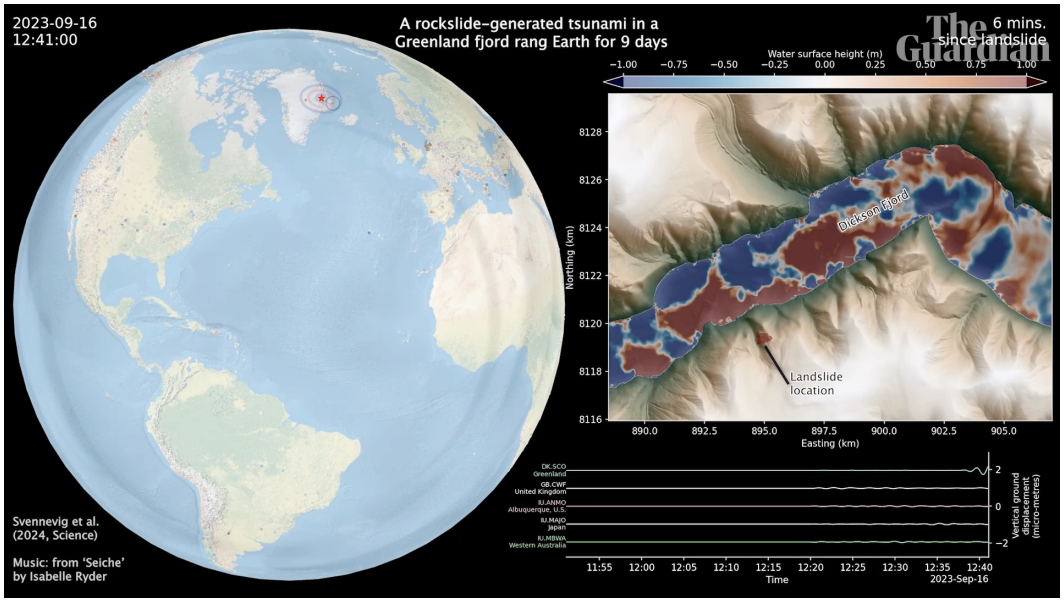
Basic Seismology

What produces seismic waves?

Any **sudden movement of materials** within the Earth causes seismic waves

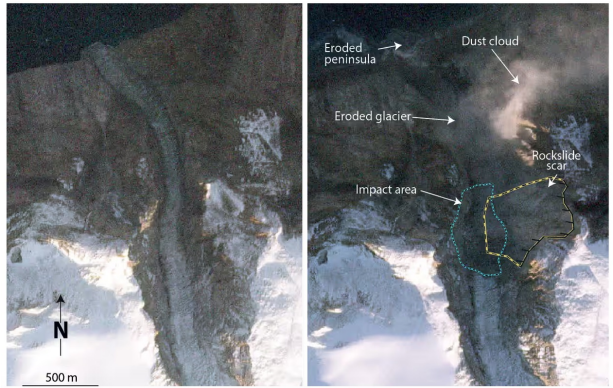
This movement can be an **earthquake, volcanic eruptions** (magma movements), **landslides, explosions**, etc



The Guardian

Entire Earth vibrated for nine days after climate-triggered mega-tsunami

Landslide in Greenland caused unprecedented seismic event that shows impact of global heating, say scientists

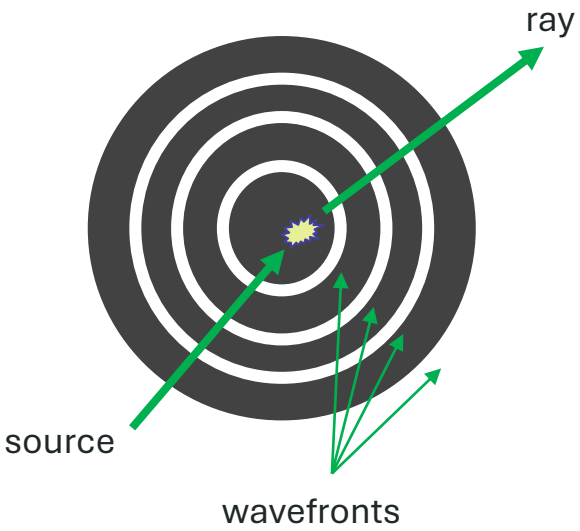


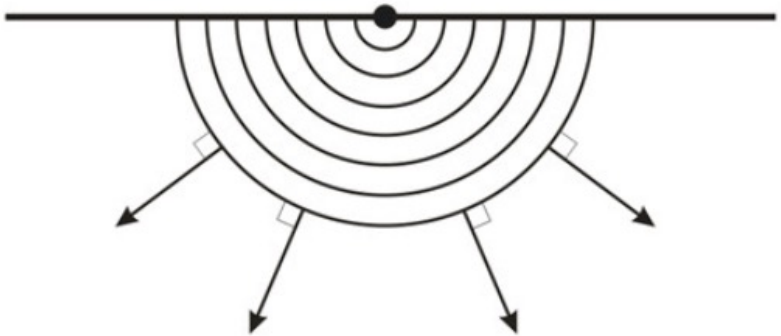
The fjord system before (left) and after landslide and tsunami. Photograph: Planet Labs

Seismic wavefronts and rays

Wavefronts are a collection of points of the seismic wave that are doing the same thing at the same time.

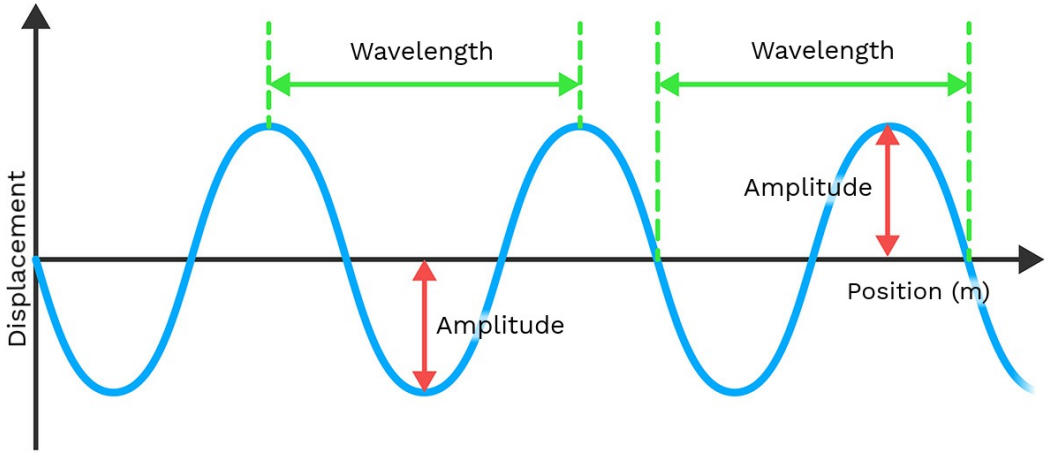
A seismic ray is a representation for how a wave moves through a medium. Rays are lines drawn perpendicular to wavefronts and go off in all directions.





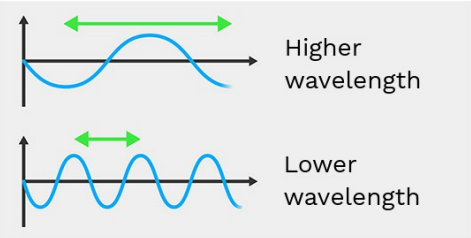
Terminology

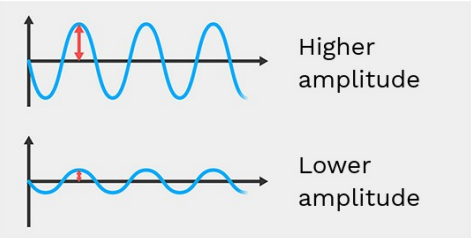
Wavelength & Amplitude



Wavelength is the *distance* between two repeating points on a wave (for example, peak to peak).

Amplitude is the *height* of the wave, measured from the resting (middle) position to the peak.



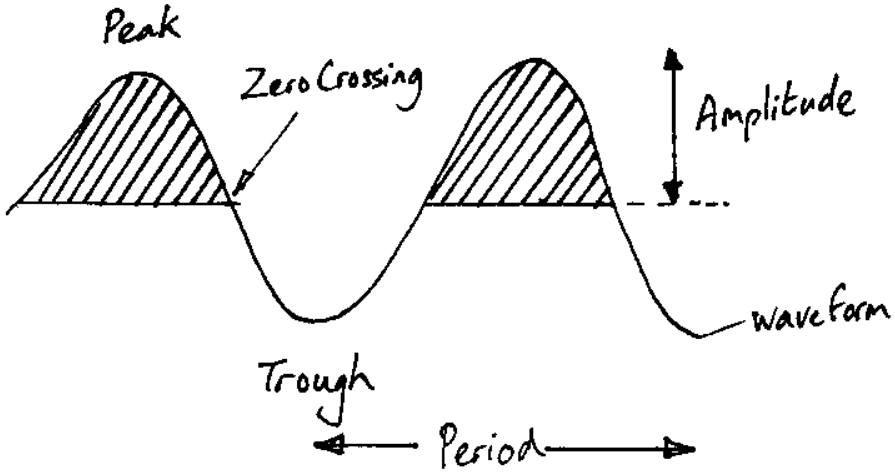


Basic definitions

Period - time between peaks, troughs or zero crossing on a waveform; measured in seconds (s)

Frequency - number of times a wavelet repeats a second; measured in hertz (Hz = s-1)

Velocity = Frequency x Wavelength



Questions

Two seismic waves are recorded at the same station. Wave X arrives later and shows **larger amplitudes** but **longer spacing between peaks** than Wave Y.
Which wave has:
a) Greater ground displacement?
b) Longer period?

Questions

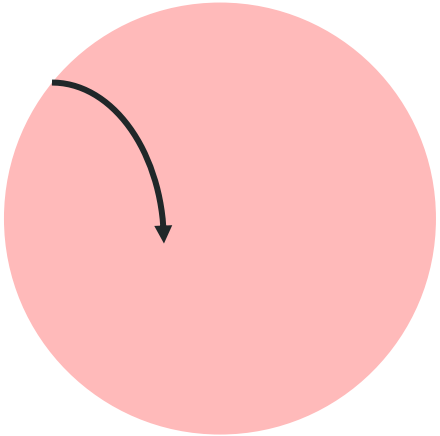
On a seismogram, Wave X has **twice the amplitude** of Wave Y, but Wave Y has **half the period** of Wave X.
Which wave is associated with:
a) Stronger shaking?
b) Faster oscillations?

Questions

A seismic wave travels at a velocity of **6 km/s** and has a frequency of **2 Hz**. What is its wavelength?

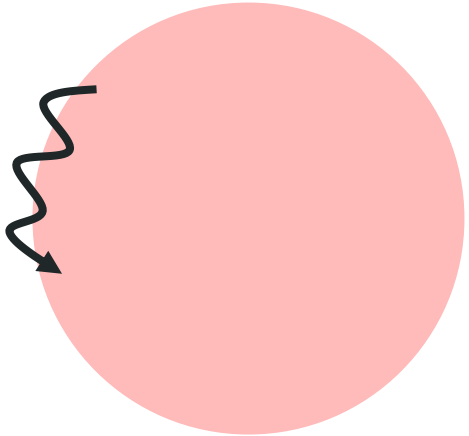
Types of Seismic Waves

Body waves



Body waves can travel through Earth’s interior.

