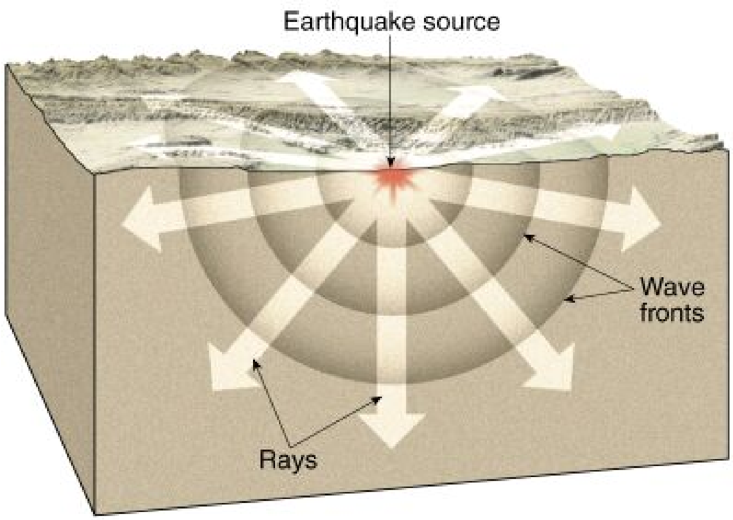
Seismology and Earth's Interior

There are two categories of earthquake waves. **Body waves** can travel deep into the Earth; **Surface waves** can only travel very near the surface of the Earth. There are **two kinds of body waves**, and **two kinds of surface waves**. As you might imagine, only body waves can give us any information about the deep interior of the Earth.

As discussed all earthquakes are relatively shallow, with the deepest at about 700 km depth. An earthquake generates body waves that spread out in all directions, like light from a naked light bulb. Notice in the diagram below that you can think of earthquake waves as moving out like **rays** (arrows) or as **wave fronts** (spherical shells). Surface wave rays travel out in all horizontal directions (like the arrows on the top of the block pictured below), like ripples moving out from a pebble dropped into a pond.

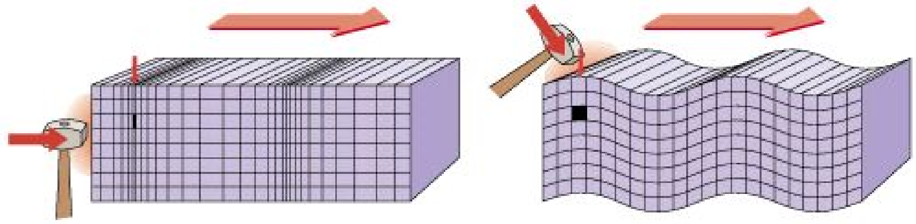


All over the surface of the Earth are seismograph stations which can detect all of the waves that arrive at that location. By recognizing what kinds of waves have arrived, exactly when they arrived, and knowing where and when the earthquake occurred (or sometimes the earthquake location and time itself is determined by seismograph stations), we can learn about the deep interior of the Earth. This is because these waves refract (bend) and reflect at boundaries in the Earth.

Body Waves:

There are two kinds of body waves corresponding to the two fundamental ways you can deform an object: you can squeeze it (or stretch it, which is like "negative squeezing"), or you can shear it.

P Waves



The diagram on the left above illustrates a **P wave**. These are also called **compressional** or **longitudinal** waves. Material is compressed and stretched in the horizontal direction, from left to right, and the wave (disturbance) also travels in the horizontal direction. P waves travel faster than any other type of wave. They **can travel through fluid or solid** materials. Ordinary **sound waves in air are P waves**.

P comes from **primary** wave, because they arrive first, but a mnemonic is push-pull wave

P wave velocity depends on a material's "plane wave modulus" and its density:

$$V_P = \alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{\frac{4}{3}K + \mu}{\rho}}$$

Where l is Lamé's constant, m is shear modulus, K is bulk modulus, and r is density. Notice that density is in the denominator, so denser rocks should be slower. However, although the density of rock in the Earth generally increases with depth, the rigidity, as expressed in the various elastic constants, increases even more rapidly with depth. Hence, P wave velocity generally increases with increasing depth.

