

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 03: Body wave travel time, JB model, Body wave phases and nomenclature

CONCEPTS COVERED

- Body wave travel time
- Jeffreys-Bullen(JB) earth model
- Body wave phases
- Body wave phases nomenclature
- Unusual characteristic surface reflected phases

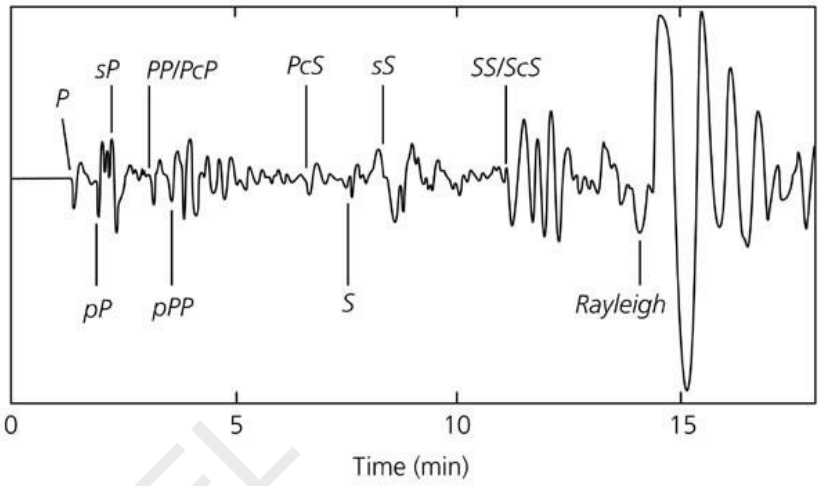
Body wave phases

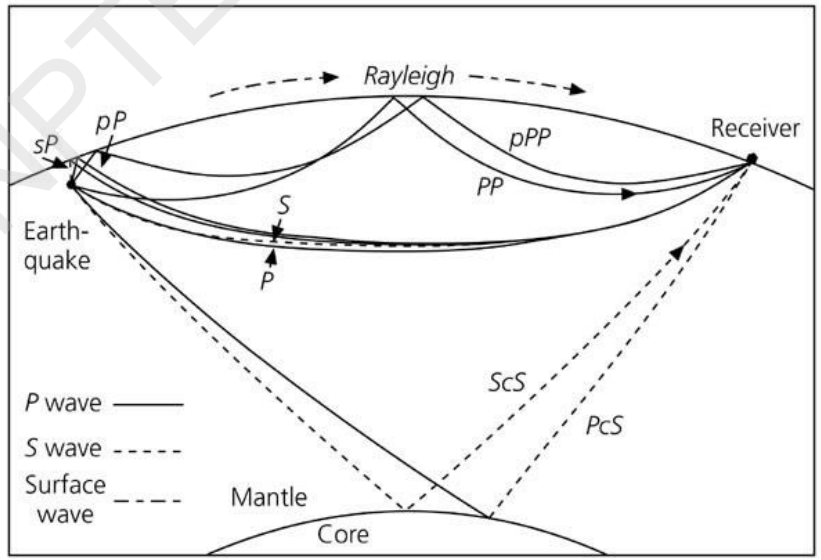
What are phases?

Seismogram contains many arrival corresponding to different travel paths, are called phases.

Body waves are the one which travel through the Earth's interior.

Figure 3.5-2: Selection of body phases and their ray paths.





Earthquake from Tonga subduction zone in Hawaii.

Table 3.5-2: Body wave phase nomenclature

Name	Description
P	Compressional wave
S	Shear wave
K	*P* wave through outer core
I	*P* wave through inner core
J	*S* wave through inner core
PP	*P* wave reflected at surface
PPP	*P* wave reflected at surface twice
SP	*S* wave reflected at surface as *P* wave
PS	*P* wave reflected at surface as *S* wave
pP	*P* wave upgoing from focus, reflected at surface
sP	*S* wave upgoing from focus, converted to *P* at surface
c	Wave reflected at core-mantle boundary (e.g. *ScS*)
i	Wave reflected at inner core-outer core boundary (e.g. *PKiKP*)
P′	Abbreviation for *PKP*
P_d or P_{diff}	*P* wave diffracted along core-mantle boundary

