NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

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Module 08 : Composition of the mantle and core
Lecture 04: Composition of the D” layer and the Core

CONCEPTS COVERED

- Composition of the D” layer (Continued..)
- Composition of the Core
- Summary

Recap

- The β phase transforms to a γ, or spinel, structure known as ringwoodite at a pressure of ~15 GPa, corresponding to the less dramatic seismic discontinuity at 520 km.

- γ spinel breaks down to a perovskite structure and (Mg, Fe)O magnesiowustite at 660 km discontinuity.

- A simple univariant phase change causes a sharp discontinuity in velocity while a complicated multivariant phase change produces a velocity gradient.

- The olivine α-to-β reaction should occur over a narrow depth range and β-to-γ transformation should occur over a broader depth range which aggress well with the lab predictions.

- The γ -spinel to perovskite and magnesiowustite transition should occur over a narrow depth range, consistent with the observed sharpness of the 660 km seismic discontinuity.

Recap

- For the D“ layer four possible models describe the observed characteristics. First is, a simple convection model, with cold material sinking to the CMB, heating up from contact with the core, and then rising again.

- Second model predicts that, the subducted slabs do not reach the top of the core, but remain separated by a chemically distinct layer.

- Another possibility is that the part of the subducted lithosphere that started as basaltic ocean crust and then transformed to eclogite transforms to a material that is seismically faster than the rest of the lower mantle

Composition of the mantle

- olivine (or Forsterite, α-phase, orthorhombic crystal system) → Wedsleyite (β-phase, β-Spinel cubic
  - at 410 km
  - hcp to ccp, P-increases to 12 GPa
  - No change in mineralogy only structure changes

Wedsleyite (β-phase, β-Spinel cubic → Ringwoodite (γ-spinel)
- at 520 km
- Pressure increases to 15 GPa

Ringwoodite (γ-spinel) → Perovskite (or Bridgmanite)
- at 660 km
- Pressure increases to 24 GPa

Perovskite (or Bridgmanite) → Post-Perovskite
- at D”

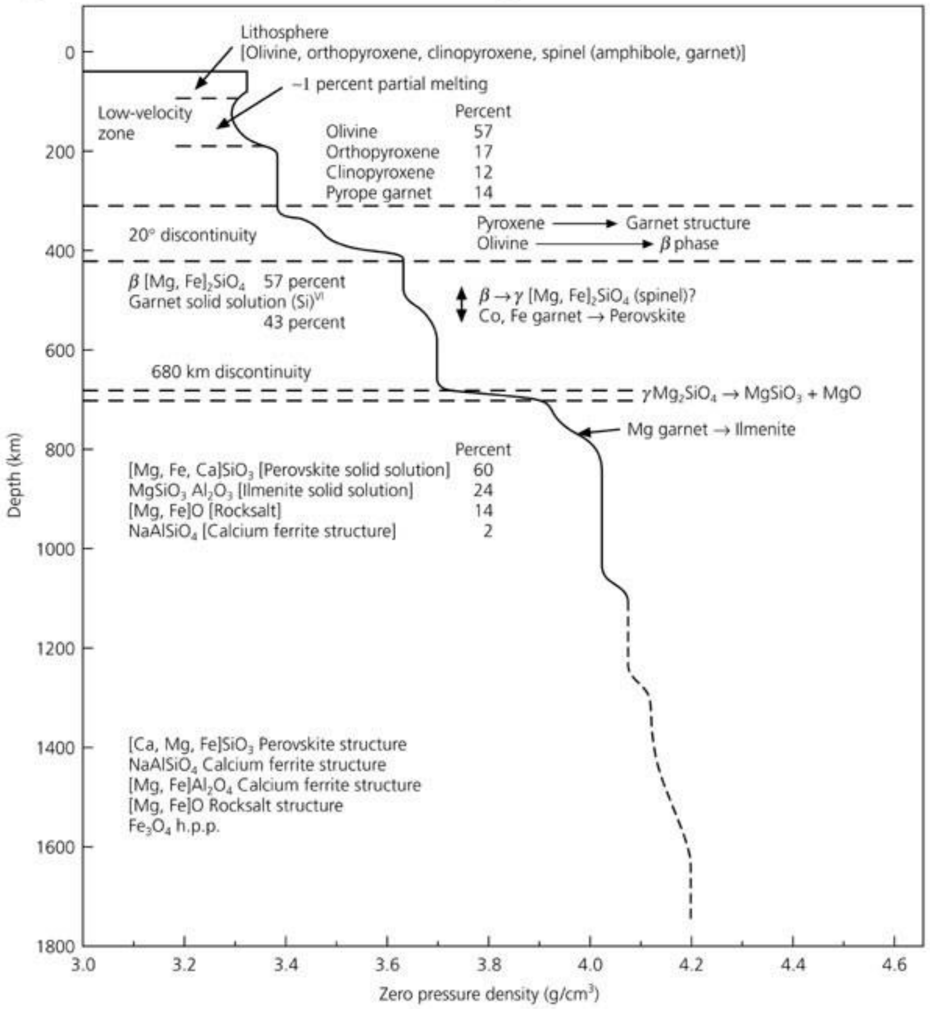
Perovskite (or Bridgmanite): No change in mineralogy only structure changes, most abundant in earth (~70% of lower mantle)

Pyroxine → Garnet
- below 200 km
- Pressure increases

Garnet → Perovskite (or Bridgmanite)
- at 660 km

Composition of the mantle

Figure 3.8-8: Predicted mineral assemblages for the mantle.