Since solids, liquids and gasses have a finite bulk modulus, P waves can travel through any of these

S Waves

The diagram on the right above illustrates an **S wave**. These are also called **shear waves**. S comes from **secondary wave**. Material is sheared, so that an imaginary square drawn on the side of the block becomes diamond shaped. The material vibrates up and down (or side to side, in and out of the screen, if the hammer had struck the side of the block instead of the top) but the wave (disturbance) travels in the horizontal direction from left to right. S waves travel more slowly than P waves. They **can only travel through solid materials**. Plucking a guitar string generates a kind of shear wave; the string vibrates side to side, but the wave travels along the string.

S-wave velocity depends on a material's shear modulus, m, and density, r:

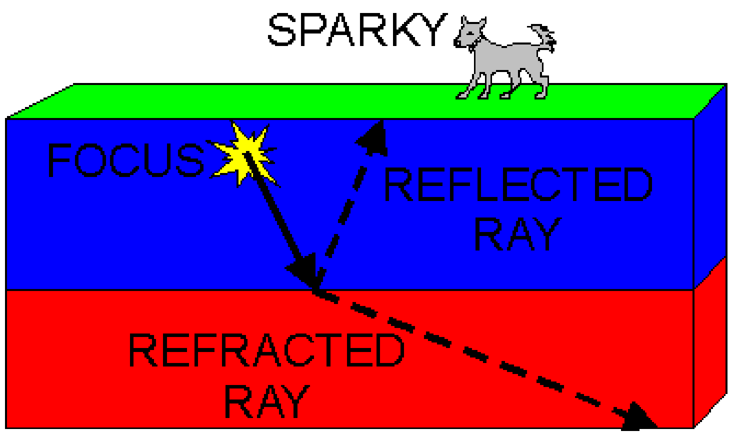
$$V_S = \beta = \sqrt{\frac{\mu}{\rho}}$$

Since fluids (liquids and gasses have zero shear modulus, S waves cannot travel through fluids.

Comparing the velocity expressions, you can see that $V_P > V_S$ for any material.

For both types of body waves:

- P and S waves travel faster in rigid, dense rocks. Rocks generally get more rigid and denser with depth, so the velocity of P and S waves generally increases with depth.
- P and S waves are refracted and reflected at boundaries.
- In the diagram below, the earthquake location (**focus**) is shown in yellow. The ray we've shown coming out of the earthquake travels in a straight line in the blue layer. When it reaches the red layer (which might be slower or faster), the ray splits: some of the energy goes into the red layer but is bent (refracted), and some of the energy is reflected back up to the surface. An analogy: When you stand in front of a store window, you can usually see your reflection, proving that some of the light reflects back at you. But people in the store can also see you, so some of the light goes through the glass.



Reflections, Refractions, Snell's Law

Reflections

Reflections occur when there is an acoustic impedance contrast between two layers:

$$\text{acoustic impedance} = V_1\rho_1$$

$$\frac{A_r}{A_i} = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1}$$

where

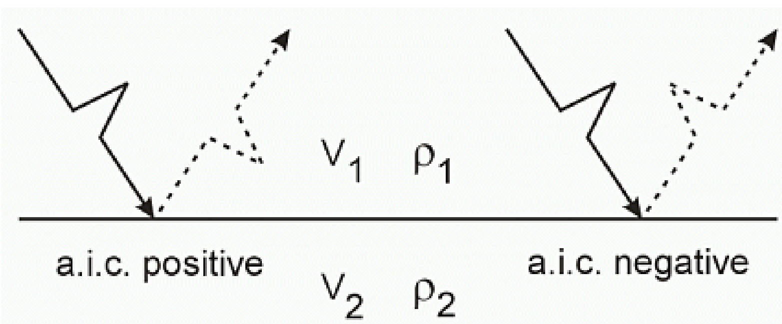
$V_2\rho_2 - V_1\rho_1$ is the acoustic impedance contrast

