NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 08 : Composition of the mantle and core
Lecture 02: Temperature in the Earth and composition of the mantle

CONCEPTS COVERED

- **Temperature in the Earth**
- **Composition of the mantle**
- **Summary**

Recap

- The ratio of the moment of inertia to the mass gives a scalar that depends on the density distribution.
- Adams–Williamson equation relating the velocity structure to the derivative of density with radius,

$$\frac{d\rho(r)}{dr} = \frac{-\rho(r)Gm(r)}{\Phi(r)r^2} = \frac{-\rho(r)g(r)}{\Phi(r)}$$

- The drawback of Adams– Williamson equation is that, it does not take the account of changes in the mineral phase with depth.
- Modified Adams–Williamson equation which includes superadiabatic gradient is:

$$\frac{d\rho}{dr} = -\frac{\rho g}{\phi} + g\tau\alpha$$

α: coefficient of thermal expansion

τ: portion of the temperature gradient exceeding the adiabatic gradient.

- Inhomogeneity in the earth can be identified using the function 1 − (1/g)dϕ/dr.
- Pressure inside the earth can be computed as: $P(r) = -\int_0^r g(r)\rho(r)dr$

Temperature in the Earth

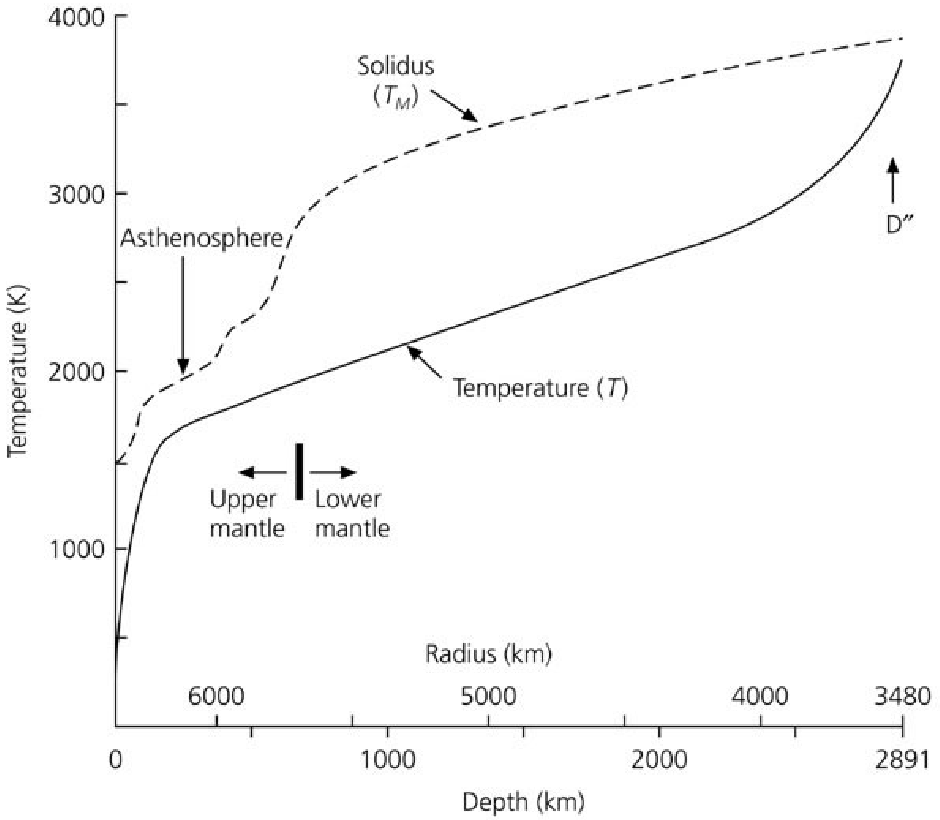
- Geotherm is variation of the temperature as a function of radius.
- Seismology gives insight into the geotherm which may provide information of the composition, mineralogy, and evolution of the Earth.
- The geotherm depends on the sources of heat and modes by which the heat is transferred upward in the Earth.
- Thermal convection occurs in the mantle and manifests at the mid-ocean ridges (hot upwelling limbs) and subducting plates (cold downwelling limbs).

Temperature in the Earth

- A geotherm is inferred by:
    - ➔ Modeling radioactive generation of heat in the crust and the mantle.
    - ➔ Conduction of heat across the lithosphere, CMB, and inner core.
    - ➔ Adiabatic temperature gradients associated with convection in the mantle and the outer core.

