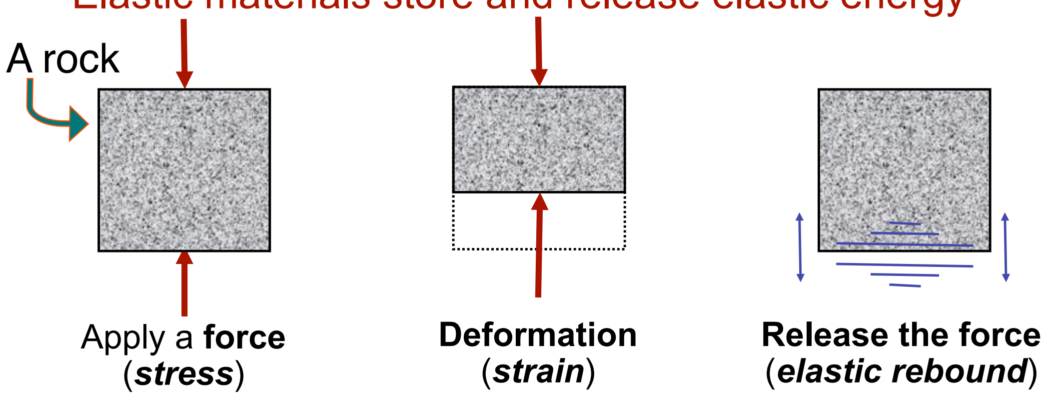
Nearly real-time global seismicity from the USGS National Earthquake Information Center (NEIC)
Most M > 4 earthquakes worldwide

http://www.iris.edu/seismon/

Monday January 23: Intro to seismic waves
Wednesday January 25: seismometry

Elastic materials store and release elastic energy

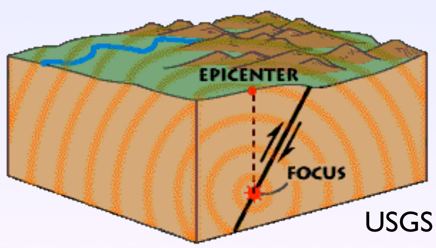


The Earth acts like this if strains are tiny and temporary (as in, transmitted disturbances, i.e. seismic waves)

If there is too much strain, the rock will either
1) deform or flow (*plastic or ductile deformation*)
2) break, or slip along an existing fault (*brittle deformation*)

When an earthquake happens, where does the pent-up elastic energy go?

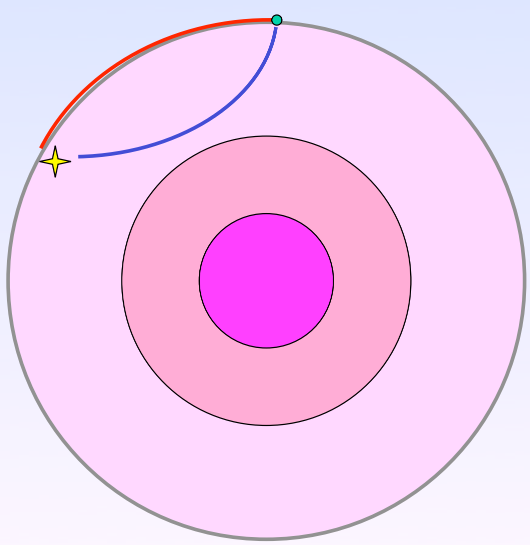
- permanent deformation, cracking and pulverizing rock along the fault, generating heat, and...
- seismic waves, which can travel far from the earthquake hypocenter (just a **tiny** % of the total energy!)



Two categories of seismic waves

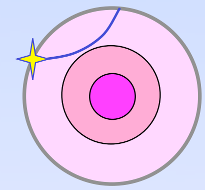
Body waves travel inside materials (the Earth)

Surface waves travel along boundaries between materials

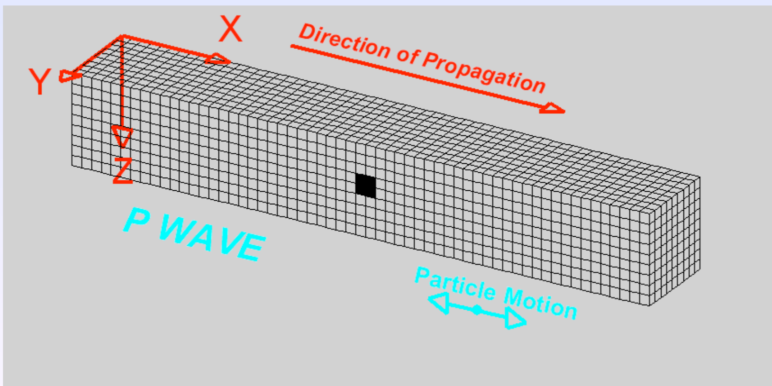


P wave (Primary wave)

body waves



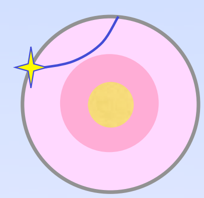
- compression and extension of the solid, like a sound wave
- particles move in same direction wave propagates
- fastest type of seismic wave: about 6 km/second in continental crust



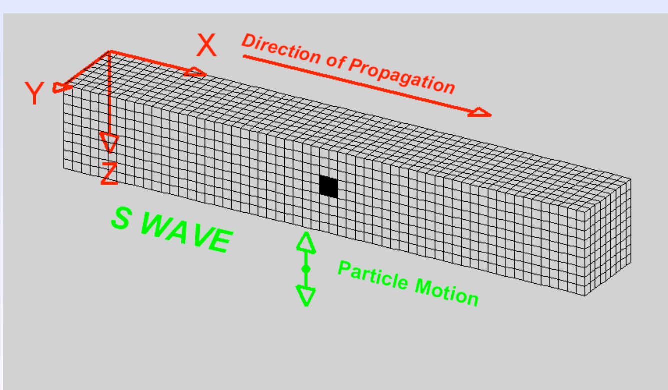
http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm Larry Braile

S wave (Secondary wave)

body waves



- shearing distortion of the solid
- particles move perpendicular to direction wave propagates
- slower than P wave: about 3.5 km/second in continental crust. Cannot pass through fluids!



