The McGraw-Hill Companies

Exploring Geology

16 Earthquakes

Earthquakes

- What are earthquakes?
  - Energy release in waves; causes; elastic rebound theory
- Location and detection
  - Focus, epicenter, link to fault scarps
  - Seismometers, seismic waves, and size (magnitude)
  - Location of epicenters using seismic travel times
- Global patterns of earthquake activity
  - Tectonic settings
- Earthquake consequences and prediction
  - Destructiveness, ground motion, and other effects (landslides, tsunamis, fires, building collapse, liquefaction)

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

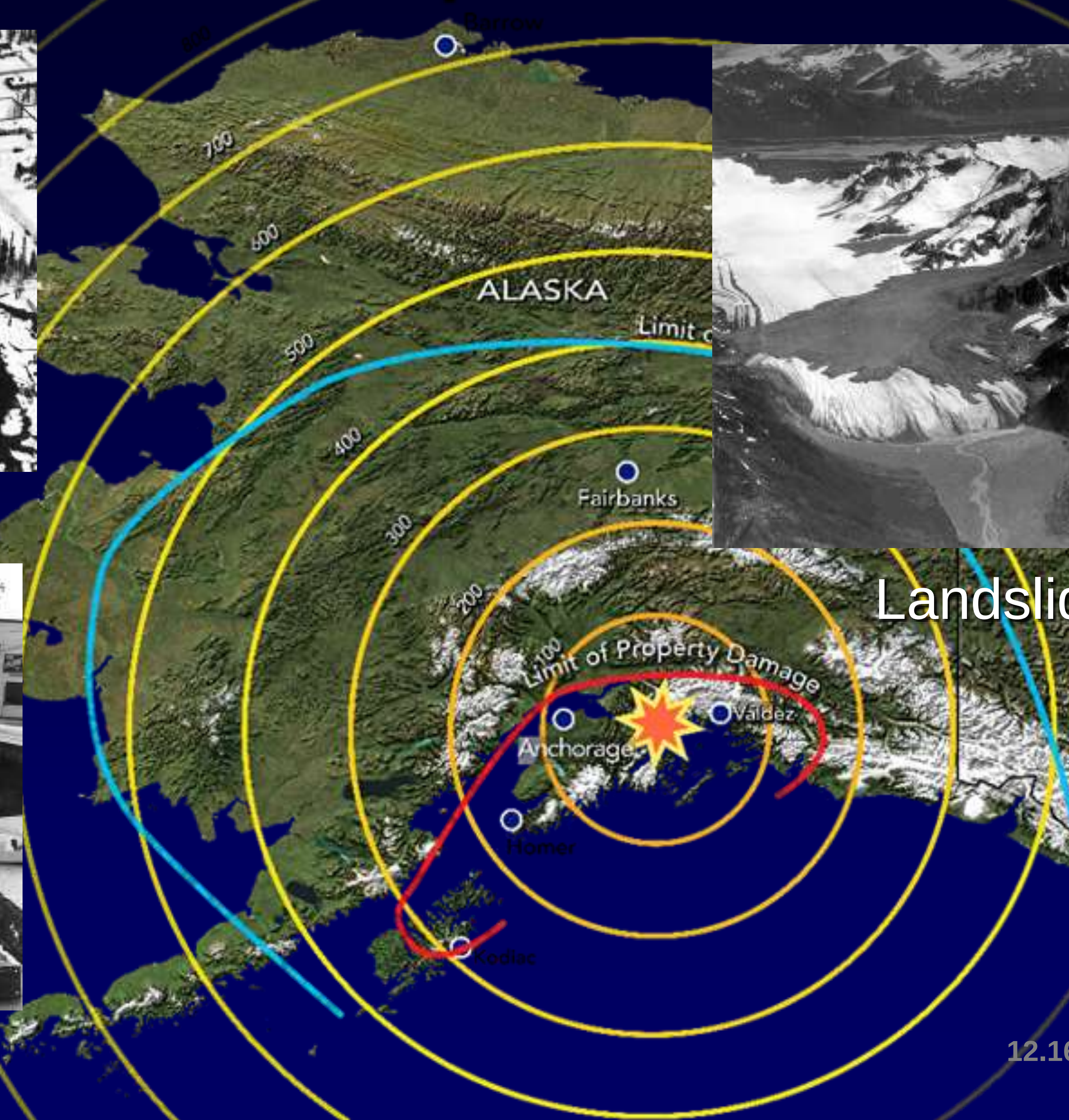
  - ***Fire*** is a problem just after earthquakes because of broken gas and water mains and fallen electrical wires
  - ***Landslides*** can be triggered by ground shaking, particularly in larger quakes
  - ***Liquefaction*** occurs when water-saturated soil or sediment sloshes like a liquid during a quake

  - ***Permanent displacement of the land surface*** can also occur, leaving fractures and scarps

Great Alaskan Earthquake of 1964

Sliding along clay

Shaking and sinking

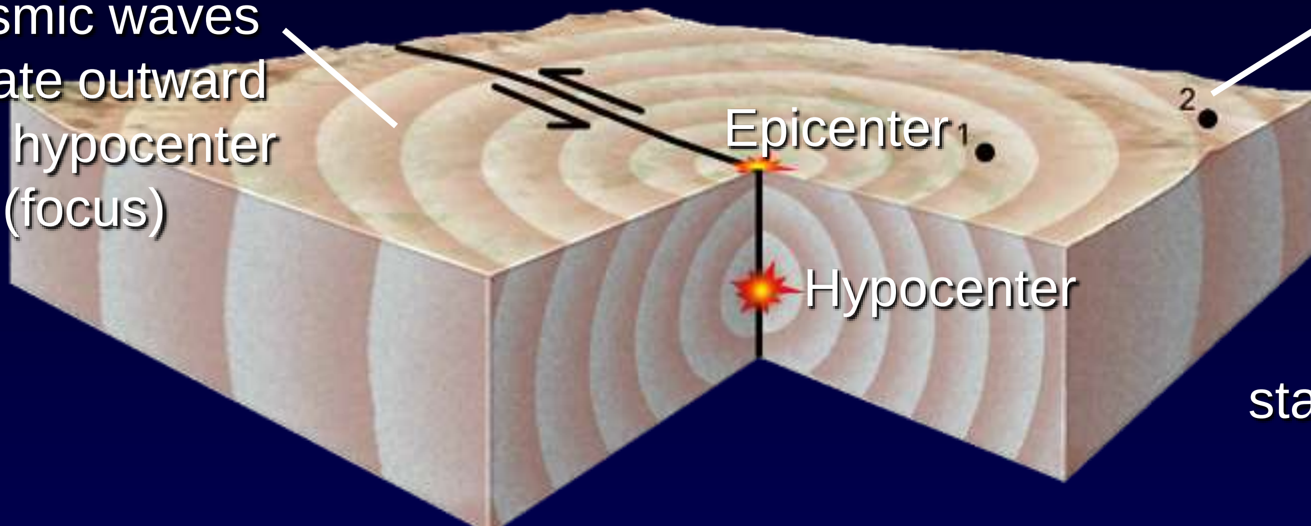


Landslides

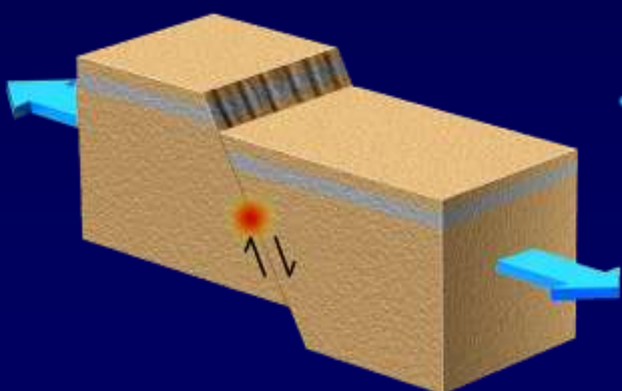
12.16.a

Figures 4.27 property damage from the 1964 earthquake in Anchorage, Alaska

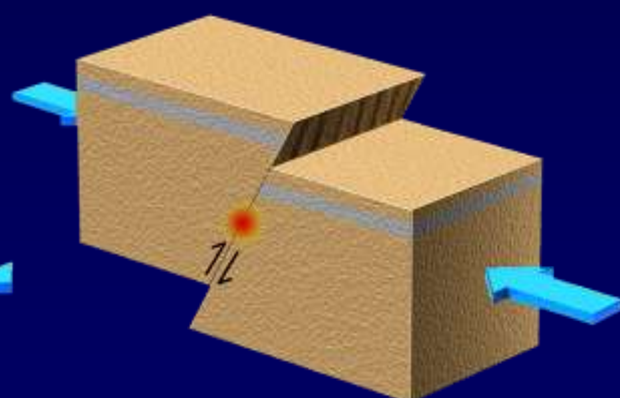
Describing Earthquakes



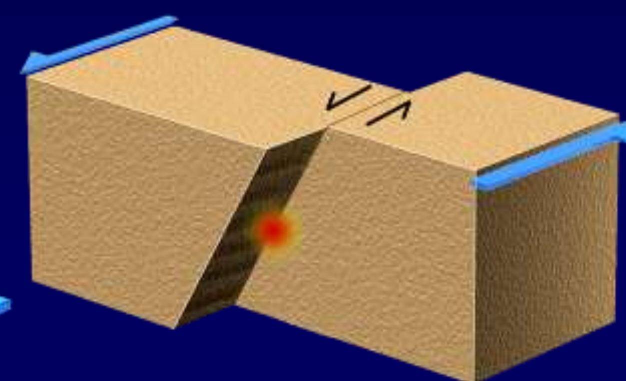
What causes most earthquakes?



Normal faults



Reverse and thrust faults



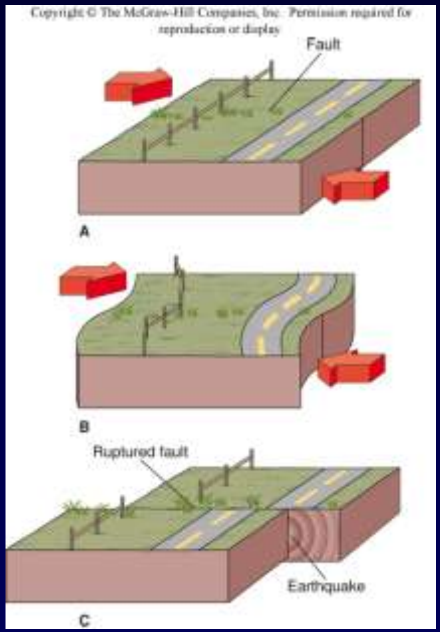
Strike-slip faults

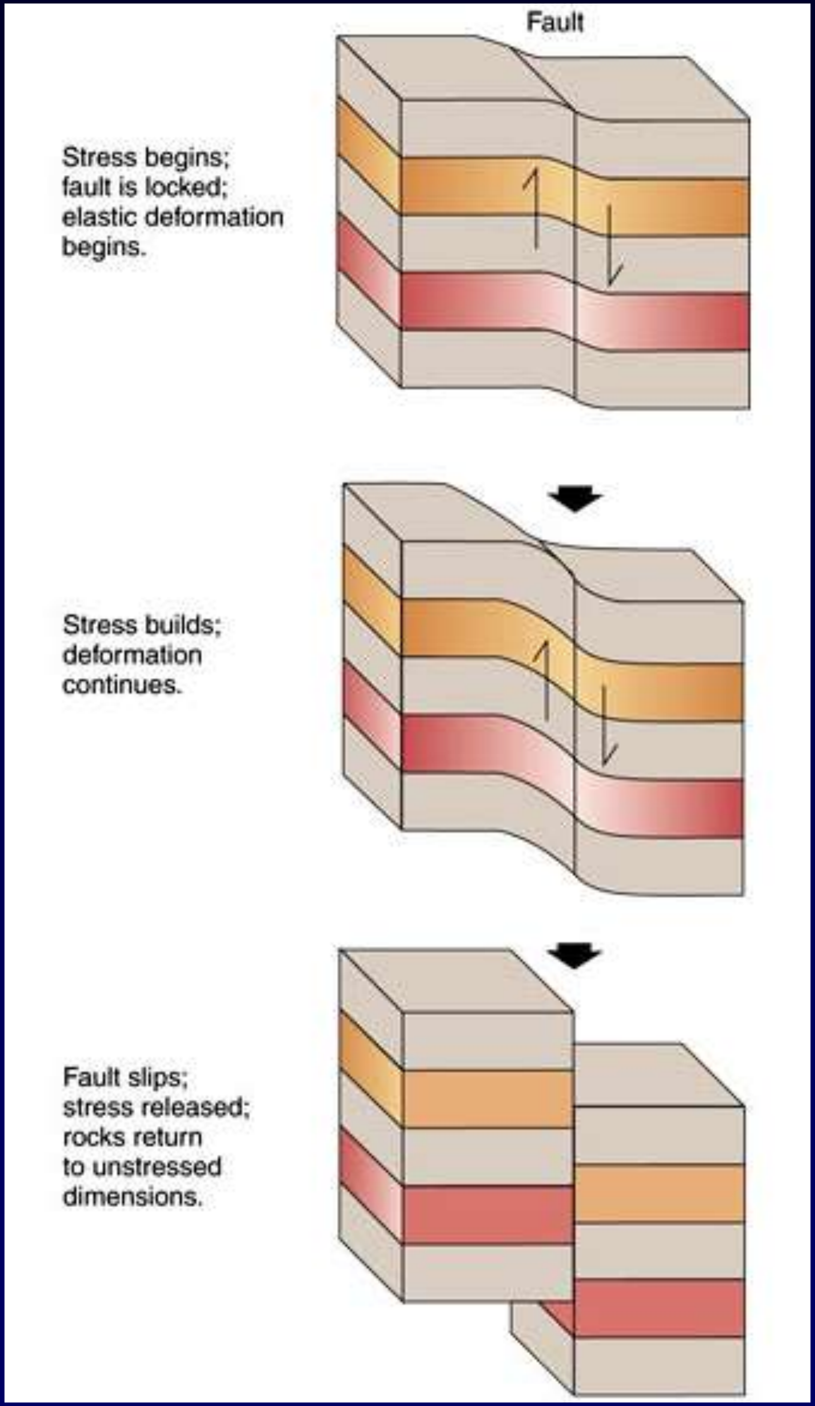
Basic Theory

- Earthquakes represent a release of built-up stress in the lithosphere
- Earthquakes occur along faults
- Faults are planar breaks in rock. There is displacement of one side relative to the other along faults
- Creep (aseismic slip), movement along faults occurs gradually and relatively slowly and smoothly. Fault displacement without significant earthquake activity

Earthquakes

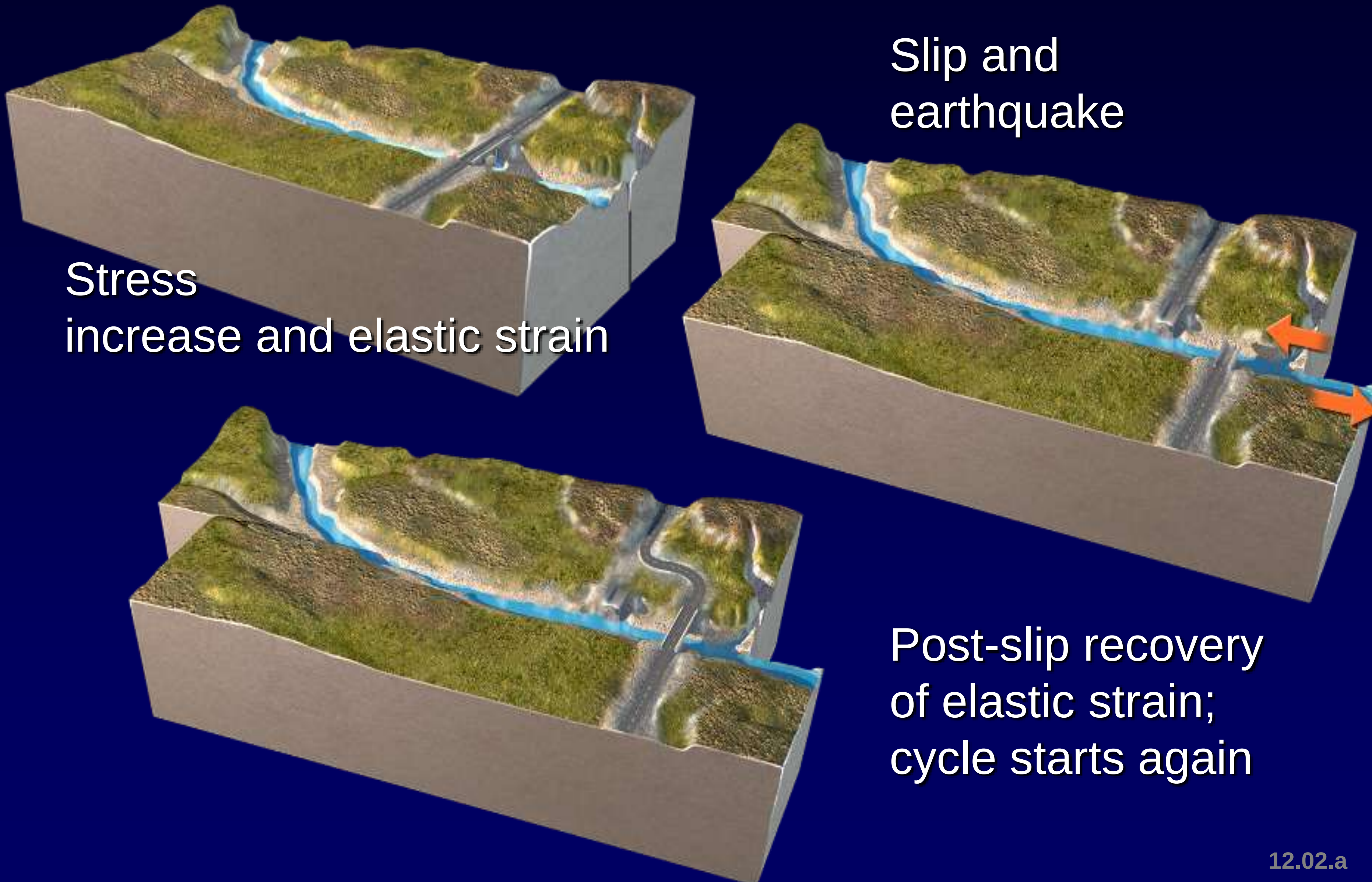
- An ***earthquake*** is a trembling or shaking of the ground caused by the sudden release of energy stored in the rocks beneath Earth's surface
  - Tectonic forces within the Earth produce stresses on rocks that eventually exceed their elastic limits, resulting in brittle failure
- Energy is released during earthquakes in the form of ***seismic waves***
  - Released from a position along a break between two rock masses (fault)
- ***Elastic rebound theory*** - earthquakes are a sudden release of strain progressively stored in rocks that bend until they finally break and move along a ***fault***





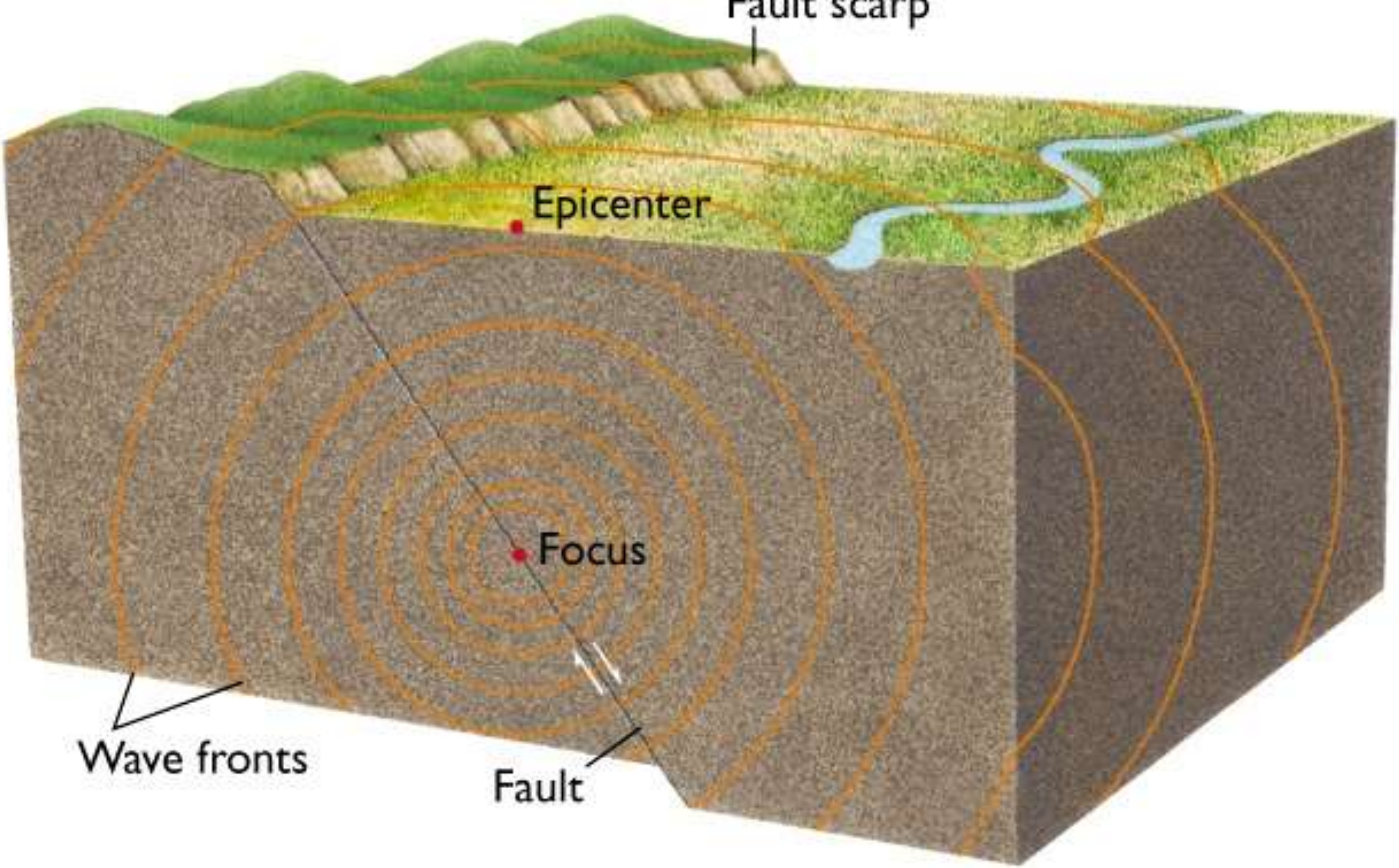
elastic rebound

Before, During, and After an Earthquake



What are earthquakes and what are their causes?

- Violent movement of the Earth’s interior and surface by transmission of energy in waves (analogies with sound and water waves)
- Causes
  - Volcanism
  - Explosions
  - Landslides
  - Fault movements
- Elastic rebound theory
  - Strain builds up in the elastic part of the crust until it snaps (brittle behavior)

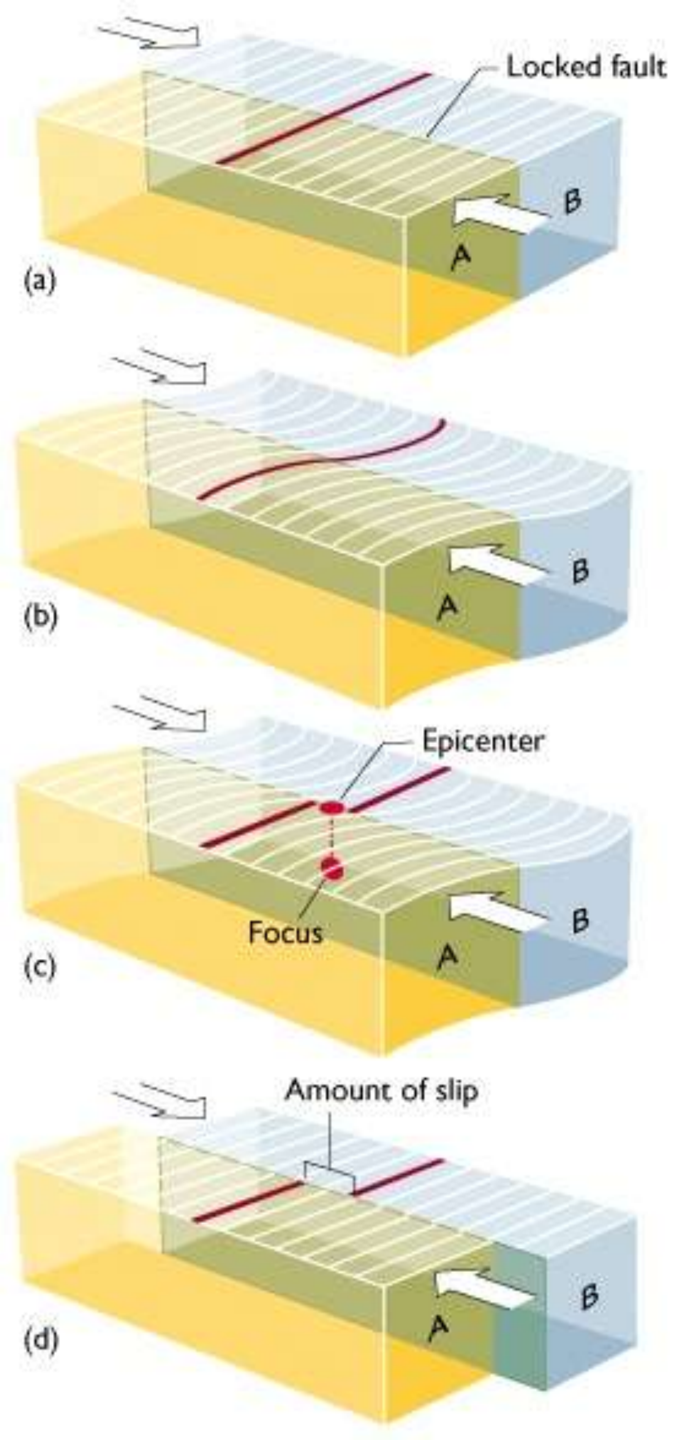

Fault scarp
Epicenter
Focus
Wave fronts
Fault

Basic Theory

- **Earthquakes (seismic slip)**
  - Friction between rocks against slipping generates elastic deformation and builds up energy before failure
  - When the stress exceeds the friction (or rupture strength of the rock), a sudden movement occurs to release the stress
- Elastic Rebound:

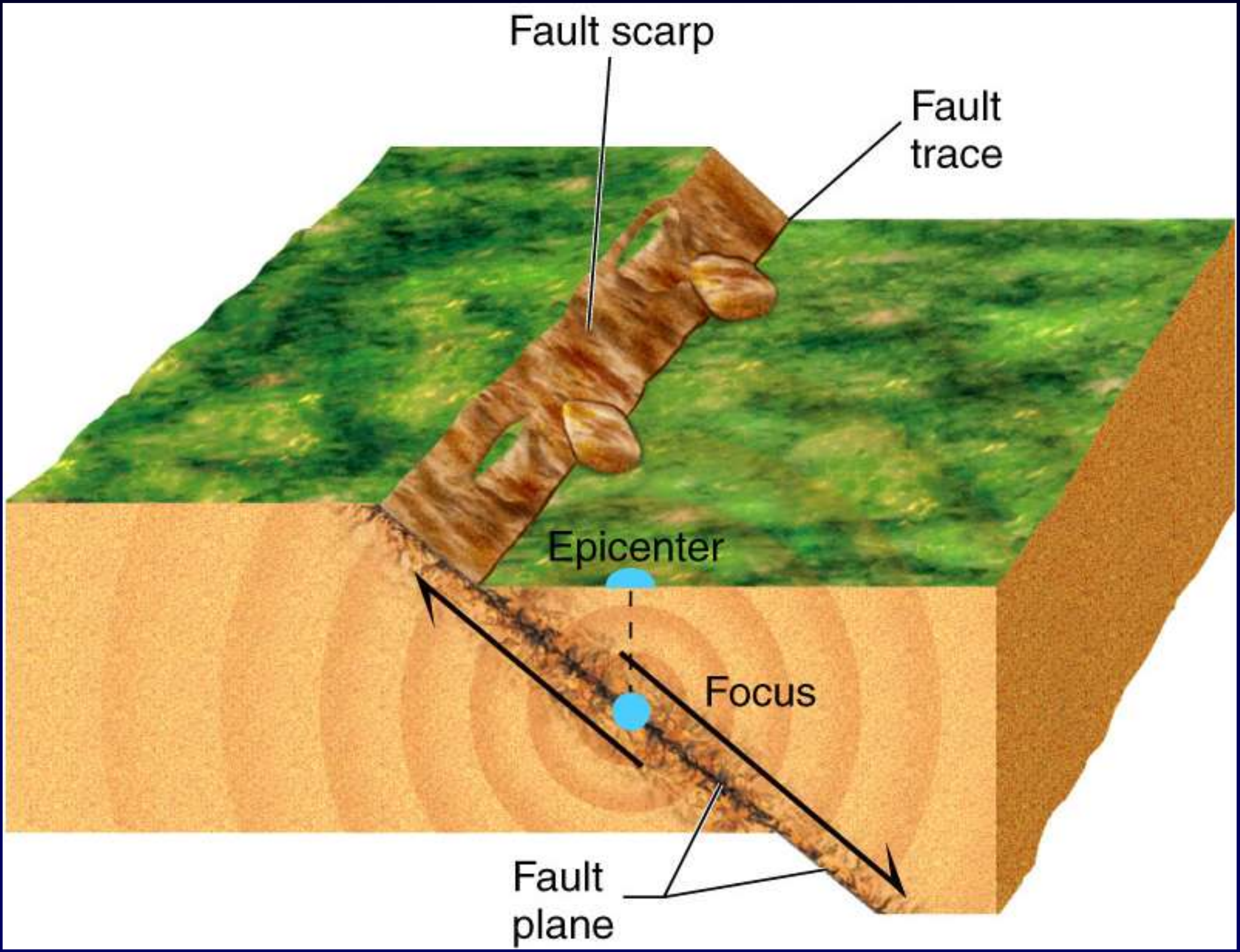
  the rock snaps back elastically to their previous dimensions after the sudden displacement and associated stress release

- Elastic rebound theory
  - Friction prevents slip
  - Strain builds up
  - Rupture



Earthquake or Seismic Slip

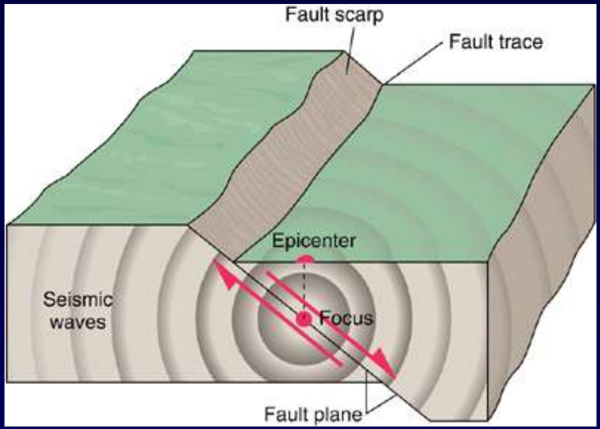
- Energy releases from a dynamic earth occur along faults
- Earth's crust moves very slow
  - over time enough stress builds up and a brittle release occurs - an Earthquake
- Stress is released and transferred
  - Elastic Rebound
- Actual site of the first movement along a fault is the **focus (or hypocenter)**
- Actual point on the earth's surface directly above the focus is the **epicenter**



Simplified diagram of a fault

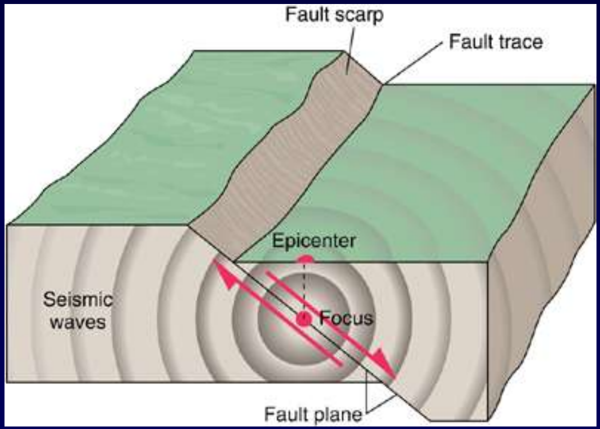
Seismic Waves

- ***Focus*** (or *hypocenter*) - the point of initial breakage and movement along a fault, where seismic waves originate
- ***Epicenter -*** point on Earth's surface directly above the focus



Seismic Waves

- Two types of seismic waves are produced during earthquakes
  - ***Body waves -*** travel outward from the *focus* in all directions through Earth's interior
  - ***Surface waves -*** travel along Earth's surface away from the *epicenter*