A_i is the incident ray amplitude

A_r is the reflected ray amplitude

$\frac{A_r}{A_i}$ is the reflection coefficient

Sign determines whether polarity reversal occurs:



In upper crust, changes in r sometimes small, so

$$\frac{A_r}{A_i} \approx V_2 - V_1$$

Refractions

Refractions occur when velocities differ:

$$V_2 \neq V_1$$

Snell's Law (note that it applies to **refractions** and **reflections**)

$$\frac{\sin i}{V_{S1}} = \frac{\sin r_s}{V_{S1}} = \frac{\sin r_P}{V_{P1}} = \frac{\sin f_s}{V_{S2}} = \frac{\sin f_P}{V_{P2}}$$

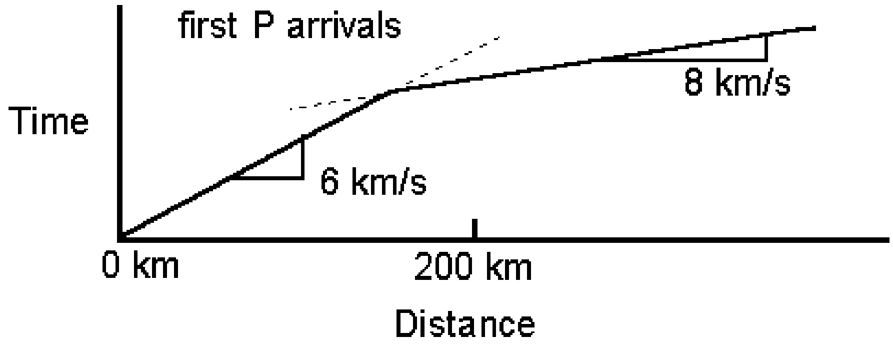
Earthquake Seismology and the Interior of the Eartth

The main points about using earthquakes waves to determine the internal structure of the Earth are summarized here, then explained in more detail:

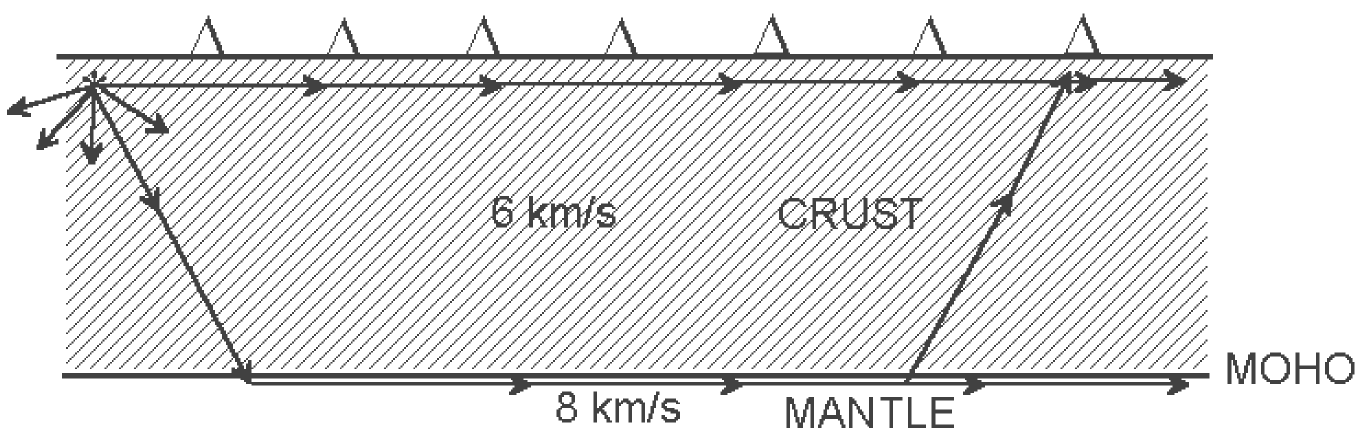
- By measuring travel times of earthquake waves to seismograph stations, we can determine velocity structure of Earth
- By making graphs of travel time versus distance between earthquakes and seismograph stations, we find
  - velocity generally increases gradually w/ depth in Earth, due to increasing pressure and rigidity of the rocks
  - however, there are abrupt velocity changes at certain depths, indicating layering
- The 4 major layers in the Earth, from outside in, are the crust, mantle, outer core, and inner core.
  - The **crust** is very thin, averaging about 30 km thick in the continents and 5 km thick in the oceans
  - The **mantle** is 2900 km thick (almost halfway to the center of the Earth. It is made of dark, dense, ultramafic rock (**peridotite**).
  - The **outer core** is 2300 km thick and is made of a mixture liquid iron (90%) and nickel (10%)
  - The **inner core** is at the center of the Earth and has a 1200 km radius; it's made of solid iron (90%) and nickel (10%).