Temperature in the Earth

Figure 3.8-6: Geotherm and solidus for the mantle.



- A sample geotherm for the mantle is shown in Figure below.
- The most striking feature is: the contrast between the shallow temperature gradient in the mid-mantle and the steep gradients in the upper and lower thermal boundary layers, the lithosphere and D".
- The difference reflects the assumptions that heat is conducted primarily through the boundary layers, giving the steep gradients, but is convected between them, yielding a shallower near-adiabatic gradient.

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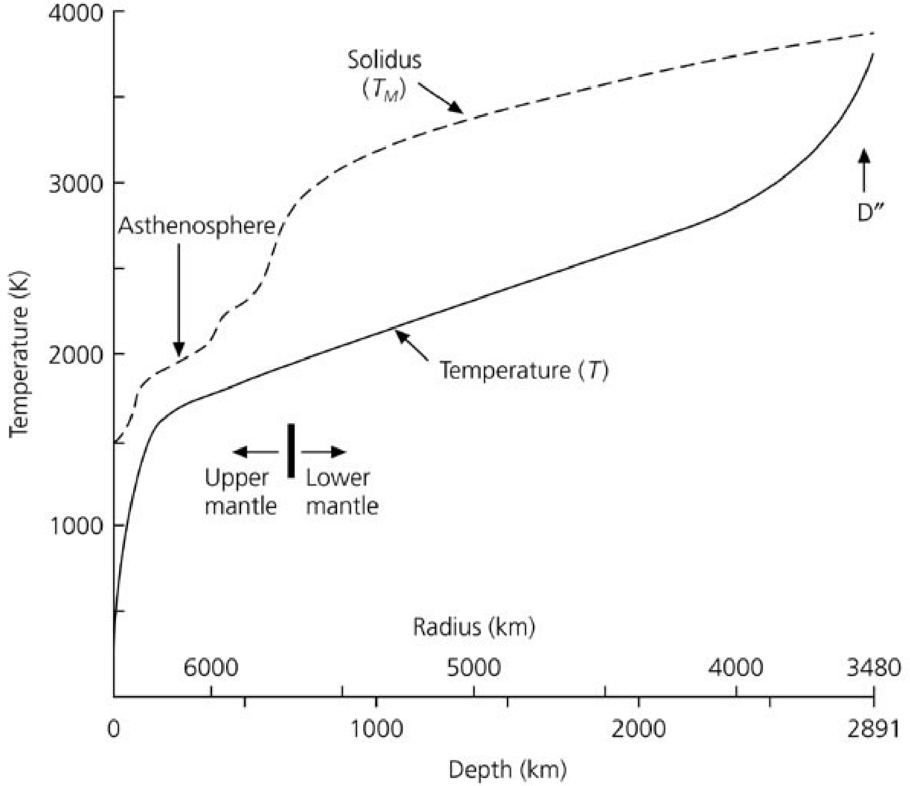
Temperature in the Earth

Figure 3.8-6: Geotherm and solidus for the mantle.



- **Upto 100 km, temperature rises from 0°C at the surface to about 1300°C, giving an average thermal gradient of 13°C/km.**

- **From 100 km to the base of the mantle - the temperature rises only another 1600°C, corresponding to a low gradient of only about 0.6°C/km.**

- **Over the bottom few hundred kilometers of the mantle, however, the temperature rises another 1400°C to a CMB temperature of about 4300°C.**

- **Thus the temperature changes across the boundary layers at the surface and CMB are comparable.**

Temperature in the Earth

- **The geotherm gives insight into the variations with depth of seismic velocity and attenuation and the strength, or stress, the material can support.**

- **Higher temperatures reduce seismic velocity and strength, but increase attenuation. Conversely, higher pressures increase the velocity and strength, but reduce attenuation.**

- **The cold lithosphere has high velocity and low attenuation, and behaves as rigid plates.**

- **However, the rapidly increasing temperature with depth brings the geotherm close to, if not above, the solidus, or melting temperature curve.**

- **This yields the low velocity zone, where there is high attenuation and weak material that forms the asthenosphere underlying the moving plates.**

Temperature in the Earth

- In the lower mantle, temperatures are only slightly greater than in the asthenosphere, so the higher pressures make the rock stronger.

- So the lower mantle’s viscosity is about 100 times greater than the upper mantle.

