CE/SC 10110-20110

A Violent Pulse: EARTHQUAKES!

Earth

Portrait of a Planet

Fifth Edition

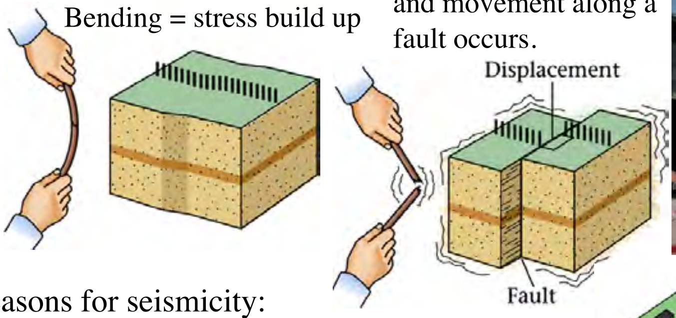
Chapter 10

Earthquake Generation

Brittle Deformation

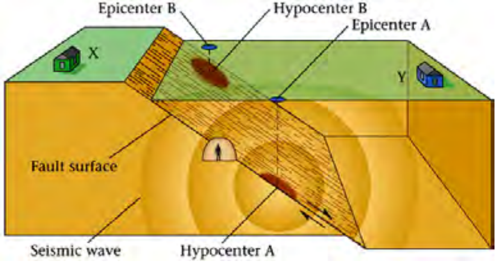
Bending = stress build up

Break = energy release and movement along a fault occurs.



Reasons for seismicity:

- Formation of a new fault;
- Movement along an existing fault;
- Sudden change in atomic packing of minerals;
- Magma movement;
- Volcanic eruption;
- Giant landslides;
- Meteorite impact;
- Nuclear bomb tests;
- Mine subsidence

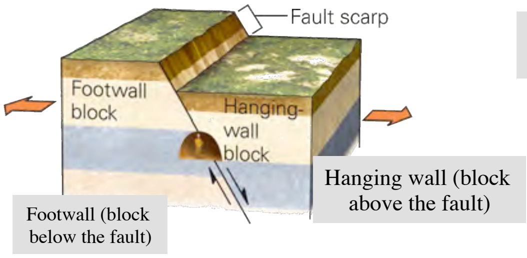


Hypocenter (Focus): point in the earth where the seismic waves originate (i.e., on a fault plane and at the point of maximum movement).

Epicenter: point on the earth's surface directly above the focus.

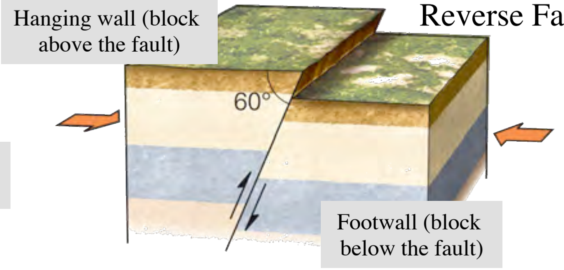
Faults

Faults are planar breaks in the crust. Most faults are sloping (vertical faults are rare). The type of fault depends on the relative motion of blocks.

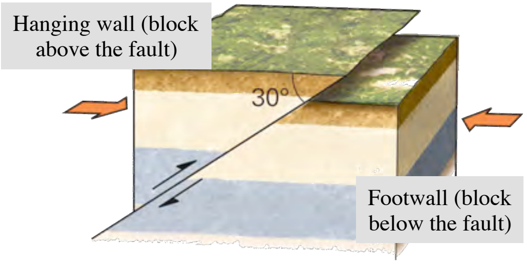


Normal Fault

Reverse Fault

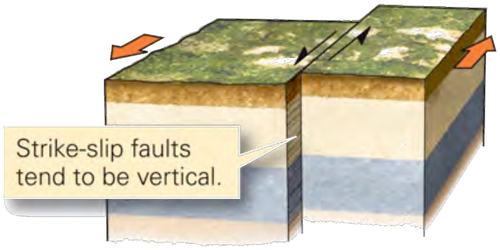


The slope (dip) of a reverse fault is steep.



Thrust Fault

A thrust fault is low angle reverse fault.

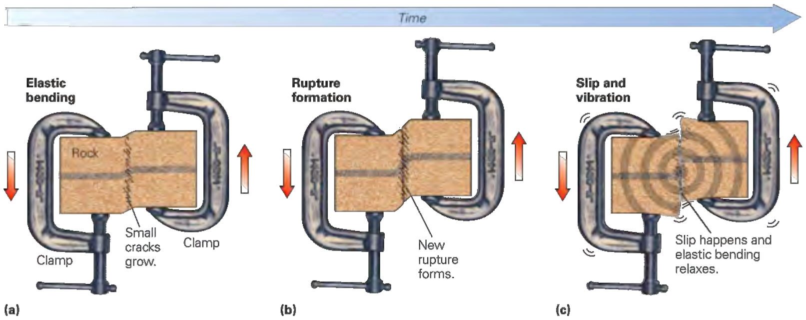


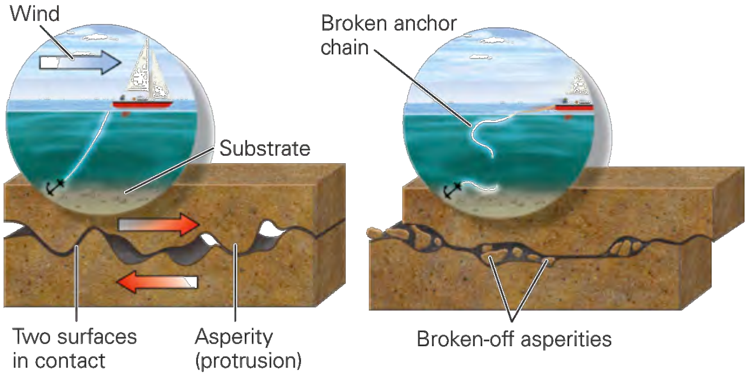
Strike-Slip Fault

Vertical fault plane.

Faults

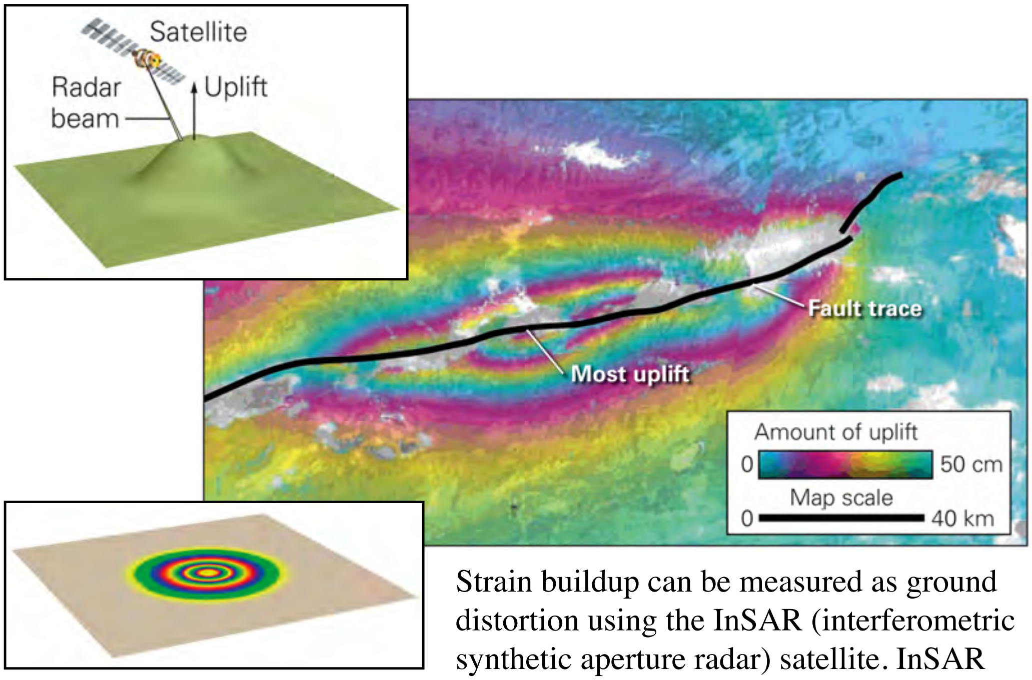
Faults form when tectonic forces add stress (push, pull, or shear) to rock.





When a fault moves, it is quickly slowed by friction due to ***asperities*** (bumps) along the fault. Eventually, strain will build up again and cause another episode of failure and motion.

Elastic Strain

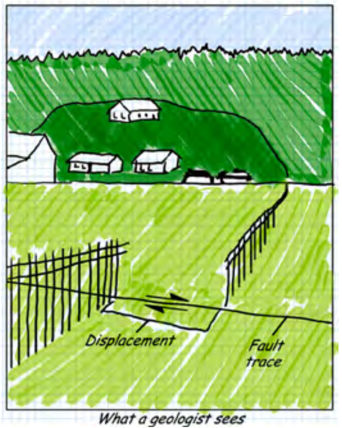


Strain buildup can be measured as ground distortion using the InSAR (interferometric synthetic aperture radar) satellite. InSAR compares ground elevation changes over time and creates maps that display distortion as color bands

Earthquake Generation

Displacement: amount of slip on a fault.

