A Violent Pulse: Earthquakes

Edited and augmented for this course by

Olivia Jensen

Professor of Geophysics

McGill University

Montreal, Canada

Updated by:

Rick Oches, *Professor of Geology & Environmental Sciences*

Bentley University

Waltham, Massachusetts

Based on slides prepared by:

Ronald L. Parker, *Senior Geologist*

Fronterra Geosciences

Denver, Colorado

Introduction

- Earth shaking caused by a rapid release of energy.
  - Energy moves outward as an expanding sphere of waves.
  - This waveform energy can be measured around the globe.
- Earthquakes are common on this planet.
  - They occur every day.
  - More than a million detectable earthquakes per year.
- Most earthquakes result from tectonic plate motion.

Introduction

- Most earthquakes are small.
- Large earthquakes, however:
  - Destroy buildings and kill people.
    - 3.5 million deaths in the last 2,000 years.
  - Several hundred per year.

Introduction

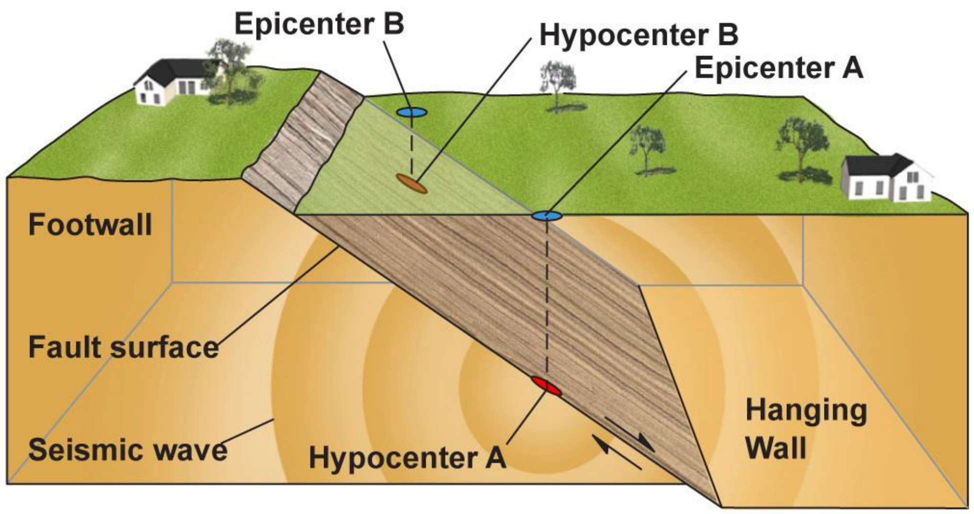
- Most earthquake damage is due to ground shaking.
- Earthquakes also spawn devastating tsunamis.
  - December 26, 2004 — Indian Ocean tsunami.
  - March 11, 2011 — eastern coast of Honshu, Japan.

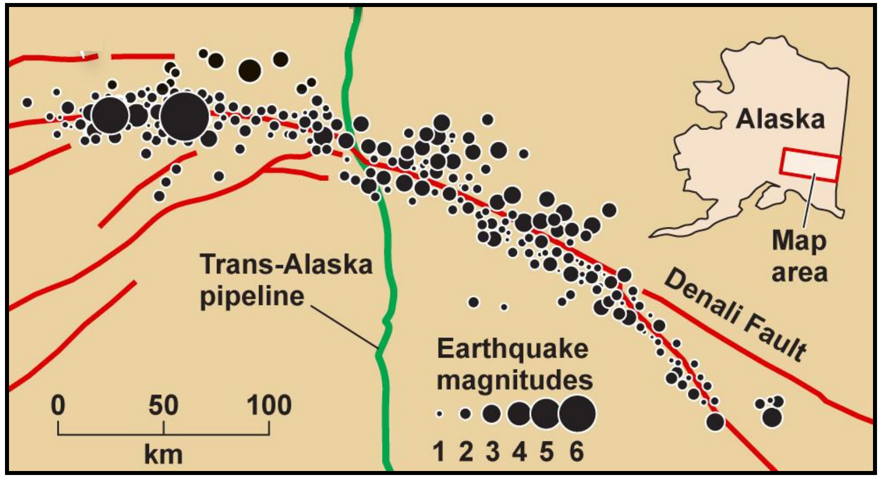
What Causes Earthquakes?

- Seismicity (earthquake activity) occurs due to:
  - Sudden motion along a newly formed crustal fault.
  - Sudden slip along an existing fault.
  - A sudden change in mineral structure (very deep focus).
  - Movement of magma in a volcano.
  - Volcanic eruption.
  - Giant landslides.
  - Meteorite impacts.
  - Nuclear detonations.
- Fault slip is, by far, the most common cause.

What Causes Earthquakes?

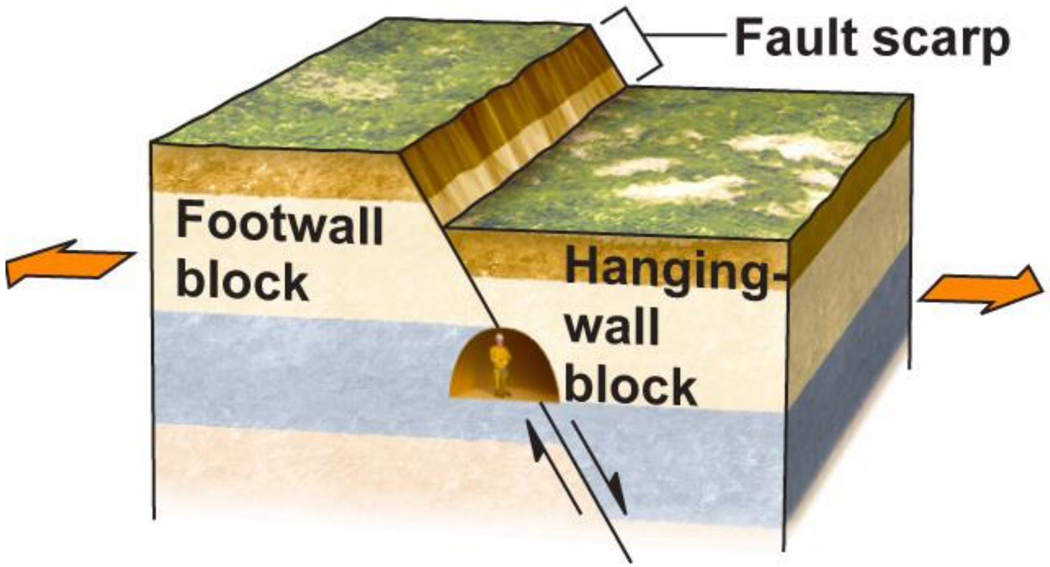
- Hypocenter (focus)—the place were fault slip first occurs.
  - Usually occurs on a fault surface.
  - Earthquake waves expand outward from the hypocenter.
- Epicenter—land surface right above the hypocenter.
  - Maps often portray the location of epicenters.





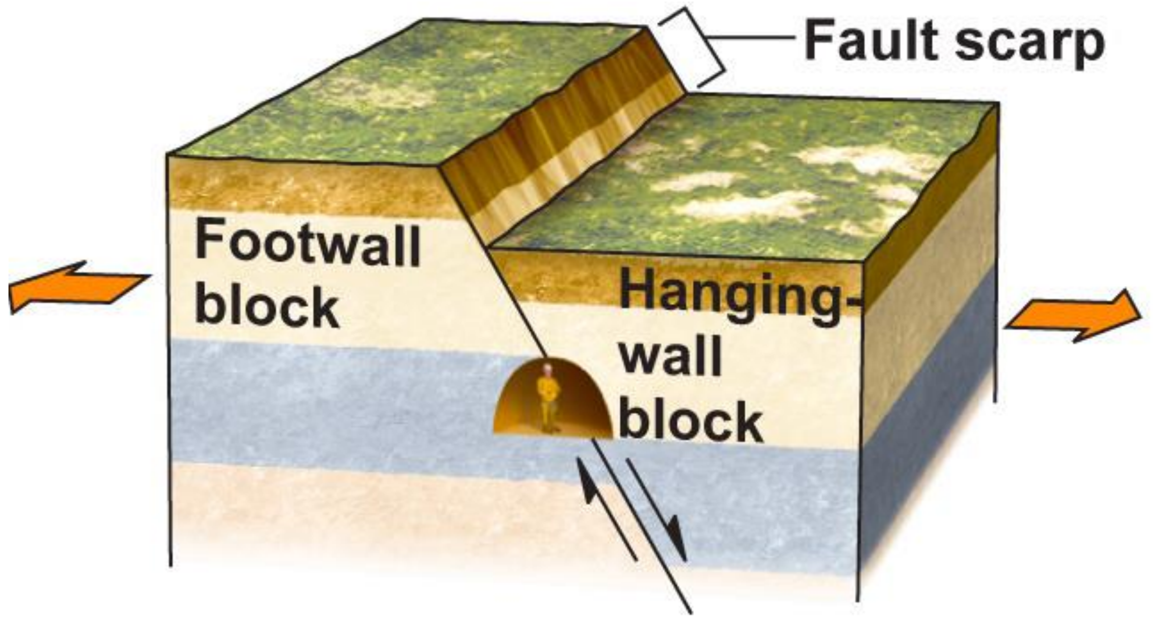
Faults in the Crust

- Faults are crustal breaks where movement occurs.
  - Displacement is a measure of movement.
  - Fault trace is the ground surface expression of a fault.
- On a sloping fault, crustal blocks are classified as:
  - Footwall (block below the fault).
  - Hanging wall (block above the fault).



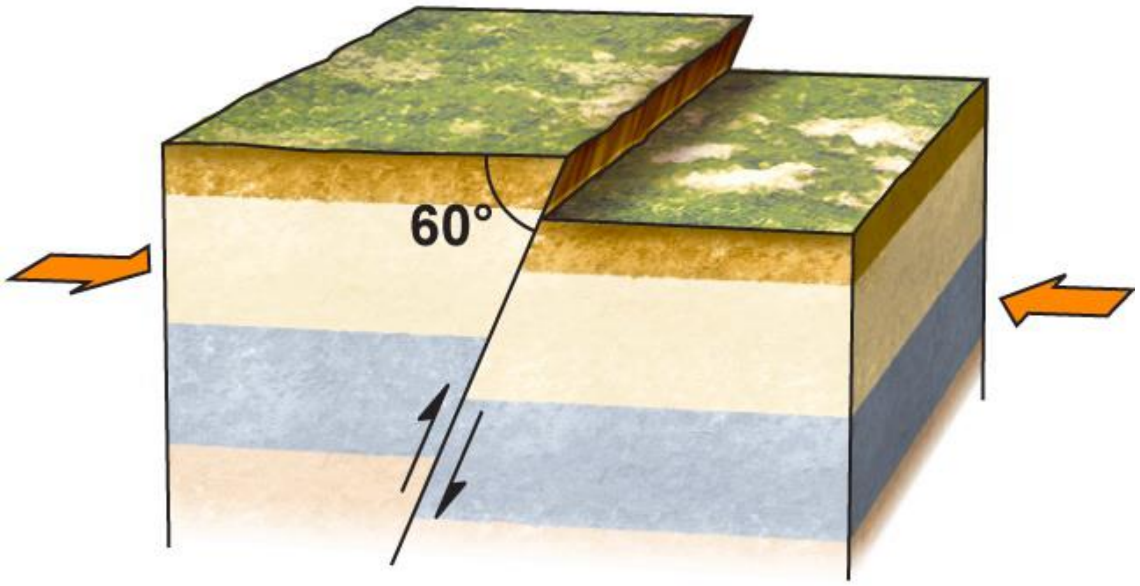
Faults in the Crust

- The fault type is based on relative block motion.
  - Normal fault.
    - The hanging wall moves down relative to the footwall.
    - Results from extension (pull-apart or stretching).



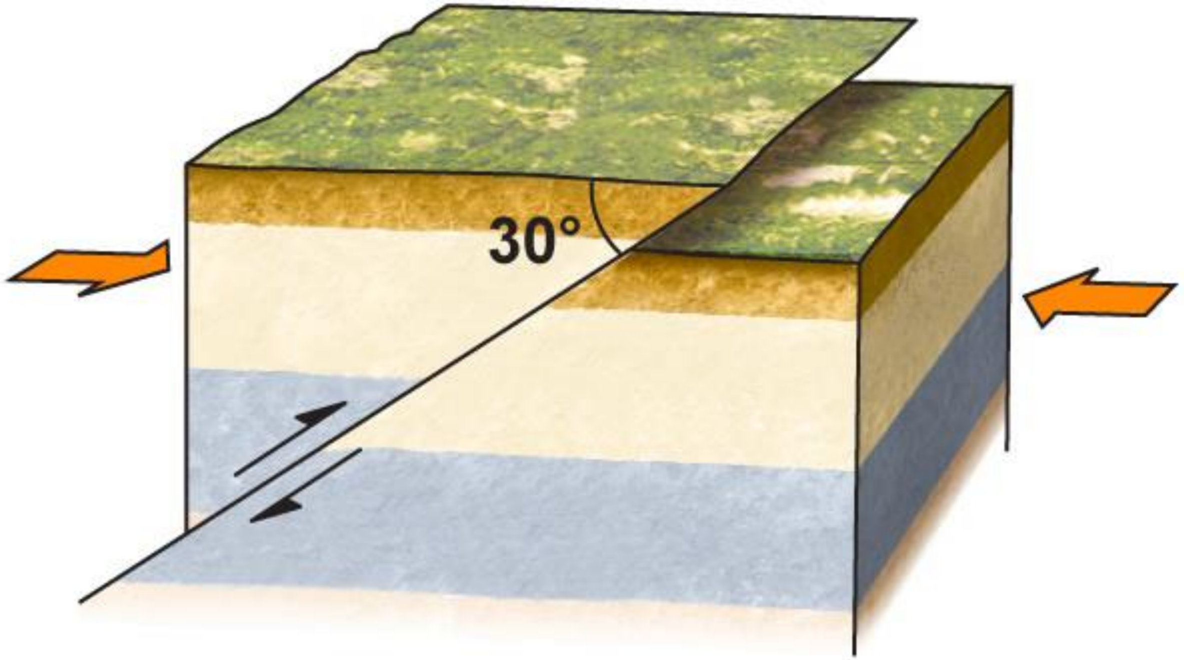
Faults in the Crust

- The fault type is based on relative block motion.
  - Reverse fault.
    - The hanging wall moves up relative to the footwall.
    - Results from compression (squeezing or shortening).
    - The slope (dip) of fault is steep.



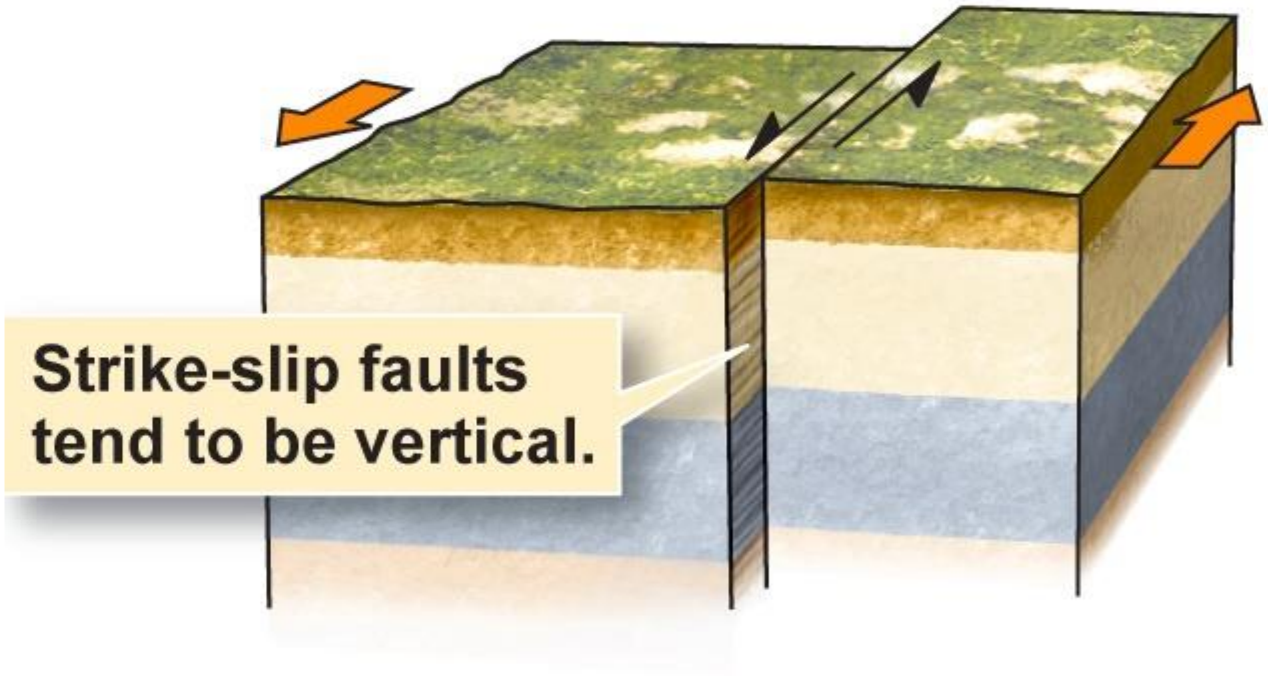
Faults in the Crust

- **The fault type is based on relative block motion.**
  - **Thrust fault.**
    - **A special kind of reverse fault.**
    - **The slope (dip) of fault surface is much less steep.**
    - **Common fault type in compressional mountain belts.**