Crust - Mantle Boundary

- The crust mantle boundary was discovered in 1909 by a seismologist named Mohorovici (Yugoslav), as a result of his study of an earthquake in Croatia at that time.
- He found that, out to about 150 km, the time it took for the earthquake waves to reach each seismograph station was proportional to the distance the station was from the earthquake. He used the familiar time/distance/rate equation (distance = rate*time, or rate = distance/time) to determine that the velocity of the upper crust must be about 6 km/s. In the graph below, this corresponds to the straight line segment on the left, which has a slope of corresponding to 6 km/s.
- However, for stations greater than about 150 km from the earthquake, waves did not take as much longer to arrive as if they were traveling at only 6 km/s. In fact, the slope of the second line segment corresponds to a velocity of 8 km/s.



- Furthermore, Mohorovici figured out that the distance at which the change in slope occurred (about 150 km) can be used to calculate the depth to velocity increase from 6 to 8 km/s. He calculated that the depth to this velocity jump was about 30 km.
- We interpret this velocity jump as the crust-mantle boundary, and often refer to it as the **Mohorovicic discontinuity**, or **Moho**, for short.
- The diagram below shows a cross-section of the crust and mantle, with the earthquake on the left. The triangles on the surface are meant to be seismograph stations at different distances from the earthquake. At short distances, the "direct waves" that travel along the surface will arrive first. However, at greater distances, the waves that travel down to the mantle, and are bent and travel along the top of the mantle at the higher velocity, can arrive before the waves traveling directly along the surface. These refracted waves make up for the extra distance by traveling faster for most of their path.

