GEOTECTONICS/GEODYNAMICS

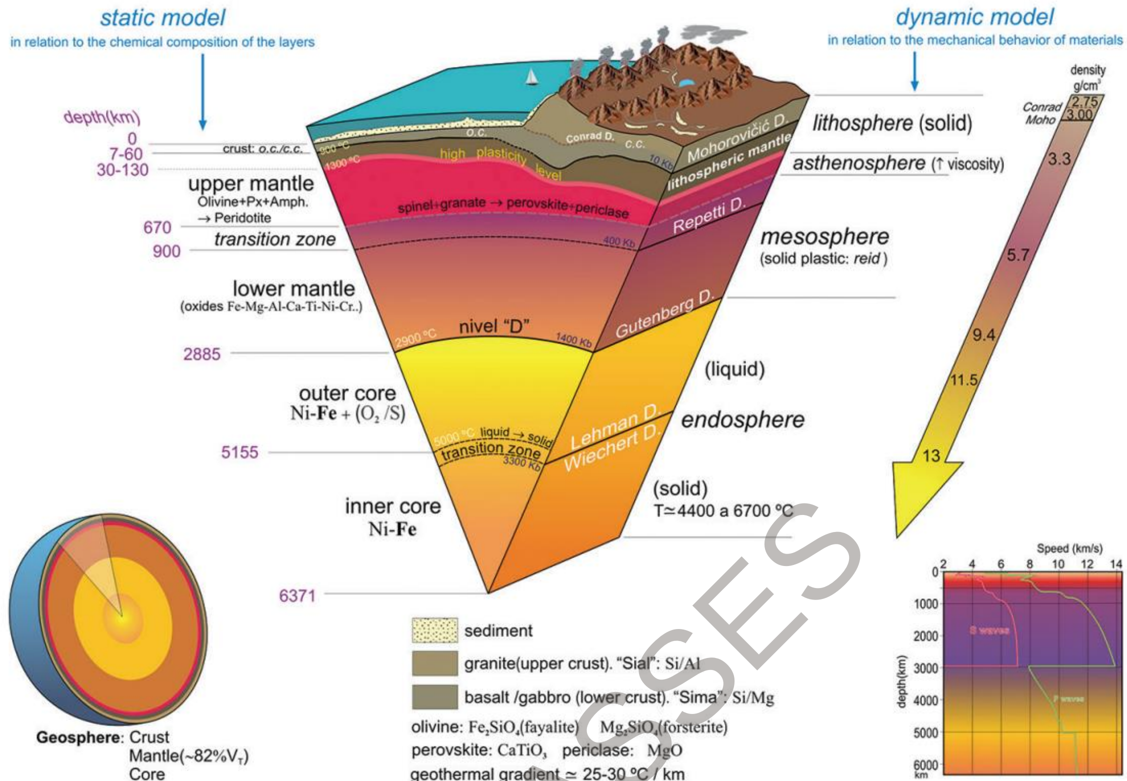
Contents

Chapter 1: The Interior of the Earth

In this article chapter, we will discuss the interior of the earth. Understanding the basic structure of earth is very important to learn higher concepts well. Also, the origin of many phenomena like earthquakes, volcanoes, tsunami etc. are linked with the structure of earth's interior.

1.1 Structure of the earth's interior

- The Earth can be divided into one of two ways: **mechanically or chemically**.
- **Mechanically (or Rheologically)** meaning the study of liquid states – it can be divided into the lithosphere, asthenosphere, mesospheric mantle, outer core, and the inner core.
- But **chemically or by composition**, which is the more popular of the two, it can be divided into the crust, the mantle (which can be subdivided into the upper and lower mantle), and the core – which can also be subdivided into the outer core, and inner core.



1.2. Rheological layers of the Earth:

The Earth can also be broken down into five distinct physical layers based on how each layer responds to stress. While there is some overlap in the chemical and physical designations of layers, specifically the core-mantle boundary, there are significant differences between the two systems. Rheologically or mechanically Earth is divided into five layers such as lithosphere, asthenosphere, mesosphere or mantle, outer core, and inner core.