Surface waves

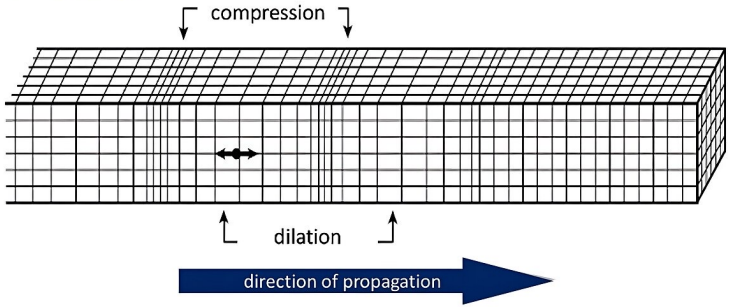


Surface waves propagate only at the interface between two different media (e.g. Earth’s surface).

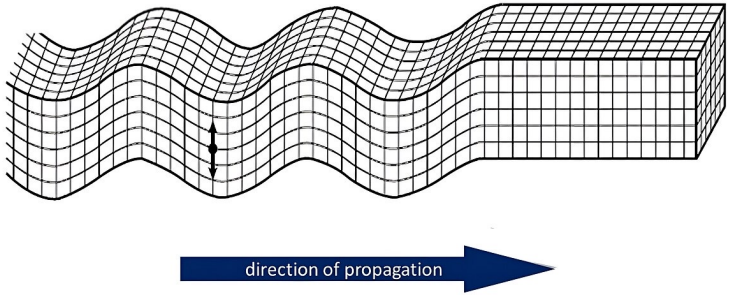
Types of seismic waves

Body Waves

P Wave

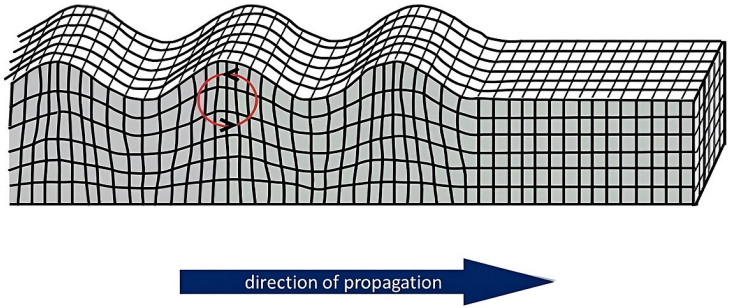


S Wave

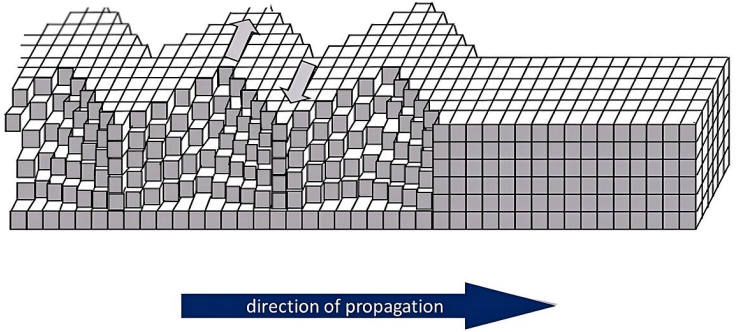


Surface Waves

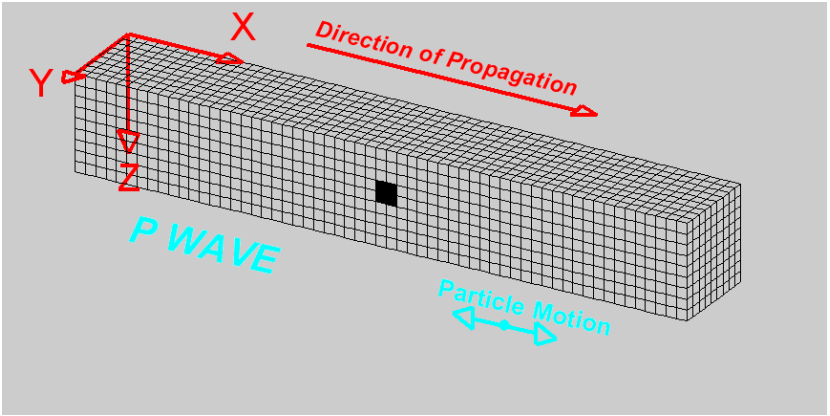
Rayleigh Wave



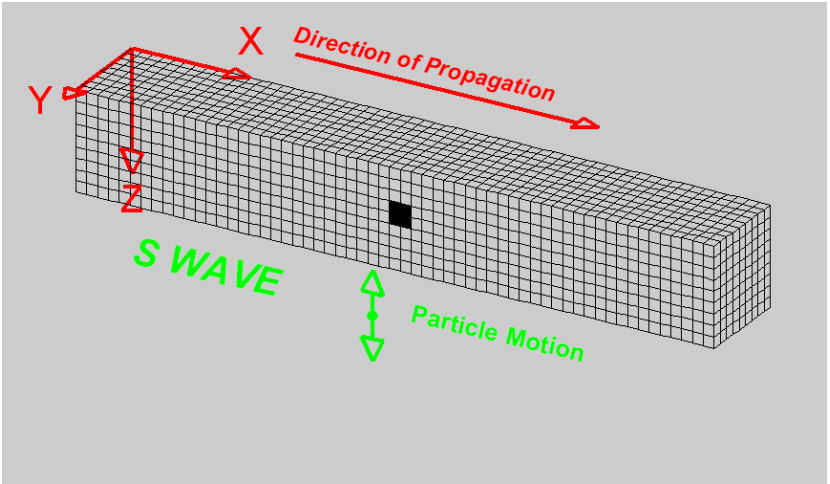
Love Wave



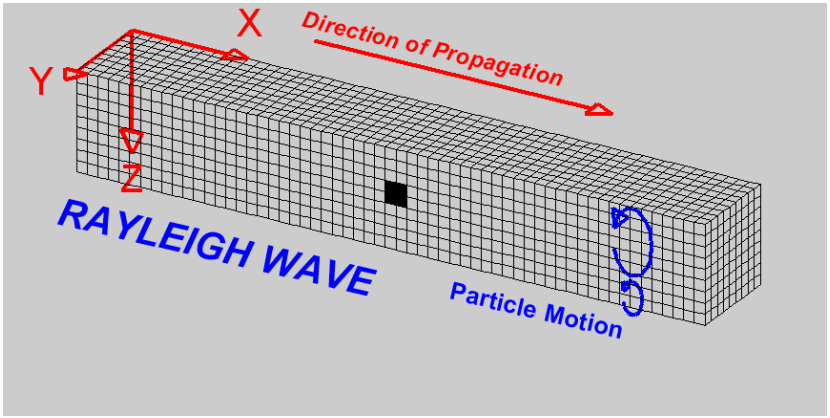
P-wave
(Pressure)
(Primary)



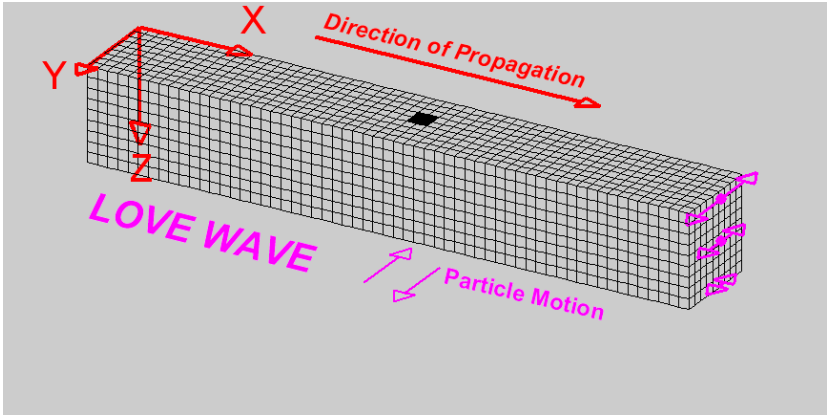
S-wave
(Shear)
(Secondary)