- Upper mantle comprises of olivine and its goes into a series of phase changes at transition zone.The α-phase transforms to β-spinel known as Wedsleyite at a pressure of ~12 GPa at 410 km discontinuity.

- The β phase transforms to a γ, or spinel, structure known as ringwoodite at a pressure of ~15 GPa, corresponding to the less dramatic seismic discontinuity at 520 km.

- At pressures above about 24 GPa, corresponding to the 660 km discontinuity, γ spinel breaks down to a perovskite structure and (Mg, Fe)O magnesiowustite.

- The $(Mg,Fe)SiO_3$ pyroxene component also undergoes changes, beginning with a transformation to garnet below about 200 km

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Composition of the mantle

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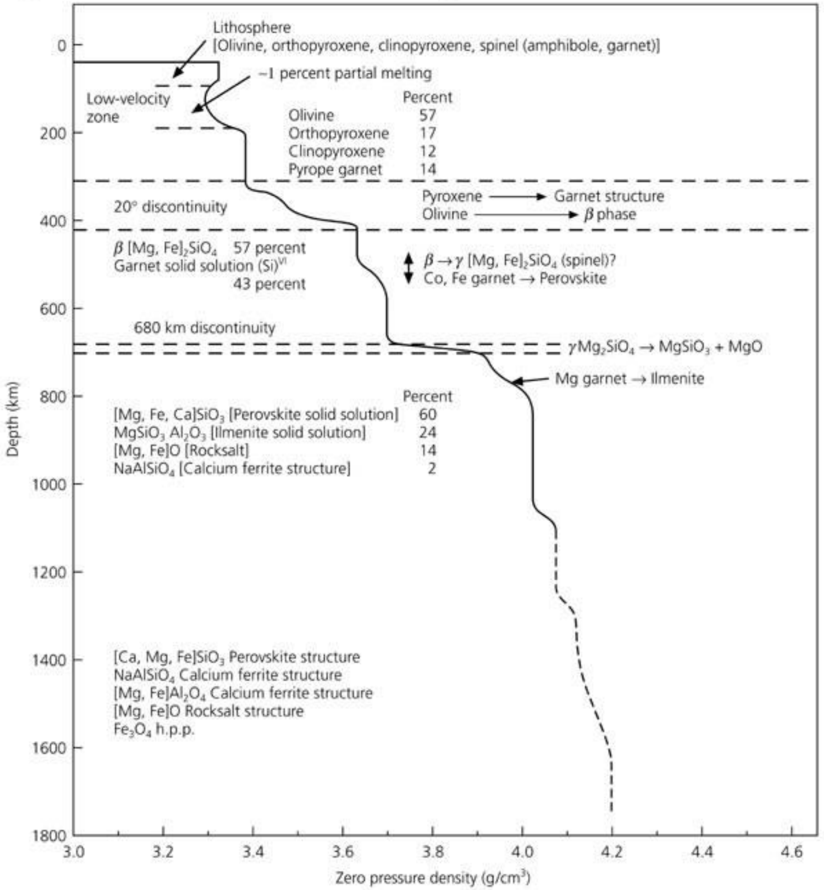


- Below 600 km, some of the Mg-bearing garnet, majorite, transforms to a structure called ilmenite.

- Beneath about 660 km, the majorite/ilmenite transforms to perovskite.

- Some of the majorite probably survives into the lower mantle as stishovite, a high-pressure phase of quartz, and an Al_2O_3 -rich phase.

- The pyroxene and garnet transformations occur gradually and contribute to a high velocity gradient through the transition zone down to about 770 km.

Composition of D″

- Seismic observations give a picture of the D″ region that includes lateral velocity variations, vertical layering, and anisotropy.

- Hence processes there may be as complex as in the lithosphere, the other major thermal boundary layer.

- This complexity may reflect factors including subducted lithosphere, the generation of mantle plumes, and interactions between the core and the mantle.

Composition of D” : Model I

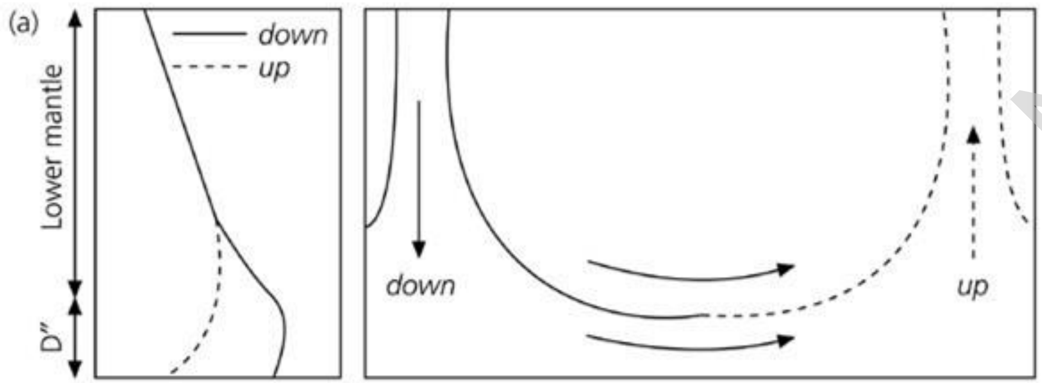
- Figure shows a simple convection model, with cold material sinking to the CMB, heating up from contact with the core, and then rising again.

