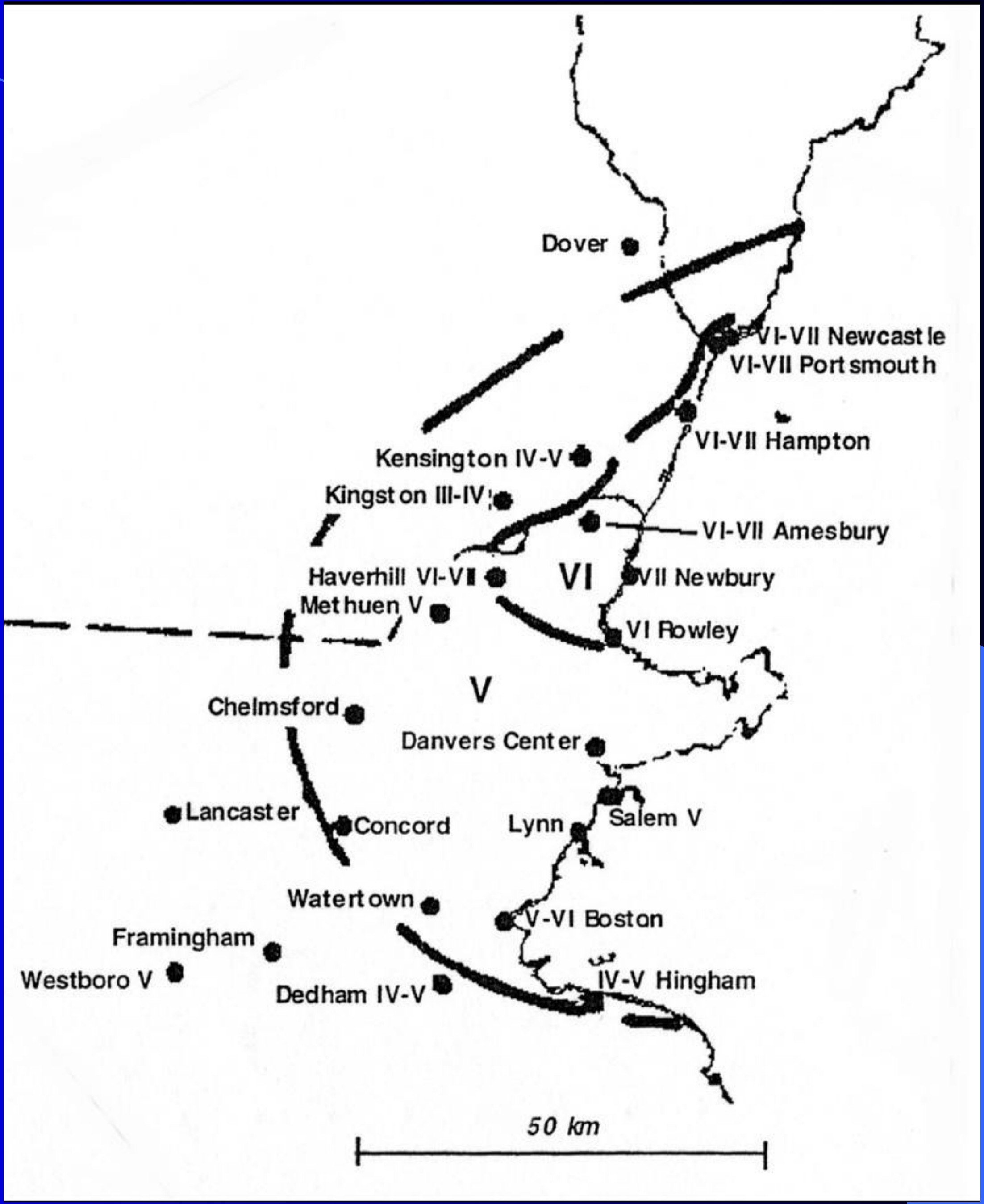
All the known or suspected earthquakes of magnitude 5.0 or greater in New England and vicinity. There were damaging earthquakes centered in New England in 1638, 1727, 1755, 1904 and 1940. The largest earthquake on this plot was about M7.5 at Charlevoix, Quebec in 1663.



1727 Newburyport Earthquake

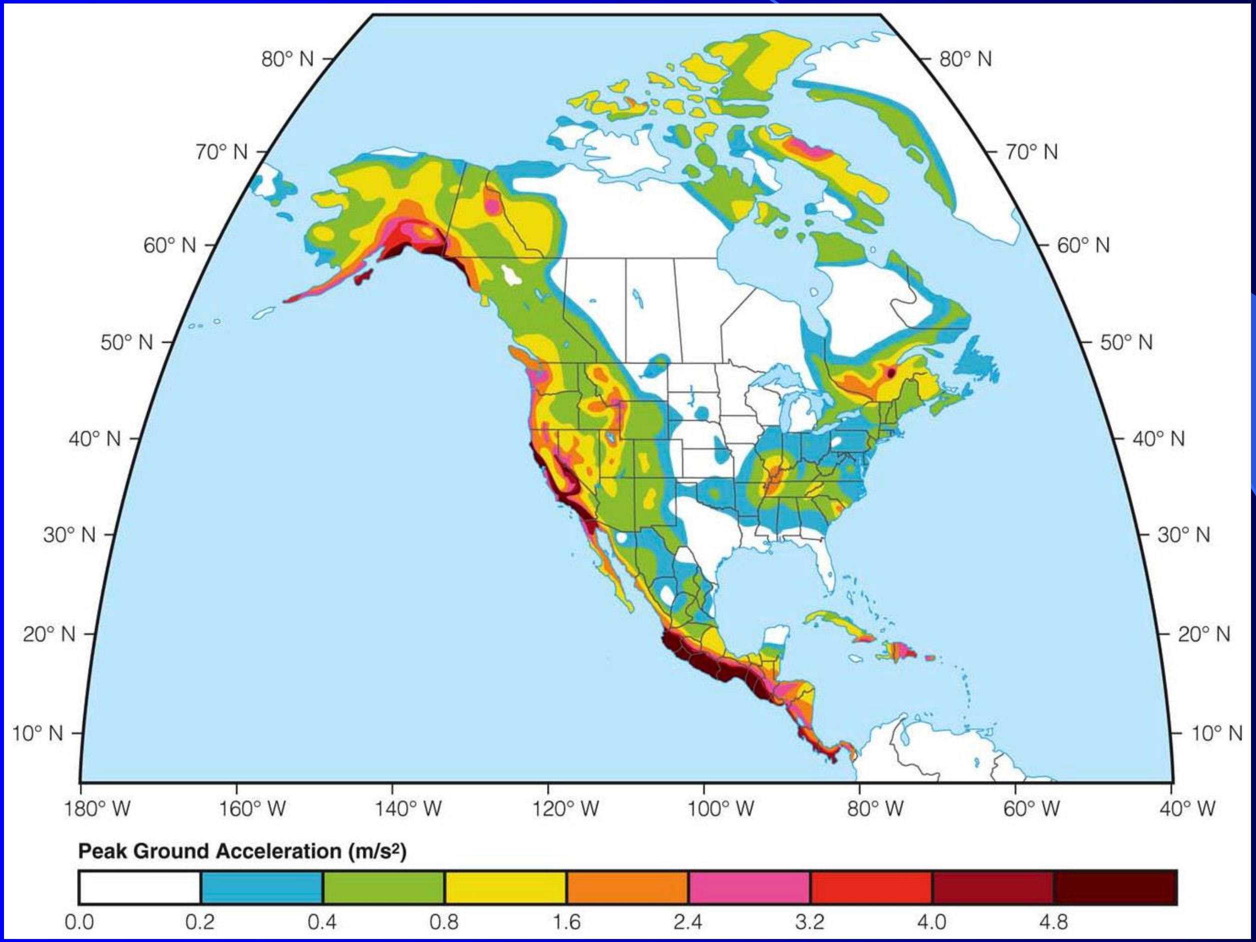
The earthquake damaged chimneys and stone walls in Newbury, Massachusetts and nearby towns. It was felt to Philadelphia and Casco Bay, Maine.

Estimated magnitude of this earthquake is 5.6.



Earthquake Hazards

- **Primary** – ground motion and surface rupture
- **Secondary** – fires, landslides, liquefaction, tsunamis



Primary effects - most earthquake damage is caused by differential movement of the land surface due to the passage of the transverse surface waves.