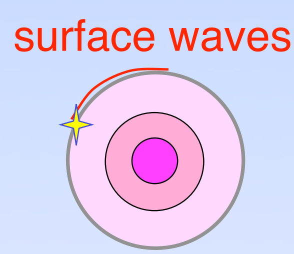
http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm Larry Braile

Seismic Body Waves

Wave Type (and names)	Particle Motion	Other Characteristics
P, **Compressional**, Primary, Longitudinal	Alternating compressions ("pushes") and dilations ("pulls") which are directed in the same direction as the wave is propagating (along the raypath)	P motion travels fastest in materials, so the P-wave is the first-arriving energy on a seismogram. Generally smaller and higher frequency than the S- and Surface waves. P waves in a liquid or gas are pressure waves, including sound waves.
S, **Shear**, Secondary, Transverse	Alternating transverse motions (perpendicular to the direction of propagation, and the raypath); commonly approximately polarized such that particle motion is in vertical or horizontal planes.	S-waves do not travel through fluids, so do not exist in Earth's outer core (inferred to be primarily liquid iron) or in air or water or molten rock (magma). S waves travel slower than P waves in a solid and, therefore, arrive after the P wave.

modified from http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

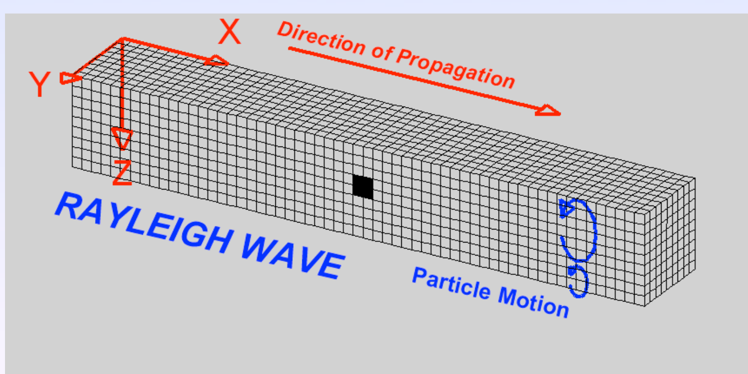
Surface waves



require an interface: ground-air, water-air, mantle-liquid outer core

slower than body waves

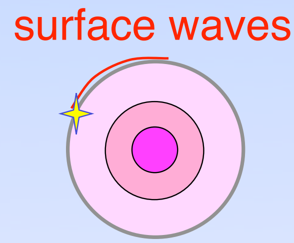
Rayleigh wave: vertical and horizontal motion parallel to wave travel direction (like an ocean wave)

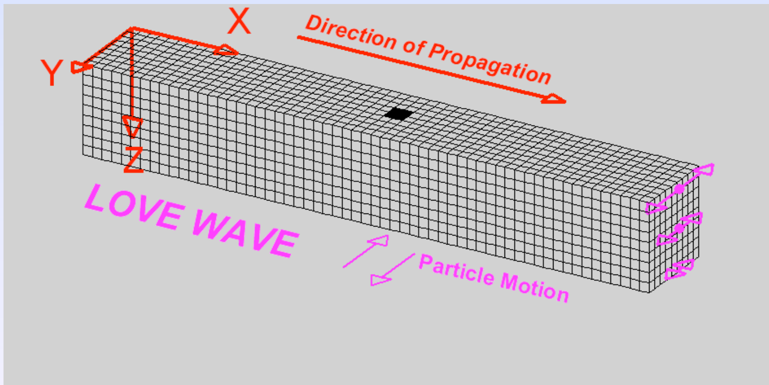


http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

Larry Braile

Love wave: horizontal movement perpendicular to wave travel direction





http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm Larry Braile

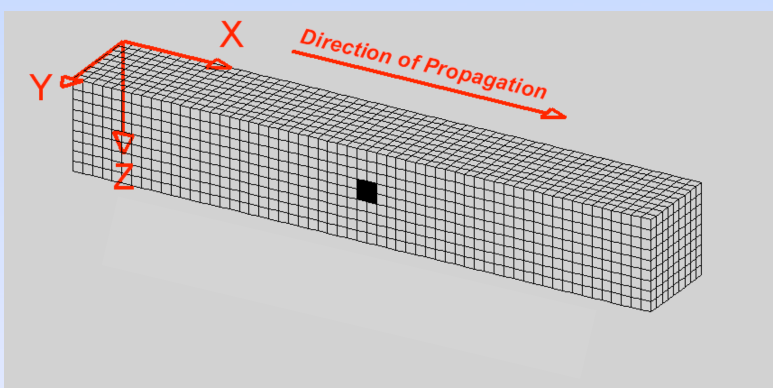
Seismic Surface Waves

L, Love waves	Transverse horizontal motion, perpendicular to the direction of propagation and <u>generally parallel to the Earth's surface</u>	$V_L \sim$ 2.0 - 4.5 km/s in the Earth depending on frequency of the propagating wave	Love waves exist because of the Earth's surface. They are largest at the surface and decrease in amplitude with depth. Love waves are dispersive, that is, the wave velocity is dependent on frequency, with low frequencies normally propagating at higher velocity. Depth of penetration of the Love waves is also dependent on frequency, with lower frequencies penetrating to greater depth.
R, Rayleigh waves, "Ground roll"	Motion is both in the direction of propagation and perpendicular (in a vertical plane). Appearance and particle motion are similar to water waves.	$V_R \sim$ 2.0 - 4.5 km/s in the Earth depending on frequency of the propagating wave	Rayleigh waves are also dispersive and the amplitudes generally decrease with depth in the Earth.

modified from http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm

Seismic waves traveling through the Earth

http://www.youtube.com/watch?v=j86XicBQiGA

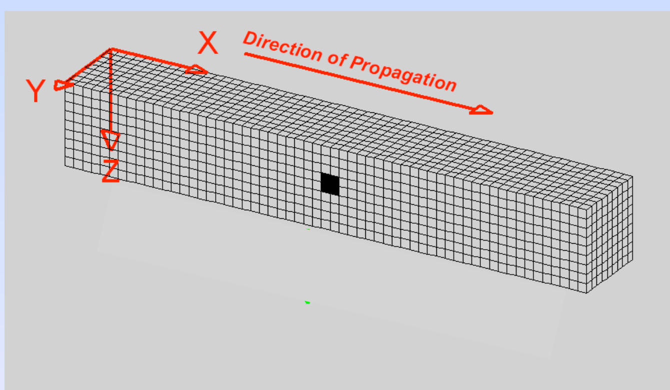


This is a ___ wave and it travels ________ the Earth.

