Seismogram Interpretation

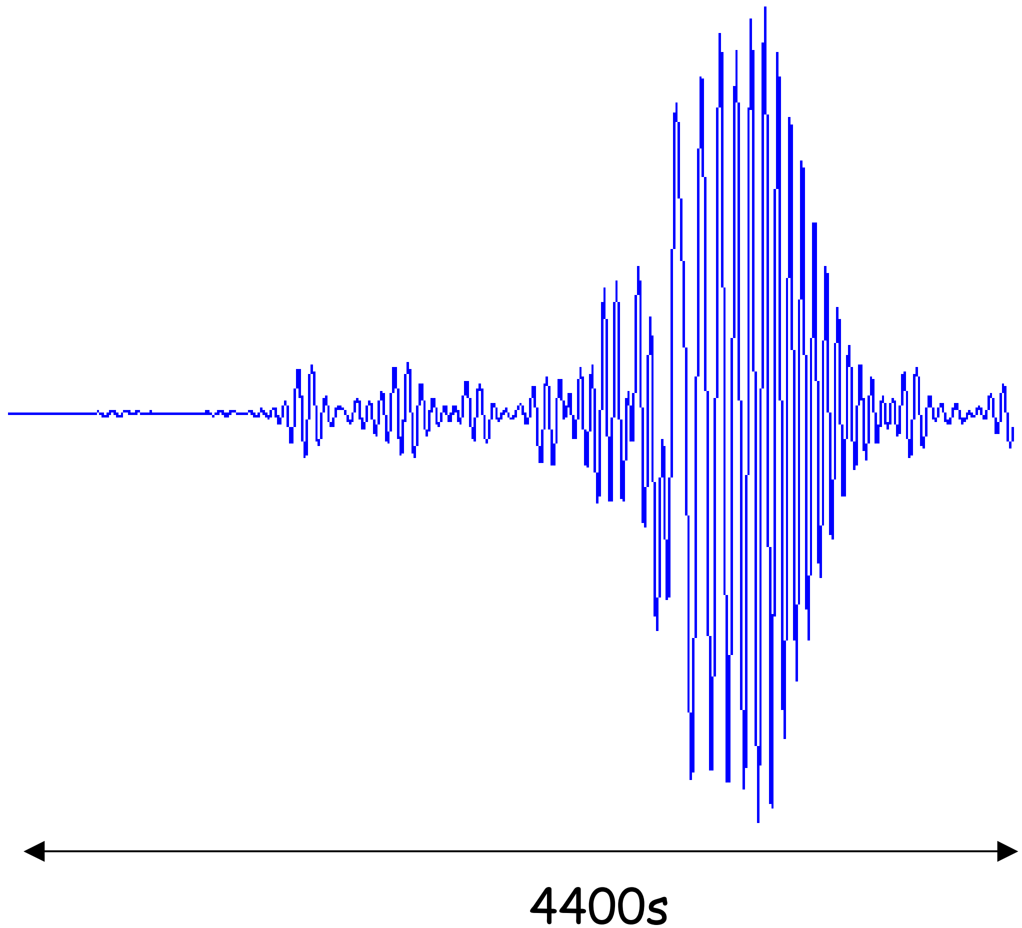
- Travel times in the Earth
- Ray paths, phases and their name
- Wavefields in the Earth: SH waves, P-SV waves
- Seismic Tomography
- Receiver Functions

Seismogram Example

Long-period transverse displacement for an earthquake at 600km depth recorded at 130^{o} (synthetic).

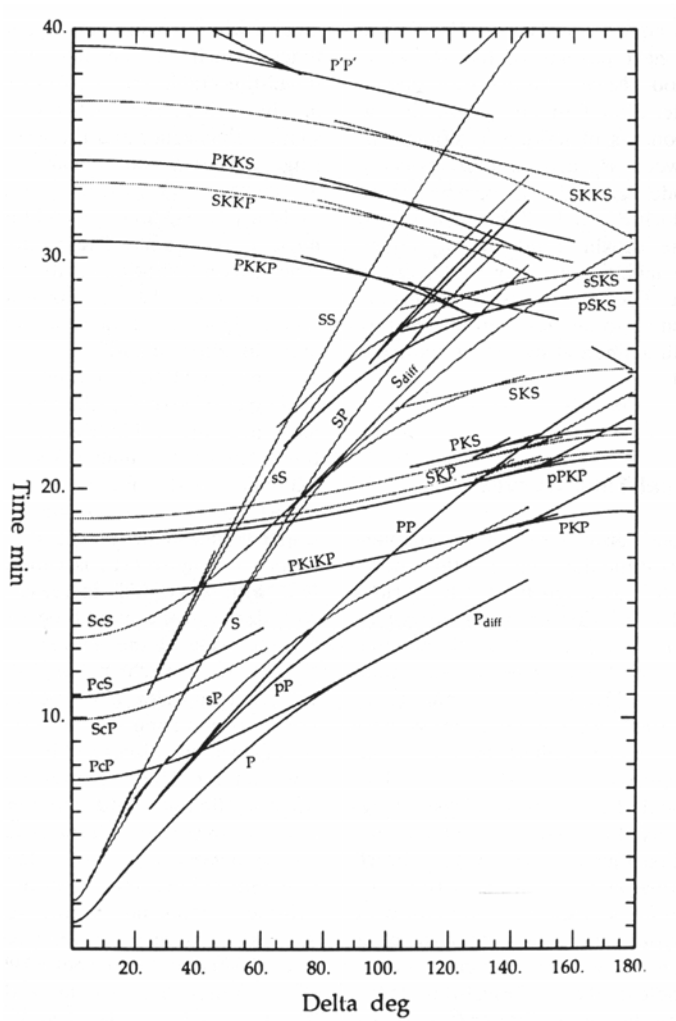
How can we extract information from seismograms on Earth structure?

-> identify phases
-> pick travel times
-> collect travel times as a function of distance

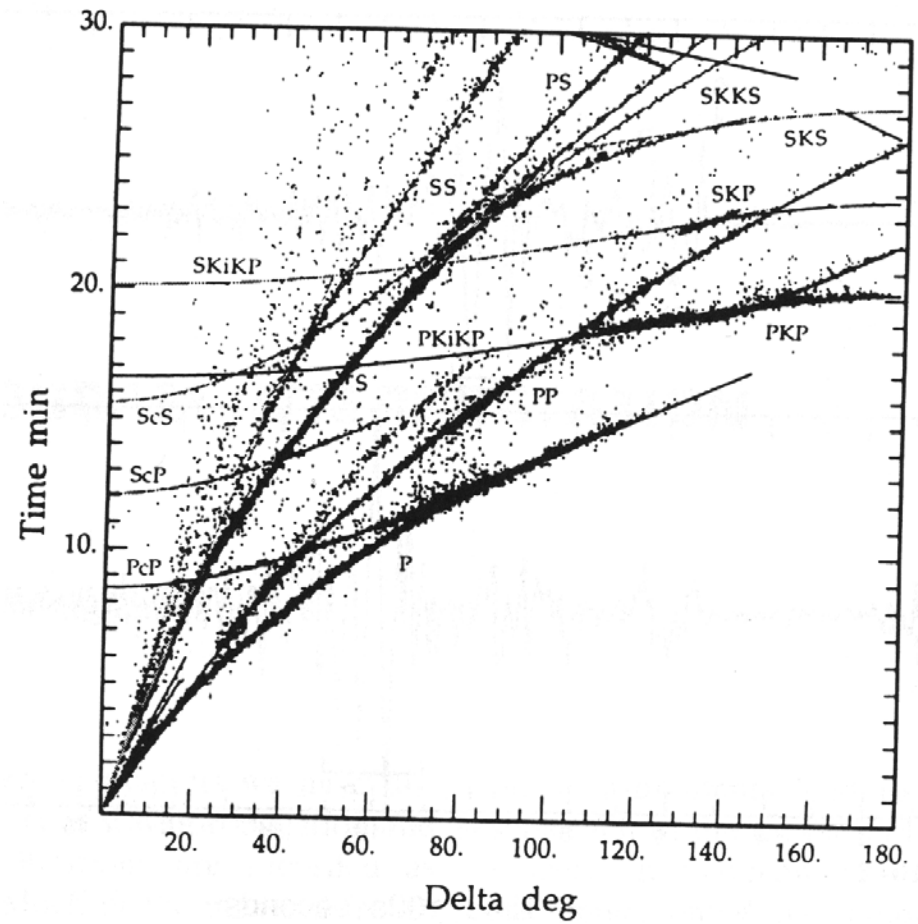


Travel times in the Earth

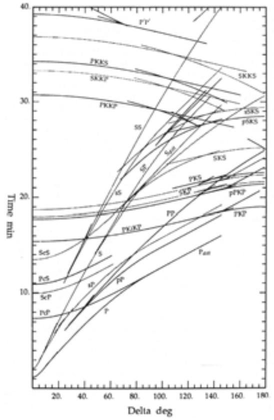
Travel times for a spherically symmetric Earth model (IASP91) Source at 600km depth



Automatic Picks from real data



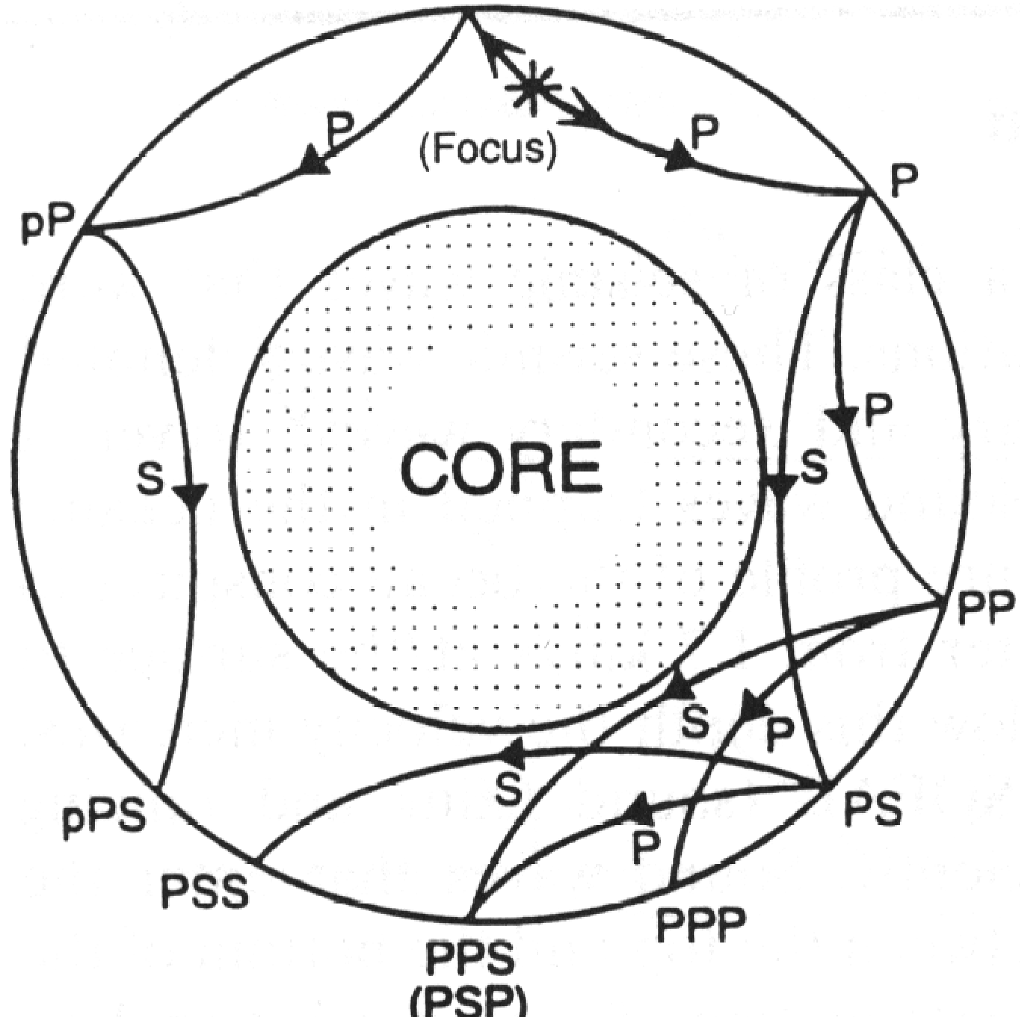
History of Travel-Times



- Harrold Jeffreys and Keith Bullen (1940), (J-B) Remarkable accuracy for teleseismic travel times (below 1%)!
- Herrin et al. (1968), with well located earthquakes.
- Dziewonski and Anderson (1981), Preliminary Reference Earth Model (PREM)
- Kennett and Engdahl (1991), most accurate radially symmetric model (iasp91)
- (2000), The first 3-D reference model with travel times?

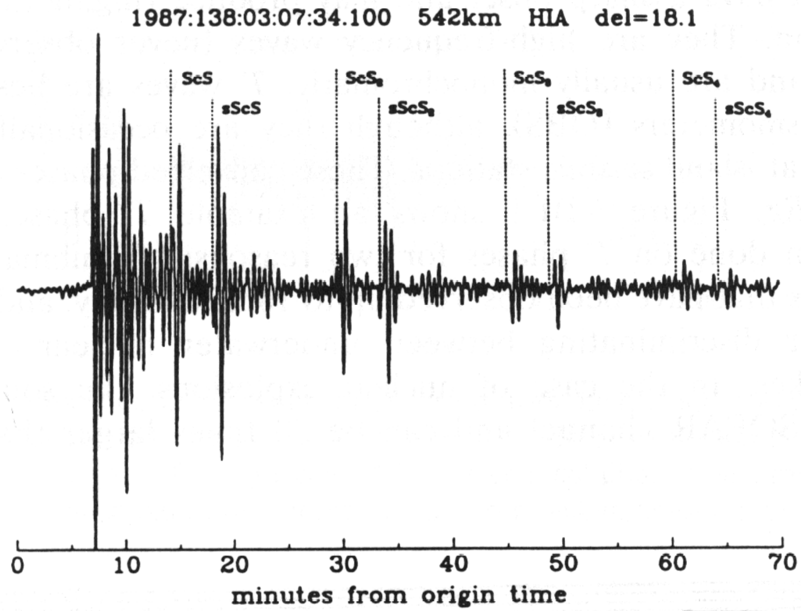
Ray Paths in the Earth (1)

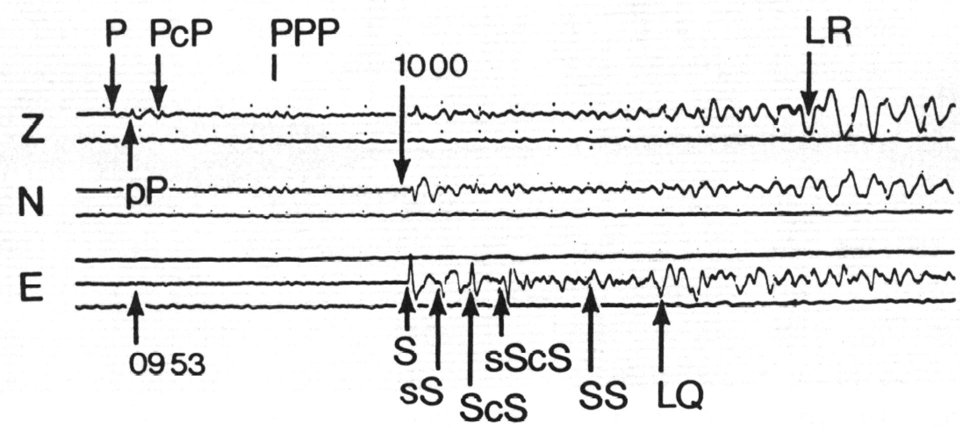
Particular phases at teleseismic distances are named after the wave types (P or S), regions they pass along their path, and emergence angle at the source (upwards or downwards).