Seismic Waves

- **First to arrive—primary (P waves)**
  - Travel through Earth, compressional (analogous to sound waves)
  - Travel through solid, liquid, or gas
- **Secondary (S waves)**
  - Travel through Earth, shear waves
  - Slower propagation rate than P waves
  - Do not exist in liquids or gases
- **Surface waves**
  - Need a free surface to exist
  - Confined to Earth's surface and outer layers
  - Rayleigh and Love

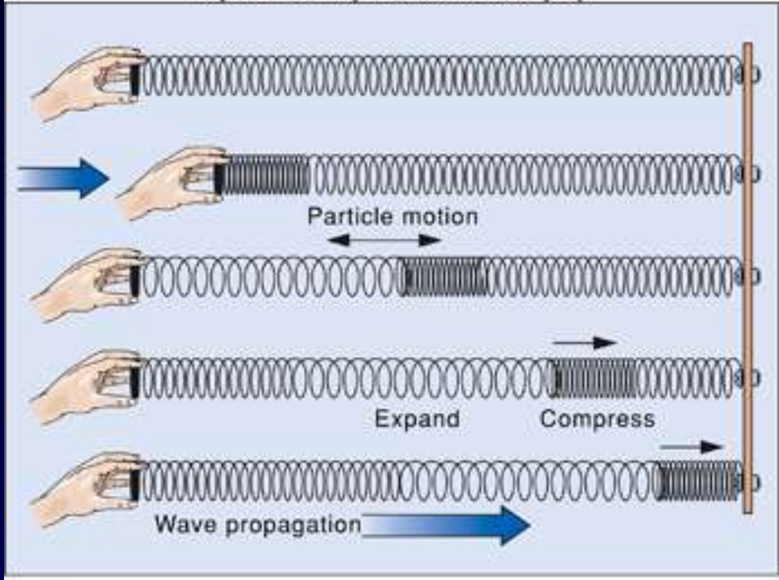
Seismic Waves

- Energy released by an earthquake will send seismic waves out from the focus
- Body Wave – travels through the interior of the earth
  - **P waves** are compression waves
  - S **waves** are shear waves but pass only through solid rock (not magma)
- Surface wave – travels along the surface
  - Larger ground displacement than body waves
  - Results in most earthquake damage

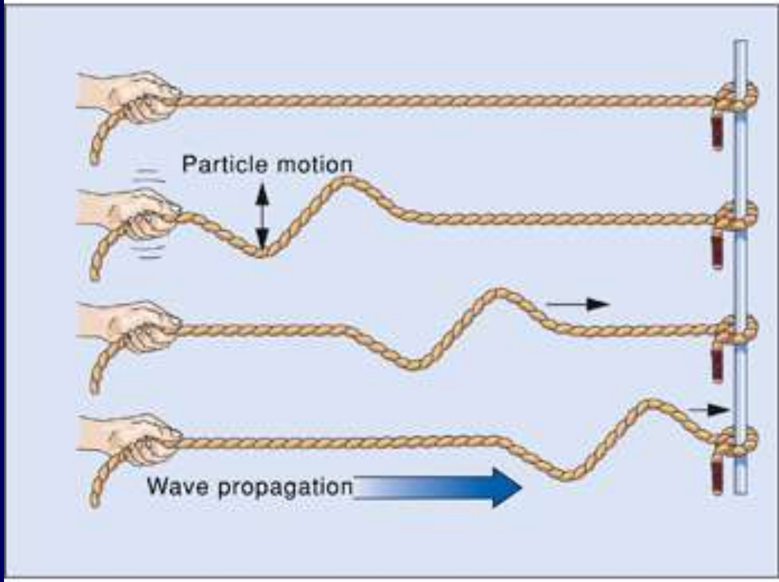
Body Waves

- *P wave* - compressional (longitudinal) body wave in which rock vibrates back and forth *parallel* to the direction of wave propagation

- *S wave* - shearing (transverse) body wave in which rock vibrates back and forth *perpendicular* to the direction of wave propagation



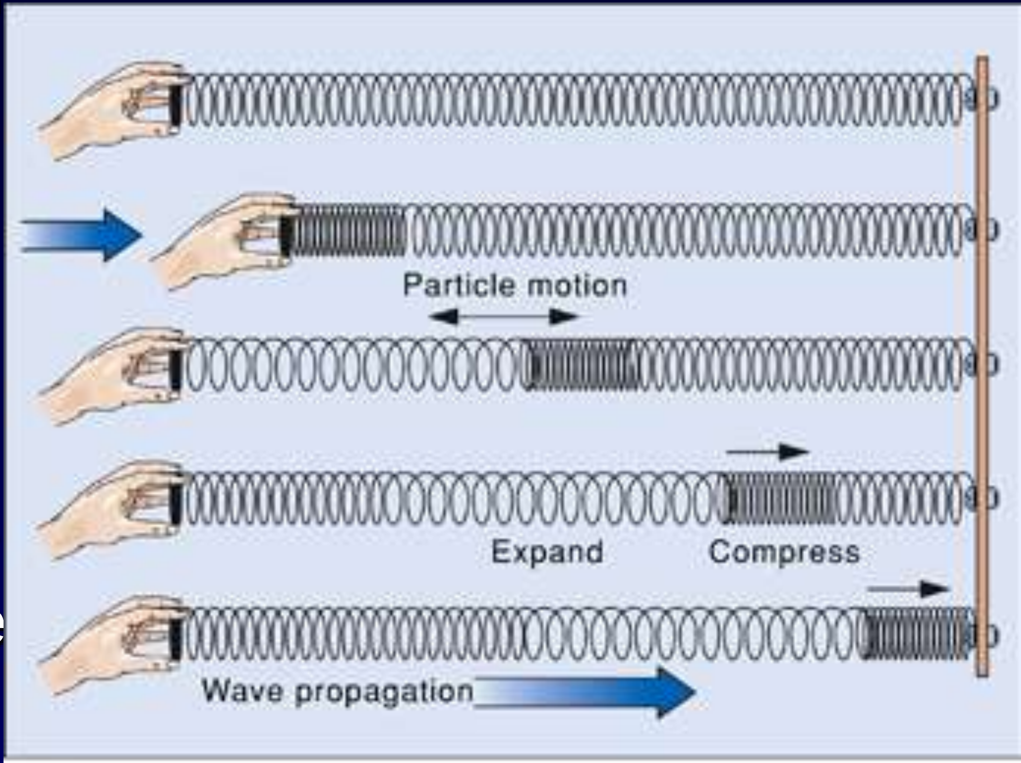
A Primary wave



B Secondary wave

Body Waves – P – primary- wave

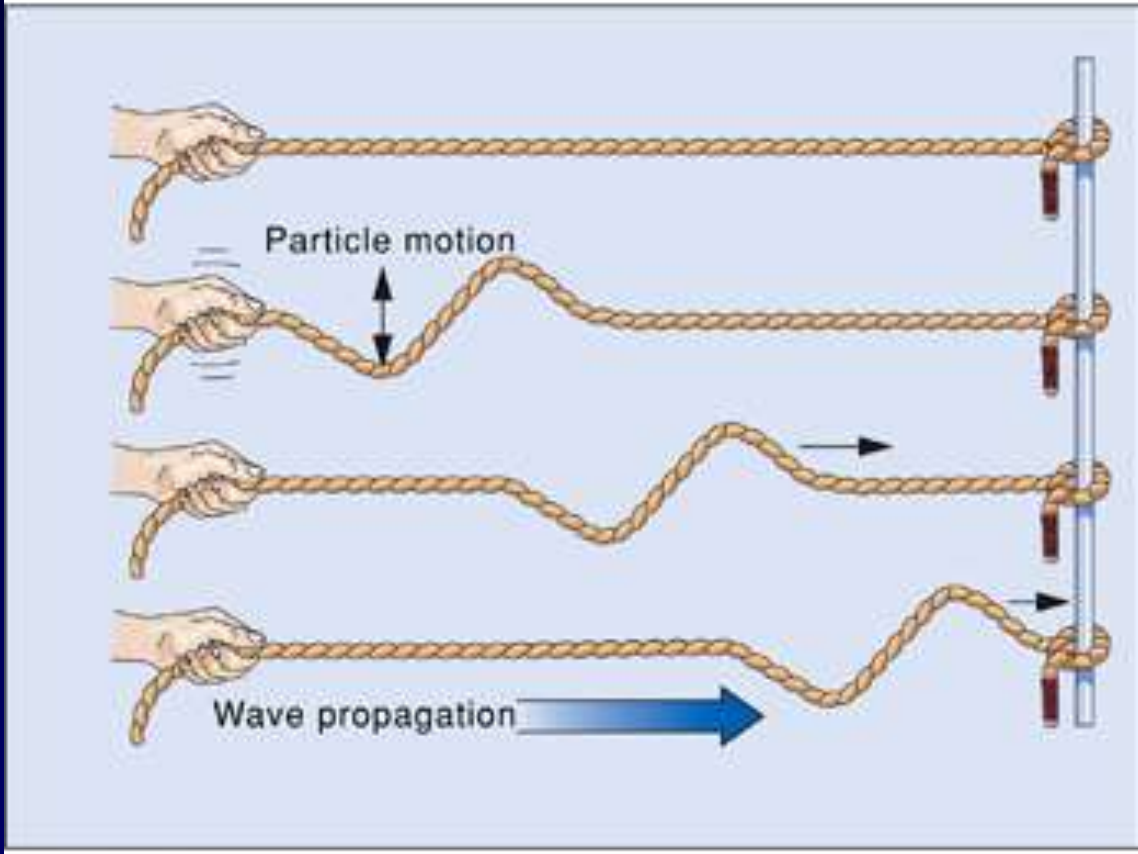
- ***P wave -*** compressional (longitudinal) body wave in which rock vibrates back and forth *parallel* to the direction of wave propagation
  - Fast (4 to 7 kms/sec) wave that is the first or ***primary*** wave to arrive at recording station following earthquake
  - Pass through *solids and fluids*



A Primary wave

Body Waves – S – Secondary- Wave

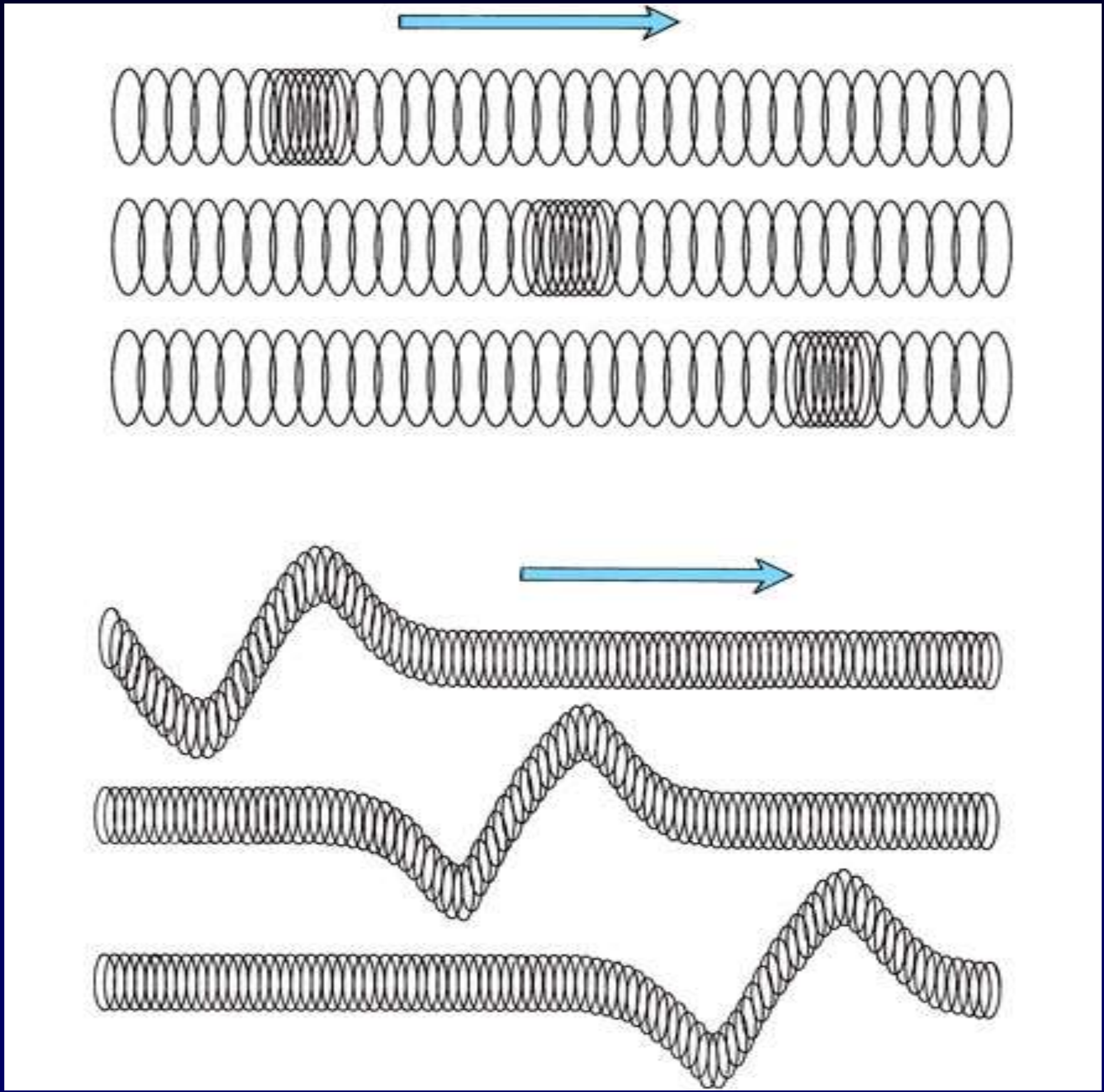
- ***S wave* - shearing (**(transverse) body wave in which rock vibrates back and forth *perpendicular* to the direction of wave propagation
  - Slower (2 to 5 km/sec) wave that is the ***secondary*** wave to arrive at recording station following earthquake
  - Pass through *solids only*



B Secondary wave

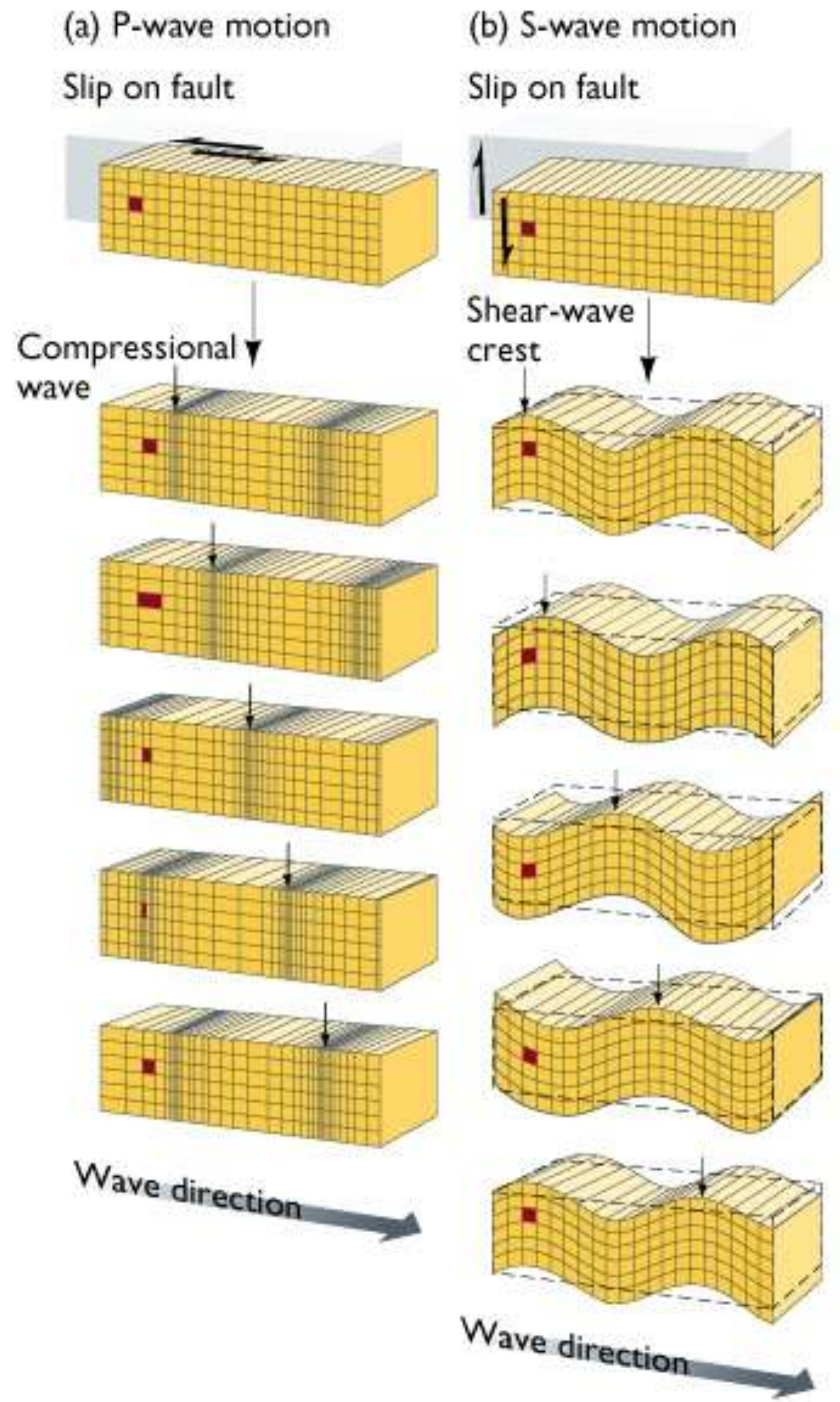
P waves

S waves



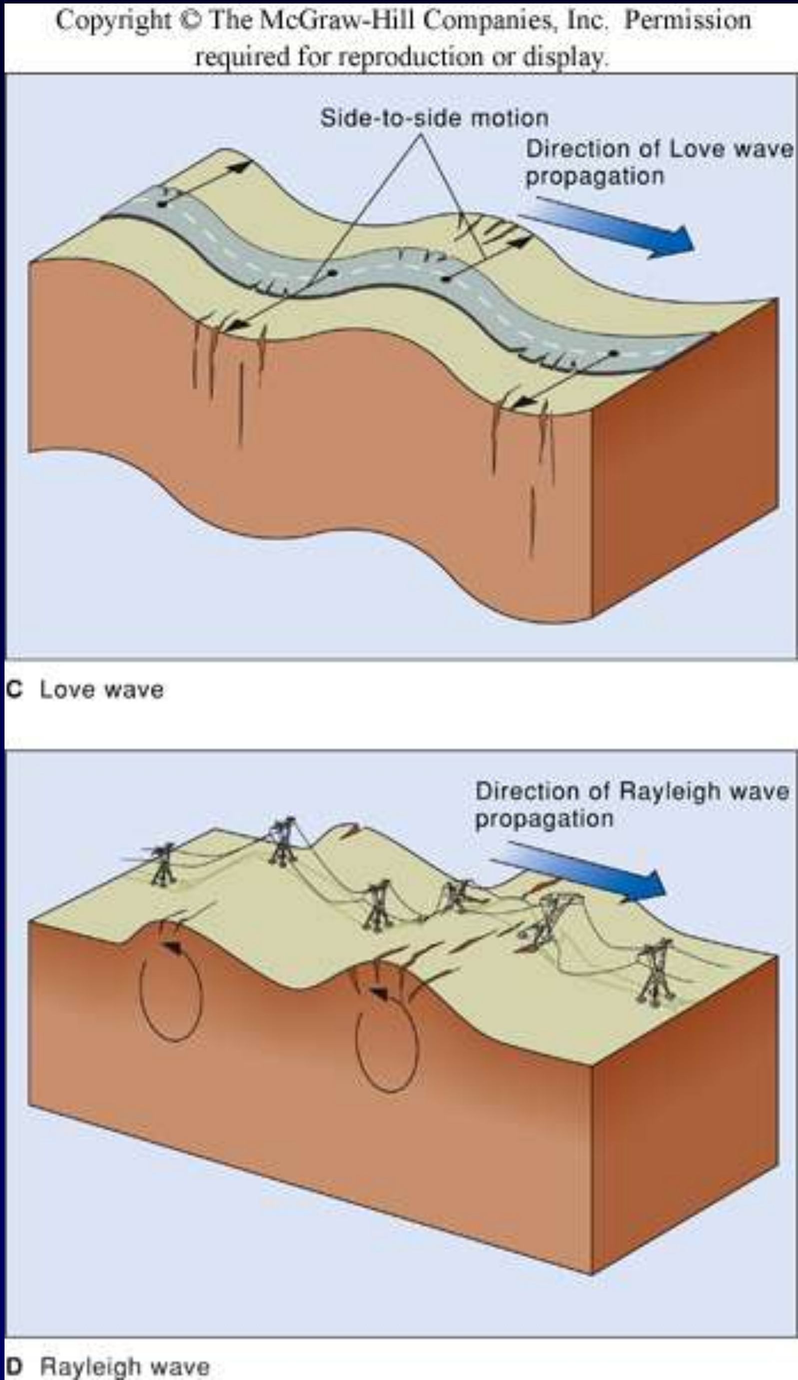
Seismic Waves

- P and S waves (body waves)
  - Compressional and shear
- Rayleigh and Love waves (surface waves)
  - Up-down and side-side



Surface Waves

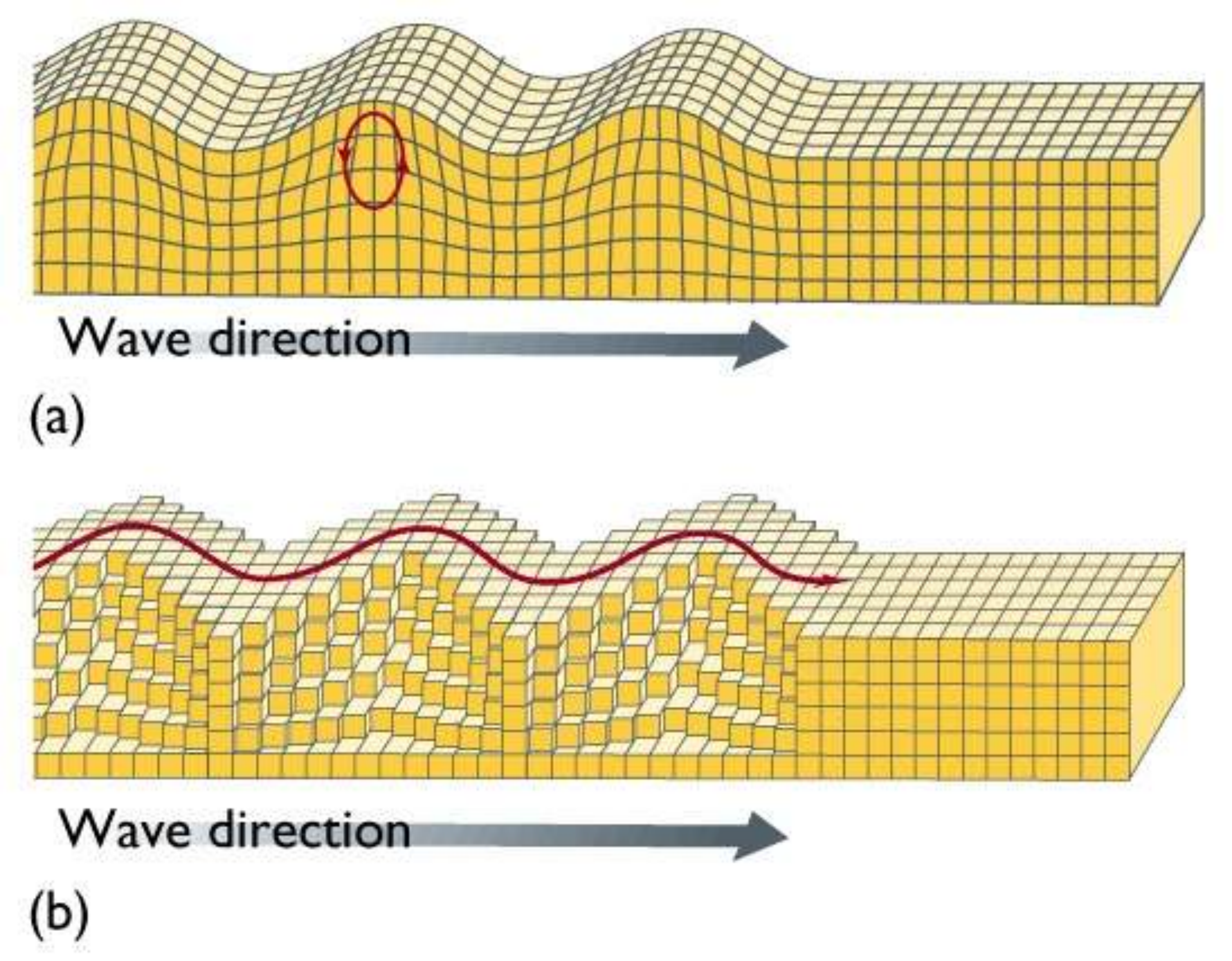
- Slowest type of seismic waves produced by earthquakes
- ***Love waves* -** side-to-side motion of the ground surface
  - Can’t travel through fluids
- ***Rayleigh waves* -** ground to moves in an elliptical path opposite the direction of wave motion
  - Extremely destructive to buildings



Surface waves

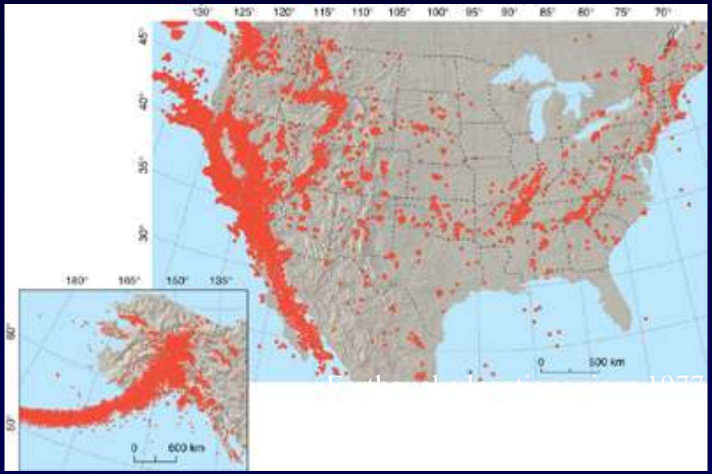
(a) Rayleigh waves

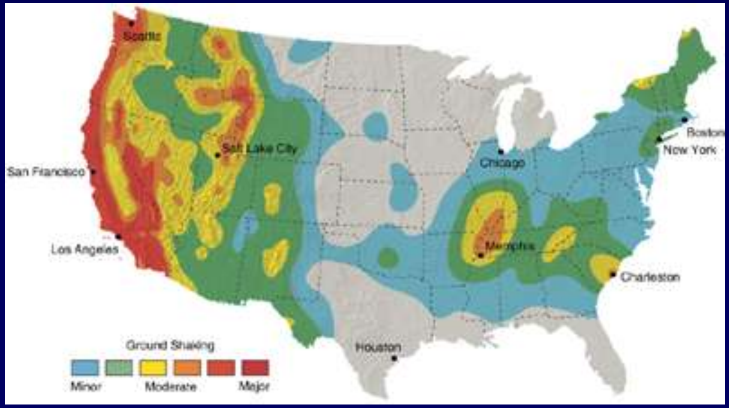
(b) Love waves

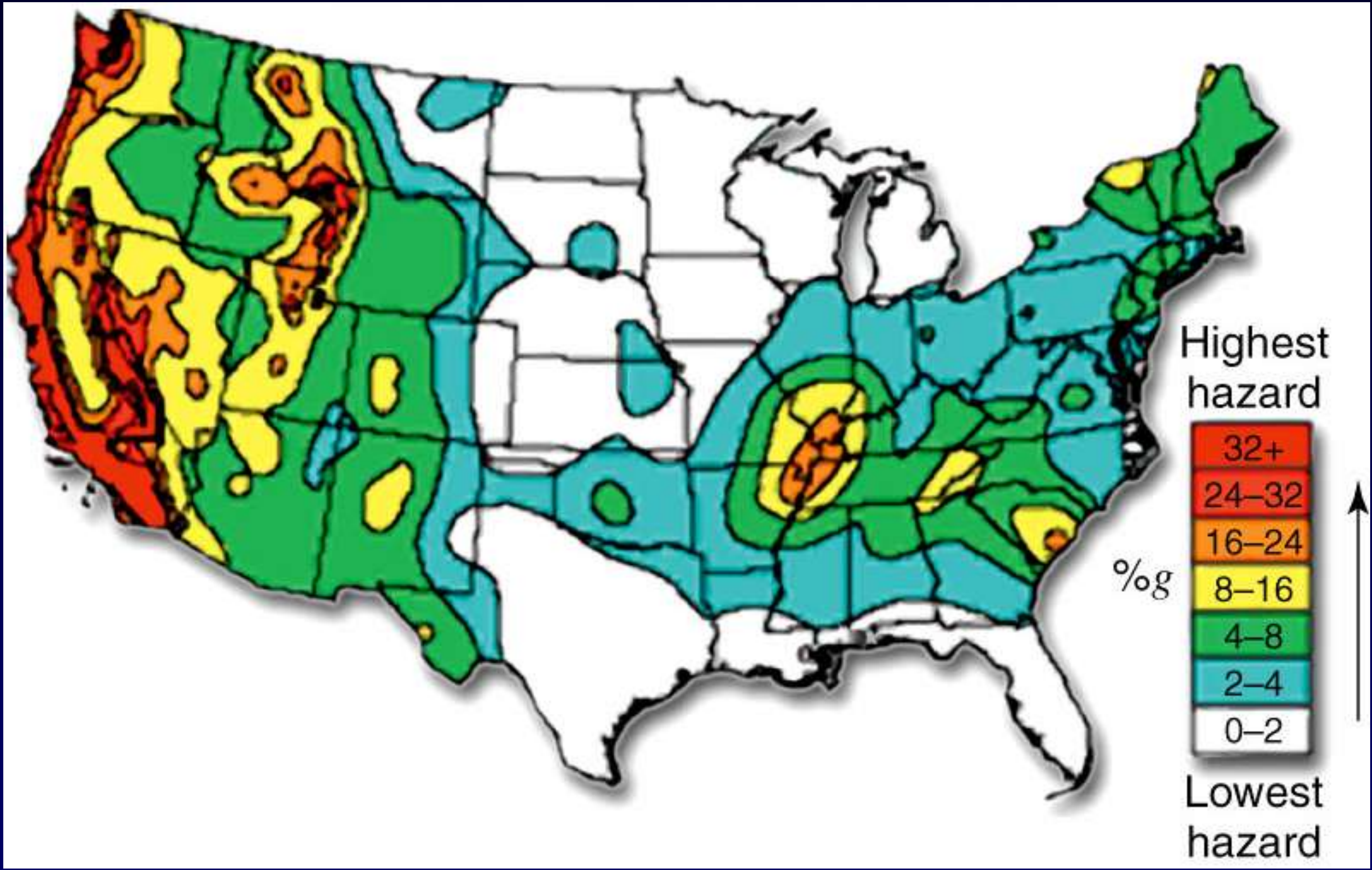


Location and Size of Earthquakes in the U.S.

