Westfälische Wilhelms-Universität Münster

GEOPHYSIK WWU MÜNSTER

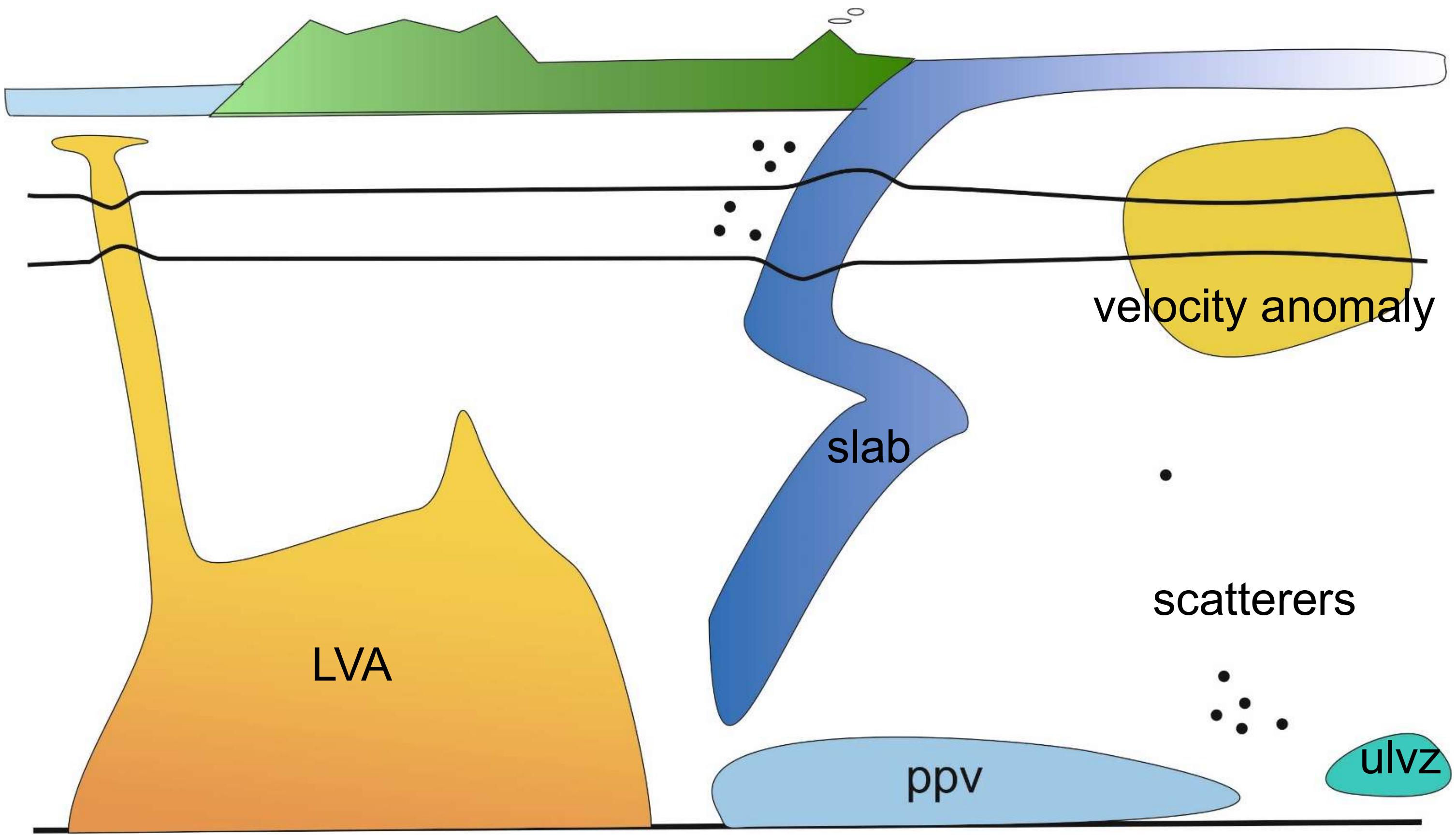
Imaging the Deep Earth with Earthquakes and Seismic Arrays

Christine Thomas

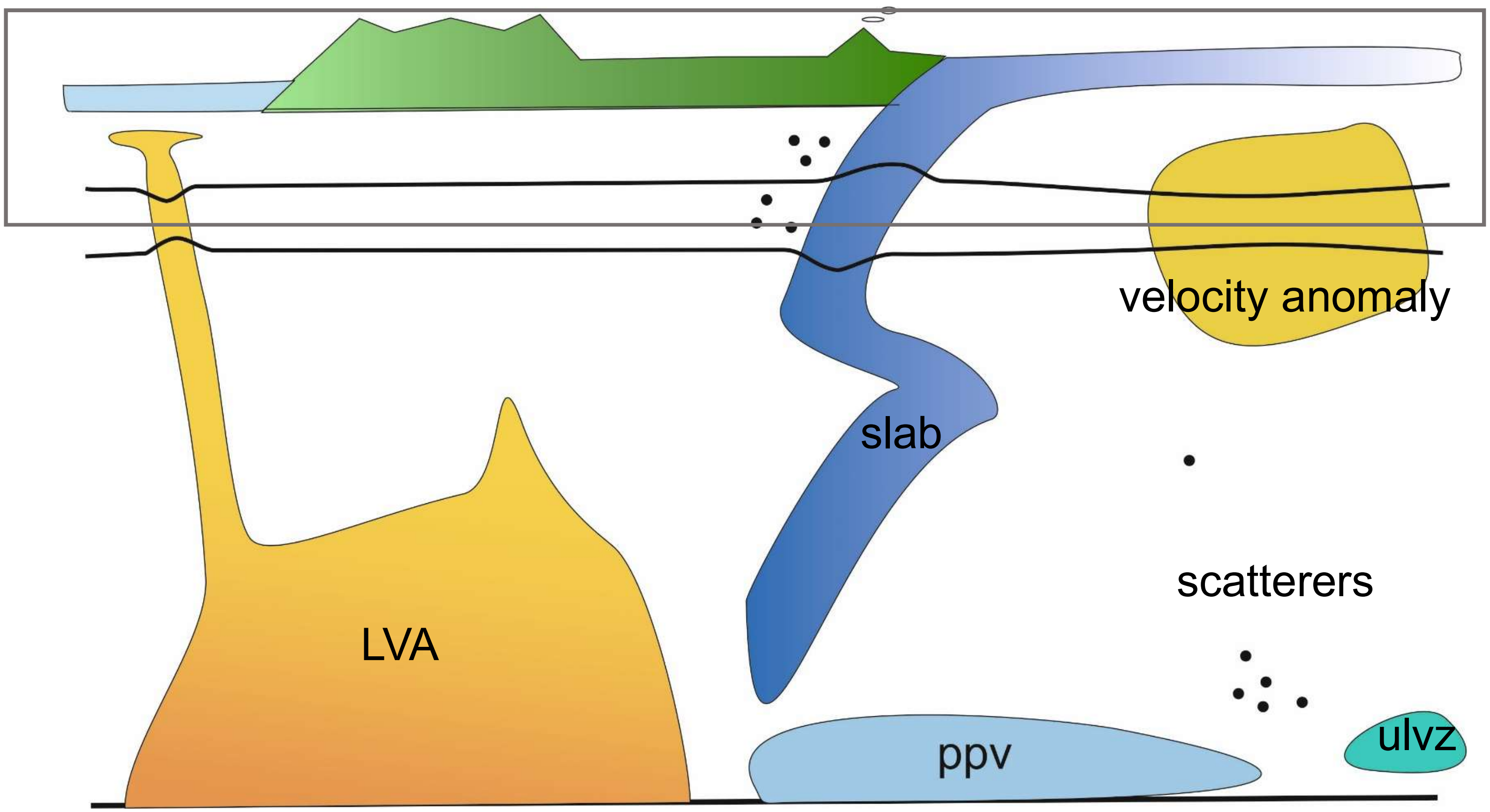
WWU Münster

including work of:
Morvarid Saki, Stephan Lessing, Lina Schumacher

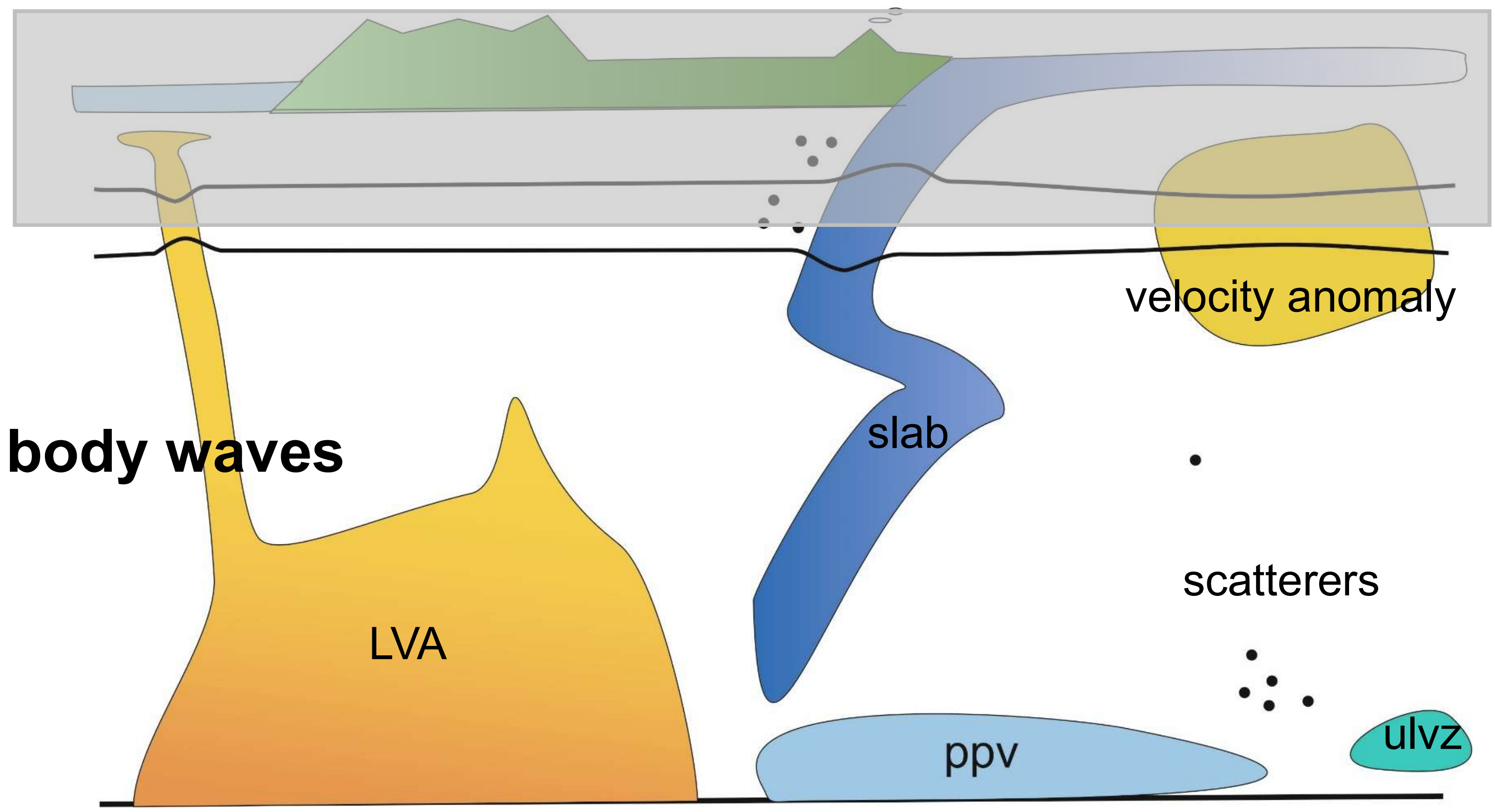
The deep Earth



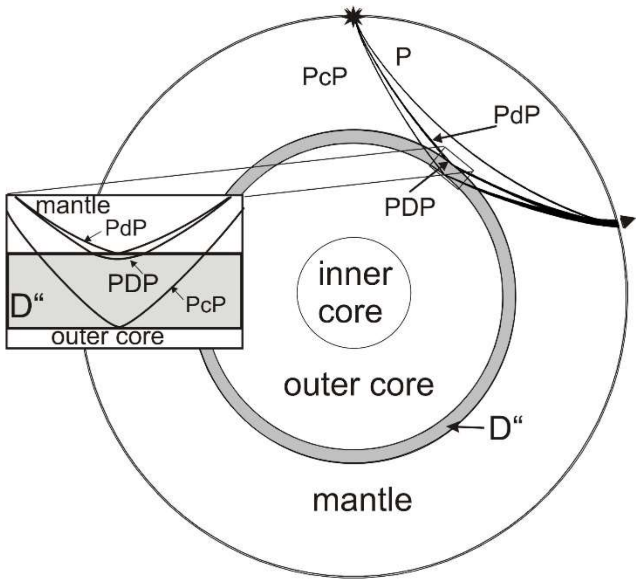
The deep Earth



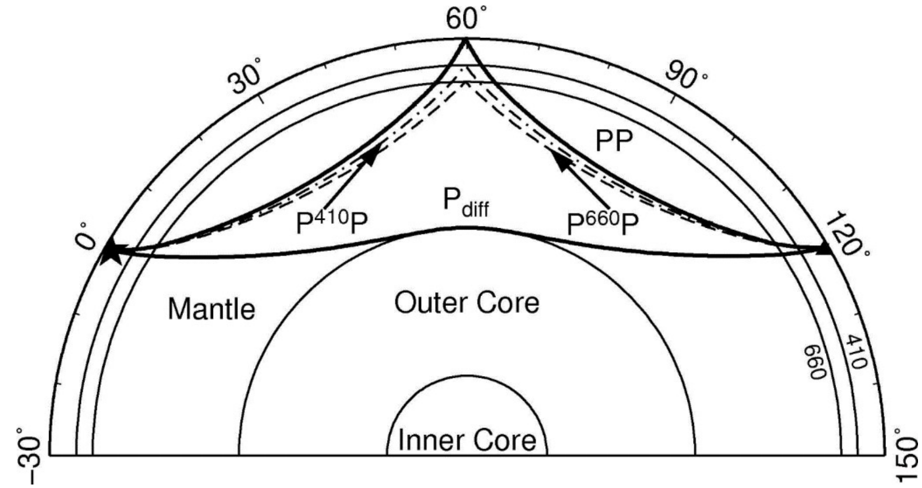
The deep Earth



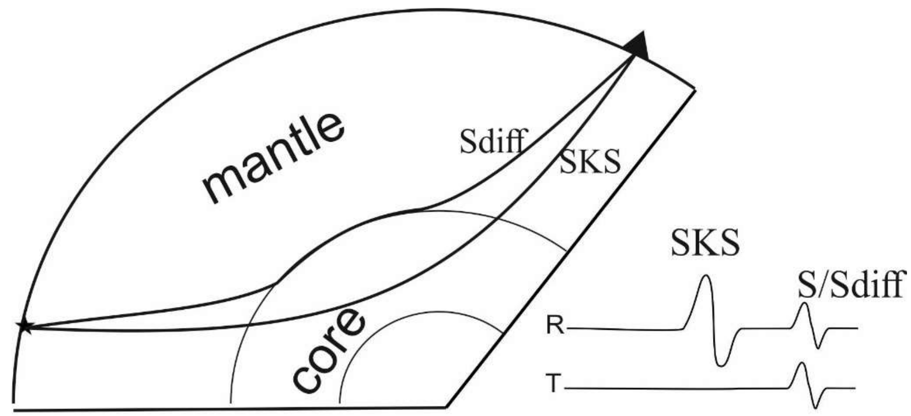
Body waves (some)



PdP/SdS: reflections off the D" structure

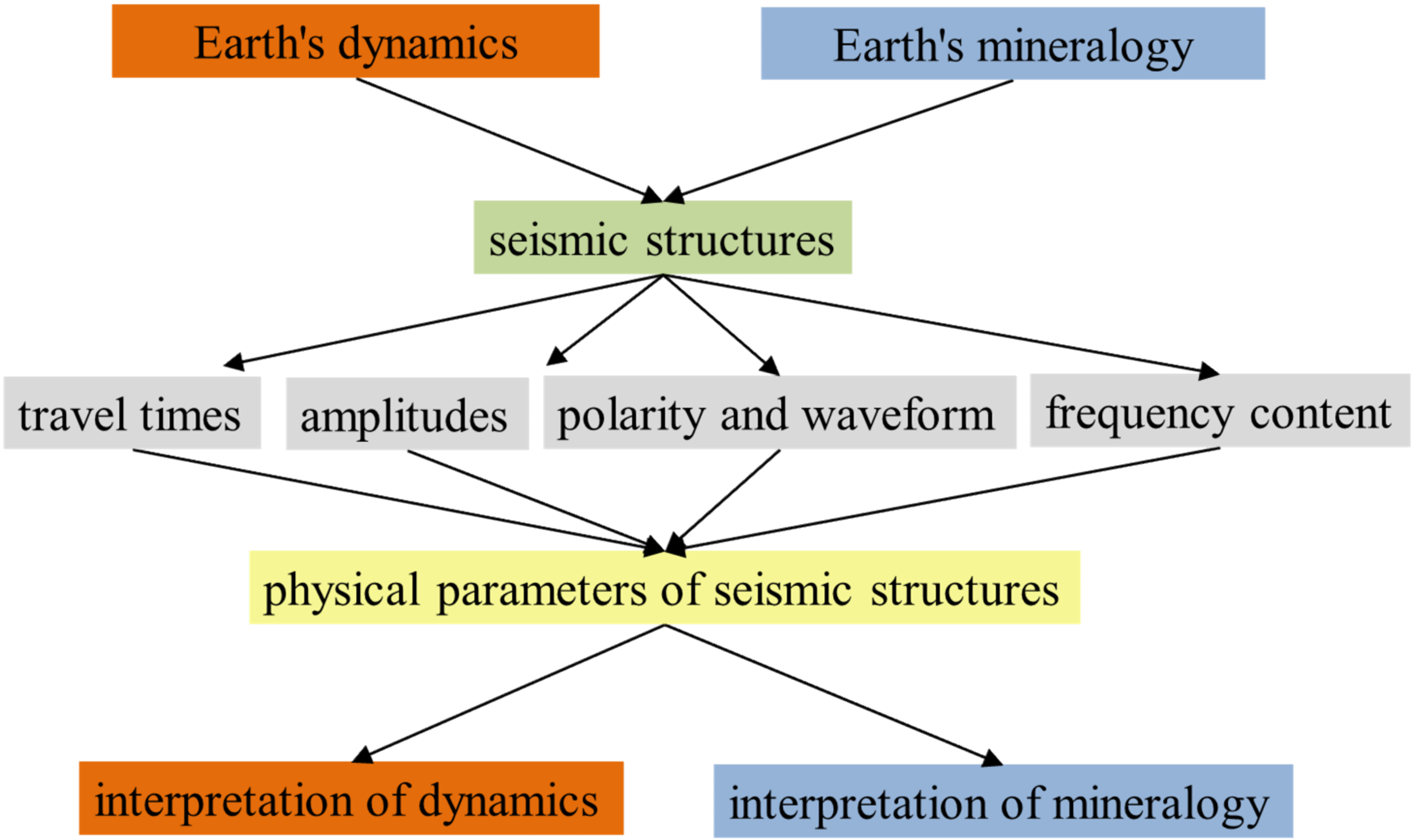


underside reflections (PP or SS precursors)



SKS and Sdiff

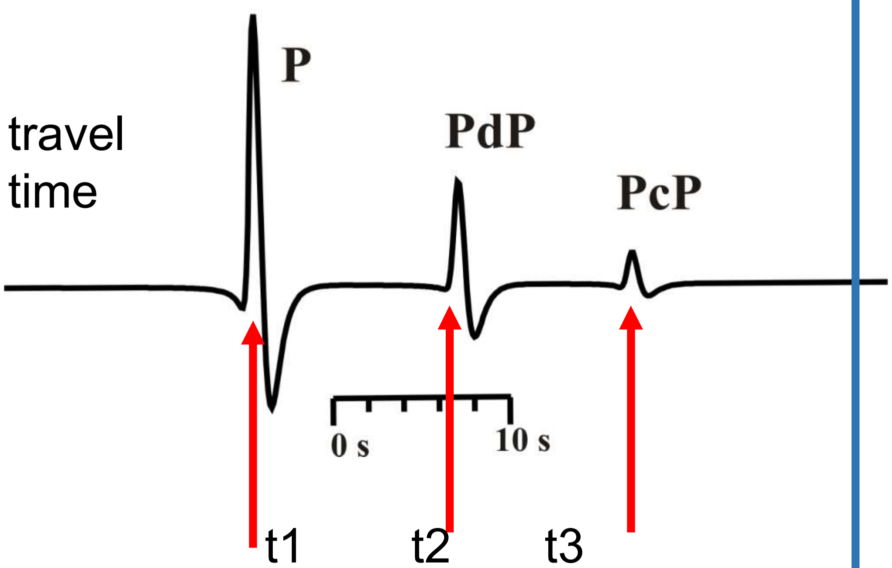
Why imaging?



