

Earthquakes



Earthquakes

- ***Earthquake:*** an event of ground shaking usually caused by the rupturing of a fault within the Earth.
- ***Seismologists:*** scientists that study earthquakes and seismicity (earthquake activity) in general

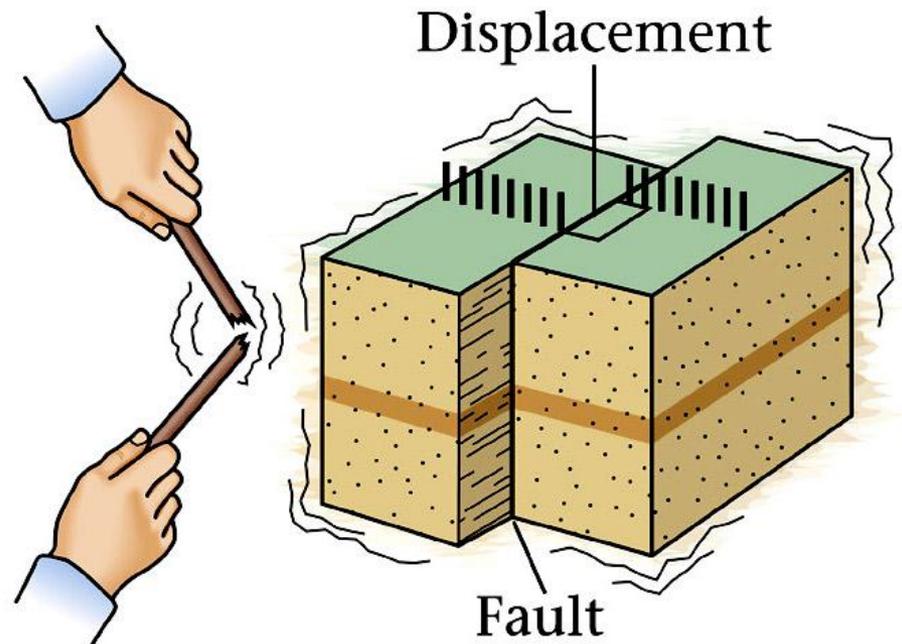
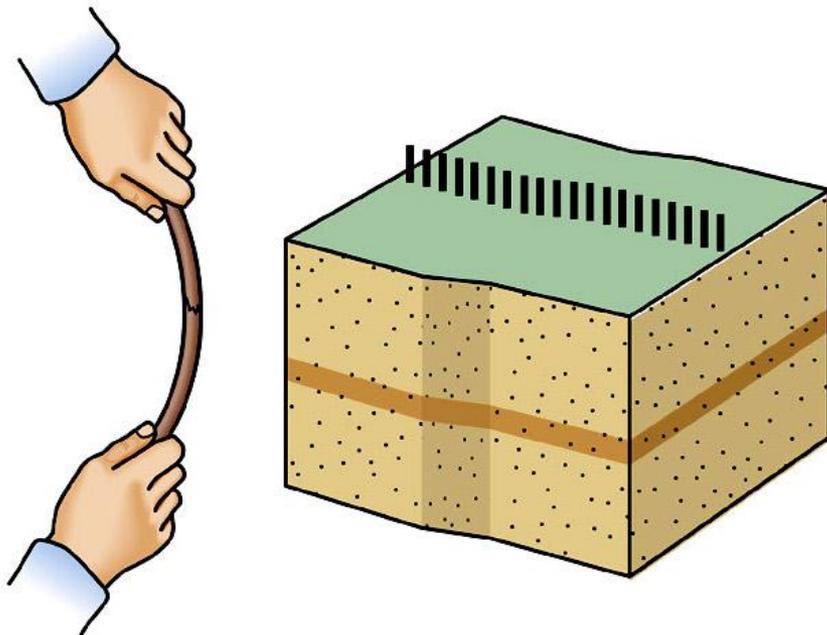


San Francisco Bay area
Faults: Red

Why Do Earthquakes Occur?

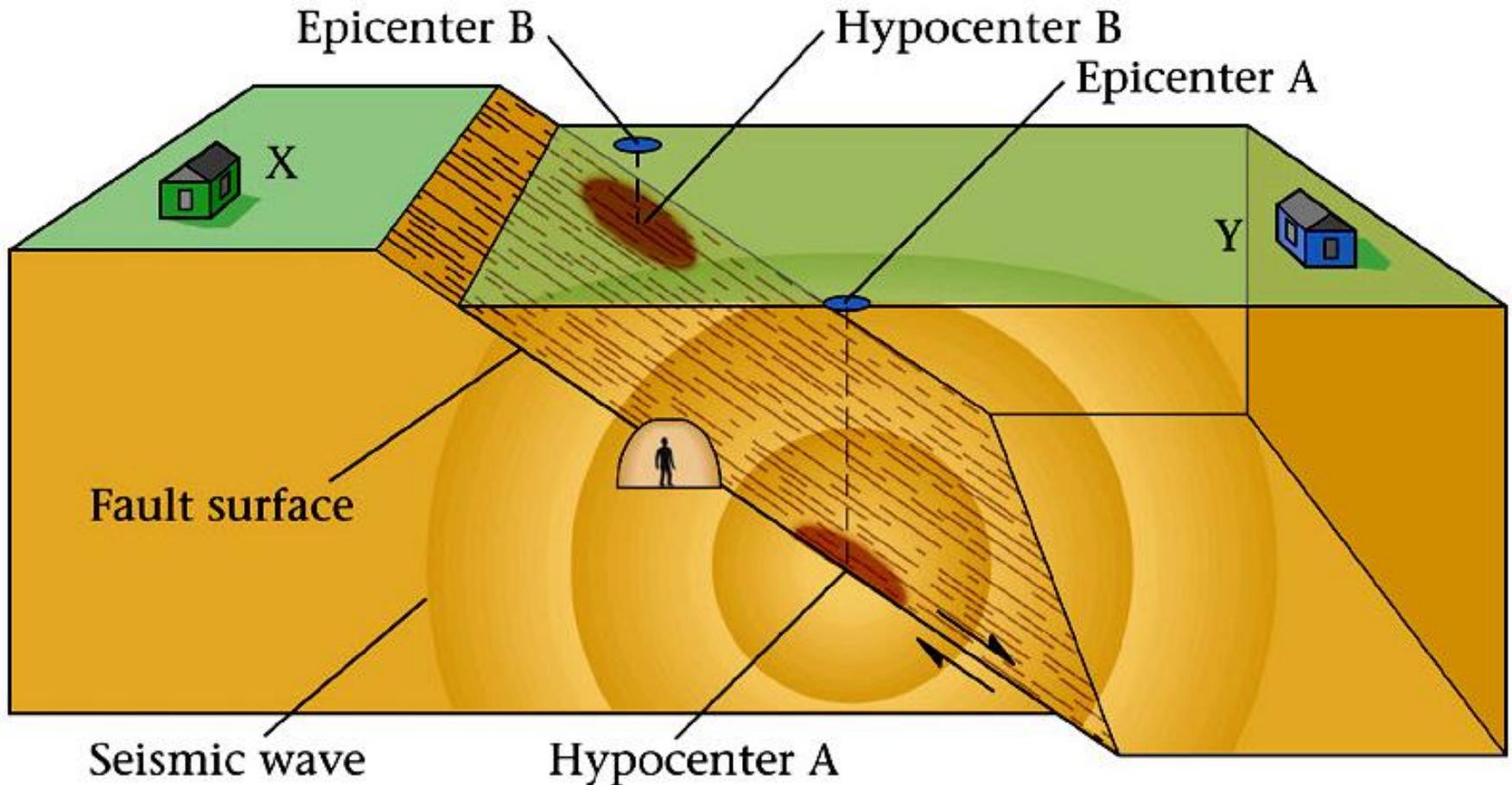
Earthquakes occur due to:

- Sudden formation of a new fault (fracture on which sliding occurs)
- Sudden slip on an existing fault ←
- Sudden change in the arrangement of atoms in the minerals of a rock
- Movement of magma in a volcano
- Explosion of a volcano
- Giant landslides
- Meteorite impact
- Underground nuclear bomb tests



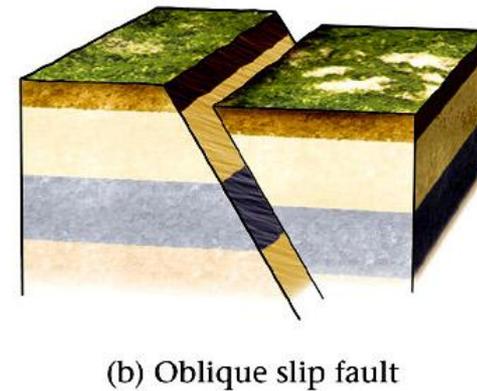
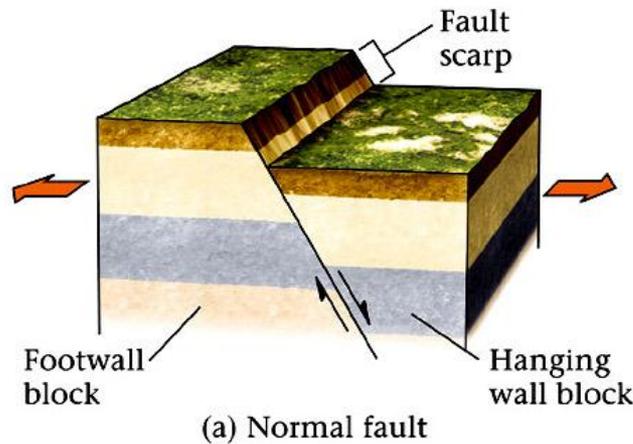
Earthquake Terminology

- ***Hypocenter (Focus)***: actual location of the earthquake at depth
- ***Epicenter***: location on the surface of the Earth above the hypocenter
- ***Hanging Wall***: top block of a fault (where a light would hang from)
- ***Footwall***: bottom block of a fault (where you would stand)

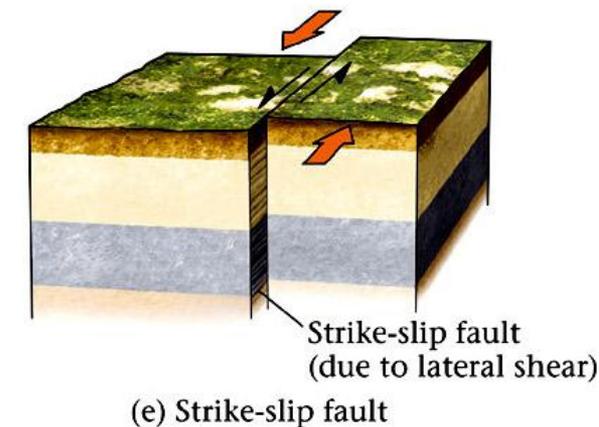
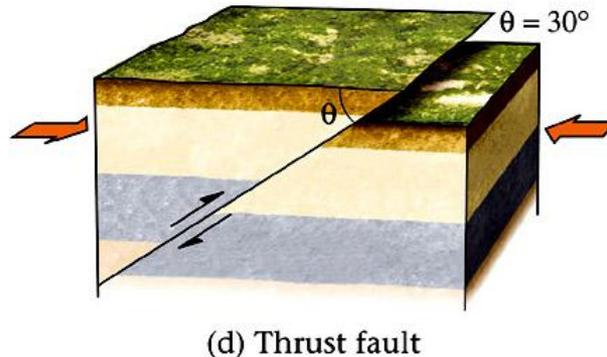
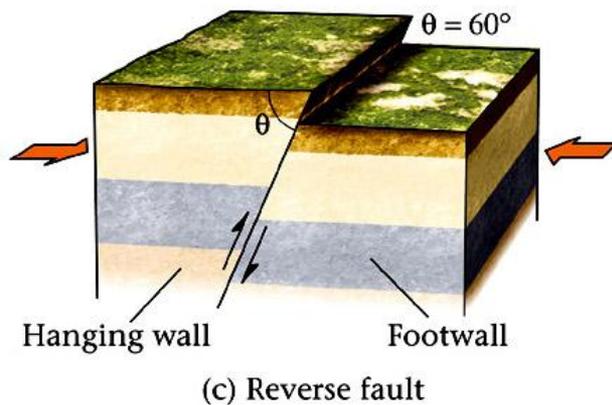


Types of Faults

- In general, faults come in three different types: *Normal*, *Reverse*, and *Strike-Slip*
- Shallow angle ($< 30^\circ$) reverse faults are called *thrust faults*
- Faults that have a mix of slip styles are called *oblique slip faults*

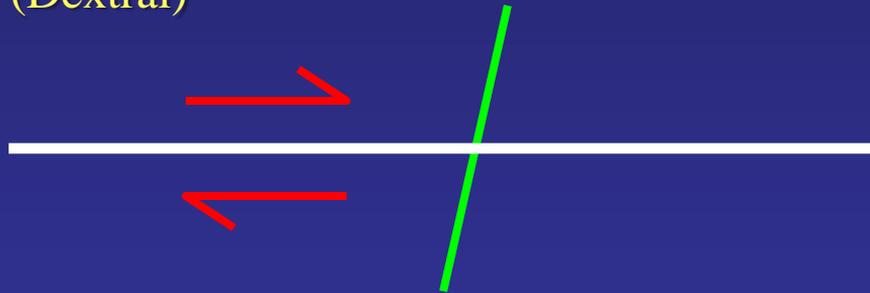


Fault animations

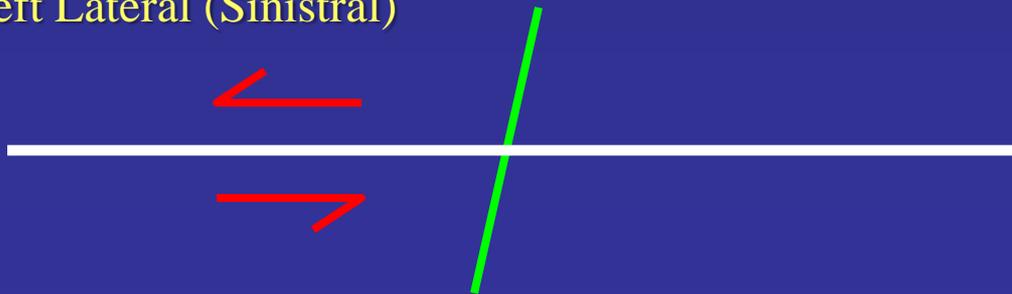


Why are there different types of faults?

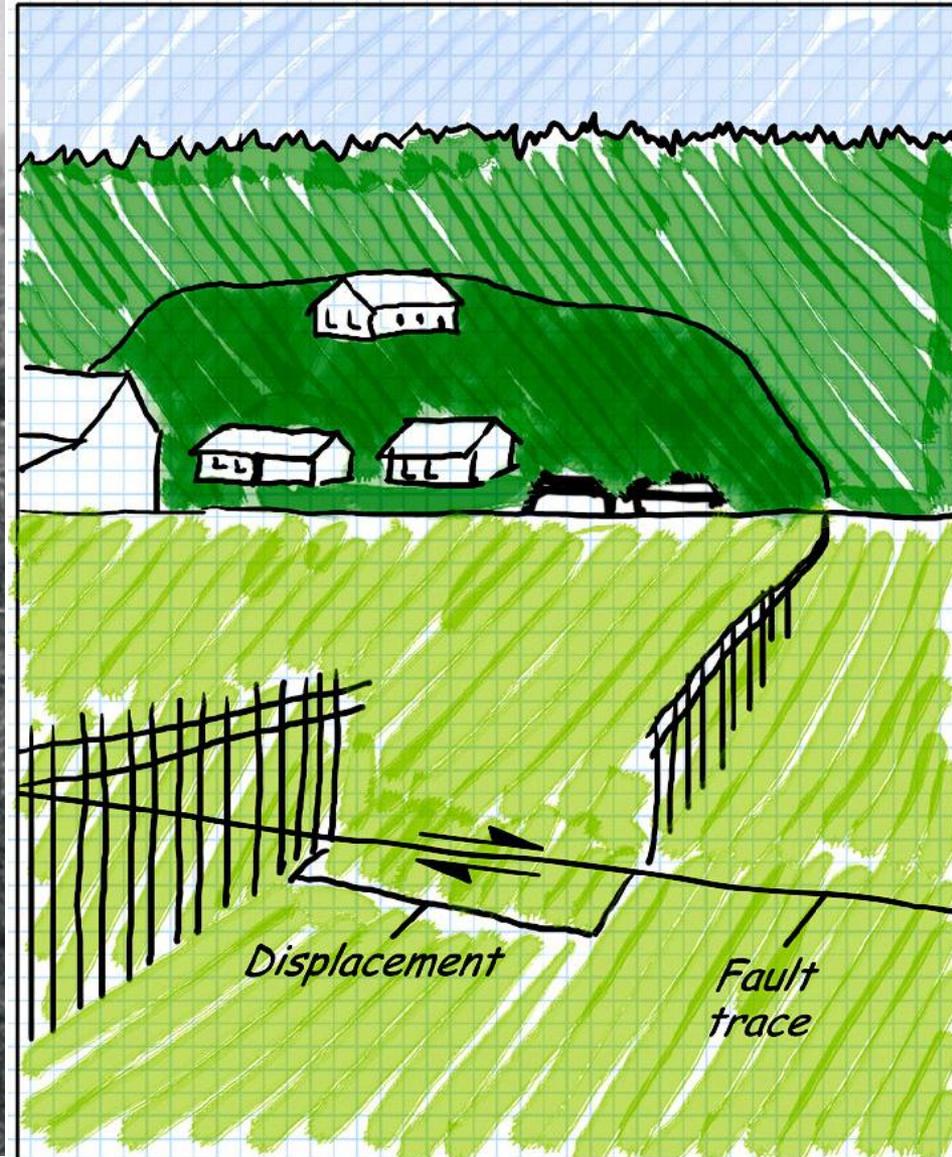
- Normal Faults: from stretching of or extending rock; points on opposite sides of a fault are farther apart after an earthquake
- Reverse Faults: from contraction or squishing rock; points on opposite sides of the fault are closer together after an earthquake
- Strike-Slip: can form in either areas of stretching or squishing, material slides laterally past each side of the fault.
 - Described by sense of motion:
 - Right-lateral (Dextral)



- Left Lateral (Sinistral)



Measuring Motion Across a Fault



What a geologist sees

M7.8 1906 Great San Francisco Earthquake

Motion Across a Fault

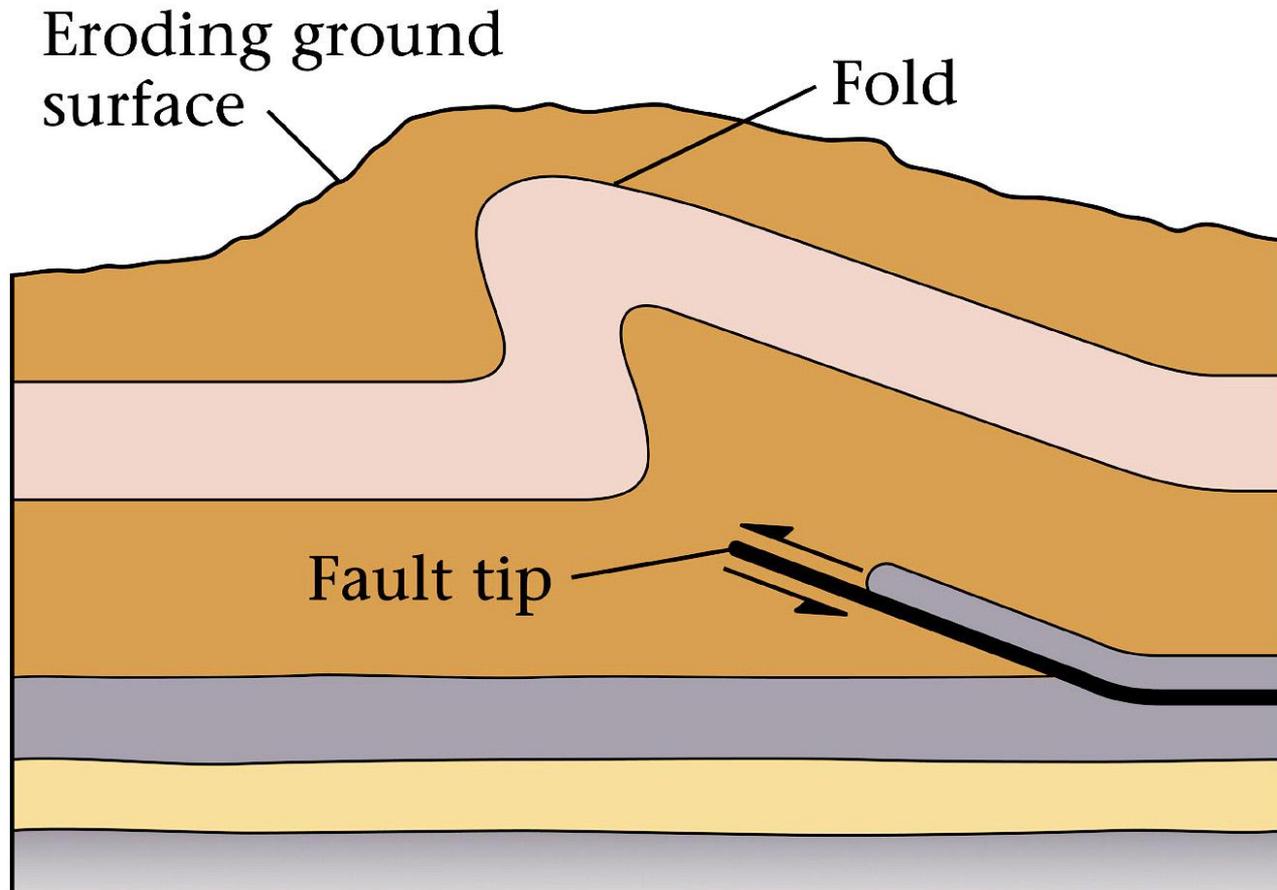
- The amount of motion along any fault is called the *slip*, *offset*, or *displacement*
- **Fault trace (line):** where the fault plane intersects the surface of the Earth
- **Active/Inactive Faults:** not all faults are likely to produce an earthquake
- **Fault scarp:** vertical motion on a fault produces a small escarpment
- What was the sense of slip here?
- *Offset stream animation*



Offset road from the Mw7.1 1999 Hector Mine earthquake

Blind Faults

- Faults that do not reach the surface of the Earth (i.e. no fault trace) are called *blind faults*.
 - Most commonly associated with reverse faulting (e.g. blind thrusts)
 - Blind faults produce folding above their upper tip
 - Common in Los Angeles (e.g. M_w 6.7 1994 Northridge earthquake)

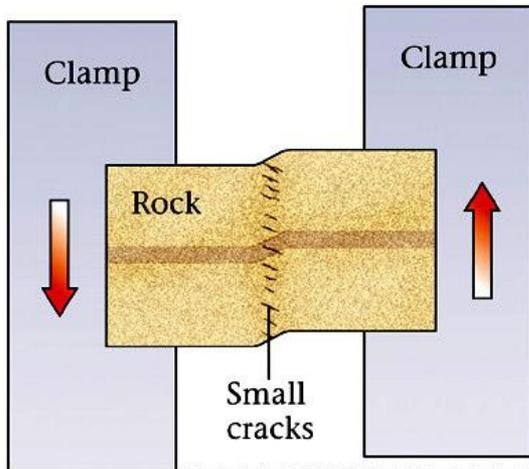


Formation of Faults

- Faults form because of stress & strain
 - Stress: a push or pull on an object (stress = force/area)
 - Strain: a change in shape or size (deformation) of an object (strain = change in length/original length)
 - The process is known as *elastic rebound theory*

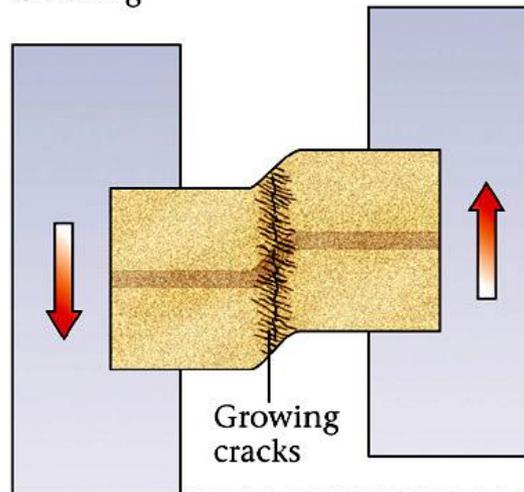
Elastic strain:
strain that is recoverable

Elastic bending



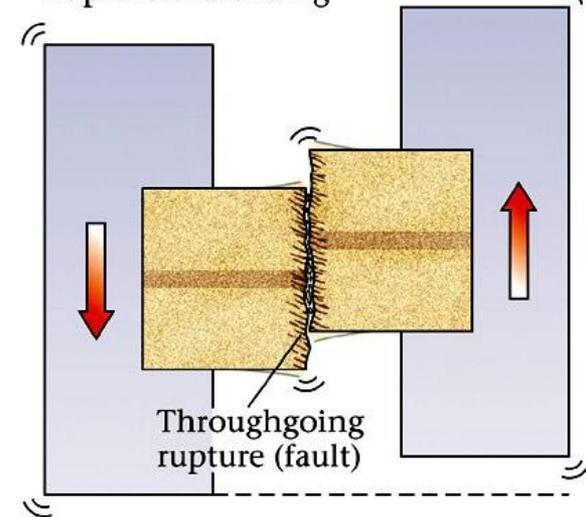
New cracks form and
link together

Cracking



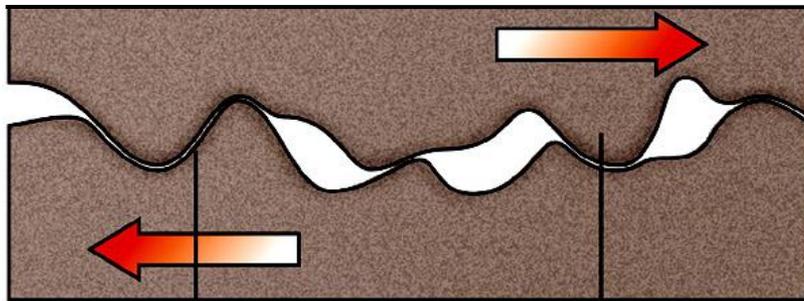
A through-going fault
forms and sliding occurs
causing a **stress drop**

Rupture and sliding



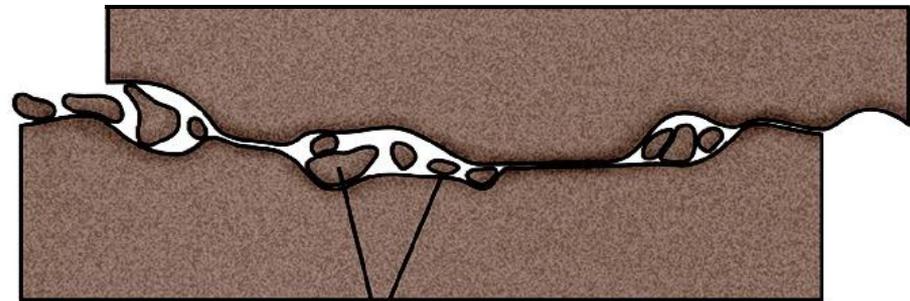
Faults & Friction

- Like a brick sliding across a table, faults, too, are subject to friction
- Friction, on the micro-scale, is caused by *asperities*, bumps and irregularities along a surface that resist sliding
- Therefore, all other things equal, faults with more cumulative slip may be smoother and therefore have lower friction (e.g. the San Andreas Fault has very low friction)
 - Once a fault is formed it is a permanent scar that is weaker than the surrounding rock



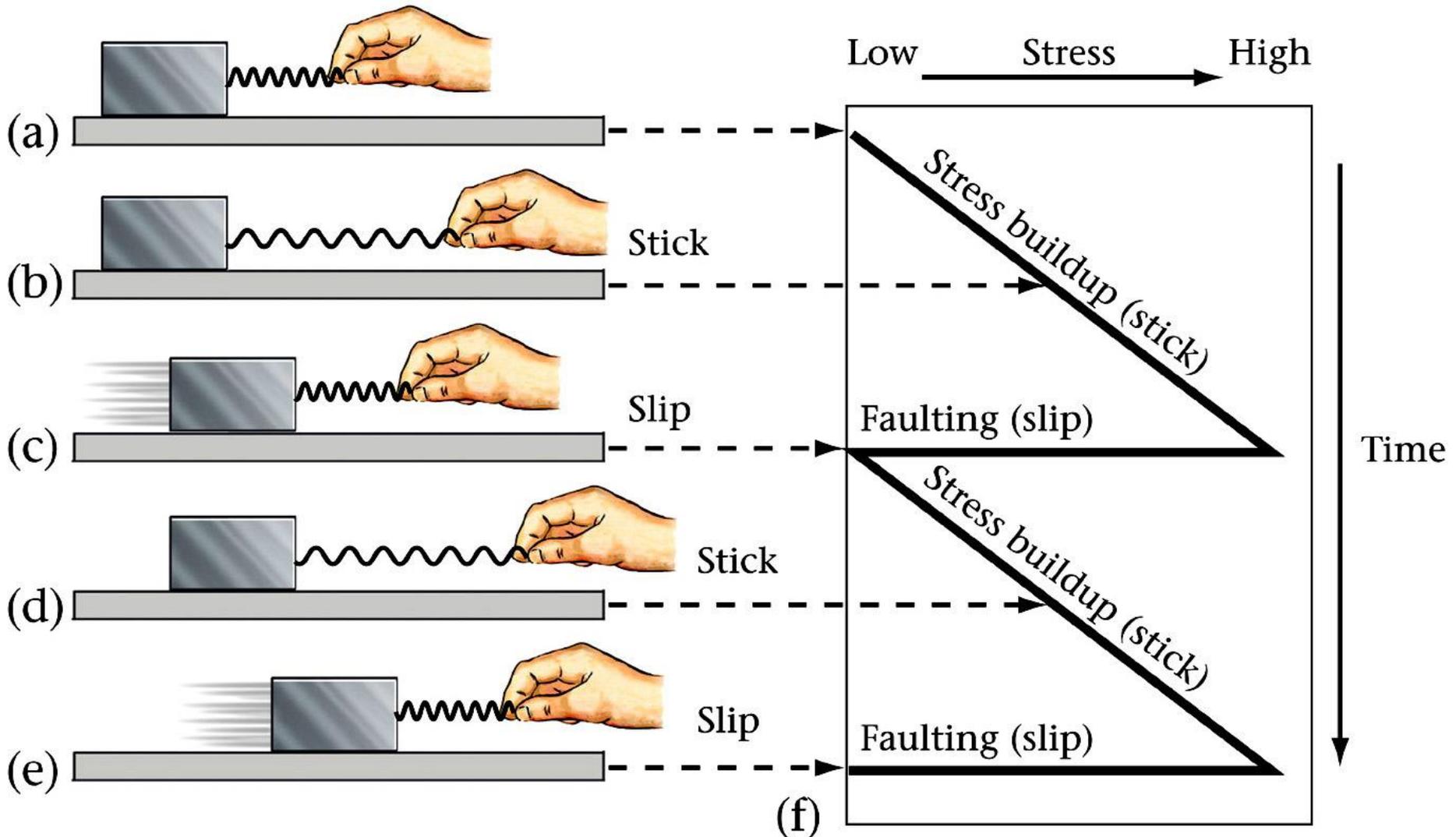
Two surfaces
in contact

Asperity
(protrusion)



