Earthquakes

- Earthquakes are one of nature's most frightening phenomena and an indication that Earth is an internally active planet.
- About 13 million people have died in earthquakes in the last 4,000 years, 2.7 million in the last century alone.

Some Significant Earthquakes

YEAR	LOCATION	MAGNITUDE	DEATHS
1556	China (Shanxi Province)	8.0	1,000,000
1755	Portugal (Lisbon)	8.6	70,000
1811-1812	USA (New Madrid, Missouri)	7.5	20
1886	USA (Charleston, South Carolina)	7.0	60
1906	USA (San Francisco, California)	8.3	700
1923	Japan (Tokyo)	8.3	143,000
1964	USA (Alaska)	8.6	131
1976	China (Tangshan)	8.0	242,000
1985	Mexico (Mexico City)	8.1	9,500
1988	Armenia	7.0	25,000
1989	USA (Loma Prieta, California)	7.1	63
1990	Iran	7.3	40,000
1993	India	6.4	30,000
1994	USA (Northridge, California)	6.7	61
1995	Japan (Kobe)	7.2	5,000 +
1997	Iran	7.3	2,400 +
1998	Afghanistan	6.1	5,000 +
1999	Turkey	7.4	17,000

Investigating the Earth

- Direct methods include
  - Drilling through the crust
  - The deepest hole ever drilled was ~12km deep
  - Although oceanic crust is only 8km thick we cannot drill to the mantle
- Mantle magmas & xenoliths
  - Some magmas bring material from depth
  - Xenoliths are fragments of other rocks

Murck and Skinner (1999)

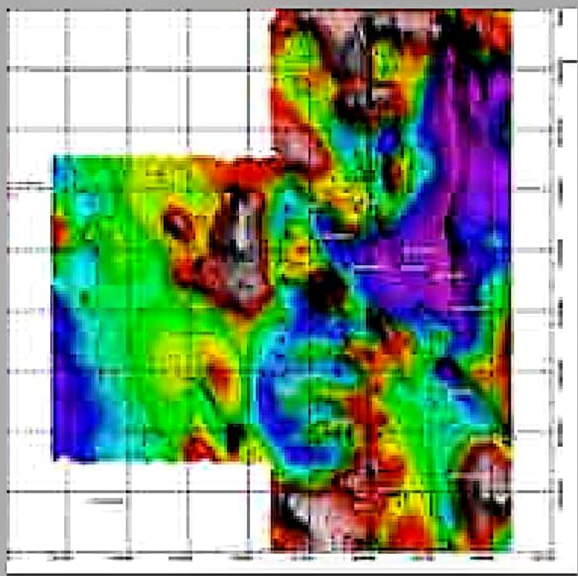
Murck and Skinner (1999)

Indirect methods

- Meteorites
  - Some meteorites were formed at the same time as the Earth and have retained that composition (primitive)
  - Others have compositions similar to the Earth's core (irons/stony irons)

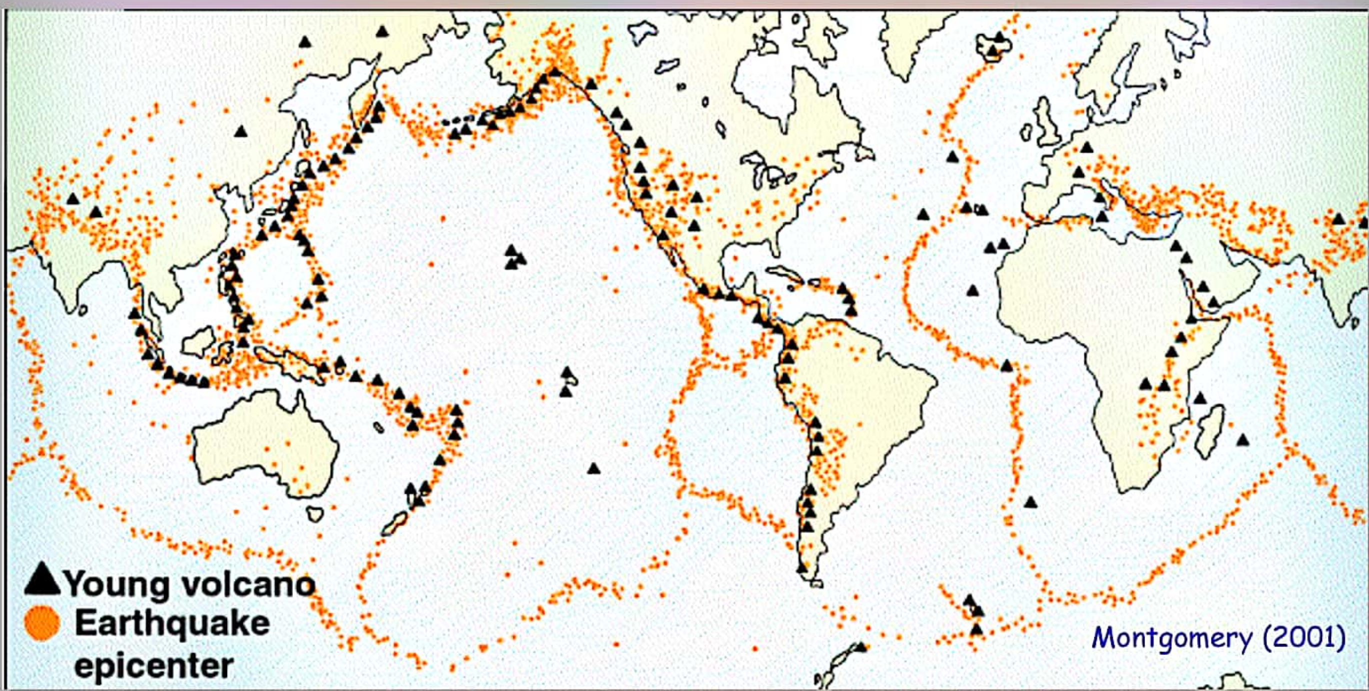
Indirect methods

- Geophysics
  - Magnetism
  - Gravity
  - Seismic surveys
  - Resistivity
  - Gas surveys
  - Conductivity
  - Ground penetrating radar
  - Satellite imagery



Aeromagnetic image courtesy of CODELCO

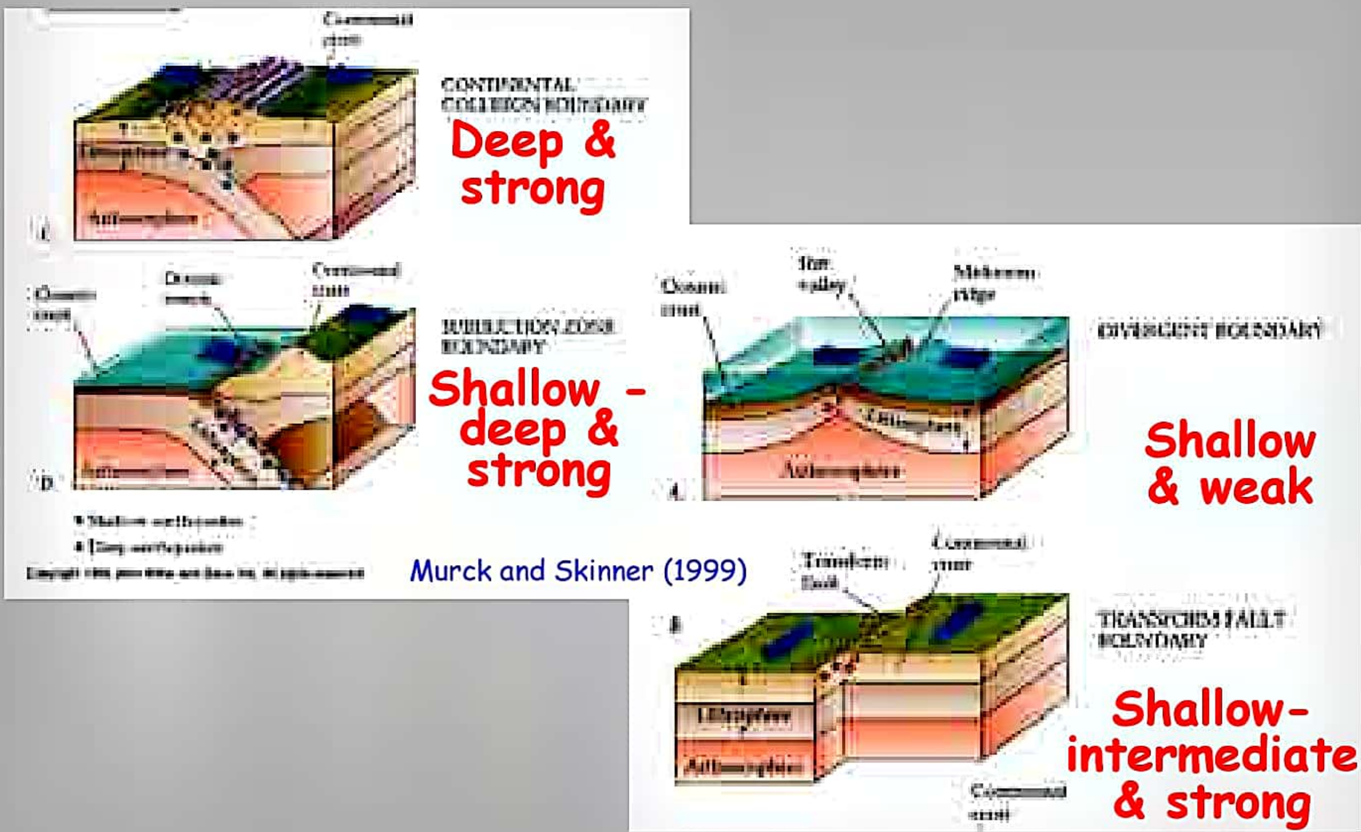
Location of earthquakes



Earthquake depth

- Based on focus-depth, there are 3 types of earthquakes:
  1) shallow-focus at depths <70 km,
  2) intermediate-focus at depths of 70-300 km
  3) deep-focus at depths >300 km.
- Of all earthquakes, 90% occur at depths <100 km and only 3% are deep-focus.