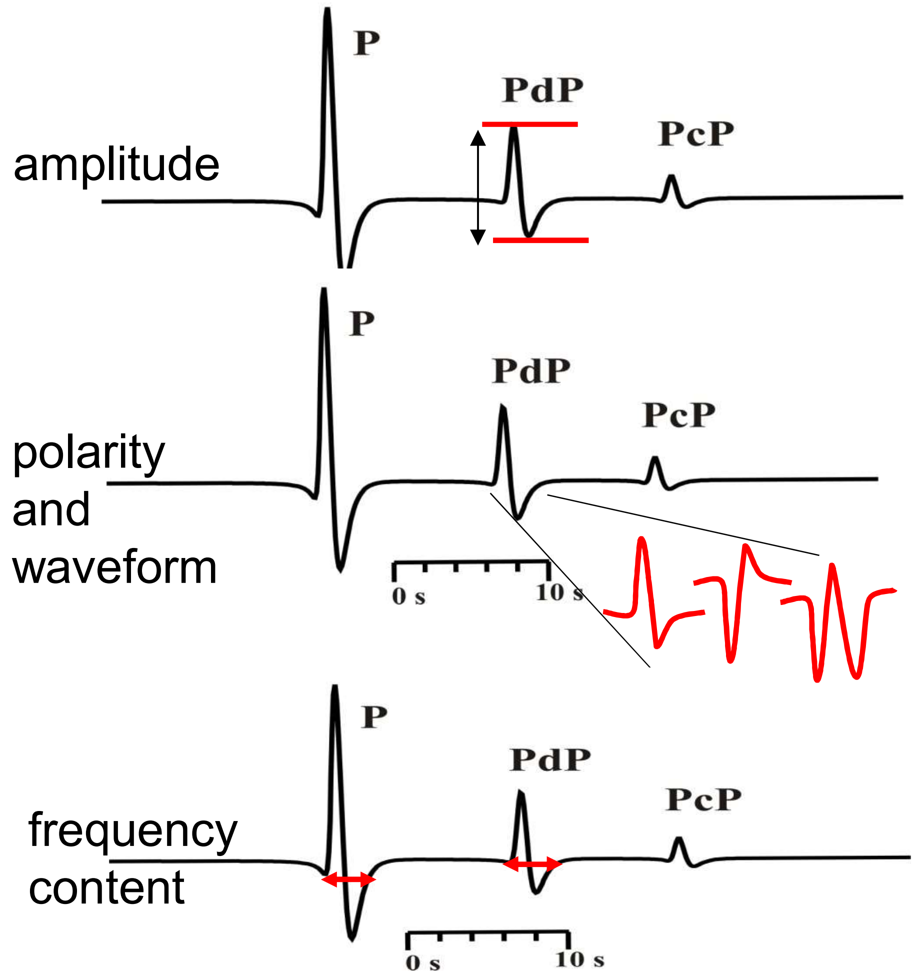
Earth's dynamics
Earth's mineralogy
seismic structures
travel times
amplitudes
polarity and waveform
frequency content
physical parameters of seismic structures
interpretation of dynamics
interpretation of mineralogy

How can we image....?

the travel time of reflections provides a measurement for the depth of the reflector
(if the velocity is correct)

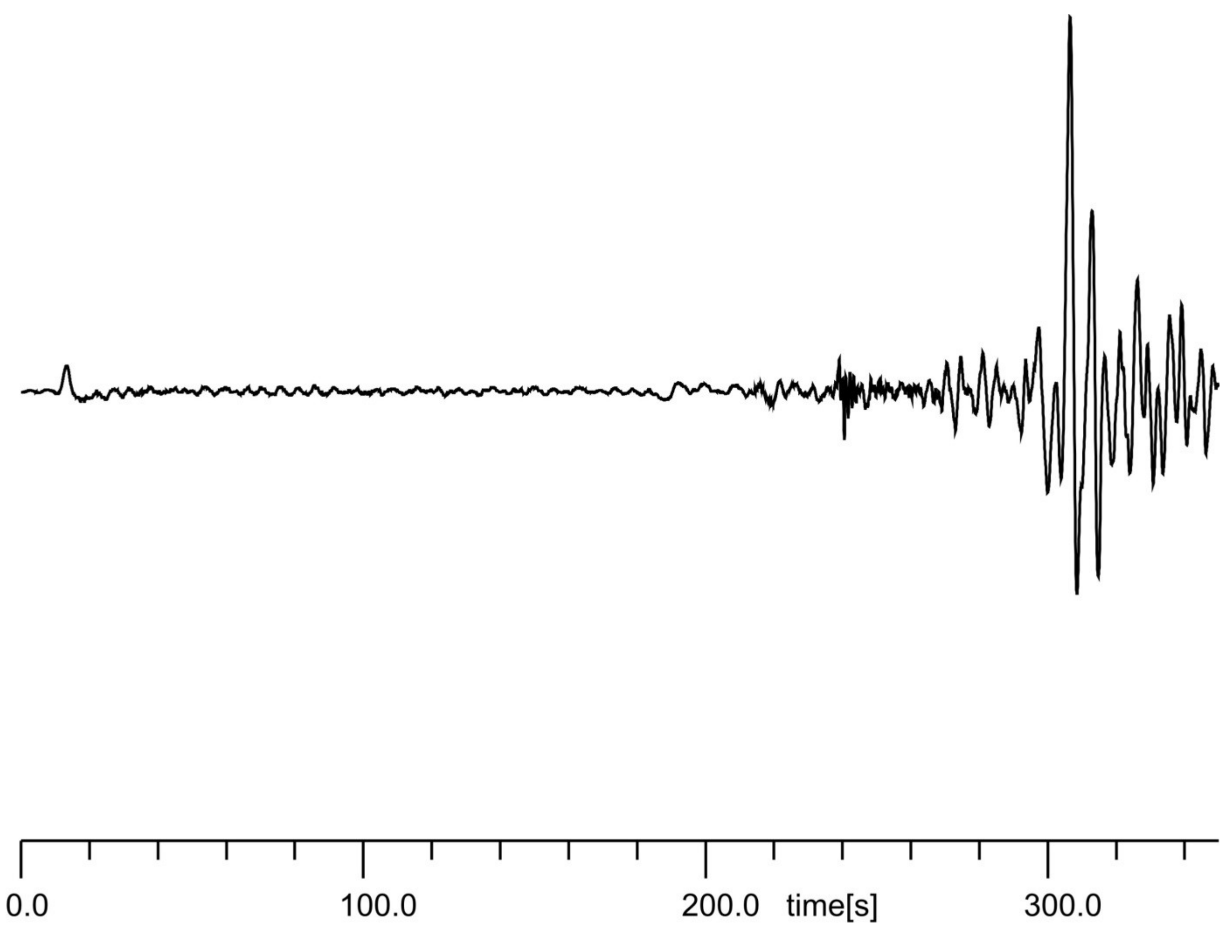


less often used:



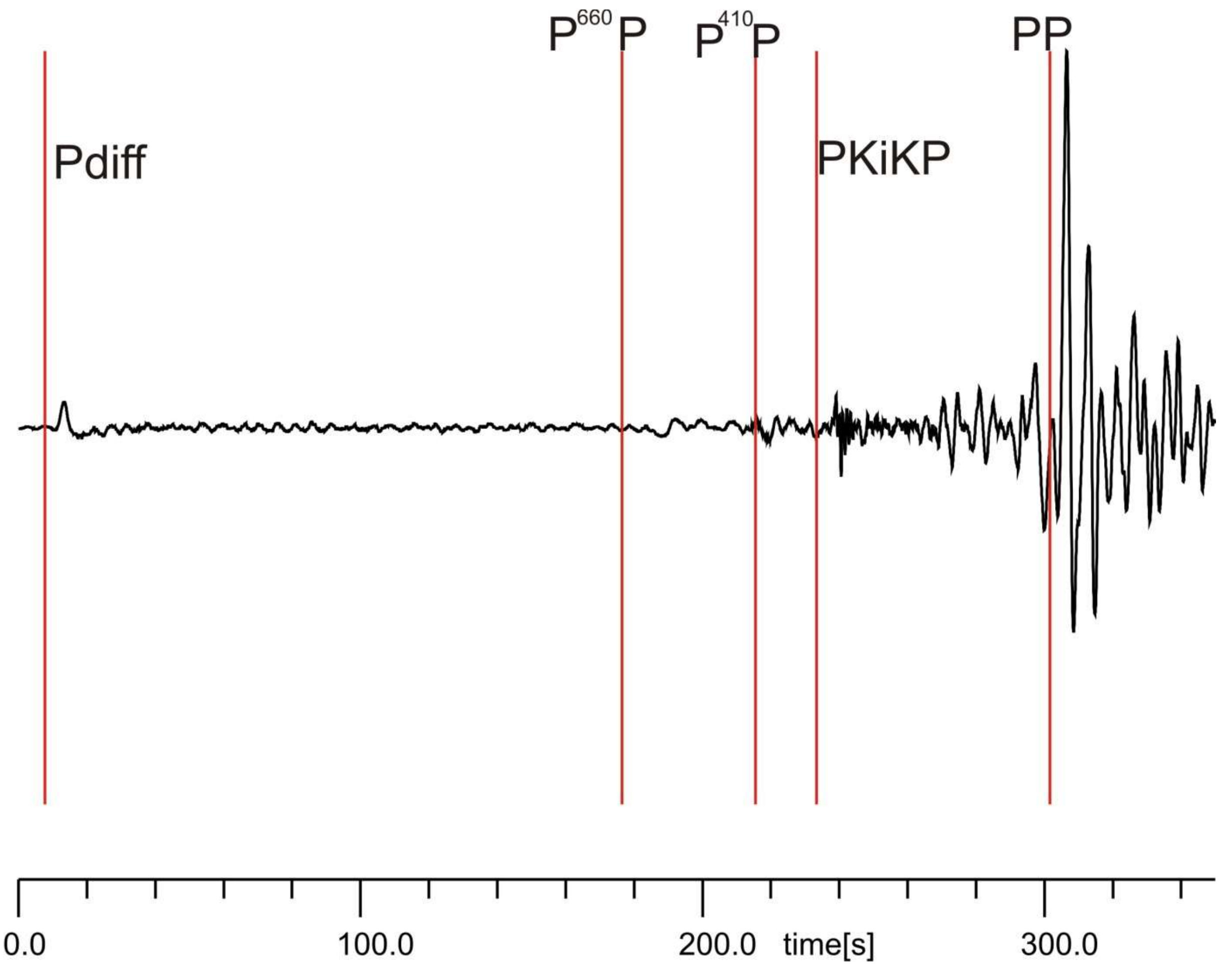
Small waves

Signals for deep Earth structures are often very small



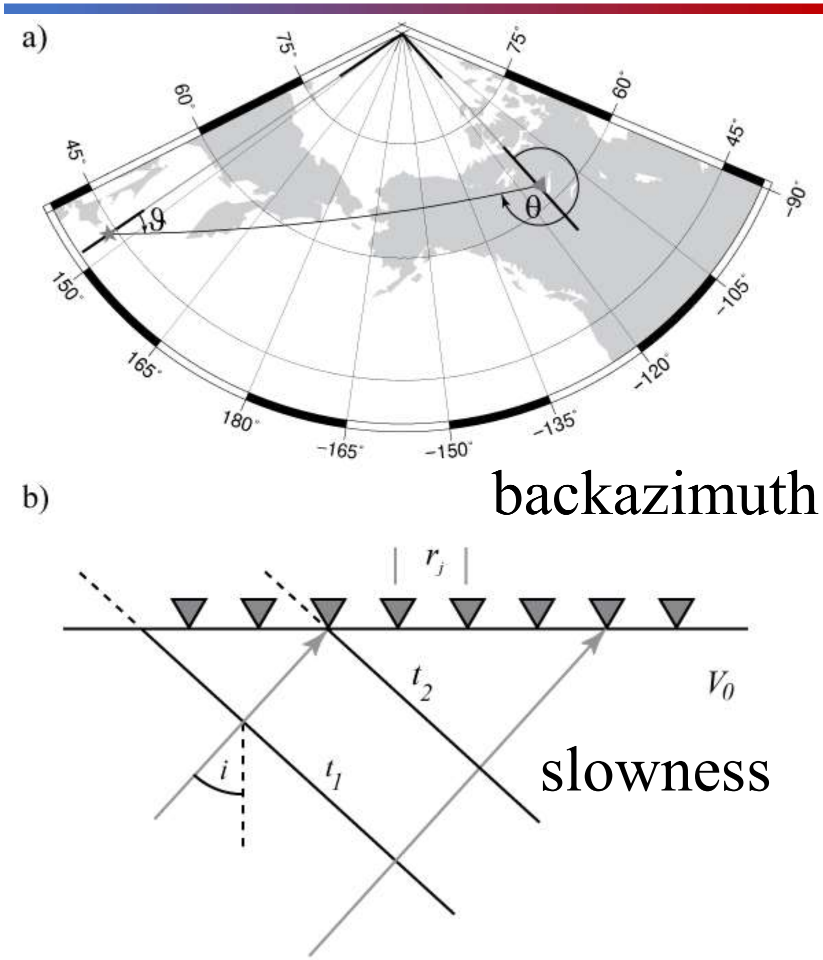
Small waves

Signals for deep Earth structures are often very small



Need to be enhanced using stacking methods

Delay and sum, Vespagrams, f-k analysis, migration

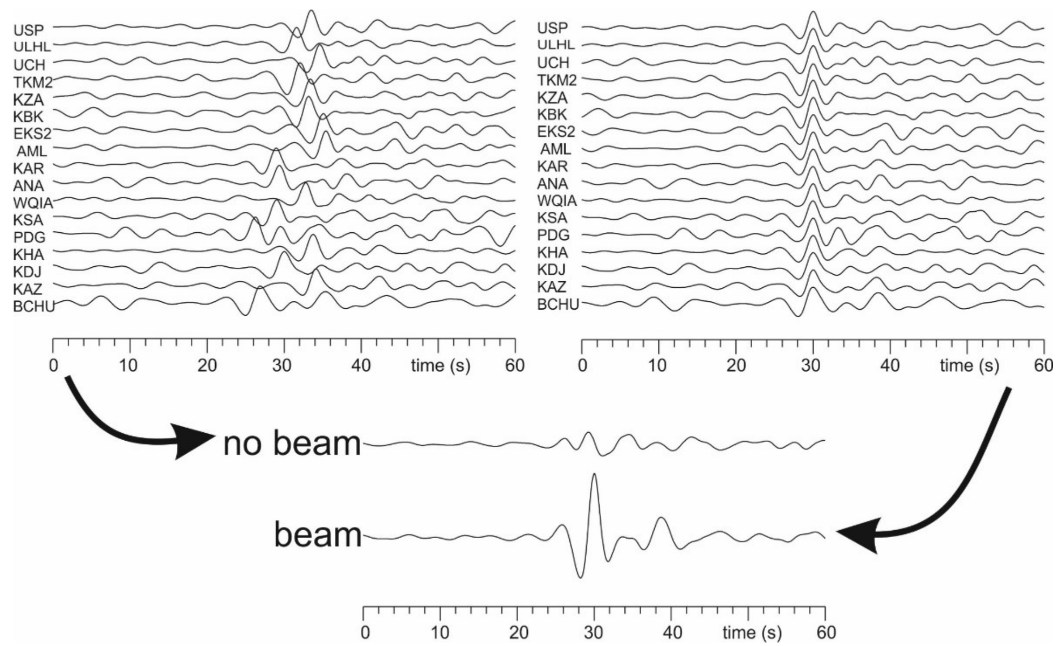


Rost and Thomas (2008): Figure 1

Delay and sum technique

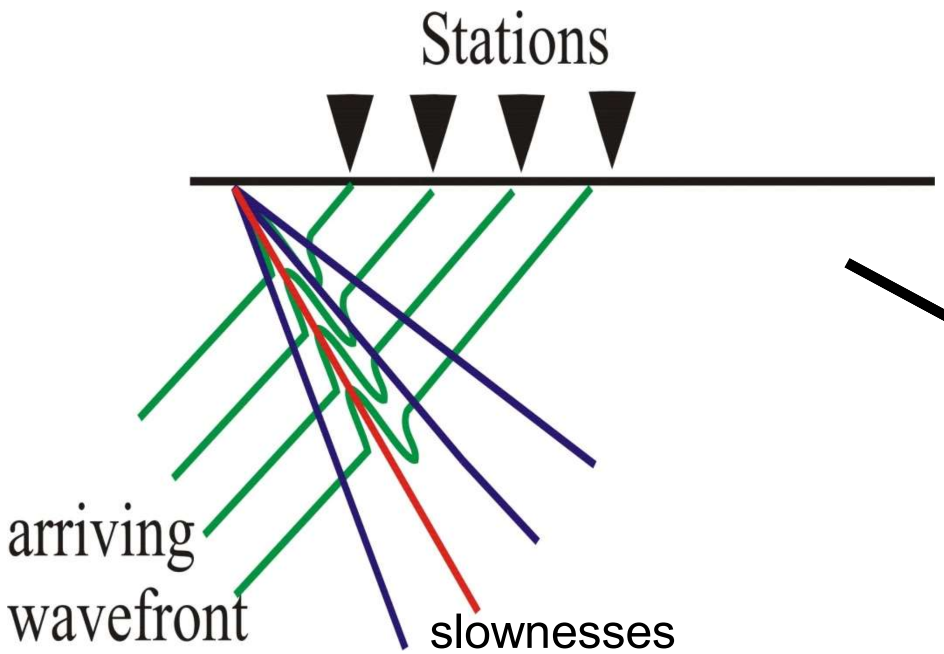
$$b(t)=\frac{1}{N}\sum_{i=1}^{N}\tilde{x}_i(t)=s(t)+\frac{1}{N}\sum_{i=1}^{N}n_i\left(t+\vec{r}_i\vec{u}_{hor}\right)$$

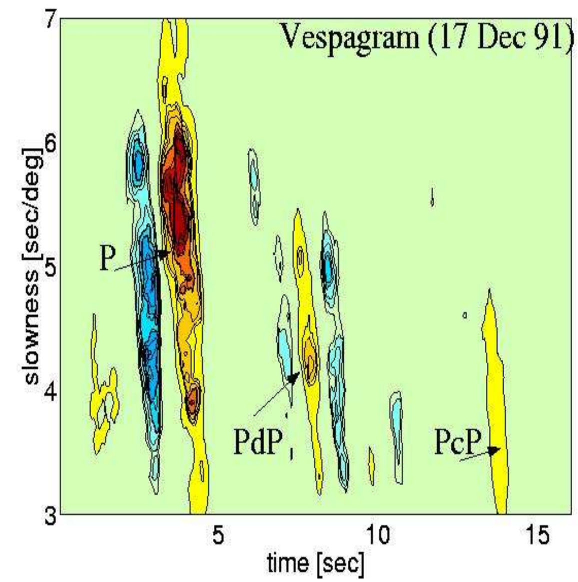
plane wave



Vespagrams

All methods are based on shifting and summing traces

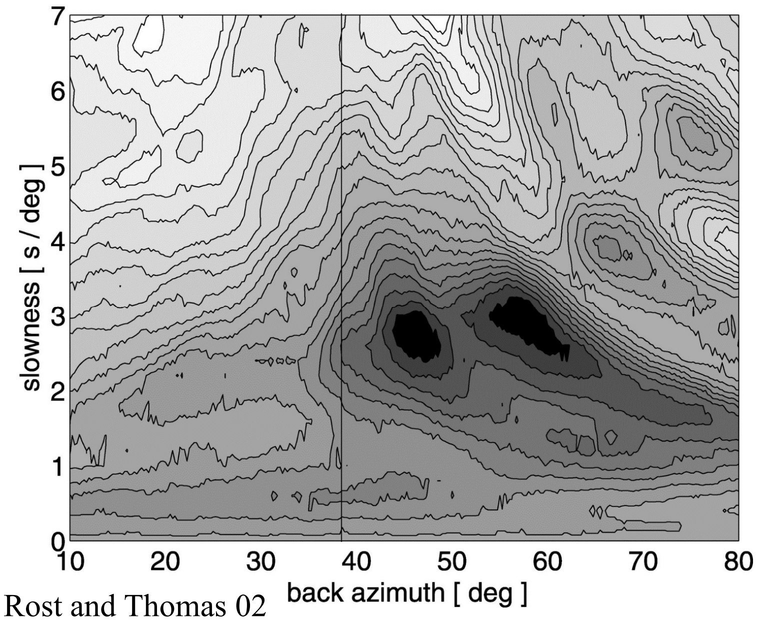




vespagram
slowness or backazimuth versus time
also called: slant stack

important: backazimuth must be known exactly
otherwise slowness values in the vespagram may be wrong.

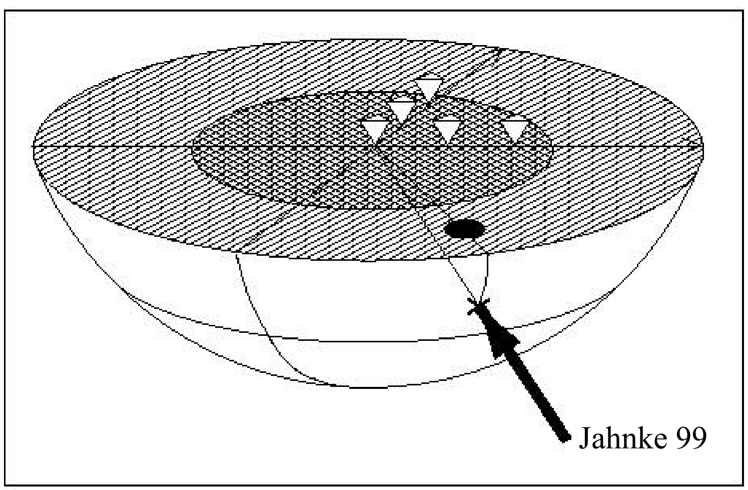
f-k analysis or slowaz (beaman)

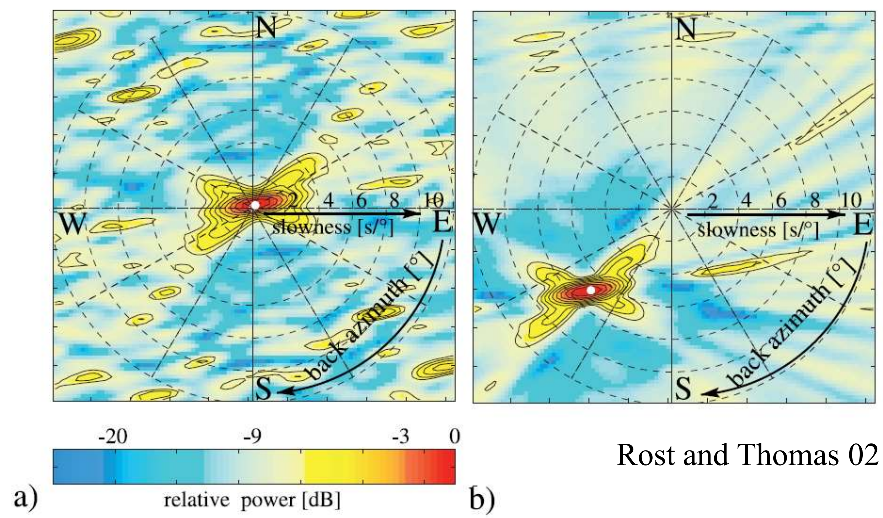


Rost and Thomas 02

Simultaneous measuring of slowness and backazimuth of one arrival.

Stacks over all slowness and backazimuth values for a (small) time window.



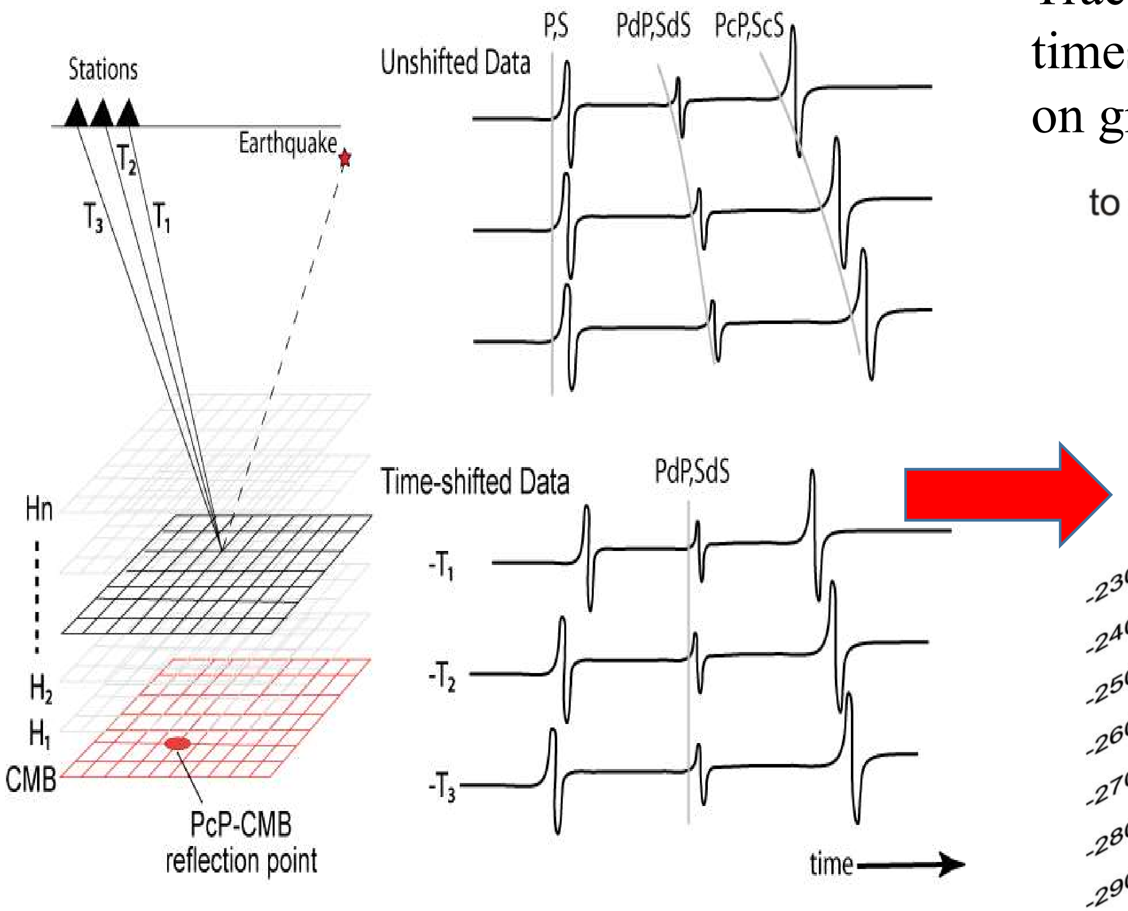


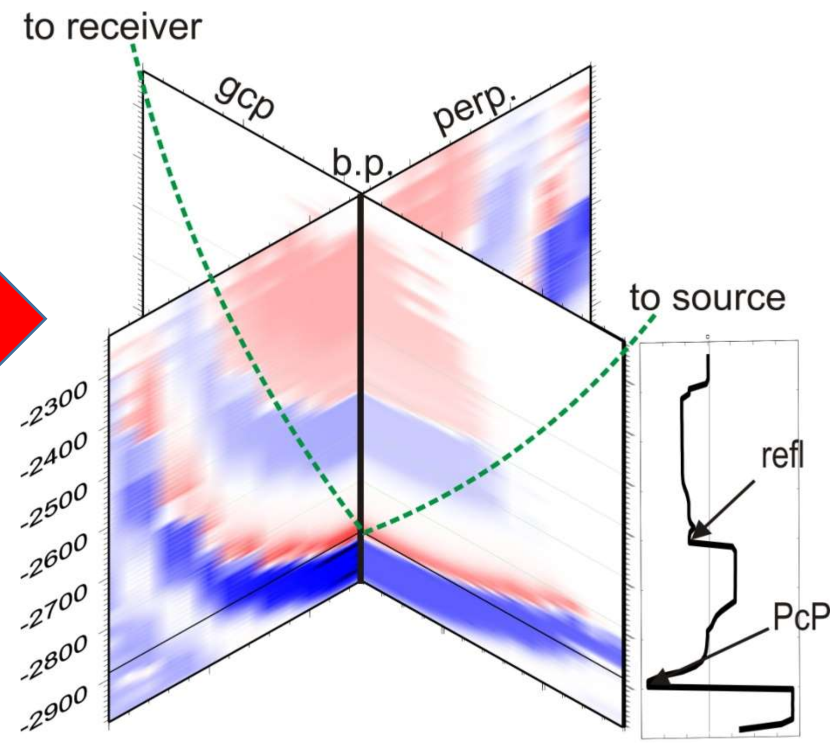
Rost and Thomas 02

Migration

For migration - no plane wave assumed

travel times from a point in the Earth to all receivers and events are calculated. Traces are shifted back with those travel times. Amplitude measured and placed on gridpoint.