Ray Paths in the Earth (2)

The core-mantle boundary has the most dominant effect on the global wavefield. Multiple reflections
from it reveal information on attenuation and the structure near the CMB.





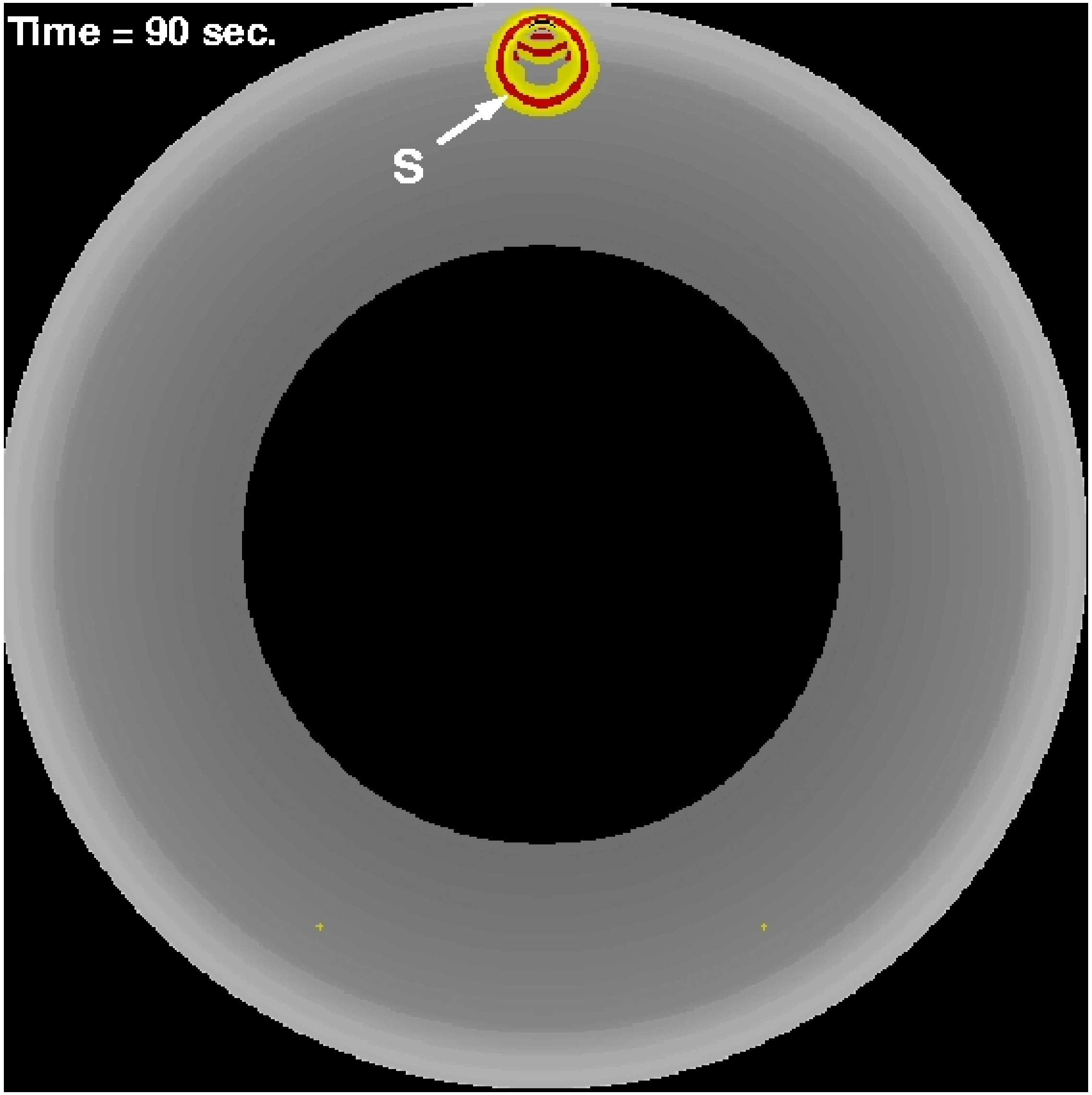
Ray Paths in the Earth - Names

P	P waves
S	S waves
small p	depth phases (P)
small s	depth phases (S)
c	Reflection from CMB
K	wave inside core
i	Reflection from Inner core boundary
I	wave through inner core

Examples:

PcP, pPcS, SKS, PKKKP, PKiKP, PKIKP, sSS, pSSS, sPcS, etc.

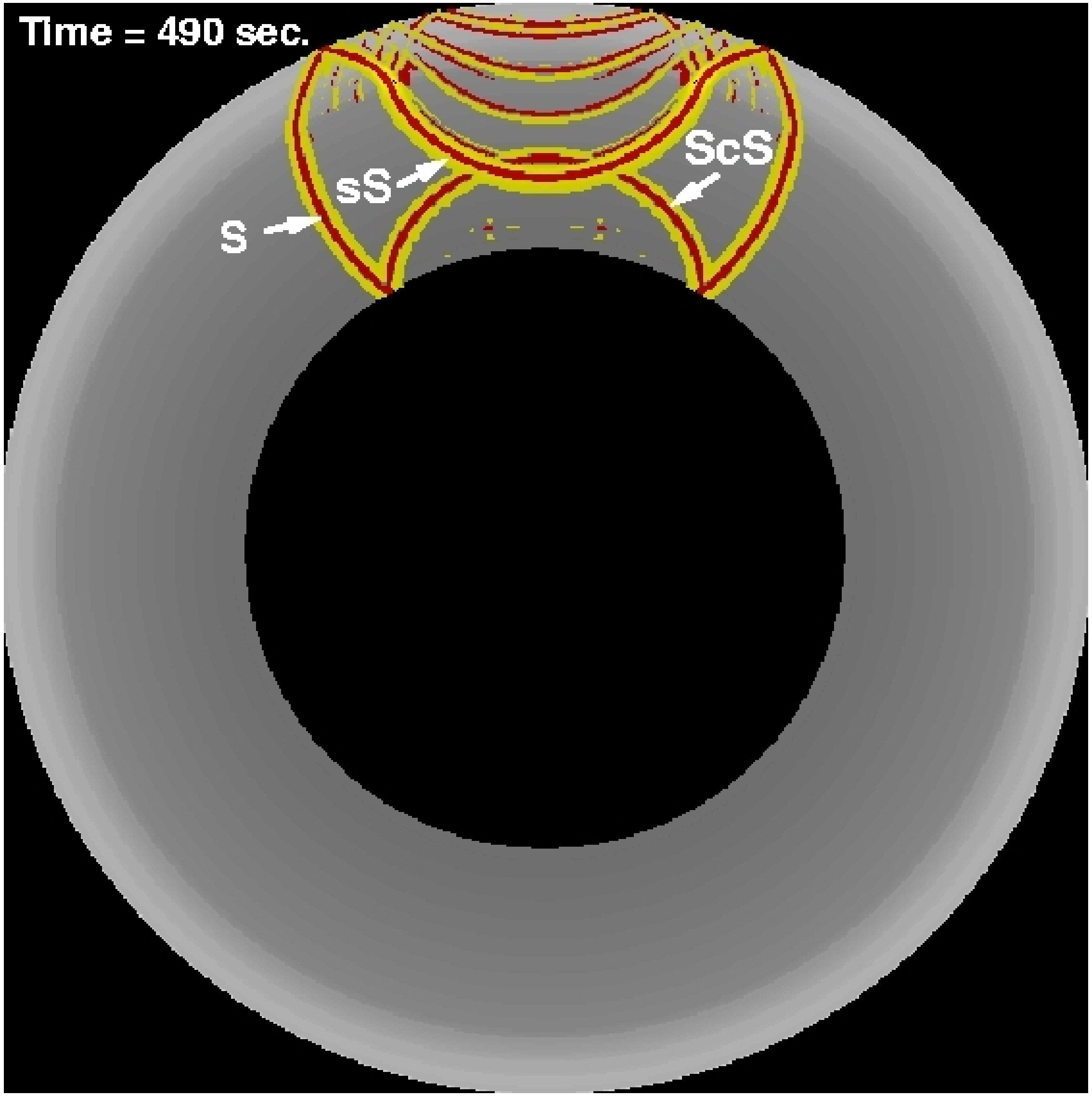
Wavefields in the Earth: SH waves



Red and yellow color denote positive and negative displacement, respectively.

Wavefield for earthquake at 600km depth.

Wavefields in the Earth: SH waves



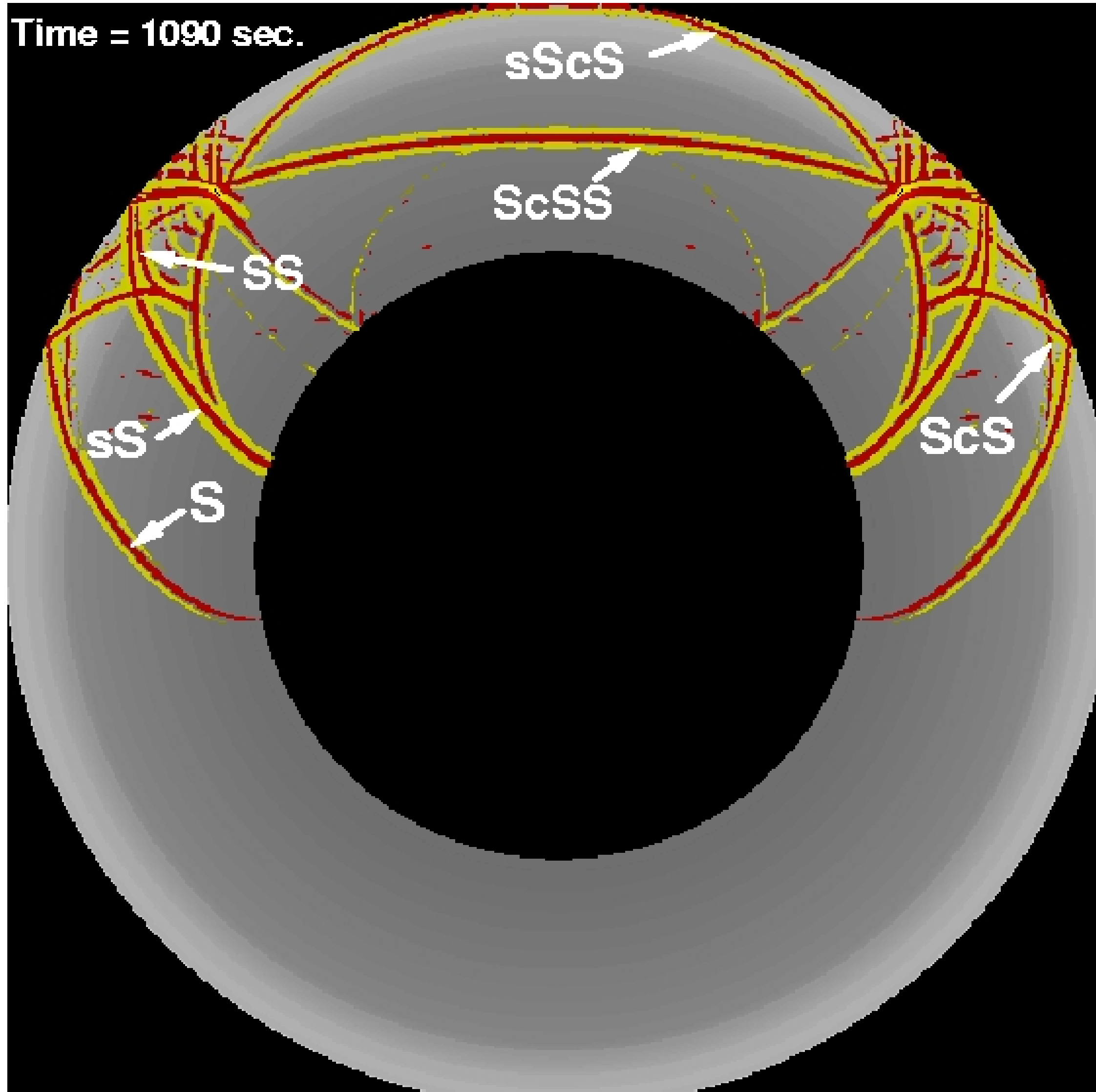
Red and yellow color denote positive and negative displacement, respectively.

Wavefield for earthquake at 600km depth.

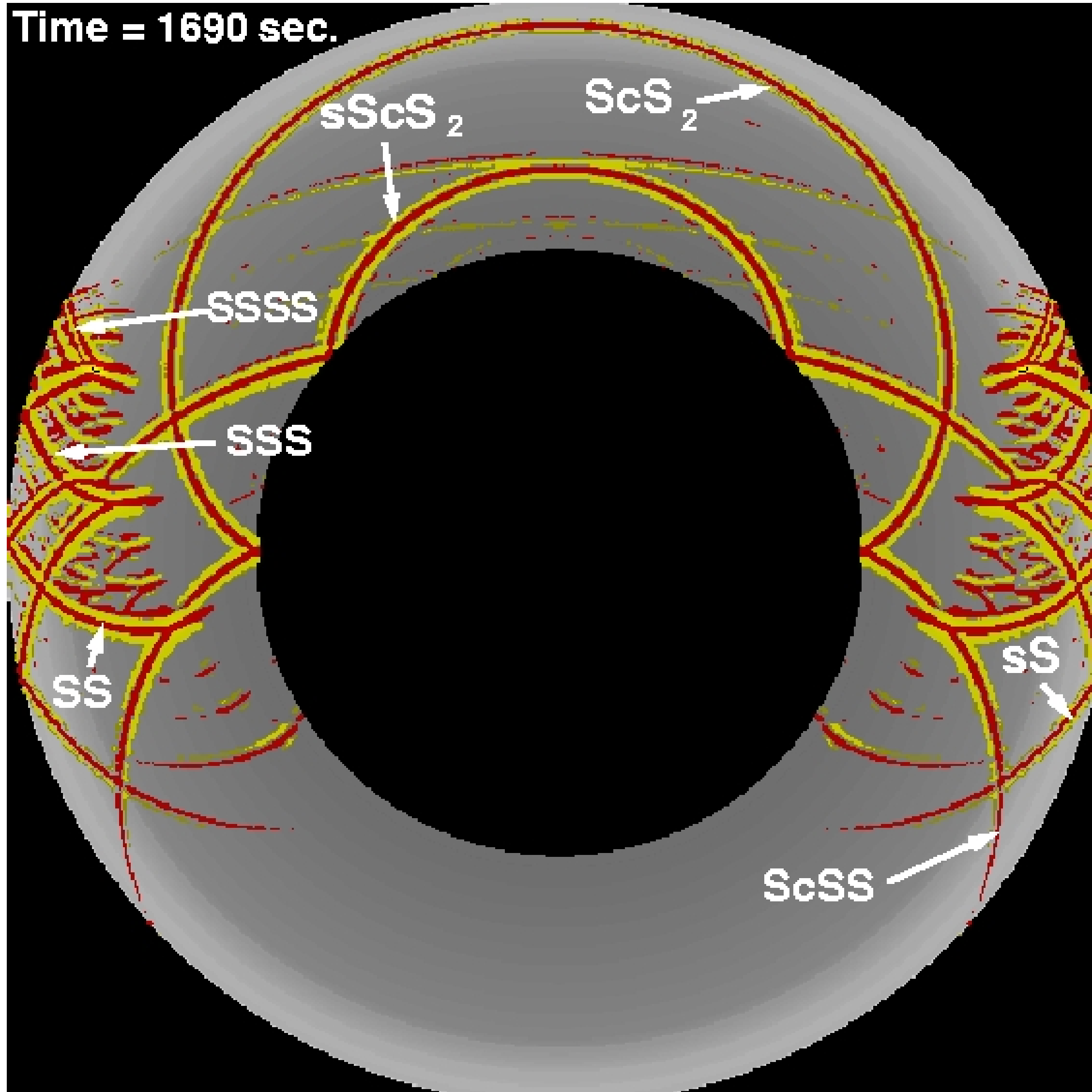
Wavefields in the Earth: SH waves

Red and yellow color denote positive and negative displacement, respectively.