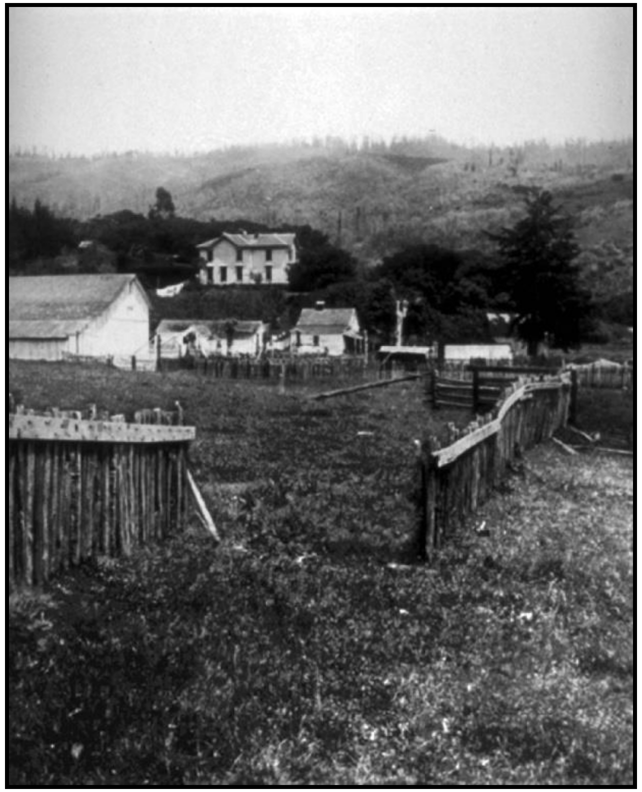
Faults in the Crust

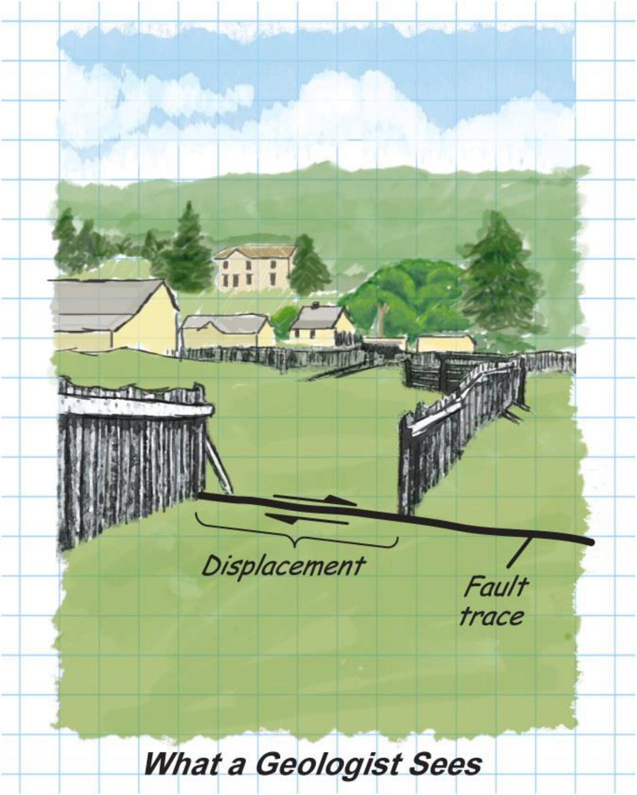
- The fault type is based on relative block motion.
  - Strike-slip fault. (transcurrent, transform)
    - One block slides laterally past the other block.
    - There is little or no vertical motion across the fault.
    - The fault plane, however, is nearly vertical.



Faults in the Crust

- Displacement—the amount of movement across a fault.
  - During earthquakes, fault blocks move.
  - Displacement, also called offset, is shown by markers.
- Displacement is cumulative over time.





Faults in the Crust

- Faults are found in many places in the crust.
  - Active faults—ongoing stresses produce motion.
  - Inactive faults—motion occurred in the geologic past.
- A fault trace shows the fault intersecting the ground.
  - Displacement at the land surface creates a fault scarp.
- Not all faults reach the surface. Blind faults are invisible.

Generating Earthquake Energy

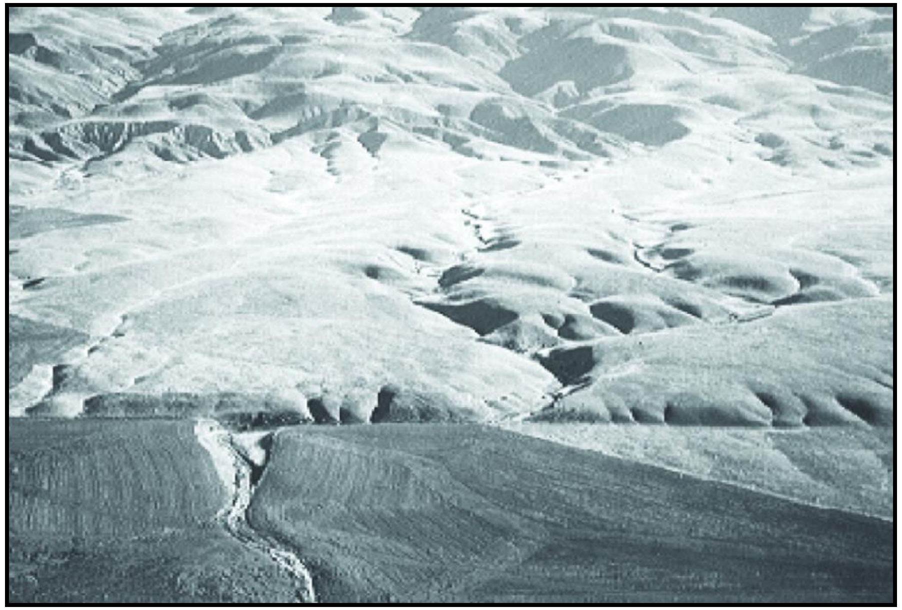
- **Earthquakes occur as the result of fault motion.**
- **Energy creating earthquakes originates when:**
  - **Rocks break to form a new fault, or**
  - **A preexisting fault is reactivated.**
- **Once created, a fault remains a zone of weakness.**

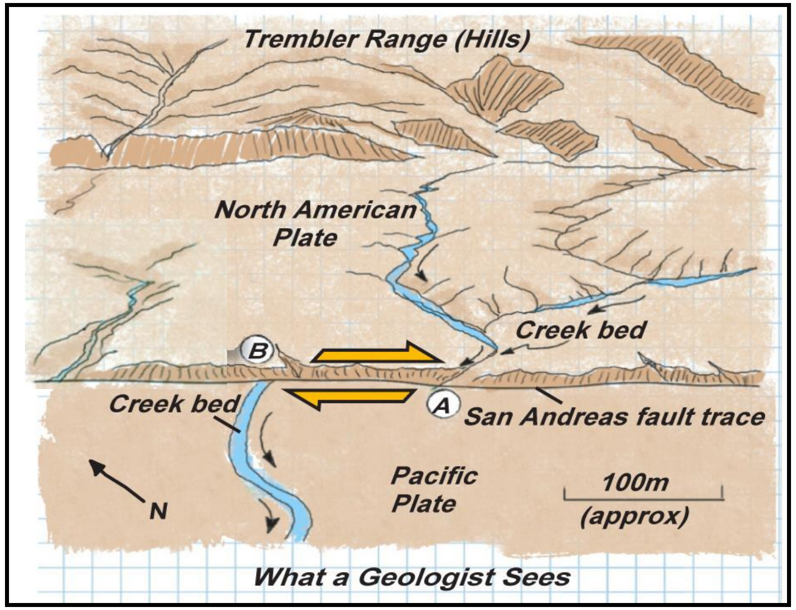
Generating Earthquake Energy

- Rocks slide past one another along a fault.
- Fault motion cannot occur forever.
- Fault motion is arrested by friction.
  - Friction is the force that resists sliding on a surface.
  - Friction is due to bumps along the fault.

Generating Earthquake Energy

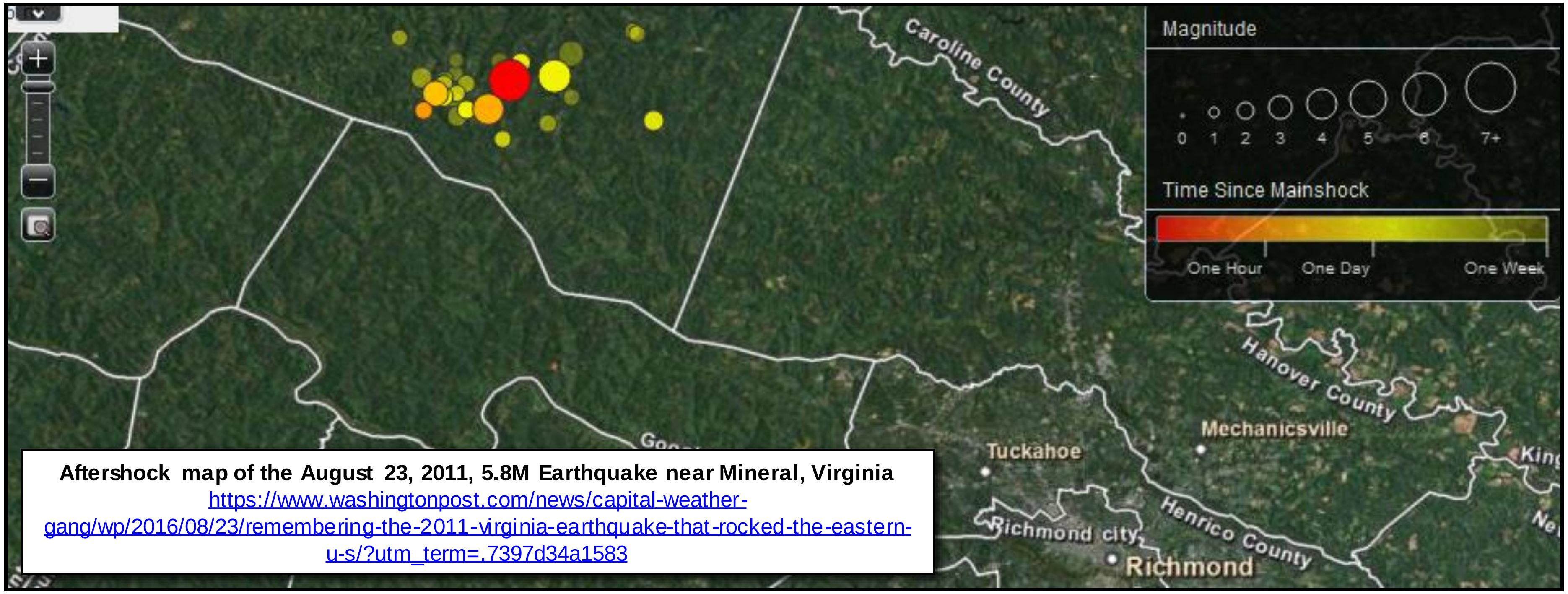
- Slip on a preexisting fault causes earthquakes.
  - Faults are weaker than surrounding crust.
  - Over time, stress builds up leading to slip along the fault.
  - This behavior is termed stick-slip behavior.
    - Stick—friction prevents motion.
    - Slip—friction is briefly overwhelmed by motion.





Generating Earthquake Energy

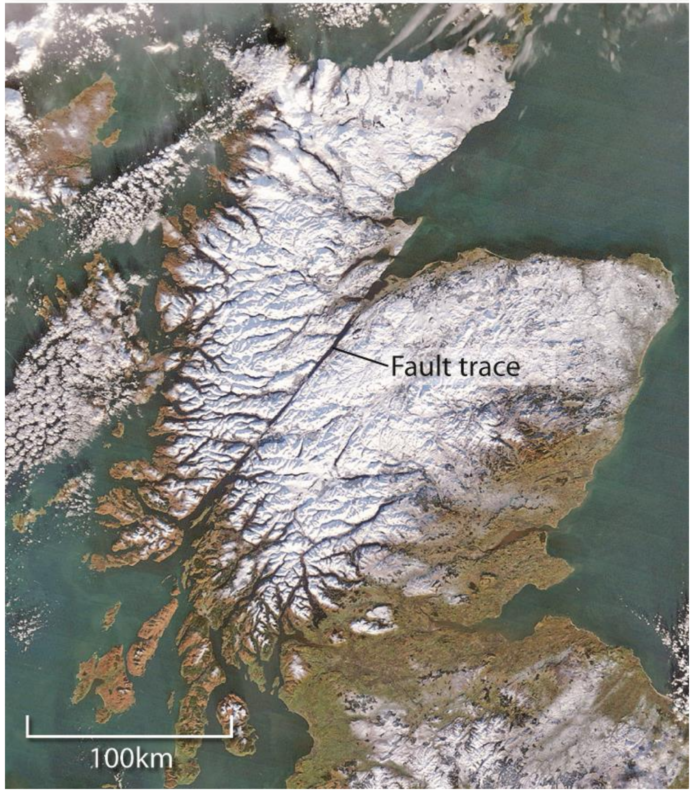
- A major earthquake may be preceded by foreshocks.
  - Smaller tremors indicating crack development in rock.
  - May warn of an impending large earthquake.
- Aftershocks usually follow a large earthquake.
  - May occur for weeks or years afterward.



Aftershock map of the August 23, 2011, 5.8M Earthquake near Mineral, Virginia
https://www.washingtonpost.com/news/capital-weather-gang/wp/2016/08/23/remembering-the-2011-virginia-earthquake-that-rocked-the-eastern-u-s/?utm_term=.7397d34a1583

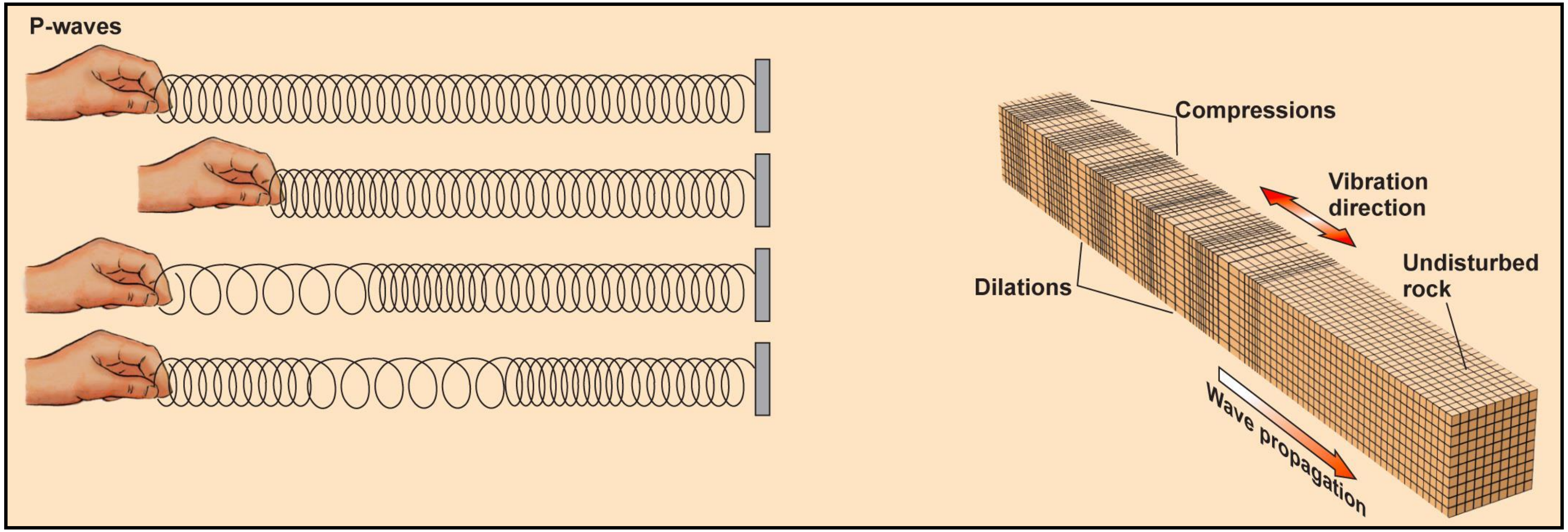
Amount of Slip on Faults

- How much does a fault slip during an earthquake?
  - Larger earthquakes have larger areas of slip.
    - Displacement is greatest near the hypocenter.
    - Displacement diminishes with distance.
- Fault slip is cumulative.
  - Faults can offset rocks by hundreds of kilometers over geologic time.