Broken-off asperities

Stick Slip Behavior

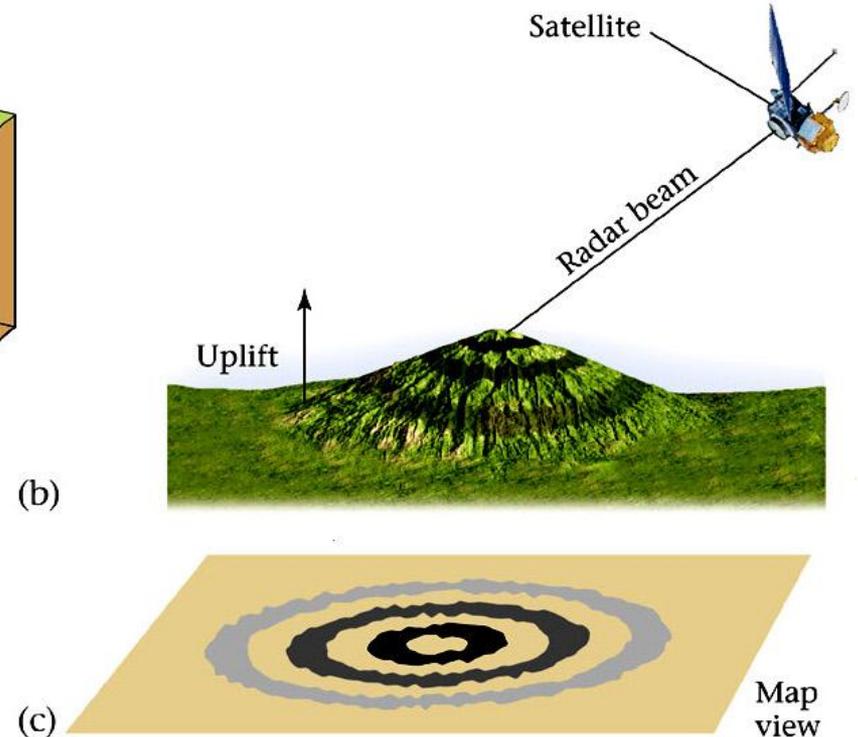
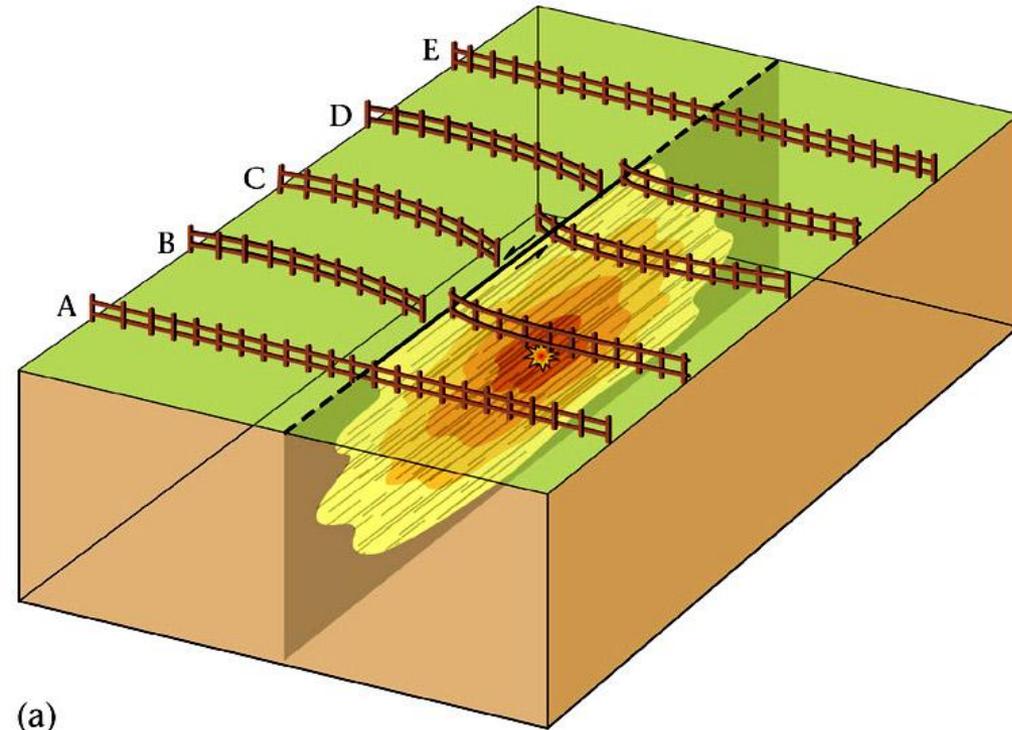


- Without stick slip behavior, earthquakes would not happen!
- Faults would constantly move (i.e. **creep**) and not build up stress

How Much of Slip Happens During an Earthquake?

- **The magnitude of an earthquake depends on:**
 - Amount of slip
 - Rupture area (length and height/depth)
- **1906 SF earthquake (M~7.8)**
 - 430 km long x 15 km deep rupture
 - 7 m max slip (~22 ft)

- **1994 Northridge earthquake (M6.7)**
 - 5 km long 18 km deep rupture
 - ~0.5 m max slip
- **2004 Sumatra earthquake (M9.3)**
 - ~1000 km x 50 km rupture
 - 20 m max slip
- ***Aftershock, Foreshock*:** earthquakes after and before an earthquake of greater magnitude. Days to years apart



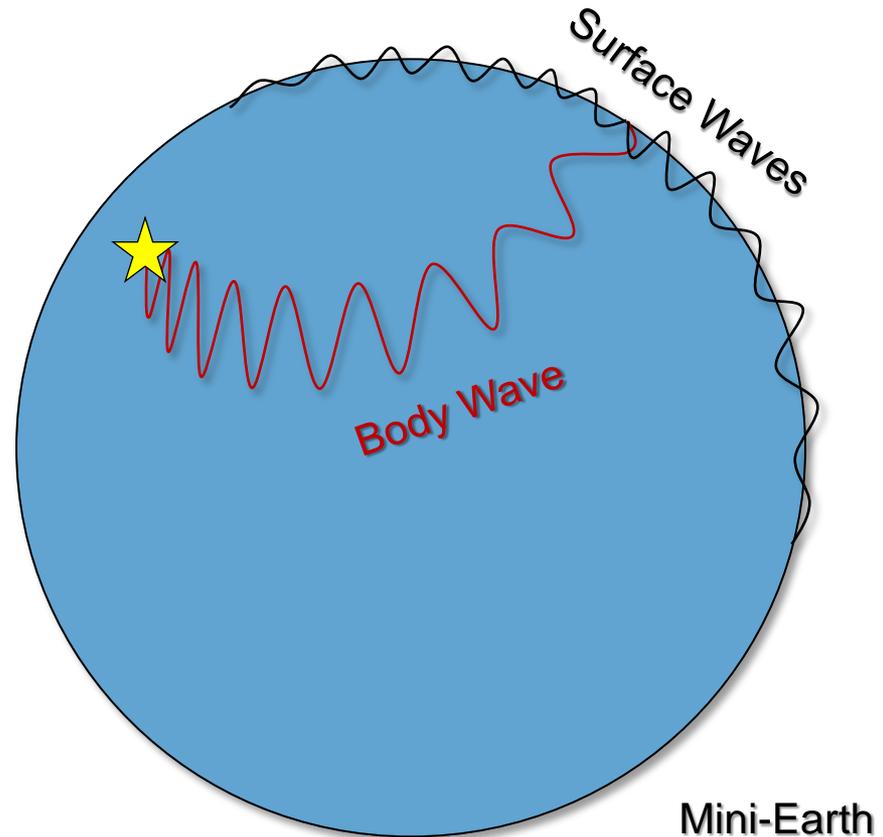
Can Faults Slip Without Earthquakes?

- Earthquakes represent brittle deformation, so they must occur within the lithosphere
- Where material is ductile, it is able to flow and stick slip behavior does not occur (no earthquakes)
- There are also certain locations where faults slip without generating large earthquakes. This kind of slip is called *aseismic slip* or *fault creep*, although very tiny earthquakes are generated (microseismicity), so creep is not completely without seismicity



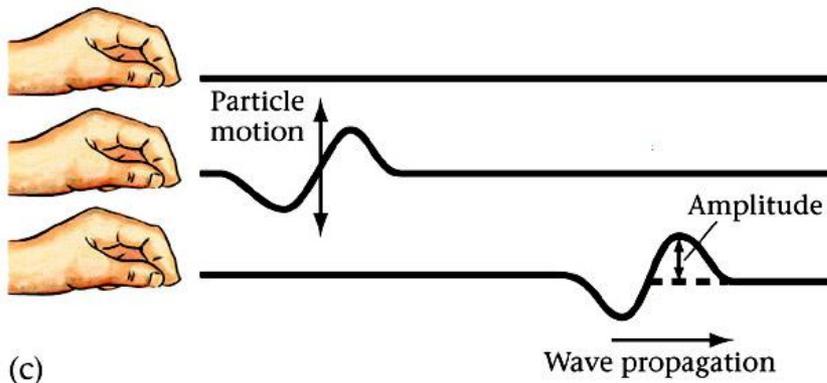
Basic Wave Types

- Radiated energy that passes through the Earth during and after an earthquake are called *seismic waves*.
- In physics, there are two basic ways to classify waves
 - Both are required to completely describe the wave type
- 1st Way: Based on what the wave is traveling through / along
 - Body wave: Motion through the interior of Earth
 - Surface wave: Motion is along the surface

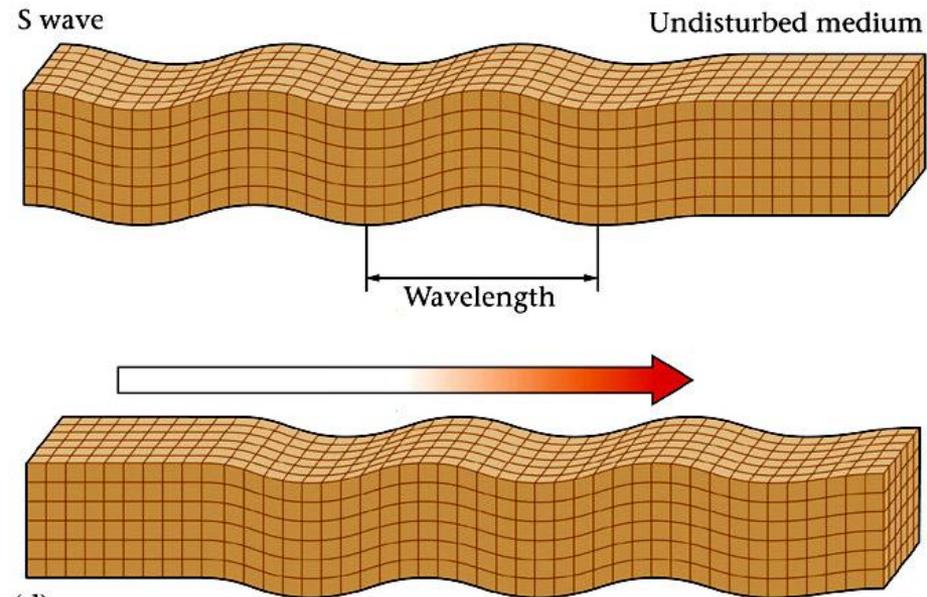


Basic Wave Types

- 2nd Way: Based on how particles are moved by the wave / how the wave causes the material it is traveling through to deform
 - Compressional (Transverse) waves
 - motion of particles is in the direction of the wave
 - causes material to contract and extend
 - Shear (Longitudinal) waves
 - motion is perpendicular to wave direction
 - causes material to shear



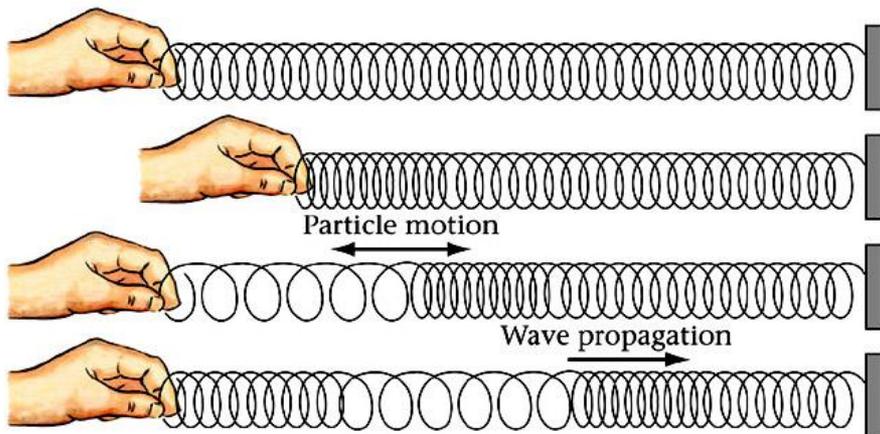
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(d)

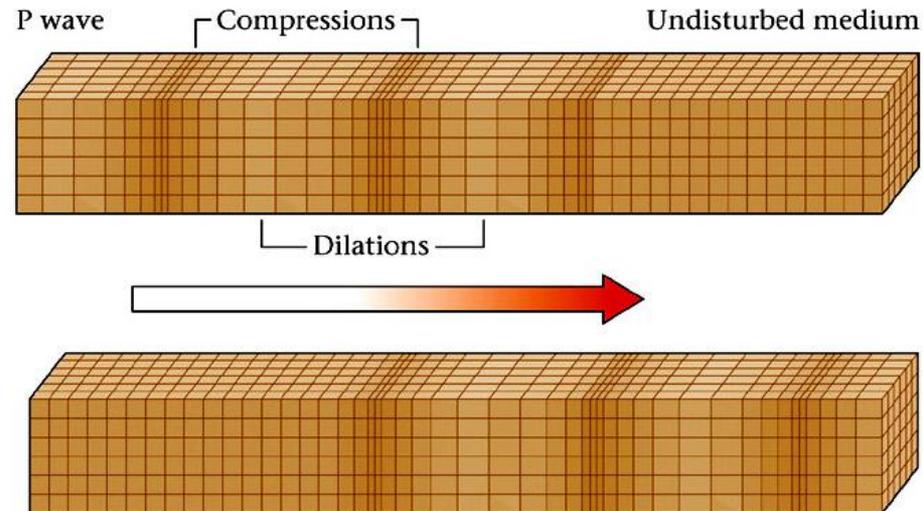
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(a)

(Animation of wave types)



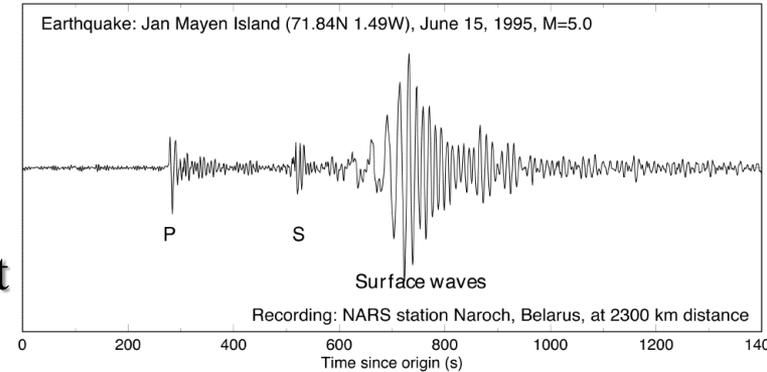
(b)

Types of Seismic Waves

Earthquakes produce four main types of waves...

Body Waves

- ***P-waves*** - compressional body waves
 - Think “primary” or “push-pull” waves
 - Travel the fastest, so they always arrive first
- ***S-waves*** - shear body waves
 - Think “secondary” or “shear” waves
 - Travel ~60% the speed of P-waves (arrive second)



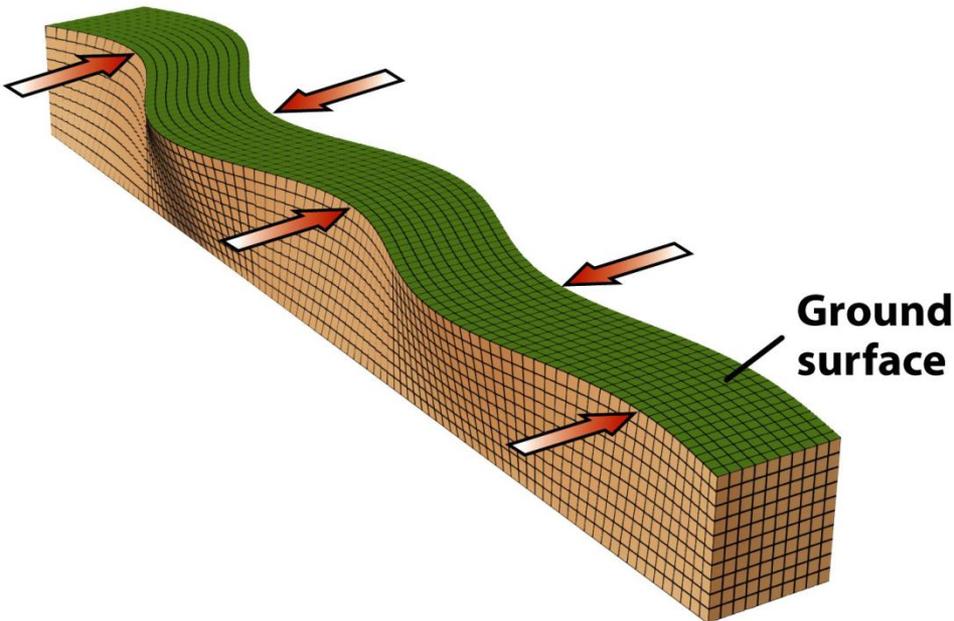
Surface Waves (slowest travel speeds)

- ***R-waves*** – (Rayleigh, named for a physicist) surface shear waves that make the ground move up and down in a retrograde elliptical pattern.
- ***L-waves*** – (Love, named for a seismologist) surface shear waves that cause the ground to move horizontally back and forth (like a snake).
- There are no surface compressional waves

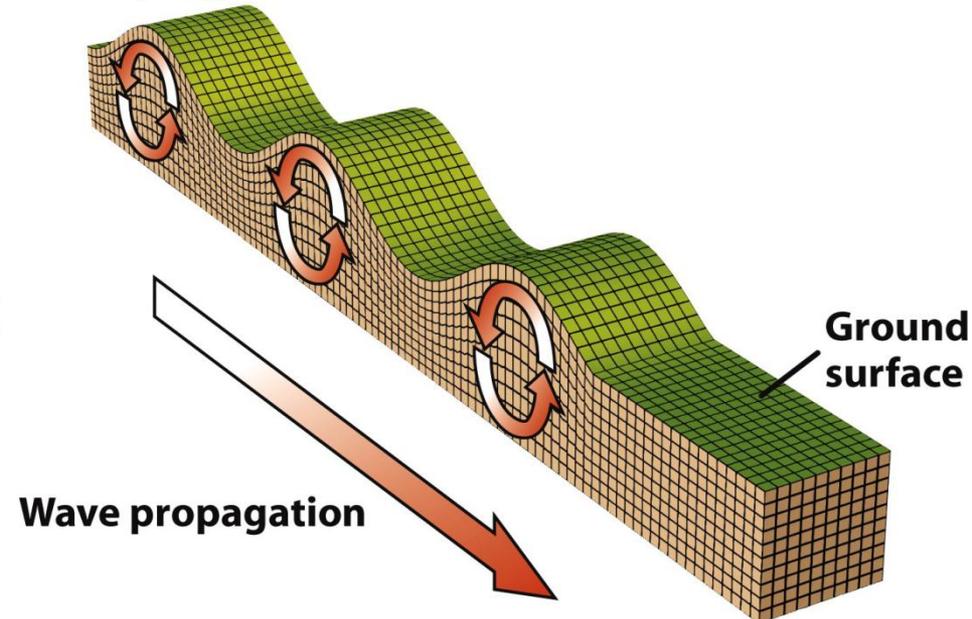
L-waves & R-waves

- L-waves – horizontal motion
- R-waves – retrograde elliptical motion in the vertical plane
 - Wave amplitude decreases (for all wave types) with distance traveled, so all things equal, the farther you are from the hypocenter the less shaking you will feel.
 - Surface waves generally do most of the damage in earthquakes
 - How do we measure ground motion?

Love wave

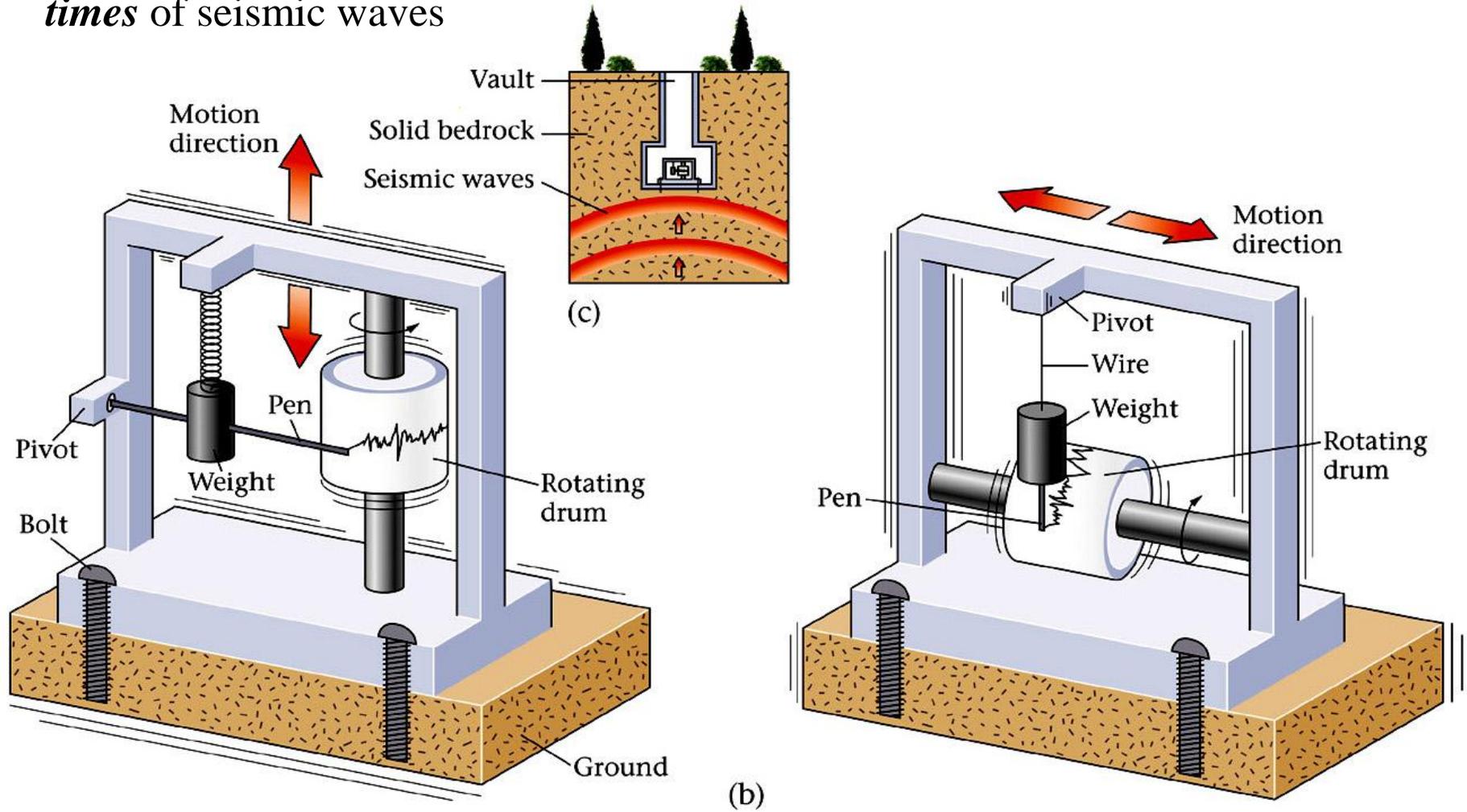


Rayleigh wave



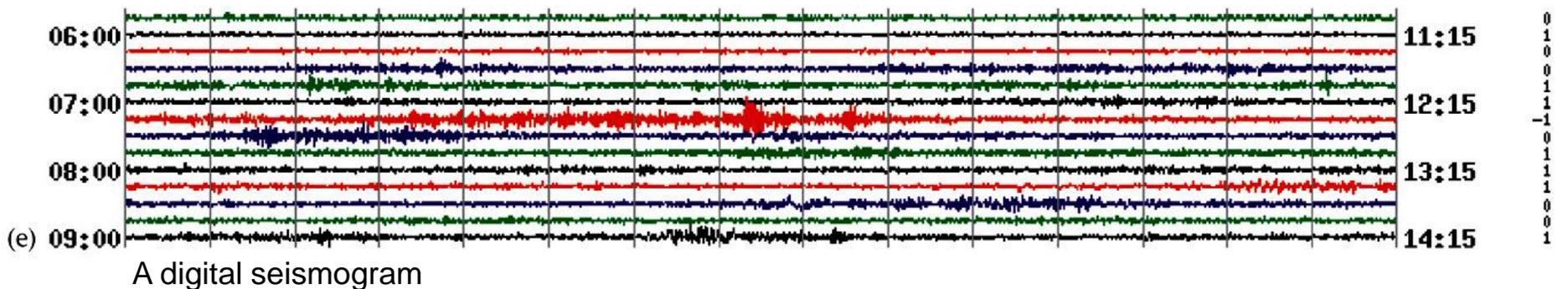
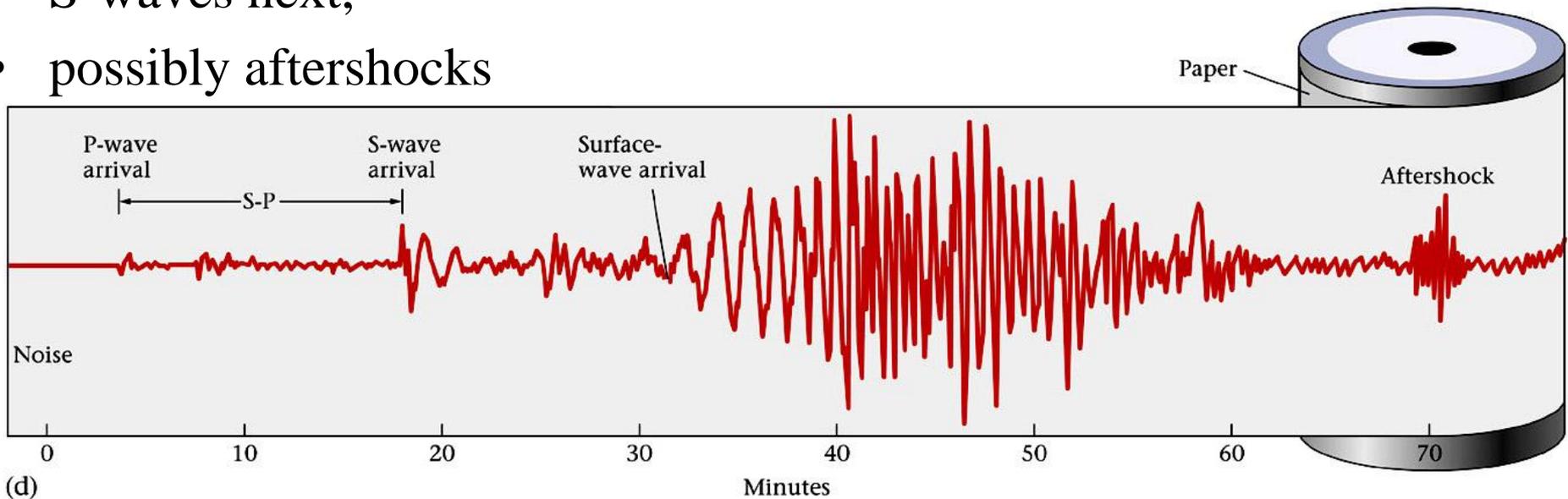
Measuring and Locating Earthquakes

- Seismologists use *seismographs* to measure motion of the Earth during and after an earthquake.
- Seismographs work because the Earth moves but the pen doesn't (animation)
- The paper that the pen writes to is called a seismogram, which records the *arrival times* of seismic waves