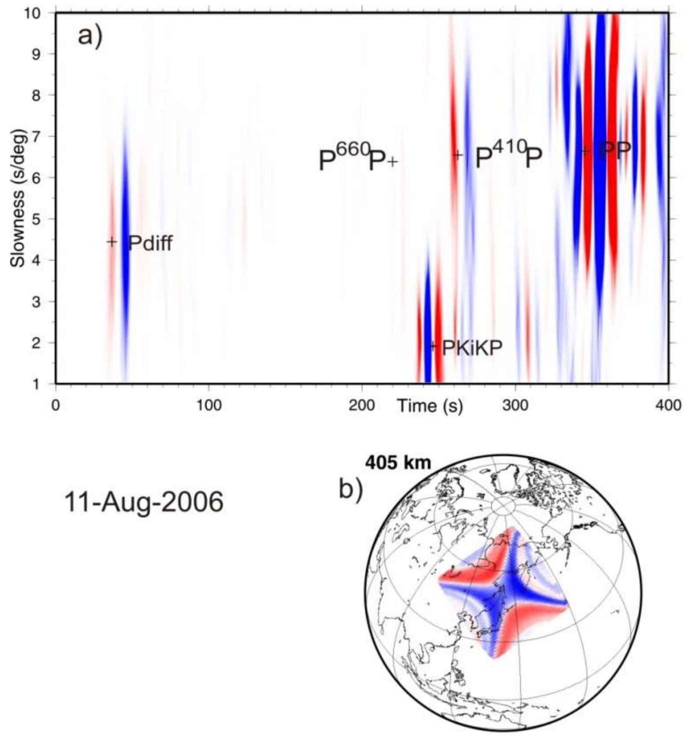


Rost and Thomas 02, 09

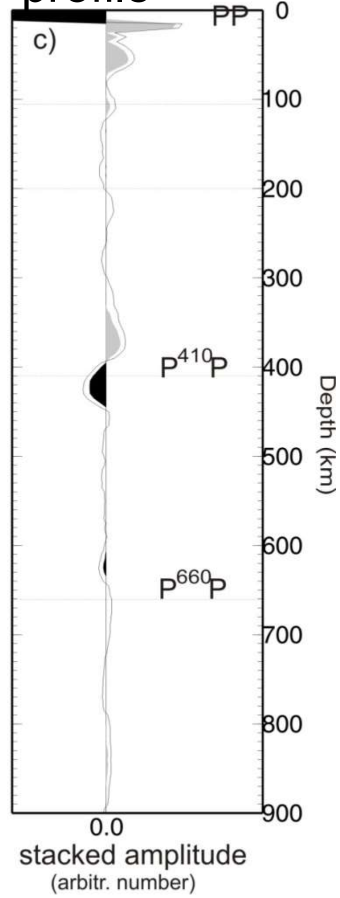
Ampl. at b.p.

Migration

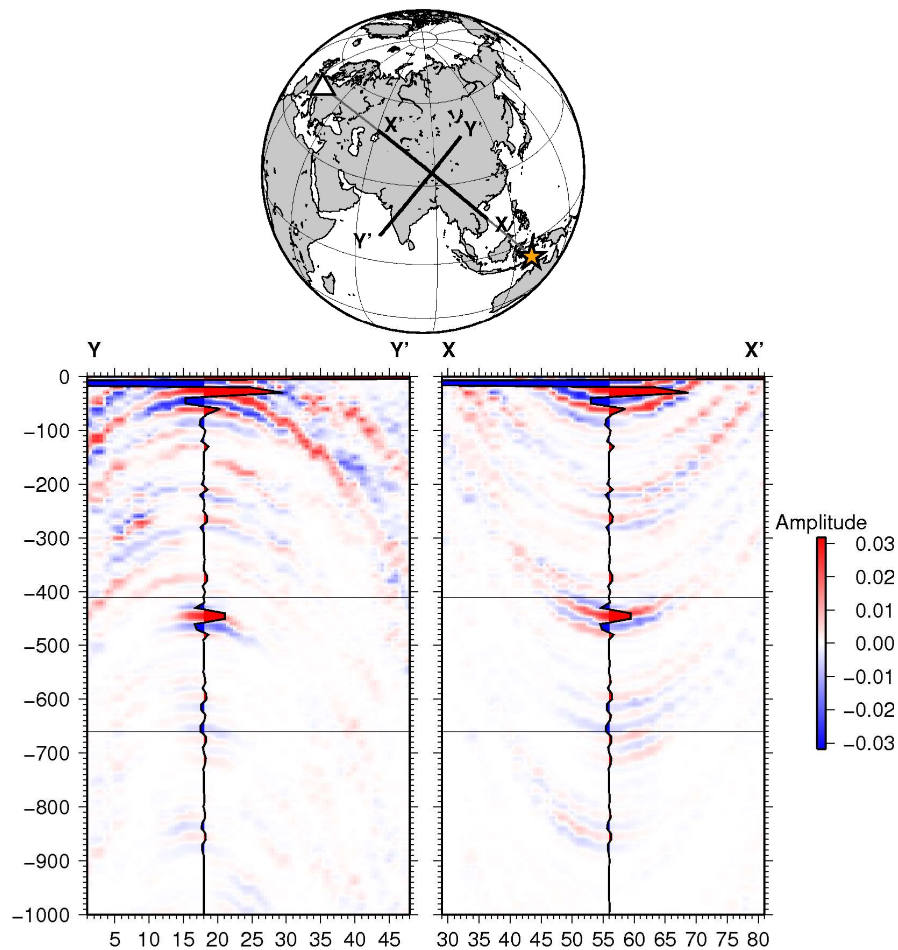
vespagram



amplitude-depth profile

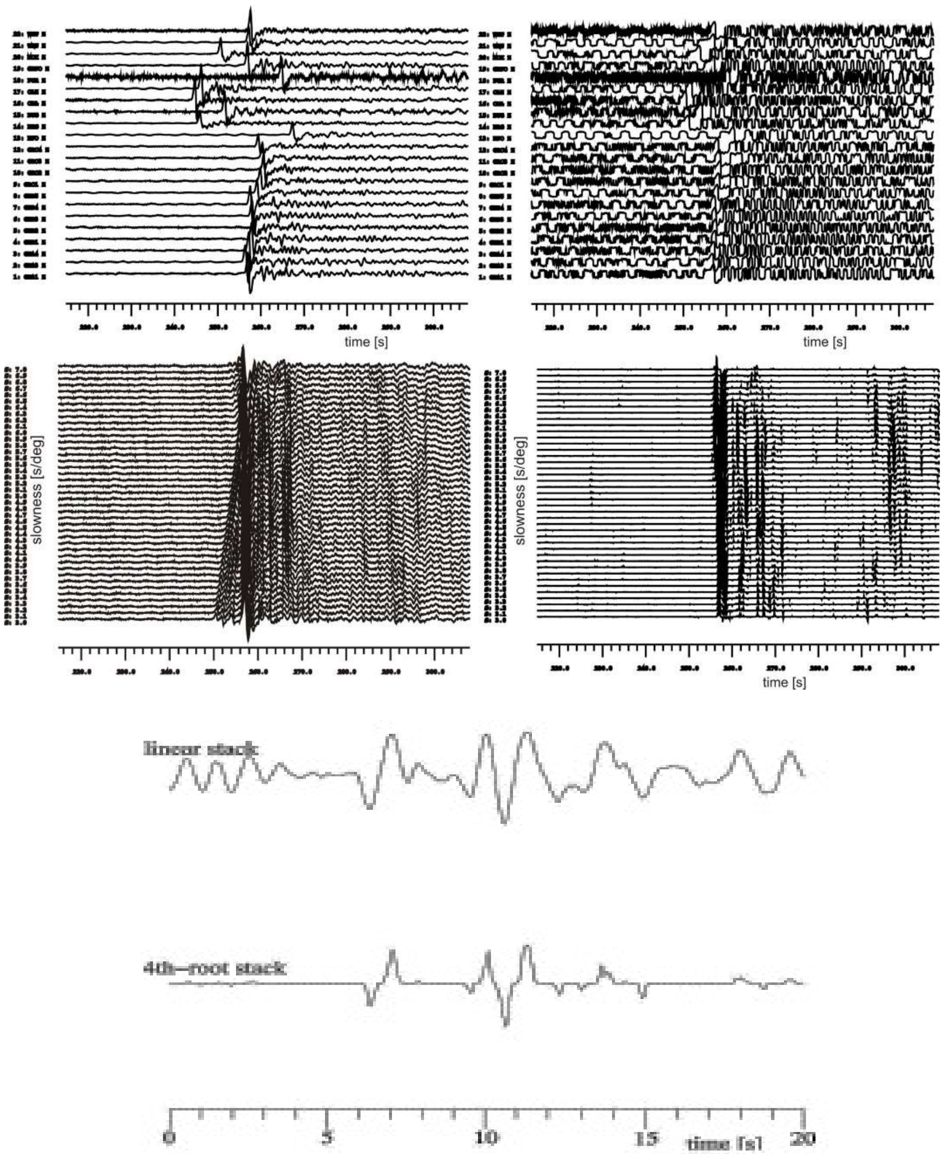


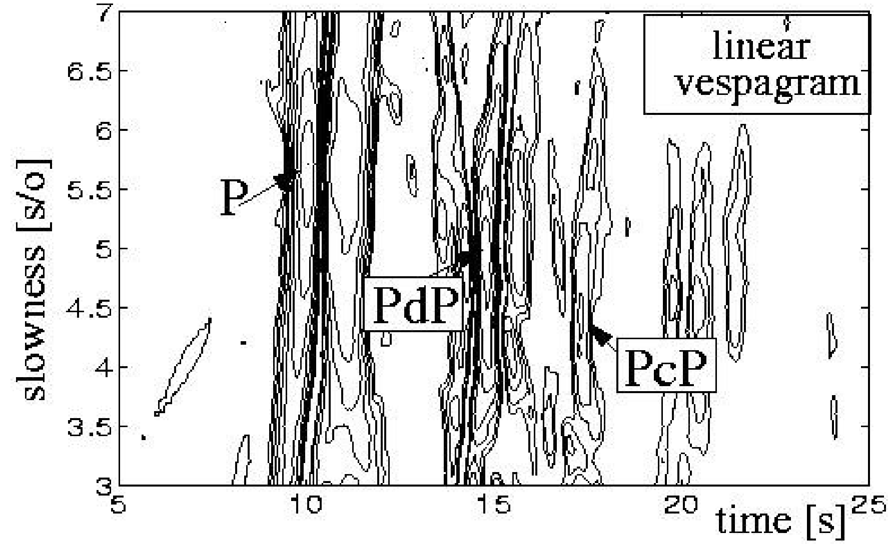
migration

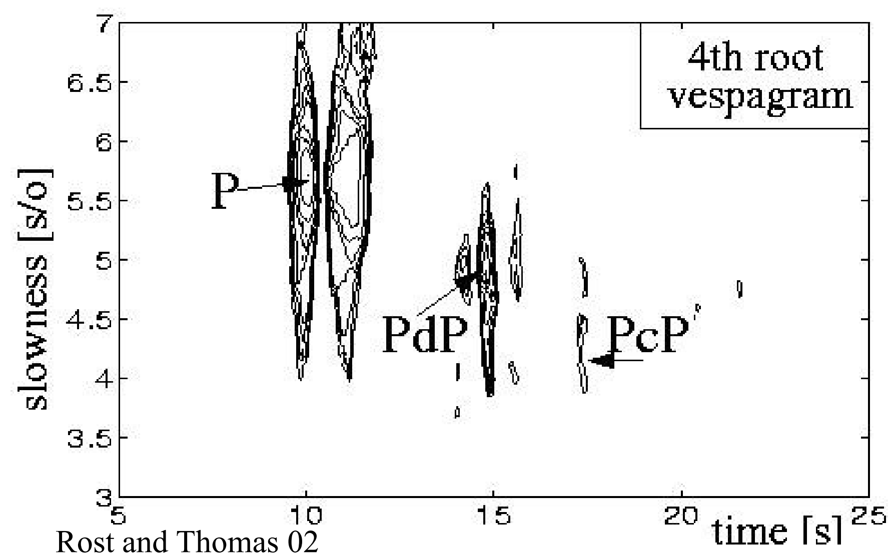


Schmerr and Thomas 2011

n-th root (enhancing coherent signals)

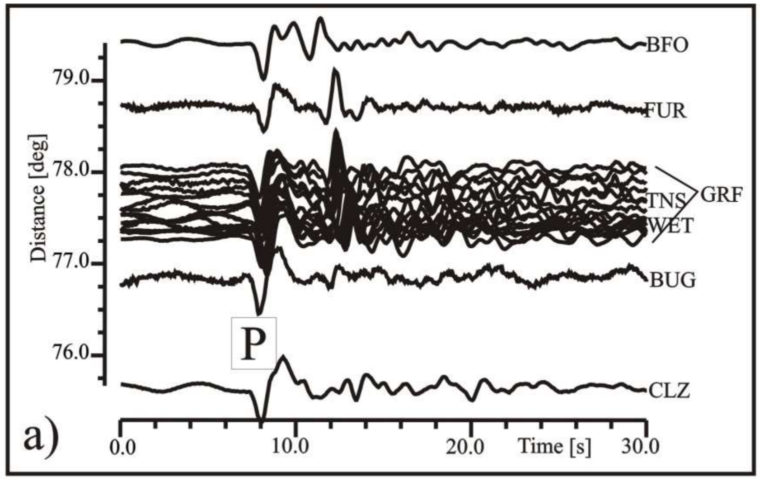






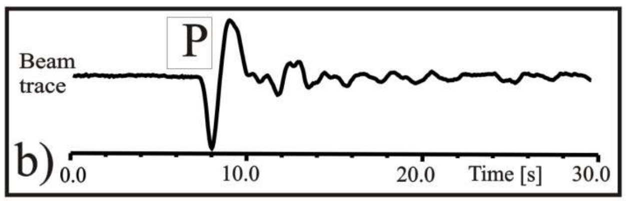
Rost and Thomas 02

Array methods

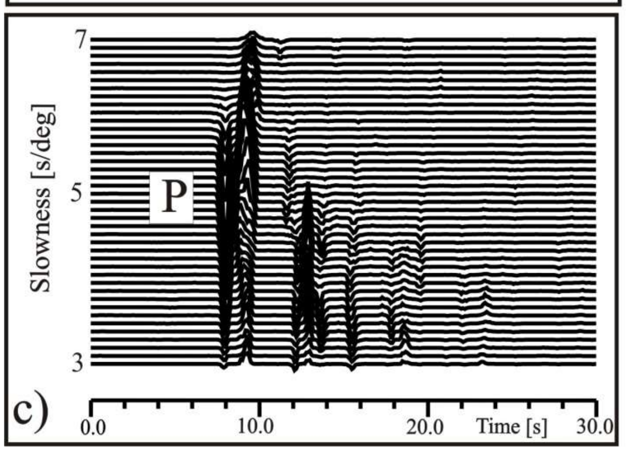


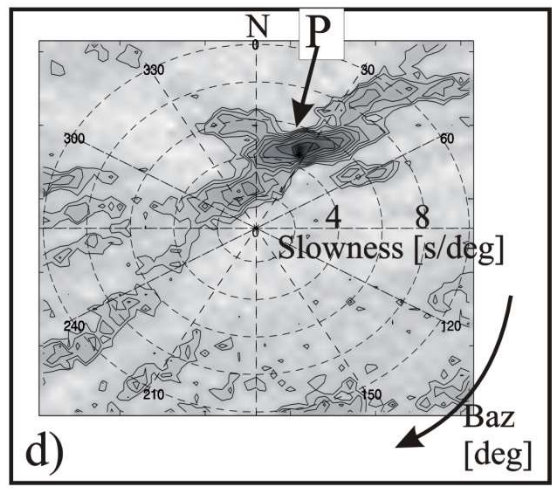
Aligned seismogram (distance dependent)

beam



vespa

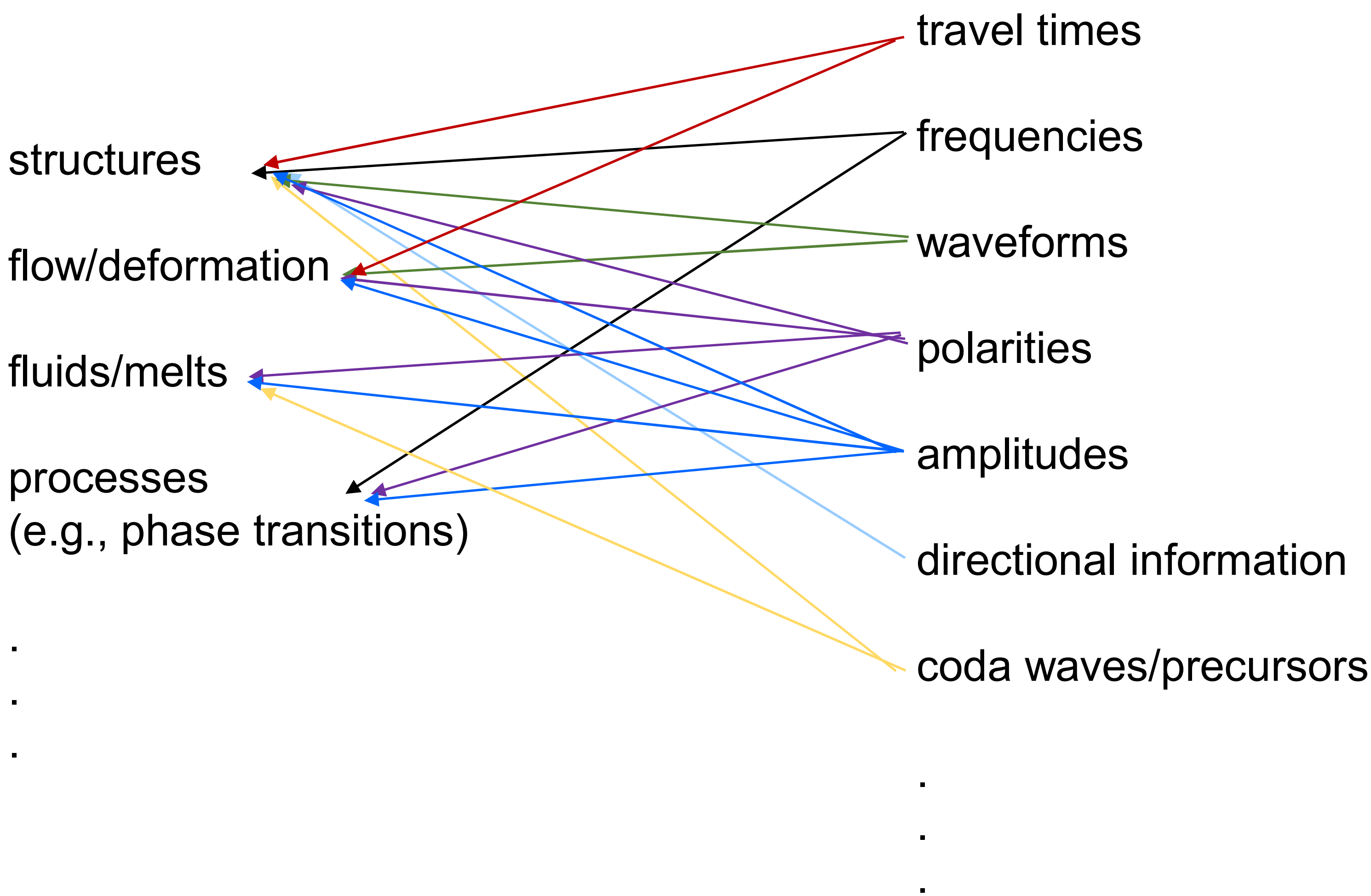




Frequency wavenumber analysis

Thomas 08

Imaging


structures
flow/deformation
fluids/melts
processes
(e.g., phase transitions)
.
.
.
travel times
frequencies
waveforms
polarities
amplitudes
directional information
coda waves/precursors
.
.
.

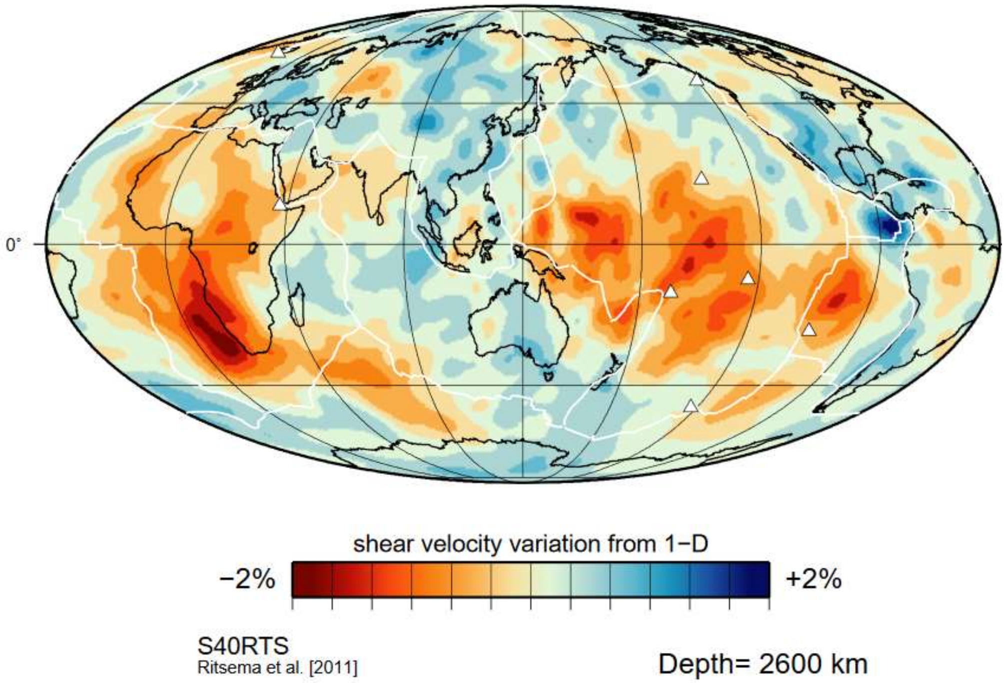
Imaging structures

Tomography

Reflections

scattered waves

...



global or local
combination of different waves,
travel times, amplitudes, and waveforms
adjoint methods, non-linear tomography (see Andrew Curtis' talk)
....