Travels downward from source

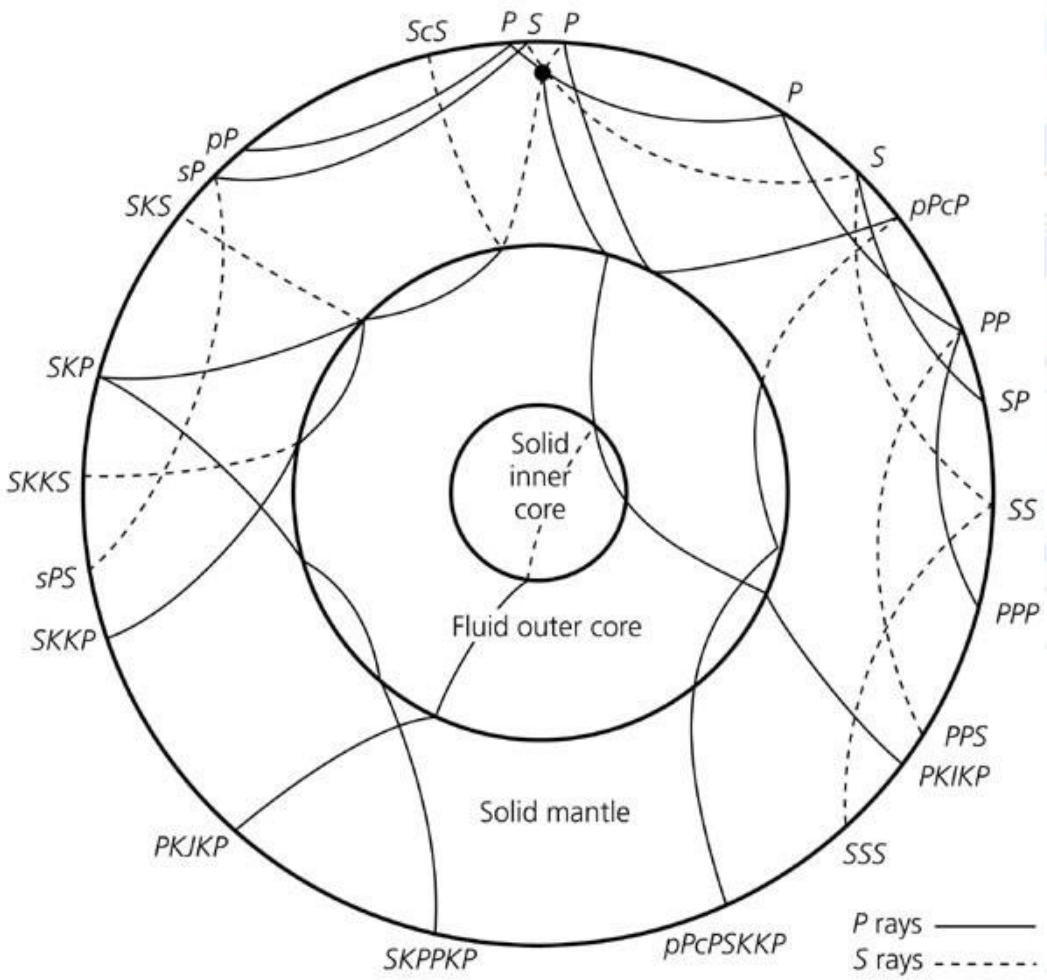
Seismic phases are named based on their paths through the Earth.

Reflections from the inner or outer core have 'i' or 'c' in their nomenclature.

A ray that travels through the outer core gets a *K* added, and for the inner core, an *I* or *J* added (for P or S waves).

Body wave phases nomenclature

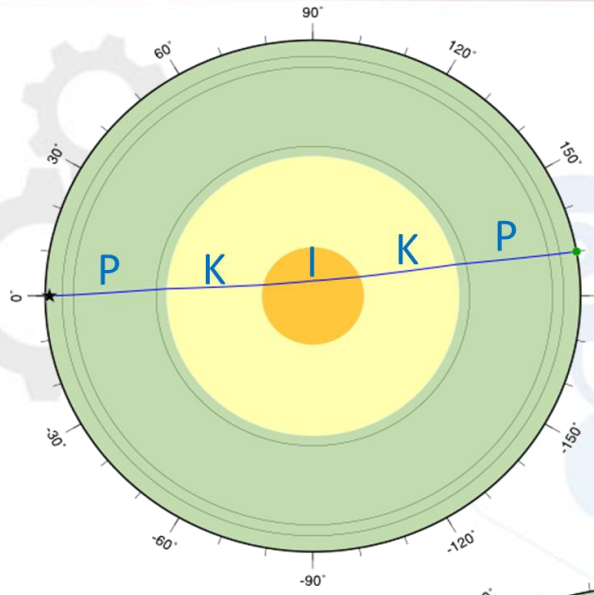
Figure 3.5-5: Illustration of various body wave phases.