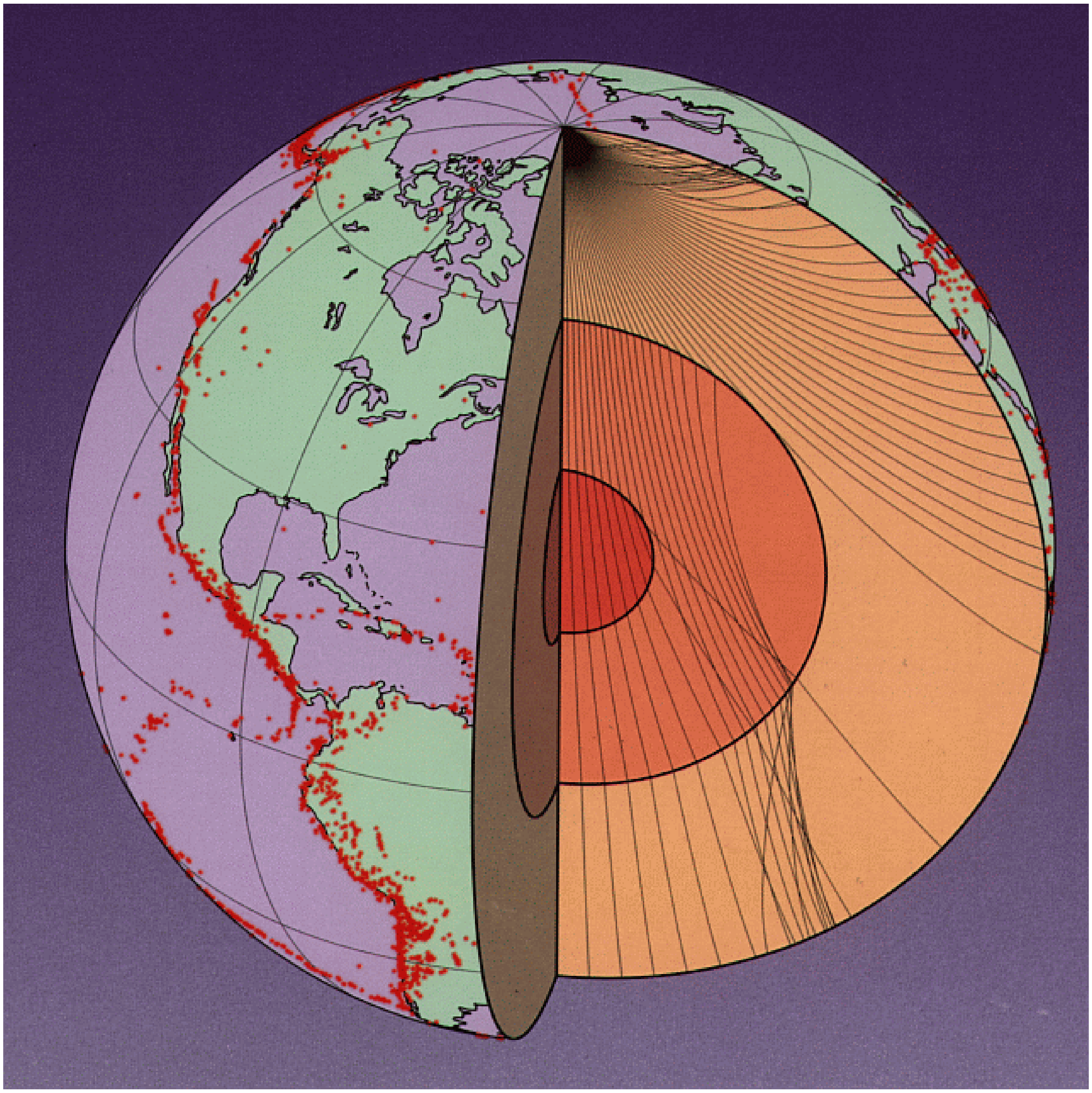


- Seismic refraction experiments like Mohorovici's have been, and still are, being conducted all over the Earth. They indicate that continental crust is about 35 km thick, but varies greatly from place to place, and oceanic crust is pretty uniformly 5 km thick.