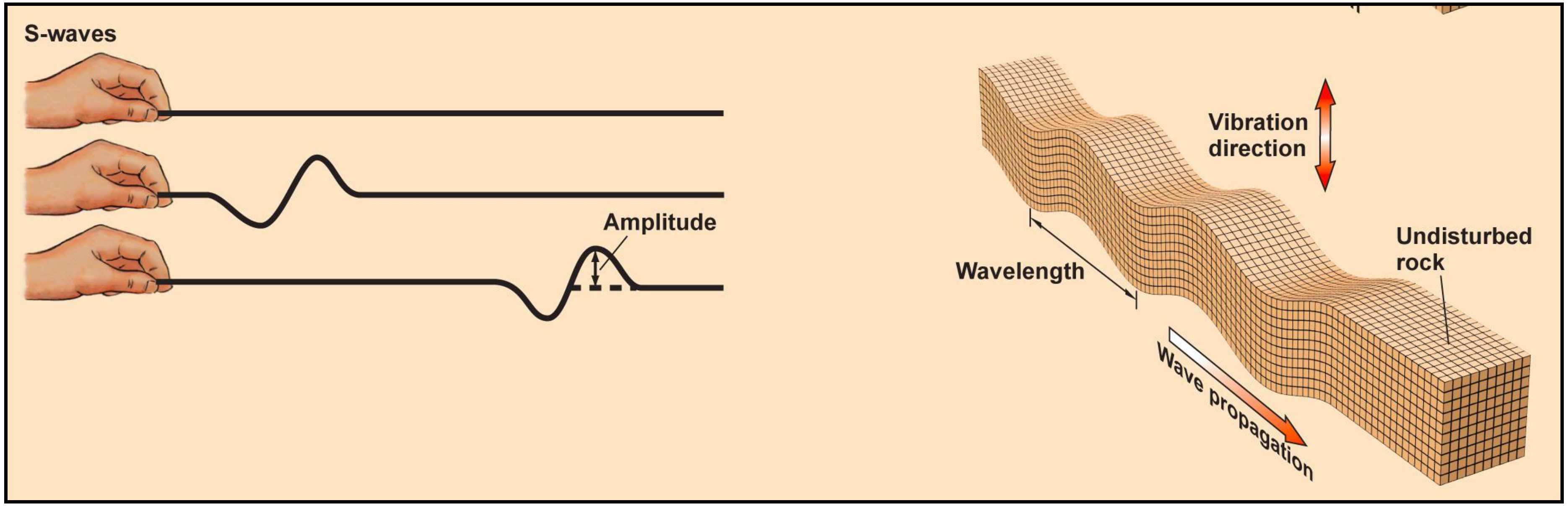
Seismic Waves

- **Body waves—pass through Earth's interior.**
  - **P-waves (primary or compressional waves).**
    - **Waves travel by compressing and expanding material.**
    - **Material moves back and forth parallel to wave direction.**
    - **P-waves are the fastest.**
    - **They travel through solids, liquids, and gases.**



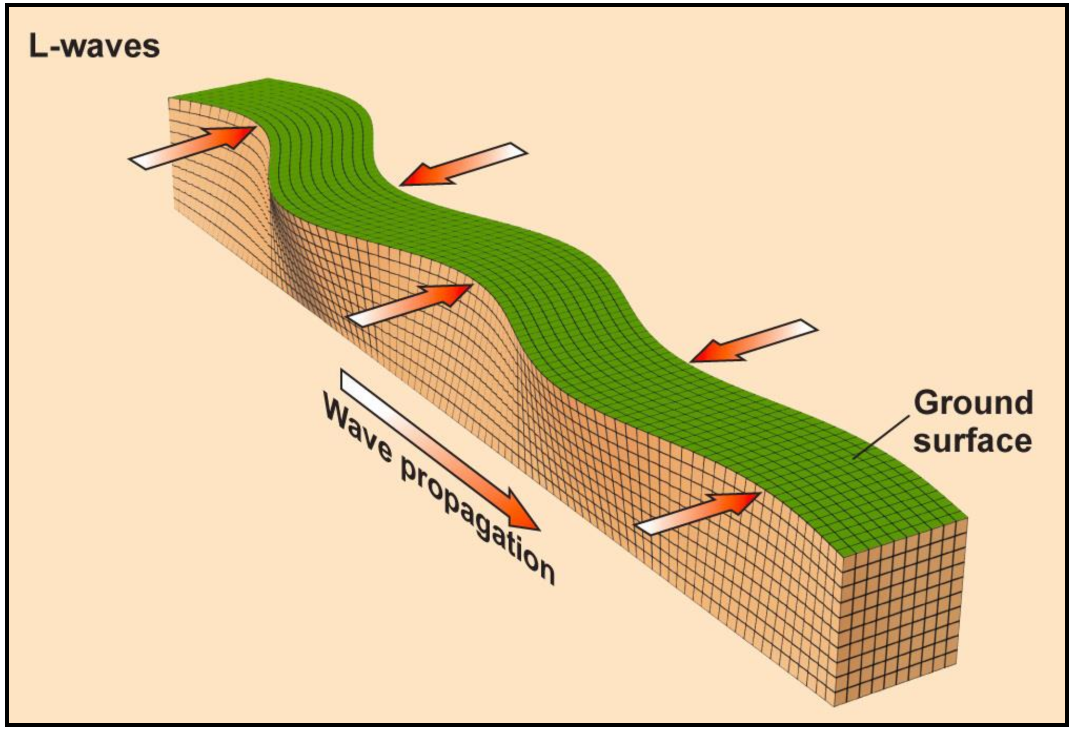
Seismic Waves

- Body waves—pass through Earth's interior.
  - S-waves (secondary or shear waves).
    - Waves travel by moving material back and forth.
    - Material moves perpendicular to wave travel direction.
    - S-waves are slower than P-waves.
    - They travel only through solids, never liquids or gases.



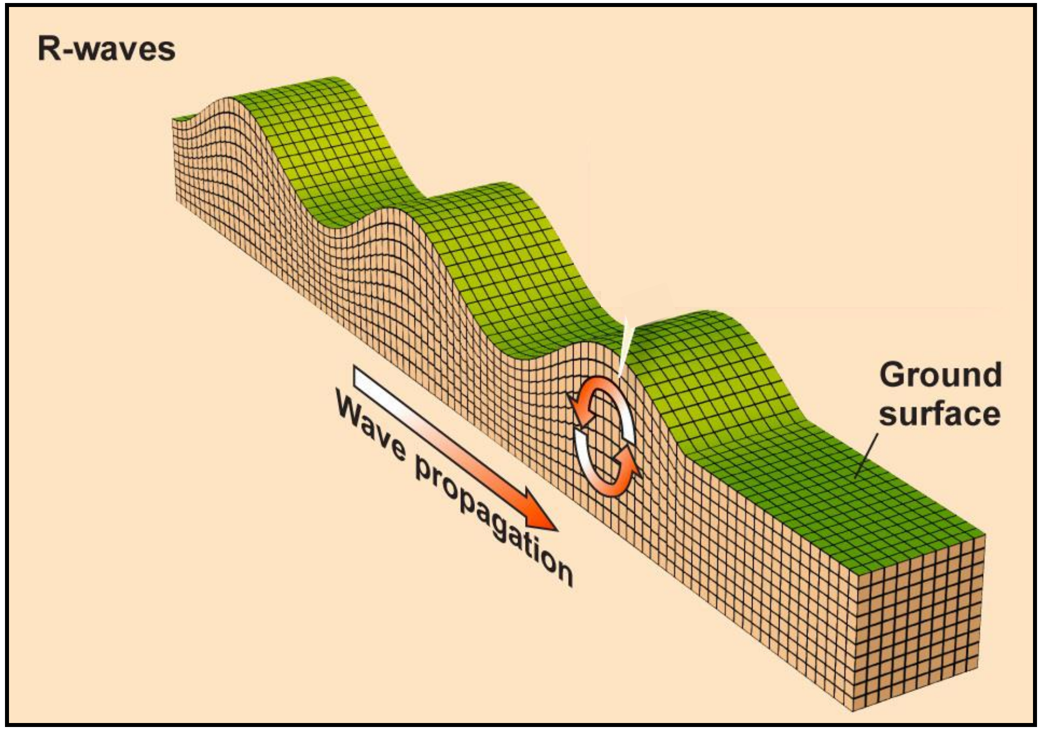
Seismic Waves

- Surface waves—travel along Earth's exterior.
- Surface waves are the slowest and most destructive.
  - L-waves (Love waves)
    - S-waves that intersect the land surface.
    - Move the ground back and forth like a writhing snake.



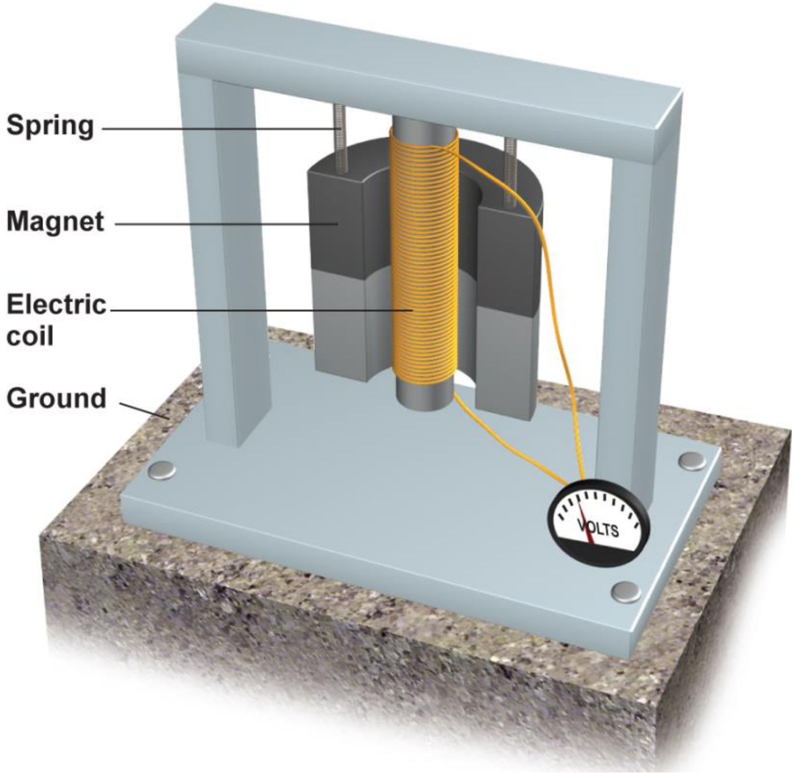
Seismic Waves

- **Surface waves—travel along Earth's exterior.**
  - **R-waves (Rayleigh waves)**
    - **P-waves that intersect the land surface.**
    - **Cause the ground to ripple up and down like water.**



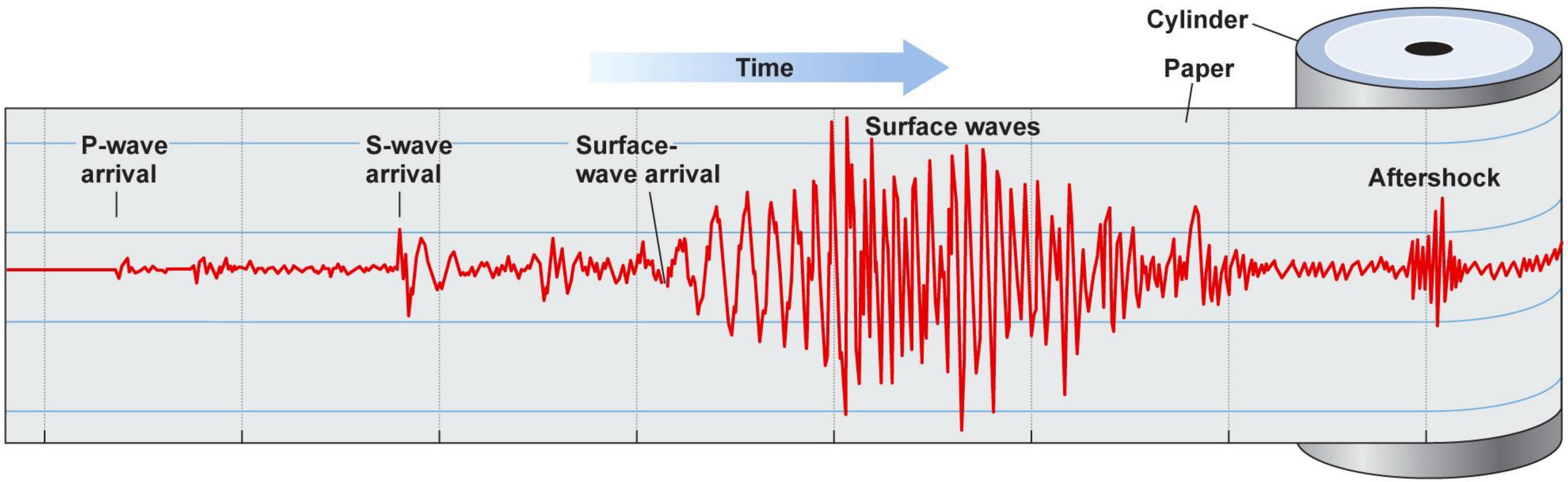
How Do We Measure Earthquakes?

- **Seismometer—instrument that records ground motion.**
  - **Modern seismometers use a magnet and electric coil.**
  - **Record data digitally.**
  - **Able to detect ground motion people cannot sense.**



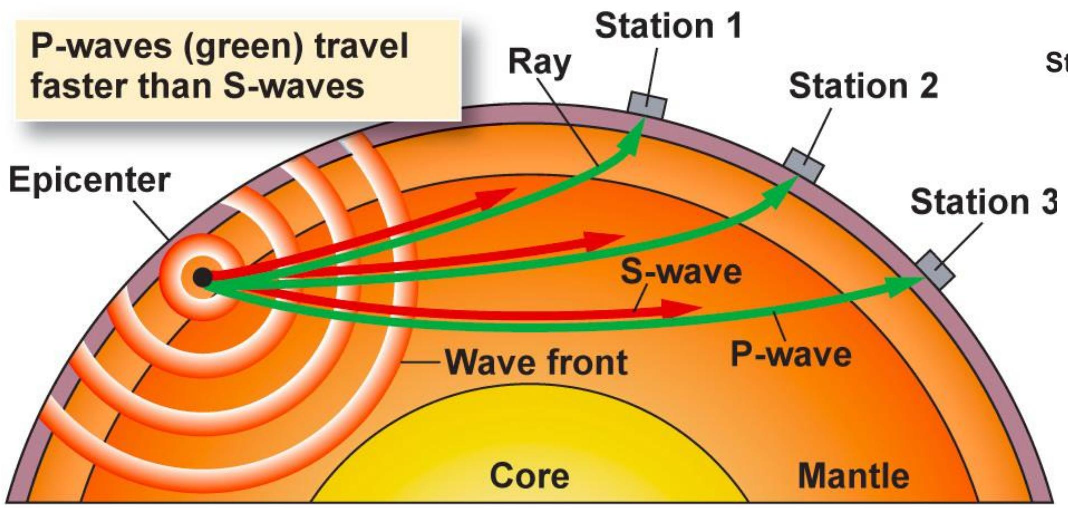
How Do We Measure Earthquakes?

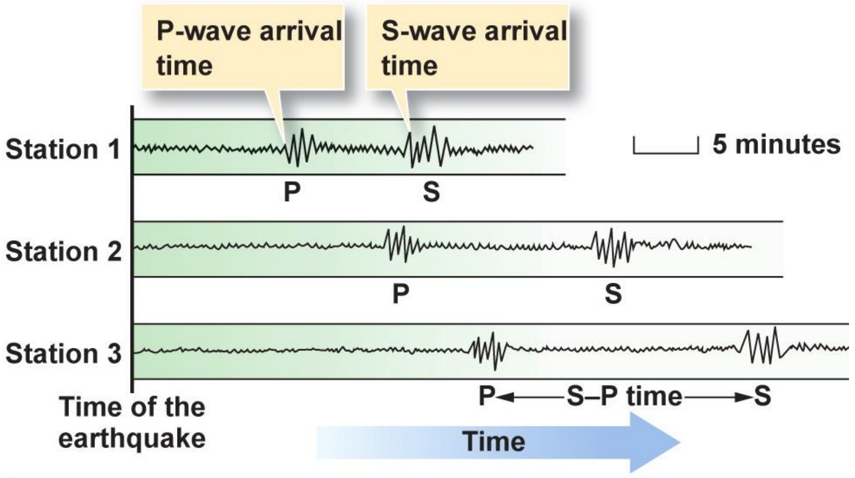
- **Seismogram—data recording earthquake wave behavior.**
  - **Earthquake waves arrive at a station in a specific order.**
    - **P-waves first**
    - **S-waves second**
    - **Surface waves last**
  - **Arrival times determine the distance to the epicenter.**



Finding the Epicenter

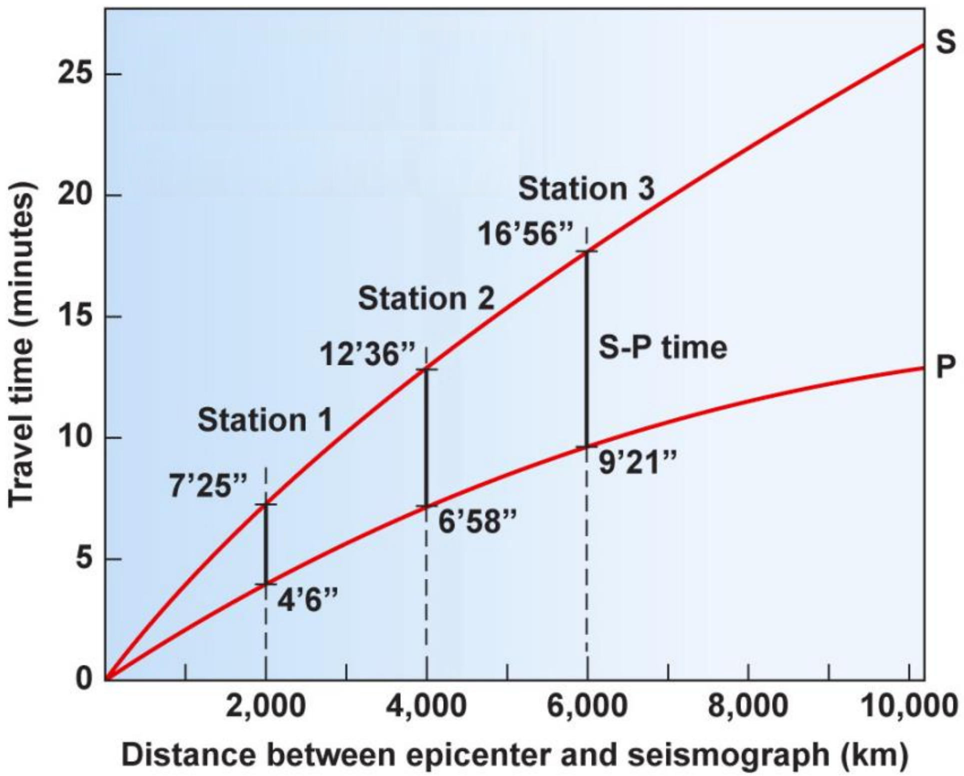
- P-waves always arrive first; then S-waves.
  - P-wave and S-wave arrivals are separated in time.
  - Separation grows with distance from the epicenter.
  - The time delay is used to establish this distance.





