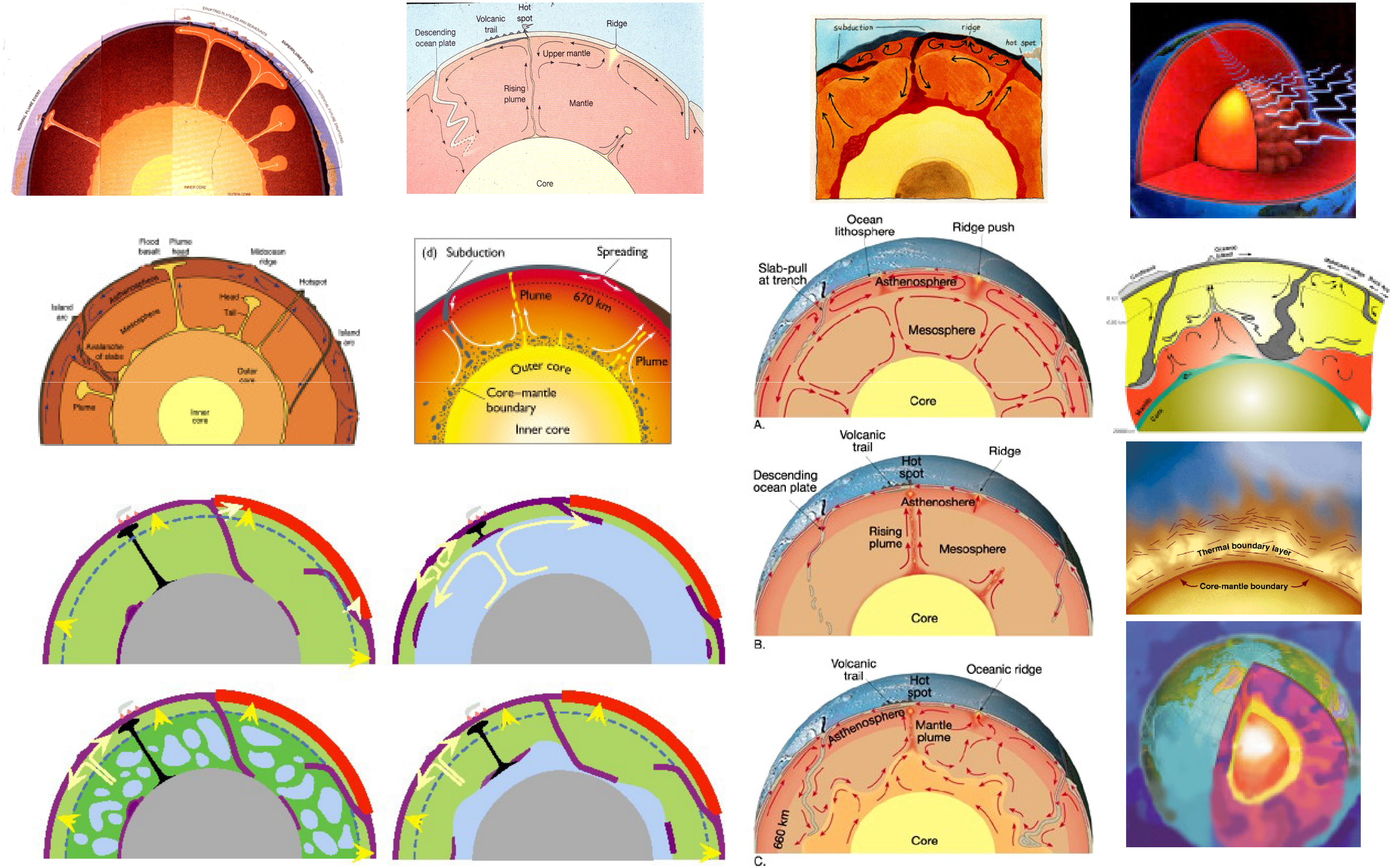
Seismic Structures in Earth's mantle

Christine Thomas

Thanks to:

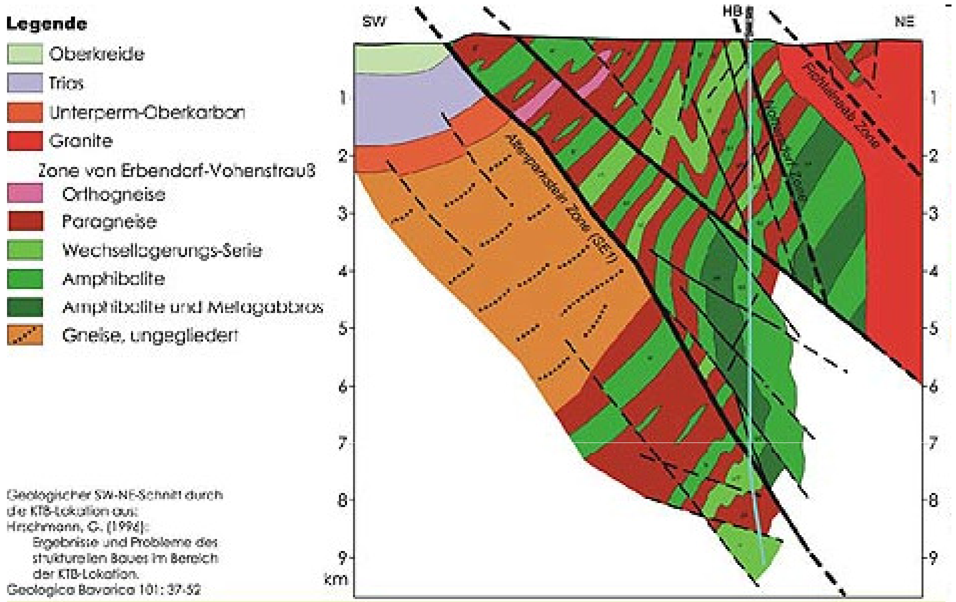
Tadashi Kito, Andreas Rietbrock, Stuart Nippress, Michael Weber, Ed Garnero, Andy Heath, Sebastian Rost, John Hernlund, Paul Tackley, Lina Schumacher, Thorne Lay, Mike Kendall, Julian Lowmann, Stefanie Hempel, George Helffrich, David Schlaphorst, Helena Dominguez-Moreno, Jesus Casal-Berbel, James Wookey,