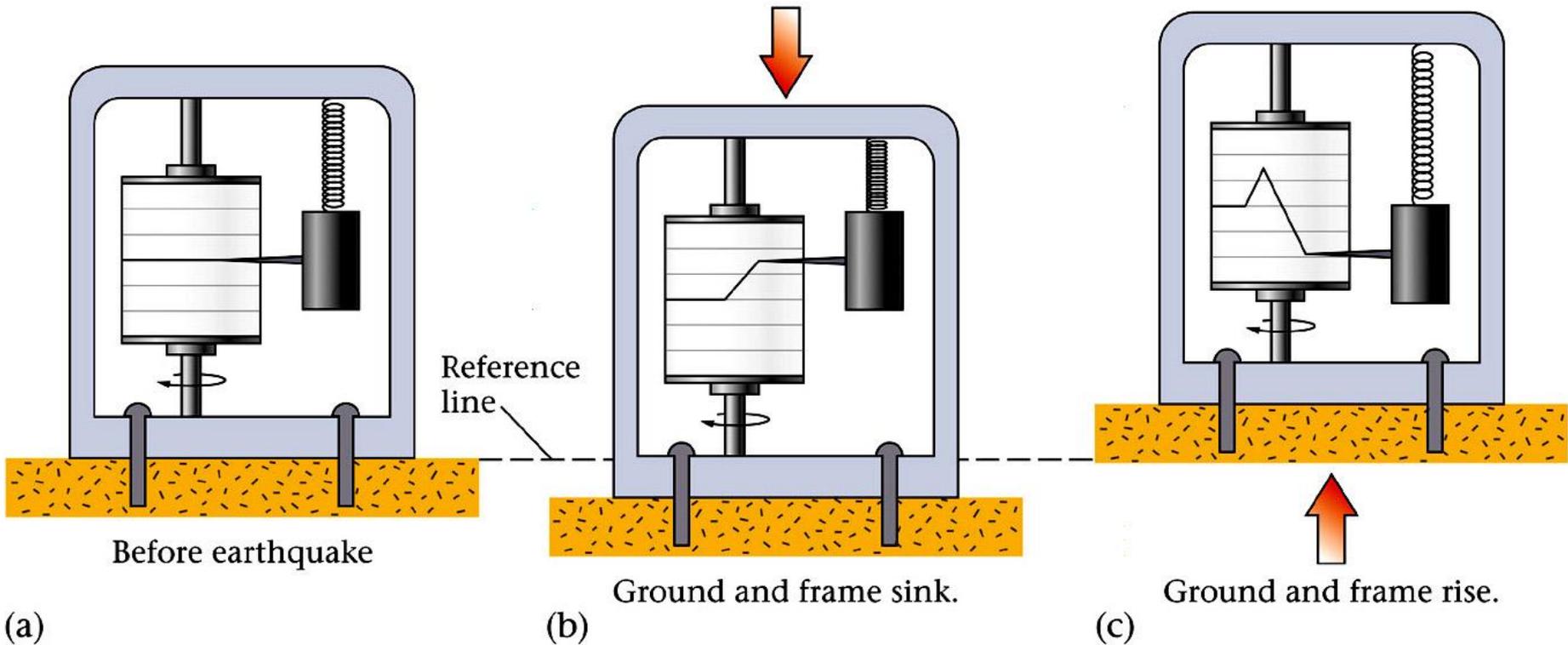
Reading A Seismogram

- On a *seismogram* (the record created by a seismograph), we see the arrival times of the various seismic waves.
- P-waves, first,
- S-waves next,
- possibly aftershocks



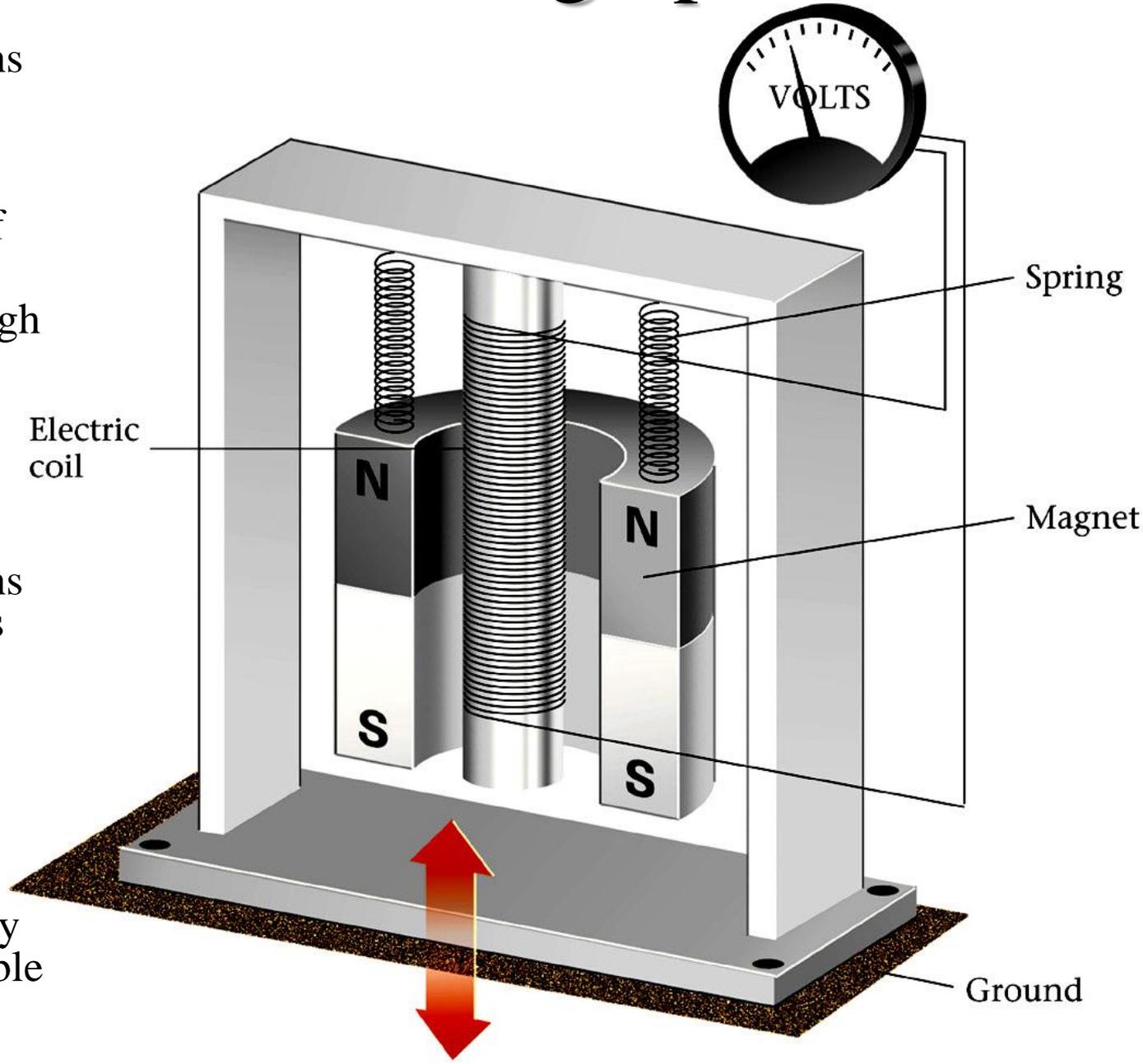
Seismograph in Action

- As the ground moves down, the seismograph records a positive slope.
- Large magnitude earthquakes are hard to measure with stations near the epicenter, because motions are so large that the needle essentially goes off the paper (e.g. the M_w 9.1 great Sumatra earthquake)



Modern Seismograph

- Modern seismographs work on the same principles as the classic design, but instead used a coil of wire inside a magnet
- Moving a wire through a magnetic field induces a current which can be measured by a computer
- Modern seismographs can measure motions of a millionth of a millimeter ($\sim 10x$ the diameter of a typical atom)
- Seismographs all around the world are calibrated so that they all generate compatible data



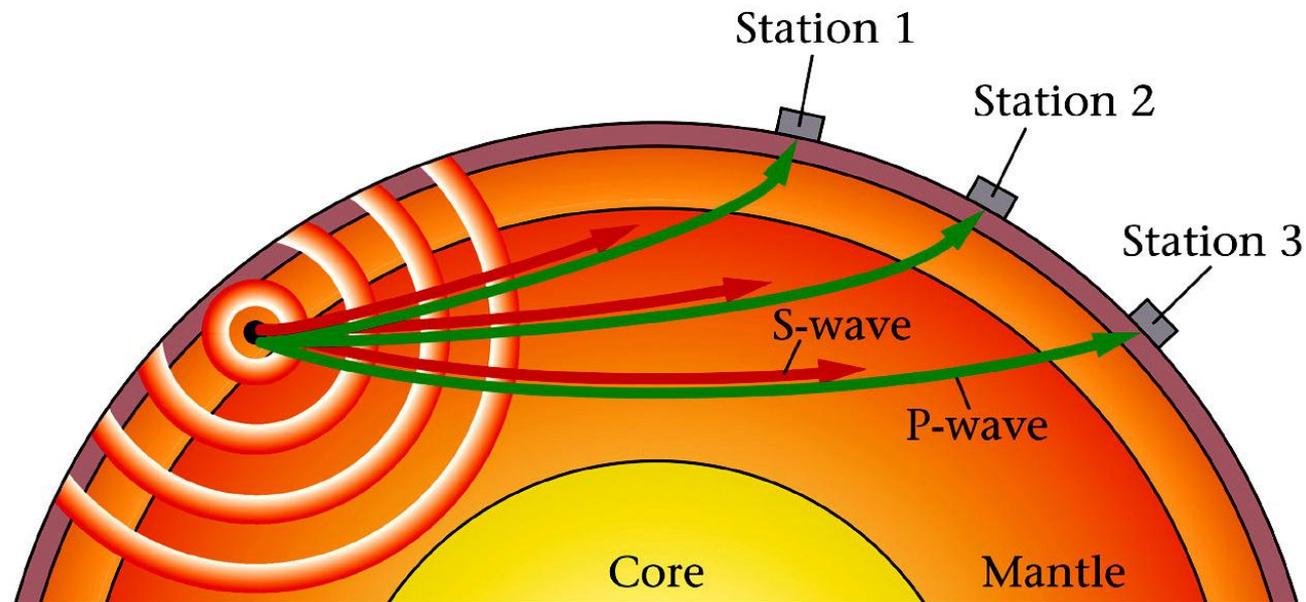
Finding the Epicenter

- Seismic waves travel in curved paths through the Earth
- Because P-waves and S-waves travel at different speeds, they will arrive at seismographs at different times
- Seismologists have defined a travel time curves for P-waves and S-waves.

P-wave

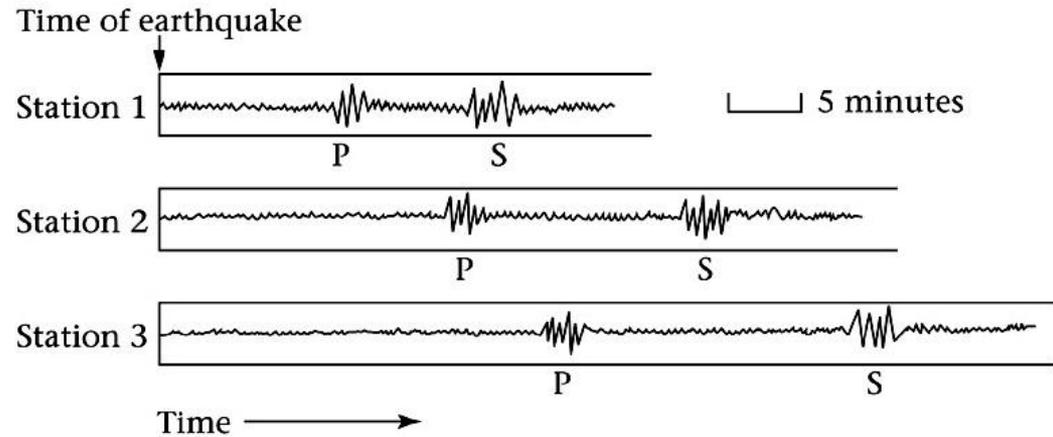


S-wave

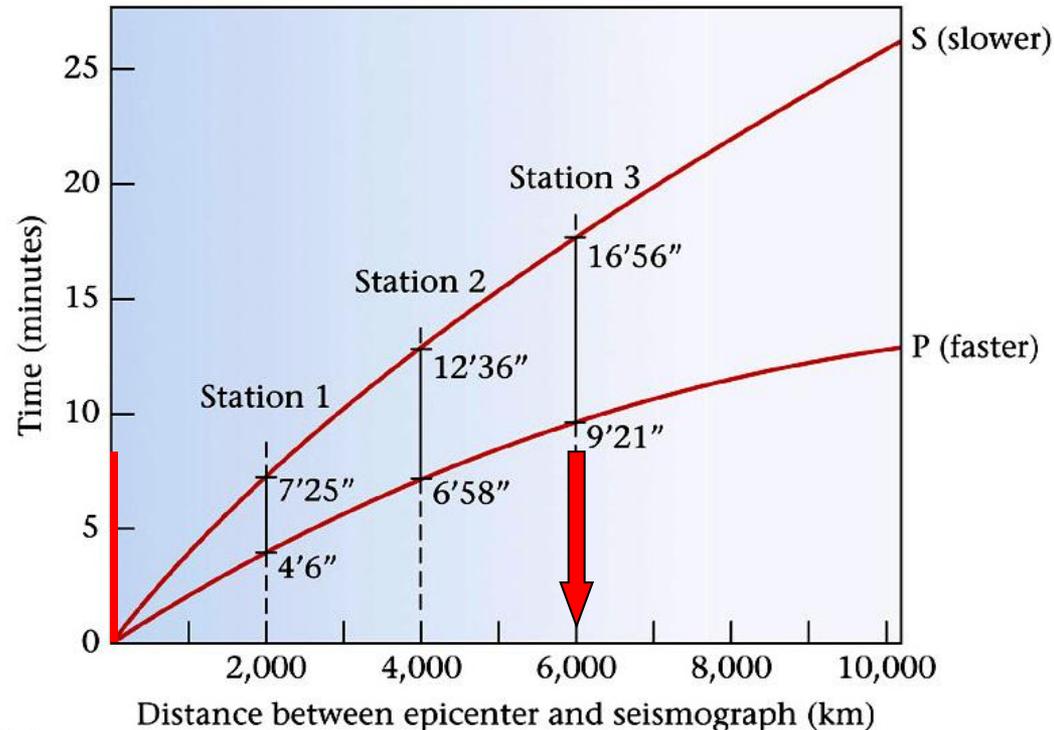


Travel Time Curves

- Lets suppose that a p-wave arrives and then 7.7 minutes later, an s-wave arrives
- We can use a P-wave S-wave travel time curve to figure out the distance from the epicenter
- We can repeat this for many stations
- Only tells you distance, not direction
- What next?

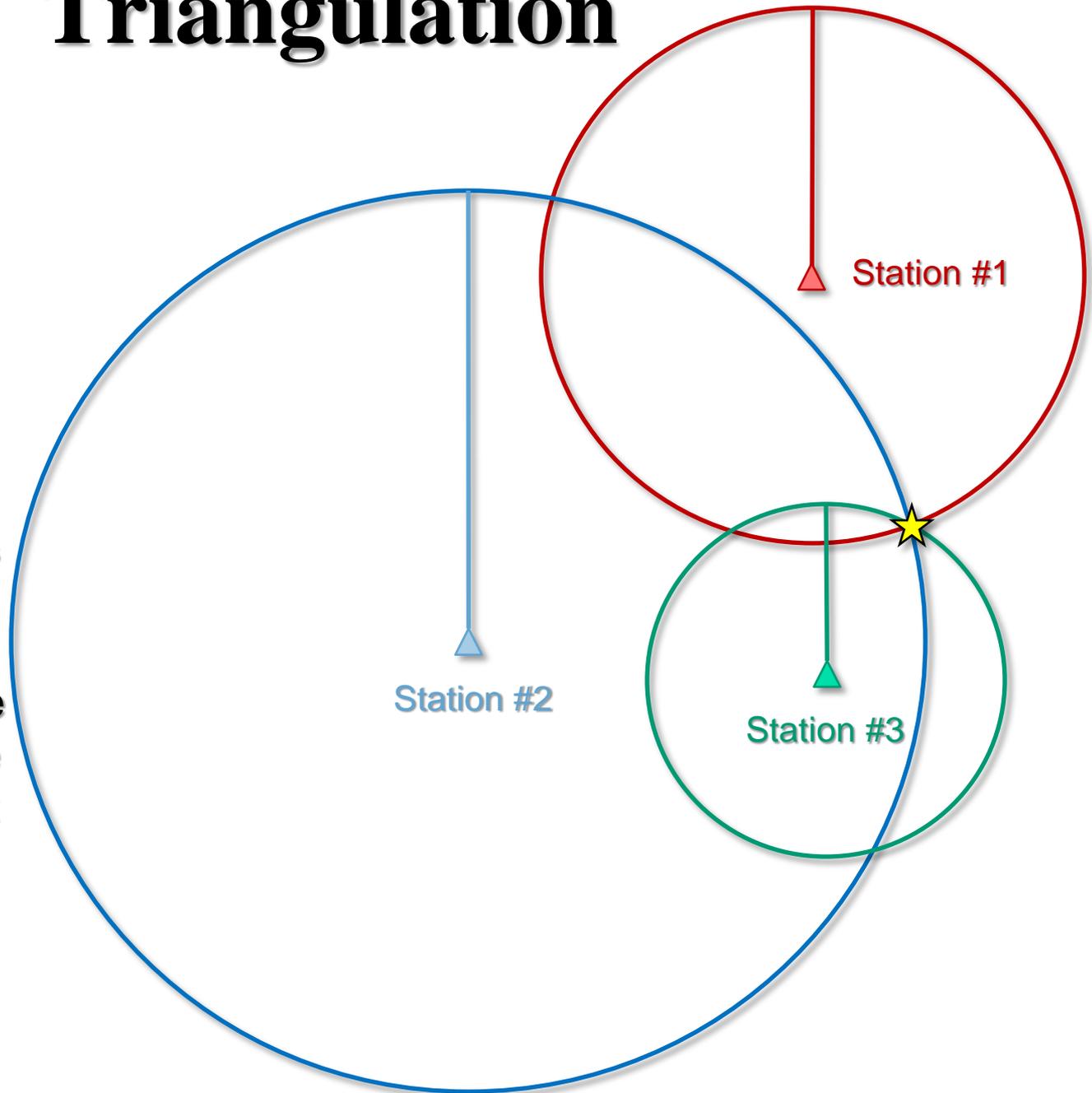


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Triangulation

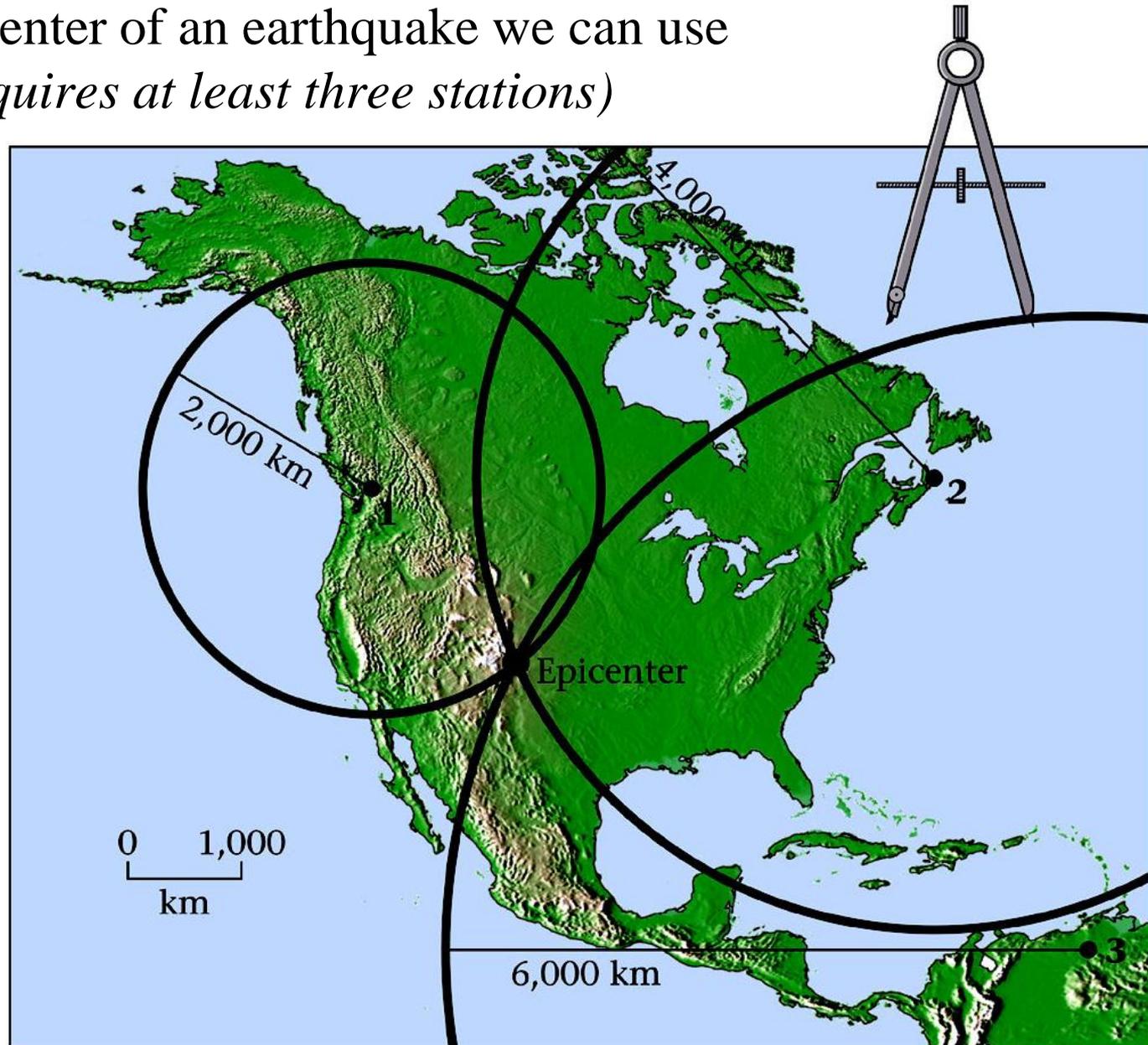
- One station gives infinite possible epicentral locations
- Two stations give two possible locations
- Three stations give one location
 - In practice there is some error
- The epicenter is located where these circles from multiple stations all intersect



Triangulation

- To locate the epicenter of an earthquake we can use *triangulation* (requires at least three stations)

- Plot the location of the seismograph on the surface of the Earth and draw a circle with a radius representing the distance calculated in the travel time curves.
- The epicenter is located where these circles from multiple stations all intersect

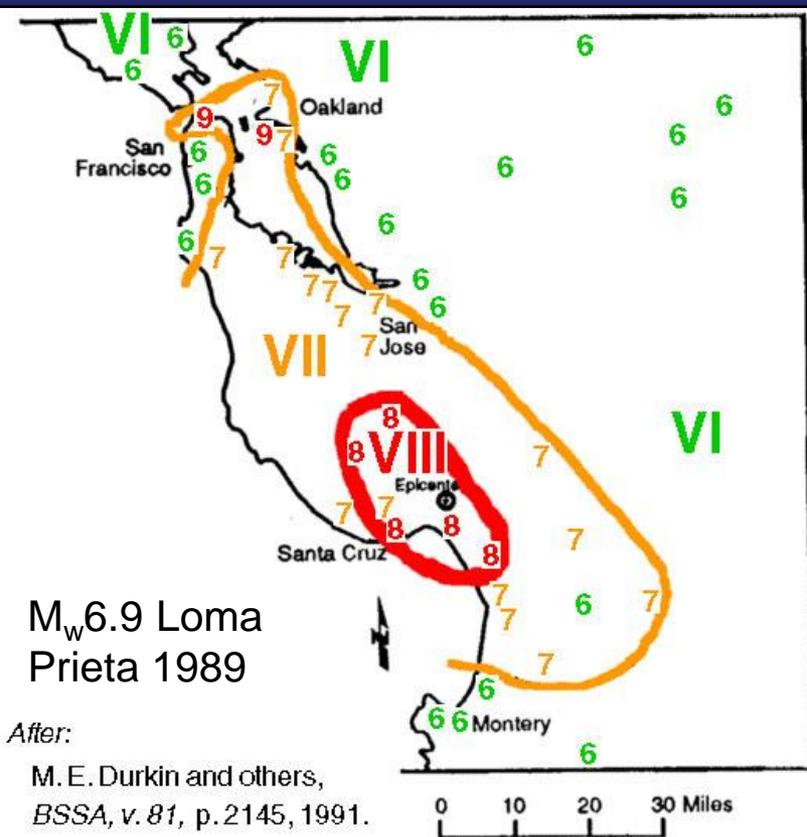


Earthquake Size

- Size of an earthquake is measured by two DIFFERENT means:
 - 1) Intensity 2) Magnitude
- **Mercalli Intensity Scale** – defines the intensity of an earthquake by the amount of damage it does and how much shaking is felt.
 - Denoted by roman numerals

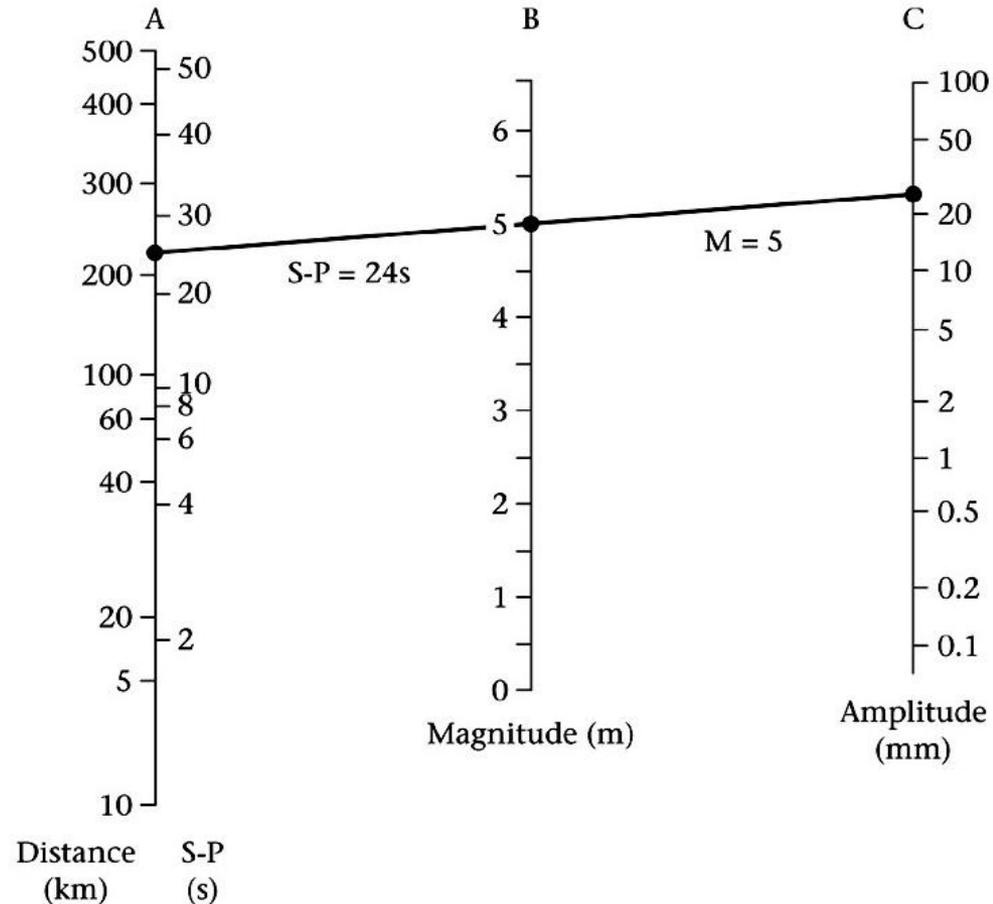
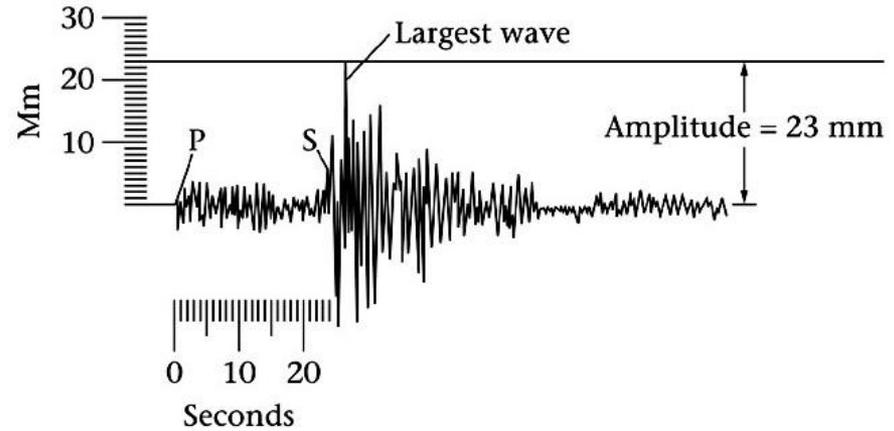
Modified Mercalli Intensity Scale

- I Not felt
- II Felt only by persons at rest
- III–IV Felt by persons indoors only
- V–VI Felt by all; some damage to plaster, chimneys
- VII People run outdoors, damage to poorly built structures
- VIII Well-built structures slightly damaged; poorly built structures suffer major damage
- IX Buildings shifted off foundations
- X Some well-built structures destroyed
- XI Few masonry structures remain standing; bridges destroyed
- XII Damage total; waves seen on ground; objects thrown into air



Earthquake Magnitude

- The size of an earthquake is also measured by its magnitude
 - Based on the maximum amplitude of ground motion measured by a seismograph
- **Magnitude does not depend on distance but Intensity does**
 - Any seismograph will record the same magnitude because it is a standardized measure
 - Intensity depends on the local geologic properties
- Earthquake magnitude was first standardized by Charles Richter, and so we call this the ***Richter scale***
 - Based on motion at 100 km distance, but can be adjusted
 - Only works well for shallow nearby earthquakes (<600 km)
 - Now called local magnitude or M_L