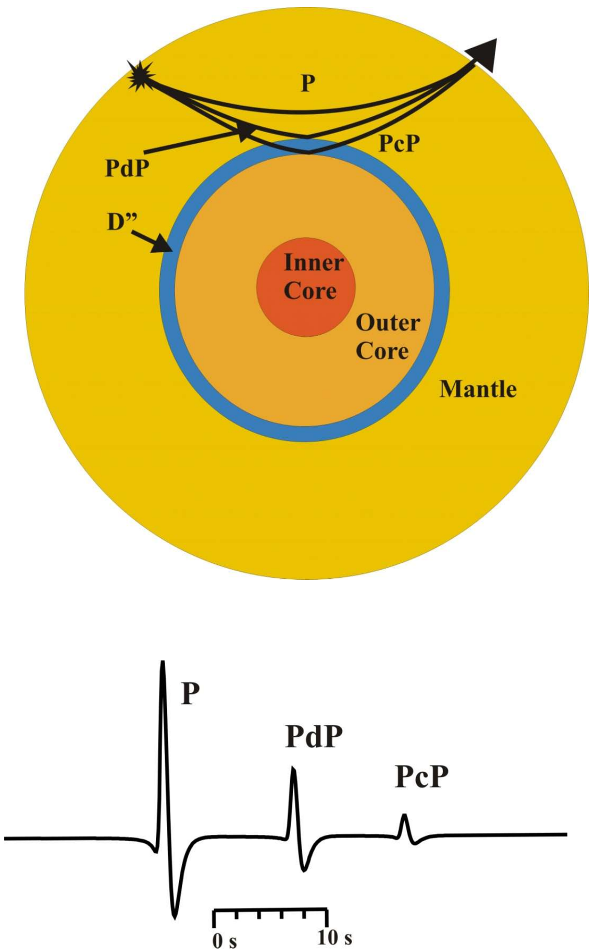
Imaging structures

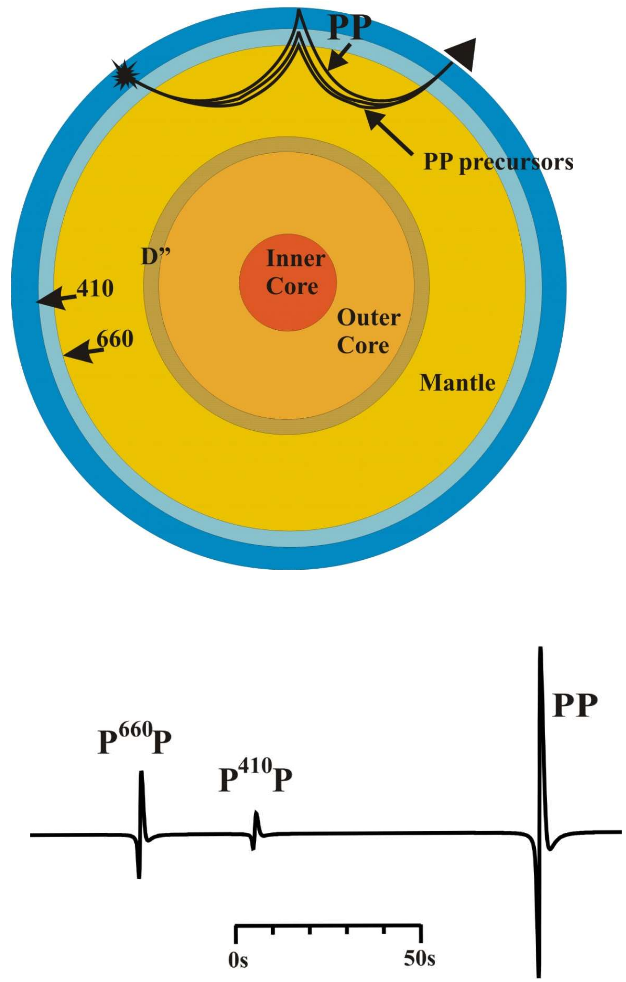
Tomography

Reflections

scattered waves

...

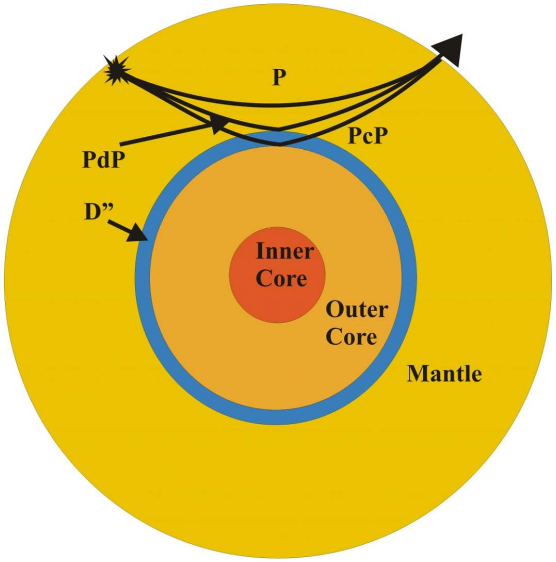


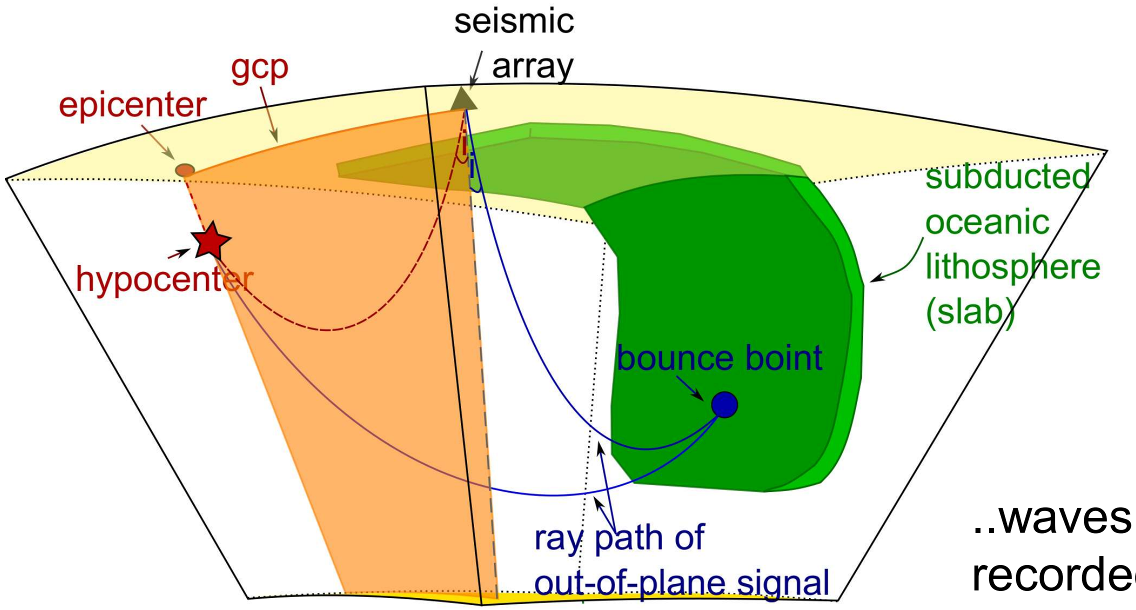


Reflections

Travel time, waveform, amplitude, polarity and path information

In addition to waves reflected on the great circle path, we can also use....

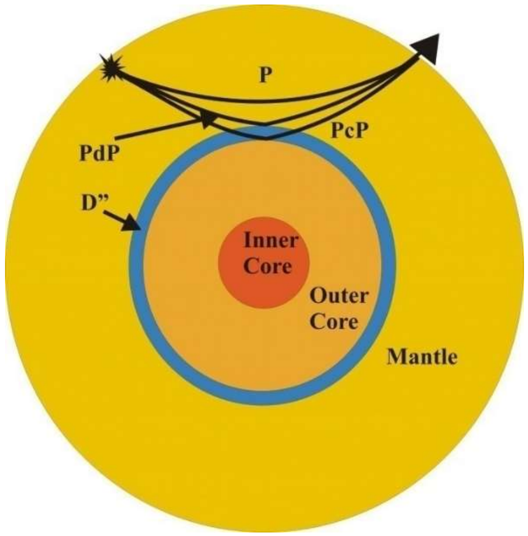


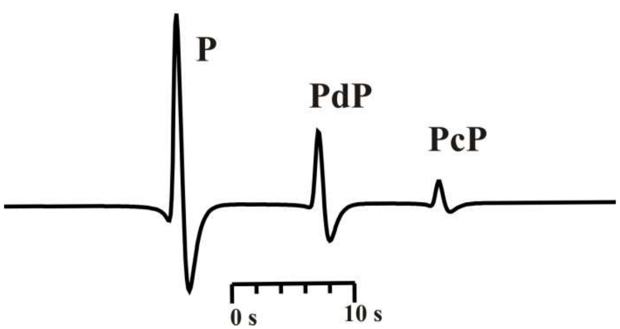


Schumacher and Thomas, 2016

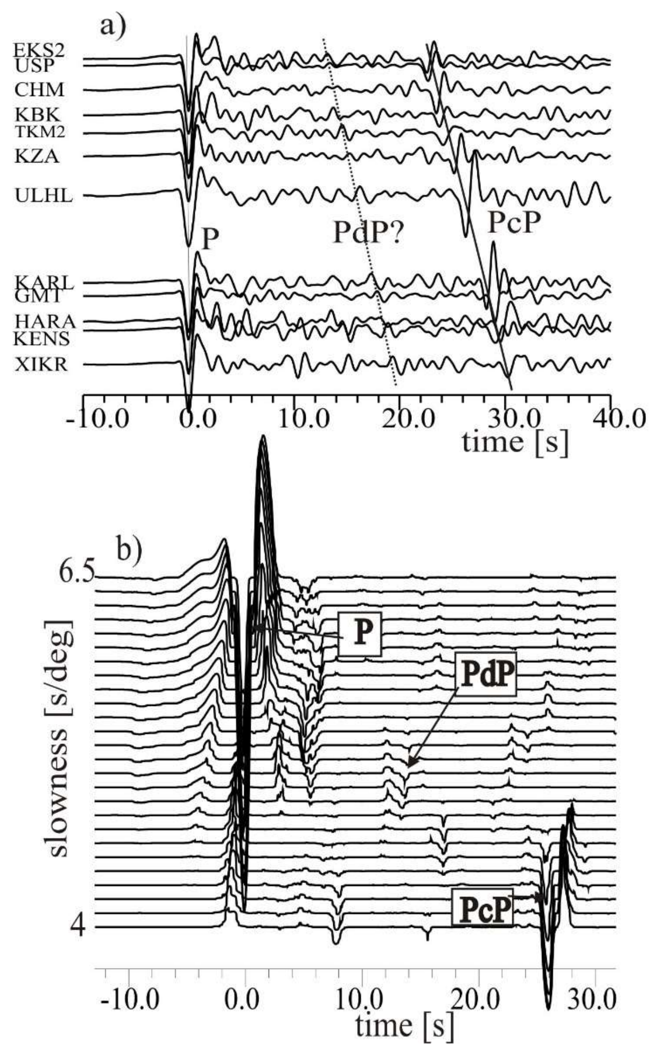
..waves reflected or scattered in the mantle, recorded as out-of-plane waves.

Reflections in D''



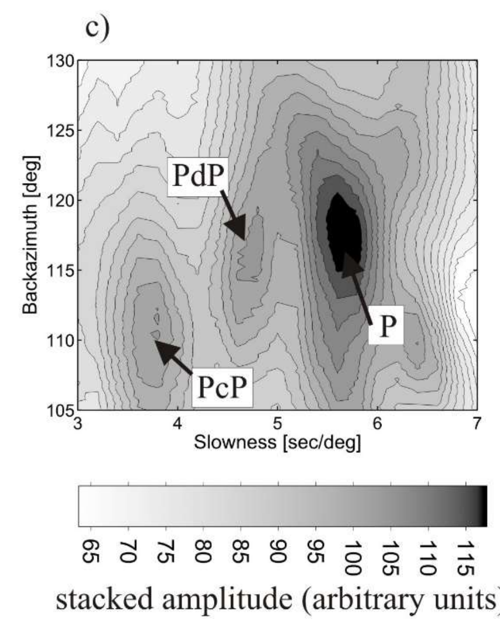


Seismic reflections from D'' are observed in P- and S-waves.



testing that origin of wave is D''

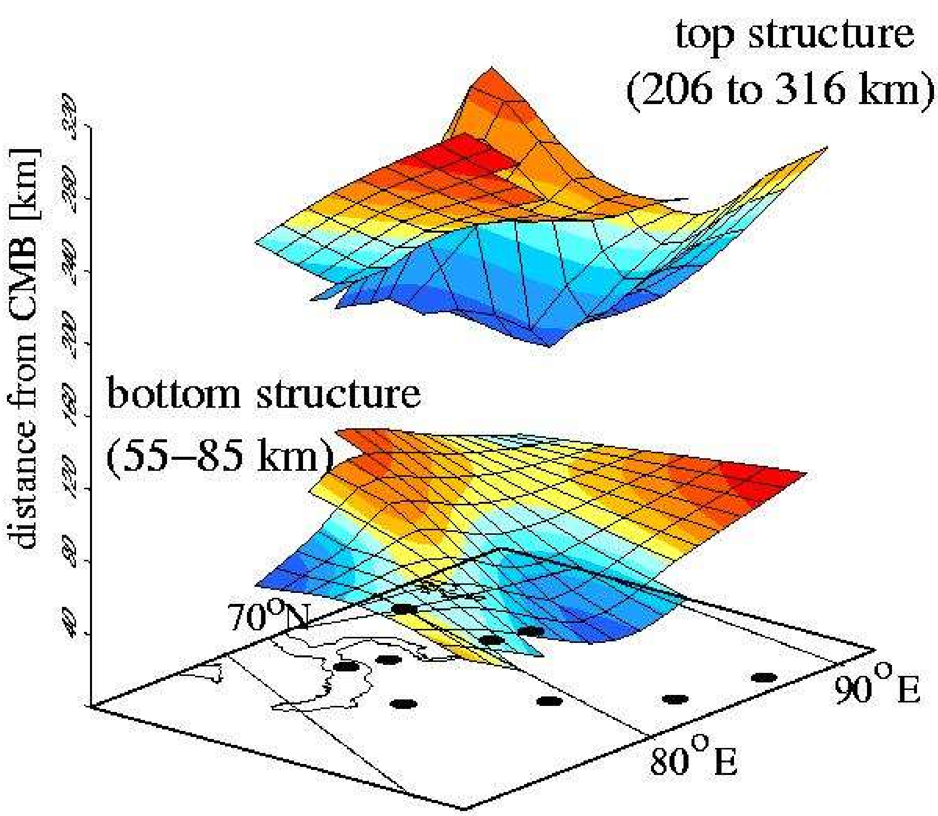
(using array methods)



Reflections in D" - travel times

travel times indicate reflector(s) with topography

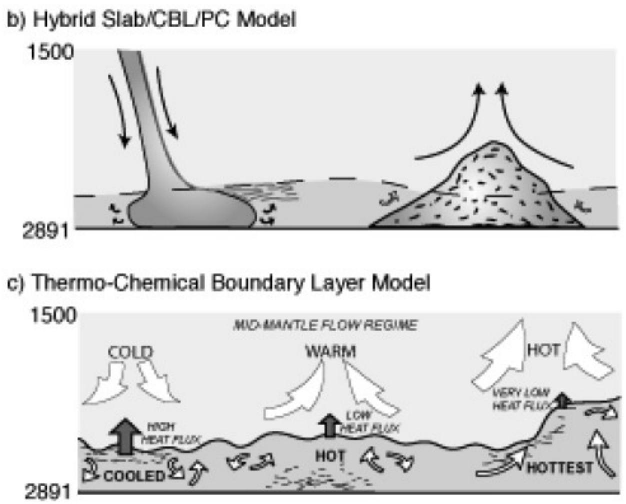
many different interpretations - one of those: post-perovskite phase transition

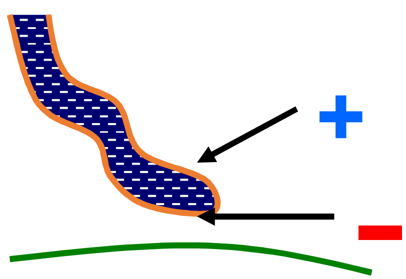


e.g., Thomas et al., 2004a,b Kito et al., 2007,
van der Hilst et al., 2007, Hutko et al., 2008

Reflections in D" - interpretations

Interpretations before 2004 included:

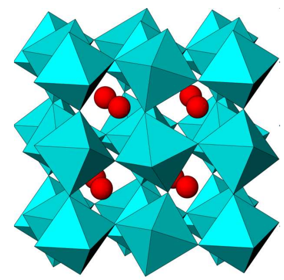




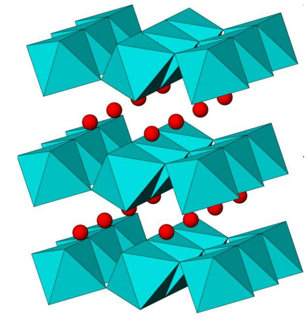
Top and Bottom of a slab

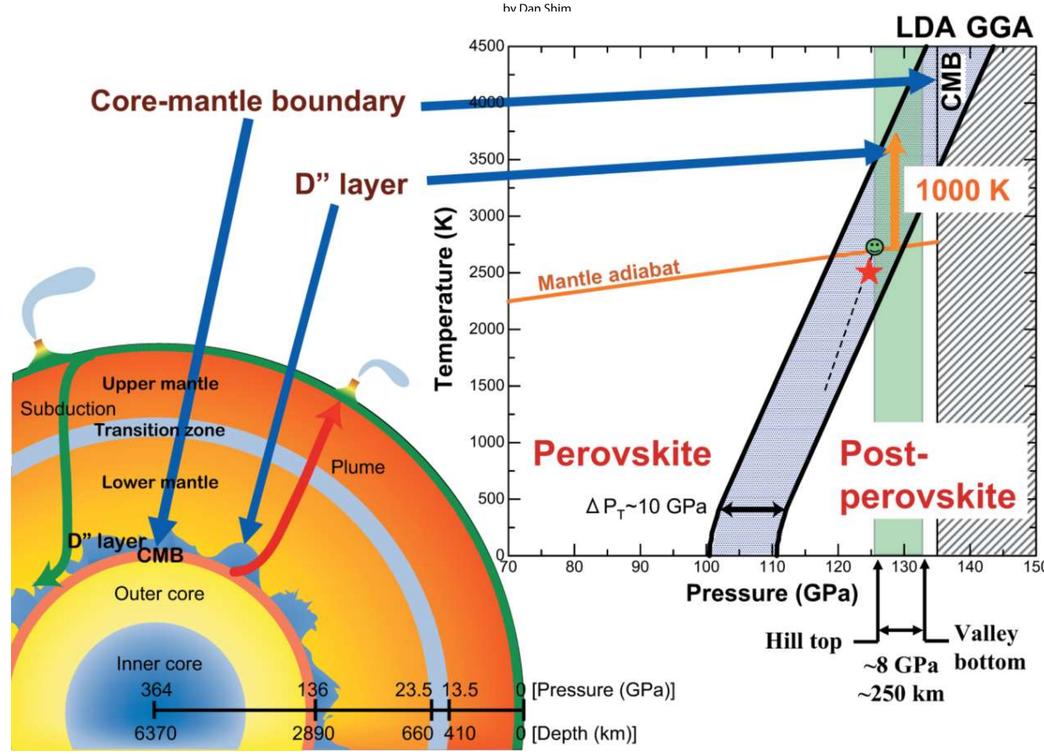
in 2004:

pv



ppv

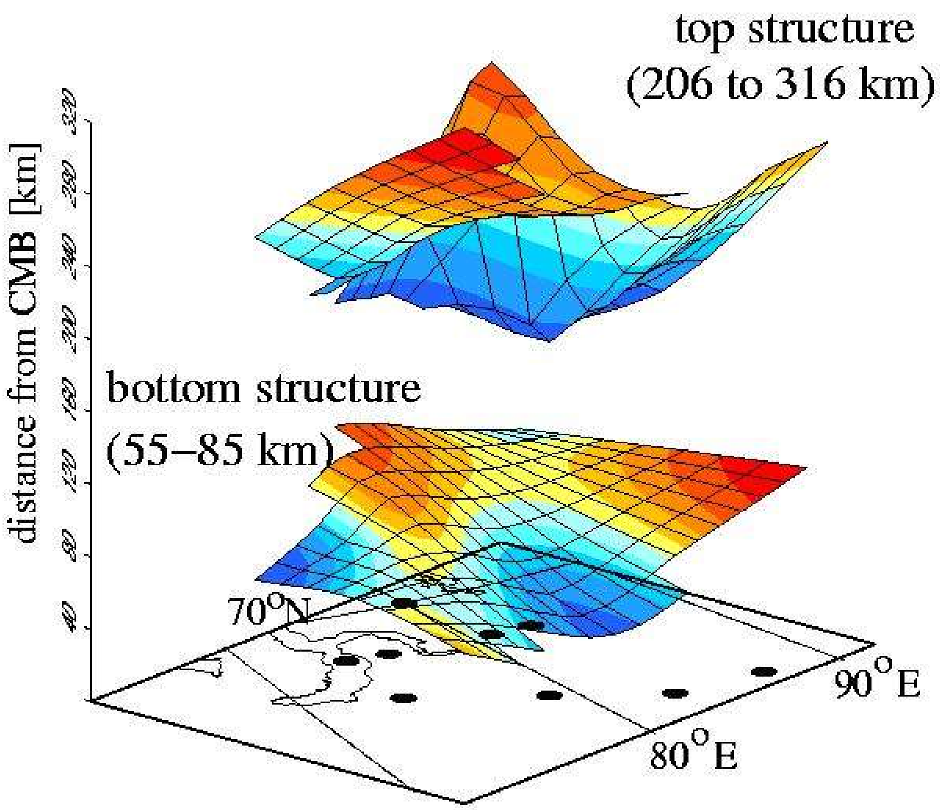


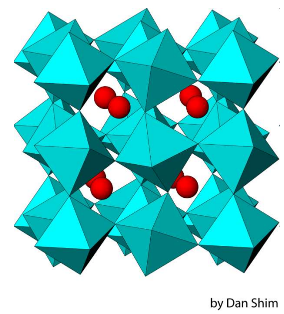


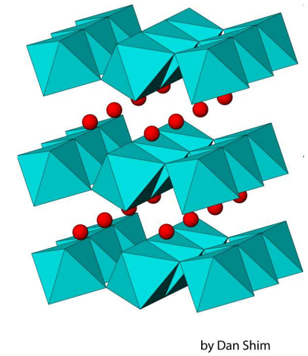
from : R. Wentzcovitch et al. 2007

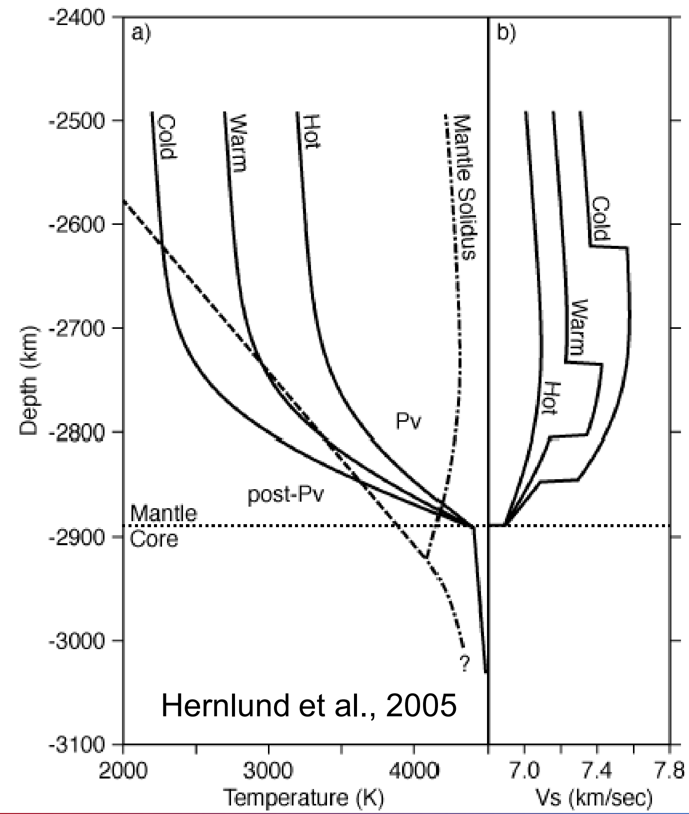
Reflections in D"

travel times - reflector(s) with topography
many different interpretations - one of those: post-perovskite phase transition



pv


ppv


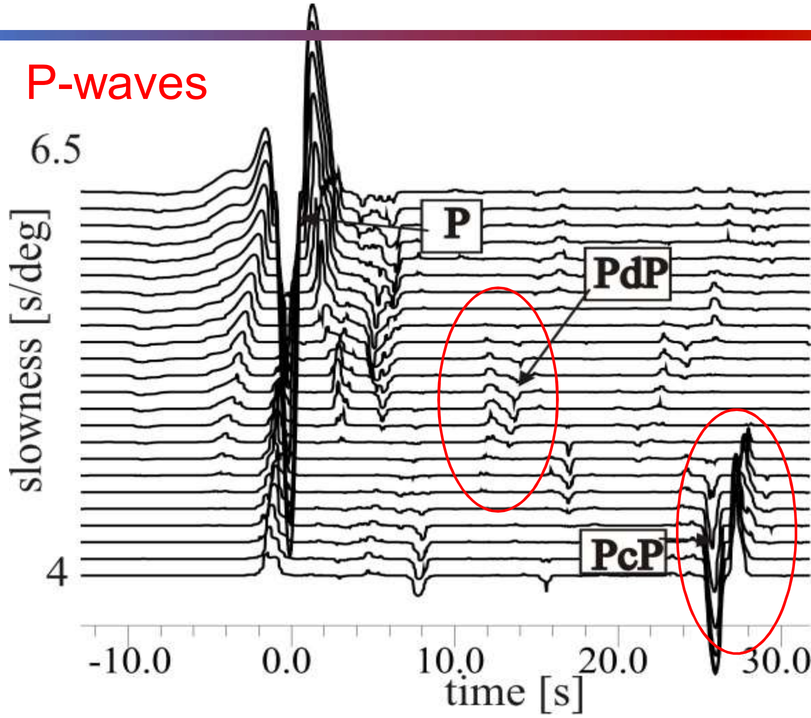


Hernlund et al., 2005

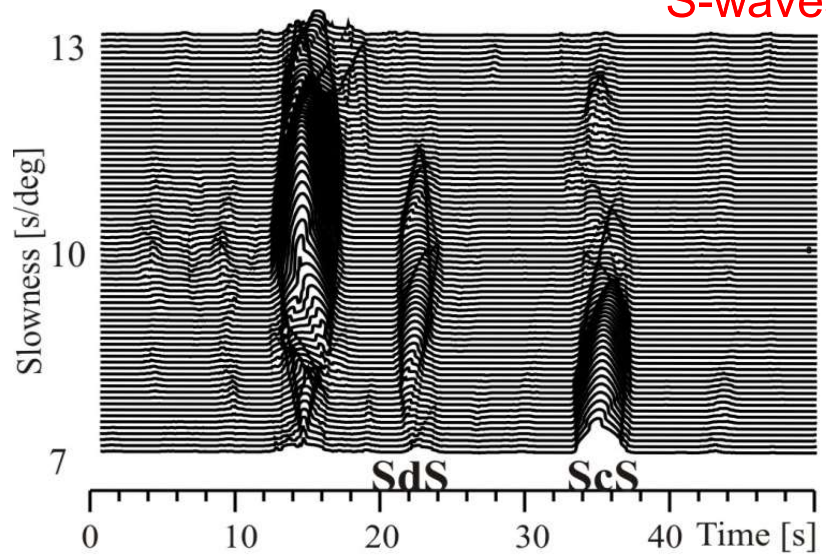
e.g., Thomas et al., 2004a,b Kito et al., 2007, van der Hilst et al., 2007, Hutko et al., 2008

