Earth's interior

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1 Introduction

Previously, Earth was understood to be a uniform sphere consisting of iron and rock. However, seismic data has been used to reveal that the Earth actually consists of differentiated layers of differing compositions and characteristics. In this handout, we will cover the mechanisms that revealed the true nature of our planet's interior.

2 Mineral phases

Minerals come in different shapes and structures due to different environments, created by parameters such as temperature and pressure. Different chemical compositions at different stages of growth also result in various types of minerals. The different structures of minerals sharing the same chemical composition are called mineral phases or polymorphs. Below is a phase diagram, indicating which structure of olivine can be observed under different conditions:

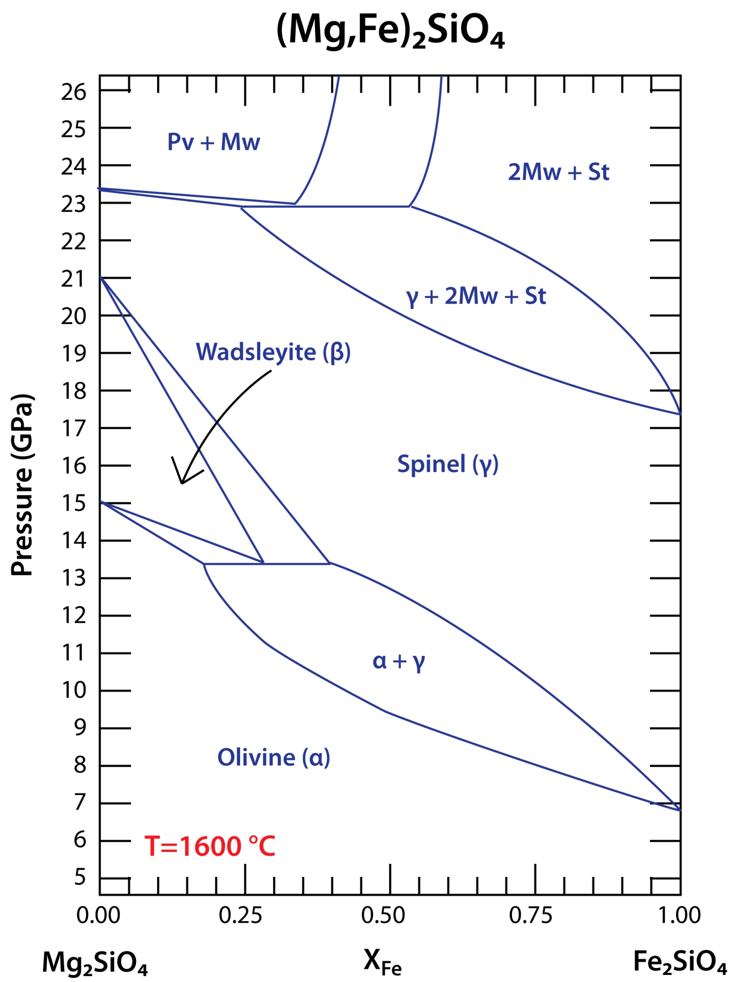


Figure 1: Olivine phases. (Source: SERC)

For magnesium-rich olivine, shown in the left y-axis, it transforms from structure α (olivine) to β (wadsleyite) at 15GPa, 1600 degC. Their distinct structure allows them to have distinct physical properties, especially seismic wave velocity.

3 To the core

Environmental conditions control the growth of polymorphic minerals. Through our way down to the core of our planet, it is the pressure and temperature that matters greatly.

- **Lithostatic pressure.** The pressure that comes from the overlying rocks or sediments is called lithostatic pressure, or overburden pressure. Under lithostatic conditions, the minerals receive the same amount of stress from all directions. **Generally, the pressure goes up on our path down the core.** Other mechanisms that may affect local pressure are subduction, extension, etc. These movements of the crust adjust the thickness of local sediments or rock formations and may enhance or reduce local lithostatic pressure.

