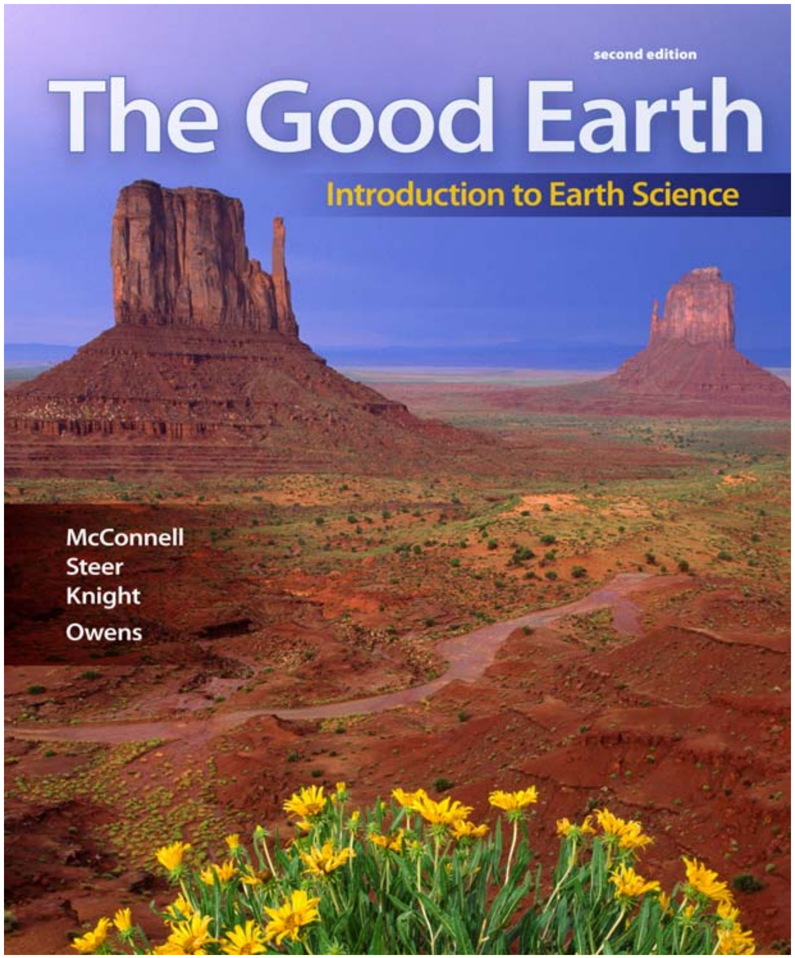
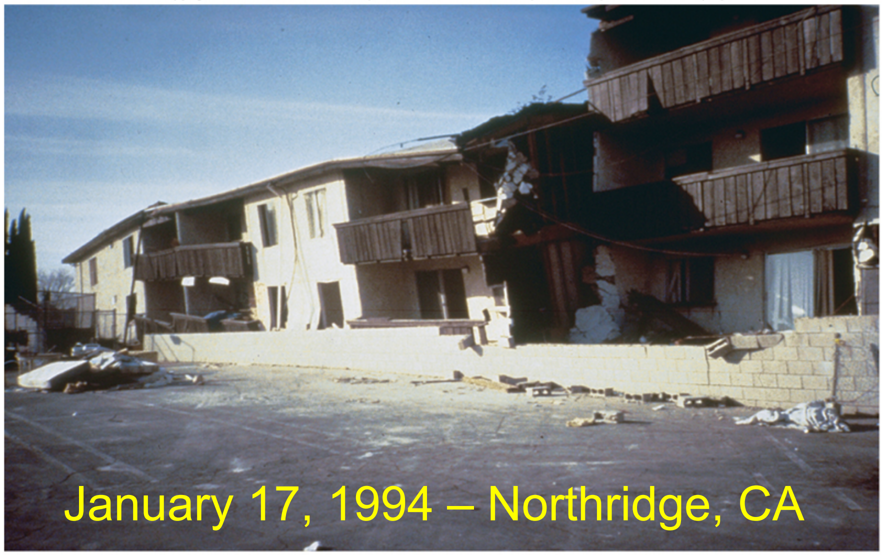
Chapter 5: Earthquakes



1. Experiencing an Earthquake firsthand
2. The Science of Ghost Forests and Mega-earthquakes
3. Faults, Earthquakes, and Plate Tectonics
4. Seismic Waves and Earthquake Detection
5. Measurement of Earthquakes
6. Earthquake Hazards

Experiencing an Earthquake Firsthand



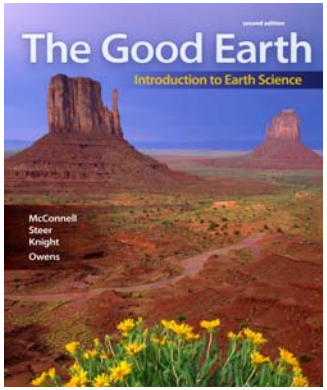
a.

© NOAA

Structures like this apartment building were damaged by an earthquake

- 57 killed, 9,000 injured
- $20 billion damage estimate

- More than 2 million people killed by earthquake hazards in 20th Century
  - 30 million US citizens in earthquake hazard zones
- Most deaths due to building collapse and tsunami
  - Indian Ocean tsunami claimed 230,000 lives



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Go to the next section: ***The Science of Ghost Forests and Mega-Earthquakes***

The Science of Ghost Forests and Mega-Earthquakes

© USGS

Ghost forests in Alaska (top) and along the coast of Washington.

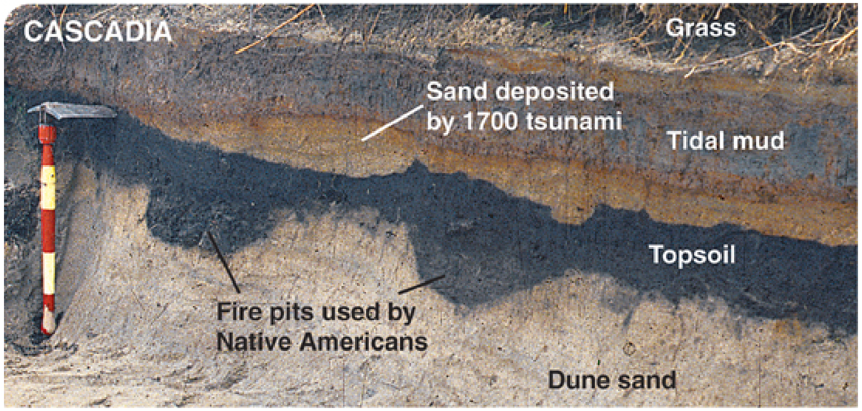
- Stands of dead trees in coastal marshes in Washington state
  - Similar to trees killed in one of the largest earthquakes ever recorded
- Where the Washington trees a signal of a past mega-earthquake?
  - Radiocarbon data indicated they died between 1680 and 1720
  - Was there a possible earthquake source nearby?

The Science of Ghost Forests and Mega-Earthquakes

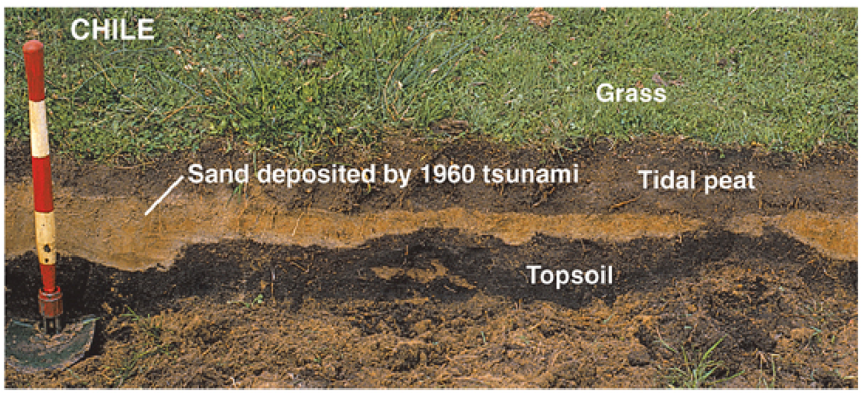
Location of the Cascadia subduction zone relative to major cities of the Pacific Northwest.

- Mega-earthquakes occur along subduction zones
  - Cascadia subduction zone is approximate size of rupture zone of 2004 Sumatra earthquake (Indian Ocean tsunami)
- A Cascadia subduction zone earthquake would have generated a substantial tsunami
  - Where is the evidence of a tsunami?

The Science of Ghost Forests and Mega-Earthquakes



a.



b.

©USGS

Tsunami sand deposits cover soil in Oregon (top) and in Chile.

- Tsunami-generated sand deposits discovered in coastal marshes of Pacific Northwest
  - Similar to sand layers formed by 1960 Chile mega-earthquake and 2004 Sumatra earthquake

On the basis of historical records, Japanese scientists hypothesized that the Cascadia earthquake occurred in January, 1700.

How did American scientists test this hypothesis?

The Science of Ghost Forests and Mega-Earthquakes

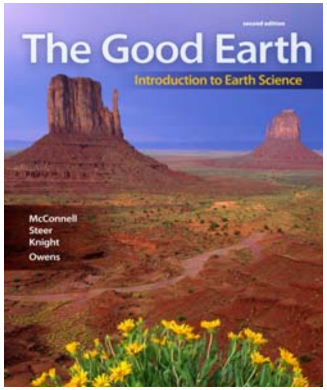
© Robert Glusic/Getty Images

- Tree ring analysis revealed the ghost forest trees died in 1700
  - Pacific Northwest cities are at risk from much larger earthquakes than was previously thought
  - Rare events, on average 500 years apart
  - Stricter building codes were established

Earthquakes Concept Survey

Briefly explain how the discovery of the potential for mega-earthquakes on the Cascadia subduction zone illustrated the following characteristics of scientific explanations:

1. Science is tentative.
2. Science is based on observations.
3. Scientific hypotheses are predictable and testable.
4. Science offers a natural cause for natural events.



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Faults, Earthquakes, and Plate Tectonics

What do you observe in these images?

a.

© USGS;

b.

© USGS;

Faults, Earthquakes, and Plate Tectonics

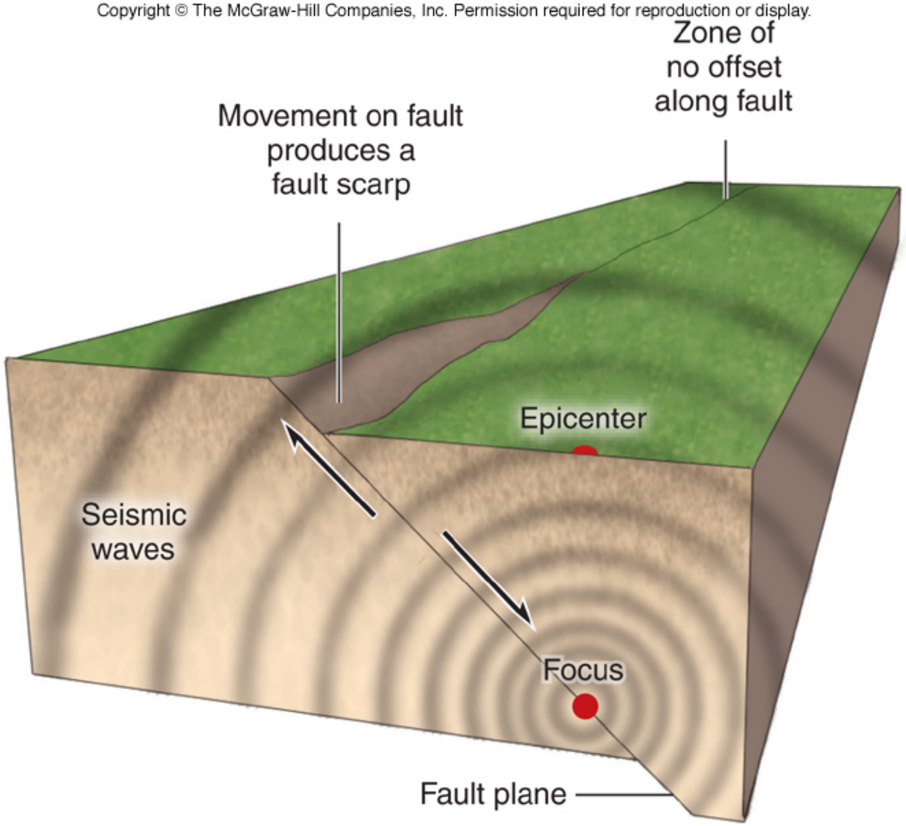
- **fault** - a fracture in the crust on which movement has occurred

a.

b.

Hebgen Lake earthquake, Montana, 1959

Faults, Earthquakes, and Plate Tectonics



Earthquake features. Only part of a fault may move during an earthquake.

- **Fault** - a fracture in the crust on which movement has occurred
  - A zone of weakness where earthquakes occur
  - Focus – location where movement begins on fault
  - Epicenter – location on surface above the focus
  - Fault scarp – "step" in land surface formed by movement on the fault
  - Only part of a fault typically breaks during an earthquake

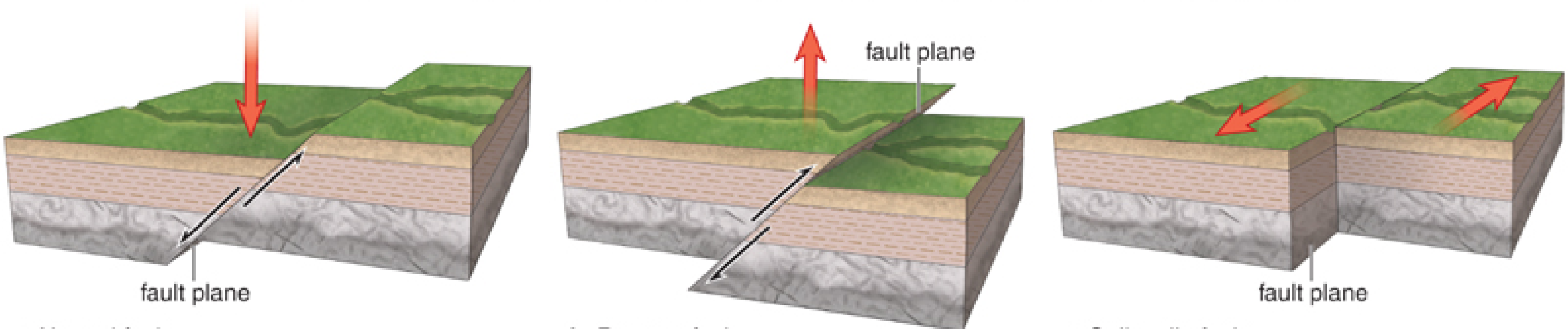
Earthquake Conceptest

An earthquake occurred on the Erie fault 5 kilometers beneath San Gabriel. Damage from the earthquake was greatest in nearby Fremont. The farthest report of shaking was recorded in Stockton. Where was the earthquake's epicenter?

A. The Erie Fault
B. San Gabriel
C. Fremont
D. Stockton

Faults, Earthquakes, and Plate Tectonics

3 Fault Types - Faults classified by relative movements of rocks on either side of fault surface

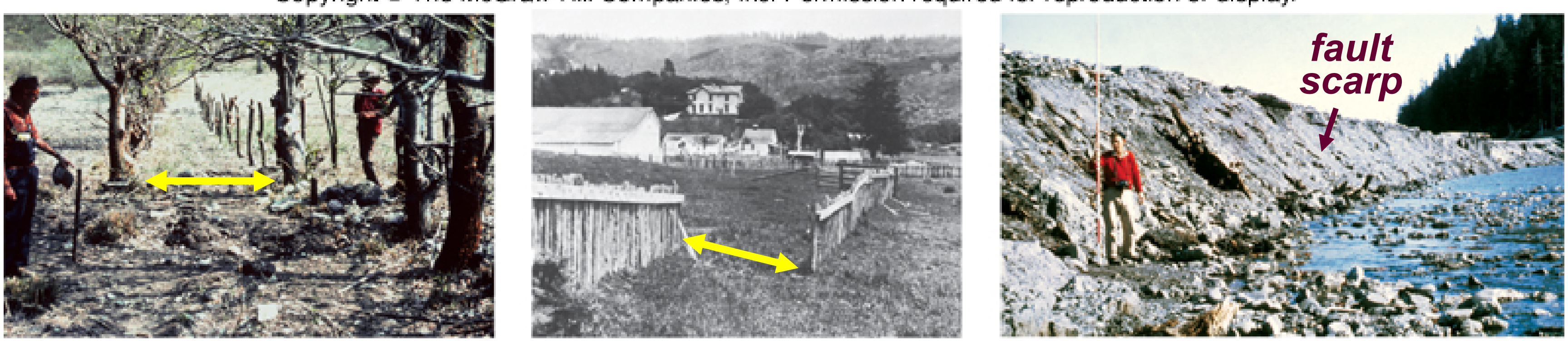


a. Normal fault　b. Reverse fault　c. Strike-slip fault

- normal fault, block above an inclined fault moves down
- reverse fault, block above an inclined fault moves up
- strike-slip fault, blocks on either side of fault move horizontally, left or right

Faults, Earthquakes, and Plate Tectonics

Faults recognized by observing offset of features or change in elevation of land surface



a. b. c.