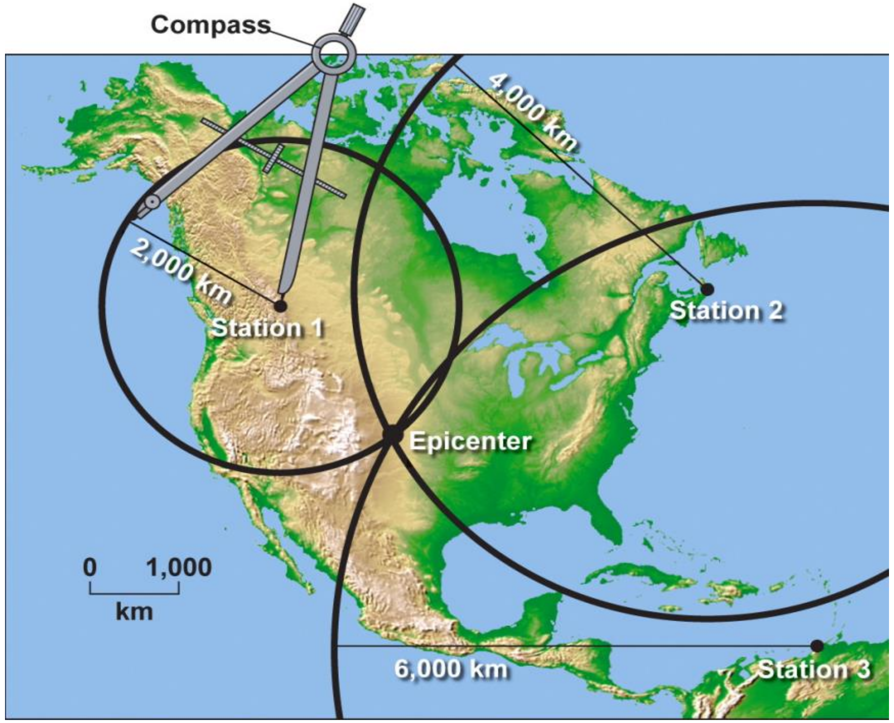
Finding the Epicenter

- P-wave and S-wave arrival times can be graphed.
- A travel-time curve plots the increasing delay in arrivals.
- The time gap yields the distance to the epicenter.



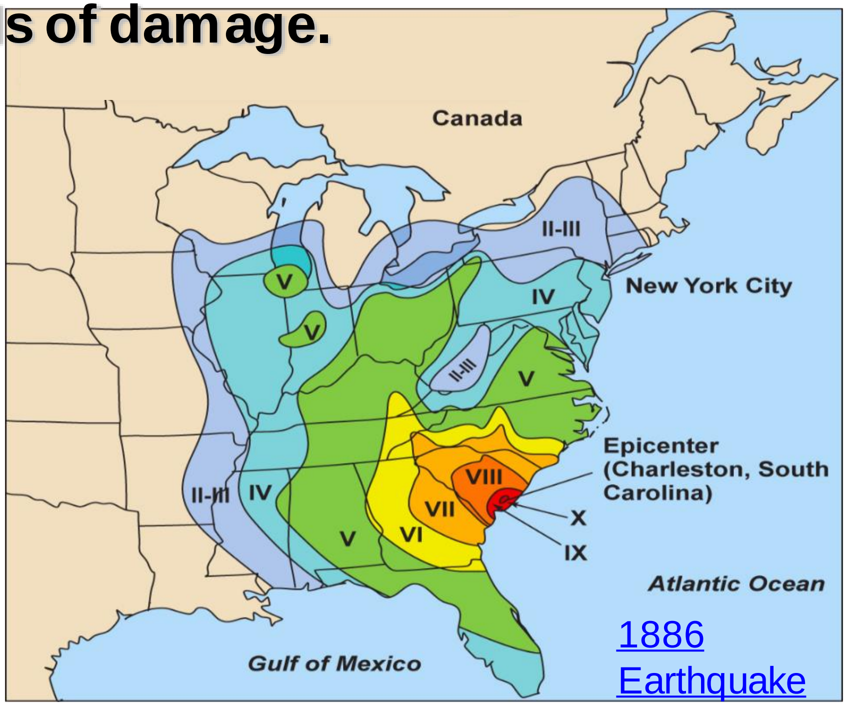
Finding the Epicenter

- Data from three or more stations pinpoints the epicenter.
  - The distance radius from each station is drawn on a map.
  - Circles around three or more stations will intersect at a point.
  - The point of intersection is the epicenter.
  - d ~ 13 (Ts – Tp) kilometres; where Ts – Tp is measured in seconds.



Earthquake Size

- **Earthquake size is described by two measurements.**
  - **The severity of damage (intensity) – a local measurement**
  - **The total radiated seismic energy measured at distance via ground motion (magnitude)**
- **Mercalli Intensity Scale -- amount of shaking damage.**
  - **Roman numerals assigned to different levels of damage.**
    - **I = low**
    - **XII = high**
  - **Damage occurs in zones.**
  - **Damage diminishes in intensity with distance.**

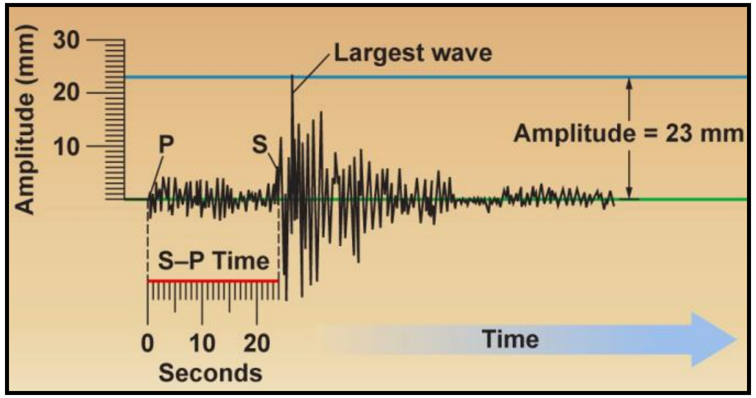


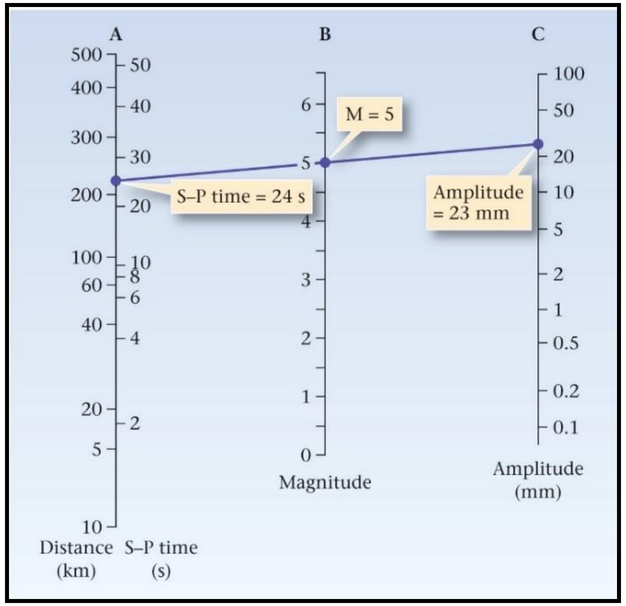
1886 Earthquake

Earthquake Size

- Magnitude—a uniform measurement of size.
  - The maximum amplitude of ground motion.
  - Measured by seismometer at a specific distance.
  - Several magnitude scales are used.
    - Richter Scale—useful near the epicenter.
    - Moment Magnitude Scale: M_w current scientific measure.

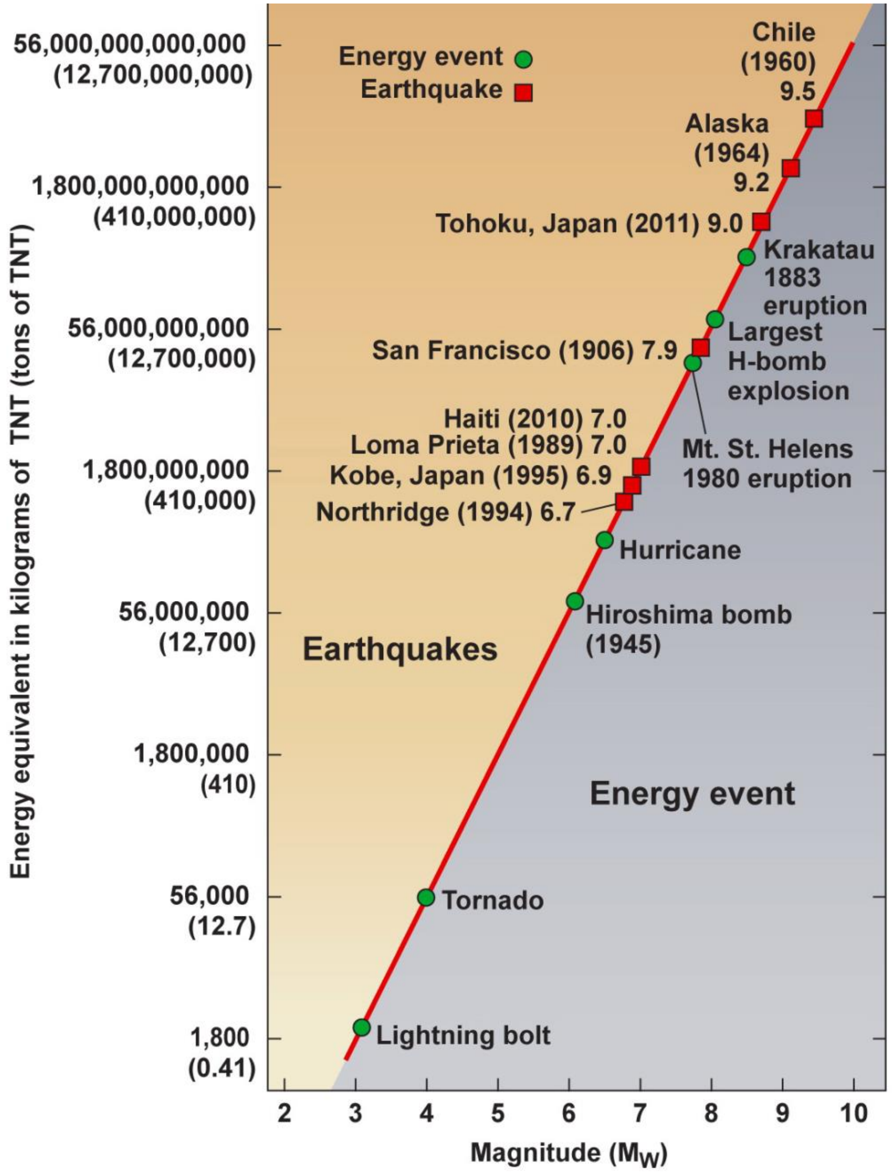
    Magnitude scales are $\log_{32}$ in energy
  - M_w 6.0 is 32 x M_w 5.0.
  - M_w 7.0 is 1000 x M_w 5.0.



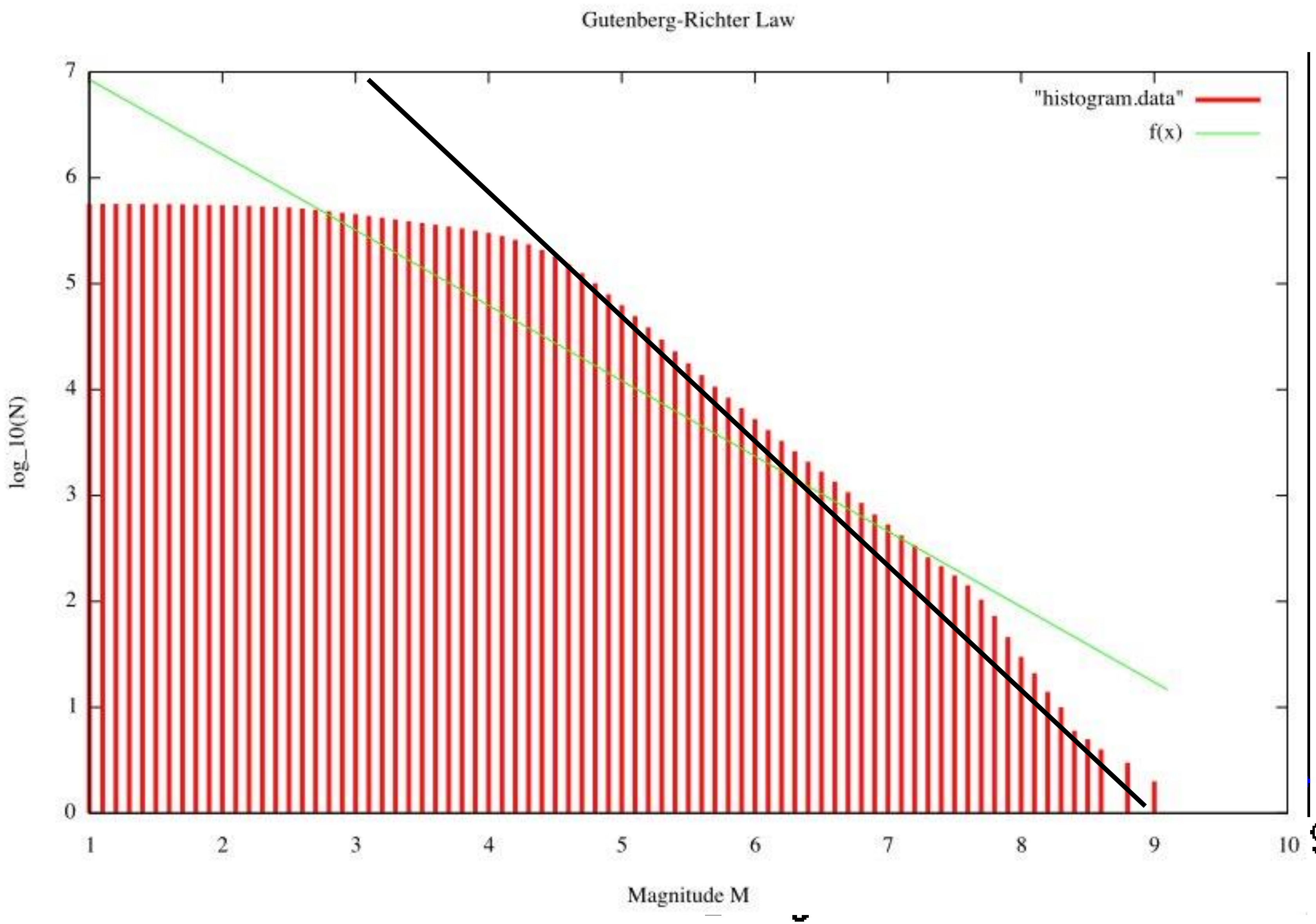


Measuring Earthquake Size

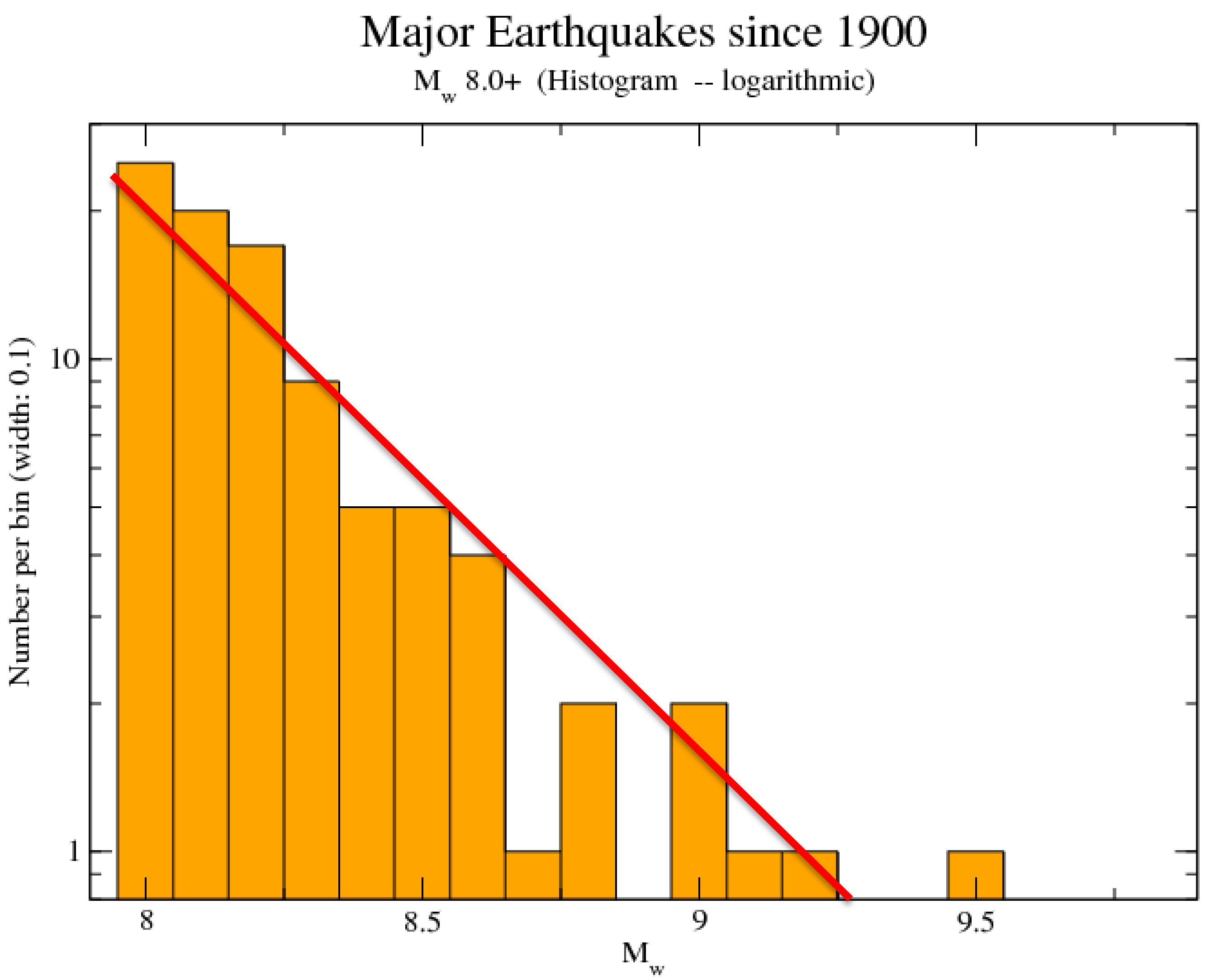
- Energy released can be calculated.
  - M_w 6.0— equivalent to the energy of the Hiroshima atomic bomb.
  - M_w 8.3 – equivalent to energy of the 1961 Tsar Bomba
  - An increase of one step in M_w is equivalent to a 32x increase in energy.