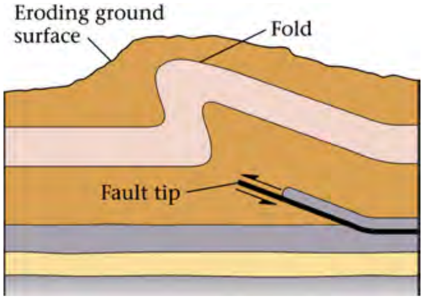
If the fault breaks the surface, it leaves a ***fault trace***, either as an offset (if lateral movement or strike slip), or a ***fault scarp*** (if vertical movement or dip slip).



What a geologist sees

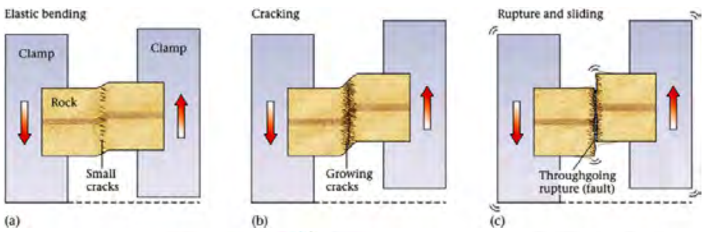
Active and inactive faults.

"Blind" faults don't break the surface.



Earthquake Generation

Stress builds up between faulting events. Stress relieved by forming new faults or movement along old faults.



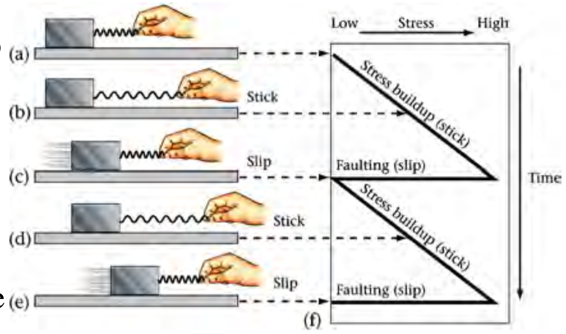
Stress drops and elastic strain decreases - the rock rebounds so that the rock near the fault are no longer bent. **Elastic Rebound Theory** (or ***Stick-Slip behavior***).

Whole fault does not move at once - the slip area starts at a certain point and migrates.

Foreshocks: development of smaller cracks that eventually link up.

Aftershocks: occur for days to weeks because movement that caused the "main event" set up secondary stresses that may be large enough to reactivate the main fault.

Both are generally of lower energy.



Aseismic Fault Movement

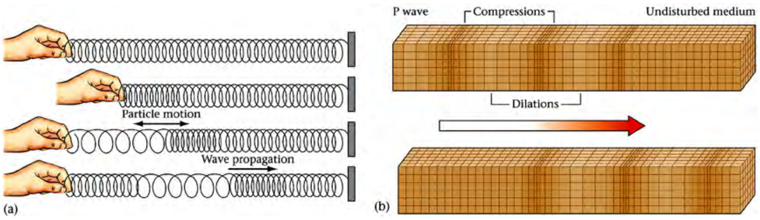
Ductile deformation is aseismic.

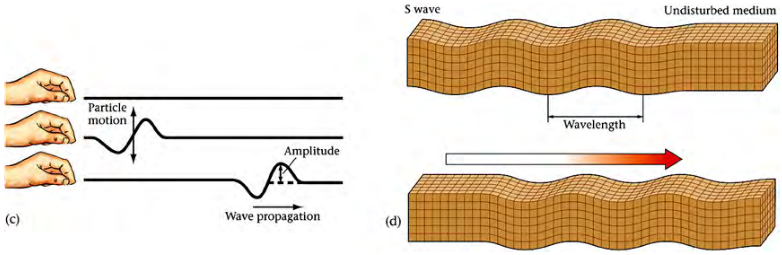
Fault Creep: movement of faults occurs slowly and steadily (low friction).

Types of Seismic Waves

Body Waves:

P-Waves – *Primary* waves; compressional (change the rock volume); are the fastest moving (4-7 km/sec). Rock vibrates ***parallel*** to the propagation direction.



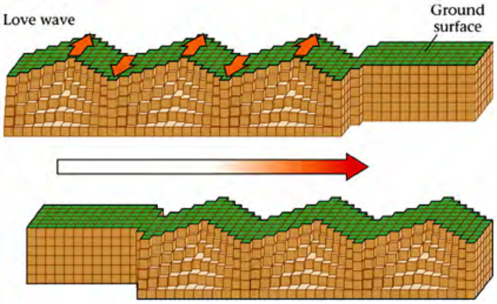


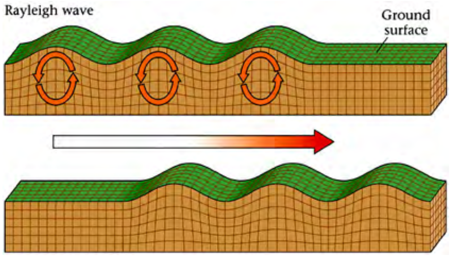
S-Waves – *Secondary* waves; shearing (change in shape); slower (2-5 km/sec); Rock vibrates ***perpendicular*** to the propagation direction.

Types of Seismic Waves

Surface Waves:

Love Waves: L-waves = horizontal shearing perpendicular to propagation direction – no vertical motion. Do not travel through liquids.





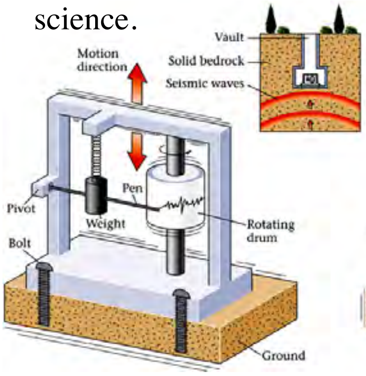
Rayleigh Waves: R-waves produce vertical motion, like rolling ocean waves.

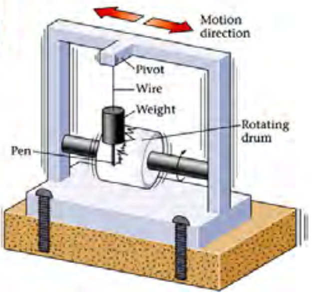
Arrival Times: Related to velocity: First = P-Waves; Second = S-Waves; Third = Surface Waves.

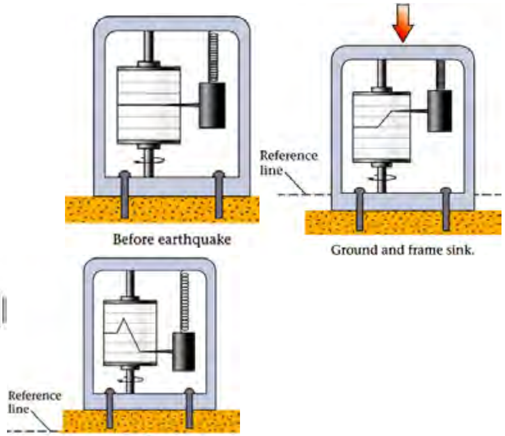
Time (distance) between the P & S arrivals related to the distance to the focus.

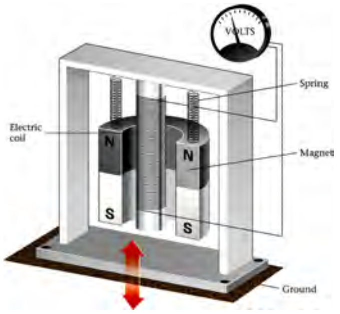
Measuring & Locating Earthquakes

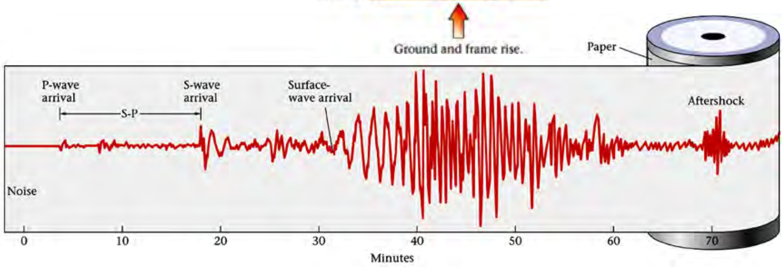
Seismometer: detector. **Seismograph/Seismogram**: measurement. **Seismology**: science.





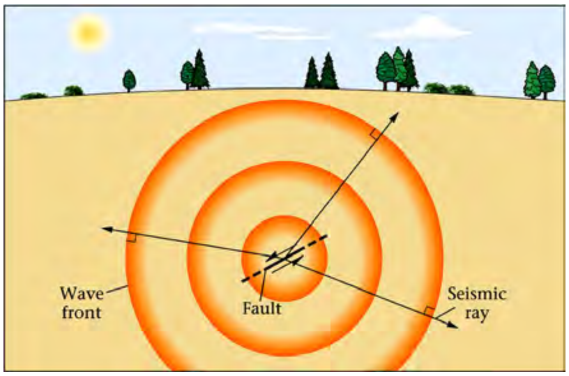




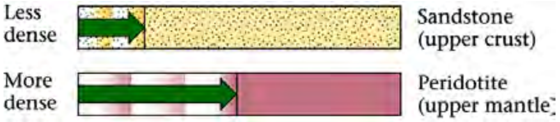


Exploring the Interior

Use travel times of various seismic waves as they pass through the interior of a planet.