Reflections - polarities

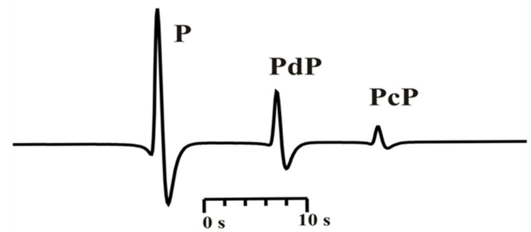
P-waves



S-waves



Caribbean /S.E. Asia



PdP opposite polarity to PcP and P
SdS same polarity to ScS and S
beneath Caribbean and SE Asia

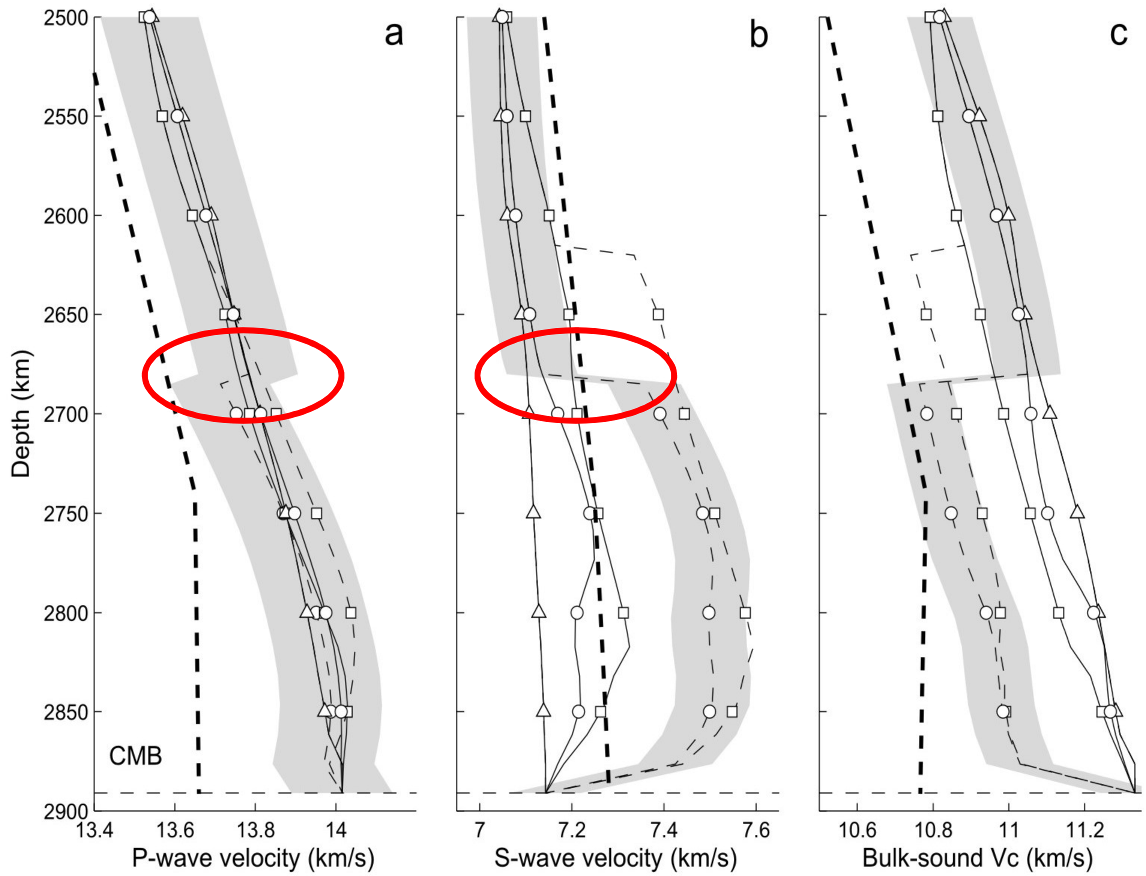
P reflection  neg. impedance

S reflection  pos. impedance

Kito et al. 2007

Chaloner et al., 2009
Thomas et al., 2004a,b
Hutko et al., 2008
Cobden and Thomas, 2013

Reflections

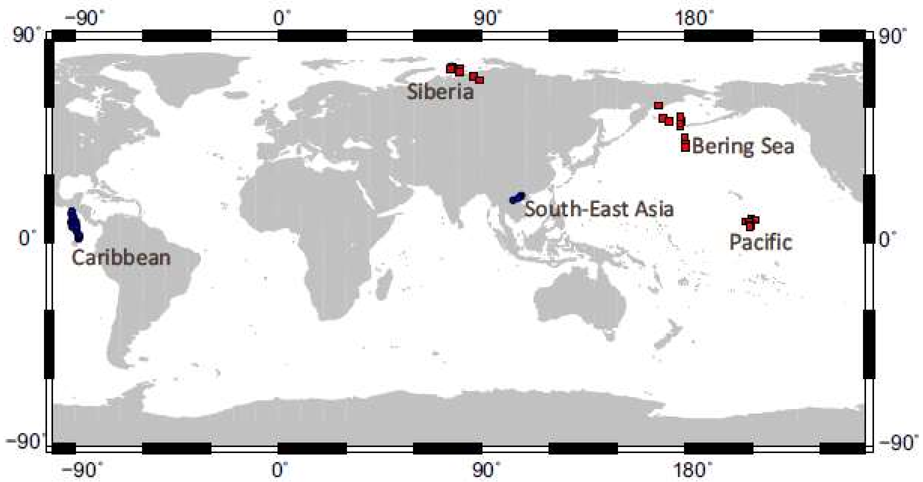


ab initio calculations (Wookey et al. 2005) predict a positive velocity contrast for S waves and negative for P-waves for post-perovskite

=> **agreement with observations beneath Caribbean and SE Asia**

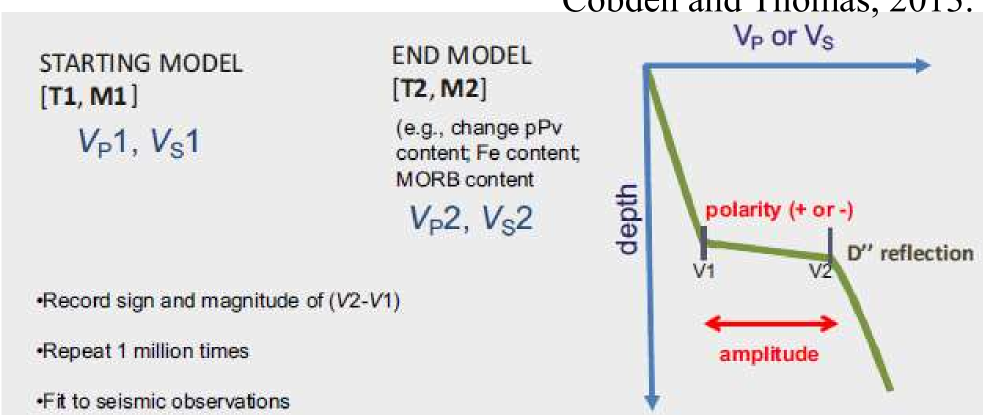
So - is post-perovskite the reason for D" reflectors?

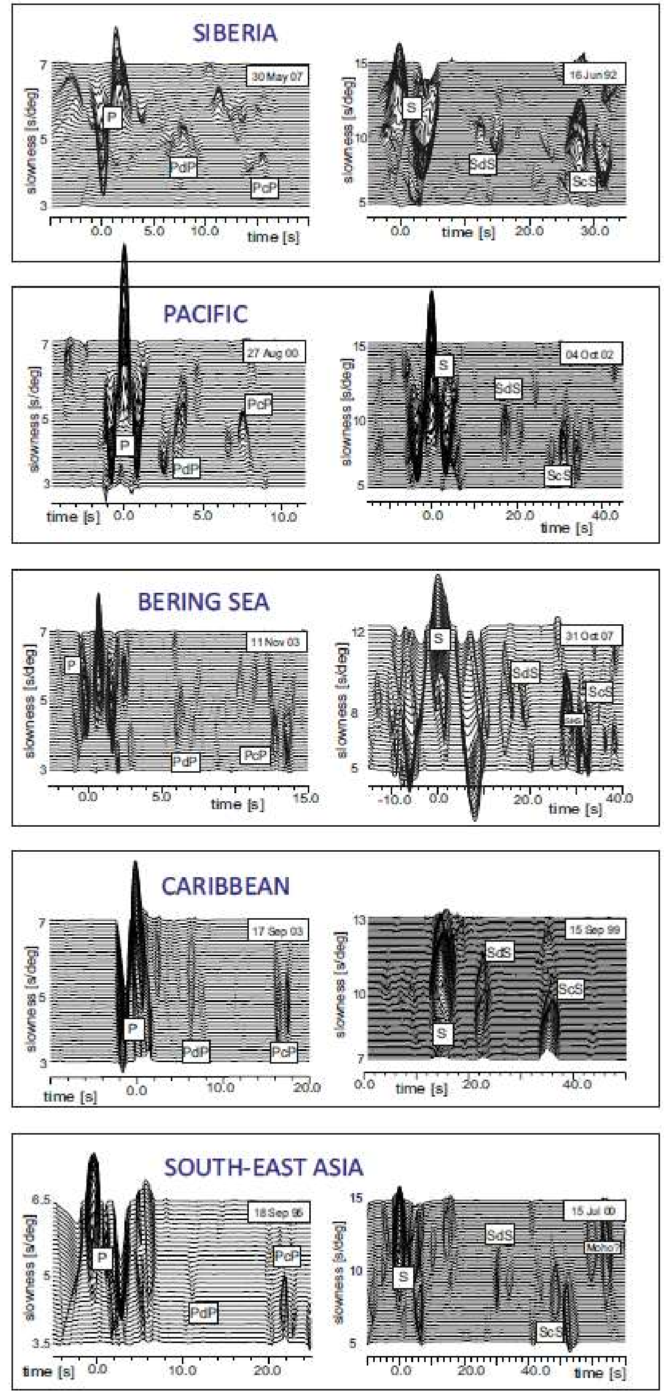
Reflections in D"



Focus on polarity and amplitude
Fit those with Monte Carlo thermodynamic modelling

Cobden and Thomas, 2013.





PdP + 1-3%
SdS + 2-3%

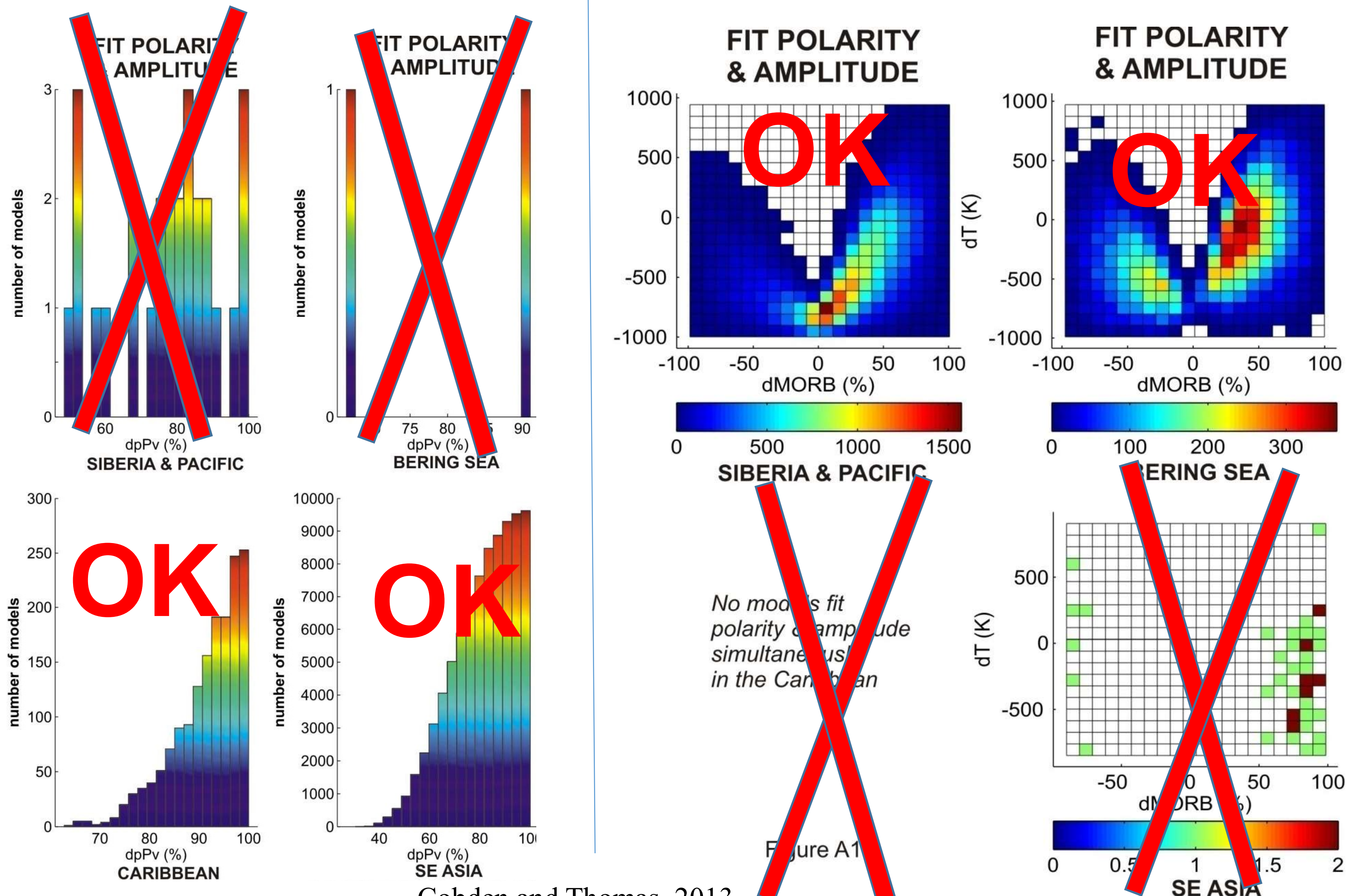
PdP + 1-3%
SdS + 2-3%

PdP + 1-1.5%
SdS + 1-2%

PdP - -2- -3%
SdS + 2-3%

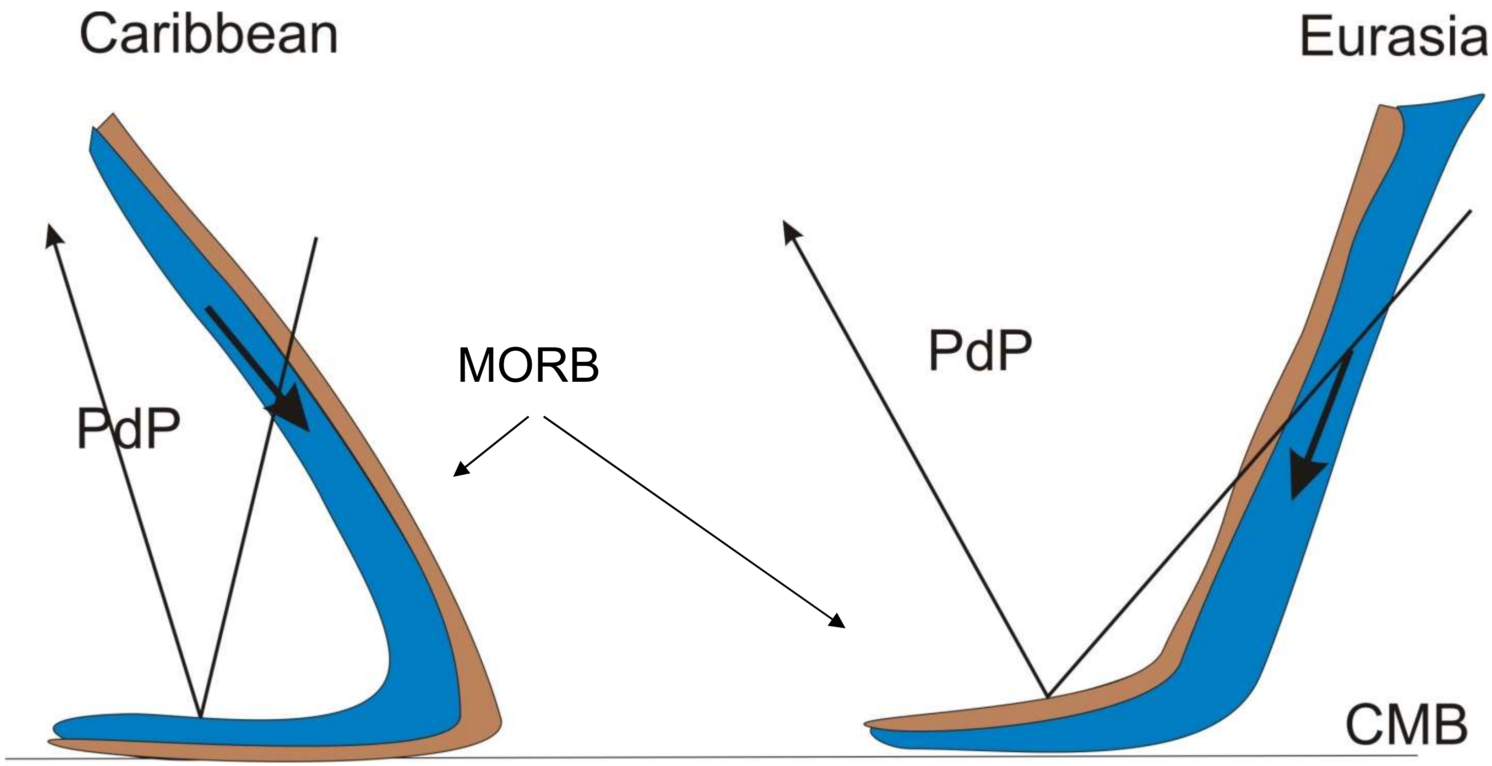
PdP - -1- -2%
SdS + 1-3%

Fitting: ppv MORB



Cobden and Thomas, 2013.

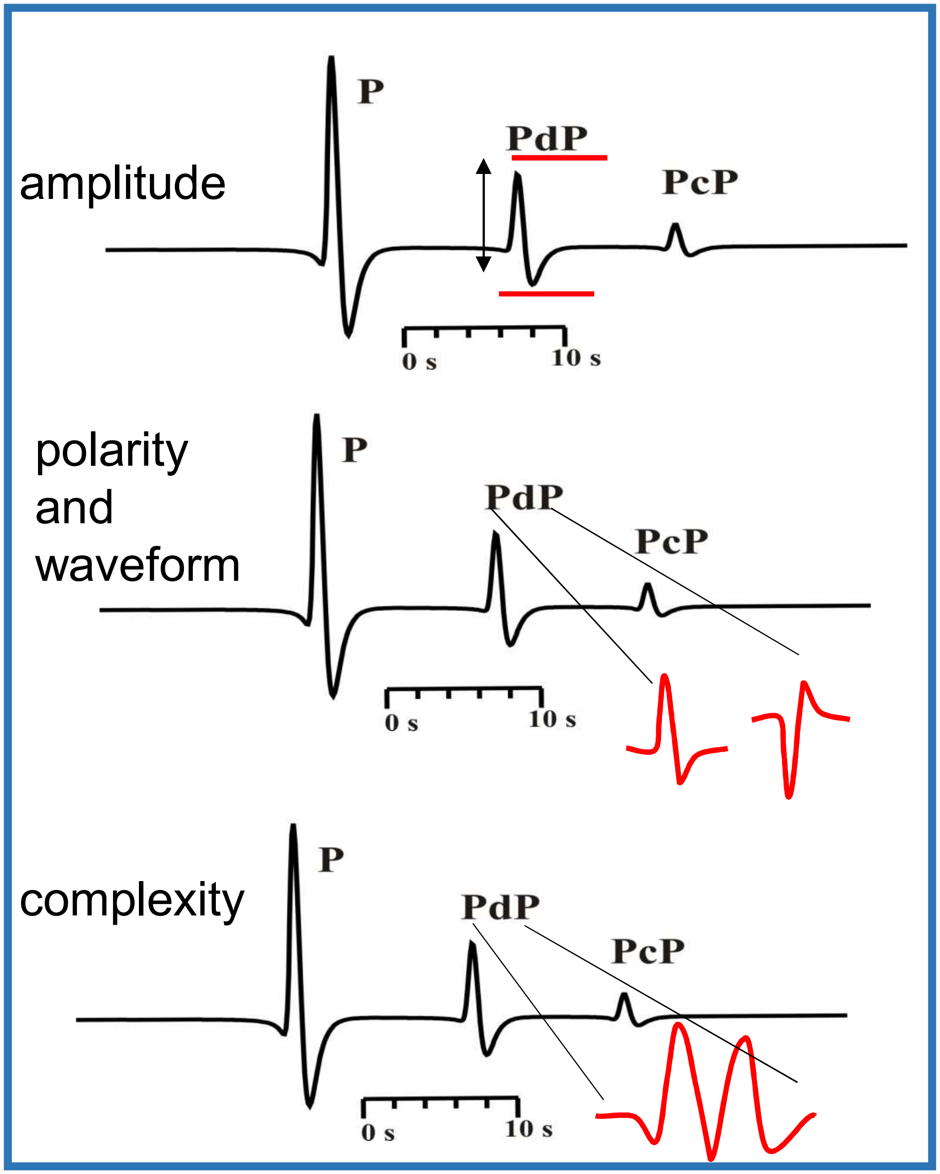
Reflections - one possible interpretation



Cobden and Thomas, 2013.

Pacific/Bering Sea: reflection off MORB
Caribbean: reflection of phase transition to ppv

Amplitude and polarity of reflections



Amplitude and polarity can be predicted by using Zoeppritz equations (energy partitioning at an interface).

Need to know velocities and density above and below the interface.

