NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

Dr. Mohit Agrawal

Department of Applied Geophysics , IIT(ISM) Dhanbad

Module 06 : Seismic waves in a spherical earth, Body wave travel time studies

Lecture 05: Velocity structure of upper mantle and lower mantle

CONCEPTS COVERED

- **Velocity structure of upper mantle**
  - **a. Subcrustal lithosphere**
  - **b. Seismic low velocity zone**
  - **c. Transition zone**
- **Velocity structure of lower mantle**
  - **a. D” layer**
  - **b. ULVZ**

Upper mantle structure

What does velocity structure of upper mantle shows?

- **velocity structure of upper mantle**
  - **Radially symmetric**
    - **Discontinuity**
    - **Velocity gradient**
  - **Lateral heterogeneity**
    - **Temperature variation due to cold subducting oceanic lithosphere**

Radial velocity structure of upper mantle

Subcrustal Lithosphere

- P- and S-wave velocity are high of about 8.1 and 4.5 in sub-crustal lithosphere.

- This subcrustal lithosphere, termed as "the seismic lithosphere" or "lid".

- Its thickness varies with location. It is approximately zero at mid oceanic ridges and ~200 km beneath the stable craton.

- As a global average, the seismic lithosphere extends to about 80-100 km depth.

Note: A craton is an old and stable part of the continental lithosphere, which consists of Earth's two topmost layers, the crust and the uppermost mantle. (wikipedia).

LVZ(Seismic Low Velocity Zone)

- **Across entire Earth, there is a ‘Low Velocity Zone (LVZ)’ beneath the lithosphere.**

- **coincides with the expected mechanically weak asthenosphere underlying the stronger lithosphere.**

- **they are mechanically different since the stronger lithosphere slides over weaker asthenosphere.**

- **it happens because the lithosphere is the cold outer thermal boundary layer of the solid earth.**

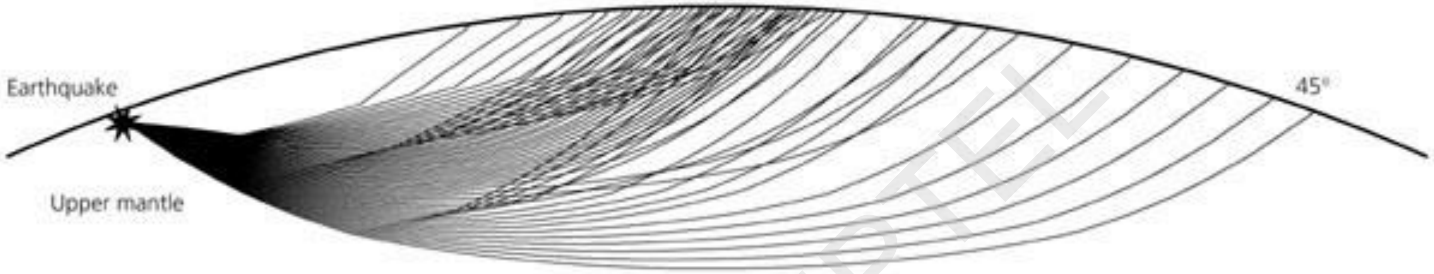
- **LVZ’s depth and magnitude vary regionally and it is well developed and shallow in tectonically active regions.**

- **deeper/less pronounced underneath stable continental region.**

Transition zone and triplication

- The velocity discontinuities at depth of 410 km and 660 km is marked as transition zone between the upper and lower mantles.

Ray paths for *P* waves through the upper mantle.



- Rapid velocity increase produces a triplication in travel time curve.

- Upper mantle travel times show two triplications around 15° and 22° caused by the 410 and 660 km discontinuities.

Difficulty in Studying the transition zone

- Travel time curves are composites of data from many earthquakes at different distances. The process of combining the data can make the details of the triplication difficult to observe.