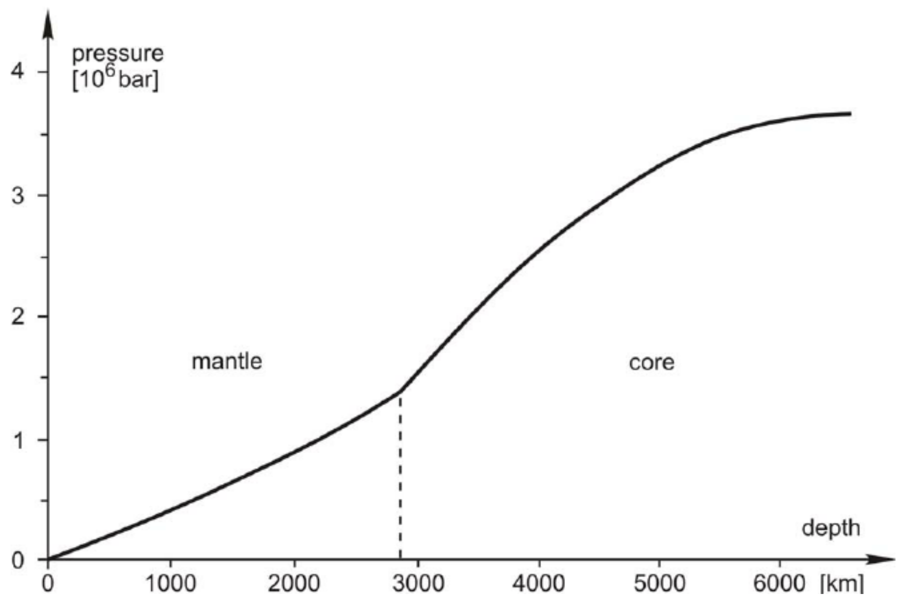


Figure 2: Pressure at different depths. (Source: Lajos Volgyesi, ReasearchGate)
Note: 1M bar=100 GPa

- **Geothermal gradient.** The geothermal gradient describes the rate at which temperature rises with increasing depth. This temperature comes from the remaining heat of the proplyd (the disk-like structure of cosmic dust that eventually gather and form our solar system, and is estimated to provide around 20 percent of the heat) and the radioactive isotopes (80 percent). **Generally, the temperature goes up on our path down the core.** Other mechanisms that may affect local temperature are magma chamber, subduction, etc.

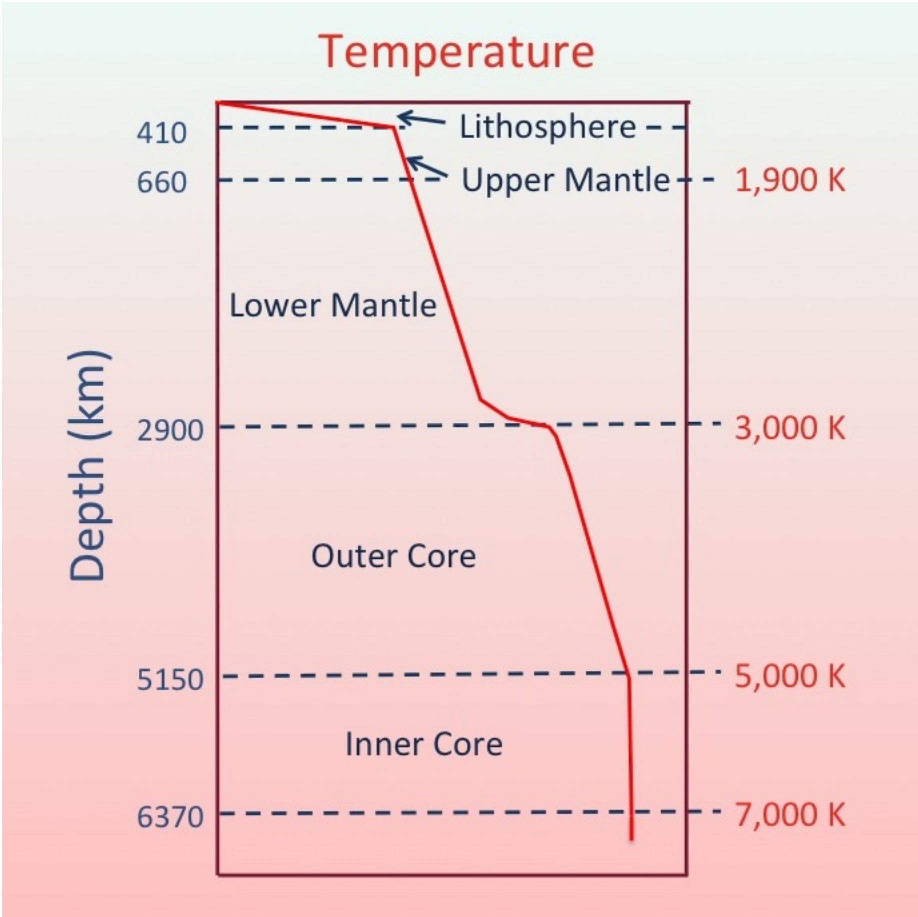


Figure 3: Temperature at different depths. (Source: Wikipedia)

Practice 3 (IESO 2016 Korea, Written Test No.2 Q18)
Temperature increases gradually as depth increases in the lithosphere. Which is correct? (More than one correct answer.)