Recent views of the Earth



from Ed Garnero

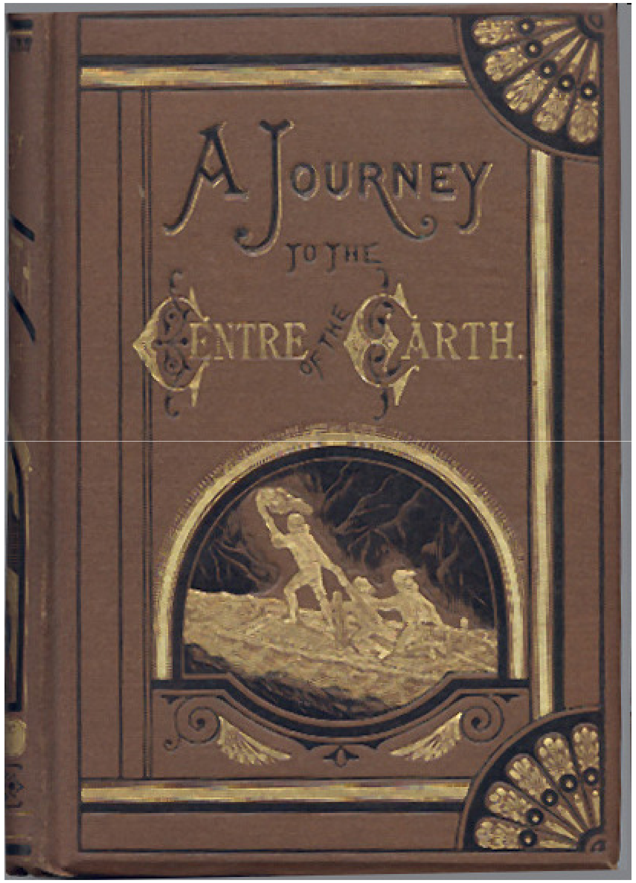
KTB drilling (depth ~ 10km)



Integrated
Ocean
Drilling
Program

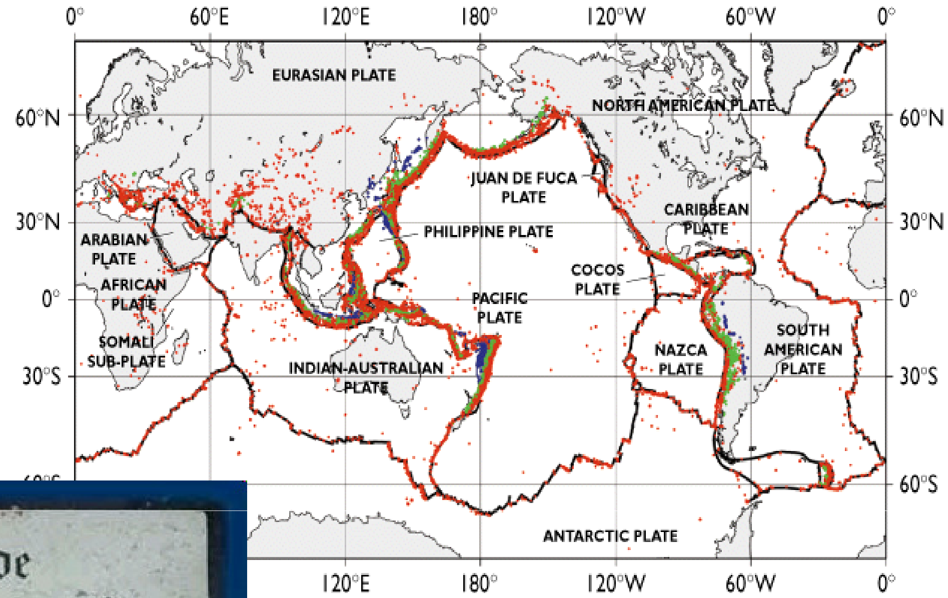
"Chikyu"

Deeper…?