© USGS

Line of trees offset 3 meters by 1976 Guatemala earthquake

Fence offset 3 meters by San Francisco earthquake (1906)

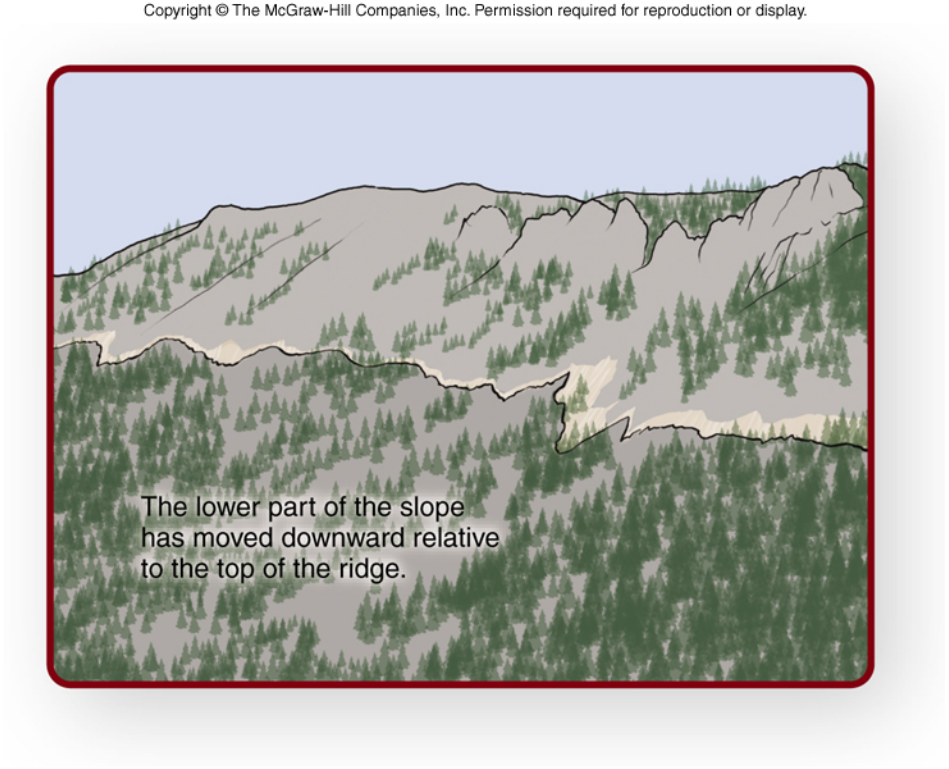
Rocks at land surface offset to form a **fault scarp** by big 1964 Alaska earthquake

Horizontal fault movements

Vertical fault movement

Earthquake Conceptest

What type of fault generated the Hebgen Lake earthquake, Montana?



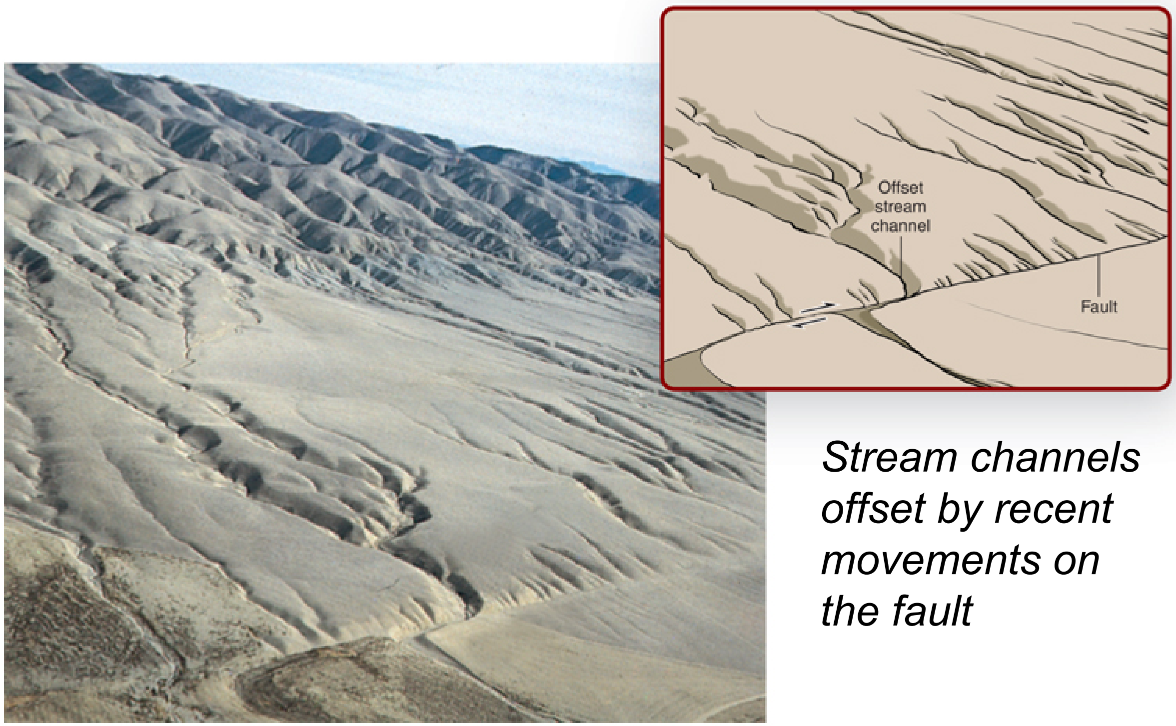
A. Normal fault

B. Reverse fault

C. Strike-slip fault

Faults, Earthquakes, and Plate Tectonics

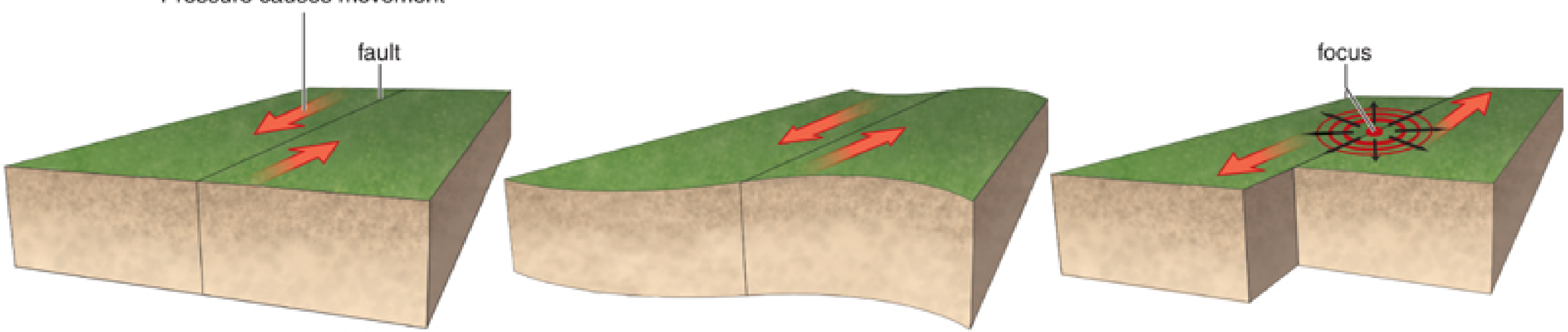
San Andreas fault, California, forms part of the boundary between the North American and Pacific plates



Stream channels offset by recent movements on the fault

Faults, Earthquakes, and Plate Tectonics

Fault movements are driven by stresses produced by plate tectonics



a. Fault stuck after last movement. **b.** Stress builds up: Rocks closer to fault bend like a bow. **c.** Earthquake: Rocks spring back and vibrate.

Friction along the fault surface is enough to cause most faults to "stick".

All rocks are slightly elastic. The build up of stress causes the rock to deform (change shape).

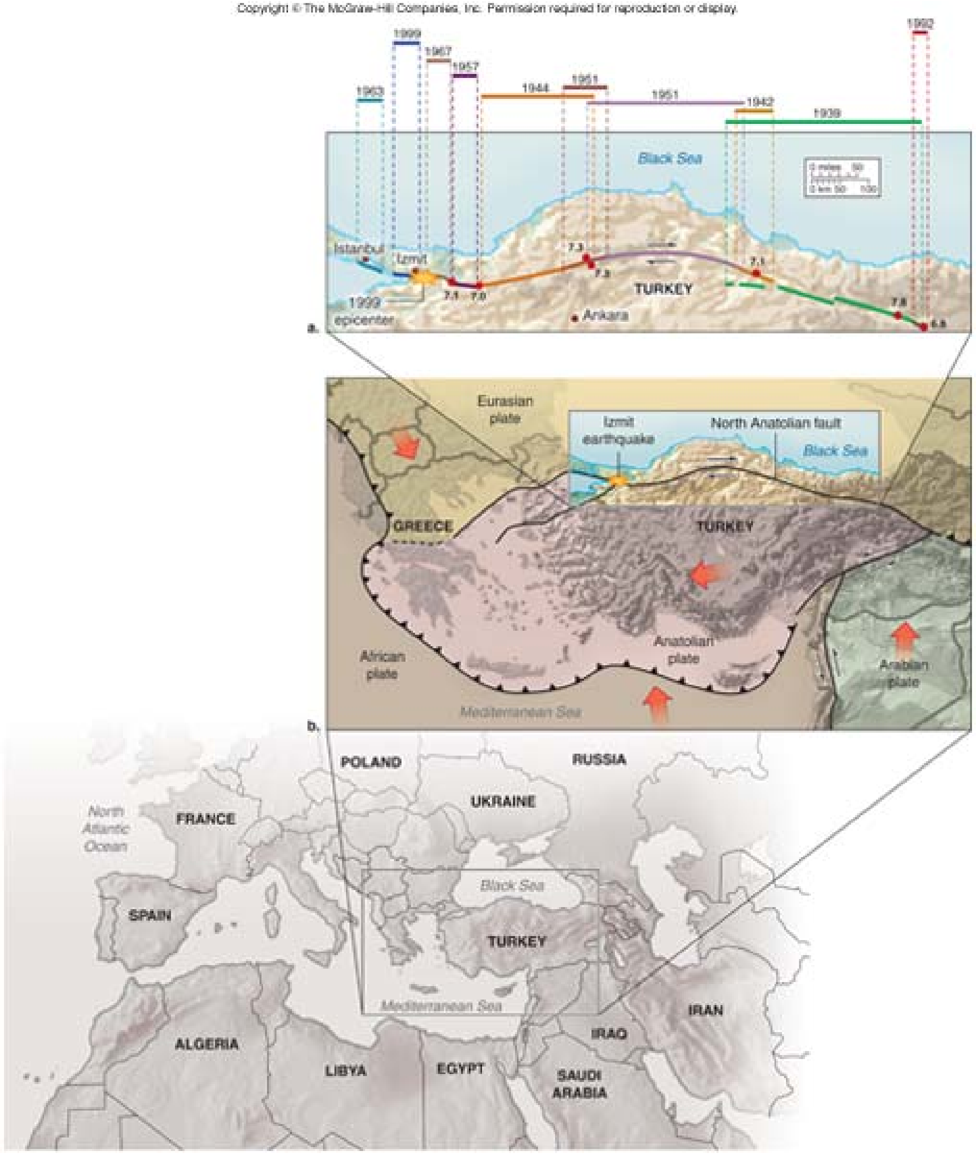
After decades or centuries, stress has built up to sufficient levels to overcome friction and cause fault movement

Faults, Earthquakes, and Plate Tectonics

© C. C. Plummer, California State University at Sacramento

- **Recurrence interval** – time for build up of stress to cause fault movement and earthquake
  - Longer recurrence intervals (100s years) for biggest earthquakes
  - Decades or less for smaller events
  - Scientists can analyze the build up of deformation using instruments that identify changes in shape or positions of rocks

Faults, Earthquakes, and Plate Tectonics



- **Seismic gap** – segments of active faults that have not experienced recent movements
  - 1999 Izmit earthquake in Turkey occurred in a seismic gap
  - Major faults break in segments. Several segments of the North Anatolian fault broke during previous years to produce big earthquakes
  - Fault is plate boundary between Anatolian plate and Eurasian plate

Earthquake Concepttest

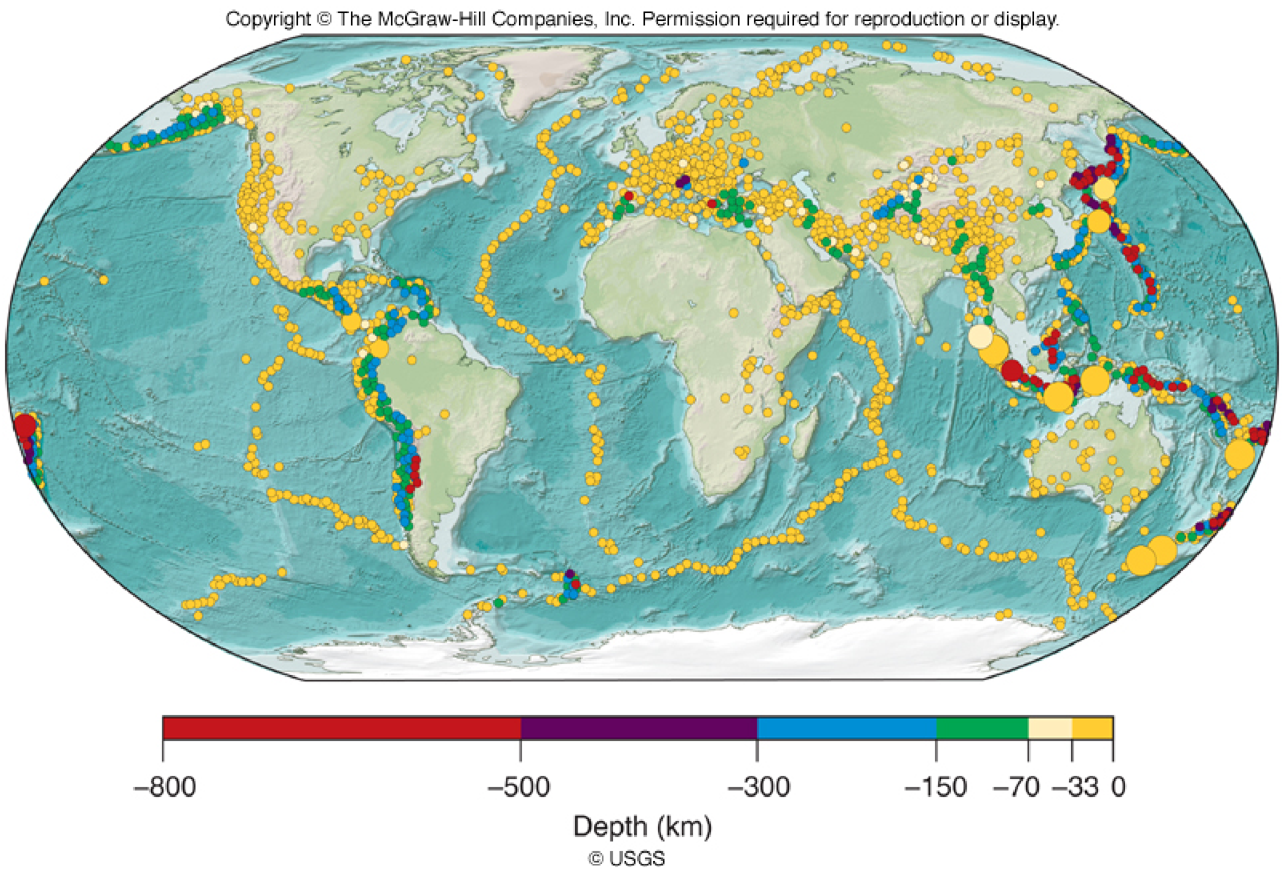
If the San Andreas fault moves 500 cm per big earthquake, and fault movement is equivalent to plate motion (2.5 cm/yr):

How many years of plate motions must accumulate to produce one big earthquake?