- Earthquakes occur throughout the U.S., but are much more common in the western states and Alaska
- **Largest *seismic risks* or *hazards*** exist near the plate boundary along the U.S. Pacific coast (e.g., San Andreas fault), and around New Madrid, Missouri
- Seismic risk determined based on the assumption that large future earthquakes *will occur where they have occurred in the past*



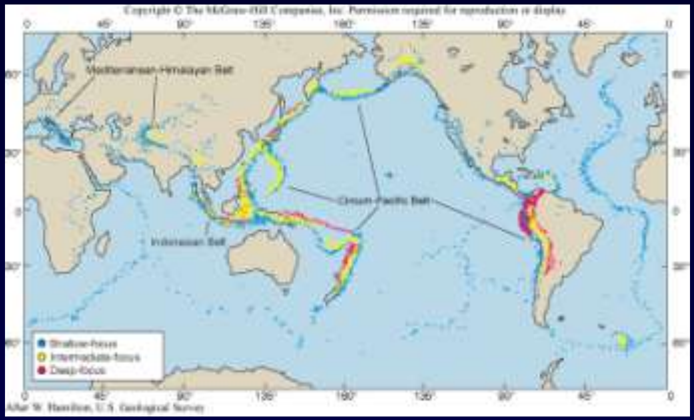


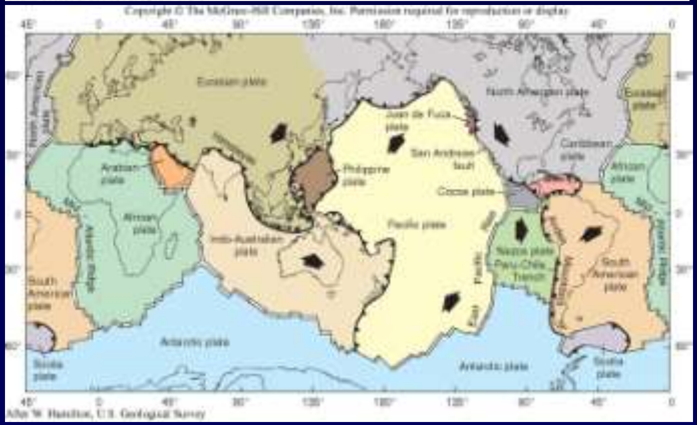


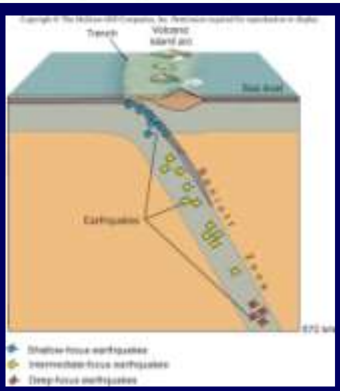
U.S. Seismic Hazard Map

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)

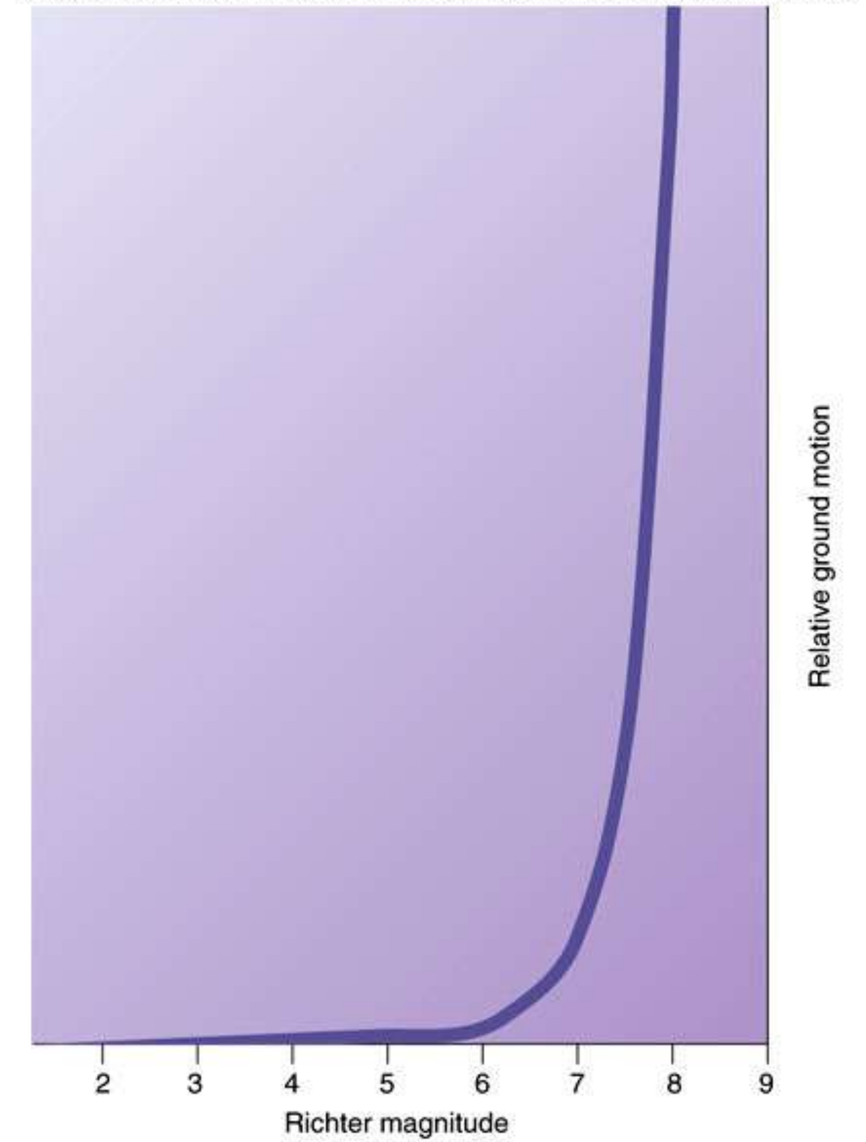


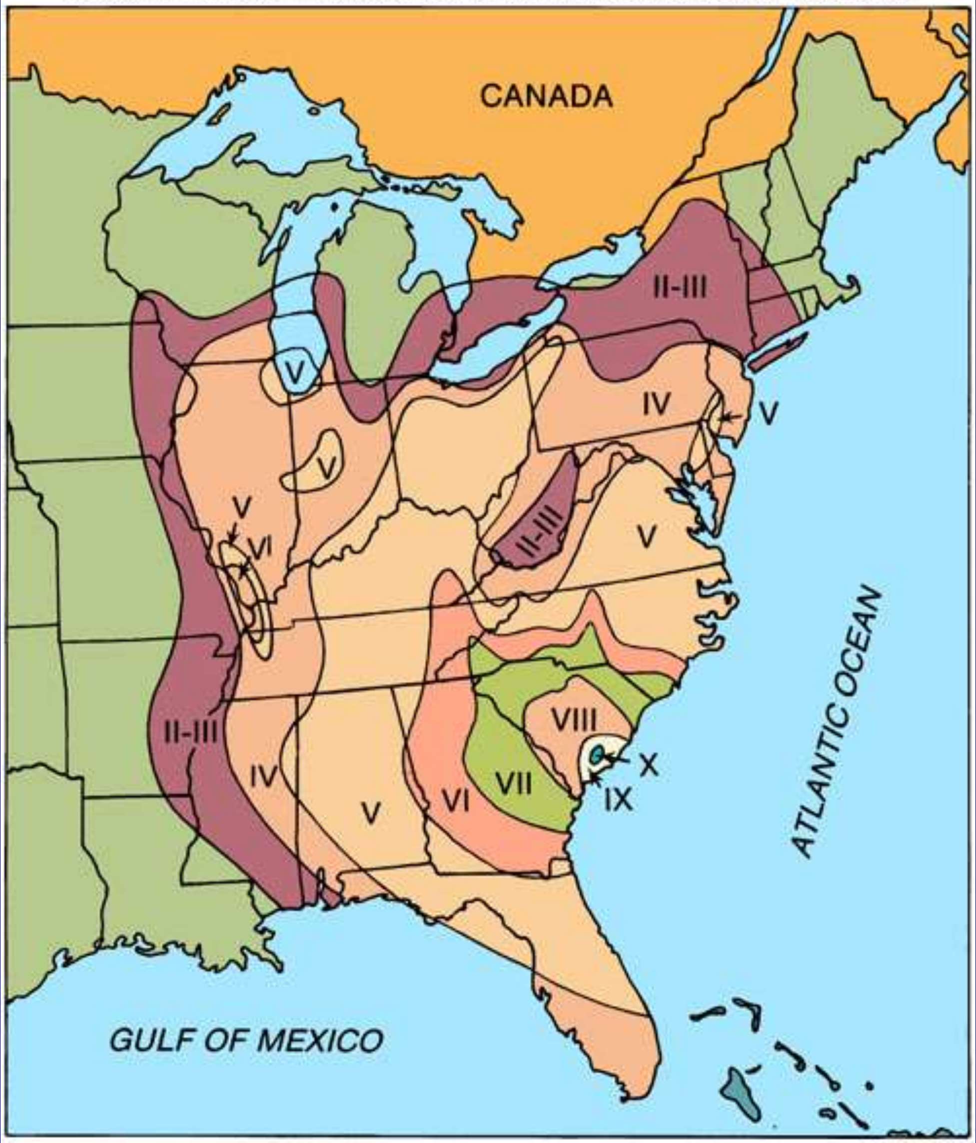


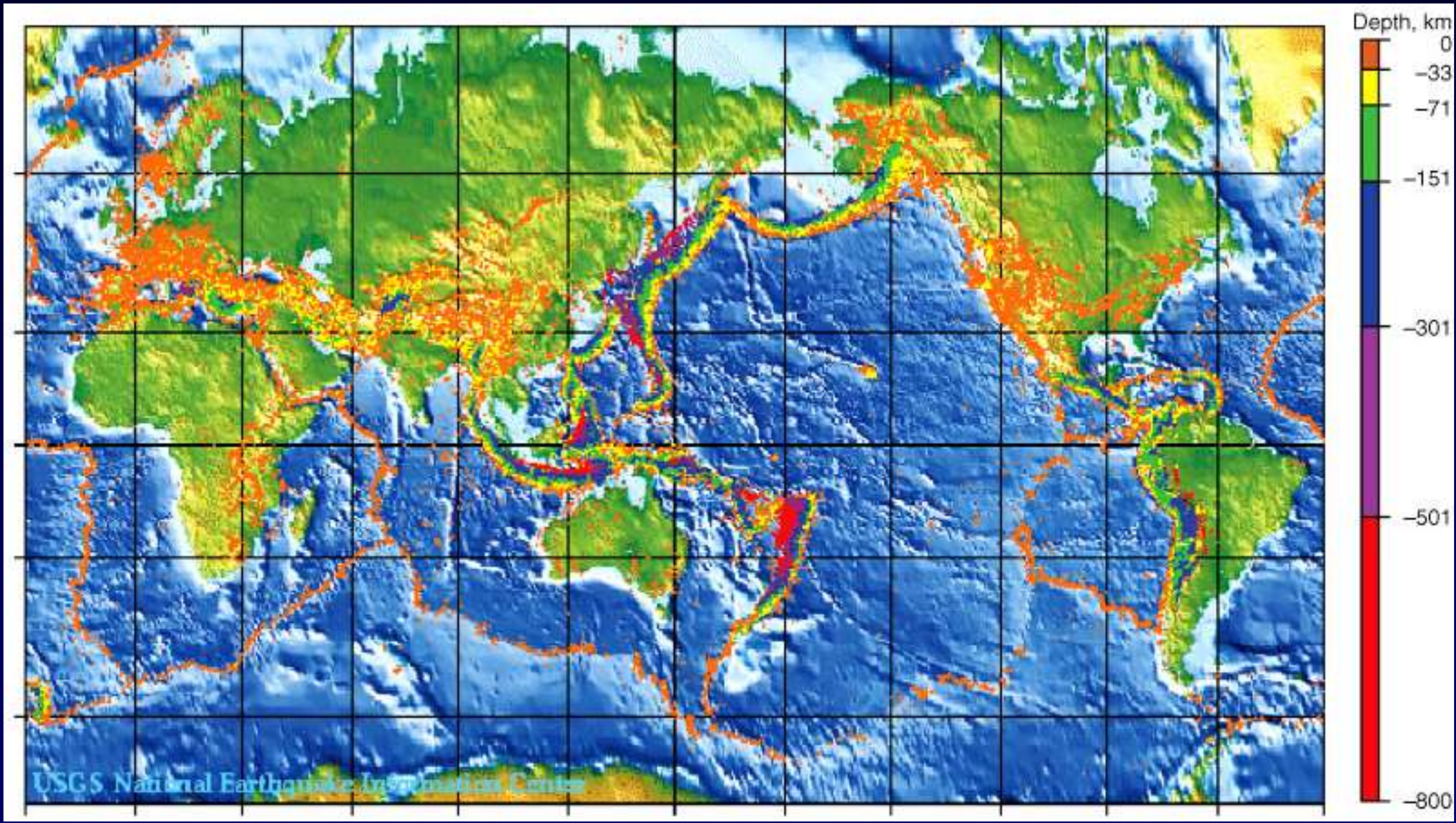


The midcontinent, intraplate earthquakes

Charleston quake and Mercalli scale



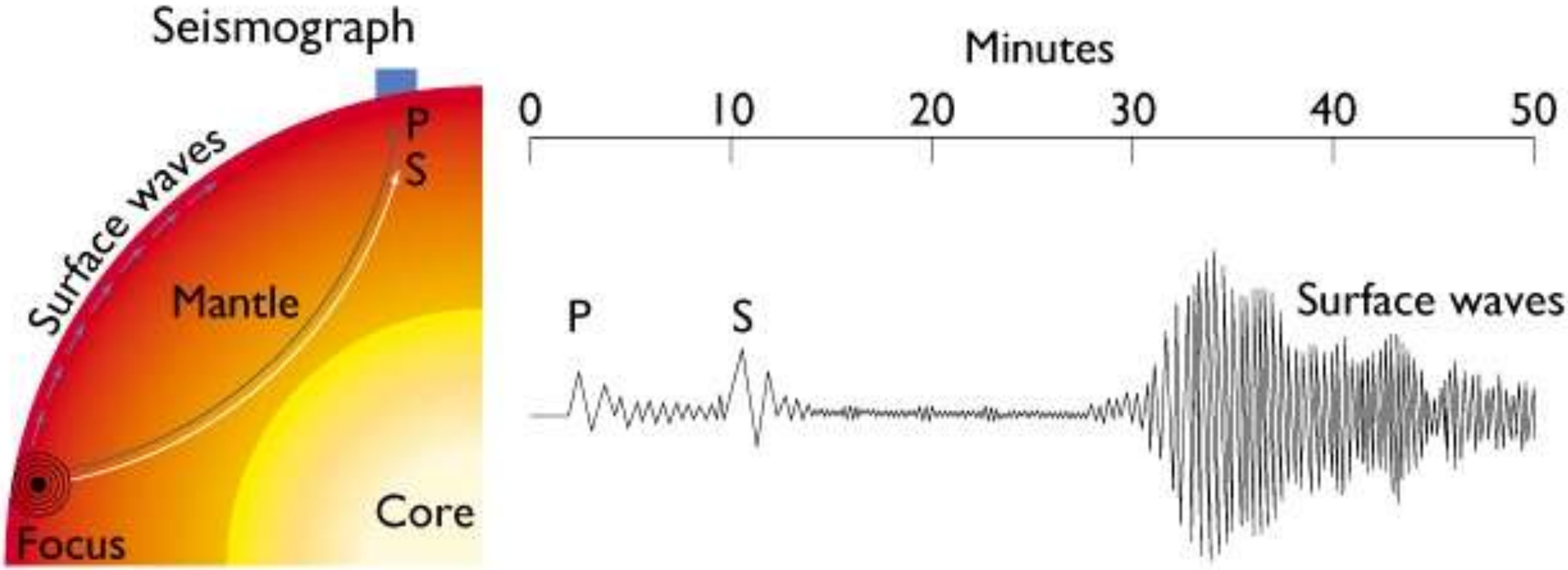




World seismicity (1979-1995)

Earthquake Locations

- Generally occur in linear belts
  - Intraplate earthquakes also occur and quite severe
- Linear belts correspond to plate boundaries
  - most earthquakes occur at plate boundaries
- Earthquake focal depths are
  - Deep
  - Intermediate
  - Shallow
- The deep-focus earthquakes are concentrated in subduction zones



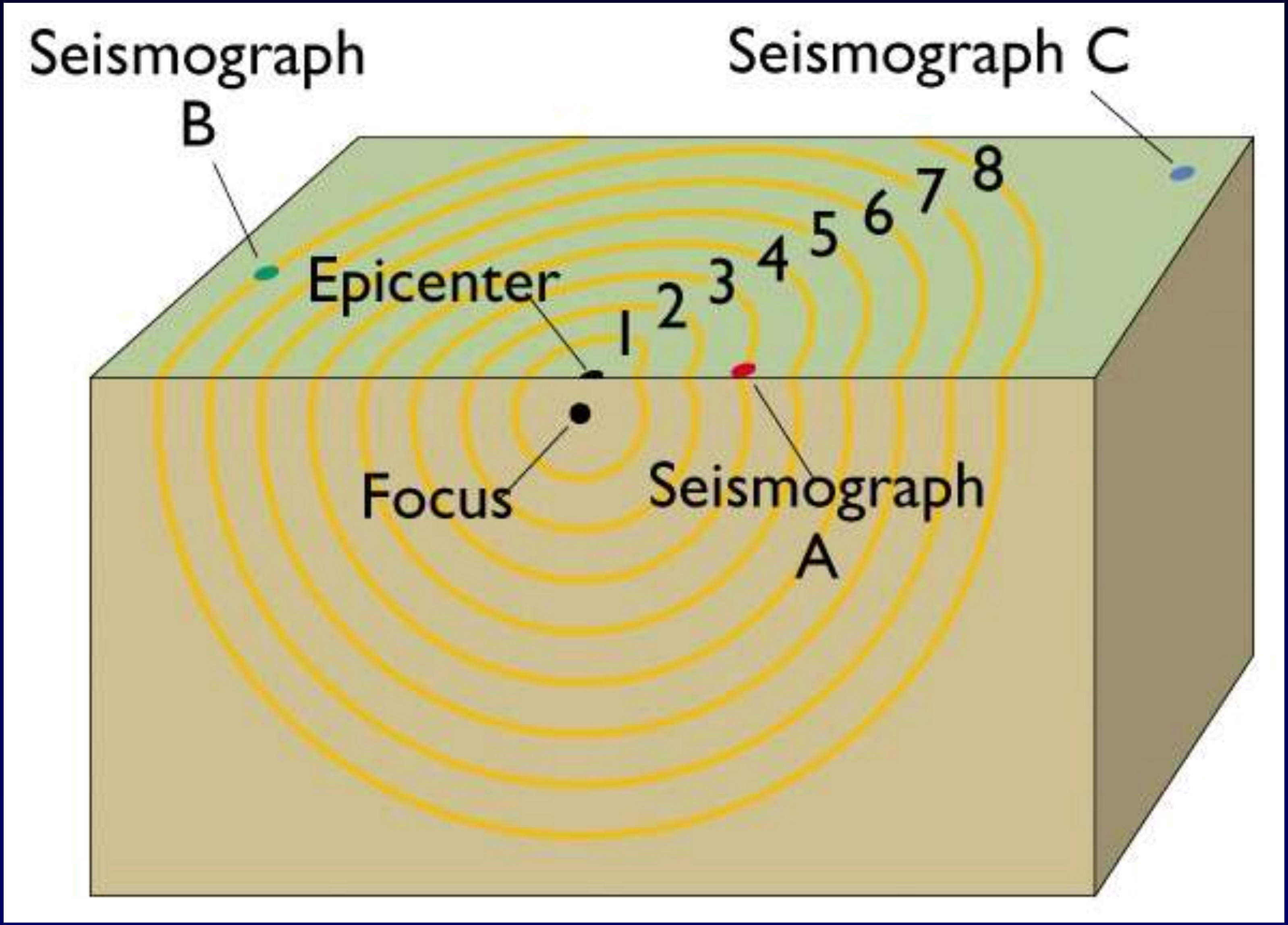
Seismograph
Surface waves
P
S
Mantle
Core
Focus
Minutes
0
10
20
30
40
50
P
S
Surface waves

Locating Earthquakes

- Plotting distances from 3 stations on a map, as circles with radii equaling the distance from the quake, locates earthquake ***epicenter***
- ***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*

Locating the Epicenter

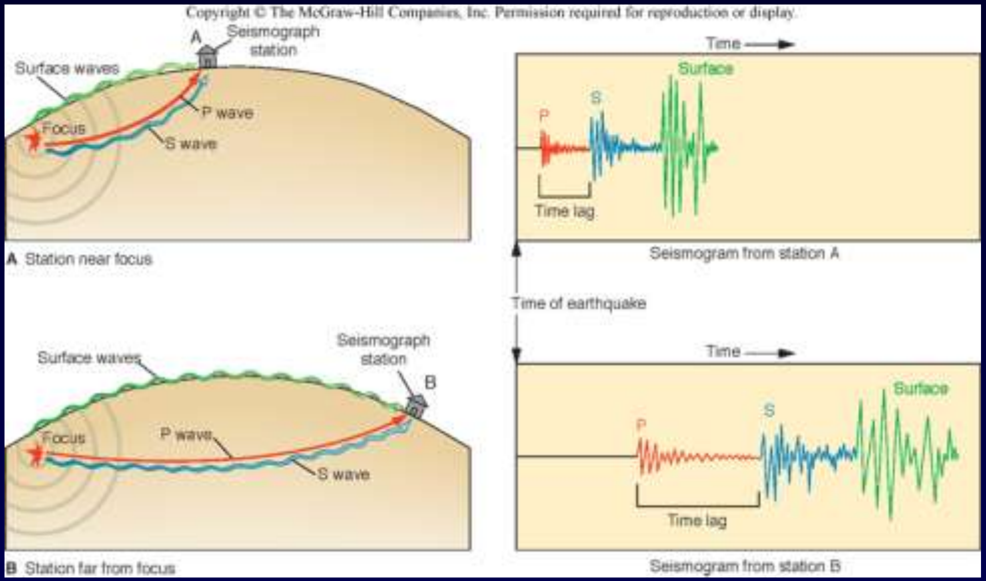
- Energy released from an earthquake must travel through the earth
  - Density of rock will affect the travel time for seismic waves
  - Waves move fast through high density rocks
  - Waves move slow through low density rocks
- Seismograph detects ground movement and can be useful in calculating the location of an epicenter
  - Records arrival of different seismic waves
  - Interval of time between the first arrivals of P waves and S waves is a function of distance to the epicenter
  - Requires at least 3 seismographs to locate an earthquake

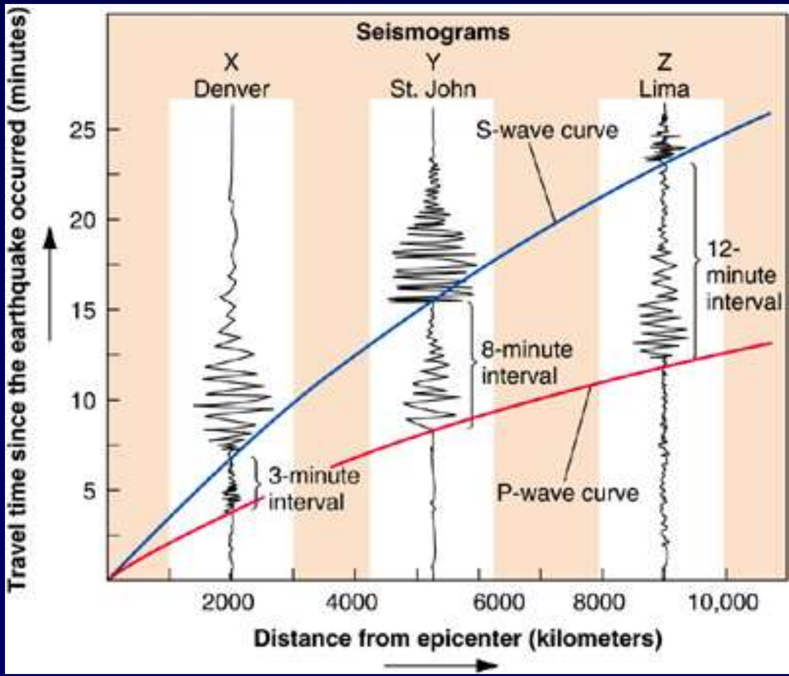


Seismograph B
Seismograph C
Epicenter
1
2
3
4
5
6
7
8
Focus
Seismograph A

Locating Earthquakes

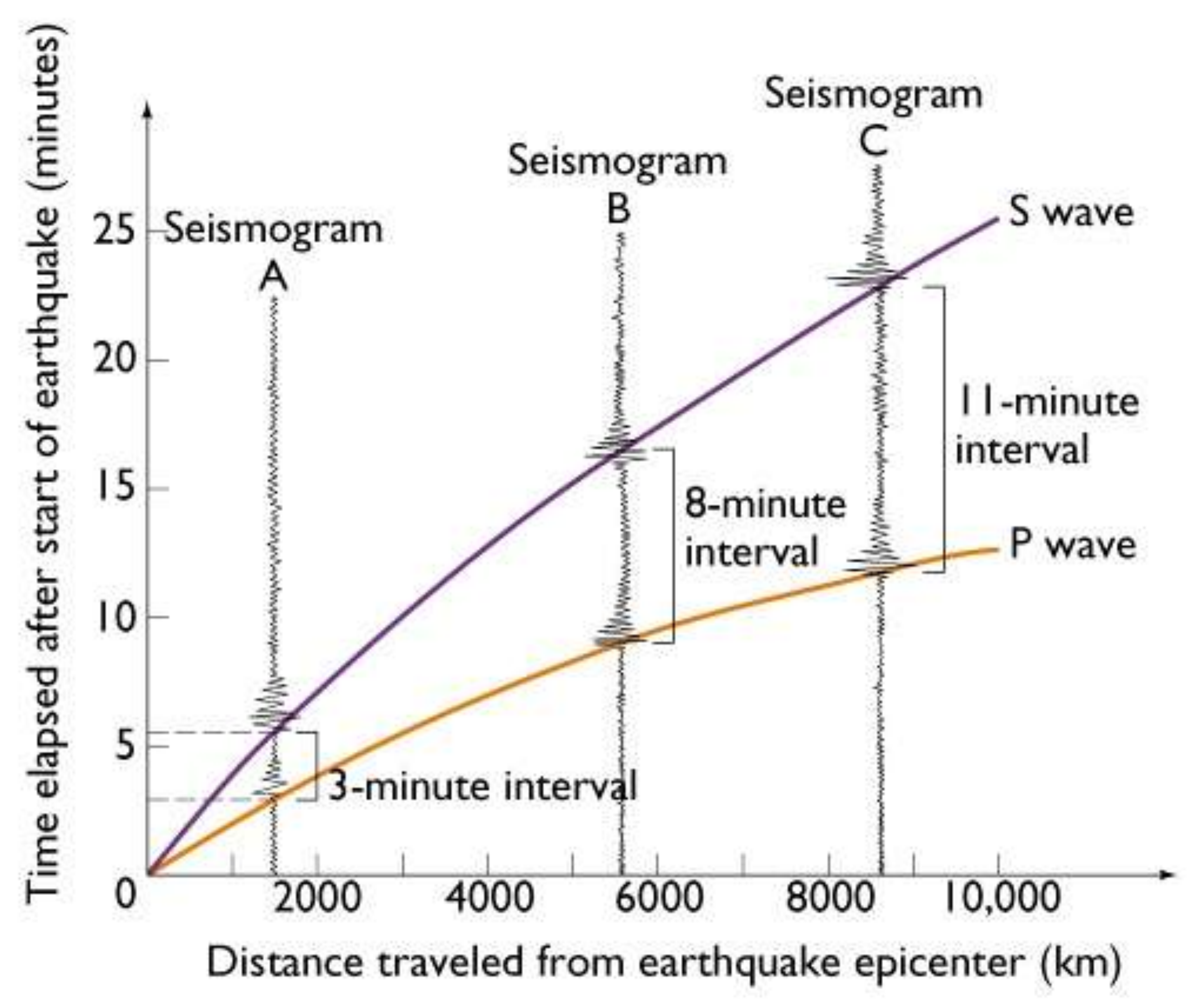
- P- and S-waves leave earthquake focus at the same time
- P-wave gets farther and farther ahead of the S-wave with distance and time from the earthquake
- *Travel-time curve* - used to determine distance to focus
  - based on time between first P- and S-wave arrivals

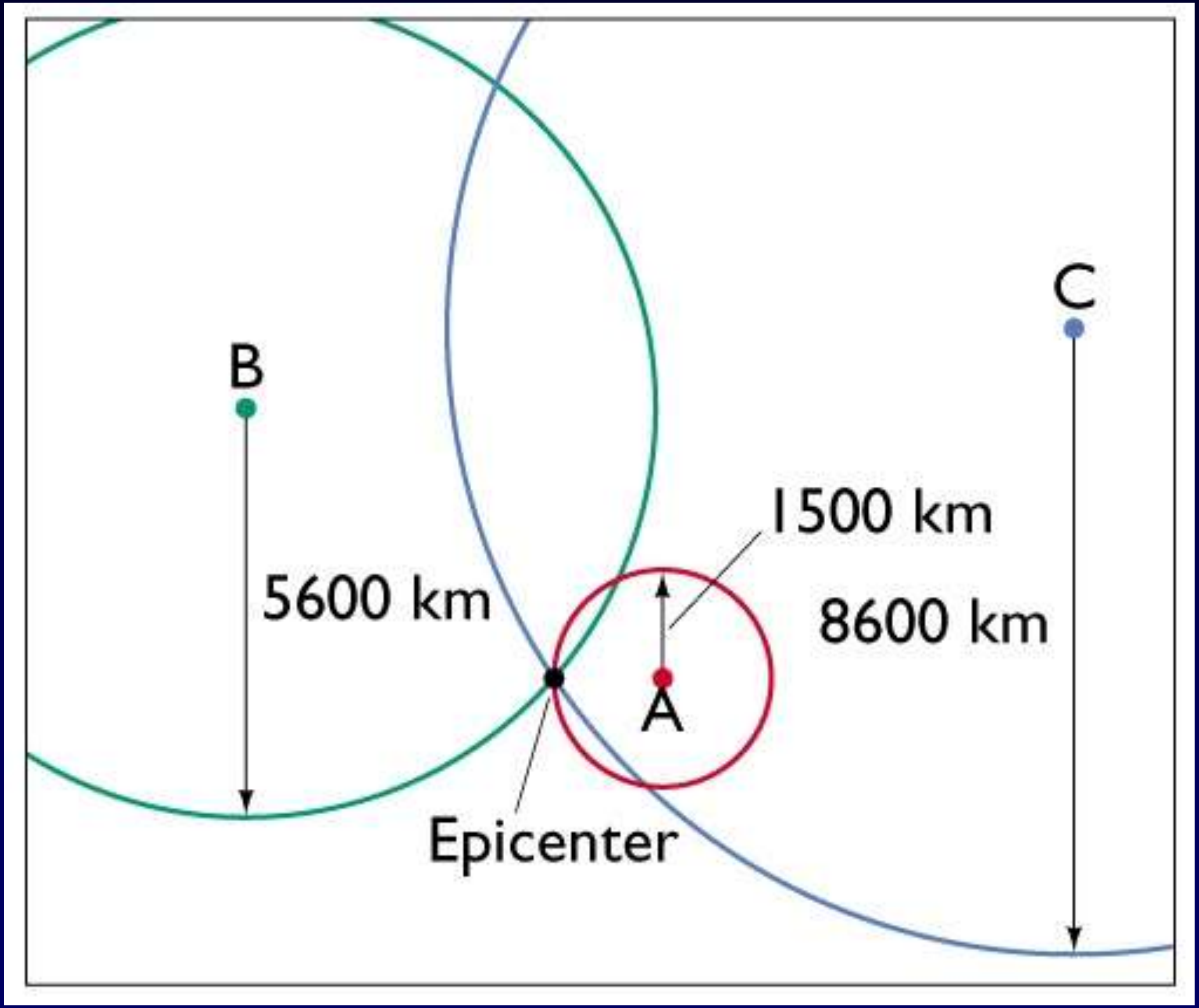




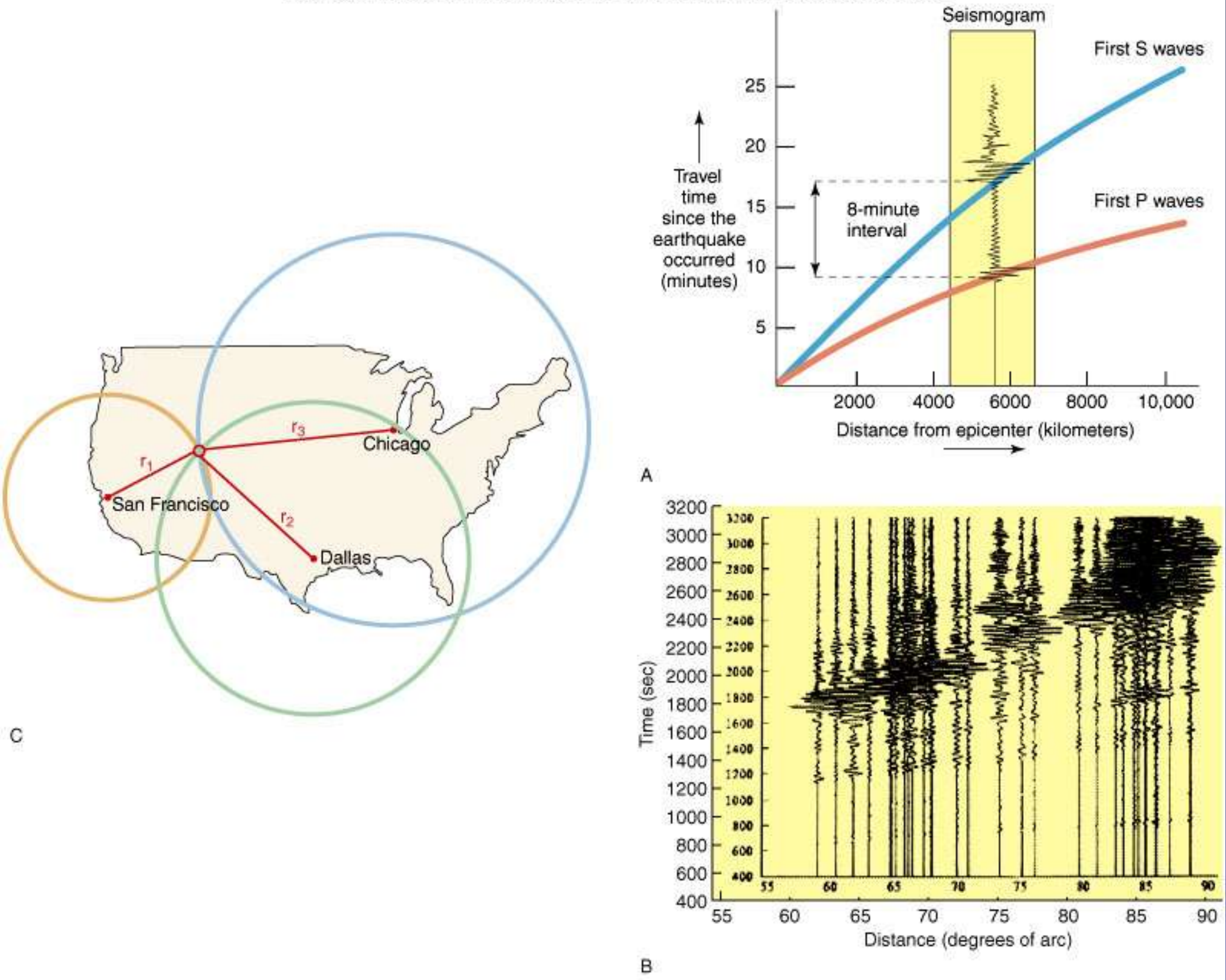
Defining Epicenter

- P waves about twice as fast as S waves
- Consequently, difference in arrival times should increase with distance from epicenter
- Energy decreases with distance
- Able to define epicenter with three observation stations (homework, lab)