- The left side of the figure shows the resulting vertical velocity profiles in regions of downwelling (solid line) and upwelling (dashed line).

- Thus the large (> ±5%) lateral seismic variations at the base of the mantle would be caused by temperature variations.

- However, given the complex seismic structures observed, this model component seems necessary but insufficient.

Figure 3.8.12: Cartoon of possible processes at work at the base of the mantle.

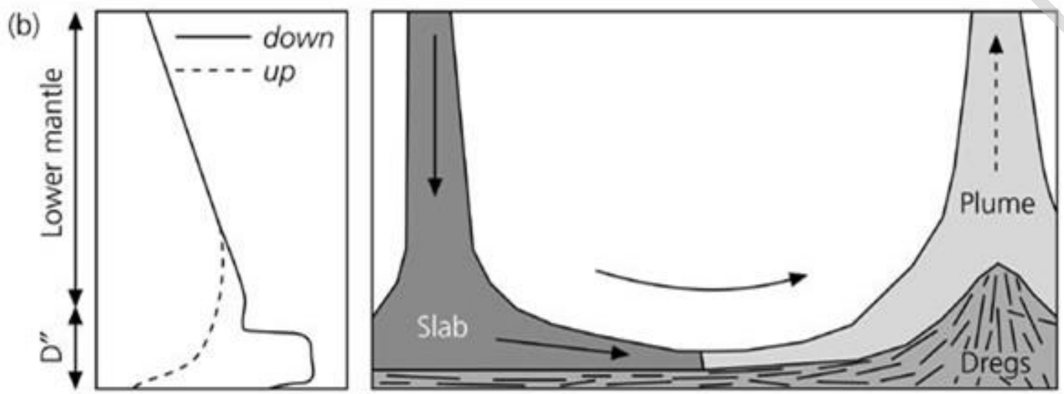


Composition of D”: Model II

- Another possibility is that, the subducted slabs do not reach the top of the core, but remain separated by a chemically distinct layer.

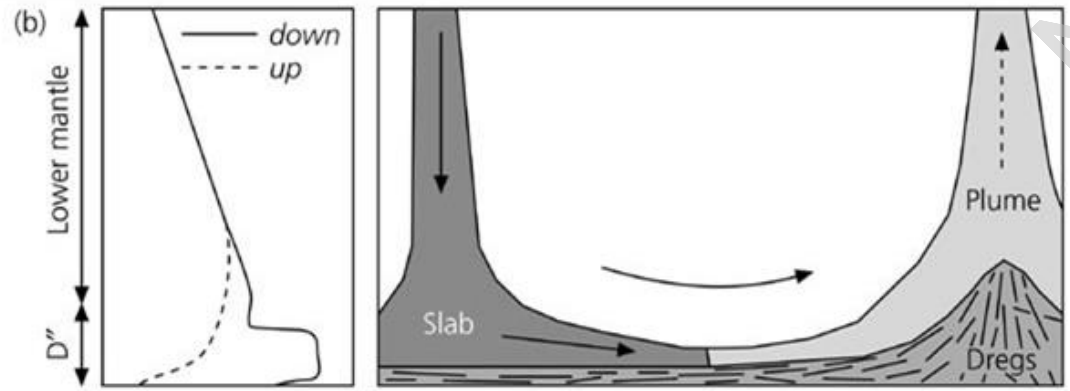
- This layer may result from early planetary differentiation, or may have grown by chemical reactions between the mantle and the core.

- High-pressure experiments imply that perovskite and magnesiowustite would react with iron. These mantle dregs might be thinned in regions of mantle downwelling, and thickened beneath upwellings.