Secondary Effects

Liquefaction

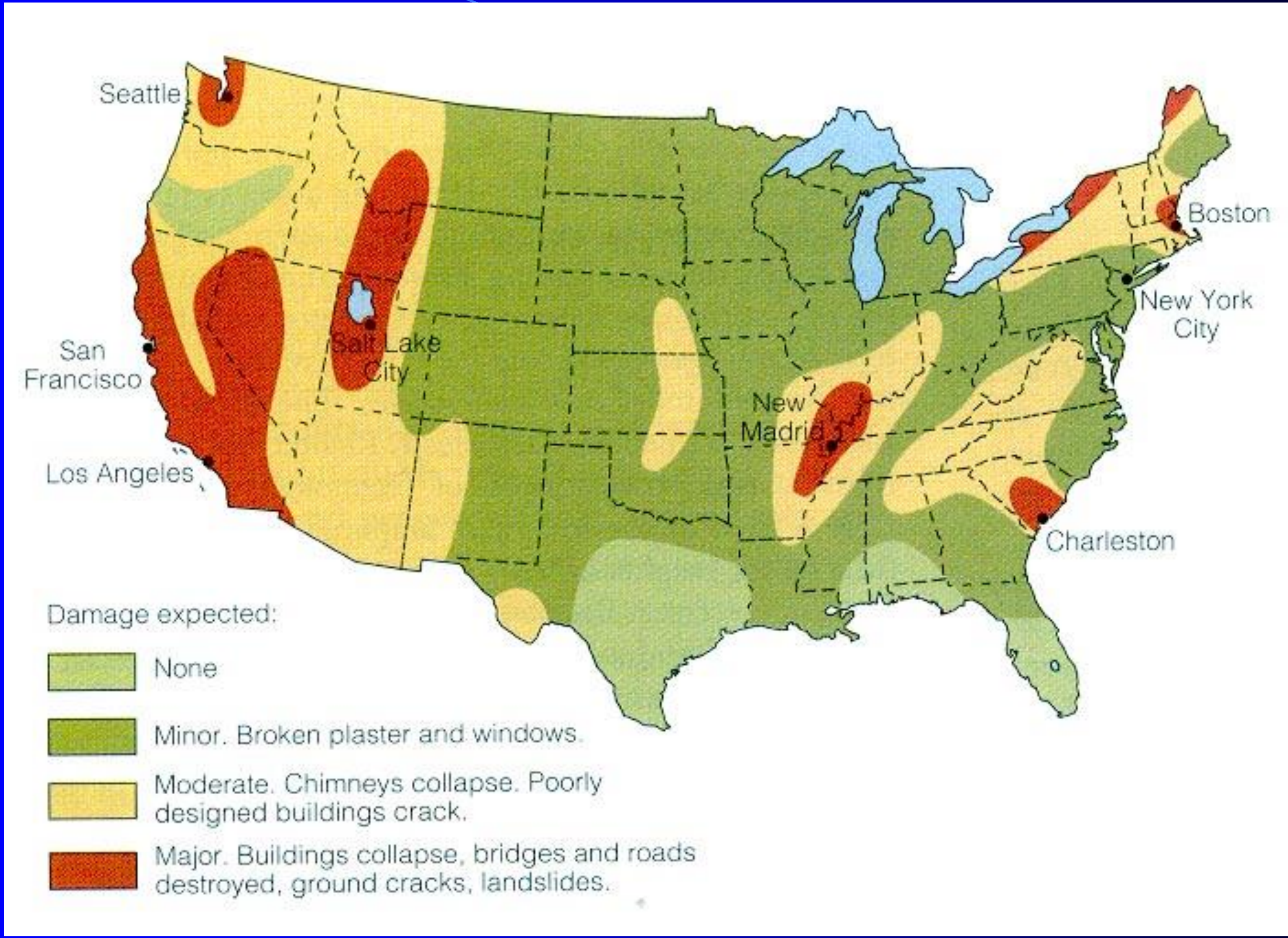
Tsunami

Landslide

Fire

Mud volcano

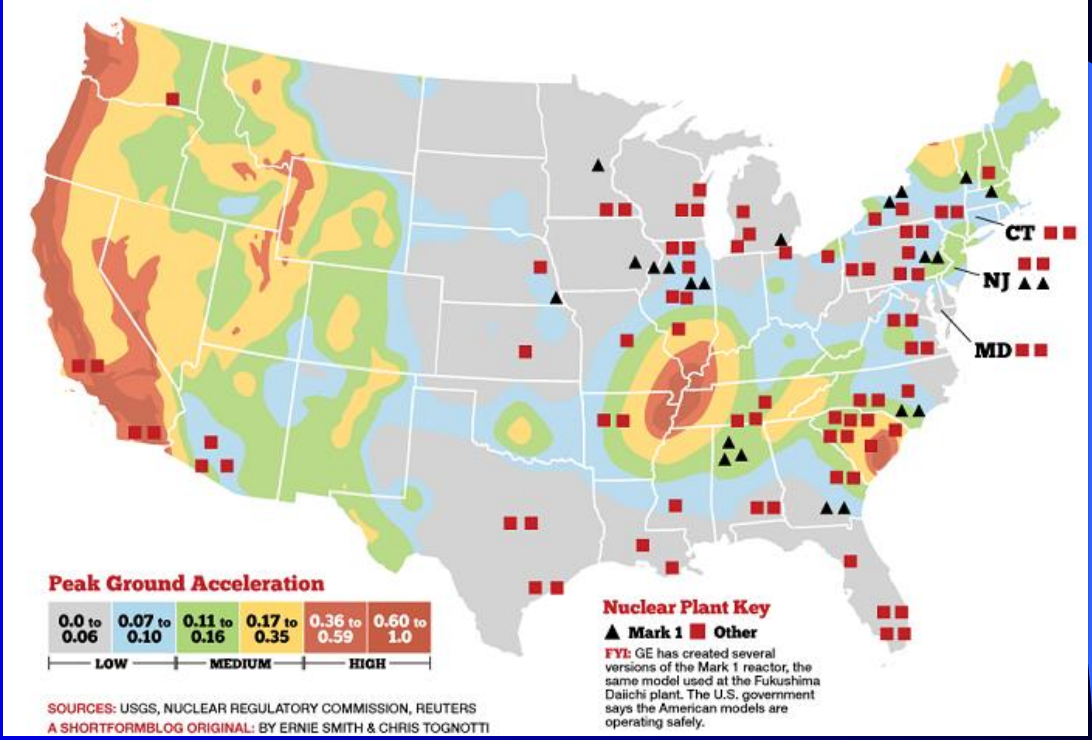
Seismic-risk map for the contiguous United States



Boston is in the same seismic-risk zone as San Francisco

Peak Ground Acceleration (PGA) in m/s^2

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	**< 0.0017**	< 0.1	Not felt	None
II-III	**0.0017 - 0.014**	0.1 - 1.1	Weak	None
IV	**0.014 - 0.039**	1.1 - 3.4	Light	None
V	**0.039 - 0.092**	3.4 - 8.1	Moderate	Very light
VI	**0.092 - 0.18**	**8.1 - 16**	Strong	Light
VII	0.18 - 0.34	**16 - 31**	Very strong	Moderate
VIII	0.34 - 0.65	**31 - 60**	Severe	Moderate to heavy
IX	0.65 - 1.24	**60 - 116**	Violent	Heavy
X+	> 1.24	**> 116**	Extreme	Very heavy



Predicting Earthquakes

1) Recurrence intervals – can only be applied to relatively frequent earthquakes

2) Seismic quiet zones – an inactive area along a fault trace represents a region in which strain is accumulating – a potential locus for failure

3) Changes in water level in wells – as rocks begin to fail voids develop (dilatancy) and groundwater moves into the voids

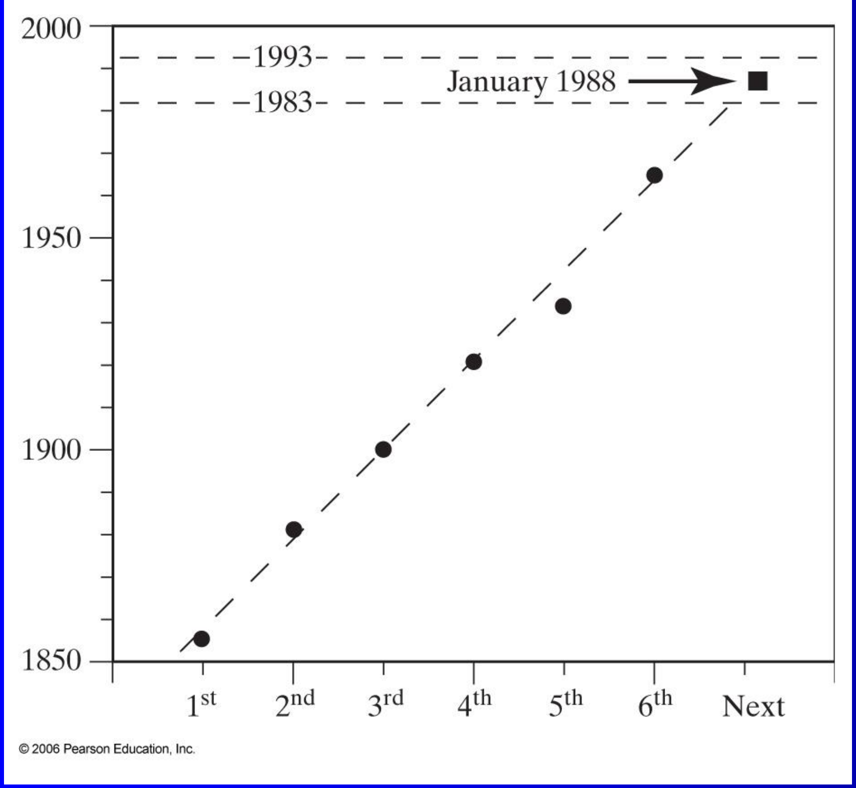
4) Increase in frequency of small earthquakes – precursor earthquakes