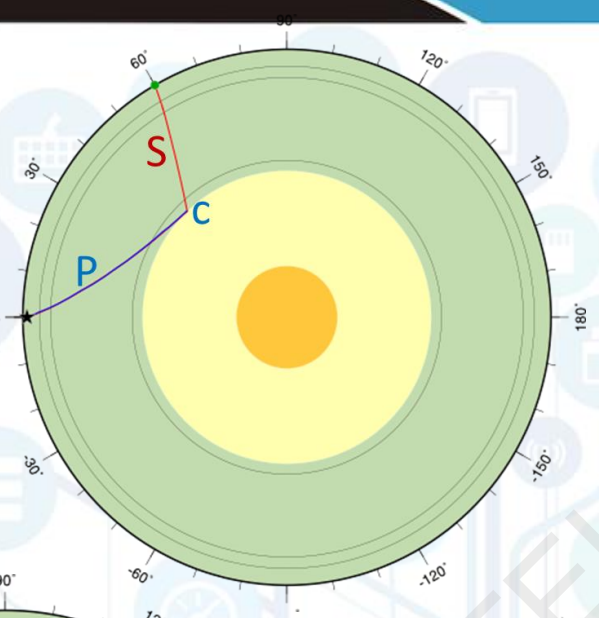


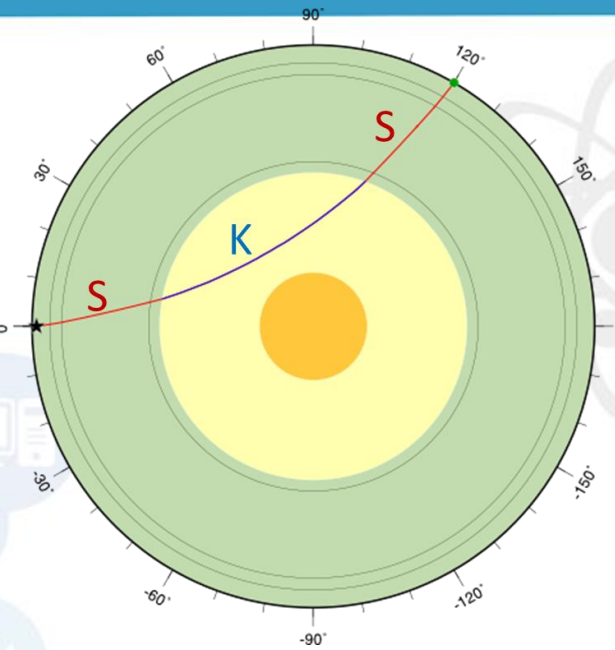
- **Direct** P-wave and S-wave arrivals are named as “P” and “S”.
- A ray that starts out from the source downward has capital ‘P or S’, while for upgoing ray from source has little ‘p or s’.
- Class of arrivals involving **reflection at the surface** are denoted by, single surface reflection as PP, and for two reflections in PPP. Similarly for S-wave reflection it is SS, SSS.
- **Converted phases**, like P waves convert to S-waves upon surface reflection, like PS vice versa.

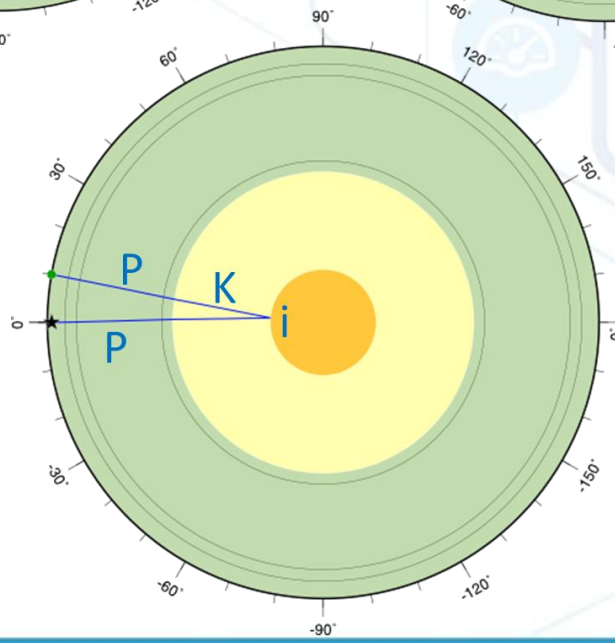
Body wave phases nomenclature

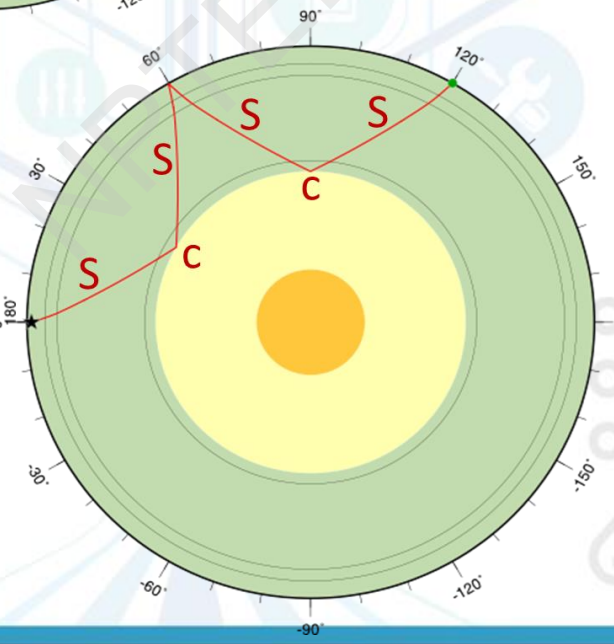
- P or S wave upgoing from focus and reflected at the surface denoted as pP, and sP
- Wave reflected at the core-mantle boundary like PcP and PcS
- Wave reflected at the inner core-outer core boundary (eg. PKiKP)
- P waves that travel through the outer and inner core is represented as "K" and "I". Everything that travels through the liquid outer core is P-wave (represented as 'K') because S-wave cannot travel through liquid.
- S waves that travel through the outer and inner core is represented as "K" and "J". "J" is very rare to observe (very weak and comes later on seismogram).
- P wave diffracted along the core-mantle boundary (P_d or P_{diff}).


