Indian Institute of Technology, Kanpur
Department of Earth Sciences

ESO213A: Fundamentals of Earth Sciences

Lecture 29. Layered Earth

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Experimental Rock Deformation Laboratory

Aims of this lecture

- Earth's interior
- Different layers and their properties

Reading:
- Marshak's Book (Chapter 2)
- Grotinger & Jordan's book (Chapter 14)
  [*for the entire week*]

Surface of the Earth

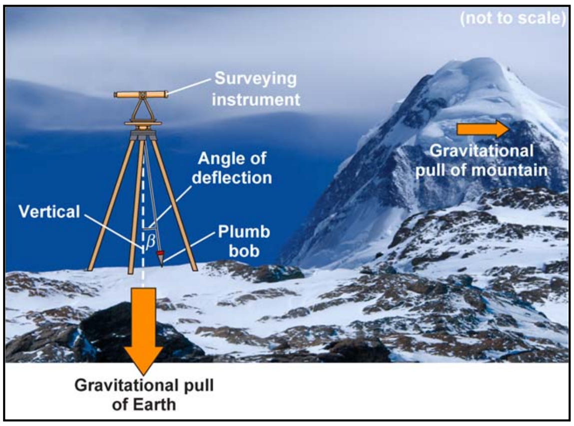
- Our experience with Earth is limited to its surface.
- Dramatic elevation changes—mountains, canyons—are tiny “scratches” on this surface.
- Our Earth is much more vast and complex than the surface suggests.

The Layered Earth

- How do we know that the Earth has a layered interior?
- Early speculations sought to explain:
  - The source of lava.
  - Gem and mineral enrichment.
  - Earthquakes.
- Early guesses were wrong.
  - Open caverns to the interior
  - Flowing lava, air, water

The Layered Earth

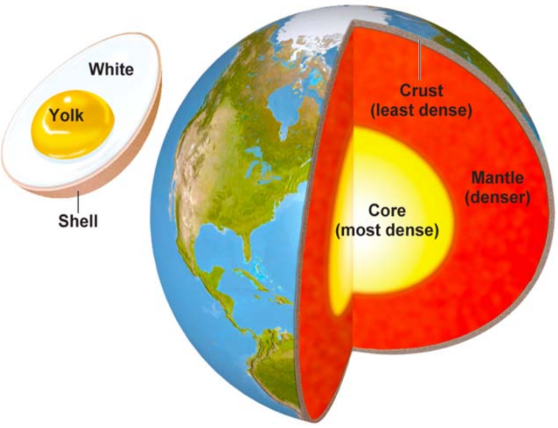
- The first key to understanding Earth's interior: density.
  - A plumb bob is deflected by a nearby mountain mass.
  - Degree of deflection can be used to calculate Earth's mass.
  - The density from this method (4.5 g/cm^3) is much higher than the density of the thin outer crust (2.5 g/cm^3).
  - This suggests that density must increase with depth.



Watch "**Schiehallion experiment**" here: https://vimeo.com/16031284

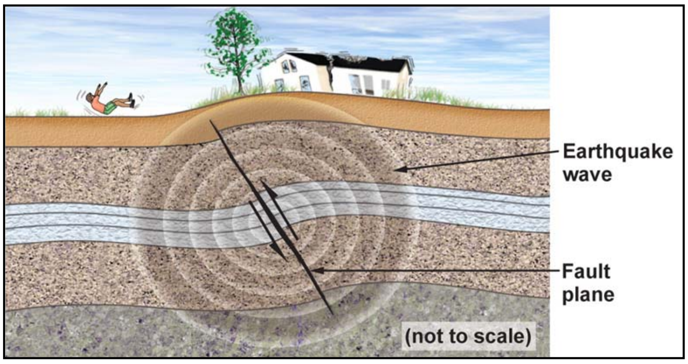
The Layered Earth

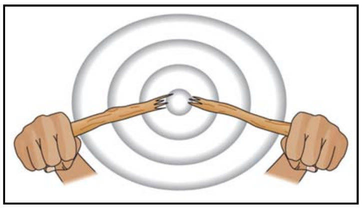
- The first key to understanding Earth's interior: **density.**
  - In 1896, Emil Wiechert made important contributions.
    - He determined that metal must be present in Earth's center
  - We now know he was correct.
  - His ideas led to a model:
    - Earth is like an egg.
      - Thin, light crust (eggshell)
      - Thicker, more dense mantle (eggwhite)
      - Innermost, very dense core (yolk)
  - Other density observations:
    - The land doesn't have large tides, hence Earth's center must be solid.