Rayleigh Wave
LR

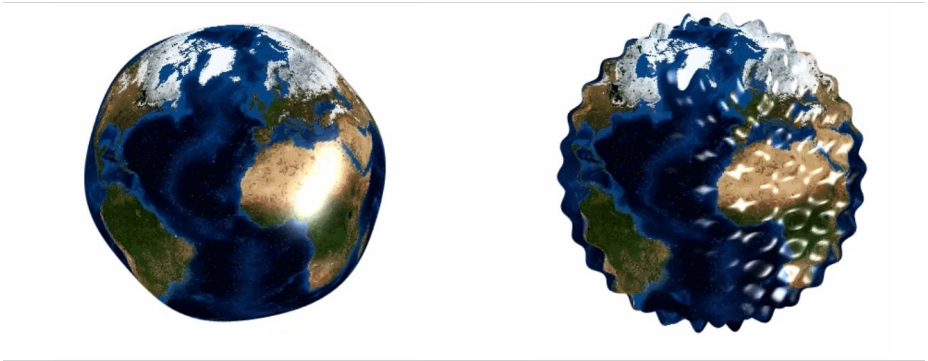


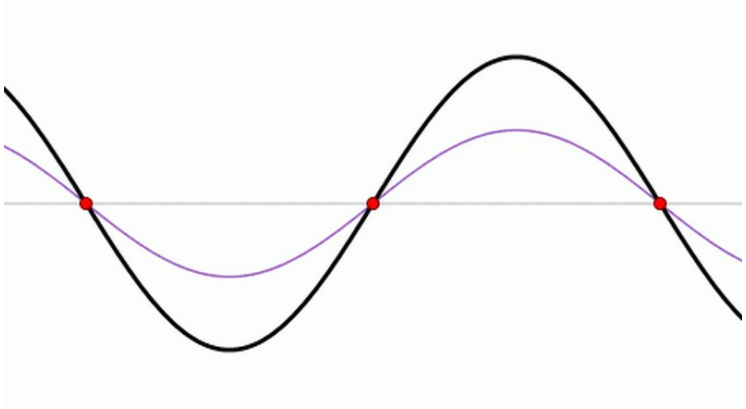
Love Wave
LQ



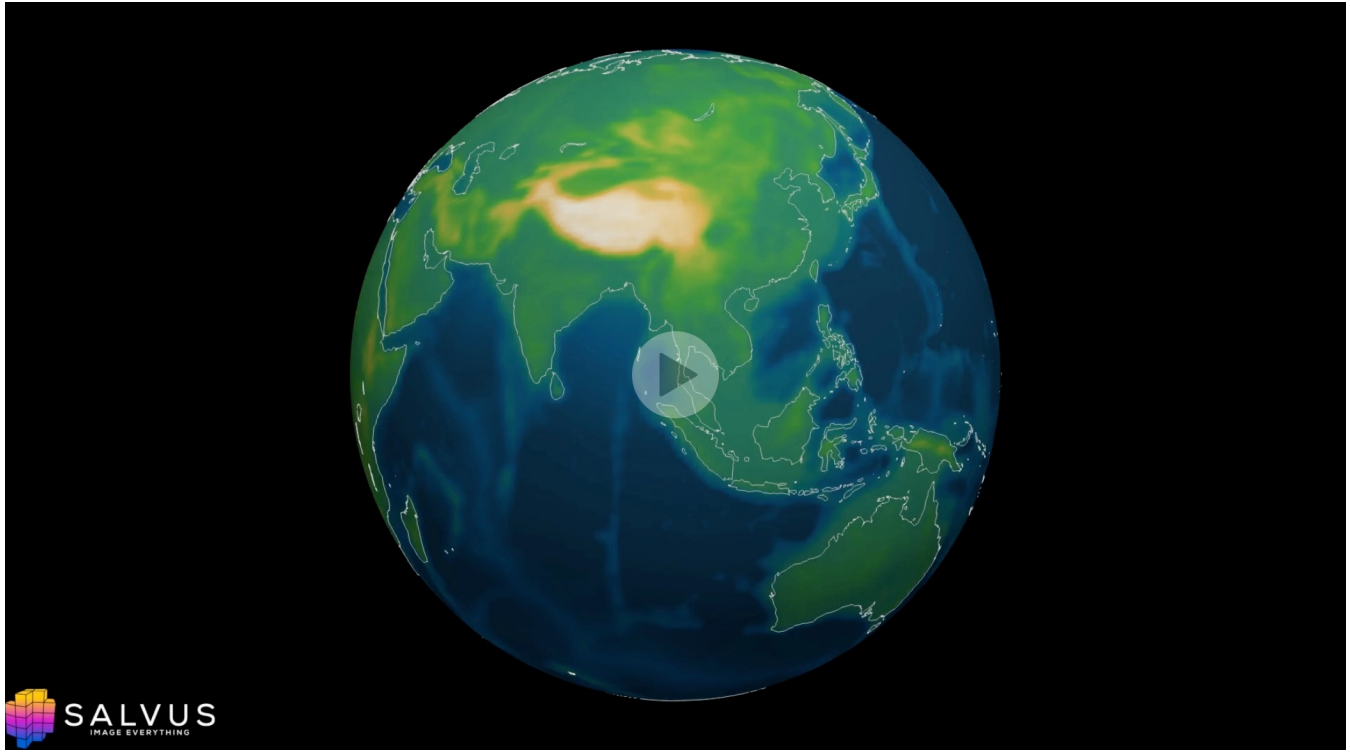
Earth’s normal modes

In seismology, the Earth’s normal modes, also known as free oscillations, refer to the natural, resonant vibrations of our planet that occur after significant seismic events, such as large earthquakes. These oscillations cause the Earth to “ring” like a bell, producing standing waves that can persist for extended periods, sometimes lasting days or even weeks.

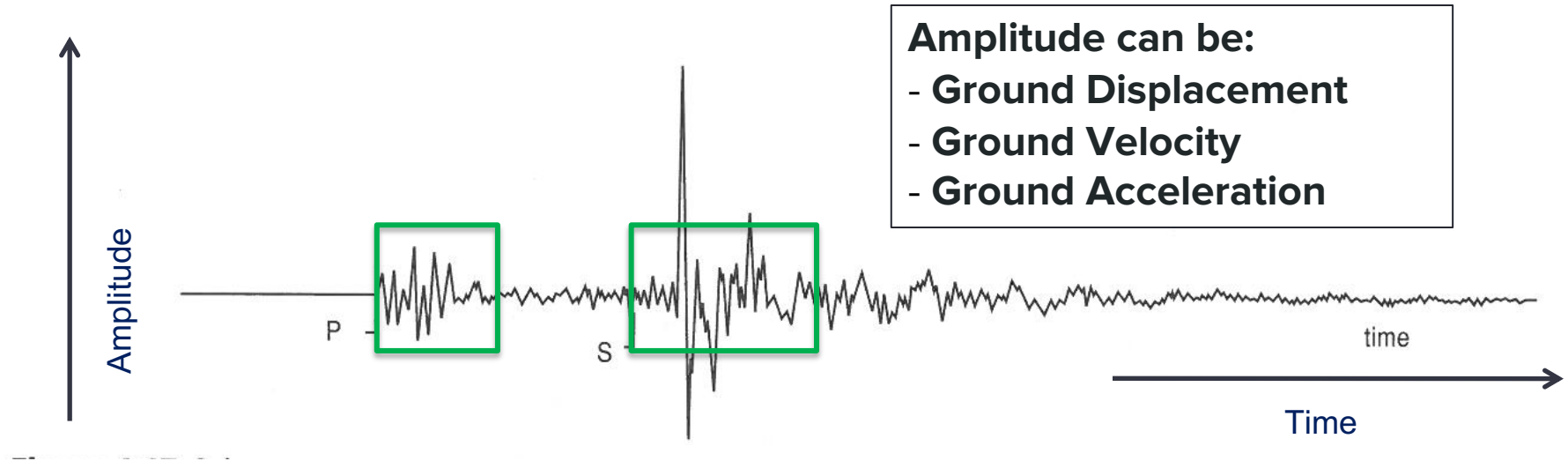




Earth’s normal modes



Idealized seismogram



What is a time series?

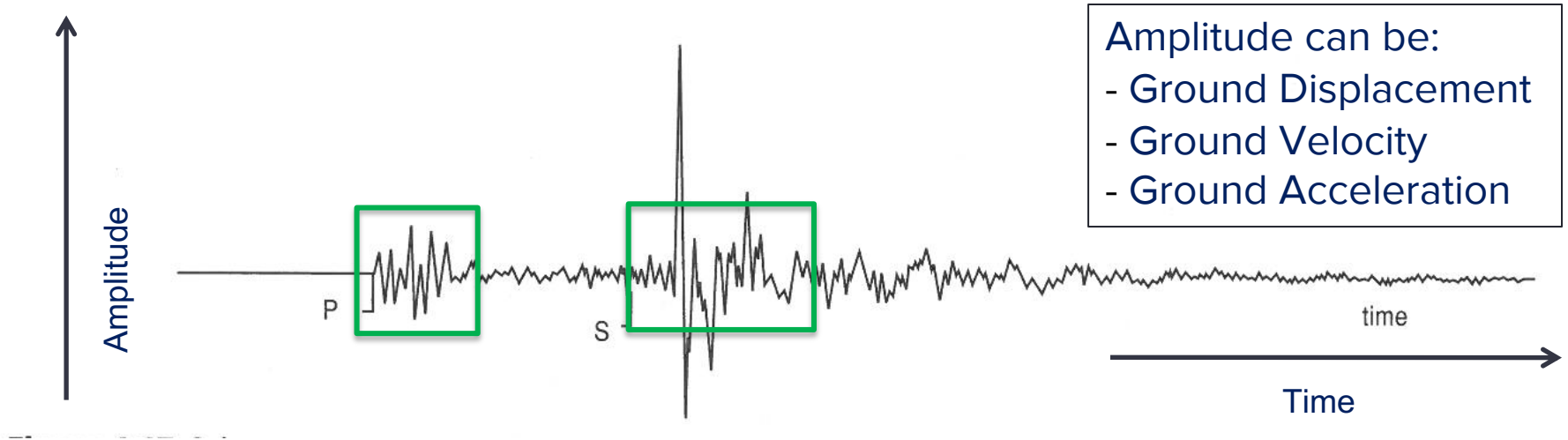
A sequence of numbers measured at a set ***sampling rate***

e.g. 0,1,5,2,8,9,4,2,7....

The sampling rate depends on the frequency we want to record.

Typical sampling rates are on the order of 100 Hz (1 sample every 0.01 seconds).

Idealized seismogram



Amplitude can be:
- Ground Displacement
- Ground Velocity
- Ground Acceleration

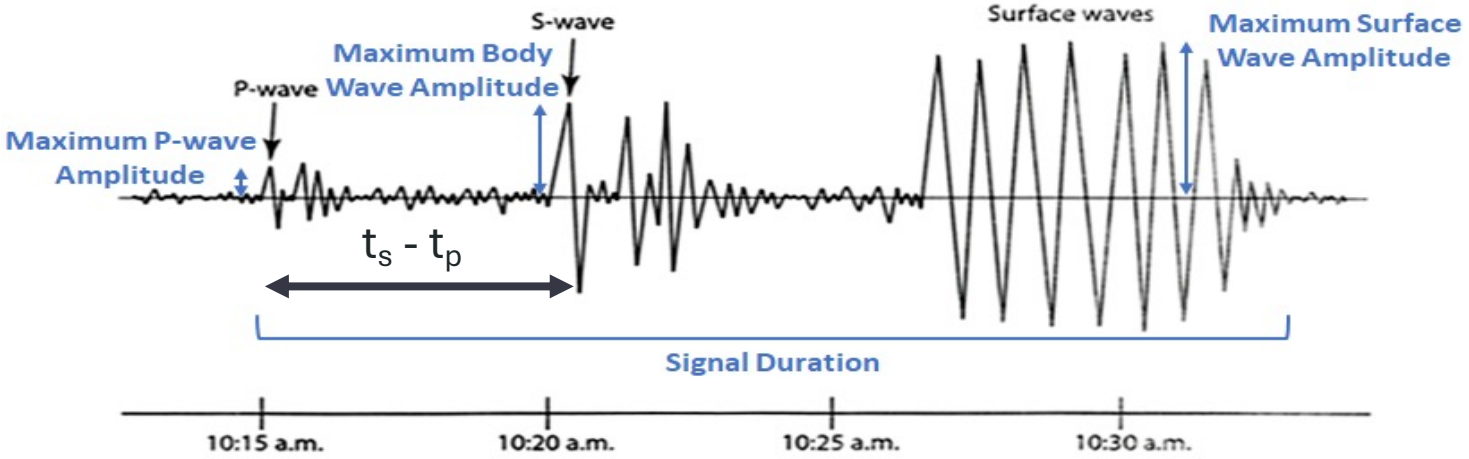
P- waves arrive fast

S-waves arrive after the P wave (how much later depends on distance)

Surface waves arrive after the S-waves (and not in this time window)

Some technical details: A typical earthquake seismogram

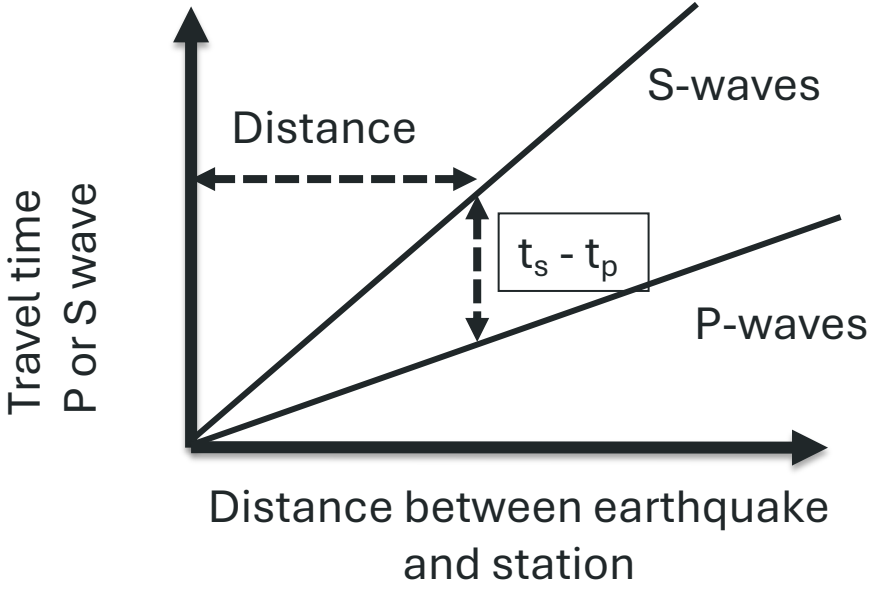
General rule of thumb:
Distance to the earthquake = 8 x (arrival time of S − arrival time of P) kilometres

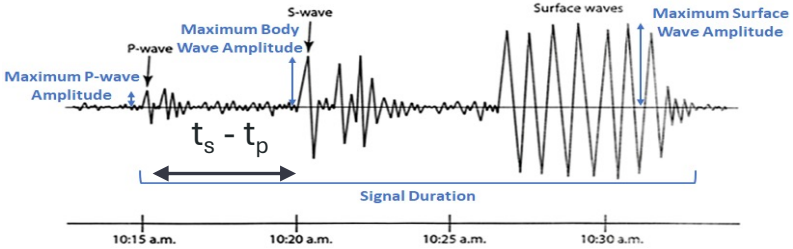


$$t_s = t0 + \frac{D}{Vs} \qquad t_p = t0 + \frac{D}{V_p} \qquad D = (ts - tp)\frac{V_s\,Vp}{V_p - V_s} \qquad D \sim (t_s - tp)\,x\ 8$$

Determining EQ location:

We can pick the arrival time of P and S waves at different seismometers around the world and use it to calculate distance to the earthquake.

