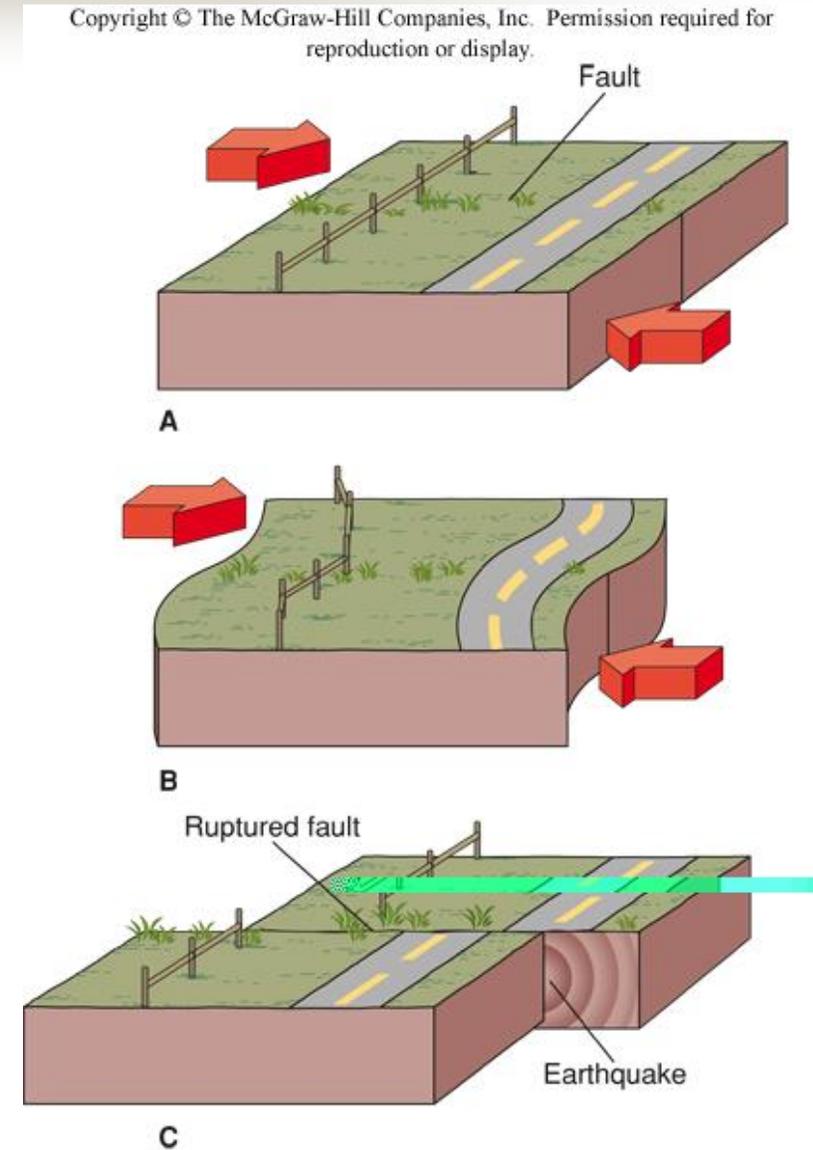


EARTHQUAKE GEOLOGY



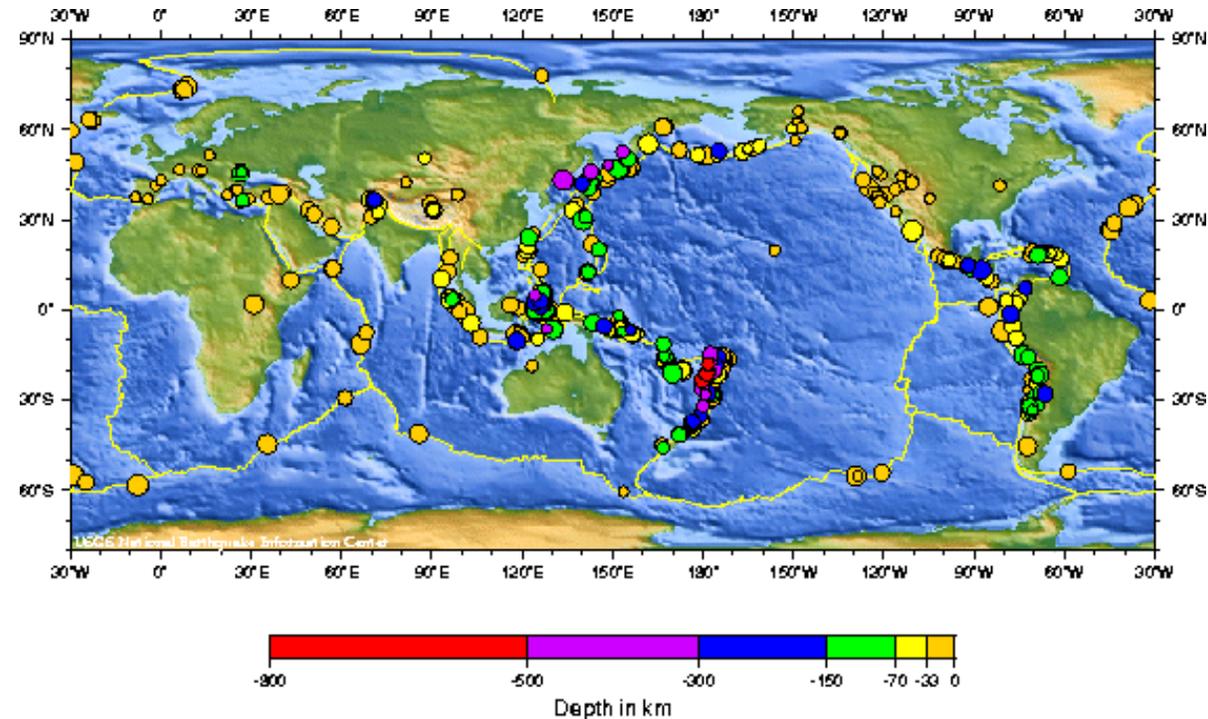
Earthquakes

- An *earthquake* is a trembling or shaking of the ground caused by the sudden release of energy stored in the rocks beneath Earth's surface
 - Tectonic forces within the Earth produce stresses on rocks that eventually exceed their elastic limits, resulting in brittle failure



What causes Earthquakes?

- ❑ **Tectonic stress** (most common),
As plates push, pull, or slip past each other, stress increases along faults.
- ❑ **Geothermal gradient** (variation due to boundary)
- ❑ Deformation is a result of the stress
- ❑ Deformation – the change to the shape of rock in response to stress



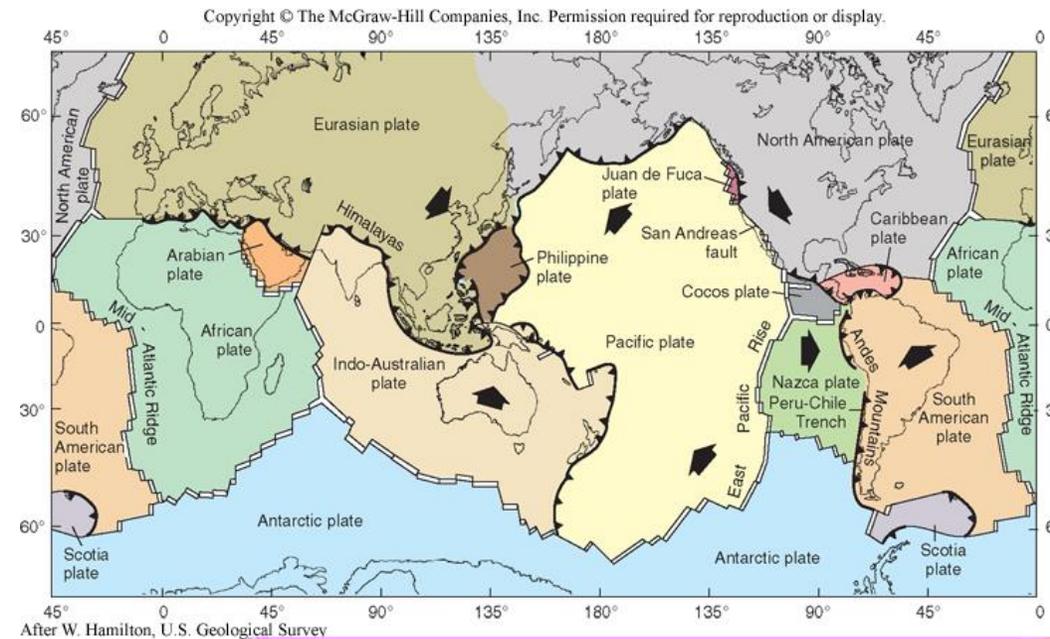
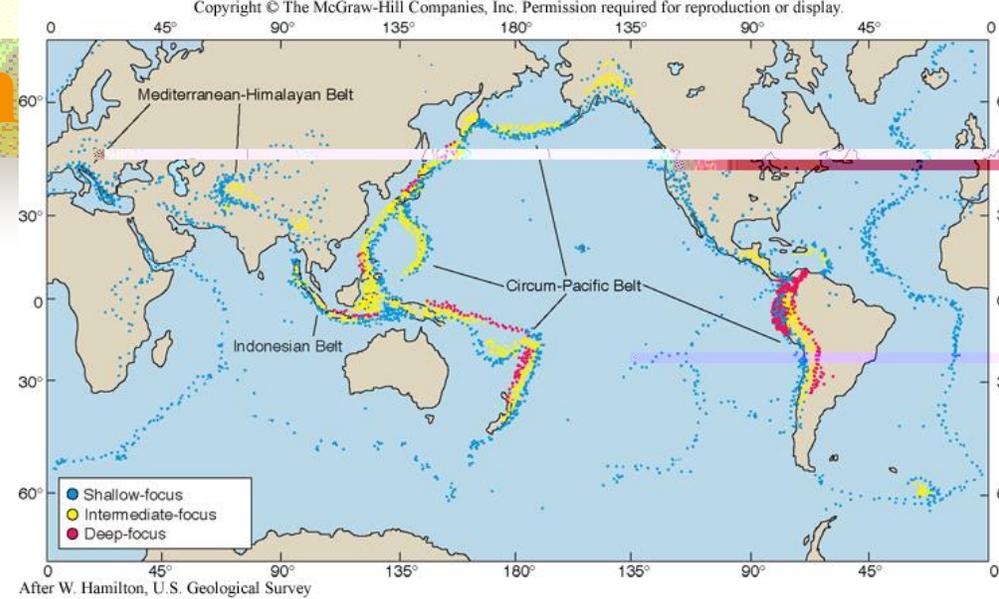


Earthquakes and Plate Tectonics

- The surface layer of the earth -- the lithosphere -- is comprised of many plates that slide over the lubricating asthenosphere layer.
- Earthquakes are caused by plate inter-actions along *tectonic plate boundaries*
- Plate boundaries are identified and *defined* by earthquakes
- Earthquakes occur at each of the three types of plate boundaries: *divergent*, *transform*, and *convergent*
 - At divergent boundaries, *tensional forces* produce shallow-focus quakes on *normal faults*
 - At transform boundaries, *shear forces* produce shallow-focus quakes along *strike-slip faults*
 - At convergent boundaries, *compressional forces* produce shallow- to deep-focus quakes along *reverse faults*

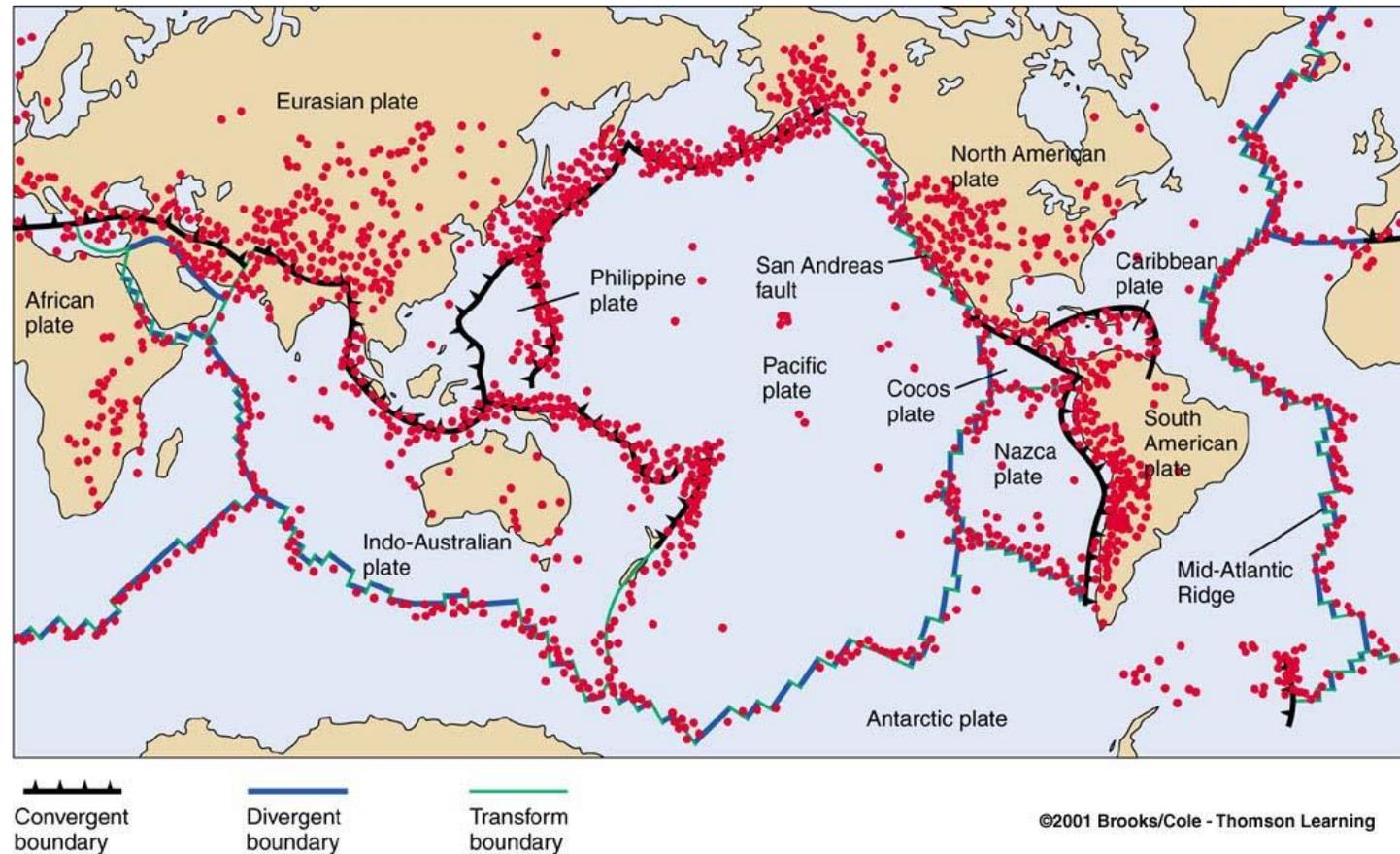
World Earthquake Distribution

- Most earthquakes occur in narrow geographic belts which mark *tectonic plate boundaries*
- Most important concentrations in *circum-Pacific* and *Mediterranean-Himalayan belts*
- Shallow-focus earthquakes common along the crests of *mid-oceanic ridges*
- Nearly all intermediate- and deep-focus earthquakes occur in *Benioff zones*
 - inclined seismic activity associated with descending oceanic plate at subduction zones)