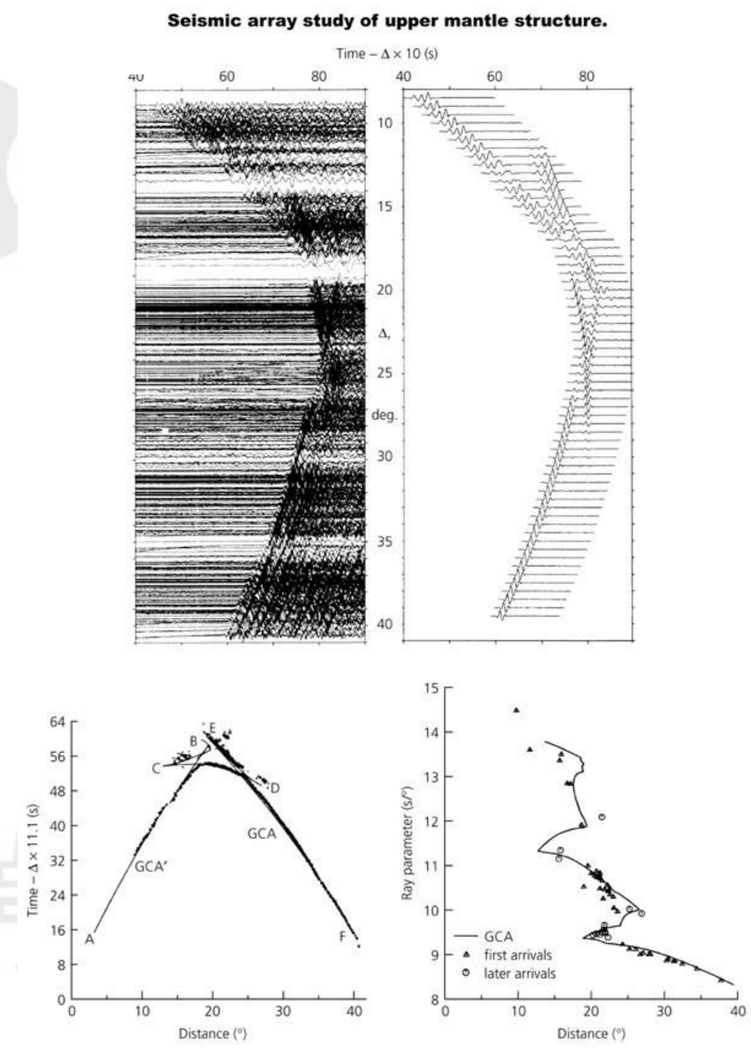
- Moreover, $dT/d\Delta$, that is used in inverting for velocity, is uncertain due to the scattered data.

How can we overcome from these issues?

- Derive information from the waveforms as well as the travel times.