Composition of D”: **Model II**

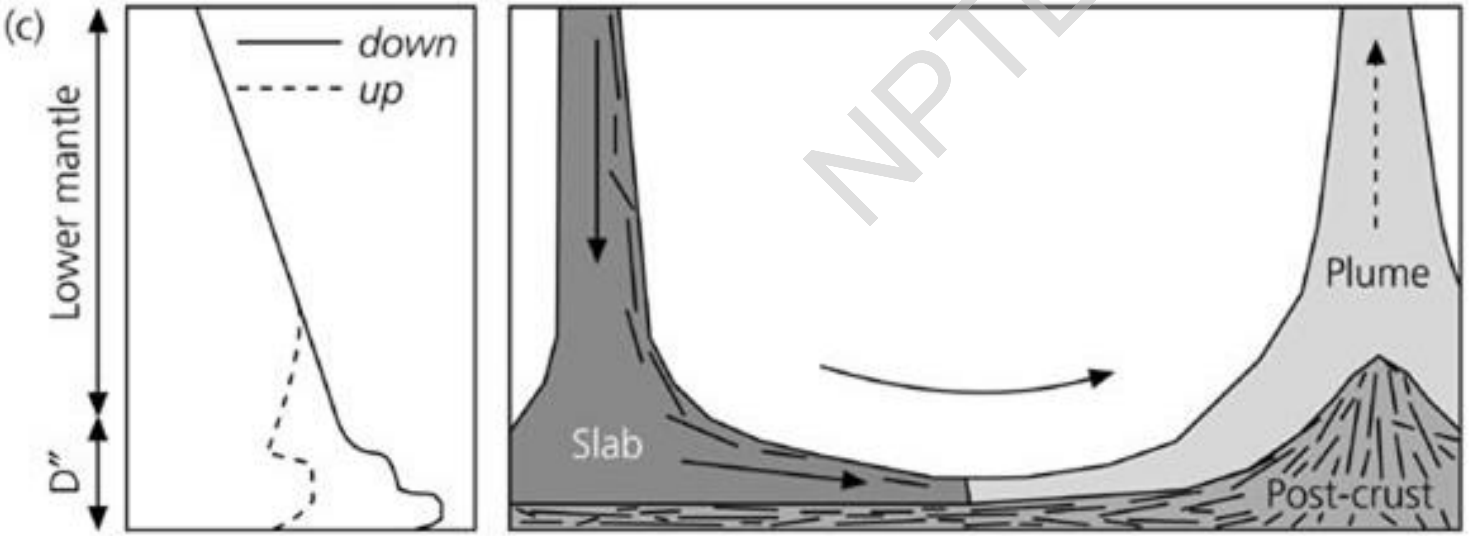
- **Layering in the dregs may explain observations of transverse isotropy in downwelling regions and azimuthal anisotropy in upwelling regions.**
- **The velocity increase of the D” discontinuity may be partly caused by ponded slab material, which will still be colder and have higher velocity than ambient rock.**
- **This discontinuity may be enhanced by dregs flowing up and over ponded slabs.**



Composition of D": Model III

- **Another possibility is that the part of the subducted lithosphere that started as basaltic ocean crust and then transformed to eclogite transforms to a material that is seismically faster than the rest of the lower mantle.**

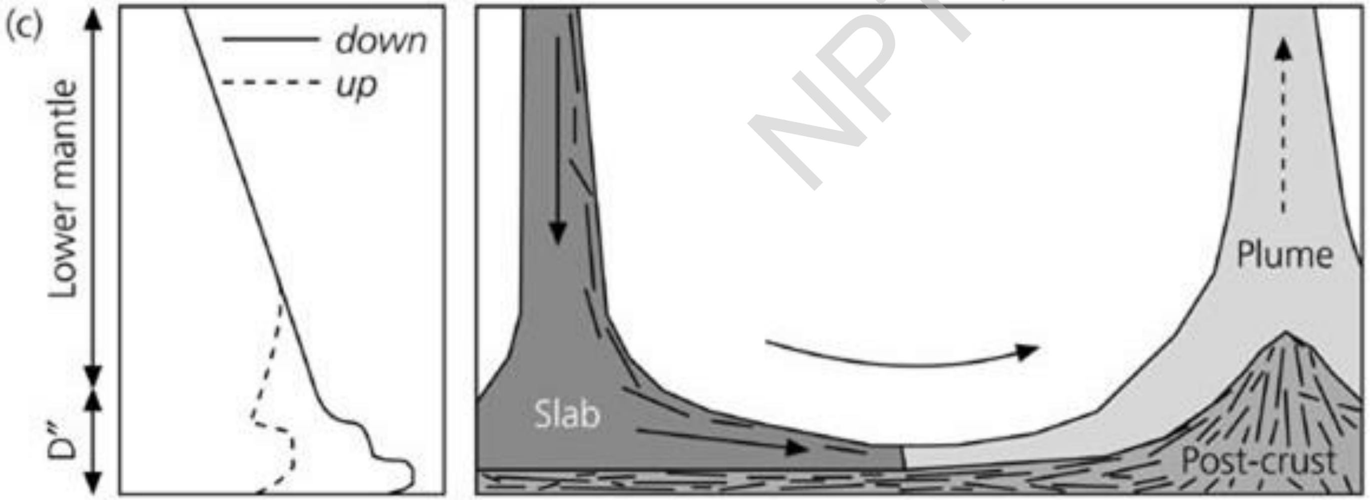
- **This phase could delaminate from the slabs and accumulate, forming a different chemical boundary layer. If it remained solid, it might partially explain the D" discontinuity.**



Composition of D″: Model III

- **Alternatively, if it melted, it might explain the ULVZ. Either way, its laminar nature might explain the observed seismic anisotropy.**

- **The lateral variations in velocity would correlate with anisotropy; SH waves would travel fast in downwelling regions because of transverse isotropy, but be slowed by the vertical laminations beneath upwellings.**