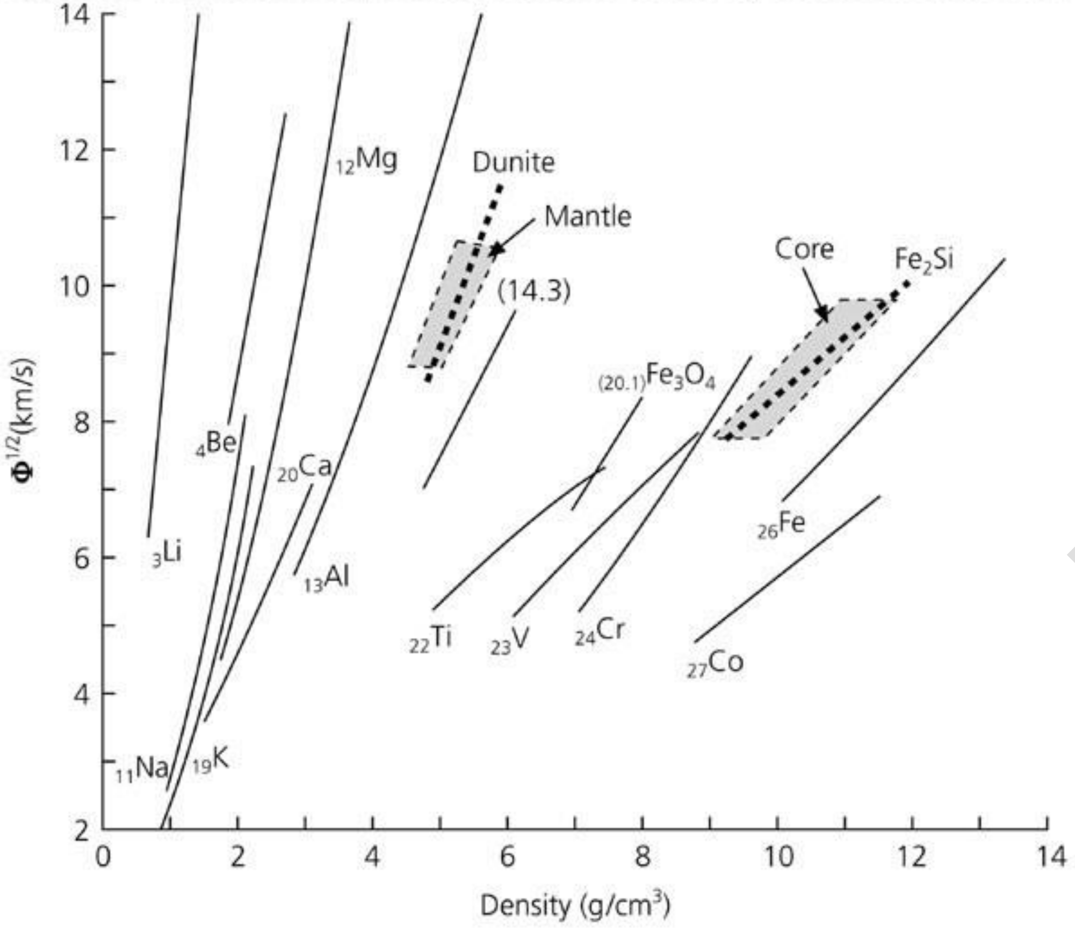
- Temperatures increase rapidly in D”, causing velocities slower than expected from the lower mantle velocity gradient.

- The high temperatures in the core keep the outer core liquid, but the rapid increase in pressure due to the weight of the outer core makes the inner core freeze into a denser solid.

- The inner core is therefore close to the melting temperature of iron, so it has low shear velocities.

Composition of the mantle

Figure 3.8-7: Bulk sound speed as a function of density for various materials.



For mantle and core composition,

➔ Let's compare bulk sound speed and densities of various materials.

➔ As shown, they are linearly related.