Numbers of earthquakes of size



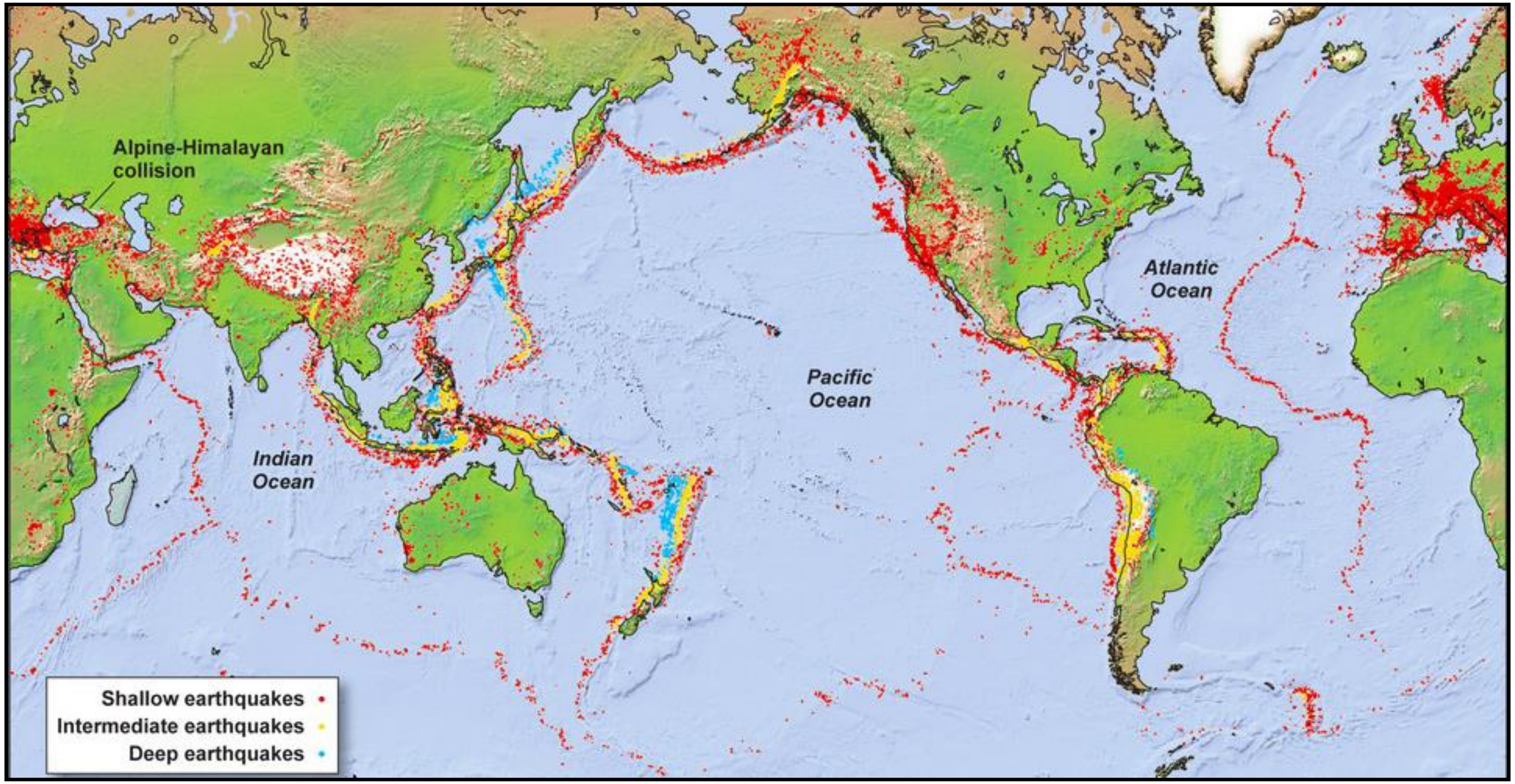
Major earthquakes since 1900



http://earthquake.usgs.gov/earthquakes/eqarchives/year/mag8/magnitude8_1900_date.php

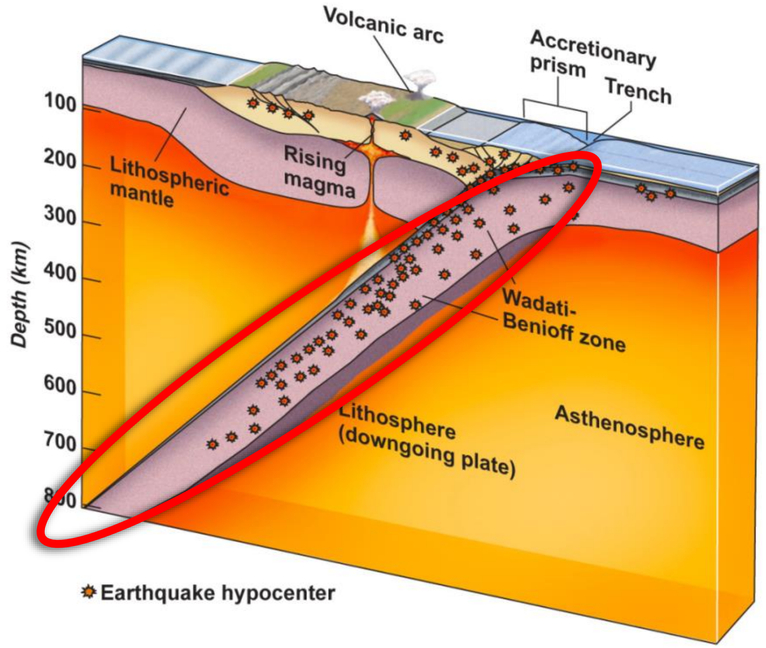
Earthquake Occurrence

- Earthquakes are linked to plate tectonic boundaries.
  - Shallow—divergent and transform boundaries.
  - Intermediate and deep—convergent boundaries.



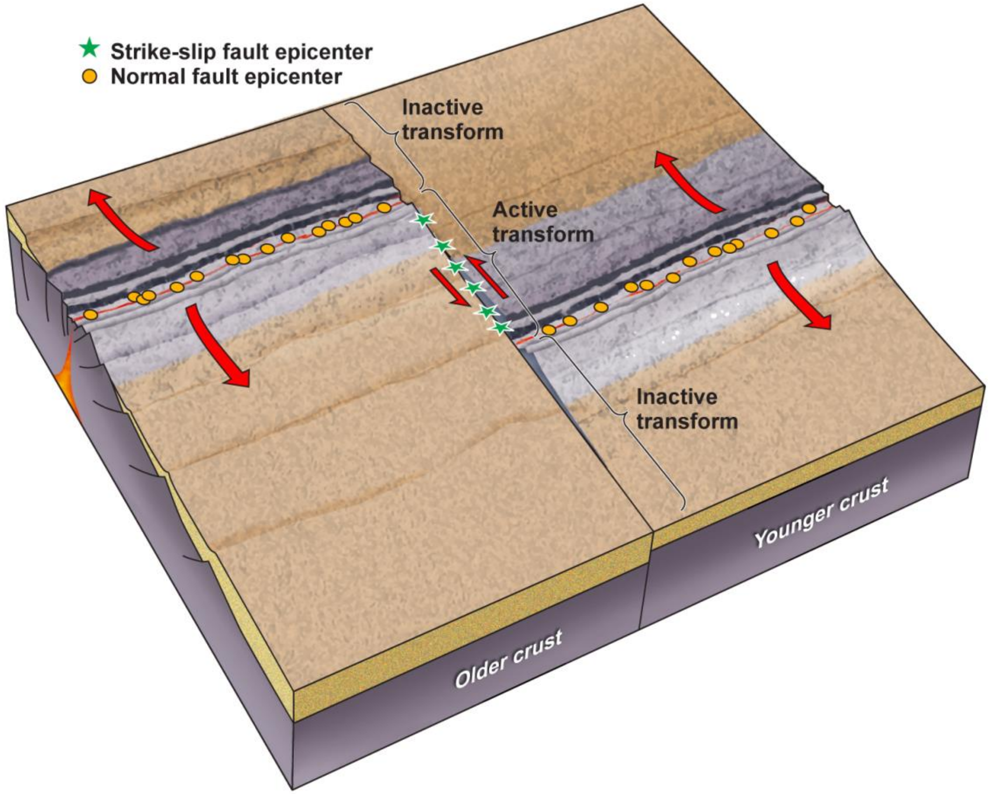
Earthquakes at Plate Boundaries

- **Convergent plate boundary—complicated boundary.**
  - **Intermediate and deep earthquakes are also common.**
    - **Wadati-Benioff zone—earthquakes trace descending slab.**
      - **Intermediate (20 to 300 km)—downgoing slab still cold and brittle.**
      - **Deep (300 to 660 km)—mineral phase changes create earthquakes.**
  - **Earthquakes rare below 660 km (mantle is ductile).**



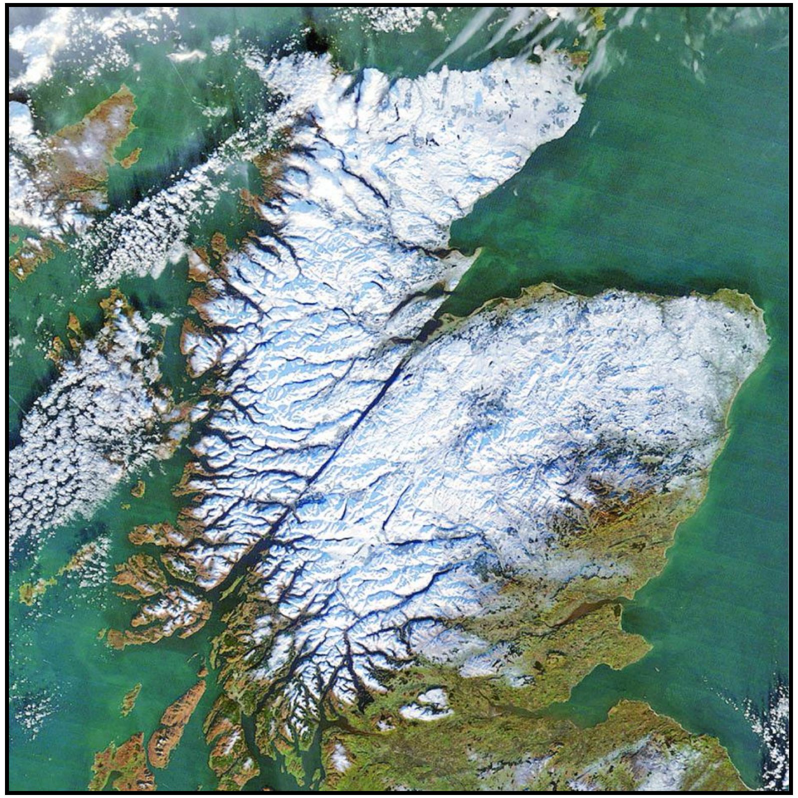
Earthquakes at Plate Boundaries

- Divergent plate boundary—mid-ocean ridges.
  - Develop two kinds of faulting.
    - Normal faults at the spreading ridge axis.
    - Strike-slip faults along transforms.
  - Shallow: <10 km deep.



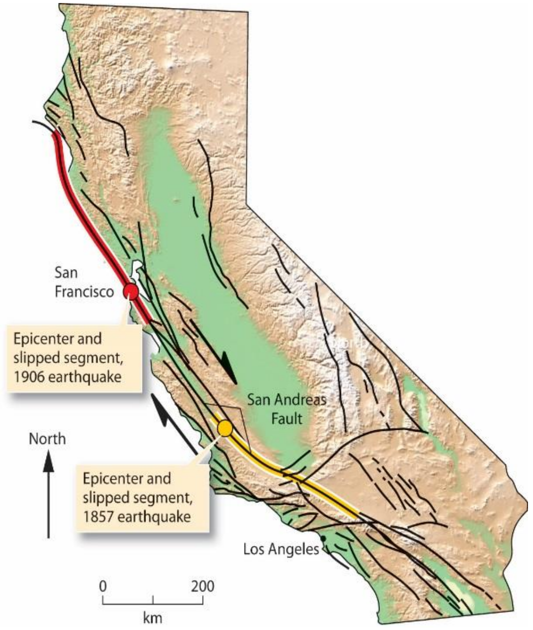
Earthquakes at Plate Boundaries

- **Transform plate boundary—plates slide past each other.**
  - **Transform earthquakes occur at shallow crustal levels.**
  - **Most transforms link segments of the mid-ocean ridge.**
  - **Some, however, cut through continental crust.**
    - **San Andreas Fault, California**
    - **Alpine Fault, New Zealand**
    - **Anatolian Fault, Turkey**
    - **Great Glen Fault, Scotland**
  - **Large transform earthquakes on continents are usually major disasters.**



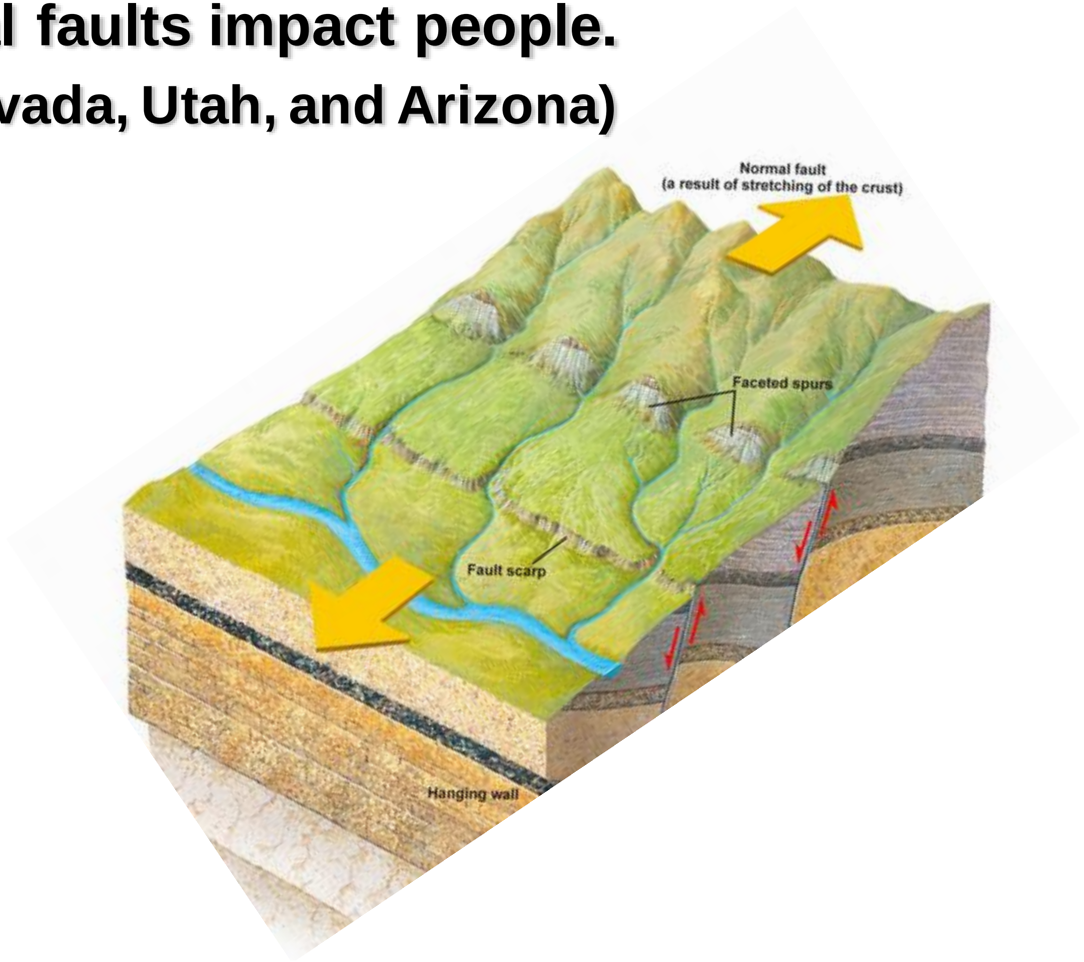
Earthquakes at Plate Boundaries

- The San Andreas Fault cuts through western California.
  - The Pacific plate shears north; the North American plate south.
- The San Andreas is a very active strike-slip fault.
  - A very dangerous fault; hundreds of earthquakes per year.
  - San Francisco was destroyed in 1906 by an ~M_w 7.9.
  - Other large earthquakes loom.