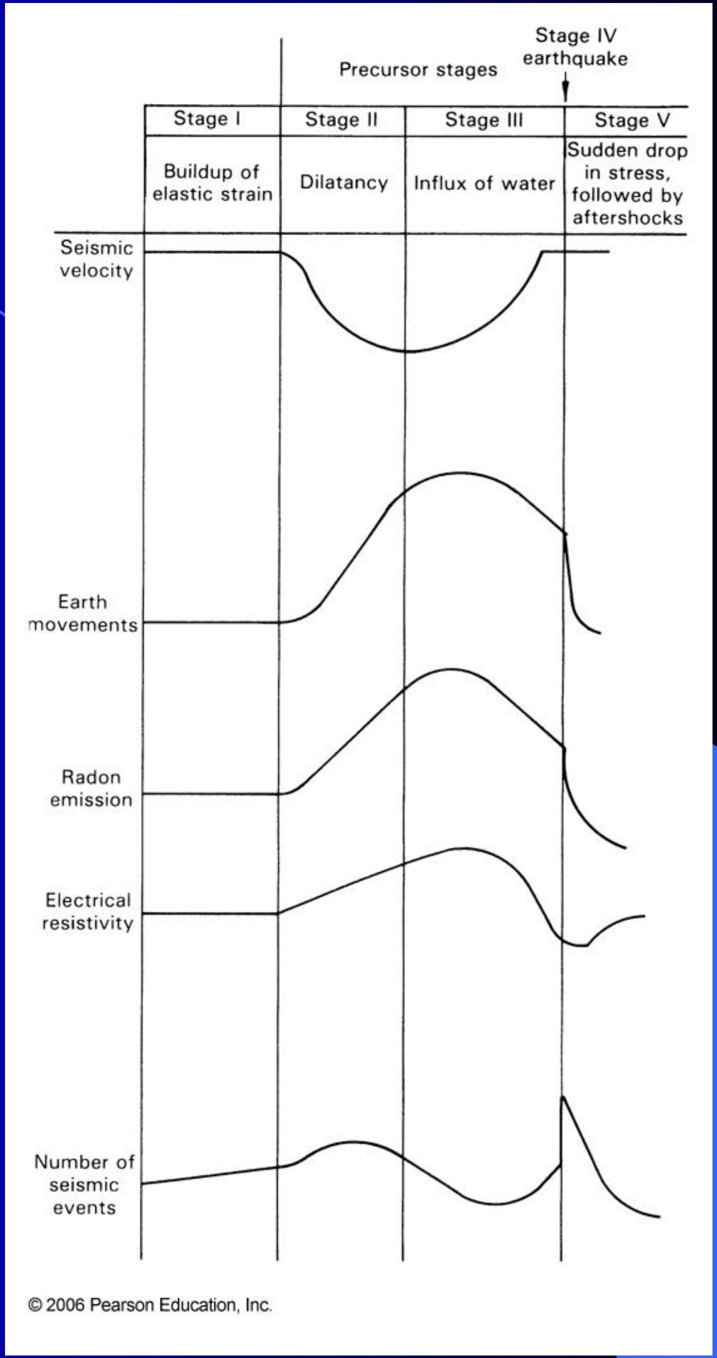
5) Strain measurements – monitor accumulation of strain

6) Folklore

Dilatancy model

Recurrence Interval





Parkfield, CA

Earthquake occurred in 2004

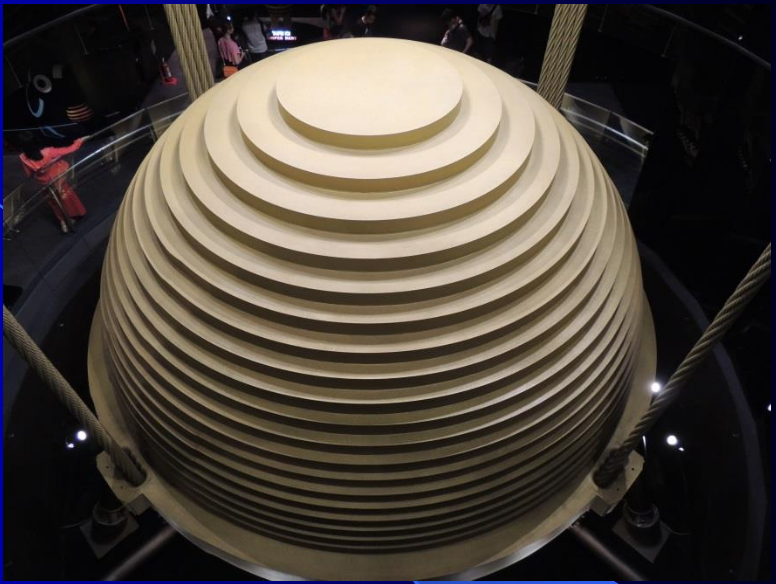
Engineering Solutions

Design structure to be earthquake resistant

1) Anchor structure to bedrock
2) Strengthen against lateral movement
3) Secure façade to building frame
4) Decouple building mass from foundation

Accept reality – there is no such thing as an earthquake proof building. Earthquakes will occur, structures will fail, and there will be loss of human life. It is doubtful that earthquake prediction will ever have the immediacy to make evacuation a viable option.


Building 101



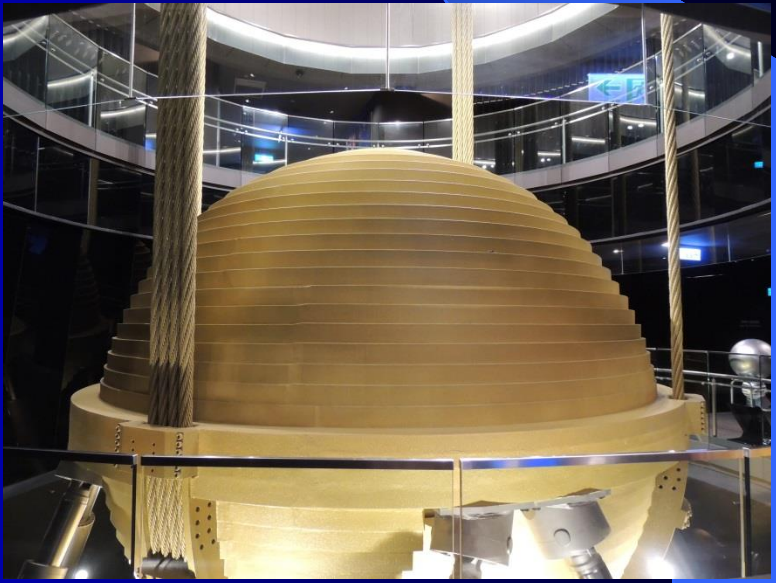


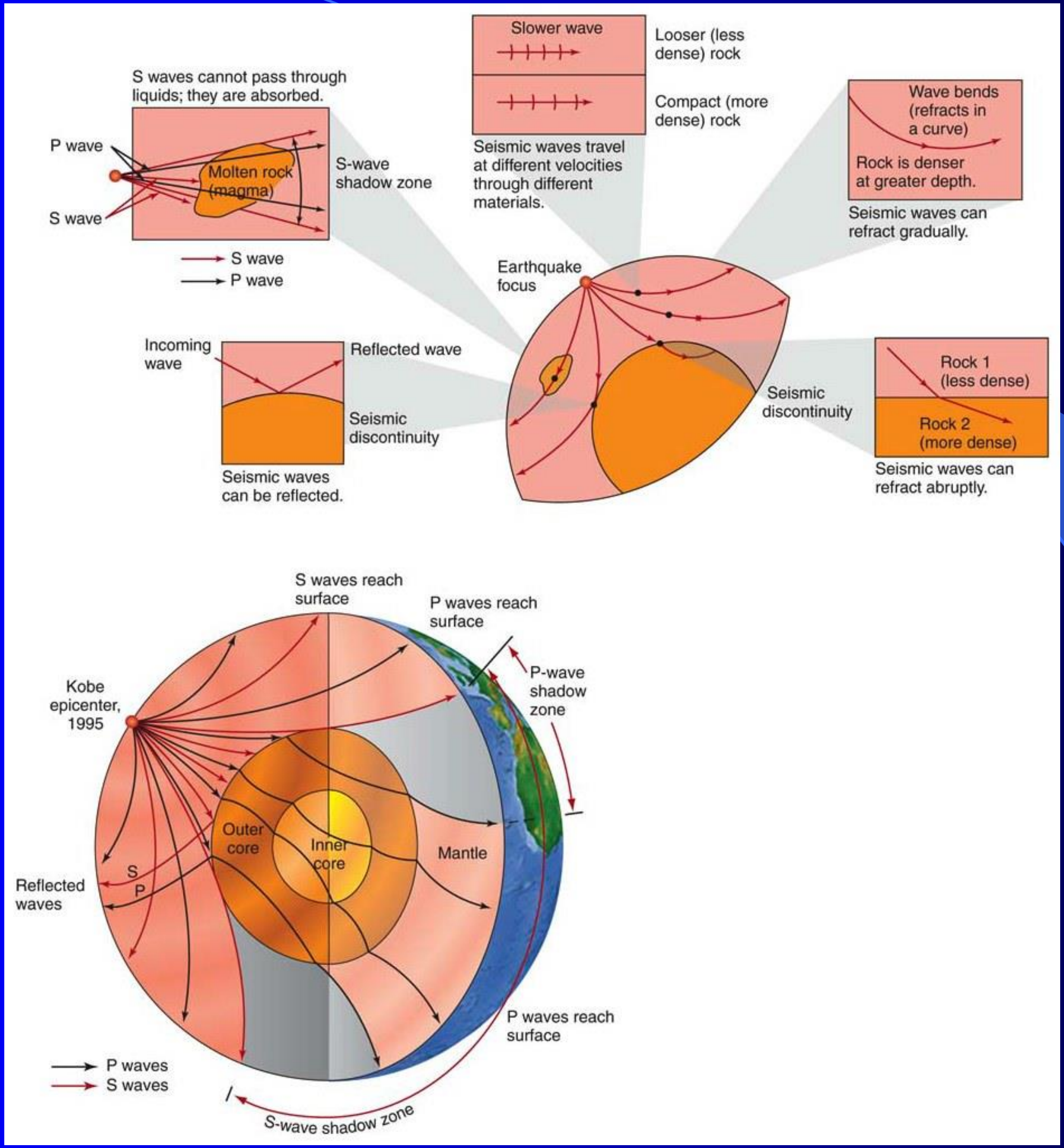
Table 8.4 Earthquake Ratings for Common Building Types