Wavefield for earthquake at 600km depth.



Wavefields in the Earth: SH waves

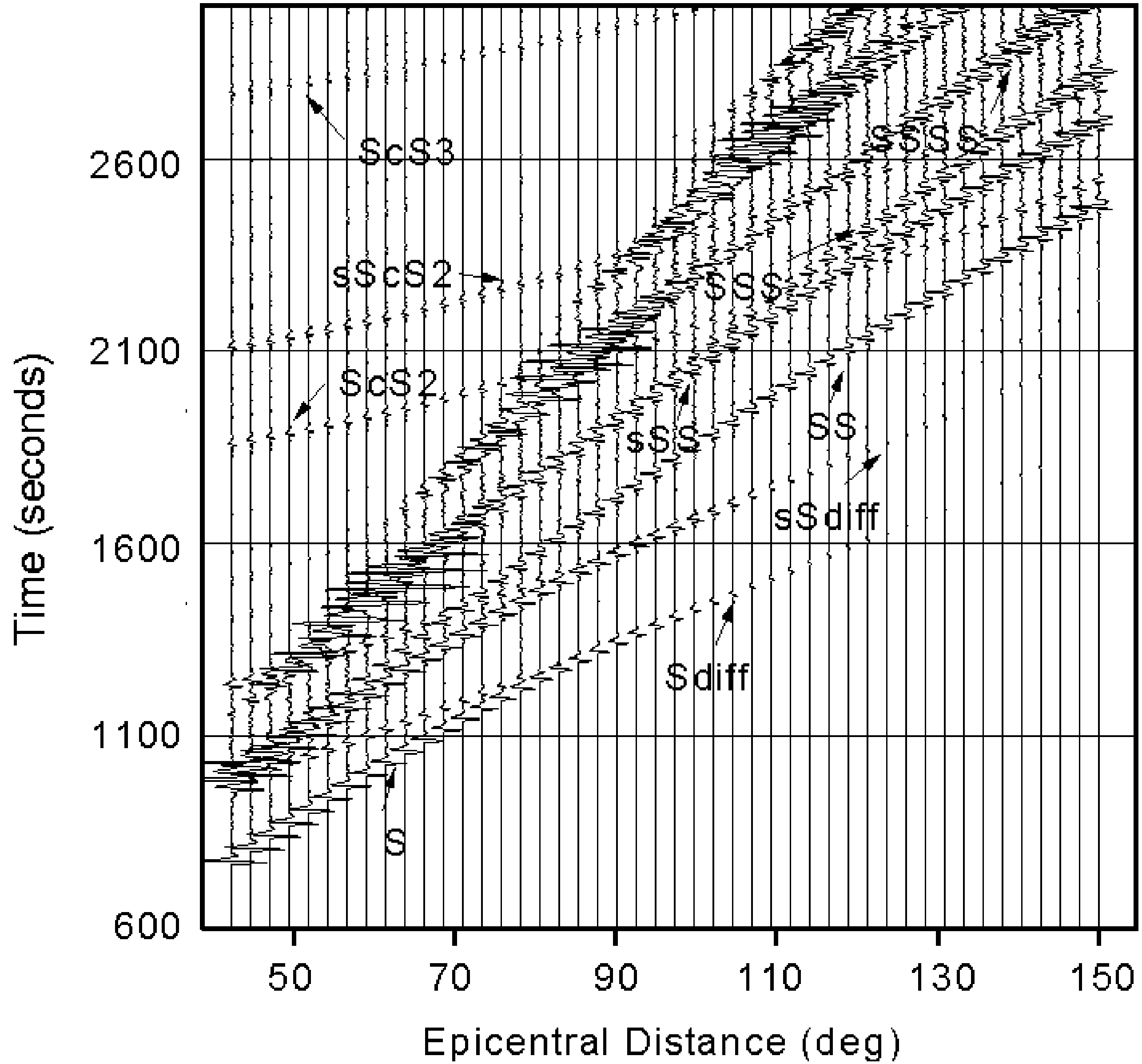


Red and yellow color denote positive and negative displacement, respectively.

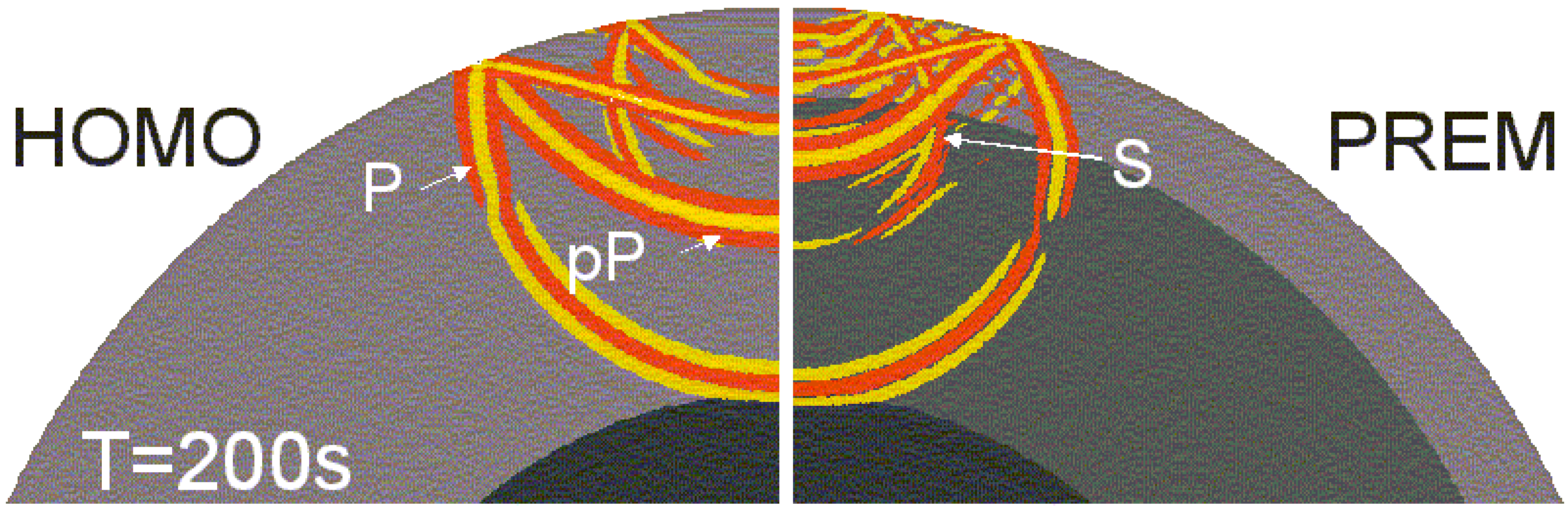
Wavefield for earthquake at 600km depth.

SH waves: seismograms

SH-seismograms for a source at 600km depth



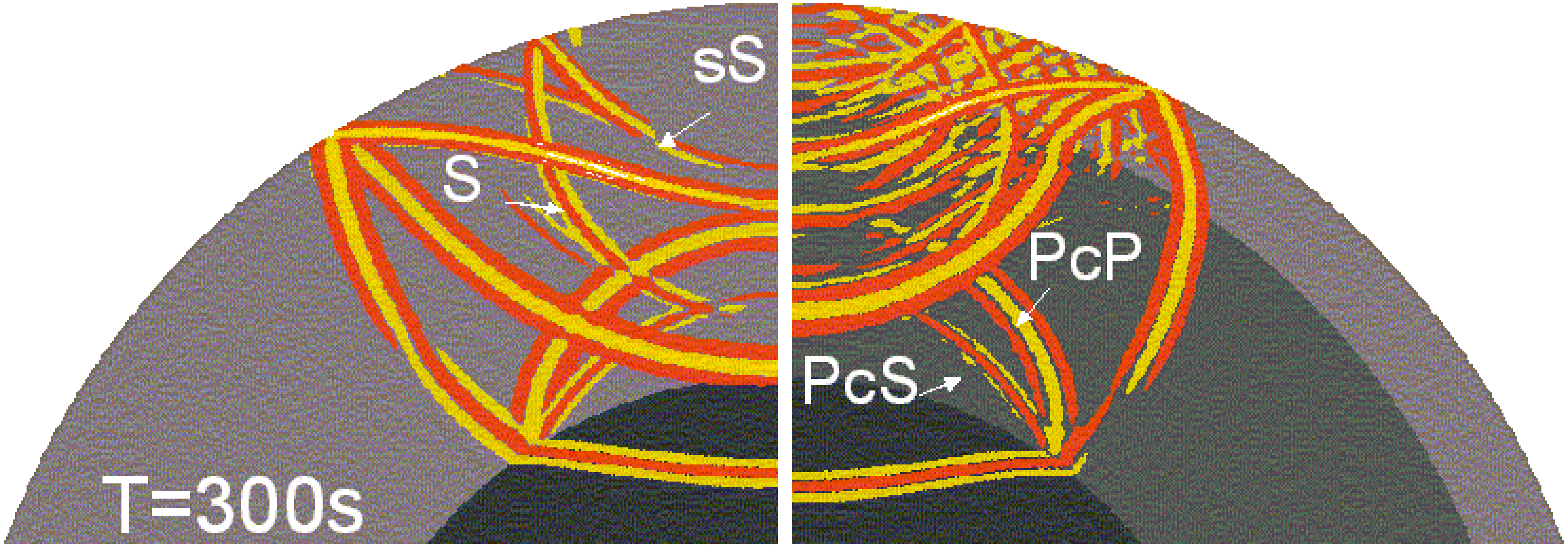
Wavefields in the Earth: P-SV waves



Red and yellow color denote positive and negative vertical displacement, respectively. Left: homogeneous mantle, right: realistic spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

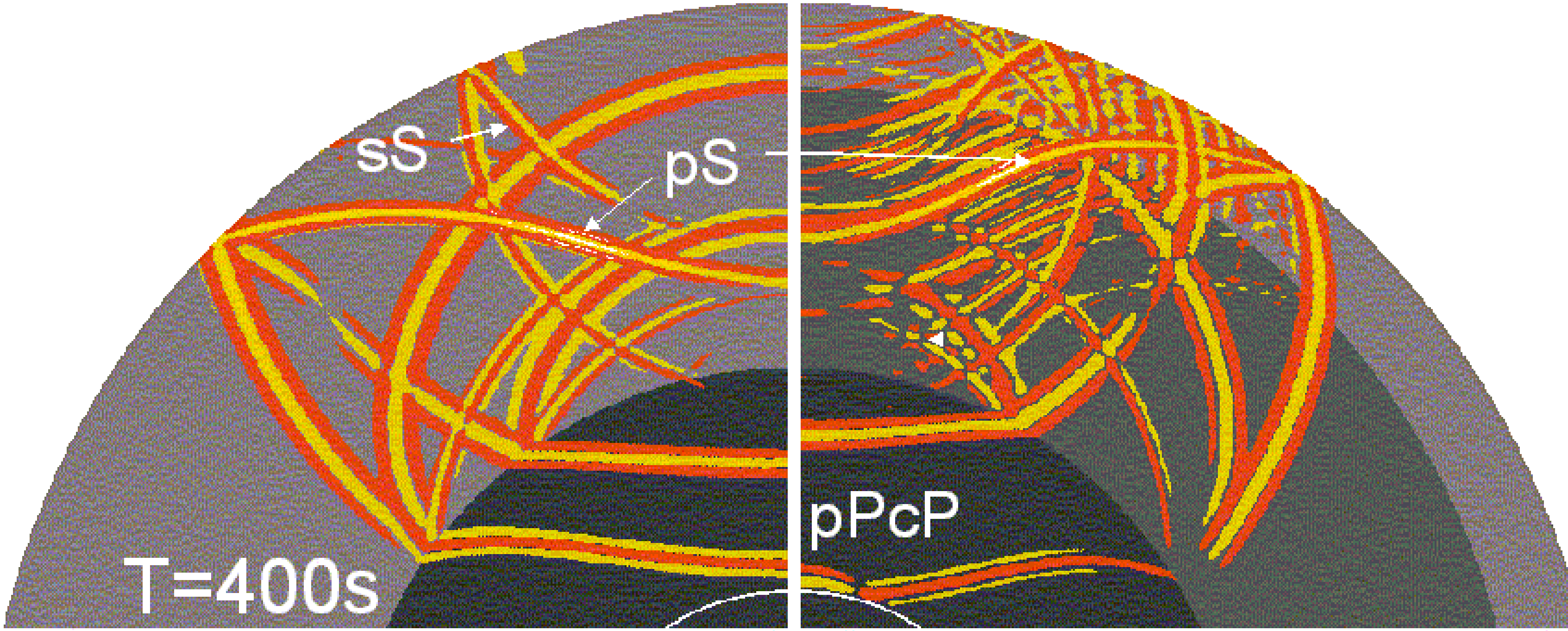
Wavefields in the Earth: P-SV waves



Red and yellow color denote positive and negative vertical displacement, respectively. Left: homogeneous mantle, right: realistic spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

Wavefields in the Earth: P-SV waves



Red and yellow color denote positive and negative vertical displacement, respectively. Left: homogeneous mantle, right: realistic spherically symmetric model (Preliminary Reference Earth Model, **PREM**)

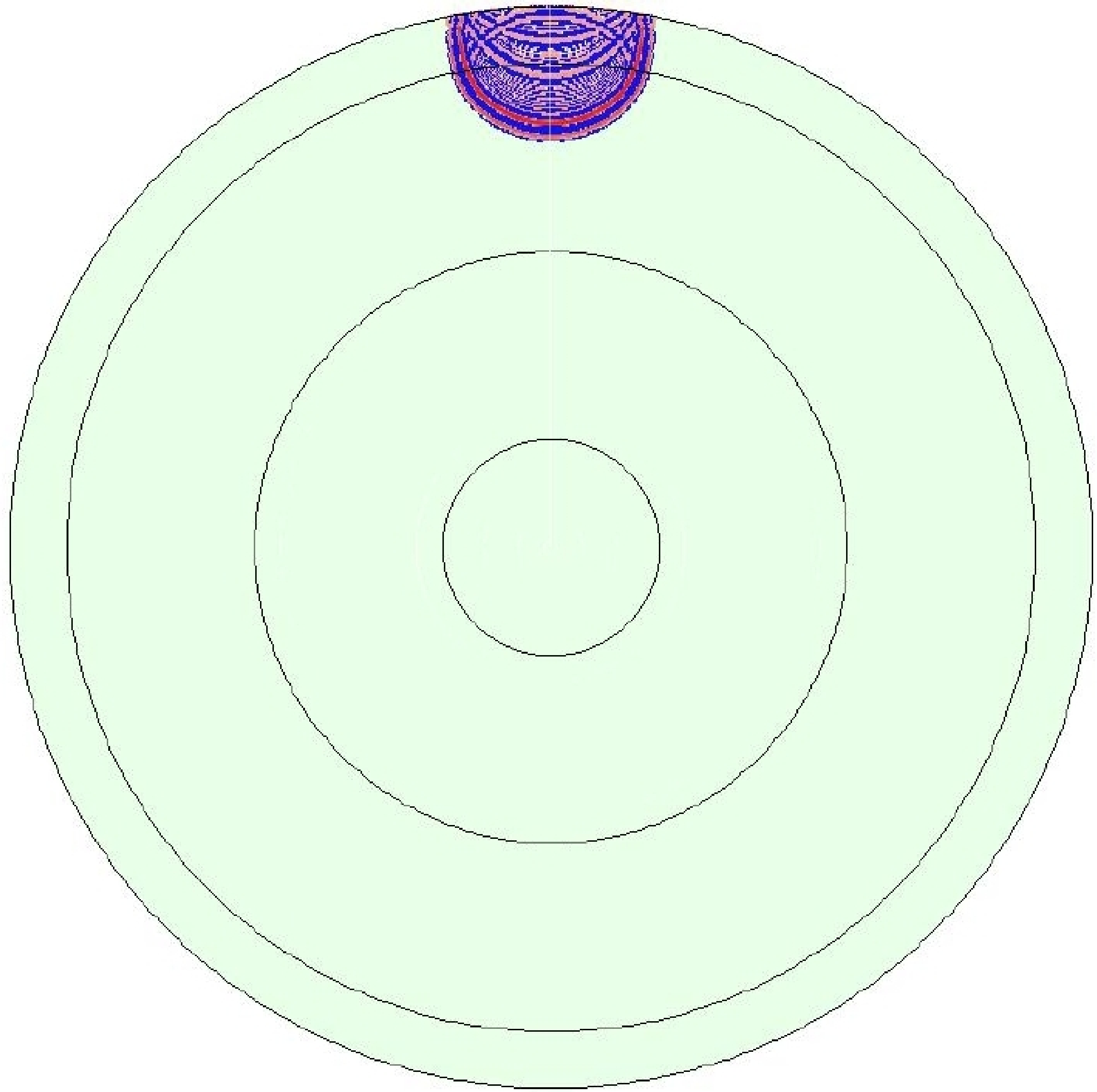
Wavefield for explosion at 600km depth.