P
K
I
K
P


S
c
P


S
K
S

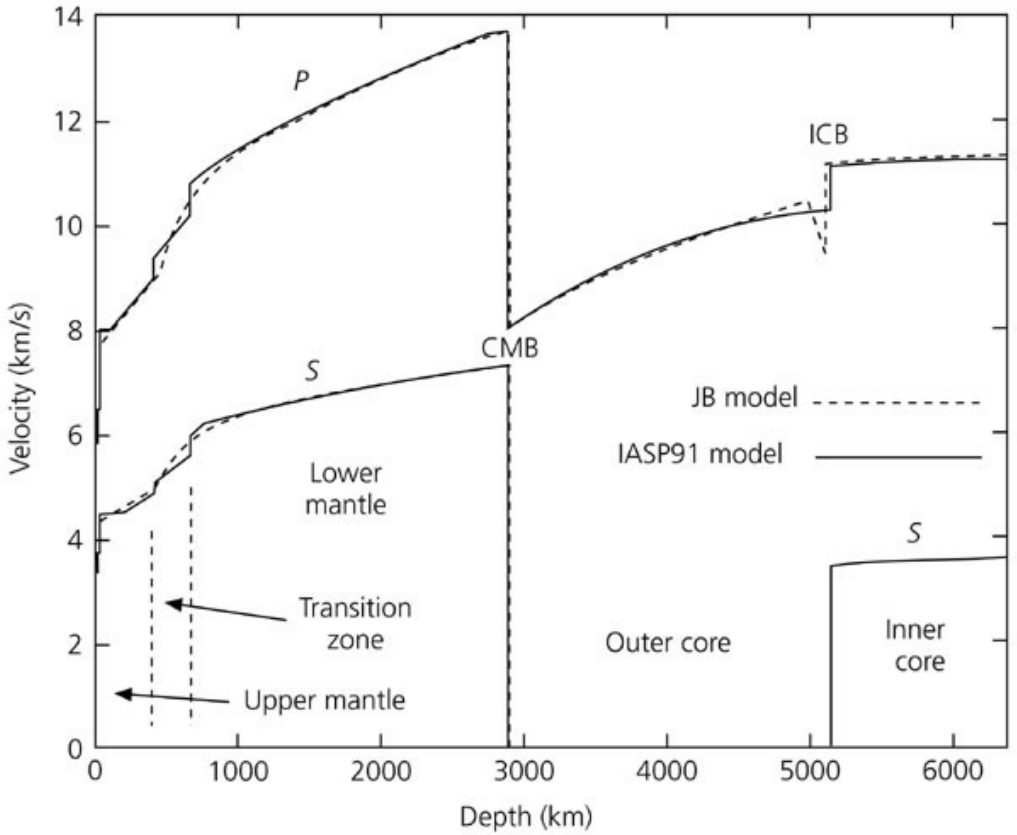

P
K
i
P


S
S
S
c
S
c

Body wave travel time

Jeffreys-Bullen(JB) earth model

Figure 3.5-1: Comparison of the J-B and IASP91 earth models.



- Travel time data are generated by combining data from numerous earthquake at different epicentral distances.
- These observations are the primary data for viewing basic features of the earth's velocity structure. The concept was largely developed in 1940s.
- Jeffreys-Bullen(JB) earth model treat the earth as a series of shells, characterized by the behaviour of velocity with depth.

Jeffreys-Bullen(JB) earth model (Other models PREM, IASP91, AK135)

Region	Depth (km)	Features of region
A	33	Crustal layers
B	413	Upper mantle: steady positive P and S velocity gradients
C	984	Mantle transition region
D	2898	Lower mantle: steady positive P and S velocity gradients
E	4982	Outer core: steady positive P velocity gradient
F	5121	Core transition: negative P velocity gradient
G	6371	Inner core: small positive P velocity gradient

- The mantle is divided into upper mantle (region B) and lower mantle (region D), both of which have smooth velocity gradients.
- Upper and lower mantle regions is separated by region C, the mantle transition zone where velocities increase rapidly with depth.
- Beneath the core-mantle boundary(CMB), the core is divided into an outer core (region E) and an inner core (region G), separated by transition zone (region F).
- The inner core boundary (ICB) separated regions F and G.

Jeffreys-Bullen(JB) earth model

- The lower mantle is divided into regions D’ (1000-2700 km depth)
- D”(2700-2900), the zone above the core-mantle boundary with a reduced velocity gradient.