The Layered Earth

- Earthquakes: seismic energy from fault motion.
  - Seismic waves provide insight into Earth's interior.
    - Seismic wave velocities change with density.
    - We can determine the depth of seismic velocity changes.
    - Hence, we can tell where densities change in Earth's interior.



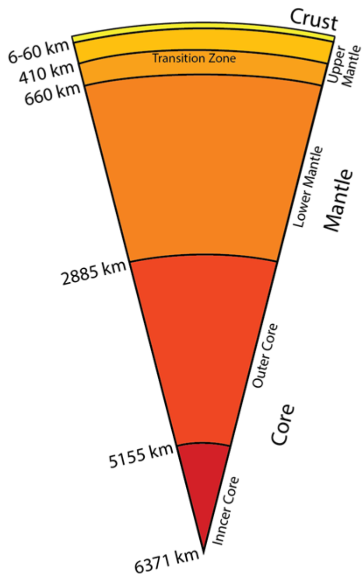


The Layered Earth

- Geologists strived to understand the nature of the layers.
  - Studied meteorites as analogues for core and mantle.
  - Conducted laboratory experiments.
    - Density measurements of rocks from the interior
    - Characteristics of mantle-derived rocks and minerals
    - Determined high P and T stability field of rocks and minerals

The Layered Earth

- End result of a century of investigation?
  - We know much about the nature of Earth's interior.
  - This knowledge continues to evolve.
- Earth's layers consist of the crust, upper, transitional, and lower mantles, and liquid outer and solid inner cores.
- Much complexity characterizes even within these layers.



The Layered Earth

- What are the boundaries?

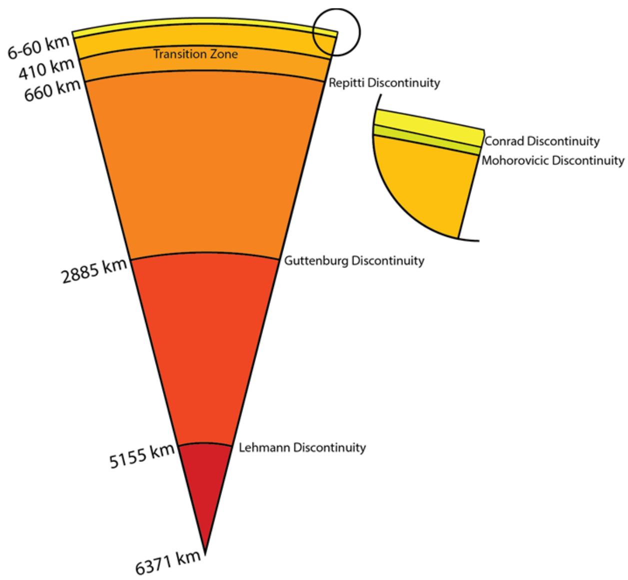
CONRAD discontinuity (15-20 km, for CC only):
between upper and lower Crust (questionable)

MOHOROVICIC discontinuity (6-60 km):
between Crust and Mantle

REPITTI discontinuity (660 km):
between upper and lower Mantle

GUTTENBURG discontinuity (2885 km):
between Mantle and Core

LEHMANN discontinuity (5155 km):
between Outer and Inner Core



The Layered Earth

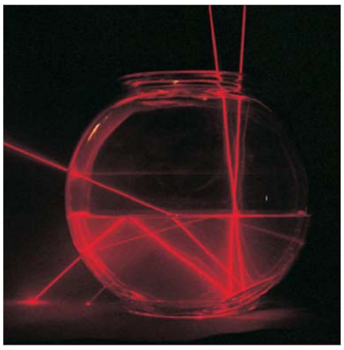
- How are the layers detected?

The velocity of waves, in general, is a function of the medium they are travelling through

The waves also reflect, and refract at the interfaces of different media

Geologists use all such wave properties, applicable to SEISMIC waves, together with a few more.