Wavefields in the whole Earth: P waves

Red and blue colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at surface.

Time: 150s

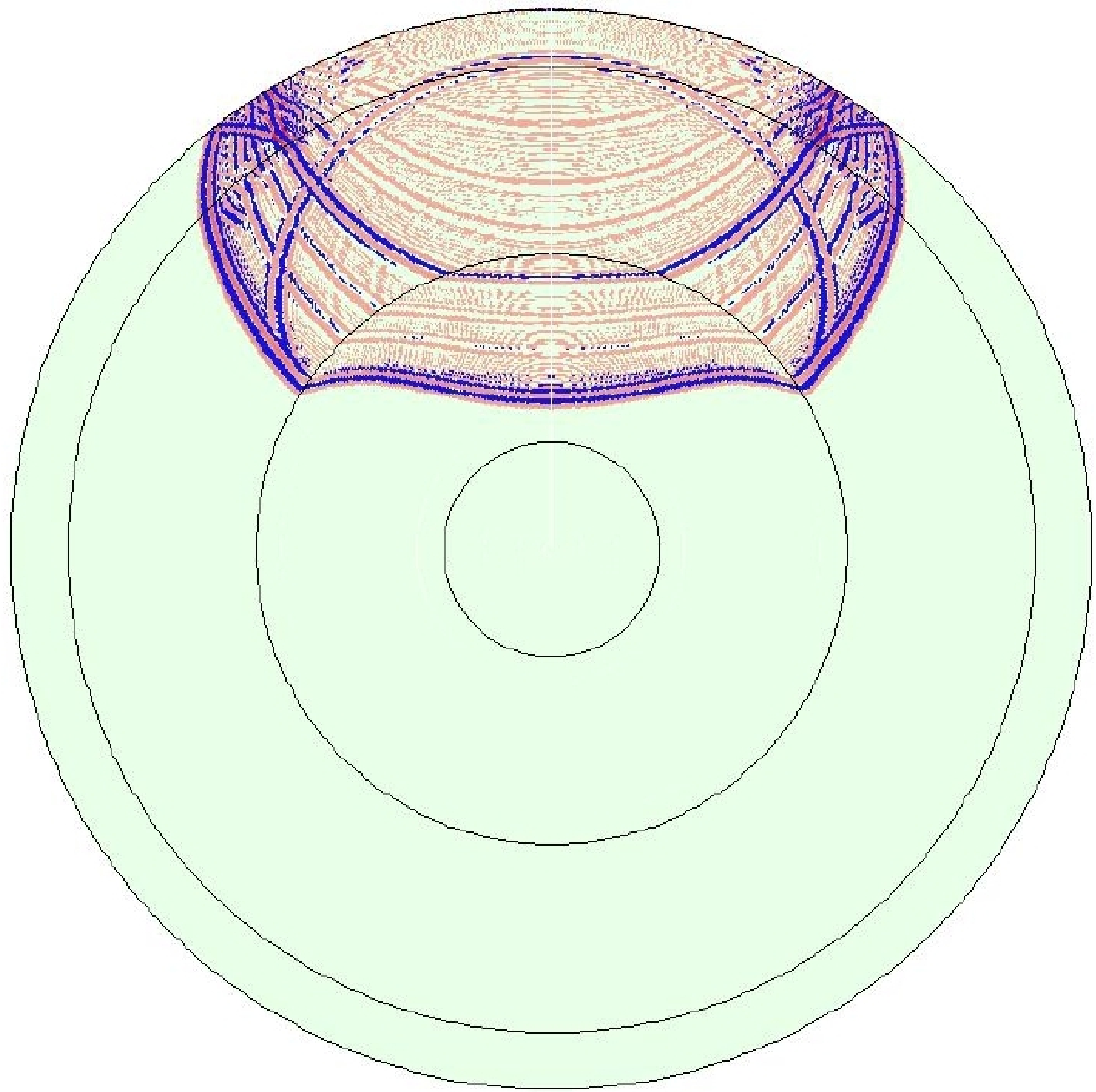


Wavefields in the whole Earth: P waves

Red and blue colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at surface.

Time: 450s

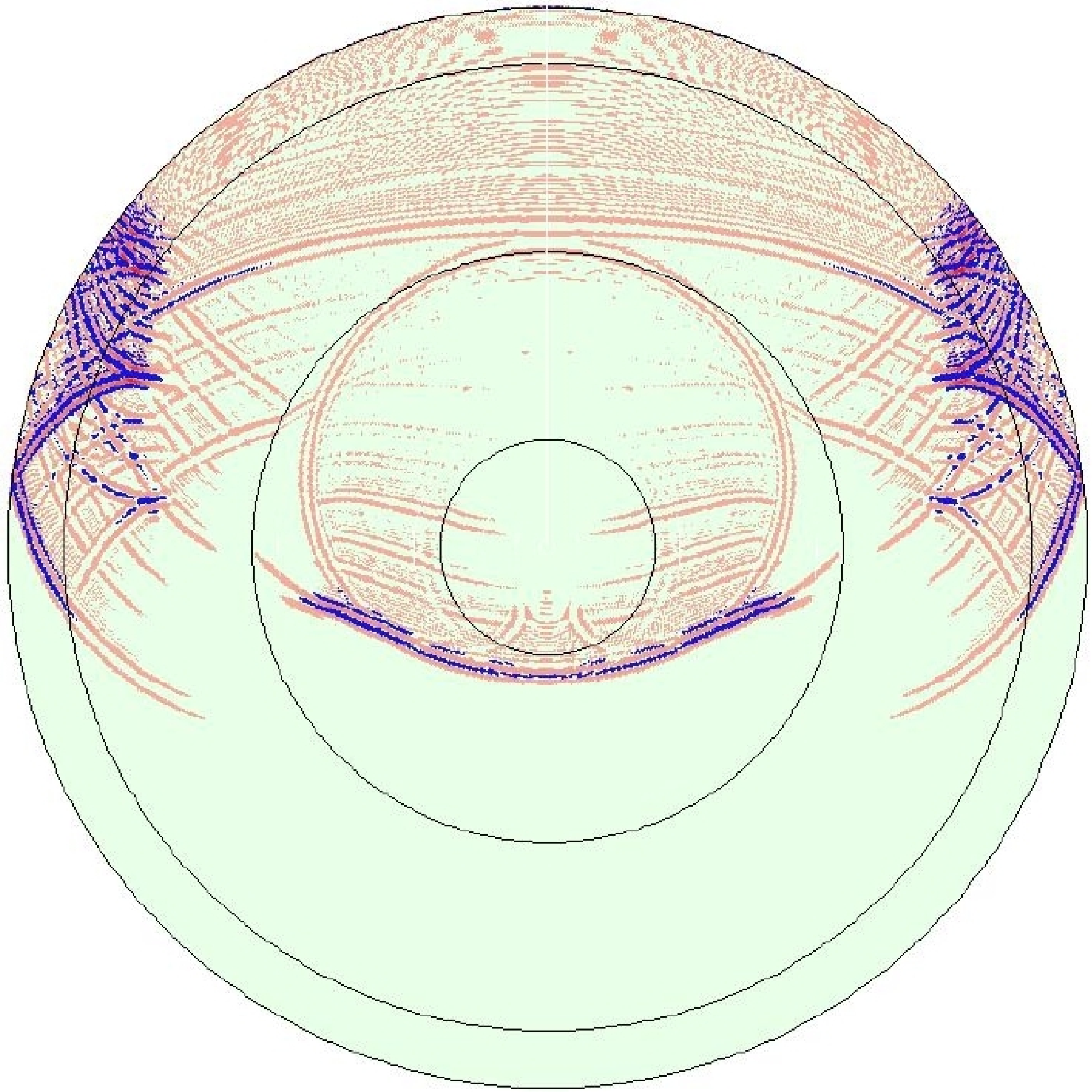


Wavefields in the whole Earth: P waves

Red and blue colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at surface.

Time: 750s

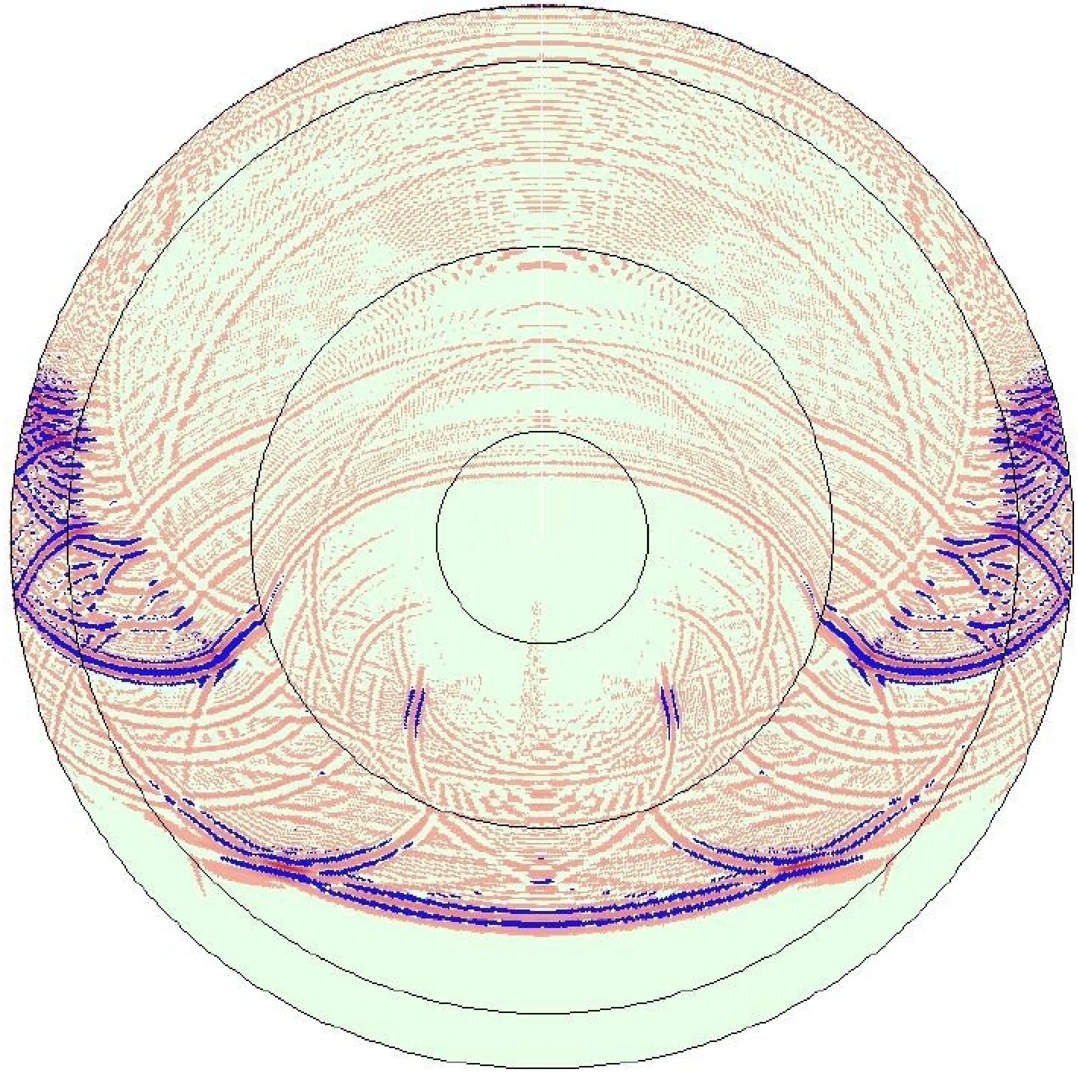


Wavefields in the whole Earth: P waves

Red and blue colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at surface.

Time: 1050s

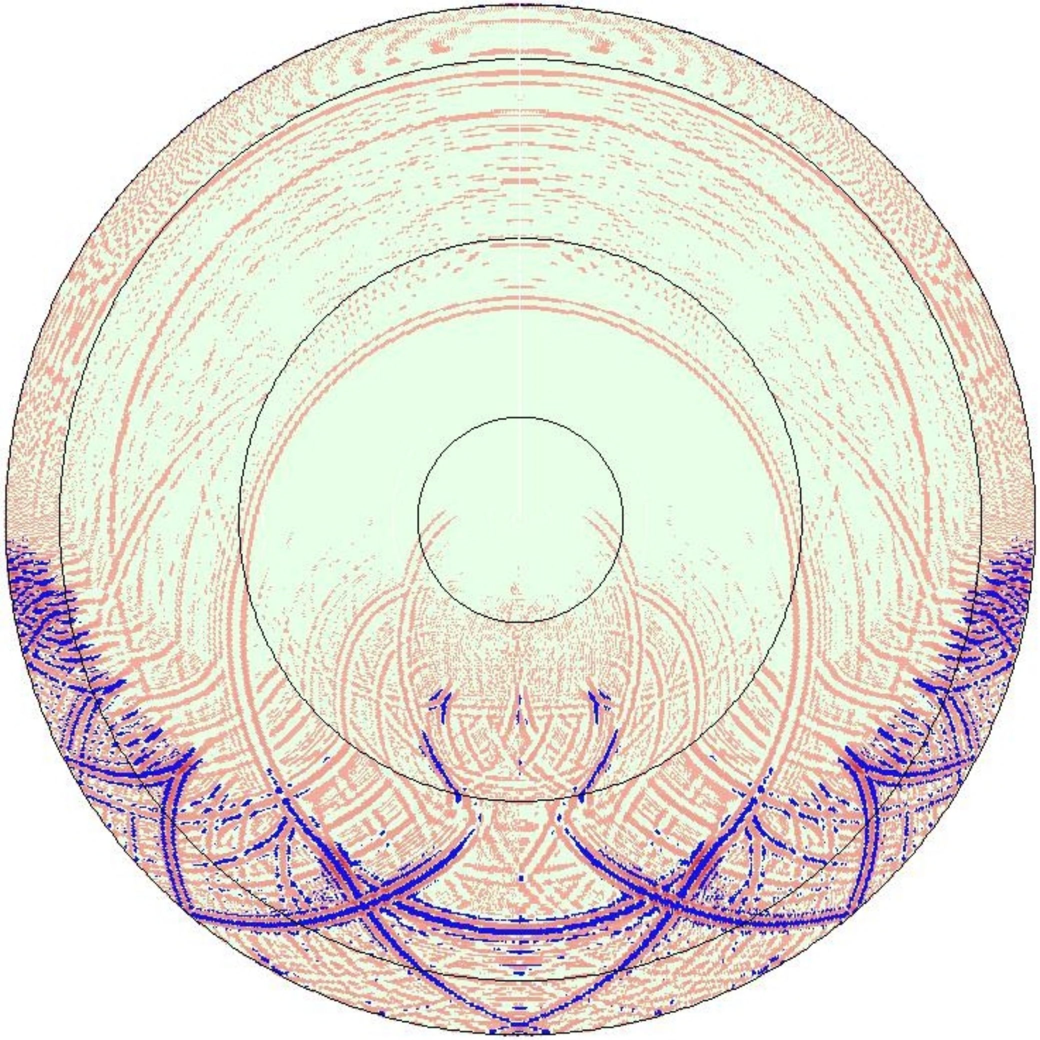


Wavefields in the whole Earth: P waves

Red and blue colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at surface.