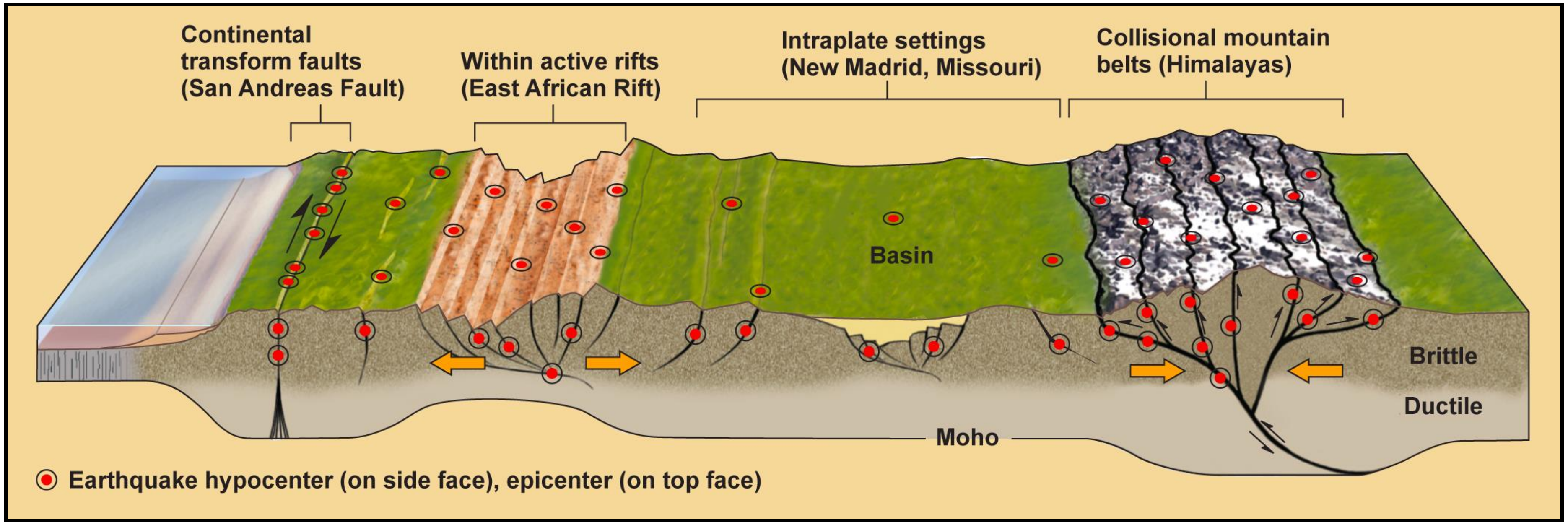
Earthquakes in Continental Crust

- Continental rifts—stretching creates normal faults.
  - Generate shallow earthquakes similar to mid-ocean ridge.
  - Unlike the MOR, these tensional faults impact people.
    - Basin and Range Province (Nevada, Utah, and Arizona)
    - Rio Grande Rift (New Mexico)
    - East African Rift



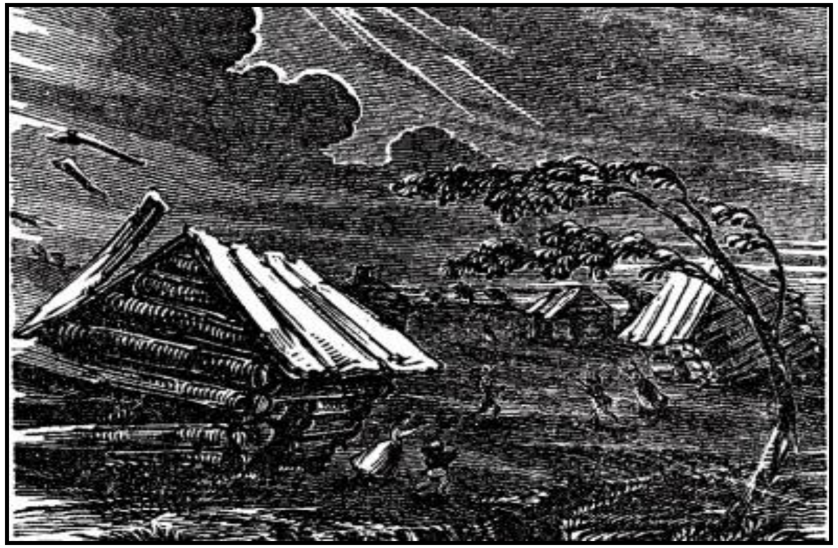
Earthquakes in Continental Crust

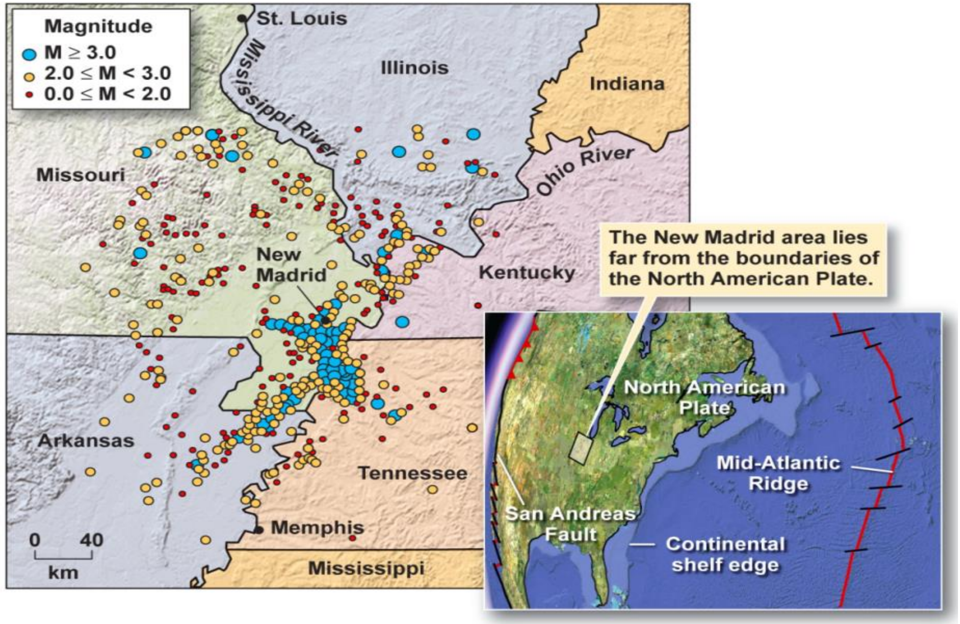
- Collision zones—orogenic crustal compression.
  - Continental lithosphere compresses along thrust faults.
  - Earthquakes can be very large.
  - Orogenic uplift creates landslide hazards.



Intraplate Earthquakes

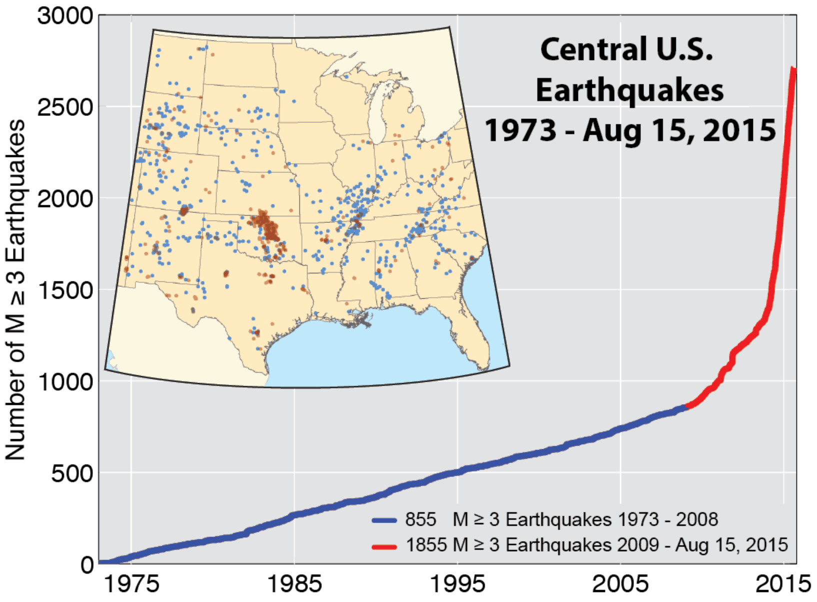
- About 5% of earthquakes are not near plate boundaries.
  - Remnant crustal weakness in former fault zones ancient plate boundaries.
- Three ~ M_w 7.0 earthquakes struck New Madrid, Missouri, in 1811–12.
  - Reversed the flow of the Mississippi.
  - Deep ancient rift zone?

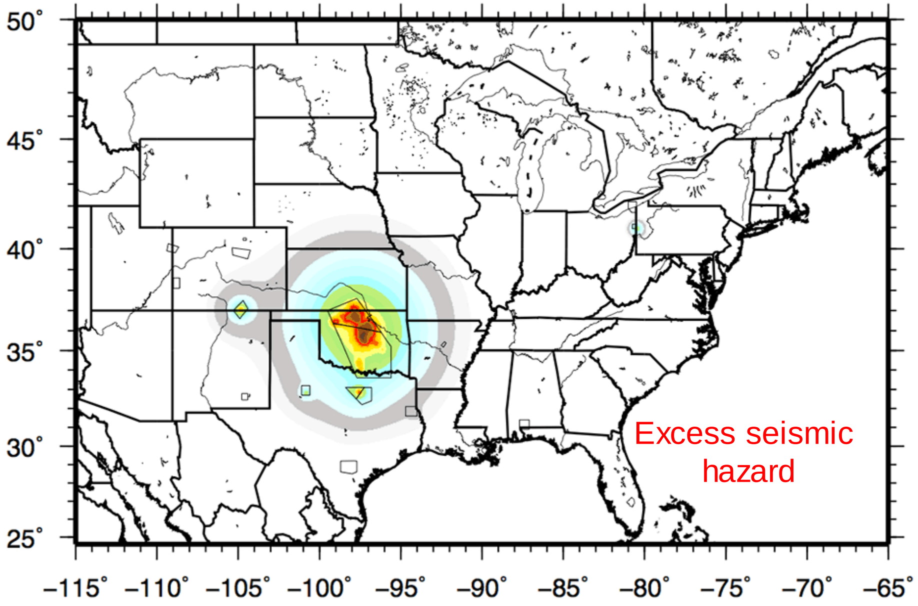




Human induced earthquakes

- Injection of fluids under very high pressure into the crust of the Earth can mobilize existing faults or even cause new fault fractures. One of the most studied areas where “fracking” for oil and gas development is causing earthquakes is in southern Oklahoma... While these are relatively small (M_w < 5) events, they are locally damaging.





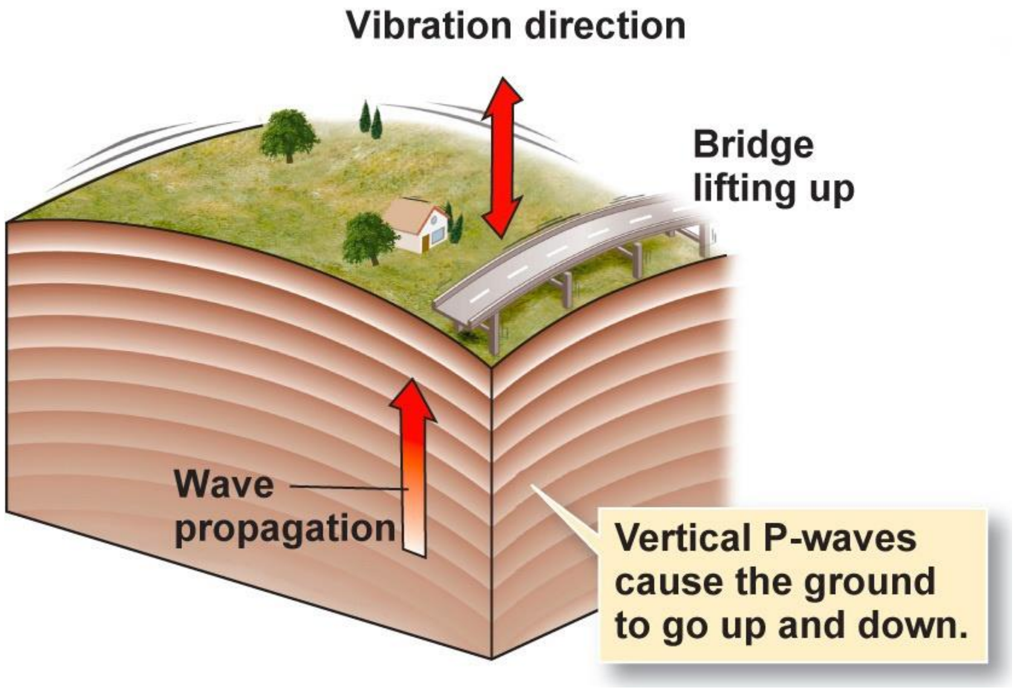
http://earthquake.usgs.gov/research/induced/

Earthquake Damage

- **Earthquakes kill people and destroy cities.**
- **Damage can be widespread, horrific, and heartbreaking.**
- **Many processes contribute to the destruction.**

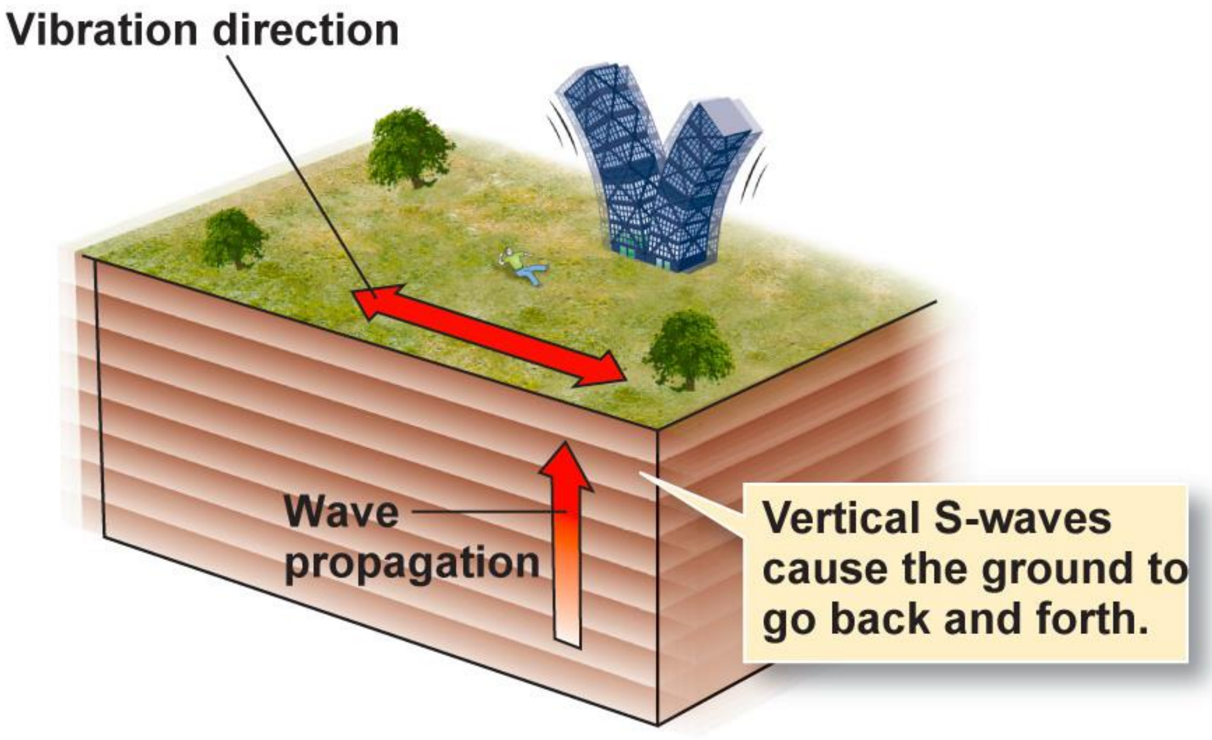
Earthquake Damage

- Ground shaking and displacement.
  - Earthquake waves arrive in a distinct sequence.
  - Different waves cause different motion.
- P-waves are the first to arrive.
  - They produce a rapid, bucking, up-and-down motion.



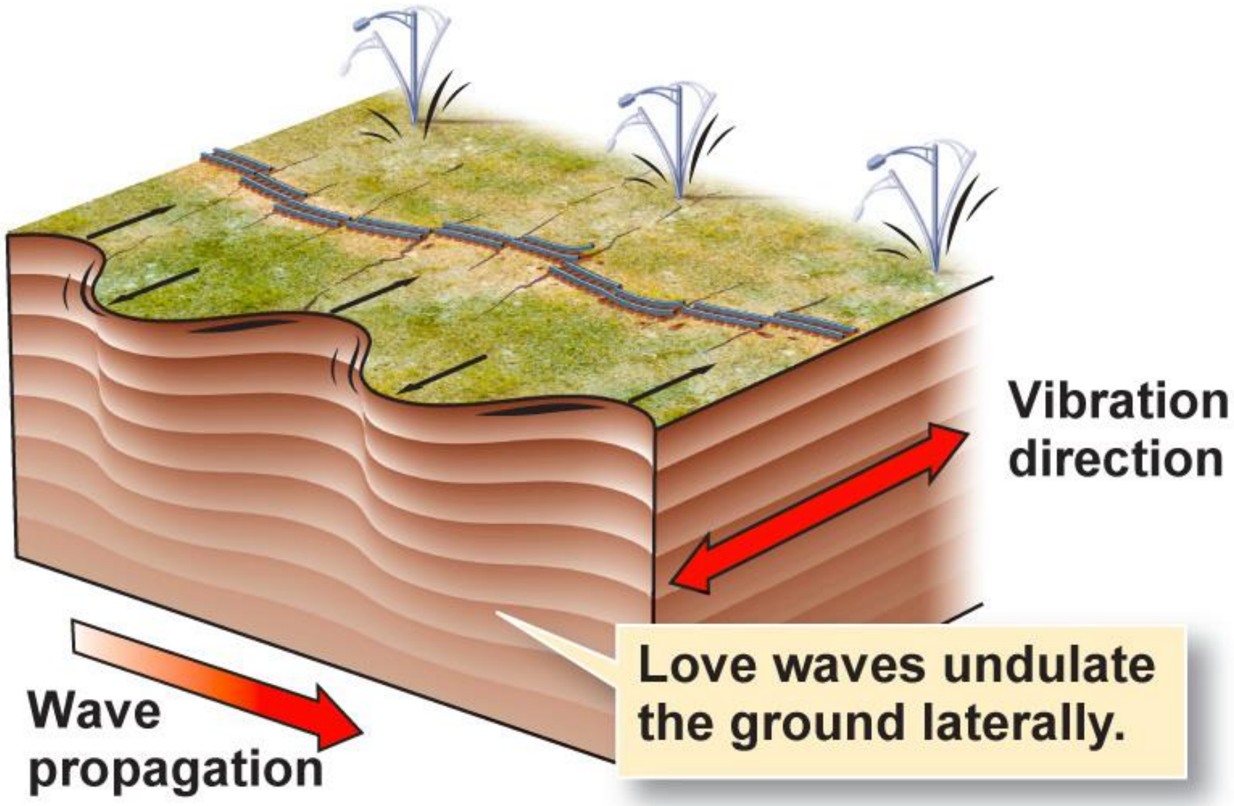
Earthquake Damage

- **S waves arrive next (second).**
  - **They produce a pronounced back-and-forth motion.**
  - **This motion is much stronger than that from P-waves.**
  - **S-waves cause extensive damage.**