High Density → higher velocity
More solid like → higher velocity

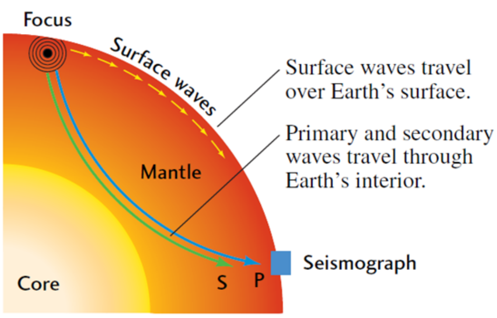


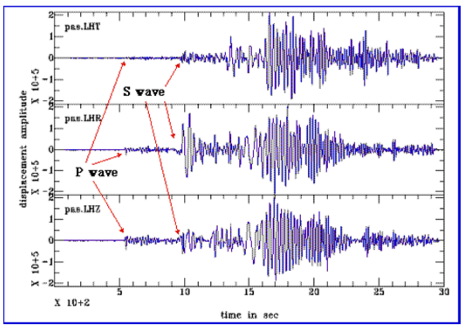
two beams of laser light enter a bowl of water from the top at slightly different angles. Both beams are reflected from a mirror on the bottom of the bowl. One is then reflected at the water-air boundary and passes through the bowl to make a bright spot on the table. Most of the light in the other beam is bent (refracted) as it passes from the water to the air, although a small amount is reflected to form a second spot on the table

The Seismic Waves

Seismic waves (*elastic waves*) are the waves of energy caused by the sudden breaking of rock within the earth or an explosion. They are the energy that travels through the earth and is recorded on seismographs.

The first waves to arrive are called primary waves, or **P waves**. The secondary waves, or **S waves**, follow. Both P waves and S waves travel through Earth's interior and known as **BODY WAVES**. Afterwards come the slower **SURFACE WAVES**, which travel around Earth's surface.



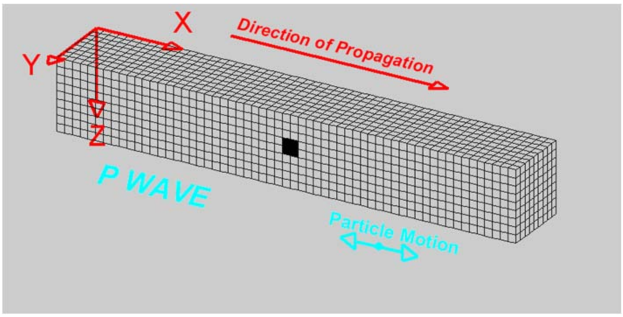


The Seismic Waves

P waves in rock are similar to sound waves in air, except that P waves travel through the solid rock of Earth's crust at about 6 km/s, which is about 20 times faster than sound waves travel through air. Like sound waves, P waves are *compressional waves,* because they travel through solid, liquid, or gaseous materials as a succession of compressions and expansions.

P waves are harmless in terms of earthquake damage.

$$V_P = \sqrt{\frac{K + \left(\frac{4}{3}\right)\mu}{\rho}}$$



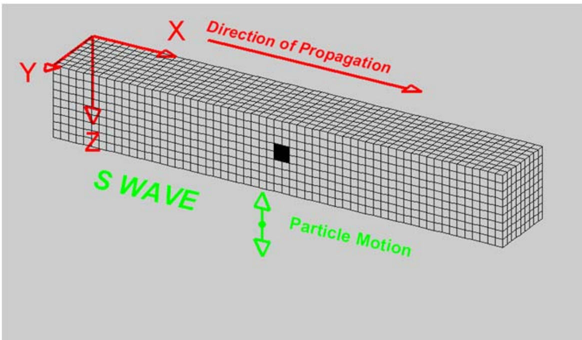
https://www.zmescience.com

The Seismic Waves

S waves (shear waves) travel through solid rock at a little more than half the velocity of P waves. They are *shear waves* that displace material at right angles to their path of travel.

Shear waves cannot travel through liquids or gases and also rarely do any significant damage

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



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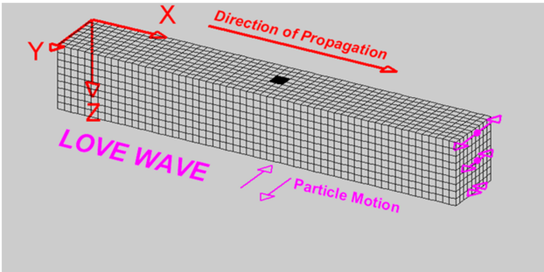
The Seismic Waves

Surface waves **(Love waves)** have a transversal (perpendicular) movement and are the most destructive outside the immediate area of the epicentre. Love waves can be devastating.