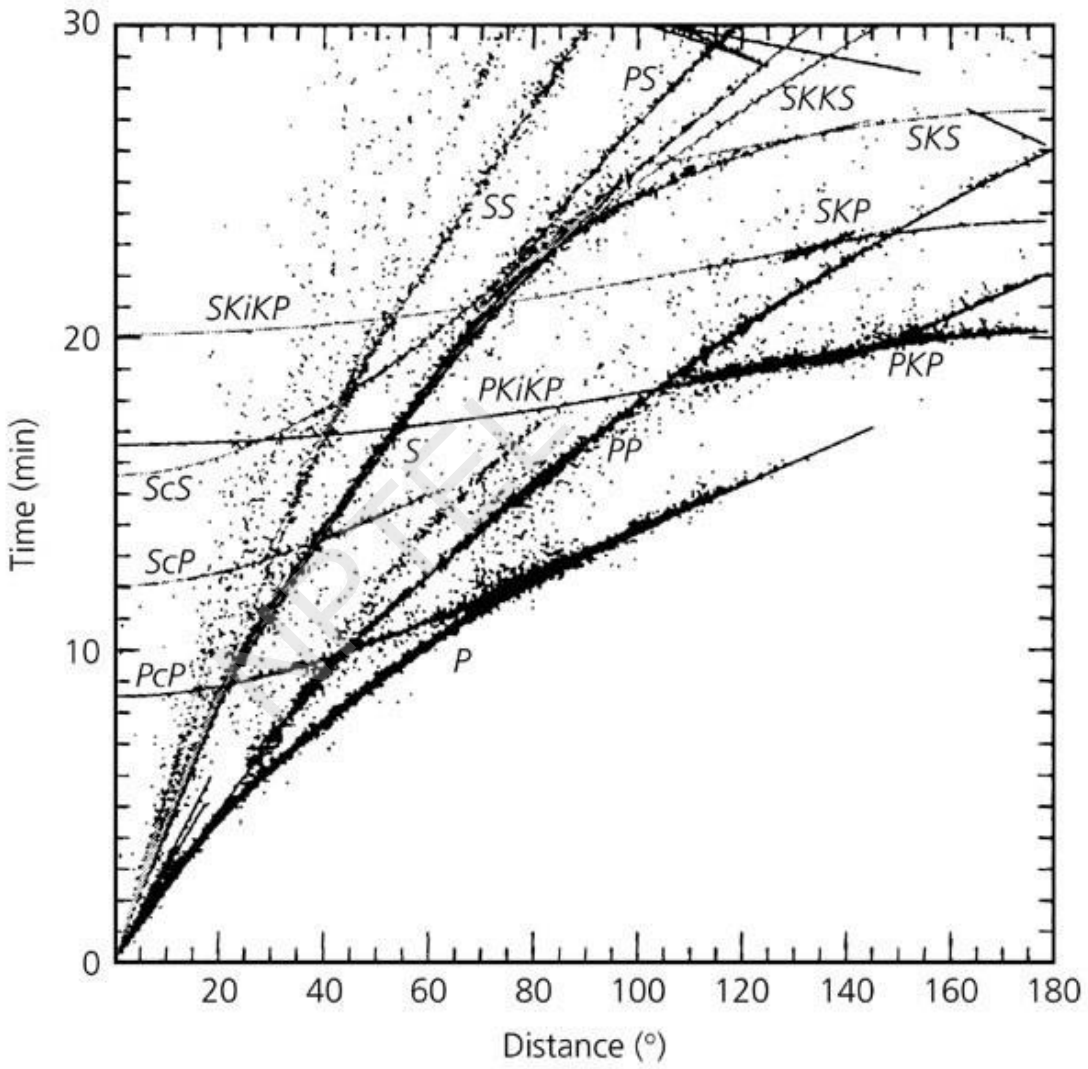
Drawback of JB earth model

- JB model did not resolve shear velocities in the inner core, whereas recent model have finite S velocity in the inner core, which implies that it is solid.
- It does not provide much detail about mantle transition zone and core-mantle boundary
- Recent models with higher resolution does not include velocity “notch” at the inner core-outer core boundary.