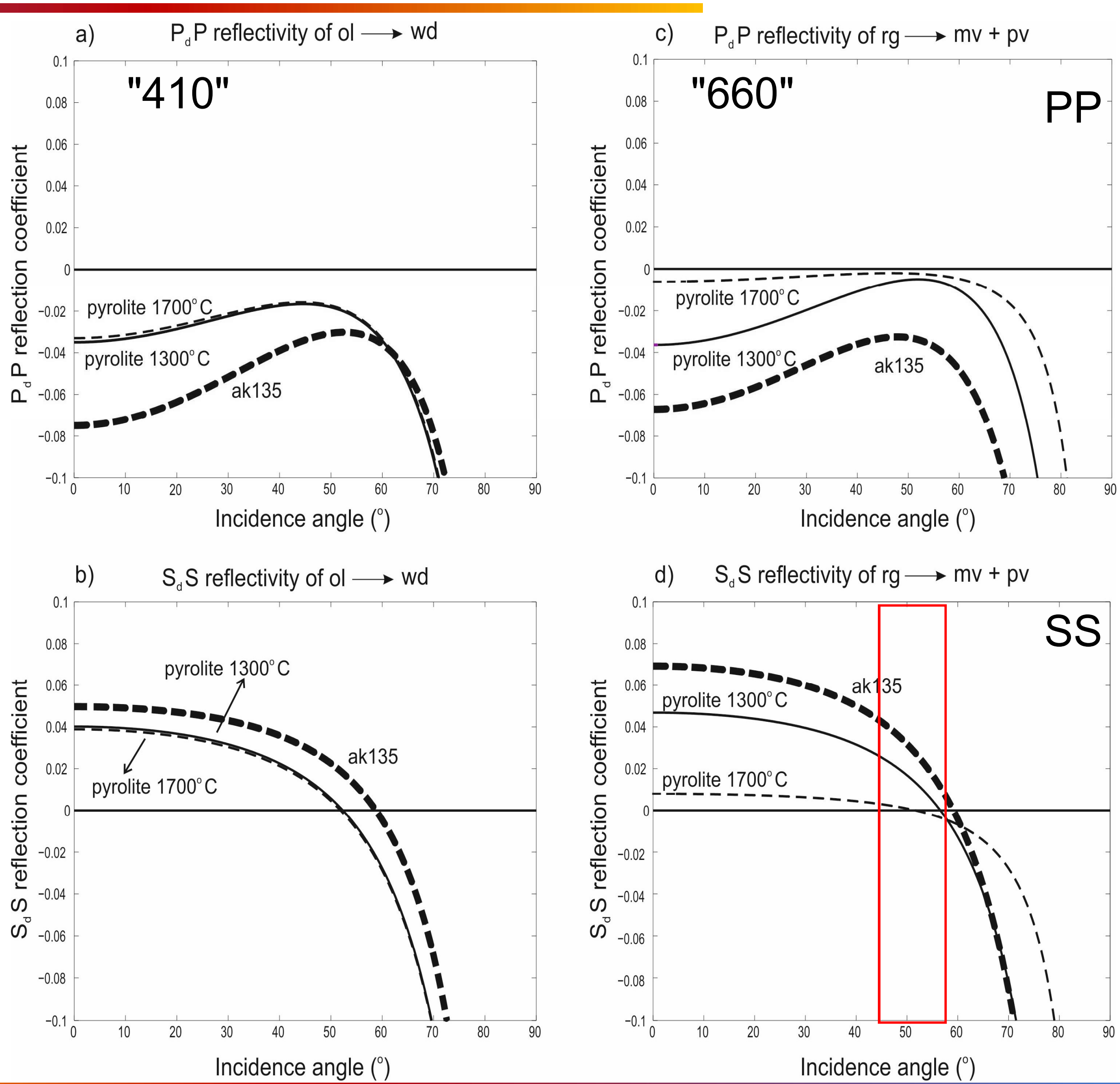
complexity of waveform can also be used.

Reflections - Zoeppritz

Zoeppritz equations:

for a given impedance contrast, amplitude and polarity also change with angle of incidence at the boundary.

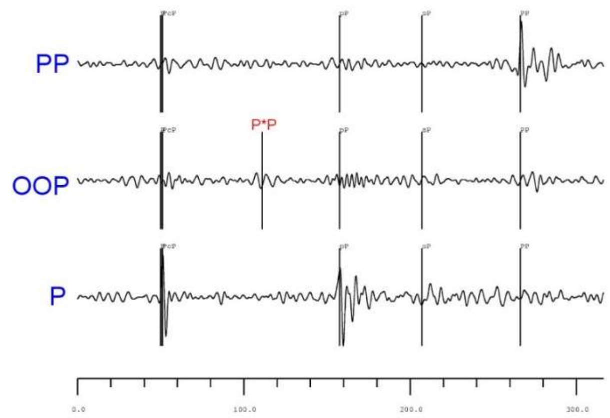
Modelling is important!



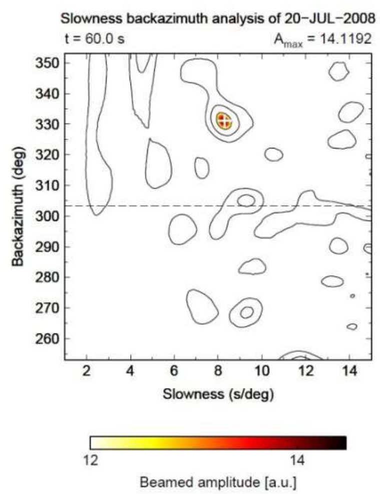
Lessing et al., 2015

Out-of-plane reflections

Using arrays it is possible to determine direction of incoming waves (e.g. Kito et al., 2008, Rost et al., 2008, Kaneshima and Helffrich, 2009, Kaneshima, 2009, Bentham et al., 2014,...)

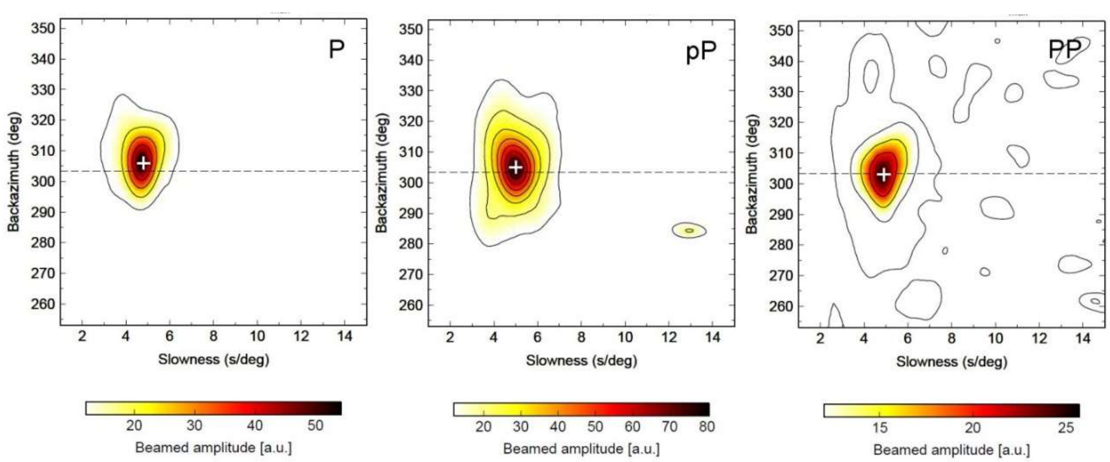


Schumacher and Thomas, 2016



Out-of-plane reflections between P and PP.

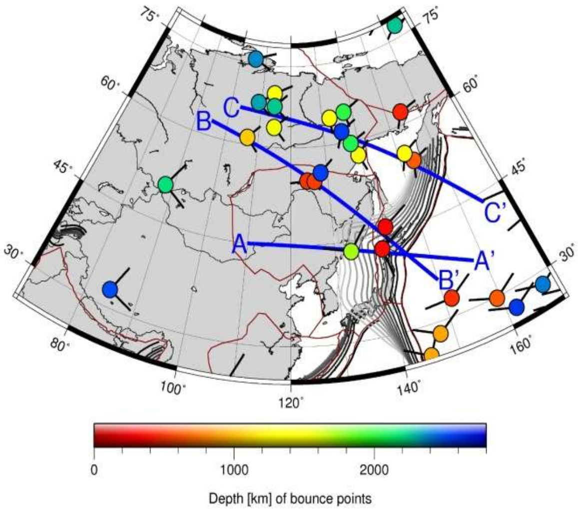
azimuth, slowness and travel time information to back-project the energy.

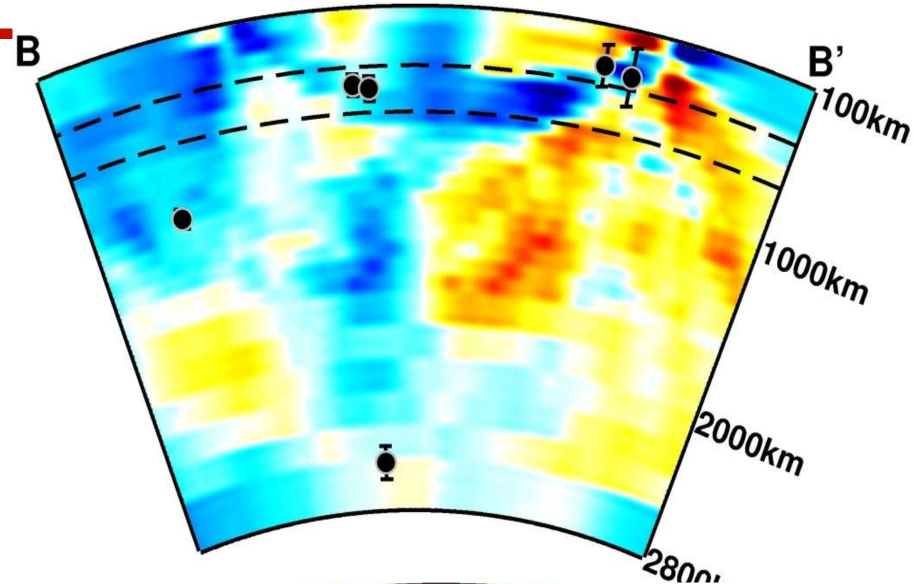


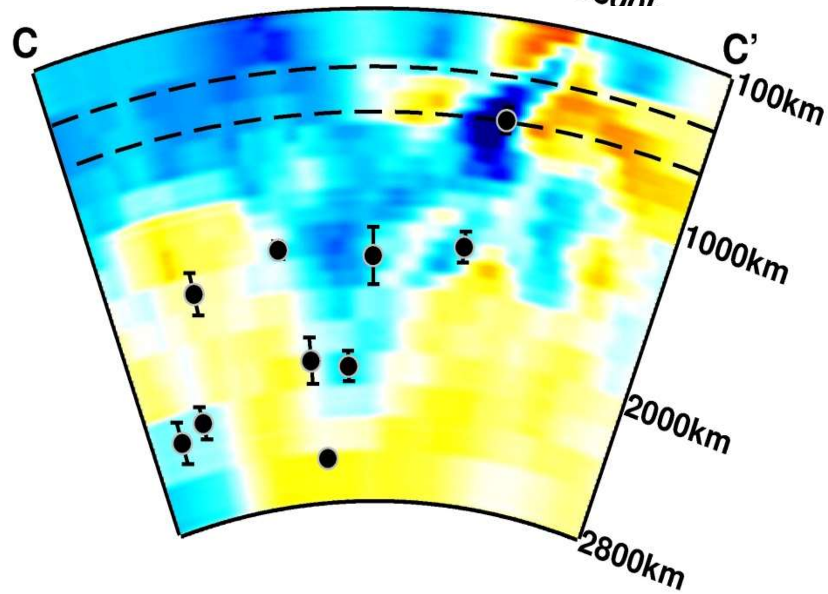
beam with measured azimuth reveals the out-of-plane phase.

Measurement of amplitude, polarity, corrections for focal mechanism.

out-of-plane reflections





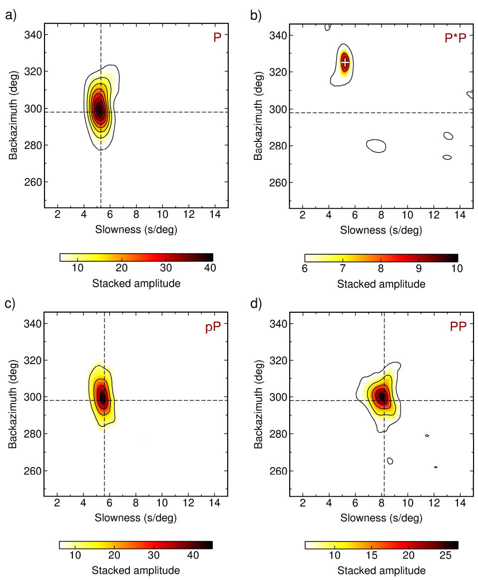


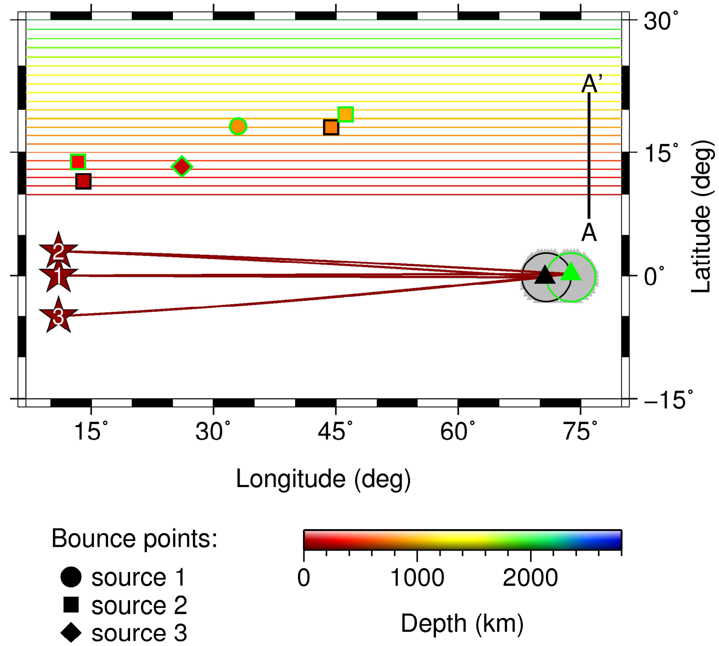
We find a number of reflections from depth below the transition zone. Reflections follow trend of fast velocity in tomographic images - likely reflections off deep slabs.

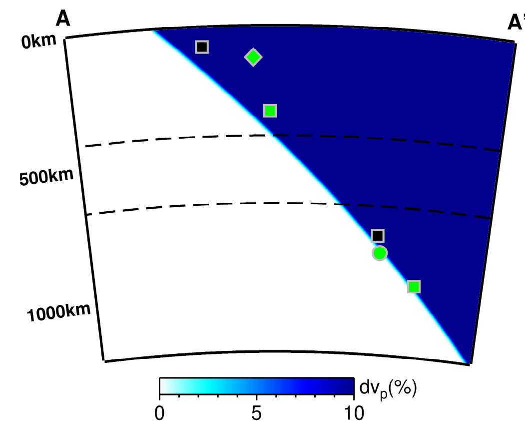
Waveforms and polarities are used to extract velocity structure at reflection point (Schumacher and Thomas 2017).

out-of-plane reflections -modelling

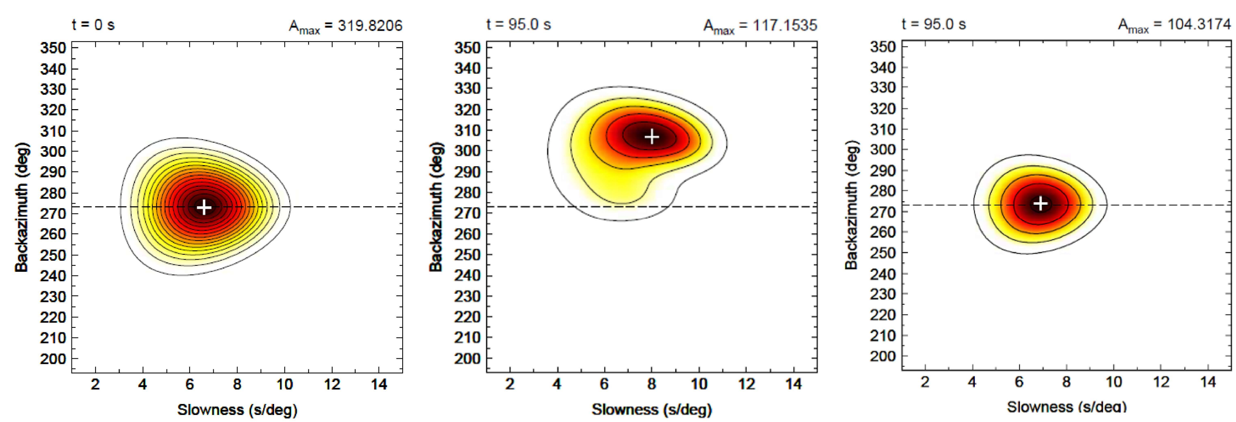
Data





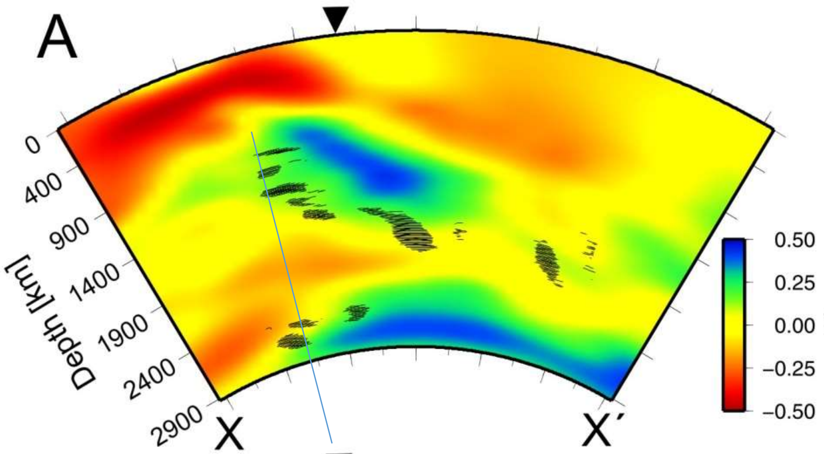


Modelling shows clear out-of-plane waves but strongly dependent on source-receiver combination

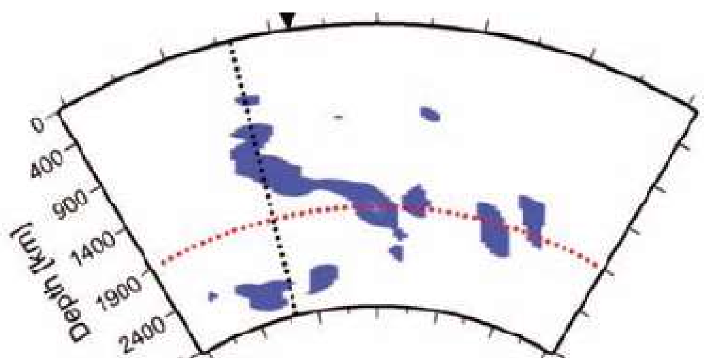


Schumacher and Thomas, 2016

Deep subduction

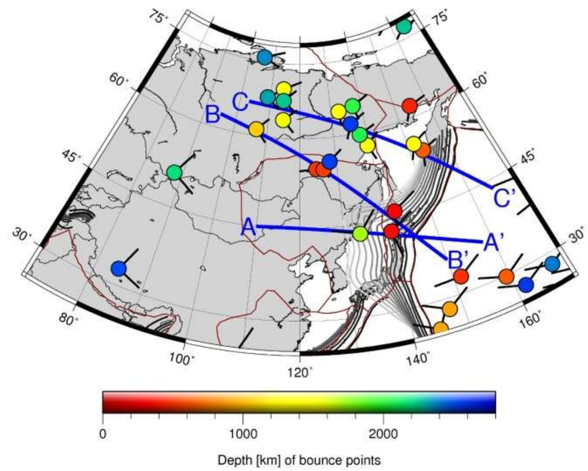


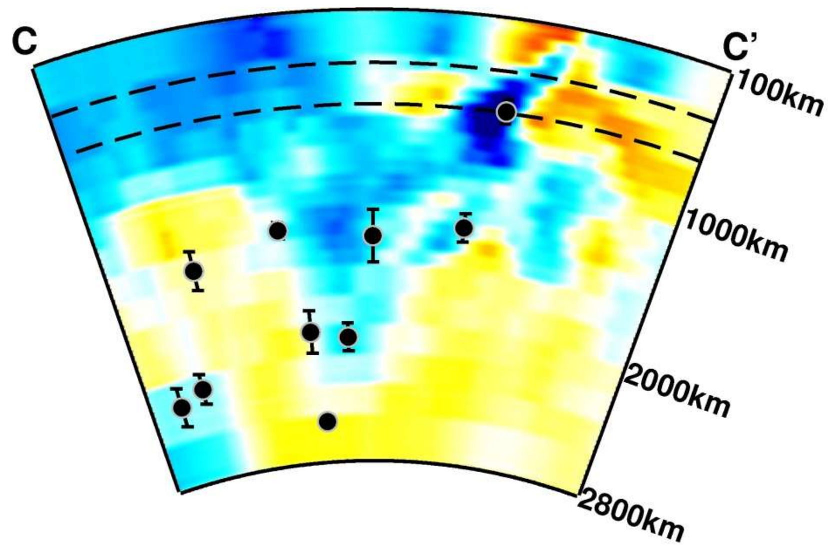
comparison with tomography (P and S)



Kito et al., 2008

Caribbean





W. Pacific

Schumacher and Thomas, 2016

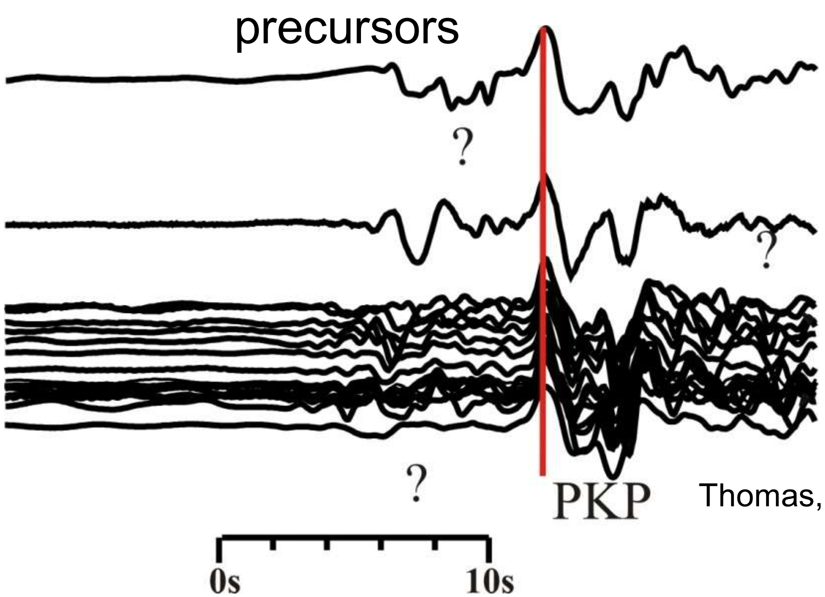
Imaging structures - scattering

Tomography

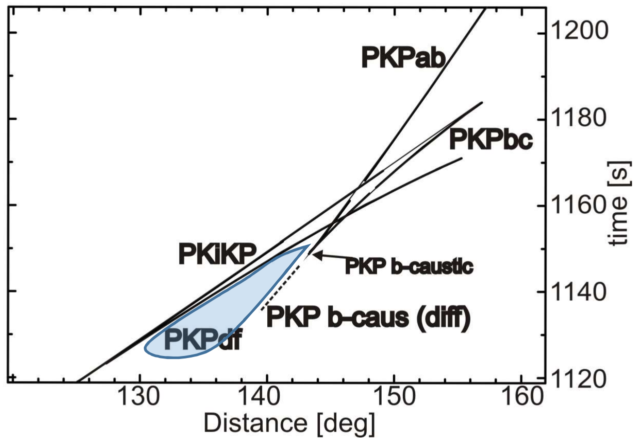
Reflections

scattered waves

...