A) Rayleigh, along the surface of
B) S, along the surface of
C) P, inside
D) P, along the surface of
E) S, inside

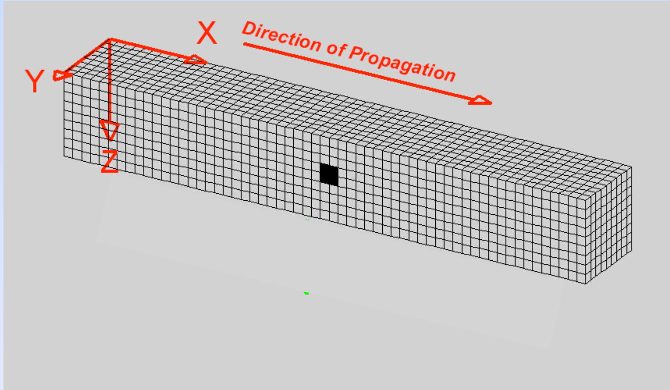
If an earthquake happens in California, the order in which the (tiny) seismic waves arrive here will be:

A) P, S, surface
B) surface, S, P
C) S, surface, P
D) P, surface, S



The Earth's outer core is liquid. Will this wave travel through it?

A) NO
B) YES

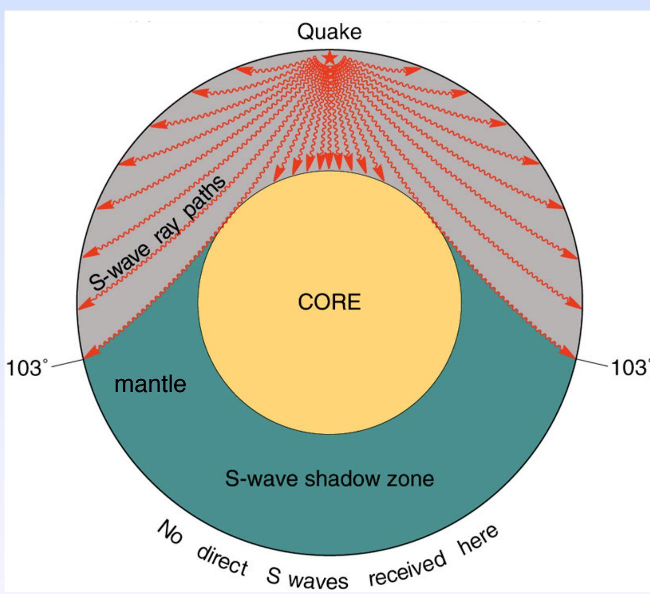


Why doesn't this body wave travel through the liquid outer core?

A) It travels along the Earth's surface and will never even make it to the core

B) It is an S wave and S waves do not travel through liquids

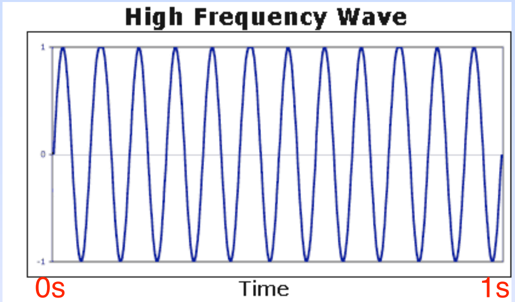
S-wave "shadow zone" confirms that the outer core is liquid



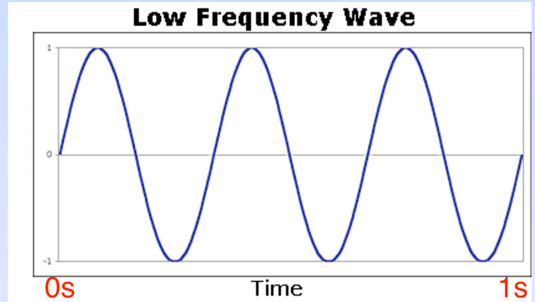
Plummer et al., 2004, F

http://www.youtube.com/watch?v=JQ27PNRe4zA&feature=player_embedded
http://www.iris.edu/hq/files/programs/education_and_outreach/aotm/18/4.ShadowZone.swf
http://whs.moodledo.co.uk/mod/resource/view.php?inpopup=true&id=13624

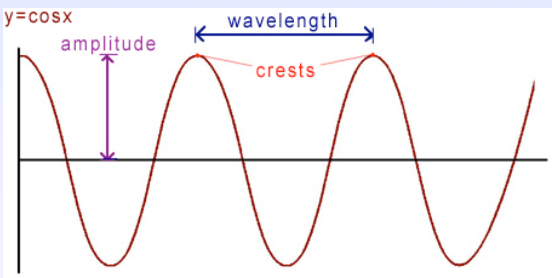
Frequency: number of waves that pass per second