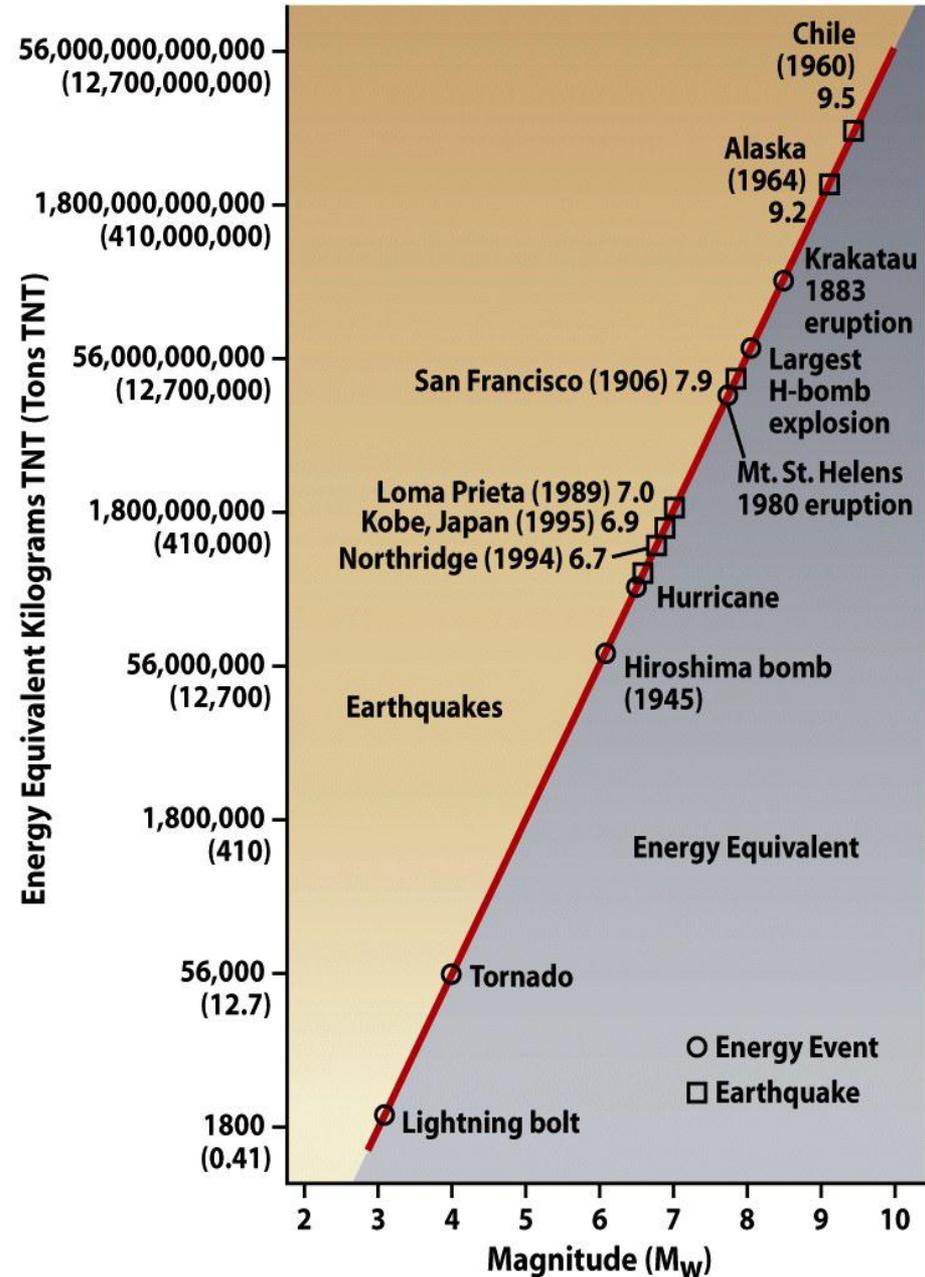


Various Magnitude Measures

- M_L : Local magnitude – i.e. “Richter Scale”
 - Only good for local shallow earthquakes
- M_s : Surface wave magnitude based on Magnitude of R-waves
 - Only good for shallow earthquakes (<50 km deep)
- m_b : body wave magnitude based on P-wave magnitude
 - With lower case “m”
- All of these are only good for small or moderate sized earthquakes
- M_w : Called the moment magnitude (Hanks and Kanamori 1979)
 - Complex calculation based on
 - Amount of fault slip and rupture area
 - Magnitudes of various seismic waves
 - The physical characteristics of the rock broken during the rupture
- Which is reported? Depends on timing, and character of the earthquake
- Different magnitude measurements may yield different answers
 - E.g. Loma Prieta (San Francisco) 1989 M_w 6.9, M_s 7.1 , M_L 6.7

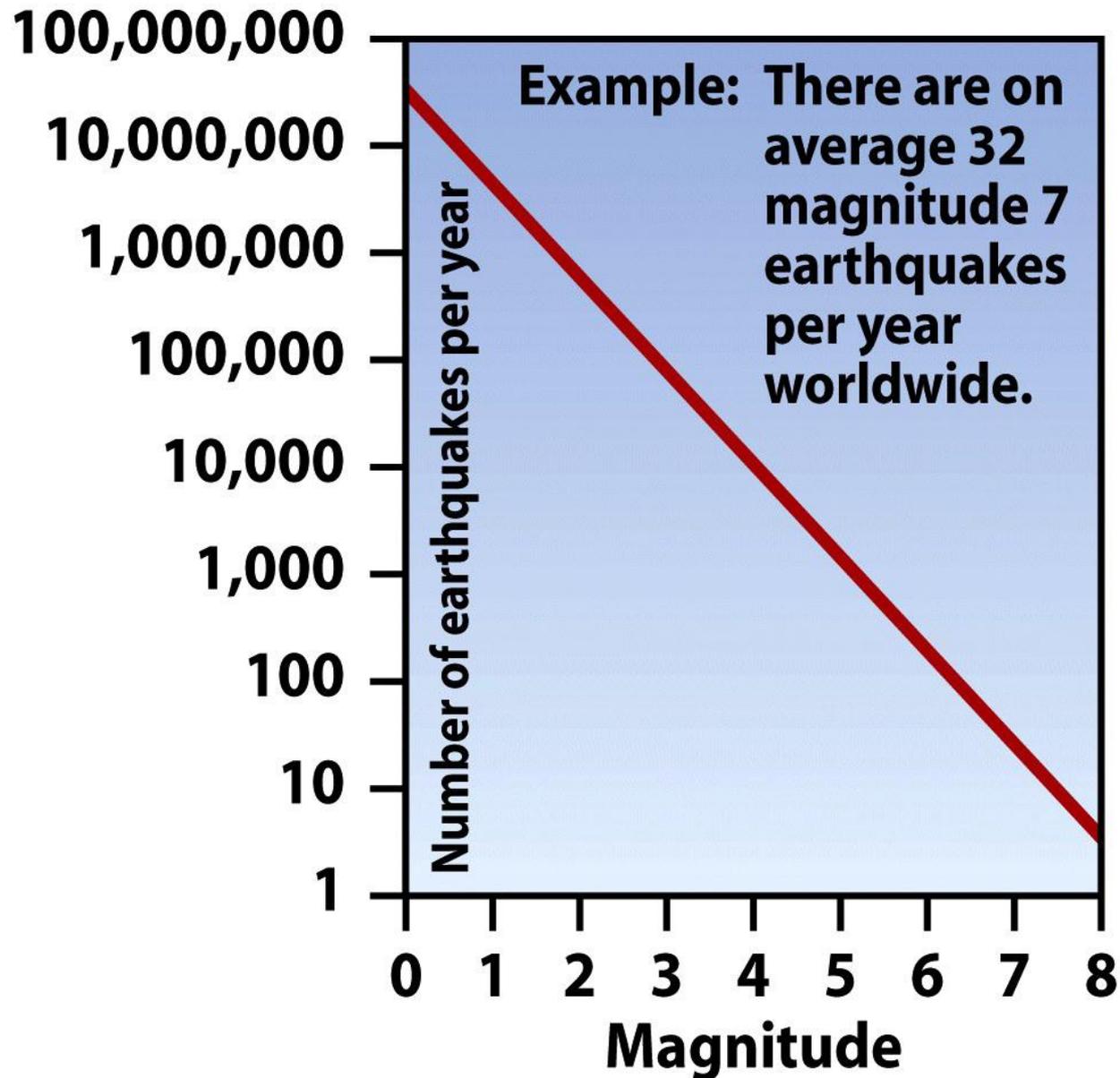
Magnitude...Its Logarithmic!

- Magnitude scales are all logarithmic
 - i.e. a magnitude 8 earthquake moves the ground 10x more than a 7 and 1000x more than a 5.
- Not a 10 point scale
 - Can have a -1 or 10.5
 - >10 is unlikely because the fault would have to be almost impossibly large
- Magnitude measures energy release during an earthquake
 - On average an M8.9 earthquake releases the same energy as all the global earthquakes in one year
 - Annual earthquake energy is only 1/1000th of the energy that we get from the sun every year



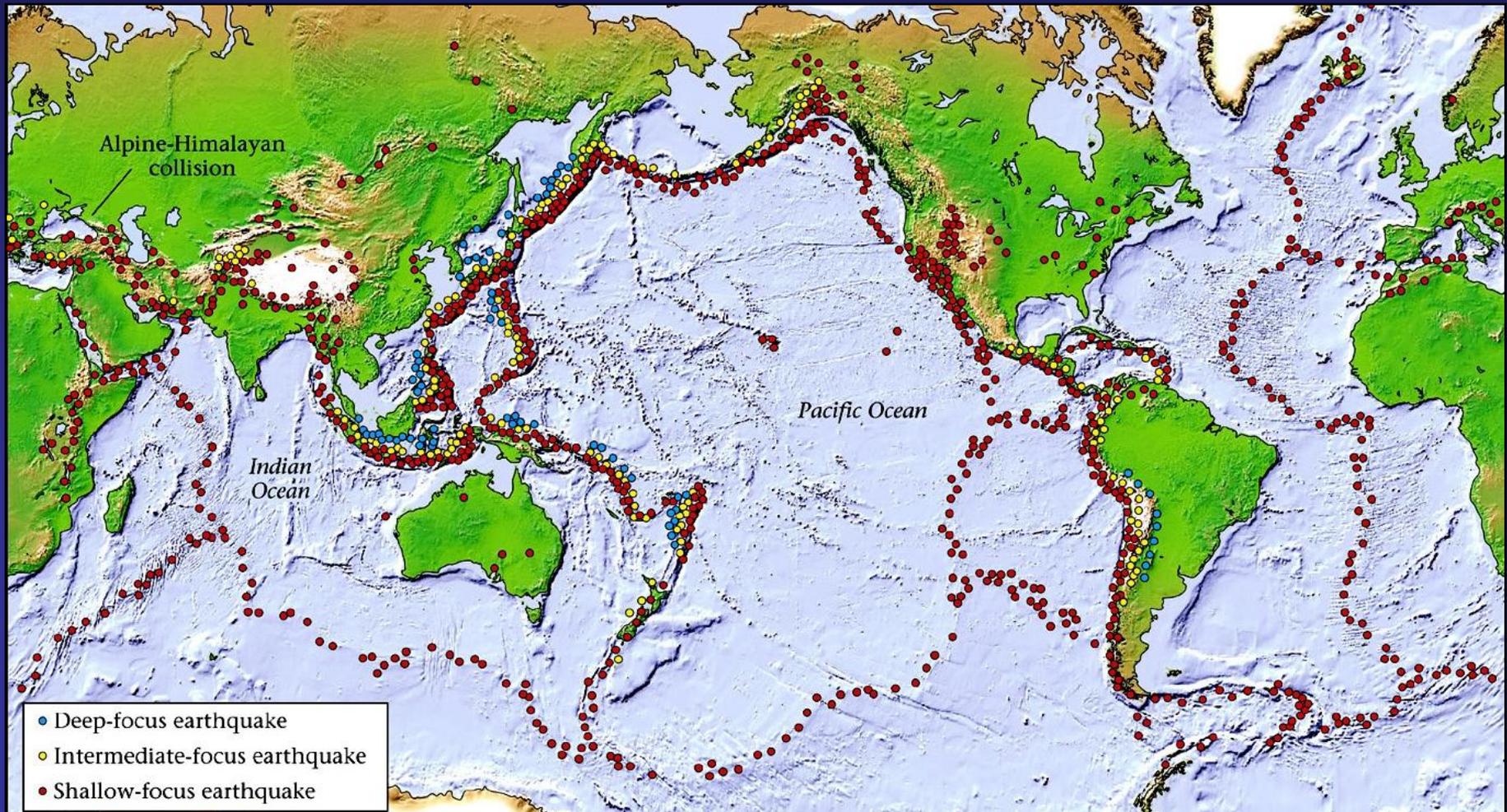
Numbers of Earthquakes Per Year

- How many earthquakes happen each year?
- Small earthquakes are common, large ones are less common
 - About 32 M7 Earthquakes per year
 - > 10,000,000 M1 or less per year



Where Do Earthquakes Occur?

- Most earthquakes occur in narrow zones around the globe called *seismic belts*
- Most seismic belts correlate with plate boundaries, but not all
- Some earthquakes occur in *intraplate* settings (within a tectonic plate)



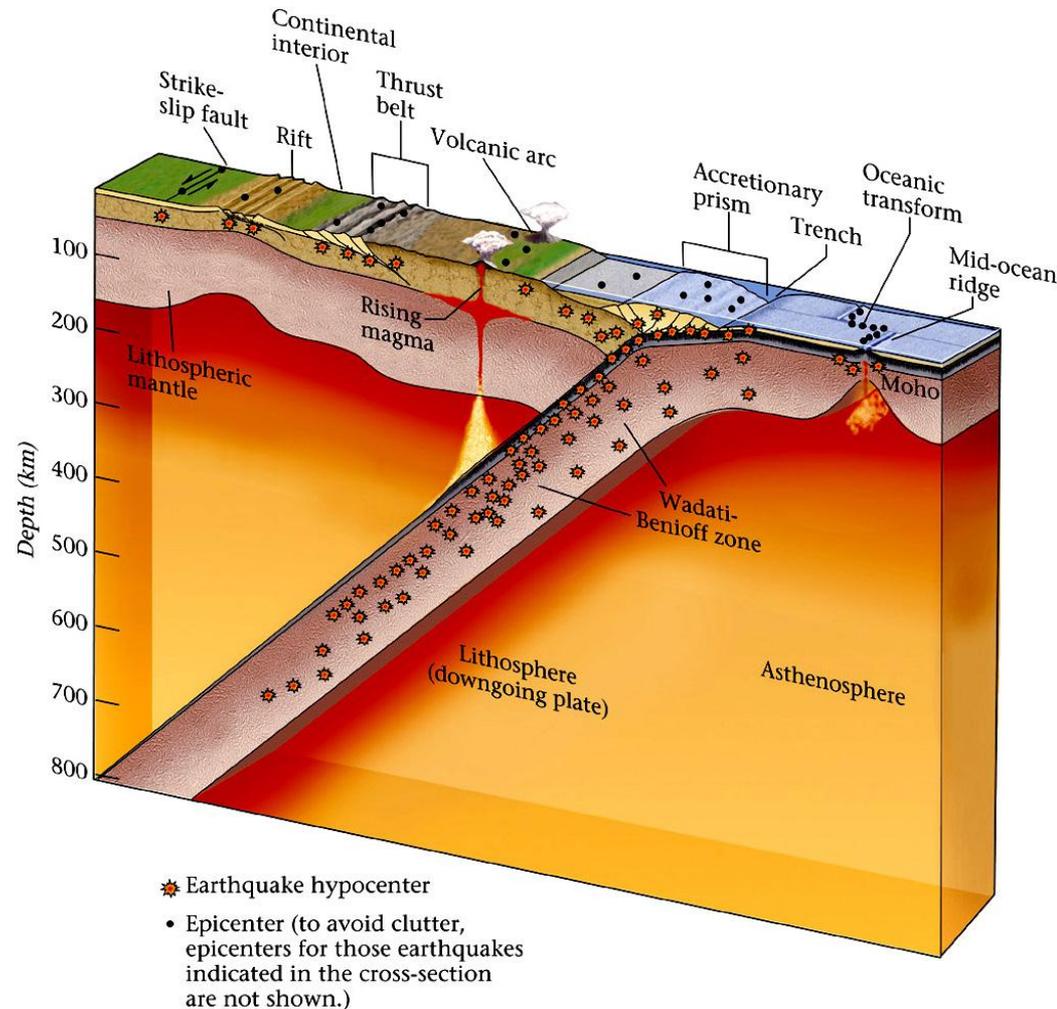
Divergent Boundary Earthquakes

What types of faults are present?

- Crustal stretching/extension: Normal faults
- Divergent boundaries (mid ocean ridges) are segmented and linked by transform faults: Strike-slip faults
- Seismicity is usually shallow-focus (<10 km) because heat flow is high
 - Rocks become ductile (asthenosphere) at shallow depths preventing stick-slip
 - Potential rupture area is small causing divergent earthquakes to rarely exceed ~M7.5
- Since most divergent boundaries are in the middle of oceans; these earthquakes are usually not very dangerous
 - Exception: Iceland
 - Not *generally* associated with tsunamis, although tsunamis are possible (due to vertical motion on normal faults)

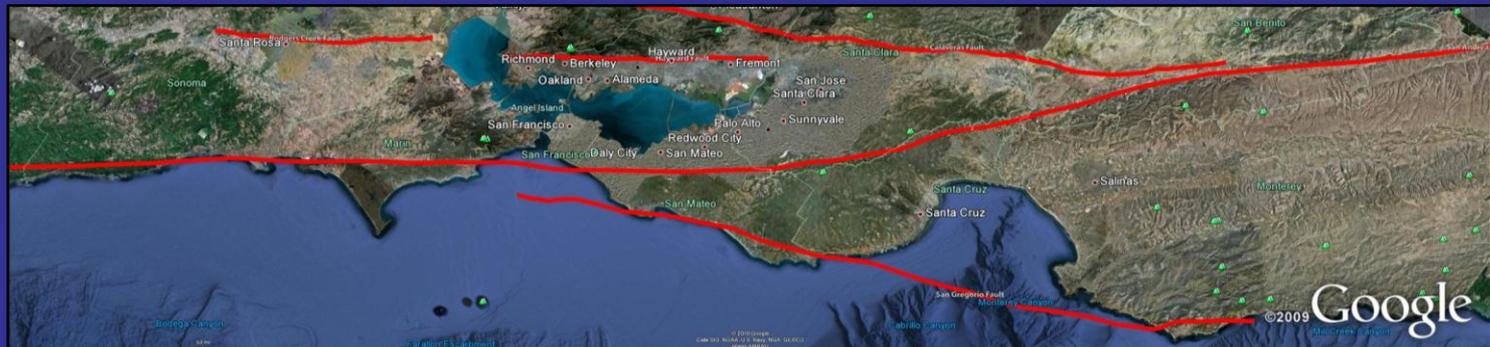
Convergent Boundary Earthquakes

- Crustal contraction = **Reverse & Thrust Faults**
- Earthquake hypocenters trace out the subducting plate: ***Wadati-Benioff zone***.
- The plate is cold, therefore earthquakes can happen to very deep depths (up to ~650 km).
- The cold deep plate leads to a large potential rupture area --> have the potential to be the largest in the world (i.e. > M9)
 - E.g. Chile 1960 $M_L 9.5$
 - Sumatra 2004 $M_W 9.3$,
 - Alaska 1964 $M_W 9.2$
- Shallow earthquakes can also occur in the overriding plate depending on the amount of contraction and bending on the upper plate.



Transform Boundary Earthquakes

- Involves either stretching or contraction of the crust, but results in the shearing of the crust along **Strike-Slip Faults**.
- Most transform faults link mid ocean ridges, but some continental strike-slip boundaries are present world wide
 - E.g. the San Andreas fault, The Alpine fault, New Zealand, The Dead Sea Transform, The North Anatolian Fault, Turkey
- Usually $< M8$ and occasionally up to $M9$.
- Not as potentially large because the brittle-ductile transition (lithosphere-asthenosphere contact) typically happens in these environments at < 20 km depth making the maximum possible rupture area smaller than subduction zones.

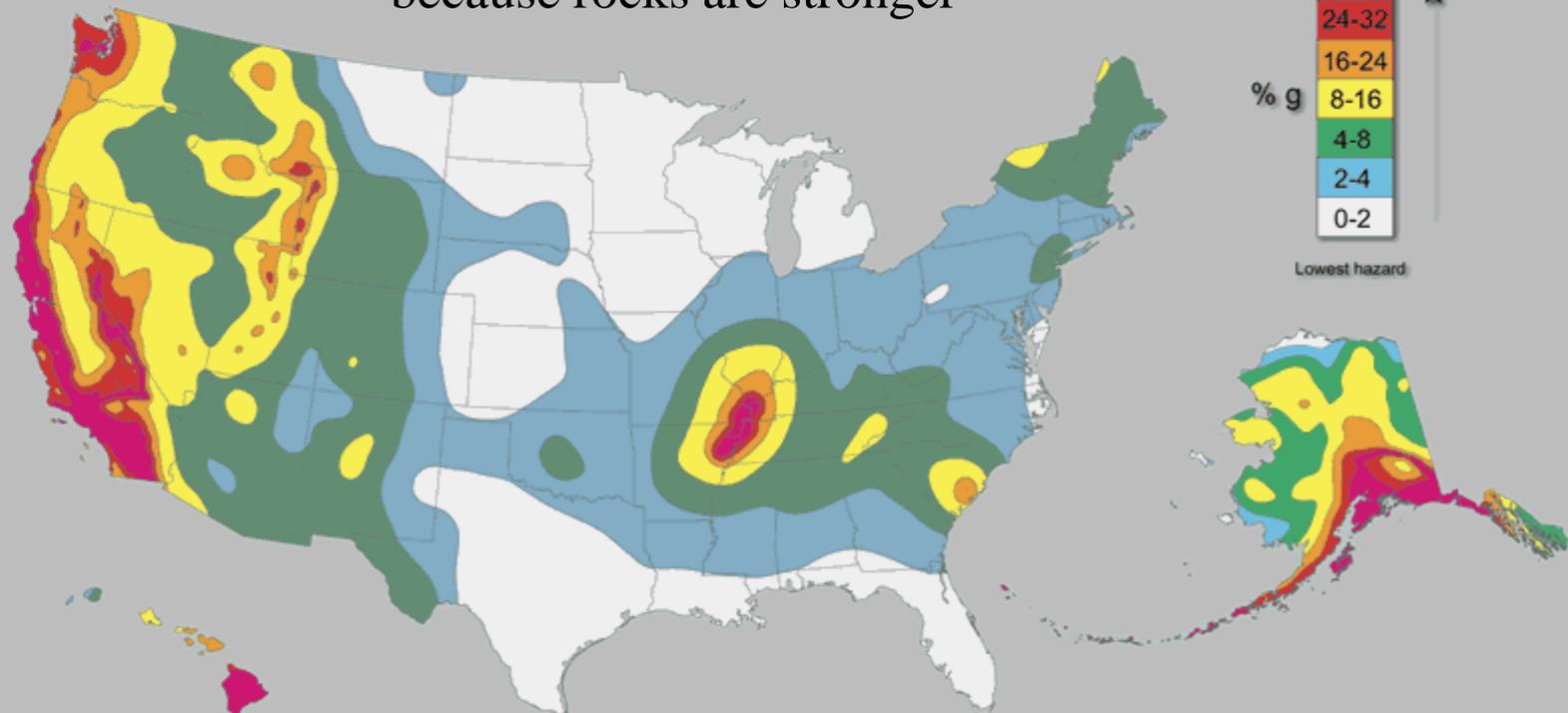


Intraplate Earthquakes

- Not all earthquakes happen at plate boundaries some occur within plates and are called *intraplate earthquakes*
- In the US, intraplate earthquakes occur in clusters
 - e.g. new Madrid fault zone, Wasatch front, UT.

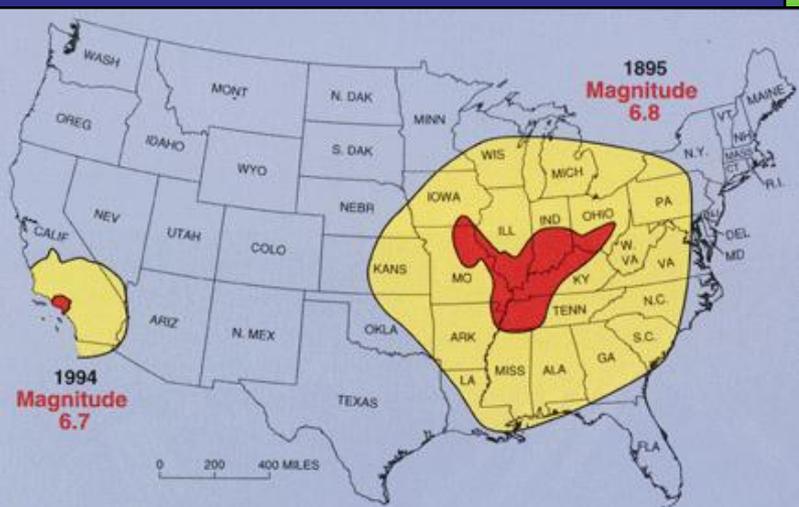
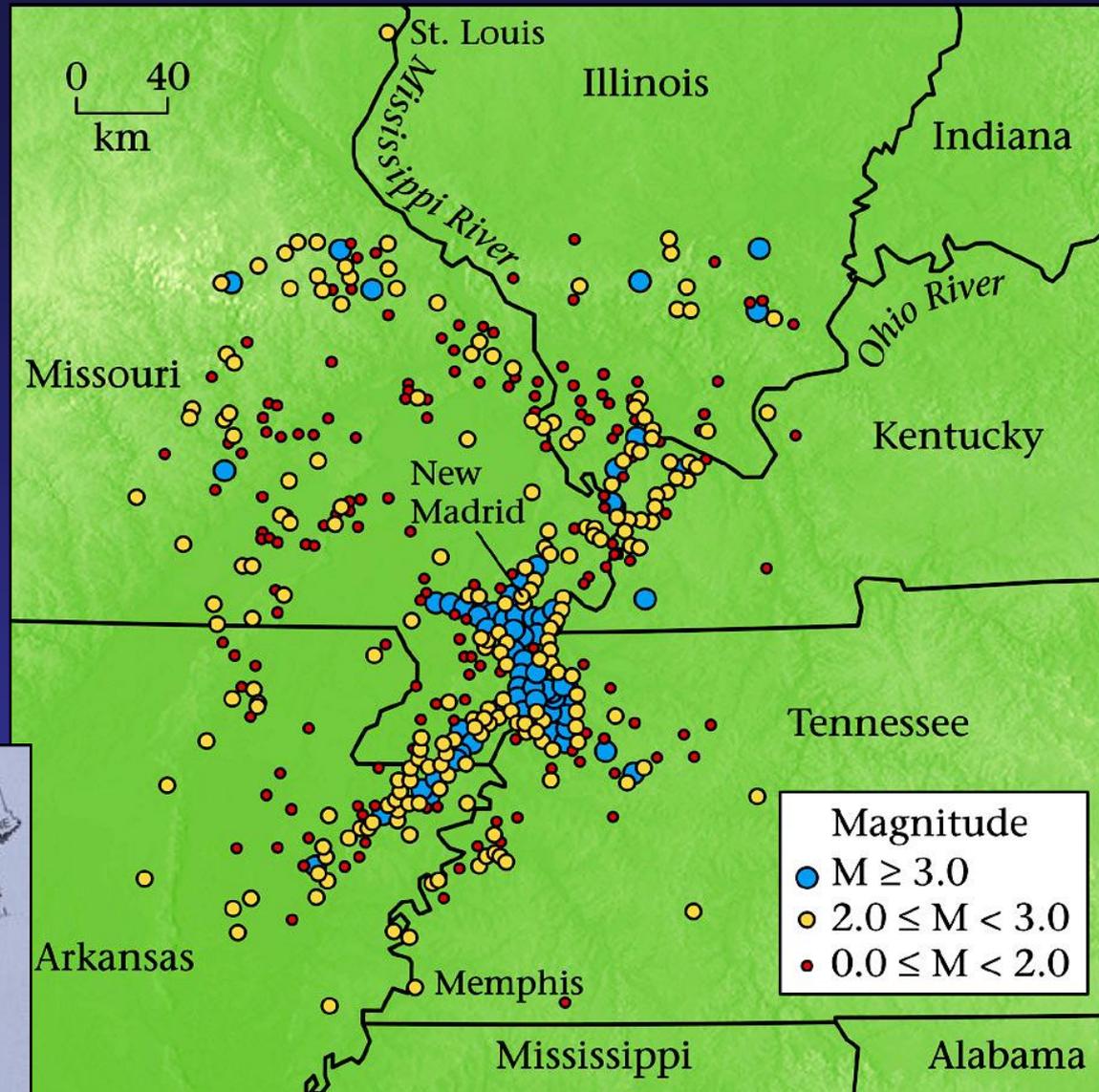


- Seismic waves are felt over longer distance in intraplate environments because rocks are stronger



New Madrid Fault Zone

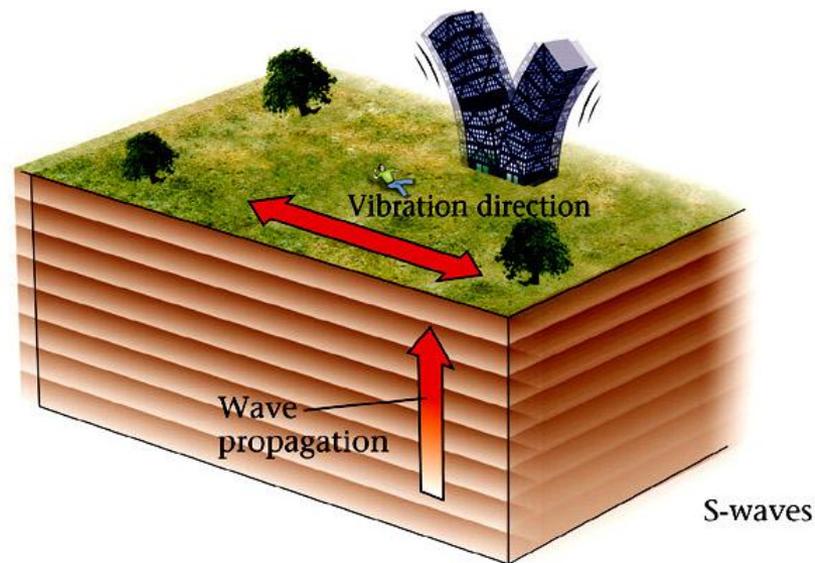
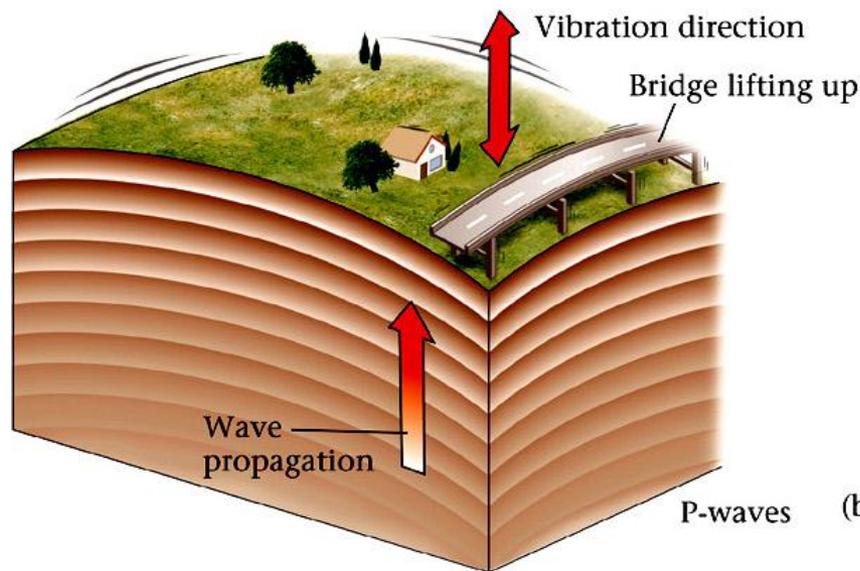
- 1811 ~M8 earthquake on the New Madrid Fault zone
- Largest earthquake ever felt in the lower 48 states
- Rang church bells in Boston 1,000 miles away
- Made the Mississippi river flow backwards (because of uplift) for a few weeks



Anthropogenic Earthquakes

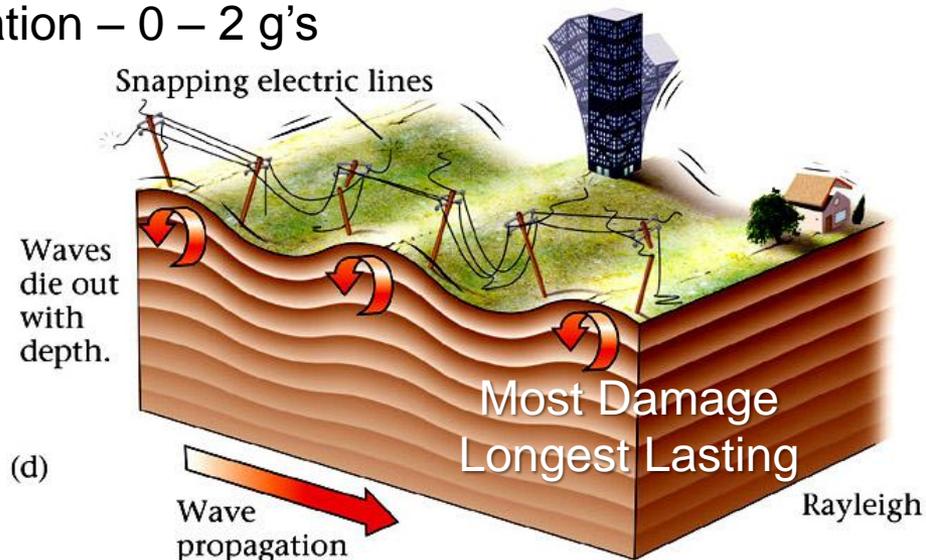
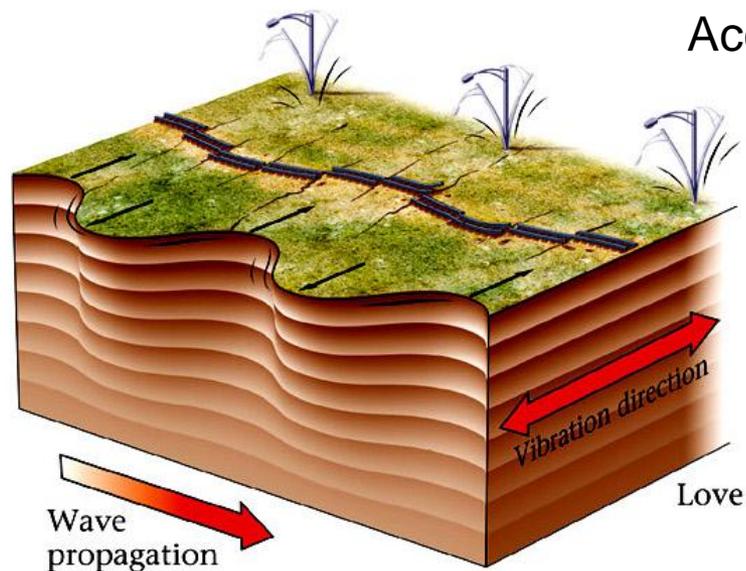
- *Anthropogenic*: arising from the influence of humans
- Humans can cause earthquakes, mainly due to changes in groundwater. This is called *induced seismicity*.
- Groundwater pressure can push apart faults, thereby reducing the friction on the fault, causing it to slip (earthquake).
 - *E.g.* Denver, waste water from a military installation was pumped into a deep well causing earthquakes. Also happened in Ohio
 - When valleys are flooded to make reservoirs (e.g. Lake Mead, NV&AZ) the additional groundwater pressure can lubricate faults in the region. Also the weight of the lake may bend the land forming normal faults.