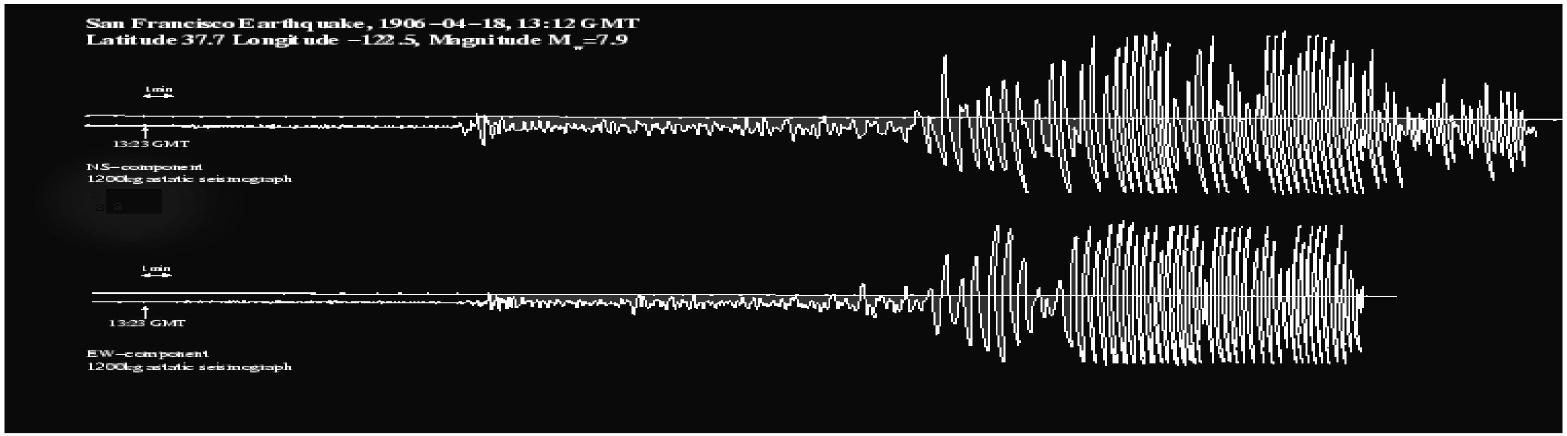


Still science fiction…. ?