Simplified Description of Structural Types	Relative Damageability (in order of increasing susceptibility to damage)
Small wood-frame structures, i.e., dwellings not over 3000 sq ft, and not over 3 stories	1
Single or multistory steel-frame buildings with concrete exterior walls, concrete floors, and concrete roof. Moderate wall openings	1.5
Single or multistory reinforced-concrete buildings with concrete exterior walls, concrete floors, and concrete roof. Moderate wall openings	2
Large-area wood-frame buildings and other wood-frame buildings	3 to 4
Single or multistory steel-frame buildings with unreinforced masonry exterior wall panels; concrete floors and concrete roof	4
Single or multistory reinforced-concrete frame buildings with unreinforced masonry exterior wall panels, concrete floors, and concrete roof	5
Reinforced-concrete bearing walls with supported floors and roof of any materials (usually wood)	5
Buildings with unreinforced brick masonry having sandlime mortar and with supported floors and roof of any materials (usually wood)	7 up
Bearing walls of unreinforced adobe, unreinforced hollow concrete block, or unreinforced hollow clay tile	Collapse hazards in moderate shocks

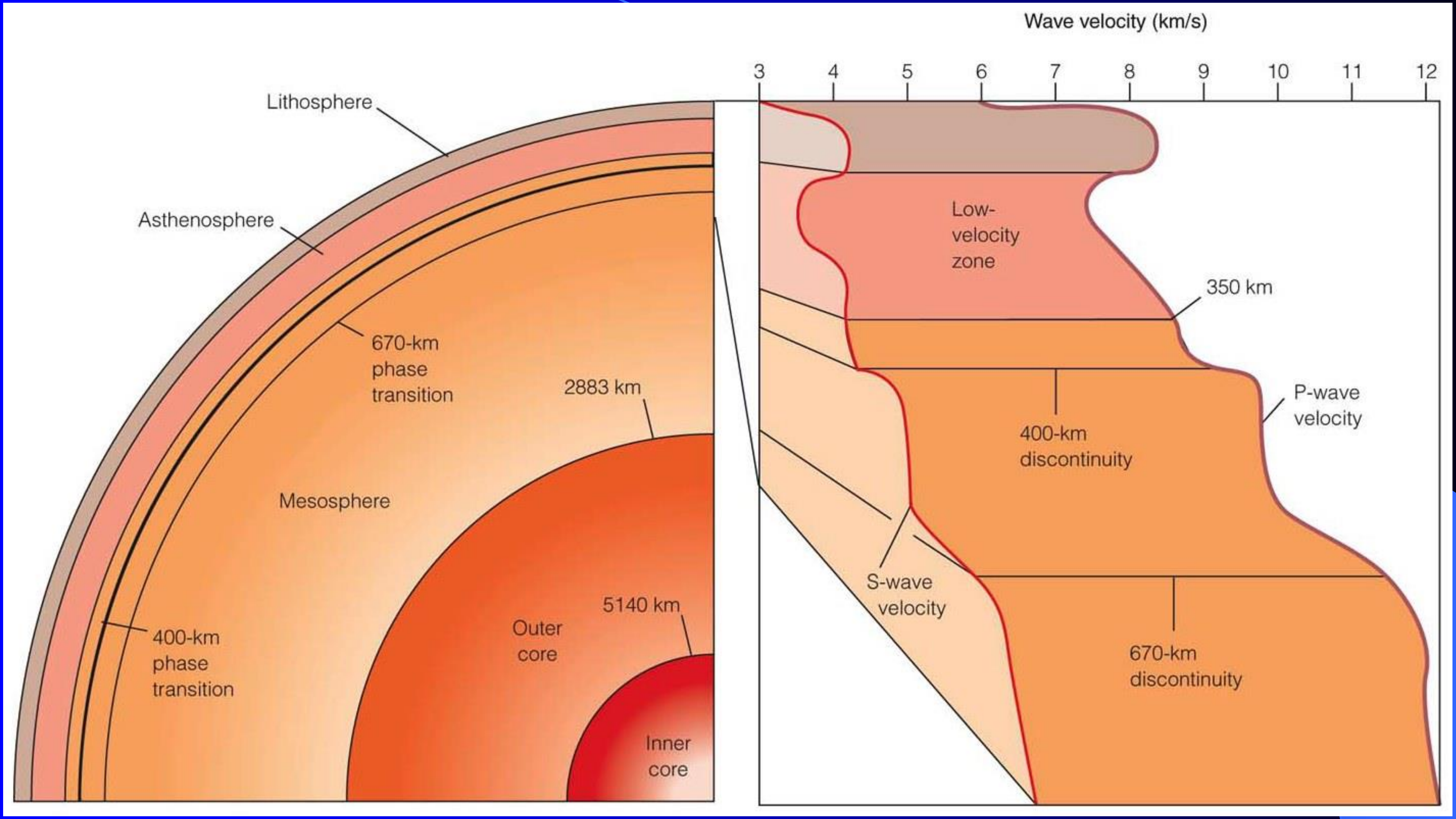
Source: From D. Armstrong, 1973, *The Seismic Safety Study for the General Plan*, Sacramento, Calif.: California Council on Intergovernmental Relations.

Note: This table is not complete. Additional considerations would include parapets, building interiors, utilities, building orientation, and frequency response.