12 cycles per second



3 cycles per second

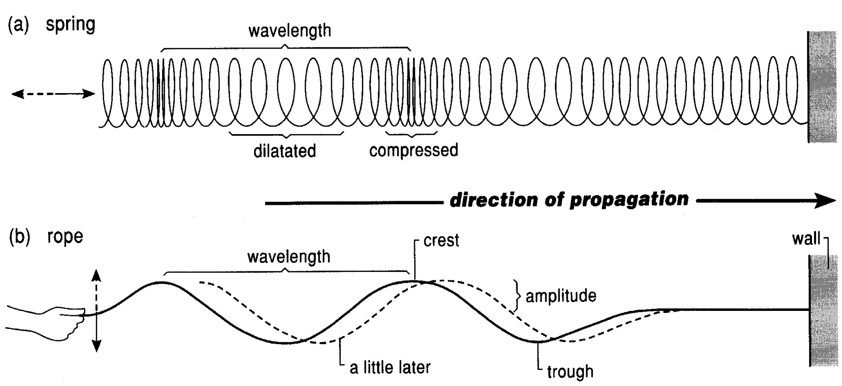


0m 1000m

300 meters

Wavelength: length of a wave in meters (trough to trough or peak to peak)

E. Hearn



Frequency and wavelength are related to wave speed

speed = frequency x wavelength

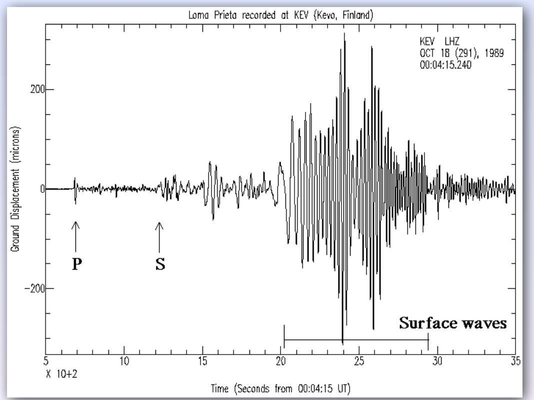
m/s cycles/s m/cycle

Music: Middle C (in air)

- frequency = 261.63 Hz
- wavelength = 1.32 m
- speed of sound in air = 345 m/s

Seismic waves contain many different frequencies jumbled together, but one can be dominant (Fourier sum)

seismogram



seismogram: IRIS

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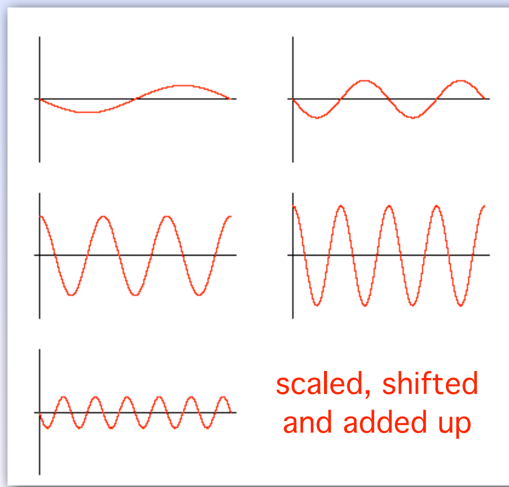


E. Hearn

Sine waves (in a particular place)