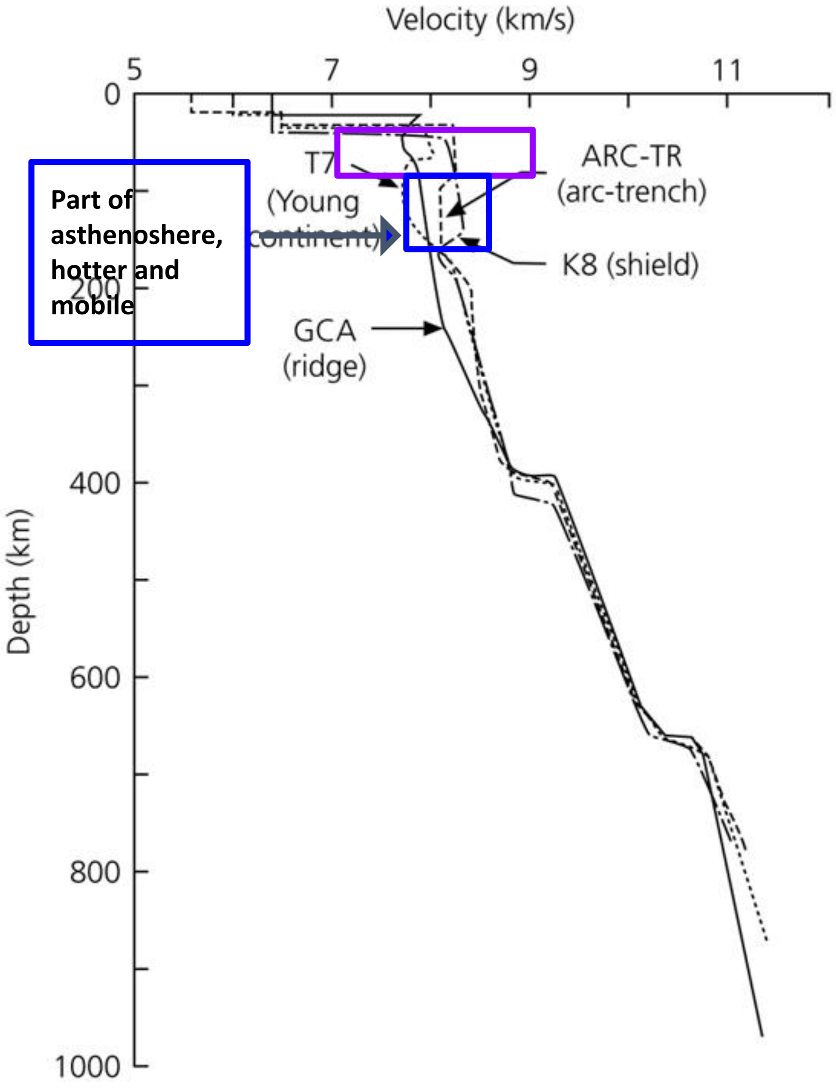
- Use arrays of seismometers spaced closely enough to identify arrivals corresponding to the different branches of triplications.

Case study of triplication



- Example of array study of upper mantle P-wave velocities under the Gulf of California spreading centre.
- Ten earthquake data are used for distance 9^0-40^0.
- Two triplications appears, at 15^0 due to 410 km discontinuity, and another aat 22^0 due to 610 km.
- Travel time and synthetic seismograms are predicted by velocity structure (GCA).
- The effect of discontinuities is also observed on p(Δ) for two groups of arrivals where p increases with Δ.

Figure 3.5-14: Upper mantle velocity models.



In summary,

1. A high velocity lid, or "seismic lithosphere".

1. It is not trivial to relate this directly to the mechanical lithosphere.

→ Both are well developed in the oceans, and less so in the continents.

→ Under cratons, higher velocities seem to go down to 200-250 km depth.

→ This is often associated with "tectosphere" (also more viscous and dense due to water removal).

→ Cratons consist of highly melt depleted mantle that seems to protect the overlying crust from deformation and melting.

Lower mantle structure

- **Velocities increase rapidly with depth for roughly 100 km beneath the 660 km discontinuity, but then increase more slowly.**

- **Rapid increase implies that mineral transformations continues whereas the slow increase implies that the mineralogy and composition of the material are not changing significantly.**

- **Velocity increase are primarily due to the material being compressed by higher pressure.**

- **Weak seismic discontinuities have been reported at a variety of depths such as 900 and 1300 km, perhaps due to fragment of old subducted labs. Presence of this discontinuity may be global or local velocity anomalies.**

D” layer

- **It is present at the very base of the mantle, a fascinating and poorly understood region.**

- **D", the bottom few hundred kilometers of the mantle, was initially differentiated from the rest of the mantle (D') because the velocity gradient with depth is lower.**