Body wave phases

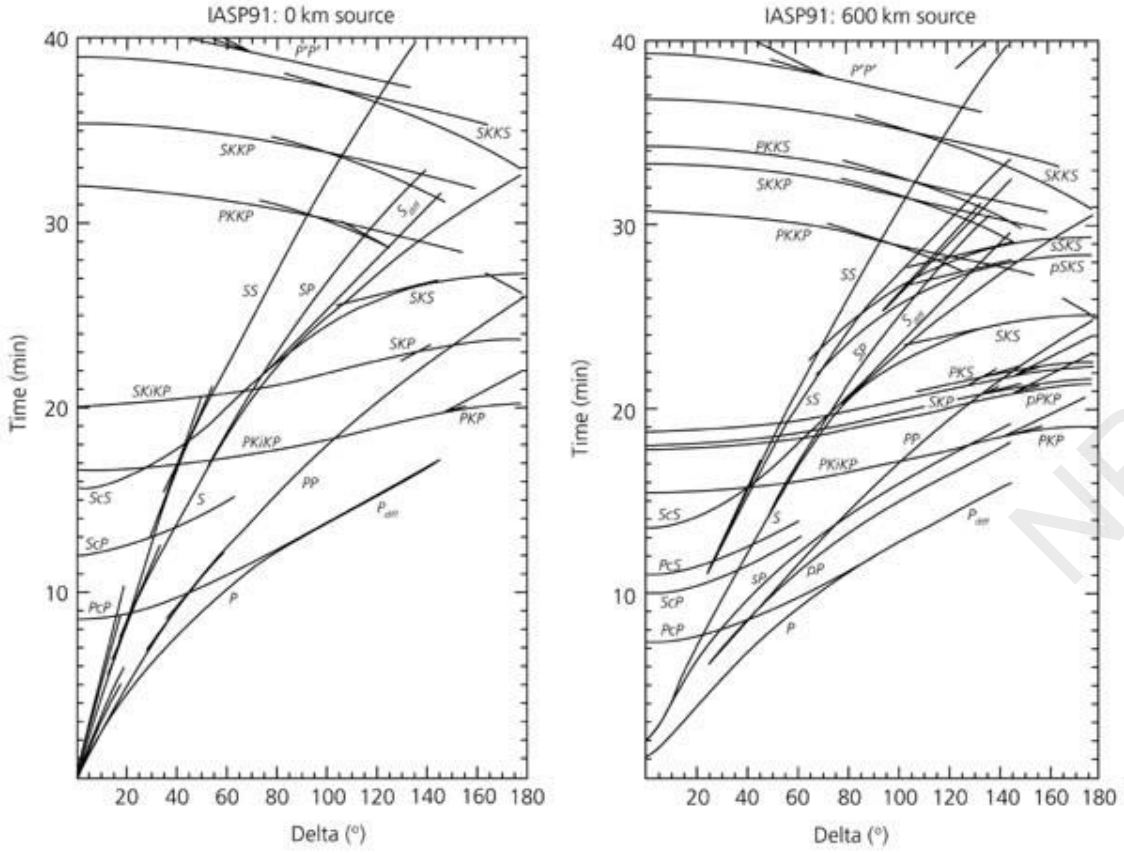
Travel time observations can be used to develop and test earth models giving P and S velocities as a function of depth.

Figure 3.5-3: Travel time data and curves for the IASP91 model.



Body wave phases

Figure 3.5-4: IASP91 travel time curves for a surface and deep source.



- Travel time curves depends on the source depth.
- As shown for a surface source and a source at 600 km depth.
- P'P' is the short for PKIKP.

The Earth-flattening transformation

The curvature of the travel time curve in spherical Earth can be simulated in a flat-Earth model: that means we can go back and forth between cartesian world to spherical world.

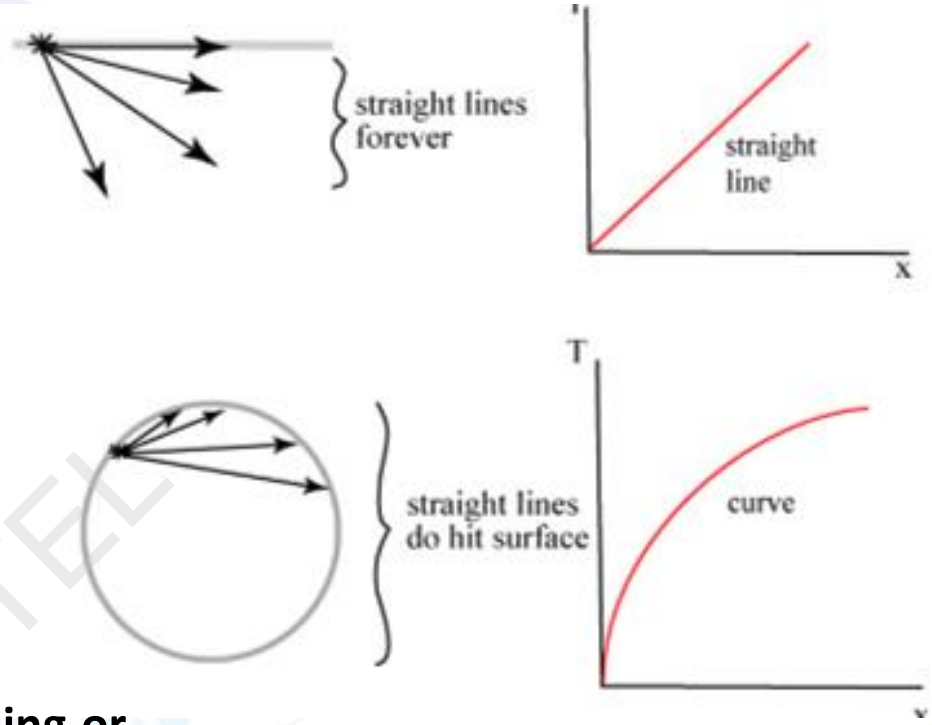
we can consider depth in terms of fractional radius (Z_f), defined as

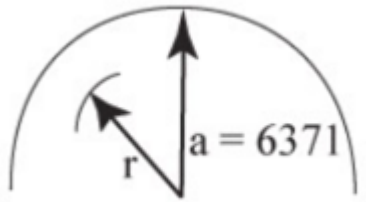
$$e^{\frac{-z_f}{a}} = \frac{r}{a}$$

or

$$z_f = -a \ln\left(\frac{r}{a}\right)$$

where, Z_f is the depth of flattening or the depth at which a layer in a flat-earth model with have to be moved in order to be equivalent to a spherical model at a given depth.