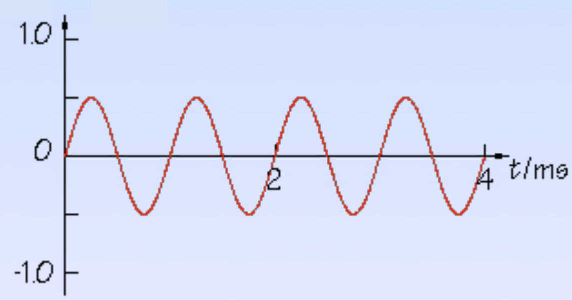
$$A(t) = Asin(2\pi ft)$$

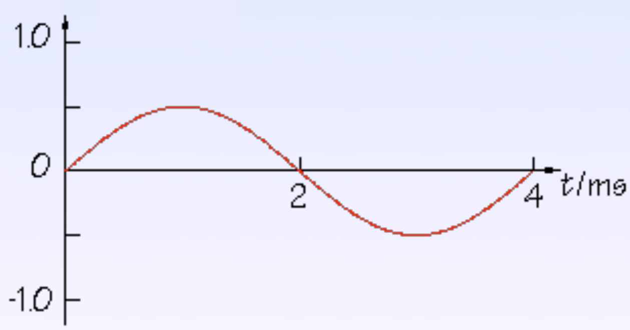
$\omega = 2\pi f$ so

$$A(t) = Asin(\omega t)$$

If the wave is shifted then

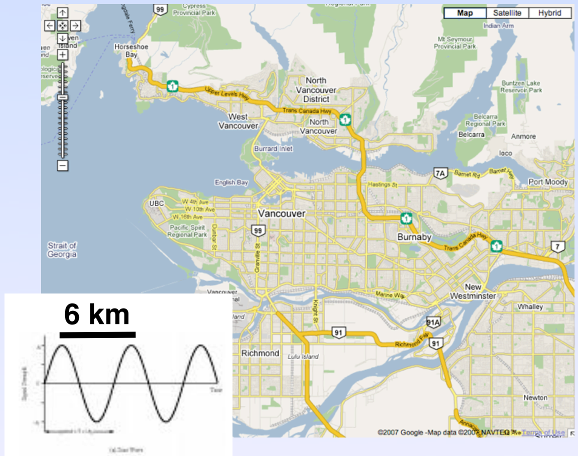
$$A(t) = Asin(\omega t + \phi)$$





http://www.doctronics.co.uk/signals.htm

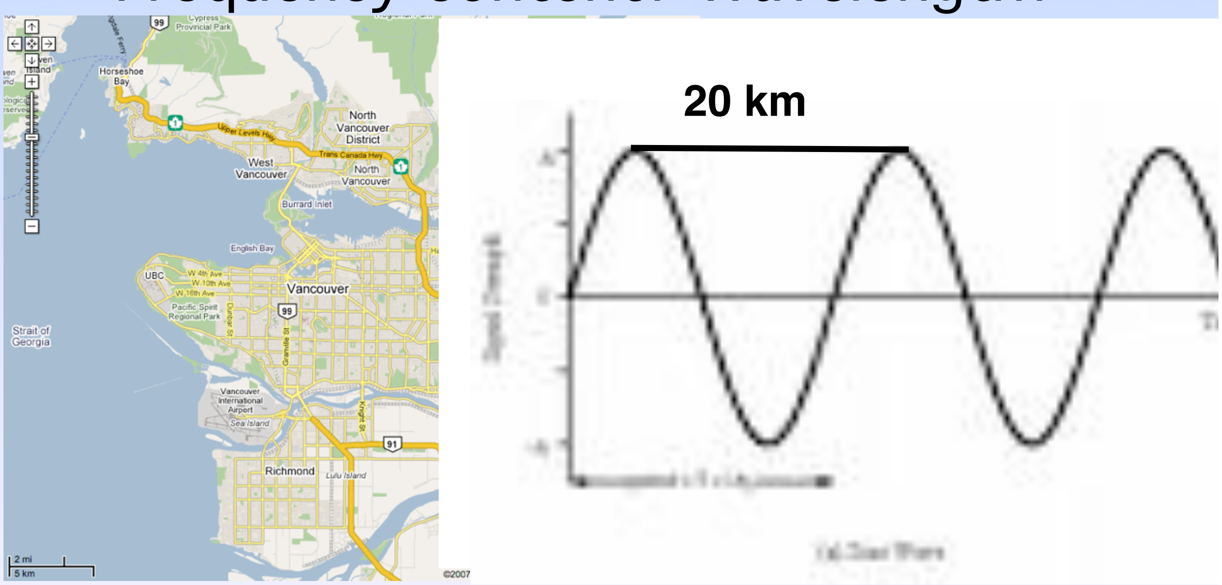
Frequency content? Wavelength?



speed = frequency   x   wavelength

Average P-wave crustal velocity: ~6000 m/s or 6 km/s
Frequencies: very broad range, usually 1 to 20 Hz
- for 10 Hz waves, wavelength = 600 m
- for 1 Hz waves, about 6 km

Frequency content? Wavelength?



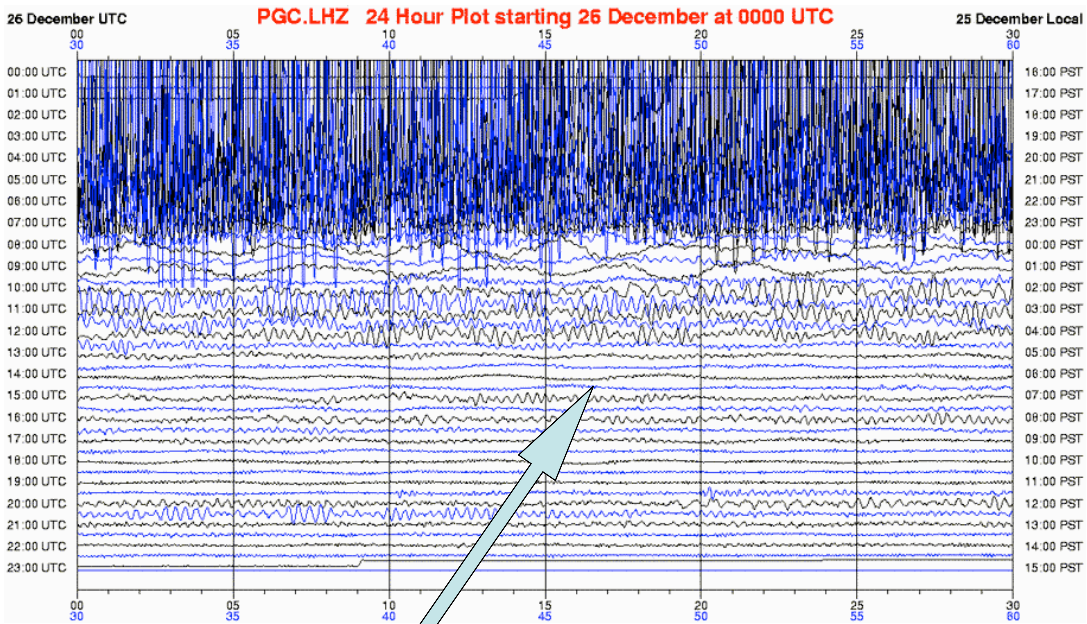
Surface wave velocities: ~ 2 km/s

speed = frequency   x   wavelength

Frequencies: lower than body waves (typically .1 to 0.002 Hz)
- for 0.1 Hz waves, wavelength = 20 km

Amplitude? Up to a **meter** at the epicentre, smaller with distance
at 90 degrees away: M3 and M9 = 10^{-8} and 10^{-2} m
(very low frequency for M9: periods of many minutes)

Sumatra Earthquake: 26 December 2004



These low-frequency waves 16 hours later are still from the same earthquake. Higher sensitivity instruments show that the Earth rang like a gong for days, really long period (low-frequency) waves!

How fast do seismic waves travel?

Speed depends on the material properties

1) incompressibility (K) ← resistance to volume change

2) rigidity (μ) ← resistance to distortion or bending (=0 for fluids)

3) density (ρ) ← mass per cubic meter

All of these are related to temperature, pressure, and composition

As density increases, K and μ increase ***even more***.

P Waves

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

S Waves

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

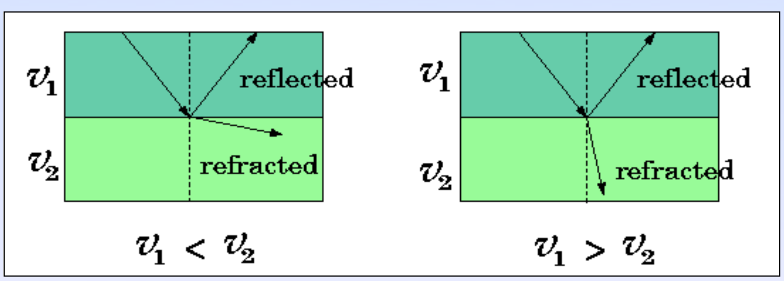
Waves travel fastest through rigid, hard-to-compress rocks.
$\mu = 0$ for fluids: fluids aren't rigid. Therefore...