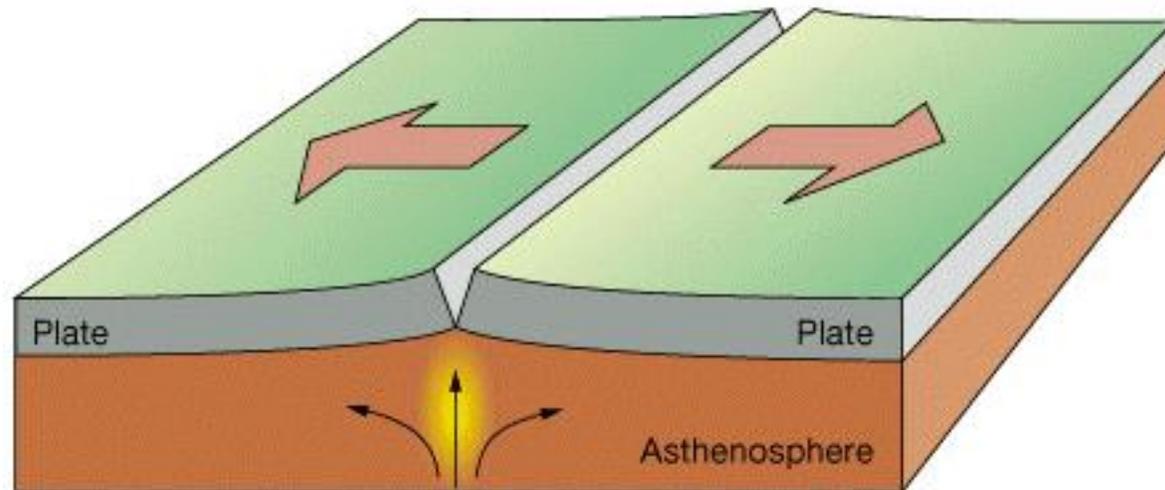
Where Do Earthquakes Occur and How Often?

- ~80% of all earthquakes occur in the circum-Pacific belt
- ~15% occur in the Mediterranean-Asiatic belt
- ~remaining 5% occur in the interiors of plates and on spreading ridge centers
 - more than 150,000 quakes strong enough to be felt are recorded each year



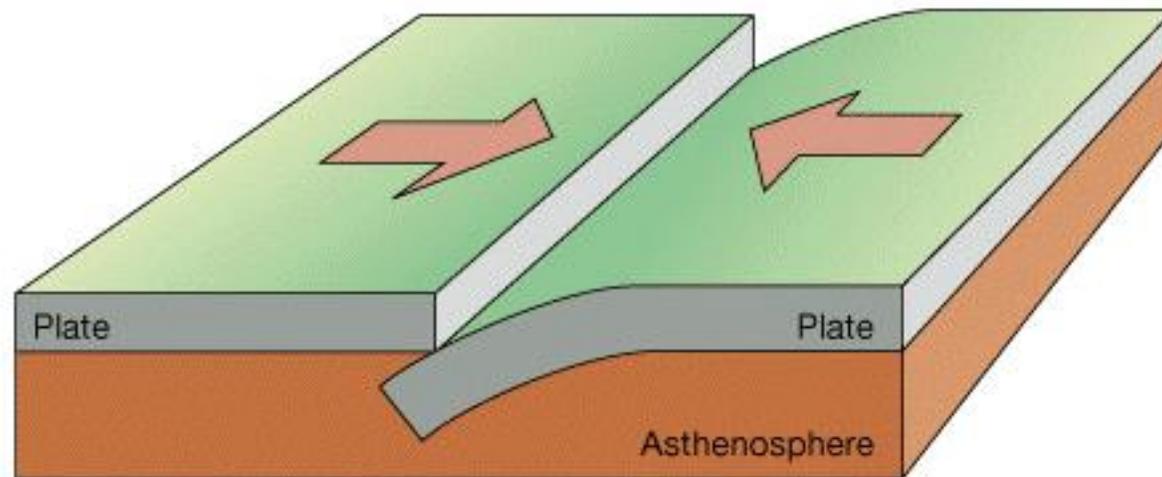
The key principles: Types of plate boundaries

Divergent boundary, also called accreting or constructive, plates are moving away from each other, and new plate material, derived from the mantle, is added to the lithosphere. The divergent boundary is represented by the **mid ocean ridge system**.



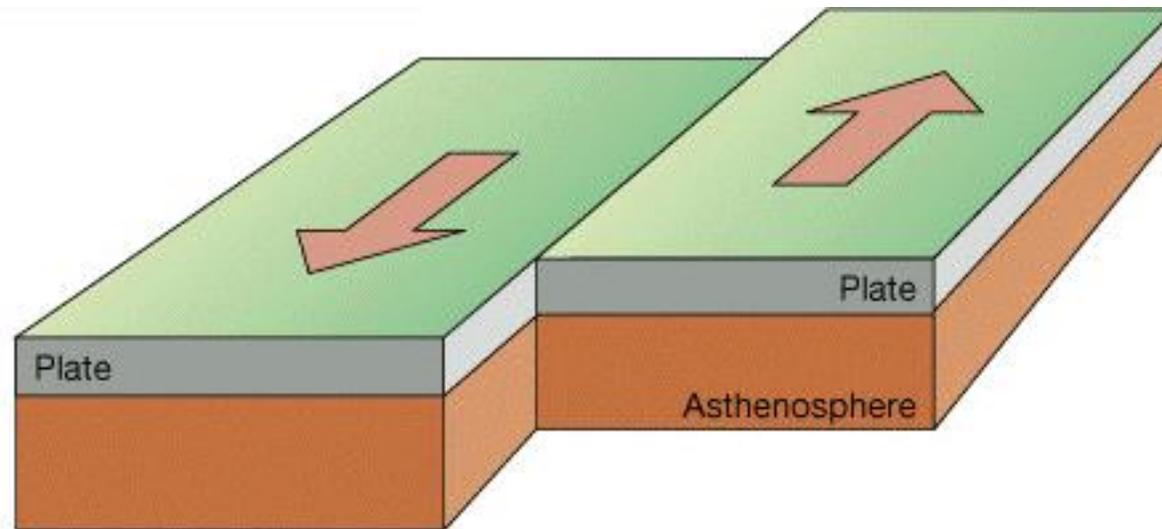
The key principles: Types of plate boundaries

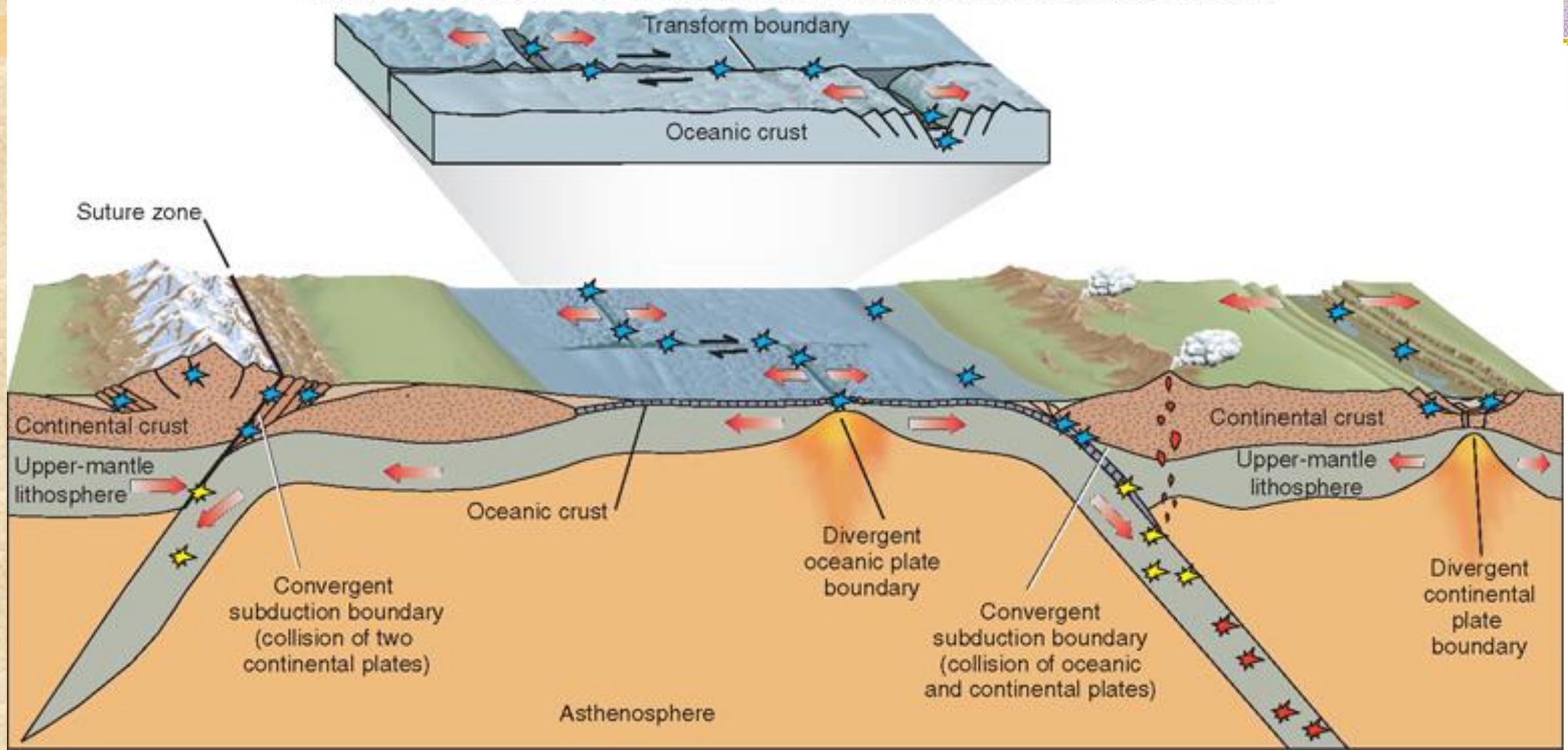
Convergent boundary, also called consuming or destructive, plates are approaching each other. These boundaries are represented by the **oceanic trench**, **island arc** systems or **subduction zones** where one of the colliding plates descends into the mantle and is destroyed.



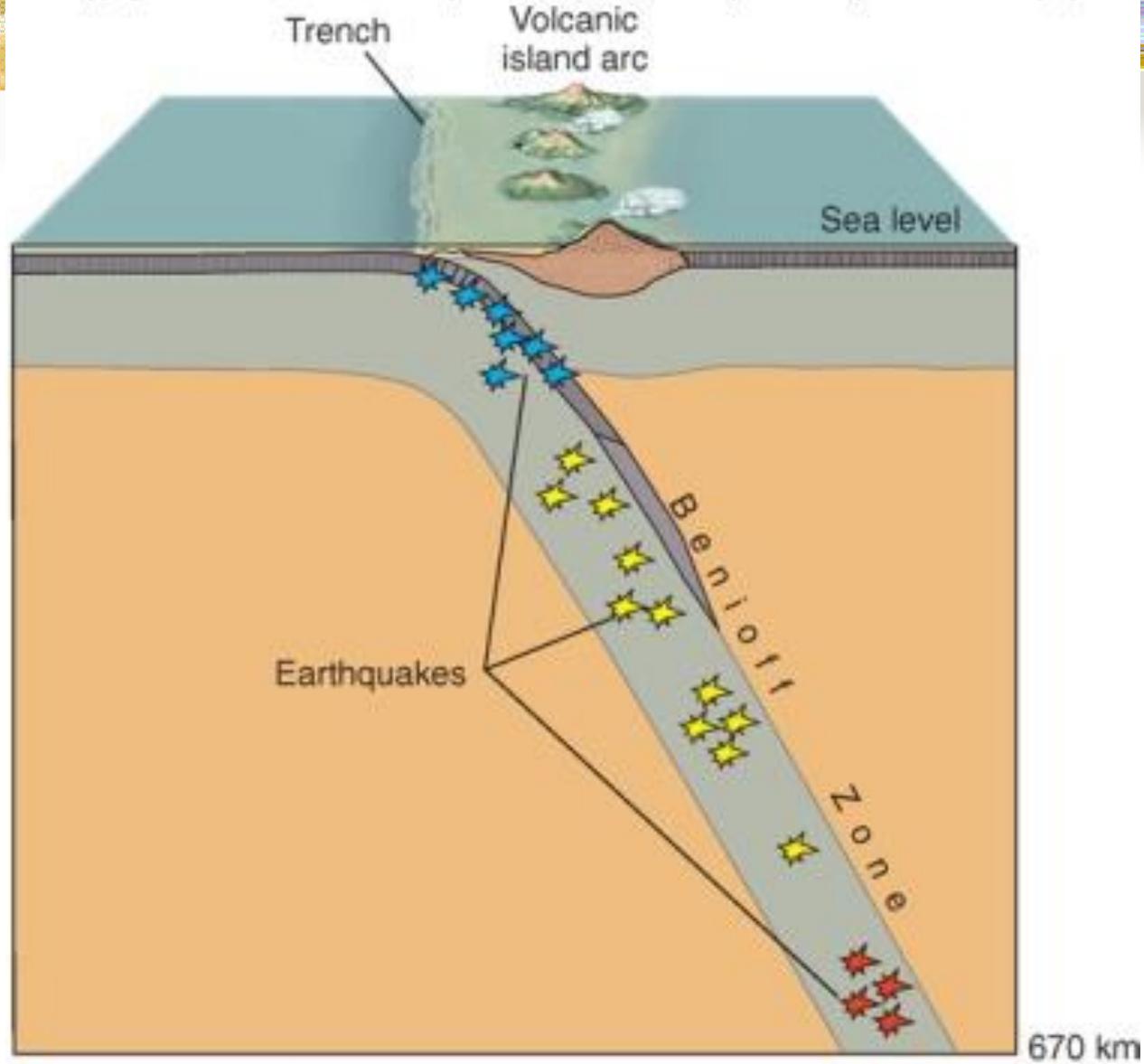
The key principles: Types of plate boundaries

Conservative boundary, lithosphere is neither created nor destroyed. The plates move laterally relative to each other. These plate boundary are represented by **transform faults**.