Ground Shaking and Displacement During an Earthquake



Displacement – a few mm- a few meters

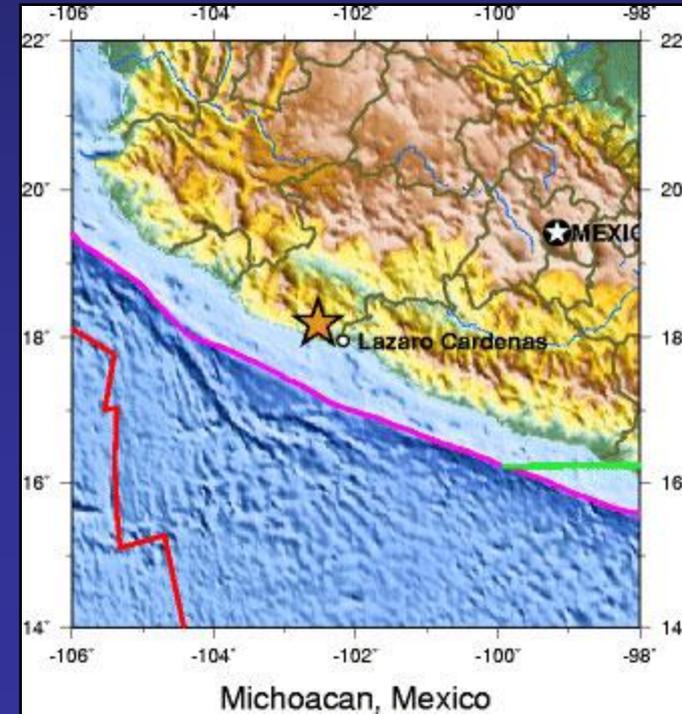
Acceleration – 0 – 2 g's



Severity of Shaking Depends On:

- Magnitude of the earthquake
- Distance from hypocenter
- The nature of the substrate at your location
 - Unconsolidated rock shakes a lot more, basins can amplify waves
 - E.g. 1985 Mexico city M8.0 300 km away
- The frequency of the seismic waves
 - High frequency waves do most damage but do not travel very far
 - Car stereo analogy (bass)

- *[TerraShake Animations]*



Buildings - Mexico City, 1985

After



Before



Secondary Effects of Earthquakes

- Earthquakes can also cause *landslides*
- Especially bad in California where faults have uplifted shorelines very quickly before the rock had time to completely lithify
- California will not sink into the sea, but homes on the coast may.



More Secondary Effects

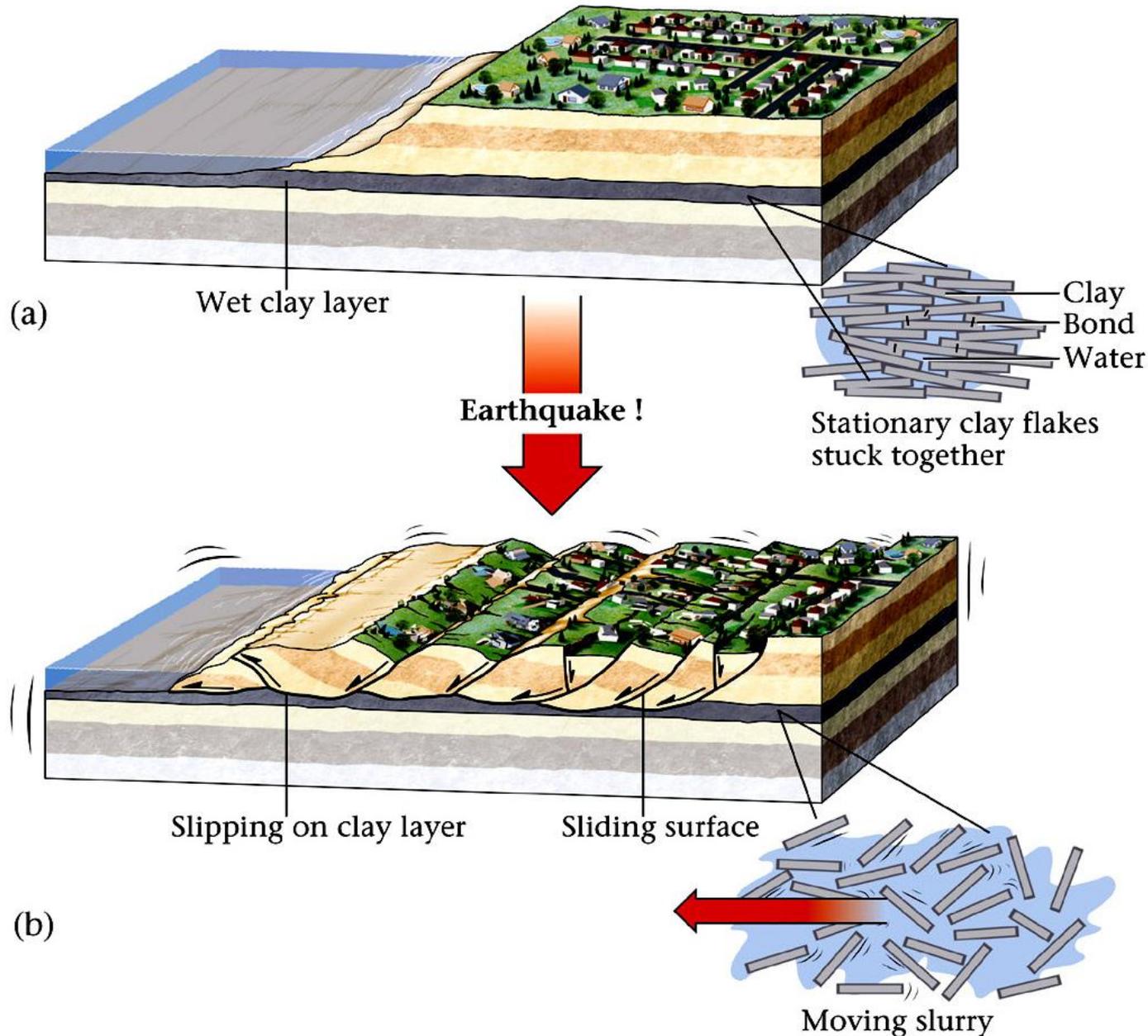
- An earthquake may cause wet sediment to liquefy. This is called liquefaction
 - Similar to quicksand



Liquefaction after an earthquake in Taiwan

Liquefaction

- Liquefaction can occur on a large scale
- The ground may separate into several coherent slump blocks if a basal layer liquefies.
- This happened to a housing development after a large earthquake near Anchorage Alaska in 1964.

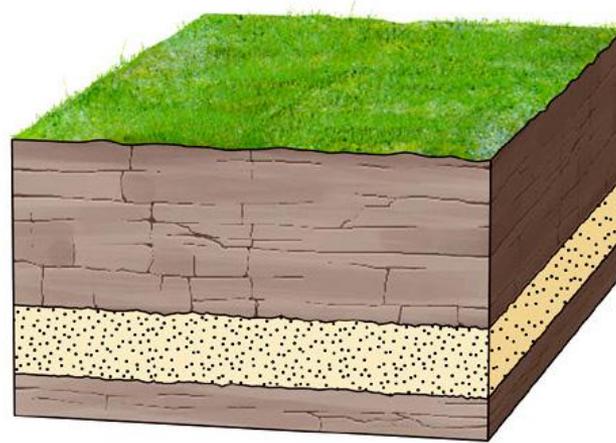


Turnagain Heights Disaster, AK 1964

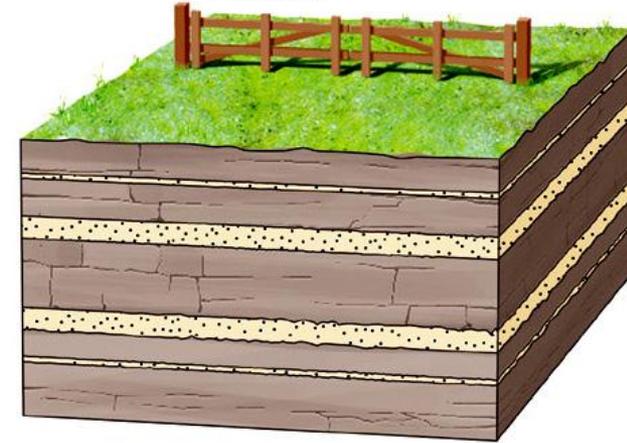


Sand Volcanoes / Sand Boils

Before

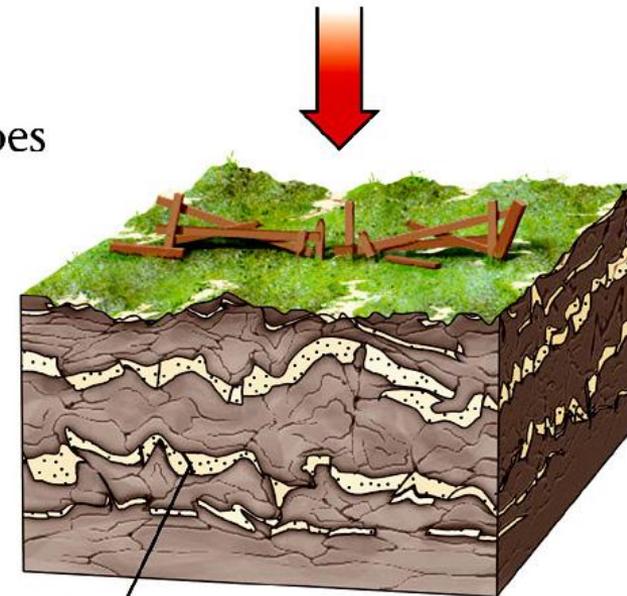
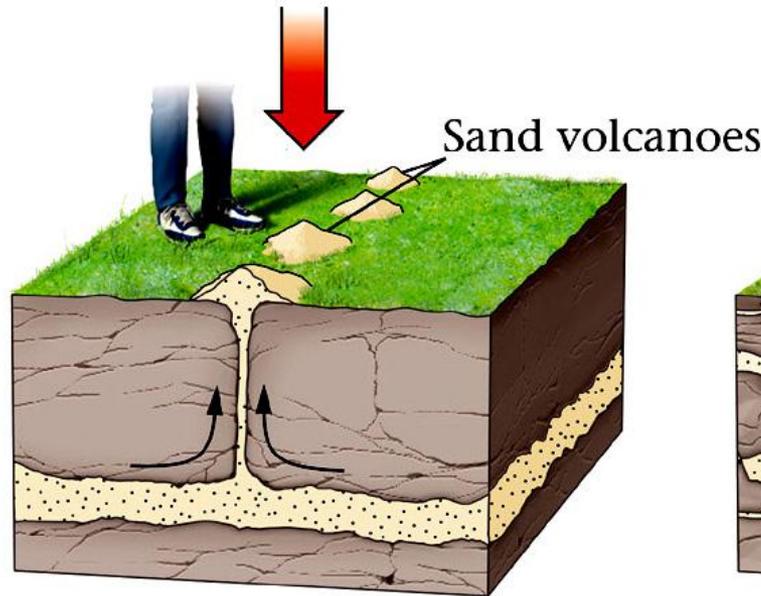


Fence



- Shaking during an earthquake can also mobilize sand layers creating **sand boils** or **sand volcanoes**, which may eject sand 10 m into the air during an earthquake.

After



Disrupted bedding

Sand Volcano



Disrupted Bedding



Fire!

- Earthquakes can break gas lines and knock down power lines causing numerous fires.
- Fires were responsible for most of the deaths during the 1906 great San Francisco earthquake

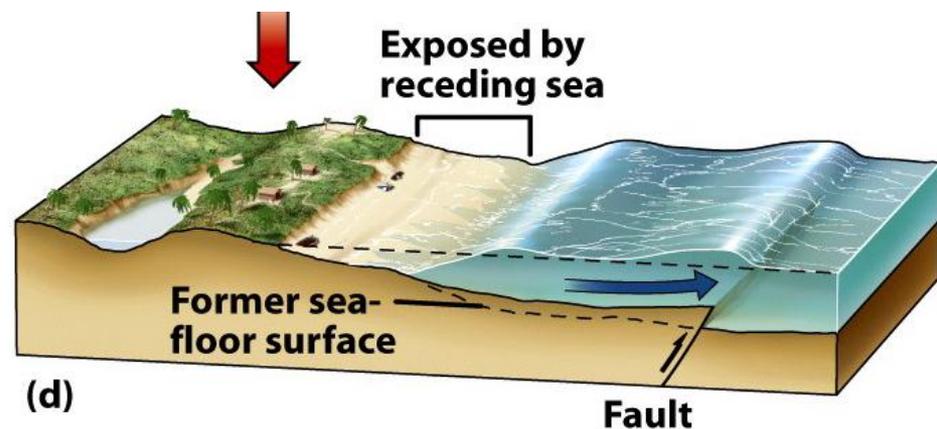
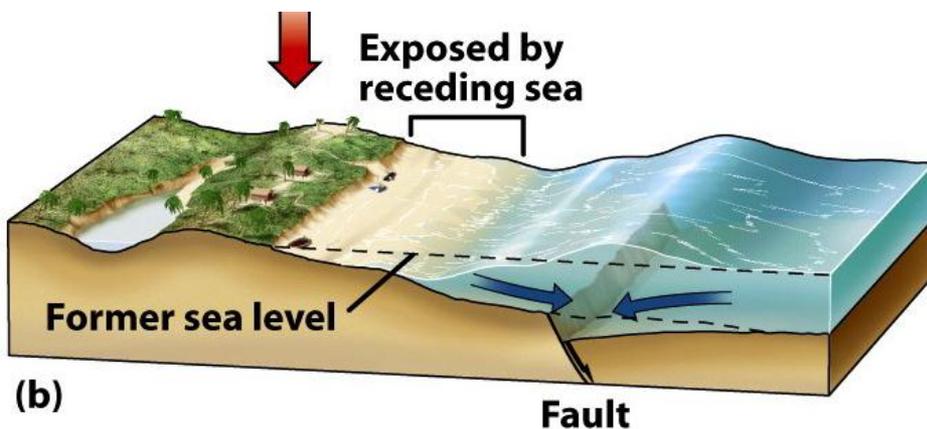


Fire - San Francisco, 1906



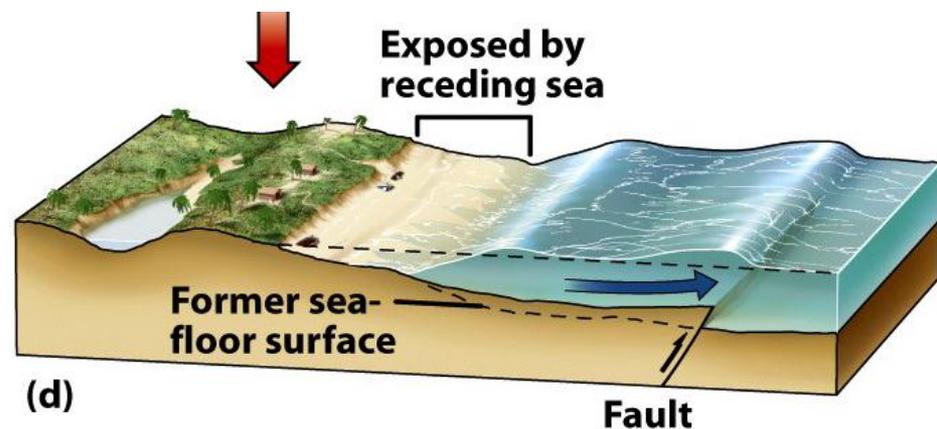
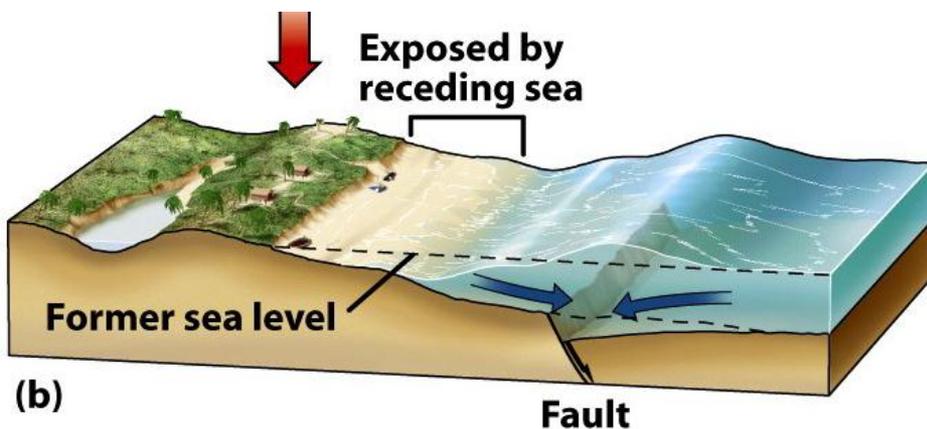
Tsunamis

- **Tsunami:** a large wave that is generated by an **earthquake**, landslide, or meteor impact
 - Not “Tidal Waves”; They have nothing to do with tides
 - Result when earthquakes cause a large vertical displacement of the seafloor.
 - Water rushes in to fill the lowered points; a wave is formed
 - Associated with normal and reverse faults
 - Subduction zones can produce the largest earthquakes (most slip and rupture length) they can also generate the largest tsunamis



Tsunami Occurrence

- Destructive tsunamis occur frequently - about 1/yr.
- Many tsunami disasters dot recorded history.
 - 94 destructive tsunamis in the last 100 years.
 - 51,000 victims
 - not including 12/26/04: ~230,000 deaths & 3/11/11 ~22,000 deaths
- Future tsunami disasters are inevitable.
 - Growing human population in low-lying coastal areas.
- Education about tsunamis can save many lives.



Tsunami vs. Wind Waves

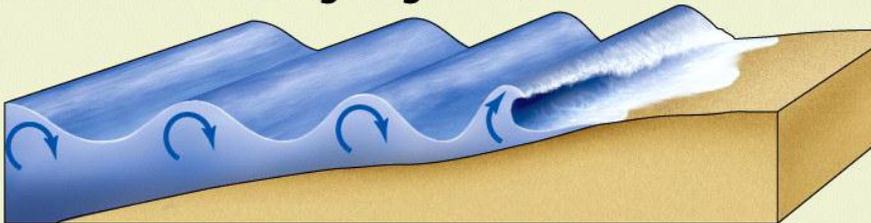
- Wind waves

- Influence the upper ~100 m.
- Have wavelengths of several 10s to 100s of meters.
- Wave height and wavelength related to windspeed.
- Wave velocity maximum several 10s of kph.
- Waves break in shallow water and expend all stored energy.

- Tsunami waves

- Influence entire water depth
- Have wavelengths of several 10s to 100s of kilometers.
- Wave height and wavelength unaffected by windspeed.
- Wave velocity maximum several 100s of kph.
- Waves come ashore as a raised plateau of water that pours onto the land.

Wind-driven waves contain a small volume of water, and do not submerge higher areas.



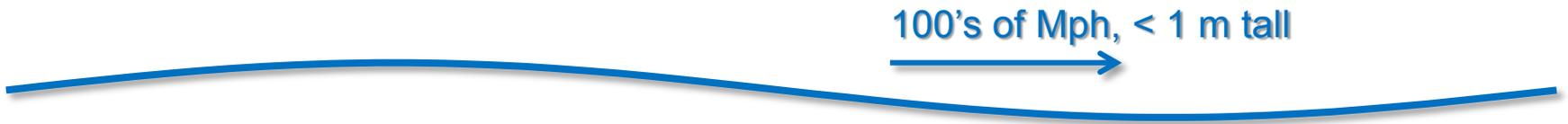
Tsunamis are so wide (measured perpendicular to shore) that, like a plateau of water, they submerge the land.



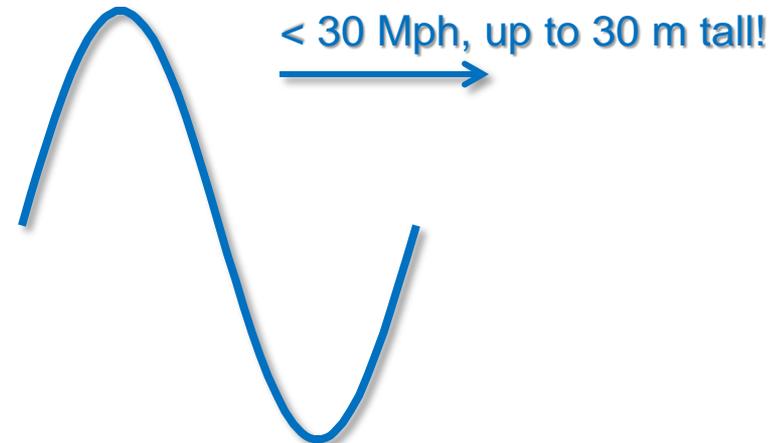
Tsunami Mechanics

How do tsunamis move?

- Tsunamis travel very fast in the open sea with very small amplitude and long wavelengths



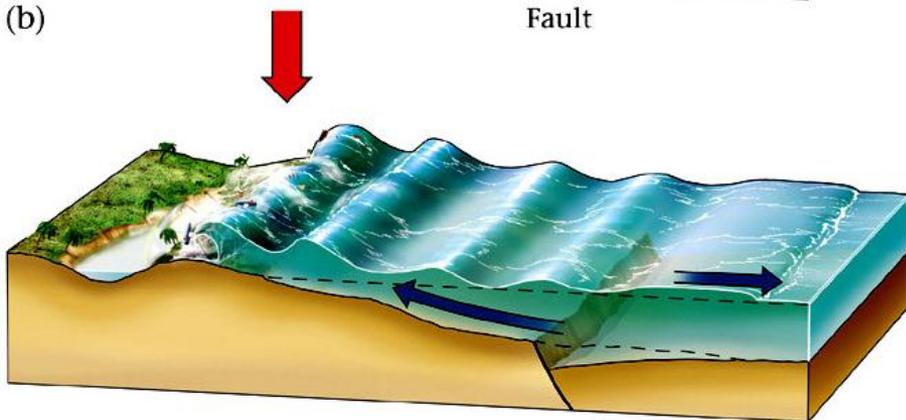
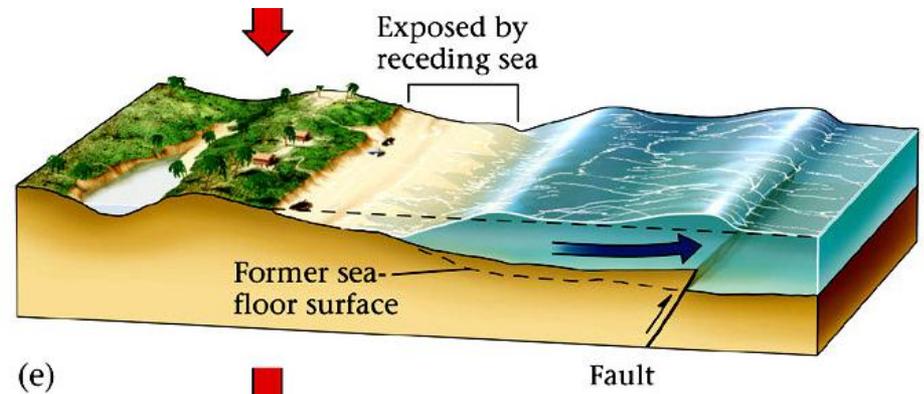
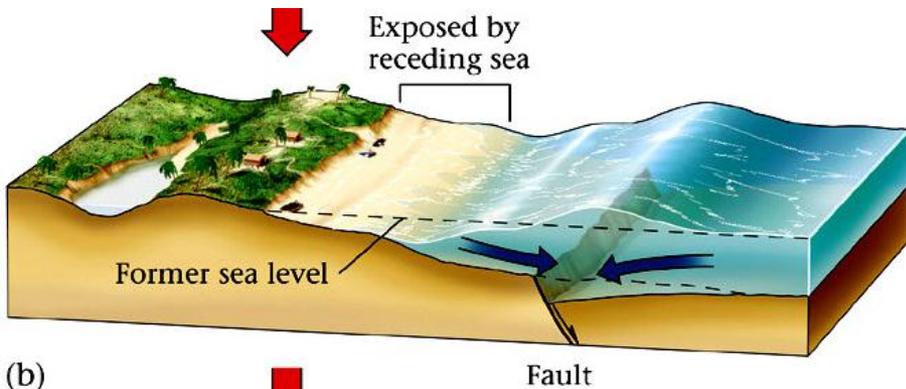
- As tsunamis approach shore, friction with the seafloor bottom slows the wave front down and the wave grows in amplitude and lowers in wavelength



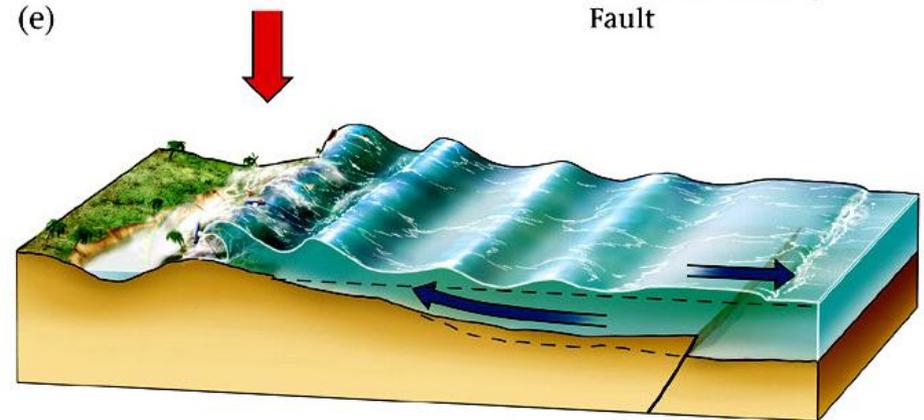
Tsunami Mechanics

How do tsunamis arrive at the coast?