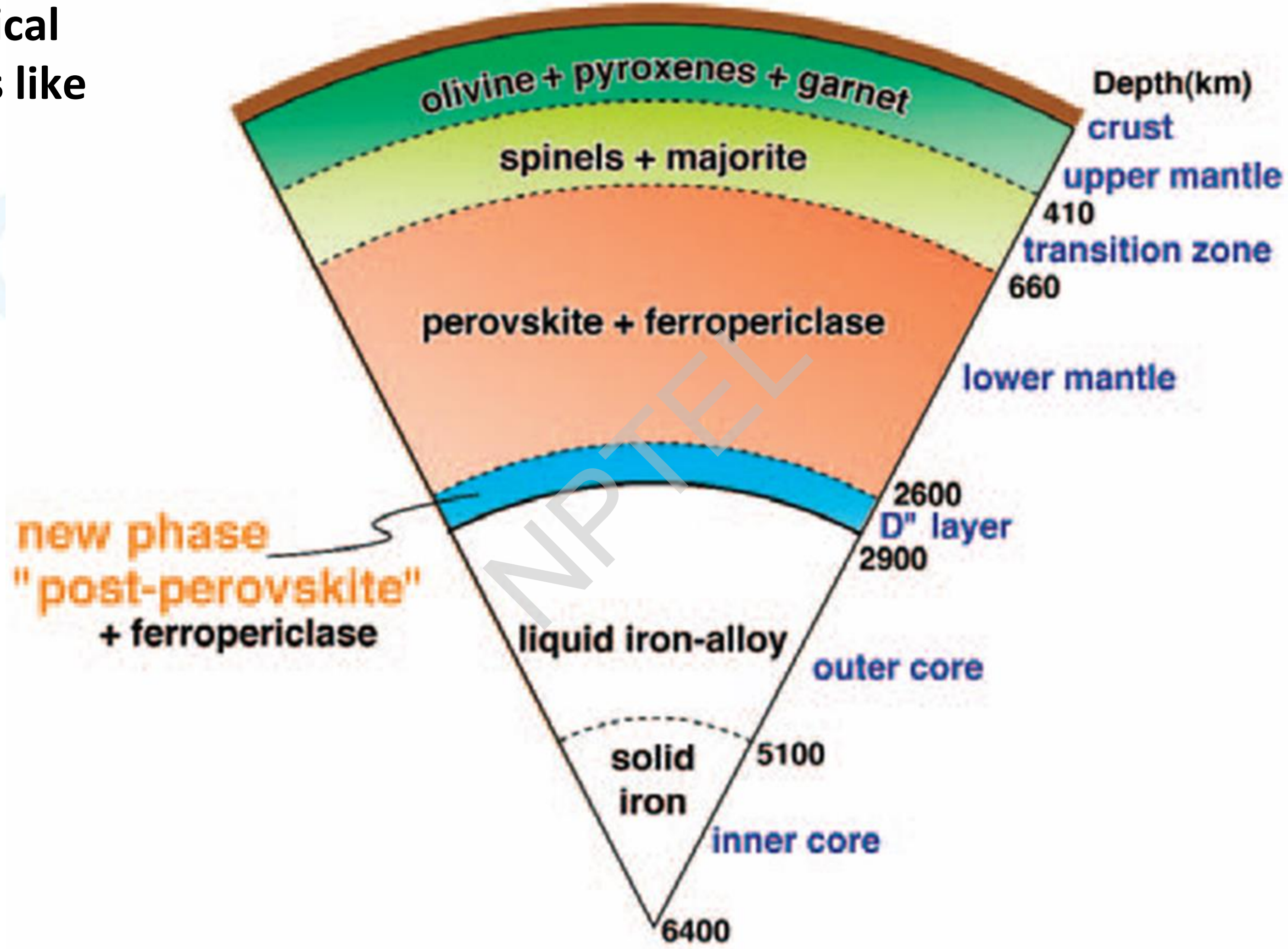
➔ Dunite, a rock containing 92% olivine, which in turn is 90% forsterite, fits the mantle data.