A. 2 years
B. 20 years
C. 200 years
D. 2000 years

Faults, Earthquakes, and Plate Tectonics

World Distribution of Earthquakes



Most earthquakes occur along plate boundaries, relatively few in interiors of plates

Shallow earthquakes much more common than deep events

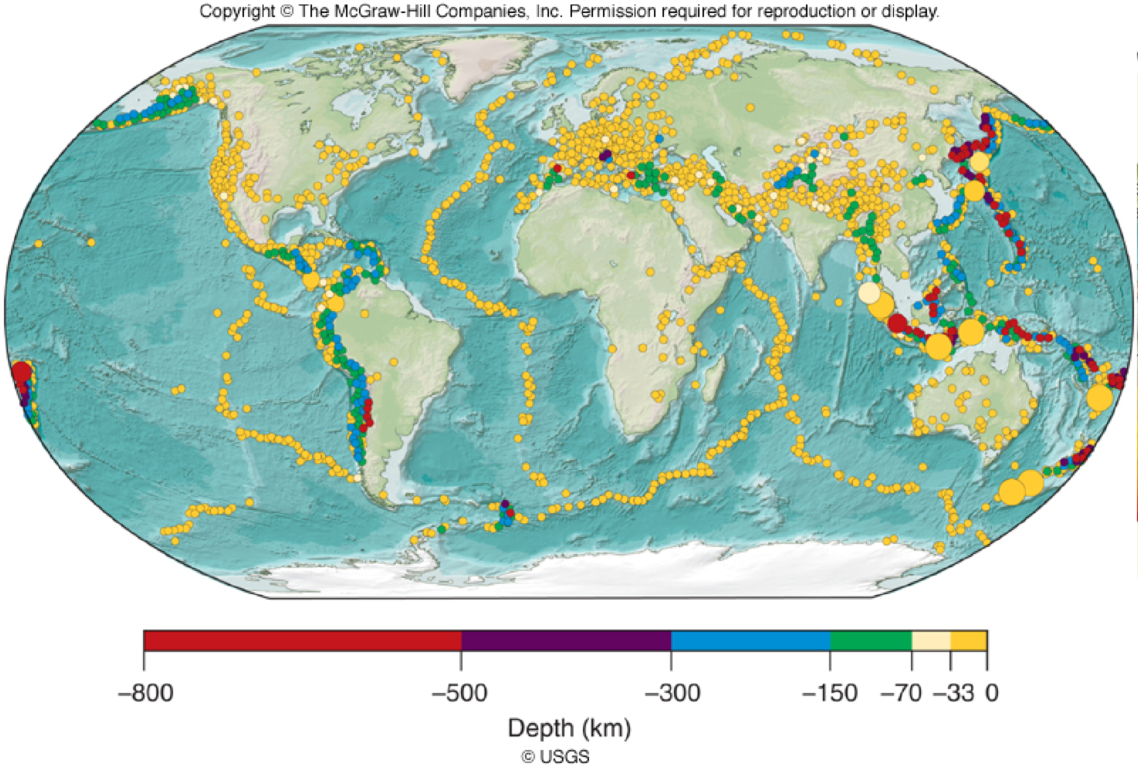
Divergent plate boundaries (oceanic ridges) characterized by earthquakes with shallow focal depths (0-33 km)

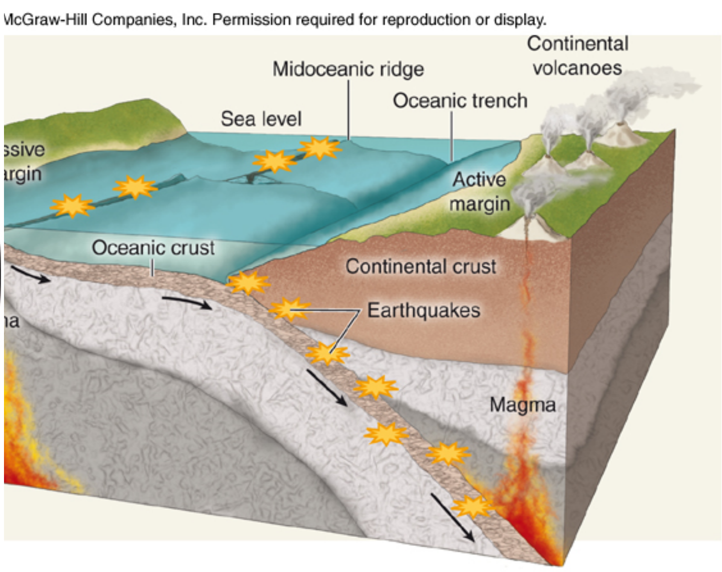
Faults, Earthquakes, and Plate Tectonics

World Distribution of Earthquakes

Largest earthquakes found in association with convergent plate boundaries

Convergent plate boundaries (oceanic trenches) characterized by earthquakes with a range of focal depths (0-800 km)





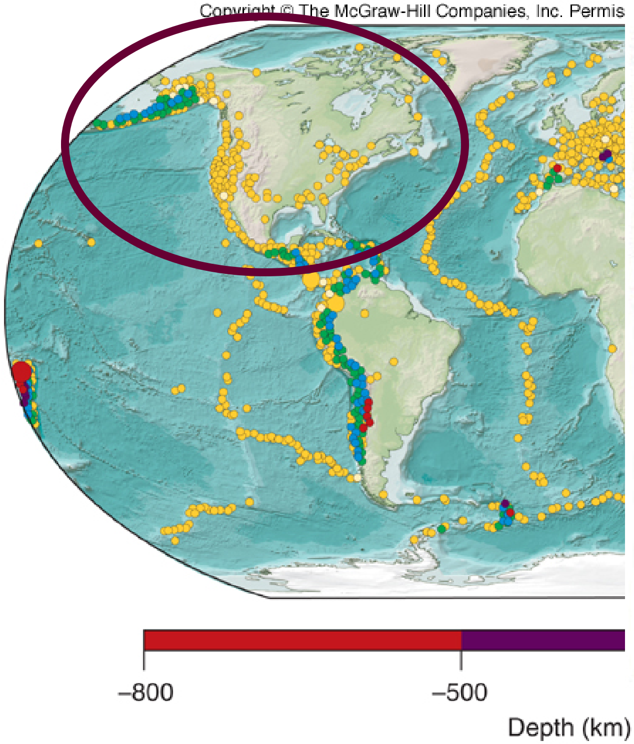
Faults, Earthquakes, and Plate Tectonics

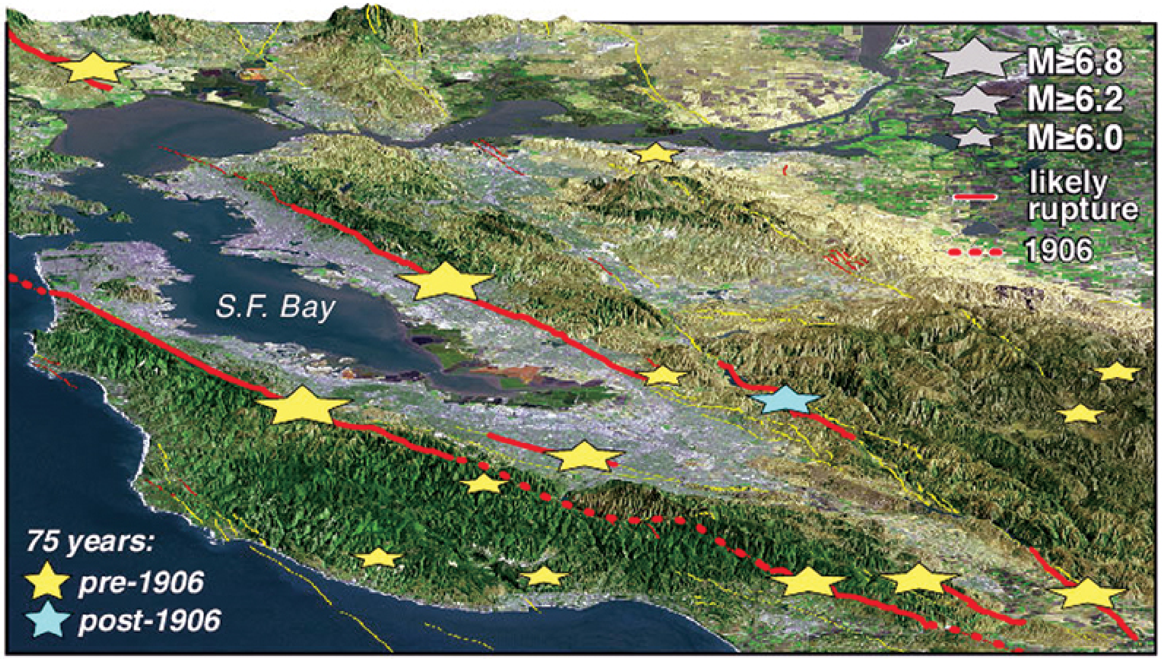
US Earthquakes

Largest, most frequent, US earthquakes along convergent plate boundary south of Alaska

Most US earthquake damage occurs in populous California

- 62% chance of a large earthquake in San Francisco Bay area by 2032





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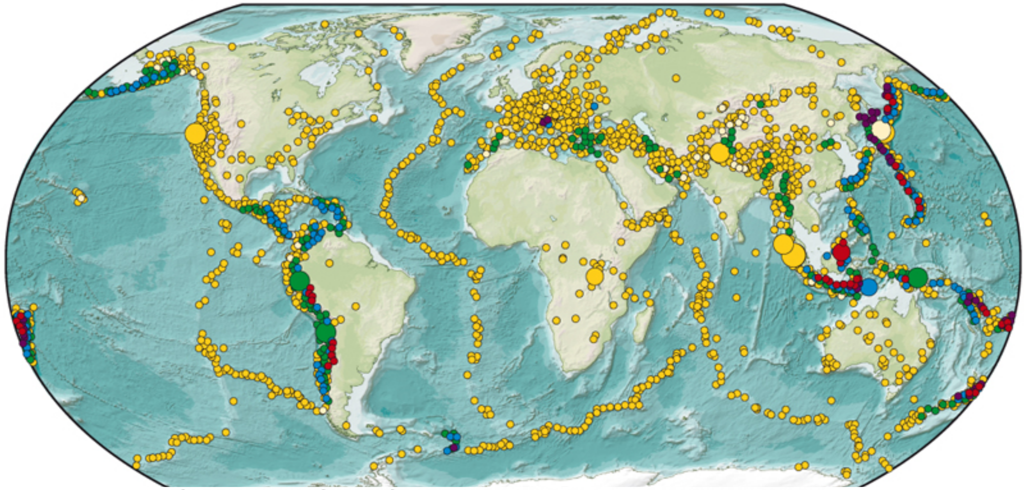
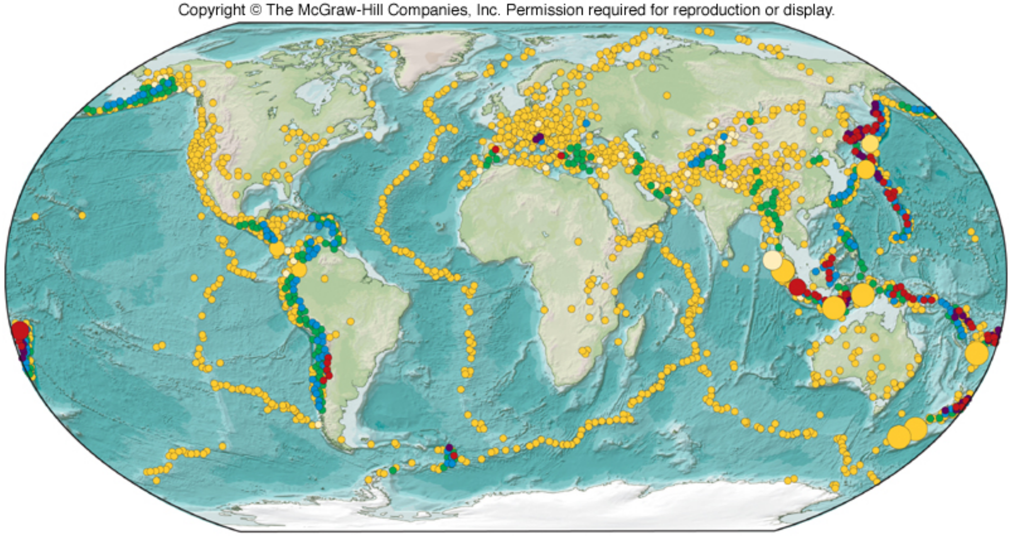
Faults, Earthquakes, and Plate Tectonics

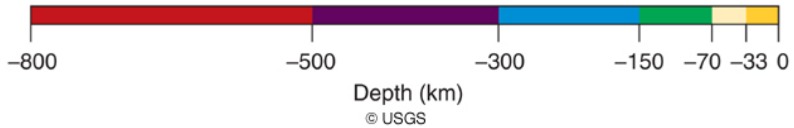


How Consistent is Earthquake Activity?

Global distribution of earthquakes, 2005



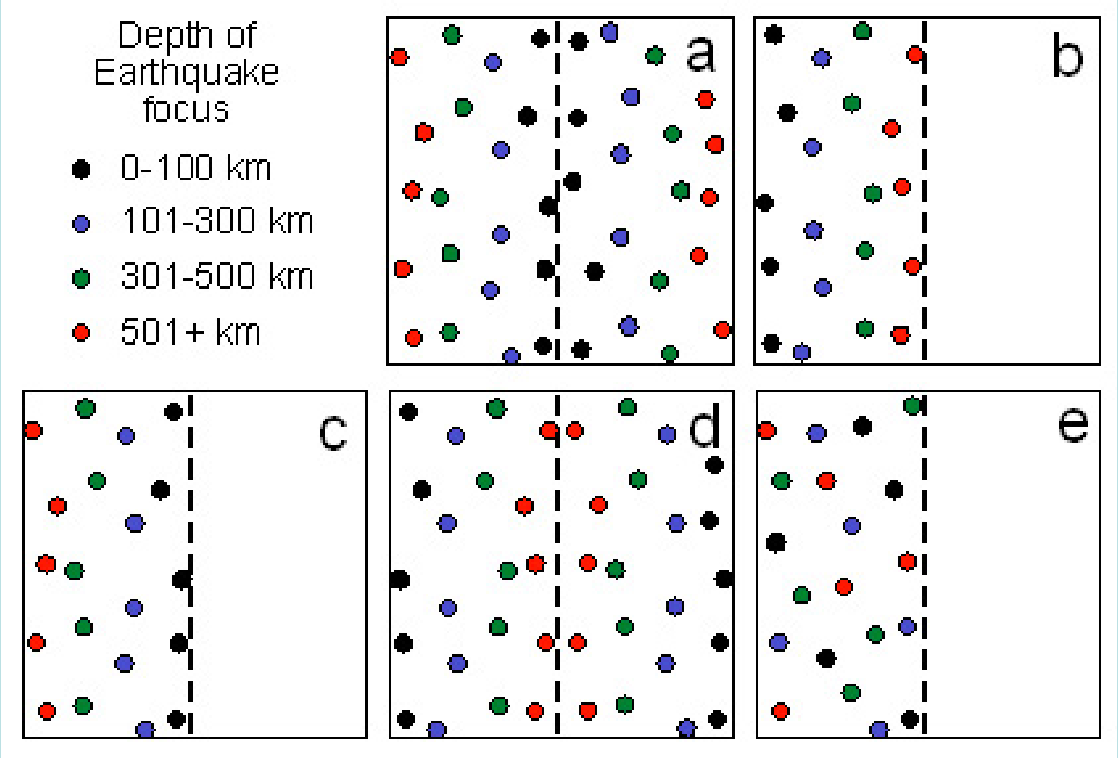
Global distribution of earthquakes, 2004



Earthquake Concept test

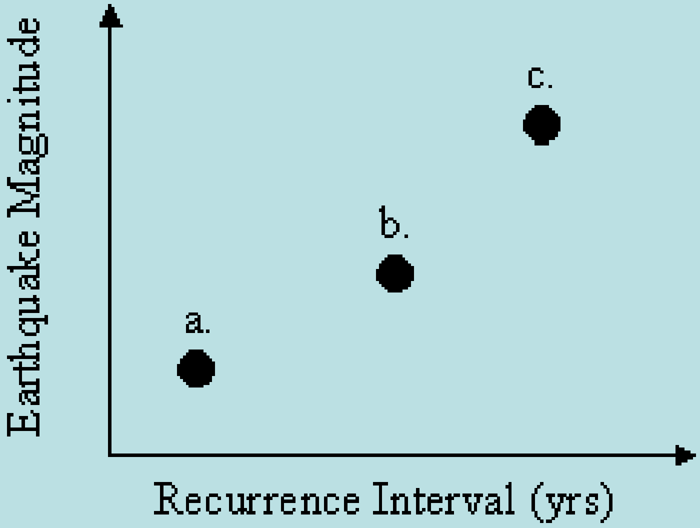
The figures below show the location of a plate boundary (dashed line) and the distribution of earthquake foci (filled circles). The color of the filled circle indicates the depth of the earthquake.