Earthquakes

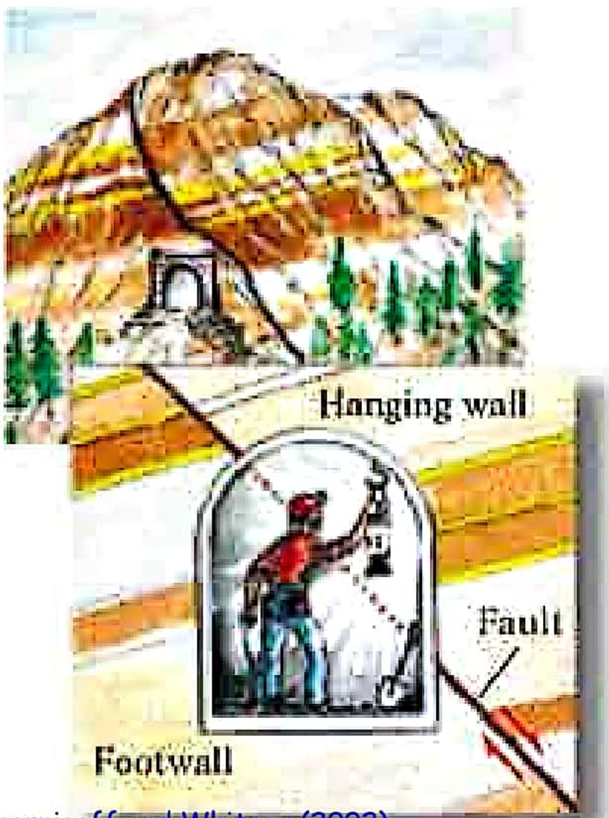


Earthquakes

- There is a clear association between earthquakes and plate boundaries
- But what exactly is an earthquake?
- Earthquake refers to the shaking or trembling of a portion of Earth's surface caused by a sudden release of energy, usually by slippage of rocks along a fracture (faulting).
- After an earthquake, continuing adjustments along the fracture may generate a series of generally smaller quakes known as aftershocks.

Hanging wall & footwall

The footwall block lies beneath the fault plane and the hanging wall block lies above



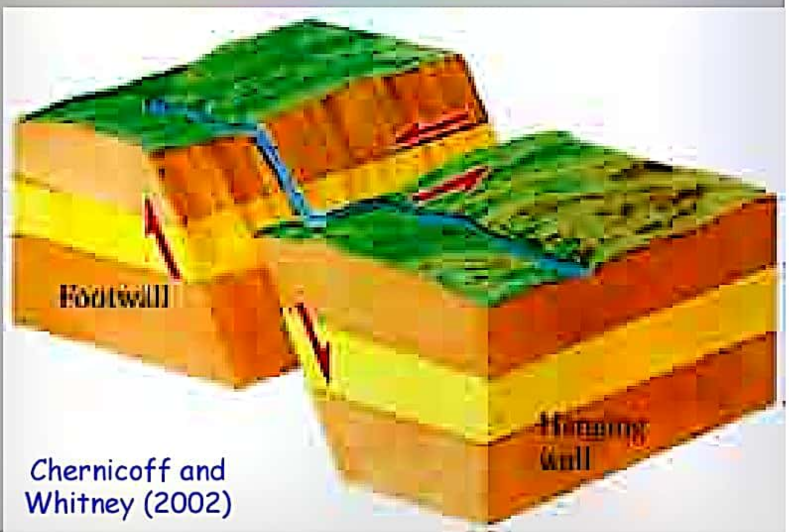
Chernicoff and Whitney (2002)

Fault types

We can only think of the movement on faults in terms of relative movement

- **Normal or dip-slip faults**
- **Reverse faults**
- **Strike slip faults**
- **Oblique slip faults**

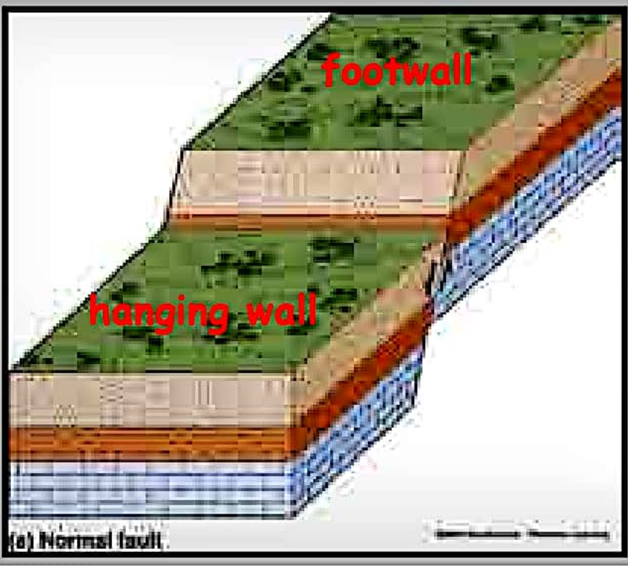
– some combination



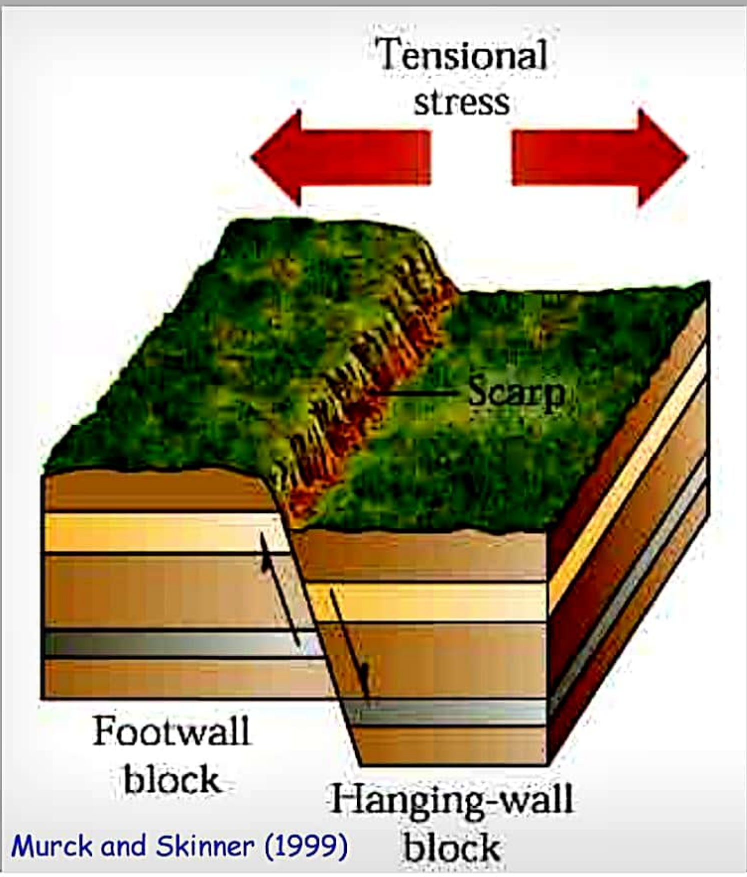
Chernicoff and Whitney (2002)

Normal dip-slip faults

- All movement on a dip-slip fault is parallel to the dip of the fault plane, that is, movement is up or down the fault plane.
- In a normal fault, the hanging wall moves down the fault plane. Normal faults result from tensional stress.