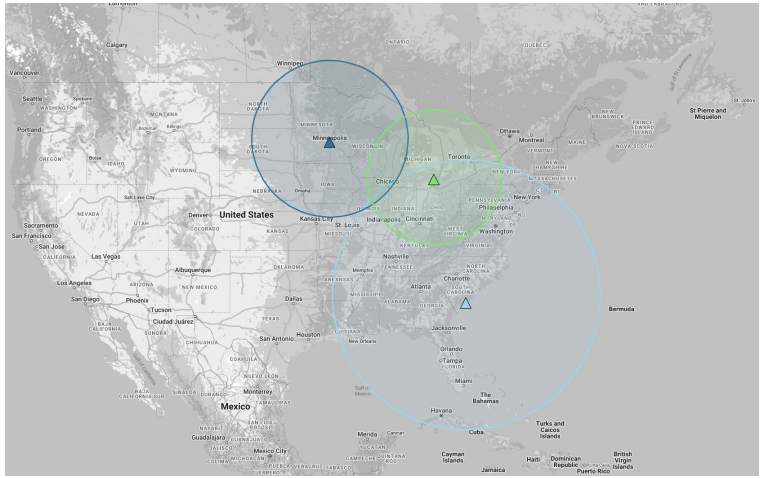


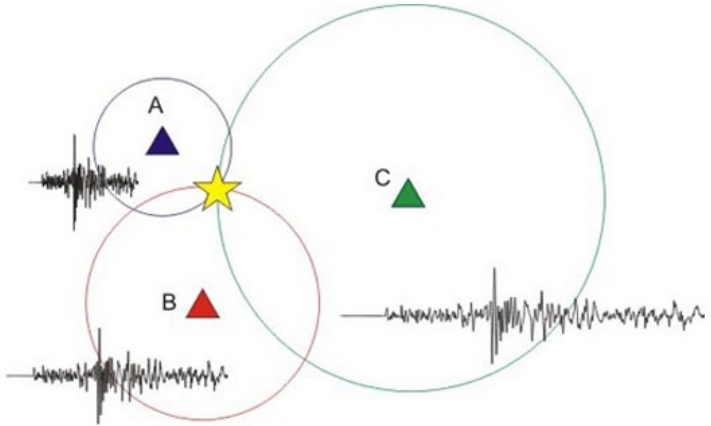


< 100 km : local eq
100 to1400 km: regional eq
>1400 km: teleseismic eq

Earthquake location via triangulation

Once we know the distance to an earthquake from three seismic stations, we can determine the location of the earthquake. Draw a circle around each station with a radius equal to its distance from the earthquake. The earthquake occurred at the point where all three circles intersect.

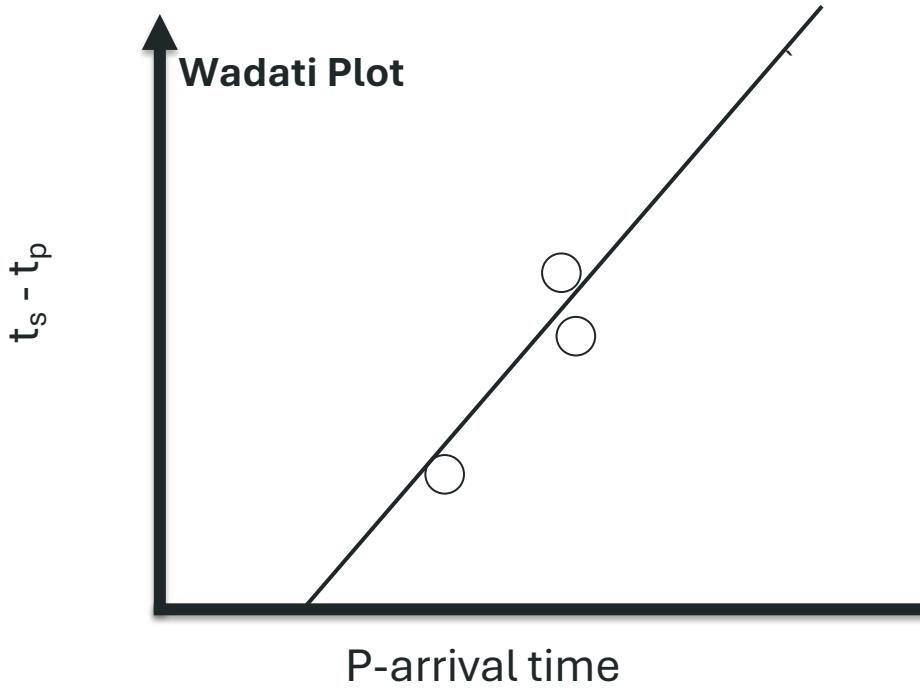




Determining earthquake origin time

What can we estimate using t_p and t_s-t_p?

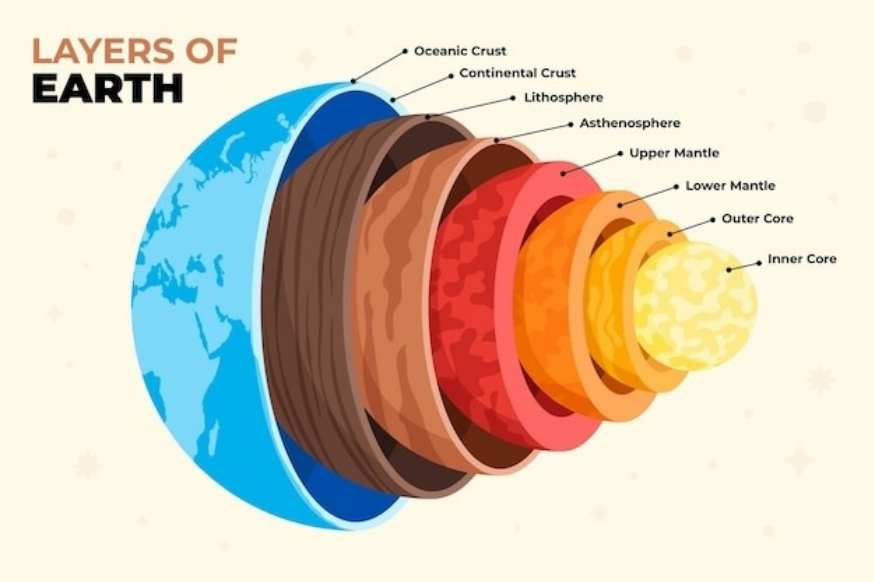
The origin time of an earthquake can be determined with a very simple graphical technique, called Wadati plot (Wadati, 1933). The time separation of the P and S phase (ts-tp) is plotted against the arrival time of the P-wave. Since ts-tp = 0 at the hypocentre, a straight line fit on the Wadati diagram gives the origin time at the intercept with the P-arrival-time axis

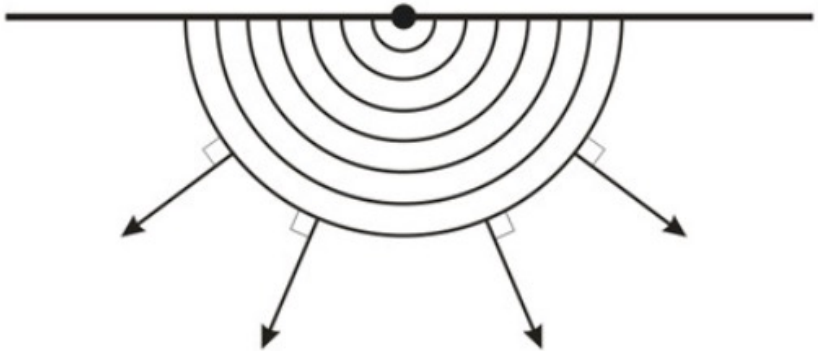


Do you think seismic ray paths are straight lines in the Earth?

Do you think seismic ray paths are straight lines in the Earth?

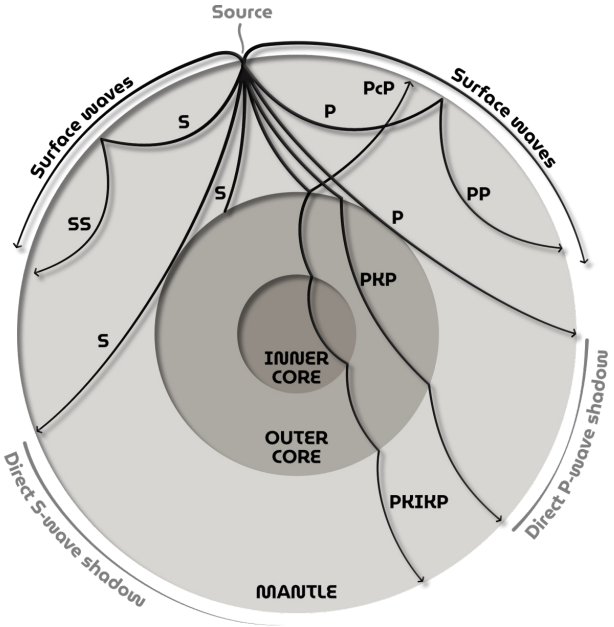
NO! Because the Earth has differences in material composition, pressure, temperature, that cause seismic waves to follow curved pathways.