- ★ Shallow-focus earthquakes (< 50 km deep)
- ★ Intermediate-focus earthquakes (50-300 km deep)
- ★ Deep-focus earthquakes (> 300 km deep)



- ★ Shallow-focus earthquakes
- ★ Intermediate-focus earthquakes
- ★ Deep-focus earthquakes



Stress and Strain: Rock Behavior

Strain - the result of stress or deformation

elastic deformation - when stresses are removed, rock returns to original shape

plastic deformation - permanent deformation. when stresses are removed, rock stays bent

rupture - breakage and fracturing of the rock, causing an earthquake.

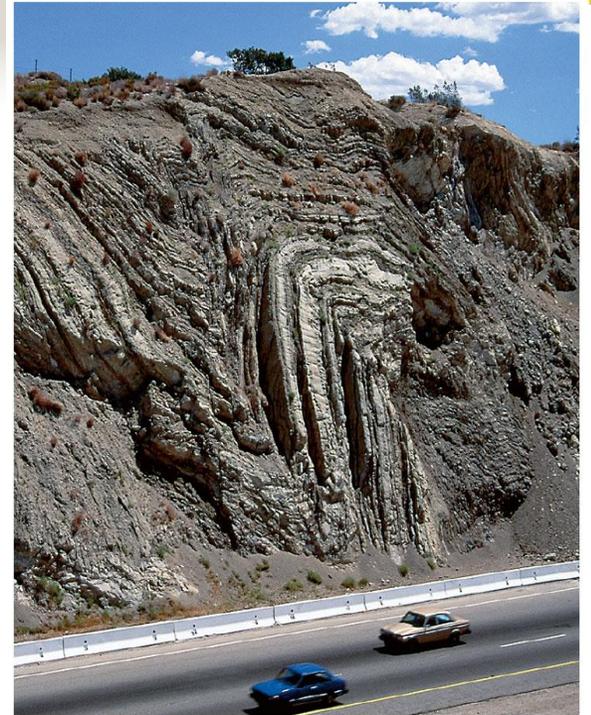
Brittle materials break during elastic deformation.

■ Plastic Deformation

- Deforms like a piece of molded clay
- Does not cause Earthquakes

■ Elastic Deformation

- Deforms like a rubber band
- Leads to Earthquakes
- it breaks when energy is released
- Broken pieces return to their unstretched shape

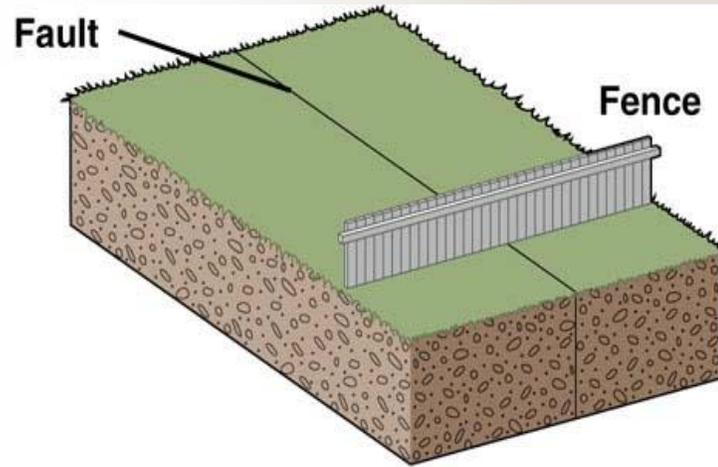




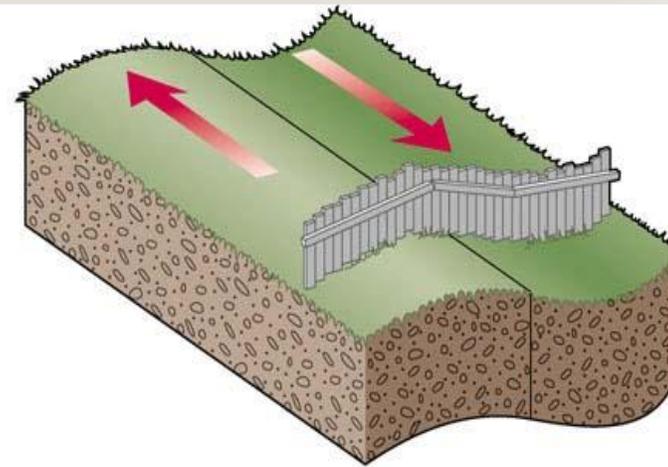
Elastic Rebound

- ❑ **Elastic rebound theory** explanation to how earthquakes occur.
- ❑ Plate movement concentrates energy in crust
- ❑ When the stored energy exceeds the strength of the crust, the crust ruptures
- ❑ The rupture generally occurs along faults because this is the weakest point
- ❑ The sudden return of elastically deformed rock to its original shape
- ❑ Occurs when more stress is applied to rock than the rock can withstand
- ❑ Energy is released
- ❑ Travels as seismic waves, which cause an Earthquake

What is the Elastic Rebound Theory?

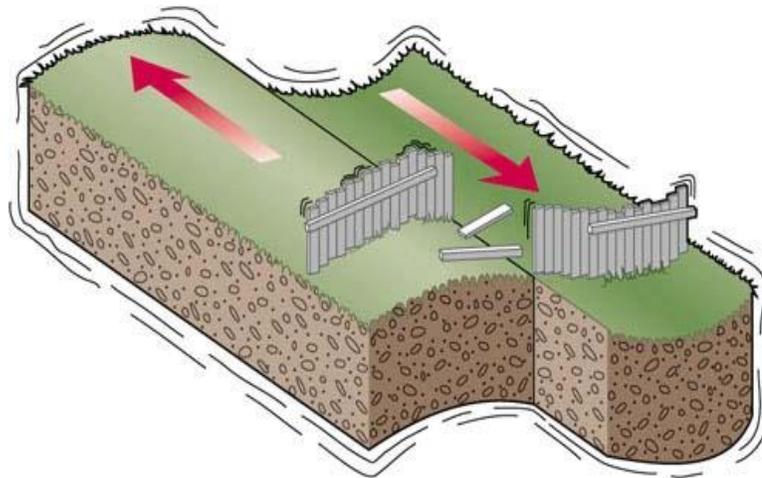


Original position

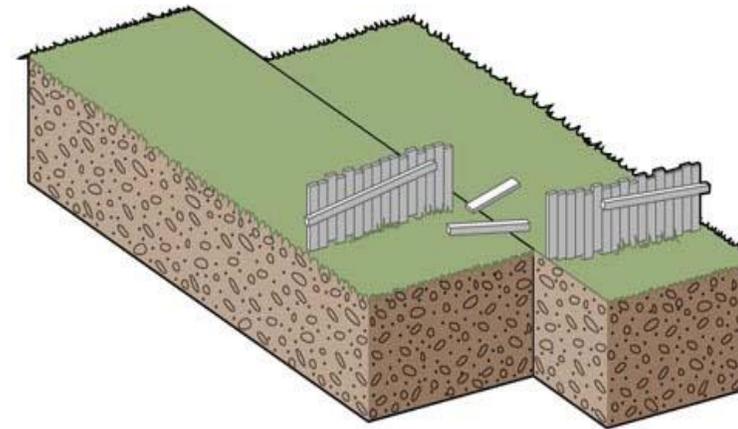


Deformation

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Rupture and release of energy



Rocks rebound to original undeformed shape

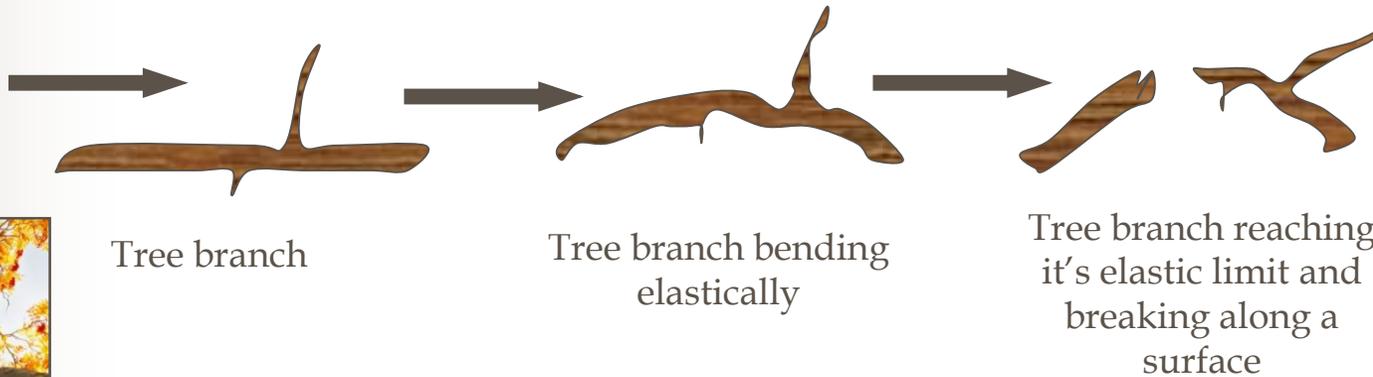


Faults

- ❑ Energy is released during earthquakes in the form of seismic waves
 - ❑ Released from a position along a break between two rock masses (fault)
- ❑ Strains and tensions produce stress and strain cracks on the plates, which are called faults

Faults

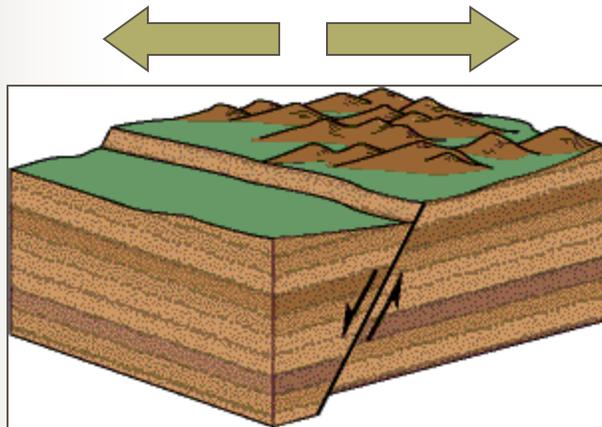
- ❑ Faults -- breaks in the earth's crust where the blocks of rock on each side are moving in different directions
- ❑ Earthquakes are much more common along fault lines than they are anywhere else on the planet
- ❑ Faults are classified by the kinds of movement that occur along them



Fault Types

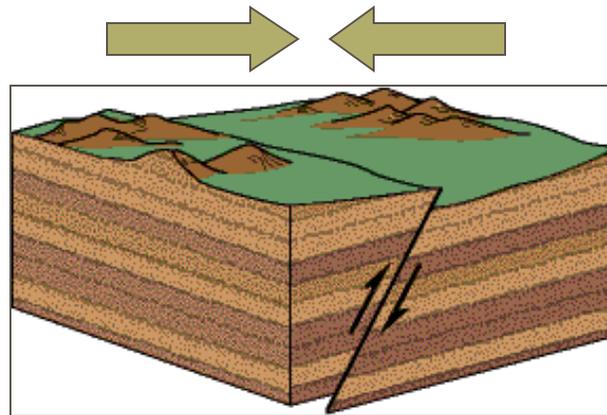
Fault surfaces are surfaces along which rocks move under, over, or past each other. Rocks may get “stuck” along the fault surface, causing a build-up of strain energy, and resulting in an earthquake when the rocks break free of each other. There are 3 types of stress that can affect rocks, resulting in 3 different types of faults:

1. Tension pulls rocks apart resulting in normal faults



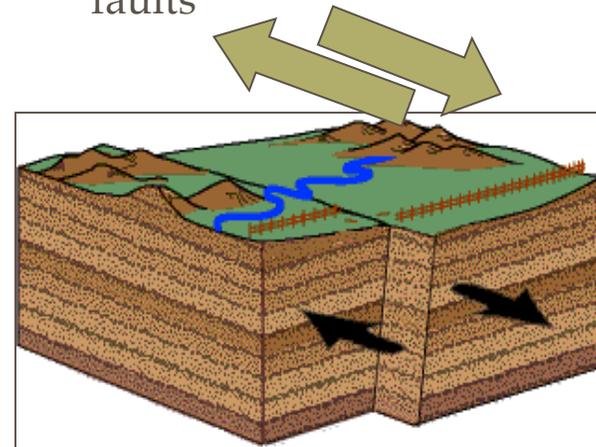
(Credit: U.S. Geological Survey
Department of the Interior/USGS)