Time elapsed after start of earthquake (minutes)
25
20
15
10
5
0
2000
4000
6000
8000
10,000
Distance traveled from earthquake epicenter (km)
Seismogram A
Seismogram B
Seismogram C
S wave
P wave
3-minute interval
8-minute interval
11-minute interval


C
B
1500 km
5600 km
8600 km
A
Epicenter

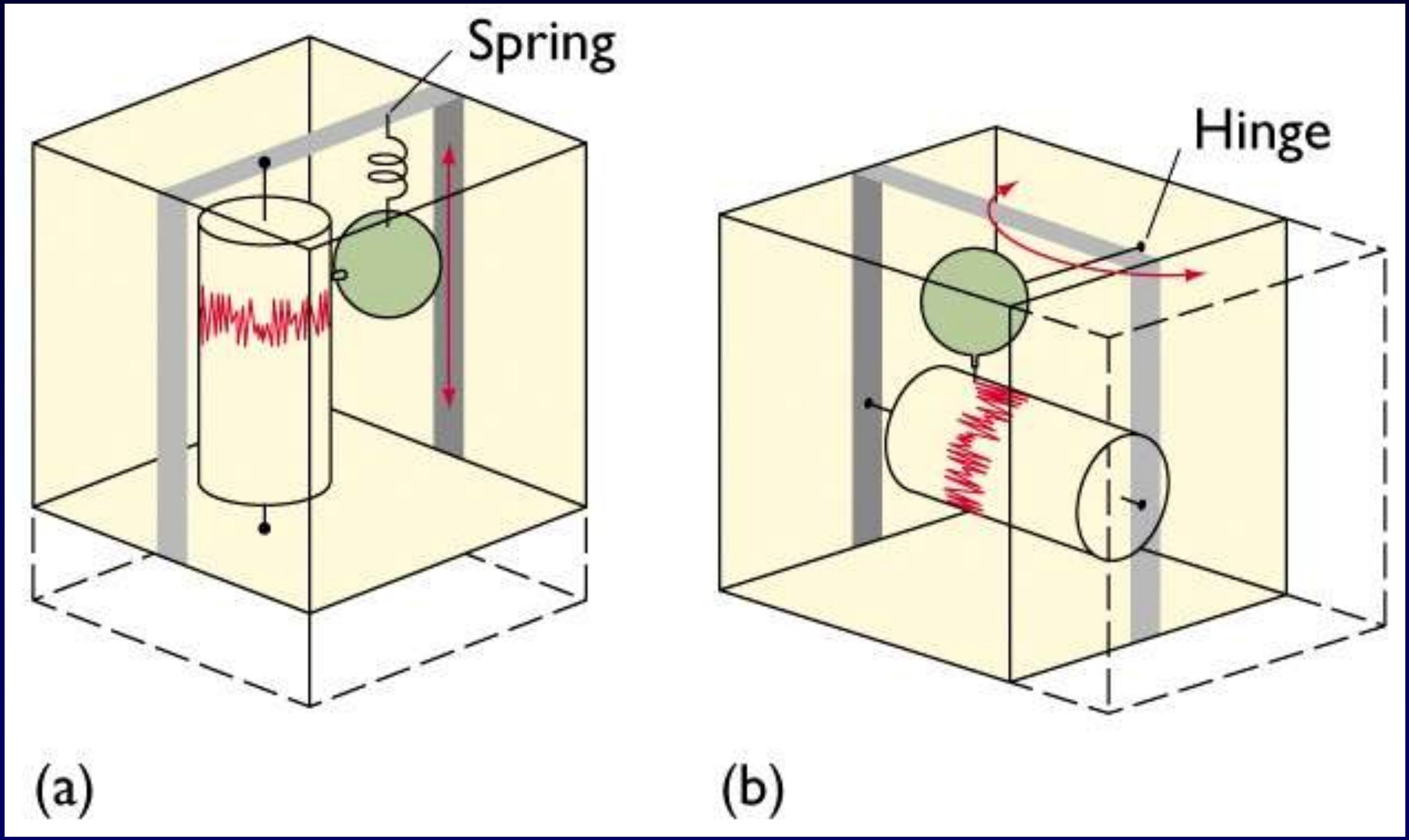
Locating earthquake epicenters



Earthquake Energy

- Energy is released during an earthquake
  - As the waves of energy are transmitted through the rock, this energy with be felt by people at the surface
- Magnitude – the amount of ground motion related to an earthquake
- Intensity – effect on humans, and their structures, caused by the energy released by an earthquake

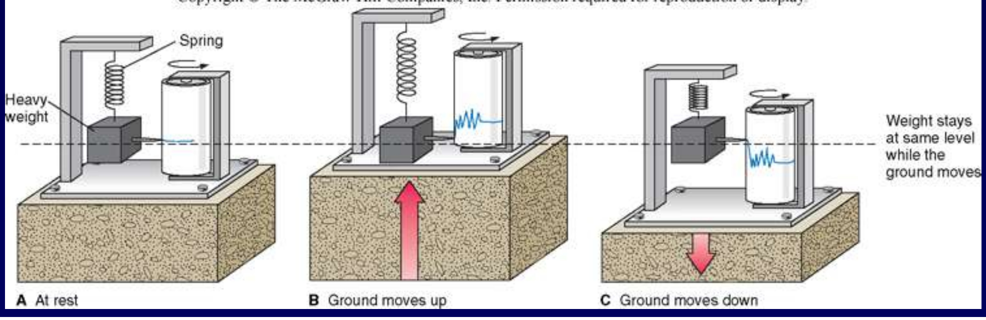
Seismograph

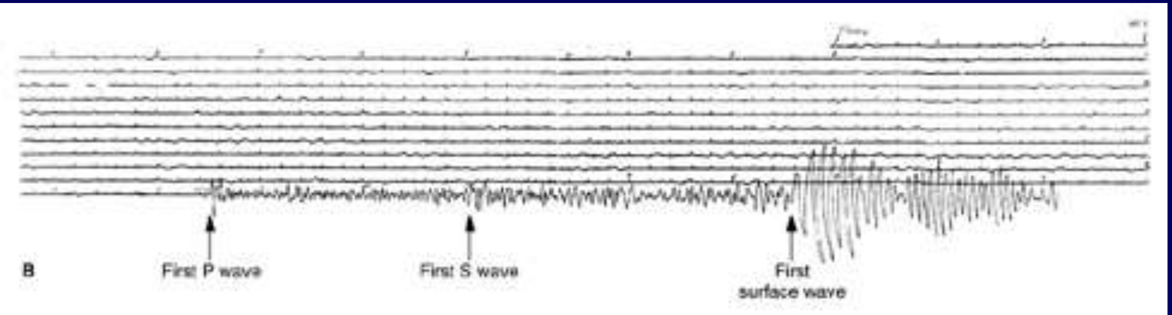


- Vertical and horizontal components

Measuring Earthquakes

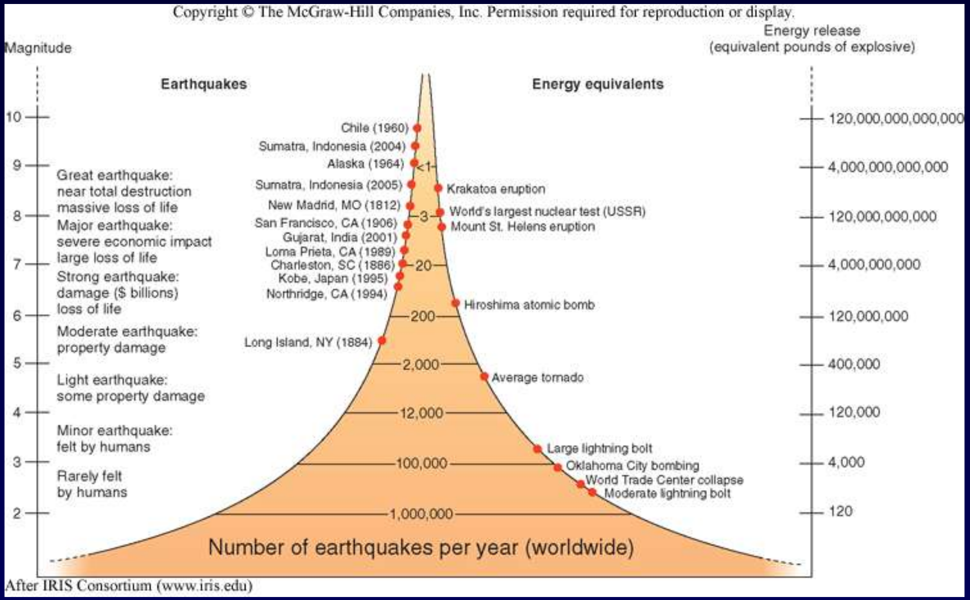
- *Seismometers* - used to measure seismic waves
- *Seismographs* - recording devices used to produce a permanent record of the motion detected by seismometers
- *Seismograms* - permanent paper (or digital) records of the earthquake vibrations
  - Used to measure the earthquake strengths



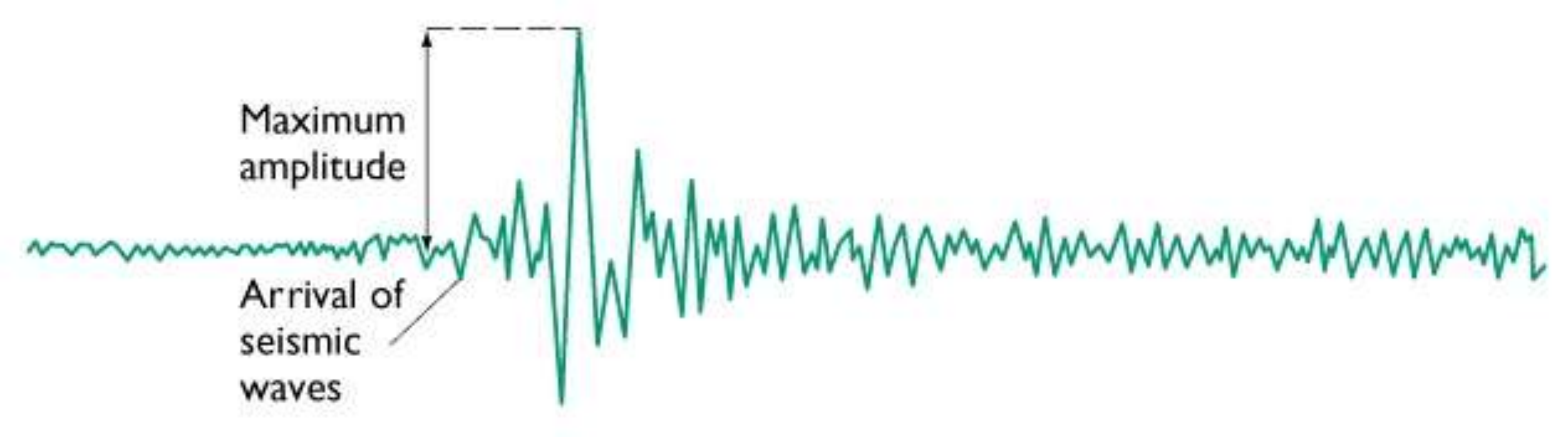


Measuring the “Size” of Earthquakes

- Size of earthquakes measured in two ways - *intensity* and *magnitude*
- *Magnitude* is a measure of the amount of energy released by an earthquake
  - ***Richter scale***
- *Moment magnitude* - more objective measure of energy released by a major earthquake
  - **Uses rock strength, surface area of fault rupture, and amount of movement**
  - ***Smaller earthquakes are more common than larger ones***

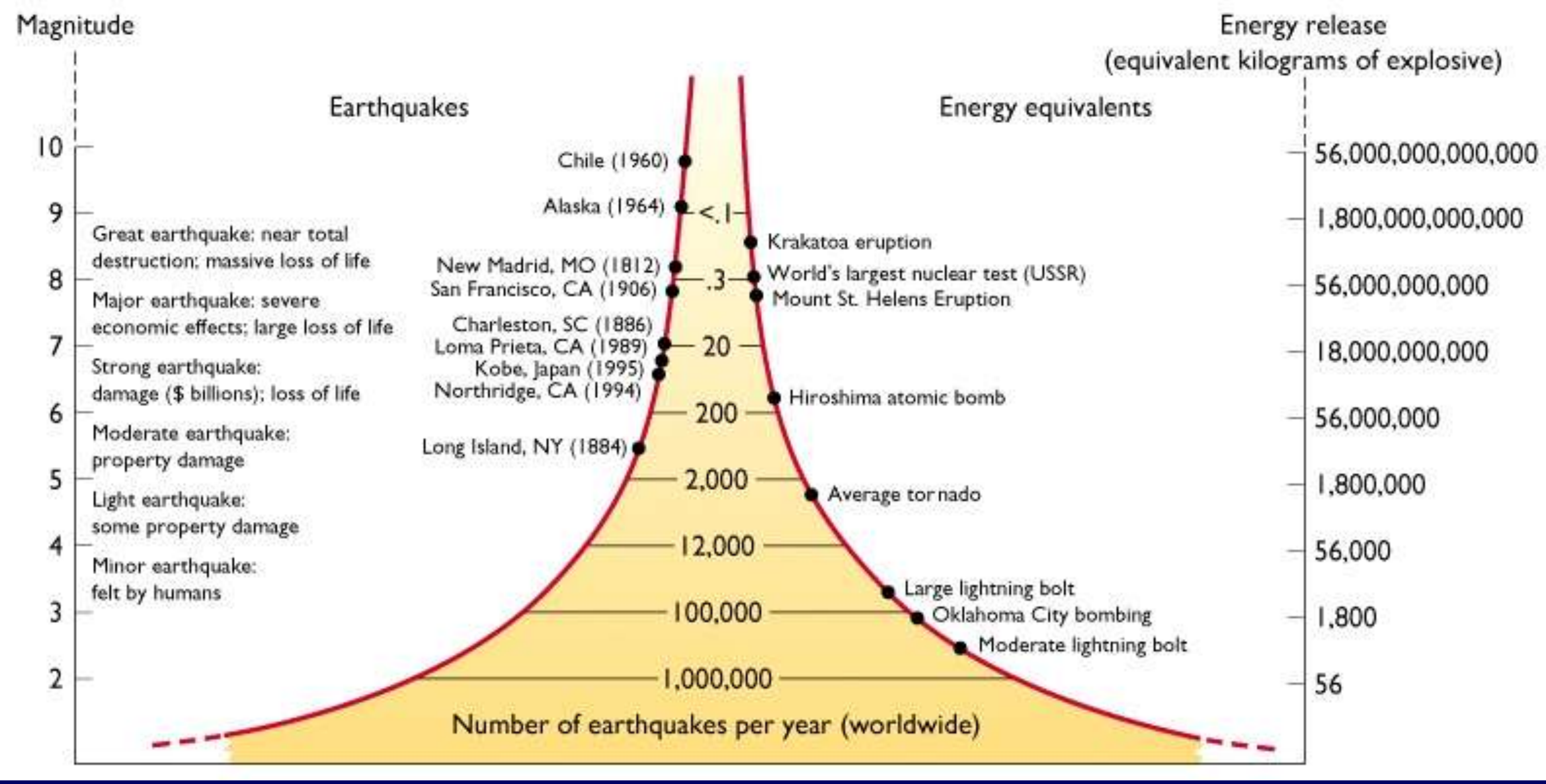


Measures of size (magnitude)



- Richter (measure of ground motion)
- Moment (measure of energy released at focus)
- Modified Mercalli (damage)

Energy release



Earthquake Magnitude

- Measured by a seismograph
- Richter magnitude scale most common
- Richter scale is logarithmic
  - An earthquake of magnitude 4 causes 10 times more ground movement as one of magnitude 3
  - The energy released by an earthquake of magnitude 4 releases about 30 times more energy than an earthquake of magnitude 3

TABLE 4.2

Frequency of Earthquakes of Various Magnitudes

Descriptor	Magnitude	Number per Year	Approximate Energy Released (ergs)
great	8 and over	1 to 2	over 5.8×10^{23}
major	7–7.9	18	$2–42 \times 10^{22}$
strong	6–6.9	120	$8–150 \times 10^{20}$
moderate	5–5.9	800	$3–55 \times 10^{19}$
light	4–4.9	6200	$1–20 \times 10^{18}$
minor	3–3.9	49,000	$4–72 \times 10^{16}$
very minor	<3	[mag. 2–3 about 1000/day]	below 4×10^{16}
		[mag. 1–2 about 8000/day]	

Source: Frequency data and descriptors from National Earthquake Information Center.

Note: For every unit increase in Richter magnitude, ground displacement increases by a factor of 10, while energy release increases by a factor of 30. Therefore, most of the energy released by earthquakes each year is released not by the hundreds of thousands of small tremors, but by the handful of earthquakes of magnitude 7 or larger.

Earthquake Intensity

- Measures the impact of an earthquake event on humans and surface features
- Many local factors are considered such as local geology, construction practices, and distance to the epicenter
- Modified Mercalli Intensity Scale is widely used in the United States
- Intensities are reported as roman numerals ranging from I (for ‘not felt’) to XII, for (‘damage nearly total’)

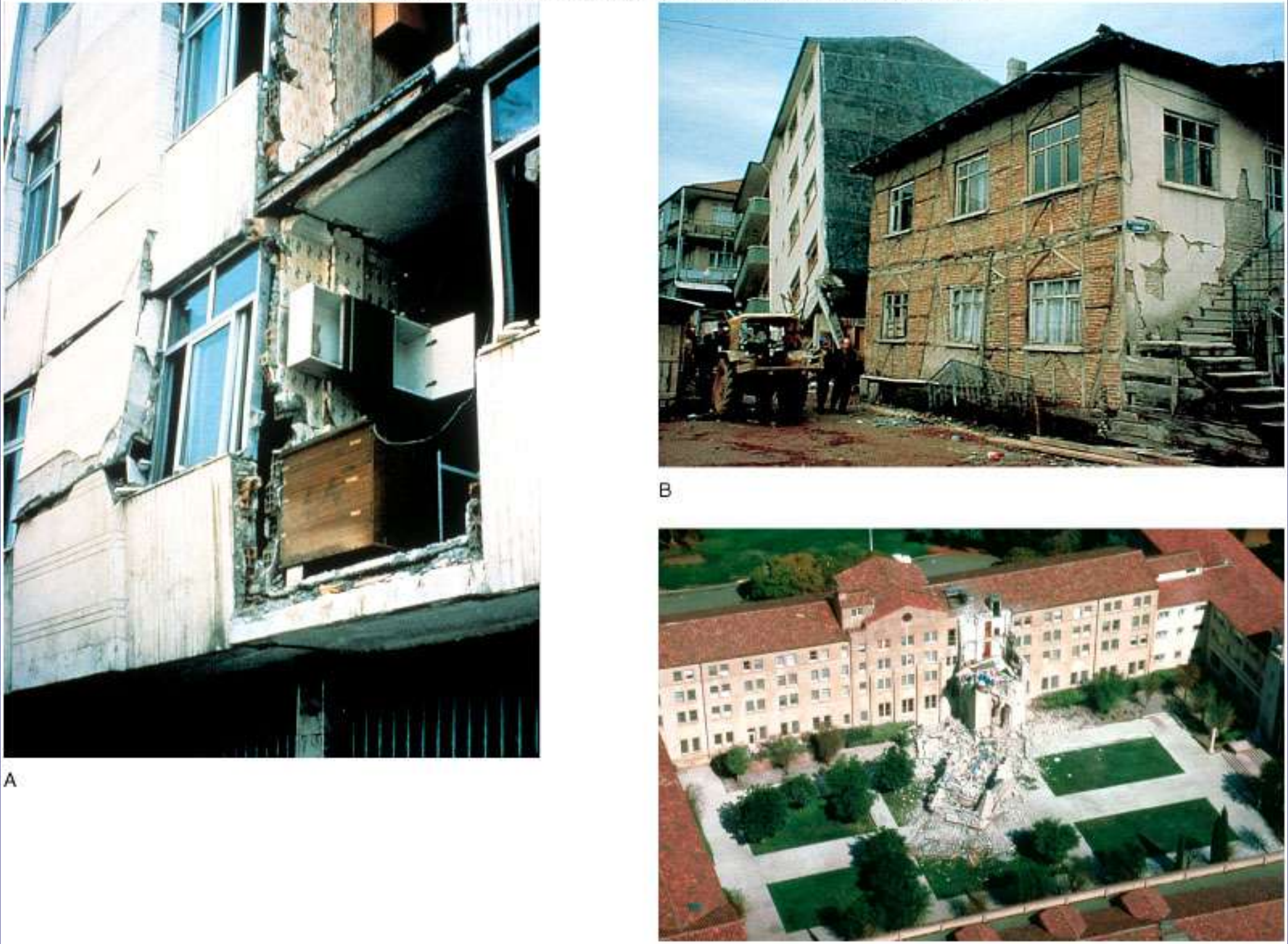
Modified Mercalli Intensity Scale (abridged)

Intensity	Description
I	Not felt.
II	Felt by persons at rest on upper floors.
III	Felt indoors—hanging objects swing. Vibration like passing of light trucks.
IV	Vibration like passing of heavy trucks. Standing automobiles rock. Windows, dishes, and doors rattle; wooden walls or frame may creak.
V	Felt outdoors. Sleepers wakened. Liquids disturbed, some spilled; small objects may be moved or upset; doors swing; shutters and pictures move.
VI	Felt by all; many frightened. People walk unsteadily; windows and dishes broken; objects knocked off shelves, pictures off walls. Furniture moved or overturned; weak plaster cracked. Small bells ring. Trees and bushes shaken.
VII	Difficult to stand. Furniture broken. Damage to weak materials, such as adobe; some cracking of ordinary masonry. Fall of plaster, loose bricks, and tile. Waves on ponds; water muddy; small slides along sand or gravel banks. Large bells ring.
VIII	Steering of automobiles affected. Damage to and partial collapse of ordinary masonry. Fall of chimneys, towers. Frame houses moved on foundations if not bolted down. Changes in flow of springs and wells.
IX	General panic. Frame structures shifted off foundations if not bolted down; frames cracked. Serious damage even to partially reinforced masonry. Underground pipes broken; reservoirs damaged. Conspicuous cracks in ground.
X	Most masonry and frame structures destroyed with their foundations. Serious damage to dams and dikes; large landslides. Rails bent slightly.
XI	Rails bent greatly. Underground pipelines out of service.
XII	Damage nearly total. Large rock masses shifted; objects thrown into the air.

Earthquake-Related Hazards

- Ground shaking: ground shaking and movement along the fault are obvious hazards
- Considering both structures and bedrocks
- Designing “earthquake-resistant” buildings
- Knowing the characteristics of the earthquakes in a particular region
- The best building codes are typically applied only to new construction
- Liquefaction and Landslides can be a serious secondary earthquake hazard in hilly areas

Figures 4.10 a, b, and c



A

B

C

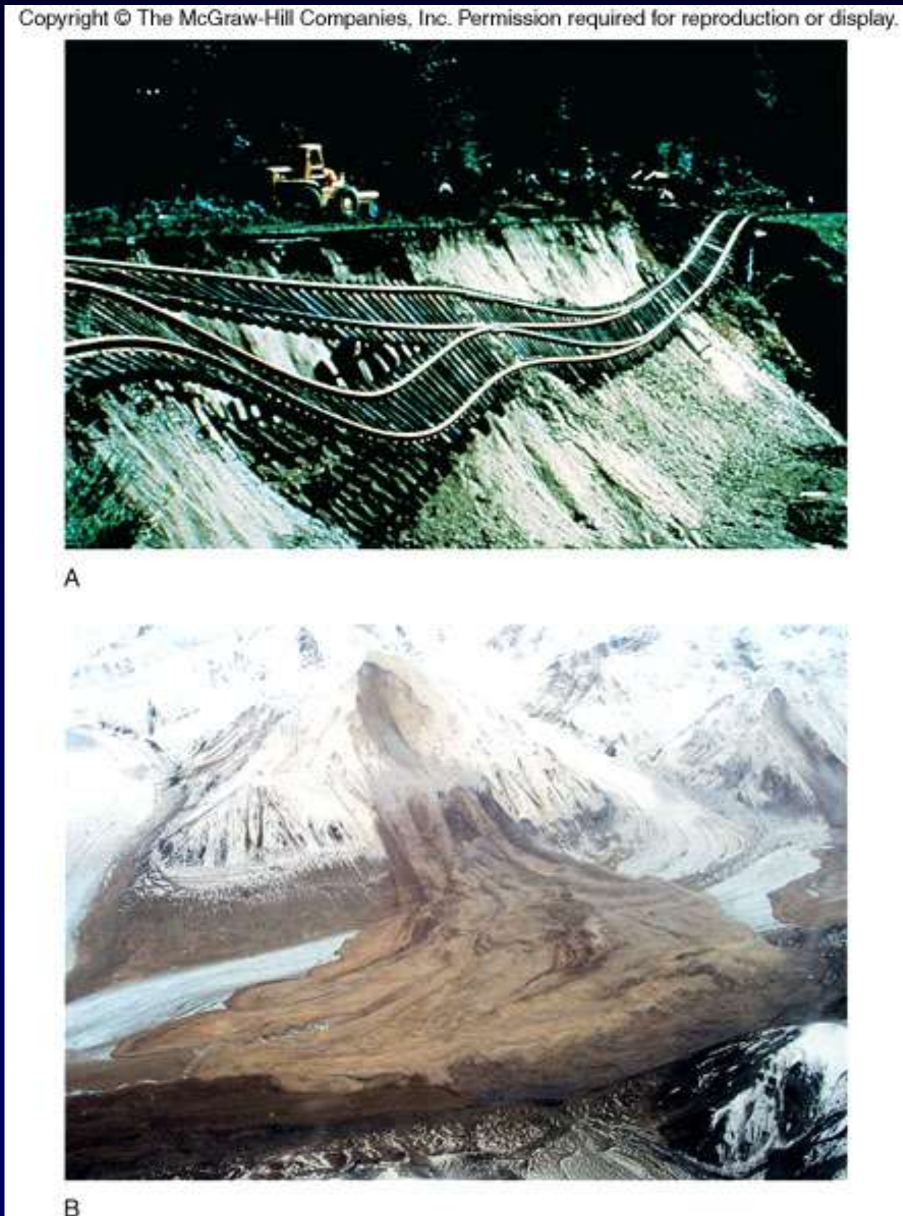
Figure 4.11

A

B

Figure 4.12 and Figure 4.13

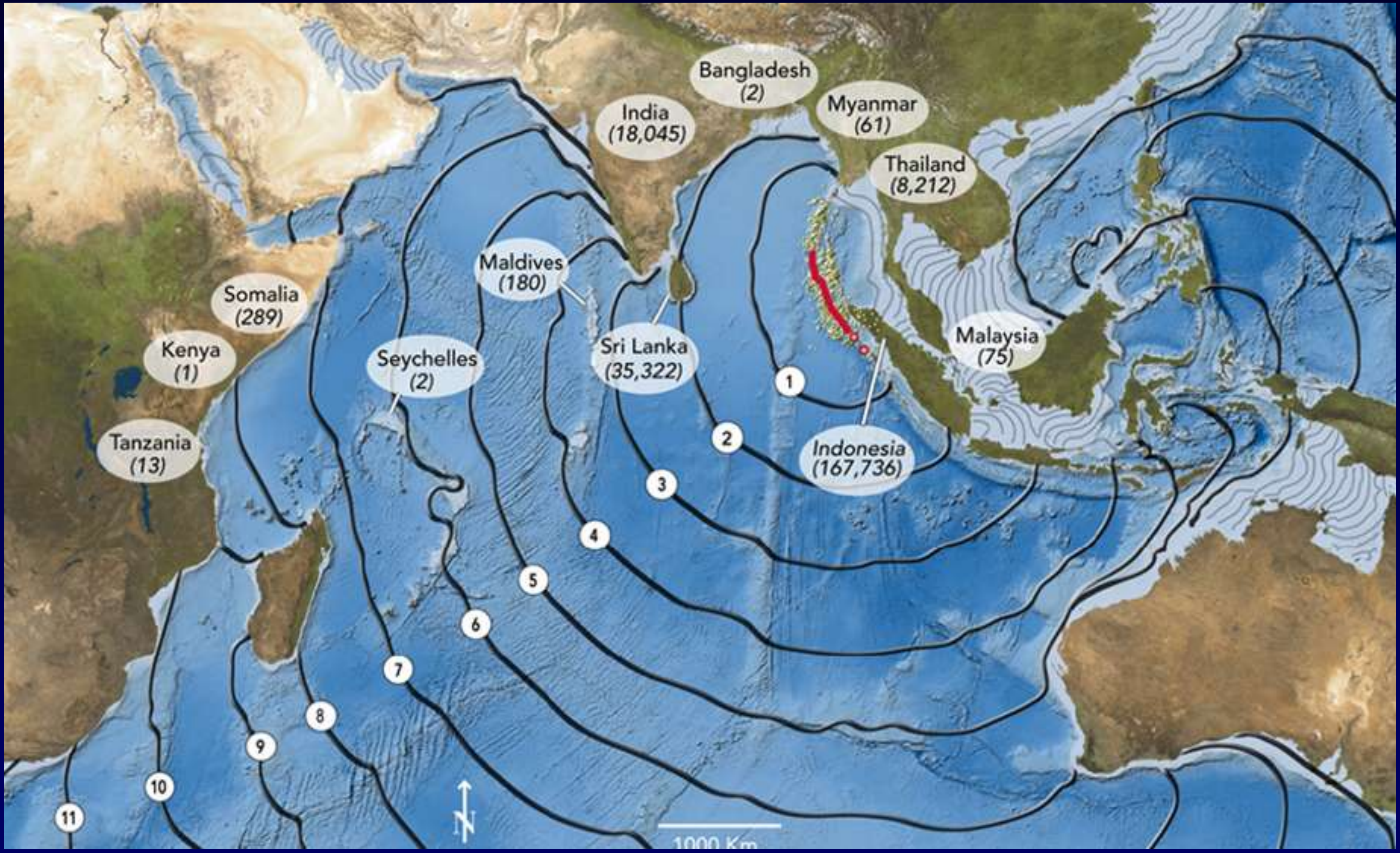
Figure 4.16 and Figure 4.17



Tsunami and Coastal Effects

- Tsunamis are seismic sea waves. When an undersea or near-shore earthquake occurs, sudden movement of the sea floor may set up waves traveling away from that spot, like ripples in a pond caused by a dropped pebble
- Other Coastal Effects
- Fire is caused by broken gas lines and infrastructure
- Downed power lines