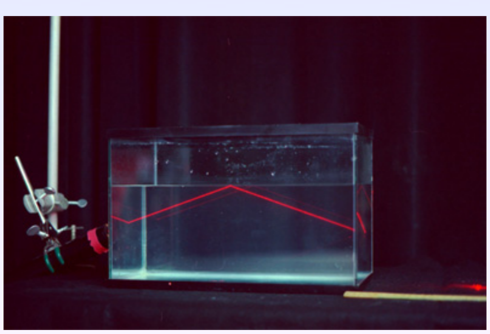
> S waves do not travel through fluids!
> Also, P waves are slowed down traveling through fluids.

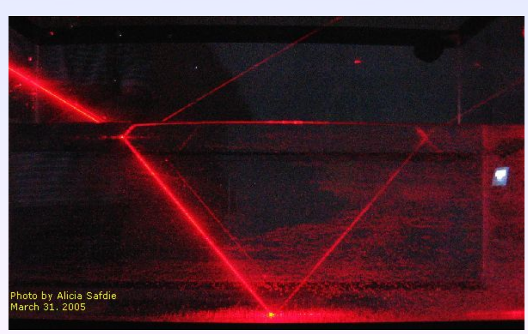
Surface waves: slower than body waves. Lowest frequencies travel fastest.

Like other waves, body waves refract and reflect

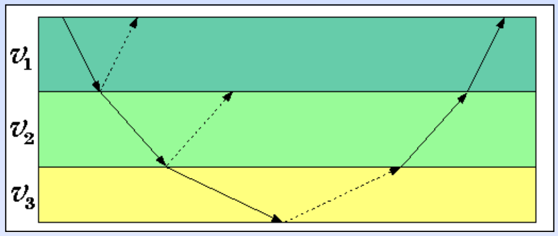
- reflection and refraction (bending) at sudden interfaces



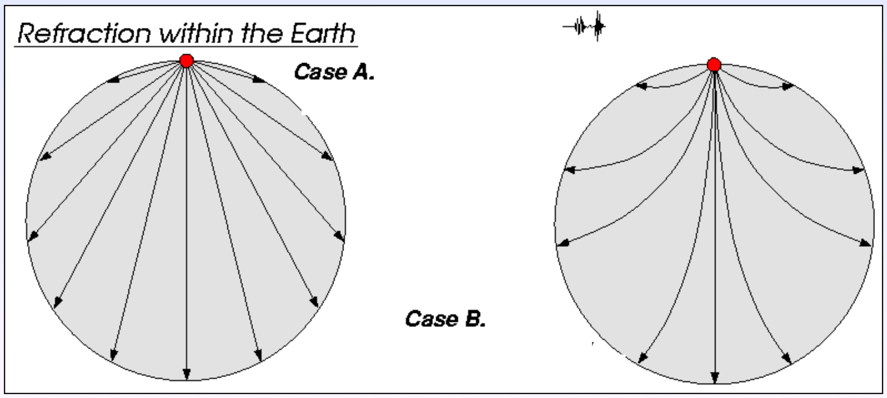




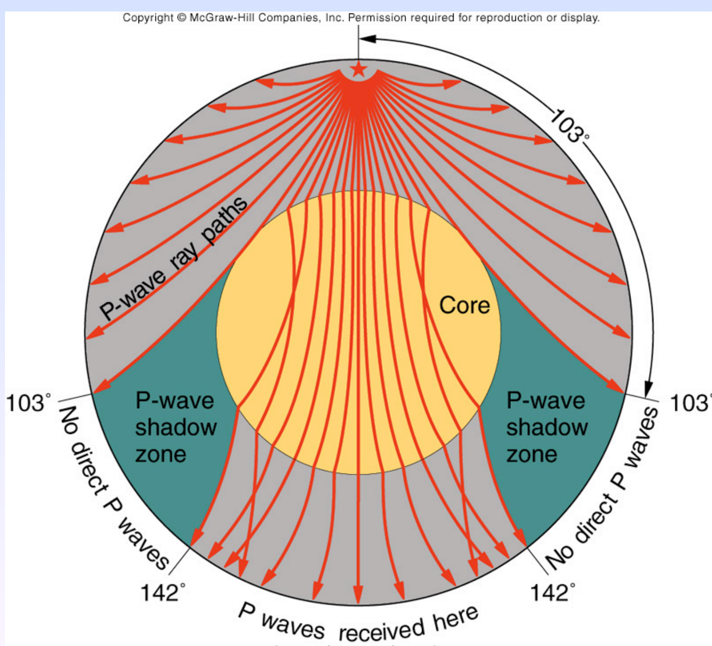
- reflection and refraction in continuously changing media



- this is why the seismic wave paths are curved...



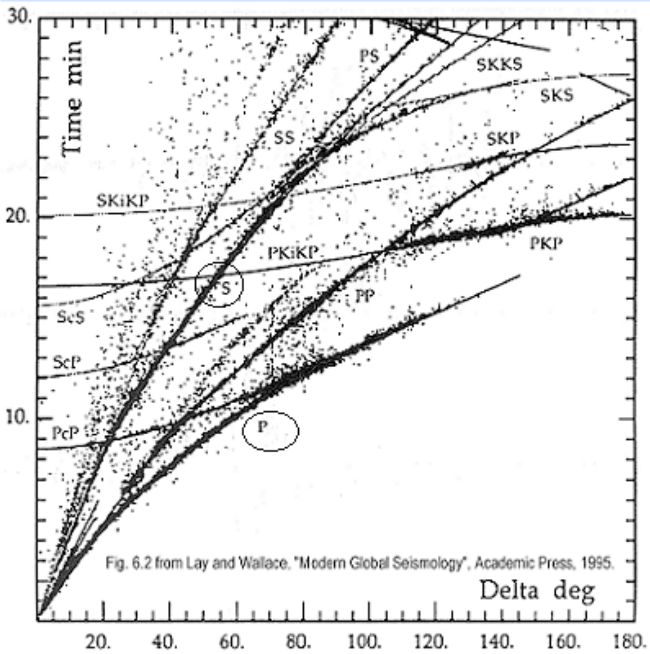
P-wave "shadow zone": outer core has a slow P-wave velocity so ray paths refract a lot at the core-mantle boundary