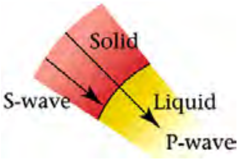


Seismic waves travel at different velocities through rocks of different densities.



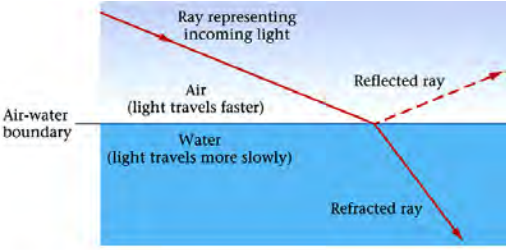
Seismic waves travel faster through a solid than a liquid.

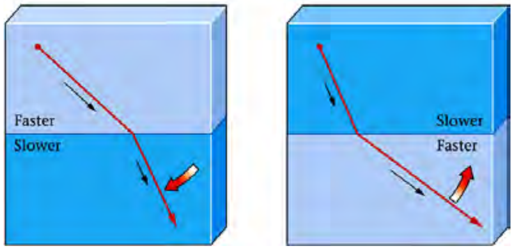
P- and S-waves travel through solids, but only P-waves travel through liquids.



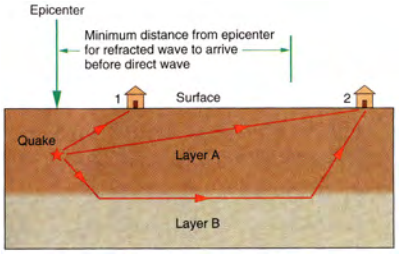
Exploring the Interior

Seismic Reflection and Refraction



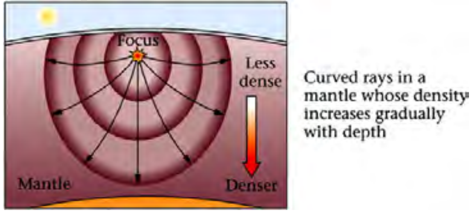


Since wave velocity increases with depth, wave fronts are oblong and seismic rays curve.



In a stack of rocks where waves travel the fastest in the lowest layer, waves eventually curve around and head back to the surface.

If the mantle density gradually increases with depth, the wave travel path would be a smooth curve.



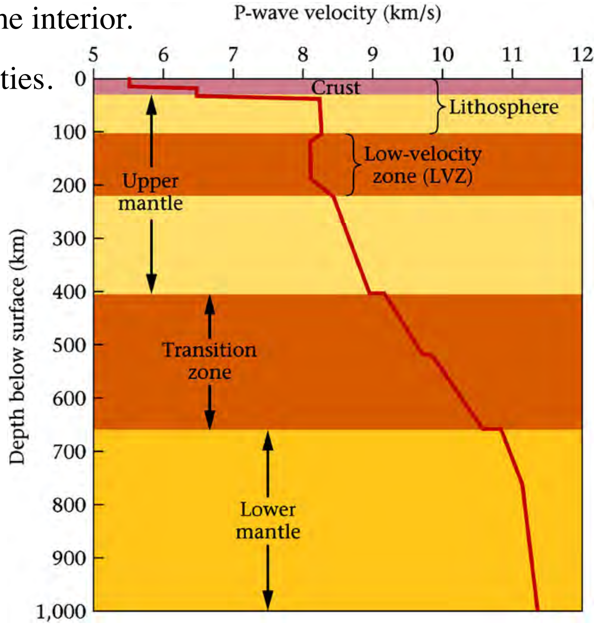
Exploring the Interior

We use these relationships to integrate data from a worldwide network of seismometers to define the structure of the interior.

Looking for seismic velocity discontinuities. These can occur when there is:

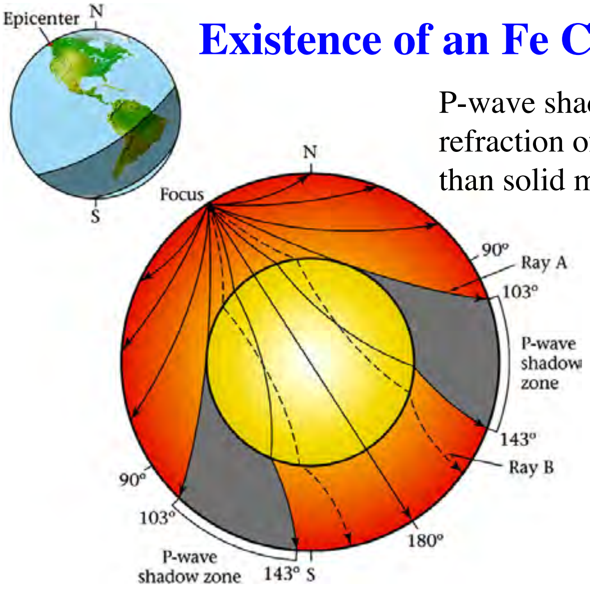
1. A major change in rock type/density (e.g., the Moho);
2. A melt phase present (e.g., the low-velocity zone);
3. Minerals contract to more closely packed structures.

410 km: olivine contracts to a Mg-spinel structure;
660 km: olivine contracts again to the denser perovskite structure.
Therefore, 410-660 km is sometimes called the “transition zone”.
Transitions known from experimentation + modeling.



Exploring the Interior

Existence of an Fe Core

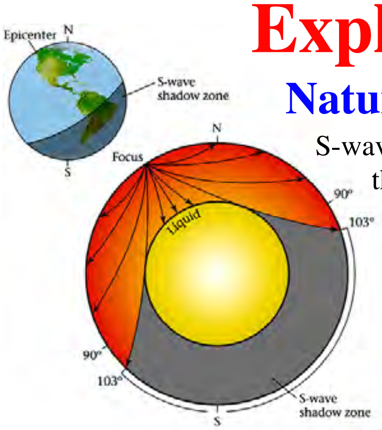


P-wave shadow zone demonstrates the intense refraction of P-waves - there is something other than solid mantle. This is the Fe core.

The extent of the shadow zone indicates the size of the core.
The core-mantle boundary occurs around 2,900 km.
P-wave refraction indicates material below is less dense.

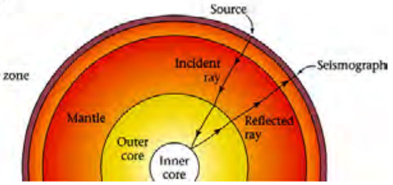
Exploring the Interior

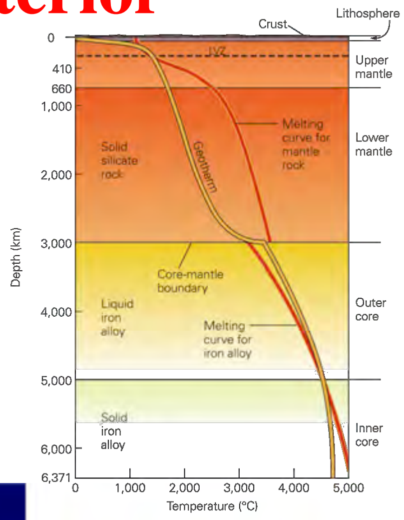
Nature of the Core



S-wave shadow zone shows the outer core is liquid.

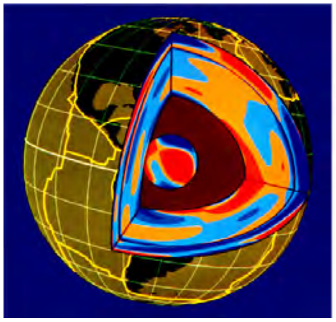
P-waves are reflected off a boundary within the core - the inner core is solid.

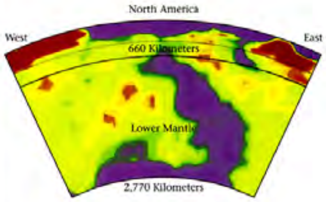




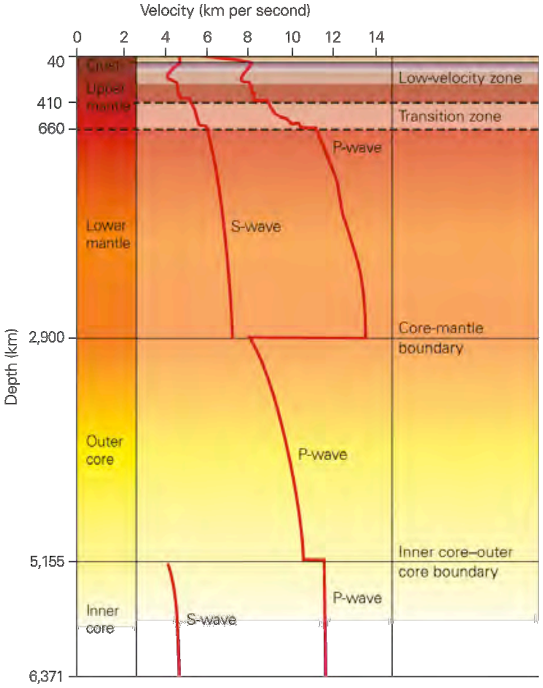
Seismic Tomography

3D mapping of seismic velocities with depth. Detects remnants of ancient subducted plates and demonstrates mantle convection (slower velocities = hotter material).