Which figure best illustrates a **convergent plate boundary** between oceanic and continental plates?

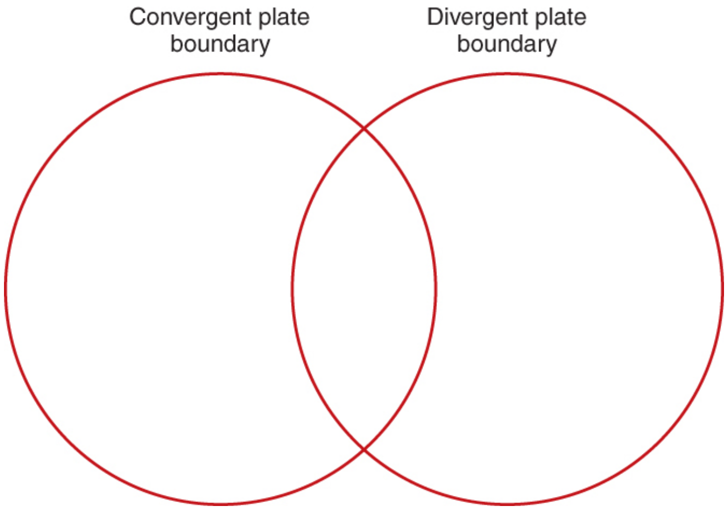


Earthquake Conceptest

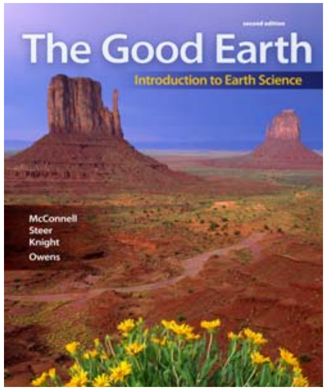
Which point on the graph shown below is most likely a mega-earthquake?



Place the phrase in the most appropriate location on the Venn diagram.



1. Intermediate and deep focal depths
2. Earthquakes in Gulf of California
3. Frequent earthquake activity
4. Depth increases in direction of plate motion
5. Earthquakes of magnitude 5 or less are common
6. More common for US earthquakes
7. Earthquakes off coasts of Alaska, Washington and Oregon
8. Earthquakes occur along the oceanic ridge system
9. Shallow focal depths
10. Large magnitude (6+) earthquakes



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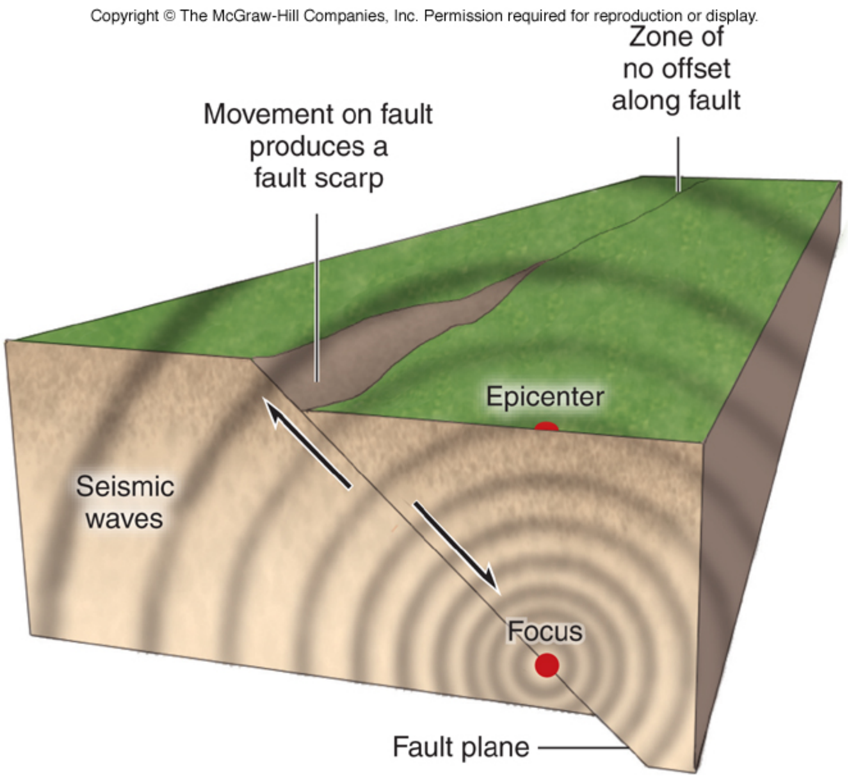
Seismic Waves and Earthquake Detection



- **Seismic waves** – vibrations caused by an earthquake
  - Travel in all directions from the focus
  - Recorded on **seismograph** instrument
  - A **seismogram** is the printed record from a seismograph

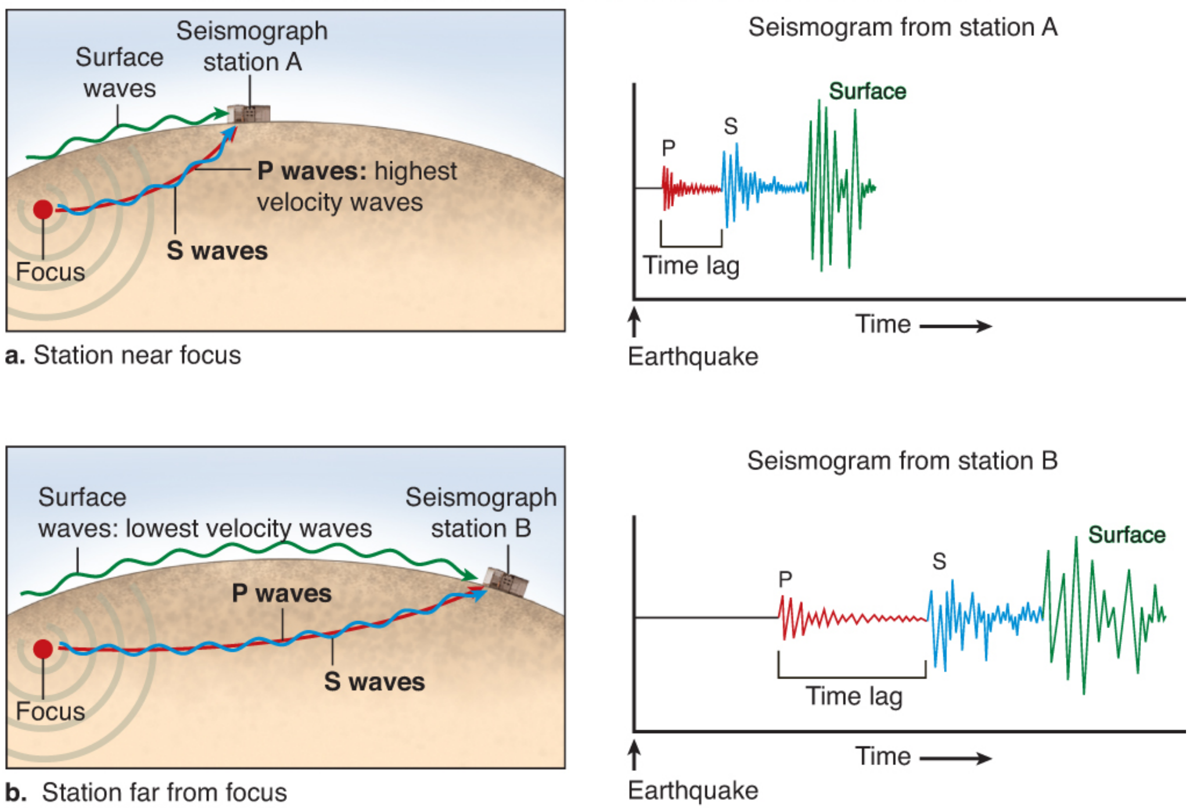
Seismic Waves and Earthquake Detection

- **Seismic waves** – vibrations caused by an earthquake
  - Travel in all directions from the focus
  - Recorded on **seismograph** instrument
  - A **seismogram** is the printed record from a seismograph

Credit: U.S. Geological Survey; Department of the Interior/USGS
U.S. Geological Survey/photo by J.K. Nakata, U.S. Geological Survey

Seismic Waves and Earthquake Detection

2 forms of seismic waves

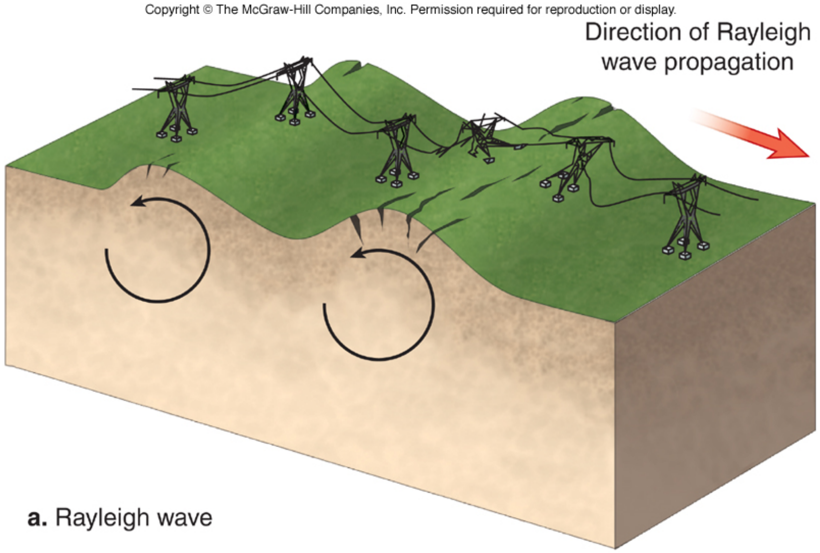


a. Station near focus

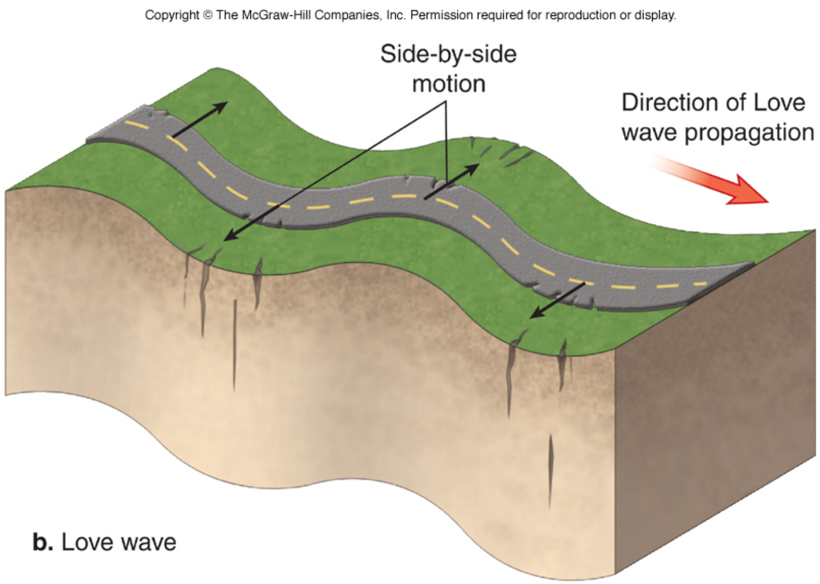
b. Station far from focus

- Slower **surface waves** travel along Earth's surface
- Faster **body waves** travel through Earth's interior
  - P waves
  - S waves

Seismic Waves and Earthquake Detection



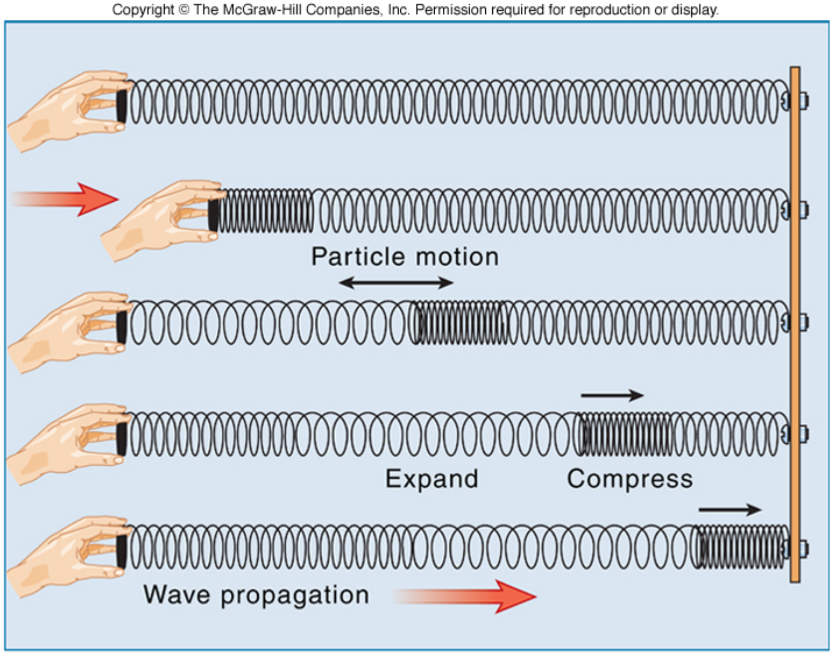
a. Rayleigh wave



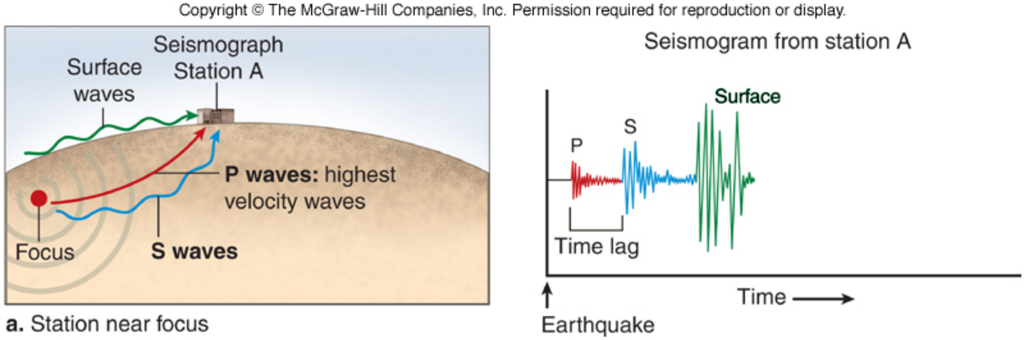
b. Love wave

- **2 types of surface waves**
  - **Rayleigh waves** result in vertical movement of surface
  - **Love waves** produce a side-to-side movement
  - Surface waves are responsible for much of earthquake damage