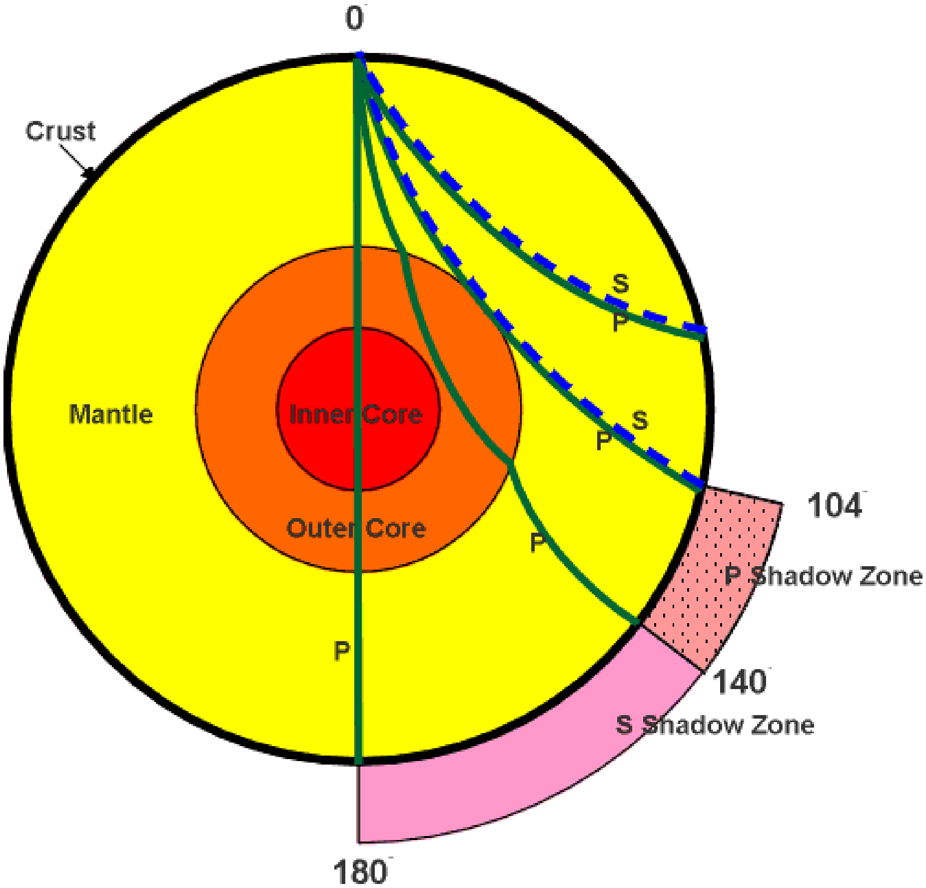
Core - Mantle Boundary

- The core-mantle boundary was discovered in 1913 by a seismologist named Gutenberg. Seismologists had noticed that P waves are not recorded at seismograph stations which are from 104^{o} to 140^{o} away from an earthquake (the angle is the angle made by drawing a line from the earthquake to the center of the Earth, and then from there to the seismograph station.

- Gutenberg explained this Shadow Zone with a **core** which slowed and bent P waves



- Later, an S wave shadow zone was recognized, meaning no S waves were received at seismographs stations from 104^{o} to 180^{o} from an earthquake; the S wave shadow zone is caused by the outer core, which is liquid iron/nickel.



- Modeling of seismic waves traveling through the Earth allowed seismologists to determine that the core begins at a depth of 2900 km, or in other words, the **mantle** is 2900 km thick; its composition is probably **ultramafic** rock (**peridotite**). This is based on the velocity of the waves, meteorites, mass of the Earth and other lines of evidence.

Inner Core - Outer Core Boundary

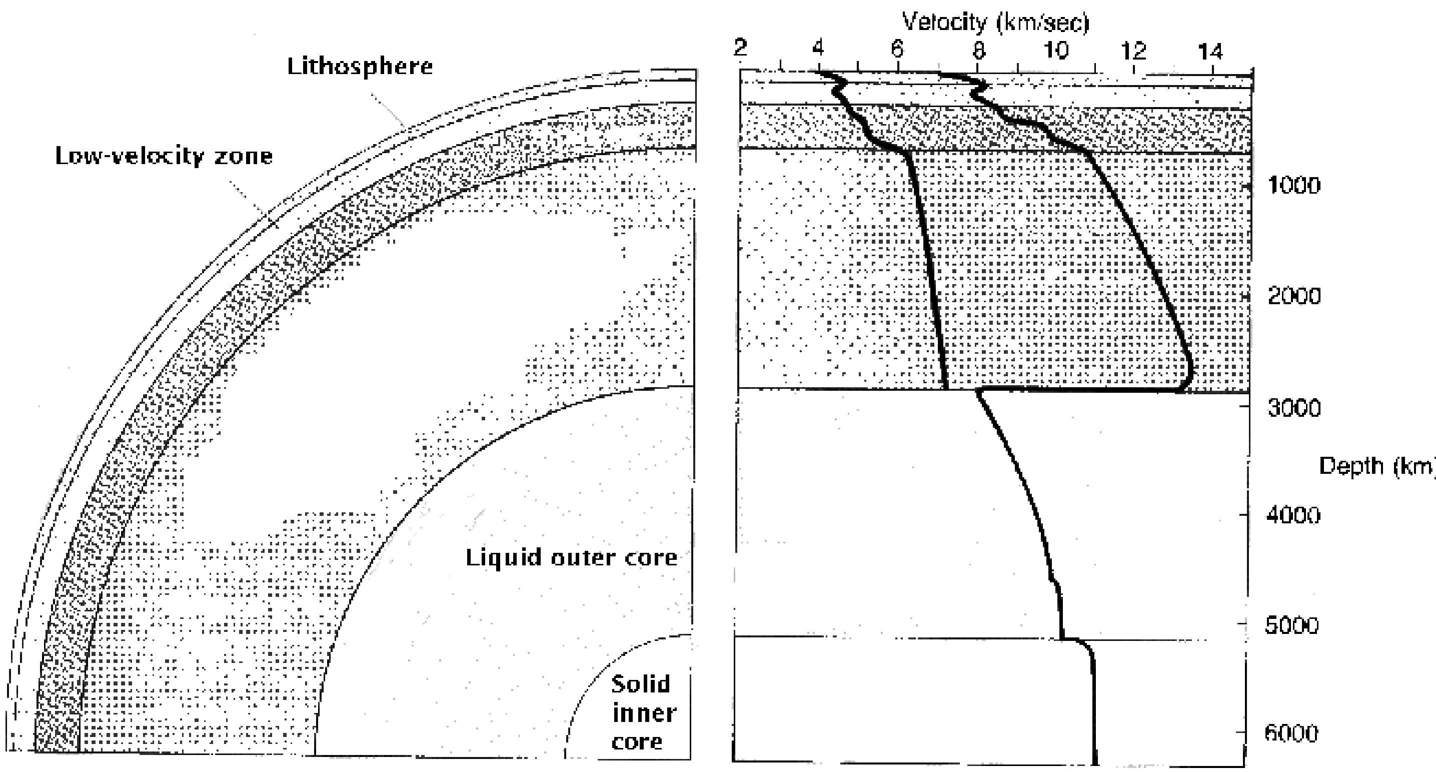
- In 1936, a Swedish seismologist named Inge Lehmann recognized waves which were reflected from a boundary deep within the Earth. She correctly interpreted this as the outside of the inner core, which is solid iron and nickel.
- In the 1960's, nuclear blasts allowed for a more precise determination of the radius of the innner core. U.S.'s nuclear blasts were always at a known spot, and were detonated exactly at a specified time. This eliminated much of the uncertainty seismologists have to deal with with natural earthquakes, whose precise origin time and location must be worked out by the travel times themselves!