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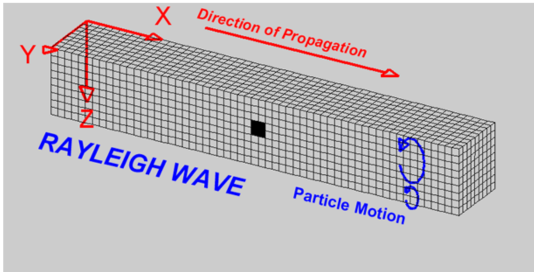
Surface waves (Rayleigh waves) do by far the most damage. As opposed to S and P, they propagate on the surface and carry the vast majority of the energy felt on the surface.



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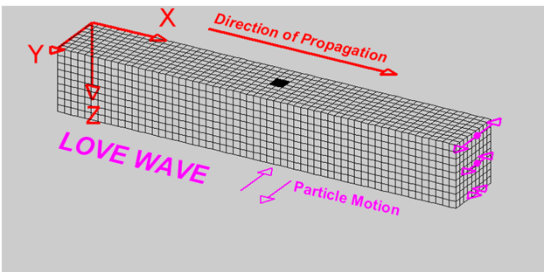

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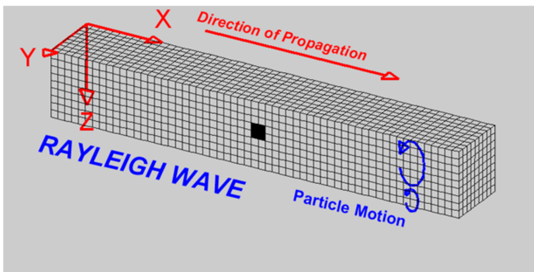

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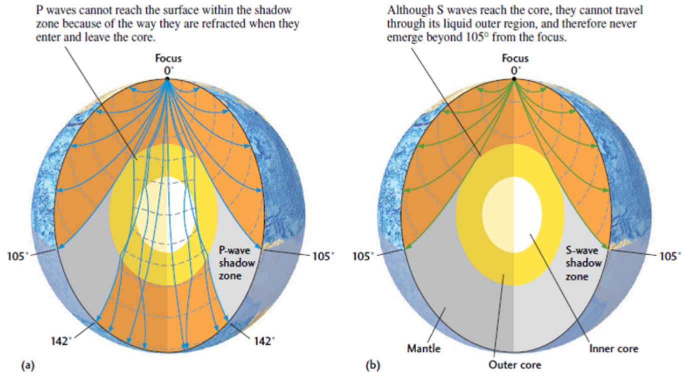
Seismic Waves through Earth’s interior

Observations of travel times and the amount of upward refraction of the ray paths, suggest that P waves travel much faster through deep Earth than at Earth’s surface → THIS IS OKAY.

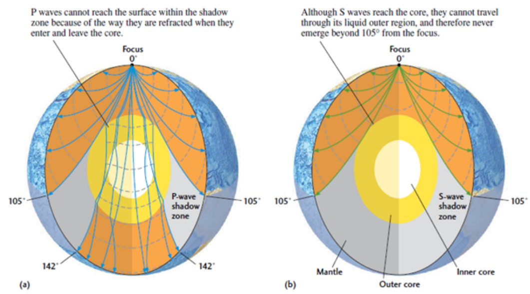
Interestingly, the P and S waves disappear beyond about 11,600 km (105°) from the source [each degree measures 111 km at the surface). Beyond about 15,800 km from the focus (142°), the P waves suddenly reappeared, although they were much delayed compared with their expected travel times. The S waves never reappeared.→ WOW