Seismic Waves and Earthquake Detection



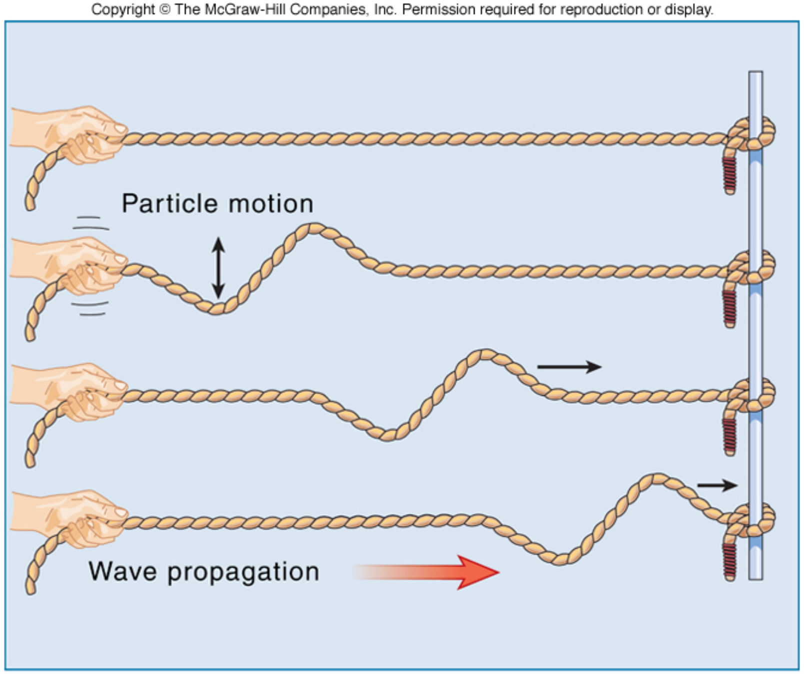
a. Primary wave



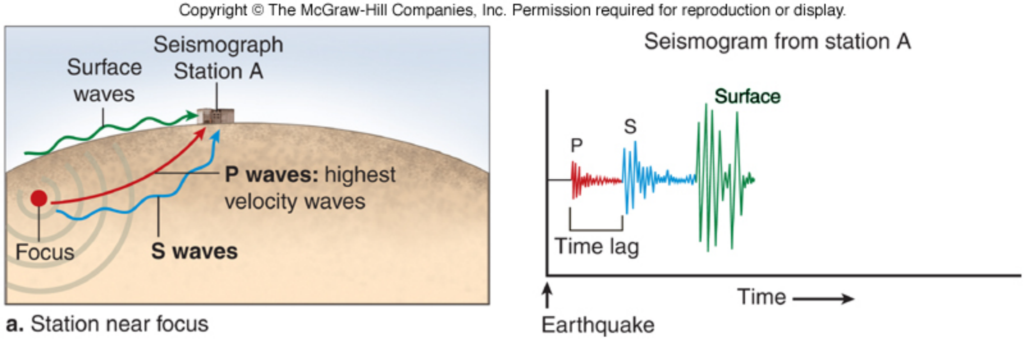
a. Station near focus

- **2 types of body waves**
  - **P (primary) waves** are the first to arrive at a seismograph station
    - 4-6 km/s in crust
  - Compress material parallel to travel direction
    - Slinky analogy

Seismic Waves and Earthquake Detection



b. Secondary wave

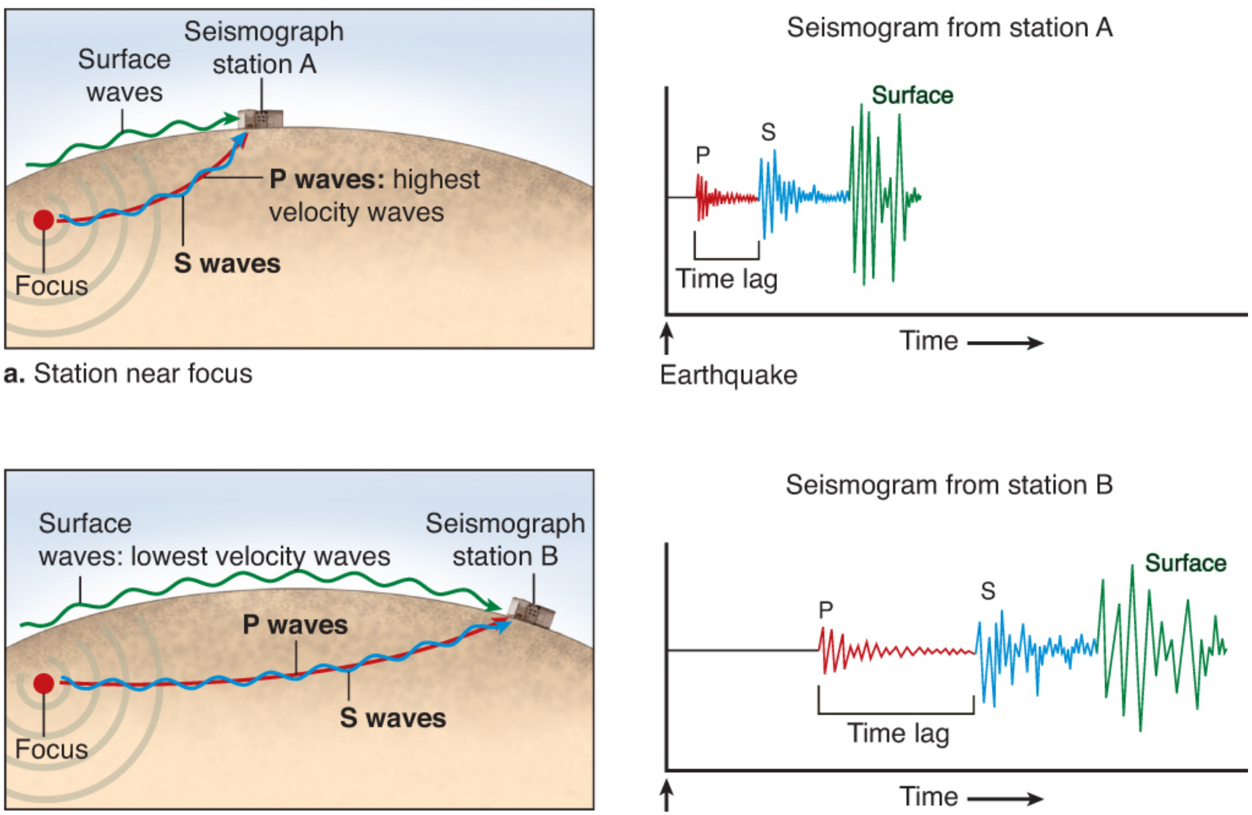


a. Station near focus

- **2 types of body waves**
  - **S (secondary or shear) waves** arrive at recording station after P waves but before surface waves
    - 3-4 km/s in crust
  - Vibrate material perpendicular to travel direction
    - Wave in rope analogy
  - Can not pass through liquids (e.g., outer core)

Seismic Waves and Earthquake Detection

- Time it takes seismic waves to reach a seismograph station increases with distance from the focus



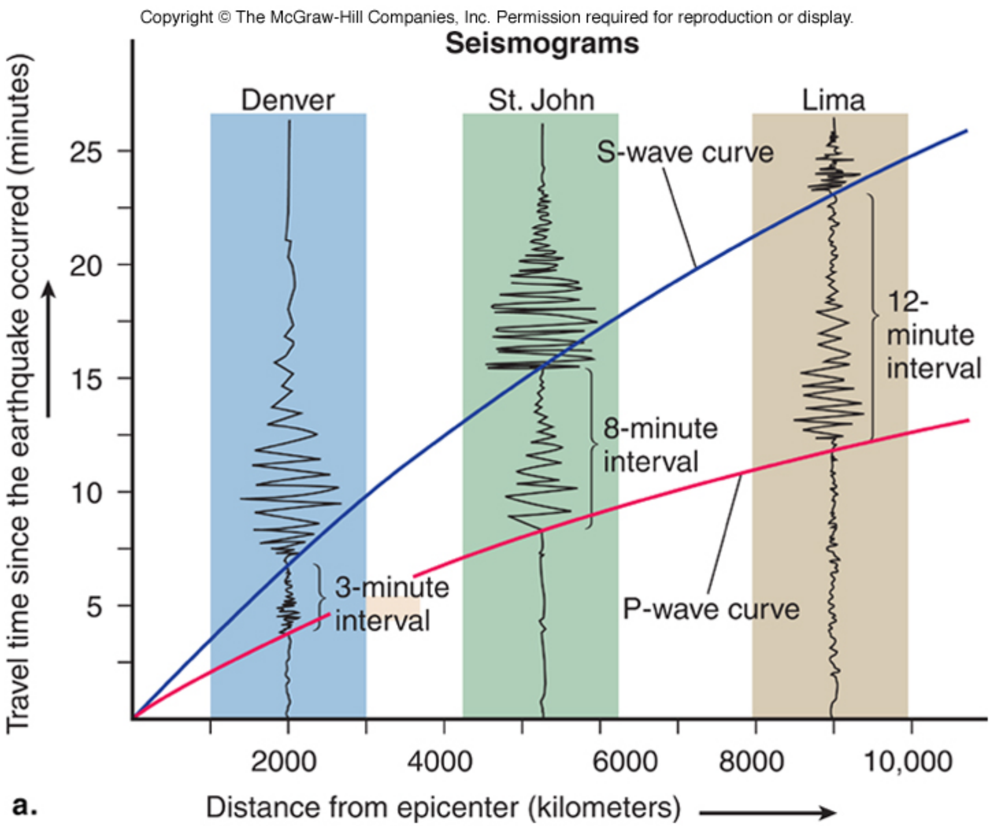
a. Station near focus

b. Station far from focus

  - Time interval between the arrival of P, S, and surface waves also increases with distance
  - Difference in arrival times of P and S waves can be used to estimate distance from earthquake

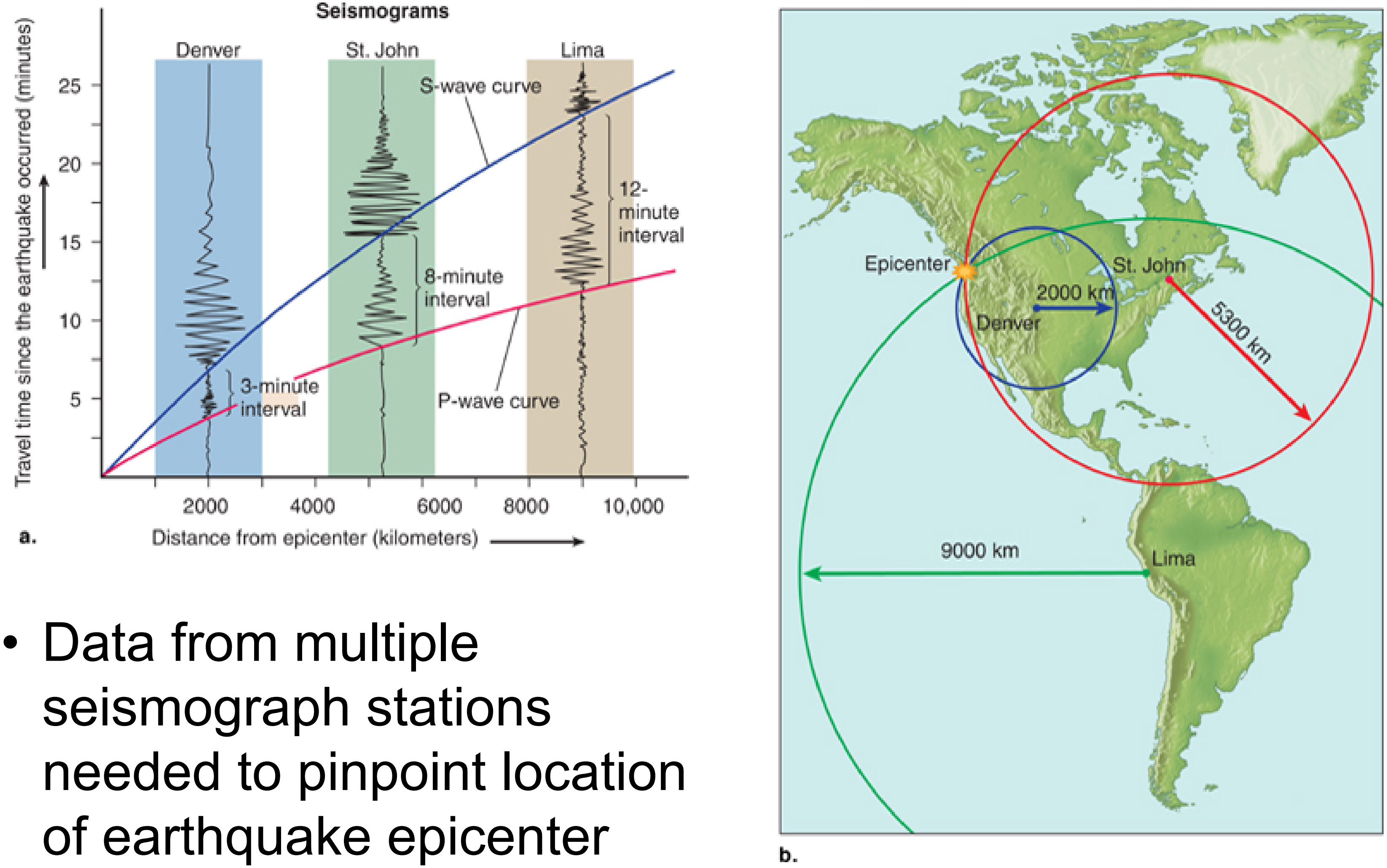
Seismic Waves and Earthquake Detection

- Time it takes seismic waves to reach a seismograph station increases with distance from the focus



- Time interval between the arrival of P, S, and surface waves also increases with distance
- Difference in arrival times of P and S waves can be used to estimate distance from earthquake
  - Example: Denver is closer to epicenter

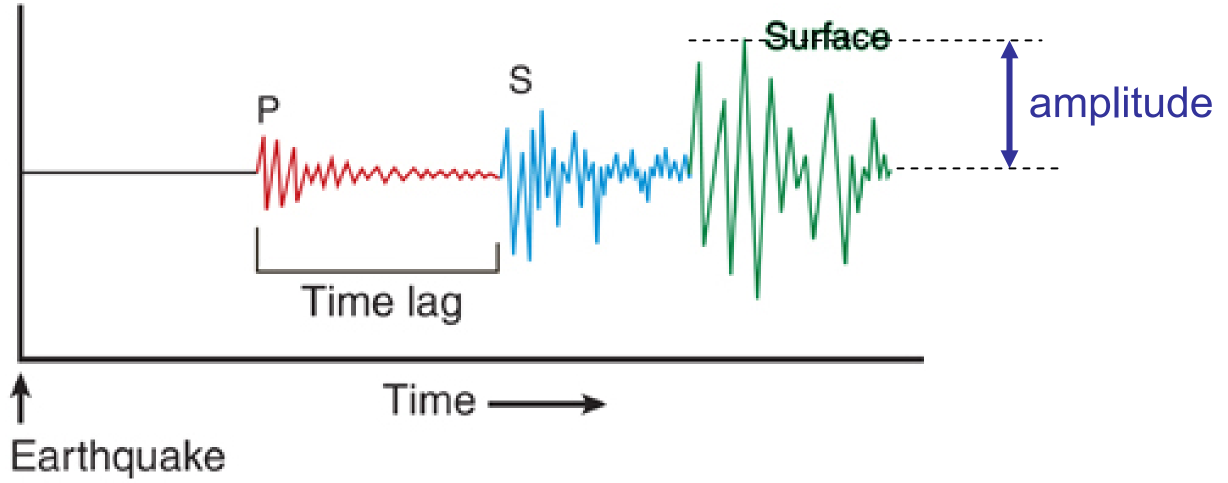
Seismic Waves and Earthquake Detection



- Data from multiple seismograph stations needed to pinpoint location of earthquake epicenter

Seismic Waves and Earthquake Detection

- **Earthquake size** can be determined by measuring the amplitude (height) of the seismic waves
  - Equations take account of distance and materials



Earthquake Conceptest

Suppose you were near an epicenter of an earthquake and felt the earth move as if you were in the ocean. What type of seismic wave would you have experienced?