Normal faults

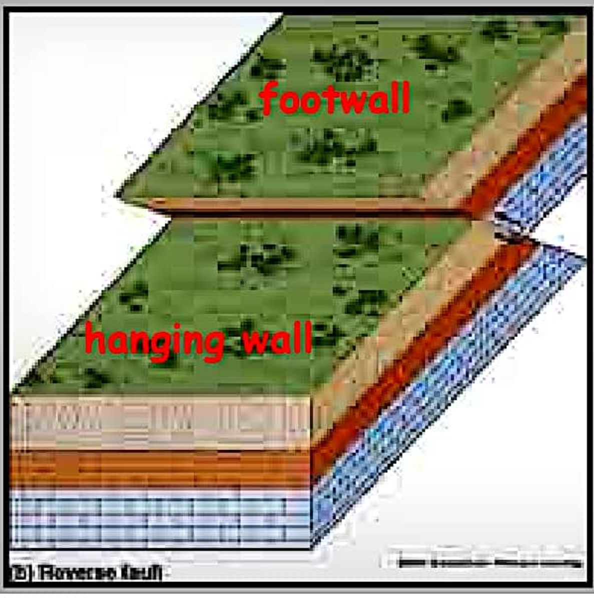


Murck and Skinner (1999)

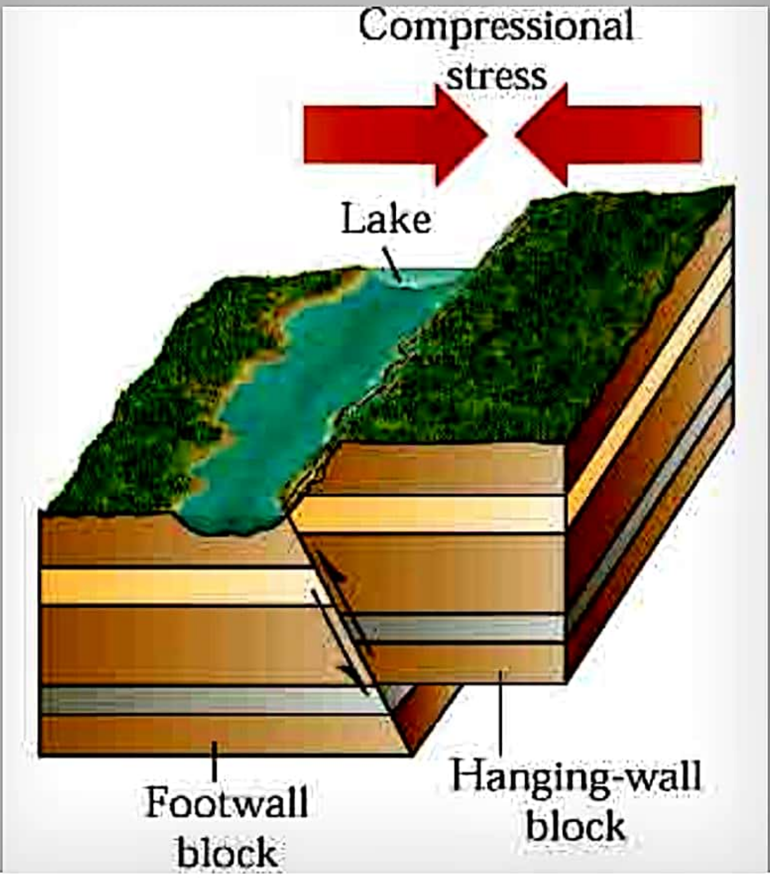

Thompson and Turk (1998)

Reverse dip-slip faults

Reverse faults are dip-slip faults where the hanging wall has moved up the inclined fault plane. In reverse faults, the dip of the fault plane is >45°. Formed by compressional stress



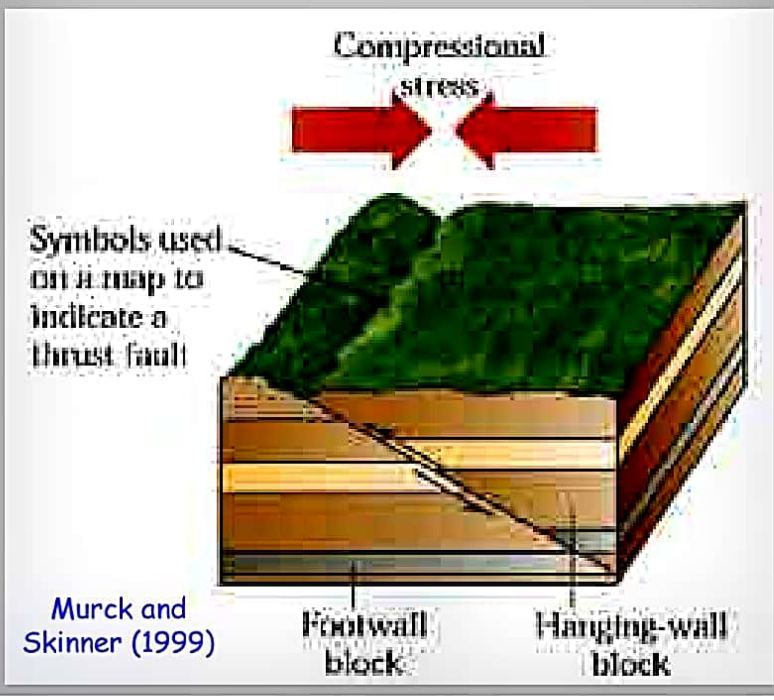
Reverse faults



Murck and Skinner (1999)

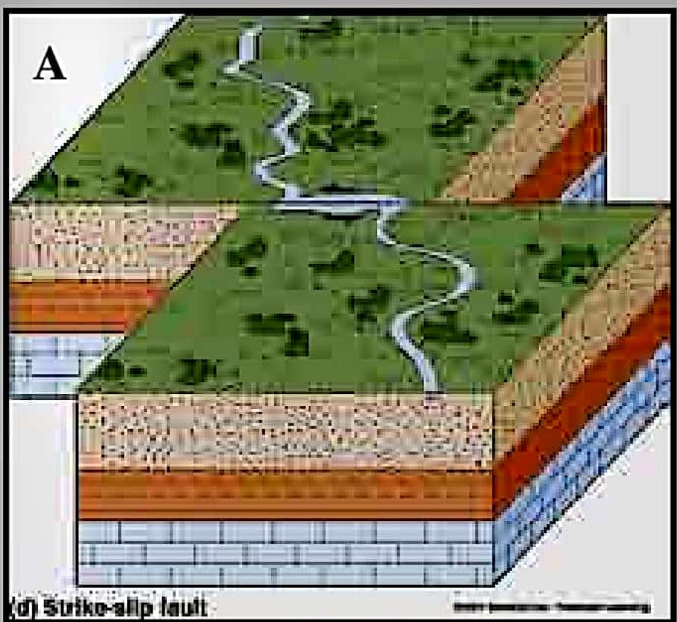
Thrust faults

Reverse faults with fault plane dips of <45° are called thrust faults



Strike-Slip Faults

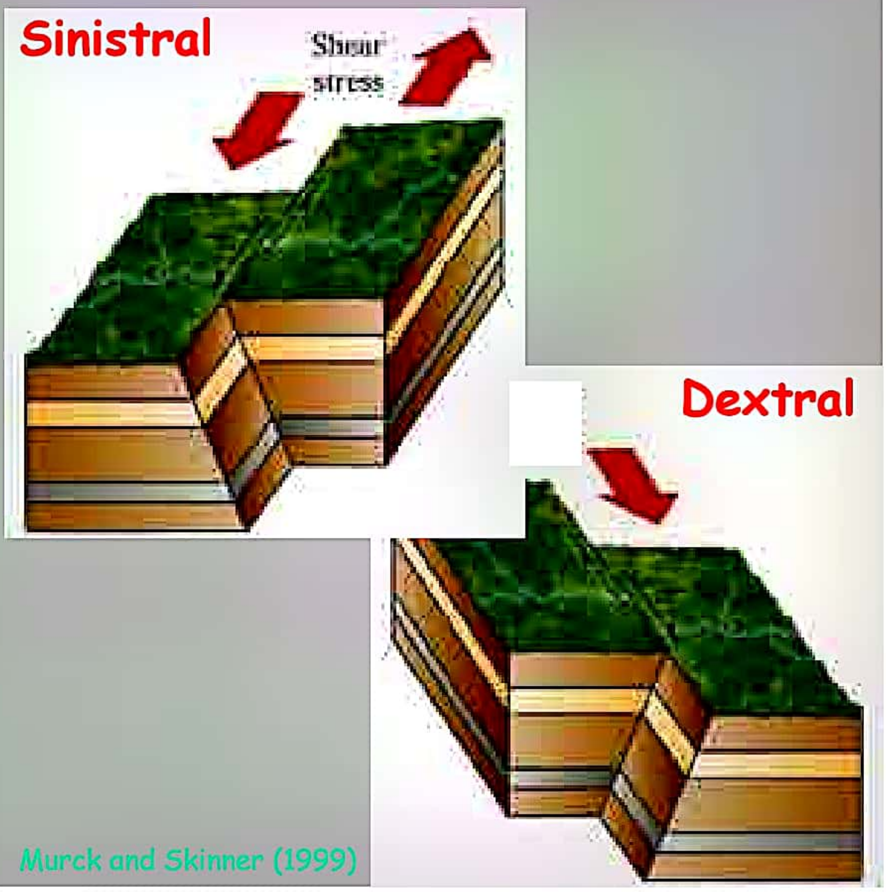
Strike-slip faults are caused by shearing forces, which cause blocks on either side of the fault plane to slide laterally past one another.



Wicander and Monroe (2002)

Strike-slip faults

As the observer looks across the fault plane to the opposite side, the offset feature will lie to the left for a left-lateral (sinistral) fault strike-slip fault and to the right for a right-lateral (dextral) strike-slip fault.