Earthquakes and the Earth's Interior



Seismic Discontinuities



Planet Earth – the megascopic scale

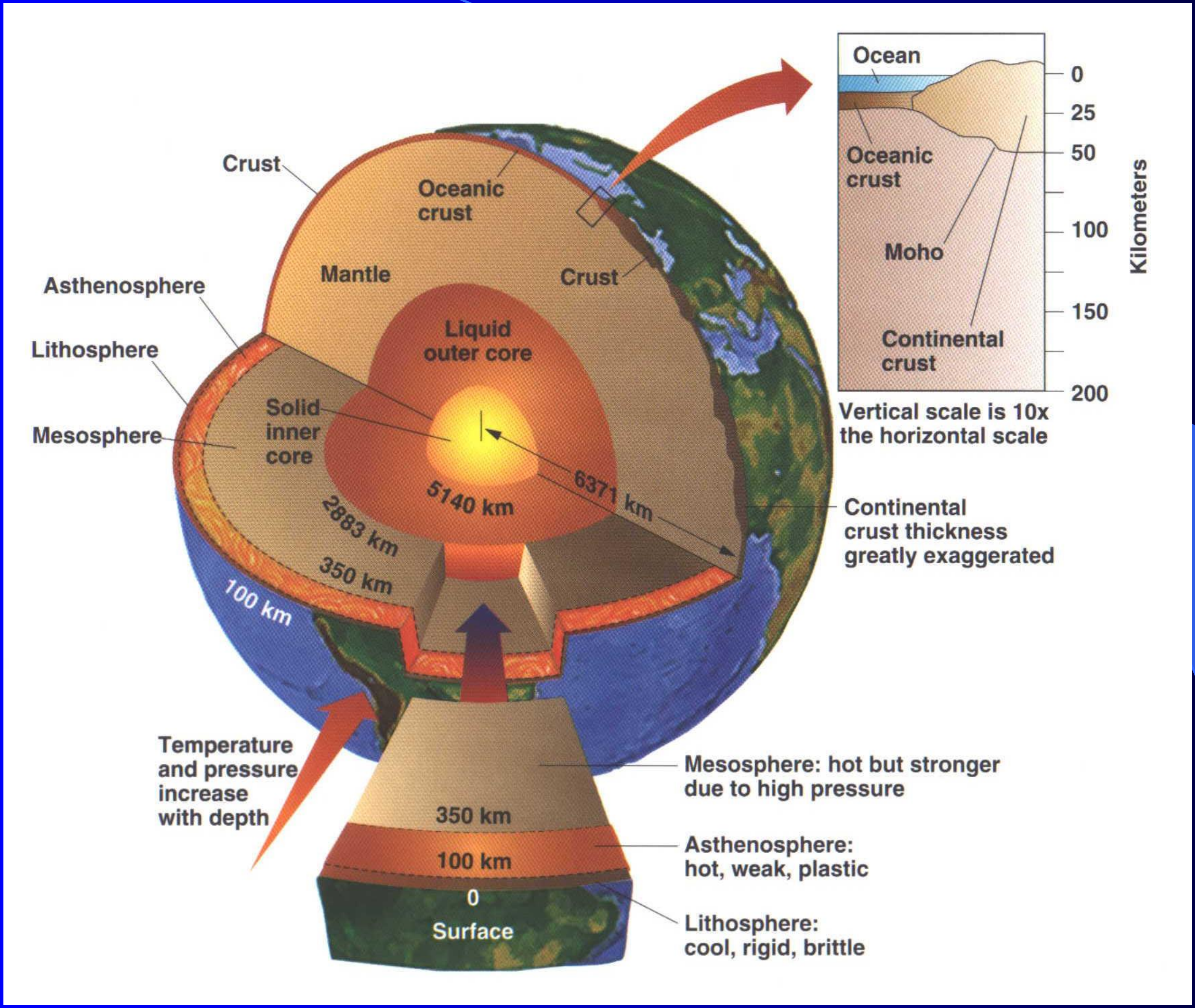
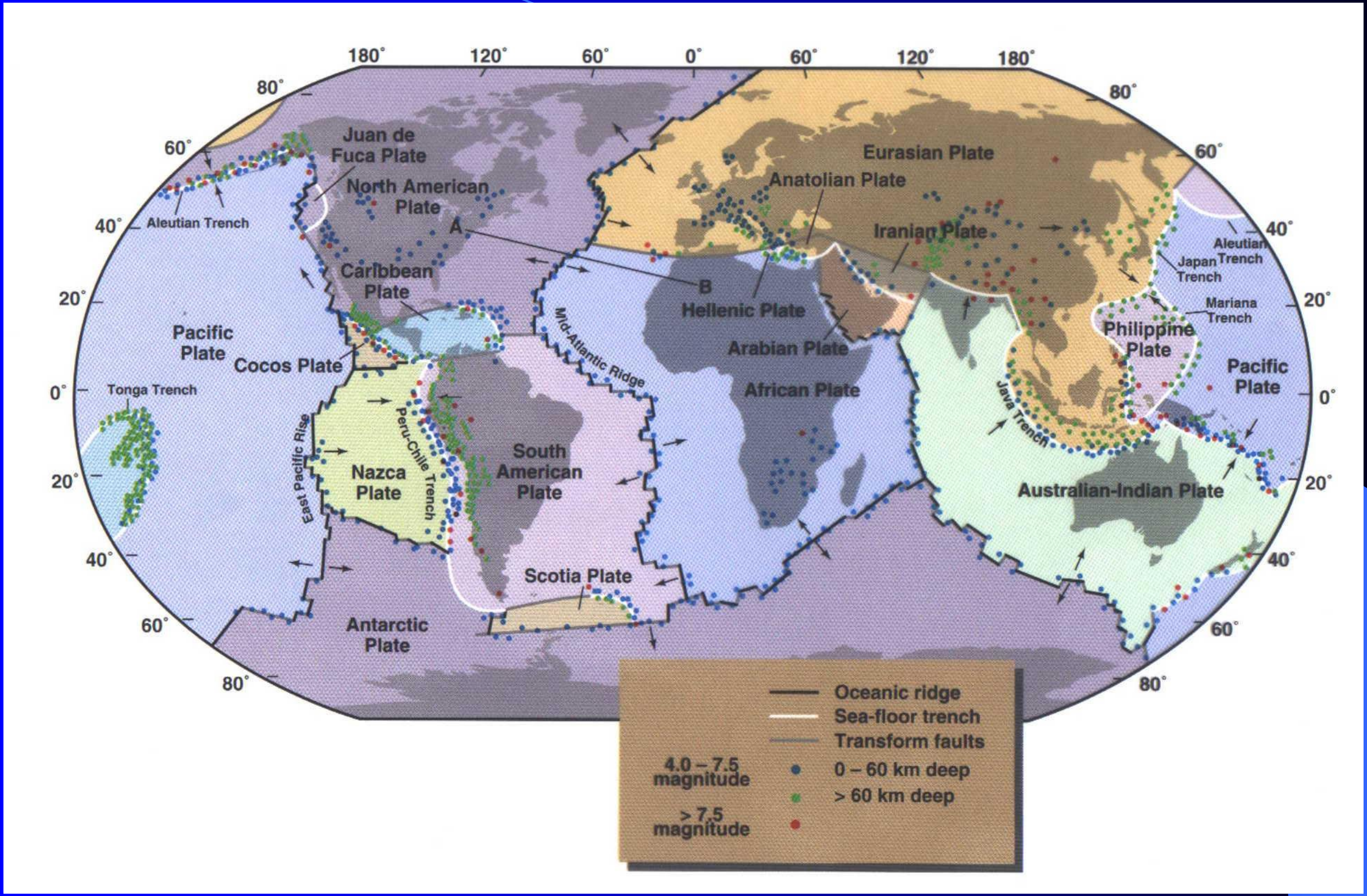
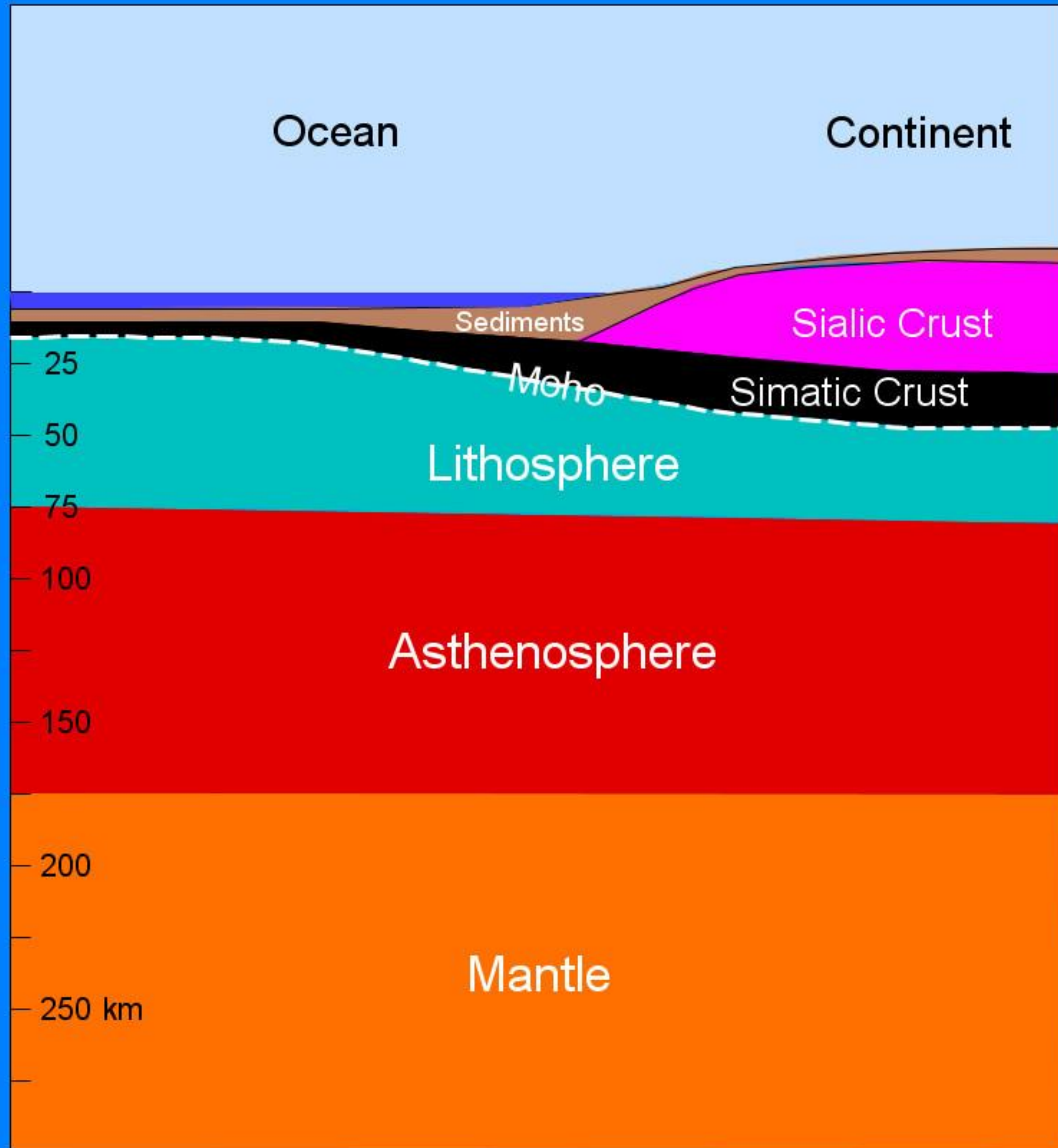