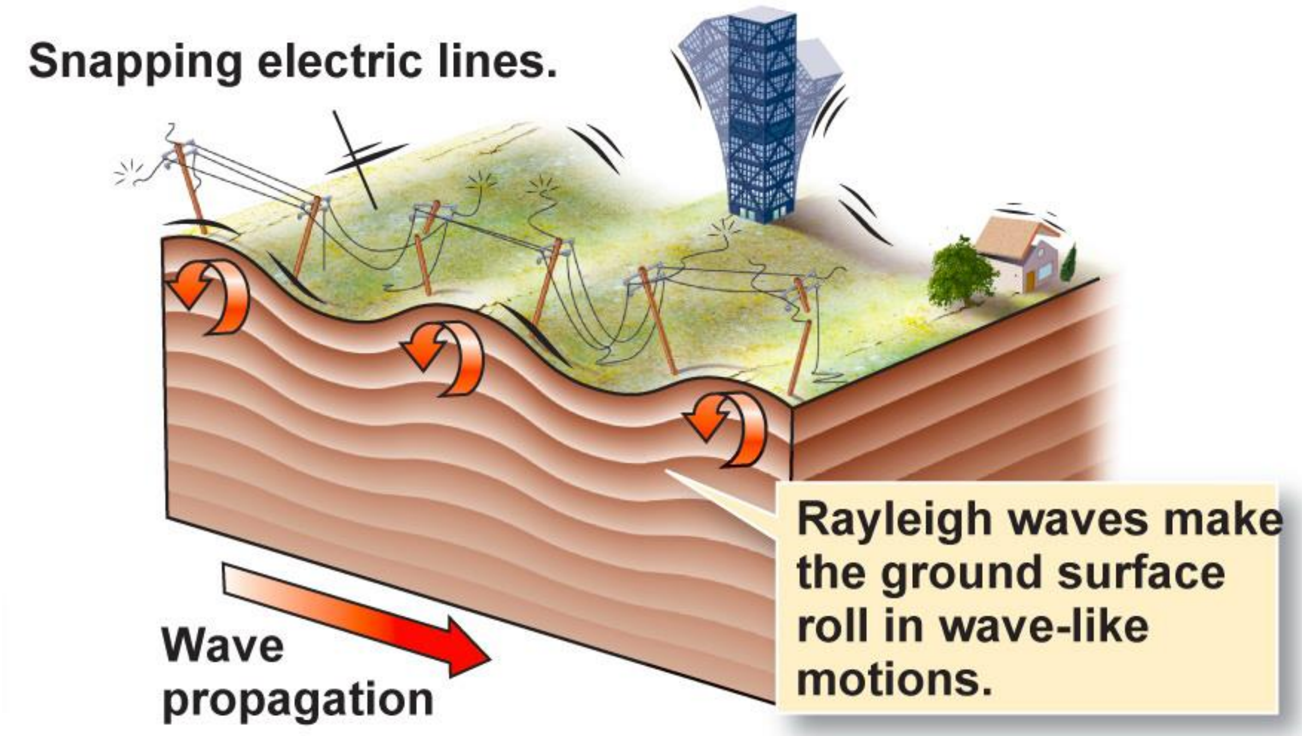
Earthquake Damage

- **Surface waves are delayed traveling along the exterior.**
  - **L-waves follow quickly behind the S-waves.**
  - **They cause the ground to writhe like a snake.**



Earthquake Damage

- R-waves are the last to arrive.
  - The land surface undulates like ripples across a pond.
  - These waves usually last longer than the other kinds.
  - R-waves cause extensive damage.



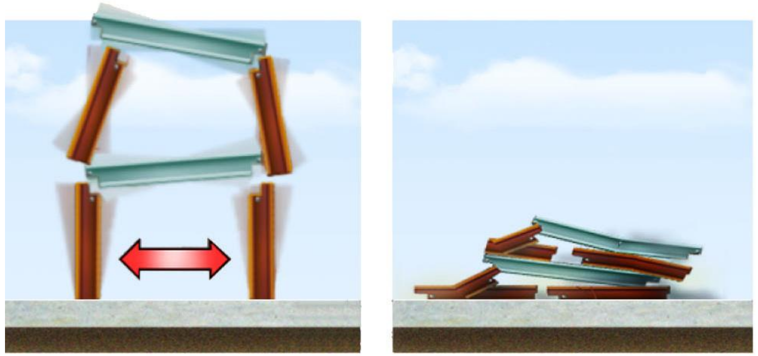
Earthquake Damage

- Severity of shaking and damage depends on:
  - The magnitude (energy) of the earthquake.
  - The distance from the focus.
  - The nature of the subsurface material.
    - Bedrock transmits seismic waves quickly = less damage.
    - Sediments reflect and refract waves = amplified damage.
  - The frequency of the earthquake waves.

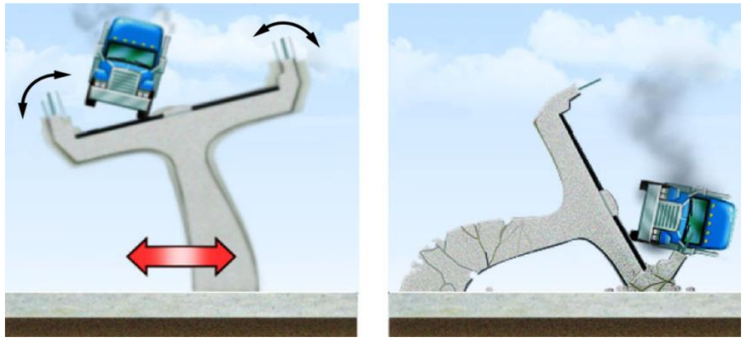
Cypress St. Viaduct, Nimitz Freeway

Earthquake Damage

- Ground shaking
  - Building floors "pancake."

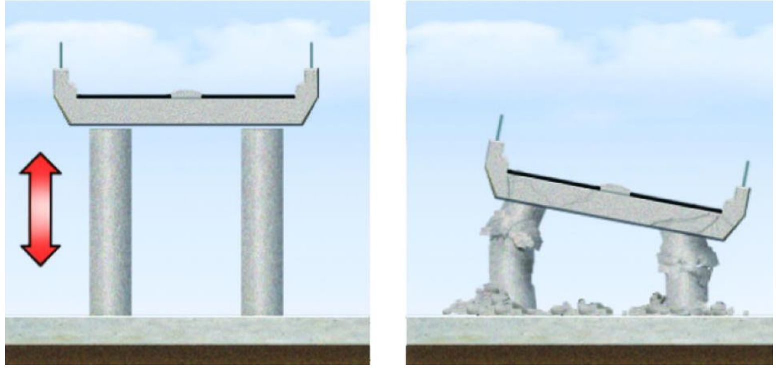


  - Bridges and roadways topple.



Earthquake Damage

- Ground shaking.
  - Bridge supports are crushed.



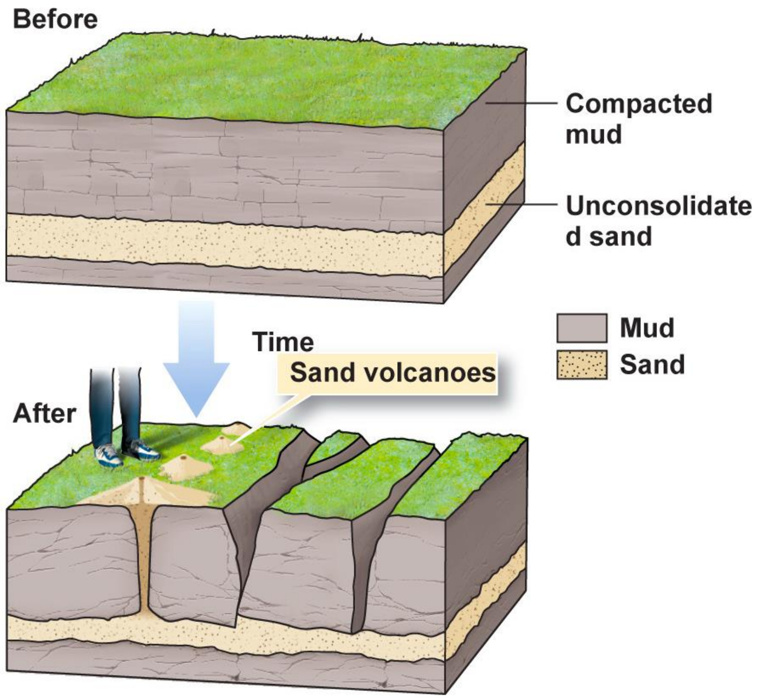
  - Masonry walls break apart.

Earthquake Damage

- Landslides and avalanches.
  - Shaking causes material on steep slopes to fail.
  - Hazardous slopes bear evidence of ancient slope failures.
  - Landslides frequently accompany earthquakes in uplands.

Earthquake Damage

- Liquefaction—waves liquefy H_2O-filled sediments.
  - Groundwater forces grains apart reducing friction.
  - Liquefied sediments flow as a slurry.
  - Sand becomes “quicksand”: clay becomes “quickclay.”
  - Sand blows and sand volcanoes disrupt ground surface.



Liquefaction

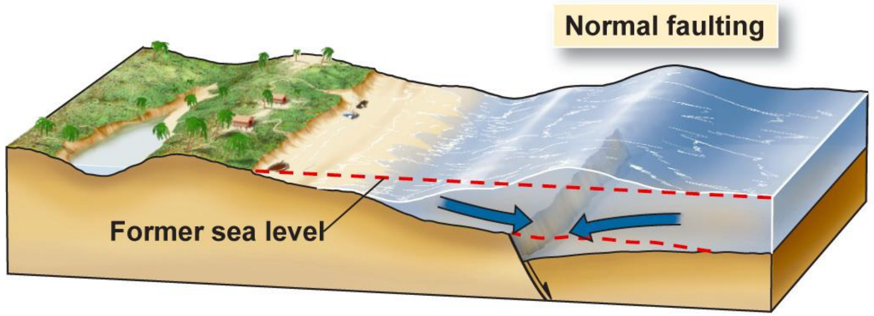
- Liquefaction causes soil to lose strength.
- Land, and the structures on it, will slump and flow.
- Buildings may founder and topple over intact.

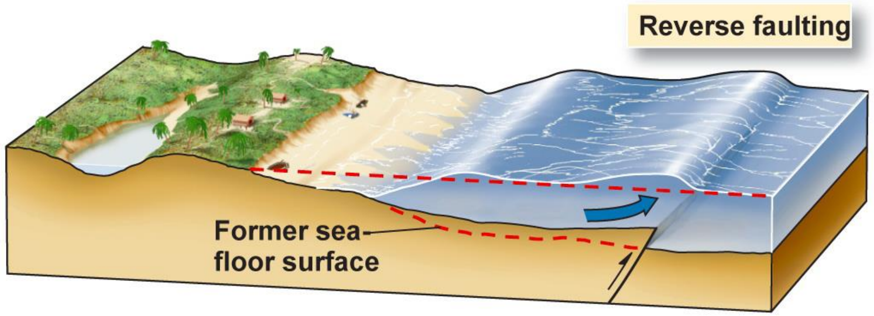
Earthquake Damage

- Fire is a frequently realized earthquake hazard.
  - Shaking topples stoves, candles, and power lines.
  - Broken gas mains and fuel tanks ignite a conflagration.
  - Infrastructure (water, sewer, electricity, roads) destroyed.
  - Firefighters are often powerless to combat fire.
    - No road access, no water.
    - Too many hot spots.
  - Fire may greatly magnify the destruction and toll in human lives.

Earthquake Damage

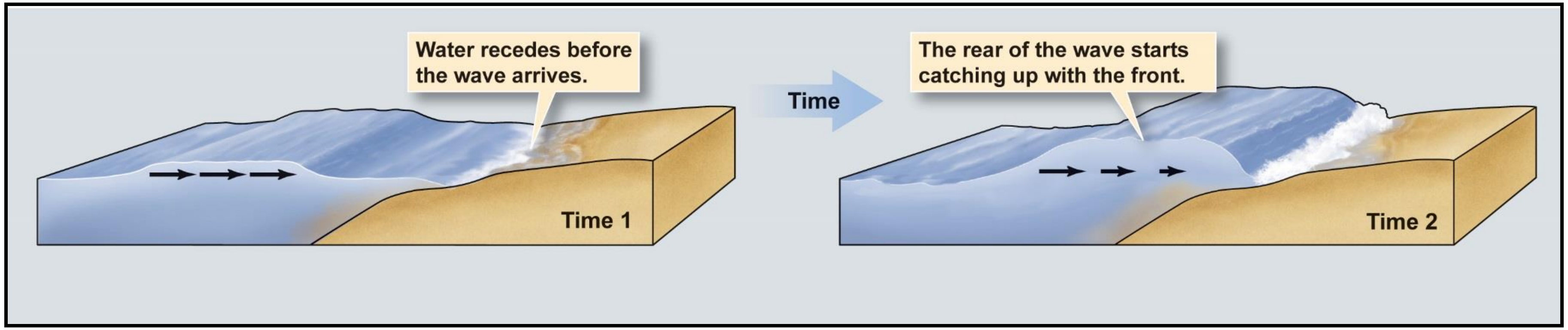
- Tsunami (Japanese for *harbour wave*)
  - Tsunamis result from displacement of the sea floor.
    - Earthquake, submarine landslide, or volcanic explosion.
  - Faulting displaces the entire volume of overlying water.
    - A giant mound (or trough) forms on the sea surface.
    - This feature may be enormous (up to a ten thousand square mile area).
    - Feature collapse creates waves that race rapidly away.





Earthquake Damage

- Destructive tsunamis occur frequently—about one a year.
  - There have been 94 destructive tsunamis through the 20th century
  - They have caused about 350,000 human deaths. Future tsunami disasters are inevitable.
  - Growing human population in low-lying coastal areas.
- Education about tsunamis can save many lives.

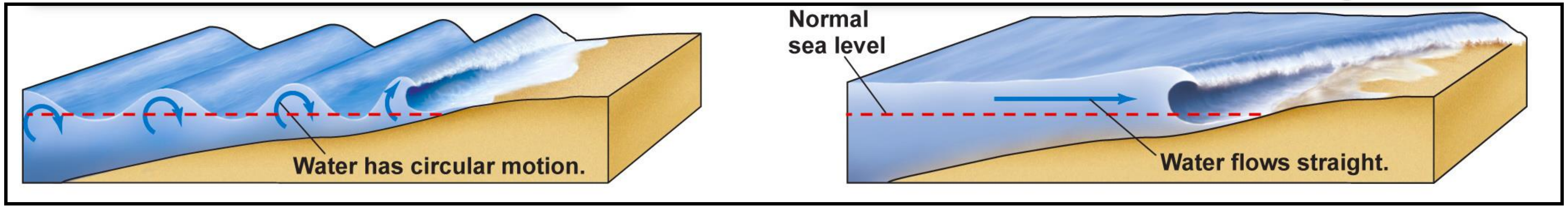


Earthquake Damage

- Tsunamis race at jetliner speed across the ocean.
- They may be almost imperceptible in deep water.
  - Low wave height (amplitude), long wavelength (frequency).
- As water shallows, waves slow from frictional drag.
  - Waves grow in height, reaching 10 to 15 m or even more.
- Tsunami waves are very different from wind-driven waves.

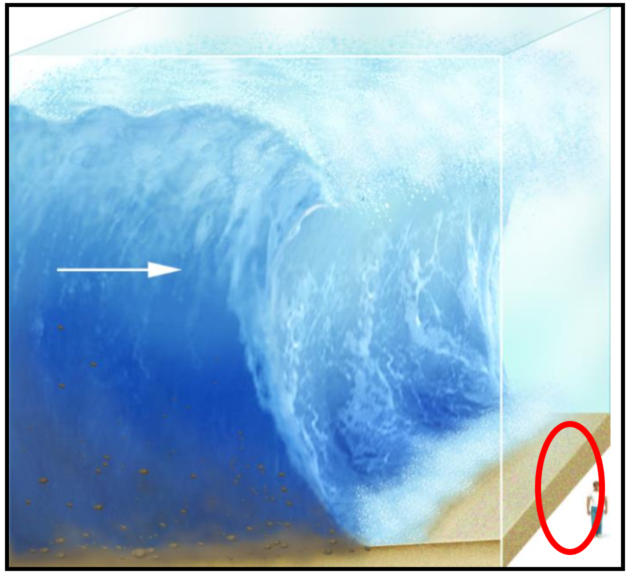
Earthquake Damage

- **Wind waves**
  - Influence the upper ~100 m.
  - Have wavelengths of several tens to hundreds of m.
  - Wave height and wavelength related to wind speed.
  - Wave velocity maximum several tens of km per hour.
  - Waves break in shallow water and expend all stored energy.
- **Tsunami waves**
  - Influence entire water depth.
  - Have wavelengths of several tens to hundreds of kilometers.
  - Wave height and wavelength unaffected by wind speed.
  - Wave velocity maximum several hundreds of km per hour.
  - Waves arrive as a raised plateau that pours onto the land with minor dissipation.