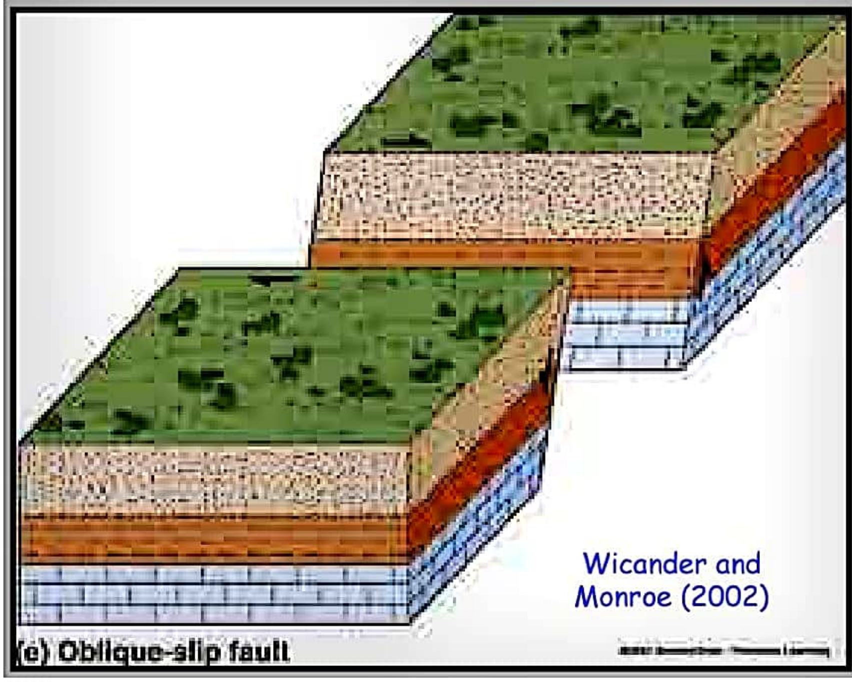
San Andreas fault.

- **The Pacific plate appears to be moving NW relative to the North American plate**

Chernicoff and Whitney (2002)

Oblique-Slip Faults

Movement on most faults is either primarily dip-slip or primarily strike-slip. On oblique-slip faults, both dip-slip and strike-slip movement occur. This oblique-slip fault has undergone a combination of normal dip-slip and right-lateral strike slip movement.



Earthquakes

- The movement of the plates past each other generates stress
- This causes rocks on either side of a fault to fracture

Murck and Skinner (1999)

Earthquakes

- The movement along the faults is not smooth
- Rather the strain energy is built up until friction is overcome
- This sudden release of energy is an earthquake

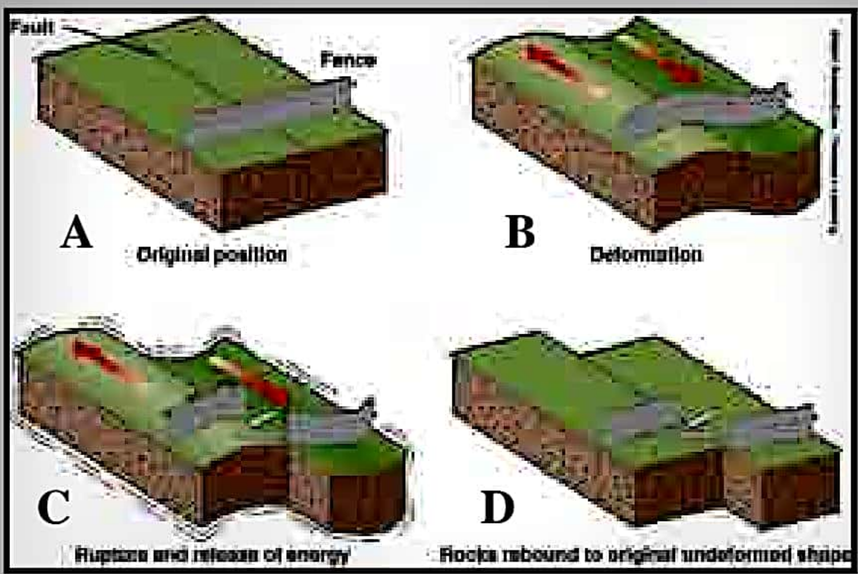
Murck and Skinner (1999)

Elastic rebound theory

- This is based on the fact rocks undergo elastic deformation (reversible changes in volume or shape)

Elastic Rebound Theory

This explains how energy is released during earthquakes. On Earth's surface, any straight line like a road or a fence (A) crossing a fault would be gradually deformed or bent (B) as rocks on one side of the fault move relative to those on the other side.

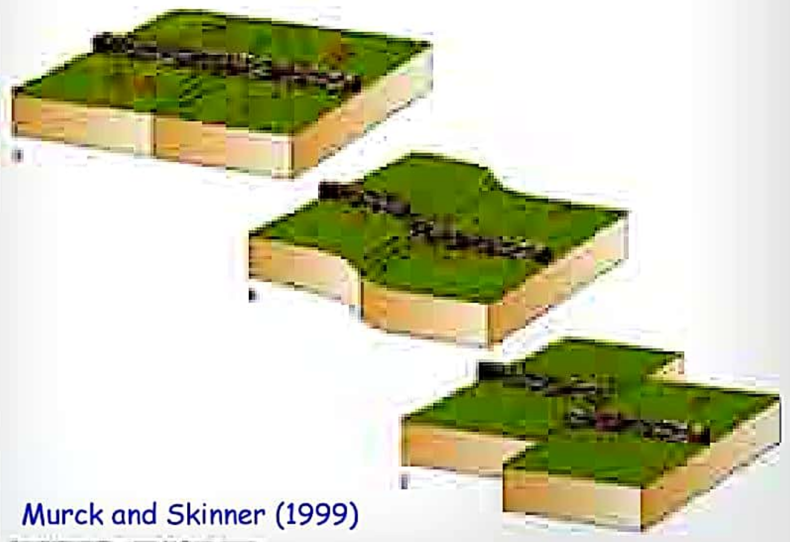


When the strength of rock is exceeded, movement occurs along the fault and energy is released, causing an earthquake (C). After energy is released, the rocks rebound or "snap back" to their original undeformed shape (D).

Wicander and Monroe (2002)

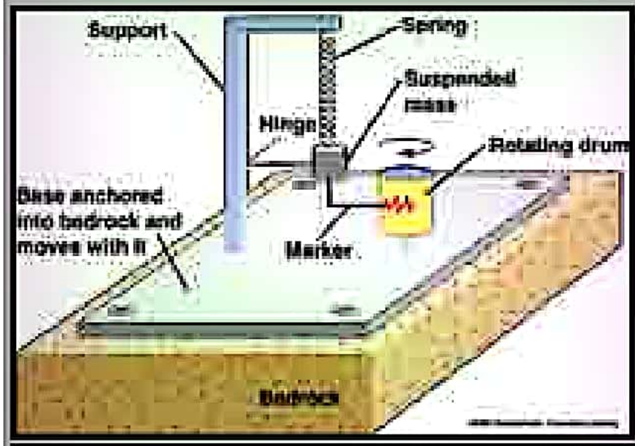
Elastic Rebound Theory

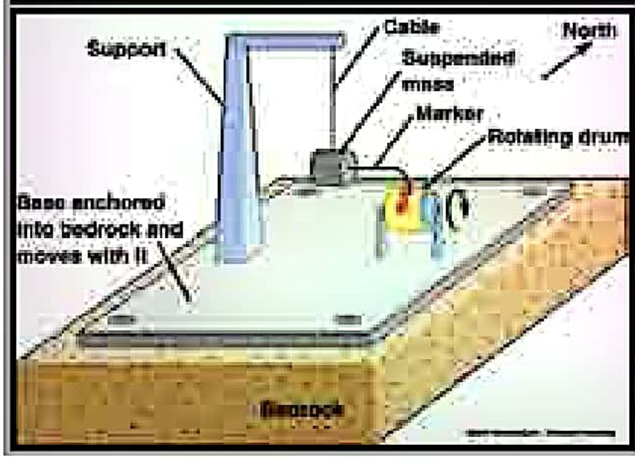
- The first evidence to support this theory came from the San Andeas fault
- Precise measurements from 1874 onwards showed that in places the crust was being bent
- However, near San Francisco the fault was locked
- On April 18, 1906 the stored energy was released



Murck and Skinner (1999)

What Is Seismology? Pg 278



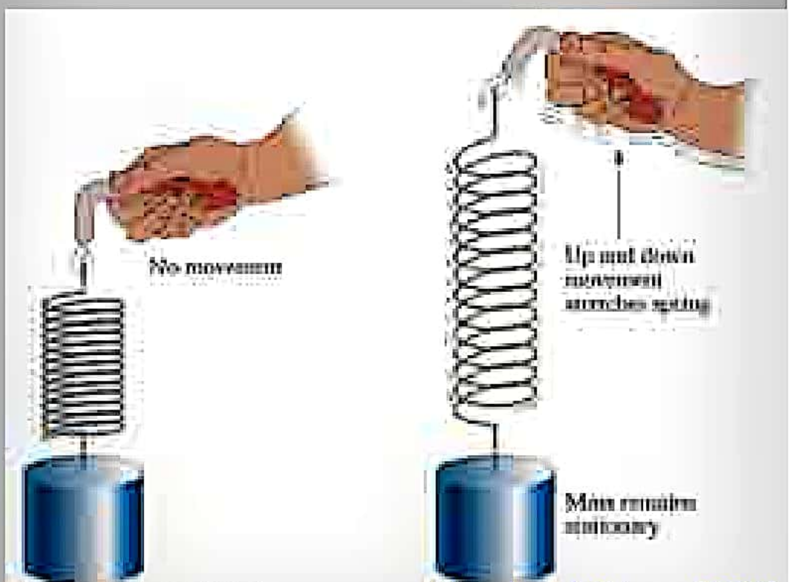


Seismology is the study of earthquakes. The energy released by movement along a fault travels as seismic waves outward in a concentric pattern from the place of movement. The passage of these waves through Earth materials is detected, recorded, and measured by seismographs.The record made is a seismogram.