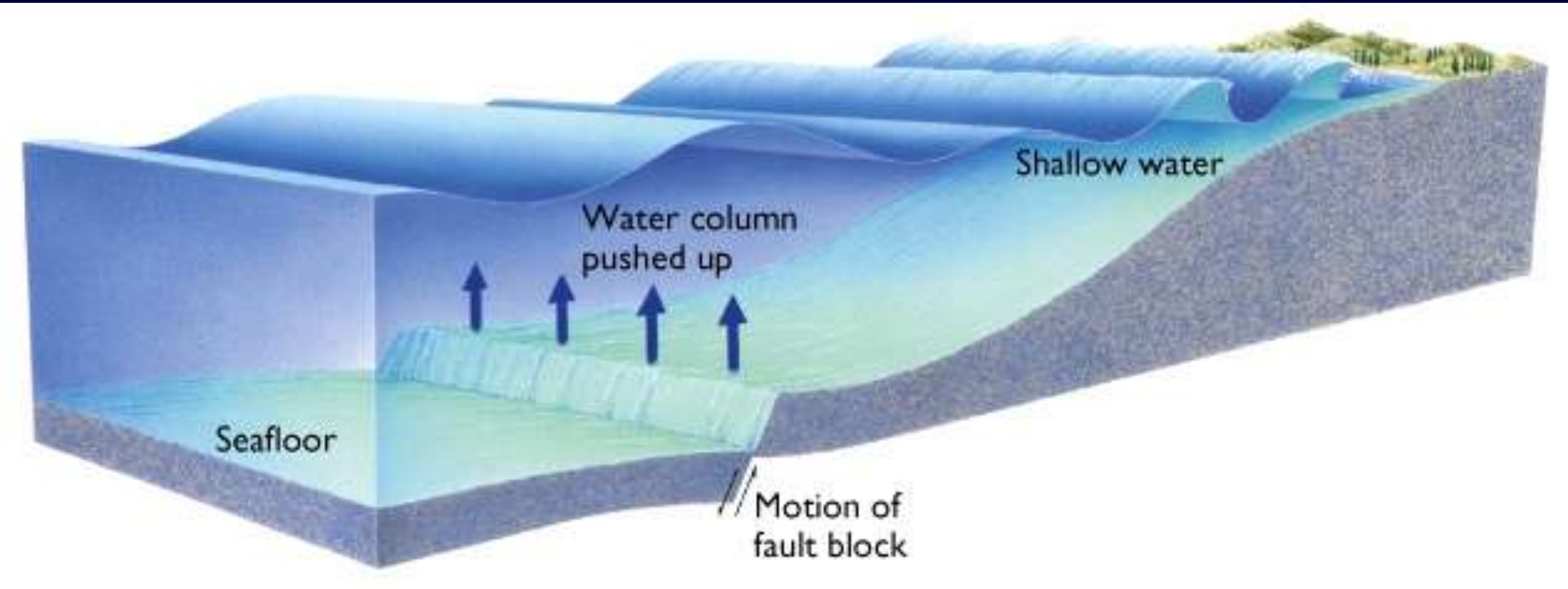
Indonesian Earthquake and Tsunami



Number of deaths and missing shown in ovals

12.00.a1

Tsunamis and other phenomena

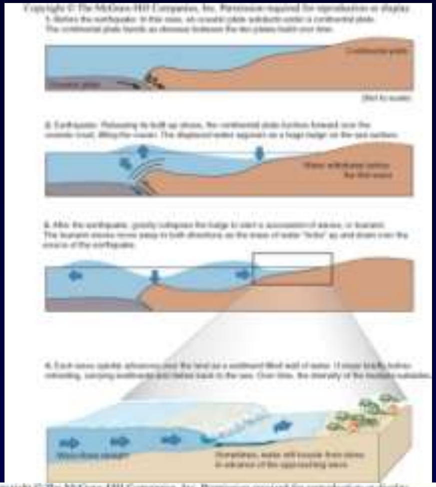


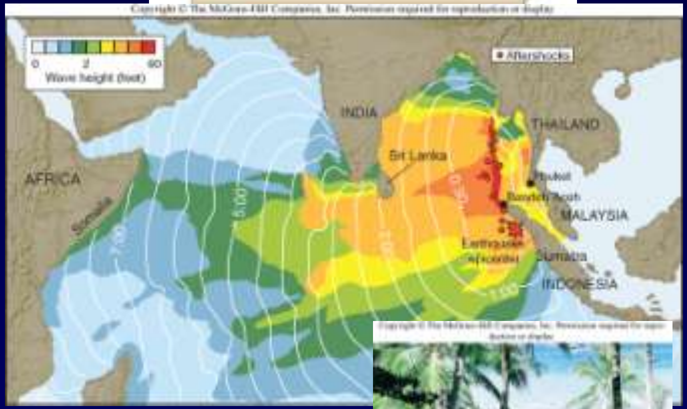
Indonesian Earthquake and Tsunami

Destruction of Banda Aceh

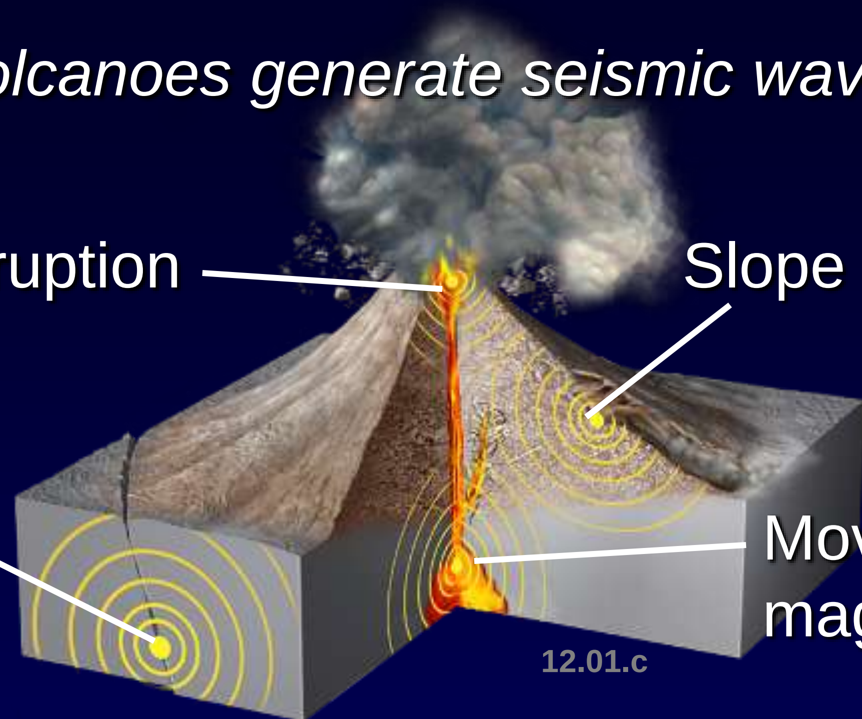
Tsunami

- ***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

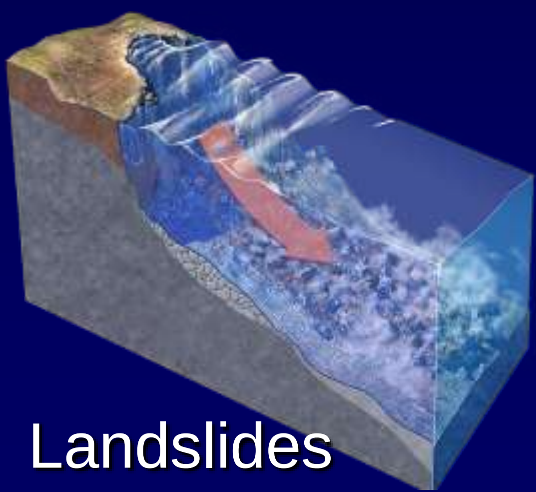




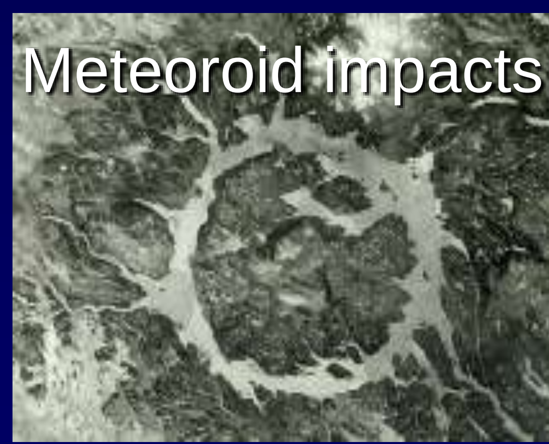
How could volcanoes generate seismic waves?

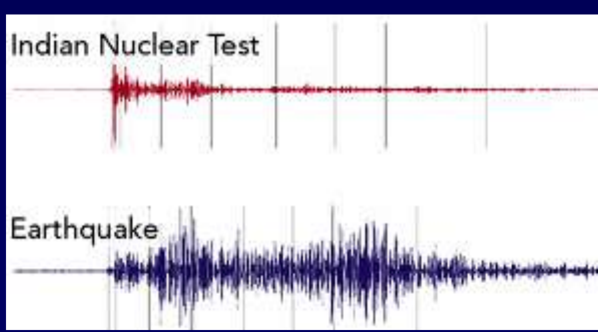


What else can cause seismic waves?

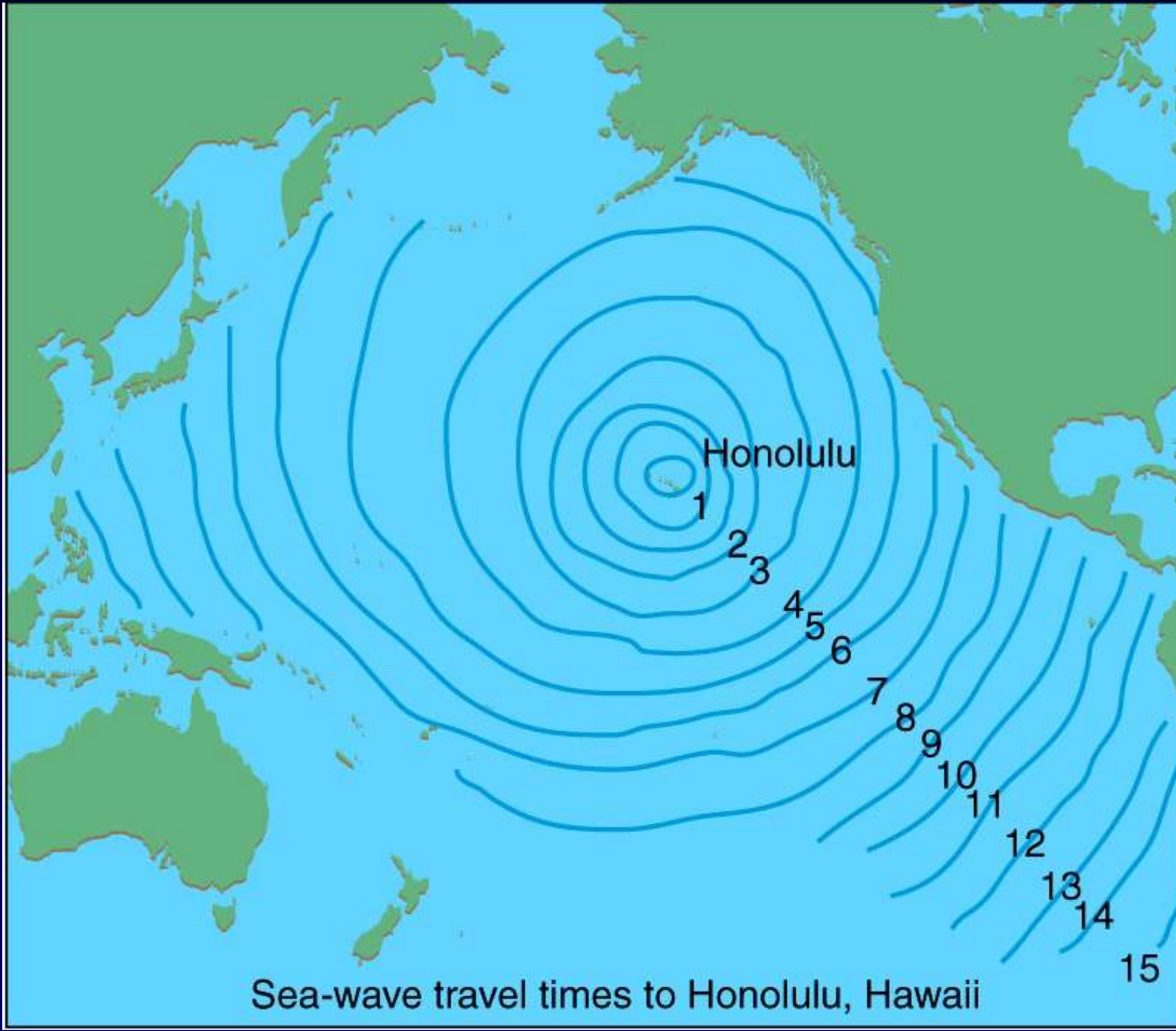


Landslides





Explosions


Honolulu
1
2
3
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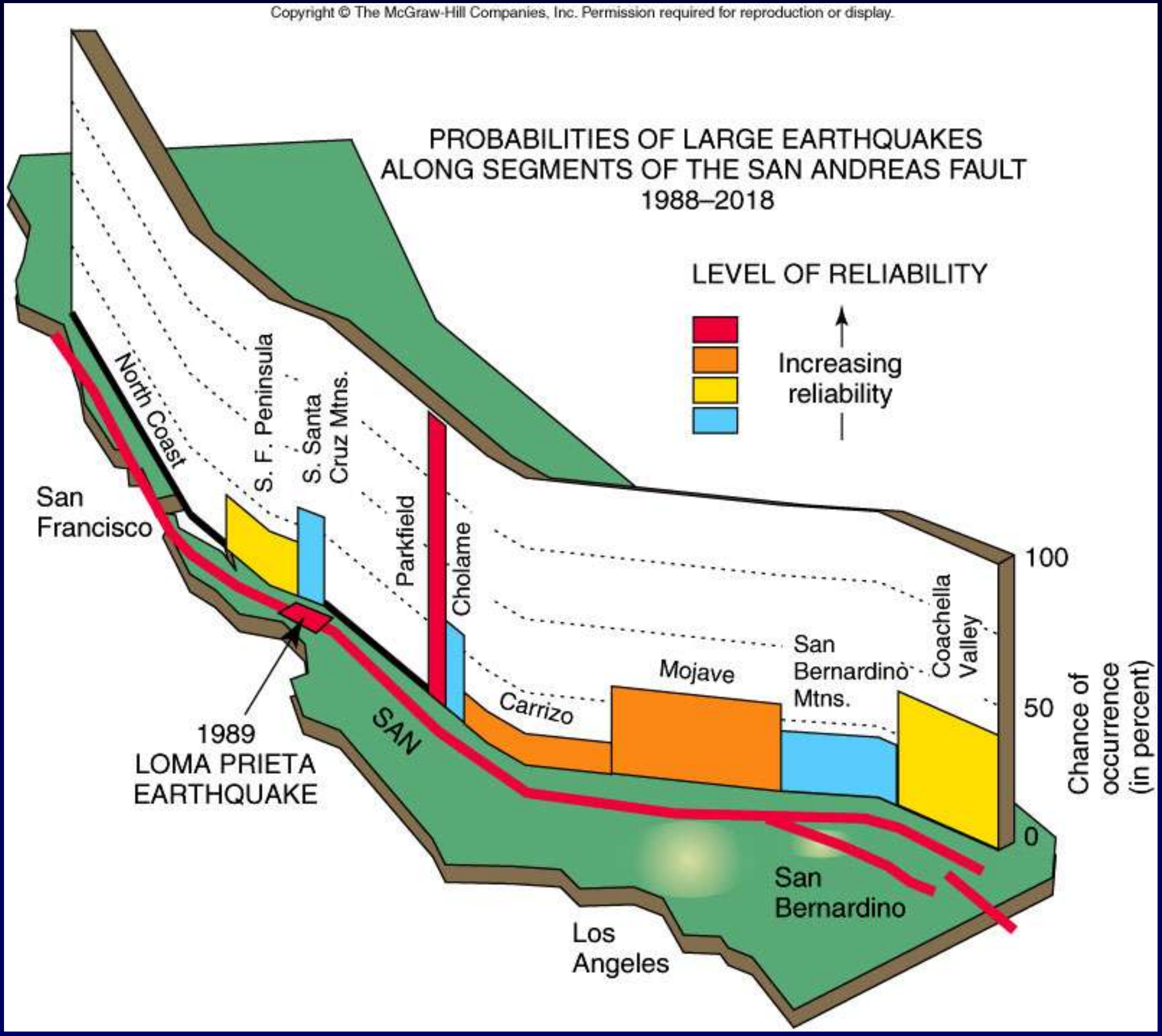
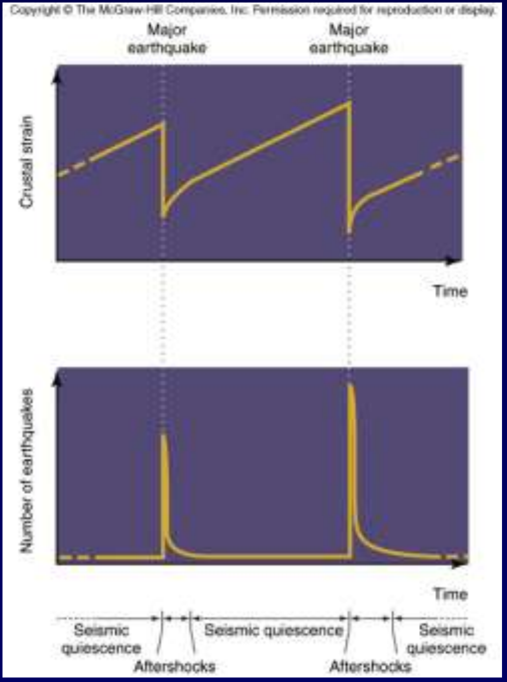
14
15
Sea-wave travel times to Honolulu, Hawaii

Predication and Forecasting

- Seismic gaps: quiescent (dormant) sections of fault zones with little or no seismic activity along major faults
- Seismic gaps are “locked” segments of faults along which friction is preventing slip
- Seismic gaps may be sites of future serious earthquakes. Large earthquakes may be expected in the future
- Precursors: uplifted and tilted ground surface, change of seismic-wave velocities, change of electrical resistivity, change of water table, and change of radon
- Prediction: problematic, unreliable
- Forecasting: who knows?

Figures 4.25, 4.21, and 4.23





Earthquake Control

- Fluid injection: fluids in fault zones may facilitate movement along a fault.
- Fluid injection: might be used along locked sections of major faults to allow the release of built-up stress through small earthquakes
- However, could lead to the release of all the stress at once in a major earthquake
- Better to plan away from earthquake zones

Northridge, CA

Measuring the "Size" of Earthquakes

- Earthquake "size" measured two ways - ***intensity*** and ***magnitude***
- ***Intensity*** - a measure of the *effects* an earthquake produces (on both structures and people)
  - ***Modified Mercalli scale***

Table 16.1

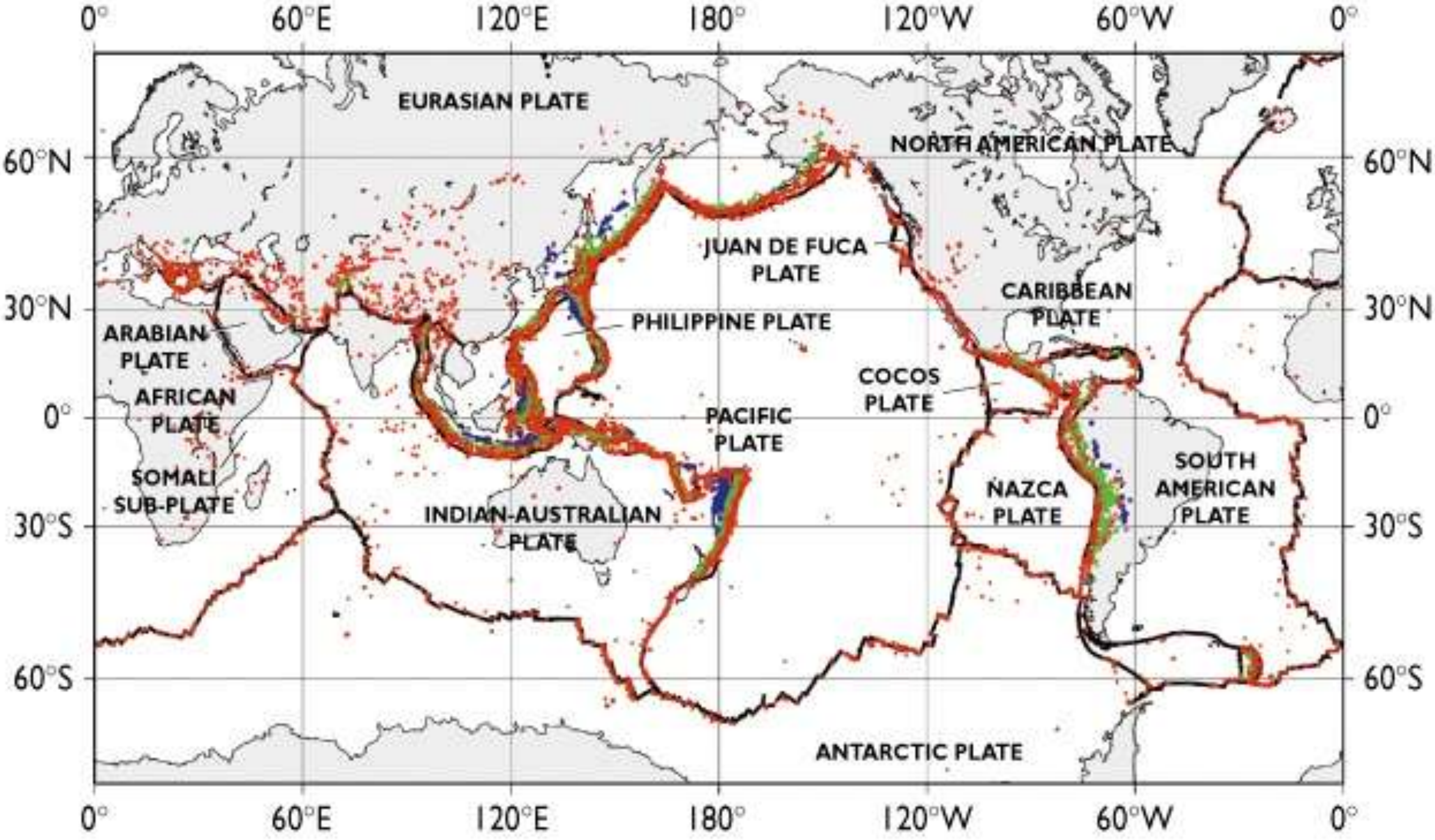
Modified Mercalli Intensity Scale of 1931 (Abridged)

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 (slopped) 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.

From Wood and Neumann, 1931, *Bulletin of the Seismological Society of America*

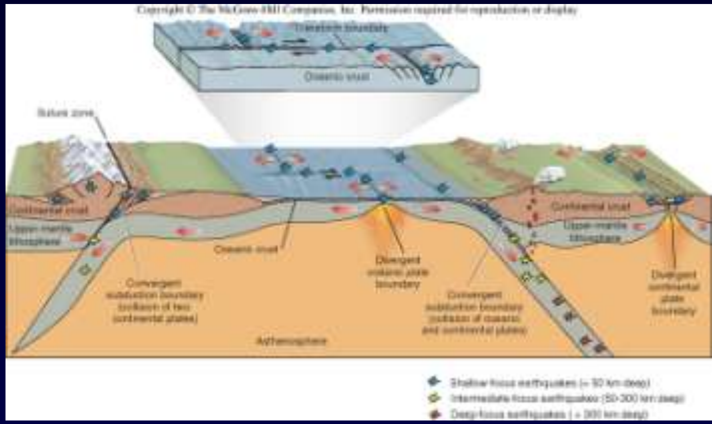
Distribution of seismicity

Shallow, intermediate, and deep earthquakes



Earthquakes and Plate Tectonics

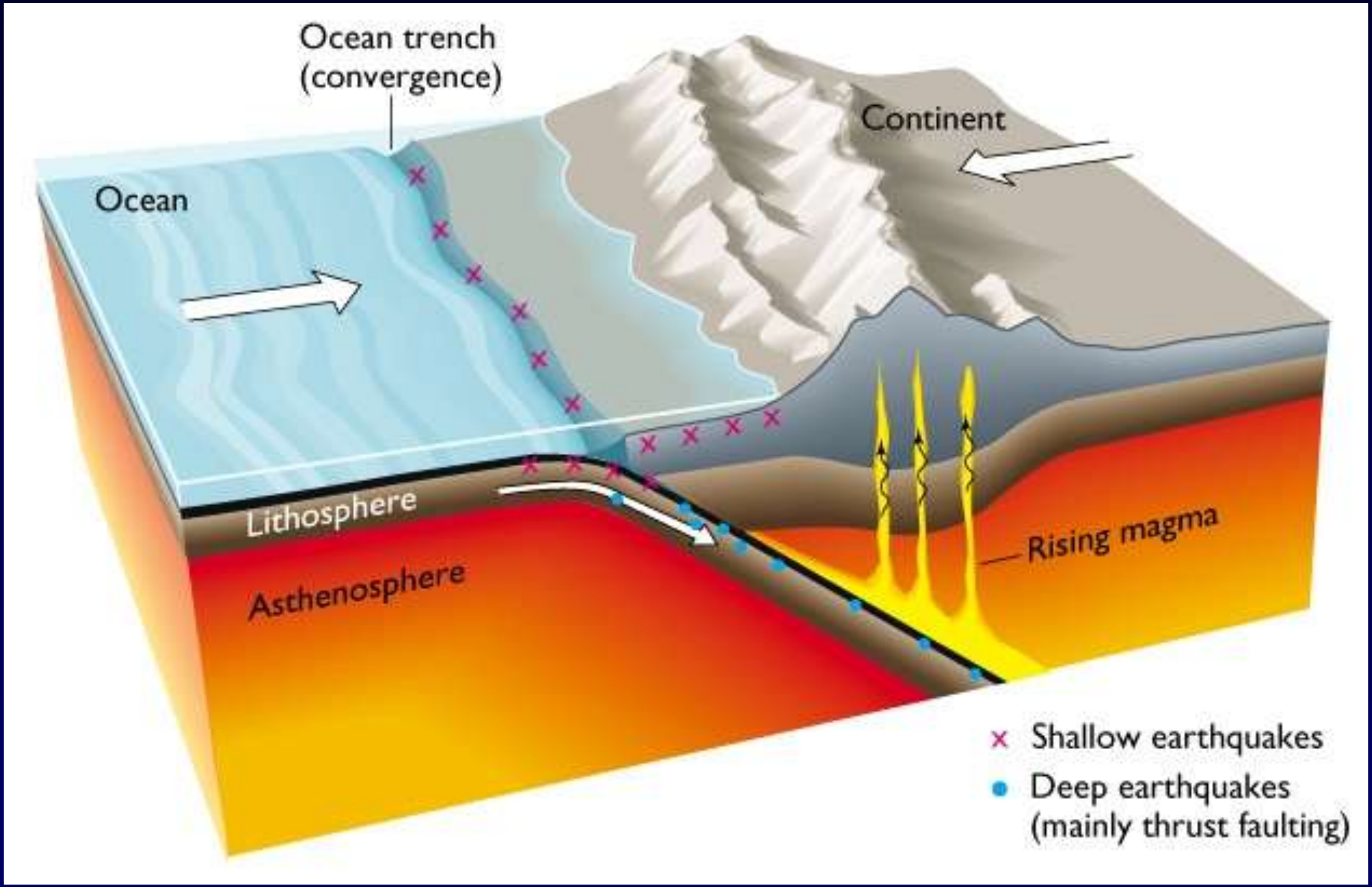
- Earthquakes are caused by plate inter-actions ***along tectonic plate boundaries***
- Plate boundaries are identified and *defined* by earthquakes
- Earthquakes occur at each of the three types of plate boundaries: ***divergent, transform*, and *convergent***
  - At divergent boundaries, ***tensional 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***



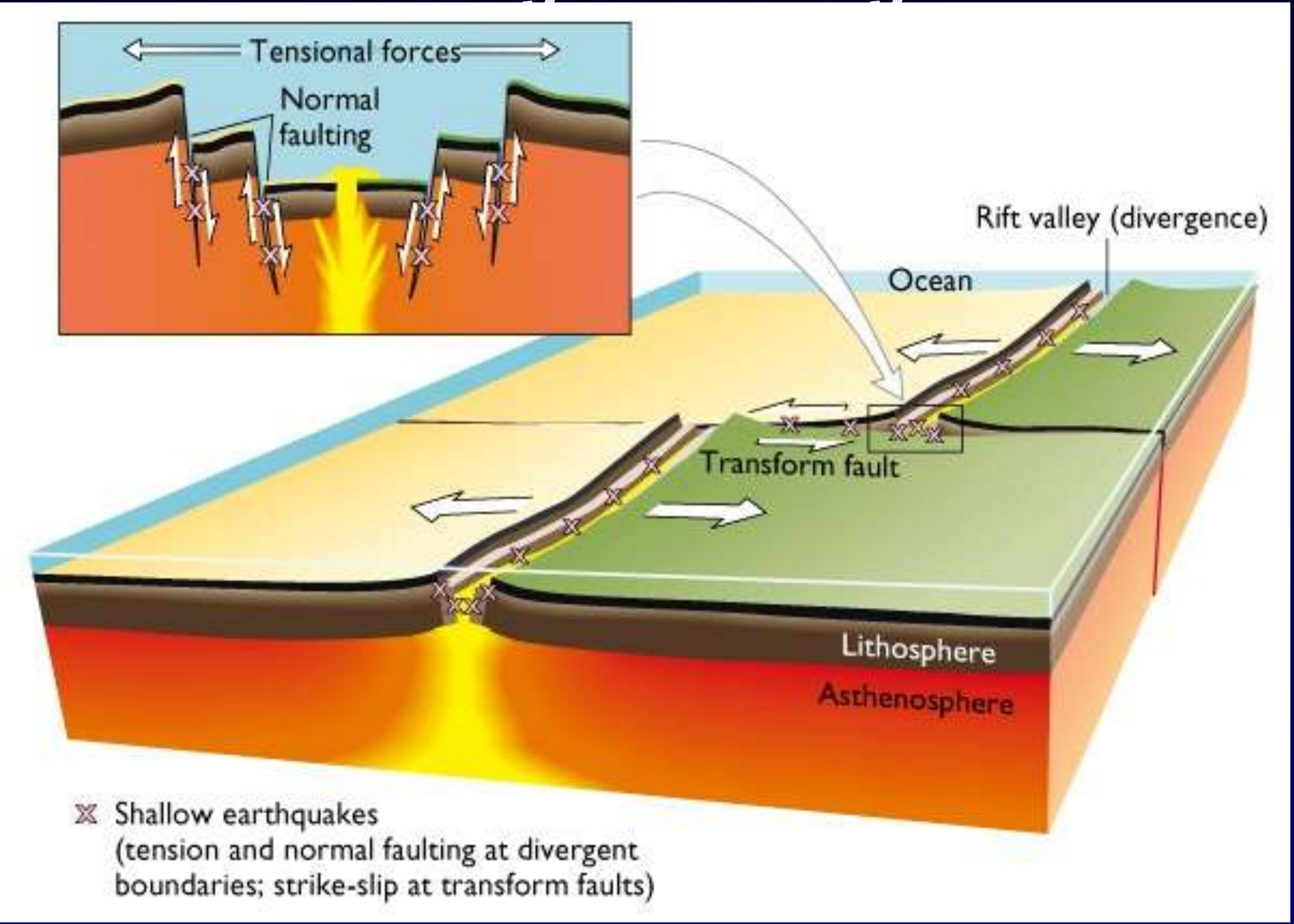
Tectonic Settings

- Convergent boundaries: compressional, shallow and deep
- Divergent boundaries: extensional, shallow only
- Transform: shear, shallow to intermediate