Seismic Waves through Earth’s interior

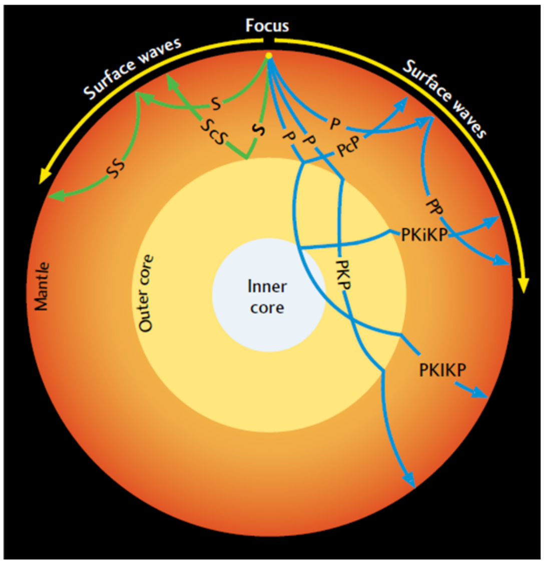
P waves missing from 105-142°: At 105°, ray paths of P waves encounter the core-mantle boundary. At that boundary, P-wave velocity drops by almost a factor of two because of density contrast. The waves are refracted downward into the core and emerge at greater angular distances after the delay caused by their detour through the core.

S waves missing after 105°: Earth a liquid outer core (R. D. Oldham, 1906). S waves cannot travel through the outer core, because it is liquid, and liquids have no resistance to shearing. Thus, there is an S-wave **shadow zone** beyond 105 from the earthquake focus, where S-wave ray paths encounter the core-mantle boundary.



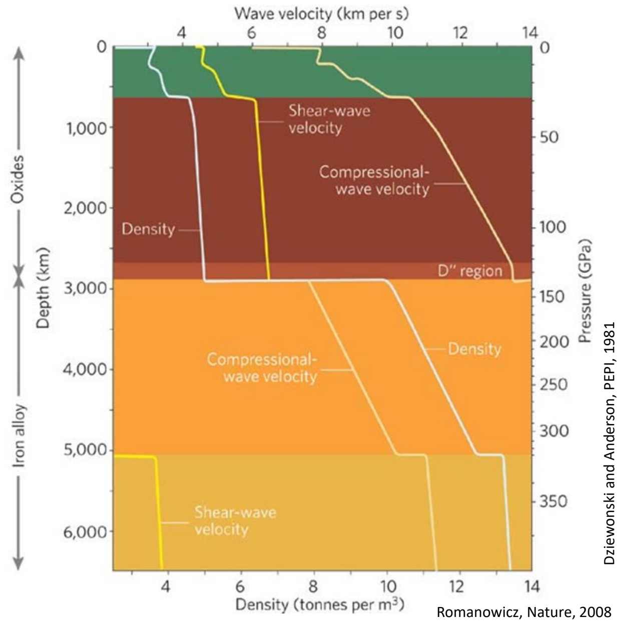
Seismic Waves through Earth's interior

Geologists use a simple labelling scheme to describe the various ray paths taken by seismic waves.
PcP and ScS are compressional and shear waves, respectively, that are reflected by the core.
PP and SS waves are internally reflected from Earth's surface.
A PKP wave travels through the liquid outer core, a PKIKP wave travels through the solid inner core, and a PKiKP wave is reflected by the inner core.



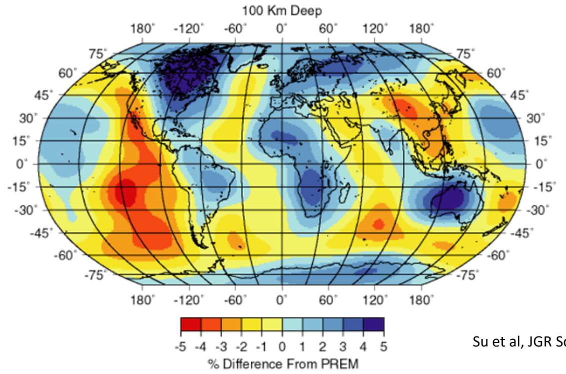
Seismic Waves through Earth's interior

The first-order structural units of Earth — its suite of concentric shells and their approximate composition — were established over the first half of the twentieth century from measurements of the travel times of seismic waves refracted and reflected inside Earth, whereas proof of the solidity of the inner core had to await the capability to record and digitize long time series and measure the frequencies of free oscillations. The '660 km' discontinuity is a phase change, and possibly a compositional change, in the silicate mantle. This illustration is of the Preliminary Reference Earth Model (PREM)