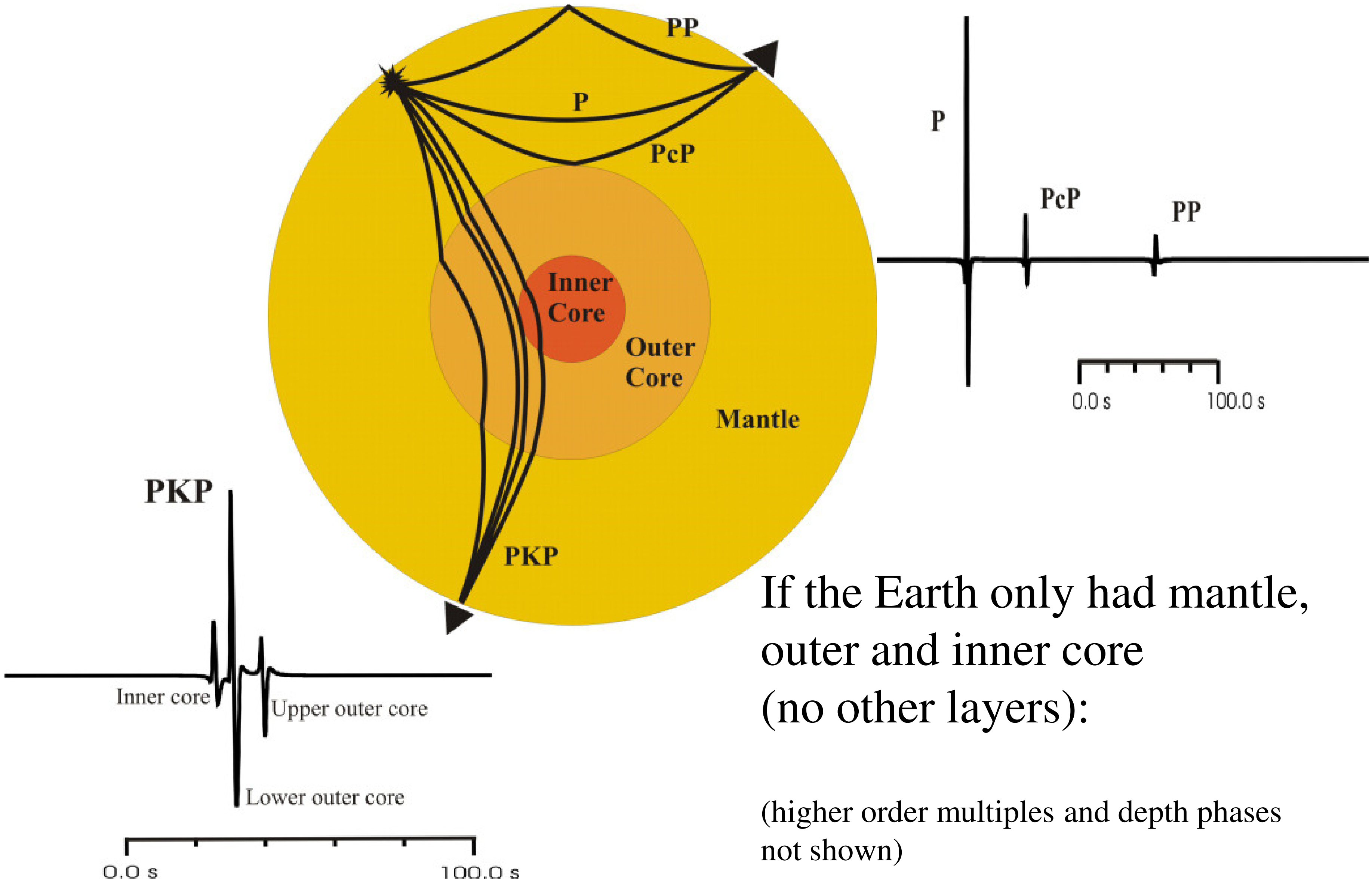
Seismology



San Francisco 1906



A simple Earth

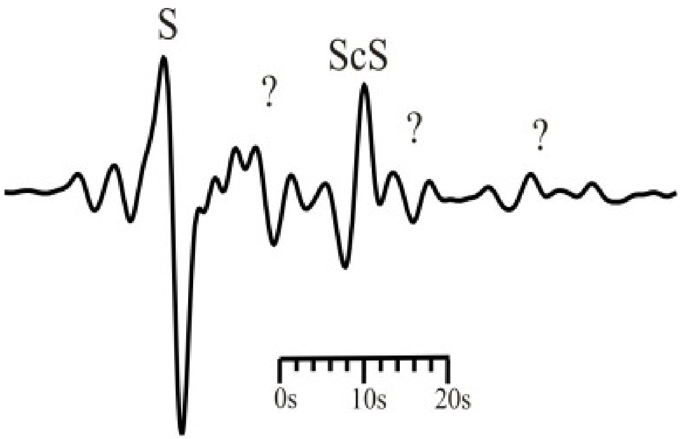


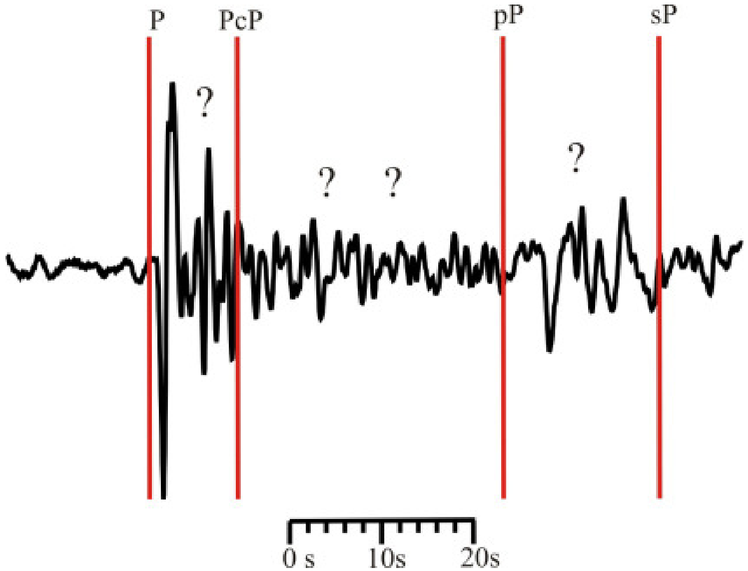
If the Earth only had mantle, outer and inner core (no other layers):

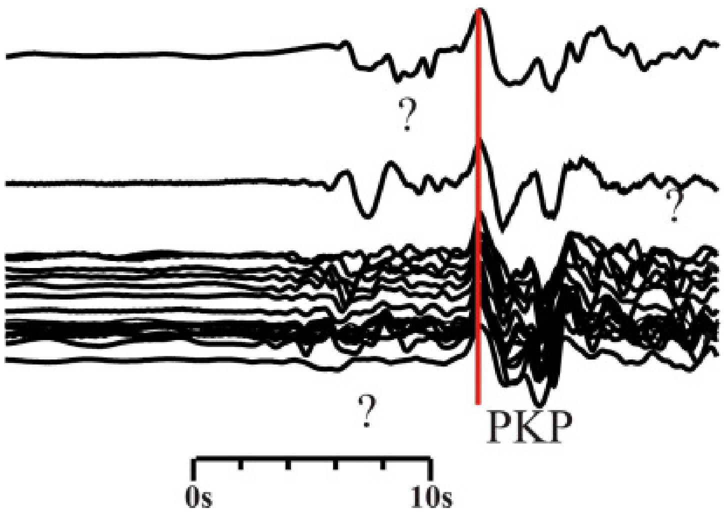
(higher order multiples and depth phases not shown)

A not quite so simple Earth

Real seismograms show that the Earth is more complex:

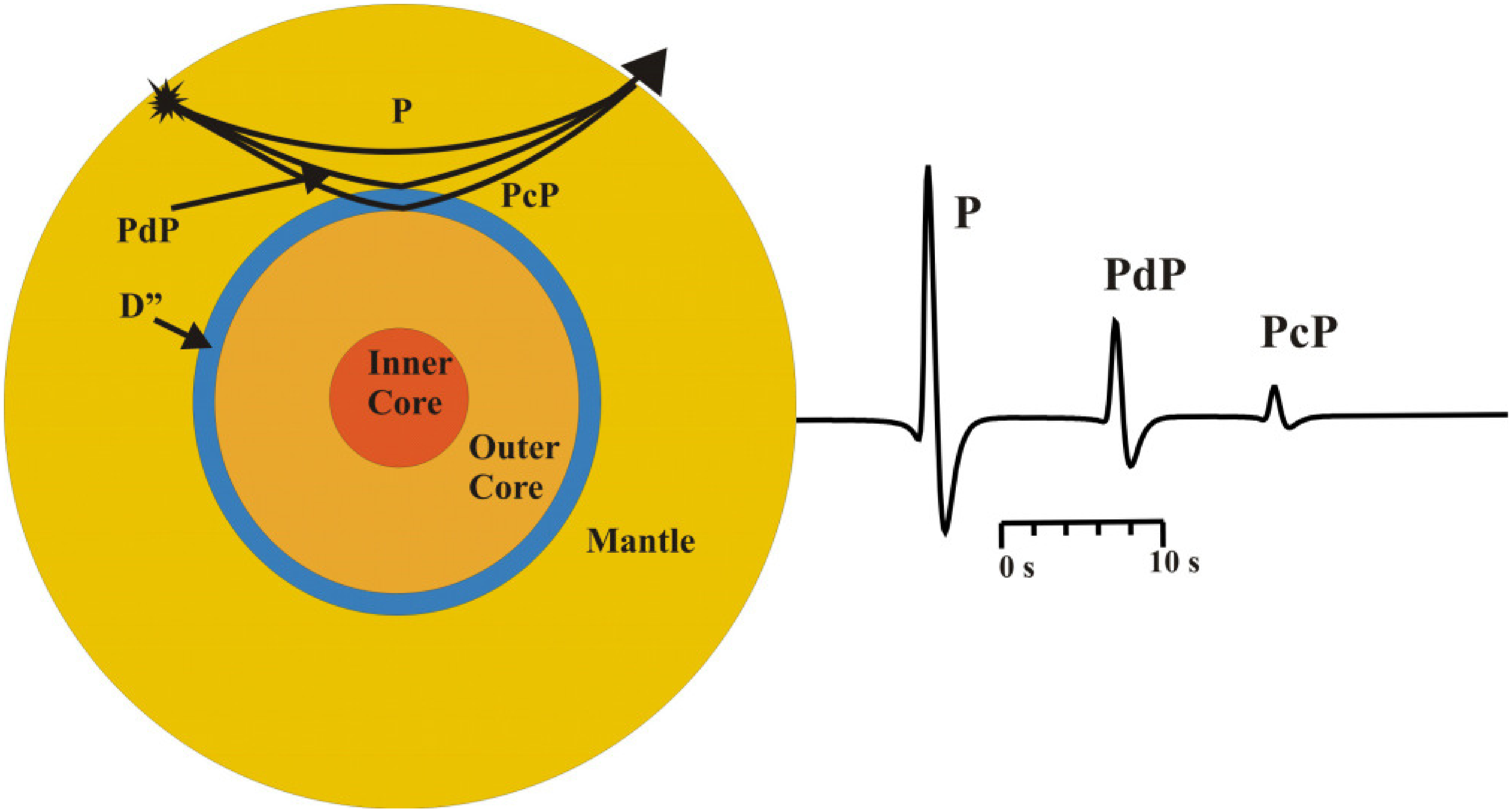






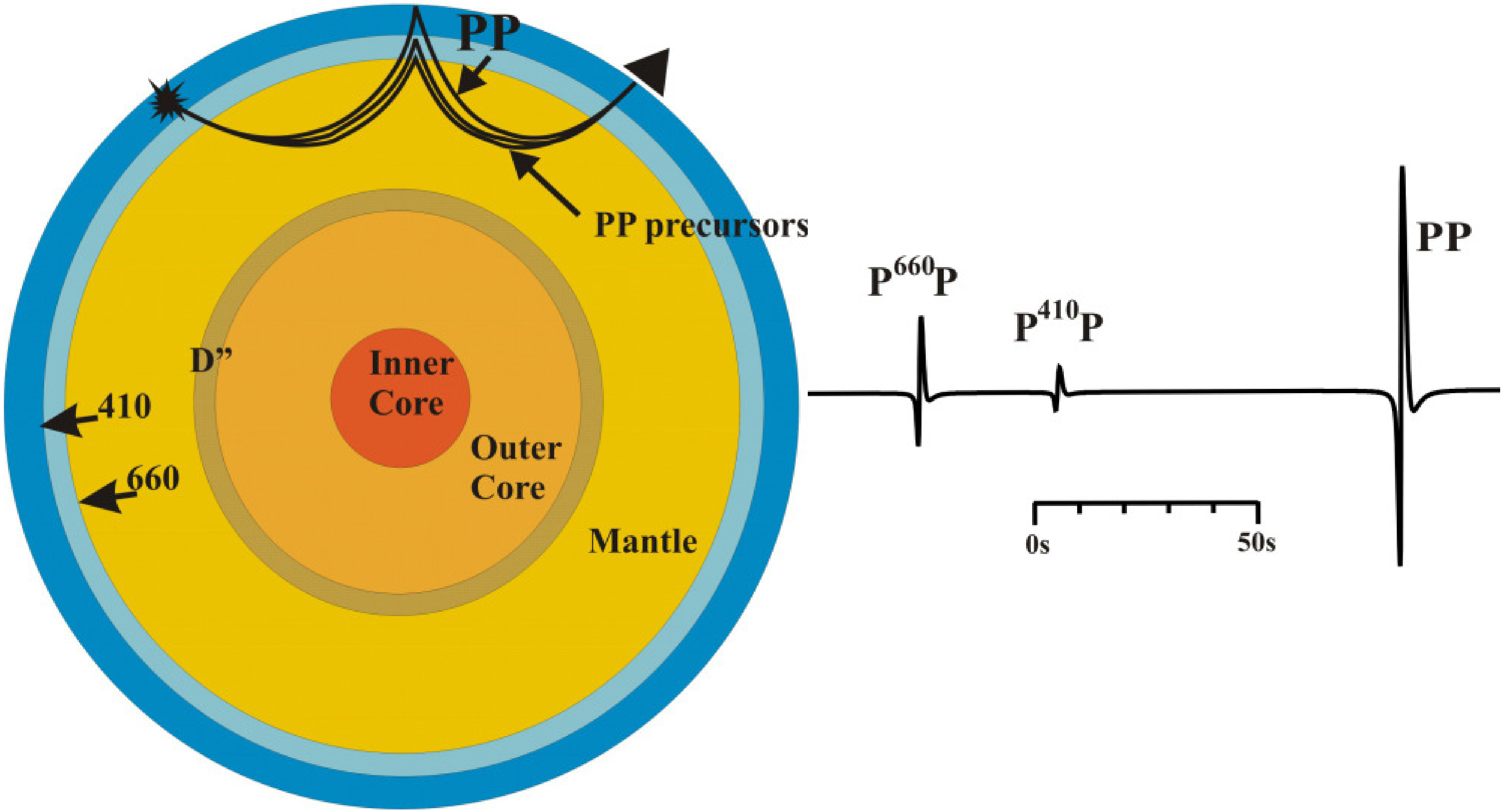
More layers in our simple Earth

If we add more layers to the simple Earth, we expect more arrivals in the seismogram:



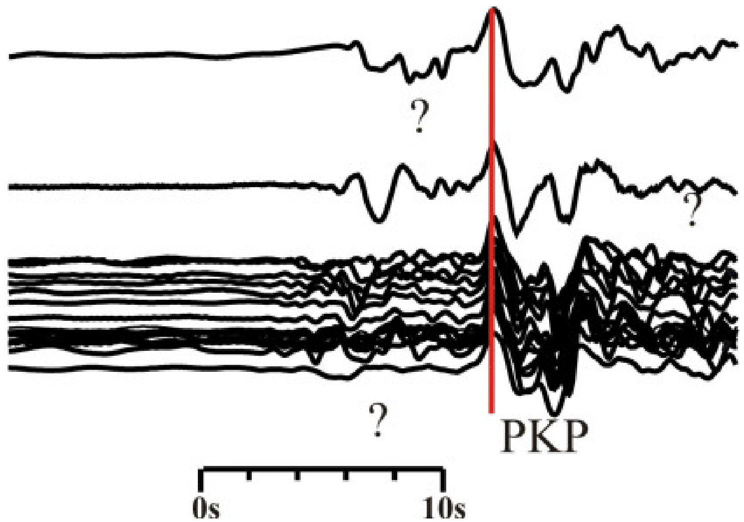
More layers in our simple Earth

Introducing upper mantle discontinuities
(660 km and 410 km discontinuities):



More layers in our simple Earth

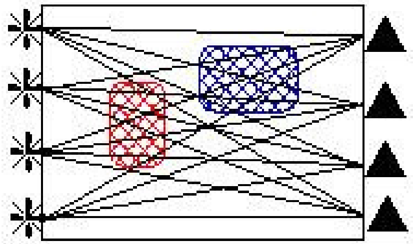
small scattering structures cause waves that arrive as precursor or coda to standard seismic phases.



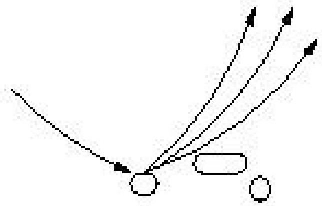
Every new structure creates a new seismic wave in the seismogram

How can we study the interior of the Earth?