(A) The geothermal gradient is the same at all points of the lithosphere.
(B) The geothermal gradient is steeper/higher in areas where extension thinned the lithosphere.
(C) The geothermal gradient is steeper/higher in continental areas where the crust is thick.
(D) The geothermal gradient is steeper/higher in areas of intense volcanism.

Solutions or Suggested Answer:
B and D.

4 Investigation methods

Scientists gathered data from places we can't reach mainly by observing seismic data. However, other methods may also provide additional information. Here are some common methods:

- **Hole-digging.** This is probably the easiest way that one can think of. However, it is not effective and allows only a small proportion of our planet to be investigated. To be specific, the deepest hole human has made for data collection is the Kola Superdeep Borehole of 12.2 km deep, and no holes exceed 13km.

- **Xenoliths.** Xenoliths are rock fragments brought to the surface of the Earth by volcanic activities or collisions, and they give us information about the chemical composition or environment at the place of their birth.

- **High P-T experiments.** This method consists of putting some minerals or compounds under known temperature and pressure and seeing what mineral structure comes out. It often serves as useful evidence to explain the data collected by seismic methods, or verification of the environment of an obtained xenolith.

- **Seismic data analysis.**Investigation of seismic waves can be done actively (by creating explosions on the ground and receiving reflected or scattered seismic waves) or passively (by gathering data of a natural earthquake). There are two main types of waves: transverse waves and longitudinal waves. **Particles in a transverse wave are displaced perpendicular to the direction the wave travels, while they are displaced parallel to the direction of longitudinal waves.** In Earth Science, **P waves (P for "primary", "pressure", or "compressional") are longitudinal waves, and S waves (S for "secondary" or "shear") are transverse waves**. Their comparisons are shown below:

	type	average velocity in the crust	average velocity in the mantle	
P wave	longitudinal	6 km/s	8 km/s	
S wave	transverse	4 km/s	5 km/s	cannot propagate in fluids

A typical seismic wave pattern looks like the one below: (The three rows are waves of the z-axis, the North-South axis, and the East-West axis.)

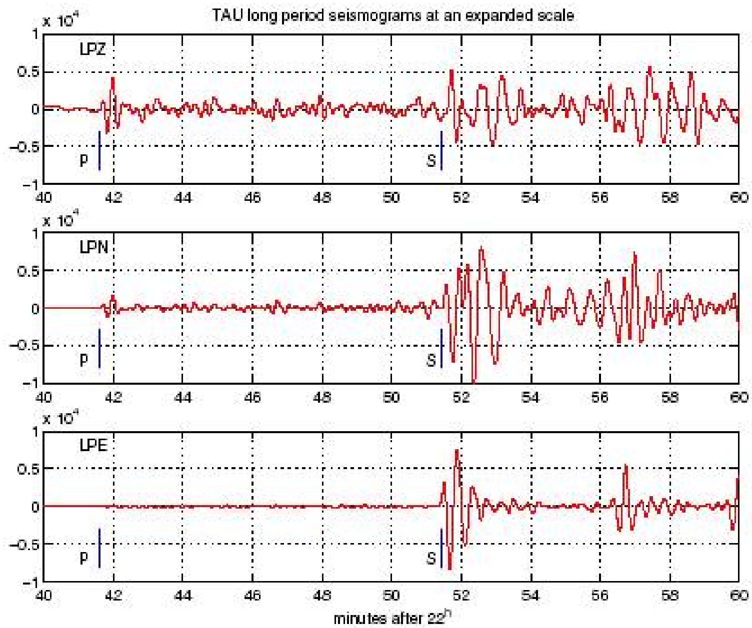


Figure 4: Seismic wave pattern. (Source: UCL)

And with these data from various earthquakes, geologists thus found that some parts of the Earth are not able to receive seismic waves (the shadow zone), so they inferred that the Earth may not be a uniform ball. With some calculations, they receive the velocity of seismic waves of different depths and define the Earth's layers.