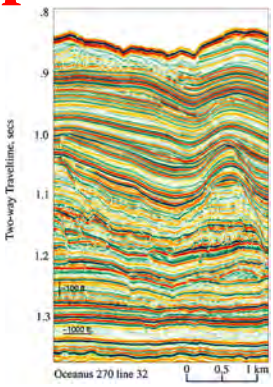


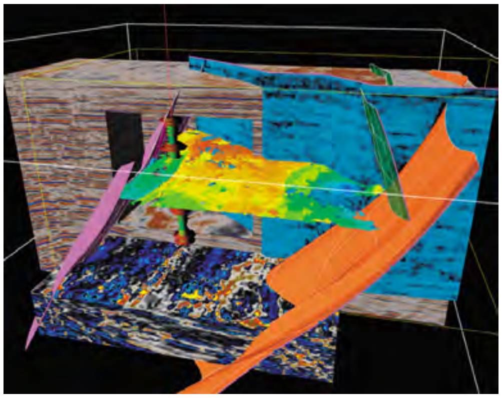
Exploring the Interior



Exploring the Interior

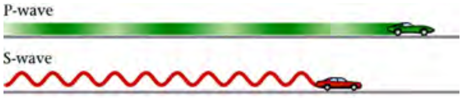
Seismic Reflection Profiling

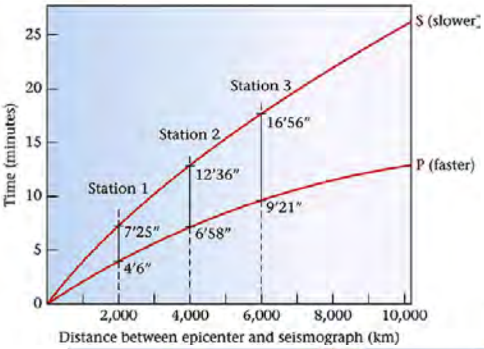


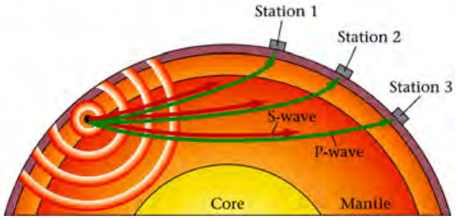


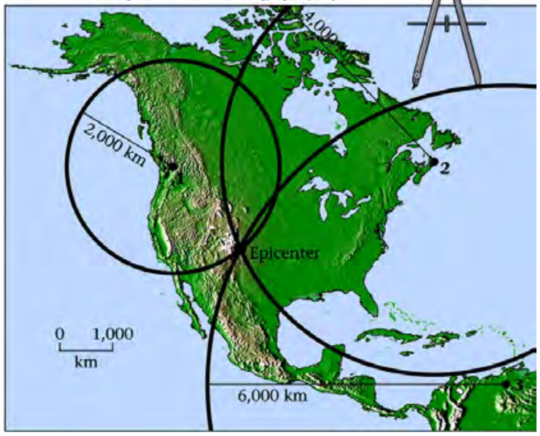
Measuring & Locating Earthquakes

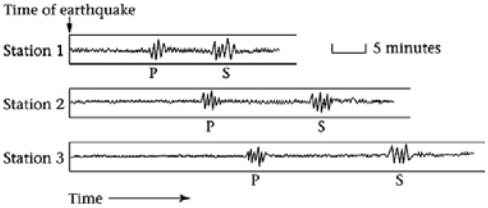
Need 3 seismometers at different locations to give location of earthquake by triangulation. First need a ***travel-time curve***.











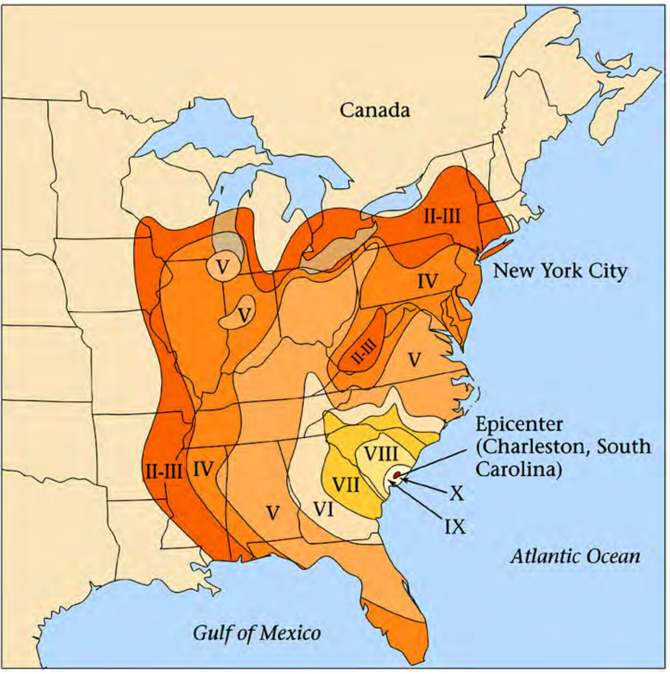
Measuring & Locating Earthquakes

Depth of Focus: Arrival of body waves vs. surface waves.

0-20 km = Shallow
20-300 km = Intermediate
300-670 km = Deep.

Mercalli Scale: uses intensity of damage (measurement of earthquake's effect on buildings & people), but this diminishes away from epicenter – different intensities reported for the same earthquake.

Problems: Buildings are of variable construction and geological foundation.



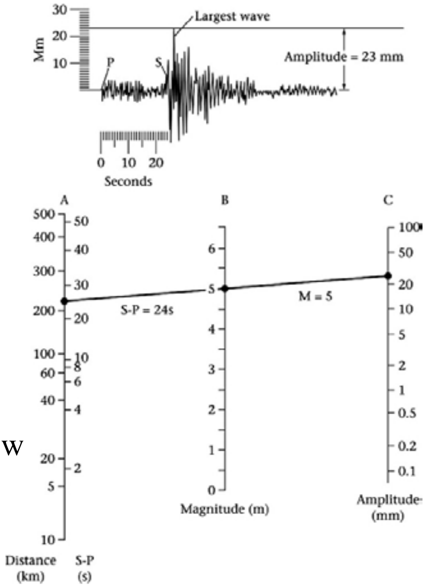
Different Mercalli intensities associated with the 1886 Charleston earthquake.

Measuring & Locating Earthquakes

Magnitude Scales: Amount of energy released as determined by the maximum amplitude of ground motion (up-down or side-to-side).

Magnitude is based on amplitude recorded by any seismogram record, although distance from the event must be accounted for.

Richter Scale: Richter magnitude determined by measuring the largest amplitude generated by waves that have a 1 sec period (1/frequency) recorded 100 km away. Use a chart to adjust for variable distance, but only works well with shallow (<15 km) , nearby (<600 km) earthquakes. Number on the original Richter scale = ***local magnitude*** (**M_L**).



Measuring & Locating Earthquakes

Alternate Magnitude Scales: Amplitudes of R-waves used to give a ***Surface-wave Magnitude*** (**M_S**) - only good if hypocenter is < 50 km.

Body-wave Magnitude (**m_b**) - based on P-wave amplitudes.
M_L, m_b, and M_S cannot define large earthquake magnitudes - use the ***Moment Magnitude*** (**M_W** -most accurate).

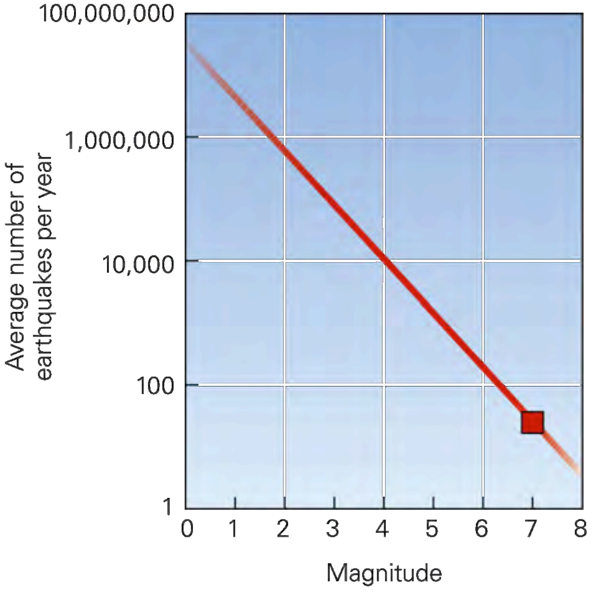
To calculate M_W:
- measure the amplitude of a number of different seismic waves;
- determine the area of the slipped portion of the fault;
- determine how much slip occurred;
- define the physical characteristics of the rock that faulted.