Plate Boundaries and Earthquakes



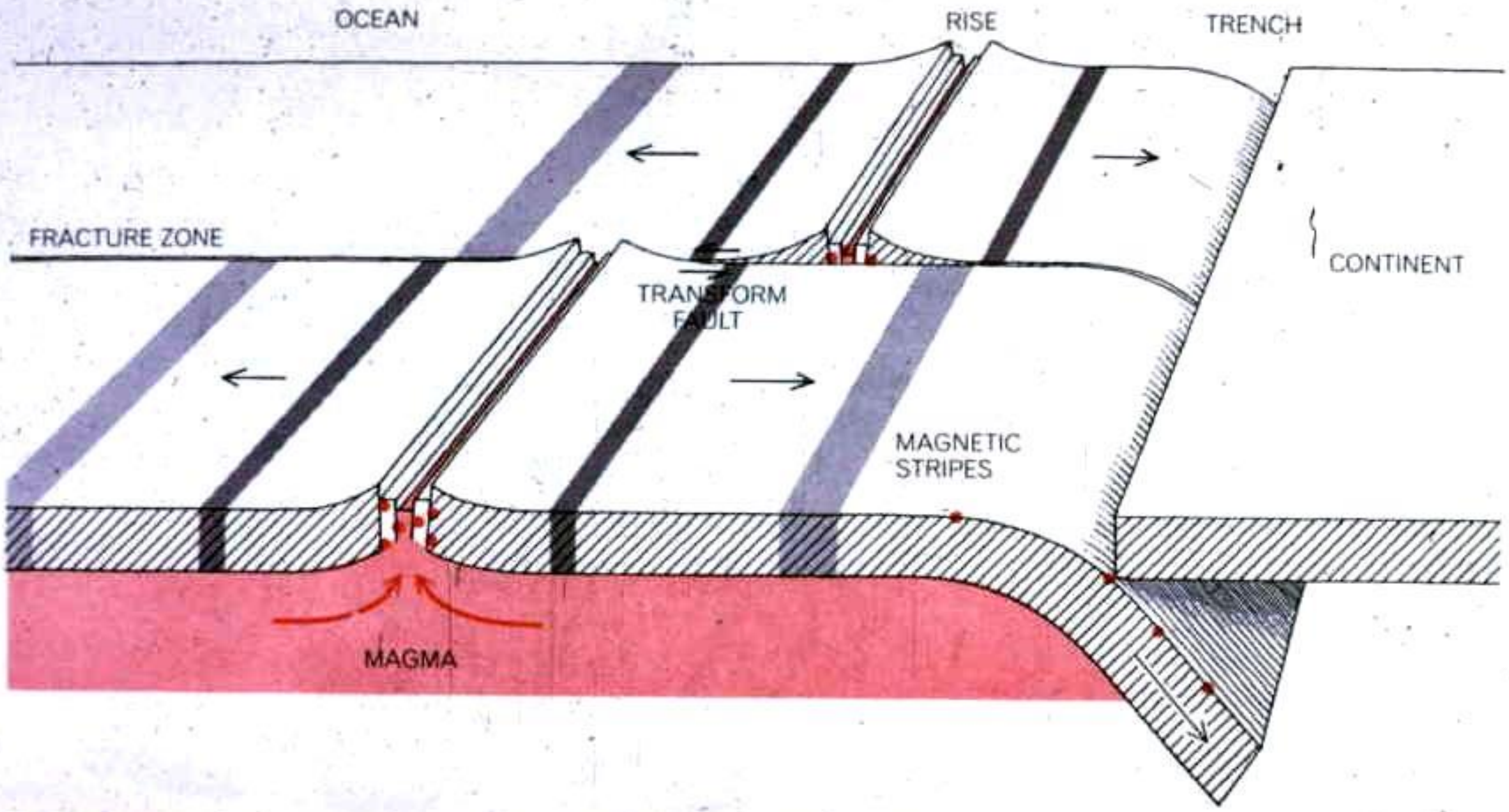
A tectonic plate consists of the crust of the earth and the upper part of the mantle (the lithosphere). The lithosphere behaves as a rigid solid. The Moho is a seismic discontinuity within the lithosphere that marks the boundary between the crust and the mantle. The tectonic plate moves on the asthenosphere, a portion of the mantle that behaves plastically.



Four types of seismic activity characteristic of plate boundaries

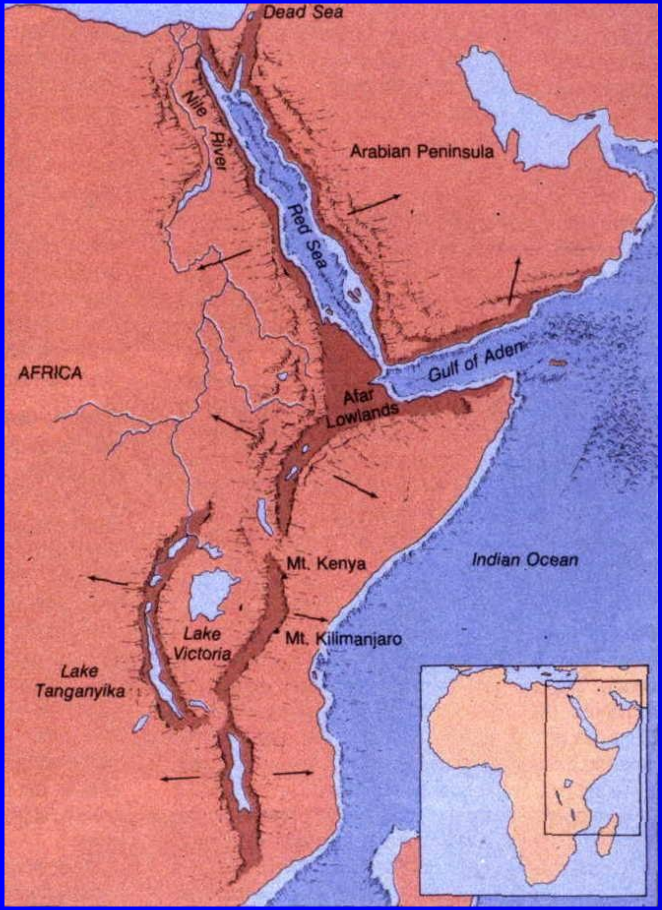
1. **Spreading ridges:** shallow earthquakes, relatively low magnitude, occurring in lines
2. **Transform faults:** shallow focus, sometimes very powerful earthquakes
3. **Continental collisions:** shallow-deep focus in broad bands, can be very powerful
4. **Subduction zones:** deepest and most powerful earthquakes, some megathrust, some tsunami

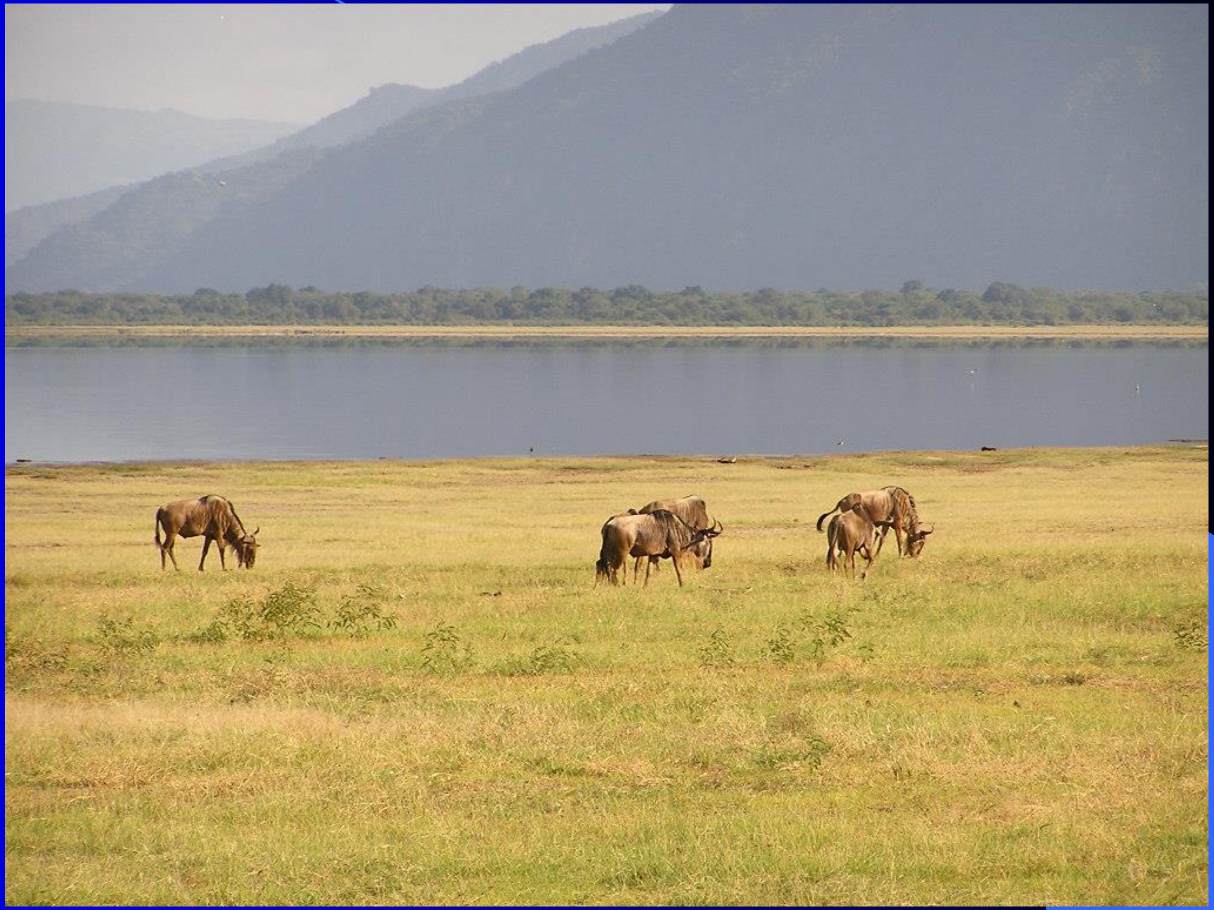
Three types of plate boundaries – (1) spreading centers, (2) subduction zones, and (3) strike-slip faults (plates are sliding past each other).