2. Compression squeezes rock together resulting in reverse faults



(Credit: U.S. Geological Survey
Department of the Interior/USGS)

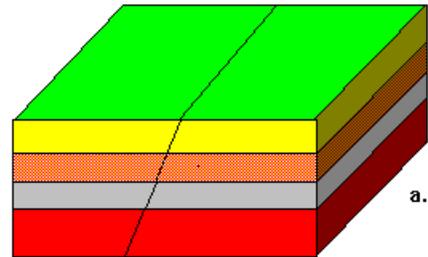
3. Shear stress causes rocks to slide past each other resulting in strike-slip faults



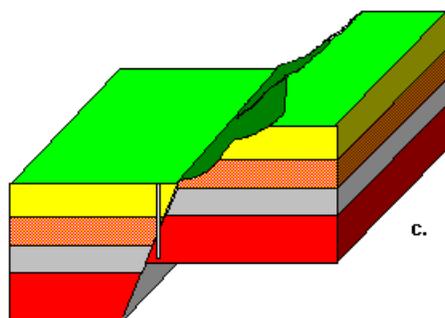
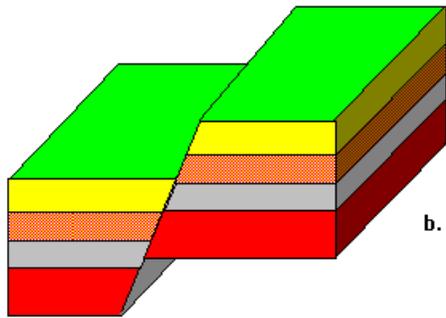
(Credit: U.S. Geological Survey
Department of the Interior/USGS)

Normal Fault

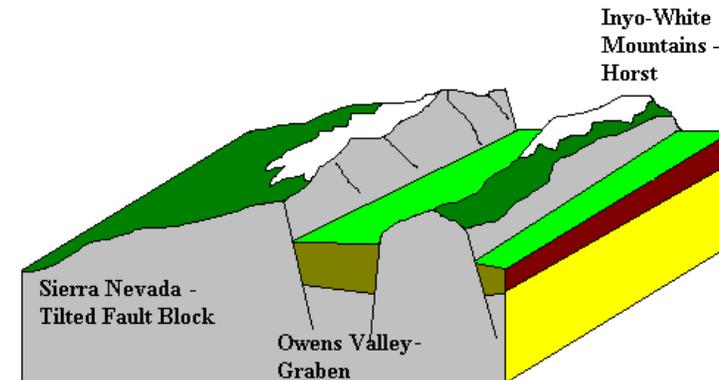
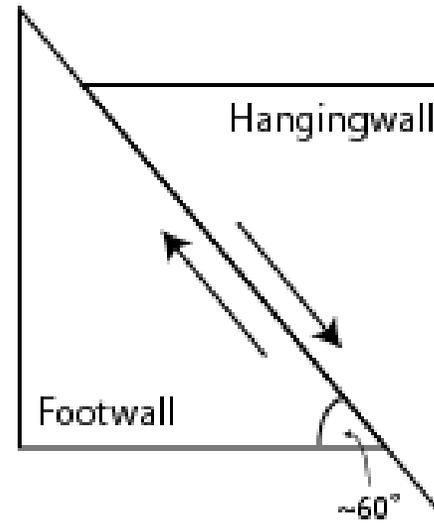
- ❖ Faults caused by blocks of crust pulling apart under the forces of tension are called **normal faults**.
- ❖ In a normal fault, the hanging-wall block moves down relative to the foot-wall block.
- ❖ The footwall is the underlying surface of an inclined fault plane.
- ❖ The hanging wall is the overlying surface of an inclined fault plane.



Normal Faulting
a. A block of crust before faulting
b. After faulting. Note that the block becomes longer.
c. An eroded normal fault. Note that the well misses the gray layer completely.

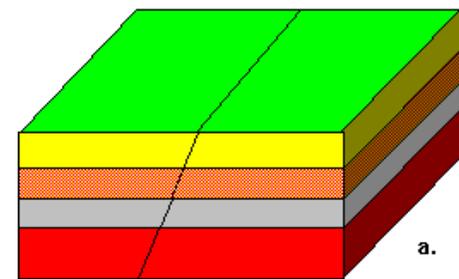
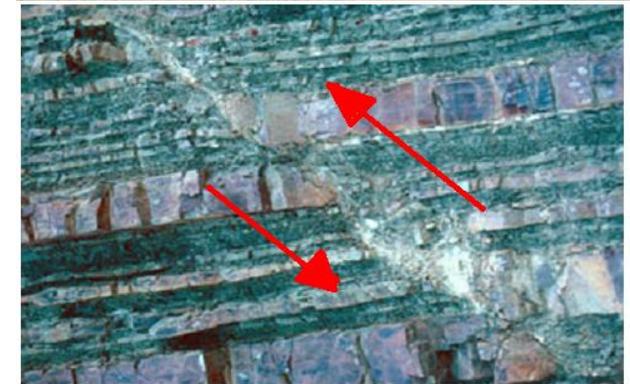


Normal fault

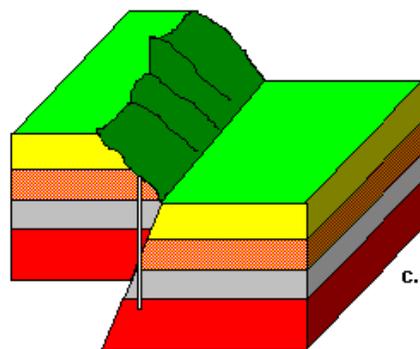
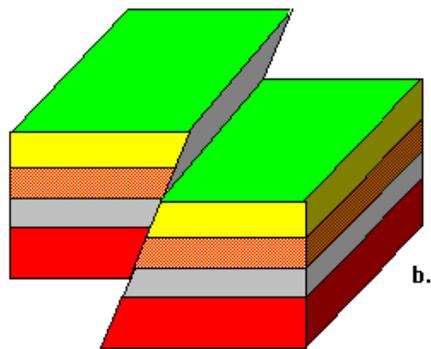


Reverse Fault

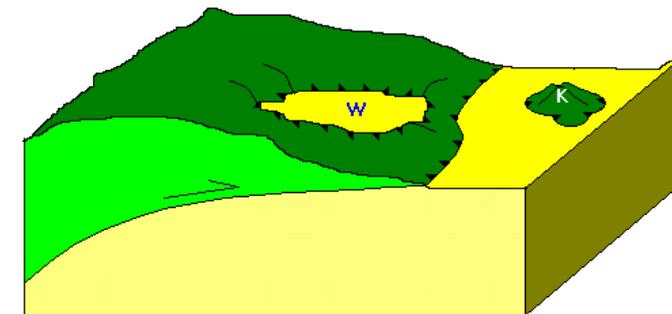
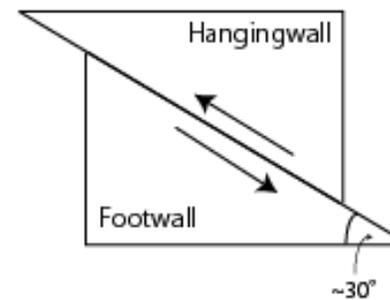
- ❖ Faults caused by blocks of crust colliding under the forces of compression are called reverse faults.
- ❖ Reverse faults are a prevalent feature in continent-continent collisions. Usually, there is also accompanying folding of rocks.
- ❖ During reverse faulting, the hanging wall block moves upward (and over) relative to the footwall block.



Reverse or Thrust Faulting
a. A block of crust before faulting.
b. After faulting. Note that the block becomes shorter.
c. An eroded reverse fault. Note that the well passes through several layers twice.

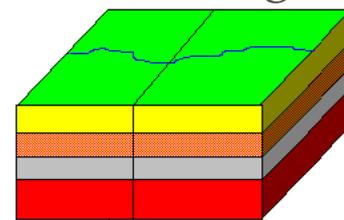
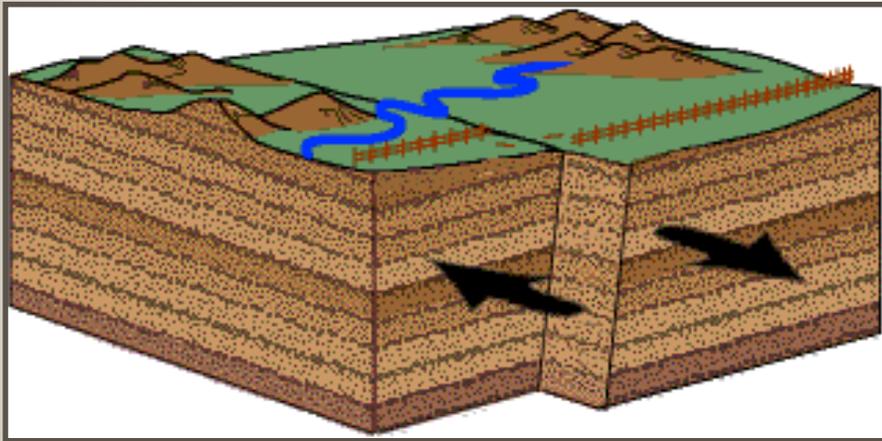


Reverse (thrust) fault

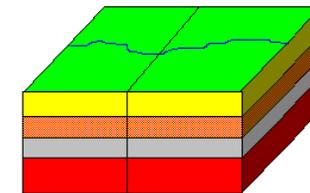
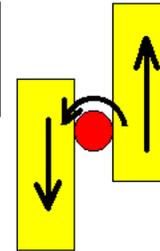
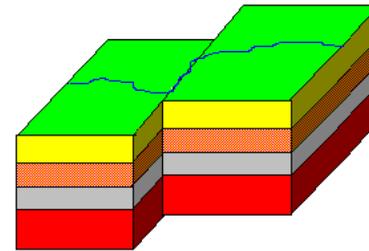


Faults: Strike-slip faults

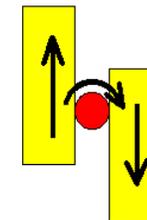
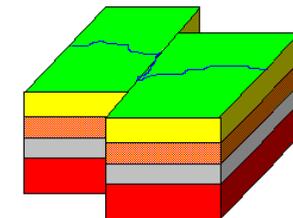
- Strike-slip faults occur when two blocks move in horizontal but opposite directions of each other.
- Depending on the direction of offset, it can be a “right-lateral offset” or a “left-lateral offset.”



Left Lateral



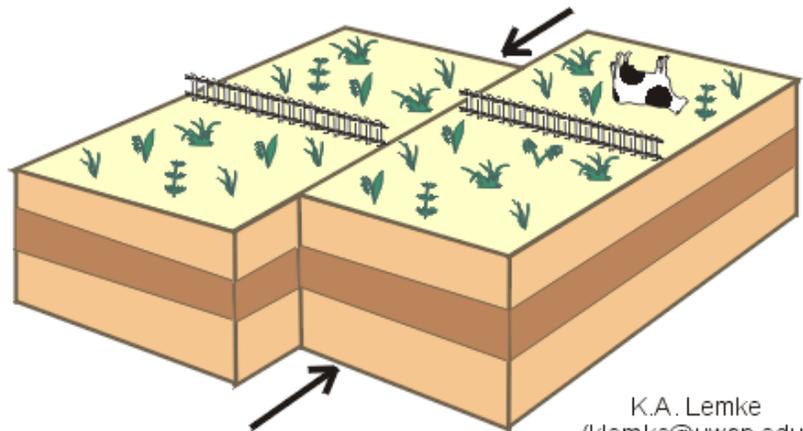
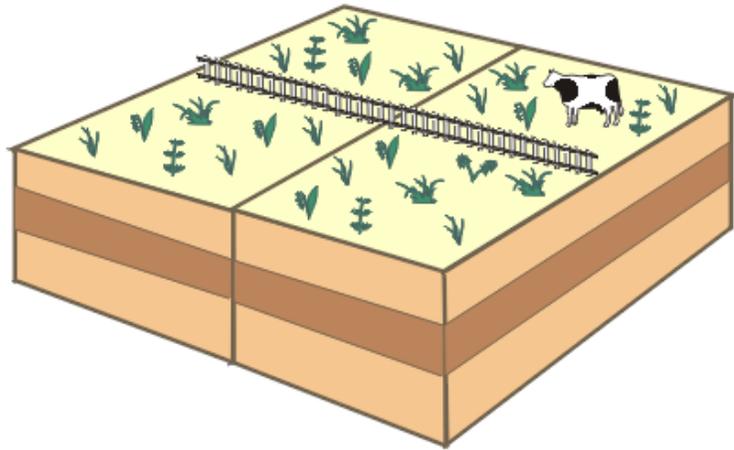
Right Lateral



The photograph above displays a light-colored pegmatite vein offset to the right in a schistose matrix. Photo courtesy of K. McCarney-Castle.