Preliminary magnitude often reported, which is M_L, m_b, or M_S. Once the necessary data have been collected, M_W is then reported.

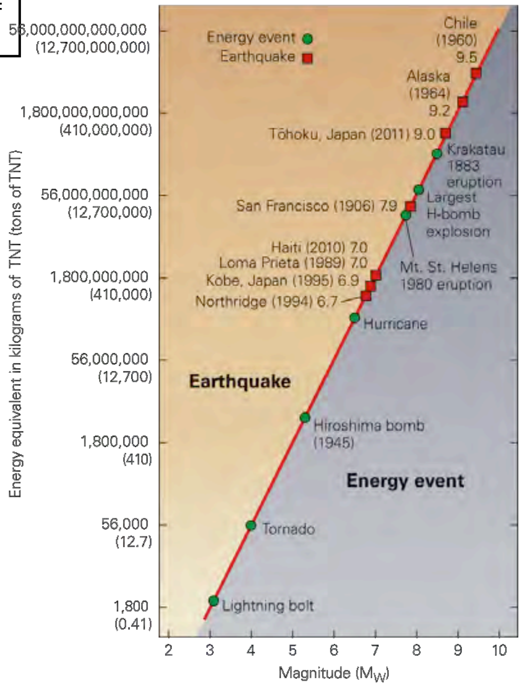
Fortunately, there are many more small magnitude earthquakes than larger magnitude ones each year (~100,000 mag. 3 per year; one mag. 8 occurs every 3-5 years.

Measuring & Locating Earthquakes

Fortunately, large earthquakes are relatively rare. Every year, there are 32 $M_W = 7.0$ earthquakes but only one $M_W = 8.0$ earthquake.

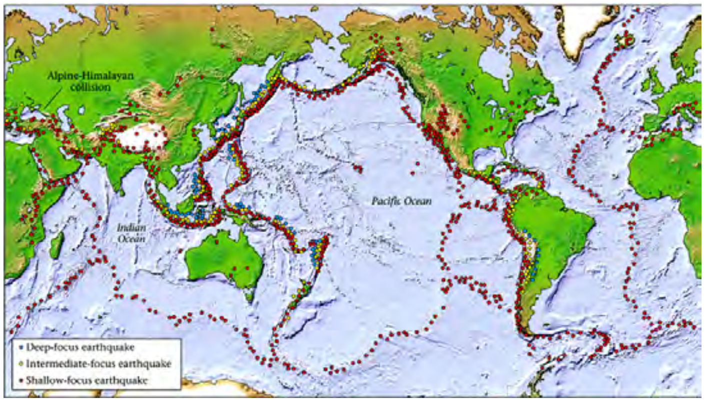


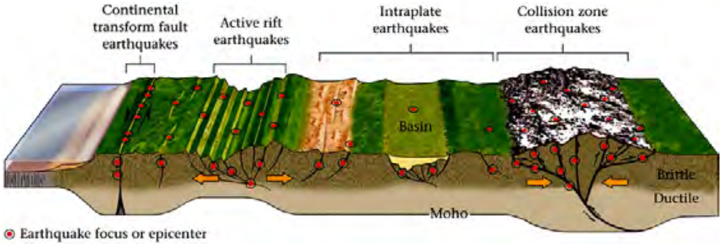
Small earthquakes are much more abundant than large ones.



Earthquake Occurrence

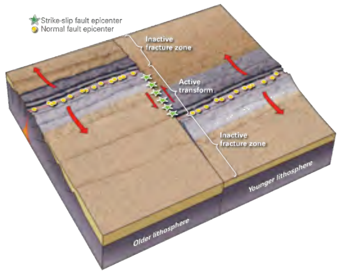
Earthquakes occur mainly at plate boundaries in seismic belts/zones.
Shallow focus earthquakes cause the most damage.





Divergent Plate Boundaries: two types of faults - normal at the rift and transform where the ridge is offset. Also due to magma movement. Focii usually <10 km.

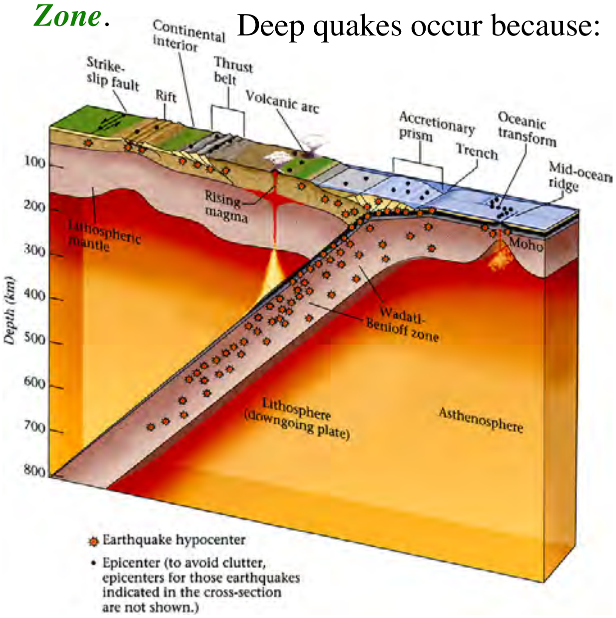
These earthquakes are only a problem in Iceland!



<u>Continental Rifts</u>: East African; Rio Grande.
<u>Collisional Zones</u>: thrust faults.

Earthquake Occurrence

Convergent Plate Boundaries: shallow to deep focus earthquakes as the slab goes down. Shallow quakes are due to friction between the plates and bending of the downgoing slab. Intermediate and deep earthquakes define the ***Wadati-Benioff Zone***.



Deep quakes occur because:

- It takes time for rocks to heat up and undergo ductile deformation;
- Mineral phase changes.

Transform Plate Boundaries: San Andreas Fault, California; Alpine Fault, New Zealand.

Major Earthquakes

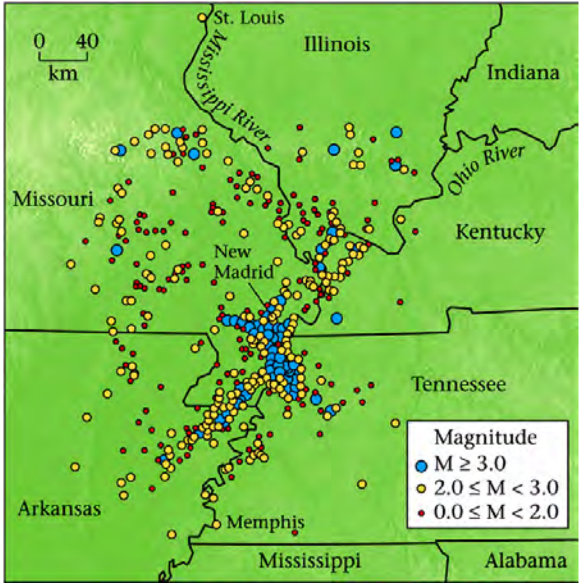
April 18, 1906: 5:12 a.m. San Francisco. City destroyed, 3,000 dead. Fires. M_W ~7.9.

October 17, 1989. Loma Prieta, San Francisco. Magnitude = 7.1. 63 deaths, substantial damage. Liquefaction.

Collapsed double-decked Cypress freeway in Oakland after the 1989 Loma Prieta earthquake.

Earthquake Occurrence

Intraplate Earthquakes



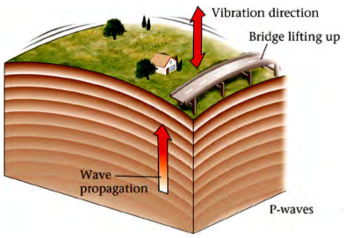
Shallow focus events. Could be in response to forces at plate margins, or tension between lithosphere and asthenosphere, or bending of plate over a curved surface, or readjustments of the crust to loads (i.e., glaciers).

Charleston 1886: Mag. 7.3.
New Madrid, 1811-1812: three Mag. 8.0-8.5 quakes.

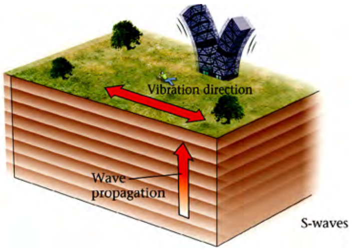
Memphis and St. Louis have no engineering codes for earthquakes!

Earthquake Damage

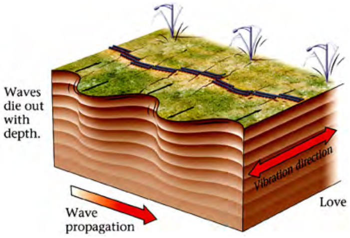
First arrival: P-waves



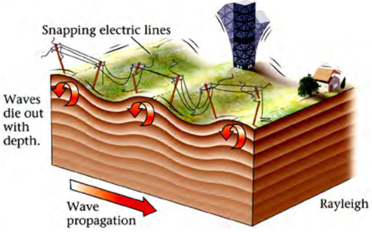
Second arrival: S-waves



Third arrival: L-waves



Closely followed by R-waves



R-waves last longer and cause the most damage.