Wicander and Monroe (2002)

Seismographs

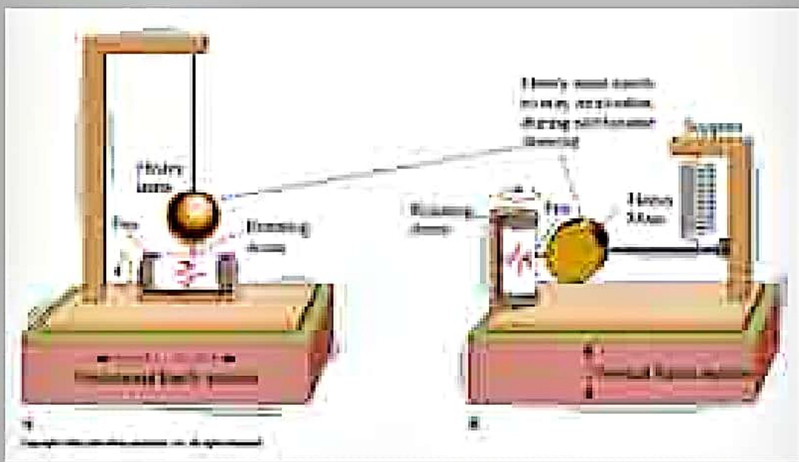
- **Because seismographs sit on the Earth's surface there is no fixed frame of reference for measurements**
- **So most rely on inertia**



Murck and Skinner (1999)

Seismographs

- **When the ground vibrates the spring expands and contracts but the mass remains stationary**
- **Difference between the movement of the ground and the pendulum serves as a measure of ground motion**



Murck and Skinner (1999)

What Are Seismic Waves?

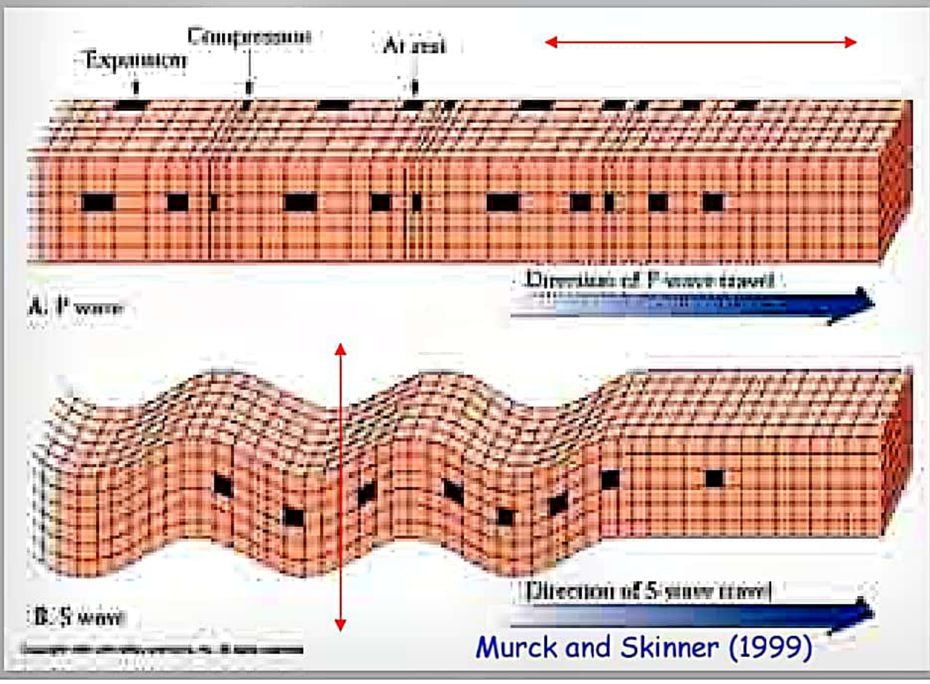
Seismic waves are produced as energy is released by movement along a fault. The passage of seismic waves through Earth materials produces vibrations that cause an earthquake. Body waves are seismic waves that travel through the solid body of Earth, much like sound waves. Surface waves travel along the ground surface and are similar to waves on water.

Wicander and Monroe (2002)

Body waves

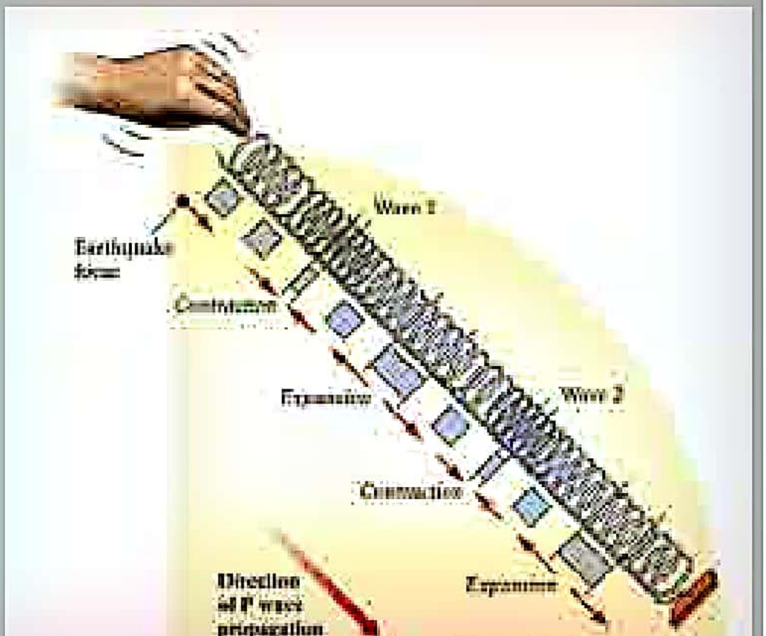
Compressional waves - P waves

Shear waves - S waves



Primary waves

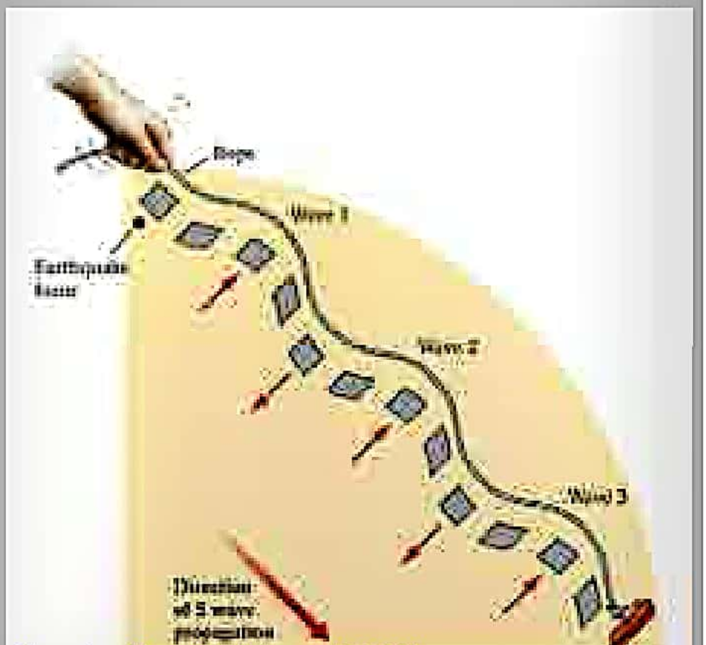
- These compressional waves behave like sound waves
- Move through solids, liquids and gas
- 6 km/s



Chernicoff and Whitney (2002)