1.2.1. Lithosphere: *Lithos* is Greek for stone, and the lithosphere is the outermost physical layer of the Earth. It is grouped into two types: oceanic and continental. Oceanic lithosphere is thin and relatively rigid. It ranges in thickness from nearly zero in new plates found around mid-ocean ridges, to an average of 140 km in most other locations. Continental lithosphere is generally thicker and considerably more plastic, especially at the deeper levels. Its thickness ranges from 40 to 280 km. The lithosphere is not continuous. It is broken into segments called plates. A plate boundary is where two plates meet and move relative to each other. Plate boundaries are where we see plate tectonics in action—mountain building, triggering earthquakes, and generating volcanic activity. Lithosphere consists of crust and the upper part of upper mantle, Gutenberg layer. Lithosphere is the solid, rigid, and elastic which overlies asthenosphere. The lithosphere may extend up to 100km depth.
Lithosphere plate may be oceanic, continental or both.
The composition is basaltic and the average density is ~3.5 g/cc.

1.2.2. Asthenosphere**:** The asthenosphere is the layer below the lithosphere. *Astheno*- means lacking strength, and the most distinctive property of the asthenosphere is movement. Because it is mechanically weak, this layer moves and flows due to convection currents created by heat coming from the earth's core cause. Unlike the lithosphere that consists of multiple plates, the asthenosphere is relatively unbroken. Scientists have determined this by analyzing seismic waves that pass through the layer. The depth at which the asthenosphere is found is temperature-dependent. It tends to lie closer to the earth's surface around mid-ocean ridges and much deeper underneath mountains and the centers of lithospheric plates. This layer is semi-solid, non-rigid and elastic which lies within upper mantle. The average density is 3.5 to 4 g/cc and the composition is same as the lithosphere i.e., basaltic. The asthenosphere lies in between 80 to 200km depth.

1.2.3. Mesosphere: The mesosphere, sometimes known as the lower mantle, is more rigid and immobile than the asthenosphere. Located at a depth of approximately 410 and 660 km below the earth's surface, the mesosphere is subjected to very high pressures and temperatures. These extreme conditions create a transition zone in the upper mesosphere where minerals continuously change into various forms or pseudomorphs. Scientists identify this zone by changes in seismic velocity and sometimes physical barriers to movement. Below this transitional zone, the mesosphere is relatively uniform until it reaches the core.

Mesosphere covers ~83% of Earth by volume and 68% by mass. The mesosphere or mantle is divided into two parts i.e. upper mantle and lower mantle. The upper mantle is again divided into two layers – upper Gutenberg layer and lower Golitsyn layer.

1.2.4. Outer core and inner core: The outer core is the only entirely liquid layer within the Earth. It starts at a depth of 2,890 km and extends to 5,150 km, making it about 2,300 km thick. In 1936, the Danish geophysicist Inge Lehmann analysed seismic data and was the first to prove a solid inner core existed within a liquid outer core. The solid inner core is about 1,220 km thick, and the outer core is about 2,300 km thick.

It seems like a contradiction that the hottest part of the Earth is solid, as the minerals making up the core should be liquified or vaporized at this temperature. Immense pressure keeps the minerals of the inner core in a solid phase. The inner core grows slowly from the lower outer core solidifying as heat escapes the interior of the Earth and is dispersed to the outer layers. The earth's liquid outer core is critically important in maintaining a breathable atmosphere and other environmental conditions favourable for life. Scientists believe the earth's magnetic field is generated by the circulation of molten iron and nickel within the outer core. If the outer core were to stop circulating or become solid, the loss of the magnetic field would result in Earth getting stripped of life-supporting gases and water. This is what happened, and continues to happen, on Mars

The core is also known as Barysphere that covers 16% by volume and 31% by mass of the Earth. The core is divided into outer core and inner core separated by a transition zone. The core extends from 2900km to the core of the Earth i.e., 6371 km and separated from the lower mantle by Gutenberg discontinuity (2900km). Lehman discontinuity at depth of 5100km separates outer core and inner core. The outer core is liquid and the inner core consists of iron and Nickel mainly.

1.3. Structure Based on composition

The planet Earth is made up of three main shells: the very thin, brittle crust, the mantle, and the core; the mantle and core are each divided into two parts. Although the core and mantle are about equal in thickness, the core forms only 15 percent of the Earth's volume, whereas the mantle occupies 84 percent. The crust makes up the remaining 1 percent.

1.3.1 Crust:
Crust covers less than 1% of Earth's volume and 0.4% of the Earth's mass. Oceanic and continental crusts are the two parts of crust.