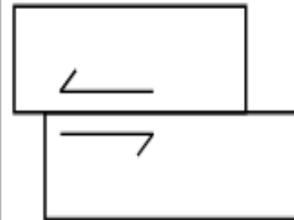
In the example above, the fence has been offset to the right, therefore it is called a right lateral strike-slip fault. (Credit: U.S. Geological Survey Department of the Interior/USGS)

Strike-Slip Fault

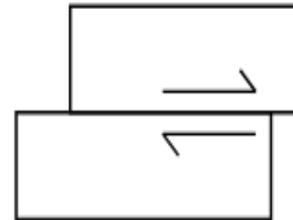


K.A. Lemke
(klemke@uwsp.edu)

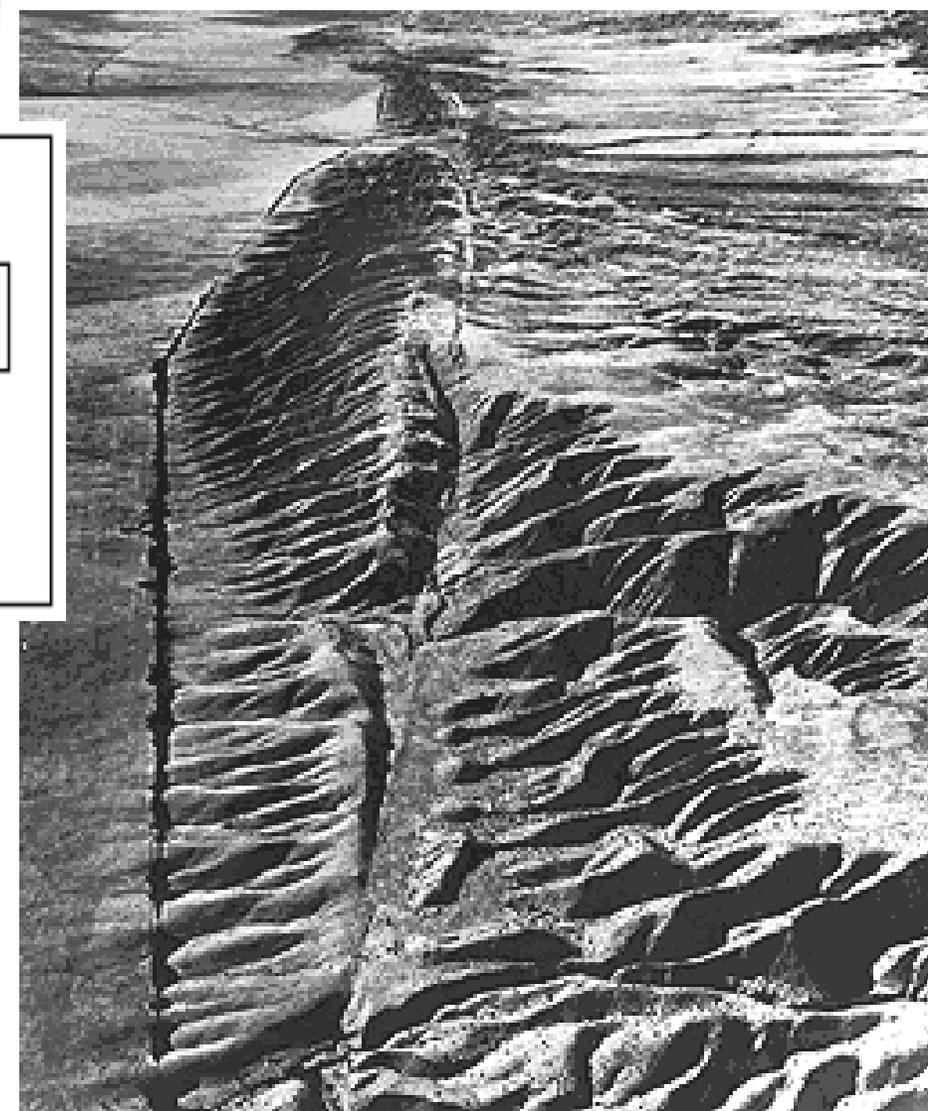
Sinistral (left-lateral)
strike-slip fault



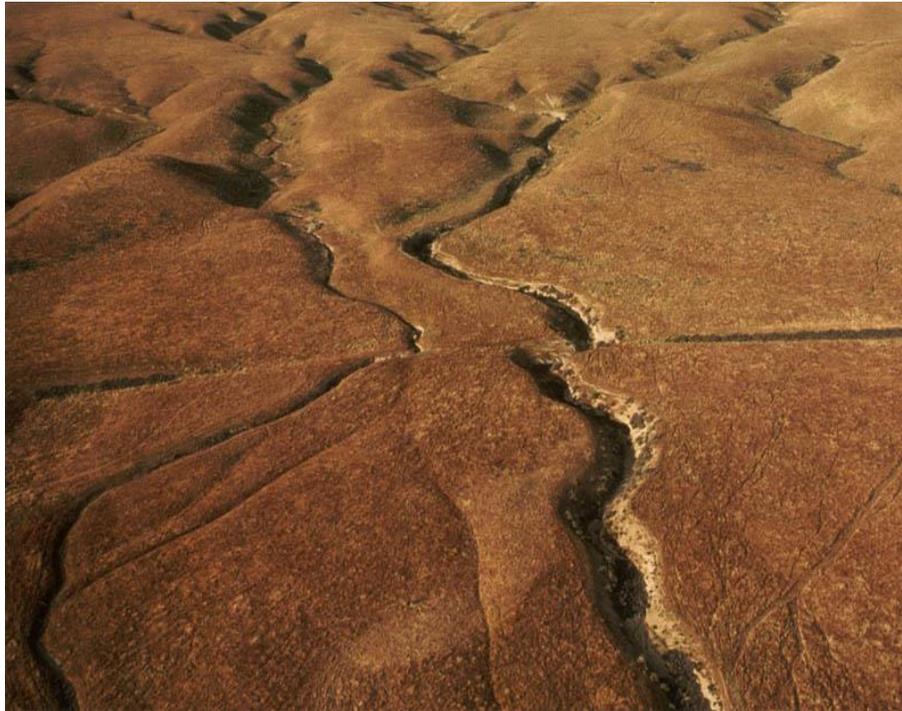
Dextral (right-lateral)
strike-slip fault



This is a plan view of the Earth's surface



EXAMPLES OF STRIKE-SLIP FAULTS



San Andreas Fault, CA
<http://education.usgs.gov/california/pp1515/chapter2/fig2-21.jpg>



Right Lateral Slip, Izmit, Turkey, 1999 Quake
<http://www.geo.uib.no/jordskjelv/index.php?topic=earthquakes&lang=en>

Seismic Waves



The shaking during an earthquake is caused by seismic waves. Seismic waves are generated when rock within the crust breaks, producing a tremendous amount of energy. The energy released moves out in all directions as waves, much like ripples radiating outward when you drop a pebble in a pond.

Two types of seismic waves are generated at the earthquake focus:

1. **Body waves** spread outward from the focus in all directions.
2. **Surface waves** spread outward from the epicenter to the Earth's surface, similar to ripples on a pond. These waves can move rock particles in a rolling motion that very few structures can withstand. These waves move slower than body waves.

Body Waves

Travel through the earth

- 2 types, have different motion:

Primary (P) waves

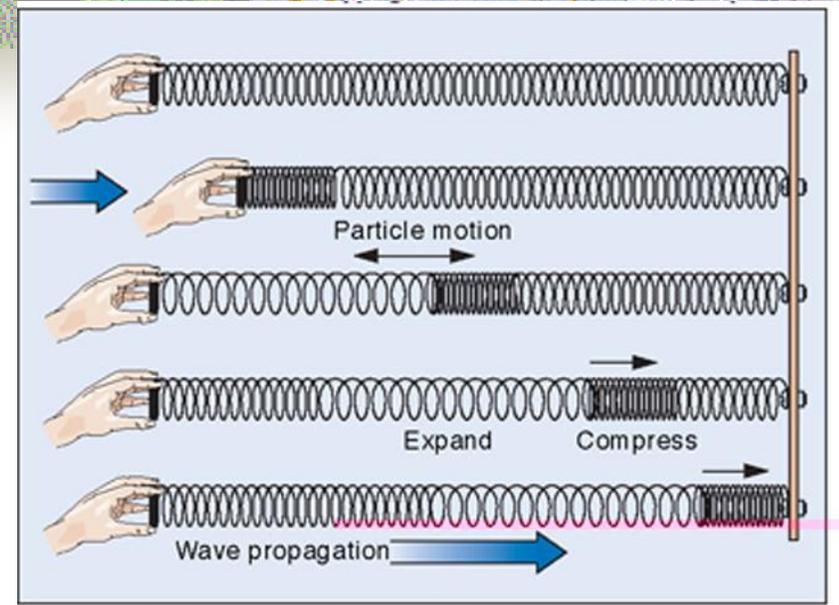
Compressional wave (travels in the same direction the waves move). Example: A slinky.

- Particle motion is parallel to wave direction
- Travel fastest (4-7 km/second, arrive first)
- Travel through solid or fluid

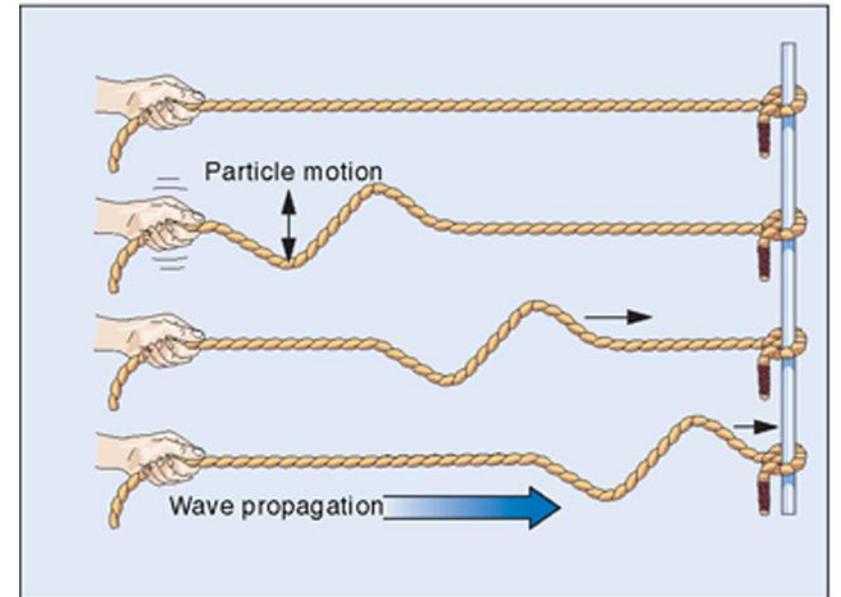
Secondary (S) waves

Transverse wave (travels perpendicular to the wave movement). Example: Shaking a rope.

- Particle motion is perpendicular to wave direction
- Travel slightly slower (2-5 km/second)
- Only travel through solid