RIFT IN OCEAN FLOOR (*color*) initiates three major features of oceanic plate tectonics. The rift is bordered by a rise or ridge created by magma pushed up from the mantle below. The magma solidifies with a magnetic polarity corresponding to that of the earth. When, at long intervals, the earth's polarity reverses, the polarity of newly formed crust reverses too, resulting in a sequence of magnetic "stripes." A trench results when an oceanic plate meets a continental plate. A fracture zone and transform fault result when two plates move past each other. Earthquakes (*dots*) accompany these tectonic processes. The earthquakes in the vicinity of a rise and along a transform fault are shallow. Deep-focus earthquakes occur where a diving oceanic plate forms a trench.

Spreading center – mid-ocean ridge system and the East African rift system and rift valley





Subduction zone

Earthquakes associated with oceanic trenches extend to great depths. This was a puzzle because for earthquakes to occur rocks must behave as elastic solids. At depths greater than 70 km rocks ***do not*** behave as elastic solids. Something else must be going on. The interpretation, backed by gravity and heat flow data, was that the seafloor was returning to the mantle of the earth. This process is referred to as ***subduction***.

Fig. 4-9 Schematic map of distribution of earthquake epicenters for deep-focus earthquakes between the Tonga trench and the Fiji Islands, north of New Zealand. Locate this on Figures 3-12 and 4-7. (Based on data of L. R. Sykes, 1966, *Jour. Geophys. Res.*, *71*, 2981-3006.)

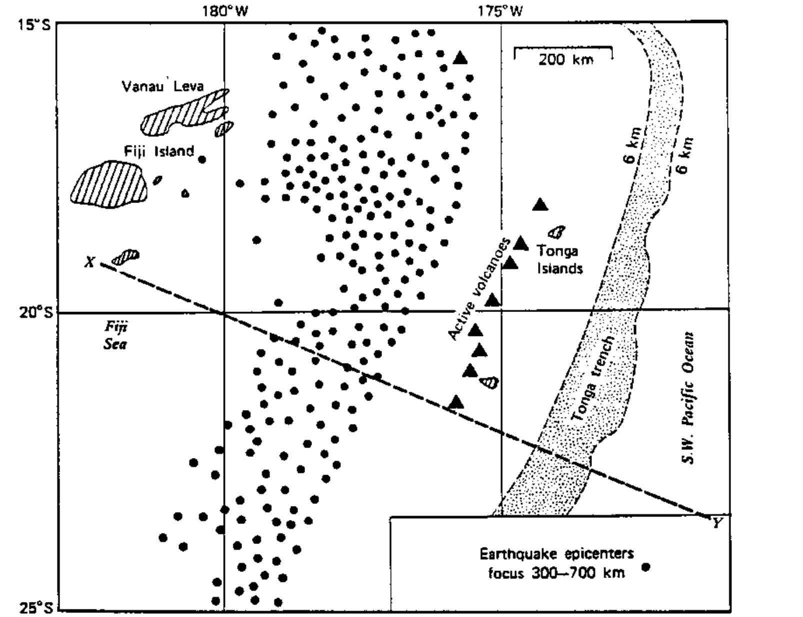
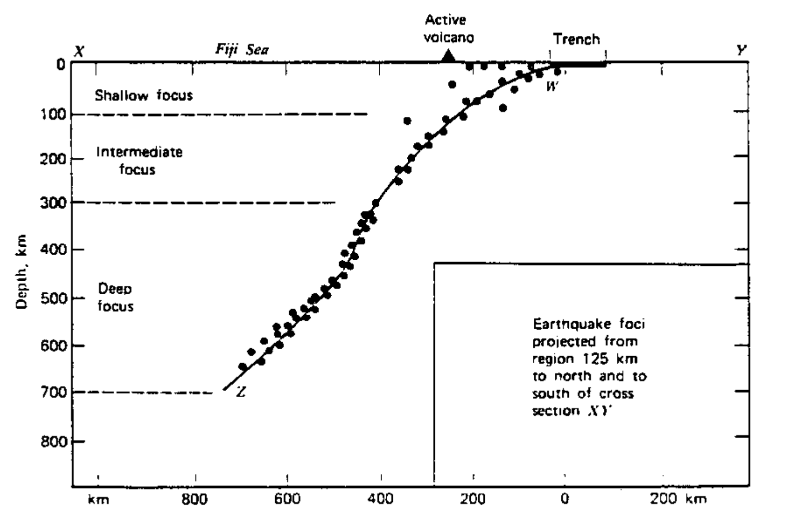


Fig. 4-10 Vertical cross section through line *XY* in Figure 4-9, showing schematically the distribution of earthquake foci down to depths of 700 km. The foci lie close to line *WZ* extending downward from the ocean trench. (Based on data of L. R. Sykes, 1966, see Figure 4-9.)



Strike-slip fault – two plates sliding by each other

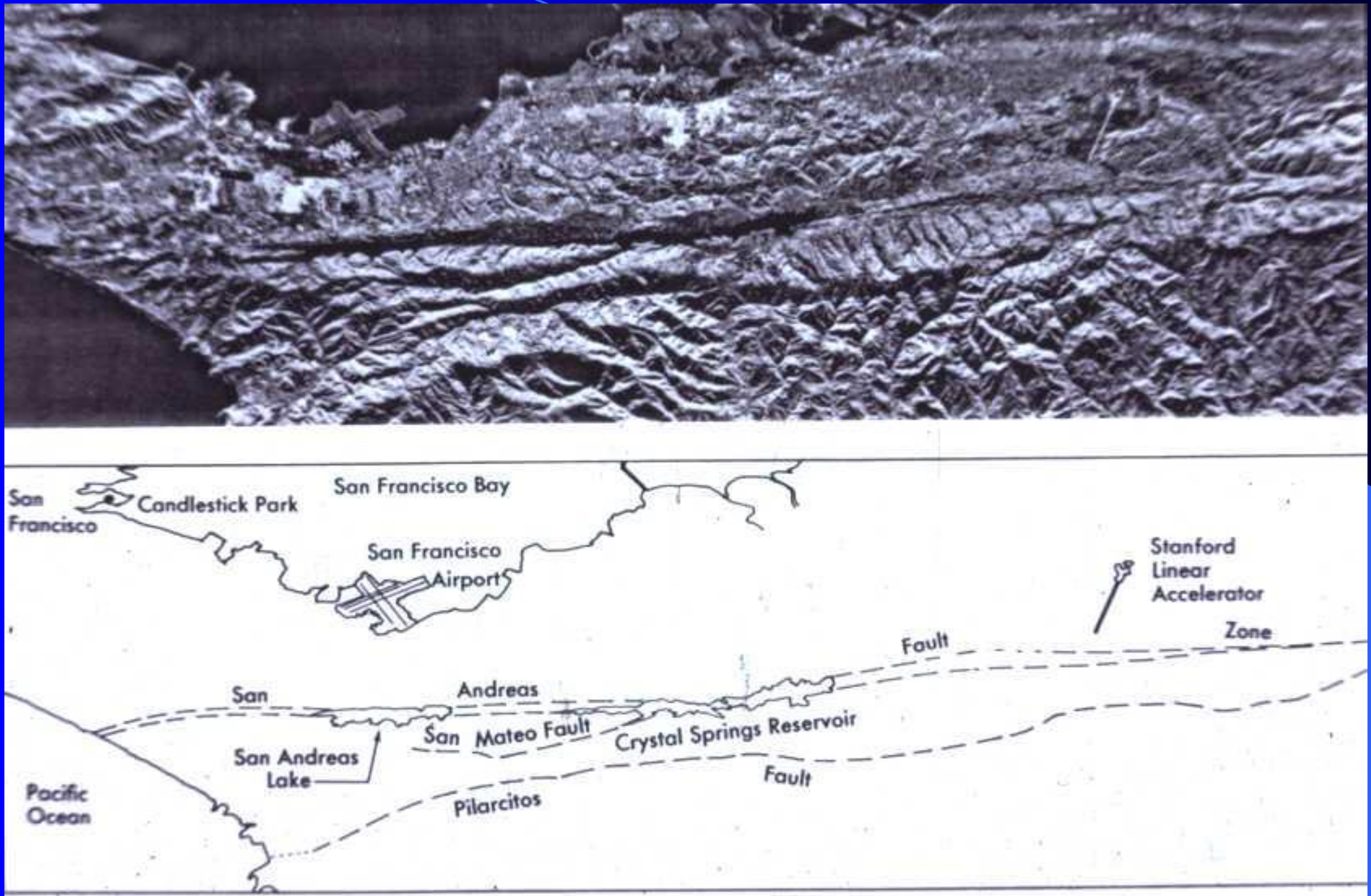
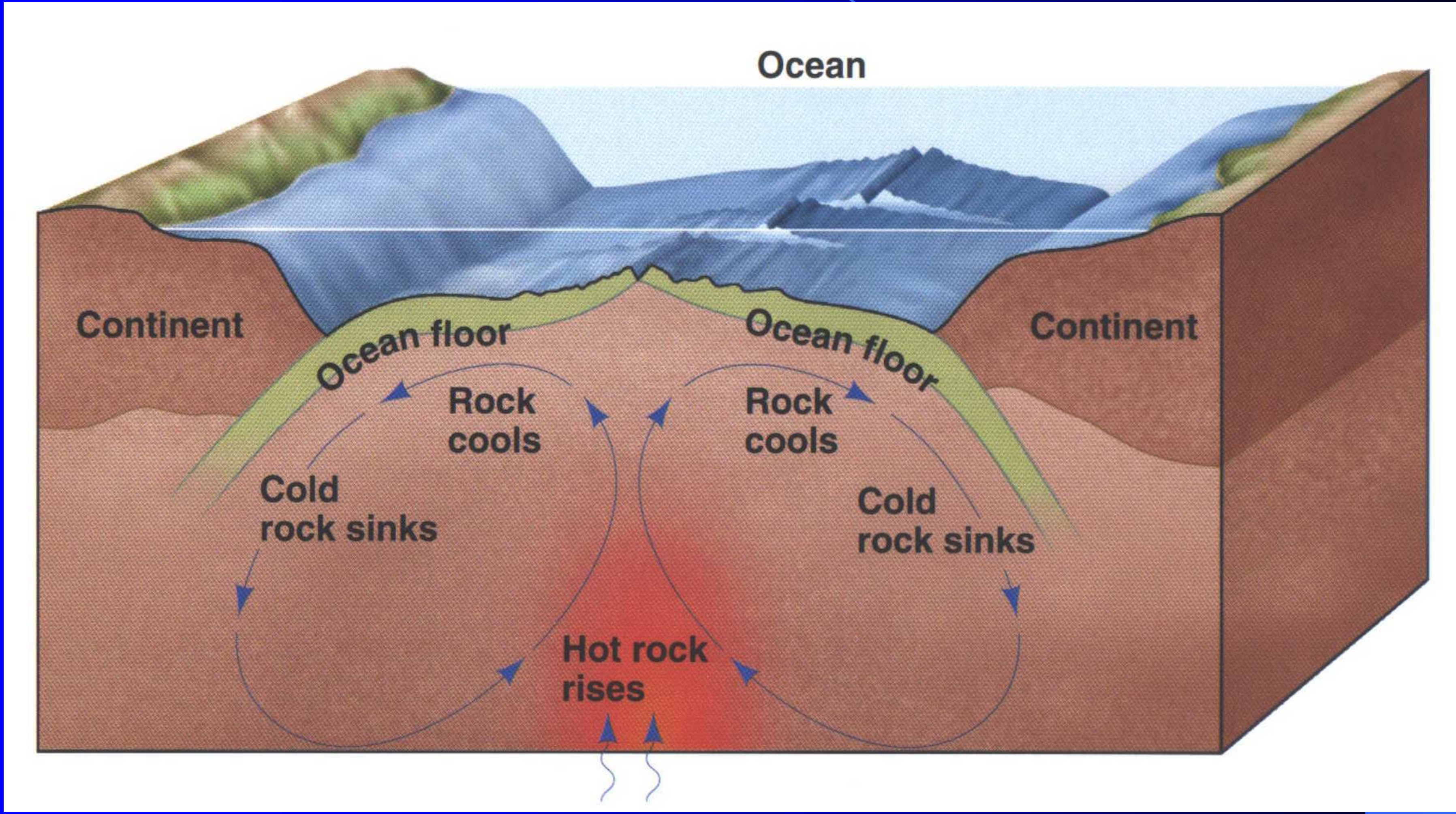