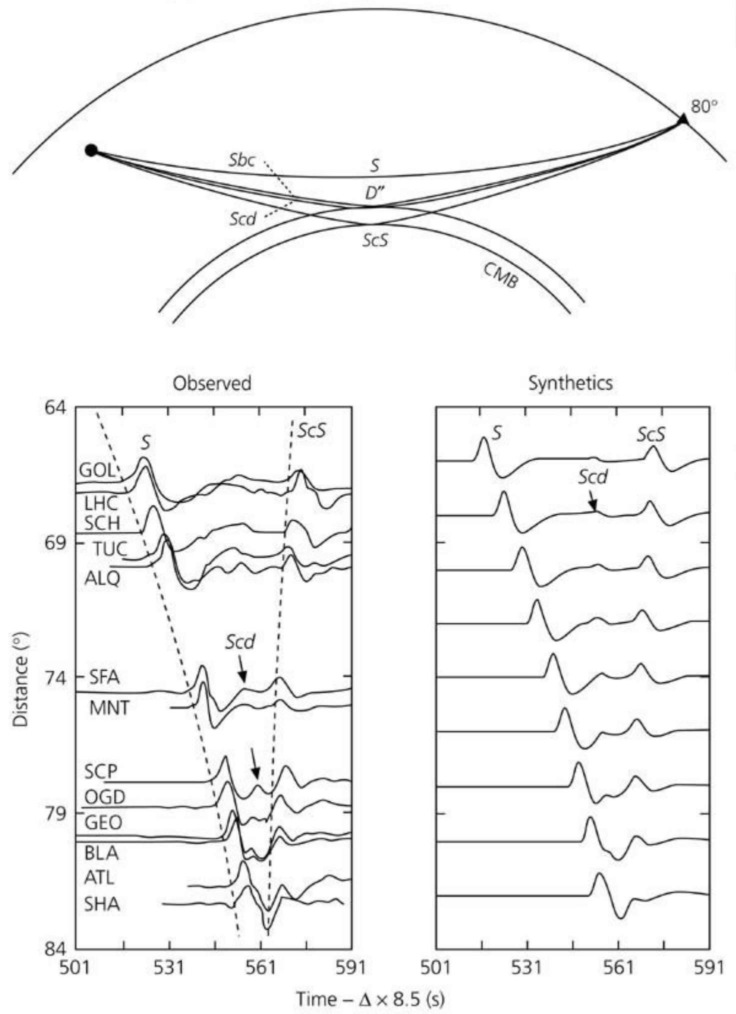
- **D" is now often delineated by the location of the discontinuous velocity increase, which averages about 250 km above the CMB.**

- **D" was first named for a region of lower than expected velocities.**

- **The uncertainties about D", by describing its thickness as 250 ± 250 km (Jeanloz, 1990).**

How to observe D” discontinuity?

Figure 3.5-16: Ray paths and modeling of *Sbc* waves.



- PdP and SdS are used to observe the velocity increase.
- Sba reflects of D”, Scd refracts just below D”. These combine to make the phase called Sds (there is a similar Pds).
- PdP and SdS arrive between the direct (P and S) and core-reflected (PcP and ScS) phases.
- The discontinuity has been observed at many locations on the CMB.
- Although the average depth of the discontinuity is 250 km above the CMB.

D” thickness 250±250 km (Jeanloz, 1990) ?

- **It may be due to large topographic variations over small spatial wavelengths that focus and defocus waves.**

- **There may be no actual discontinuity, but that complex three dimensional velocity heterogeneities give the appearance of a discontinuity.**

- **It is possible that the increase in velocity is associated with subducted lithosphere that sank to the bottom of the mantle.**

*****D" shows additional complexities. There is strong evidence for significant seismic anisotropy. Large lateral variations at both small and large spatial wavelengths occur for velocities within D" and for topography on the CMB.**