Romanowicz, Nature, 2008

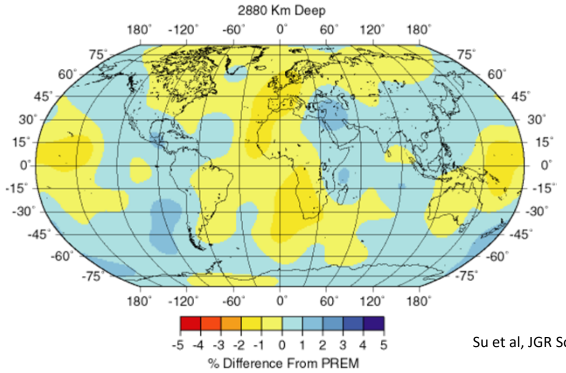
Seismic Waves through Earth's interior



Su et al, JGR Solid Earth, 1994

In shallow (~100 km) regions where material is rising from the mantle, it should be warmer, and the velocity should be lower, in regions that are old and cold, such as beneath many of the old parts of continents, we would expect to see faster regions (assuming that temperature is the only difference). The actual variations are influenced by both temperature and composition variations, but they agree well with the ideas of plate tectonics, particularly at the divergent boundaries or oceanic spreading ridges.

Seismic Waves through Earth's interior



Su et al, JGR Solid Earth, 1994

Shear wave variations at 2,880 km depth , just above the core-mantle boundary. See the lower-mantle velocity variations are more subdued than those in the more heterogeneous upper mantle. Also, note that the correlation with surface tectonics is gone, as you would expect for a complex convective system such as Earth's mantle.

The Layered Earth

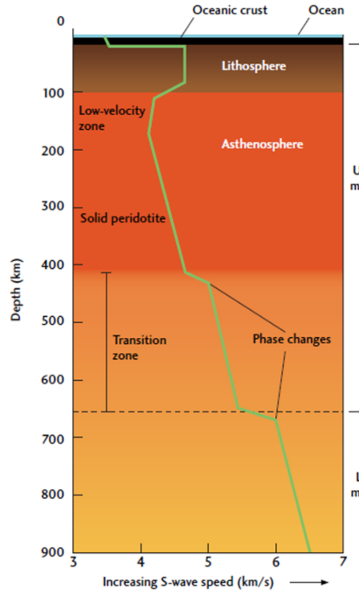
- What are the Compositions?

CRUST

- Felsic rocks typical of the upper continental crust (granite): V_P 6 km/s; 2.6 g/cc
- Mafic rocks typical of oceanic crust or the lower continental crust (gabbro): V_P 7 km/s; 2.9 g/cc
- Ultramafic rocks typical of the upper mantle (peridotite): V_P 8 km/s; 3.3 gm/cc

Mantle

- From MOHO to 410 km (peridotire: iron- and magnesium-rich silicate minerals)
- From 410-660 km (high pressure variations of olivine – the MTZ (Wadsleyite & Ringwoodite)
- From 660-2885 km (Lower Mantle – Perovskite)

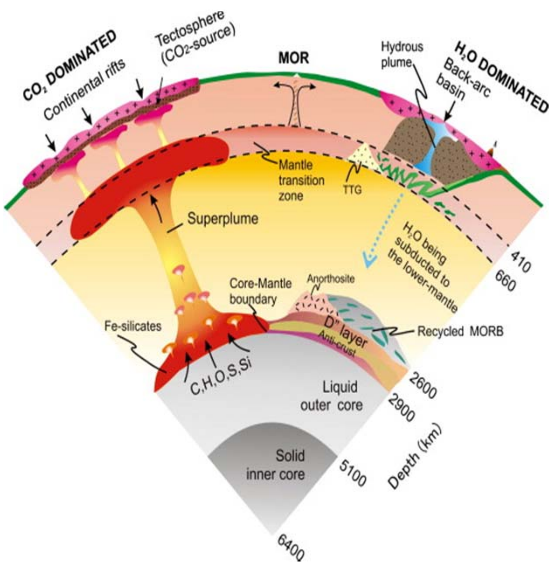


The Layered Earth

- What are the Compositions?

CORE-MANTLE BOUNDARY (CMB)

- Dramatic change in composition; from high pressure solid silicate to liquid Fe-alloy
- The last 200 km at the base of lower mantle (known as D" layer) receive extreme heat and responsible for driving the Mantle Convection.
- Plumes also originate from the CMB.
- This zone is also the graveyard of the subduccted lithosphere.



The Layered Earth

- What are the Compositions?

CORE

- Outer core Liquid and Inner Core Solid.
- Composition is Fe-Ni alloy
- We have very limited information about the core

Next Lecture

Temperature and other related properties