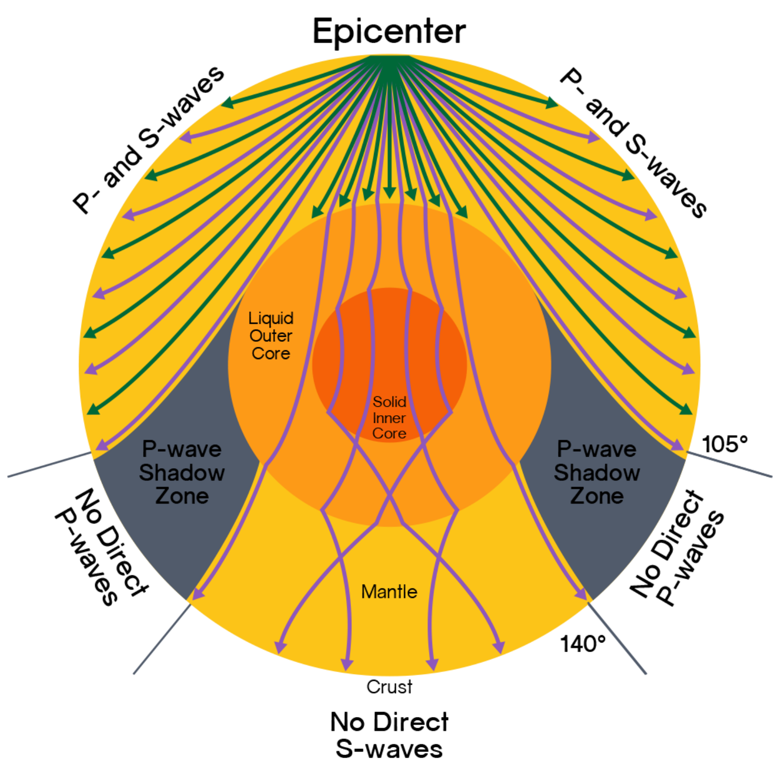


Figure 5: Seismic shadow zone. (Source: Authn, Pinterest)

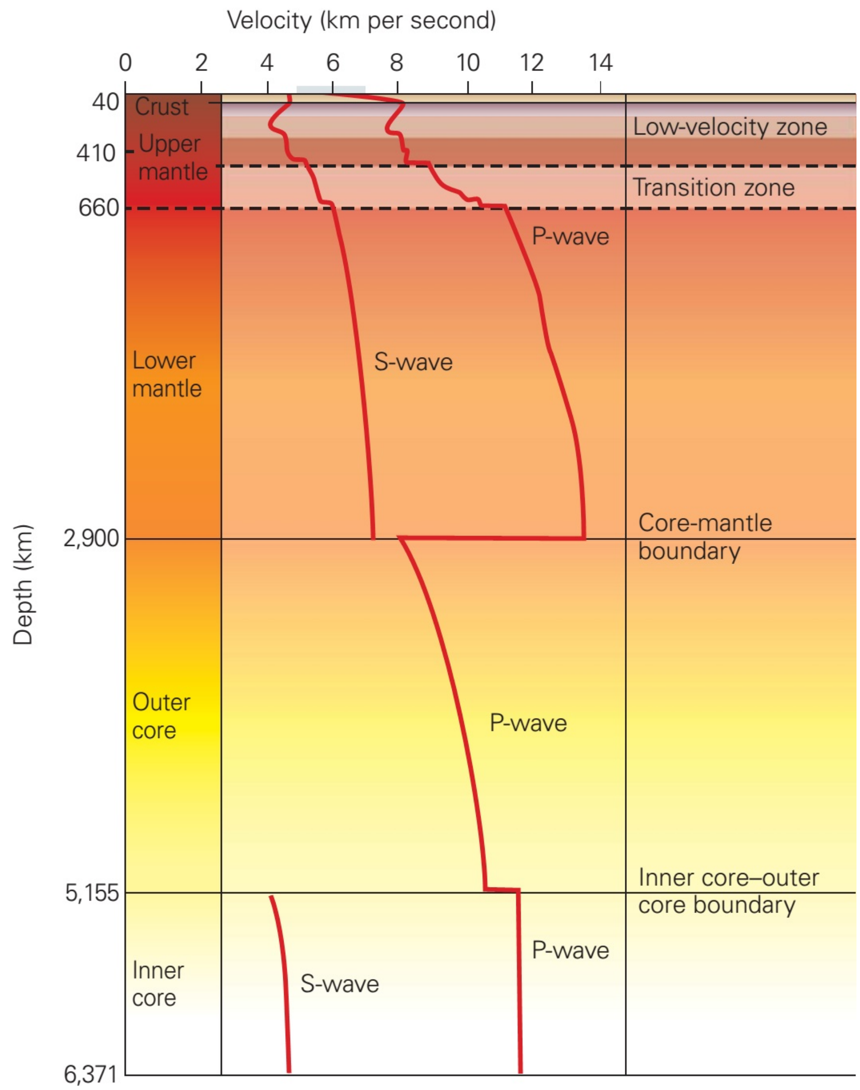
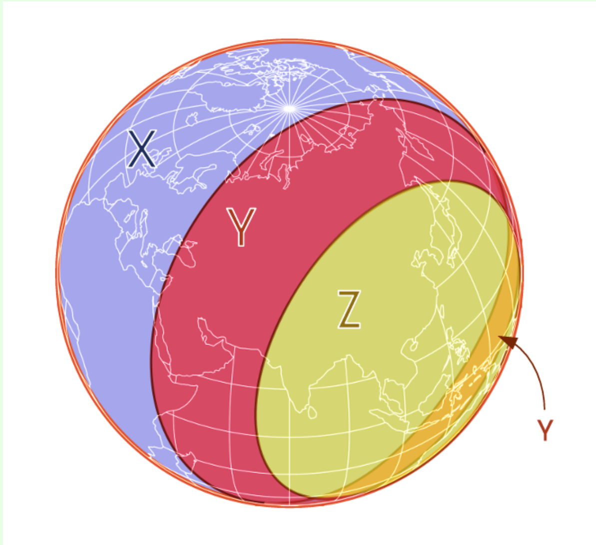