Time: 1350s

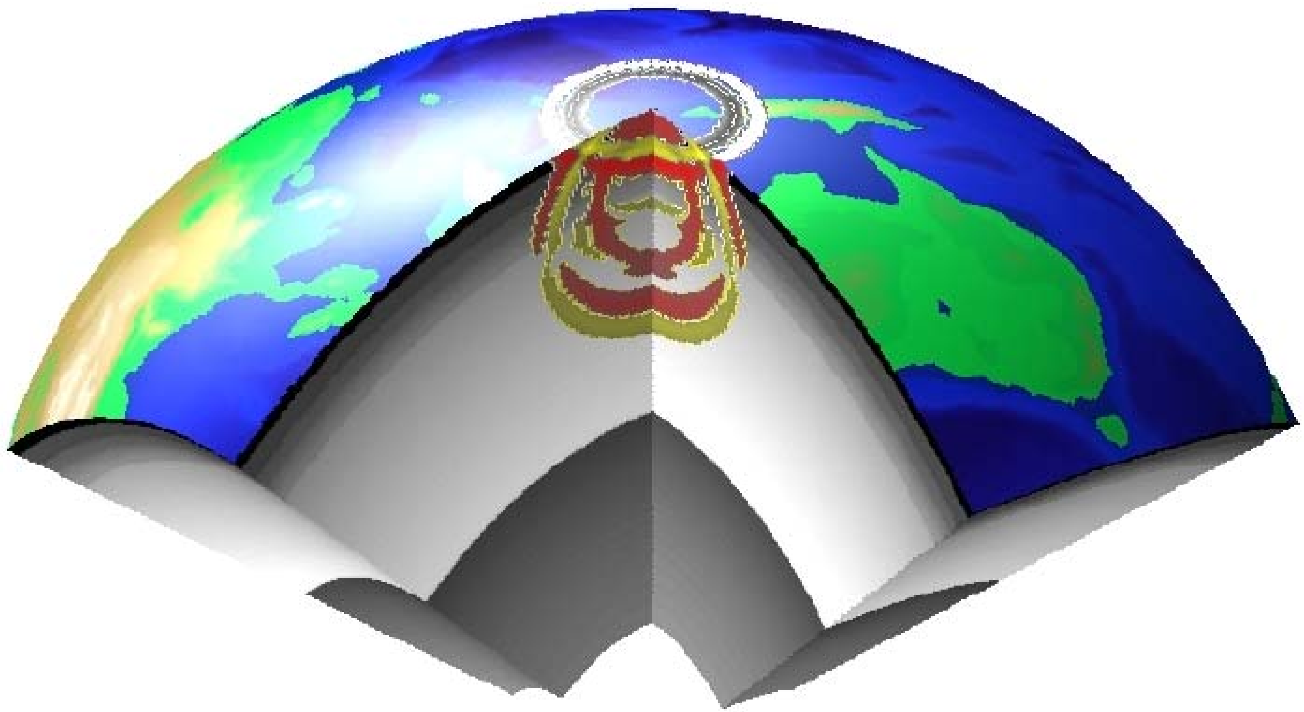


Wavefields in the 3-D Earth

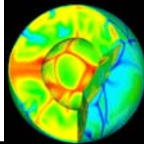
Red and yellow colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