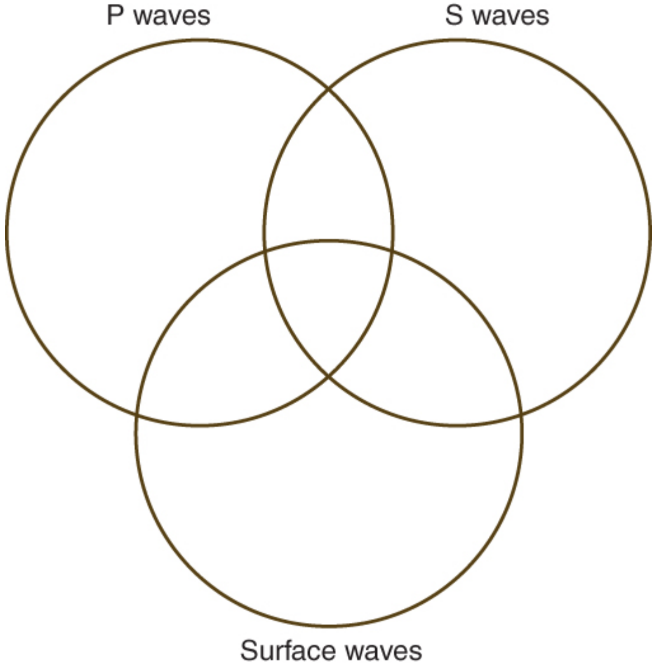
A. P-wave
B. S-wave
C. Rayleigh wave
D. Love wave

Earthquake Conceptest

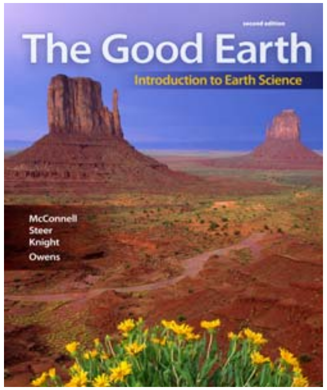
A large earthquake occurred along a fault and was recorded at a seismograph station 300 km away. The next day, a smaller earthquake occurred at the exact same location on the fault. **Which statement is most accurate?**

A. P-waves would have traveled to the seismograph station more quickly following the <u>first</u> earthquake
B. P-waves would have traveled to the seismograph station more quickly following the <u>second</u> earthquake
C. The P-waves would have taken the same time to reach the station after each earthquake

Place the phrase in the most appropriate location on the Venn diagram.



1. Most damaging
2. First arrival
3. Last arrival
4. Body wave
5. Raleigh wave
6. 4-6 km/s in crust
7. Second arrival
8. Love wave
9. Particles move in direction of wave
10. Waves generated at time of earthquake
11. On Earth's surface
12. Determines magnitude



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Measurement of Earthquakes

Two methods of measuring earthquakes

- Magnitude
  - A standard measure of the shaking and/or energy released from an earthquake calculated using a seismogram
    - Bigger fault motions produce bigger earthquakes
- Intensity
  - A measure of the effects of an earthquake on people and buildings (damage)

Measurement of Earthquakes

Table 5.1 Comparison of Relative Amounts of Ground Motion and Energy Released from Earthquakes of Different Magnitudes

Magnitude	Ground motion	Energy
1	1	1
2	10	32
3	100	1,024
4	1,000	32,768
5	10,000	1,048,576
6	100,000	33,554,432
7	1,000,000	1,073,741,824
8	10,000,000	32,359,738,368
9	100,000,000	1,099,511,627,776

- Magnitude is measured on a logarithmic scale
  - Each division represents a 10-fold increase in ground motion
  - Each division represents a 32-times increase in energy released
    - Example: a magnitude 5 earthquake exhibits 100 times more shaking and releases nearly 1,000 times more energy

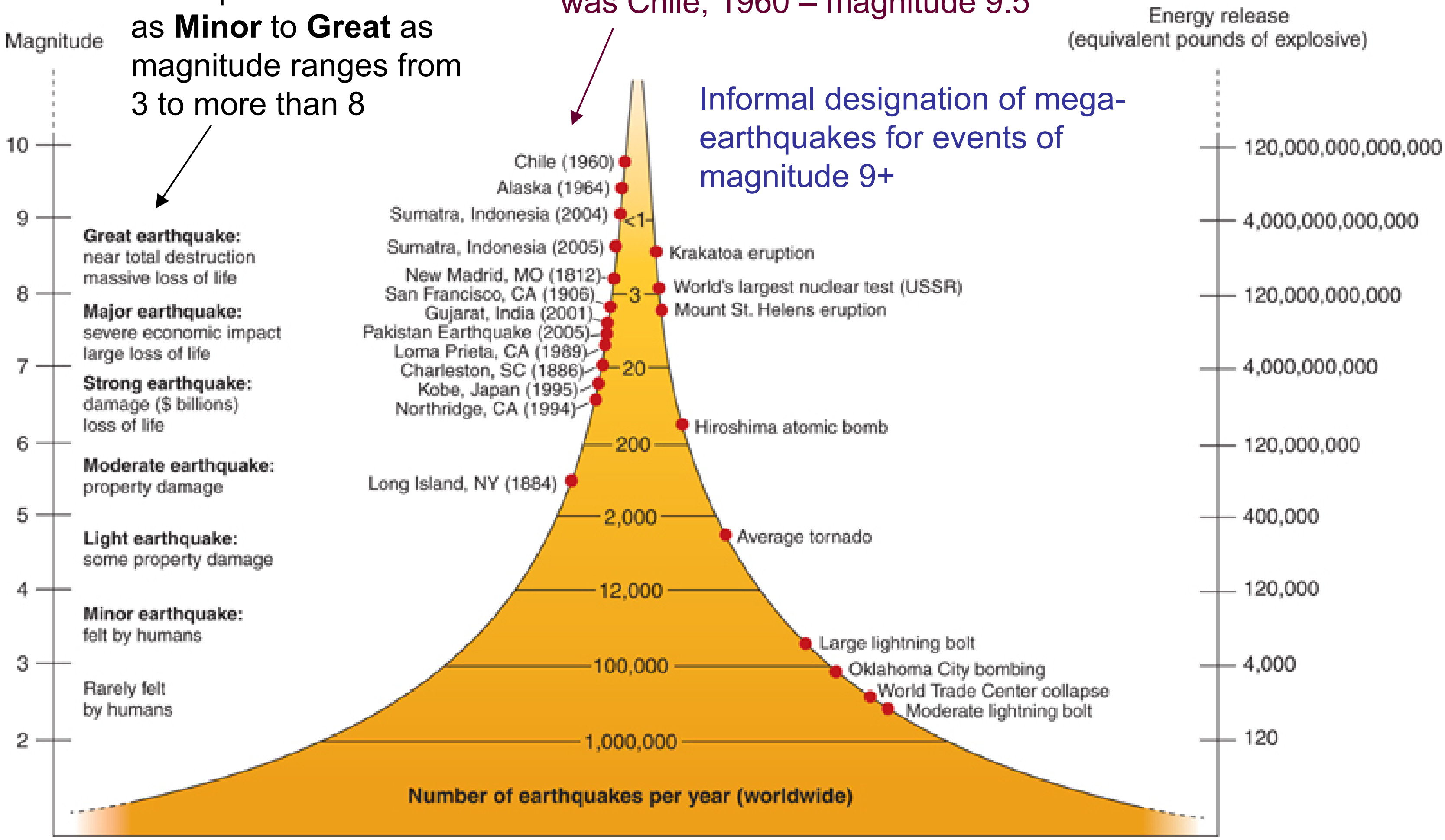
Measurement of Earthquakes

No maximum value for magnitude scale

Earthquakes described as **Minor** to **Great** as magnitude ranges from 3 to more than 8

Largest measured earthquake was Chile, 1960 – magnitude 9.5

Informal designation of mega-earthquakes for events of magnitude 9+



Earthquake Conceptest

How much would ground motion increase between a magnitude 4.5 and 5.5 earthquakes?

A. No increase
B. 5 times as much
C. 10 times as much
D. 30 times as much

Measurement of Earthquakes

Table 5.2 Modified Mercalli Scale for Earthquake Measurement

Index	Effects of earthquake on people and structures
I	Not felt by people.
II	Felt by people at rest on upper floors of buildings.
III	May be felt by people indoors. Vibrations similar to the passing of a truck. Hanging objects swing.
IV	Felt indoors by many, outdoors by few. Dishes, windows, doors rattle; walls make creaking sound. Sensation like heavy truck passing building.
V	Felt by nearly everyone; many awakened from sleep. Some dishes, windows broken; doors swing open or closed. Unstable objects overturned. Liquids slosh around in containers.
VI	Felt by all; many frightened. Windows, dishes, glassware broken. Books knocked off shelves. Some heavy furniture moved; a few instances of fallen plaster. Trees shaken. Damage slight.
VII	Difficult to stand. Drivers notice, large bells ring. Slight to moderate damage in ordinary structures; considerable damage in poorly built or badly designed structures. Some chimneys broken, falling plaster, bricks, tiles.
VIII	Difficult to steer vehicles. Branches broken from trees. Slight damage in buildings designed to withstand earthquakes; heavy damage in poorly constructed structures. Chimneys, columns, monuments, walls may fall.
IX	Considerable damage in specially designed structures. Damage great in substantial buildings; partial collapse. Buildings shifted off foundations, underground pipes broken, reservoirs damaged. General panic.
X	Some well-built wooden structures destroyed; most masonry and frame structures with foundations destroyed. Serious damage to dams and embankments; landslides.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly, underground pipelines out of service.
XII	Total damage, objects thrown into air, widespread rockslides and slope failure.

- Intensity is measured using the Modified Mercalli Scale
  - 12-point scale using Roman numerals

Intensity	=	Magnitude
I		<3
II-III		3.0-3.9
IV-V		4.0-4.9
VI-VII		5.0-5.9
VIII+		6+

Higher values depend on ground materials, other factors

Measurement of Earthquakes

Table 5.2 Modified Mercalli Scale for Earthquake Measurement

Index	Effects of earthquake on people and structures
I	Not felt by people.
II	Felt by people at rest on upper floors of buildings.
III	May be felt by people indoors. Vibrations similar to the passing of a truck. Hanging objects swing.
IV	Felt indoors by many, outdoors by few. Dishes, windows, doors rattle; walls make creaking sound. Sensation like heavy truck passing building.
V	Felt by nearly everyone; many awakened from sleep. Some dishes, windows broken; doors swing open or closed. Unstable objects overturned. Liquids slosh around in containers.
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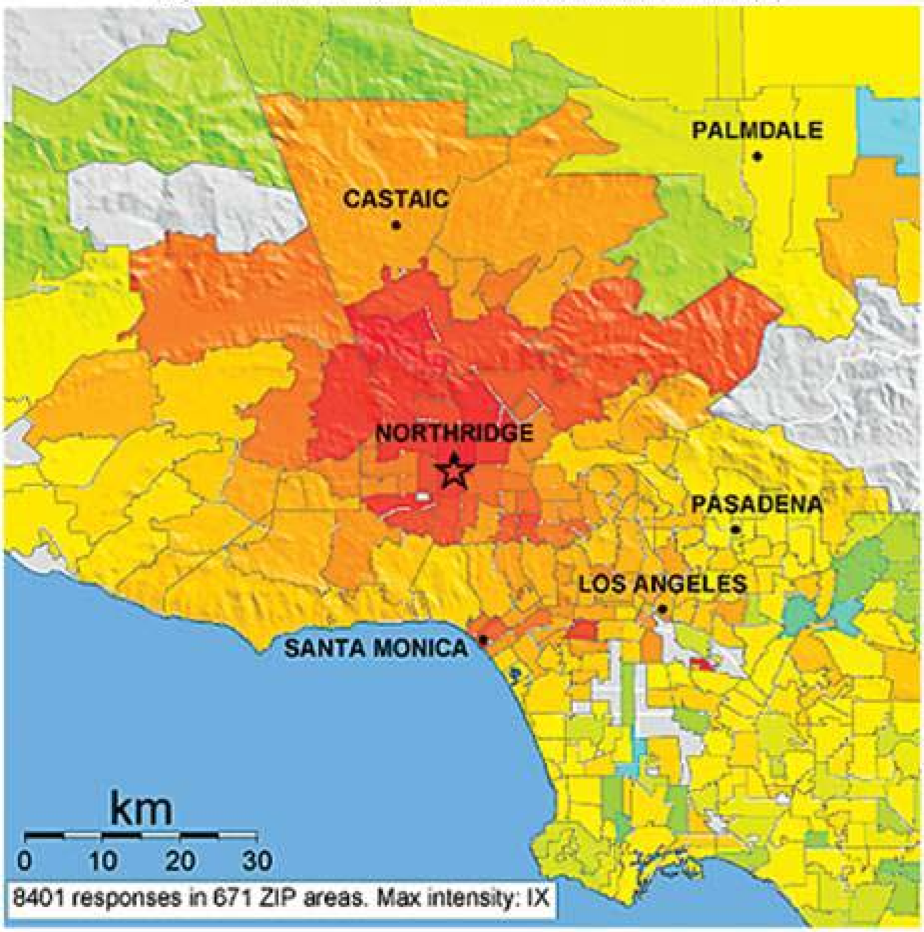
XII	Total damage, objects thrown into air, widespread rockslides and slope failure.

- Intensity is measured using the Modified Mercalli Scale
  - Difficulties in comparing earthquakes from different regions due to contrasts in
    - Population density
    - Building codes
    - Ground materials
    - Distance

Measurement of Earthquakes



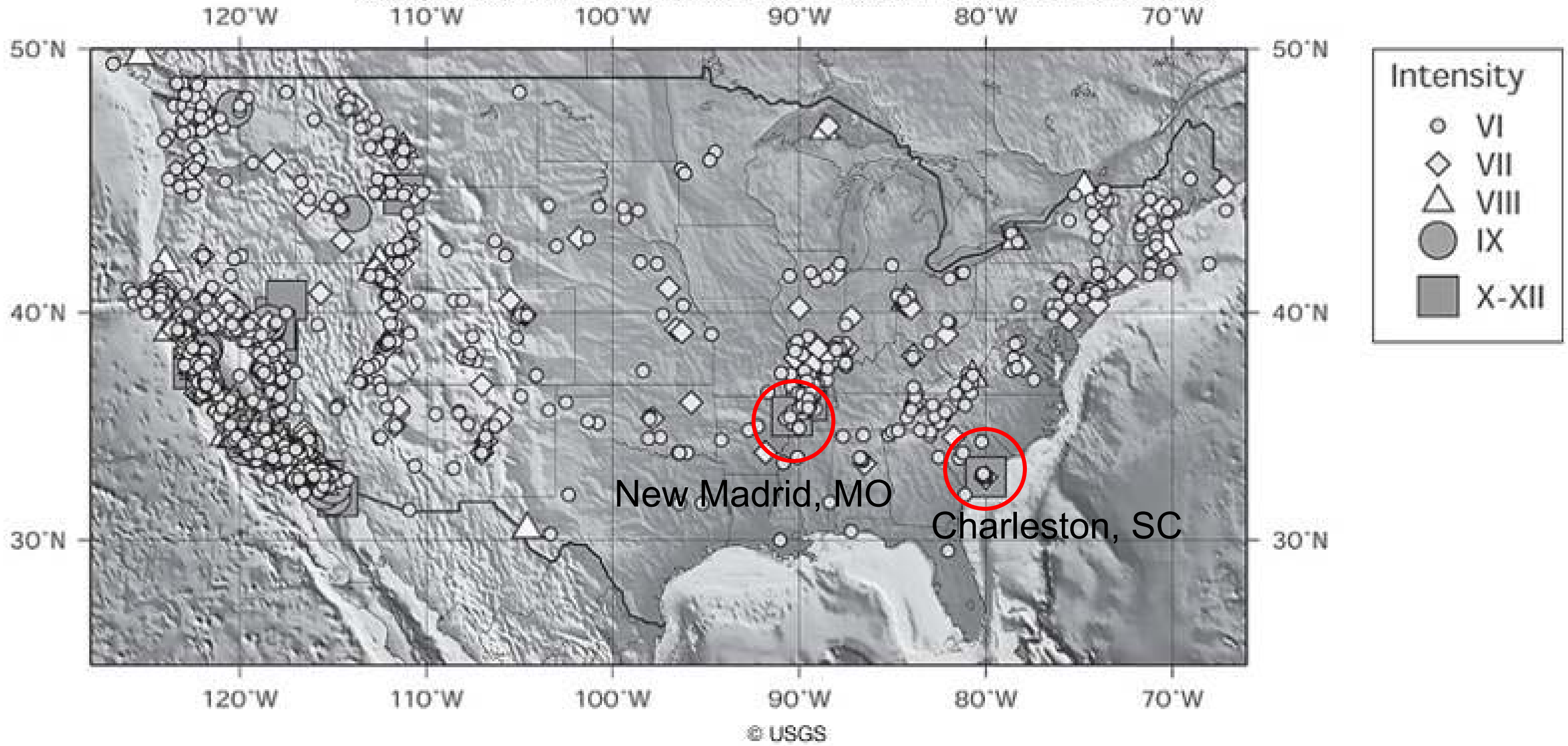
Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Strong	Violent	Extreme
Damage	None	None	None	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very heavy