Figure 6: Seismic velocity. (Source: Learning Geology)

As depicted in this seismic profile of the Earth's interior, seismic wave velocity generally increases with increasing depth. Drastic step-like changes in wave velocity, or *discontinuities*, are due to changes in composition and represent the boundaries between layers. For example, p-wave velocity decreases drastically between the lower mantle and the outer core because the lower mantle is solid, while the outer core is composed of a liquid iron-nickel alloy.

Practice 4 (USESO Training Camp Exams 2021, Geosphere Section I Q6-7)
The figure below divides Earth's surface into three regions according to the seismic waves (or lack thereof) that are observed in each after an earthquake. Note: the arrow points to a portion of region Y seen on the other side of the globe.



1. Where, approximately, did this earthquake most likely occur?
(A) Southeast Asia
(B) Off the coast of South America
(C) Near the Mediterranean
(D) The North Pole
(E) The South Pole

2. Consider if the radius of the outer core was increased. Which of the following would be true? (May have more than one answer.)
(A) Only P-waves would be observed in Y
(B) Y would move towards X
(C) Surface waves would be observed in Z
(D) Z would expand

Solutions or Suggested Answer:
1. **B.** Notice that X shows where both P- and S-waves occur, Y represents the P-wave shadow zone, and Y and Z comprise the S-wave shadow zone. One may see that the earthquake occurred in the center of X. The only plausible answer is B (not shown in the figure).
2. **B and D.** Like in the previous question, this answer is most clear using a two-dimensional view of seismic wave rays. I is false because both P- and S-waves are refracted back to the surface unobstructed. Meanwhile, the hypothetically larger outer core does obstruct their path such that the boundary between regions X and Y moves towards the center of X; II is true. III is false — surface waves would not reach the other side of the globe. Finally, IV is true because a larger core would create a larger area where core-refracted P-waves reach the surface.

5 Interior of the Earth

Because seismic data analysis is the general method that allows scientists to go through the entire planet, we define a "layer" of Earth for its similar seismic properties. The Earth is now basically divided into 4 major layers and boasts many discontinuities. Their relative positions are shown as follows:

Depth	Oceanic Crust	Continental Crust	↓	
0	Crust	Crust	Lithosphere	
~7	MOHO (oceanic)			
	Lithospheric Mantle			
~15		Conrad (continental)		
		Crust		
~40		MOHO (continental)		↓
		Lithospheric Mantle		Uppermost Mantle
100	Lithosphere-Asthenosphere Boundary, LAB		↑	
	Asthenospheric Mantle (Low Velocity Zone somewhere here)			
410	410-discontinuity			↑
	Transition Zone			
660 or 670	660(or 670)-discontinuity			
	Lower Mantle			
2700~2800				
	D" (read as "D double-prime")			Legend
2900	Gutenberg discontinuity, Core-Mantle Boundary, CMB			Crust
	Outer Core			Mantle
5100	Inner Core-Outer Core Boundary			Outer Core
	Inner Core			Inner Core
6378				Discontinuity

Figure 7: Layers of the Earth.