Lithosphere - Asthenosphere Boundary

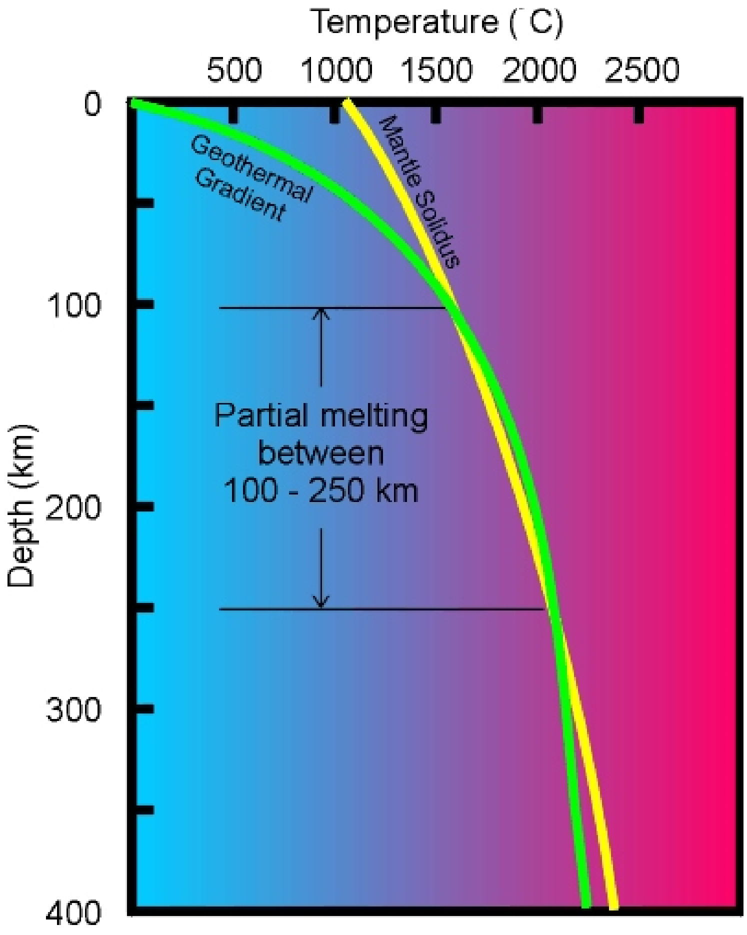
- The last important boundary in the Earth we've already discussed: the **lithosphere-asthenosphere** boundary.
- Whereas the crust-mantle boundary is a distinct, compositional boundary (different rocks above and below), the lithosphere-asthenosphere is a gradual zone in the