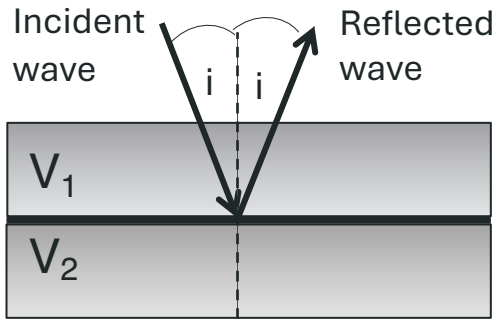


Refraction causes bending of waves

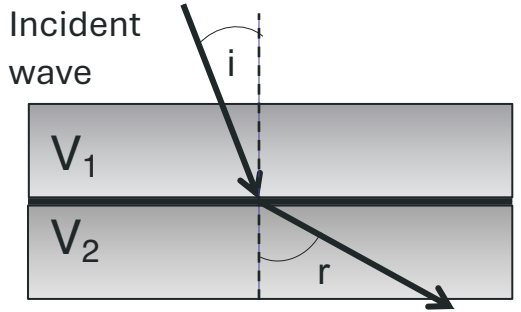
Seismic rays don't continue as a straight line. When they meet a rock with different properties, they will ***bend***.



Reflection

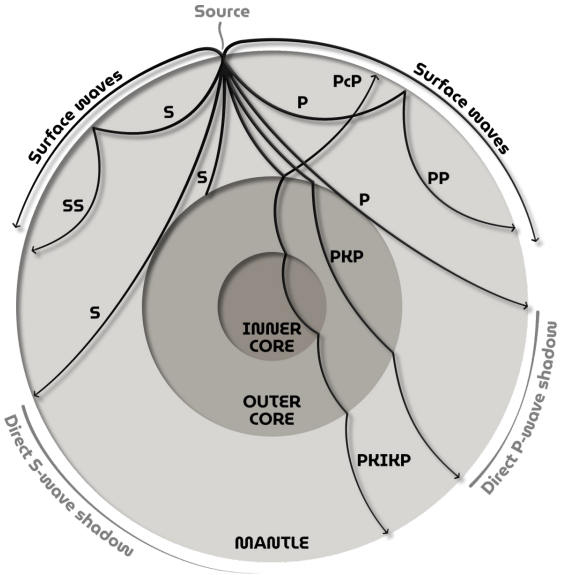


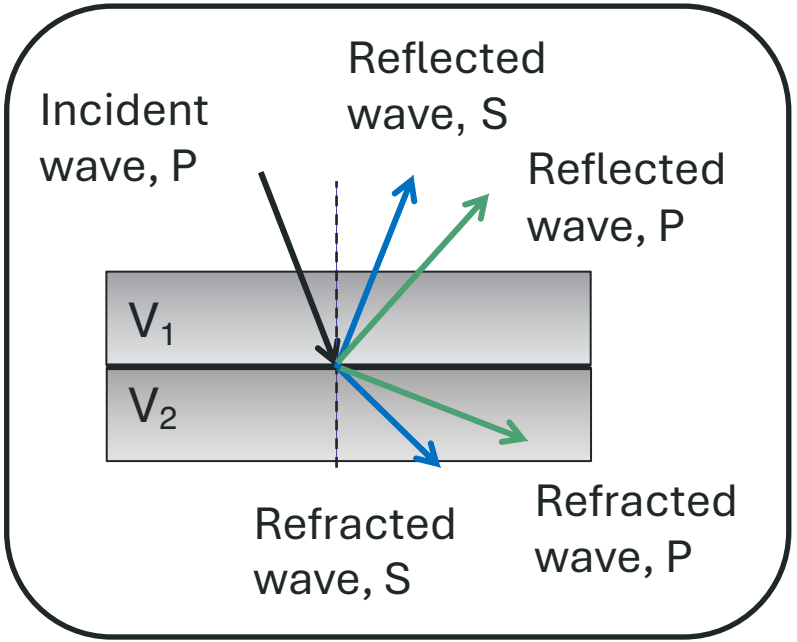
Refraction



Mode conversion

Energy from one wave type can be converted to another wave type at a boundary.
Remember: All of these waves are always created at a boundary





Mode conversion

Some key phases:

PcP P reflection from CMB
PKP ray through outer core
PKiKP reflection from inner core
PKIKP ray through inner core
SKS S through mantle, as P through outer core
ScP S through mantle, reflected P from CMB

Naming:
P = P wave in mantle
S = S wave in mantle
K = P wave in outer core
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i = P wave reflected from inner core boundary (ICB)
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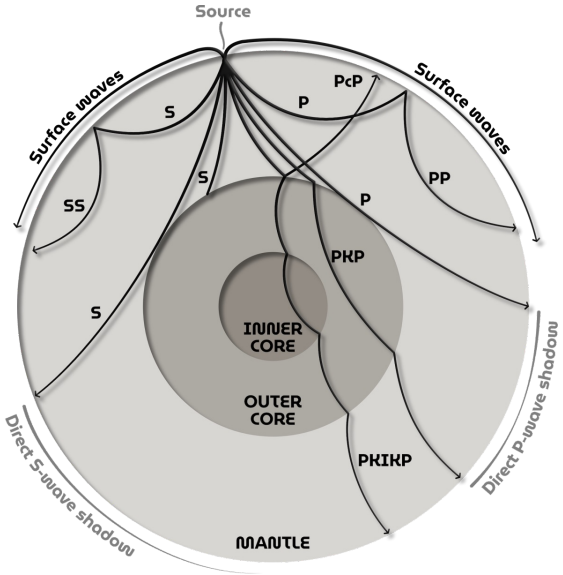

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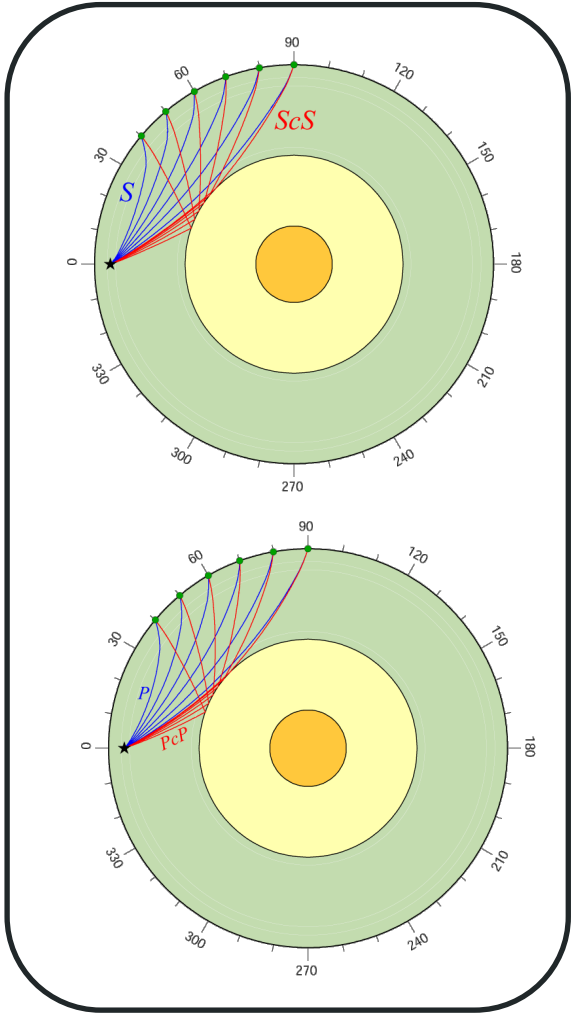

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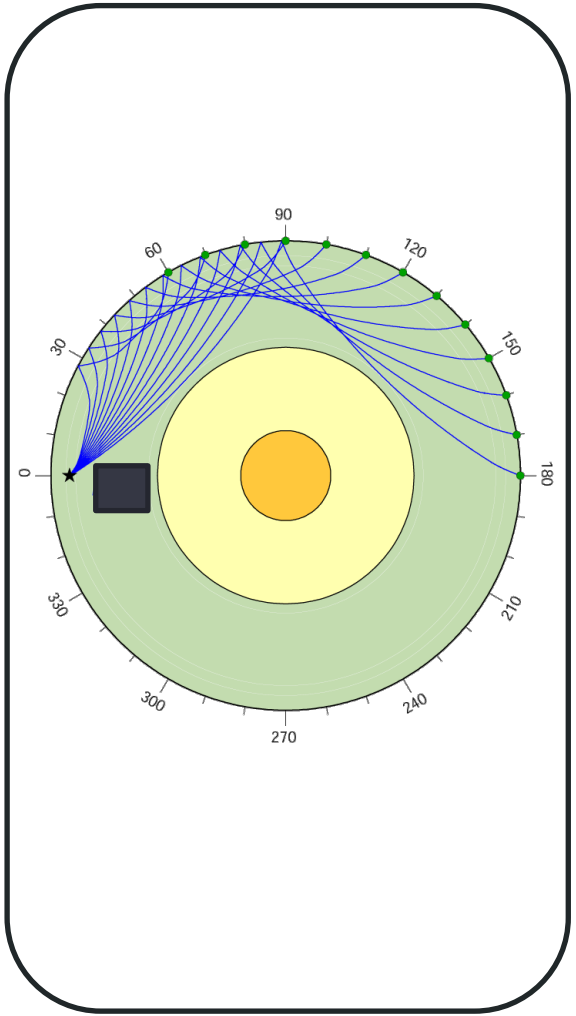

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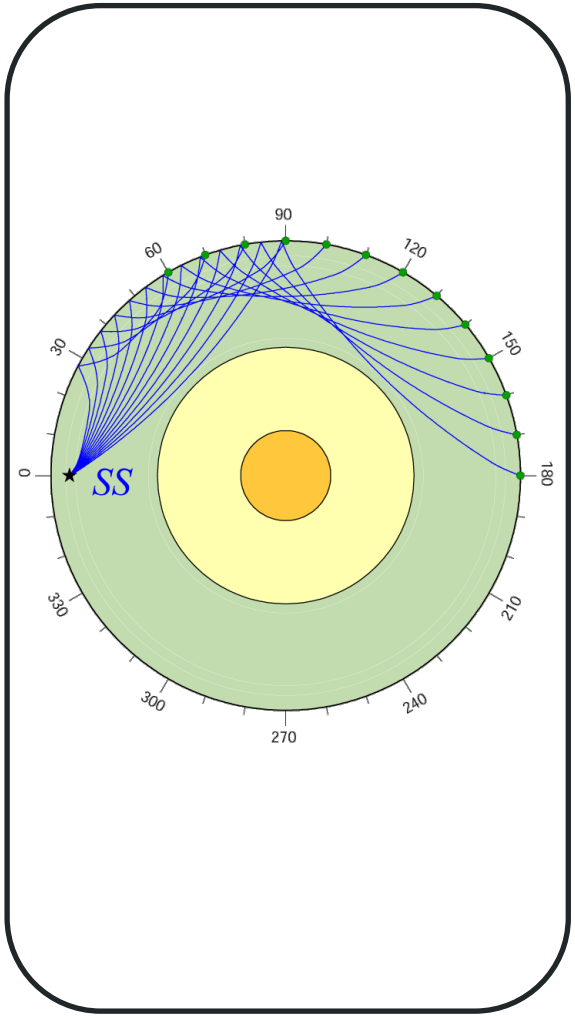