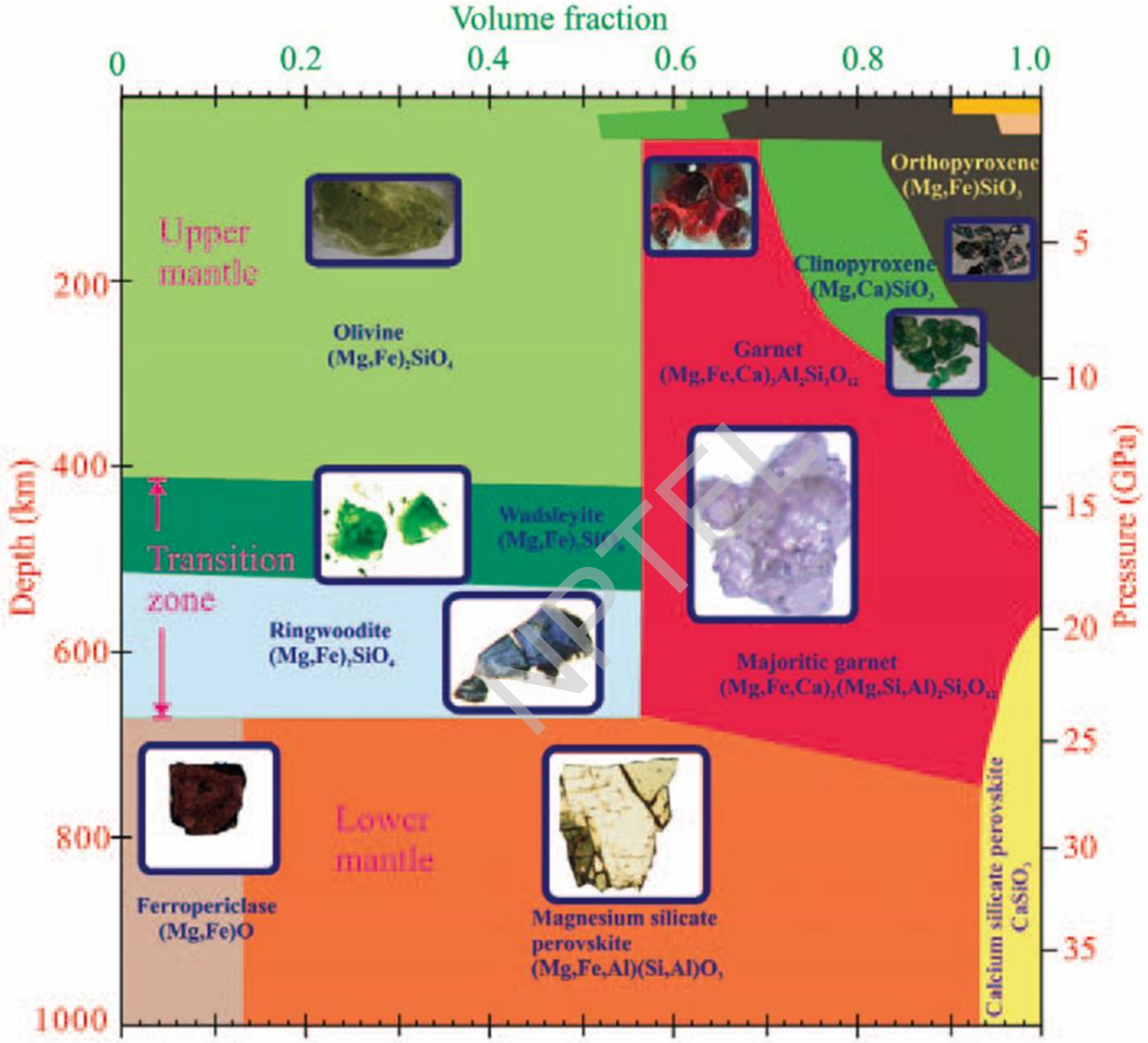
➔ The core data plot much further to the right, indicating that the core is composed of material of higher atomic number.

➔ Core data plot is left of the curve for pure iron.

➔ It says that the core is composed of iron plus a lower atomic weight element.

➔ **Earth's mineralogical composition looks like this,**





Volume fraction
0
0.2
0.4
0.6
0.8
1.0
Depth (km)
200
400
600
800
1000
Pressure (GPa)
5
10
15
20
25
30
35
Upper mantle
Olivine
(Mg,Fe)$_2$SiO$_4$
Transition zone
Wadsleyite
Ringwoodite
(Mg,Fe)$_2$SiO$_4$
Lower mantle
Ferropericlase
(Mg,Fe)O
Magnesium silicate perovskite
(Mg,Fe,Al)(Si,Al)O$_3$
Garnet
(Mg,Fe,Ca)$_3$Al$_2$Si$_3$O$_{12}$
Majoritic garnet
(Mg,Fe,Ca)$_3$(Mg,Si,Al)$_2$Si$_3$O$_{12}$
Orthopyroxene
(Mg,Fe)SiO$_3$
Clinopyroxene
(Mg,Ca)SiO$_3$
Calcium silicate perovskite
CaSiO$_3$

Crust

•its thickness is ~6 km in oceans (predominantly basaltic)

•its thickness is ~40 km in continents (mostly granitic)

Upper mantle

•from the base of crust to ~410 km.