Oceanic crust and Continental crust composition:

Oceanic crust is known as SIMA layers based on its silica and magnesium composition and continental crust is the lower SIAL layers based on silica and alumina composition. Conrad discontinuity that lies at 11km separated these two layers.

The overall composition of crust is mostly siliceous dominated by feldspar.

The continental crust is divided into two parts such as **a. Upper continental crust** and **b. Lower continental crust.**

The composition of upper continental crust is granodiorite to diorite whereas the lower continental crust is more basic in composition i.e., gabbroic and anorthositic.

The **oceanic crust** is composed of three layers such as follows.

i. **Oceanic layer-1:** The average thickness of this layer is 0.4km. This is composed of unconsolidated terrigenous sediments.
ii. **Oceanic layer-2:** This layer is of igneous origin. The main rock type is Basalt which is olivine tholeiites. The magnetisation of oceanic ridge is caused due to this layer.
iii. **Oceanic layer-3:** This layer is of Gabbroic composition with some ultramafic minerals. This layer is again divided into two layers i.e. 3A upper layer which is composed of isotropic gabbro and the lower layer or 3B consisting of cumulate gabbro.

1.3.2. Major differences between oceanic and continental crust:

There are some major differences between oceanic and continental crust as follows:

i. The oceanic crust is divided into three layers- layer 1 which consists of sedimentary deposits, middle layer 2 is made up of olivine tholeiites and the lower layer 3 consisting of serpentinized peridotites. On the other hand, continental crust is ill-defined and not divided into layers like oceanic crust.
ii. The average thickness of oceanic crust is 7km and continental crust is 40km.
iii. The oceanic crust is of 180Ma age, but the age varies as it moves from the ridge crest. The continental crust is much older than oceanic crust that is 4Ga.

iv. Oceanic crust is much more stable than continental crust which is subjected to various tectonic activity.

1.4. Mantle

1.4.1. Mantle composition:

The mantle is divided into upper mantle and lower mantle. The composition of mantle changes with depth. At a depth of 400km and at 1600^{0}C temperature, olivine is transformed into a distorted structure spinel or β-phase. This transformation is responsible for the discontinuity at 400km. Again, at a depth of 350-400km, another phase change occurs in which pyroxene changes to garnet.

The spinel structure breaks into Mg-pyroxene with perovskite and periclase. This transformation takes place at a depth of 670km. Besides, garnet transforms into an ilmenite structure at this depth. Thus, these transformations are responsible for 670km discontinuity.

1.4.2. Upper mantle characteristics:

The upper mantle is separated from the crust by the Mohorovicic discontinuity that lies at 33km depth. The upper mantle composition is mainly Peridotite or eclogite. The peridotite consists of abundant olivine and <15% garnet and in eclogite there is no olivine and 30% garnet is present.

1.4.3. The mantle transition zone:

This zone extends from 410km to 660km depth with two major velocity discontinuities due to phase changes. One is at the top of transition zone and other marks the lower boundary.

At the depth of 410km, mantle peridotite transforms to the spinel structure and perovskite at 660km depth.

Another phase transformation occurs at a 350-500km depth where pyroxene changes into the garnet.