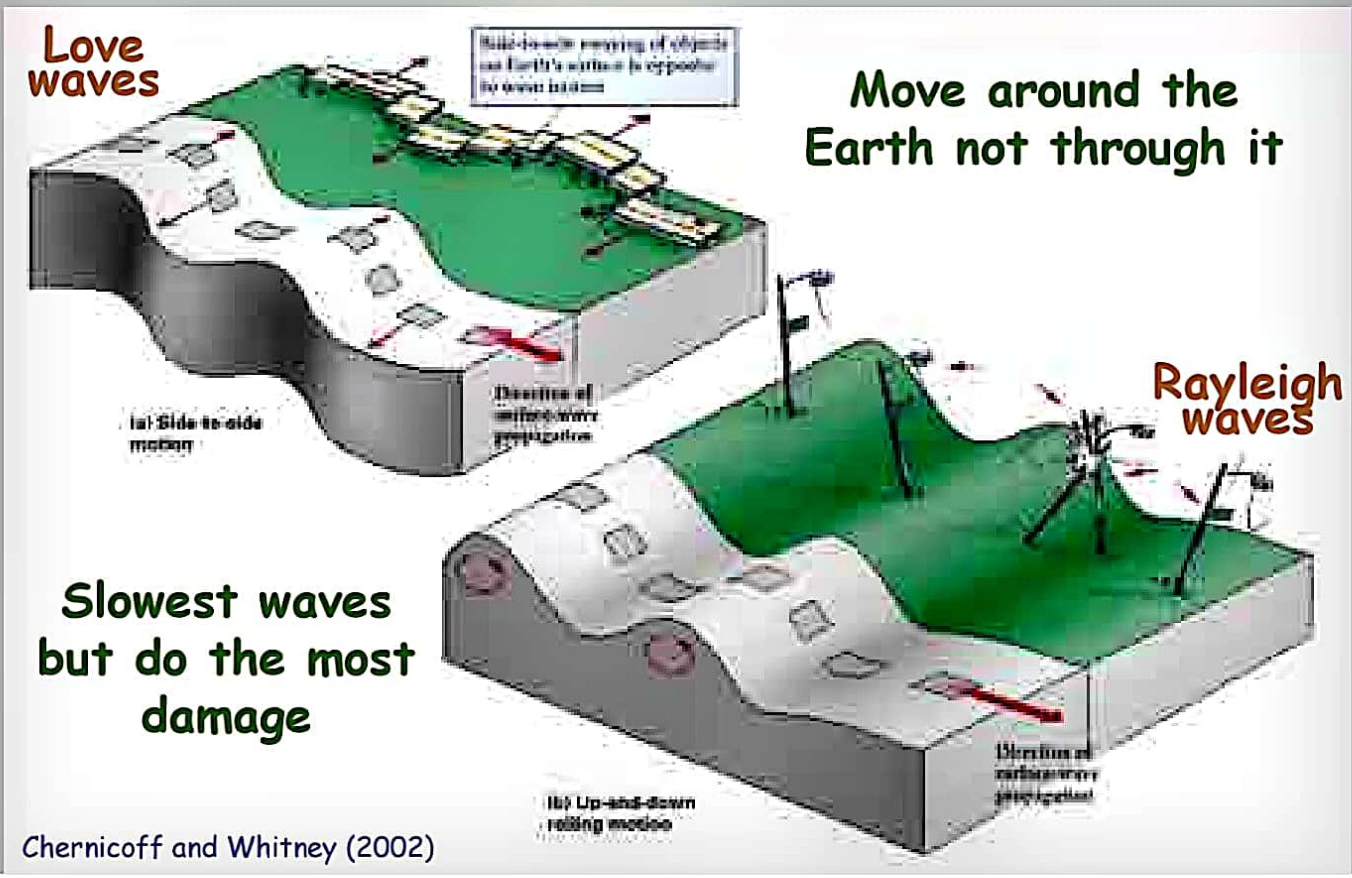
Secondary waves

- Shear waves move in alternating sideways movements
- Move through solids only
- 3.5 km/s



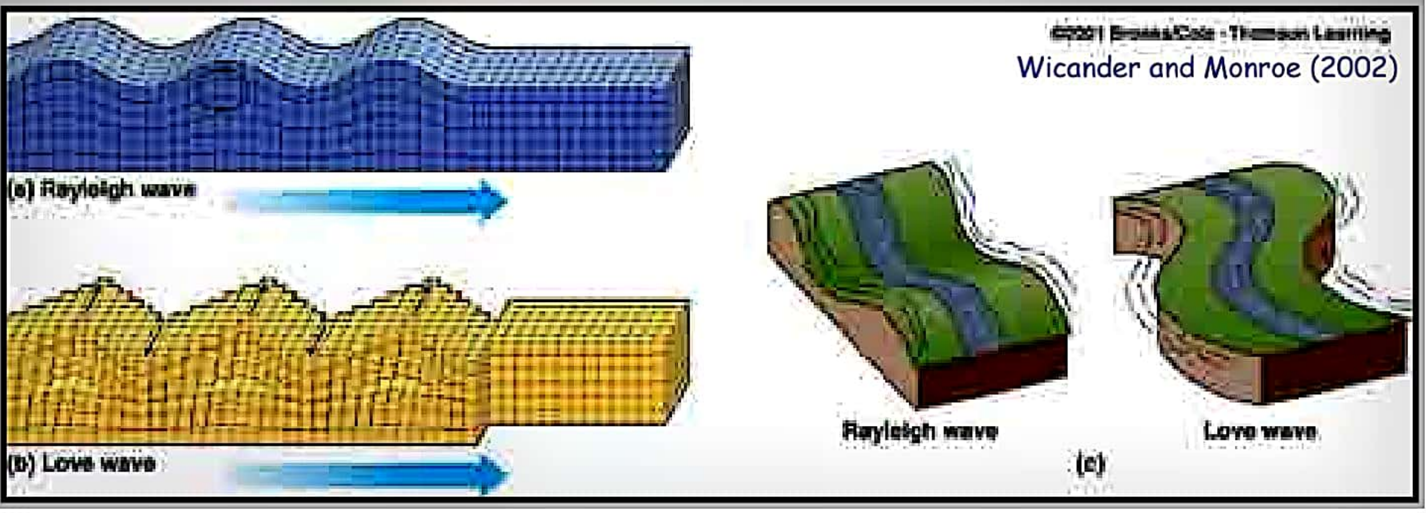
Chernicoff and Whitney (2002)

Surface waves (after P and S)

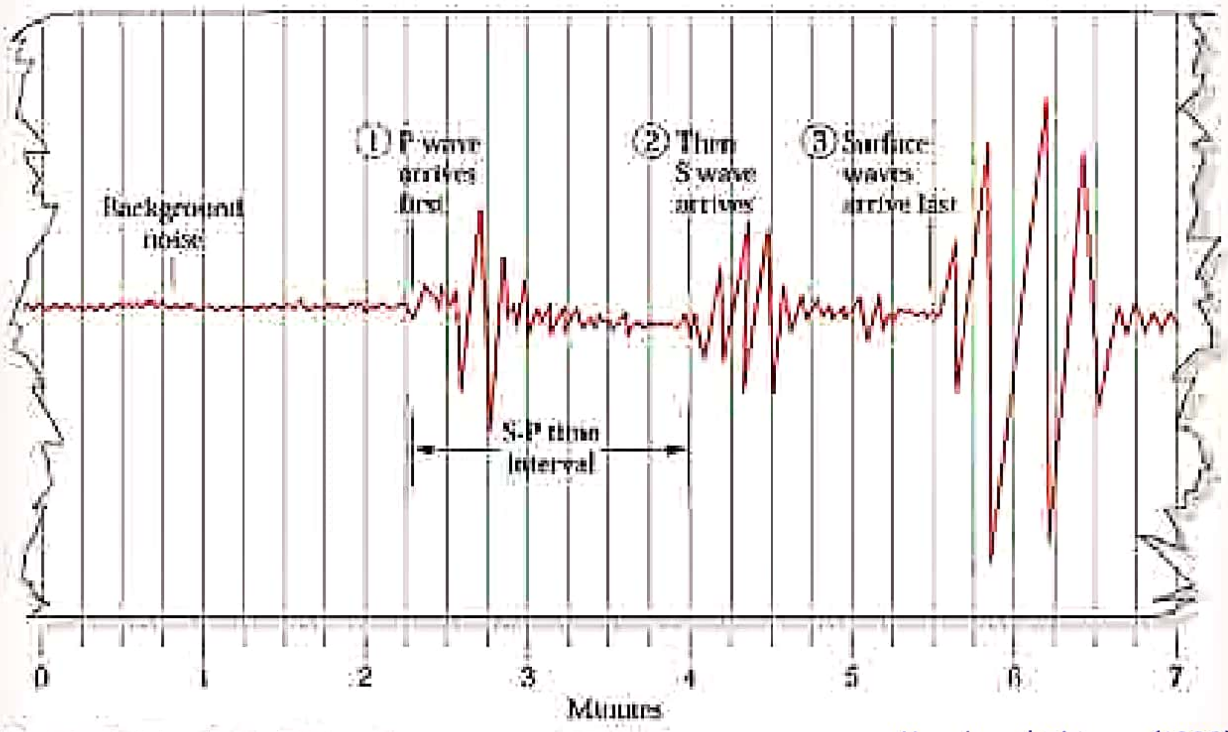


Surface Waves

Rayleigh waves, like water waves, move material in an elliptical path and are slower than Love waves. The motion of Loves waves is similar to S-waves except that movement is restricted to a horizontal plane



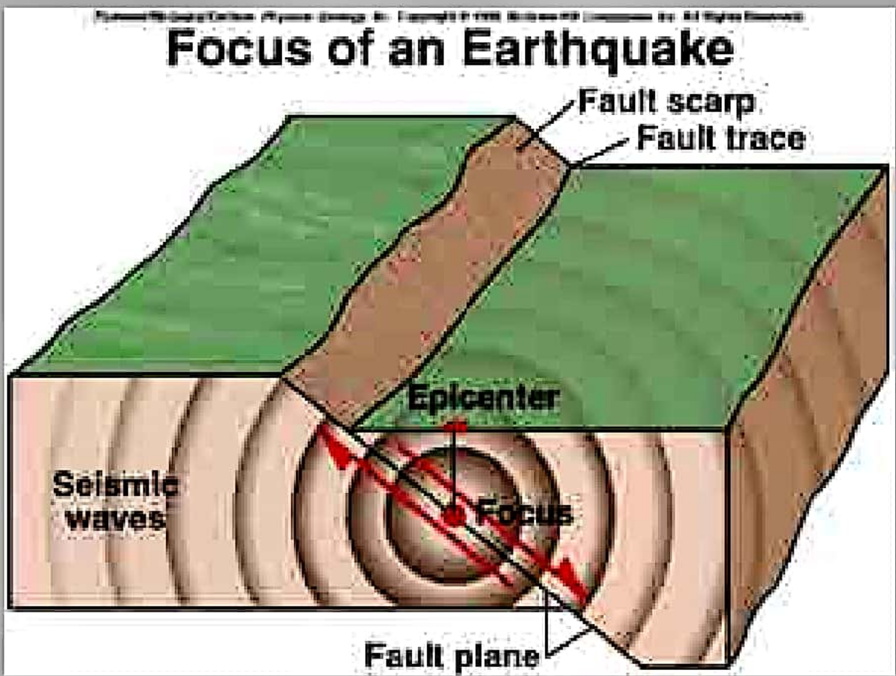
Seismograms



Murck and Skinner (1999)