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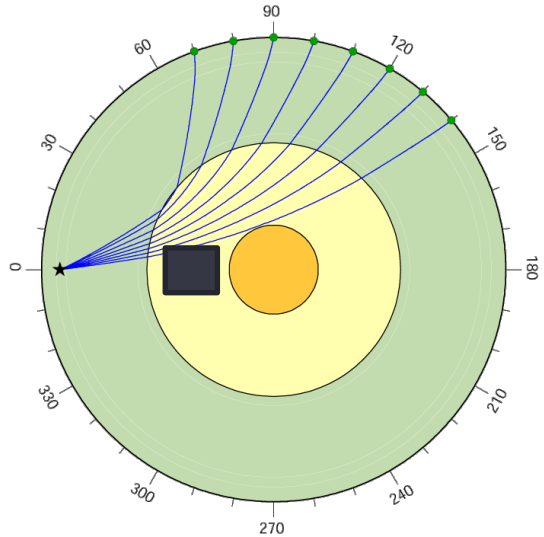

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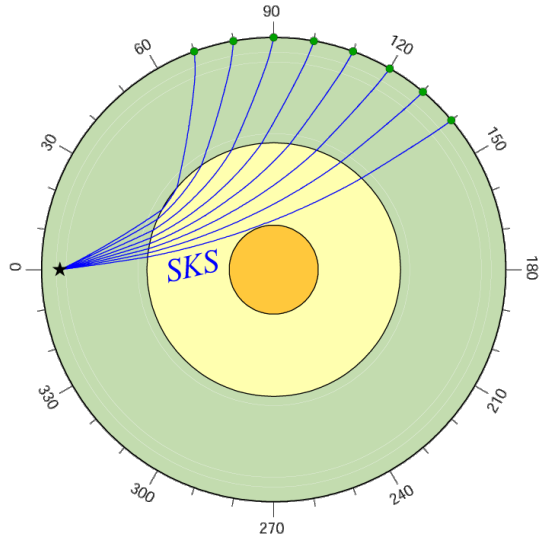

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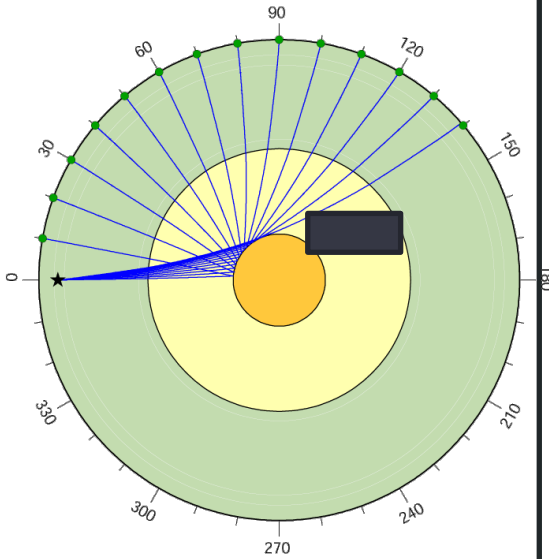

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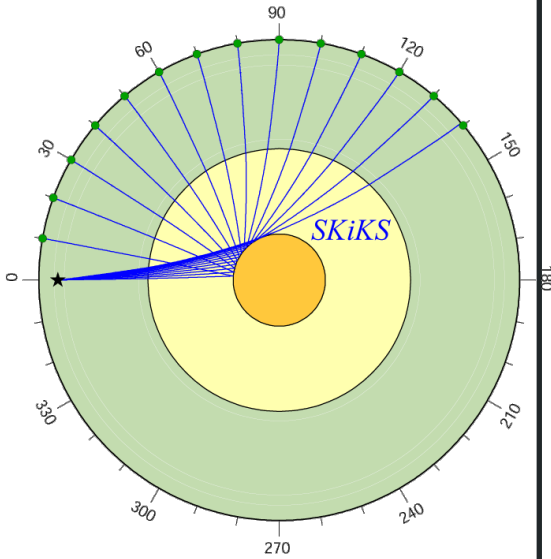
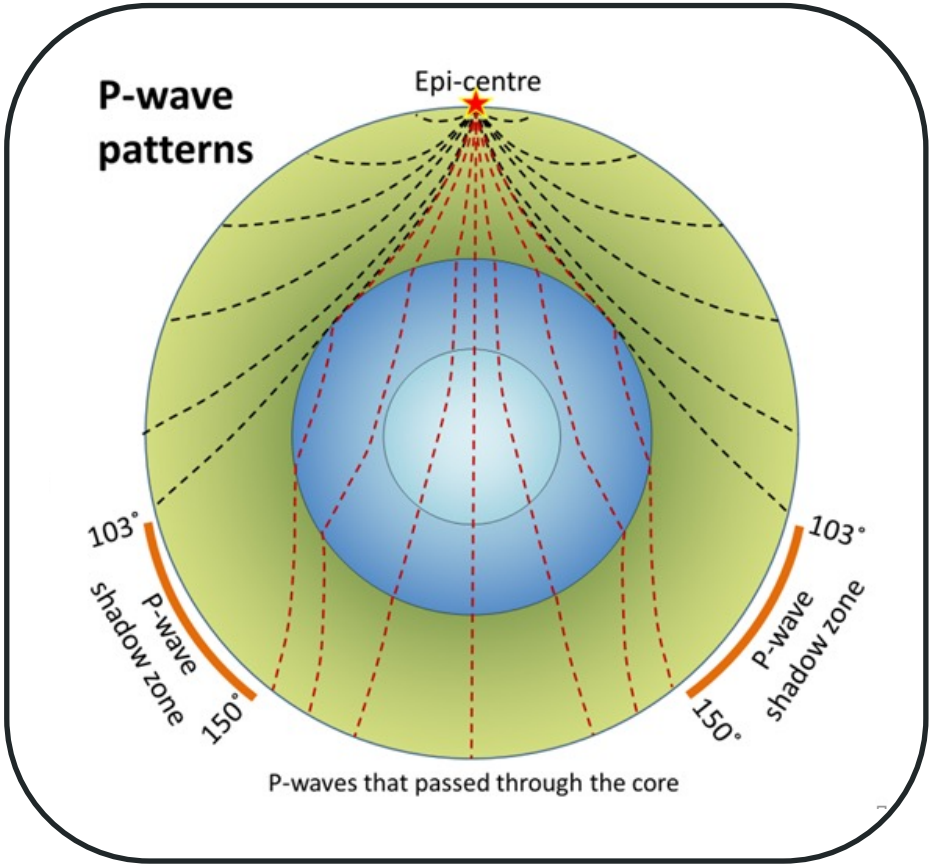


Seismic wave shadow zones

Through measuring how P waves travel through the earth and out the other side, a P wave shadow zone was discovered.

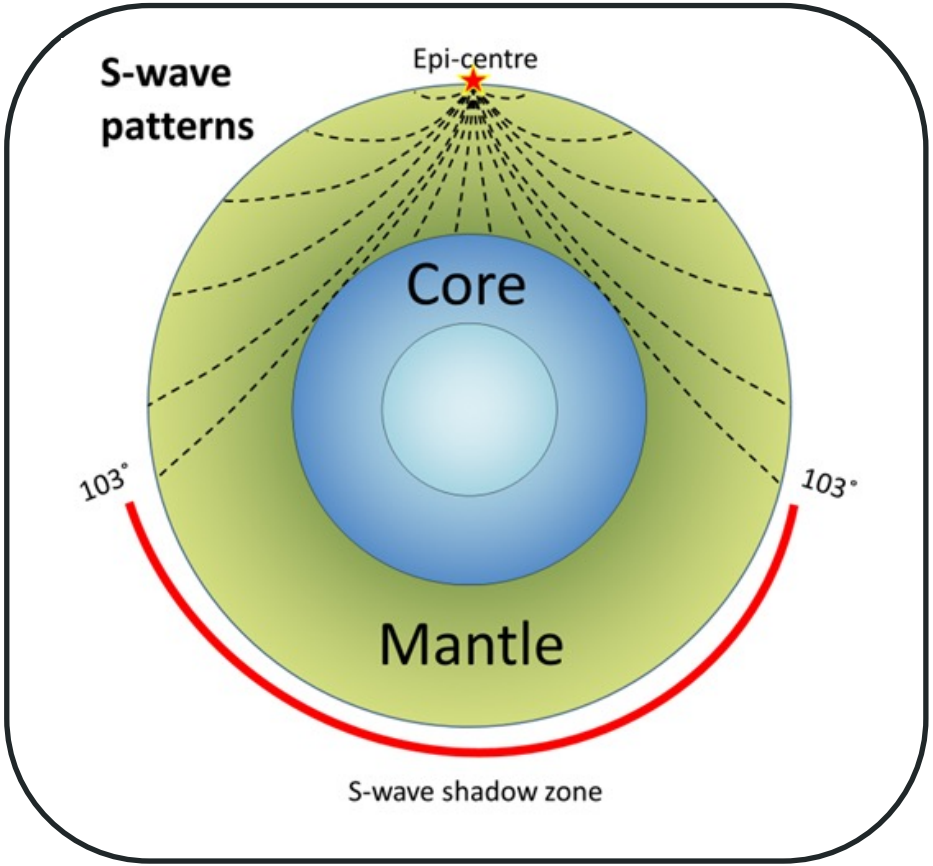
Oldham (1906) calculated that P wave velocity must reduce by about 40%. He also estimated the size of the core from the shadow zone.



Liquid outer core

In 1926 it was shown that the outer core must be liquid since no S-wave travel through it.

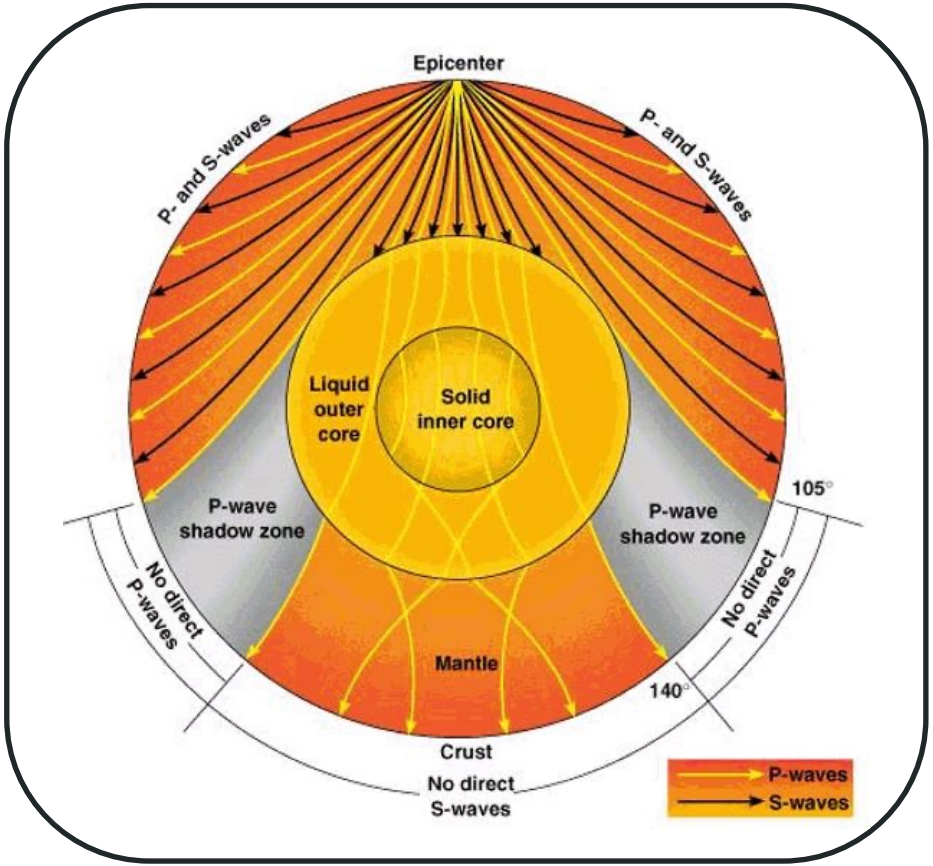
Gutenburg or Oldham-Gutenburg discontinuity at ~2900 km depth marks the core-mantle boundary



Inner Core

Inge Lehman detected arrivals within the core's shadow zone.