1.4.4. Lower mantle characteristics:

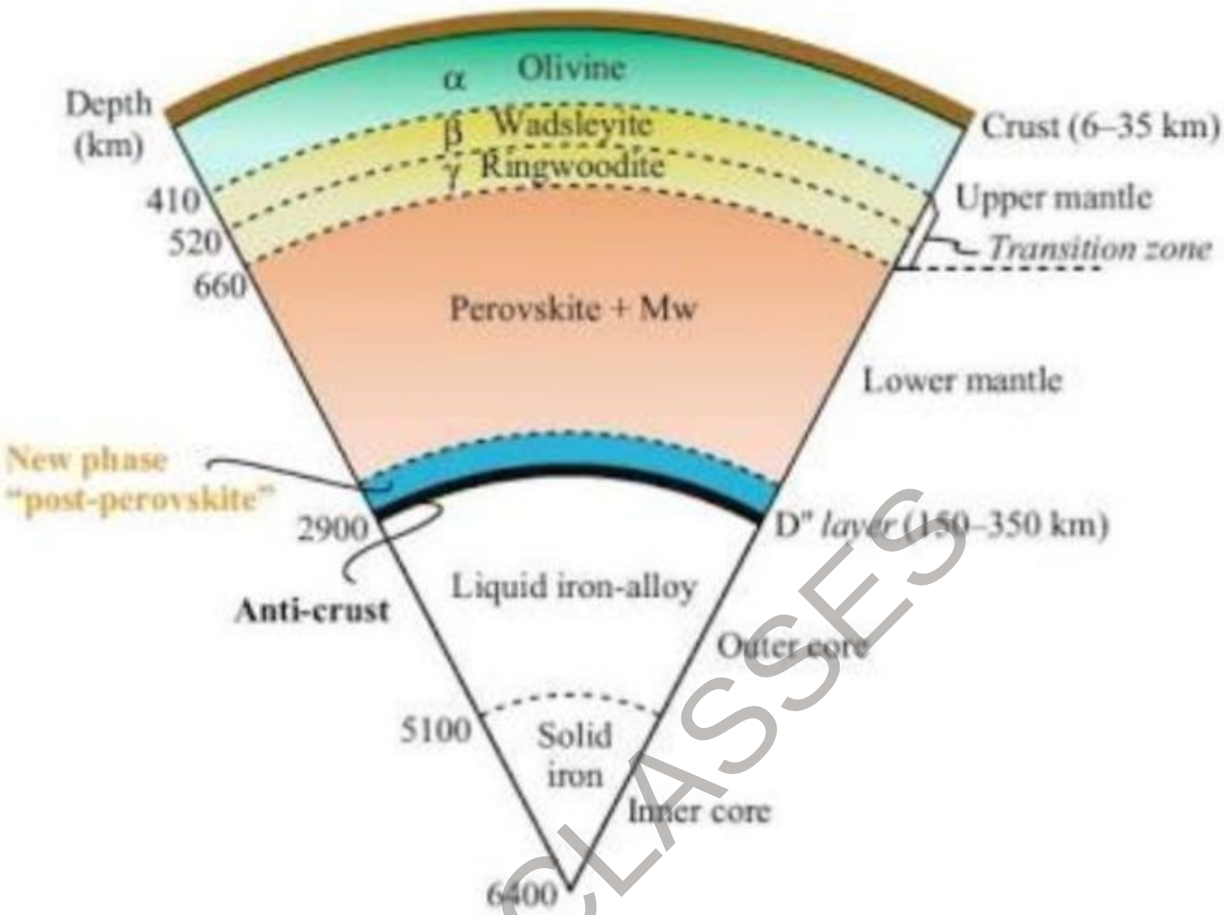
The lower mantle consists of Perovskite structure. This layer is homogeneous in its mineralogy.

1.4.5. Mantle low velocity zone:

There is a layer known as D” lies at the lowest 200-300km of the lower mantle. This layer is characterized by lower seismic velocities and high electrical conductivity.

Lower seismic velocity refers to the presence of molten material and indicating the transition between lower mantle and outer core.

D” layer is considered as the source of mantle plumes.



1.5 Seismic structure of Earth

Seismologists study shock, or seismic, waves as they travel through the Earth's interior. These waves originate from natural sources like earthquakes, and from artificial sources like man-made explosions. Knowing how the waves behave as they move through different materials enables us to learn about the layers that make up the Earth. Seismic waves tell us that the Earth's interior consists of a series of concentric shells, with a thin outer crust, a mantle, a liquid outer core, and a solid inner core. Seismic waves are of two types as follows:

1.5.1. Body waves: These waves propagate through the body of the Earth. There are two types of body waves.

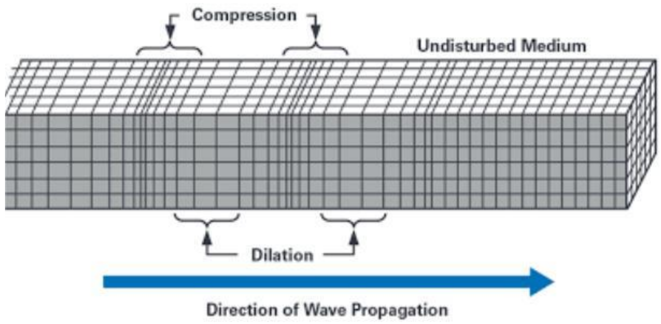
P waves: P waves are also known as primary, longitudinal, compressional, irrotational or dilutional waves. The P in P-waves stands for primary, because these are the fastest seismic waves and are the first to be detected once an earthquake has occurred. P-waves travel through the earth's interior many times faster than the speed of a jet airplane, taking only a few minutes to travel across the earth.