5.1 Layers of the Earth

Major jumps in seismic wave velocity define four layers of the Earth. Their properties are as follows:

	depth(km)	state of matter	composition	seismic wave
Crust	depends	solid	mainly silicates	slow
Mantle	40-2900	ductile solid	mainly silicates	fast
Outer core	2900-5100	liquid	iron and nickel	slow (P) none (S)
Inner core	5100-6378	solid (due to pressure)	iron	slow

There are yet other subdivisions based on the physical properties of the layers. They cause minor changes in seismic wave velocity but are not major enough to be treated as a whole layer. They are:

- **Lithosphere.** The lithosphere is the uppermost part of the Earth's surface and is made of mafic and ultramafic materials. Research shows that the lithosphere is not seamless, but rather splits into blocks that go in different directions, called plates. This body is also rigid enough to "break" and cause earthquakes.

- **Asthenosphere.** The asthenosphere is the part made of semi-solid materials that carry the lithosphere. Due to its ductility and the temperature gradient from inside the Earth (that is, hotter in the core and colder outside), the asthenosphere convects and drives the overlying plates in all directions. (Recent studies suggest that there are more mechanisms moving our plates, but the convection in the asthenosphere is still considered the main cause.)

- **Transition Zone.** This is where magnesium iron silicate transform. Figure 1 at the beginning shows that olivine changes its structure under different environments. Above the transition zone, olivines are in their most stable form (α-olivine). However, the rising pressure when we move down deeper causes the olivine compound to change into β-, γ-olivine, and eventually into magnesiowustite and perovskite (Pv+Mw).

- **Low Velocity Zone (LVZ).** As its name implies, the LVZ is a layer where seismic waves (especially S waves) travel at a relatively low speed. This indicates that some fluids are present, and studies show that this is where minerals start to go under partial melting. Partial melting also leads to high conductivity here, and this is also a demonstration that a little water can significantly cause melting.

	depth(km)	resembles
lithosphere	0-100	plates
asthenosphere	100-400	semi-solid material that carries the lithosphere
LVZ	somewhere between 80-300	where materials start to melt

5.2 Boundaries of the Earth

These boundaries are places where seismic wave velocity changes suddenly due to different environmental compositions above and below the boundaries. The following chart shows how seismic wave reacts and the reasons (what compounds contributes to the change of velocity) behind them.