FIG. 1-5. *Radar images. A. San Francisco Peninsula. Unlike conventional aerial photos, radar images can be obtained in cloudy weather or even at night. The radar penetrates the vegetation and reveals the actual surface. The bottom (west) part of this area has thick redwood forests. From U. S. Geological Survey in cooperation with NASA and Westinghouse Electric Co.*

Convection in the Earth's Mantle

Spreading occurs where mantle material rises and subduction occurs where mantle material descends.



Seismic velocity variations and mantle convection

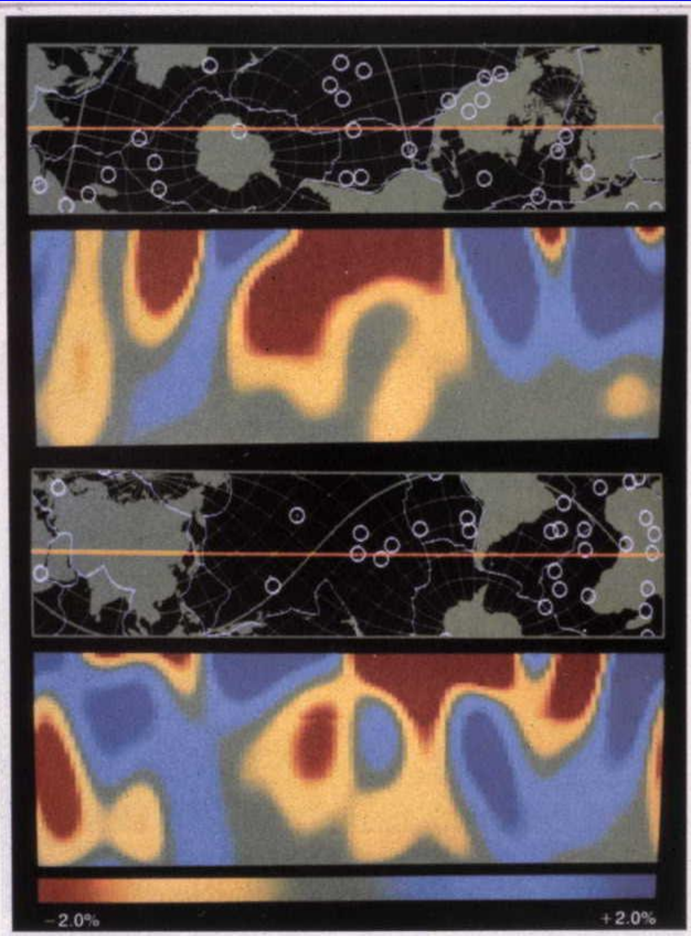


Figure 6. The great circle (*orange line*) on each of the two surface maps shows the location of the vertical cross-sectional images of the upper 670 km of the mantle. These images, which have a vertical exaggeration of 25:1, show that the velocity anomalies associated with midocean ridges and continental shields change radically at greater depths, contrary to what many geophysicists had assumed. (After Woodhouse and Dziewonski 1984.)

Seismic velocity variations can be correlated with differences in mantle density and inferred differences in temperature. Red = hot, blue = cold. Transfer of heat energy, by convection in the mantle, from the core of the earth to the surface is the driving force for plate tectonics.

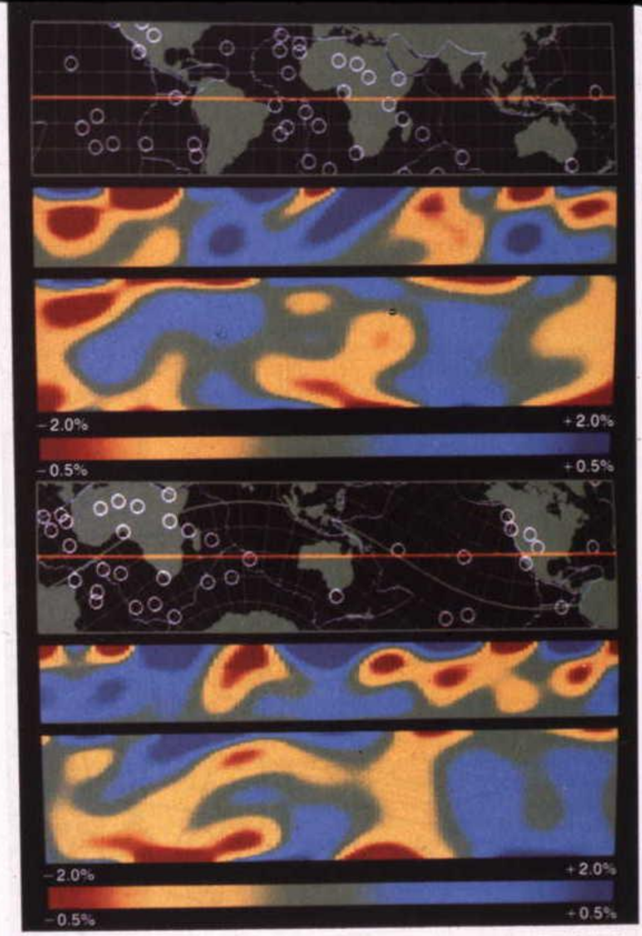


Figure 10. Each of these two cross sections combines views of the upper mantle (derived from shear-velocity anomalies, as in Fig. 6) and of the lower mantle (derived from compressional-velocity anomalies, as in Fig. 9); note the difference in velocity scale for these two regions. Vertical exaggeration is 8:1 for the upper mantle and 4:1 for the lower mantle. Such combined images cannot as yet solve the problem of whether mantle convection involves vertical flow throughout the mantle, because resolution is poor at 670 km, where the break between the models of the upper mantle and lower mantle