P-waves are predominantly compressional waves. As a P-wave passes, material compresses in the same direction the wave is moving, and then extends back to its original thickness once the wave has passed. The speed at which P-waves travel through material is determined by:

- rigidity—how strongly the material resists being bent sideways and can straighten itself out once the shearing force has passed – the more rigid the material, the faster the P-waves
- compressibility—how much the material can be compressed into a smaller volume and then recover its previous volume once the compressing force has passed; the more compressible the material, the faster the P-waves
- density—how much mass the material contains in a unit of volume; the greater the density of the material, the slower the P-waves

P-waves travel through liquids and gases as well as through solids. Although liquids and gases have zero rigidity, they have compressibility, which enables them to transmit P-waves. Sound waves are P-waves moving through the air.

P-waves travel through materials with rigidity and/or compressibility, and density	
greater rigidity	faster P-waves
greater compressibility	faster P-waves
greater density	slower P-waves



The velocity of P wave is formulated as

$V_p = \sqrt{(\lambda + 2\mu)/\rho}$

$= \sqrt{(k + 4/3\mu)/\rho}$

λ = Lame constant

μ = rigidity constant

ρ = density of the medium

S waves: The S in S-waves stands for secondary, because they are the second-fastest seismic waves and the second type to be detected once an earthquake has occurred. Although S-waves are slower than P-waves, they still travel fast, over half the speed of P-waves, moving at thousands of kilometers per hour through the earth's crust and mantle.

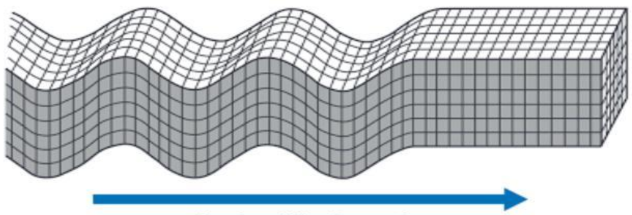
S-waves are shear waves (though that is not what the S stands for). They move by material flexing or deforming sideways (shearing) from the direction of wave travel, and then returning to the original shape once the wave passes. The speed at which S-waves travel through material is determined only by:

- rigidity — how strongly the material resists being bent sideways and can straighten itself out once the shearing force has passed – the more rigid the material, the faster the S-waves
- density — how much mass the material contains in a unit of volume – the greater the density of the material, the slower the S-waves

These are secondary, transverse, shear, rotational or polarized waves. It can travel through solid medium only.

S-waves can travel only through solids, because only solids have rigidity. S-waves cannot travel through liquids or gases.

Because the earth's mantle becomes more rigid as its depth below the asthenosphere increases, S-waves travel faster as they go deeper in the mantle. The density of the mantle also increases at greater depth, which has the effect of reducing the speed of seismic waves, but the increase in rigidity is much greater than the increase in density, so S-waves speed up as they get deeper in the mantle, despite the increased density.



The velocity is defined as

$V_s = \sqrt{(\mu/p)}$

μ= rigidity constant

ρ = density of medium

S waves separated in two planes. The wave that polarized in vertical plane is known as S_v wave and those propagating through horizontal plane is S_H wave.

1.5.2. Surface waves:

Surface wave is a seismic wave that is trapped near the earth's surface. Surface waves travel more slowly through Earth material and are generally lower in frequency than body waves. On a seismogram, they are easily distinguished. Deeper earthquakes produce weaker surface waves; shallow earthquakes produce stronger surface waves. Only the surface is affected by these waves. Due to their extended wavelength, surface waves are also known as long-period waves

Types of Surface Wave

Surface waves are further classified into two parts i.e., Rayleigh waves and love waves.

Rayleigh waves: This wave is non-dispersive in nature. It consists of P and Sv wave. The particle path is described by retrograde ellipse.

- Lord Rayleigh, a British physicist, mathematically demonstrated the Rayleigh Waves.
- A Rayleigh wave is a seismic surface wave that causes an oval shudder with no transverse or perpendicular motion.
- They behave like water waves in that they move forward while the individual particle of material moves in an elliptical path within a vertical plane oriented in the direction of wave movement.
- It moves across the land in the same way that a wave does across a lake or ocean.
- The Rayleigh wave, which can be much larger than other waves, is responsible for the majority of the shaking experienced during an earthquake.
- It rolls, which causes the ground to move up and down and side to side in the same direction as the wave