Subduction related Earthquakes

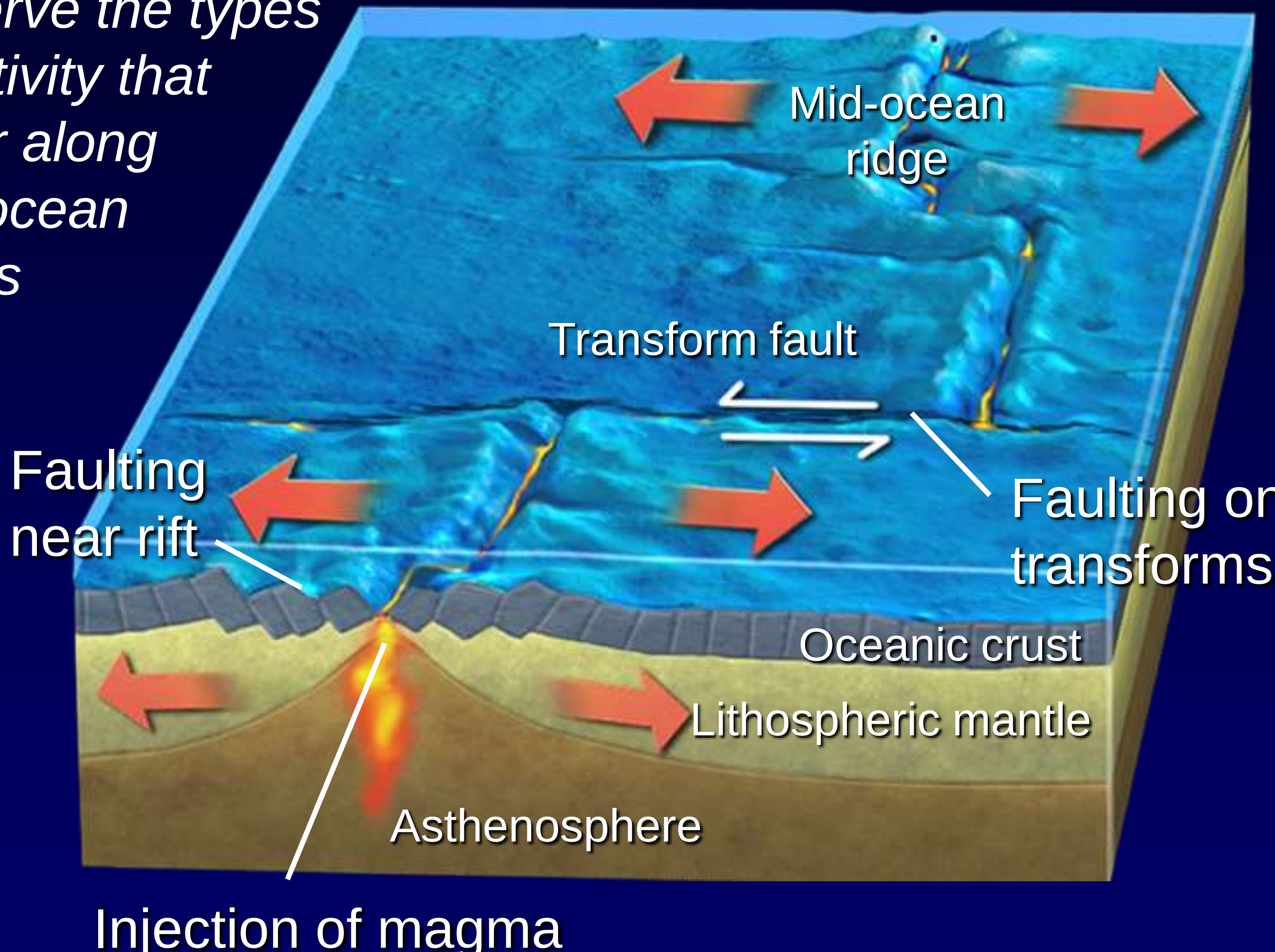


Divergent settings



Earthquakes Along Mid-Ocean Ridges

Observe the types of activity that occur along mid-ocean ridges



12.03.b

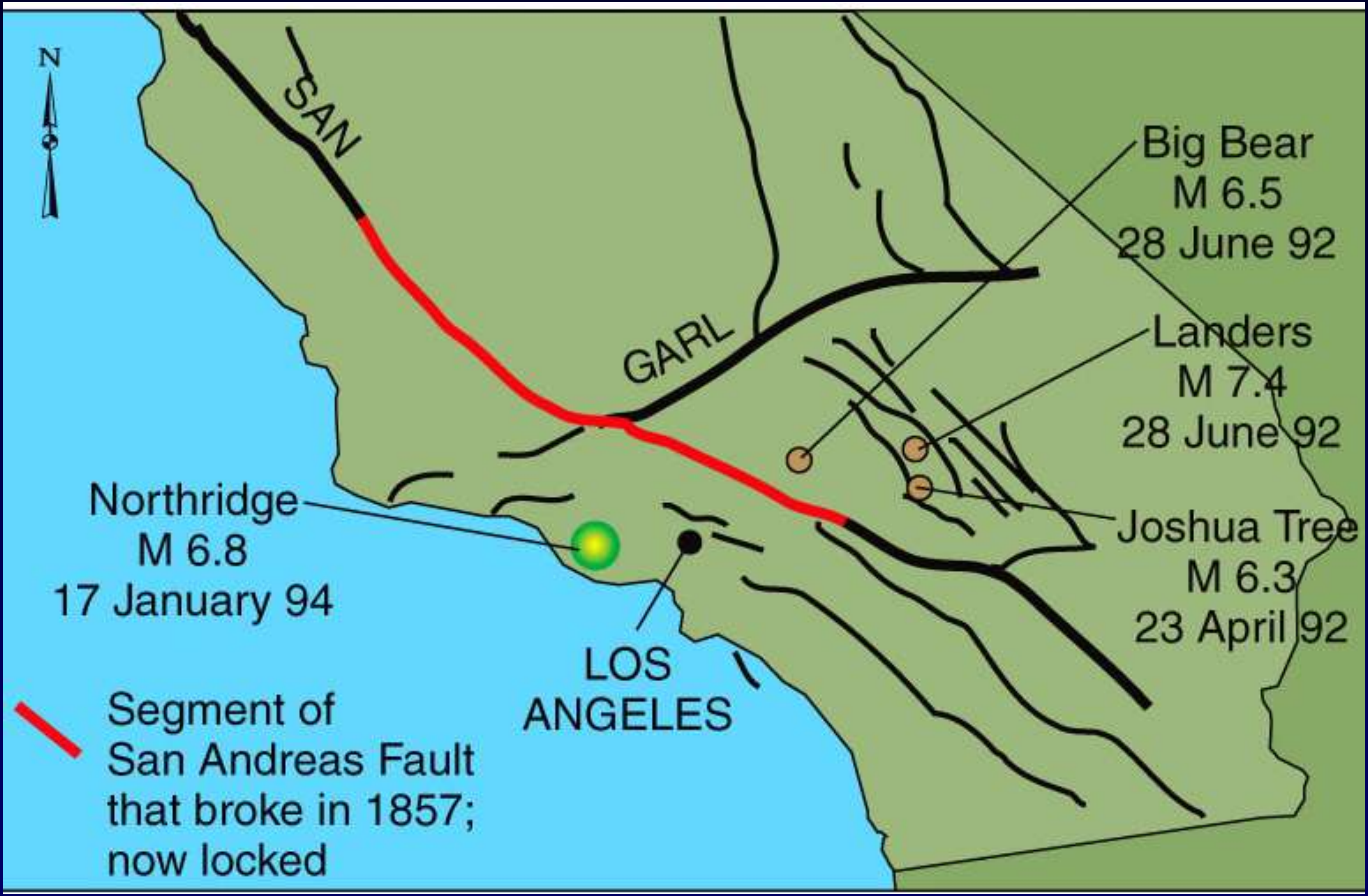


Fig. 4.28 The southern locked segment of the San Andreas Fault

What Is the Earthquake History of the San Andreas Fault and Related Faults?

Black and colored lines: recently active faults

Red: segment ruptured 1906 S.F. earthquake

Blue: creeping segment

Parkfield segment (north end of orange) ruptures every ~20 years

Orange: last fully ruptured in 1857 ("Big One" for L.A.)

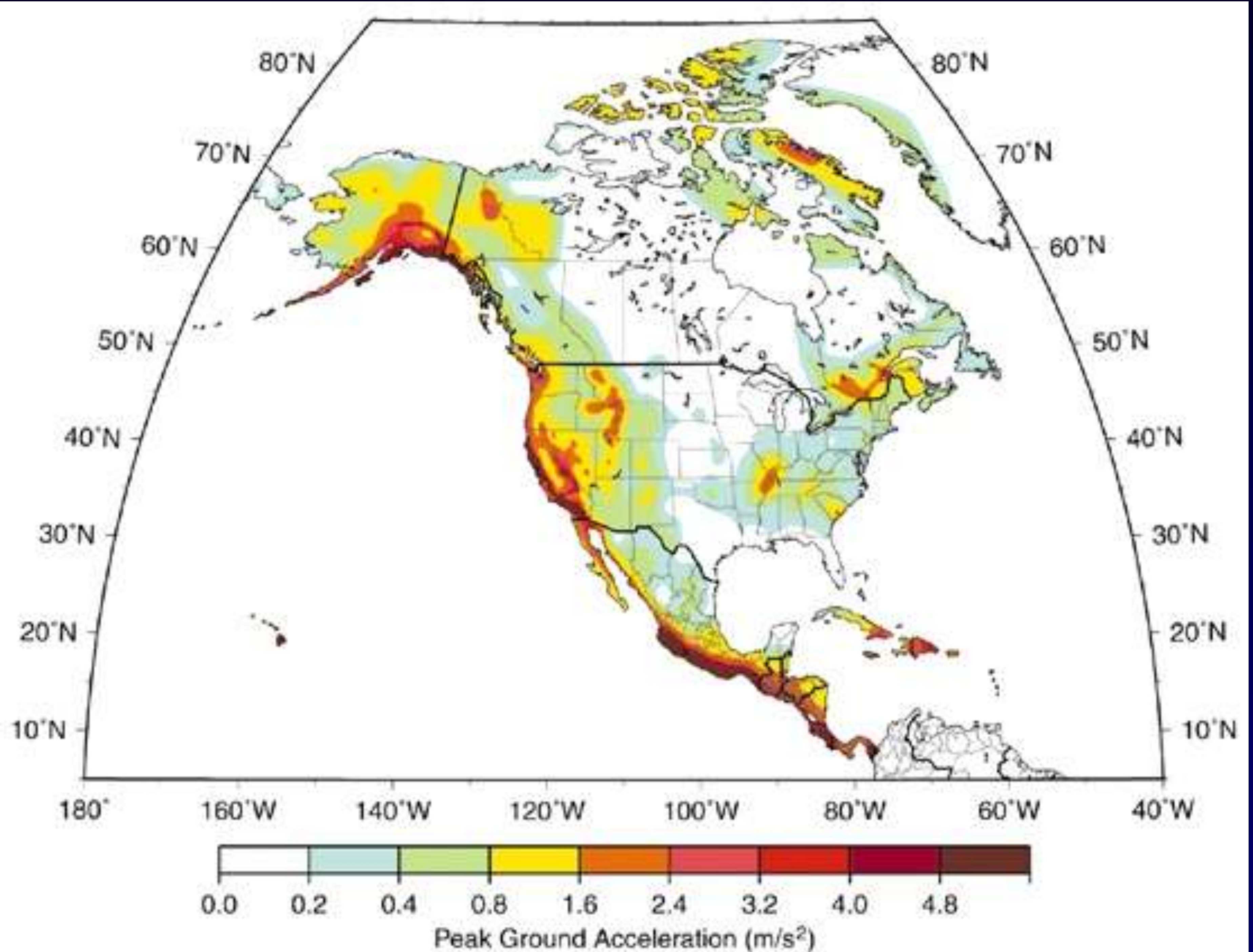
Moderate EQs along eastern zone

12.12.a1

Observe features along the San Andreas fault

12.12.a

Aerial photograph of same area

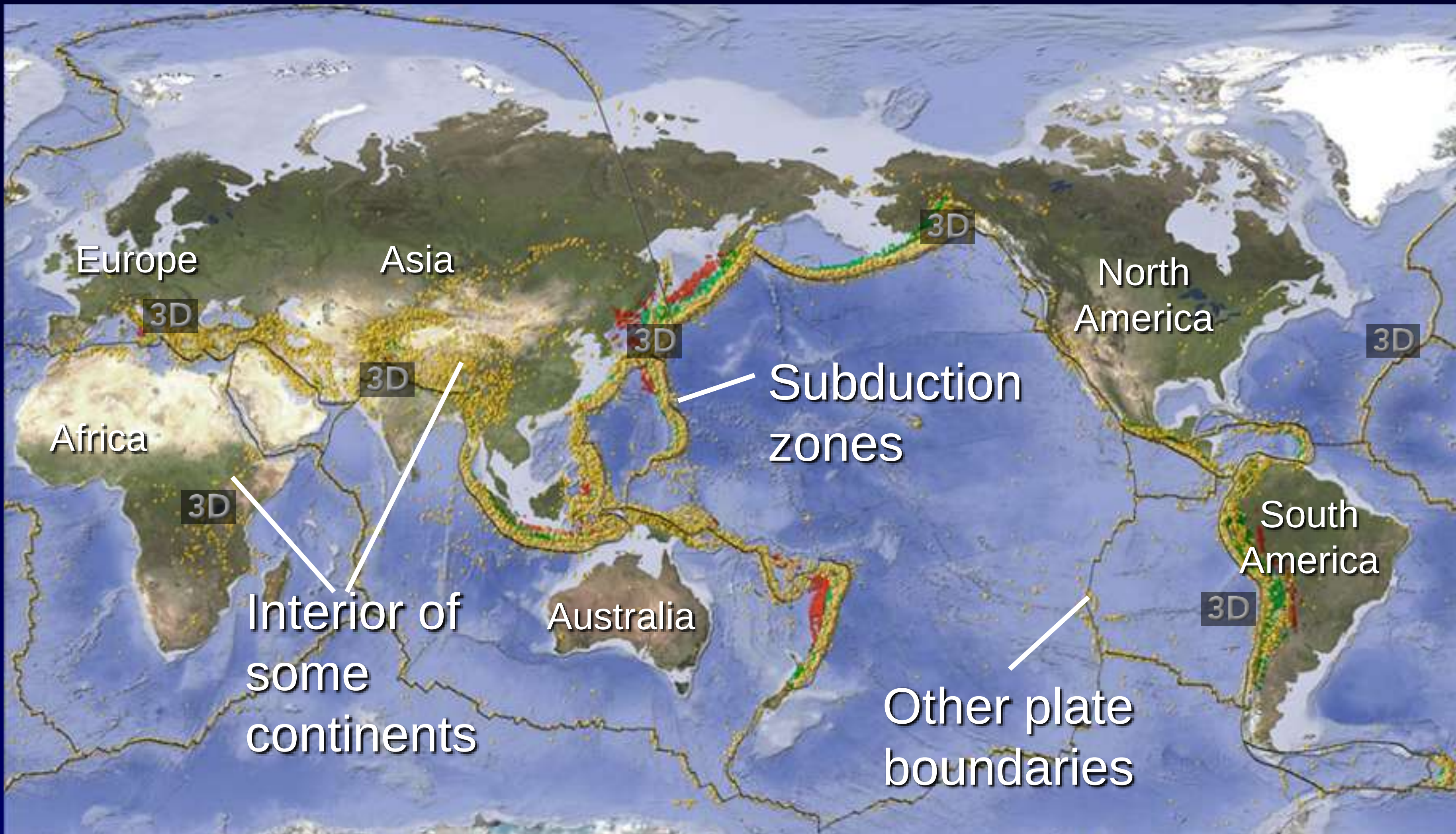


80°N
70°N
60°N
50°N
40°N
30°N
20°N
10°N
180°
160°W
140°W
120°W
100°W
80°W
60°W
40°W
0.0
0.2
0.4
0.8
1.6
2.4
3.2
4.0
4.8
Peak Ground Acceleration (m/s²)

Summary

- Earthquakes are energy release in waves
  - Elastic rebound theory
  - Seismic waves: P, S, and surface (Rayleigh and Love)
- Location and detection
  - Focus, epicenter, link to fault scarps
  - Seismometers and seismographs
  - Location of epicenters using seismic travel times
- Size (magnitude)
  - Richter, Moment magnitude, Modified Mercalli
- Global patterns of earthquake activity
  - Tectonic settings
- Earthquake consequences and prediction
  - Destructiveness, ground motion, and other effects (landslides, tsunamis, fires, building collapse, liquefaction)

Observe where earthquakes occur



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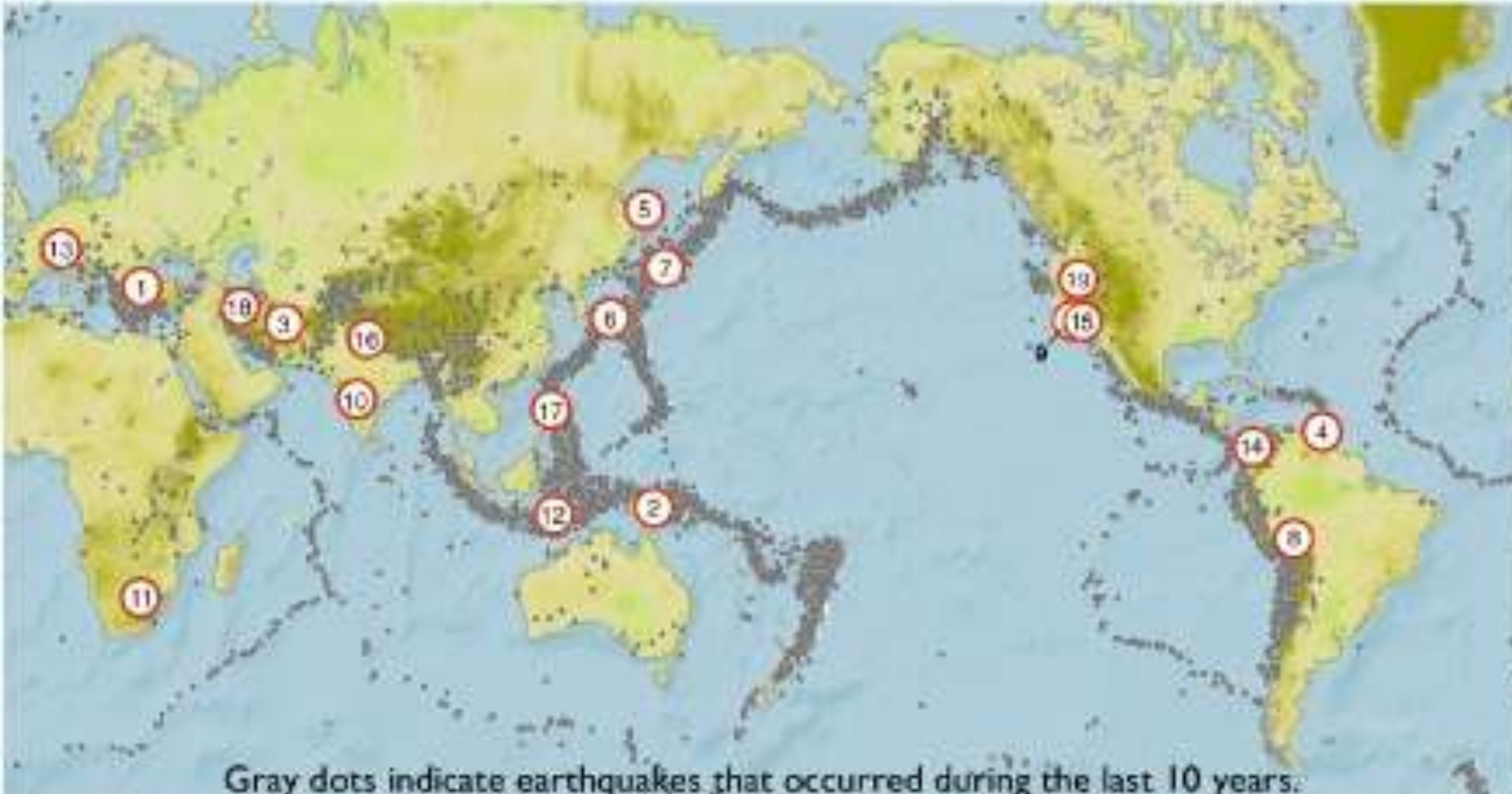
yellow - shallow; green - intermediate; red - deep

3D

Recent Earthquakes of Special Interest



Event	Magnitude	Geologic Changes	Destruction
① **Izmit, Turkey** August 1999	7.4	Seventh in a series since 1939; migrating westward along the strike-slip North Anatolian fault; maximum right-lateral displacement of 5 m	15,000 killed, thousands missing
② **Papua New Guinea** July 1998	7.0	Tsunami as high as 7 m	3000 killed, several villages destroyed
③ **Northern Iran** May–June 1997	7.3	Landslides; rare sequence of large earthquakes	1567 killed, 2300 injured, 50,000 homeless, extensive damage
④ **Windward Islands** April 1997	6.7	One of the largest known earthquakes in or near Trinidad and Tobago	None reported
⑤ **Sakhalin Island** May 1995	7.5	None noted	1989 killed, 750 injured
⑥ **Kobe, Japan** January 1995	6.8	Surface faulting for 9 km with horizontal displacement of 1.2 to 1.5 m; soil liquefaction	5502 killed, 36,896 injured, 310,000 homeless, severe damage
⑦ **Kuril Islands** October 1994	8.3	Tsunami as high as 346 cm	10 killed or missing, extensive damage throughout islands
⑧ **Northern Bolivia** June 1994	8.2	At 637 km depth, the largest deep earthquake; first earthquake from this part of South America to have been felt in North America including Canada	Several people killed
⑨ **Northridge, CA** January 1994	6.8	A maximum uplift of 15 cm occurred in Santa Susana Mountains; many rock slides; ground cracks; soil liquefaction	60 killed, 7000 injured, 20,000 homeless, severe damage
⑩ **Southern India** September 1993	6.3	Large intraplate earthquake	9748 killed, 30,000 injured, extreme devastation
⑪ **Republic of South Africa** May 1993	3.8	Event related to mine collapse	Several people killed
⑫ **Flores region** December 1992	7.5	Tsunami run-up of 300 m with wave heights of 25 m on Flores; landslides; ground cracks	2200 killed or missing

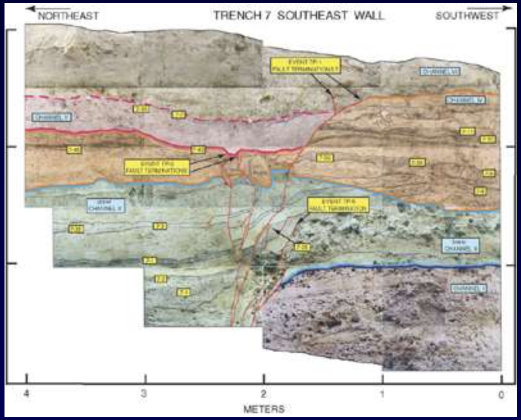
⑬ **Switzerland** November 1992	3.7	Accidental explosion of a munitions cavern	6 killed
⑭ **Northern Colombia** October 1992	7.3	Explosion of a mud volcano; landslides; soil liquefaction; small island emerged from the Caribbean Sea off San Juan de Uraba	10 killed, 65 injured, 1500 homeless
⑮ **Landers, CA** June 1992	7.6	Surface faulting along a 70-km segment with as much as 5.5 m of horizontal displacement and 1.8 m of vertical displacement	1 killed, 400 injured, substantial damage
⑯ **Northern India** October 1991	7.0	Two events 1.6 s apart; landslides; 30-m-deep crack	2000 killed, 1800 injured, 18,000 buildings destroyed
⑰ **Luzon, Philippines** July 1990	7.8	Landslides; soil liquefaction; surface faulting	1621 killed, 3000 injured, severe damage
⑱ **Western Iran** June 1990	7.7	Landslides	40,000–50,000 killed, 60,000 injured, 400,000+ homeless, extensive damage
⑲ **Loma Prieta, CA** October 1989	7.1	Maximum intensity in parts of Oakland and San Francisco; landslides; soil liquefaction; small tsunami at Monterey	60 killed, 3757 injured; U.S.$5.6 billion in damage

SOURCE: After IRIS Consortium: www.iris.edu

Earthquake Prediction and Seismic Risk

- Accurate and consistent short-term earthquake prediction not yet possible, three methods assist in determining probability that an earthquake will occur:
  - Measurement of changes **in *rock properties*,** such as magnetism, electrical resistivity, seismic velocity, and porosity, which may serve as ***precursors*** to earthquakes
  - Studies of the ***slip rate*** along fault zones
  - ***Paleoseismology*** studies that determine where and when earthquakes have occurred and their size

    Average intervals between large earthquakes and the time since the last one occurred can also be used to assess the risk (over a given period of time) that a large quake will occur

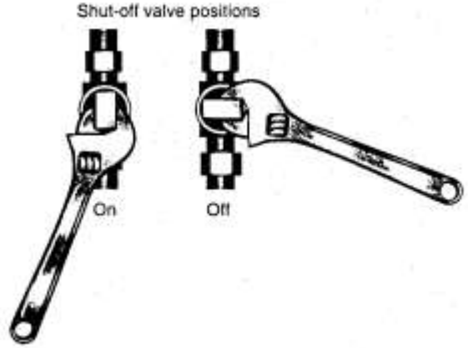


From U.S. Geological Survey

Earthquake Safety

1. Nail plywood to ceiling joists to protect occupants from falling chimney bricks.
2. Anchor hanging lamps with closed hooks or relocate.
3. Secure top-heavy furniture to wall studs with metal braces.
4. Keep all breakables in low or secure cabinets.
5. Know the locations of main electrical and gas switches for emergency shutoff.
6. Stabilize water heater with metal straps to wall studs.
7. Use flexible connectors where gas lines meet appliances, if local codes permit.
8. Keep fire extinguisher in accessible place.
9. Keep emergency supplies on hand, including drinking water, canned or dried foods, first-aid kit, flashlight, and portable radio with extra batteries.
10. Place secure latches on cupboards to prevent doors from swinging open.
11. Keep heavy, unstable objects away from exit routes, and anchor wheels.
12. Replace heavy hangings over beds with lightweight alternatives.

◉ FIGURE 4.56 How to minimize earthquake damage in the home in advance.



◉ FIGURE 4.57 Keep a small crescent wrench at the gas meter. Turn off the gas by turning the valve end 90°.

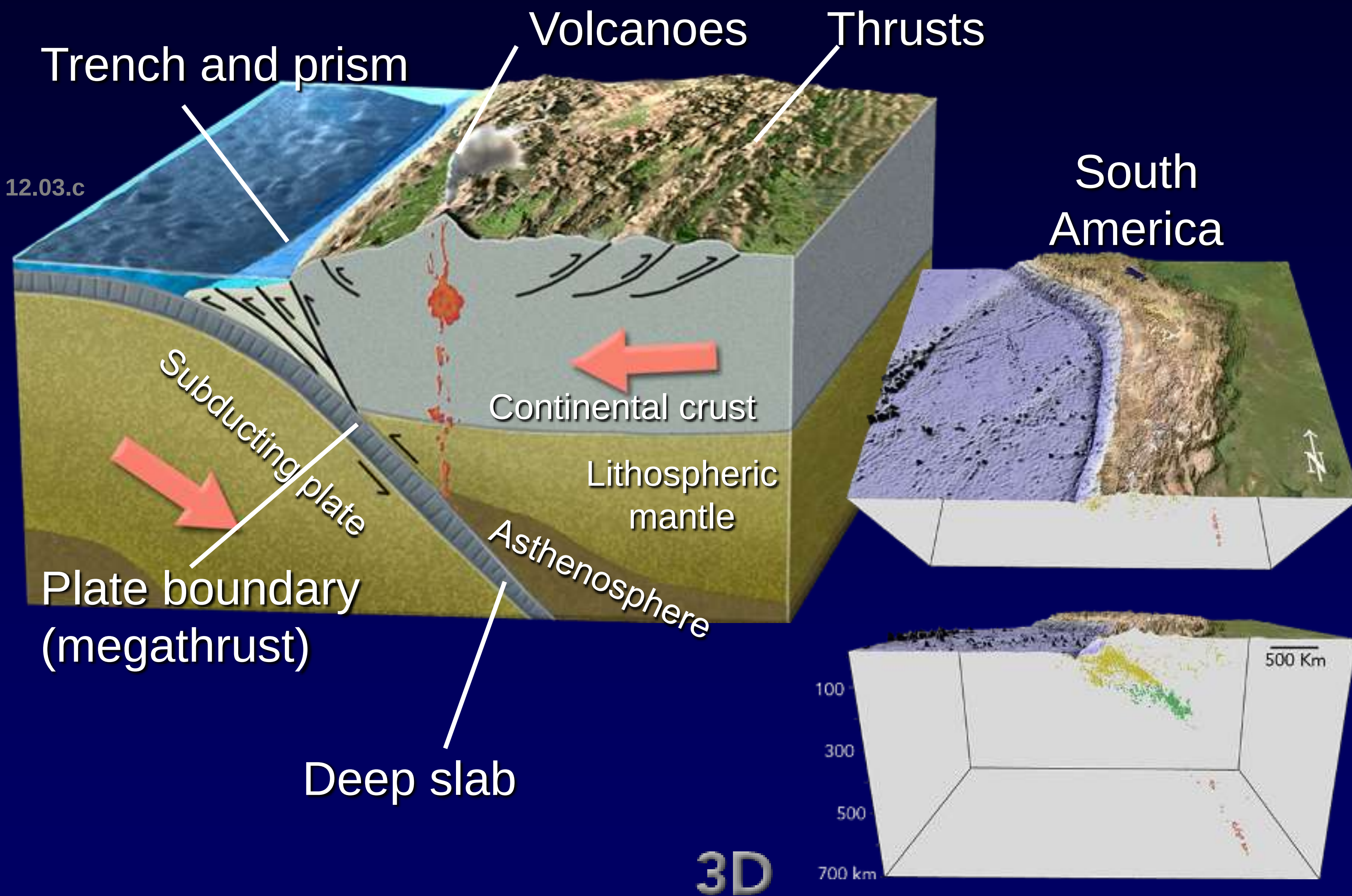
DURING AN EARTHQUAKE:

- Remain calm and consider the consequences of your actions.
- If you are indoors, stay indoors and get under a desk, bed, or a strong doorway.
- If you are outside, stay away from buildings, walls, power poles, and other objects that could fall. If driving, stop your car in an open area.
- Do not use elevators, and if you are in a crowded area, do not rush for a door.

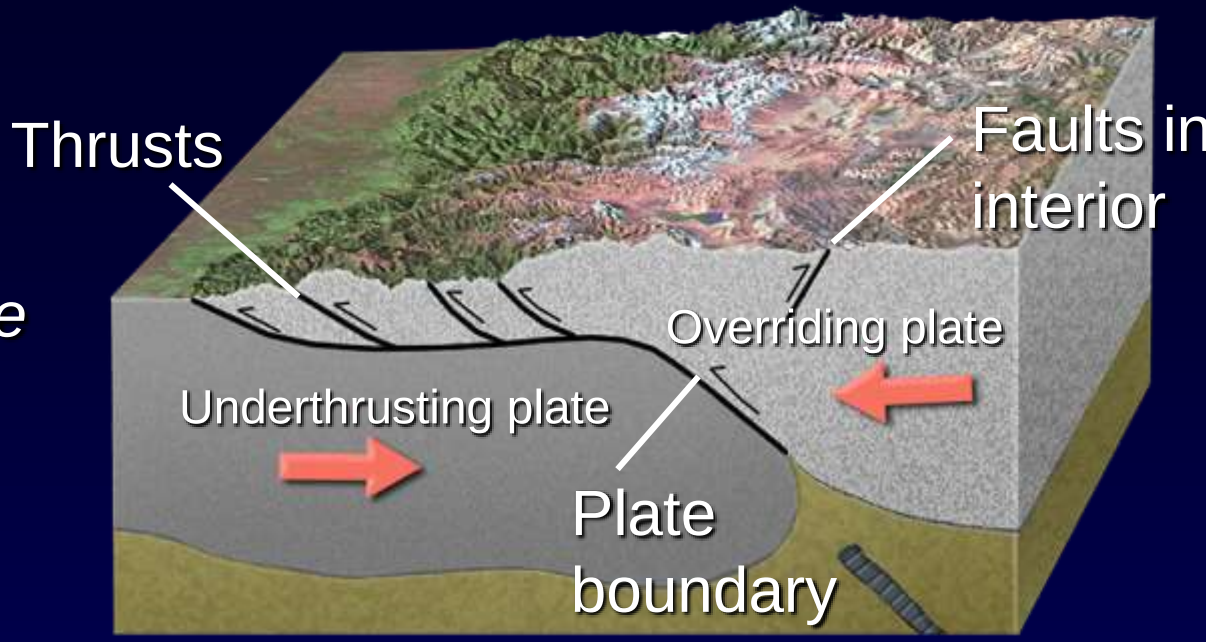
AFTER AN EARTHQUAKE:

- Turn off the gas at the meter (◉ Figure 4.57).
- Use portable radios for information.
- Check water supplies, remembering that there is water in water heaters, melted ice, and toilet tanks. Do not drink waterbed or pool water.
- Check your home for damage.
- Do not drive.