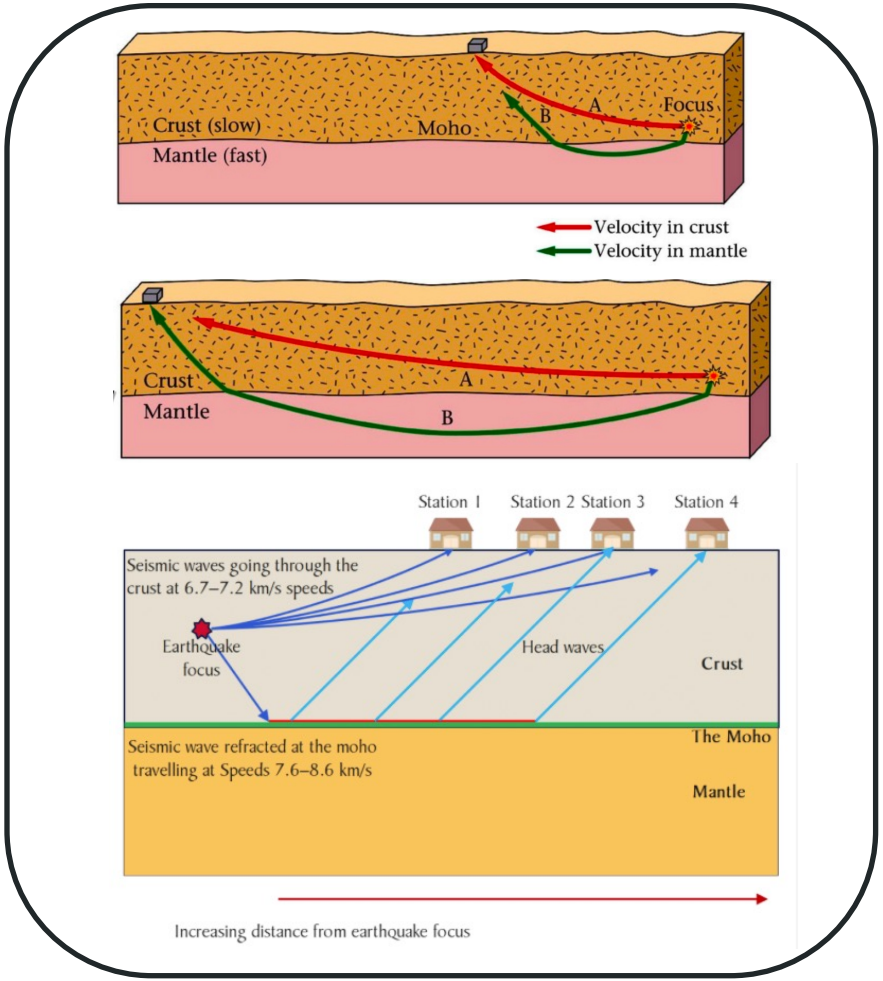
She hypothesised this was due to a solid boundary within the liquid core.



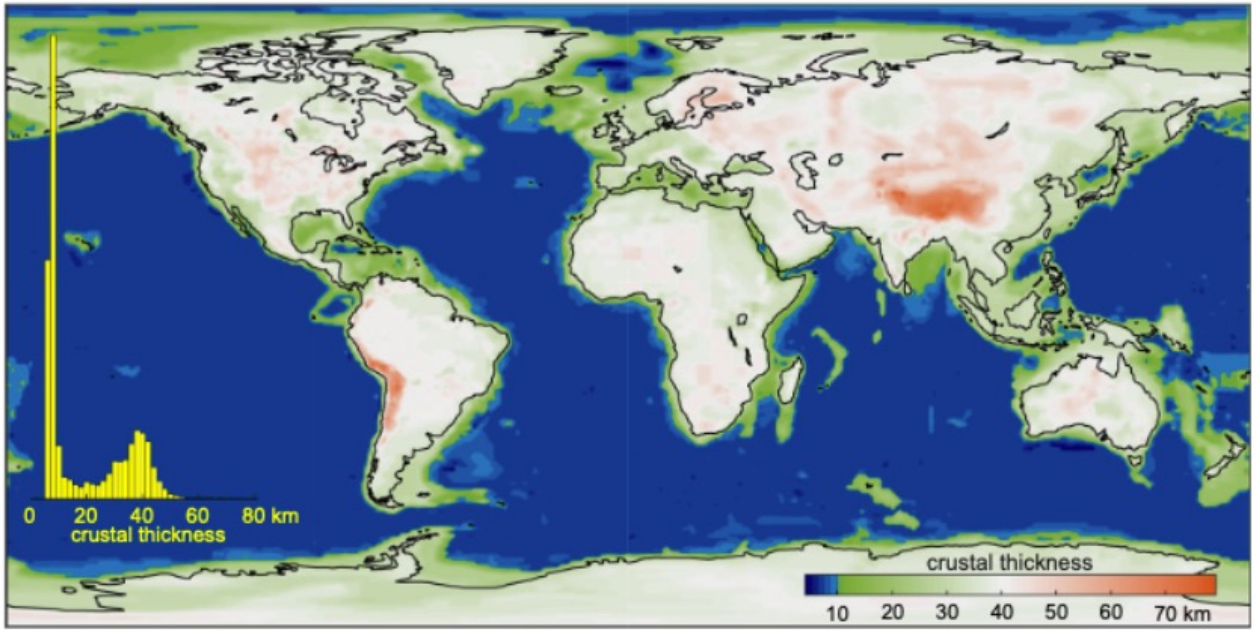
Moho

Mohorovičić discovered the boundary between the crust and mantle (1909)

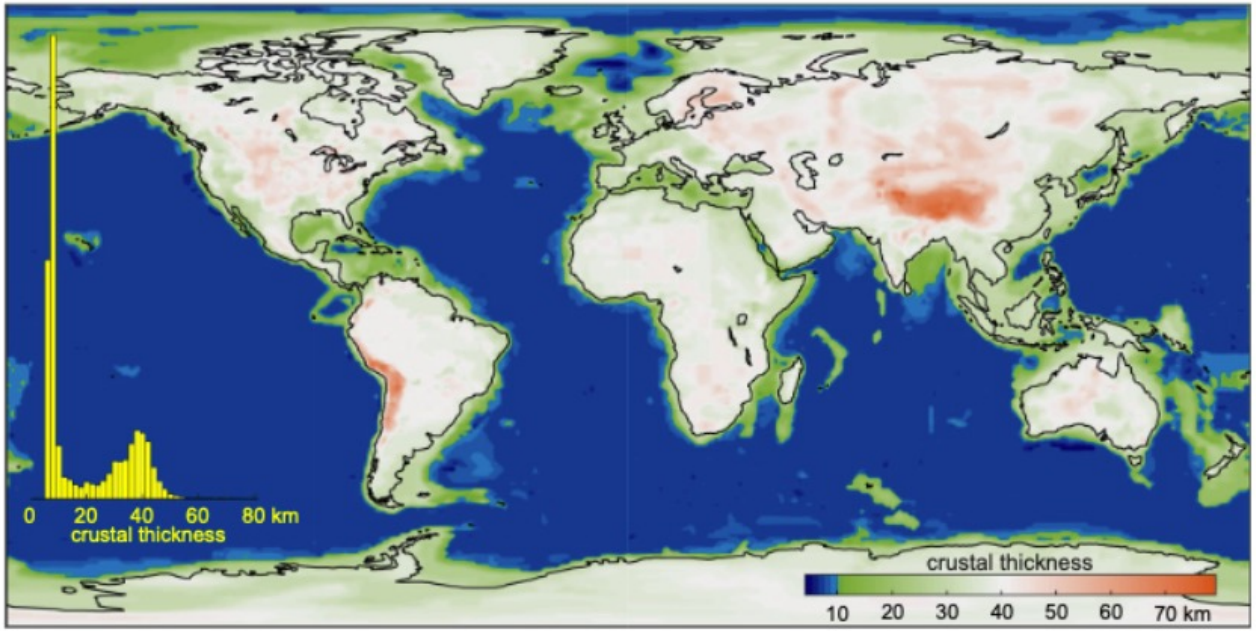
He observed that seismic waves arrived at certain stations sooner than anticipated and deduced that this was because of a deeper fast layer.



What do you notice here?

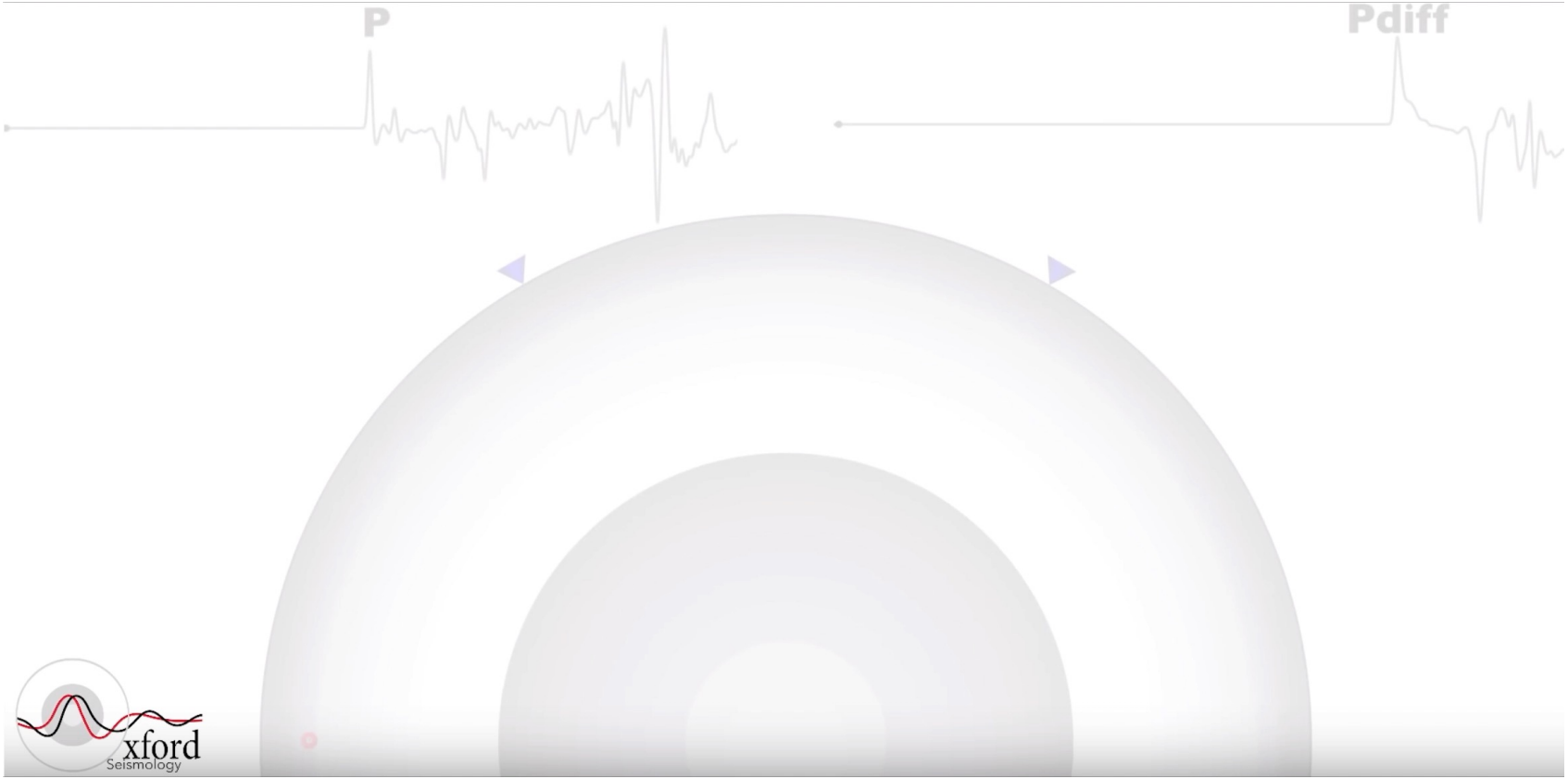


What do you notice here?