Severity of shaking depends upon:

1. Quake magnitude;
2. Distance from hypocenter;
3. Nature of the substrate;
4. Quake frequency.

Number 4 is related to the resonance of a quake (when each new waves arrives at just the right time to add more energy). If this is the same as building resonance…..e.g., Mexico City, Sept. 19, 1985: up to 30,000 killed.

Earthquake Damage

Buildings collapse (especially facades) - this kills the most; bridges collapse; road and rail disrupted; gas, electric and phone lines broken; waves - can set up rhythmic motions in lakes (“***seiche***”) that can build waves up to 10 m).

Earthquake Damage

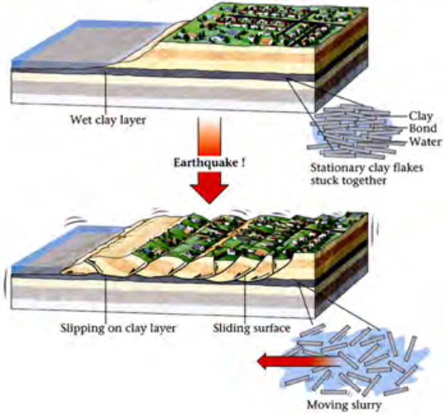
Landslides and Avalanches

Quakes promote avalanches and slope instability.

Sediment Liquefaction

Water in pore spaces of sand/silt is pressurized during quakes - friction is reduced.

In certain damp clay (“**quickclay**”), clay flakes are held by weak H-bonds. Shaking breaks these and the clay acts as a viscous liquid. *Liquefaction* promotes slope instability.

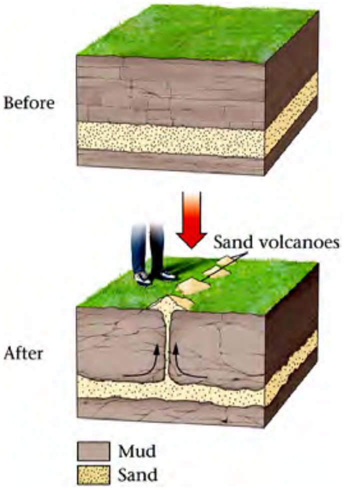


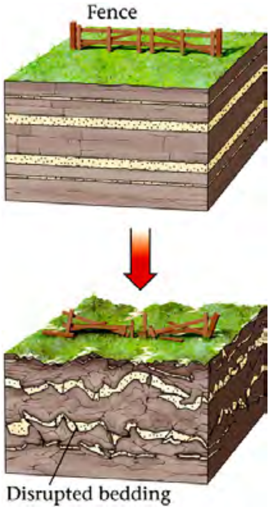
Can cause buildings to topple.

Earthquake Damage

Sediment Liquefaction

1964 Alaska 9.2 quake saw Anchorage sink by up to 3 m because of liquefaction.





Liquefaction can produce “**sand volcanoes**” (or “**sand boils**”) when sand in the sub-surface erupts.

Liquefaction also disrupts bedding and cracks the surface.

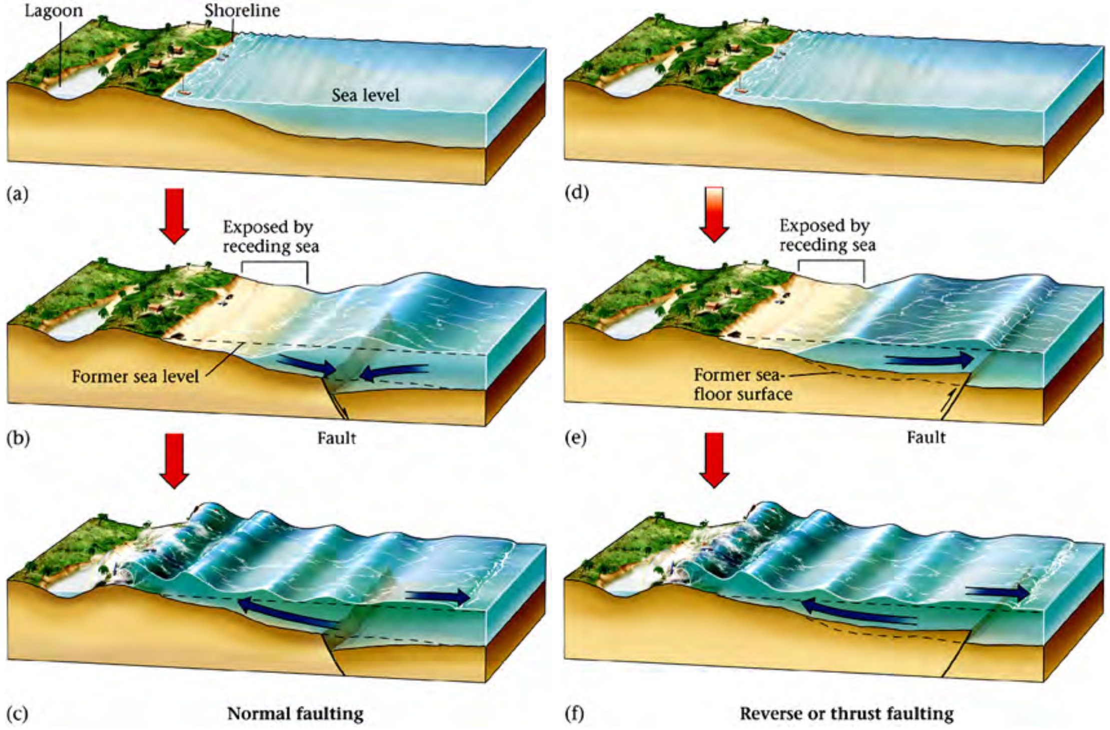
Earthquake Damage

Sediment Liquefaction

Earthquake Damage

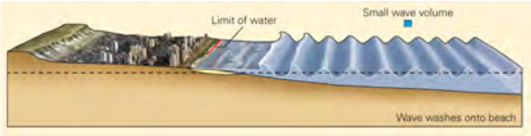
Fire!

Tsunamis

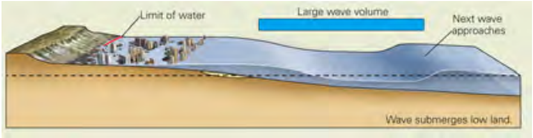


Tsunamis

- Wind waves
  - Influence the upper ~100 m
  - Have wavelengths of several tens to hundreds of meters
  - 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.



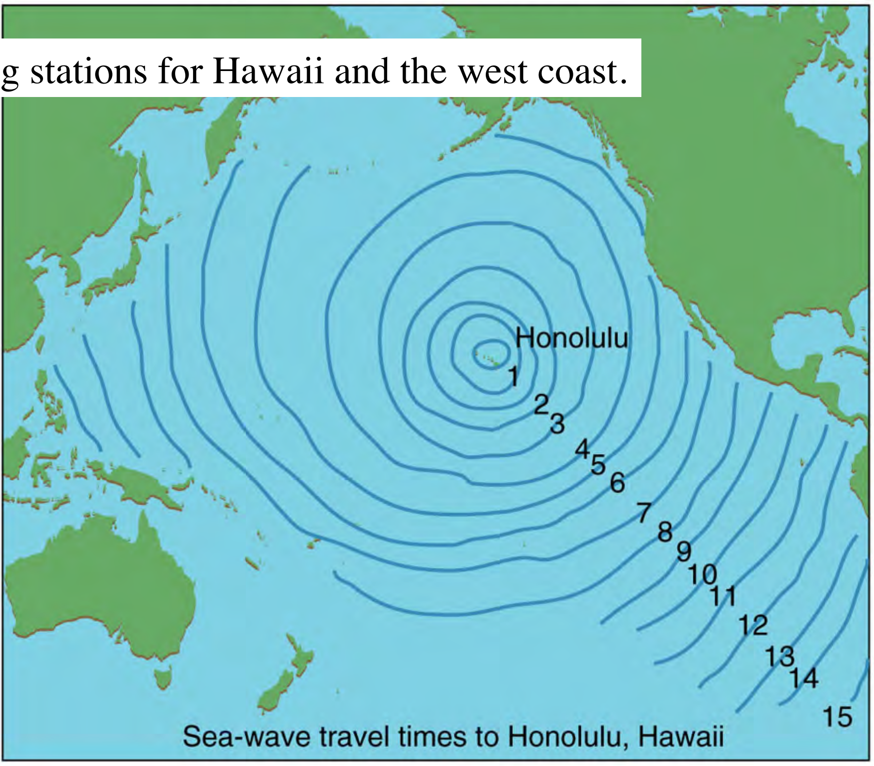
- Tsunami waves
  - Influences the entire water depth
  - Have wavelengths of several tens to hundreds of kilometers
  - Wave height and wavelength unrelated to wind speed.
  - Wave velocity maximum several hundreds of km per hour.
  - Water arrives as a raised plateau that pours onto the land with no dissipation.



Tsunami Travel Times (in hours) to Hawaii.

Tsunami warning stations for Hawaii and the west coast.

No warning stations, as yet, in the Indian Ocean



Tsunamis

Tsunamis originate because:
- Underwater dip-slip faults;
- Landslides;
- Volcanic eruptions;
- Meteorite impact.