Time: 125s



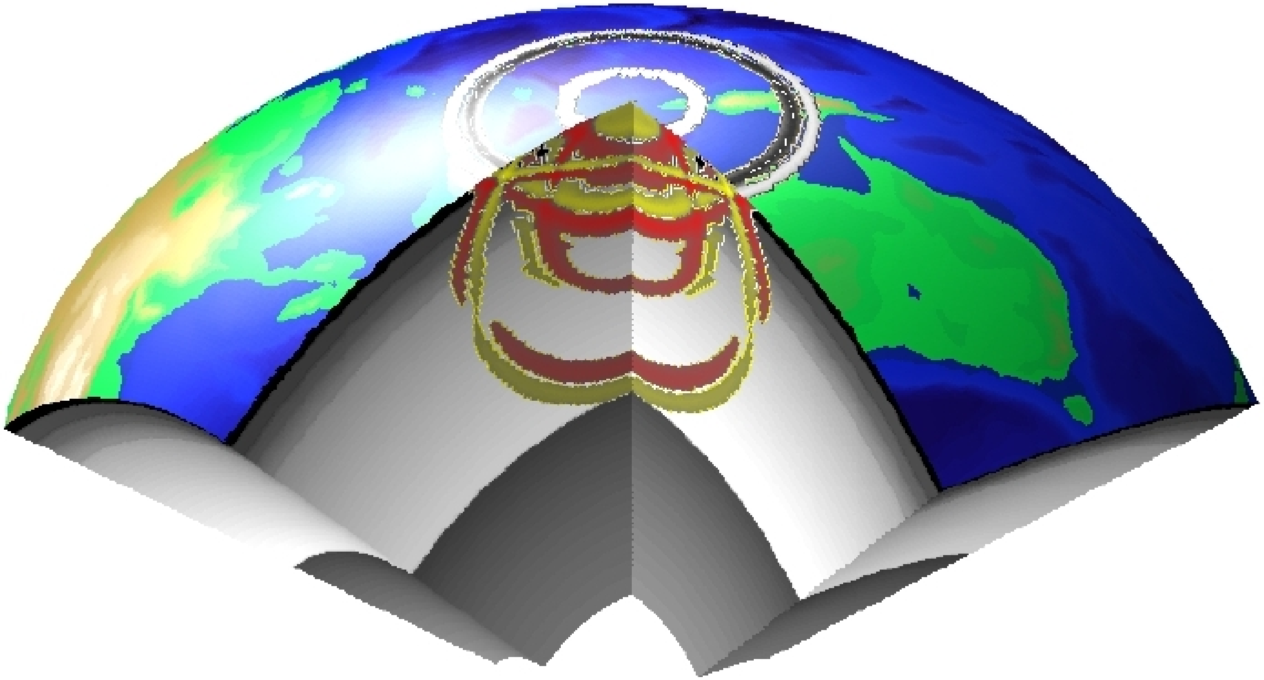
Wavefields in the 3-D Earth



Red and yellow colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

Time: 250s

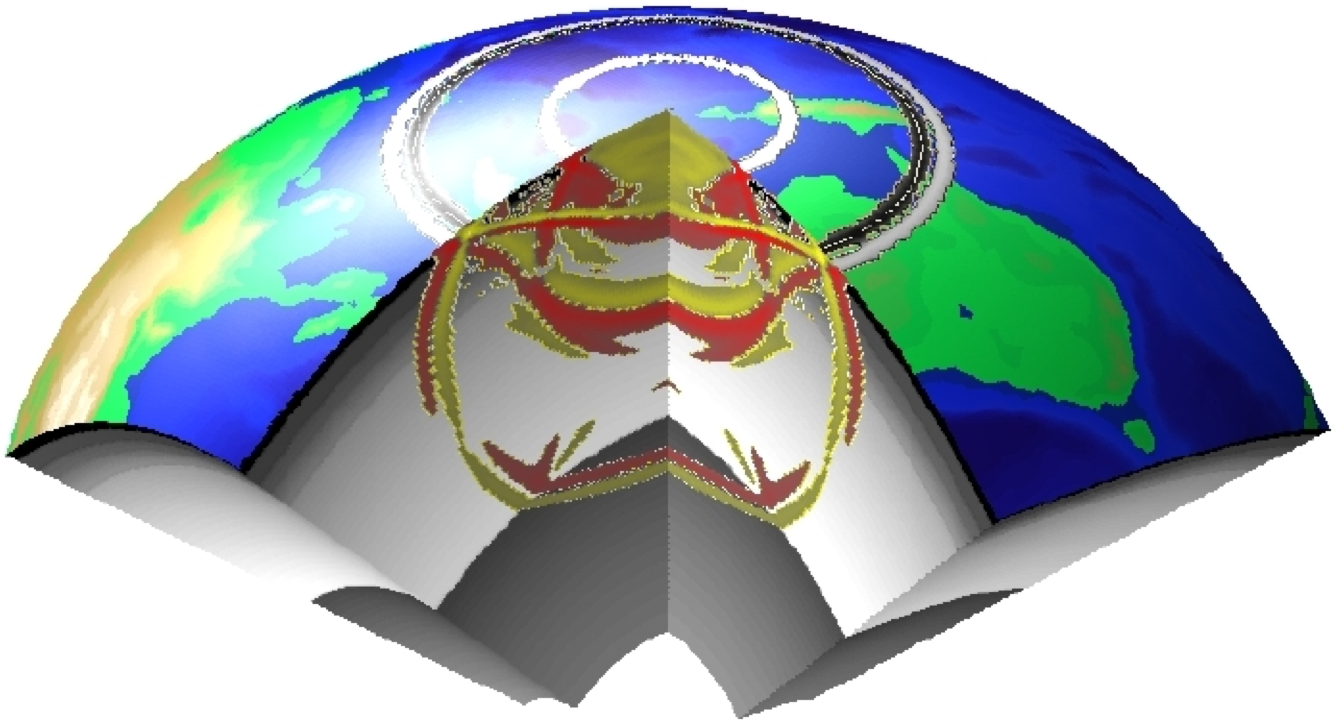


Wavefields in the 3-D Earth

Red and yellow colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

Time: 320s

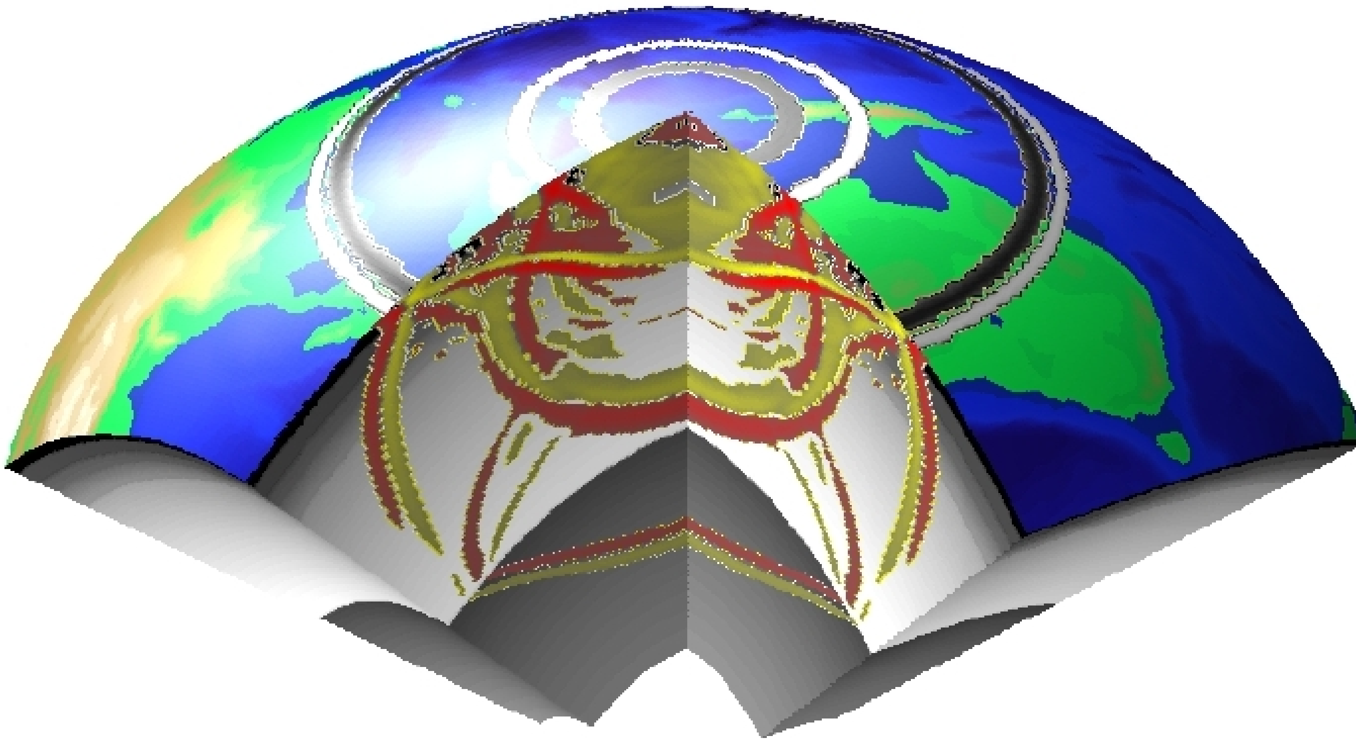


Wavefields in the 3-D Earth

Red and yellow colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

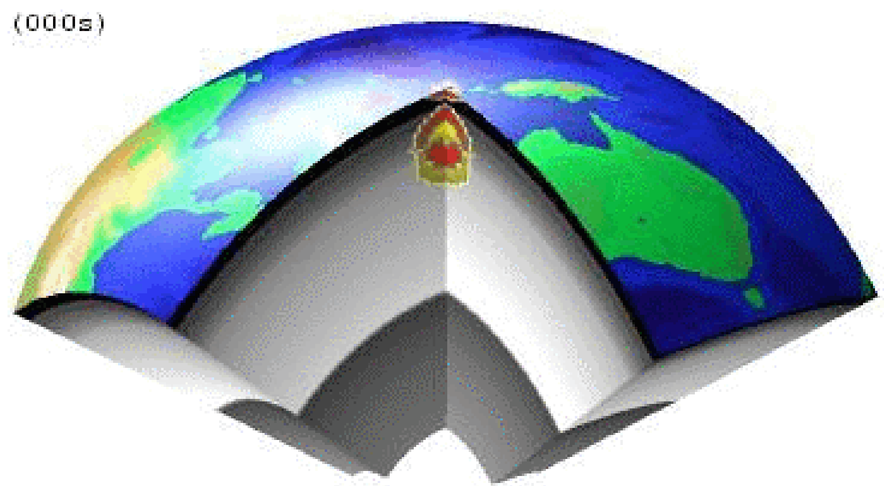
Time: 410s



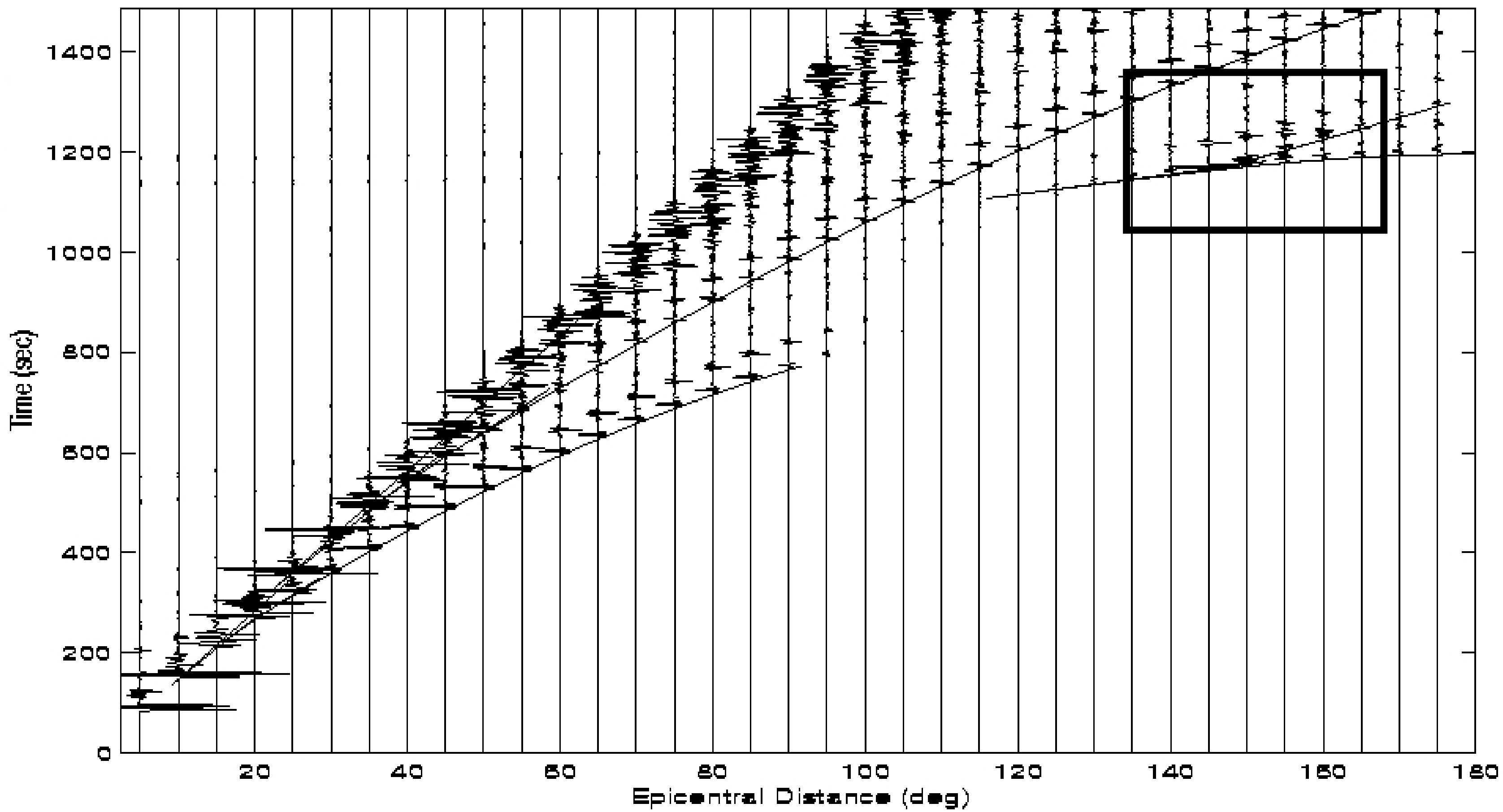
Wavefields in the 3-D Earth: the Movie

Red and yellow colors denote positive and negative vertical displacement, respectively. Spherically symmetric model (Preliminary Reference Earth Model, PREM)

Wavefield for explosion at 600km depth.

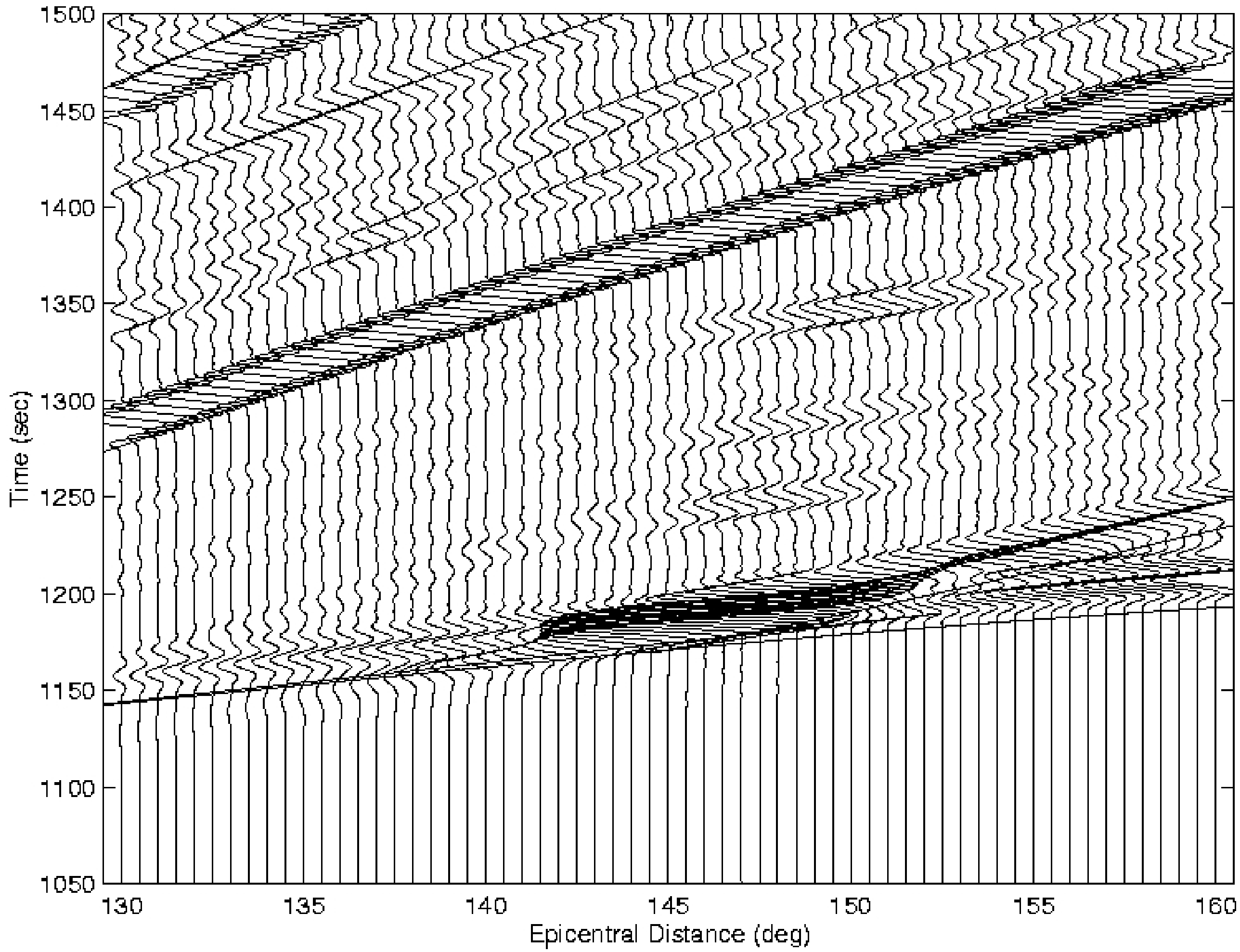


P-wave seismograms



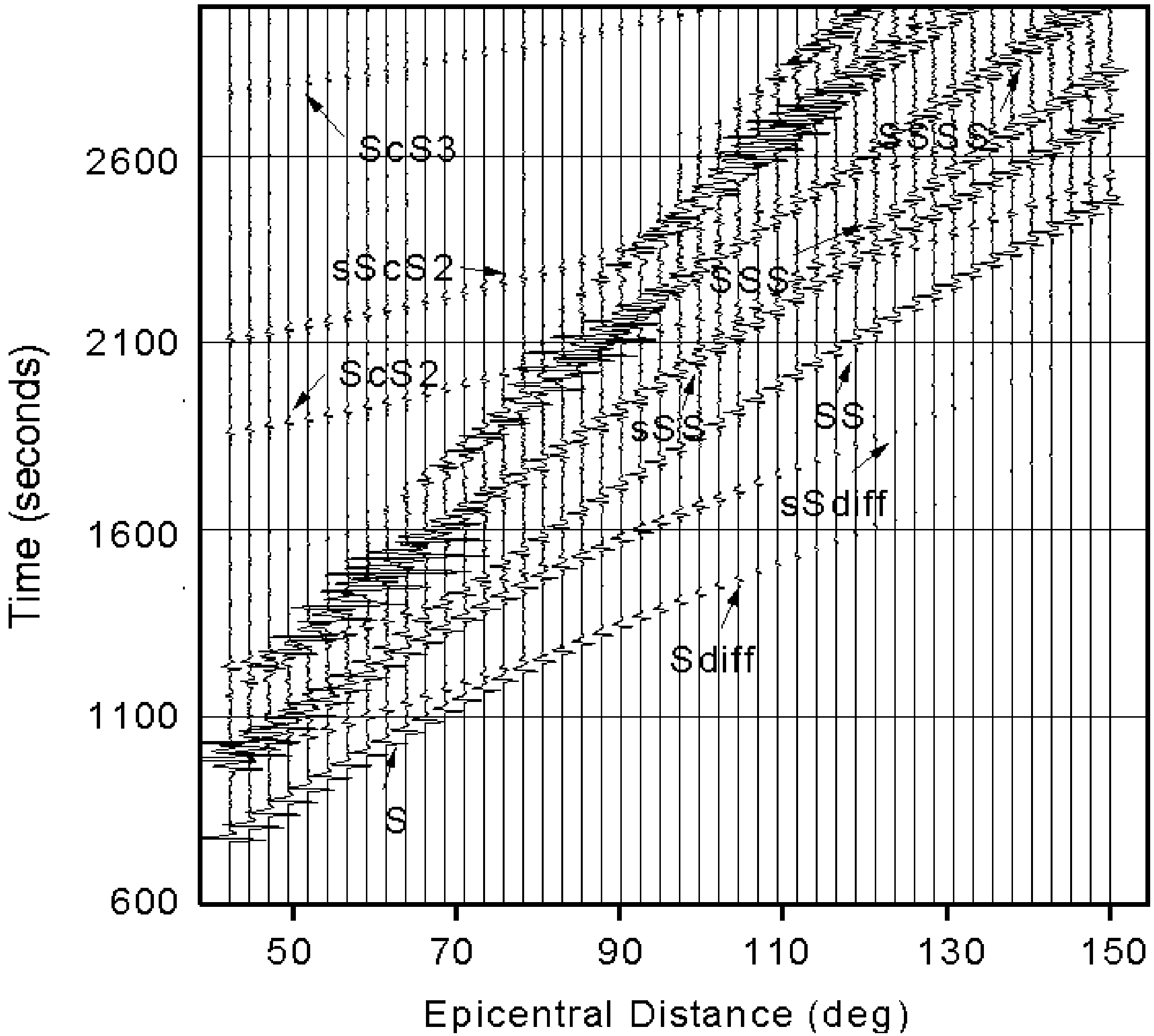
P-wave seismograms for a source at 200km depth, can you identify some phases? Ray-theoretical travel times are added for the direct P wave, the PP and the PKP phase.

P-wave seismograms (PKP)



PKP phase at 145° distance (source at surface). Note the sudden change of amplitude! Why?

SH-wave seismograms



SH seismograms for a source at the surface.

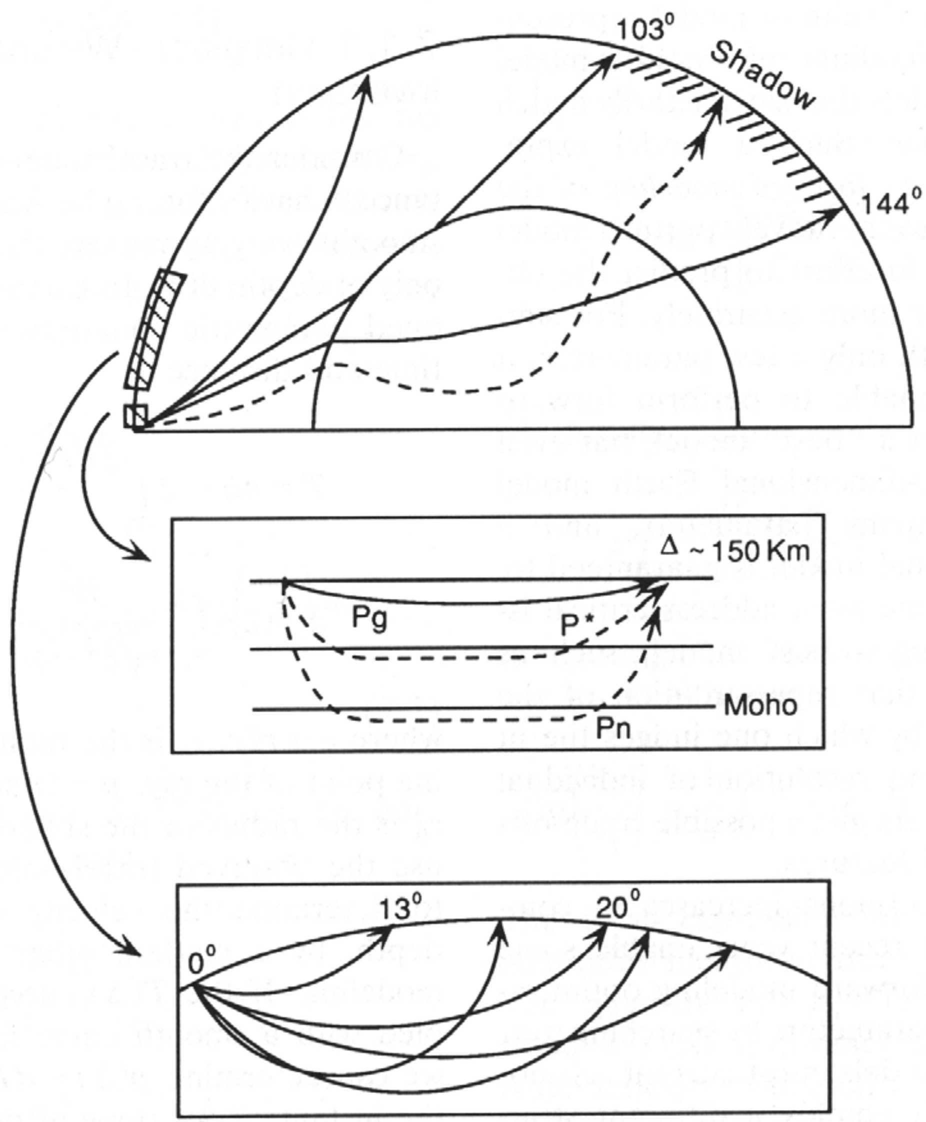
Epicentral Ranges

Three characteristic ranges used in seismic studies:

0°-13° near-field or regional range: crustal phases, spherical geometry can be neglected

13°-30° upper-mantle distance range. Dominated by upper mantle triplications.

30°-180° teleseismic range: waves that sample lower mantle, core, upper mantle reverberations.