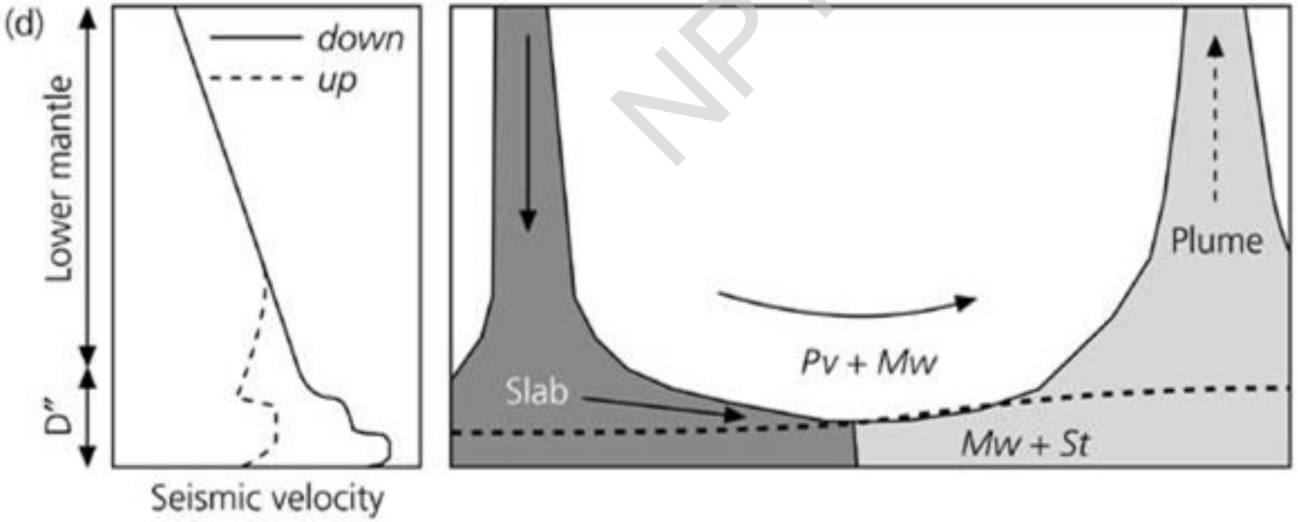


Composition of D”: Model IV

- D” may also signify the bottom of the perovskite stability field.

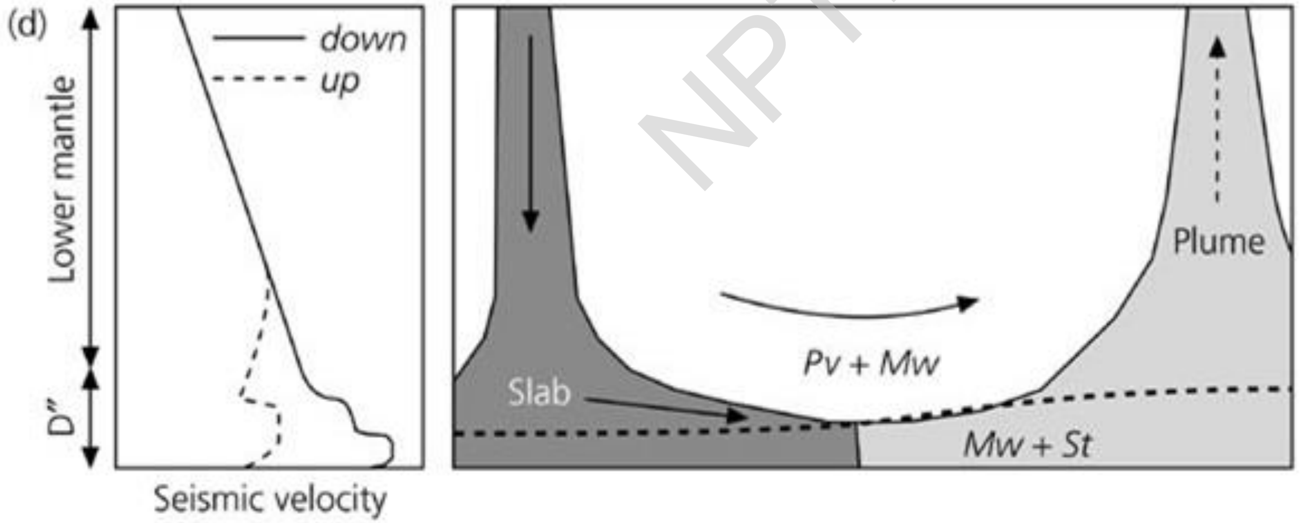
- Large radial changes in temperature and/or composition at the base of the mantle could move perovskite or a secondary phase out of its range of stability, causing a phase transformation.

- One possibility is a transformation of perovskite to stishovite and magnesiowustite, which occurs with an increase in the iron/magnesium ratio.



Composition of D”: Model IV

- Stishovite has high seismic velocities and might contribute to the D” discontinuity.
- In this case, anisotropy might reflect orientation of crystals due to lateral flow.
- The denser magnesiowustite might settle to the bottom, forming the ULVZ. Given our limited knowledge, D” may involve these and other effects.



Composition of the Core

- The density and bulk sound speed data suggest that the core has a composition similar to that of iron, but with a less dense element of lower atomic number added.