- On a beach the coastline will first migrate out to sea
 - The trough arrives first
- The wave will then inundate low-lying areas (called run-up)



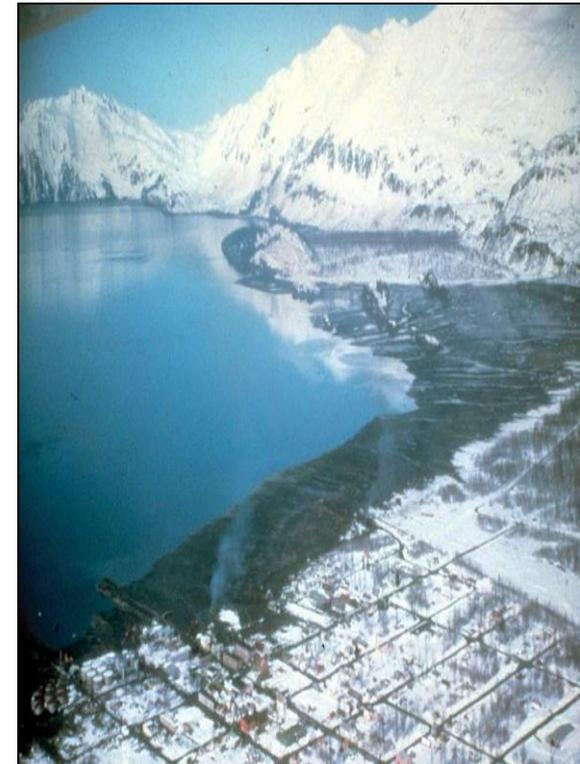
Normal faulting



Reverse or thrust faulting

Tsunami Mechanics

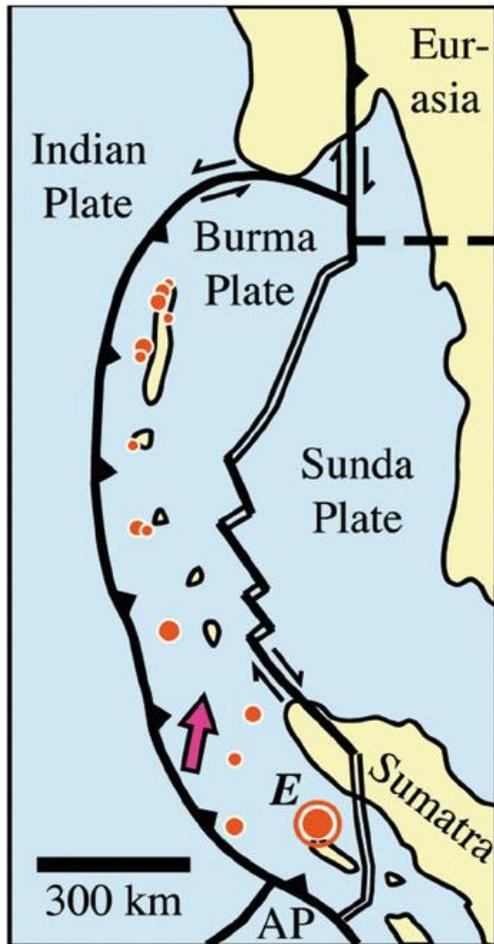
- Tsunami destruction of the coast depends upon...
 - Offshore bathymetry.
 - Broad shallows increase amplitude but attenuate wave energy.
 - Quick deep-to-shallow transition – Deadliest condition.
 - Waves have maximum energy.
 - Wave heights are modest.
 - Water pours onto land as a sheet.
 - Topography of shore.
 - Broad, low land – Maximum damage.
 - Steep rise of land – Less damage.



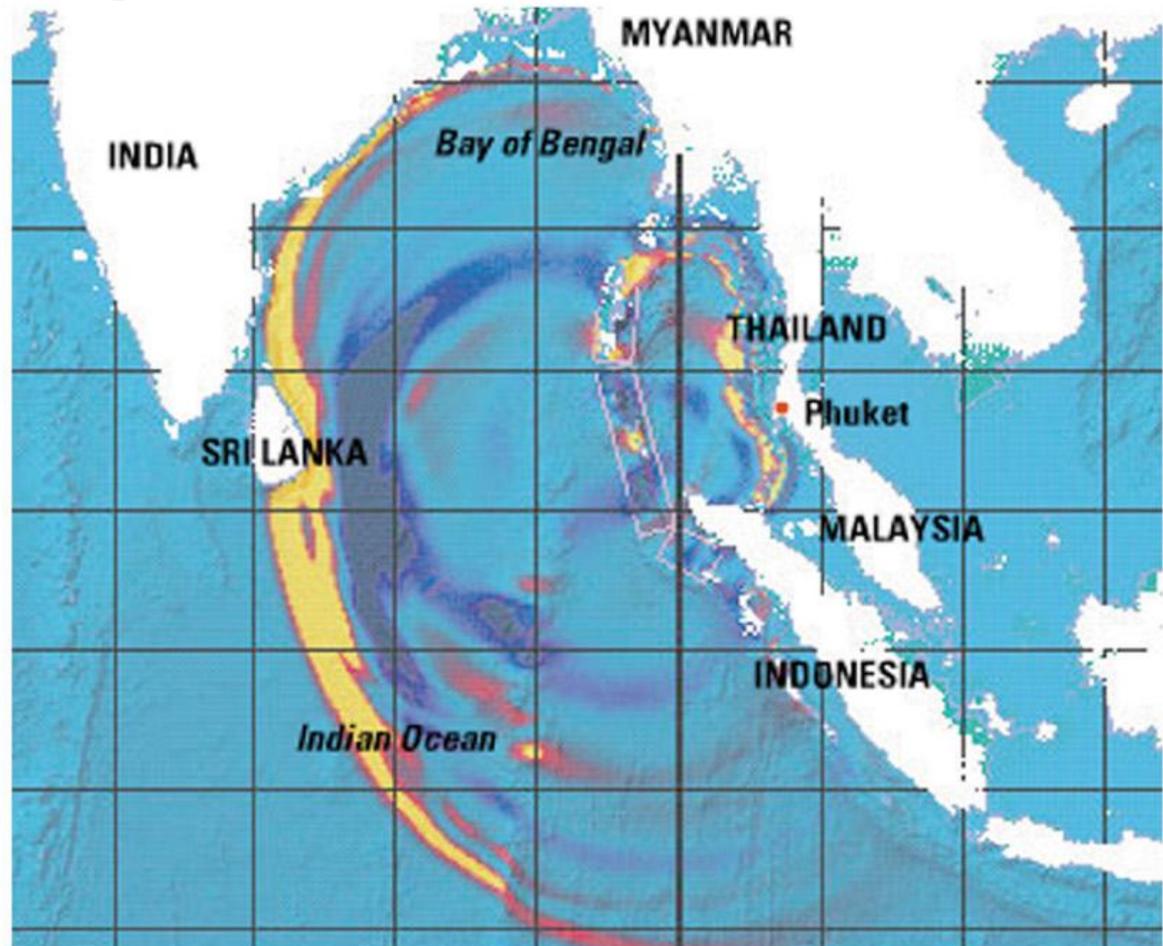
Tsunami damage after 1964 Alaska EQ

The Great Sumatra Earthquake and Tsunami

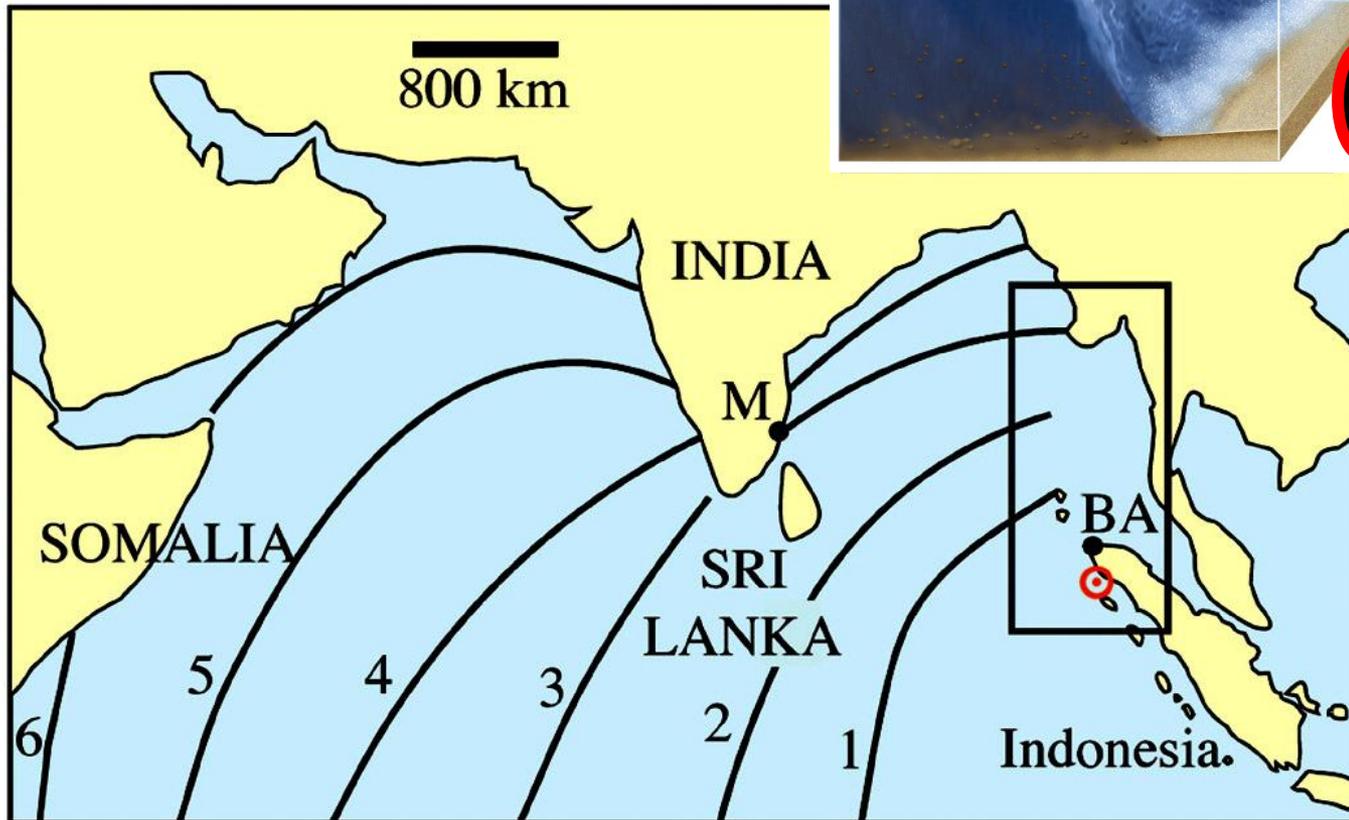
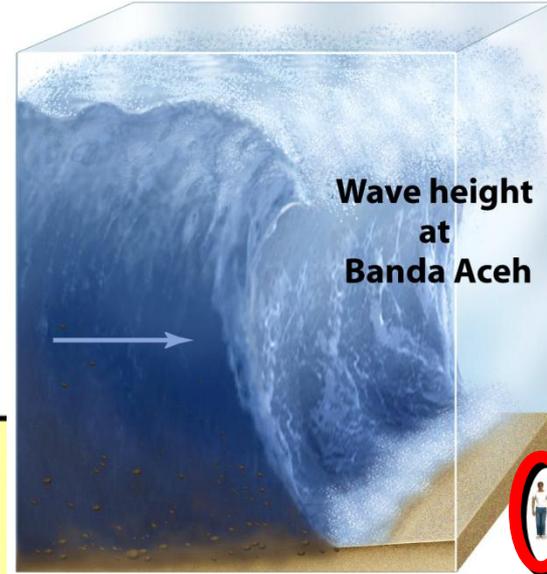
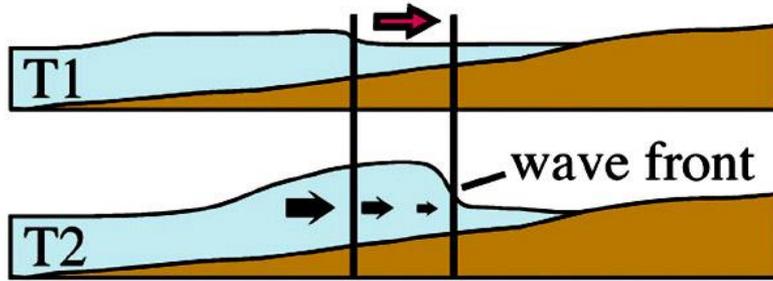
- On December 26, 2004 a Mw 9.1-9.3 earthquake occurred on the Sunda trench mega thrust
- The amount of energy released was immense (2nd or 3rd largest EQ measured by instruments)
- > 230,000 deaths, >1,000,000 displaced



(b)



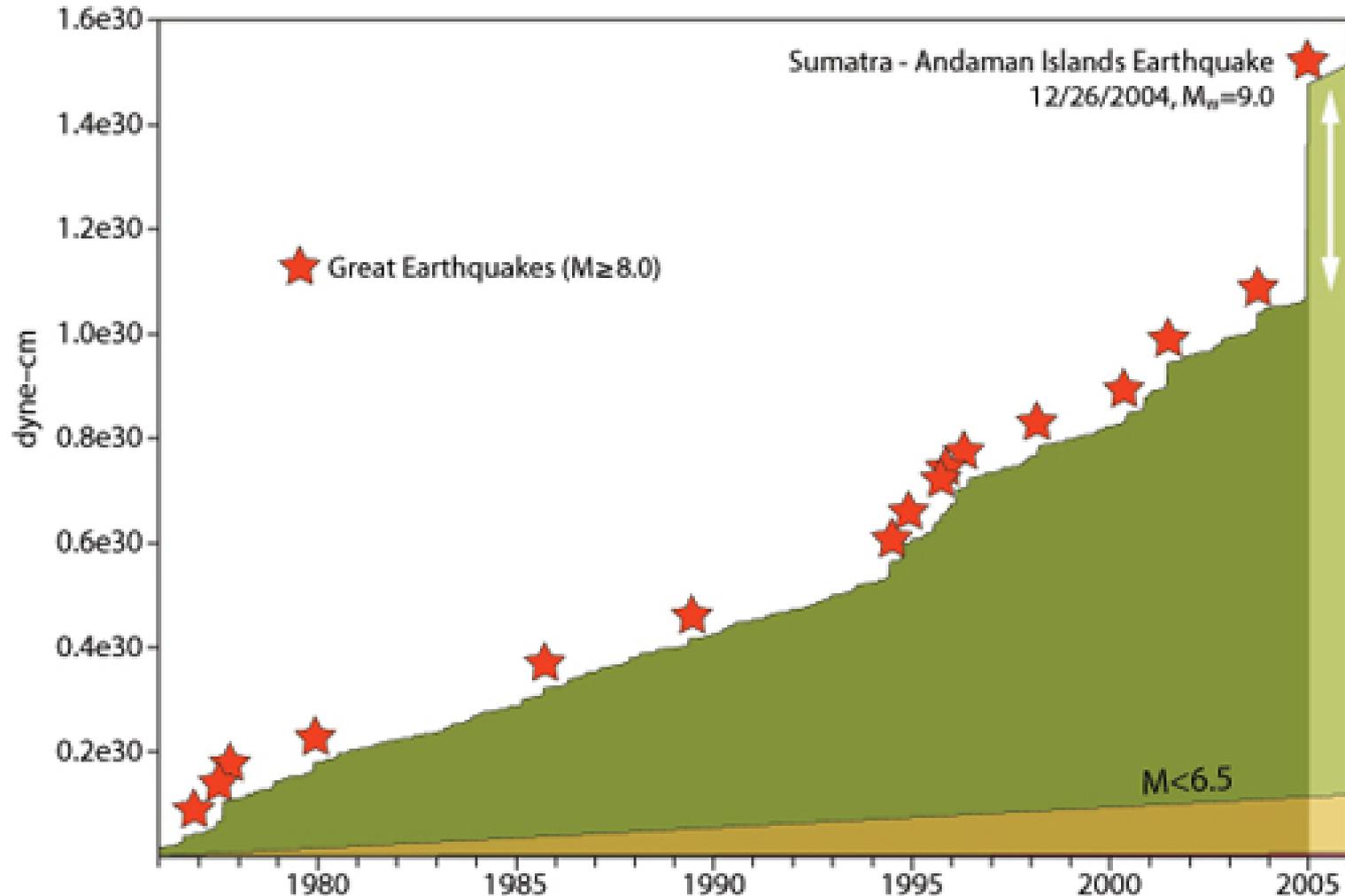
2004 Sumatra Tsunami



Global Seismic Energy Release

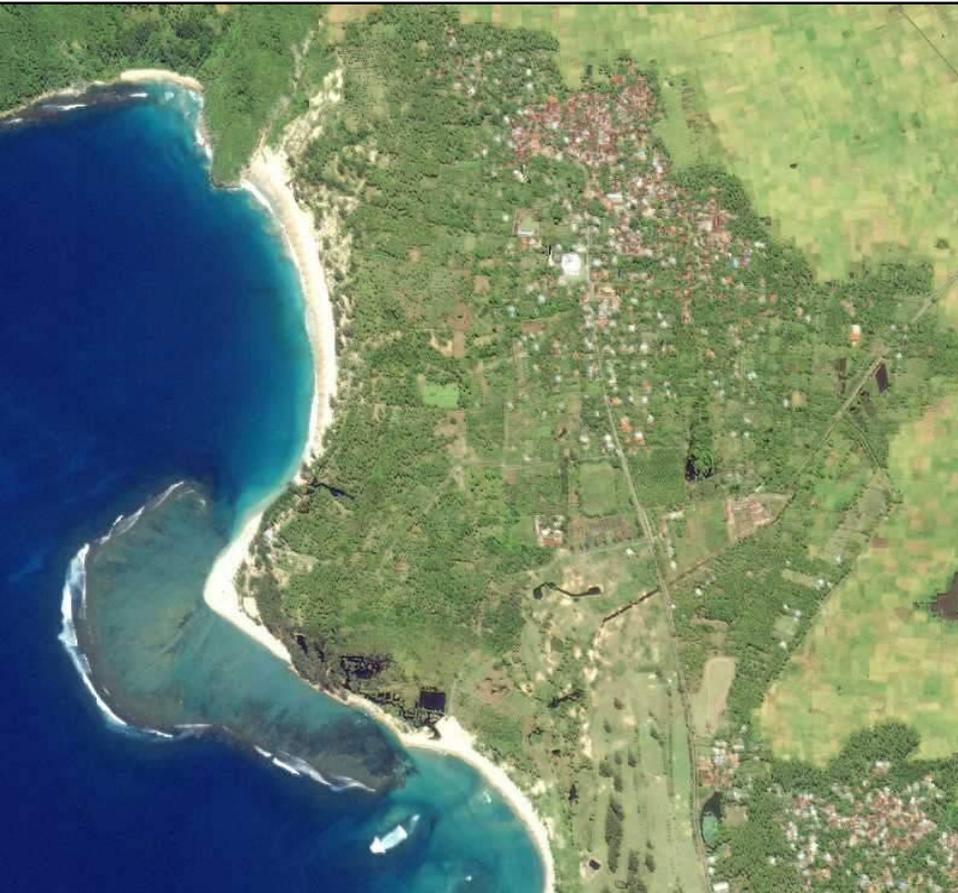
- The Sumatra earthquake significantly altered the amount of seismic energy released globally

Cumulative moment release since 1976



The Indian Ocean Tsunami

- Complete devastation below “run-up” elevation.
 - Dense coastal development in Banda Aceh hardest hit.
 - Entire communities were erased – buildings and people.





After the Sumatra Tsunami 2005



After the Sumatra Tsunami 2005



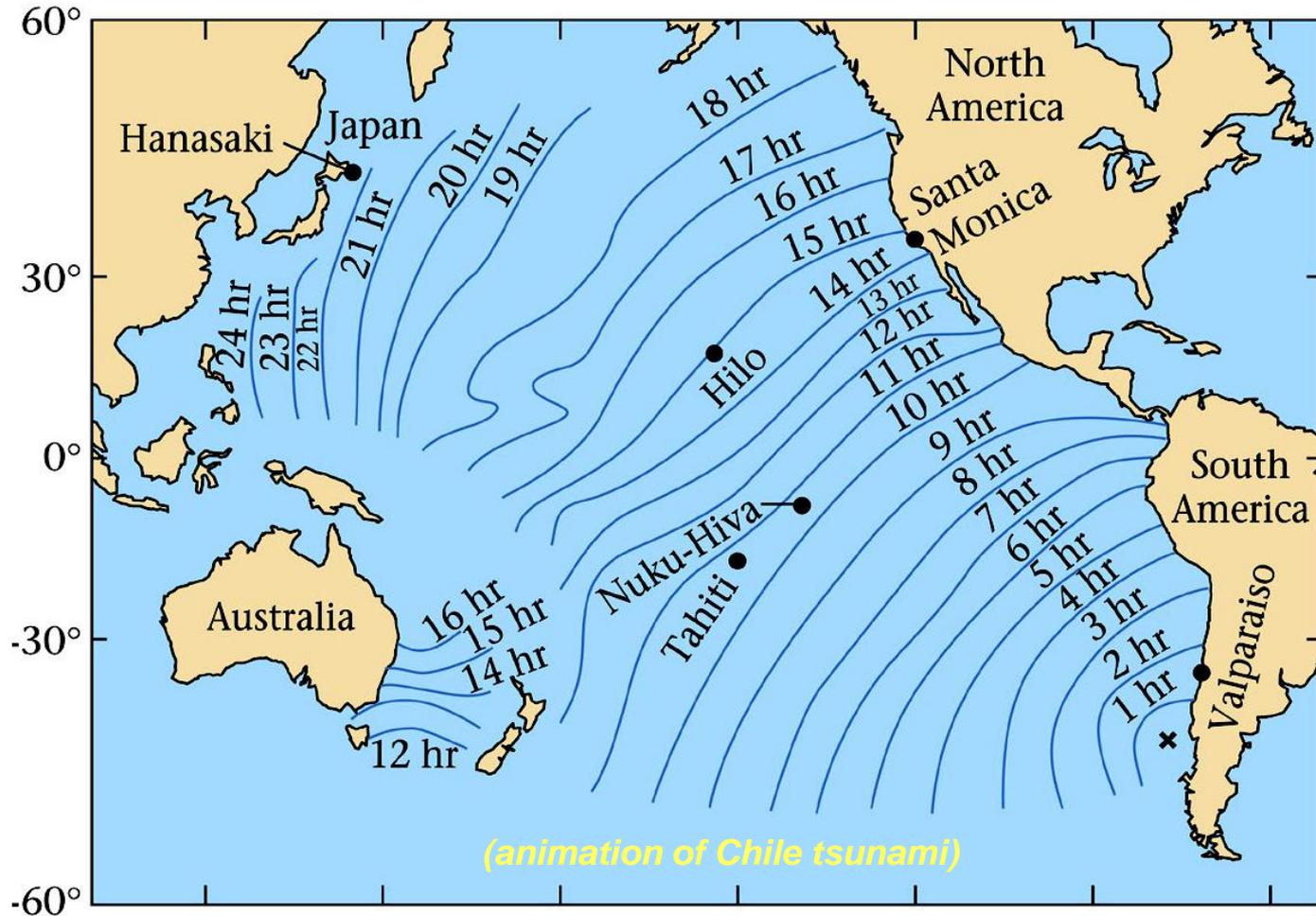
Why no Tsunami After the M8.7 2005 Quake?

- The M_w 9.1-9.3 2004 earthquake
 - Bigger, more slip, more rupture
 - Occurred in deeper water
- The M_w 8.7 2005 earthquake
 - 33% smaller (remember that magnitude is a logarithmic scale!!)
 - Occurred in shallow water
 - Presence of islands minimized the amount of water that was displaced



1964 Chile Earthquake and Tsunami

- Tsunamis can travel great distances

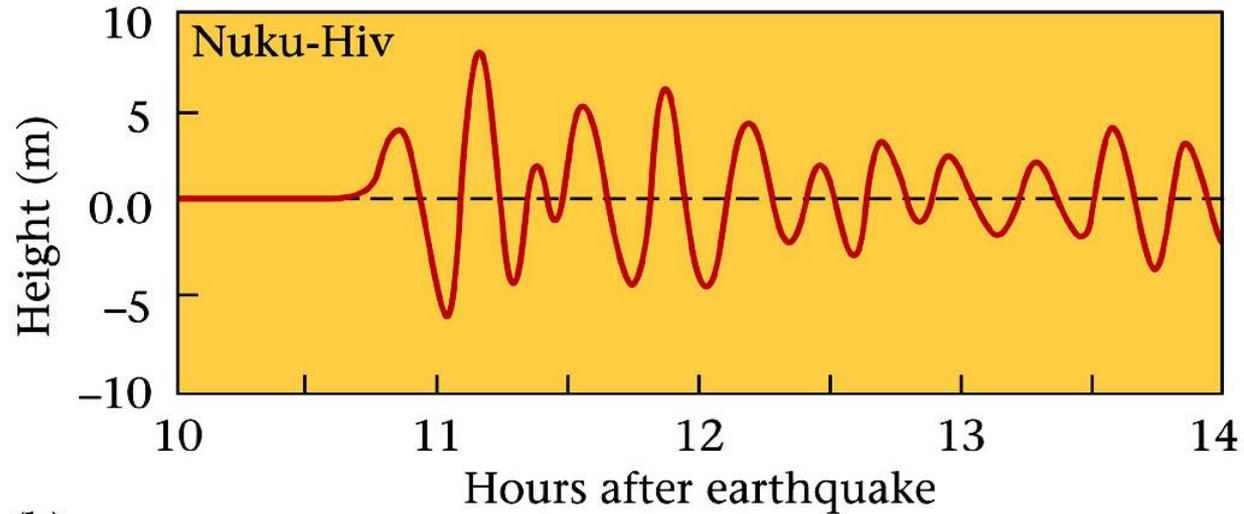


7 hr / Passage of tsunami crest, hours after earthquake

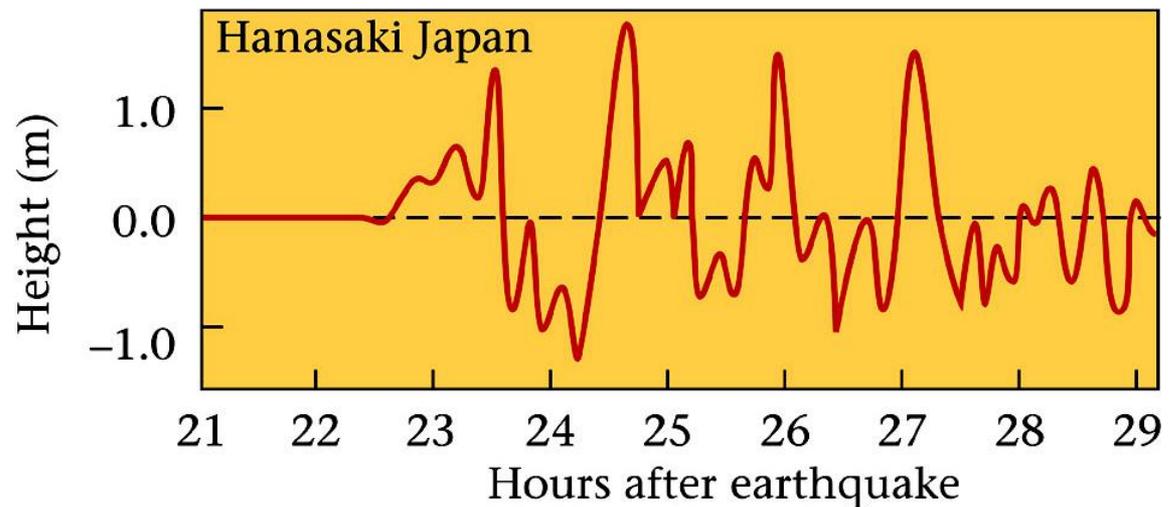
Epicenter x
19:11 GMT

Tide Gauges

- We can monitor tsunamis by the motions of *tide gauges* placed throughout the oceans of the world.
- The Indian Ocean didn't have a tsunami warning system
- The Pacific Ocean tsunami warning system gave an alert after the Sumatra quake, but there was no method to deliver this message to residents of the Indian Ocean regions, nor was there and evacuation plan



(b)



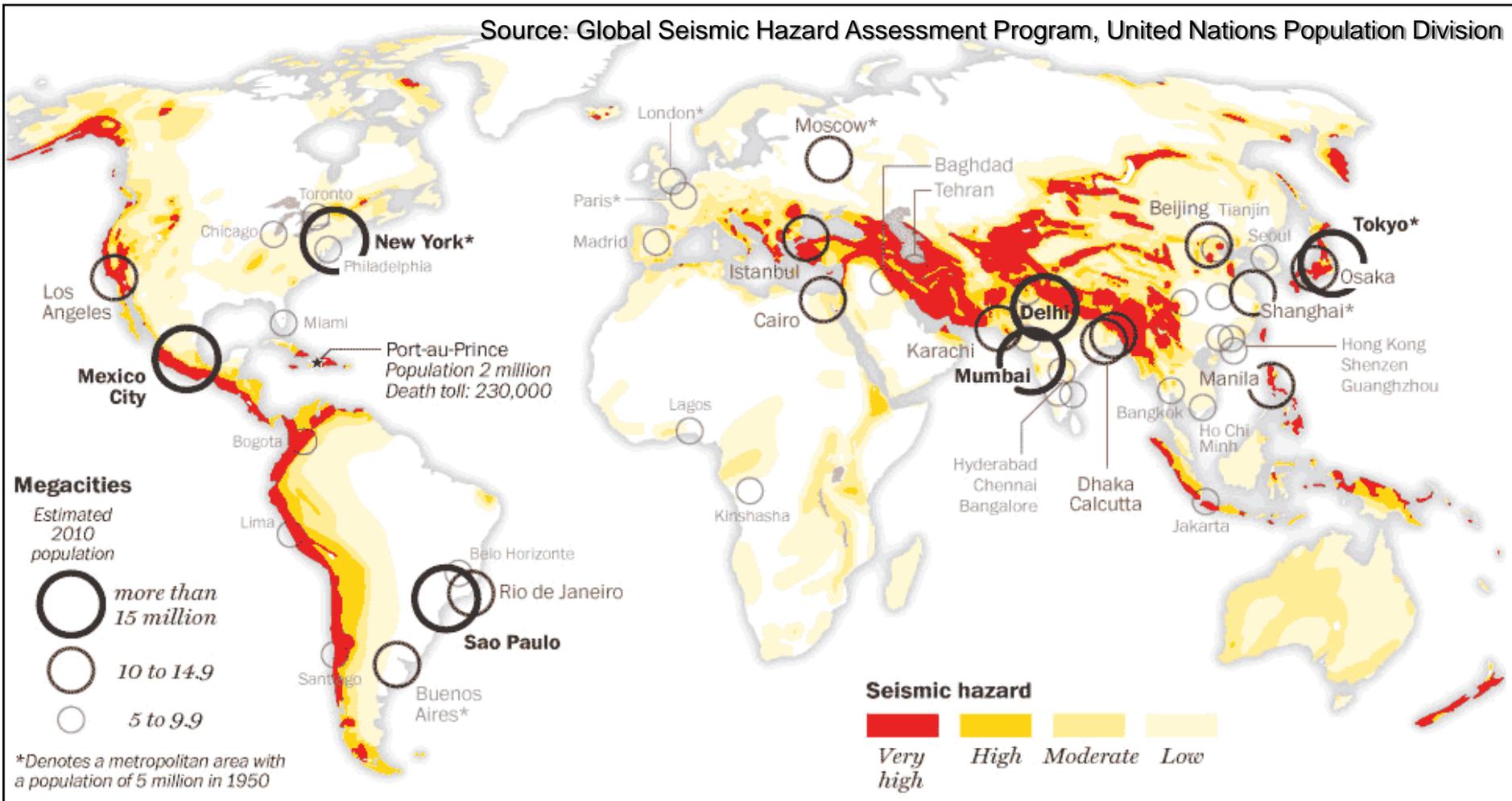
Earthquake Prediction (?)