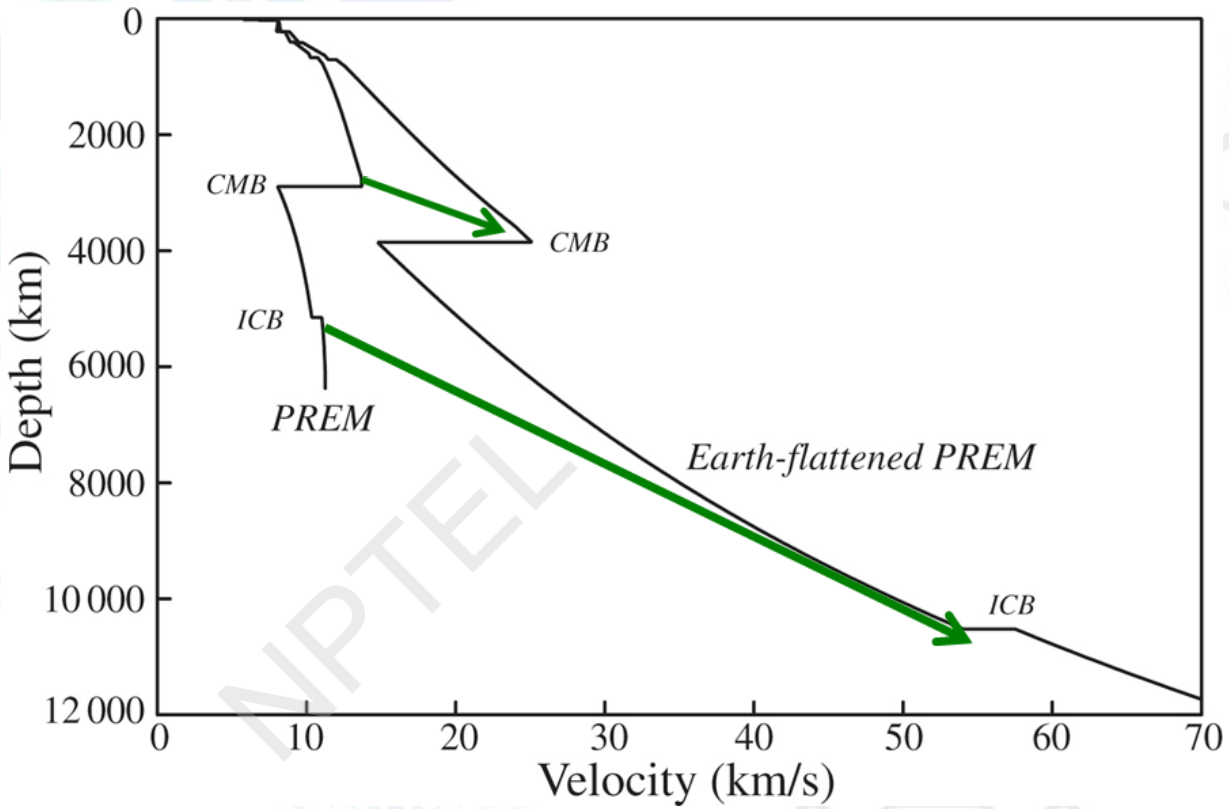
The velocity transform for the same is given by