upper mantle, caused by increasing temperature with depth.

- Above this zone, material is rigid even on long time scales. This is the lithosphere, comprised of crust and uppermost mantle.
- Below this zone, the mantle is fluid on geologic time scales. This is the asthenosphere.
- The asthenosphere is a region where seismic waves travel slowly. This low-velocity zone (**LVZ**) may be a zone of partial melting of the mantle, but in any event the mantle in this region is "soft" on long time scales.

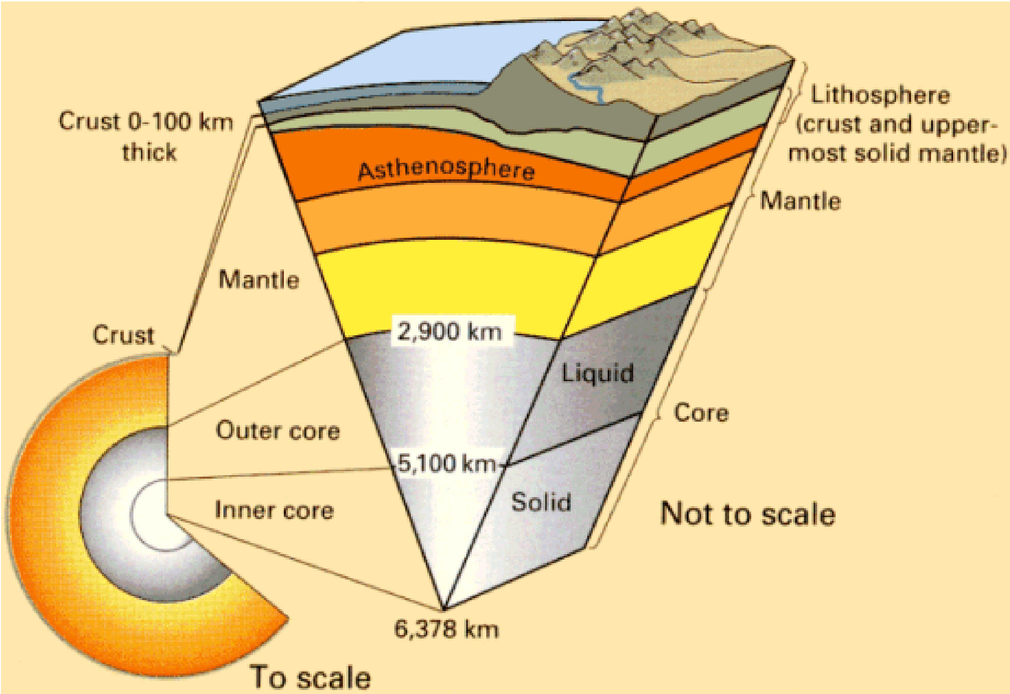


- In the diagram below, the green line represents the temperature in the Earth as a function of depth. The yellow line represents the temperature at which mantle rocks just begin to melt; notice that pressure raises the melting temperature of mantle rocks. Between about 100 and 250 km depth, the "geotherm" grazes the "mantle solidus;" this is where the mantle is softest and may even be partially molten in some areas.



Structure of the Earth

Finally, the structure of the Earth is summarized in this diagram. Please note, however, that the thickness of the layers is not to scale. For example, the crust is much thinner than shown in this diagram! Also remember that the lithosphere-asthenosphere boundary is really a gradual transition, not a sharp break in material behavior.



? Earth Structure: Seismology Self-Quiz ?