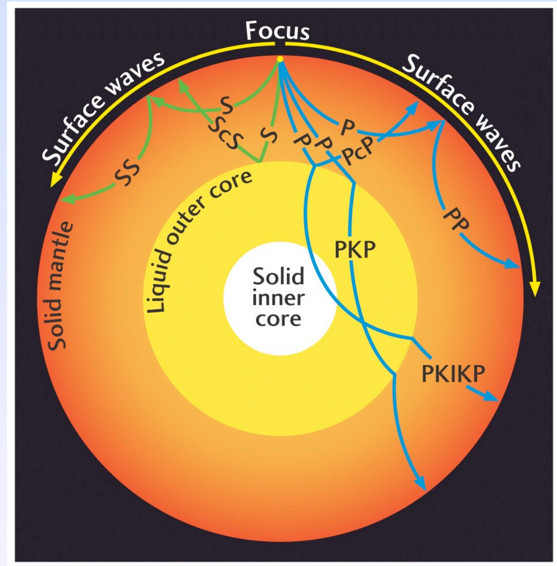


(20 minutes later)

Plummer et al., 2004, Fig. 4.8

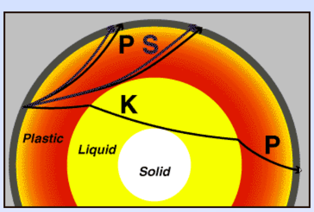
Reflection of seismic waves from boundaries can complicate seismograms recorded far from an earthquake



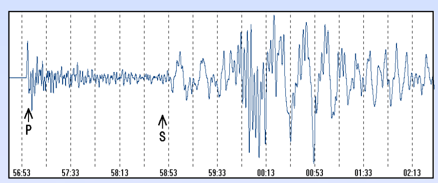


http://www.youtube.com/user/IRISEnO#p/c/8FDF28B8FD0C2E56/3/wSqxDDFZZpM

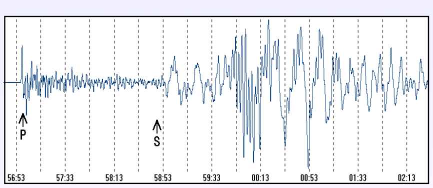
- If we know the travel path, the behaviour of waves can be calculated. (A "forward" problem)



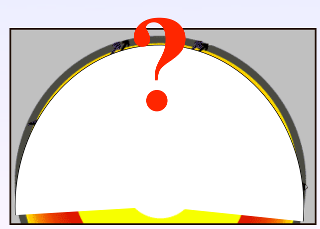
Calculations



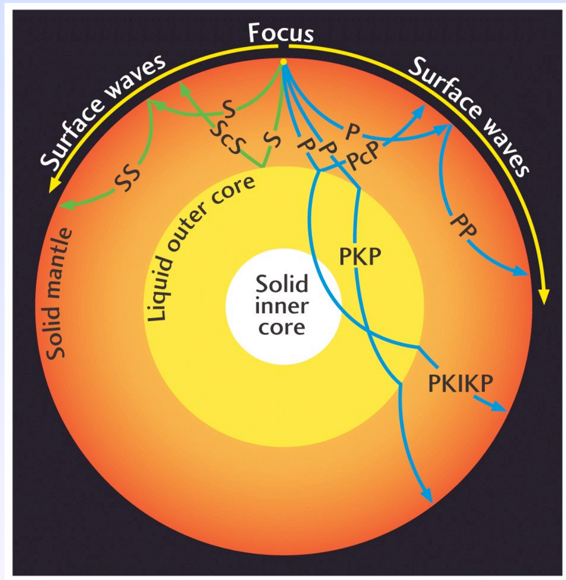
- Can we work backwards? (an "inverse" problem)
  - Make measurements of time and position …
  - Can we calculate the travel path to get structure?