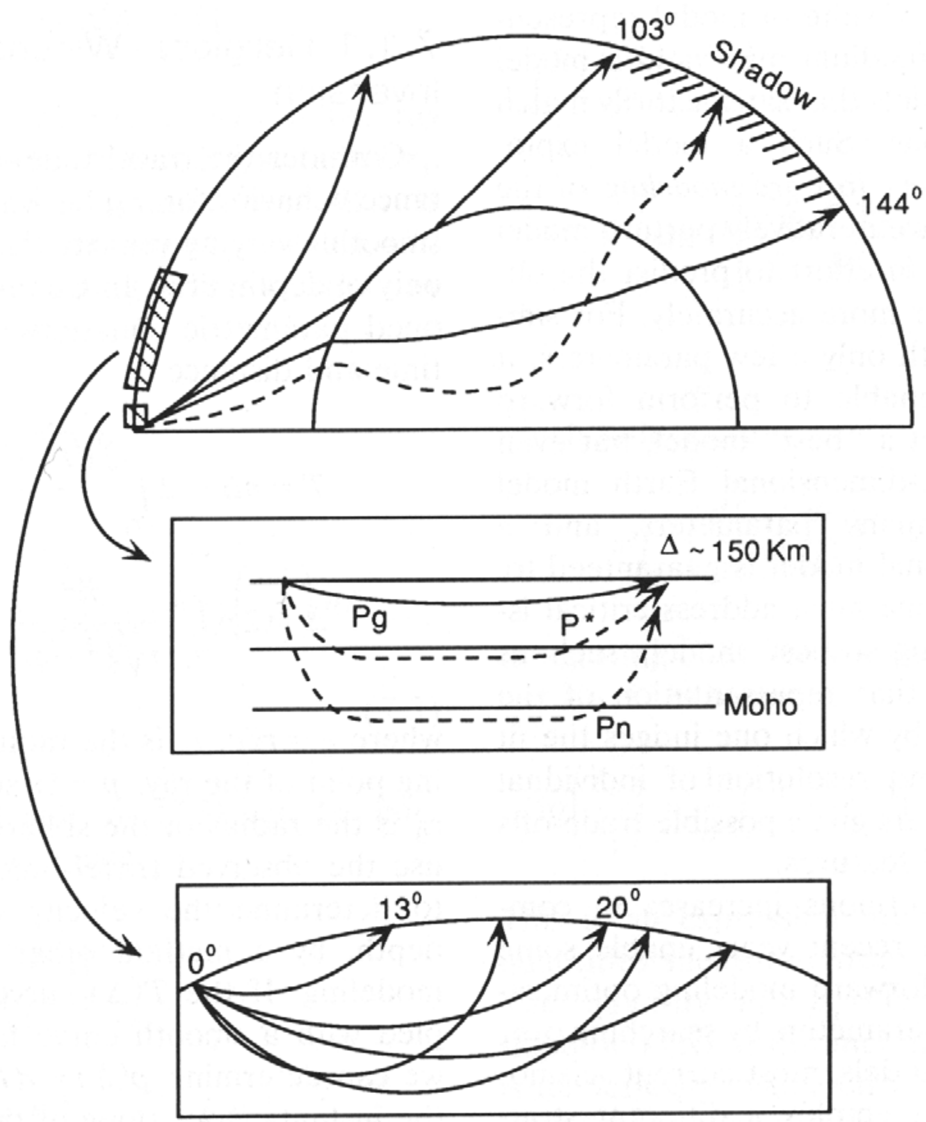
Epicentral Ranges - Experiments

Three characteristic ranges used in seismic studies:

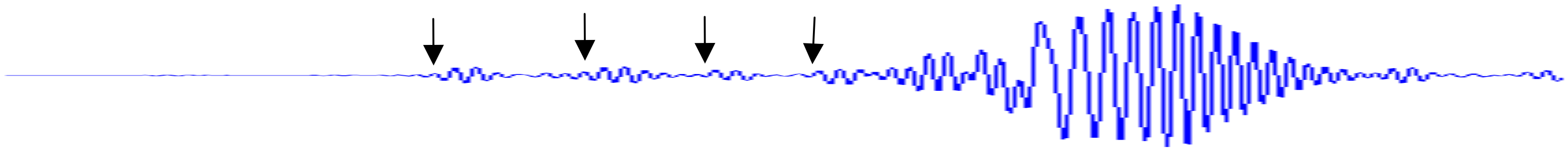
0°-13° near-field
complex crustal structure
seismic reflection and refraction methods

13°-30° upper-mantle
complex tectonic features,
high-pressure phase transitions

30°-180° teleseismic
seismic tomography, 3-D global structure



Earth Structure Inversion

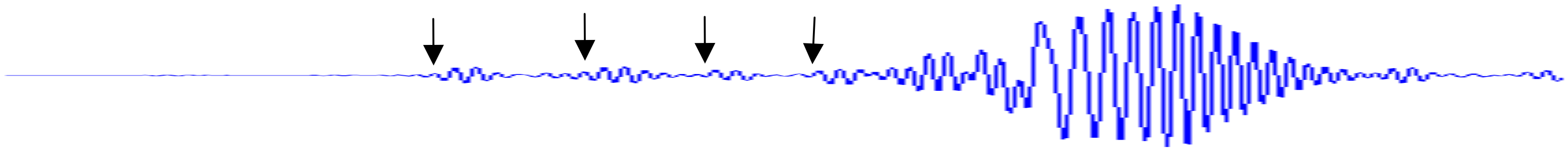


How to proceed to determine Earth structure from observed seismograms using travel times?

1. Determine epicentral distance (from P and S or Rayleigh, then compare with travel time tables)
2. Get travel times for other phases PP, ScS, pP, sS, determine differential travel times (e.g. pP-P, sS-S) to estimate source depth
3. Determine travel time perturbations from spherically symmetric model (e.g. iasp91, PREM)

- the observability of seismic phases depends on the source radiation pattern
- they are also frequency dependent
- all three components of displacement should be used for analysis

Earth Structure Inversion



We have recorded a set of travel times and we want to determine the structure of the Earth.

In a very general sense we are looking for an Earth model that minimizes the difference between a theoretical prediction and the observed data:

$$\sum_{traveltimes} T_{obs} - T_{theory}(m) = Min!$$

where m is an Earth model. For spherically symmetric media we can solve the problem analytically:

Wiechert-Herglotz Inversion

Previously we derived the travel times for a given layered velocity structure for flat and spherical media: the **forward** problem

Flat	Spherical
$T = pX + 2\int_0^z \sqrt{1/c^2(z) - p^2}\,dz$	$T = p\Delta + 2\int_{r_0}^{r_1} \frac{\sqrt{r^2/c^2(z) - p^2}}{r^2}\,dr$

The first term depends only on the horizontal distance and the second term only depends on r (z), the vertical dimension.

Wiechert-Herglotz Inversion

The solution to the **inverse** problem can be obtained after some manipulation of the integral :

$$T = p\Delta + 2\int_{r_0}^{r_1} \frac{\sqrt{r^2/c^2(z) - p^2}}{r^2} dr \Leftrightarrow \ln\left(\frac{r_0}{r_1}\right) = \frac{1}{\pi}\int_0^{\Delta_1} \cosh^{-1}\left(\frac{p}{\xi_1}\right) d\Delta$$

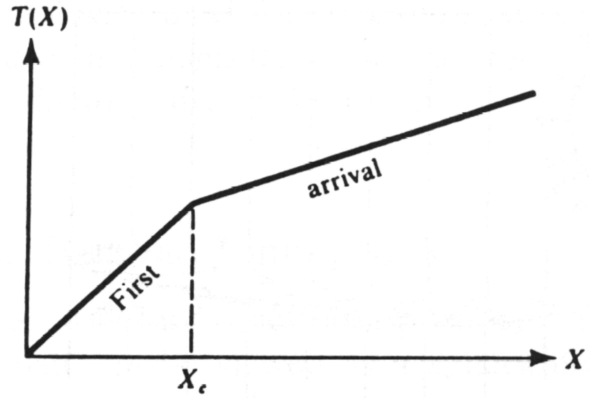
forward problem **inverse problem**

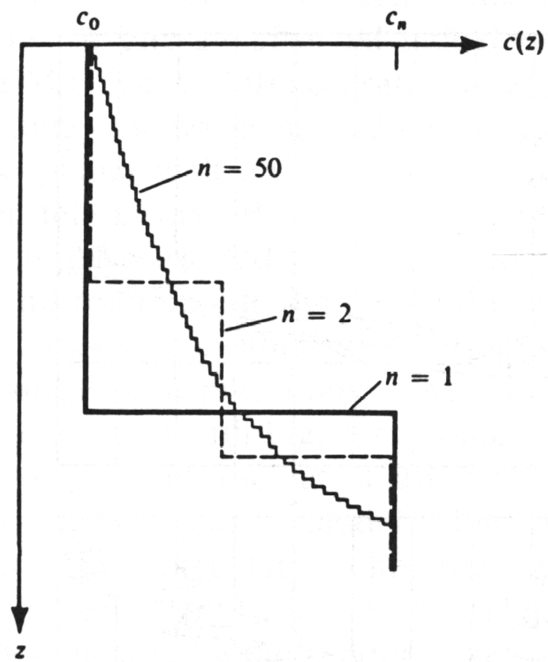
The integral of the inverse problem contains only terms which can be obtained from observed $T(\Delta)$ plots. The quantity $\xi_1=p_1=(dT/d\Delta)_1$ is the slope of $T(\Delta)$ at distance Δ_1. The integral is numerically evaluated with discrete values of $p(\Delta)$ for all Δ from 0 to Δ_1. We obtain a value for r_1 and the corresponding velocity at depth r_1 is obtained through $\xi_1=r_1/v_1$.

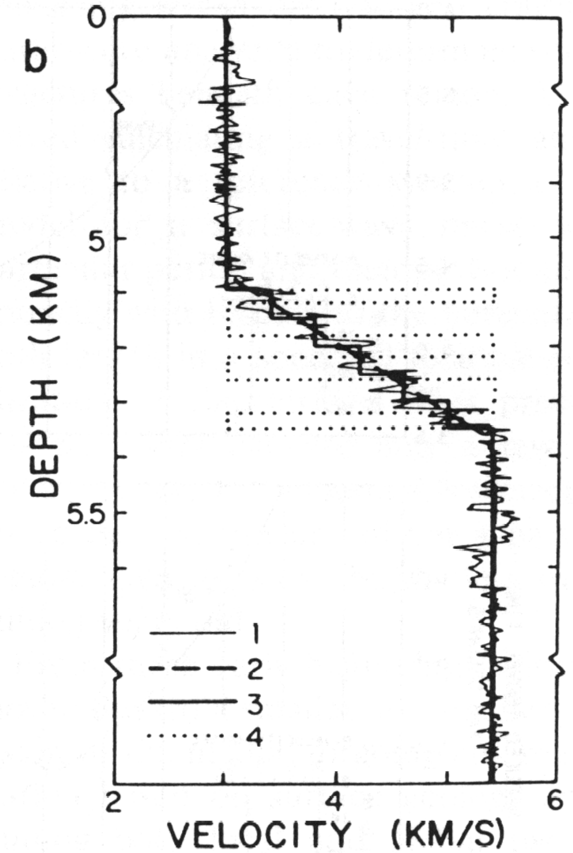
Nonuniqueness in Travel-time Inversion

A first arrival travel time curve is compatible with an infinite set of structures

-> non-uniqueness





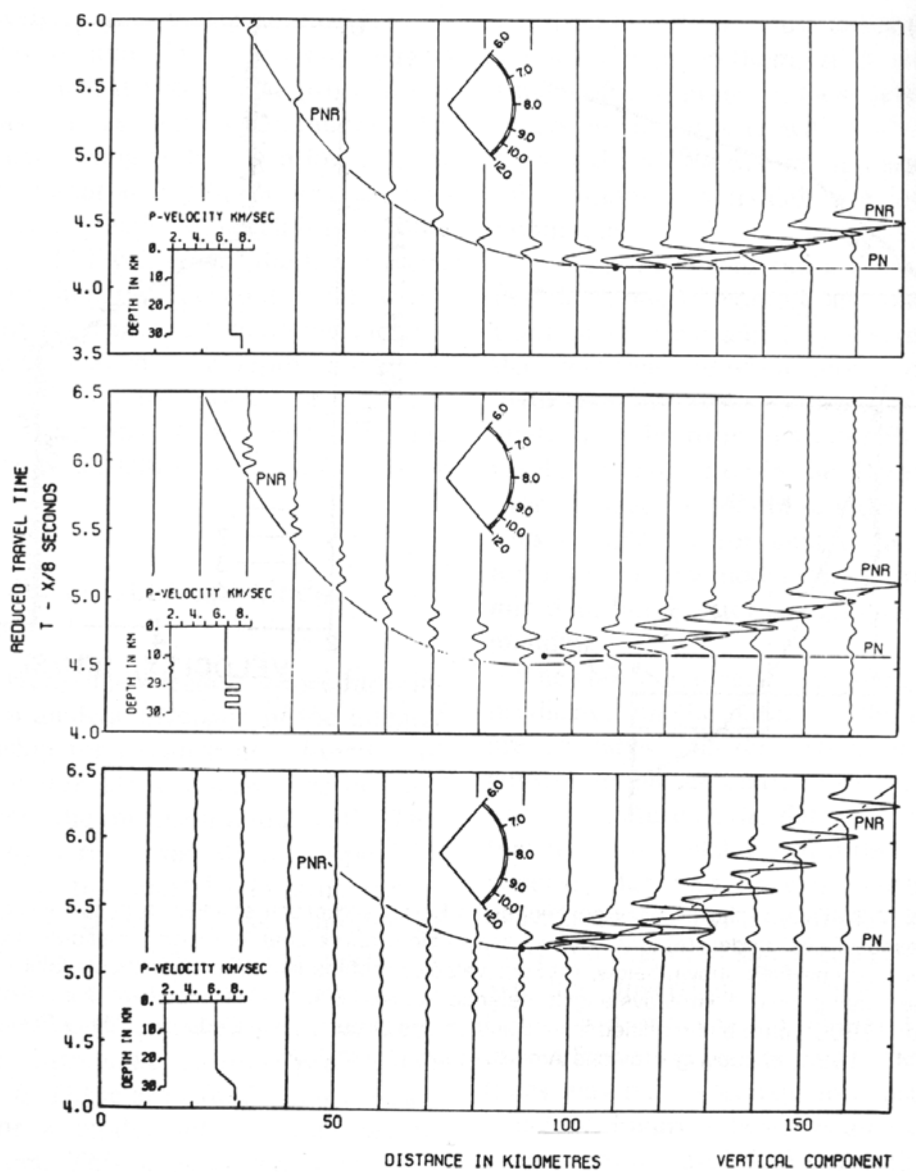


Constraints by Wavefield Effects

Structural sensitivity can be improved by using the complete wavefield information and broadband data:

waveform shape can constrain complexity

Improving full wavefield modelling and inversion is one of the most important goals in modern seismology!