- Currently scientists can't make *short term predictions* of earthquakes
 - e.g. there will be an earthquake next Tuesday at 8:07 AM.
- We can make some *long term predictions*
 - There will likely be a large earthquake on the San Andreas fault in the next hundred years.
 - In the next hundred years it is unlikely that there will be a large earthquake in central Canada
- Seismic Hazard
 - Is there a seismic source?
- Seismic Risk
 - What sort of risk does this source pose to civilization?
 - I.e. no people, no risk
- Seismic Hazard Assessments are based on:
 - Locations of faults
 - Slip rates of faults
 - Recurrence intervals (time between events)
 - Local geology effects (liquefaction / basin fill)
 - *Seismic gaps*

Population and Seismic Hazards

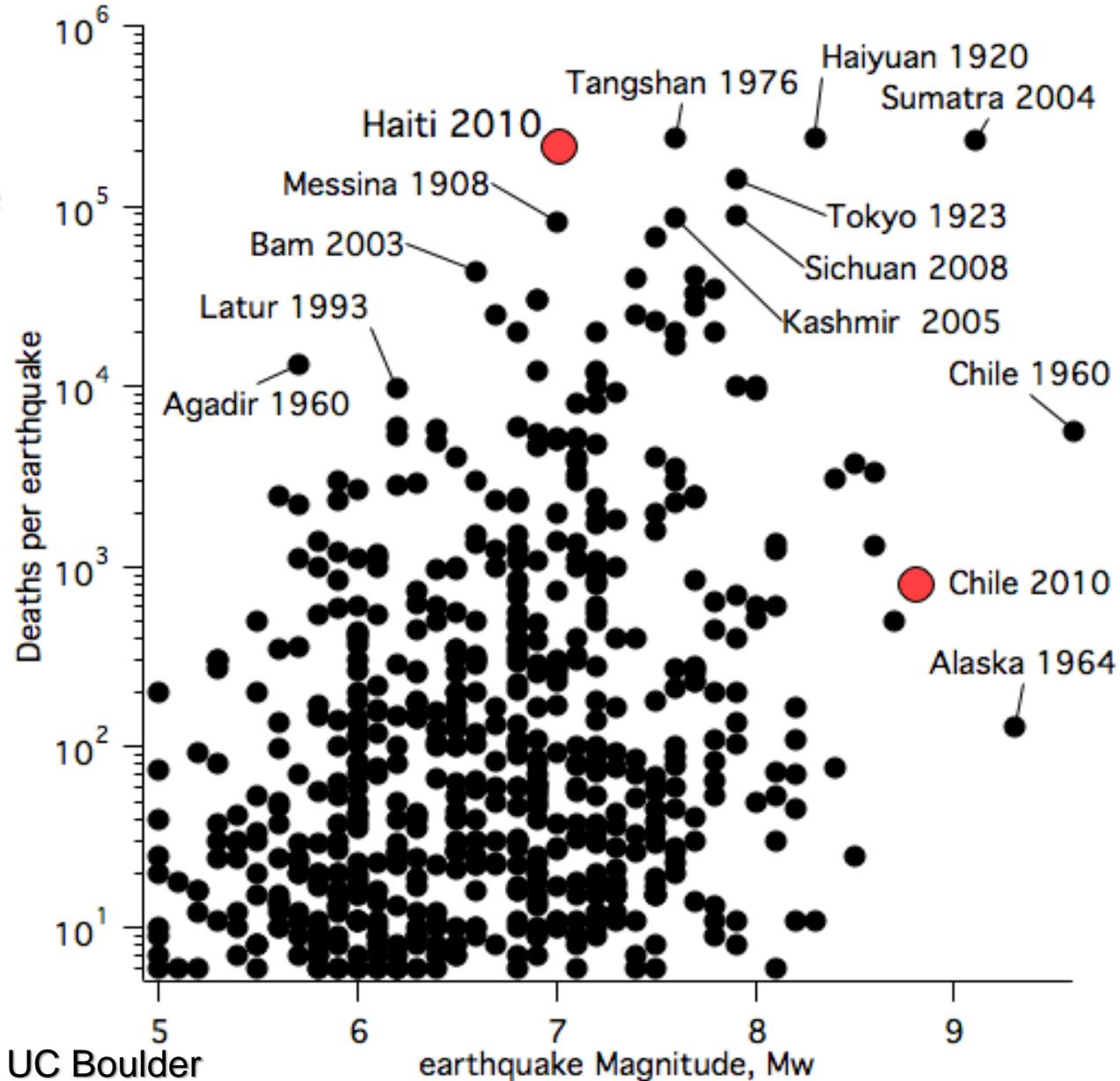
- In 1950 there were 5 cities with > 5 M people
- Currently there are > 50 “mega cities”
 - Note how many are near seismically hazardous zones

Source: Global Seismic Hazard Assessment Program, United Nations Population Division



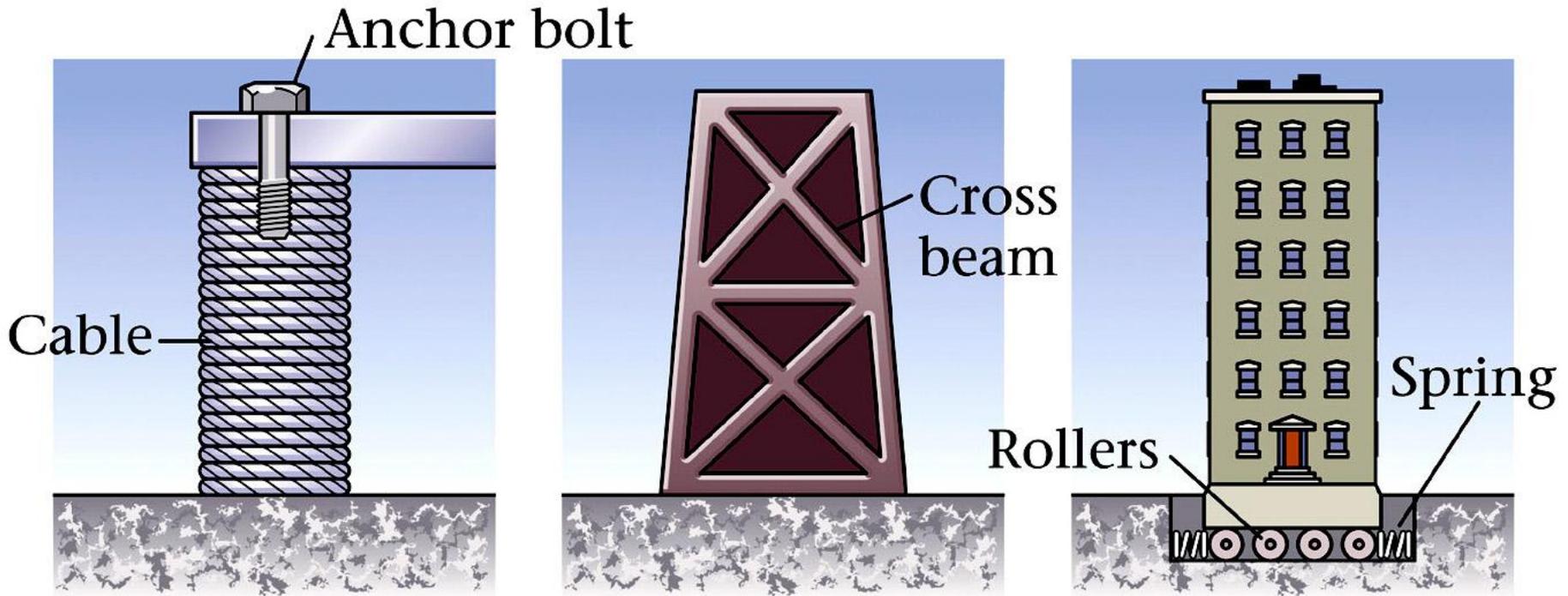
Earthquake Deaths By Magnitude

- The largest earthquakes do not typically result in the most deaths
- What kind of house you live in is more important than what kind of fault you live by



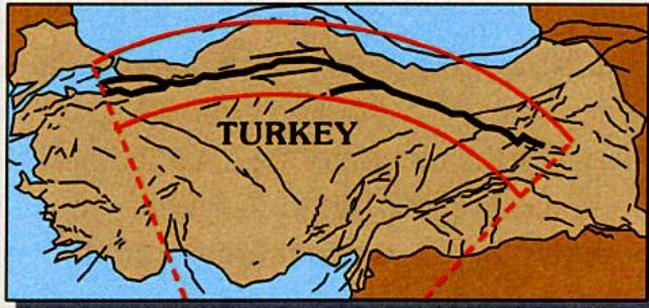
Building Codes

- In response to the 1971 M6.6 Sylmar EQ, the state of California passed new laws prohibiting the building of public buildings within $\frac{1}{4}$ mile of a mapped fault zone
 - Called “*Alquist-Priolo Earthquake Fault Zones* ” (*AP Zones*)
- Since short term earthquake predictions may be impossible, building codes are the main way to save lives in future earthquake events
 - Building codes (zoning laws) are based on seismic hazard assessments
 - Insurance companies also are very interested in seismic hazard maps



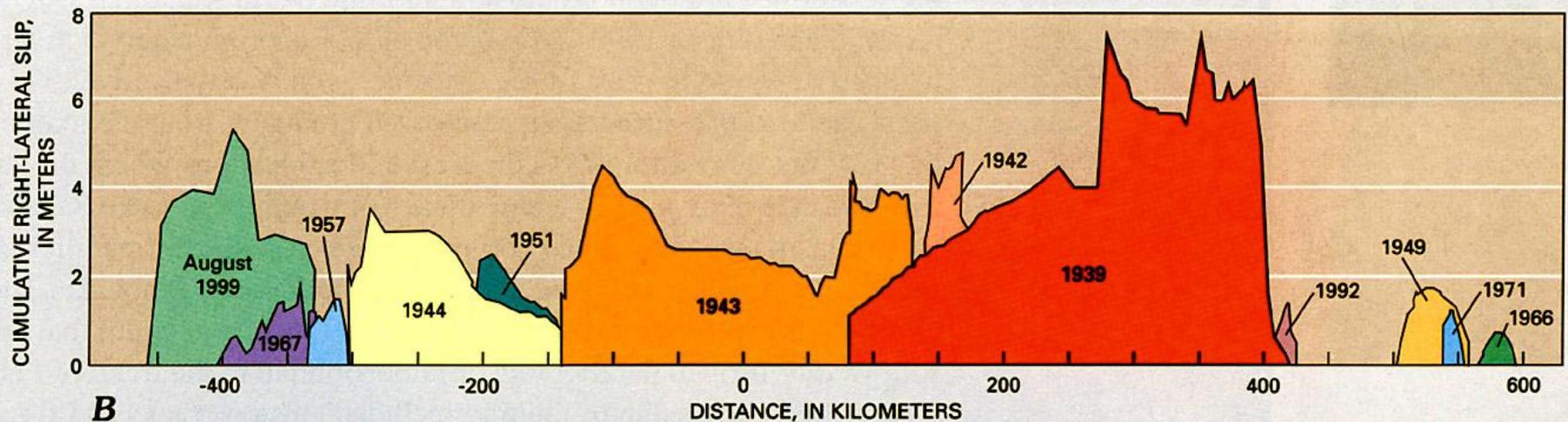
Seismic Gaps & The North Anatolian Fault, Turkey

- **Seismic Gaps:** Areas where the fault has not moved in a long time
 - These regions may be the next to go
- **Stress Triggering:** When an earthquake happens, the motion changes the stress on nearby faults, possibly making them more or less likely to fail.
 - The North Anatolian Fault is an excellent example of both of these phenomenon



(Ross Stein animations)

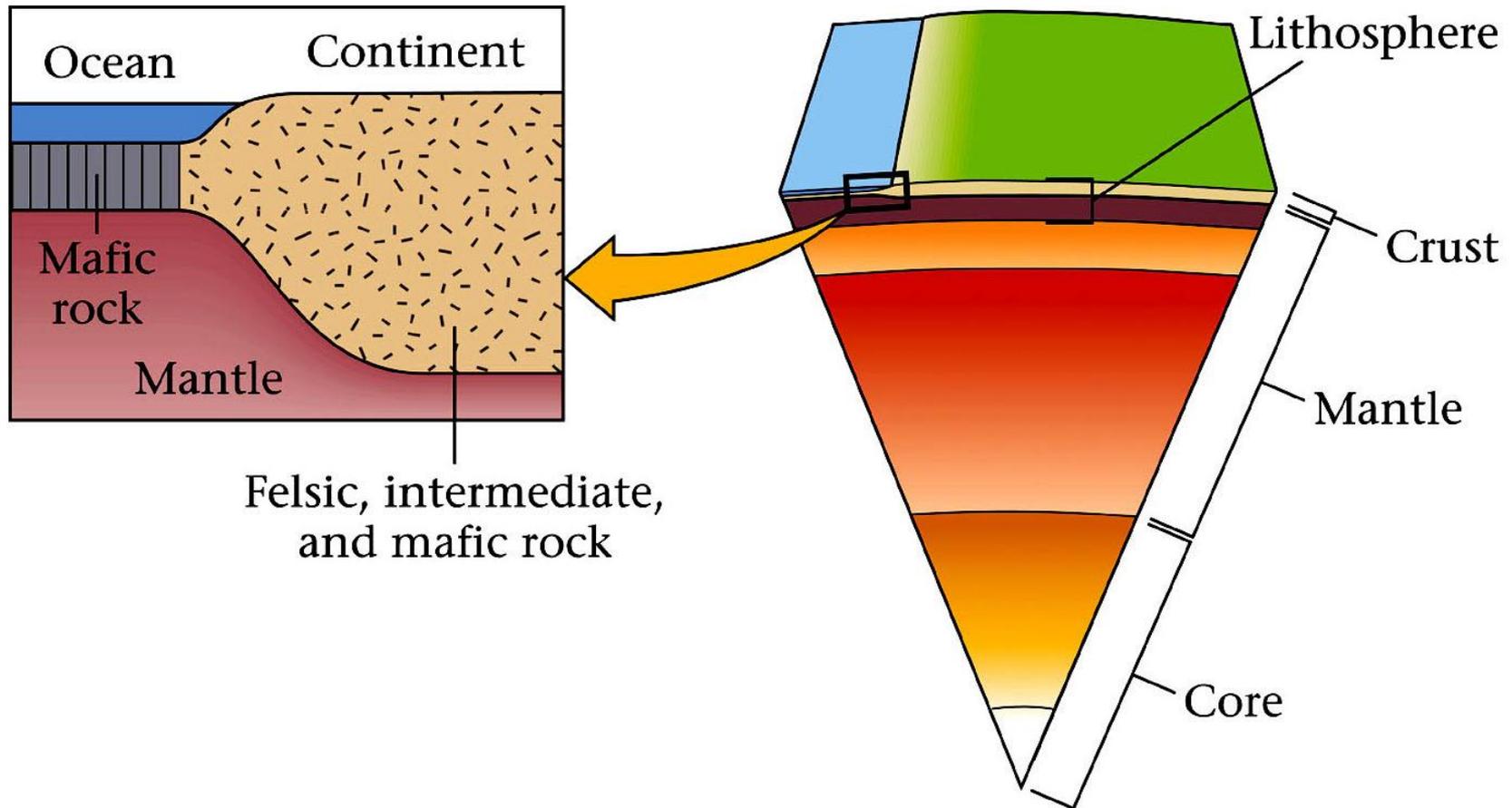
A



B

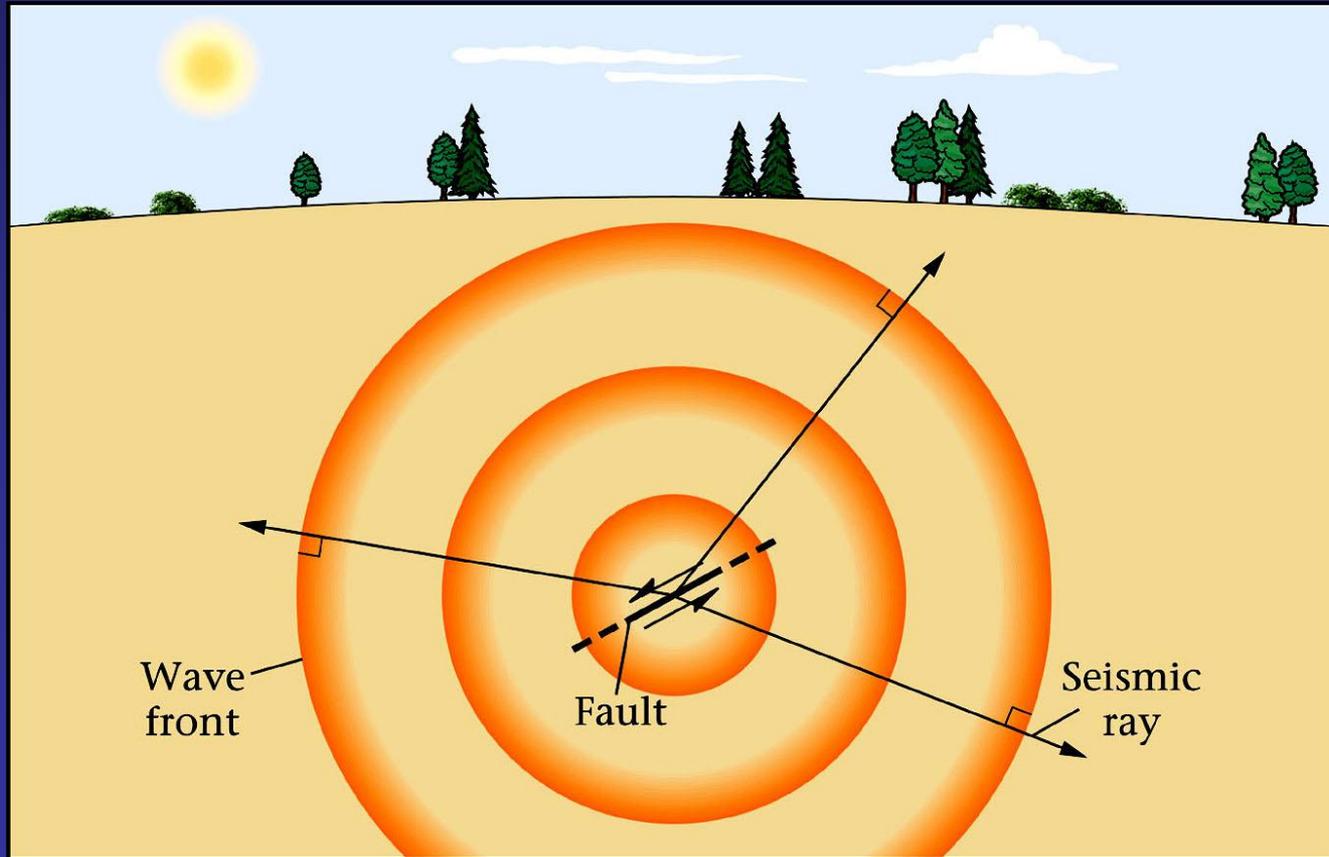
Using Earthquakes to See Inside the Earth

- Using what we have learned (and will learn now) about seismic waves, we can now look at how scientists discovered the various layers of the Earth and some of their properties.



Seismic Wave Fronts and Rays

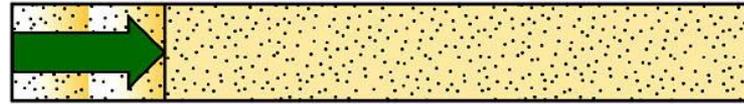
- During an earthquake, seismic waves radiate away from the source
- The **Wave Front** is the boundary between the wave and rock that the wave has not yet passed through (i.e. the “front” of the wave)
- A **Seismic Ray** traces the path of a single point along the wave front and is always perpendicular to the wave front.
- The time it takes a ray to reach a certain point is called the **Travel Time**.



Seismic Velocity and Material Properties

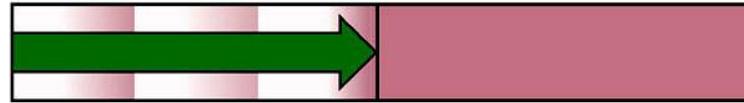
- The speed at which a seismic wave travels depends on the material properties

Less dense



Sandstone
(upper crust)

More dense



Peridotite
(upper mantle)

(a)

- Seismic waves travel faster in more dense and strong rocks

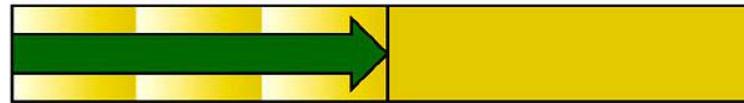
- E.g. 3.5 km/s in sandstone and 8 km/s in peridotite

Solid



Peridotite
(lower mantle)

Liquid



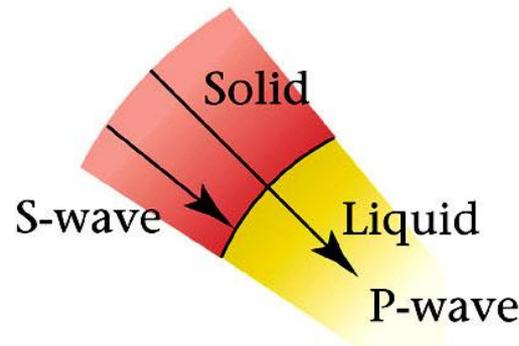
Molten iron alloy
(outer core)

(b)

- Seismic waves travel faster in a solid than a liquid

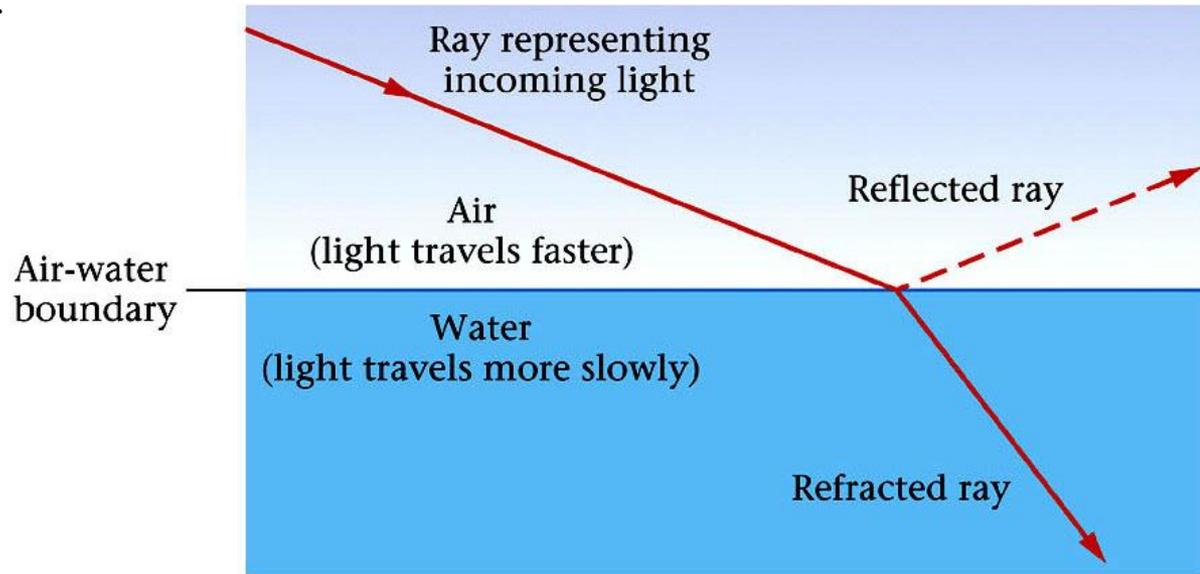
- Slower in basaltic magma than solid basalt

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

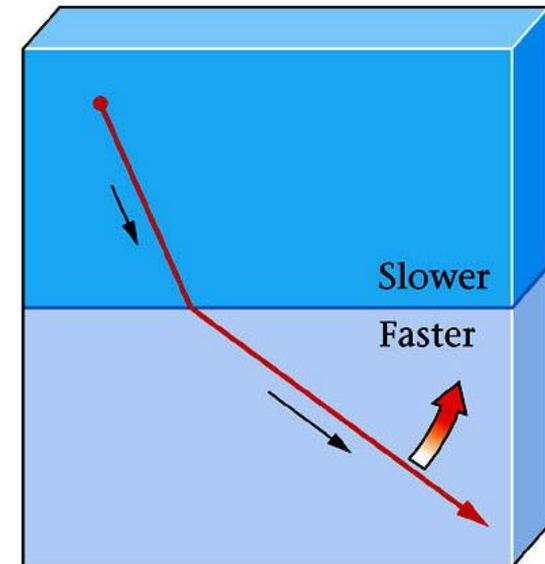
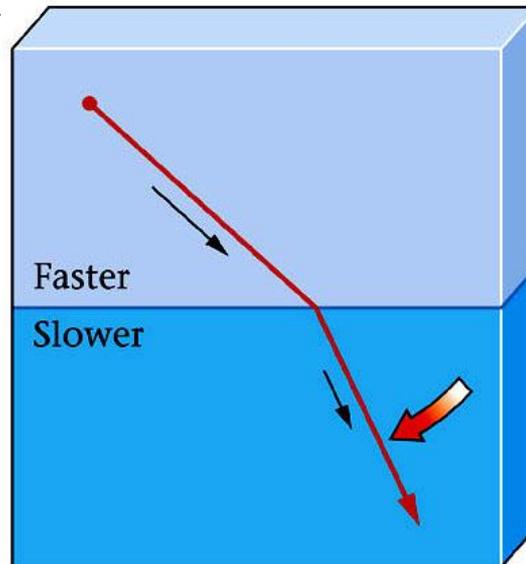


Reflection and Refraction of Wave Energy

- If you shine a light (a type of wave) into water part of the wave bounces off of the surface and is *reflected*
- The remaining portion of the wave enters the water, but at a different angle. The bending of a wave at a material interface is called *refraction*.
- Waves refract away from the interface if the material it enters causes the wave to slow
- Waves refract towards the interface if the material causes the wave to speed up.