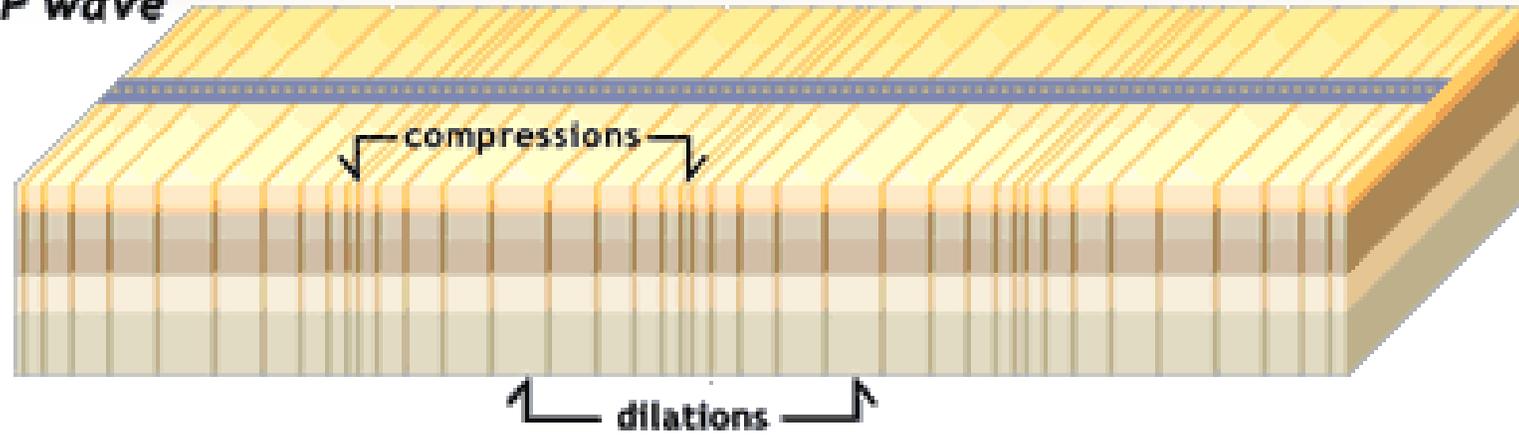
A Primary wave



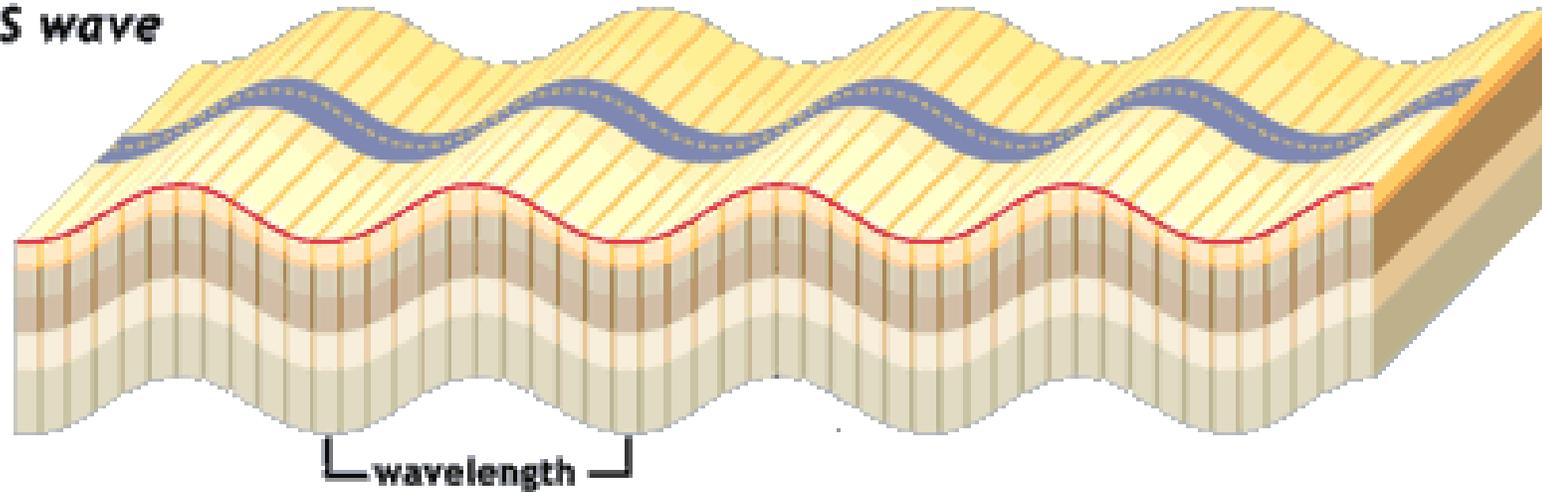
B Secondary wave

P and S Wave Motion

P wave



S wave



Seismic Waves

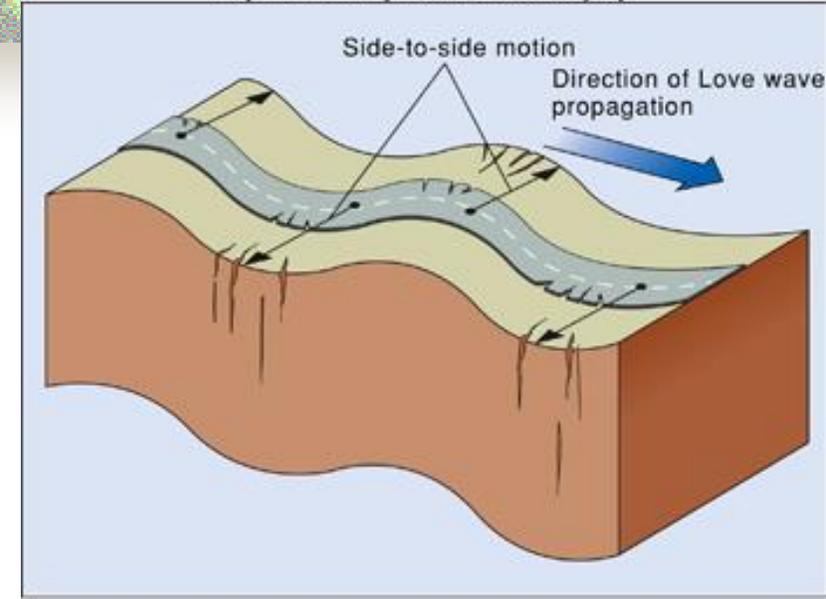
Surface Waves

Surface waves are produced when earthquake energy reaches the Earth's surface. Surface waves moves rock particles in a rolling and swaying motion, so that the earth moves in different directions.

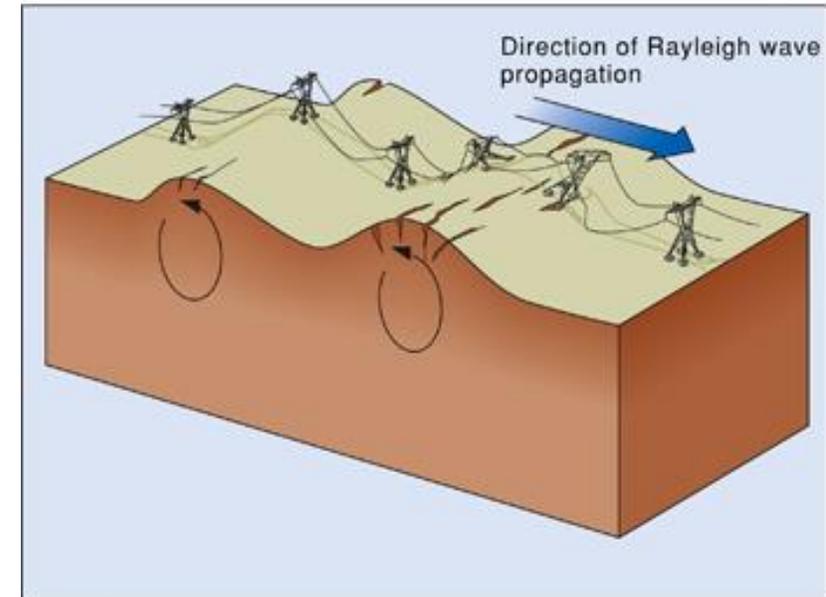
These are the slowest moving waves, but are the most destructive for structures on earth.

- **Love waves** - side-to-side motion of the ground surface
 - Can't travel through fluids
- **Rayleigh waves** - ground moves in an elliptical path opposite the direction of wave motion
 - Extremely destructive to buildings

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C Love wave



D Rayleigh wave

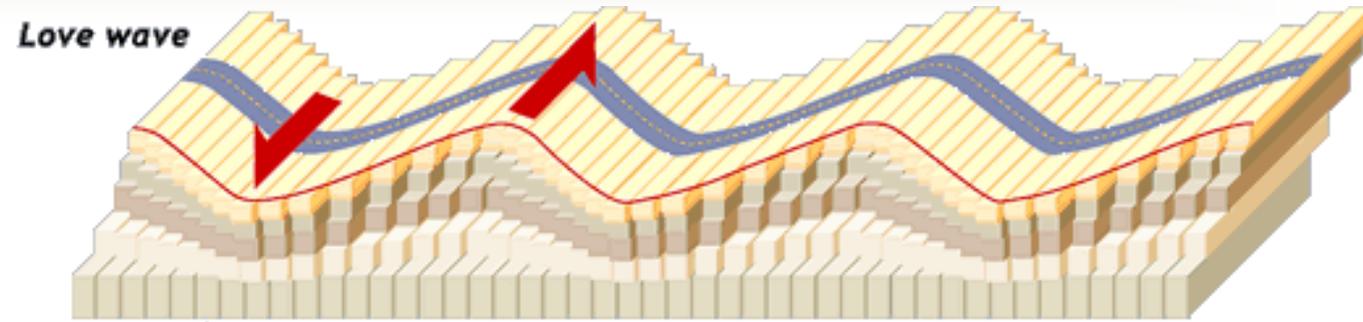
- Rayleigh Waves

Are Slower

Have a vertical motion

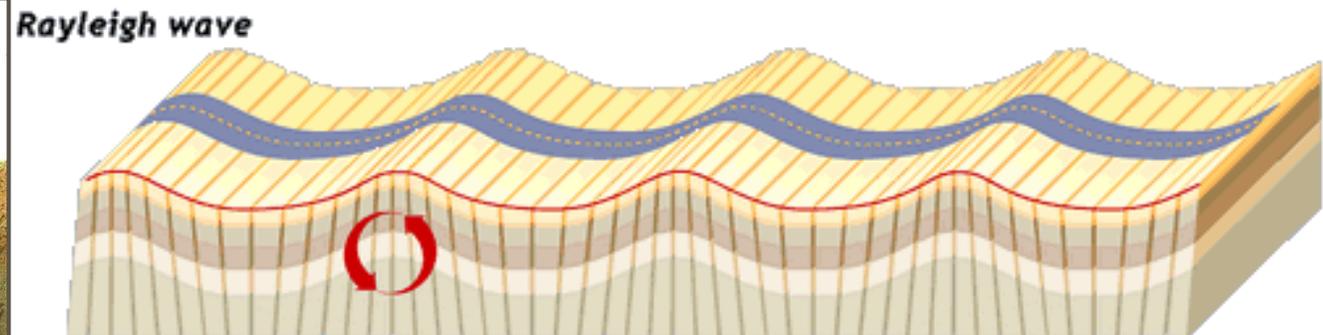
- Love Waves

Have a horizontal motion



Love wave

wave direction



Rayleigh wave

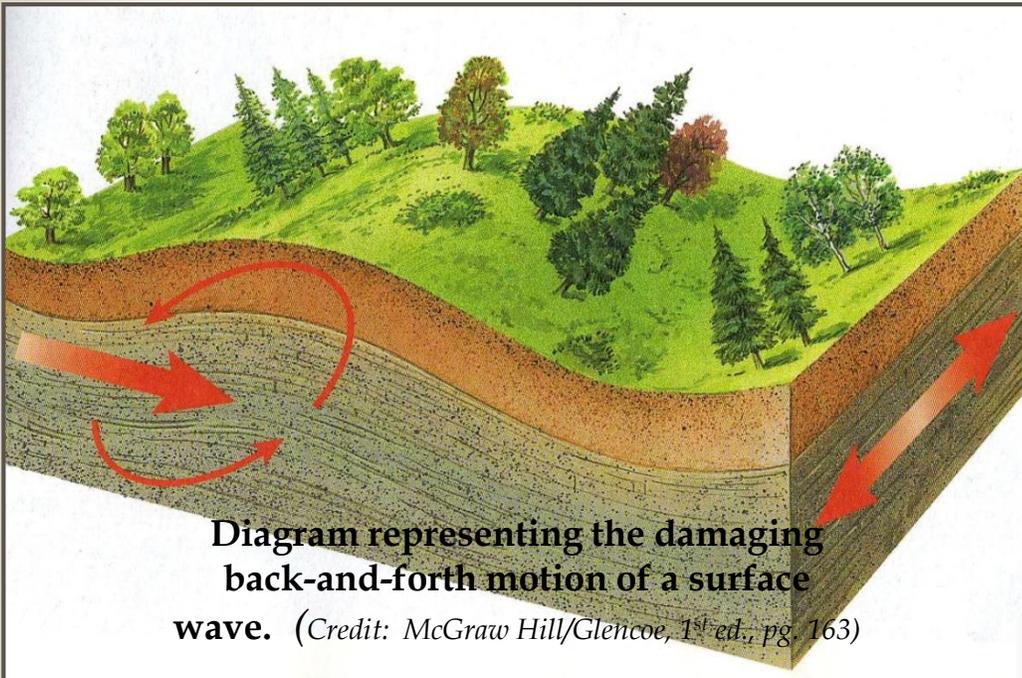
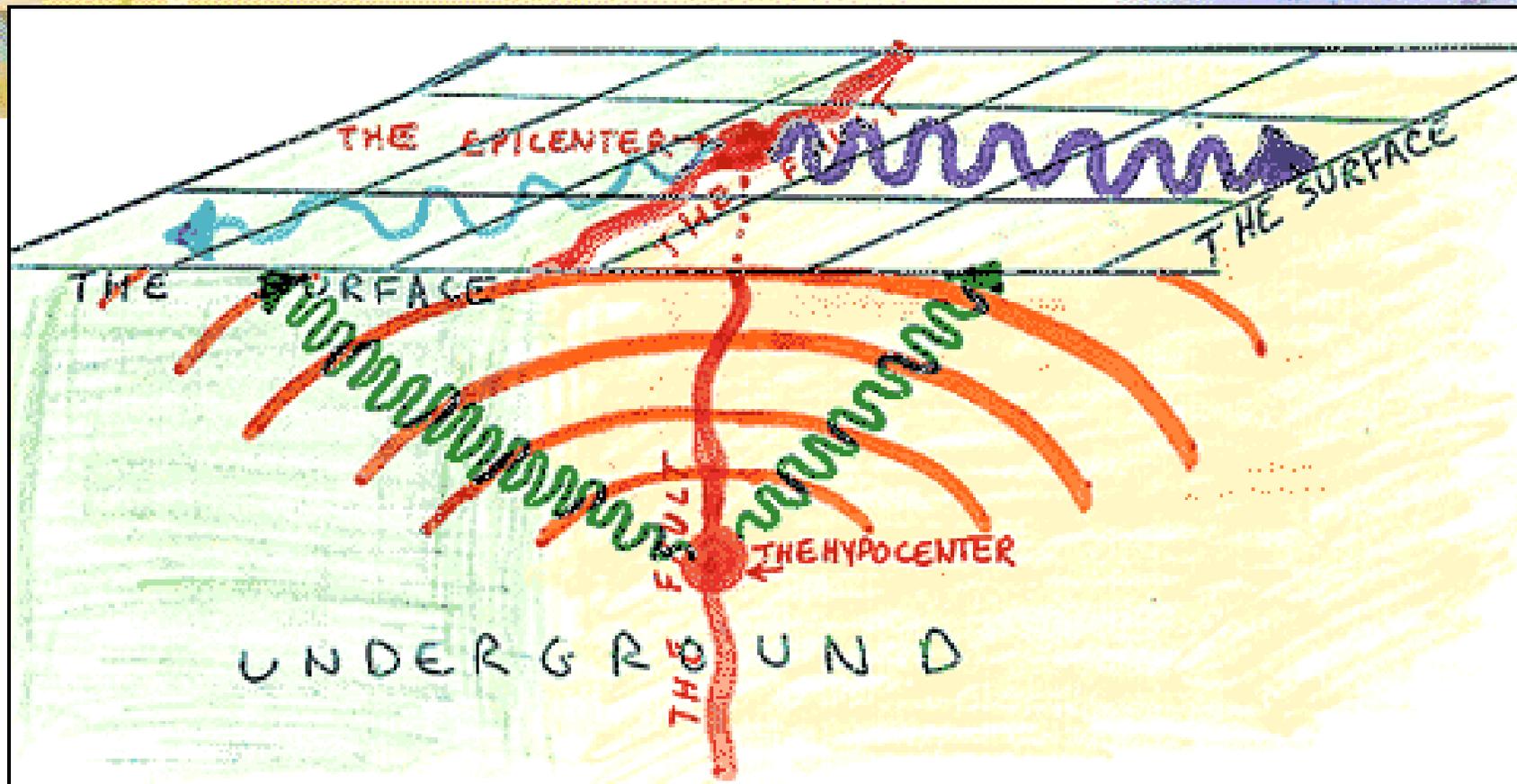


Diagram representing the damaging back-and-forth motion of a surface wave. (Credit: McGraw Hill/Glencoe, 1st ed., pg. 163)