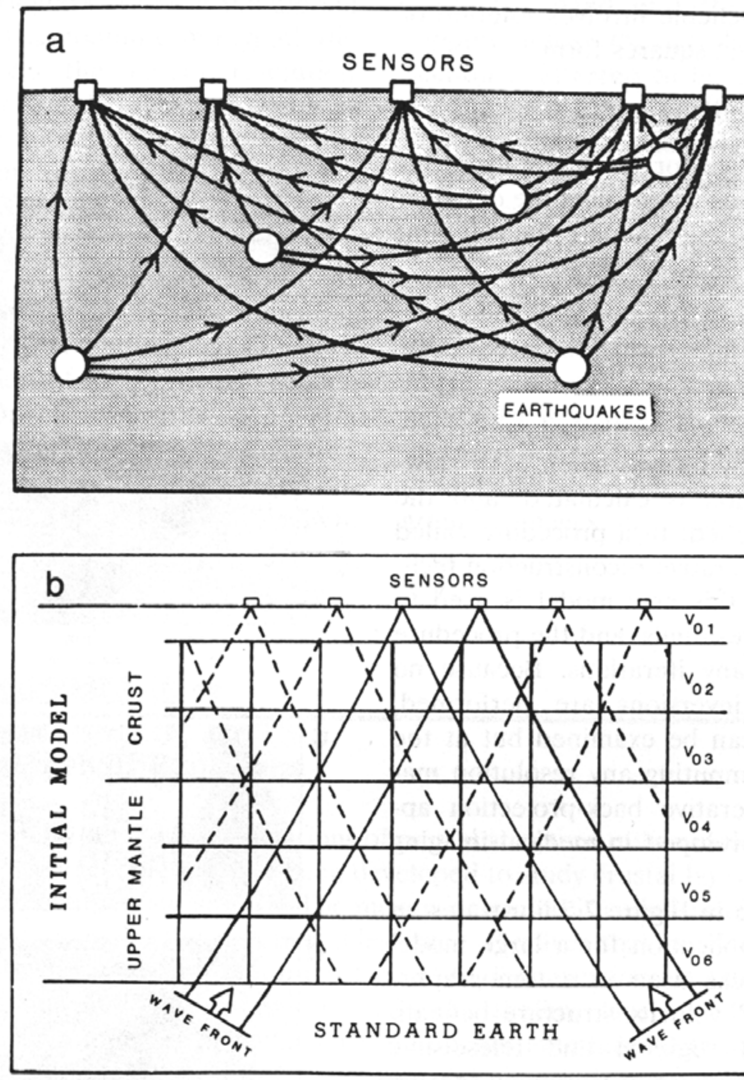


Seismic Tomography

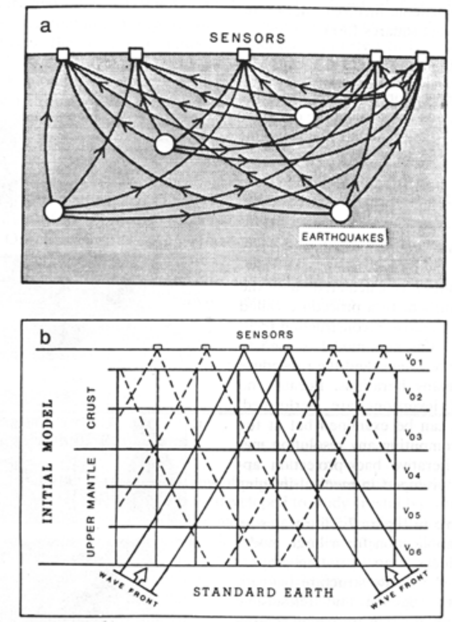
The three-dimensional variations in seismic velocities contain crucial information on the Earth's dynamic behavior!

Seismic tomography aims at finding the 3-D velocity perturbations with respect to a spherically symmetric background model from observed seismic travel times (body waves and surface waves, free oscillations)

What are the similarities and differences to medical tomography?



Seismic Tomography - Principles



A particular seismic phase has a travel time T which is given by a path integral through the medium as

$$T = \int_s \frac{ds}{v(s)} = \int_s u(s)ds$$

where u(s) is the slowness [1/v(s)] along the path s. A travel time perturbation can happen anywhere along the path

$$\int_s \Delta u(s)ds = \Delta T = T_{obs} - T_{pred}$$

A medium is discretized into blocks and thus we can calulate the path length l_j in each block to obtain

$$\Delta T = \sum_j l_j \Delta u_j \qquad \text{for many observations} \qquad \Delta T_i = \sum_j l_{ij} \Delta u_j$$

We want to find Δu_i from observed travel times -> **inverse problem**

Receiver Functions

Receiver functions have been used recently to study upper mantle structure.

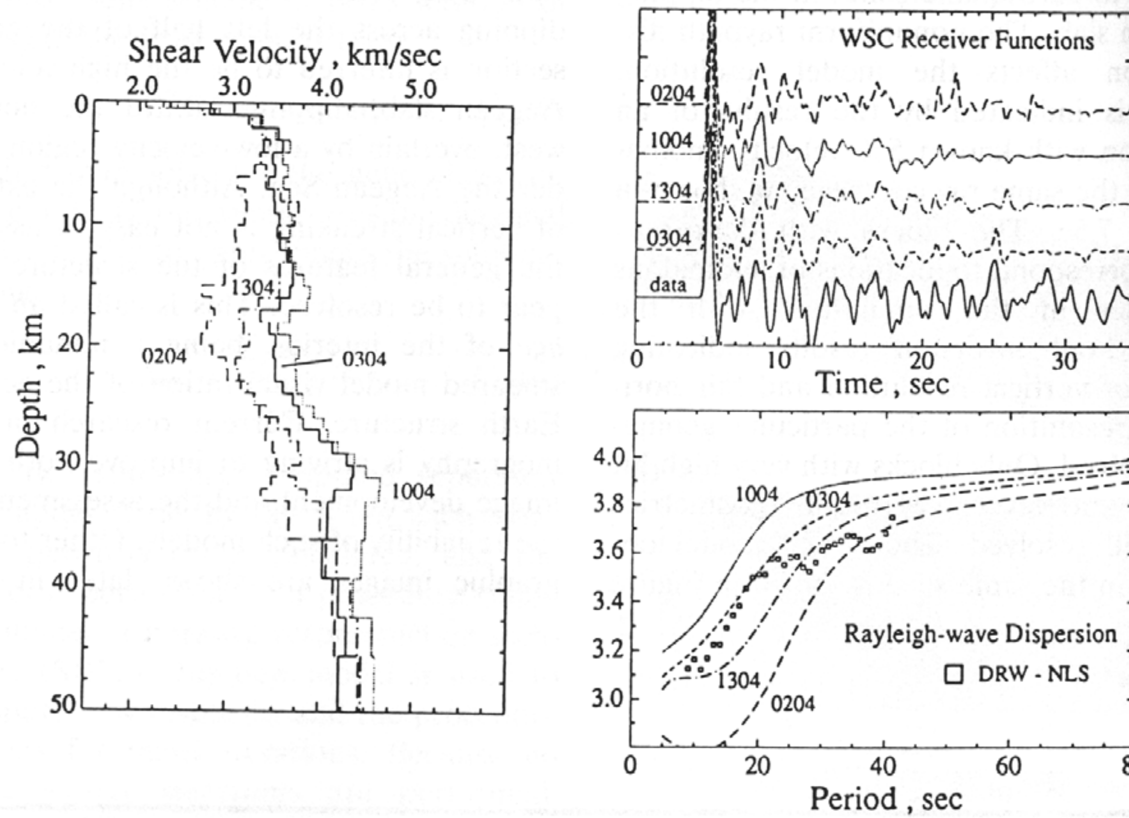
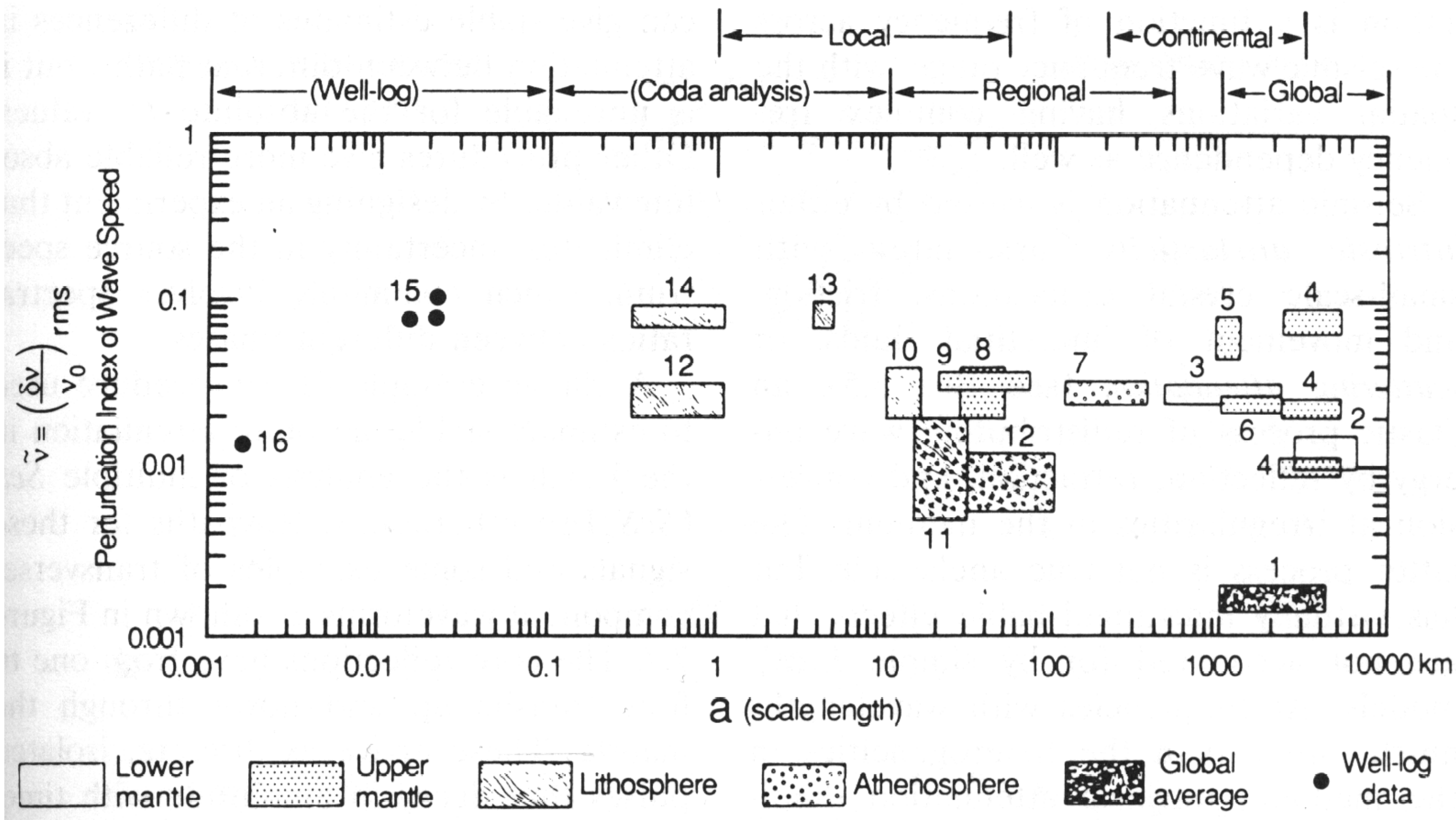


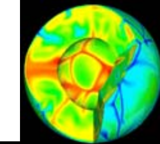
FIGURE 7.B1.1 Receiver function analysis of the crustal velocity structure under Death Valley, California. The left panel shows velocity structures obtained by inversions of the observed receiver function, labeled ''data'' in the upper-right box. The models differ because of different initial models in the inversion, but all produce reasonable fits to the data. To better resolve the structure, short-period surface-wave dispersion observations are modeled as well. (Courtesy of S. Beck and G. Zandt.)

Heterogeneities inside the Earth

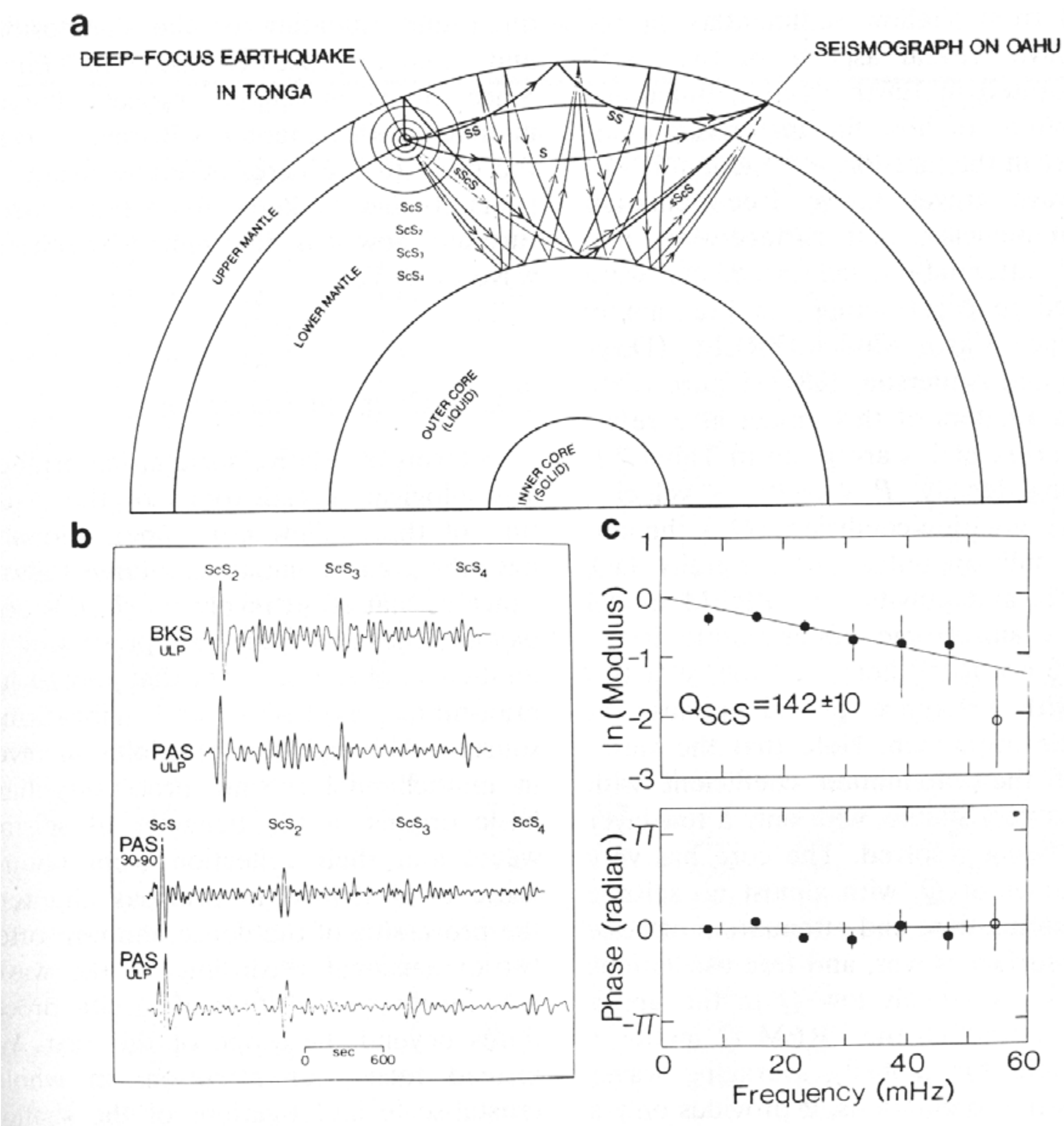


(1) Global average; (2,3) lower mantle; (4,5,6) upper mantle from surface waves; (7) asthenosphere; (8) upper mantle from body waves; (9) upper mantle; (11-14) lithosphere; (15,16) crust.

Attenuation from Multiples



Multiple reflections from the core mantle boundary can be used to infer the attenuation of seismic waves inside the mantle



Seismogram Interpretation: Summary

The most important information on the 3-D structure of the Earth is contained in the travel times of particular seismic phases (e.g. P, S, ScS, PcP, PKP, PPP, sSS, etc.) travelling thorugh the Earth's interior.

The radial structure of the Earth explains all observed travel times to within 1% accuracy. Several such structures have been determined since the 1940s (e.g. Jeffrey-Bullen, Herrin, PREM, iasp91).

The radial structure of the Earth can be estimated using first-arrival travel times and the Wiechert-Herglotz inversion technique.

The deviations of the observed travel-times from the predicted travel times for spherically symmetric models are used to estimate the Earth's 3-D seismic velocity structure. This processing is called seismic tomography.

Although the travel time data are explained to within 1% by a spherically symmetric structure, the 3-D velocity structure contains crucial information on the dynamic properties of the Earth's mantle (e.g. subducting slabs, plumes, etc.)