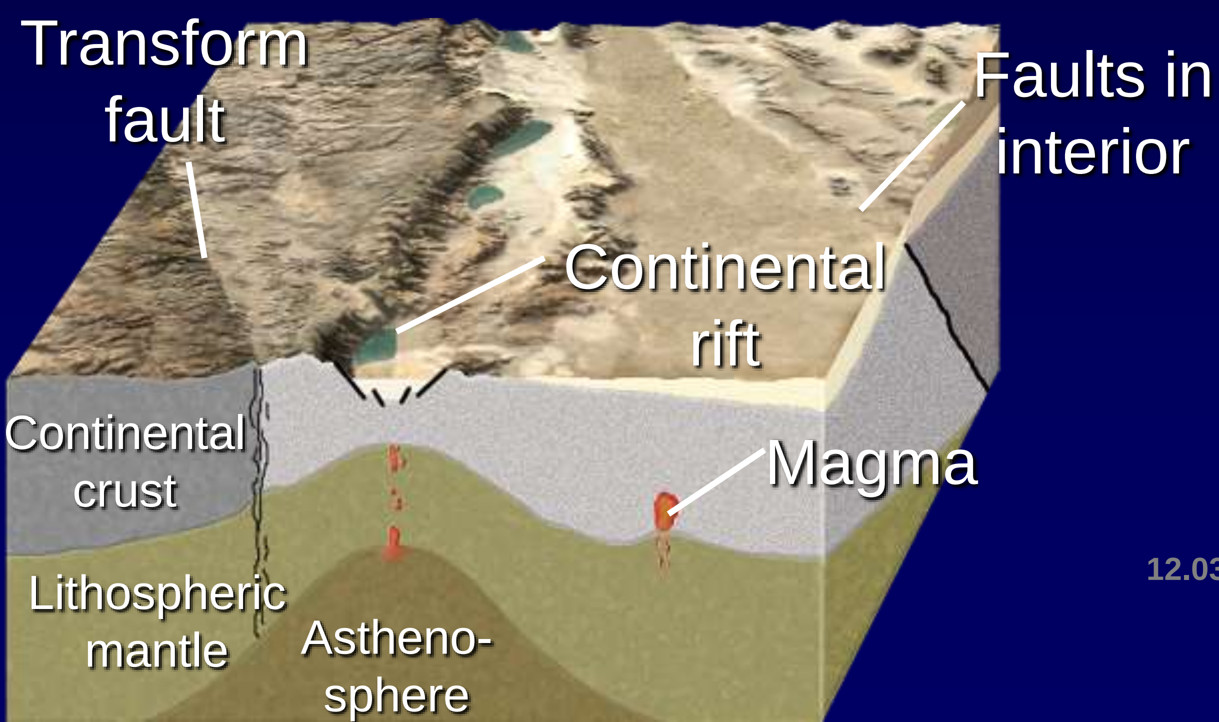
How Subduction Causes Earthquakes



How could continental collisions cause earthquakes?

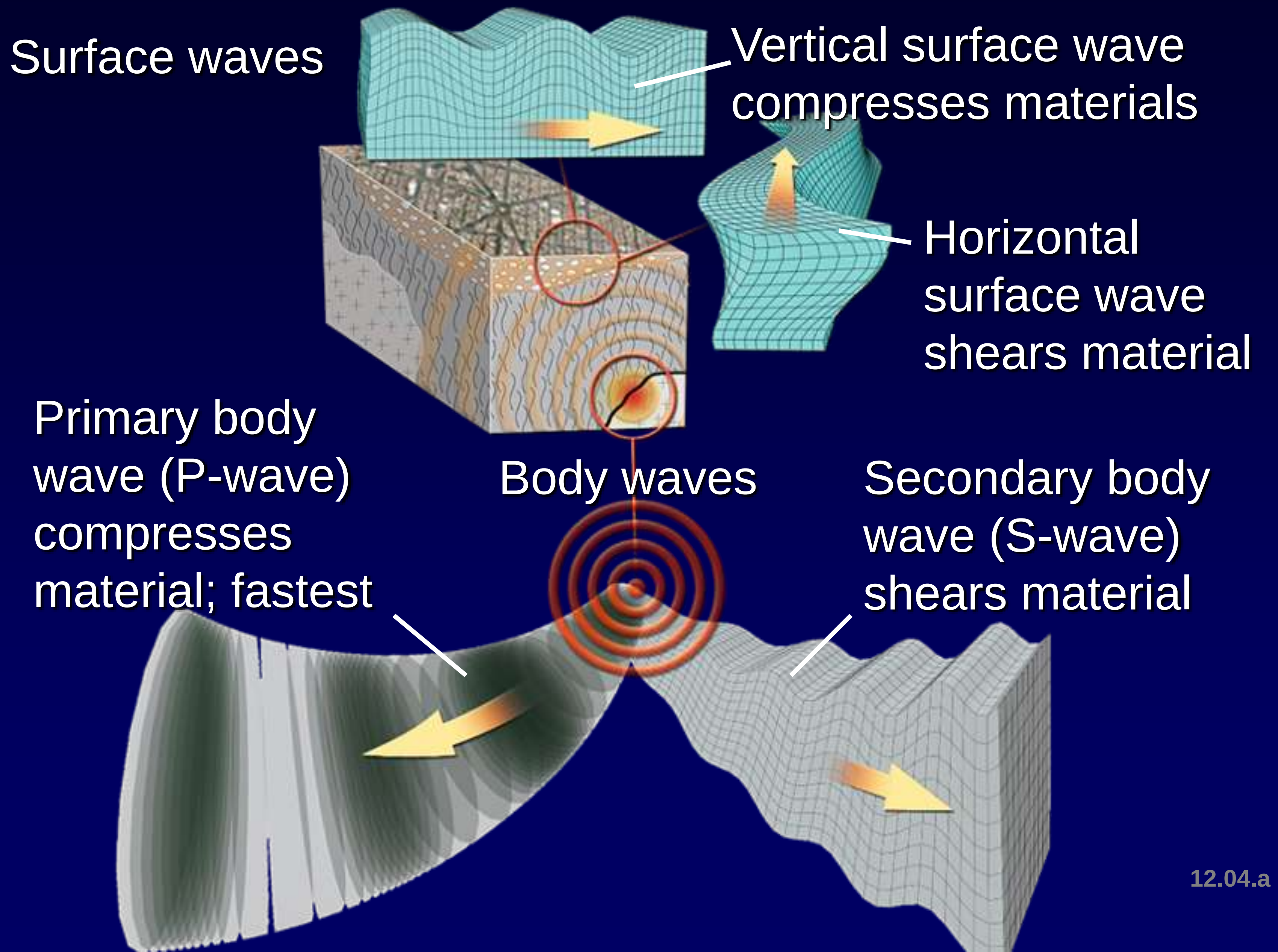


How could earthquakes be generated within continents?



12.03.d-e

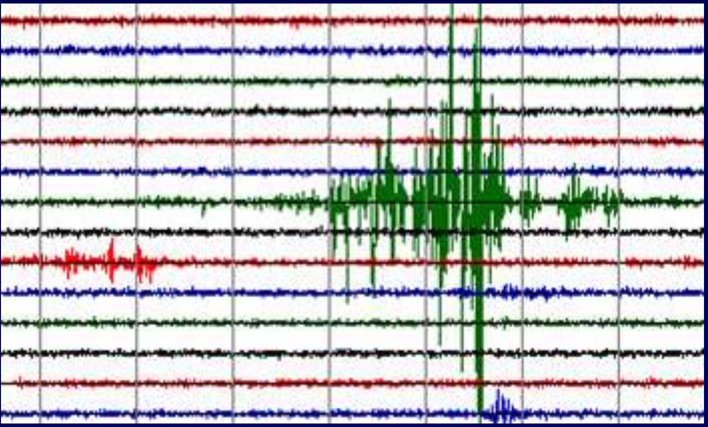
Different Kinds of Seismic Waves



How Seismic Waves Are Recorded

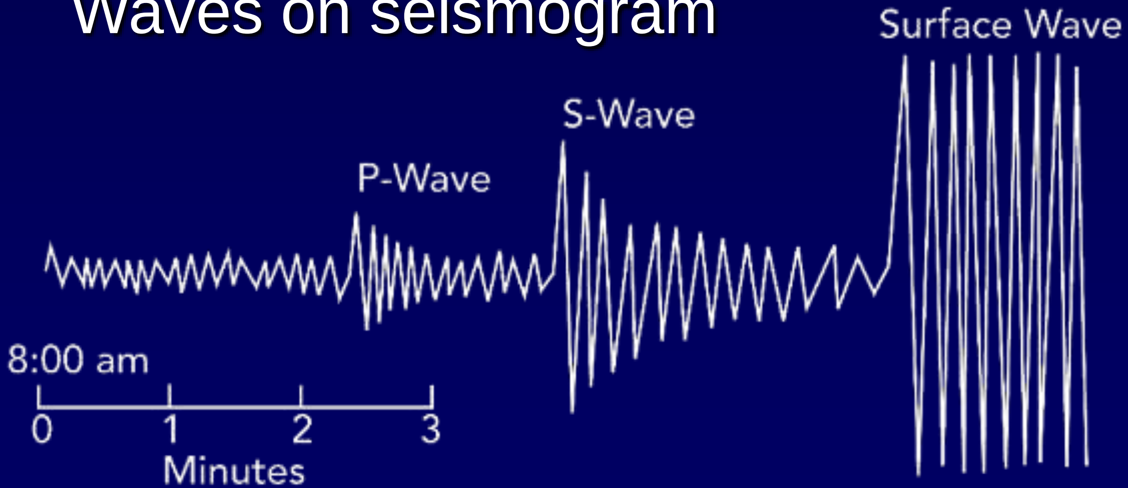
Basic seismometer

Modern seismometer



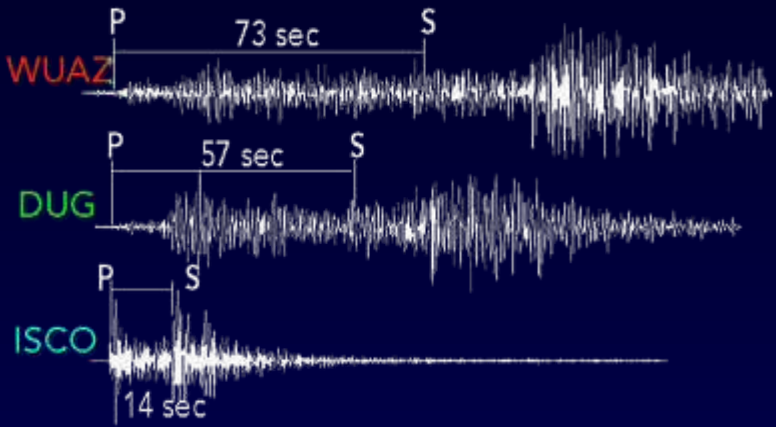
Seismogram

Waves on seismogram



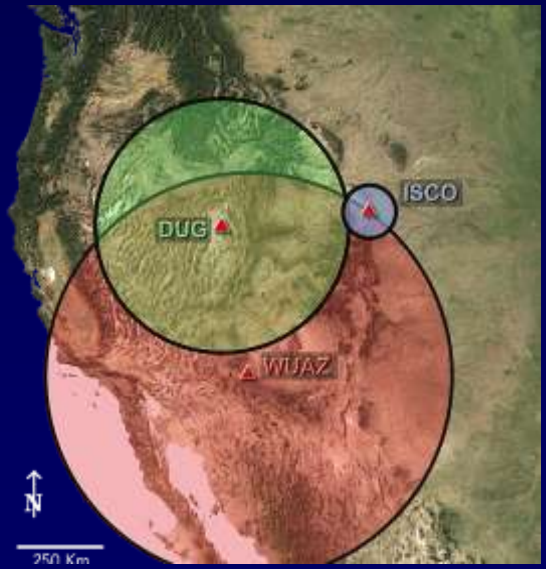
How do we determine the location of an earthquake?

Earthquake recorded by seismic network



Select earthquake records

Estimate distance

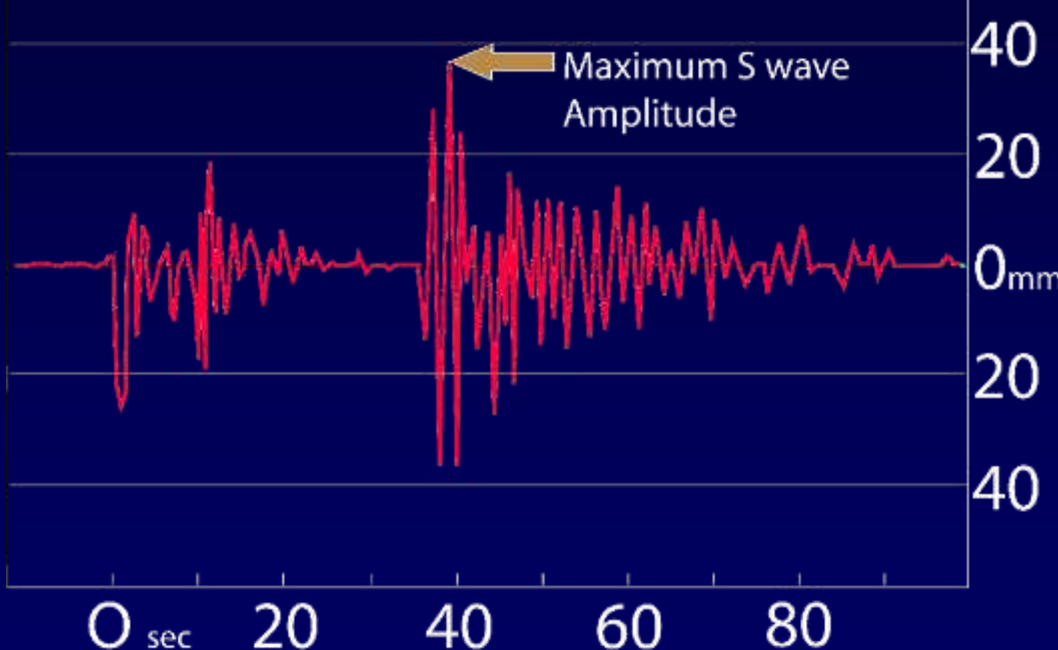


Triangulate the epicenter

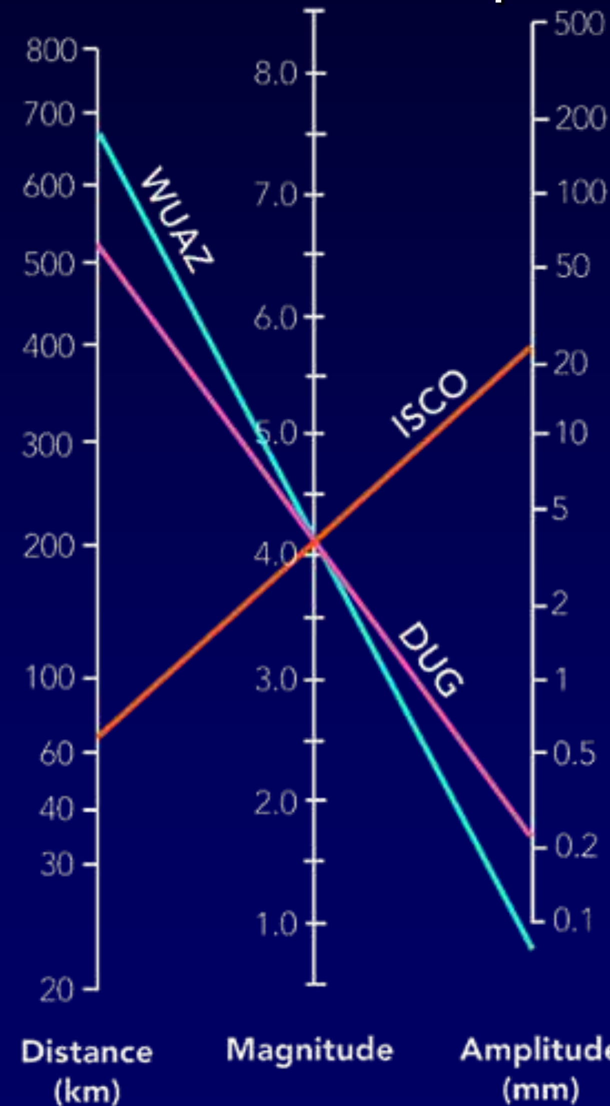
12.05.a

Measuring the Size of an Earthquake

For local magnitude (Richter): Measure S-wave amplitude

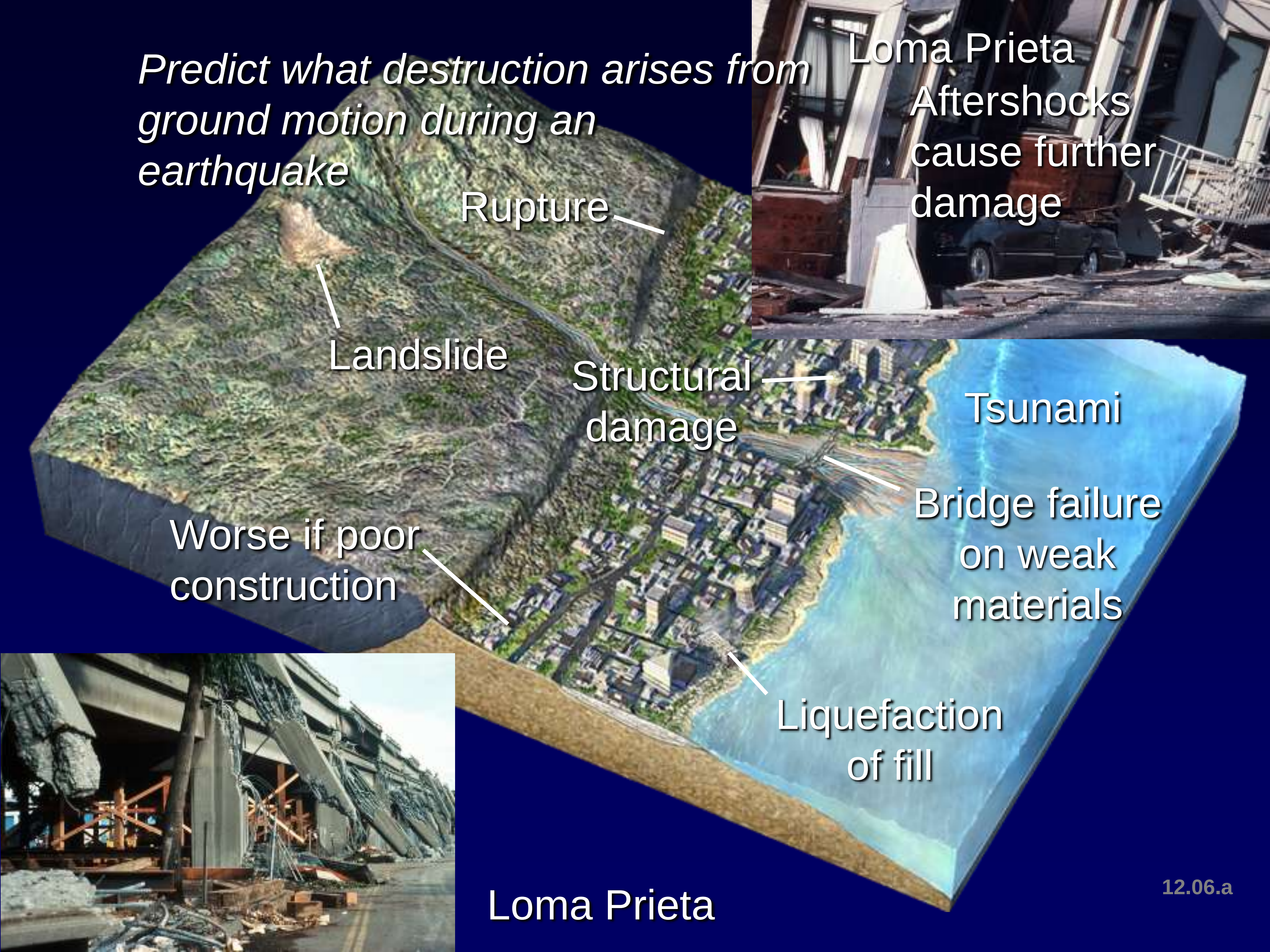


Connect amplitude and distance on plot



There are other ways we measure the size of an earthquake

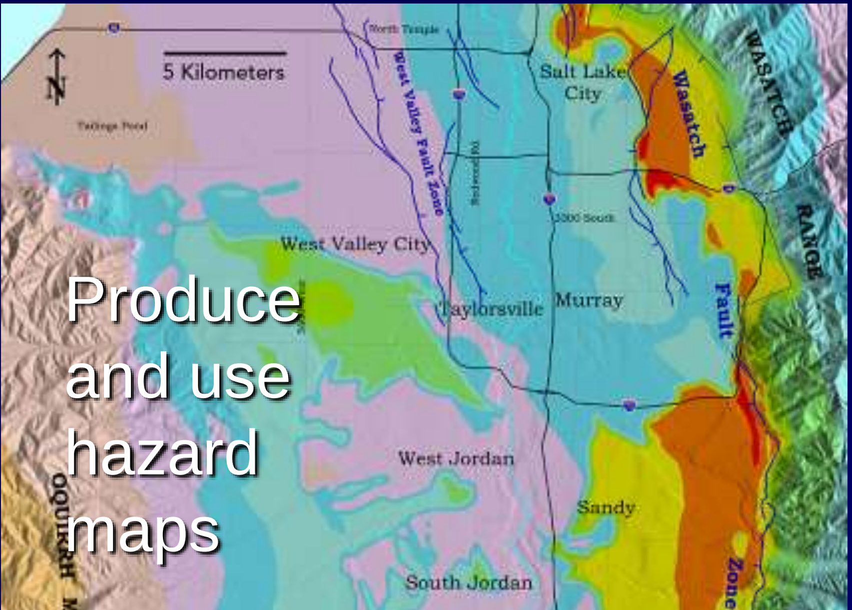
Predict what destruction arises from ground motion during an earthquake



Loma Prieta

Destruction that Can Happen After an Earthquake

Limiting Risk from Earthquakes



Improve building design (engineer for earthquake)

12.06.b-c

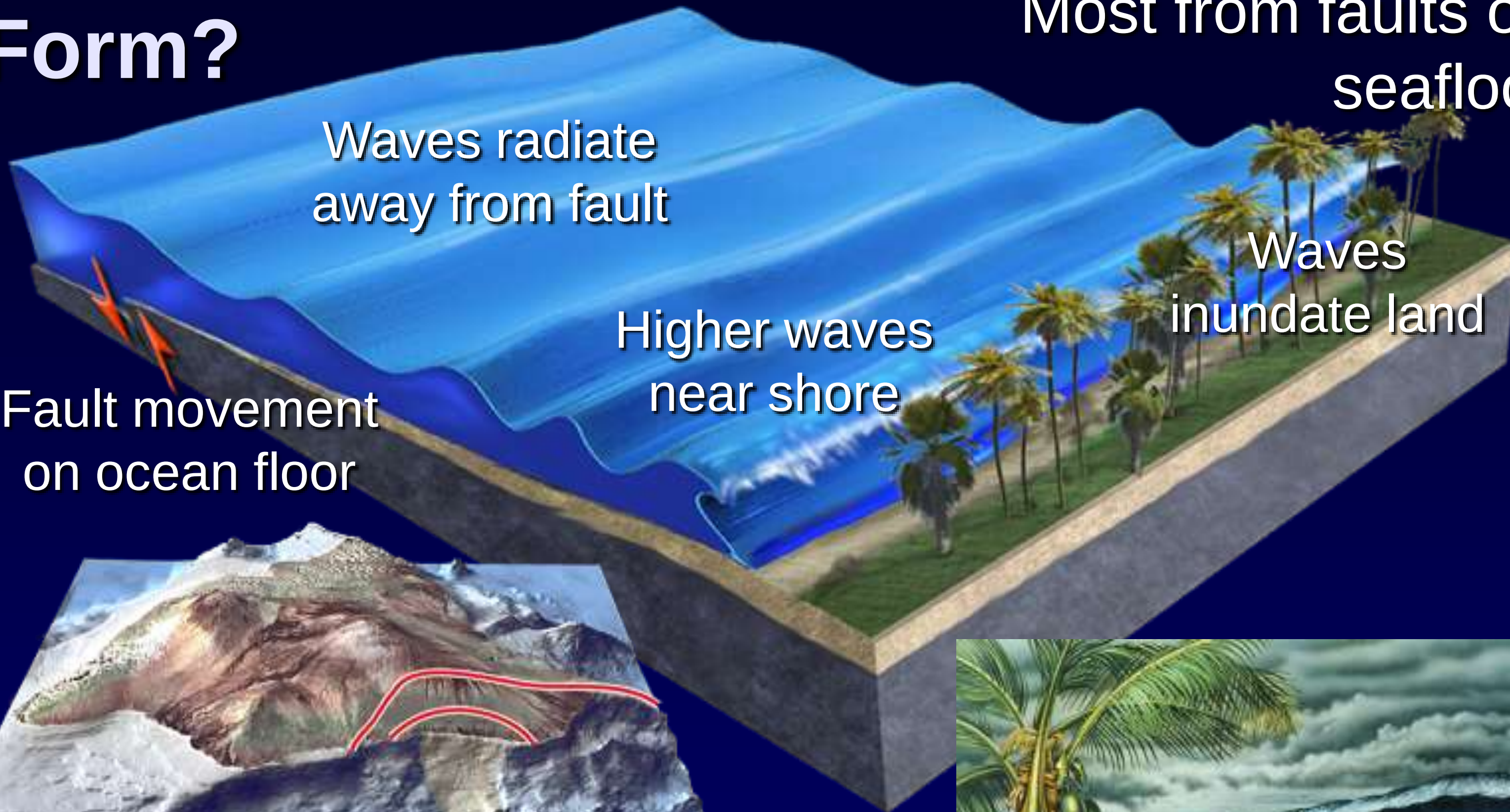
Major North American Earthquakes

Major World Earthquakes

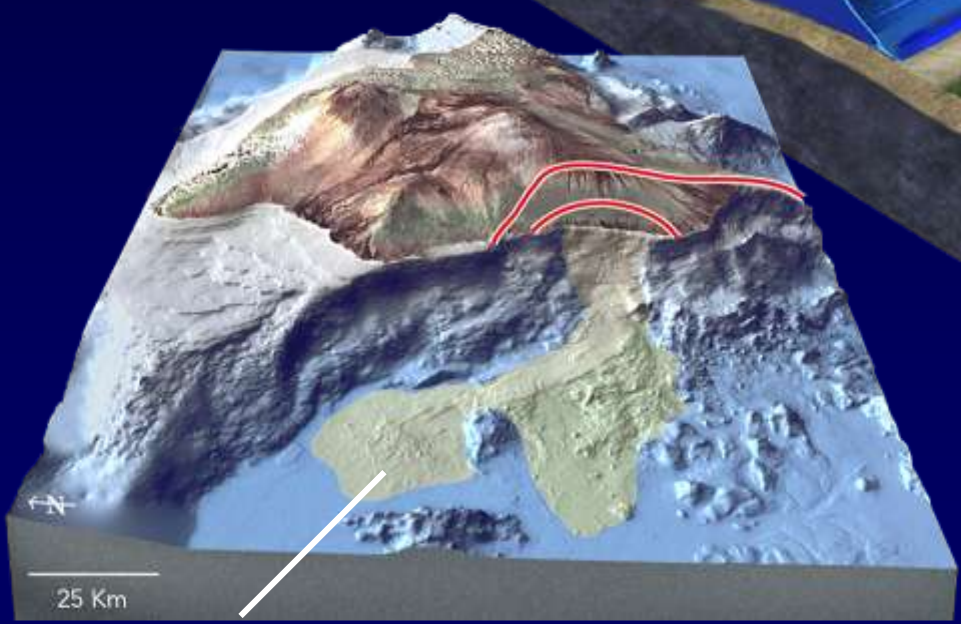
12.08.a

How Does a Tsunami Form?