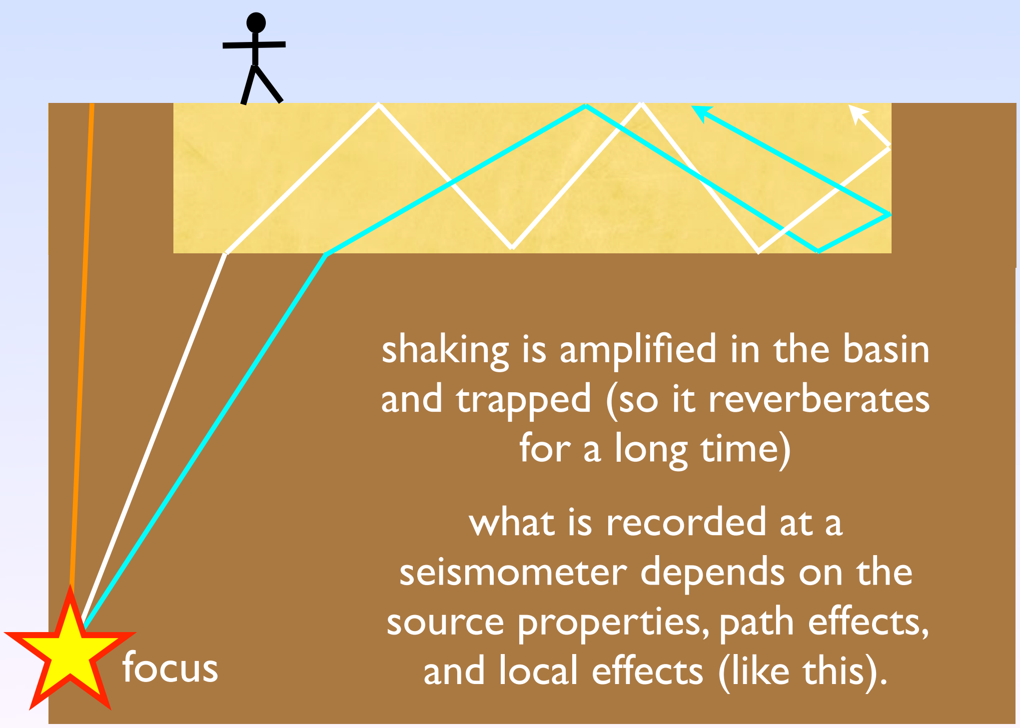
Inversion



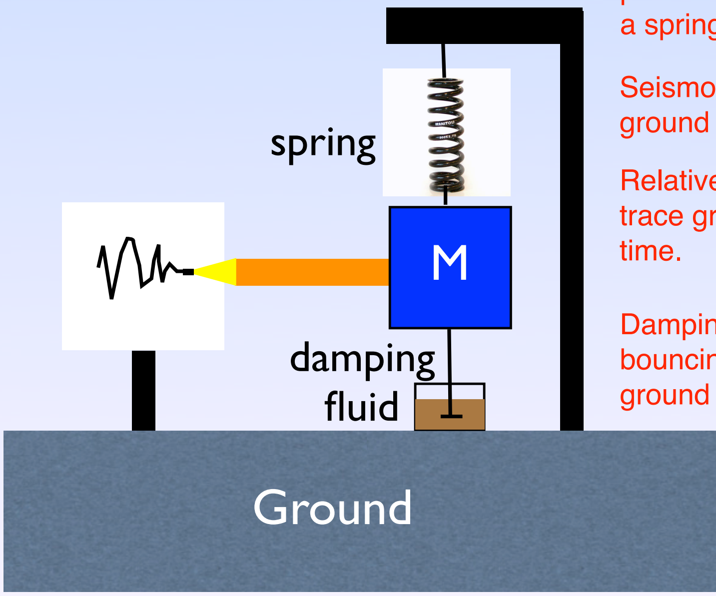
Reflection tells us where the major layers in the Earth are located...



Reflection also results in seismic waves being trapped in sedimentary basins...



Seismographs: the basic idea



Heavy mass (shown here with pencil attached) is suspended by a spring.

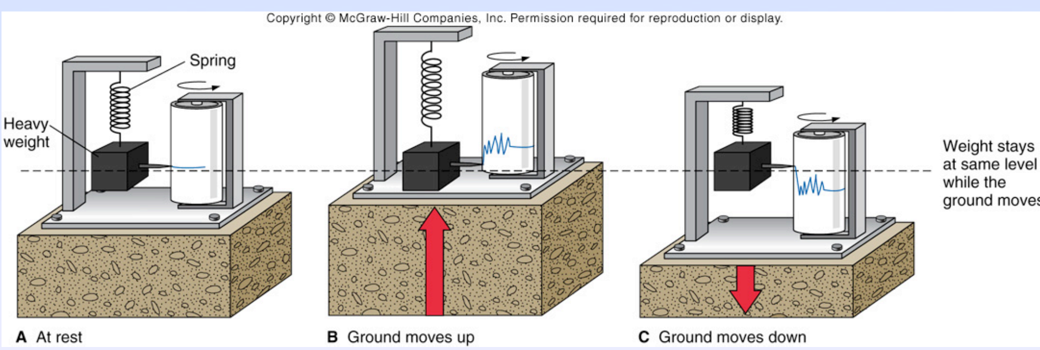
Seismograph moves with the ground but the mass stays put.

Relative motion causes pen to trace ground displacement over time.

Damping fluid stops mass from bouncing around after the ground has stopped shaking.

Vertical seismograph
http://www.youtube.com/watch?v=DX5VXGmdnAg&NR=1

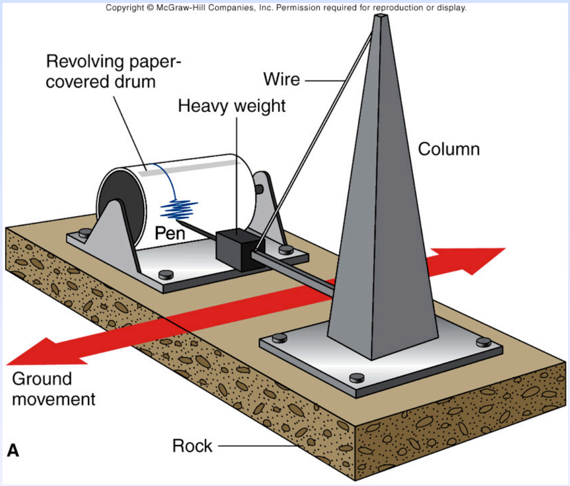
Seismographs: the basic idea



Plummer et al., Physical Geology, 2004

Vertical seismograph
http://www.youtube.com/watch?v=DX5VXGmdnAg&NR=1

Seismographs: the basic idea

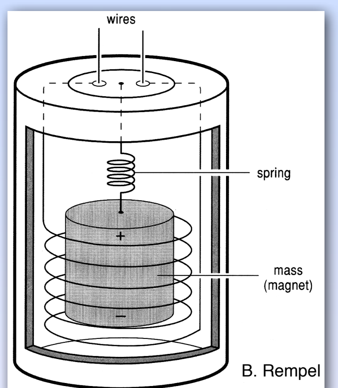


http://www.iris.edu/hq/gallery/photo/1608

- heavy mass (shown here with pen attached) is suspended by a spring
- seismograph moves with the ground but the mass stays put
- relative motion causes pen to trace ground displacement over time

Horizontal seismograph
http://www.youtube.com/watch?NR=1&v=83GOKn7kWX

Seismograph ("geophone"): a more modern version



http://www.tootoo.com/s-ps/geophone--p-727150.html

- heavy mass suspended by spring, same as before
- mass is a magnet, so it generates electric current in the wire coil when coil (and the ground) moves
- electric current readings are converted to shaking velocity
- record is velocity vs. time, can be converted to displacement vs. time

(This is NOT the state-of-the-art kind: that would be a "broadband seismometer", which works a little bit differently and costs a lot more.)

Deploying geophones
near Williams Lake, BC

Broadband seismometer
installations ($$$)