Thomas, 1999



Scattering near the CMB or in the lower mantle

Cause not yet clear (interpretations range from small-scale melt pockets to broken-off pieces of slab, CMB topography and many more)

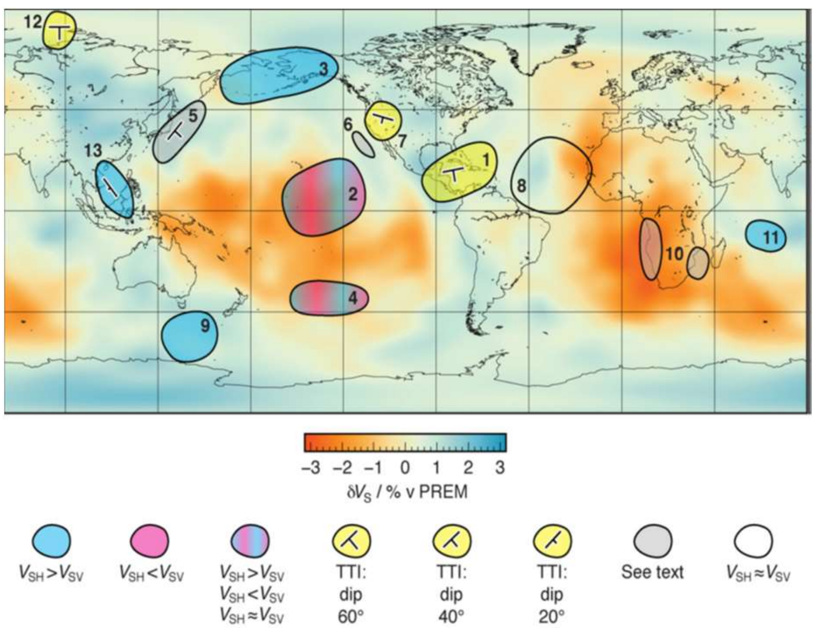
Scattering is also visible from the mid-mantle

Imaging flow/deformation

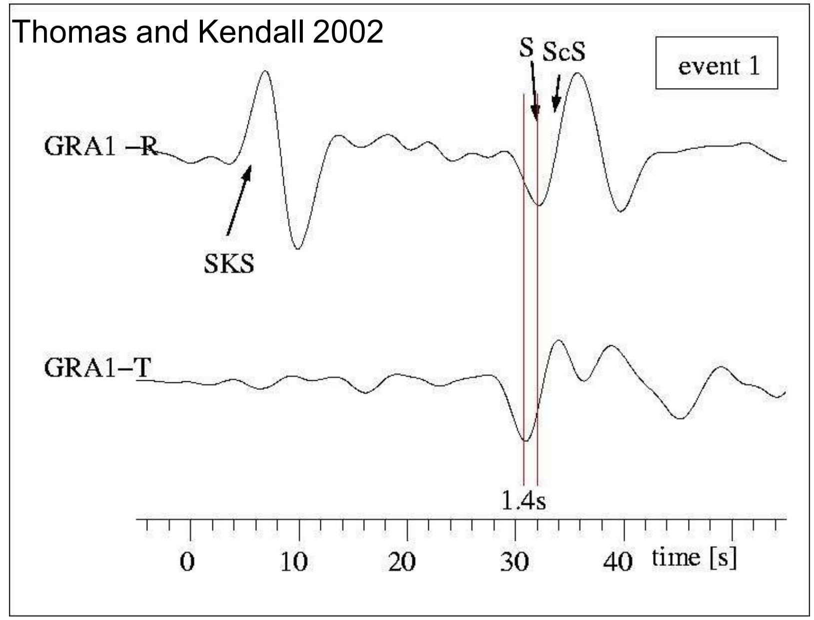
Anisotropy using S-wave spitting

Reflections

...



Nowacki et al., 2011



Shear wave splitting is often used to probe anisotropy of the deep Earth.

Travel time difference between 2 polarised shear waves.

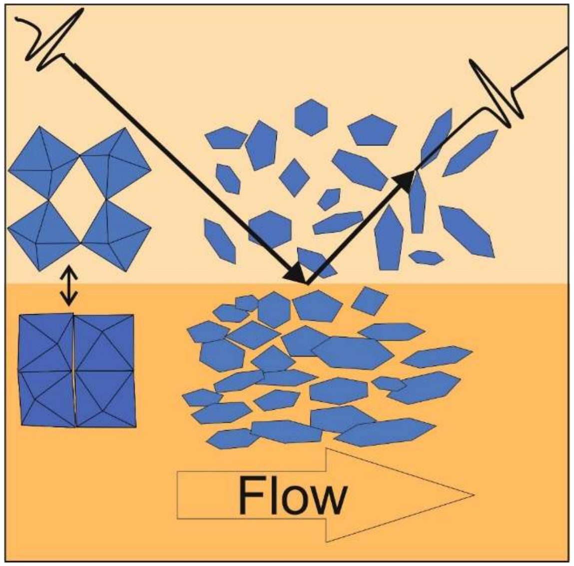
used: polarisation angle and travel time, sometimes waveform

Imaging flow

Anisotropy using S-wave splitting

Reflections

...



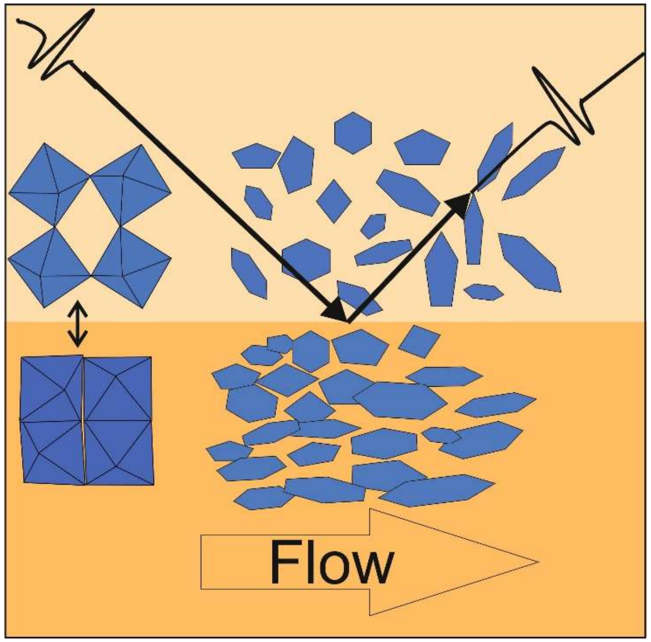
?

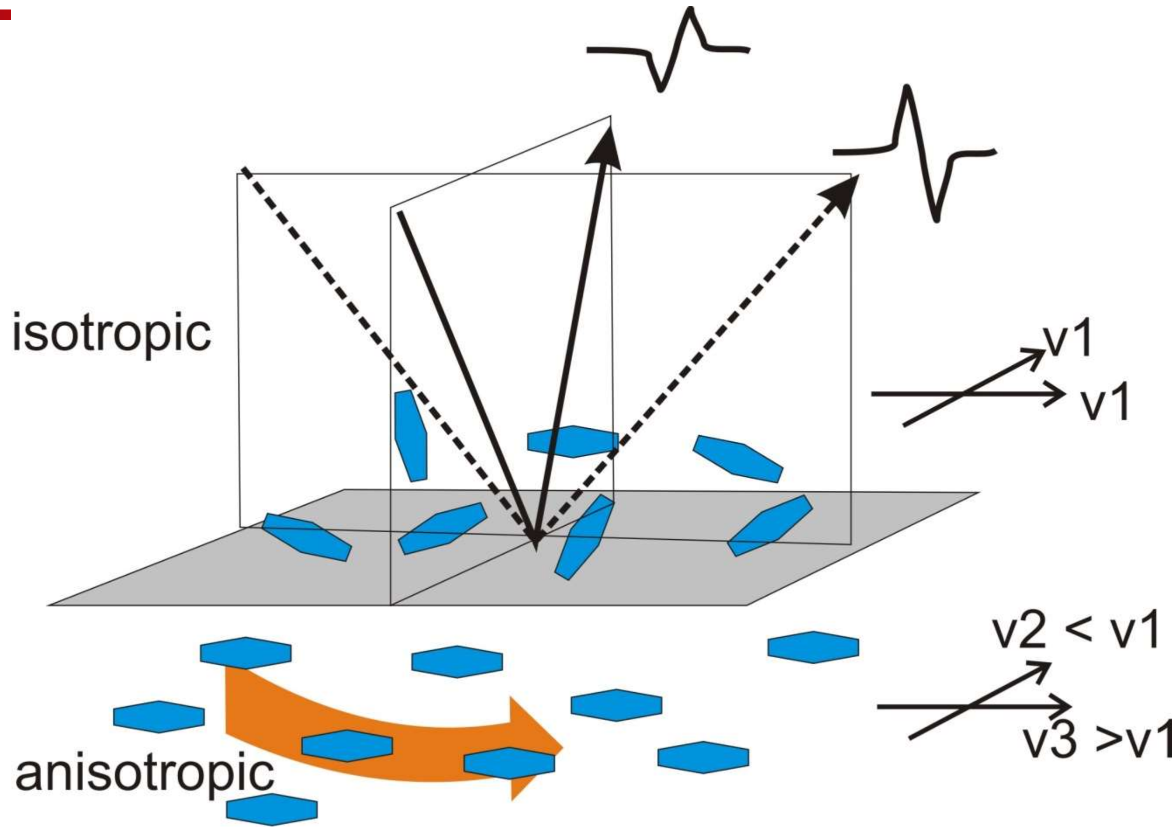
Aligned minerals (model by Ammann et al., 2010) can cause anisotropy.

Question: is this anisotropy leading to changes in reflected amplitude and polarity with travel direction?

fast and slow velocity directions (anisotropy) are superimposed on velocity increases due to phase transition.

Amplitude variation with azimuth





Velocity contrasts change with direction

-

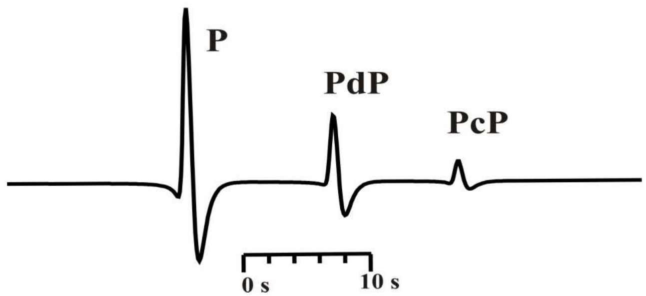
different reflection coefficients!

difference in amplitude, perhaps even polarity changes

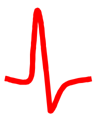
(see e.g., Thomas et al., 2011 or Saki, PhD thesis, 2016, Saki et al., 2017, Pisconti et al., 2017)

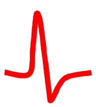
Imaging flow/deformation

Eurasia

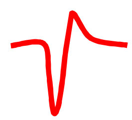


for 2 perpendicular crossing paths

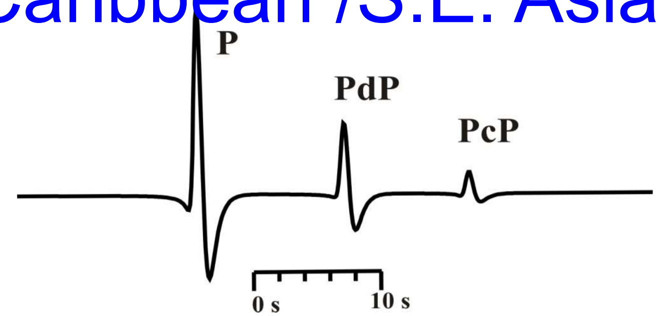
P reflection  pos. impedance

S reflection  pos. impedance

for a 45 degrees path

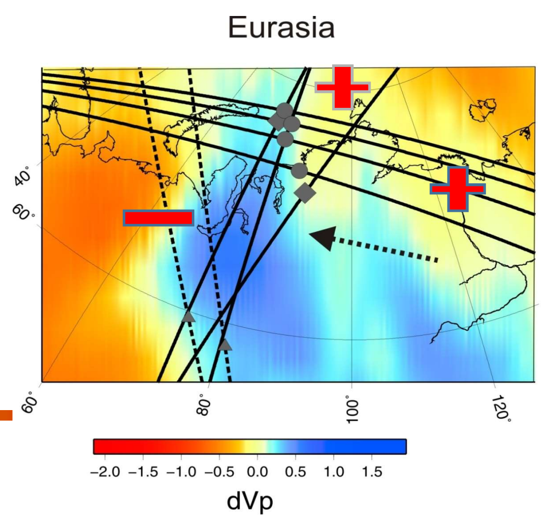
 neg. impedance

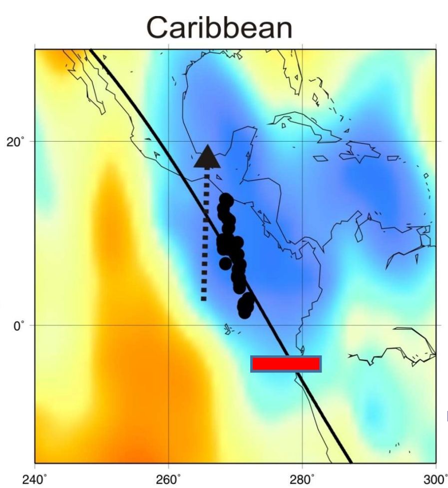
Caribbean /S.E. Asia



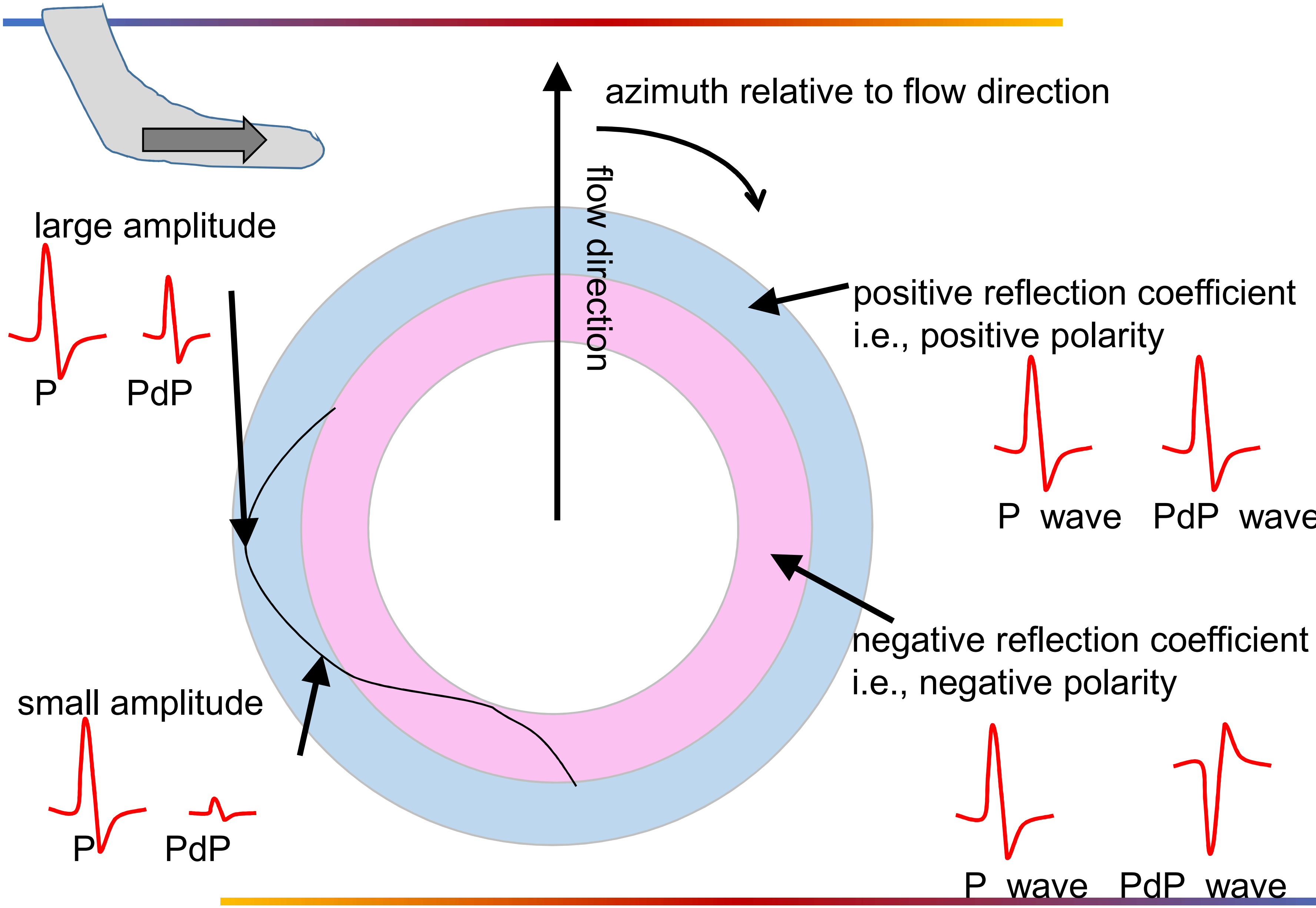
P reflection  neg. impedance

S reflection  pos. impedance

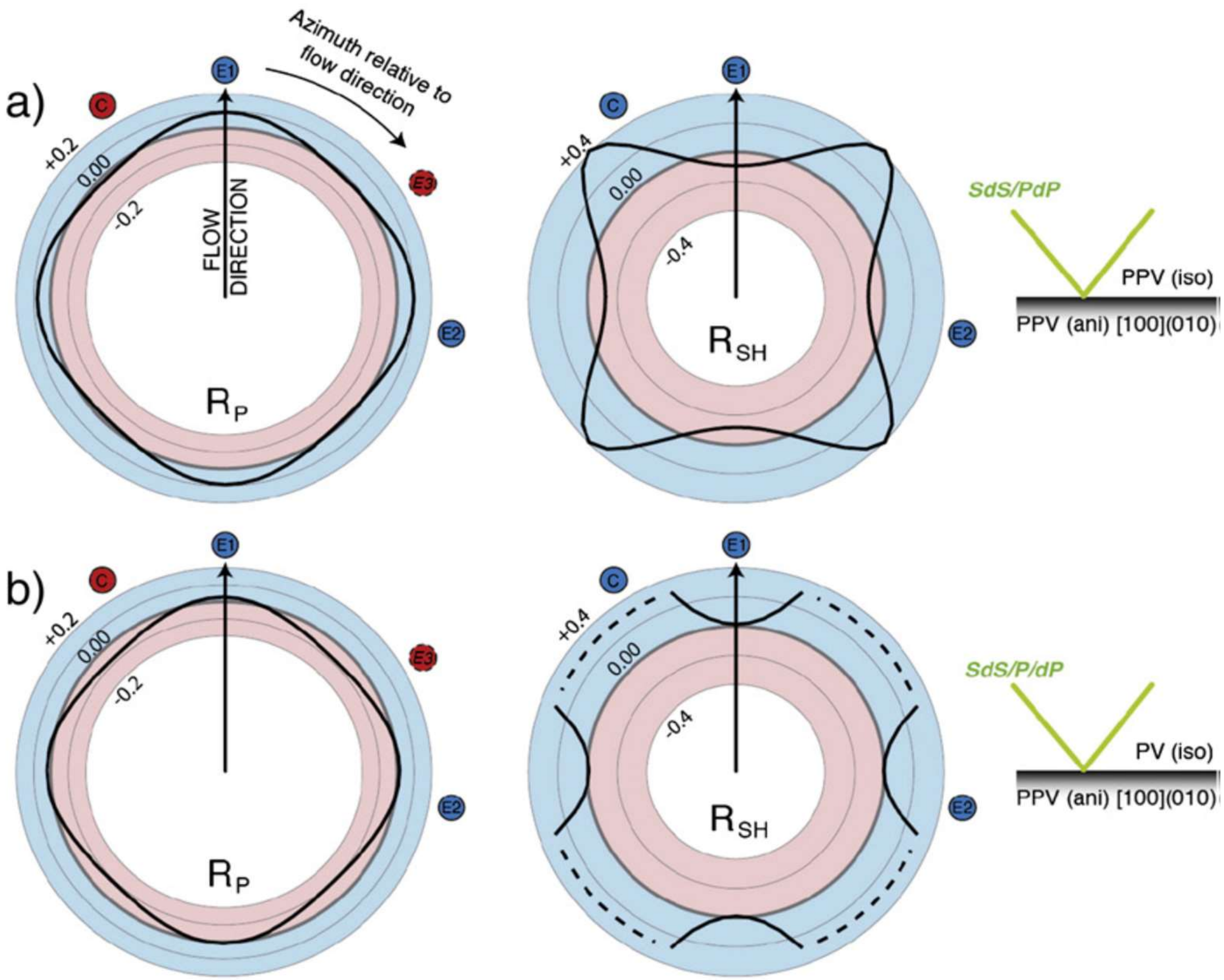




Imaging flow/deformation



Imaging flow/deformation



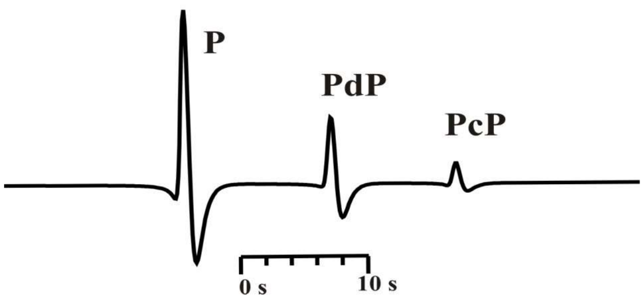
We can distinguish between models by using P and S-wave reflectivity.

Model in a) Polarity reversals for S and P.

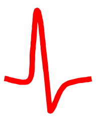
Model in b: S-wave always positive. P wave changes polarity

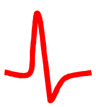
Imaging flow/deformation

Eurasia



for 2 perpendicular crossing paths

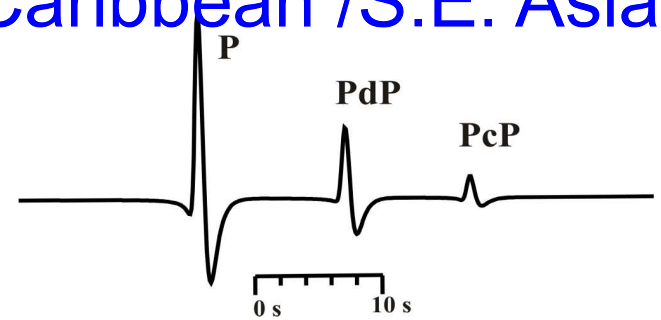
P reflection  pos. impedance

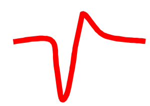
S reflection  pos. impedance

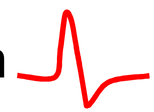
for a 45 degrees path

 neg. impedance

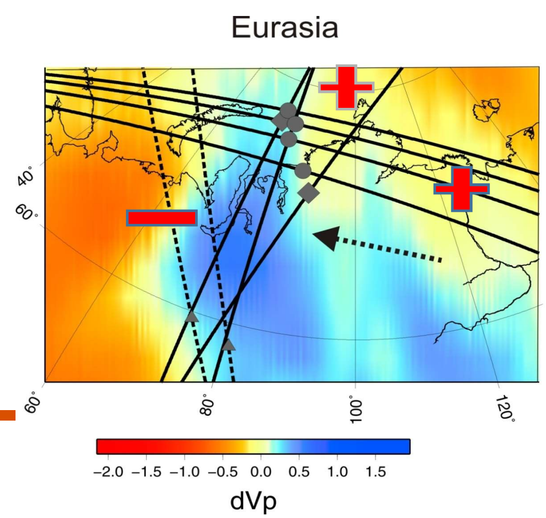
Caribbean /S.E. Asia

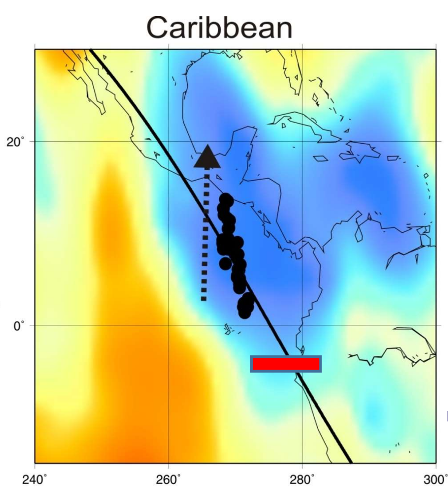


P reflection  neg. impedance

S reflection  pos. impedance

observations in Eurasia and Caribbean agree with model b) anisotropy [100](010) and phase change





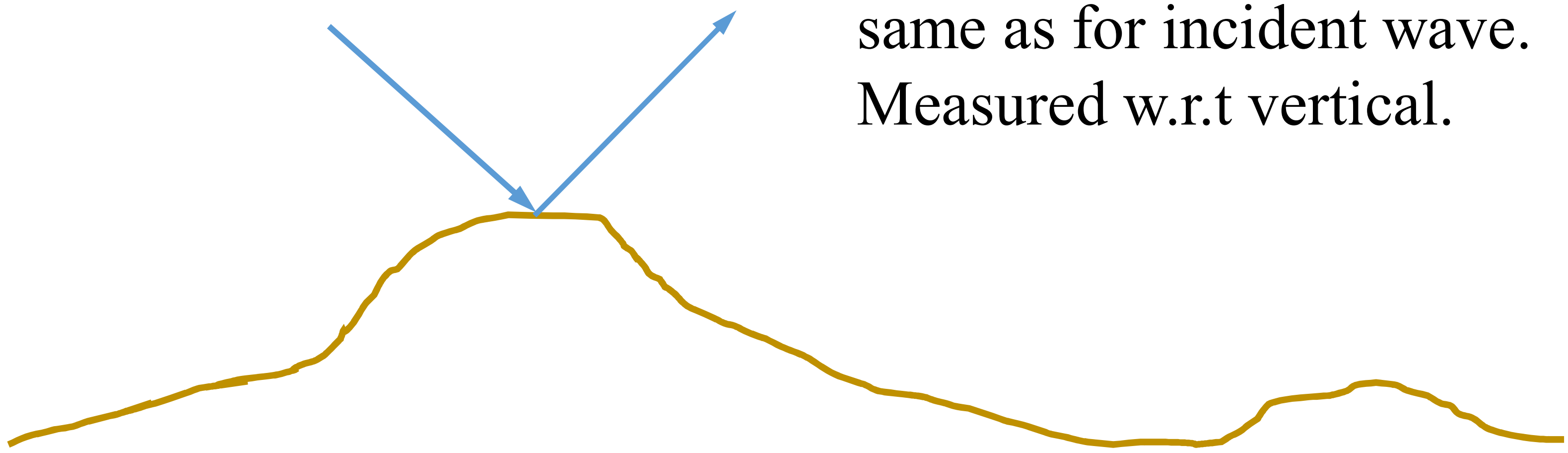
What can we interpret? - Amplitude

Amplitude

one of the most difficult measurements because amplitude is affected by many things:

source effects
receiver effects
attenuation - intrinsic and scattering
energy partitioning
structure/topography
discontinuity versus gradient
instruments
.....