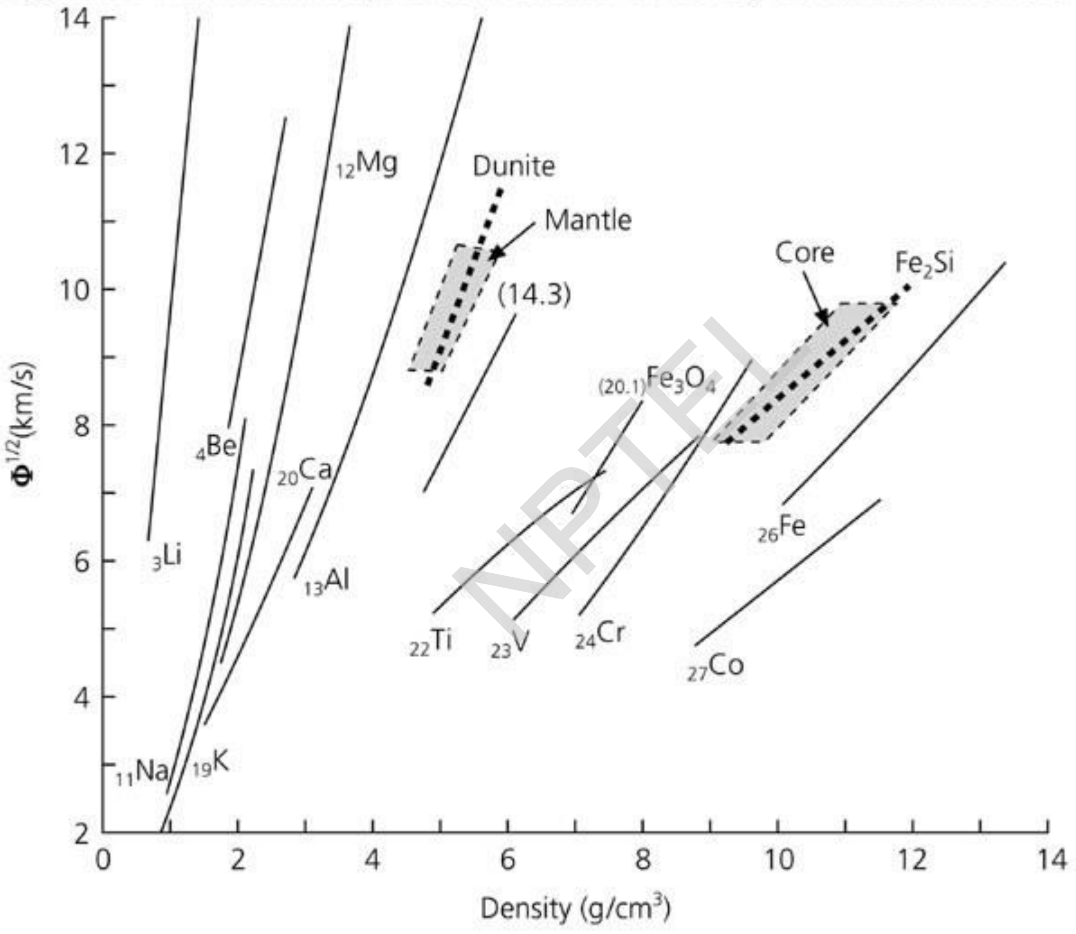
- From the cosmochemistry, meteorites are roughly divided into stony meteorites, resembling the mantle, and iron meteorites, composed of an iron–nickel alloy, which are thought to be similar to the core.

- “Convection of molten iron is also considered the only suitable mechanism for generating the earth’s magnetic field.”

- The light element lowering the core density is unknown: candidates include sulphur, silicon, oxygen, potassium, and hydrogen.

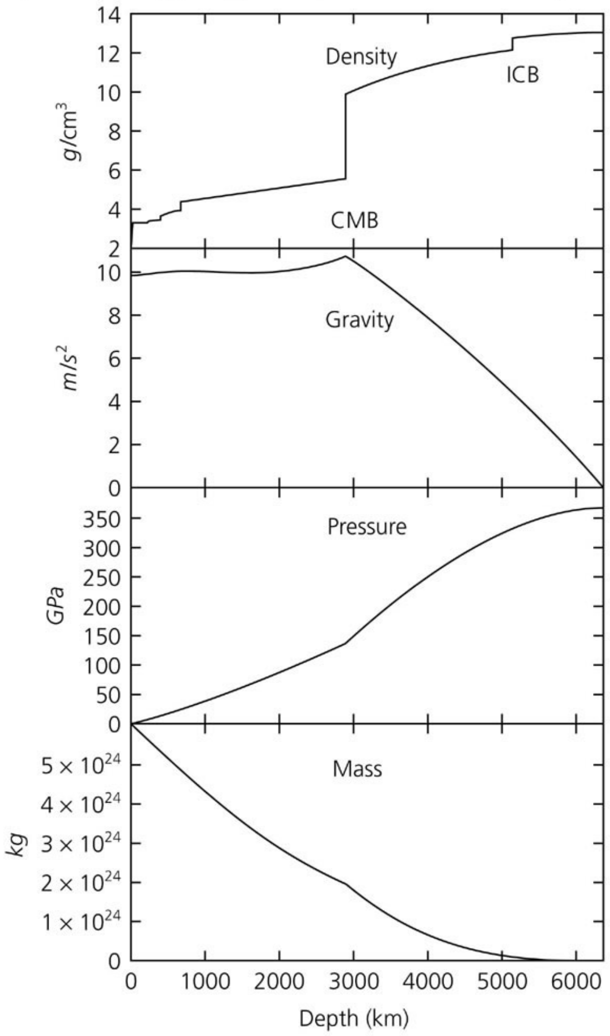
Composition of the Core

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



Composition of the Core

Figure 3.8-5: Density, gravity, pressure, and mass as a function of depth.