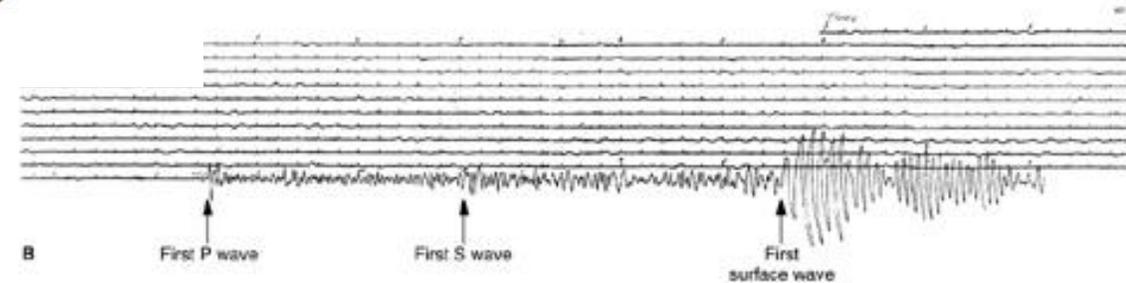
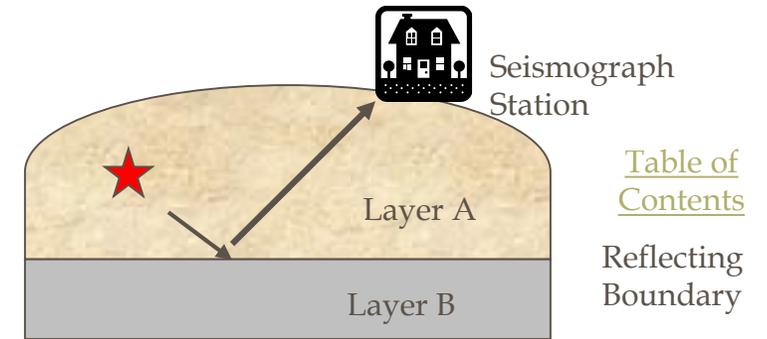
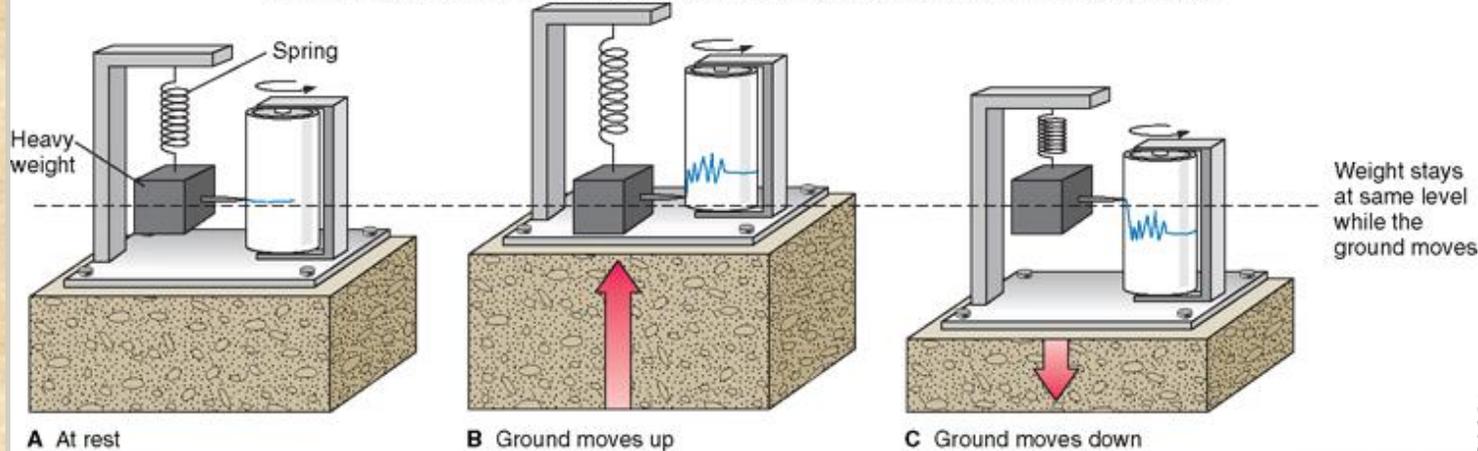


- Primary or Pressure (p) waves
 - Secondary or Shear (s) waves
 - Rayleigh waves
 - Love waves
- } body waves
- } surface waves

Measuring Earthquakes

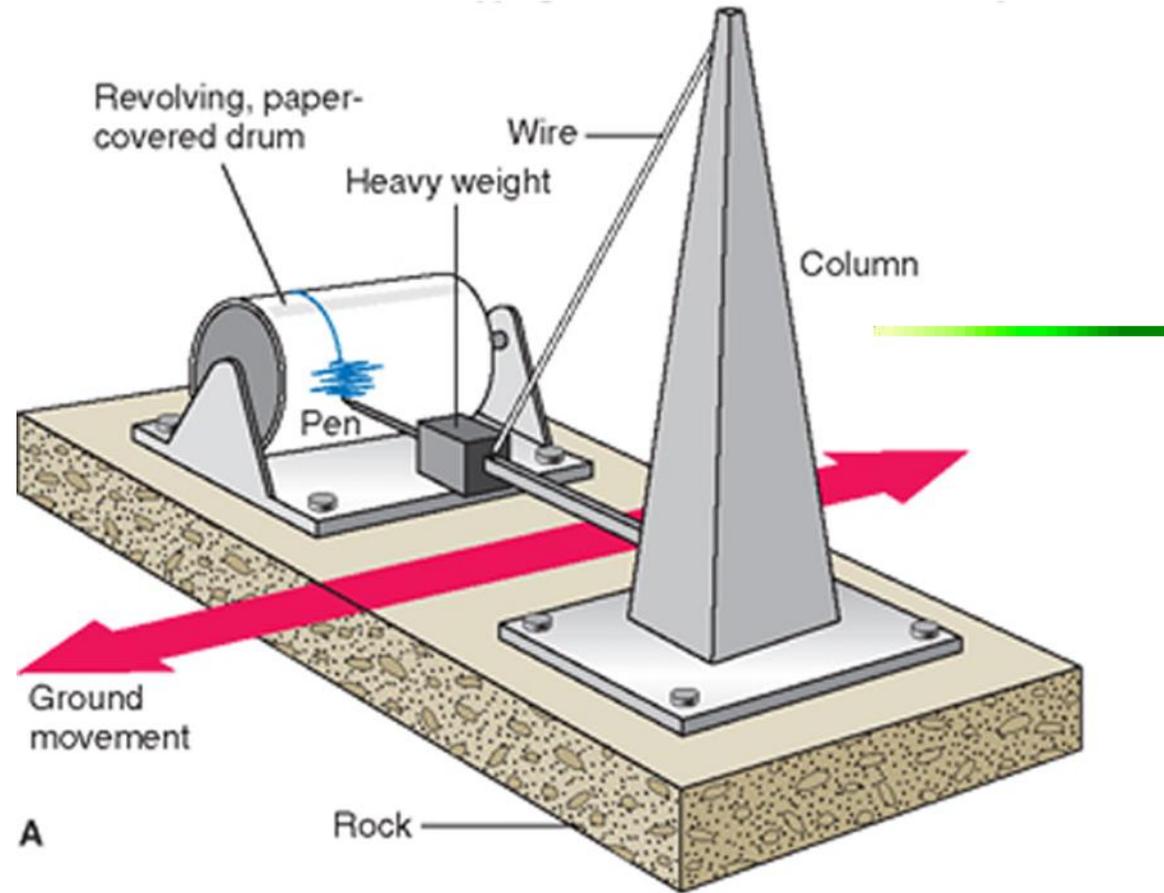
- *Seismometers* - used to measure seismic waves
- *Seismographs* - recording devices used to produce a permanent record of the motion detected by seismometers
- *Seismograms* - permanent paper (or digital) records of the earthquake vibrations
 - Used to measure the earthquake strengths

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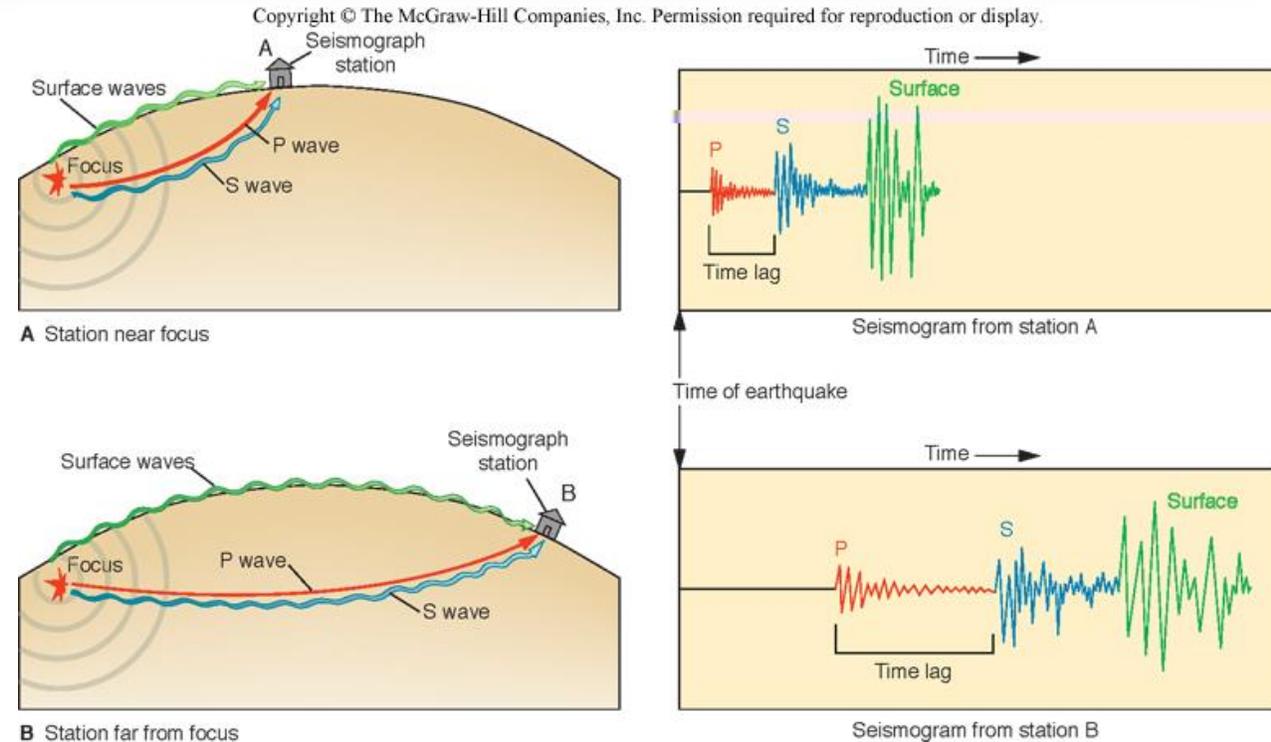
Seismograph

- Measures horizontal motion (P waves)



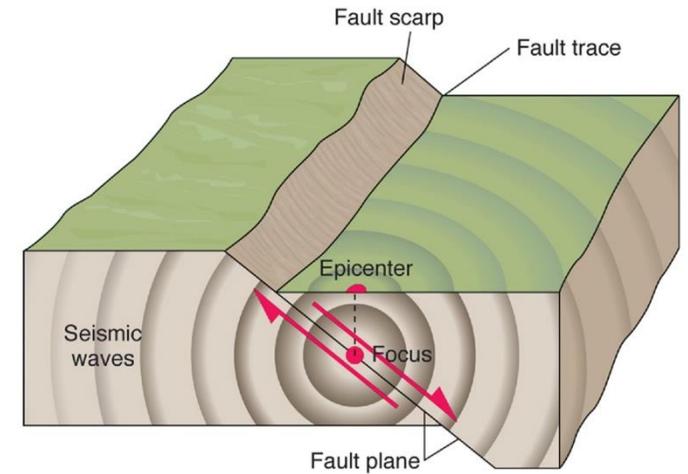
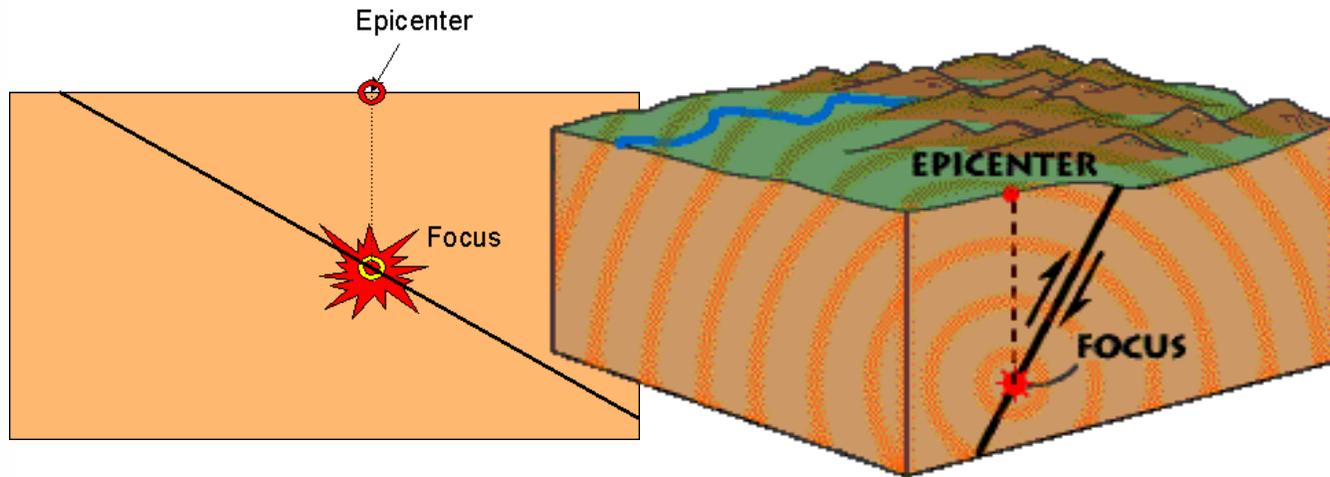
Locating Earthquakes

- P- and S-waves leave earthquake focus at the same time
- P-wave gets farther and farther ahead of the S-wave with distance and time from the earthquake
- *Travel-time curve* - used to determine distance to focus
 - based on time between first P- and S-wave arrivals



Locating Earthquakes

- ❑ **Focus**- The place within the Earth where an earthquake originates and energy is released
- ❑ **Epicenter**- The point on Earth's surface vertically above the focus.