© USGS

- Intensity is measured using the Modified Mercalli Scale
  - Useful for rapid collection of online data following earthquakes
  - USGS generates Community Internet Intensity Maps (CIIMs)
    - Example: CIIM for 6.7 magnitude Northridge earthquake (1994)
    - Note that damage is not distributed uniformly with distance from epicenter

Measurement of Earthquakes

- Modified Mercalli Scale can be applied to historical accounts of earthquakes
  - Significant earthquakes in areas with little recent activity



Earthquake Conceptest

Three sites (L1, L2, L3) record earthquake magnitude and earthquake intensity for the same earthquake. L1 is located closest to the focus and L3 is farthest away. **Where is the intensity greatest, and what happens to the earthquake magnitude calculated at the different sites?**

A. Intensity is greatest at L1; calculated magnitude is the same at each site

B. Intensity is greatest at L3; calculated magnitude is the same at each site

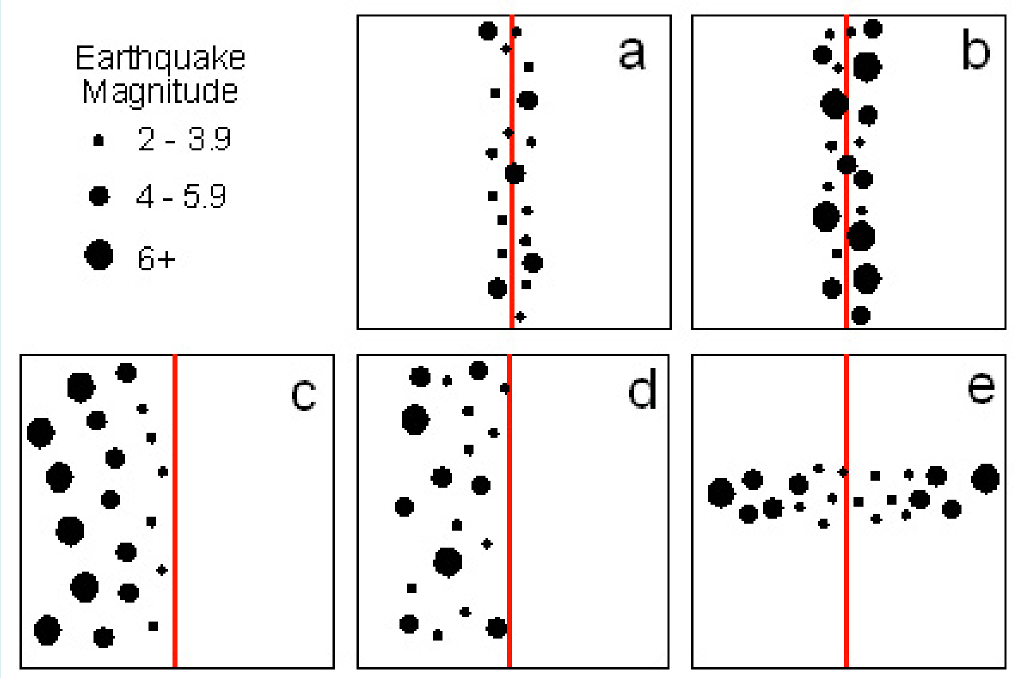
C. Intensity is greatest at L1; calculated magnitude decreases with distance from the focus

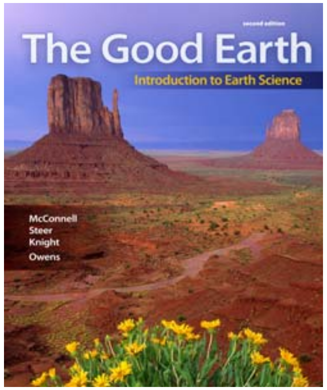
D. Intensity is greatest at L3; calculated magnitude decreases with distance from the focus

Earthquake Conceptest

The figures below show the location of a plate boundary (red line) and the distribution of earthquake epicenters (filled circles). The size of the filled circle indicates the earthquake magnitude.

Which figure best represents a **convergent plate boundary** between oceanic and continental plates?





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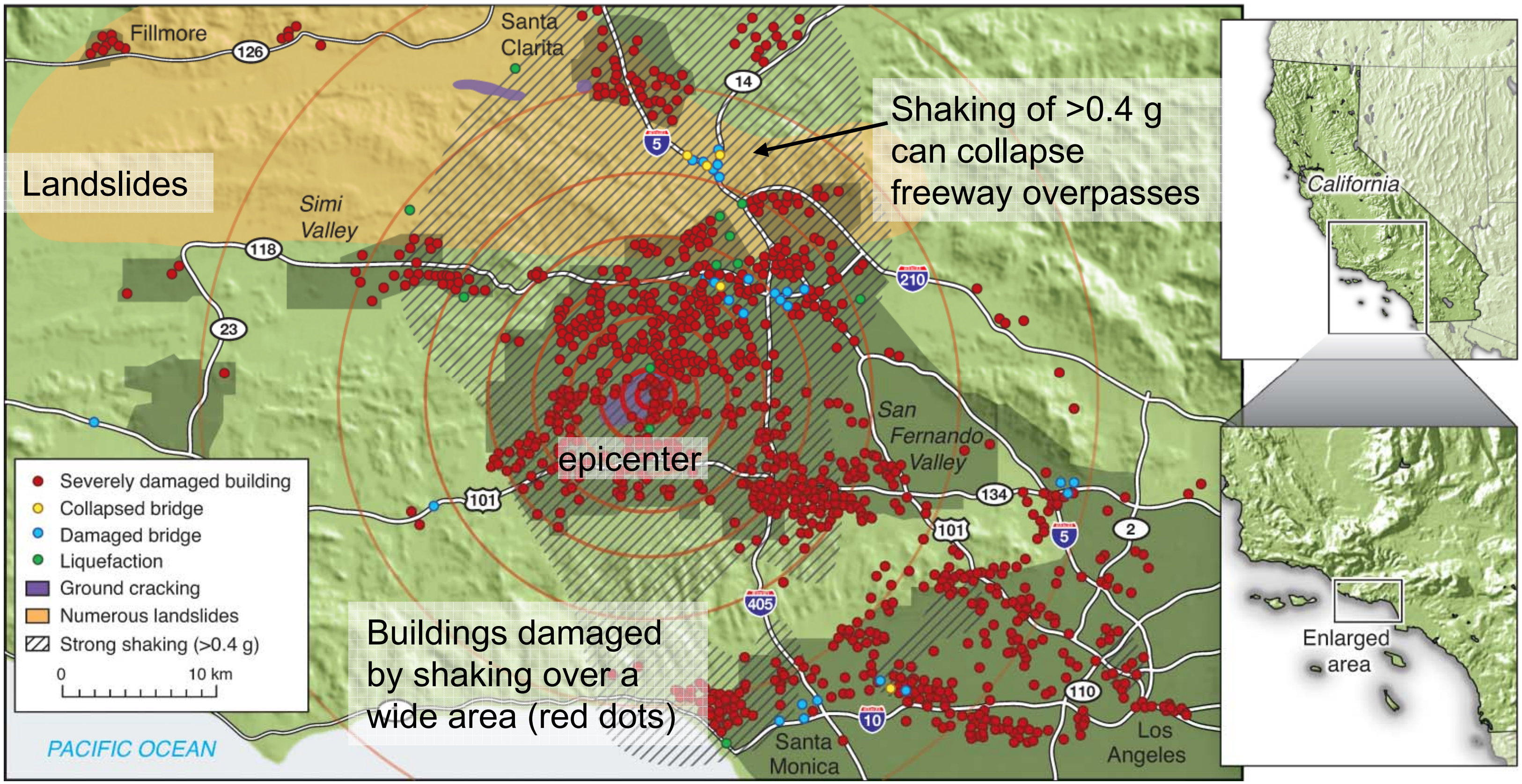
Go to the next section: ***Earthquake Hazards***

Earthquake Hazards

- Strong (magnitude 6.7) Northridge earthquake was the most recent to strike developed area
  - Hazards associated with earthquakes include
    - Ground Shaking
    - Aftershocks
    - Landslides
    - Elevation Changes
    - Liquefaction
    - Tsunami

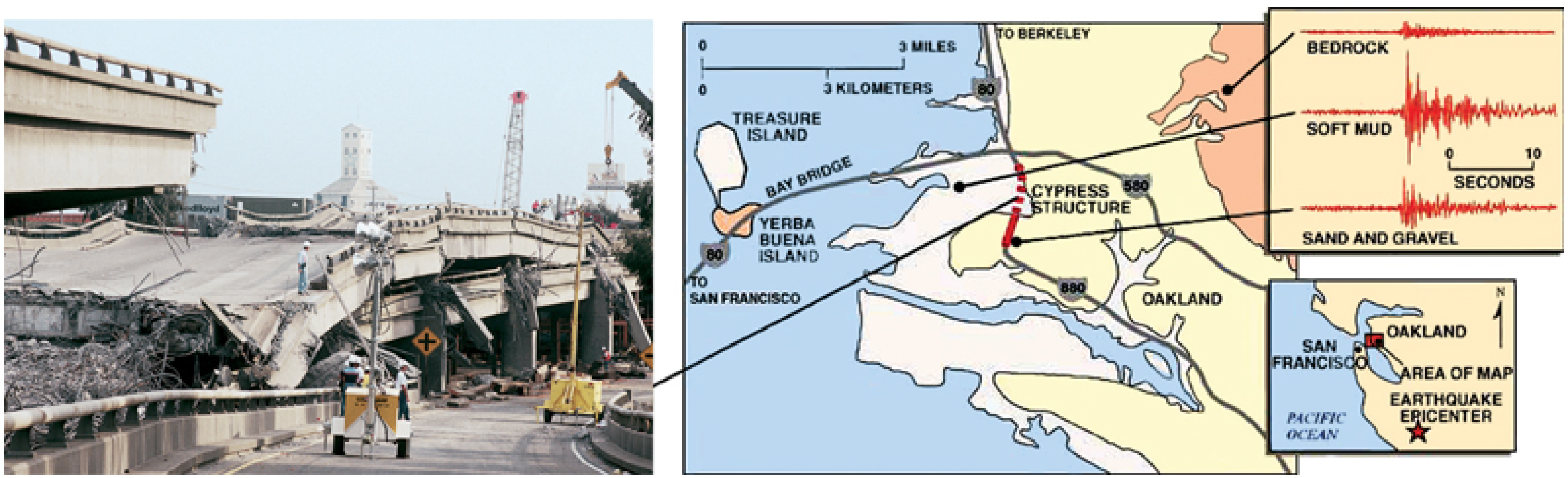
Earthquake Hazards

Map of Northridge earthquake hazards



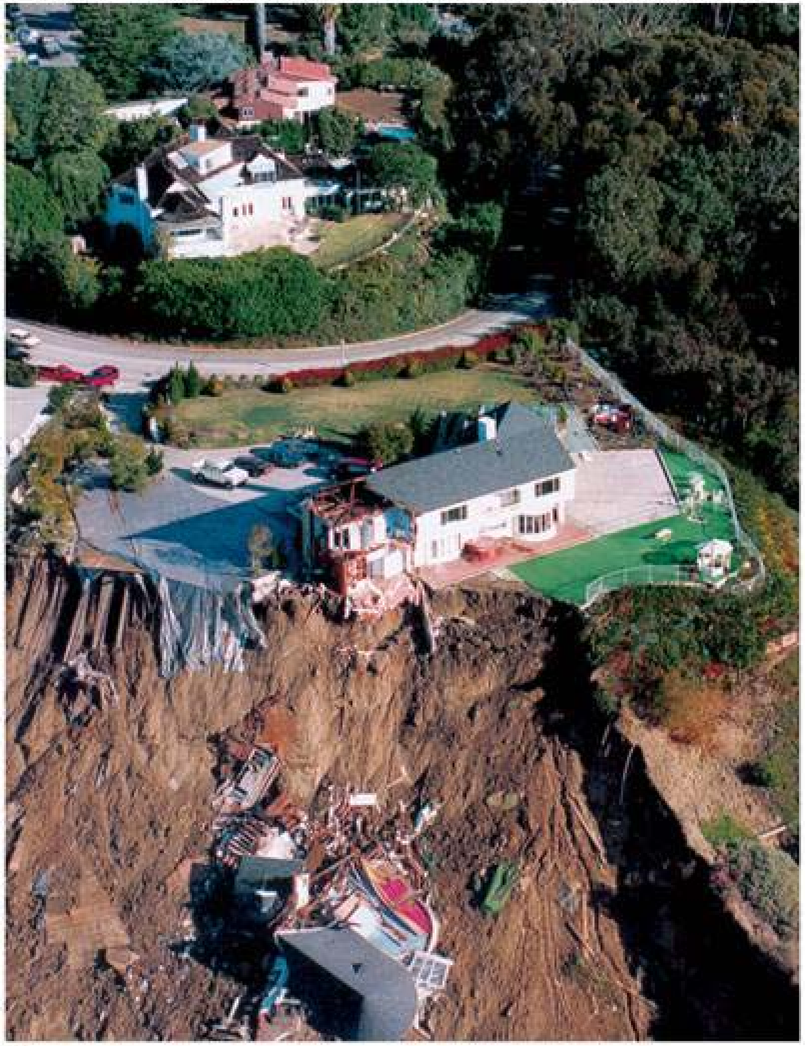
Earthquake Hazards

- Ground shaking can be exaggerated by weaker earth materials
  - Less shaking for bedrock
  - More shaking for soft mud, sand and gravel



Collapsed section of Cypress freeway following Loma Prieta earthquake, 1989

Earthquake Hazards



a.

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- Landslides common on steep slopes when shaken
  - 11,000 landslides associated with Northridge earthquake
  - 3 deaths associated with inhalation of dust containing fungal spores

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Earthquake Hazards

These trees stumps from Sumatra were originally on dry land. They were broken off by the Indian Ocean tsunami and dropped below sea level by fault movement.

- Elevation changes result from movement on faults
  - Mountains east of Los Angeles raised by 1 meter during Northridge earthquake
  - Decrease in elevation of coastline in Sumatra during 2004 earthquake

Earthquake Hazards

- Liquefaction occurs when water is released from saturated earth materials that are violently shaken
  - Material loses strength and collapses, causing subsidence

a.

Sand boils formed by liquefaction during Loma Prieta earthquake.

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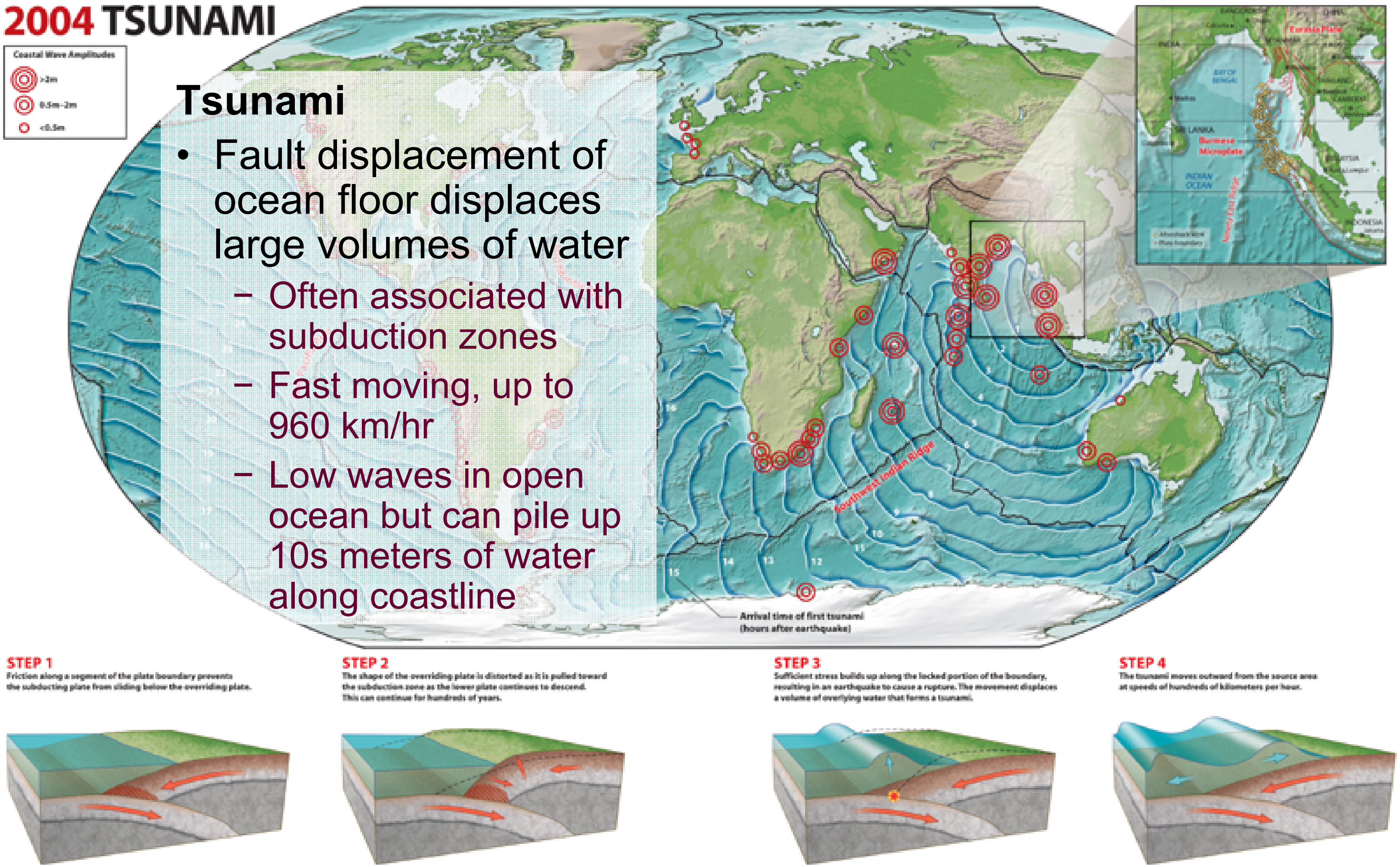
b.