It may seem surprising that the inner core is solid, because it should be at a higher temperature than the liquid outer core.

From the ICB to the center of the earth, temperature is thought to increase by only 100–200°C, or about 3% of the inner core temperatures, which are about 5000°C.

Pressure, however, is thought to increase about 11%, from about 329 GPa at the ICB to 364 GPa at earth's center.

The density inferred from the seismological data is consistent with that for solid iron expected from experiments and modeling.

Composition of the Core

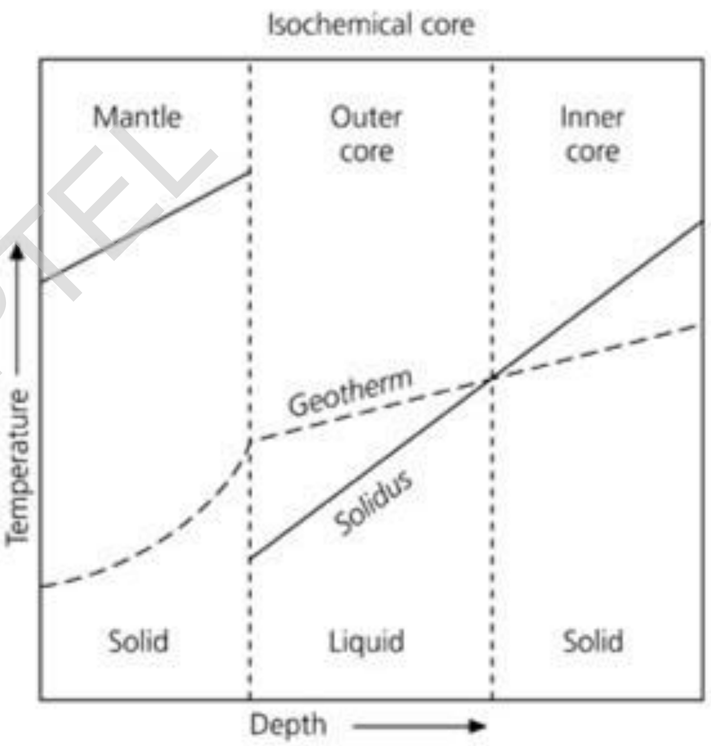
- This situation requires that the inner core geotherm be at temperatures below the melting temperature curve (solidus), whereas the outer core geotherm must be above the solidus.

- Two suggestions have been offered for this effect

Case I

<u>If the inner and outer cores were chemically identical</u>

- The solidus should rise smoothly with depth.
- The geotherm would be shallower than the solidus, so that they intersect at the ICB, but steeper than the adiabatic gradient required for convection in the outer core.



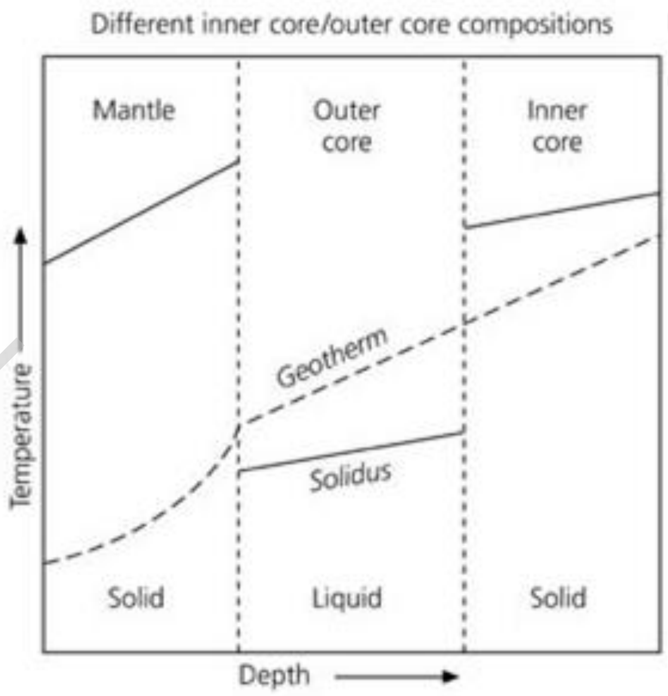
Composition of the Core

Case II

- Calculations suggest that the superadiabatic temperature gradient in the core required for convection would be steeper than the solidus.

- If so, the solid inner and liquid outer cores can be explained by assuming that the inner core is chemically different from the outer core, and thus has a different melting curve.