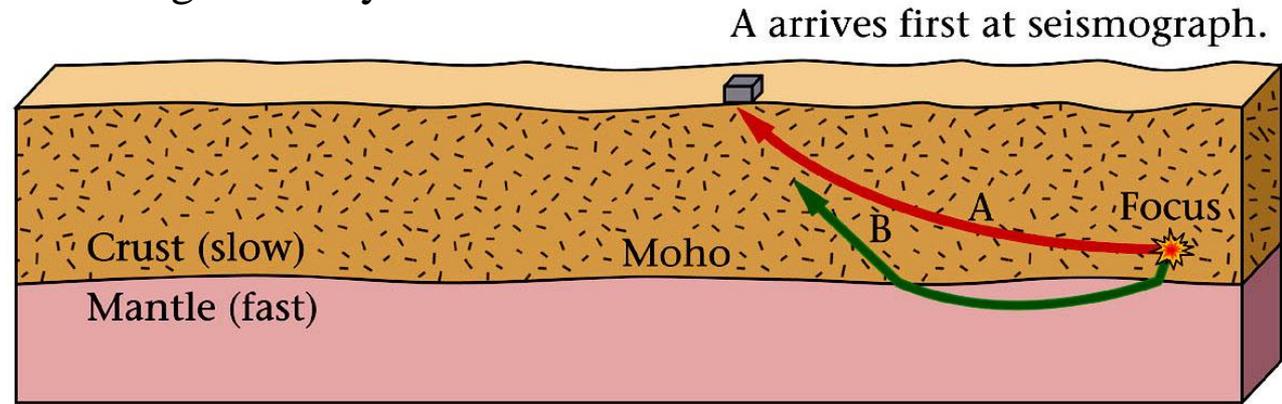
(a)



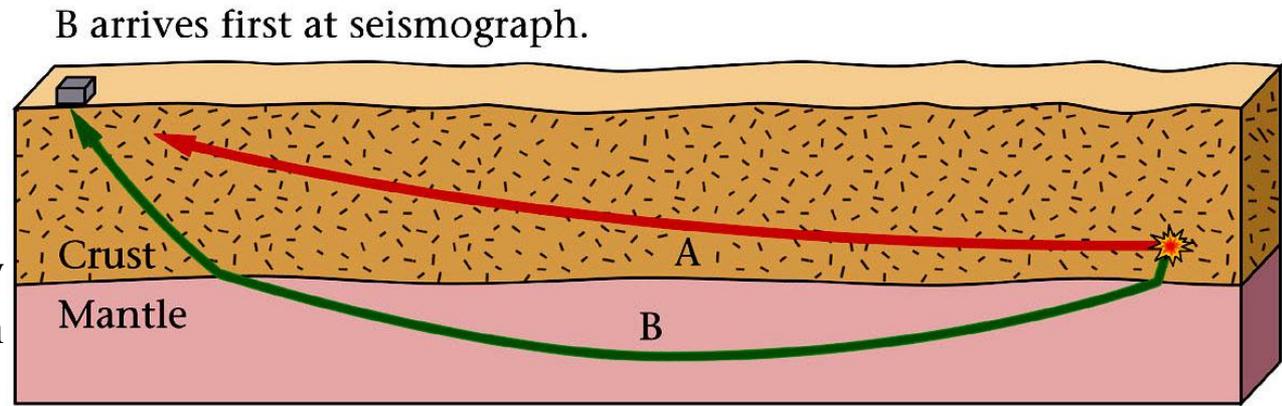
Refraction, Velocity and Arrival Times = Moho Discovery

- Because the mantle (peridotite) is more dense than the crust, seismic waves travel faster through the mantle.
- In 1909, Andrija Mohorovičić discovered that waves first arriving at seismic stations within 200 km of an epicenter had an average velocity of 6 km/s

- Stations >200 km away had average wave speeds of 8 km/s for first arriving waves
- To explain this, he proposed that nearby stations received waves that only went through the crust and far away stations received waves that travel through the mantle.
- The crust mantle boundary is now called the *Moho*, in honor of this discovery



(a)

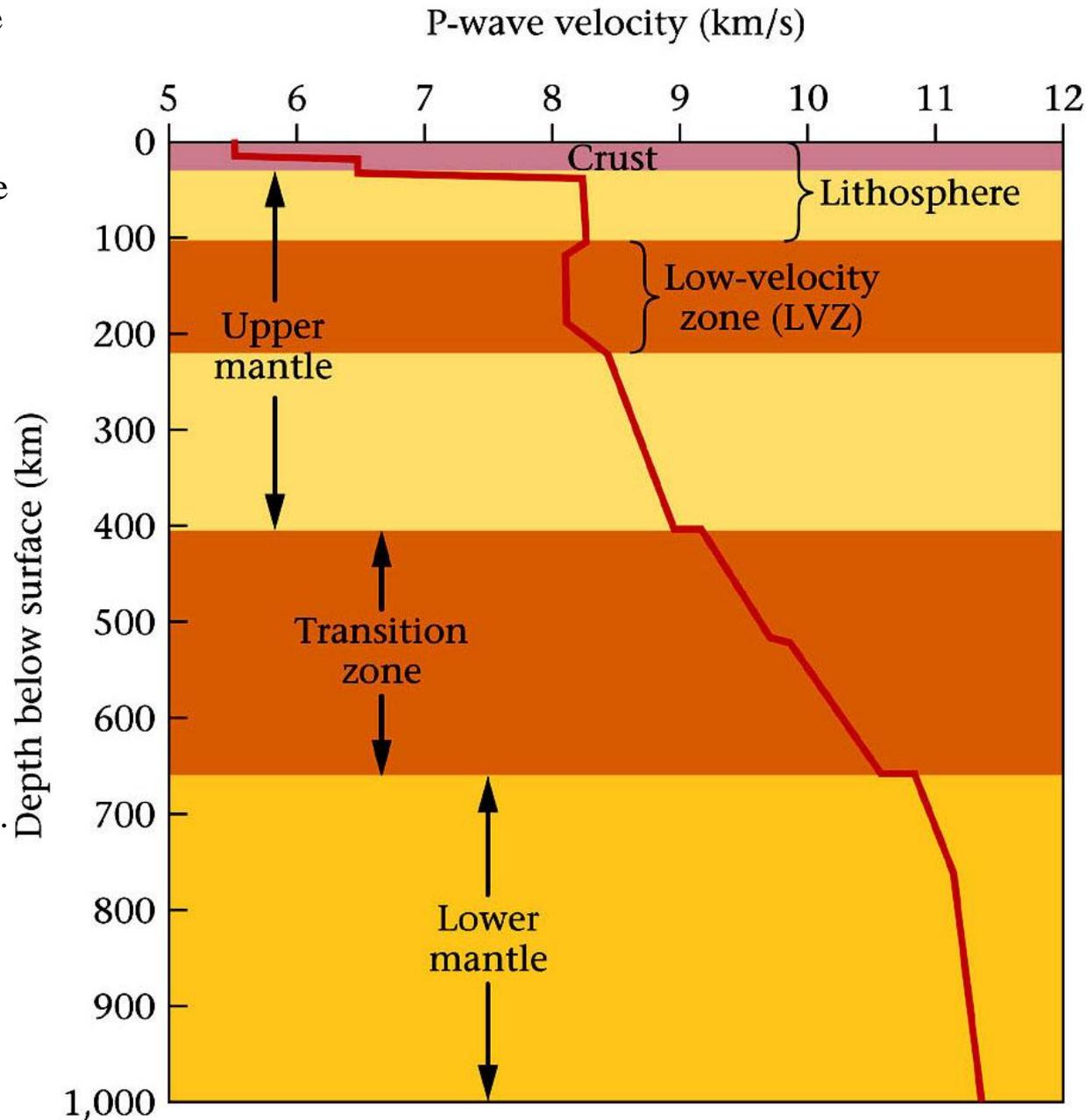


(b)

← Velocity in crust
← Velocity in mantle

Velocity of P-Waves at Depth

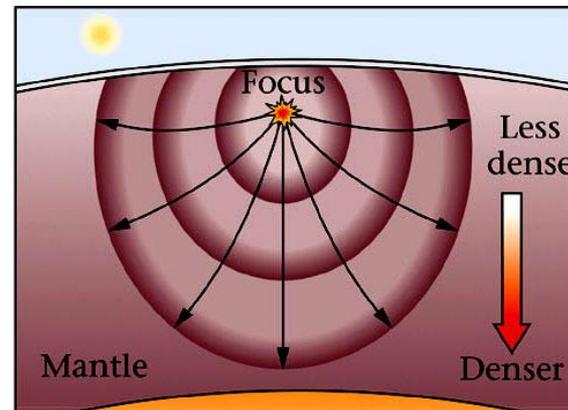
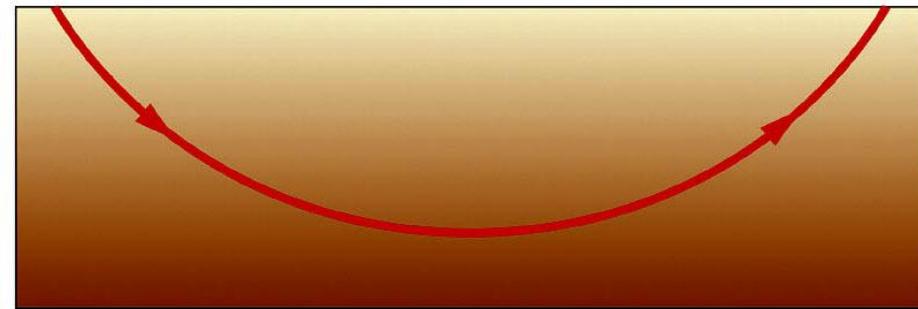
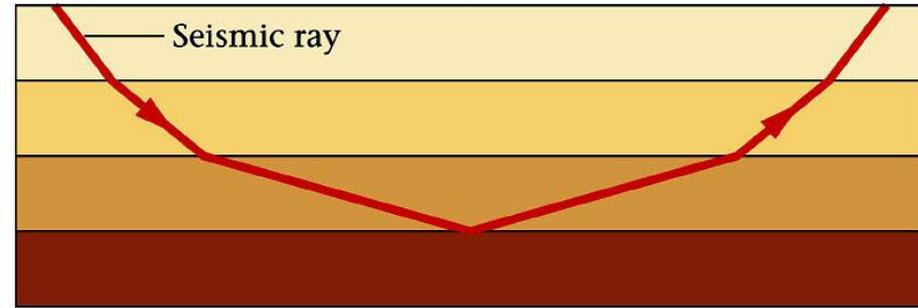
- Volcanologists determined that the mantle is roughly made of ultramafic peridotite (mostly olivine)
- If the properties of the mantle were the same (homogeneous), seismic velocities would not change and rays would travel in straight lines
- If density increases with depth, then seismic velocities should increase with depth.
- In oceanic crust (right) seismologists discovered a low-velocity zone at ~100-200 km depth.
- At this depth (pressure) and temperature, peridotite partially melts (< 2%) and since seismic waves travel slower through liquids, a low velocity zone occurs.
- This is the weak zone that permits the movement of oceanic plates.
- Below the low velocity zone, seismic velocities increase with depth...until the core mantle boundary....



Seismic Velocity Discontinuities

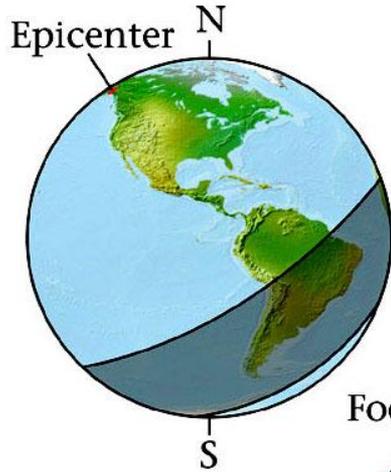
- *Why do seismic rays travel in curved paths?*

- If the Earth had a constantly increasing density with depth, refraction would cause seismic rays to travel in curved paths (similar to the Earth being made of very thin layers)
- At some depths seismic rays are relatively straight and then abruptly refract at some depth
 - These locations indicate a material property contrast (density or liquid/solid change) and are called *Seismic Velocity Discontinuities*
- These discontinuities mark phase changes of olivine → Mg spinel → perovskite
- These phase changes mark the boundaries between the upper mantle, transition zone, and lower mantle.

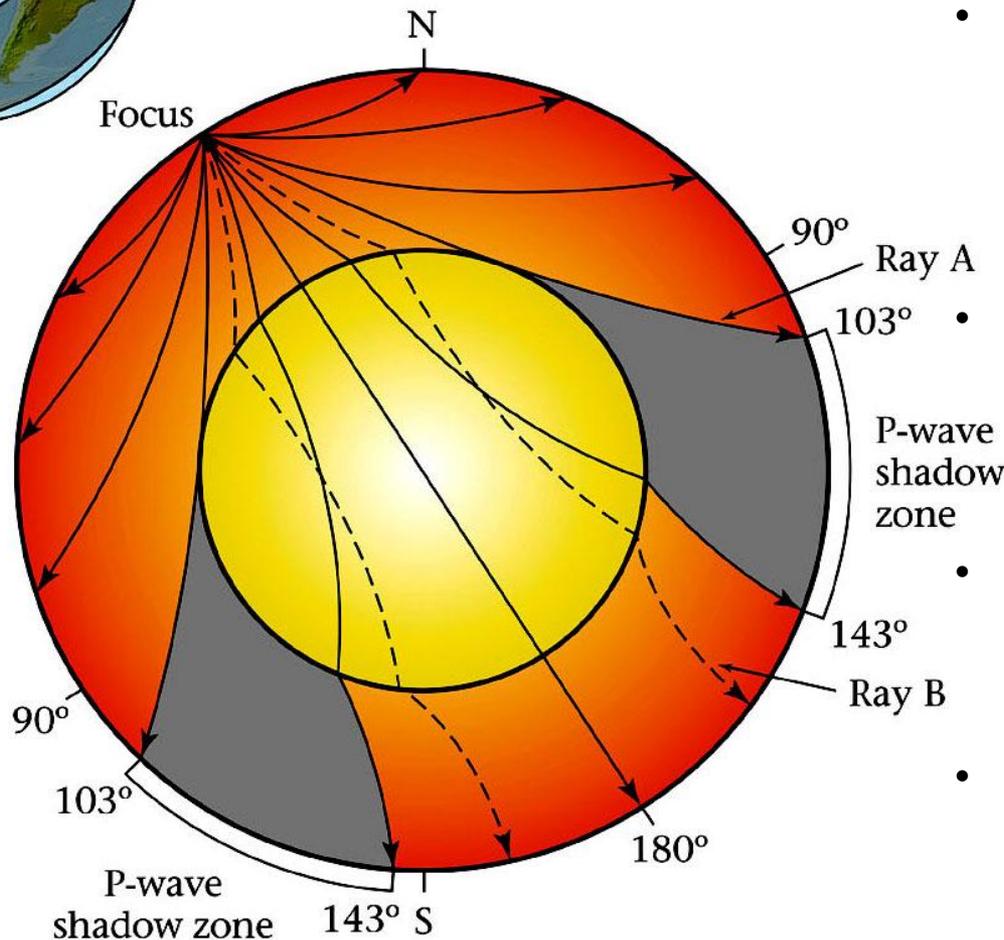


Curved rays in a mantle whose density increases gradually with depth

Discovering the Core Mantle Boundary

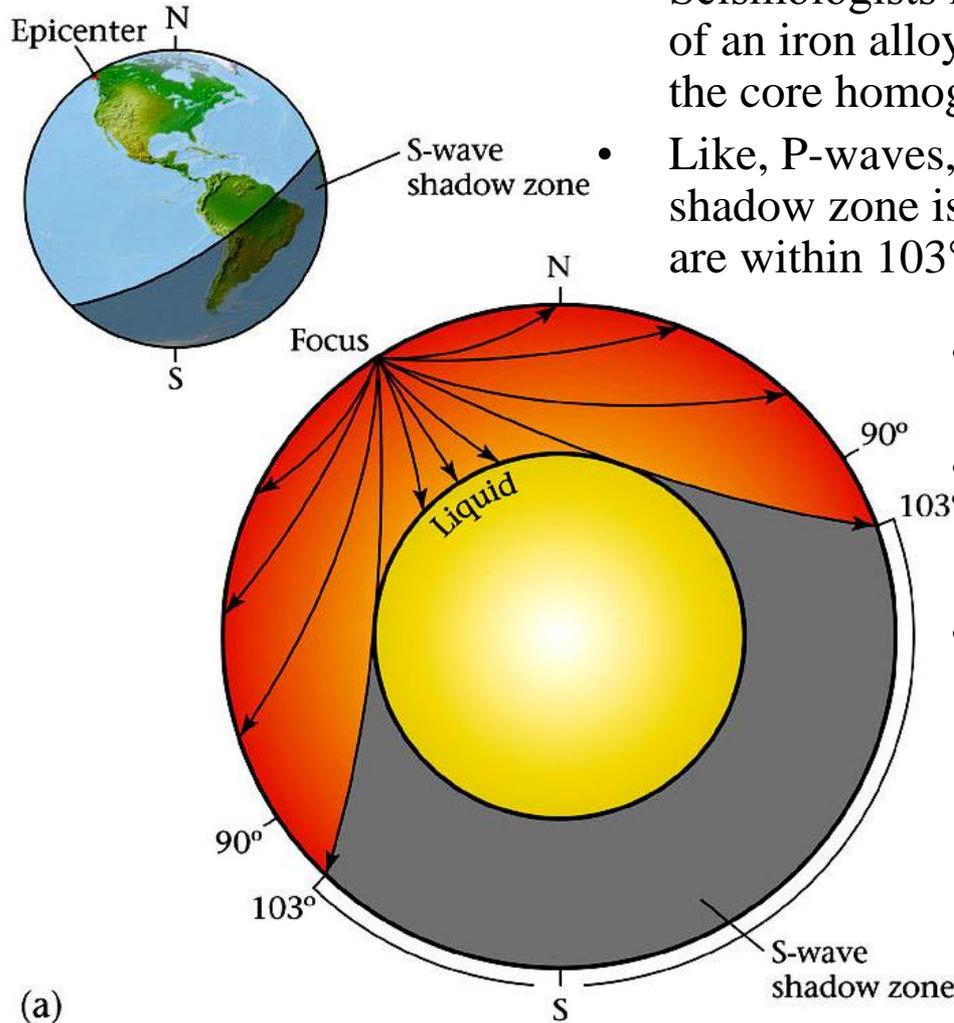


- Once a global network of seismographs was installed in the early 1900's seismologists realized that certain seismic waves were not felt at all seismic stations world wide
- If the Earth gradually increased in density with depth, waves would be recorded at all stations globally after an earthquake.



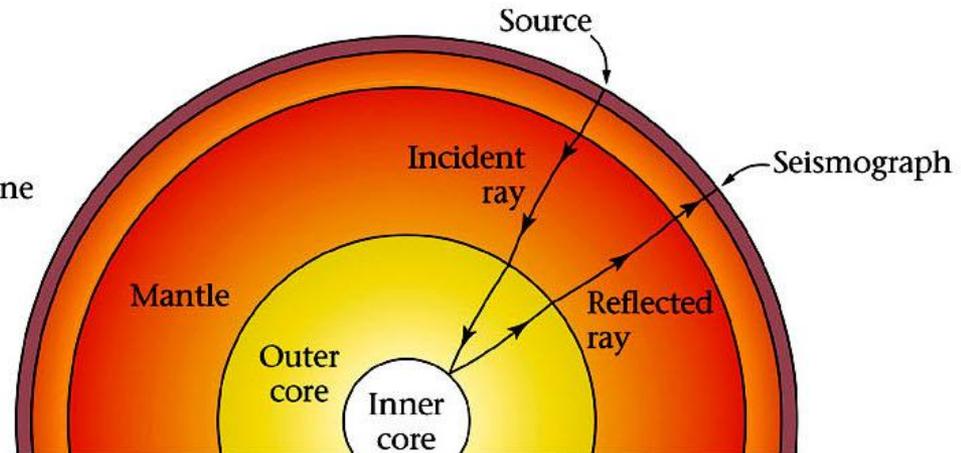
- After an earthquake it was discovered that P-waves do not reach stations between 103° and 143° . Away from the epicenter. Called the *P-wave shadow zone*
- This can be easily explained by the presence of a large seismic velocity discontinuity at depth, that we now call the core mantle boundary
- This means that seismic velocities in the core must be slower on average than the lower mantle.
- But based on density estimates of the Earth, the core must be extremely dense, so why are velocities slow?

The S-wave Shadow Zone and the Liquid Outer Core



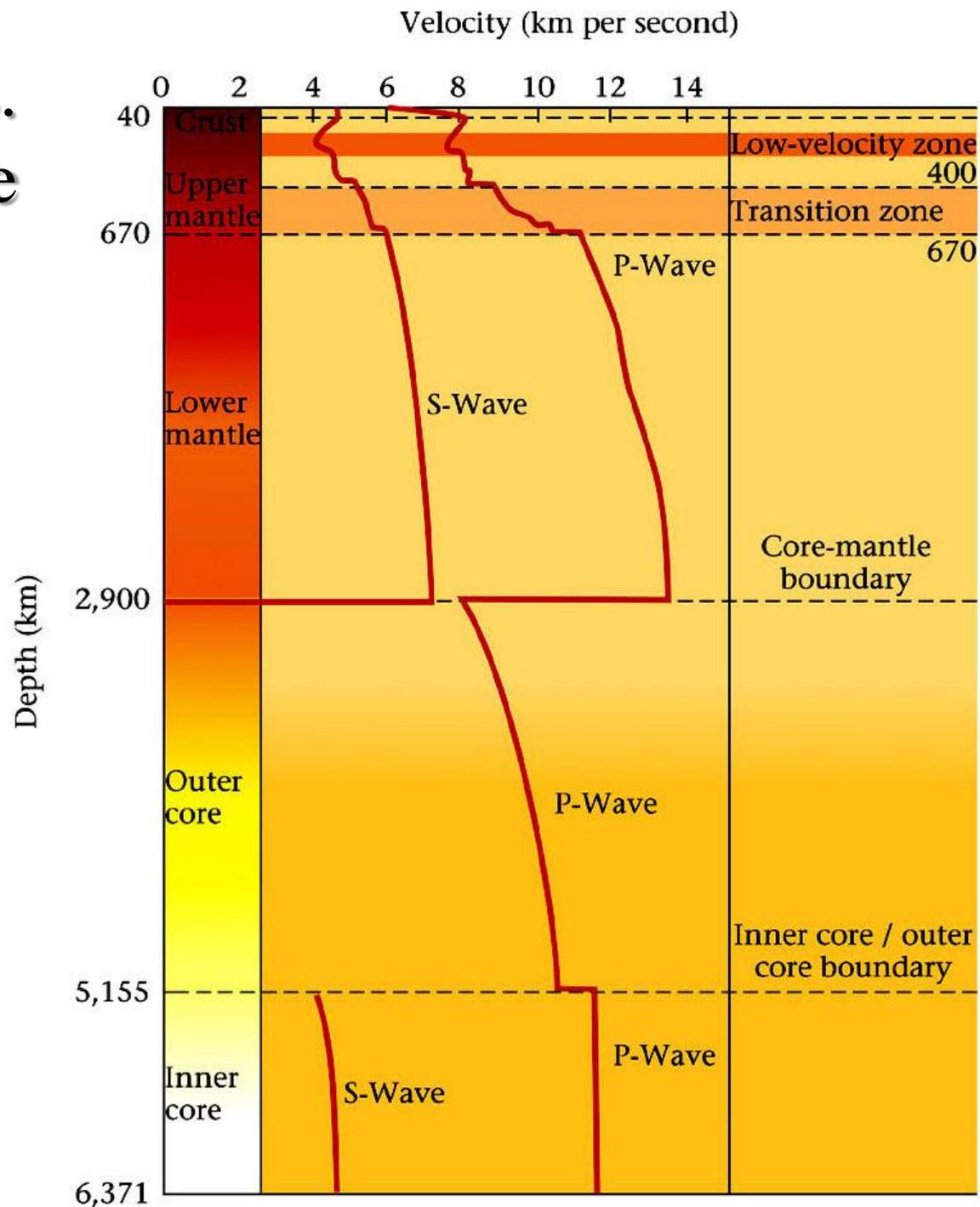
- Seismologists knew that the Earth's core was probably made of an iron alloy based on meteorites from other planets, but is the core homogeneous?
- Like, P-waves, S-waves also have a shadow zone, but the shadow zone is much larger. S-waves only reach stations that are within 103° of the epicenter.

- The S-wave shadow zone is a direct consequence of the liquid outer core.
- Seismologists have since discovered that P-waves reflect off of a discontinuity within the core suggesting a two-layer core.
- Seismic waves from nuclear bomb tests helped confirm the location of the inner core and the fact that it is solid.



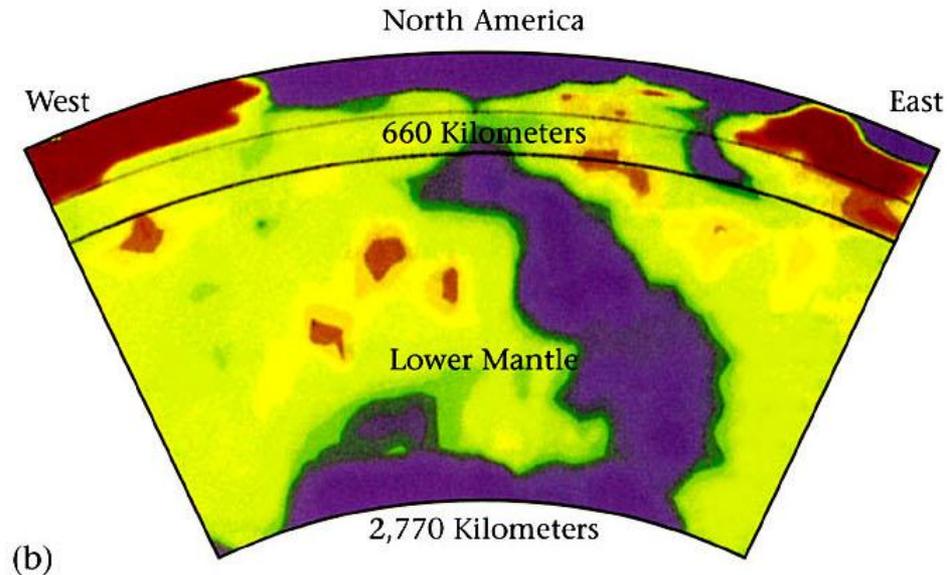
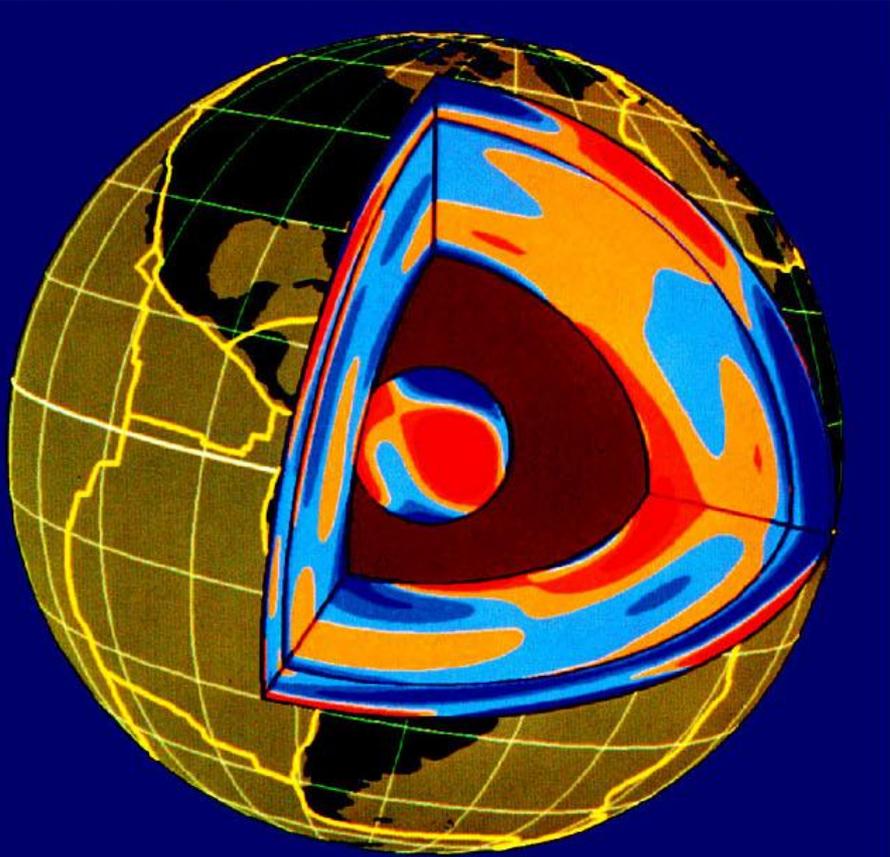
Seismic Velocity vs. Depth for the Whole Earth

- Over the past hundred years, seismologists have created a robust picture of seismic velocities at various depths within the Earth.



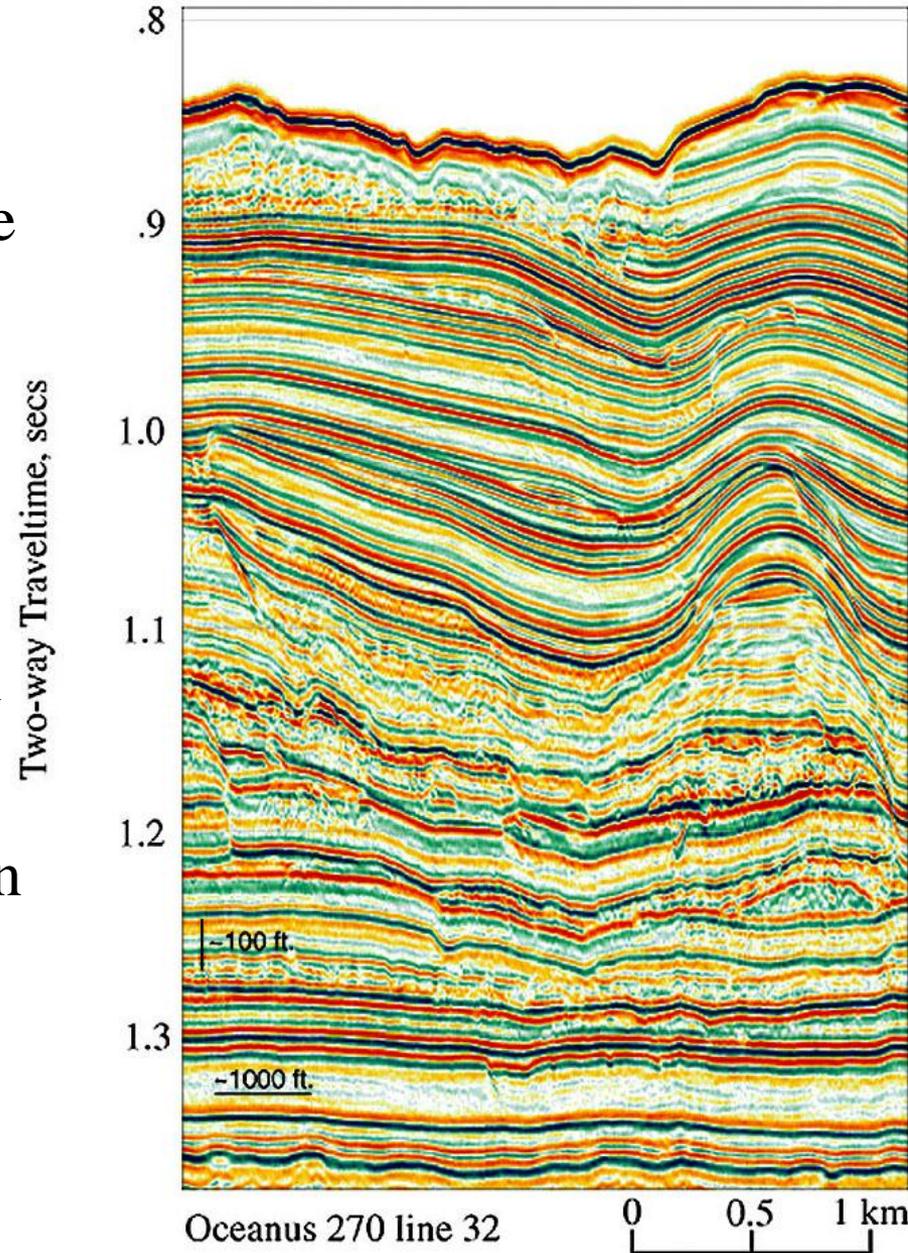
Seismic Tomography

- Recently, computers have used global seismic data to produce CAT-scan like images of seismic velocities in the Earth. These models show that the Earth is heterogeneous and that the seismic velocity vs. time plots are simplifications.
- Tomographic techniques can sometimes resolve remnant subducted plates near the core mantle boundary



Seismic Reflection Data

- Geologists don't need to wait for an earthquake to see the structure in the subsurface
- Seismic reflection studies reveal layers that reflect waves (called *reflectors*)
- The wave source can be a sledgehammer, a truck with a heavy weight, dynamite, or shotgun blasts
- This type of data is highly utilized in the oil industry



3D Seismic

- Scientists can now get high resolution 3D pictures of the subsurface using 3D seismic data
- This data is **VERY** expensive to gather, so it is mostly gathered by oil companies