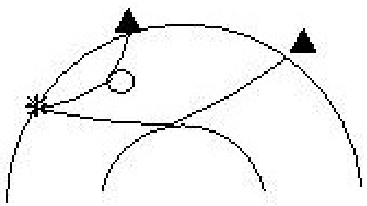
Tomography



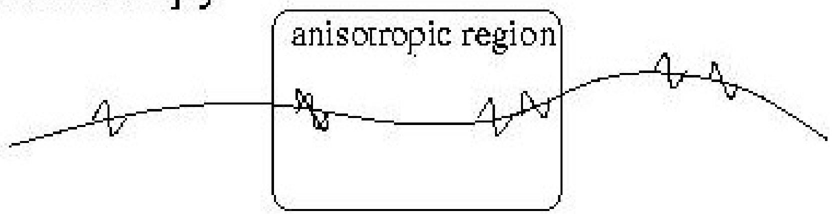
Scattered waves



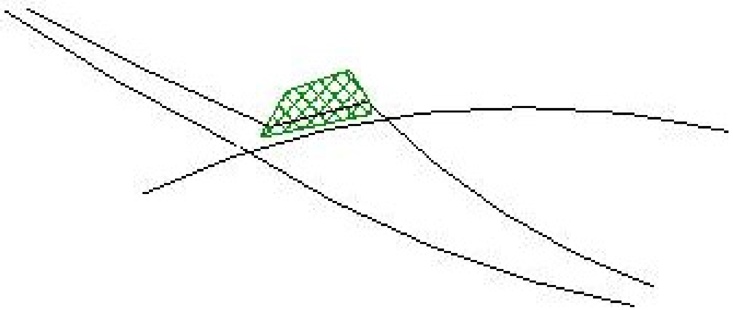
Reflections



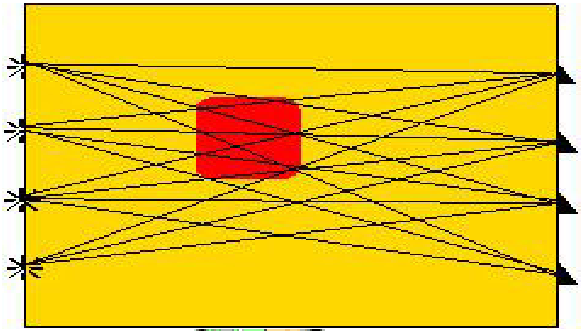
Anisotropy



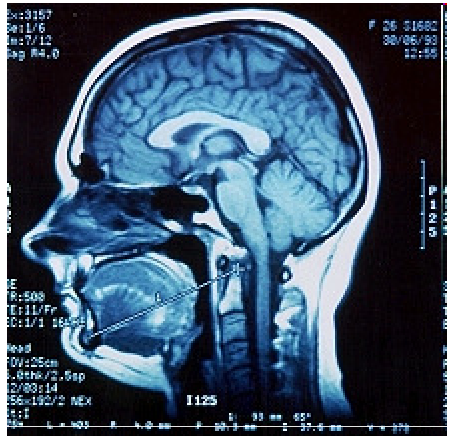
Refracted/diffracted waves

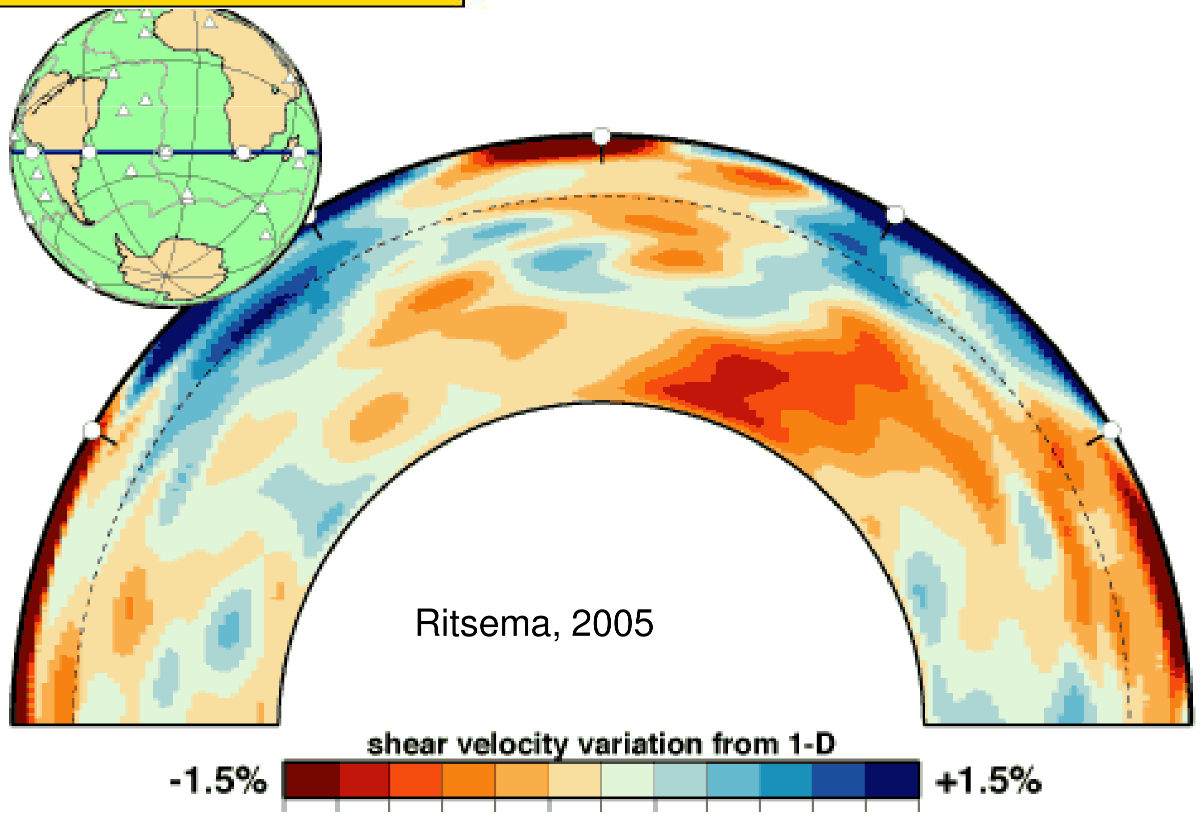


Tomography
Deviations from 1D structure