- Thus, only in the inner core does the geotherm lie below the solidus and result in a solid phase.



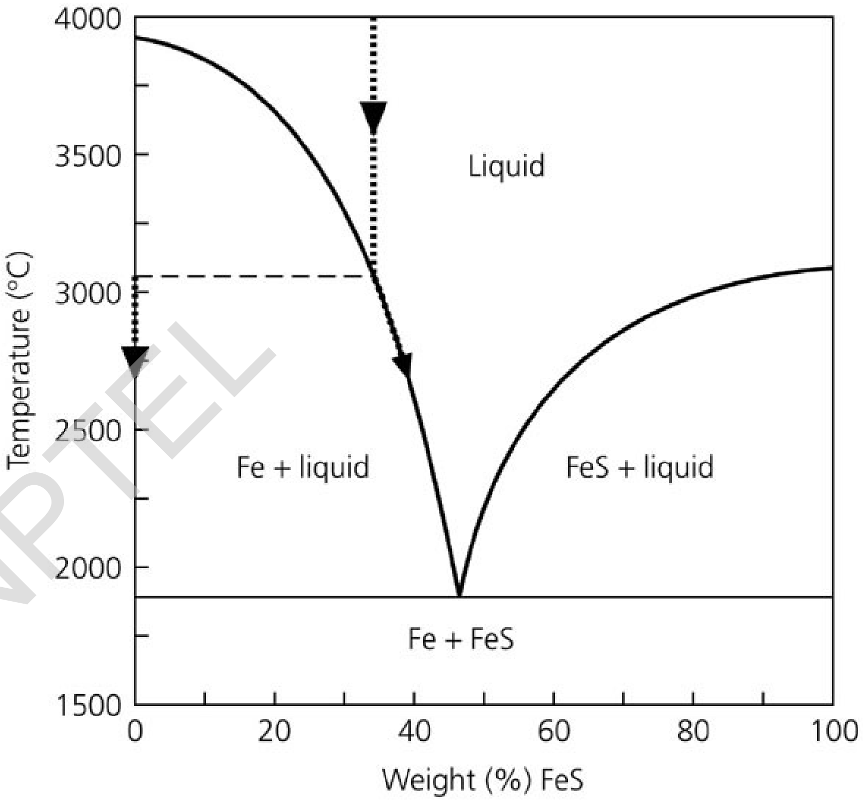
Composition of the Core

- If we assume that the light element in the core is sulfur.

- In this phase diagram for the Fe–FeS system extrapolated to core conditions, sulphur significantly lowers the melting temperature of iron.

- Cooling a liquid iron mixture with 12% sulphur, corresponding to 33% FeS, causes solid Fe to freeze out, leaving the liquid richer in FeS.

Figure 3.8-14: Melting relations for Fe-FeS at 1.4 Mbar.



Composition of the Core

- In this analogy, the outer core corresponds to the FeS-rich liquid, and the inner core to the denser Fe solid.

- The nickel would also preferentially enter the solid phase. Such a model predicts an inner core of approximately 80% Fe and 20% Ni, and an outer core with 86% Fe, 12% S, and 2% Ni.

- The inner core's freezing is thought to be crucial to the convection in the outer core, because the sinking iron releases gravitational potential energy.

- It has been estimated that the outer core's convection is driven in approximately equal fractions by this process, the latent heat of the crystallizing inner core, and the loss of primordial heat.

Composition of the Core

- Such models suggest that the boundary between the inner and outer cores is both a phase boundary and a compositional boundary, like the CMB.

- It has also been suggested that iron crystallizes at the ICB at some latitudes, and dissolves back into the outer core at other latitudes, constrained by magnetic forces.

- This effect may cause preferential alignment of iron crystals, and thus inner core anisotropy

Summary

- 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: $P(r) = -\int_0^r g(r)\rho(r)dr$

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 ($MgSiO_3$) + 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.**

Summary

- It has been also suggested that, D″ may also signify the bottom of the perovskite stability field and transformation of perovskite to stishovite and magnesiowustite, which occurs with an increase in the iron/magnesium ratio.

- The density and bulk sound speed data suggest that the core has a composition similar to that of iron, but with a less dense element of lower atomic number added.

- The density inferred from the seismological data is consistent with that for solid iron expected from experiments and modeling.

- The solid inner core and the liquid outer core requires the inner core geotherm be at temperatures below the melting temperature curve (solidus), whereas the outer core geotherm must be above the solidus.

Summary

- Two suggestions have been offered for this effect:
  - If the inner and outer cores were chemically identical , the solidus should rise smoothly with depth and the geotherm would be shallower than the solidus.
  - Solid inner and liquid outer cores can be explained by assuming that the inner core is chemically different from the outer core, and thus has a different melting curve only in the inner core does the geotherm lie below the solidus and result in a solid phase.
- The inner core's freezing is thought to be crucial to the convection in the outer core, because the sinking iron releases gravitational potential energy.
- It has also been suggested that iron crystallizes at the ICB at some latitudes, and dissolves back into the outer core at other latitudes, constrained by magnetic forces result in the anisotropy of inner core.

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THANK YOU !