Apartment buildings collapsed due to liquefaction after 1964 Niigata (Japan) earthquake.

Earthquake Hazards

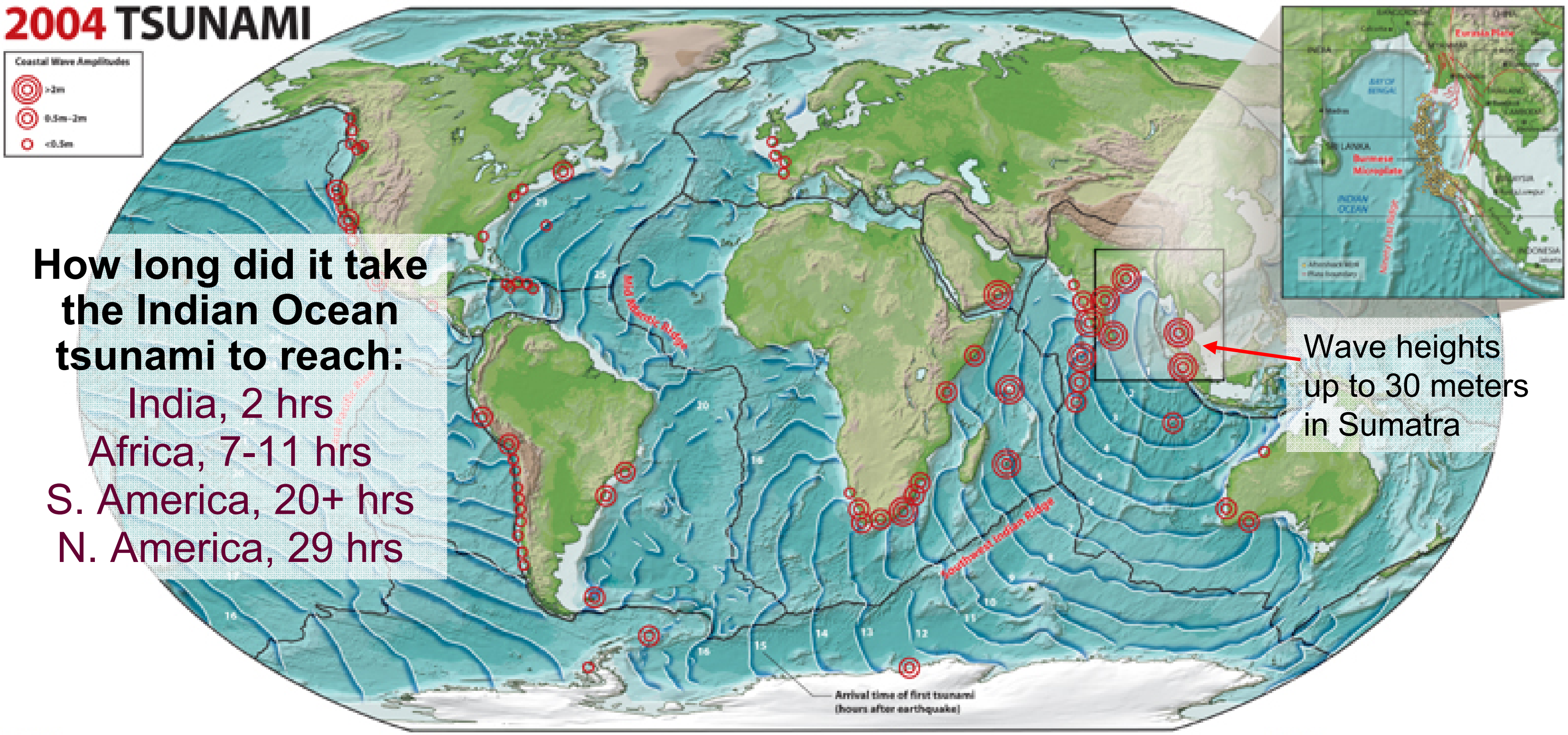


Tsunami

- Fault displacement of ocean floor displaces large volumes of water
  - Often associated with subduction zones
  - Fast moving, up to 960 km/hr
  - Low waves in open ocean but can pile up 10s meters of water along coastline

Earthquake Hazards

2004 TSUNAMI



How long did it take the Indian Ocean tsunami to reach:

India, 2 hrs
Africa, 7-11 hrs
S. America, 20+ hrs
N. America, 29 hrs

Wave heights up to 30 meters in Sumatra

STEP 1
Friction along a segment of the plate boundary prevents the subducting plate from sliding below the overriding plate.

STEP 2
The shape of the overriding plate is distorted as it is pulled toward the subduction zone as the lower plate continues to descend. This can continue for hundreds of years.

STEP 3
Sufficient stress builds up along the locked portion of the boundary, resulting in an earthquake to cause a rupture. The movement displaces a volume of overlying water that forms a tsunami.

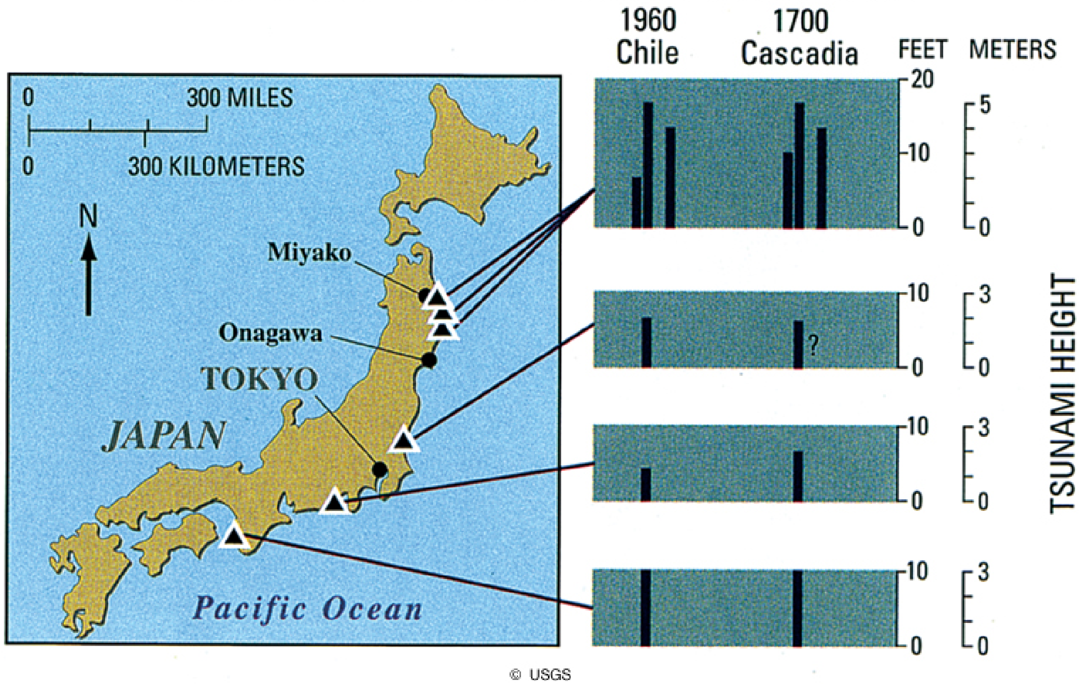
STEP 4
The tsunami moves outward from the source area at speeds of hundreds of kilometers per hour.

Earthquake Hazards

- Tsunami damage, northwestern Sumatra

© USGS

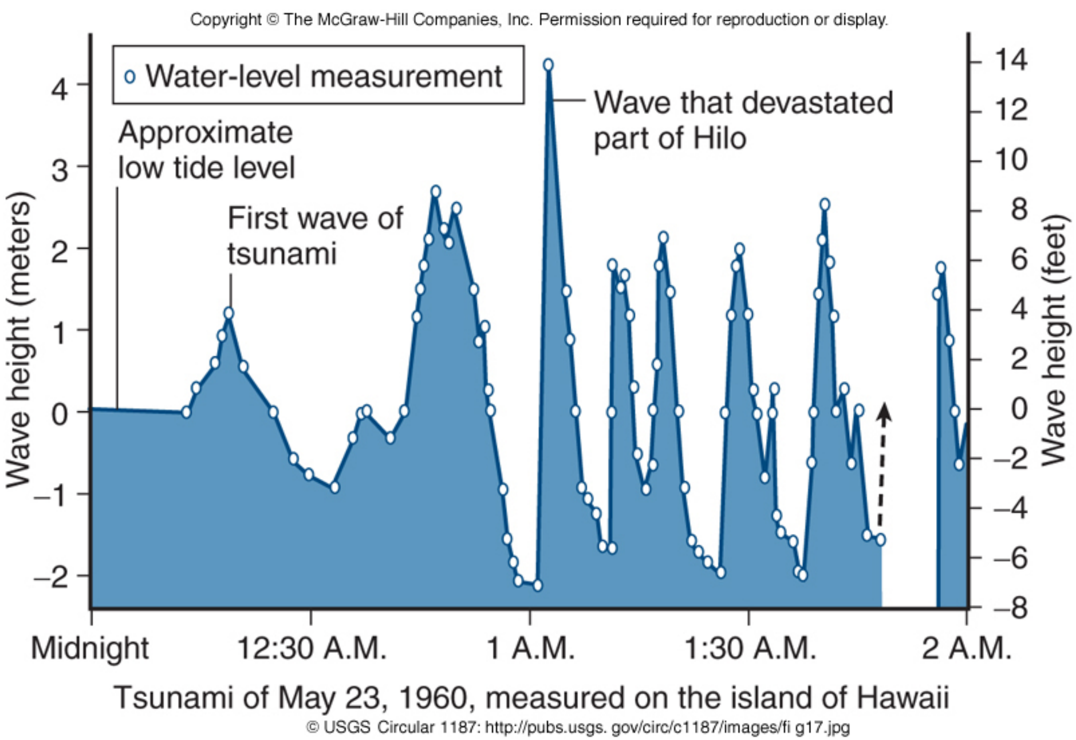
Earthquake Hazards



Tsunami heights along coast of Japan for Chile (1960) and Cascadia (1700) earthquakes

- Comparable wave heights interpreted to indicate mega-earthquakes of similar magnitude
  - Variation in wave height related to differences along coast

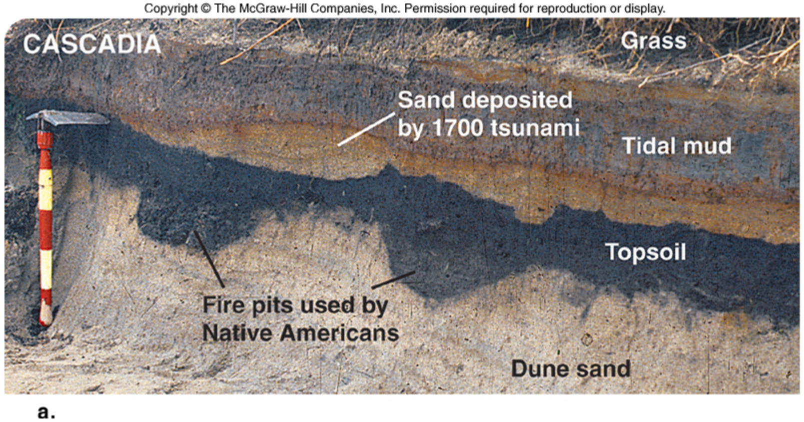
Earthquake Hazards



Water levels were both above (wave crest) and below (wave trough) low tide level.

- Multiple tsunami associated with a single earthquake (Chile, 1960)
  - Approximately 10-30 minutes between wave crests

Earthquake Hazards



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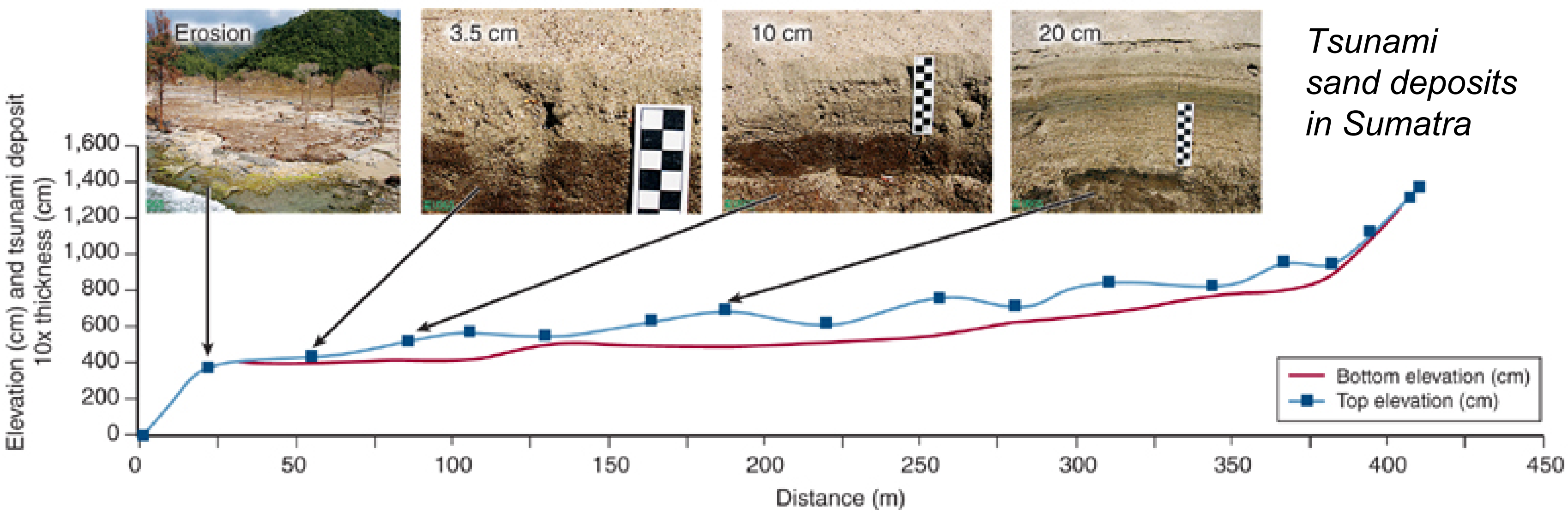
- Sand deposits generated by Indian Ocean tsunami are similar to those produced by tsunami after 1700 Cascadia earthquake



Tsunami sand deposits in Sumatra

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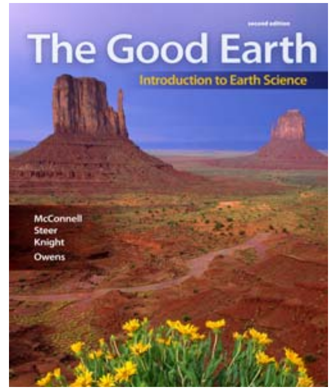

The End

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