Most from faults on seafloor



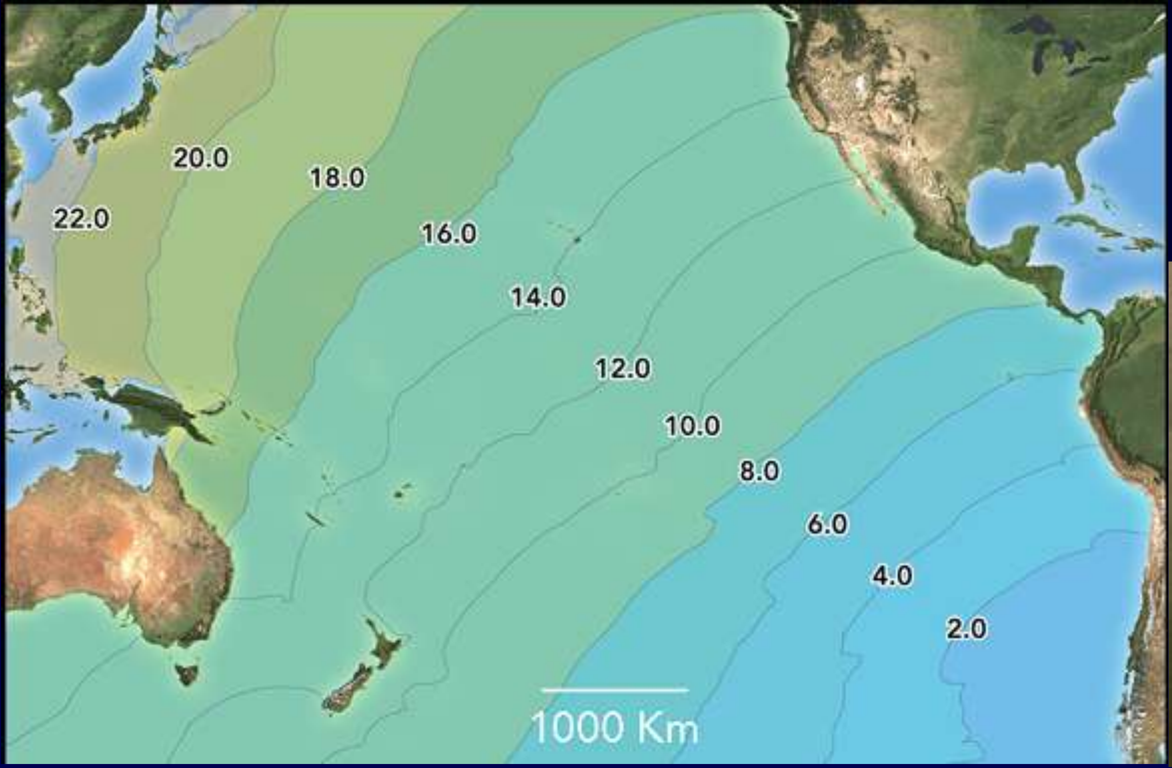
12.09a



Underwater landslides

Volcanic eruptions

Destruction by Tsunamis



12.09.b

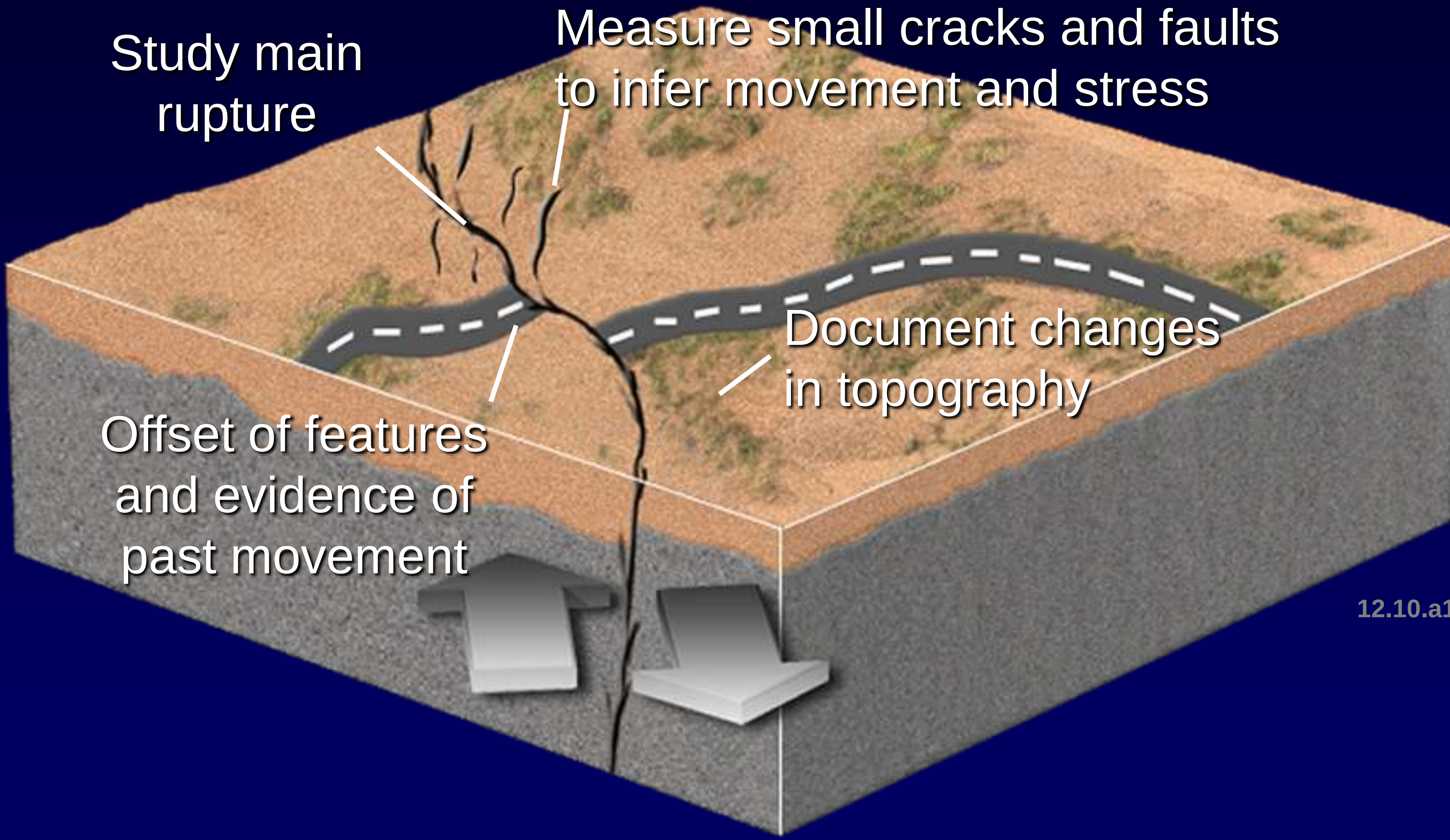
Chile, 1960

Hawaii, 1960

Japan, 1993

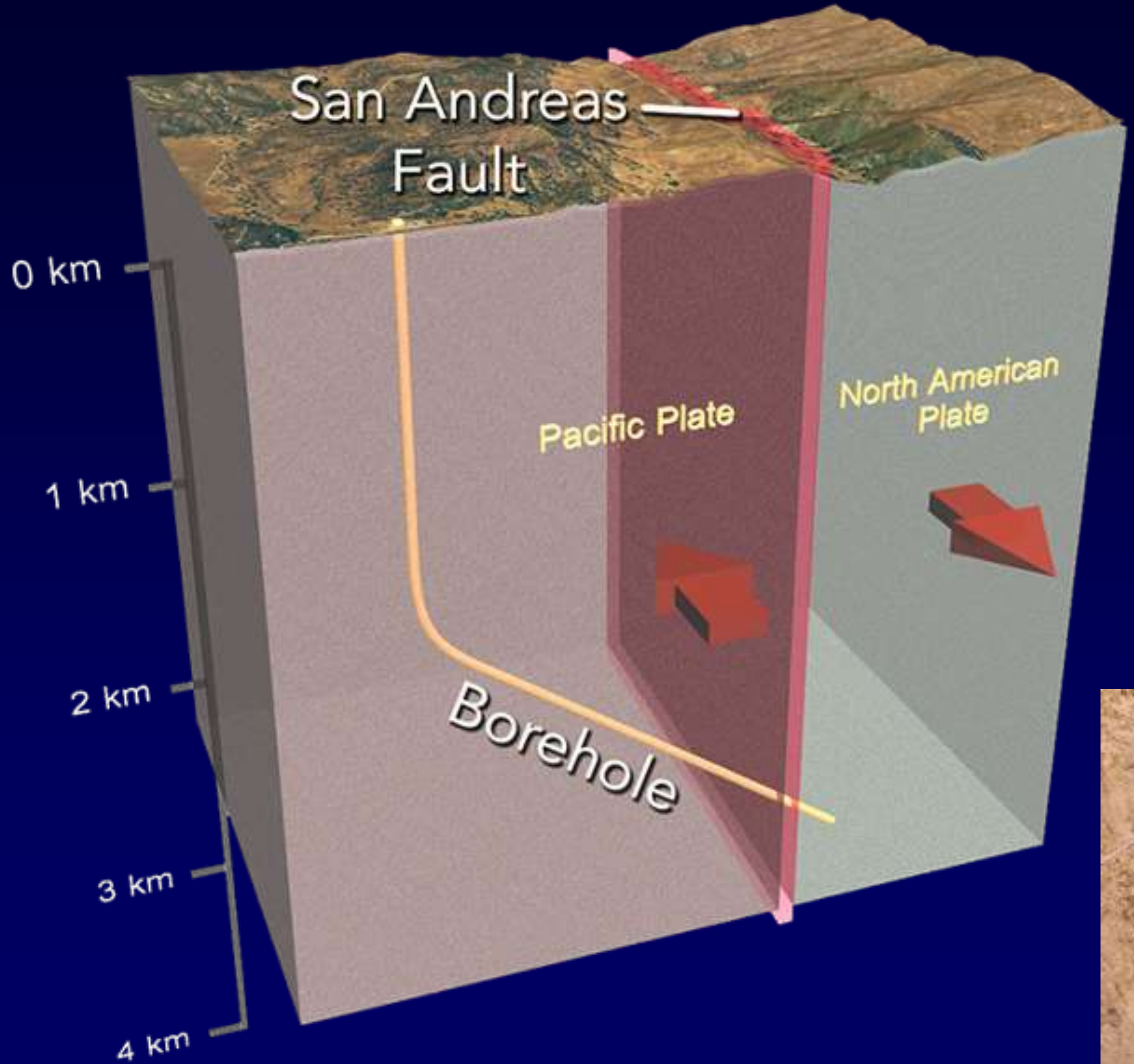
New Guinea, 1998

Studying Earthquakes in the Field



12.10.a1

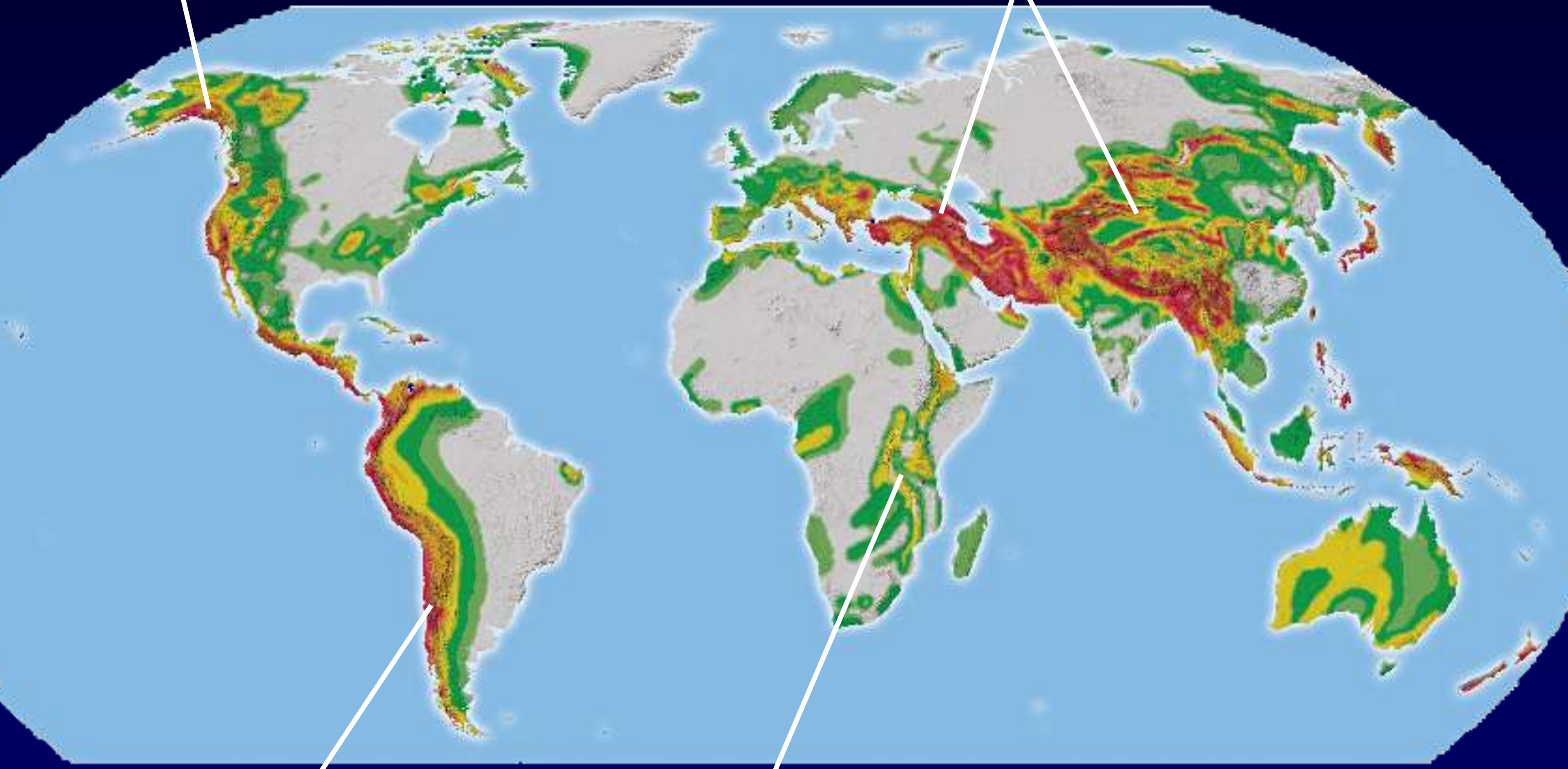
Studying the San Andreas Fault



Drilled into fault at depth to investigate rocks and conditions

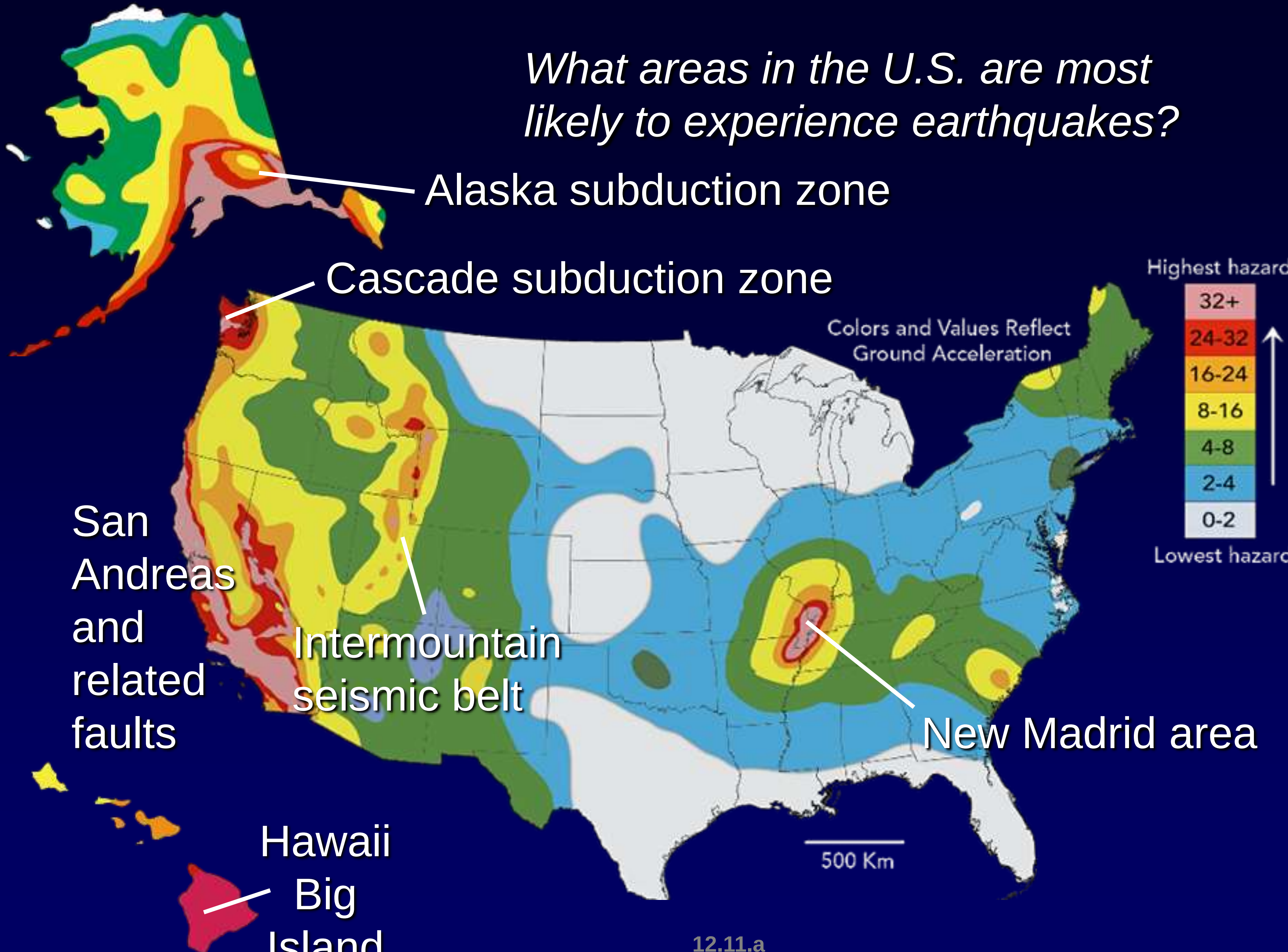
Studies of shallow trenches to document history

What areas are most likely to experience earthquakes?



12.11.a

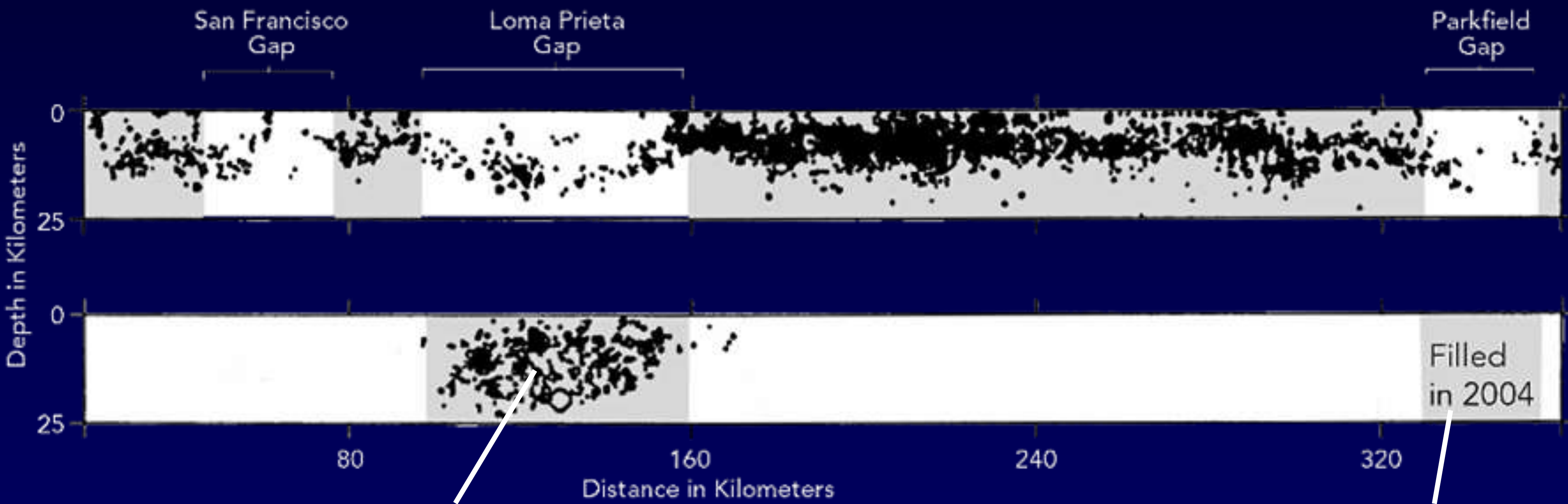
What areas in the U.S. are most likely to experience earthquakes?



12.11.a

Long-Range Earthquake Forecasting

Top graph indicates earthquakes prior to October, 1989; gaps identified based on less earthquake activity



1989 earthquake filled in Loma Prieta gap

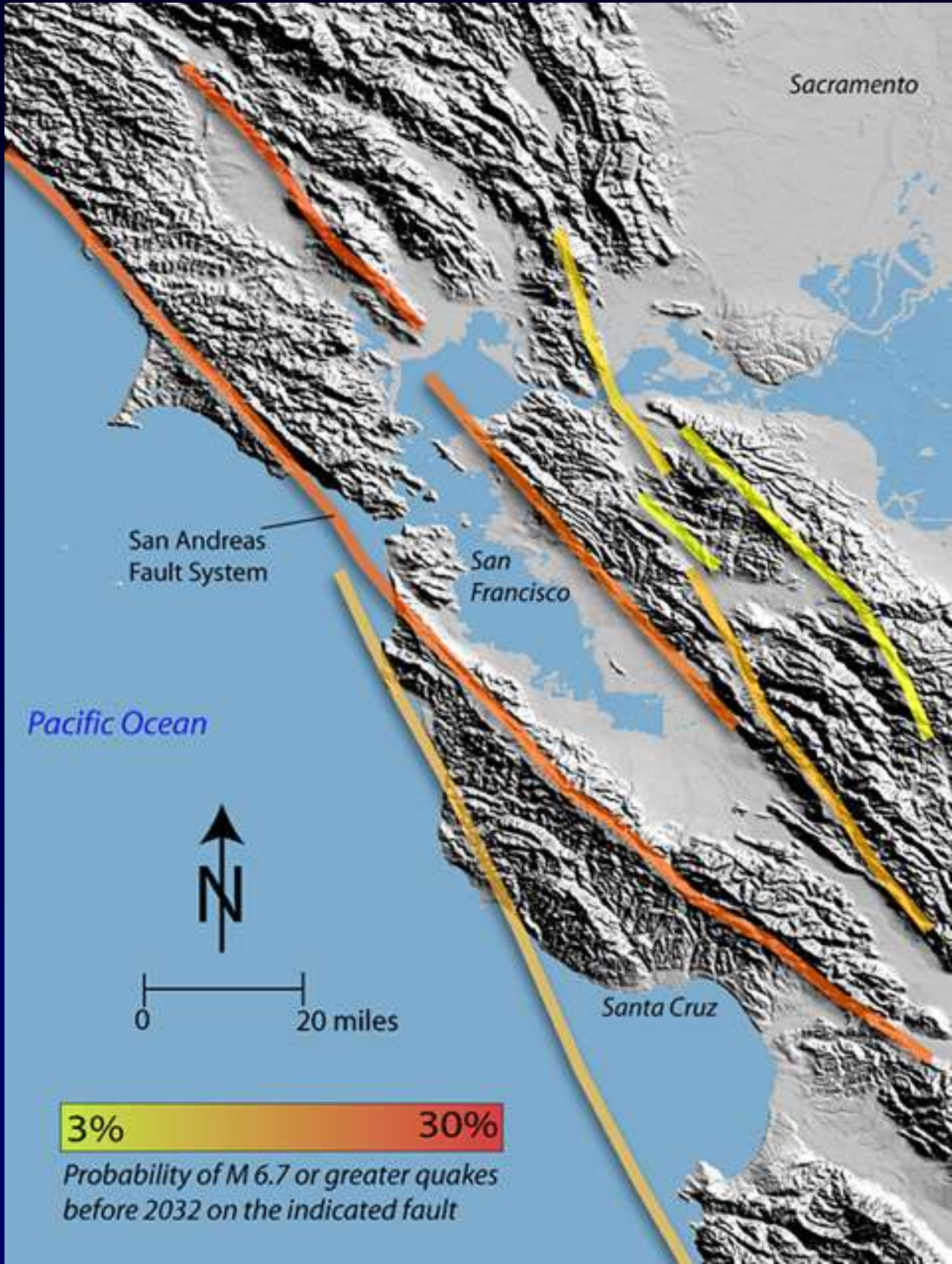
2004 Parkfield earthquake filled in other gap

When will San Francisco gap be filled?

Long-Range Earthquake Forecasting

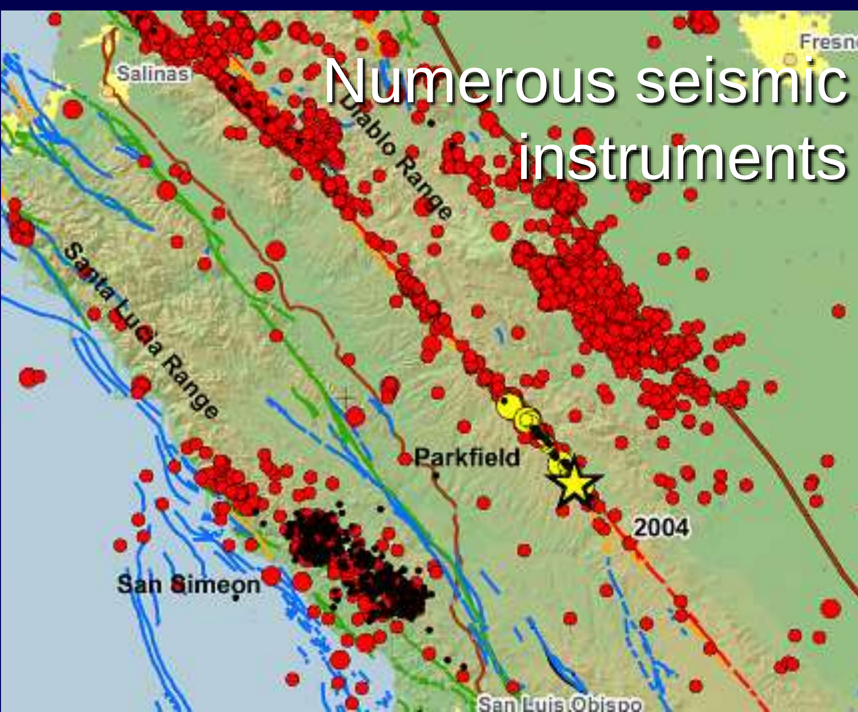
USGS assigned probability to each main fault in San Francisco area

Combined probability of major earthquake before 2032 is over 60 percent!

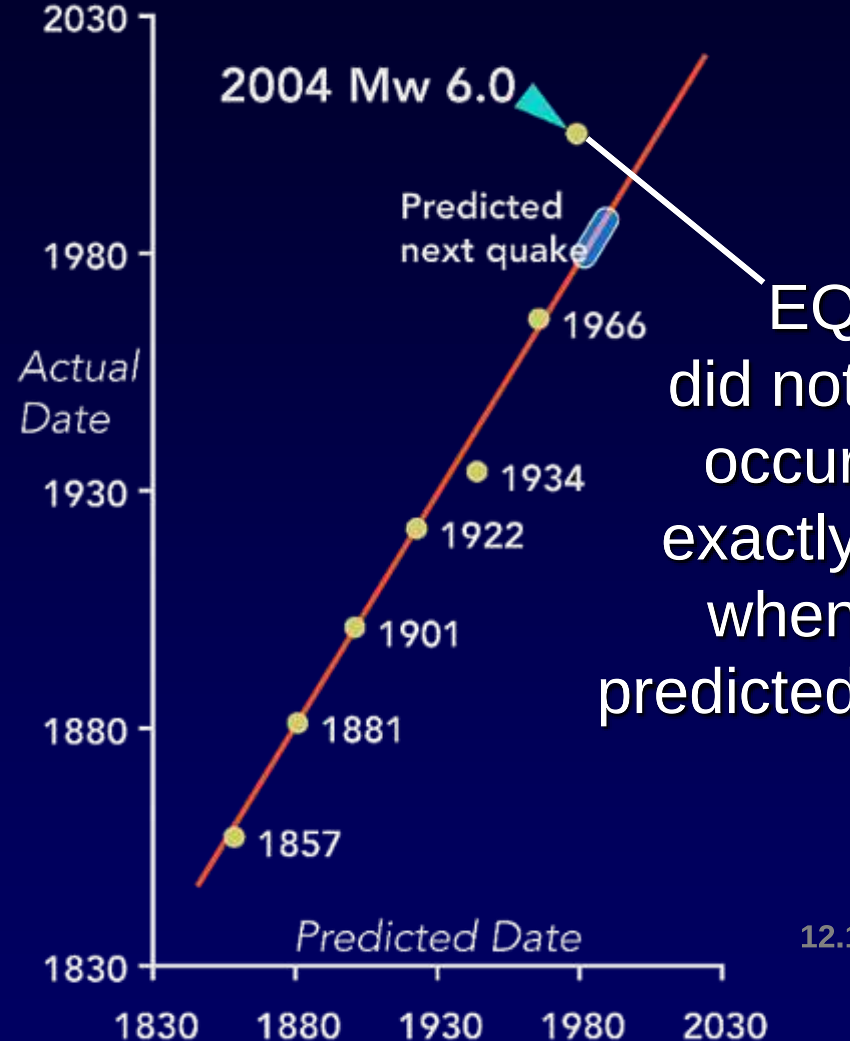


Short-Term Earthquake Prediction


Lasers monitor movement along fault



Numerous seismic instruments



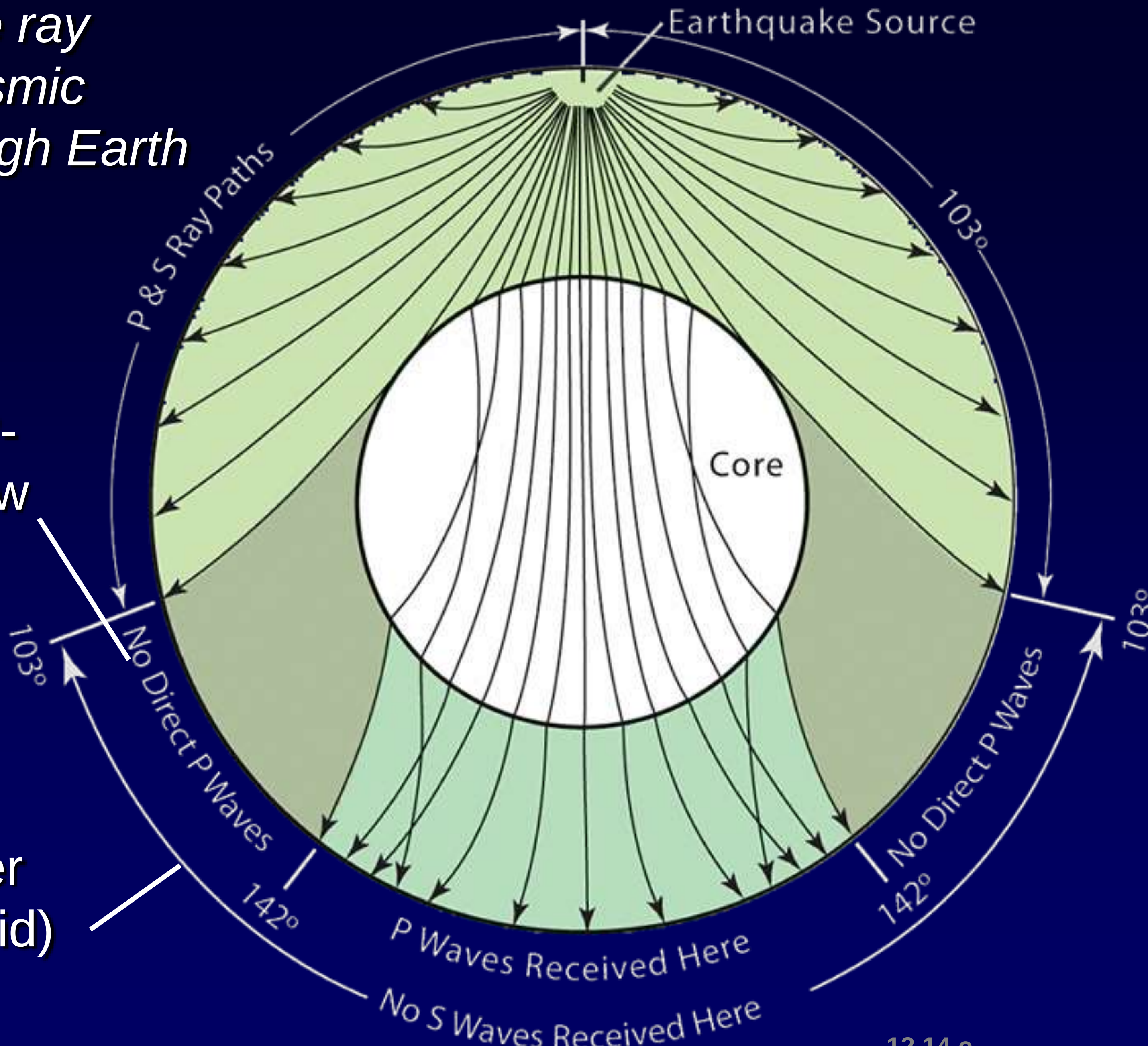
12.11.c

Predictions based on past history of Parkfield segment

Examine the ray paths of seismic waves through Earth

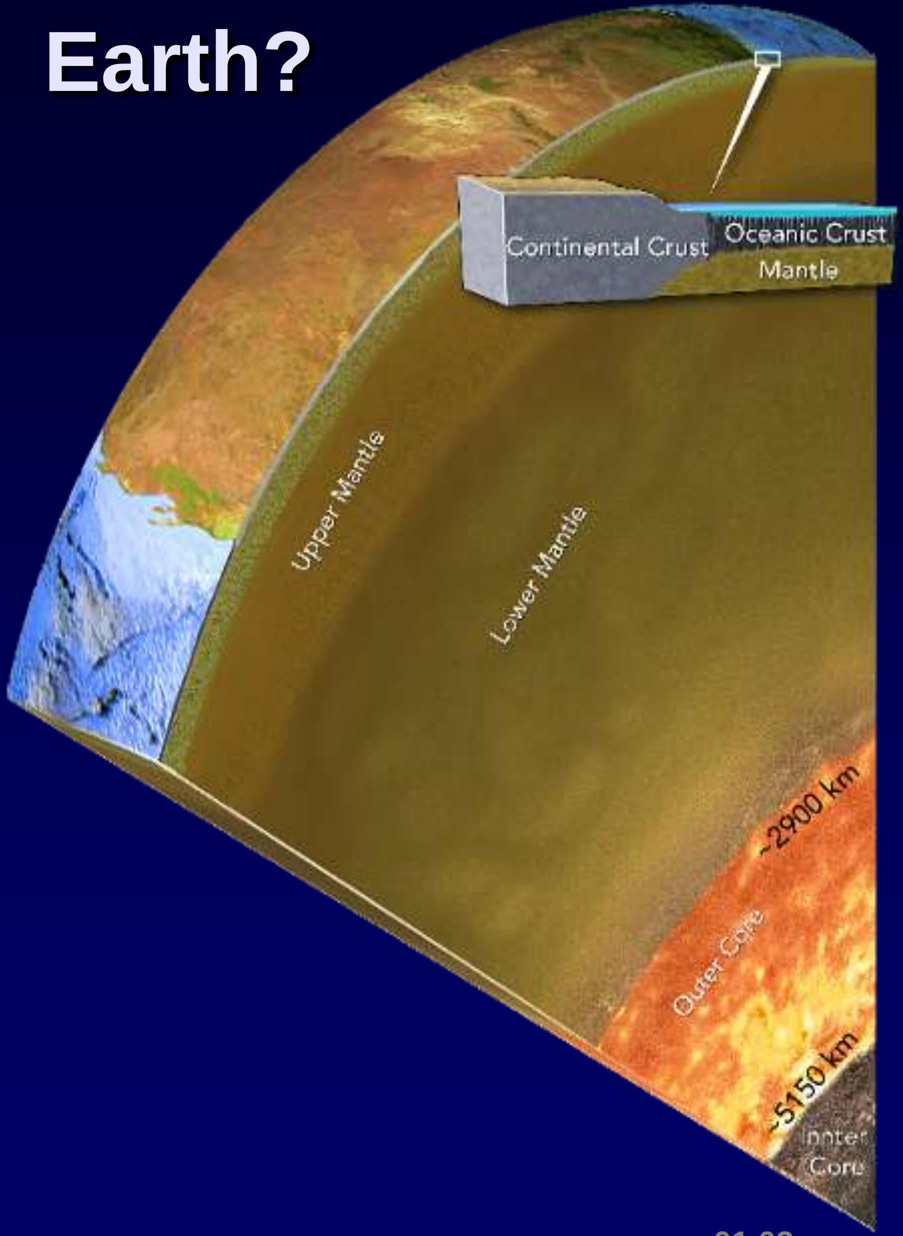
Size of core indicated by location of P-wave shadow zone

S-waves do not pass through outer core (so liquid)



12.14.c

What Is Inside Earth?



01.03.a

Upper layer is *crust;* two types:
continental *oceanic*

Thickest layer: *mantle*

Lowest layer: iron-nickel core (molten outer core; solid inner core)