$$v_f(z_f) = \left(\frac{a}{r}\right) v_s(r)$$

where $r = a - z_s$

z_s is the depth in the spherical earth

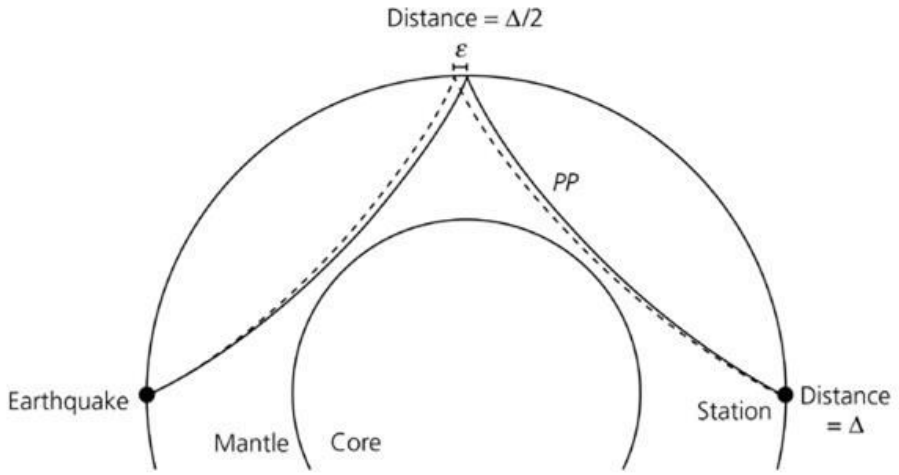
a is radius of the earth

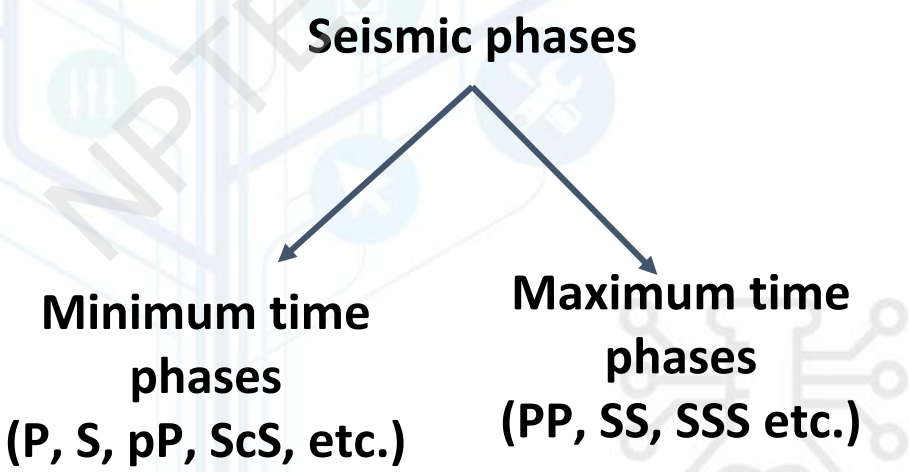


Unusual characteristic surface reflected phases.

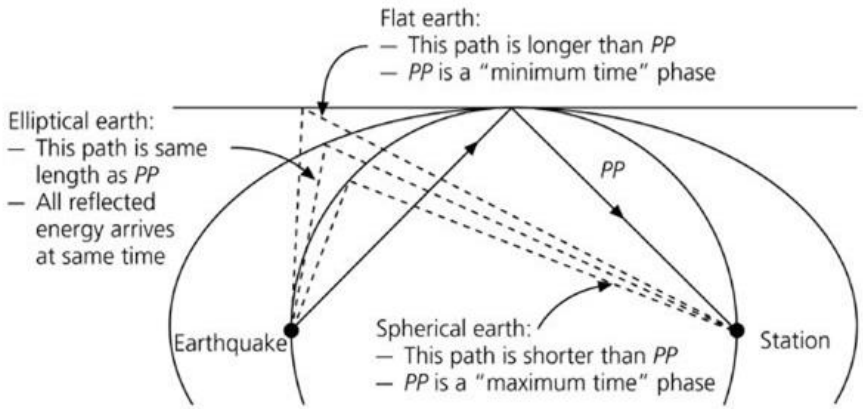
- By Fermat's principle, seismic phases have either minimum or maximum travel times with respect to adjacent paths.
- Most body waves are minimum travel time phases. But surface reflections, like PP and SS, are maximum travel time phase.

Figure 3.5-6: Explanation for PP as a "maximum time" phase.





Unusual characteristic surface reflected phases.



Consider ray paths for a surface reflection that differ slightly from the true path, so the reflection bounces off the surface a small distance ε from the actual bounce point at Δ/2, halfway between the source and the receiver.

Their travel time is thus the sum of the travel times for two legs

$$T(\Delta) = T\left(\frac{\Delta}{2} + \epsilon\right) + T\left(\frac{\Delta}{2} - \epsilon\right)$$

Using the first two terms of the Taylor series

$$T\left(\frac{\Delta}{2} + \epsilon\right) \approx T\left(\frac{\Delta}{2}\right) + \epsilon\frac{\mathrm{d}T}{\mathrm{d}\Delta} + \frac{\epsilon^2}{2}\frac{d^2T}{d\Delta^2}$$

$$T\left(\frac{\Delta}{2} - \epsilon\right) \approx T\left(\frac{\Delta}{2}\right) - \epsilon\frac{\mathrm{d}T}{\mathrm{d}\Delta} + \frac{\epsilon^2}{2}\frac{d^2T}{d\Delta^2}$$

Unusual characteristic surface reflected phases.

From last equation we have $T(\Delta) \approx 2T\left(\frac{\Delta}{2}\right) + \epsilon^2 \frac{d^2T}{d\Delta^2}$

By Fermat's principle, the true ray path, the derivative of travel time with respect to ε is zero

$$\frac{\mathrm{d}T}{\mathrm{d}\epsilon} = 2\epsilon \frac{d^2T}{d\Delta^2} = 0$$

so ε is zero, giving the expected bounce point. To see if this is a minimum or a maximum, we form the second derivative

$$\frac{d^2T}{d\epsilon^2} = 2\frac{d^2T}{d\Delta^2}$$

The direct P-and S-waves have travel time curves that are concave down, $\frac{d^2T}{d\Delta^2} < 0$ so their surface reflections PP and SS are maximum-time phases in contrast to phases reflection phases like ScS, which are minimum phases.

Summary

- Travel time data are generated by combining data from numerous earthquake at different epicentral distances.
- Jeffreys-Bullen(JB) earth model treat the earth as a series of shells, characterized by the behaviour of velocity with depth.
- JB model did not resolve shear velocities in the inner core, whereas recent model have finite S velocity in the inner core, which implies that it is solid
- The seismogram shows the arrivals of different phases, correspondent to body waves.
- Surface reflections PP and SS are maximum-time phases in contrast to phases reflection phases like ScS, which are minimum phases

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 !