Focus and Epicenter

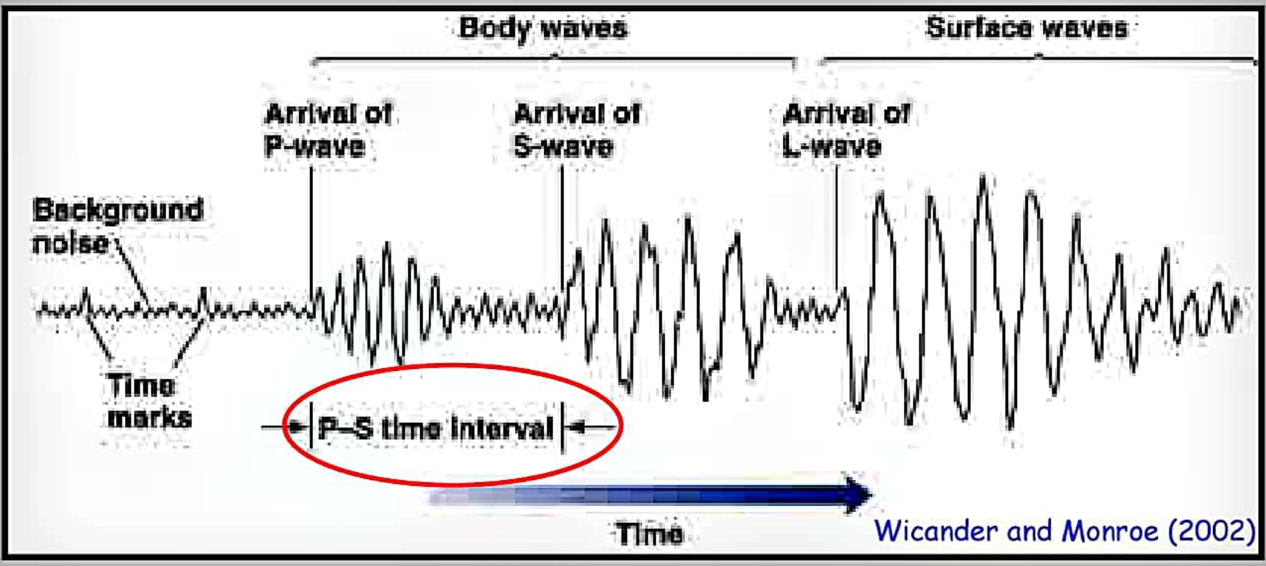
The focus of an earthquake is the point within Earth where fracturing first begins, that is, the point where energy is first released. In describing the location of earthquakes, however, news reports refer to the epicenter, the point on Earth's surface directly above the focus.



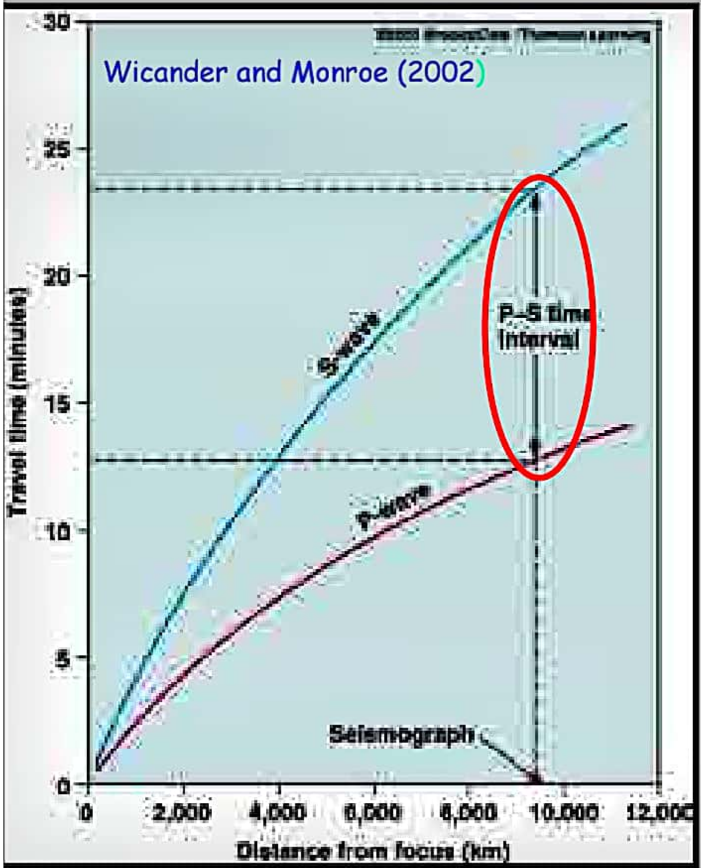
Plummer et al. (2001)

Locating the Epicenter

Earthquake epicenters are located based on the difference in the arrival time at seismograph stations of the first P- and S-waves, the P-S time interval. P-waves arrive first, followed in order by S-, Love, and Rayleigh waves.

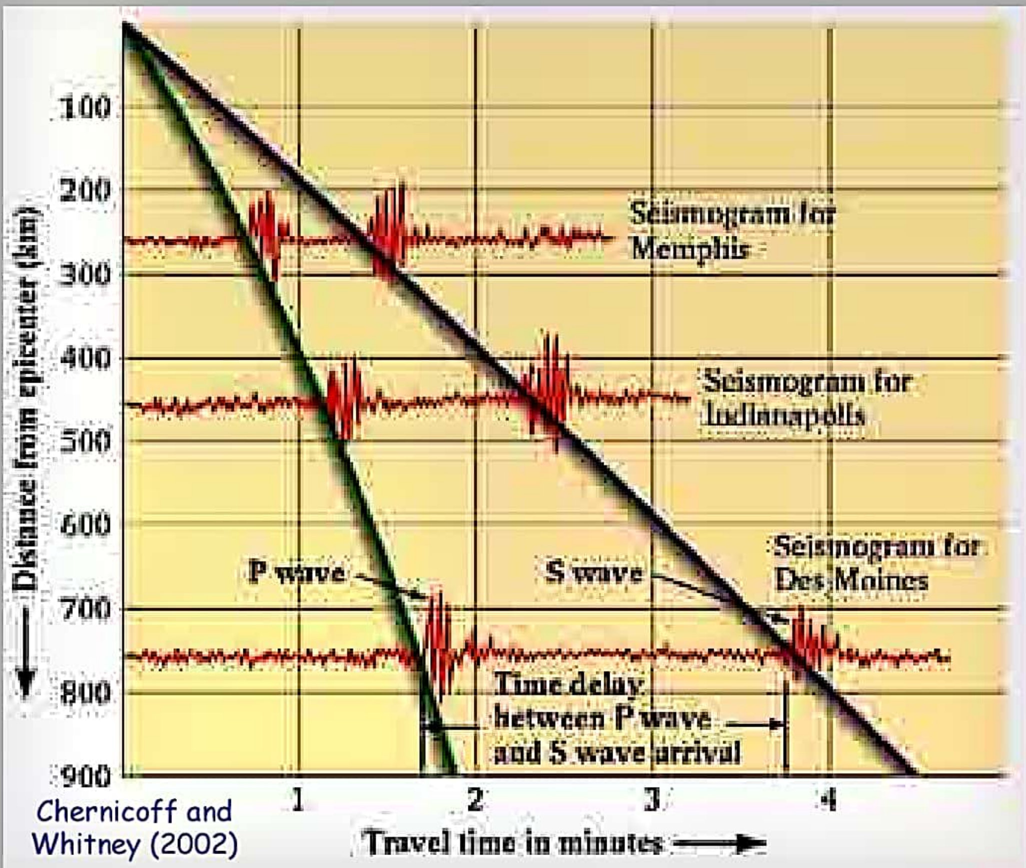


Locating the Epicenter



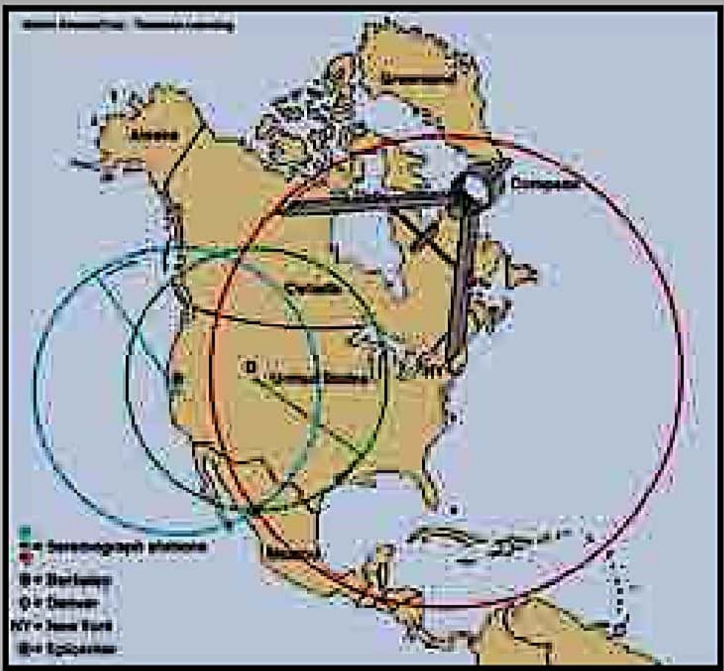
Seismologists know the average speeds of P- and S-waves. Based on these average speeds, P-S wave travel times have been determined for distances between focus and seismograph. Time-distance graphs plot "P-S time interval" versus "travel distance" and are used to locate epicenters.