Continental crusts are thicker than oceanic crusts

Seismic waves through the Earth

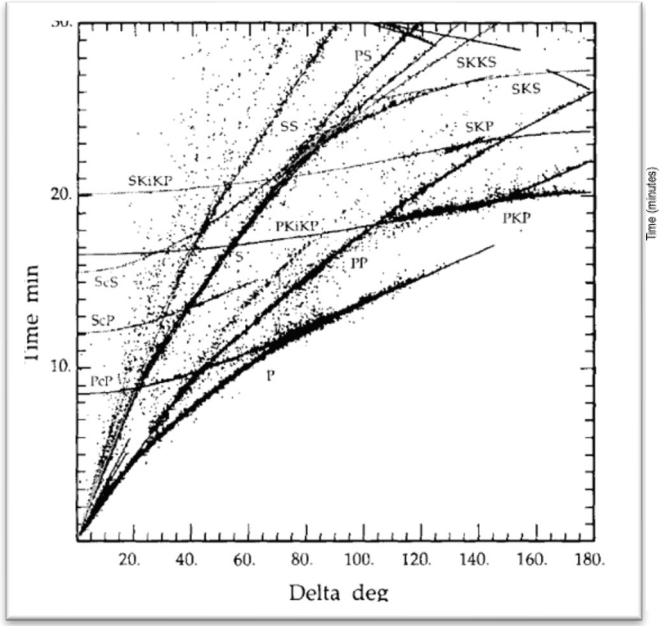


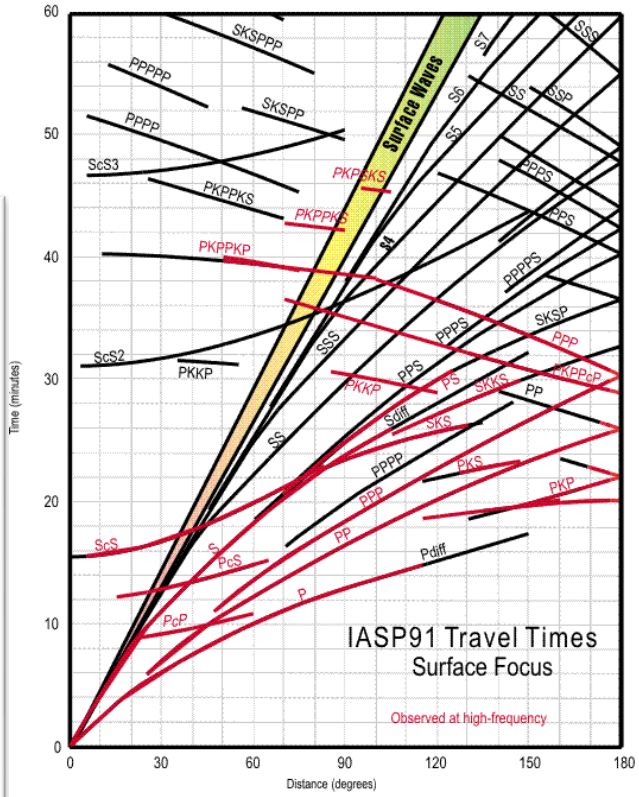
Earthquake phases and time-distance plot

Surface waves are straight lines due to constant velocity along path.

Body wave are curves because velocity changes with depth.

First done by Jeffreys-Bullen travel-time diagram for earthquake phases (1940).





How can you describe the internal structure of the Earth?

Creating a model of the Earth from travel times is called an **inversion**: we invert the data for the model that best predicts the data.

How well the model predicts the data is called the misfit.

We want to find the model with the lowest misfit.

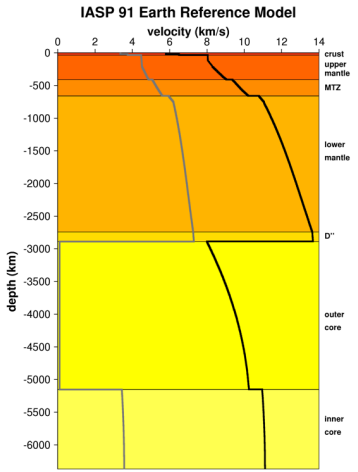
$$Velocity = \frac{Distance}{Time}$$

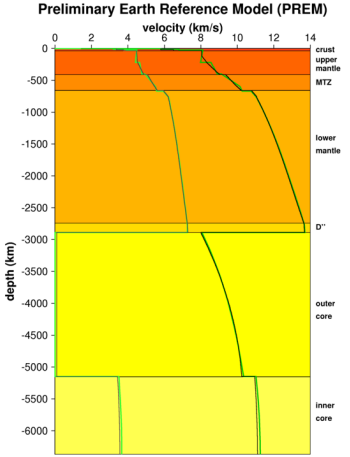
$$Velocity = \sqrt{\frac{Stiffness}{Density}}$$

$$V_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

We use inverse theory





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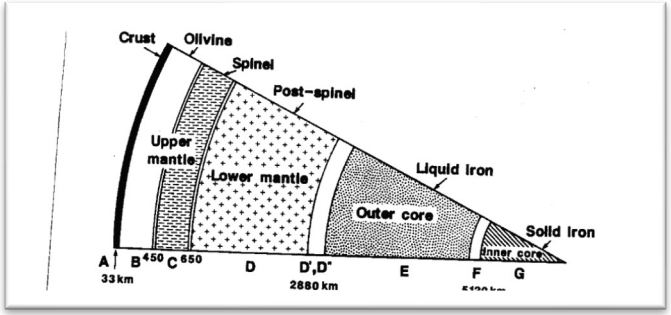
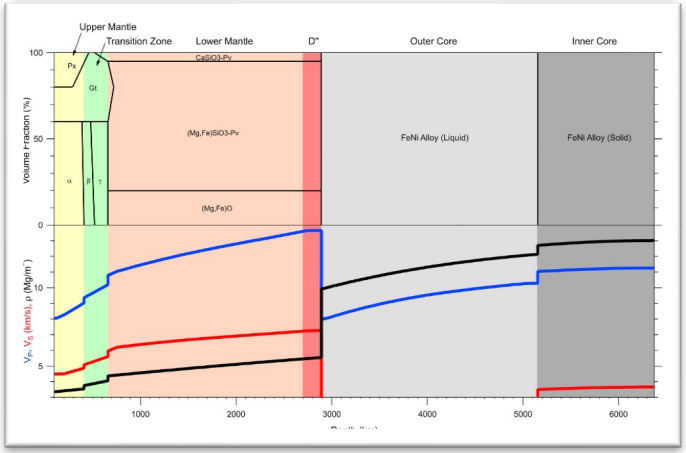
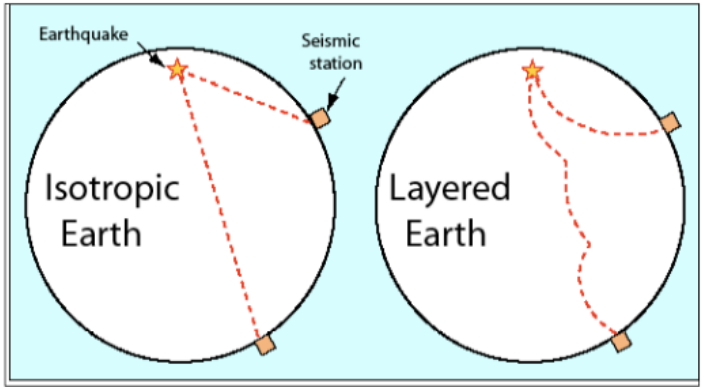
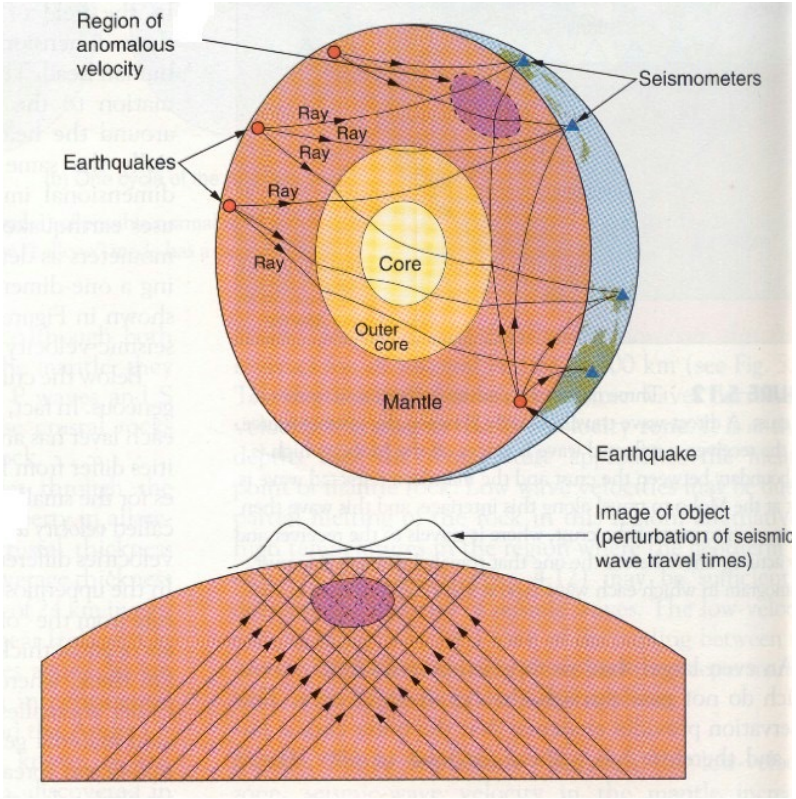




Seismic Tomography

Seismic tomography is an imaging technique that uses seismic waves generated by earthquakes and explosions to create computer-generated, three- dimensional images of Earth's interior.





Seismic Tomography: imaging Earth’s interior