If caused by uplift during faulting, water is displaced off the uplifted portion. If the seafloor drops, water rushes in to fill the depression.
2 sets of waves form & move in opposite directions.
One set attacks the nearby shore = ***local tsunami***;
the other goes out to sea = ***distant tsunami***.

In the open ocean, speeds of 600 mph (*mistake in book*) are not uncommon, but the wave height maybe no more than 1 m. BUT - the entire water column is moving.
As it approaches shore, the water column rises.

Significant tsunamis:

Mag. 9.5, Chile, May 22, 1960 - 1.6 m drop along 300 km of fault! Affected Hawaii (10.7 m high wave) as well as Chile (11 m high wave), as well as Japan (21 hours later - 50,000 homeless).

Hawaii, 1964.

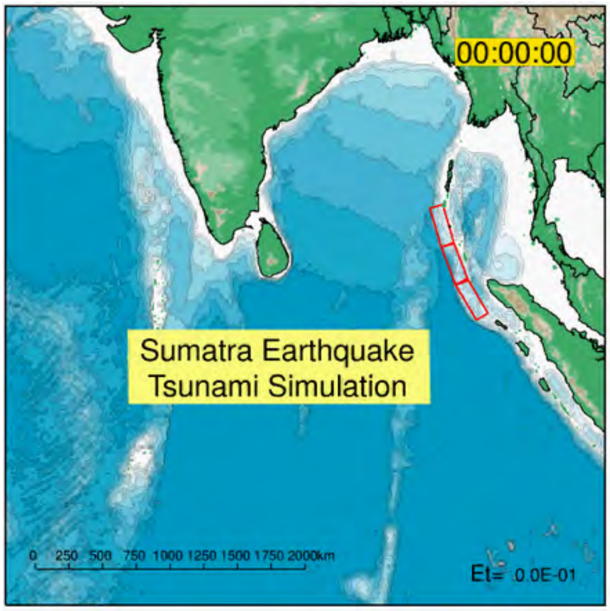
Papua New Guinea, 2000.

Sumatra, Dec. 26th, 2004.

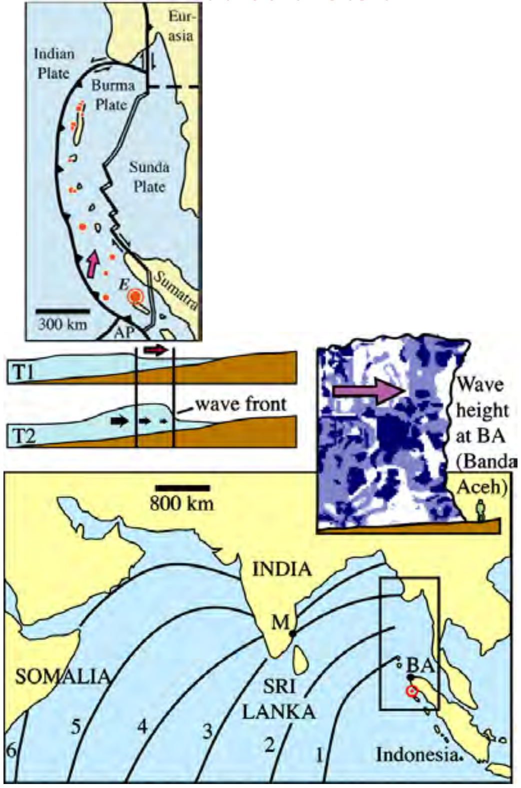
Tsunamis – seismic sea waves.

Tsunamis – seismic sea waves.

Indian Ocean, 2004: 160,000+ killed.



Tsunami2004.mov

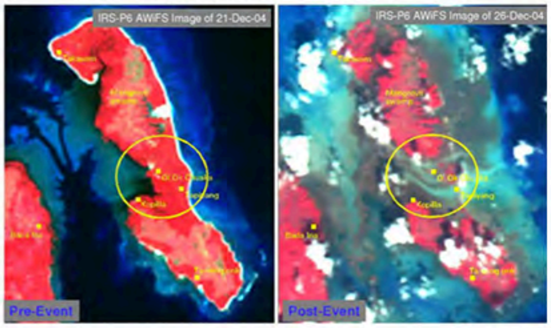


The Indian Ocean Tsunami

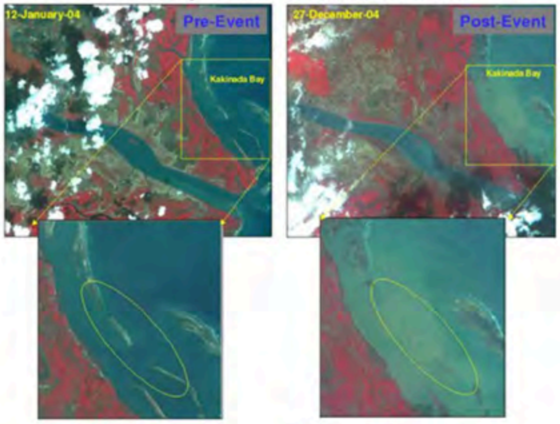
Before & After: Banda Aceh, Sumatra

Tsunami - 2004

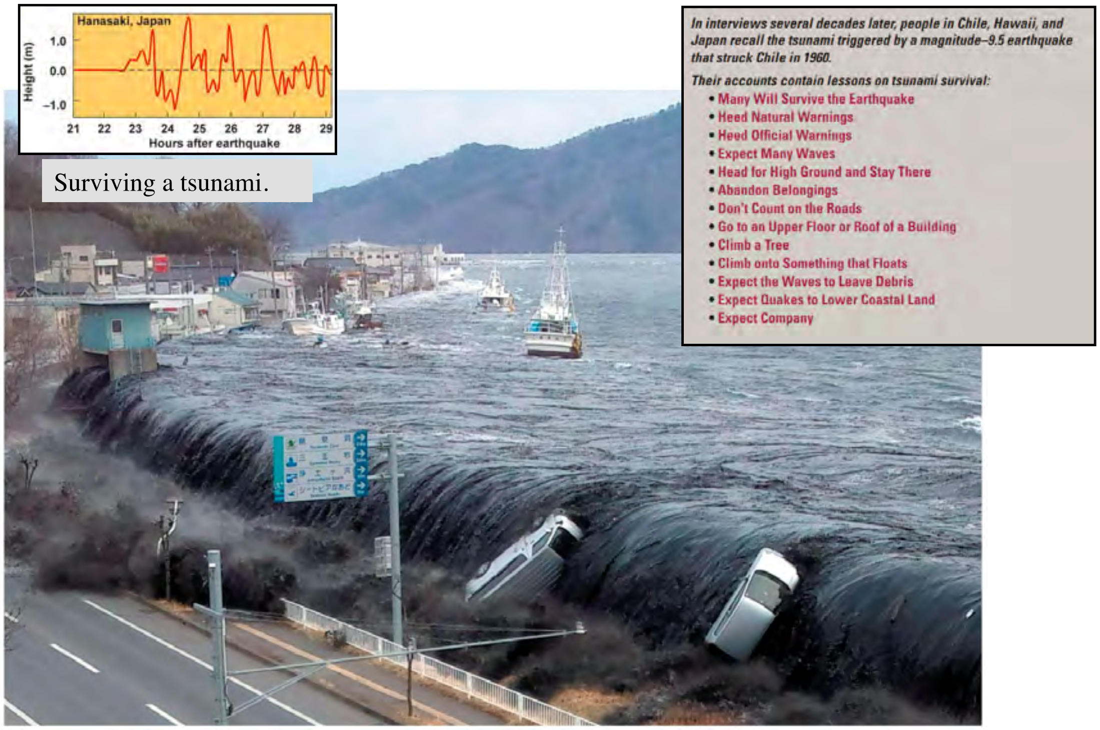
A Close View of Trinkat Island



IRS-P6 L4 MX Images showing the situation in the surroundings of Kakinada Port in Andhra Pradesh



Japan Earthquake & Tsunami, 2011



Surviving a tsunami.

In interviews several decades later, people in Chile, Hawaii, and Japan recall the tsunami triggered by a magnitude–9.5 earthquake that struck Chile in 1960.