Mainly composed of peridotite: depending upon the pressure peridotite may be in the forms such as olivine, clinopyroxene, orthopyroxene, garnet spinel, or plagioclase.

Transition zone

- ➔ In the transition zone (410 km to ~670 km), olivine transforms to its various polymorphs.

- ➔ Transition zone has 2-3 discontinuities that have positive velocity jumps. In transition zone Olivine changes to its various polymorphs depending upon temperature.

At 410 km discontinuity – Olivine changes to wadsleyite.

At 520 km discontinuity– wadsleyite changes to ringwoodite.

At 660 km discontinuity – ringwoodite turns to perovskite + magnesiowustite.
This produces the lower mantle minerals.

Transition zone

These phase changes are temperature dependent. So, we define these phase changes in terms of Clayperon slope.

Clayperon slope: dP/dT (derivative of pressure w.r.t. temperature)

- ➔ At 410 km the values of dP/dT ranges in between ~2.5 and 4 MPa/K (i.e. positive). This means that when the temperature at “410” goes up then pressure even higher OR pressure goes down when material at “410” gets colder.

- ➔ At 660 km, dP/dT lies in between -3 and -1 MPa/K (i.e. negative). This means the “660” goes down when things are colder.

- ➔ which further means that a colder Transition Zone would be thicker. Hence, Variations in composition may also be responsible for thickness variations.

Lower Mantle **(~670 – 2891 km).**

Main constituent perovskite which is now known as bridgemanite ($MgSiO_3$) + magnesiowustite/ferropericlase $(Mg,Fe)O$.

D" lies at the base of lower mantle where 2-3% S-wave velocity increase happens in between 2550-2700 km. Here, a new mineral called post-perovskite may possibly be found.

Core

Outer Core mainly composed of Liquid iron-alloy. It lies at 2891-5100km.

Inner Core mainly composed of Solid iron. It lies at 5100-6400 km.

Summary

- The geotherm depends on the sources of heat and modes by which the heat is transferred upward in the earth.

- An average thermal gradient is 13°C/km upto depth of 100 km while a low gradient of only about 0.6°C/km upto the base of the mantle.

- Higher temperatures reduce seismic velocity and strength, but increase attenuation. Conversely, higher pressures increase the velocity and strength, but reduce attenuation.

- Temperatures increase rapidly in D”, causing velocities slower than expected from the lower mantle velocity gradient.

- The high temperatures in the core keep the outer core liquid, but the rapid increase in pressure due to the weight of the outer core makes the inner core freeze into a denser solid.

Summary

- A key result from experiments is that the bulk sound speed and the density for a material are approximately linearly related for a given mean atomic weight.
- Dunite, a rock containing 92% olivine, which in turn is 90% forsterite, fits the mantle data.
- Crust is predominantly basaltic or granitic depending on the continents or ocean.
- Upper mantle mainly composed of peridotite: depending upon the pressure peridotite may be in the forms such as olivine, clinopyroxene, orthopyroxene, garnet spinel, or plagioclase.
- The transition zone corresponds to a series of solid state phase changes.

Summary

- Transition zone has 2-3 discontinuities where Olivine changes to its various polymorphs depending upon temperature.

  At 410 km discontinuity – Olivine changes to wadsleyite.

  At 520 km discontinuity– wadsleyite changes to ringwoodite.

  At 660 km discontinuity – ringwoodite turns to perovskite + magnesiowustite. This produces the lower mantle minerals.

- Lower mantle's main constituent is perovskite which is known as bridgemanite (MgSiO3) + magnesiowustite/ferropericlase (Mg,Fe)O.
- Outer Core mainly composed of Liquid iron-alloy. It lies at 2891-5100km.
- Inner Core mainly composed of Solid iron. It lies at 5100-6400 km.

REFERENCES

- Stein, Seth, and Michael Wysession. An introduction to seismology, earthquakes, and earth structure. John Wiley & Sons, 2009.
- Lowrie, William, and Andreas Fichtner. Fundamentals of geophysics. Cambridge university press, 2020.
- Kearey, Philip, Michael Brooks, and Ian Hill. An introduction to geophysical exploration. Vol. 4. John Wiley & Sons, 2002.
- https://geologyscience.com/geology-branches/structural-geology/stress-and-strain/
- Seismology course, Professor Derek Schutt, Colorado State Univ., USA.

THANK YOU !