- ***Depth of focus*** beneath Earth's surface can also be determined
 - *Shallow focus* 0-70 km deep
 - *Intermediate focus* 70-350 km deep
 - *Deep focus* 350-670 km deep

Measuring the “Size” of Earthquakes

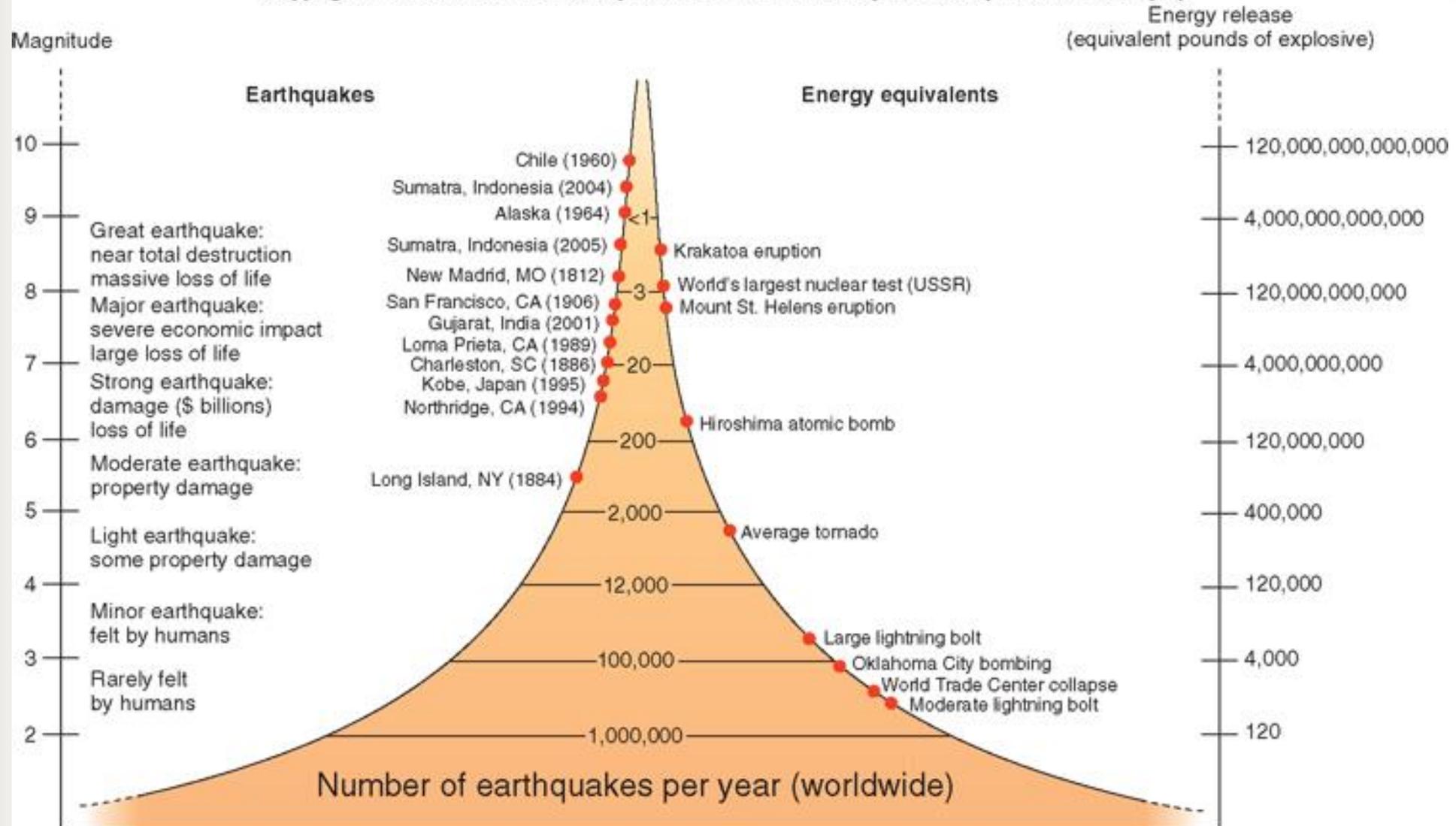
- Earthquake “size” measured two ways - *intensity* and *magnitude*.
- The magnitude of an earthquake is a measure of how destructive it is. Basically the magnitude corresponds to how much energy is released. The Richter Scale is used to express earthquake magnitude on the basis of the height (amplitude) of the largest line (seismic wave, P or S) on a seismogram.
- Intensity - a measure of the effects an earthquake produces (on both structures and people)
 - Modified Mercalli scale
 - The Mercalli scale is different from the Richter scale because it measures the intensity of how people and structures are affected by the seismic event. In essence, it measures damage. It is much more subjective and uses numbers ranging from 1 (no damage) to 12 (total destruction).

Table 16.1

Modified Mercalli Intensity Scale of 1931 (Abridged)

- I. Not felt except by a very few under especially favorable circumstances.
- II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
- III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.
- IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
- V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
- VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
- VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.
- VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
- IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
- X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Considerable landslides from river banks and steep slopes. Shifted sand and mud. Water splashed (stopped) over banks.
- XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
- XII. Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward into the air.

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After IRIS Consortium (www.iris.edu)

The Mercalli Intensity Scale

MODIFIED MERCALLI SCALE		RICHTER SCALE	
I.	Felt by almost no one.	2.5	Generally not felt, but recorded on seismometers.
II.	Felt by very few people.		
III.	Tremor noticed by many, but they often do not realize it is an earthquake.	3.5	Felt by many people.
IV.	Felt indoors by many. Feels like a truck has struck the building.		
V.	Felt by nearly everyone; many people awakened. Swaying trees and poles may be observed.		
VI.	Felt by all; many people run outdoors. Furniture moved, slight damage occurs.	4.5	Some local damage may occur.
VII.	Everyone runs outdoors. Poorly built structures considerably damaged; slight damage elsewhere.		
VIII.	Specially designed structures damaged slightly, others collapse.	6.0	A destructive earthquake.
IX.	All buildings considerably damaged, many shift off foundations, Noticeable cracks in ground.		
X.	Many structures destroyed. Ground is badly cracked.	7.0	A major earthquake.
XI.	Almost all structures fall. Very wide cracks in ground.	8.0	Great earthquakes.
XII.	Total destruction. Waves seen on ground surfaces, objects are tumbled and tossed.	8.0 and up	

Effects of Earthquakes

- Earthquakes produce several types of effects, all of which can cause loss of property and human life
 - *Ground motion* is the familiar trembling and shaking of the land during an earthquake
 - Can topple buildings and bridges
 - *Fire* is a problem just after earthquakes because of broken gas and water mains and fallen electrical wires
 - *Landslides* can be triggered by ground shaking, particularly in larger quakes
 - *Liquefaction* occurs when water-saturated soil or sediment sloshes like a liquid during a quake



Tsunami

- *Tsunami* (seismic sea waves) - very large sea waves caused by sudden upward or downward movement of the sea floor during submarine earthquakes
 - generally produced by magnitude 8+ earthquakes (“great” earthquakes - e.g., 9.3 Indonesia, 2004)
 - May also be generated by large *undersea landslides* or *volcanic explosions*
 - Travel across open ocean at speeds of >700 *km/hr*
 - Reach great heights in coastal areas with gently sloping seafloor and funnel-shaped bays

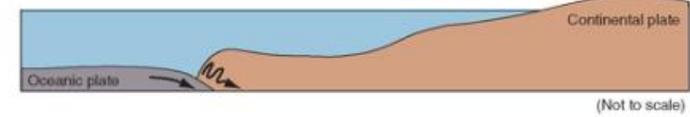
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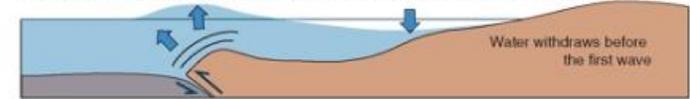
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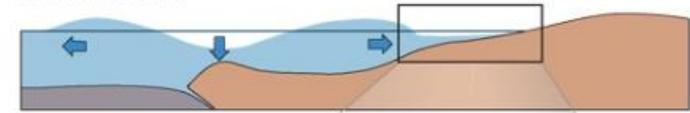
1. Before the earthquake: In this case, an oceanic plate subducts under a continental plate. The continental plate bends as stresses between the two plates build over time.



2. Earthquake: Releasing its built-up stress, the continental plate lurches forward over the oceanic crust, lifting the ocean. The displaced water appears as a huge bulge on the sea surface.



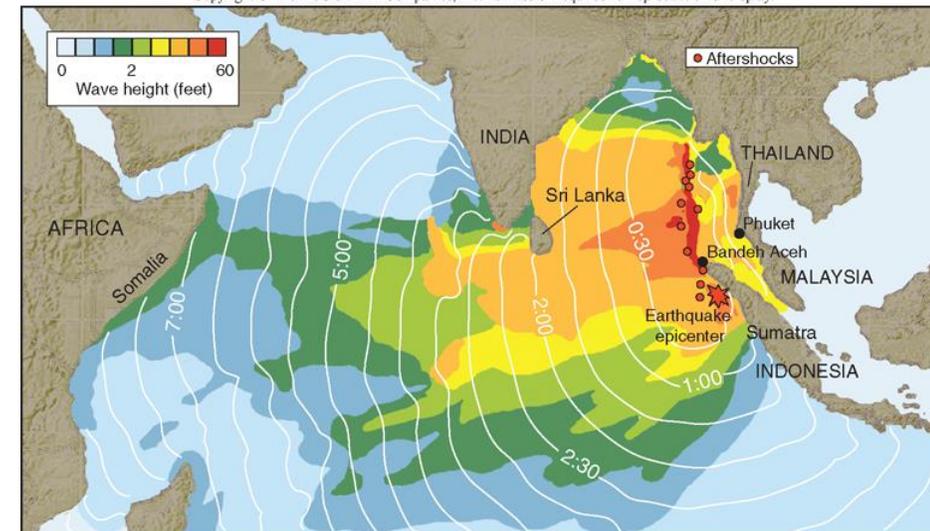
3. After the earthquake, gravity collapses the bulge to start a succession of waves, or tsunami. The tsunami waves move away in both directions as the mass of water “bobs” up and down over the source of the earthquake.



4. Each wave quickly advances over the land as a sediment-filled wall of water. It stops briefly before retreating, carrying sediments and debris back to the sea. Over time, the intensity of the tsunami subsides.



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The Richter Scale

Richter Magnitudes	Description	Earthquake Effects	Frequency of Occurrence
Less than 2.0	Micro	Micro-earthquakes, not felt.	About 8,000 per day
2.0-2.9	Minor	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9	Minor	Often felt, but rarely causes damage.	49,000 per year (est.)
4.0-4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	6,200 per year (est.)
5.0-5.9	Moderate	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Can be destructive in areas up to about 100 miles across in populated areas.	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred miles across.	1 per year
9.0-9.9	Great	Devastating in areas several thousand miles across.	1 per 20 years
10.0+	Great	Never recorded; see below for equivalent seismic energy yield.	Extremely rare (Unknown)

Complications of the Richter scale include:

1. The Richter scale originally only applied to shallow-focus earthquakes in southern California so now must be modified.
2. Magnitudes calculated from seismograms above 7 tend to be inaccurate.

The Mercalli scale of earthquake intensity

- I. Not felt except by a very few under especially favorable conditions.
- II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
- 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. Vibration similar to the passing of a truck. Duration estimated.
- 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.
- V. Felt by nearly everyone; many awakened. some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
- VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
- 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.
- 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.
- 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.
- X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rail bent.
- XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
- XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Tsunami Waves Created by Earthquakes

Tsunami waves are generated by submarine earthquakes

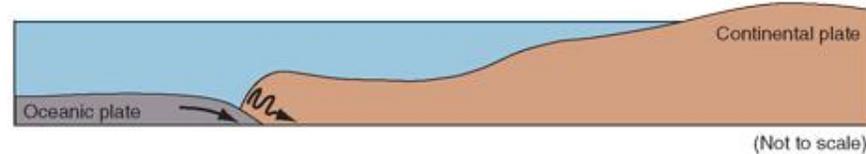
Long low waves are formed above displaced seafloor that travel for miles along the base of the seafloor.

Displacement of seawater surface can be as little as a few centimeters in the middle of the ocean.

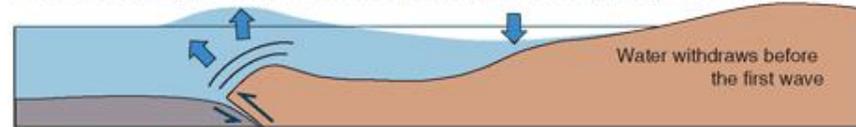
Displacements increase dramatically as they approach a continental shelf

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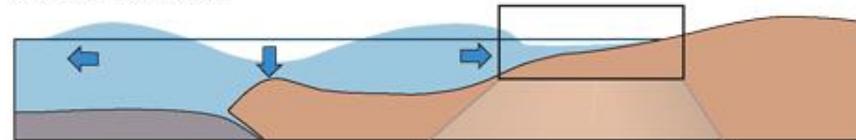
1. Before the earthquake: In this case, an oceanic plate subducts under a continental plate. The continental plate bends as stresses between the two plates build over time.



2. Earthquake: Releasing its built-up stress, the continental plate lurches forward over the oceanic crust, lifting the ocean. The displaced water appears as a huge bulge on the sea surface.



3. After the earthquake, gravity collapses the bulge to start a succession of waves, or tsunami. The tsunami waves move away in both directions as the mass of water "bobs" up and down over the source of the earthquake.



4. Each wave quickly advances over the land as a sediment-filled wall of water. It stops briefly before retreating, carrying sediments and debris back to the sea. Over time, the intensity of the tsunami subsides.





San Andreas Fault

San Francisco
Site of M7.8
Earthquake,
April 18,
1906