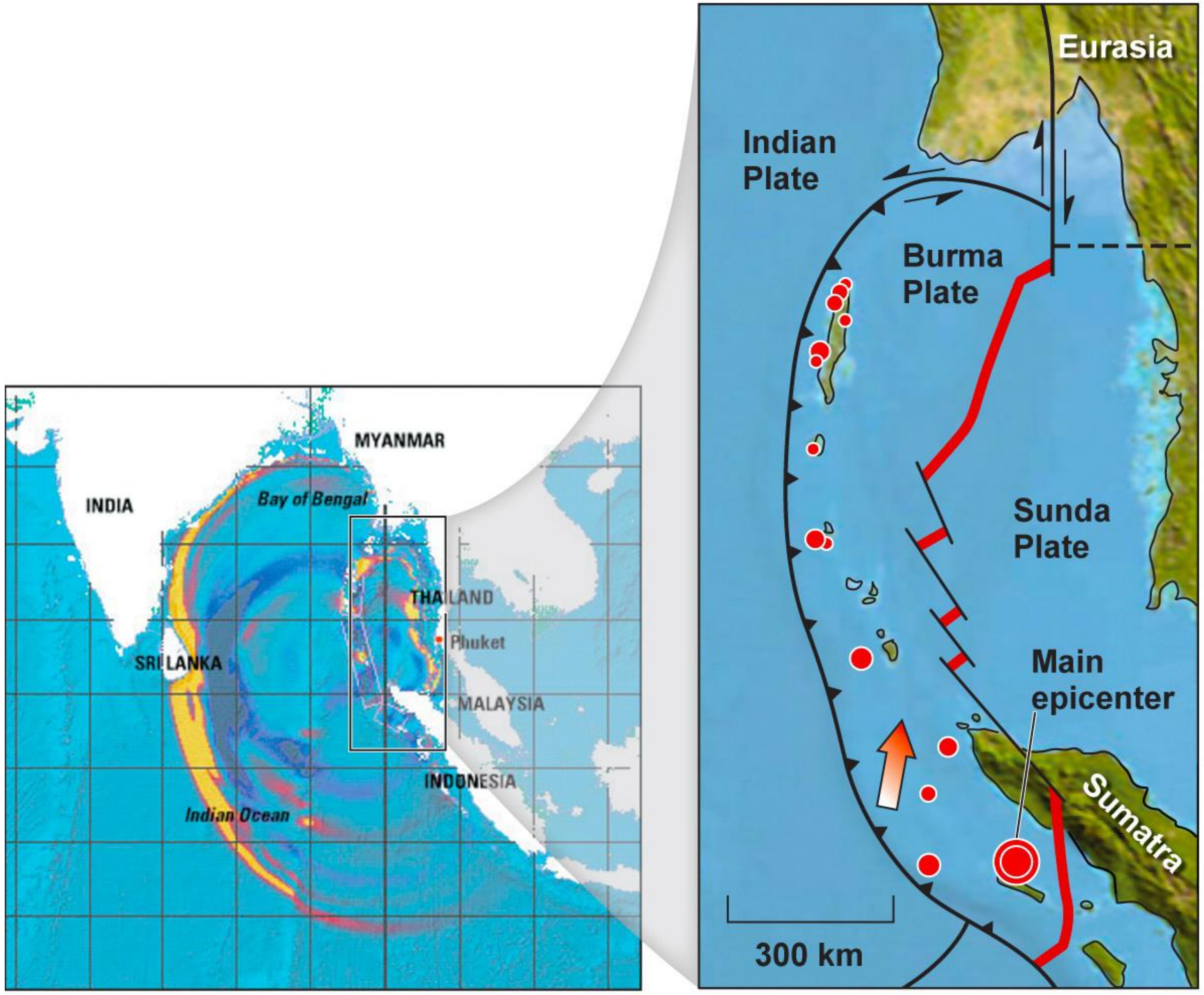
Earthquake Damage

- The catastrophic Indian Ocean tsunami (December 26, 2004).
  - A large earthquake (M_w 9.0+) -- trench off northwest Sumatra.
  - Largest earthquake in 40 years.
  - Displacement exceeded 15 m; rupture >1,300 km long.
  - Killed more than 250000 people.



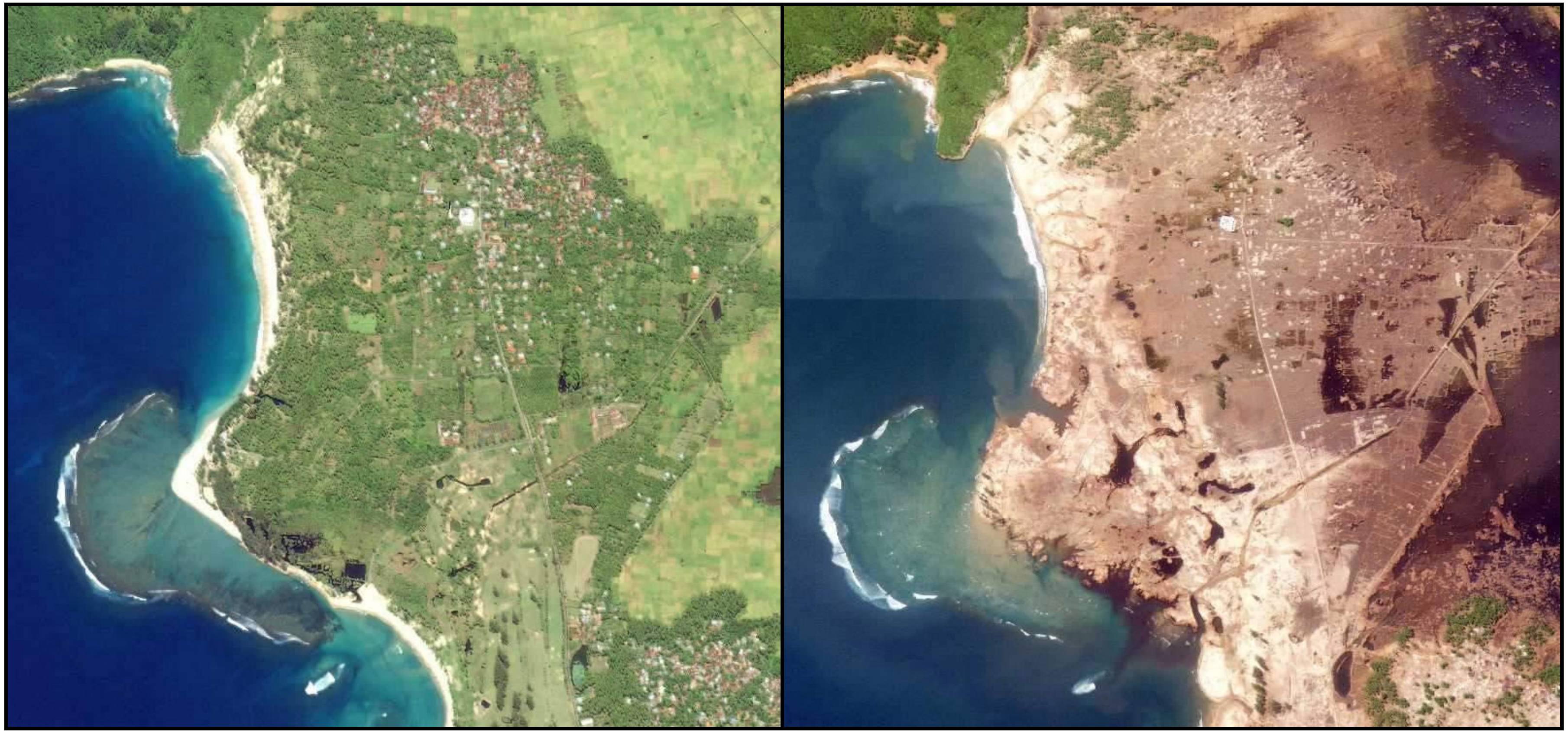
Earthquake Damage

- Tsunami destroyed coastlines around the Indian Ocean.
- Huge death tolls:
  - Northern Sumatra
  - Thailand
  - Malaysia
  - Sri Lanka



Earthquake Damage

- Complete devastation below "run-up" elevation.
  - Dense development in Banda Aceh, Sumatra, hardest hit.
  - Entire communities were erased—buildings and people.



Earthquake Damage

- **Tohoku-Oki tsunami destroyed the northeast coast of Japan.**
  - **M_w 9.0 earthquake 130 km offshore.**
  - **Tsunami waves began to arrive in 10 minutes.**
  - **Waves erased entire villages, ~ 18000 direct deaths.**

Earthquake Damage

- The Fukushima nuclear power plant was inundated.
  - Water breached the seawalls placed to protect the plant.
  - About 14 m (46 ft) of water shut down the plant.
  - Hydrogen explosions destroyed the reactor buildings.

Tsunami Prediction

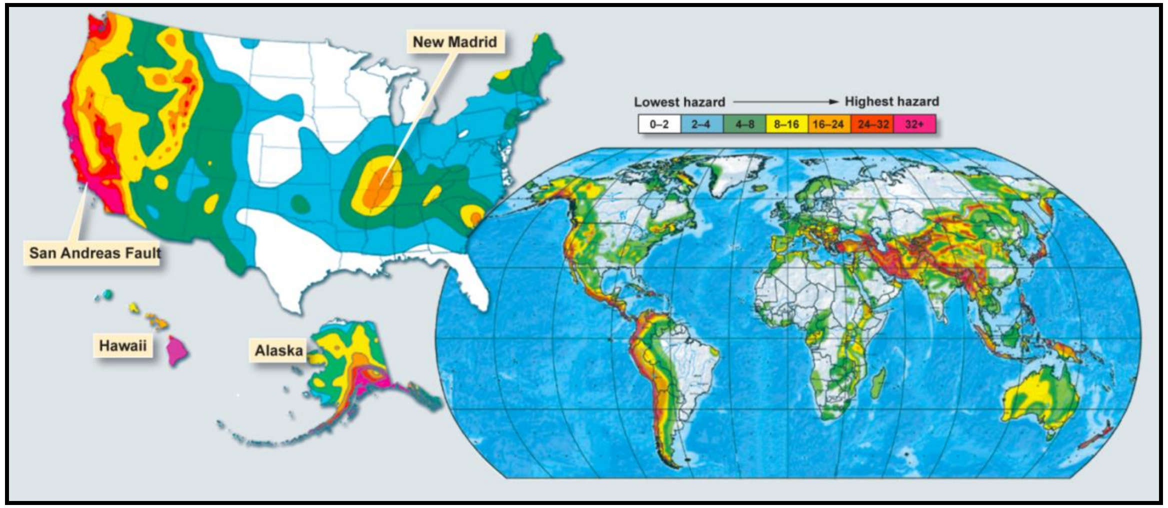
- Scientific modeling predicts tsunami behavior.
- A tsunami warning center (Hawaii) tracks Pacific quakes.
- Tsunami detection is expanding.
  - Tsunami detectors are placed on the deep sea floor.
  - Sense pressure increases from changes in sea thickness.
- Prediction/detection can save thousands of lives.

Earthquake Damage

- **Earthquake devastation fuels disease outbreaks.**
  - **Food, water, and medicines are scarce.**
  - **Basic sanitation capabilities are nonexistent.**
  - **Hospitals are damaged or destroyed.**
  - **Health professionals are overwhelmed.**
  - **There are likely to be decaying corpses.**

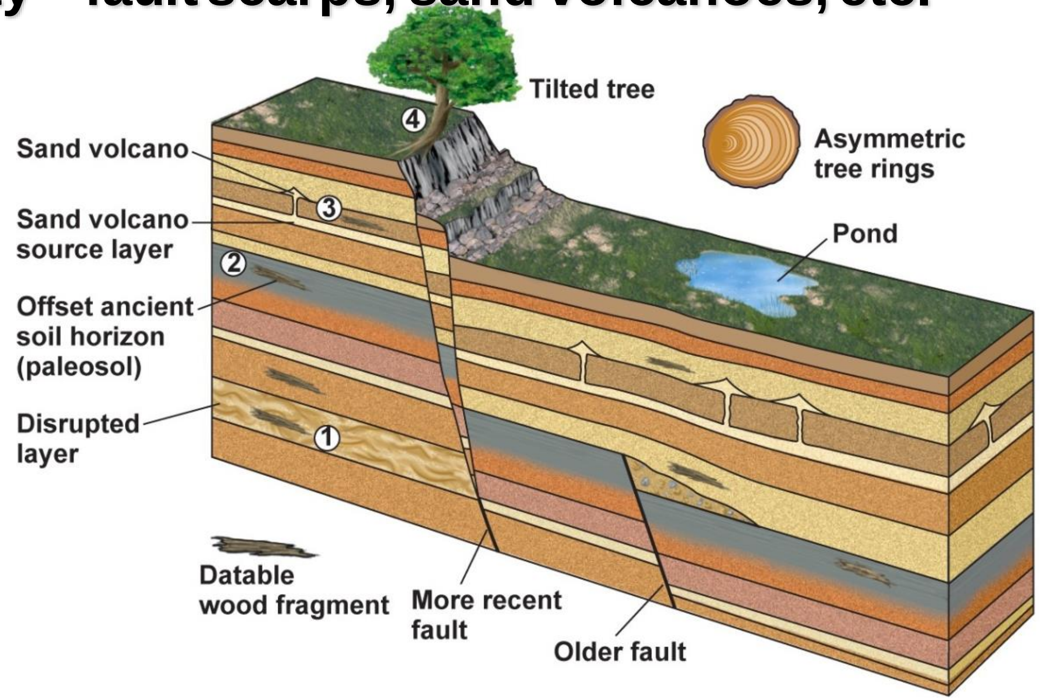
Earthquake Prediction

- Can we *predict* earthquakes? Yes and no.
  - They CAN be predicted with statistical measure in the long term (tens to hundreds of years).
  - They CANNOT be predicted in the short term (hours or weeks).
  - Hazards can be mapped to assess *risk*.
    - Developing building codes
    - Land-use planning, Disaster planning



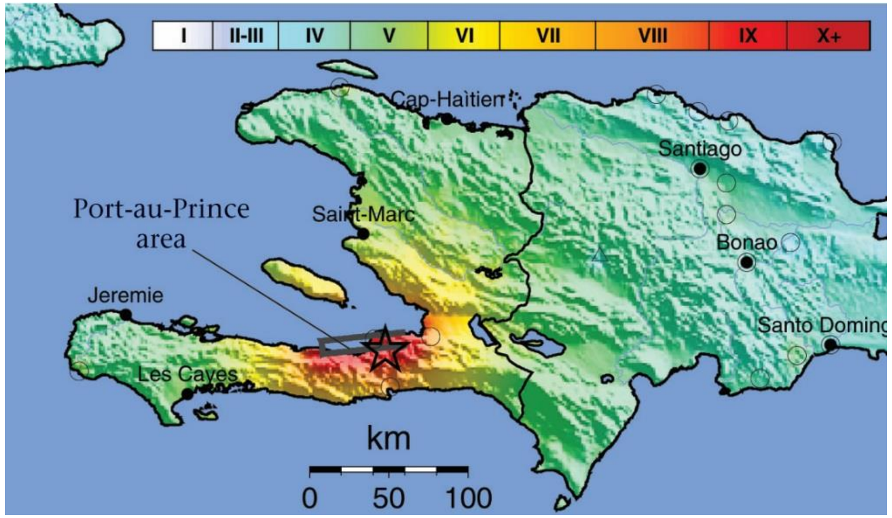
Long-Term Earthquake Prediction

- Probability of a certain magnitude earthquake occurring.
- Requires determination of seismic zones and recurrence intervals by:
  - Examining evidence of modern or ancient earthquakes (paleoseismology OJ).
    - Evidence of seismicity—fault scarps, sand volcanoes, etc.
    - Historical records.
    - Geologic evidence.
    - Pseudotachylites



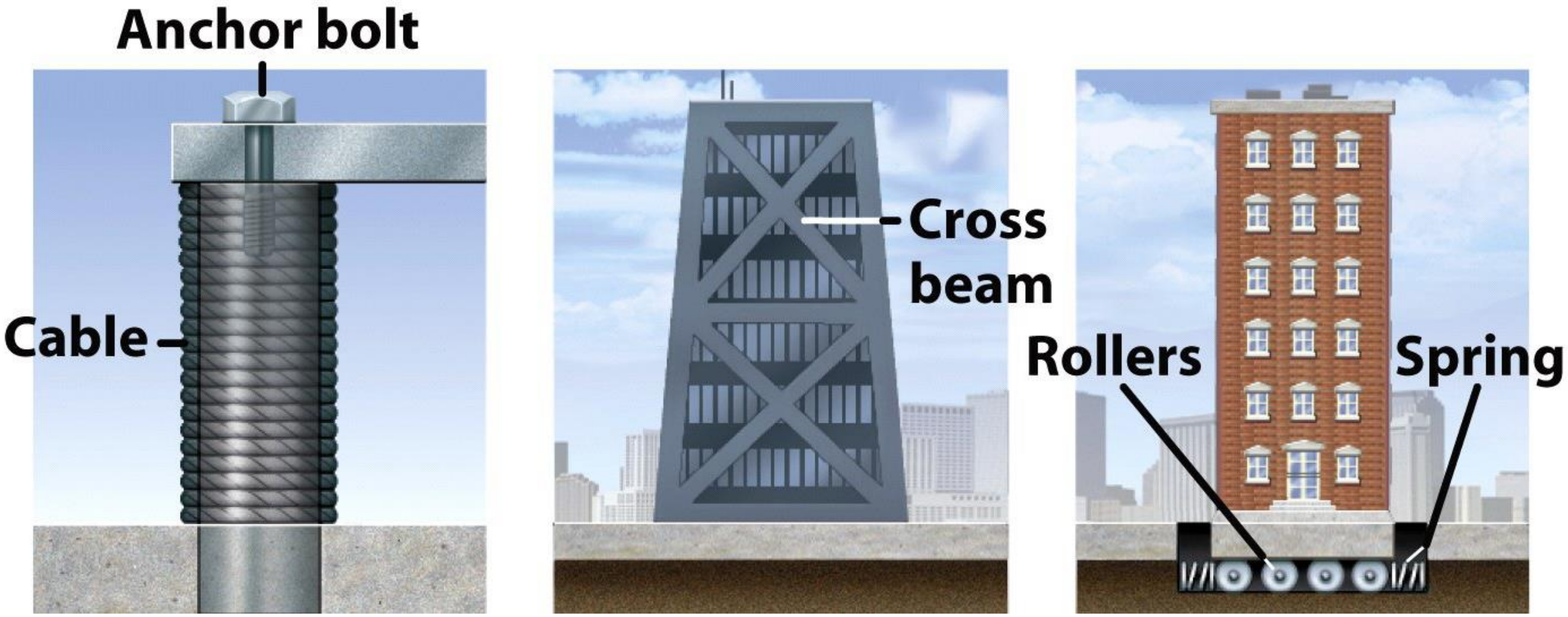
Earthquake Prediction

- Short-term predictions—on a scale of weeks or months.
  - Goal: the location and magnitude of a large earthquake.
  - Currently no reliable short-range predictions are possible. That is, we cannot accurately predict just when an event might occur or precisely where it will be focused.
  - Earthquakes do have precursors.
    - Clustered foreshocks.
    - Crustal strain.
    - Stress triggering.
    - And, possibly:
      - Level changes in wells.
      - Gases (Rn, He) in wells.
      - Unusual animal behavior.



Preparing for Earthquakes

- We can't stop them but we can be ready for them.
  - Understand what happens during an earthquake.
  - Map active faults and areas likely to liquefy from shaking.
  - Develop construction codes to reduce building failures.
  - Regulate land use to control development.



Preparing for Earthquakes

- We can't stop them but we can be ready for them.
  - Train the community in earthquake preparedness.
  - Run preparedness drills.
  - Educate individuals on safe behavior and responses.
  - Keep viable stores of emergency supplies.

Duck and hold!