What can we interpret? - Amplitude

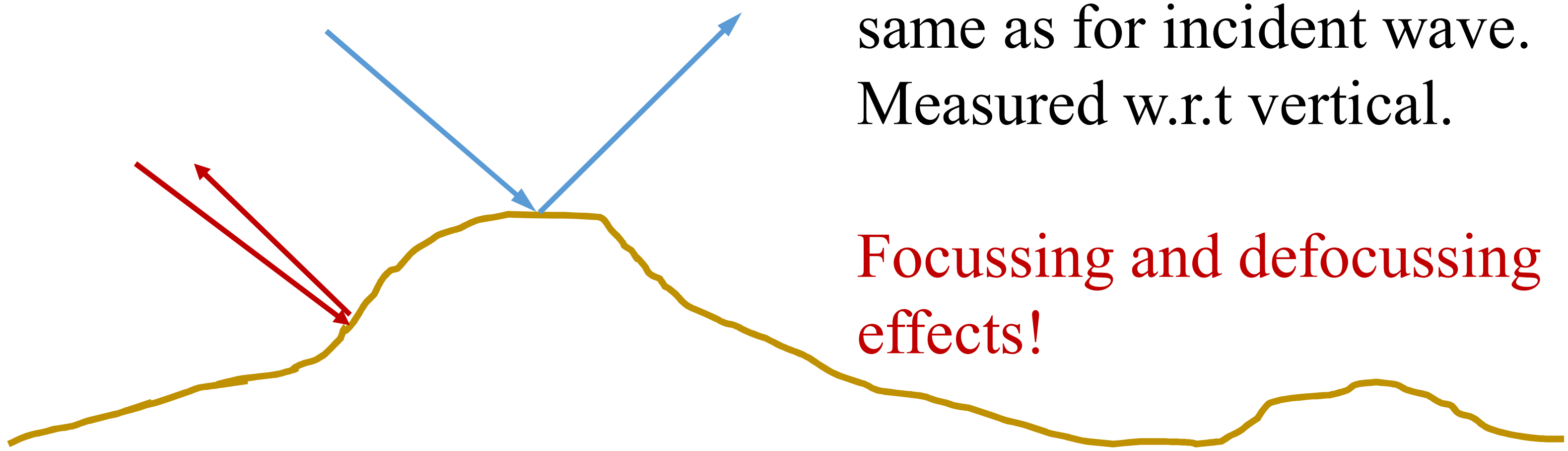


Snell's law

Ray parameter p = sin (i)/v

Reflected waves: angle is the same as for incident wave. Measured w.r.t vertical.

What can we interpret? - Amplitude



Snell's law

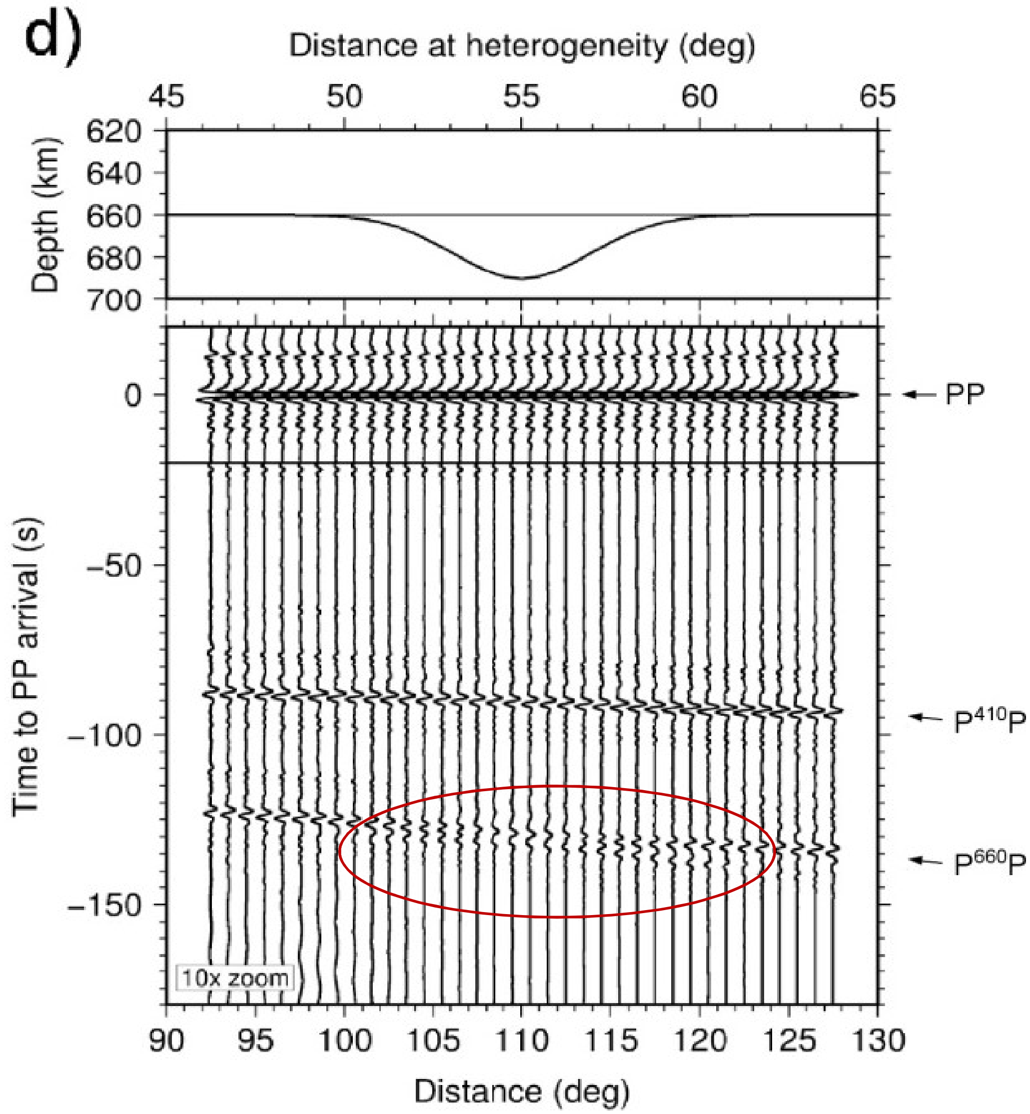
Ray parameter p = sin (i)/v

Reflected waves: angle is the same as for incident wave. Measured w.r.t vertical.

Focussing and defocussing effects!

= amplitude variations!

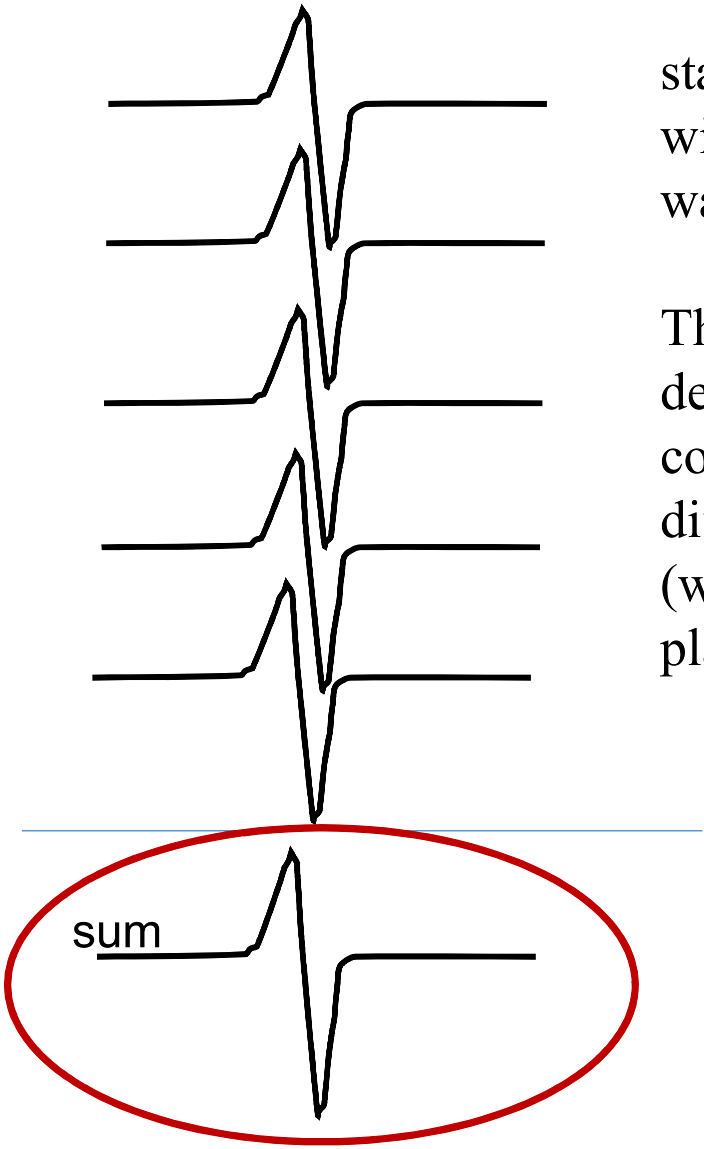
What can we interpret? - Amplitude



Focussing and defocussing effects modelled with a simple model: strong effects in amplitude and more than one apparent reflector visible in places.

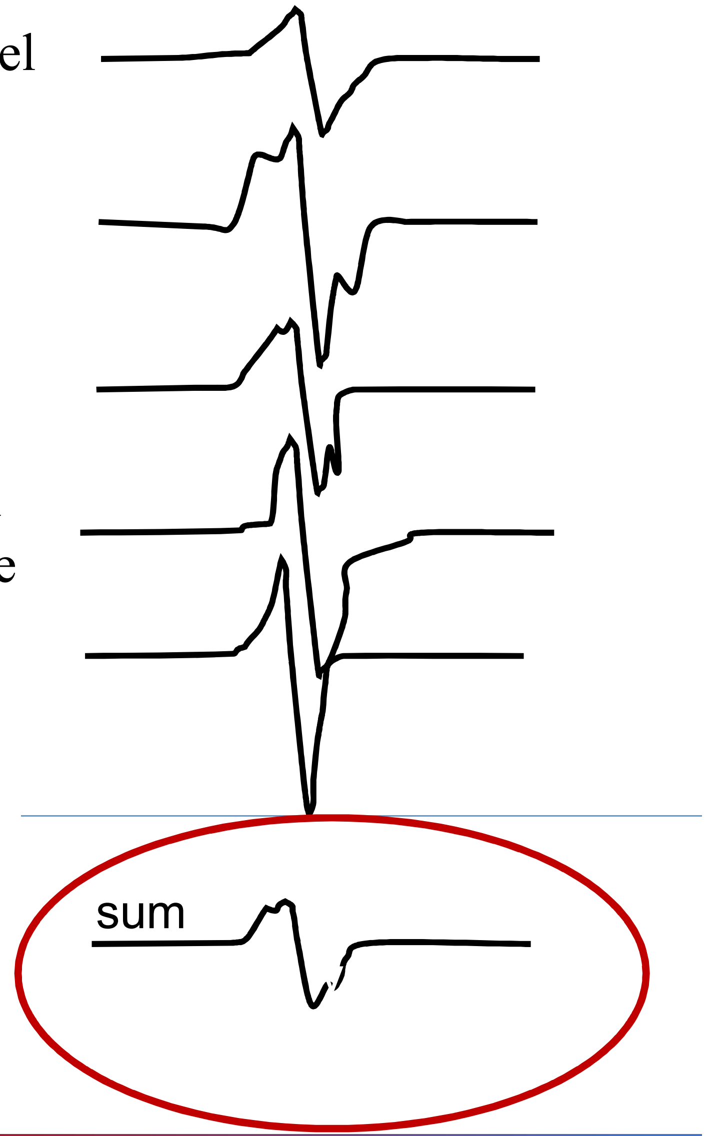
Misinterpretations possible

What can we interpret? - Amplitude



stacking a number of travel will give an average waveform.

This does not necessarily describe the structure correctly as reflections in different places are added (without correcting for the place of reflection).

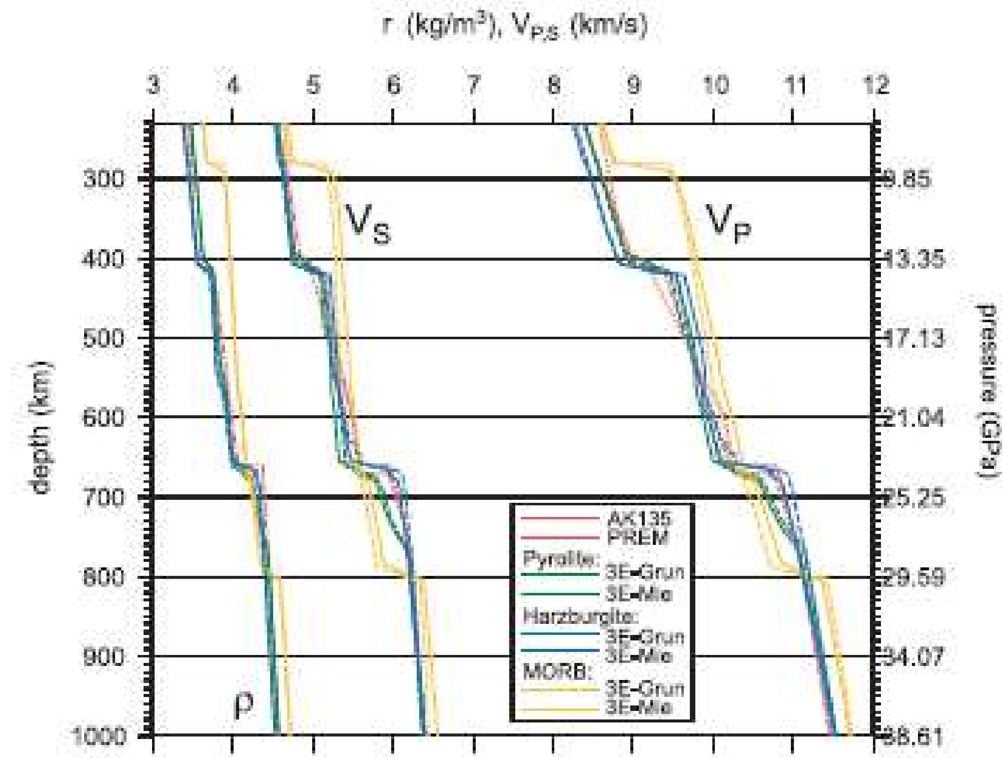


What can we interpret? - Amplitude

Seismologists often work with standard Earth models (PREM, ak135...)

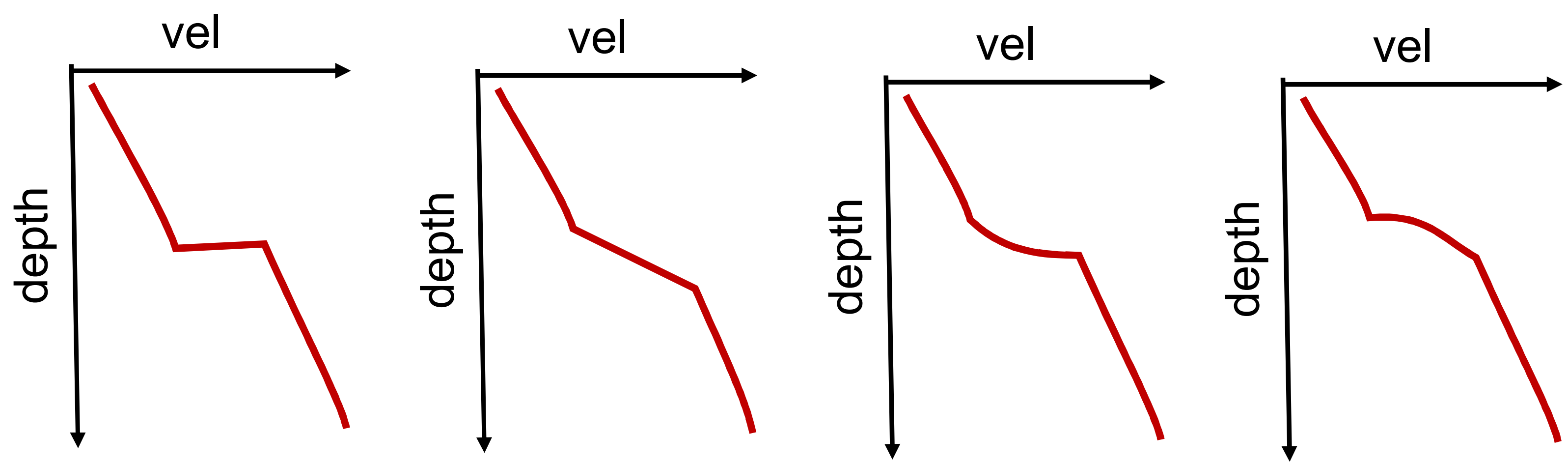
When interpreting depths, these are based on ak135/PREM etc values of discontinuities. Often pv+mw system only

Cobden et al (2008) showed that depending on mineralogy, the discontinuities change (depth and velocity/ density increase).



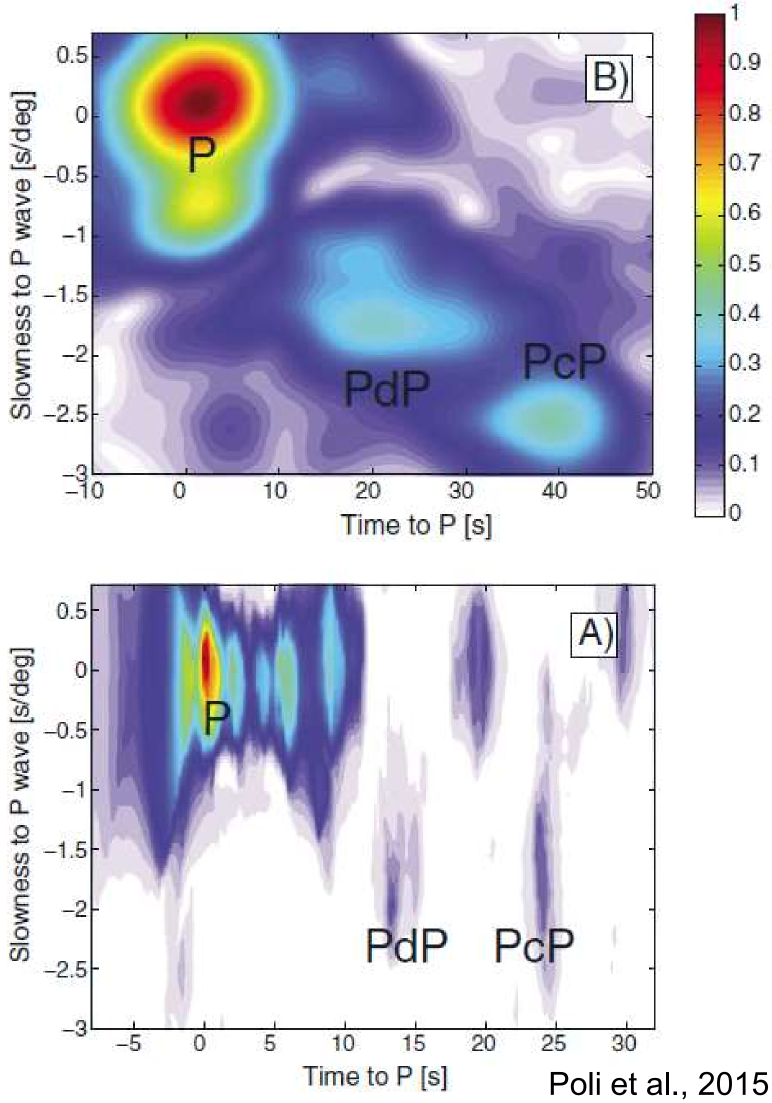
What can we interpret? - Amplitude

Sharp discontinuities reflect (or transmit) energy different from gradient zones. Often calculations are done with sharp discontinuities and then amplitudes are interpreted in terms of gradients.
Measuring gradients is difficult - frequency might help (but difficult)

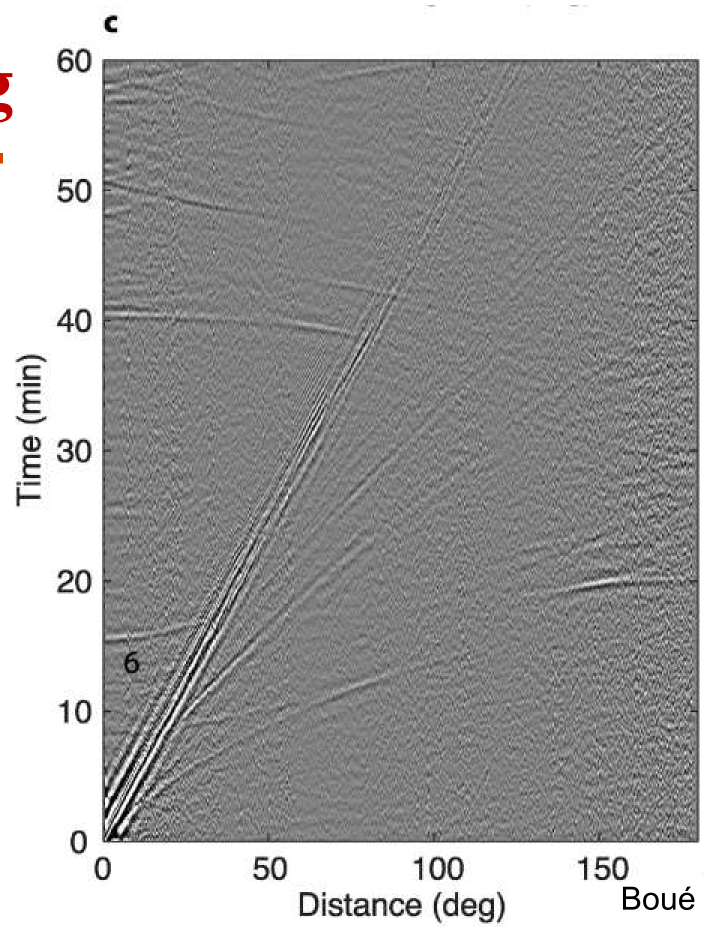


these gradients will produce different seismic waveforms
but the interpretation will be non-unique!

Extending deep Earth imaging



Poli et al., 2015



Boué et al., 2014

Reflection from D" with noise
and comparison with earthquake

see also poster by Stéphanie Durand...

Summary

- We use travel times, amplitudes, waveform, polarity of seismic body waves to image structures and/or flow
- Array methods help to increase the amplitude of (coherent) arrivals and distinguish between phases..
- Even though polarity and especially amplitude are powerful observables, care has to be taken when interpreting them.
- Can noise help to increase our coverage of the deep Earth? (splitting? scattering? receiver functions?)