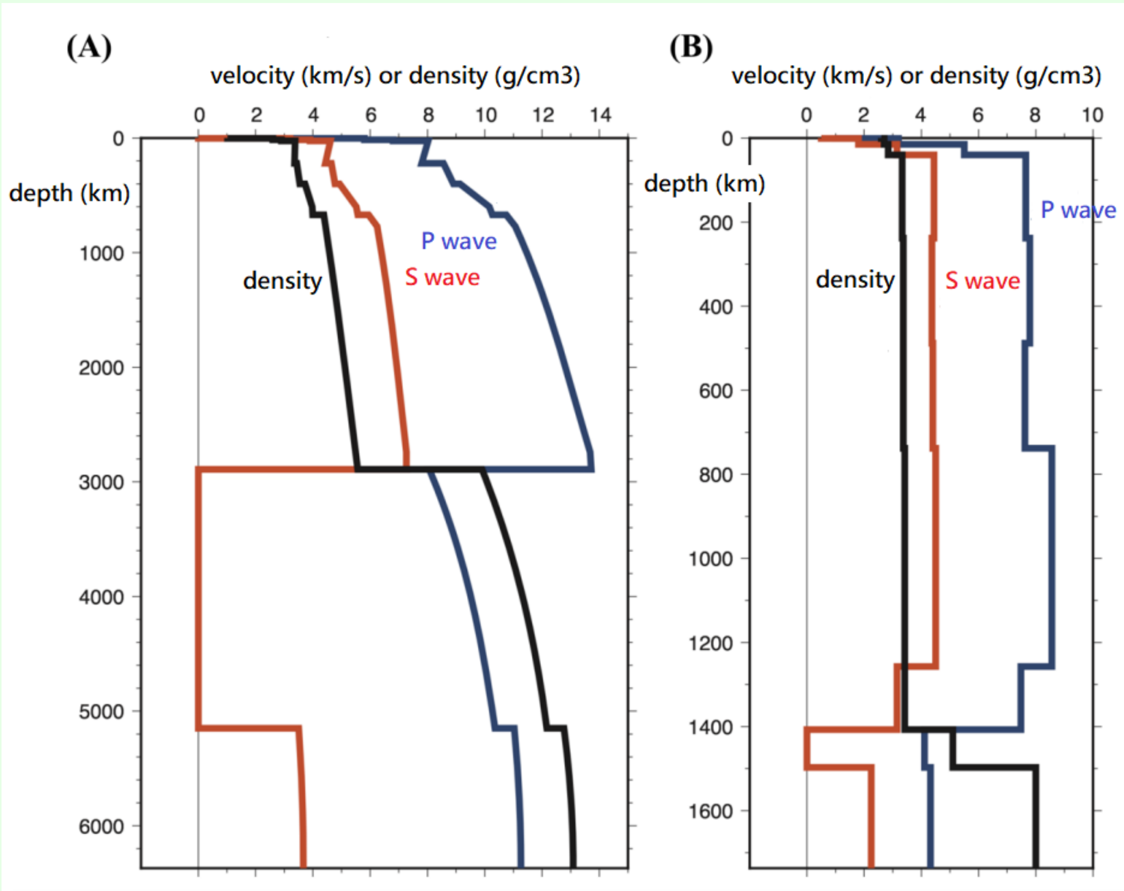
	depth(km)	composition above	composition below	wave velocity
Conrad	around 15	felsic (Sial)	mafic (Sima)	increase
MOHO	depends	mafic (Sima)	ultramafic (olivines)	increase
LAB	100	rigid	ductile	decrease
410	410	α-olivine (Olivine)	β-olivine (Wadsleyite)	decrease
660 (670)	660 (670)	γ-olivine (Spinel)	Magnesiowustite and Perovskite (Pv+Mw)	increase
D"	2750-2900	iron-poor	iron-rich	increase
CMB	2900	solid (due to pressure)	iron	decrease (no S wave below)
Core	5100	liquid	solid	increase (no S wave above)

Practice 5 (USESO Training Camp Exams 2019, Geosphere Q2)
The D" layer is a region in the lower mantle roughly 200 km in thickness. Indicate all of the following statements that are true of this region. (None, one, or more than one answer possible.)

(A) A p-wave generated by tectonic activity would increase in velocity after traveling through the D" region.
(B) The D" layer likely has highly felsic materials.
(C) Perovskites (CaTiO3) in the region likely have a sheet-like crystal structure
(D) The D" layer likely contains significant, free-flowing magma convection cells.

Solutions or Suggested Answer:
C. Below the D" layer is the liquid outer mantle, so P waves velocity would drop and no S waves would be allowed, so (A) is false. D" is located at the bottom of the mantle, so mafic materials would be there and no significant convection cells would appear, so (B) and (D) are false. They appear at the asthenosphere, with high viscosity and a slow flow, or at the outer core and generated our magnetic field.

General Practice (Taiwan-ESO National Exam 2022, Sample Question)
Graph A and B show the density and seismic wave velocity diagram of the Earth and the Moon. Indicate all of the following statements that are true. (None, one, or more than one answer possible.)



(A) The moon's plates are thicker than the Earth's.
(B) A layer of low seismic velocity can be found in the interior of the moon.
(C) A liquid layer can be found in the interior of both the moon and the Earth.
(D) The volume ratio of the moon's core to the moon, is greater than the volume ratio of the Earth's core to the Earth.

Solutions or Suggested Answer:
B and C. There are no tectonic movements nor plates on the moon, so (A) is false. Regions of depth 1250 to 1400 km indicate (B) is true. We can tell a liquid layer because the S wave is not able to propagate in fluids, (C) is true and the liquid layer of the moon is located at 1400 to 1500 km below the ground. Core refers to the region of and below which S wave velocity is zero, so (D) is significantly wrong and can be told by the ratio of the y-axis.