Locating the epicentre



Chernicoff and Whitney (2002)

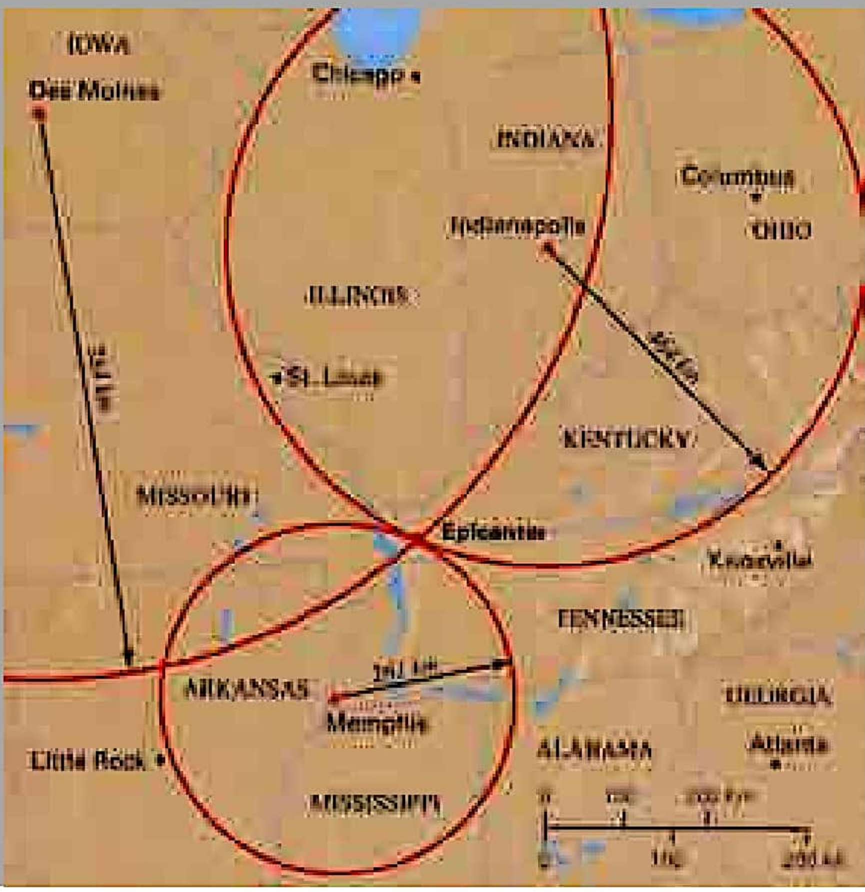
Locating the Epicenter



Wicander and Monroe (2002)

If the "P-S travel times" are known from at least three seismograph stations, then the epicenter of any earthquake can be located. Using the P-S travel time for each station, travel distance can be determined from the time-distance graph. A circle with a radius equal to the travel distance is drawn for each of the three seismograph stations. The intersection of the three circles is the location of the epicenter.

Locating the Epicenter.



Chernicoff and Whitney (2002)

Measuring earthquakes

- The Richter Magnitude Scale is a quantitative measure of earthquake magnitude, the amount of energy released by an earthquake at its source. It is determined based on the amplitude of the largest seismic wave recorded for a given earthquake. The Richter Scale ranges from 1 to 9, with 9 assigned to the largest quakes theoretically possible.
- An increase of one unit on the Richter Scale, from 5.5 to 6.5 for example, is equivalent to a 10-fold increase in the amplitude of the largest seismic wave produced.
- In terms of energy released, each one unit increase on the Richter Scale equals a 30-fold increase in energy released at the focus. It would take about 30 quakes of 5.5 magnitude to release as much energy as one 6.5 quake.

Average Number of Richter Magnitudes per Year Worldwide

MAGNITUDE	EFFECTS	AVERAGE NUMBER PER YEAR
<2.5	Typically not felt but recorded	900,000
2.5 -6.0	Usually felt; minor to moderate damage to structures	31,000
6.1-6.9	Potentially destructive, especially in populated areas	100
7.0-7.9	Major earthquakes; serious damage results	20
>8.0	Great earthquakes; usually result in total destruction	1 every 5 years

The Richter Scale

- Named after Charles Richter who developed it in 1935
- In addition to being logarithmic the Richter scale is corrected for distance
- So the magnitude for a given quake is the same no matter how far away you are
- Magnitude is the same but the effects are not
- The largest quakes recorded had amplitudes of 8.6

Measuring earthquakes (pg 278)

- **Intensity is a subjective measure of the damage done by an earthquake as well as what people felt. The Modified Mercalli Scale assesses earthquake intensity, approximating size and strength of an earthquake.**
- **The scale ranges from 1 to 12 with increasing intensity. For an earthquake of given Richter magnitude, intensity will vary with distance from epicenter, local geology, construction practices, etc. Below are characteristics of some quake intensities on the Modified Mercalli Scale.**

II Felt only by a few people at rest, especially on upper floors of buildings.

VI Felt by all, many frightened and run outdoors. Some heavy furniture moved, a few instances of fallen plaster or damaged chimneys. Damage slight.

IX Damage considerable in specially designed structures. Buildings shifted off foundations. Ground noticeably cracked. Underground pipes broken.

The Mercalli scale

- The scale was developed in 1902
- Unlike the Richter scale the Mercalli scale varies with distance.
- A IX near the epicentre would register as a I or II further away
- Dependant on rock and soil type
- Useful for classifying historic quakes but is a subjective scale

Comparing scales

Richter	Mercalli	Effects
<3.4	I	Recorded only by seismographs
3.5 - 4.2	II & III	Felt by some people indoors
4.3 - 4.8	IV	Felt by many, windows rattle
4.9 - 5.4	V	Felt by all, dishes break
5.5 - 6.1	VI & VII	Plaster cracks, bricks fall
6.2 - 6.9	VIII & IX	Chimneys fall, houses move on foundations
7.0 - 7.3	X	Bridges twisted, walls fractures, masonry buildings collapse
7.4 - 7.9	XI	Great damage, most buildings collapse
>8.0	XII	Total damage, objects thrown in air, waves seen on ground surface

The Moment Magnitude scale

- The moment magnitude scale is the scale preferred by seismolgists as the Richter scale does not accurately reflect the amount of energy released by large quakes on long faults.
- The scale uses the seismic moment which is proportional to the displacement on the fault times the rupture area on the fault surface times the rigidity of the rock.

Earthquake	Richter	Moment
Chile, 1960	8.3	9.5
Alaska, 1964	8.4	9.2
Loma Prieta, 1989	7.1	7.0
Northridge, 1994	6.4	6.7

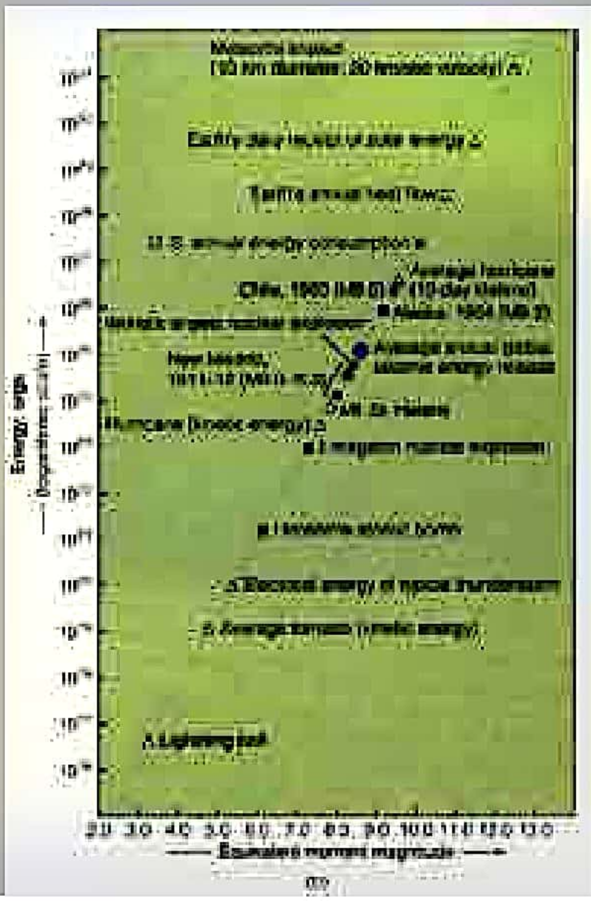
Moment Magnitude

- Moment = (total length of fault rupture) X (depth of fault rupture) X (total amount of slip along rupture) X (strength of rock).

- Measures strength of quake from its cause (rupture of rocks and distance rocks moved) rather than from its effect (seismic waves on seismograph)

The Moment Magnitude scale

Moment Magnitude	Energy Eqv.
-2	100 W bulb for 1 wk
2	Lightning bolt
4	I kiloton explosives
8	Mt St Helens, 1980
10	Annual US energy consumption



Equivalent moment magnitudes in ergs, Pipkin and Trent (1997)

The Moment Magnitude scale

- The Richter scale is based on the concept that earthquake foci are points and is still good for earthquakes where the energy is released from a small volume of rock
- The Moment scale accounts for the fact that energy may be released from a large area and accounts for variations in the properties of rock and soil