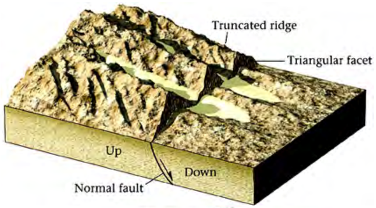
Their accounts contain lessons on tsunami survival:

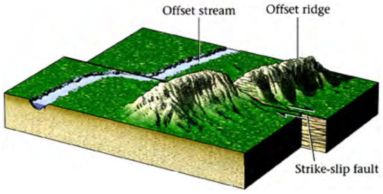
- Many Will Survive the Earthquake
- Heed Natural Warnings
- Heed Official Warnings
- Expect Many Waves
- Head for High Ground and Stay There
- Abandon Belongings
- Don't Count on the Roads
- Go to an Upper Floor or Roof of a Building
- Climb a Tree
- Climb onto Something that Floats
- Expect the Waves to Leave Debris
- Expect Quakes to Lower Coastal Land
- Expect Company

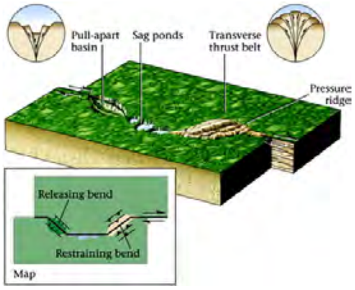
Earthquake Predictions

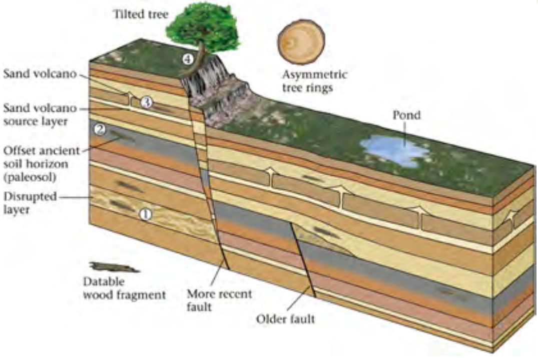
Long-Term Predictions

Decades to centuries. Can start with “epicenter maps” using historical records. Use geology (rocks and structures) to discern earthquake events before historical records were started. Try to estimate a recurrence interval.





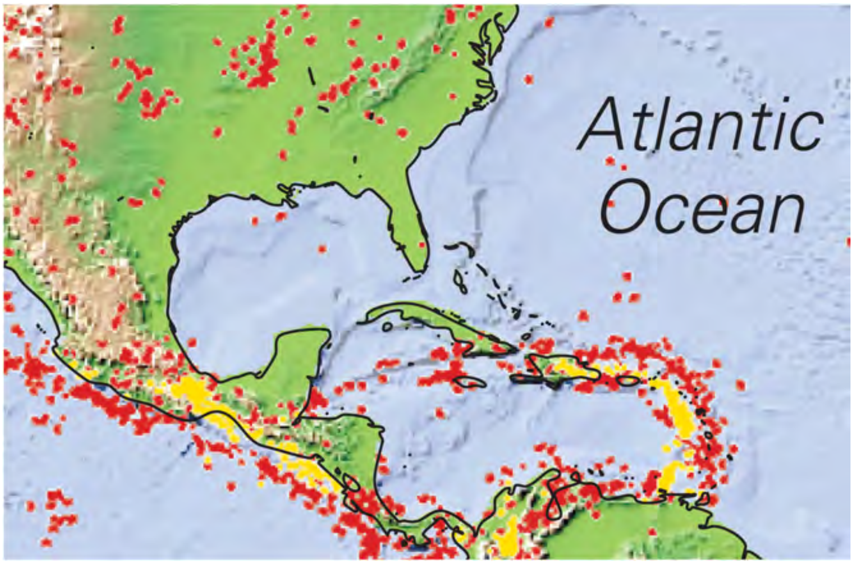




Example: examine sedimentary rocks near and active fault - see sand volcanoes were erupted at various times. Can ^{14}C date the organic material buried by the sand. Obtain an average recurrence interval, but this is not precise nor accurate.

Earthquake Predictions

Long-Term Predictions – Seismic Gaps



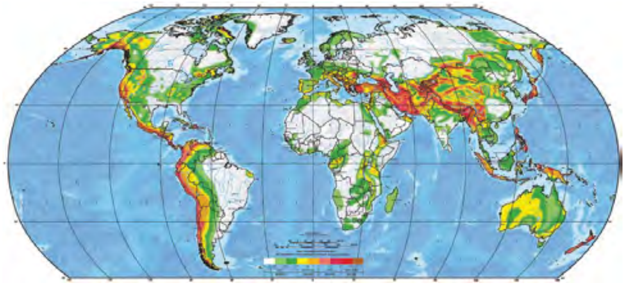
Seismic gaps are places that haven’t slipped recently. They can be particularly dangerous.

Earthquake Predictions

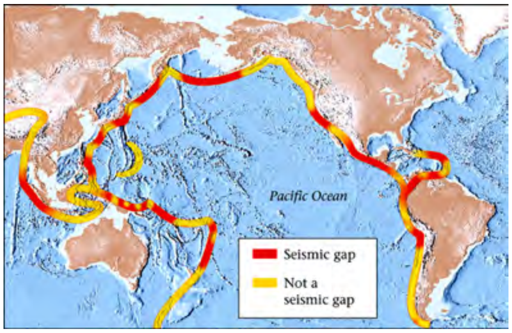
Short-Term Predictions

Weeks to years. Many seismologist consider seismicity to be random and unpredictable! However, there are precursors:
Detecting foreshocks: swarm of small quakes may indicating cracking that precedes a major rupture. BUT - these don’t always occur and if they do, are usually only recognized in hindsight.
Precise laser surveying of the ground (land under stress, bulging, sinking, bending of linear features).

Modeling of stress build up: **Seismic gaps** = potential problems along a fault - either aseismic fault creep is occurring or the fault is bound and stress is building.

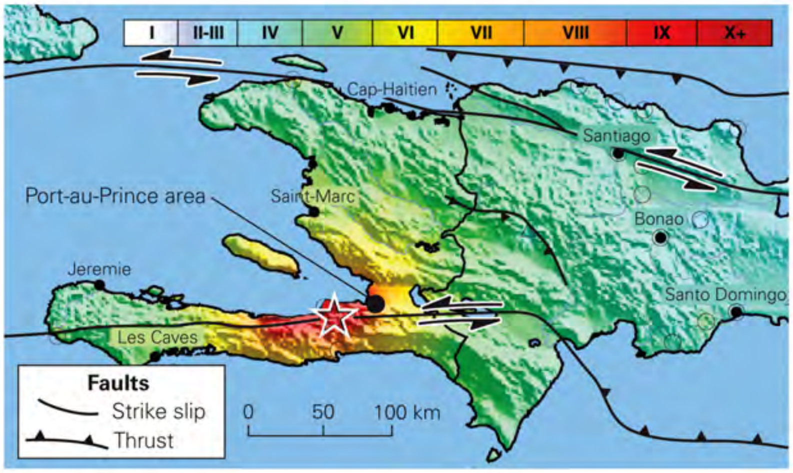


Global Seismic Hazard Map.



Earthquake Predictions

Short-Term Predictions



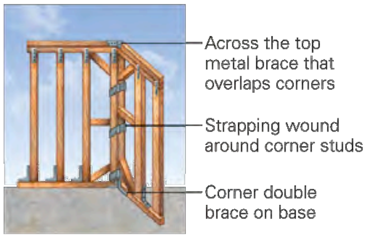
Currently, no reliable short-range predictions are possible.

Earthquakes have precursors:

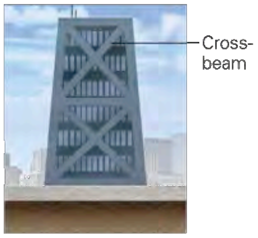
- Clustered foreshocks
- Crustal strain
- Level changes in wells
- Gases (Rn, He) in wells
- Unusual animal behavior

Earthquake Preparedness

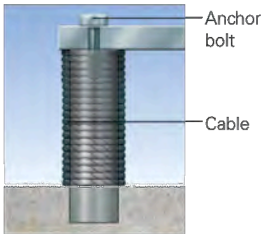
Geological & Engineering Principles



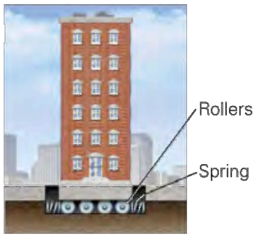
Adding corner struts, braces, and connectors can substantially strengthen a wood-frame house.



Buildings are less likely to collapse if they are wider at the base and if crossbeams are added for strength.



Wrapping a bridge's support columns in cable and bolting the span to the columns will prevent the bridge from collapsing so easily.



Placing buildings on rollers or shock absorbers lessens the severity of the vibrations.

- Map active faults and areas likely to liquefy from shaking.
- Develop construction codes to reduce building failures.
- Regulate land use to control development in hazard areas.

Summary

Earthquake Generation: Brittle Deformation, Hypocenter/Focus, Epicenter, Fault Trace, Fault Scarp, Blind Faults, Elastic Rebound Theory, Foreshocks, Aftershocks, Fault Creep.

Types of Seismic Waves: P-, S-, L-, R-waves, Arrival Times.

Exploring the Interior: Relative Seismic Velocities, Reflection & Refraction, Mantle Structure, Core Structure, Seismic Tomography, Seismic Reflection Profiling.

Measuring & Locating Earthquakes: Seismometer, Seismograph, Seismology, Travel-Time Curve, Depth of Focus, Mercalli Scale, Richter Scale (M_L), Surface-Wave Magnitude (M_S), Body-Wave Magnitude (m_b), Moment Magnitude (M_W).

Earthquake Occurrence: Divergent/Convergent/Transform Plate Boundaries, Continental Rifts, Intraplate.

Earthquake Damage: Wave Arrival Sequence, Quake Magnitude, Distance from Hypocenter, Nature of the Substrate, Quake Frequency, Landslides & Avalanches, Liquefaction.

Tsunamis: Local & Distant.