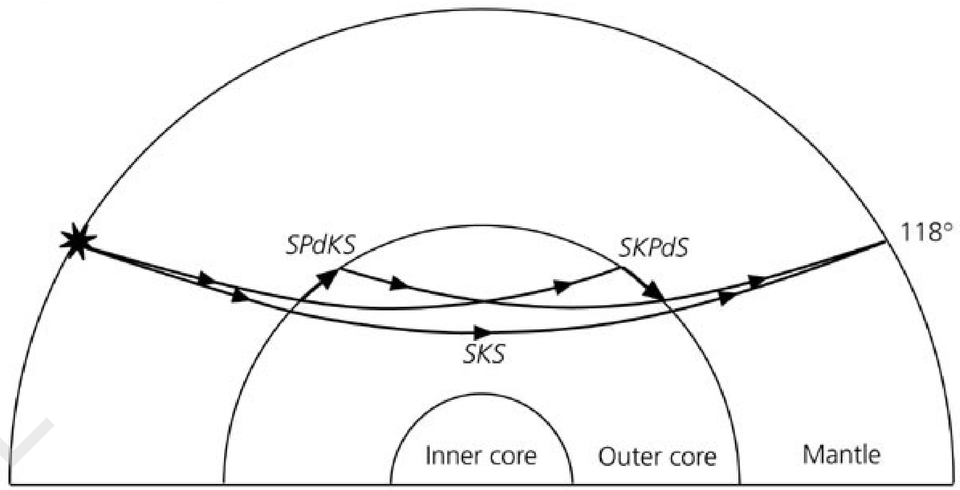
ULVZ(Ultra-low-velocity zone)

Ultra-Low-Velocity Zone (ULVZ) at the very bottom 10-20 km of the mantle.

It is denser than surrounding mantle which may be partly due to iron from the core which makes the partial melt denser.

V_p and V_s may be 10% and 30% lower than the rest of D".

Figure 3.5-18: Ray paths of the *SPdKS* phase.



It is observed with an unusual body wave phase, SPdKS, which is similar to SKS but travels partly as a diffracted P wave.

SPdKS appears as a shoulder of the SKS arrival, and is very sensitive to the P-wave velocity structure just above the CMB.

Summary

- The ray parameter for the spherical earth is given as $p = \dfrac{r \sin i}{v}$

- Ray path travel time and angular distance for spherical earth is expressed as

$$T(p) = \int \frac{ds}{v} = 2\int_{r_p}^{r_0} \frac{\zeta^2 dr}{r(\zeta^2 - p^2)^{\left(\frac{1}{2}\right)}} \qquad \Delta(p) = \int d\theta = 2p \int_{r_p}^{r_o} \frac{dr}{r(\zeta^2 - p^2)^{1/2}}$$

- For a triplication, the back branch meets the two forward branches at two points on the travel time and p(Δ) curves, for triplication $\dfrac{dp}{d\Delta} = \infty$

- Herglotz–Wiechert integral is an approach which gives the distance traveled by a ray with ray parameter p as a function of the velocity structure

$$\Delta(p) = 2p \int_{r_p}^{r_o} \frac{dr}{r(\zeta^2 - p^2)^{1/2}}$$

- Travel time data are generated by combining data from numerous earthquake at different epicentral distances.

Summary

- **Surface reflections PP and SS are maximum-time phases in contrast to phases reflection phases like ScS, which are minimum phases.**

- **For the core, the shadow zone occurs for distances between ~98° to ~145° fo the P-wave and seismic energy also enters the shadow zone via P and S waves that diffract around core.**

- **"K" denotes passage through the outer core, reflections off the CMB are denoted by a lower-case "c" and P waves in the inner core are denoted by "I".**

- **Sub-crustal lithosphere is characterised by the high P- and S-wave velocity about 8.1 and 4.5 km/s respectively. It is approximately zero at mid oceanic ridges and ~200 km beneath the stable craton.**

- **Across entire Earth, there is a 'Low Velocity Zone (LVZ)' beneath the lithosphere coincides with the expected mechanically weak asthenosphere underlying the stronger lithosphere.**

Summary

- Velocity differences between the crust and the mantle results from their different compositions.

- The velocity discontinuities at depth of 410 km and 660 km is marked as transition zone between the upper and lower mantles

- Upper mantle travel times show two triplications around 15° and 22° caused by the 410 and 660 km discontinuities.

- At the very bottom 10-20 km of the mantle , there is an evidence of ultra-low-velocity zone(ULVZ)

- D'' layer is present at the very base of the mantle, a fascinating and poorly understood
region and show strong evidence for significant seismic anisotropy.

REFERENCES

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- **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 !