imaging the 3D structure of the Earth





Ritsema, 2005

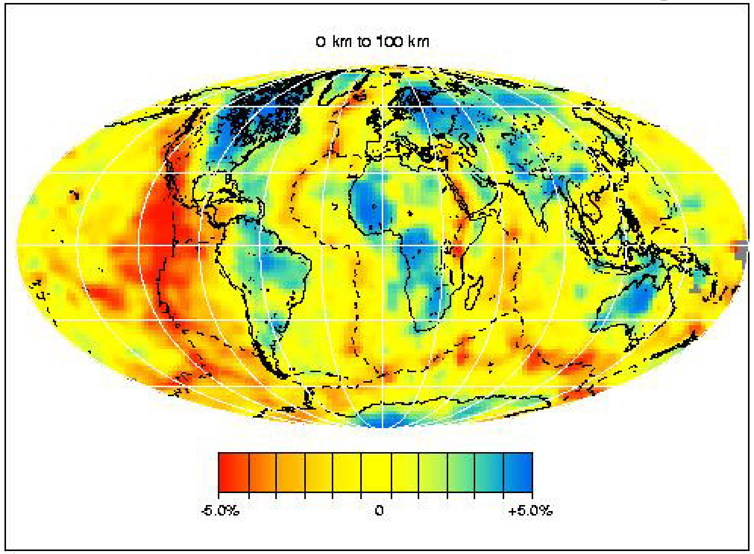
red: slow

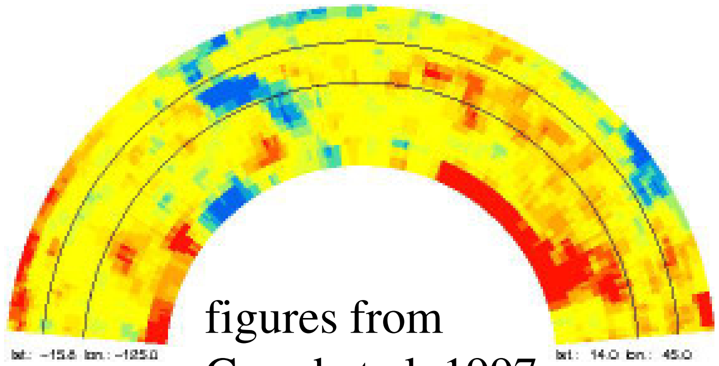
blue: fast

blue: cold, mostly thermal

red: hot and perhaps also chemical origin?

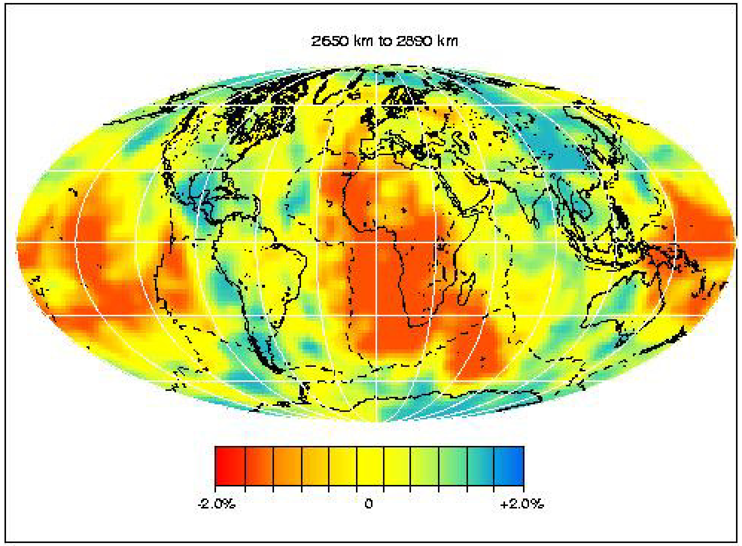
Tomographic images

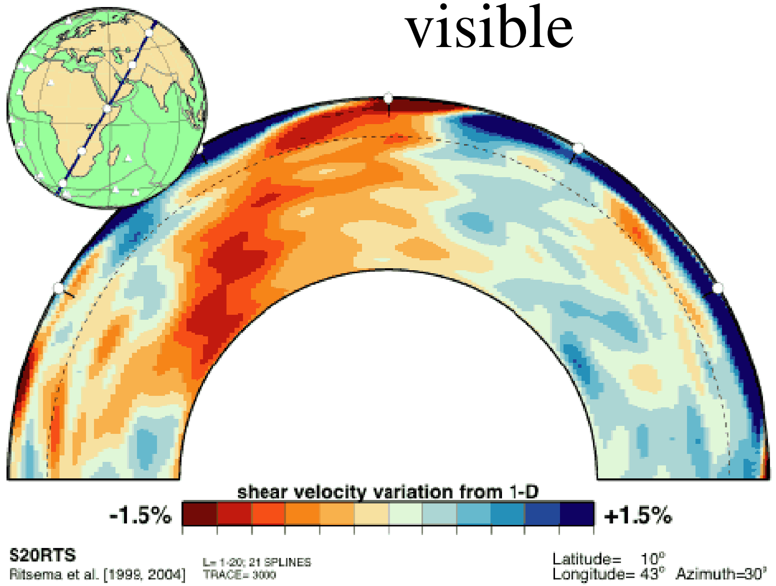




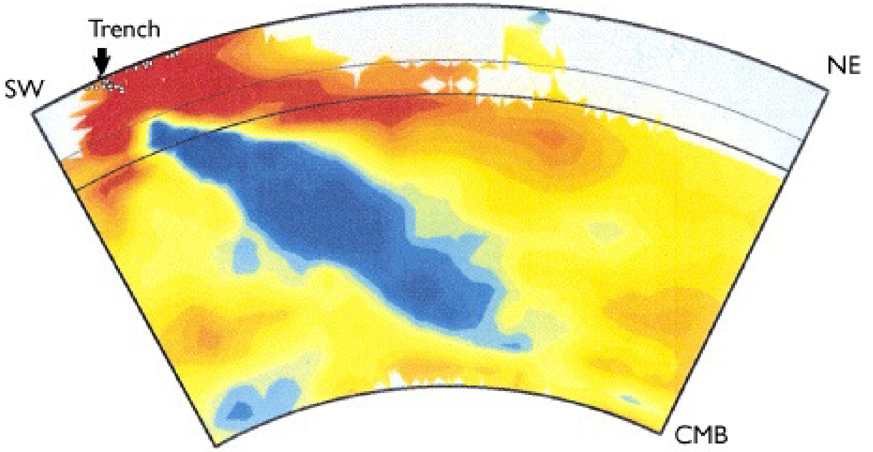
figures from
Grand et al. 1997

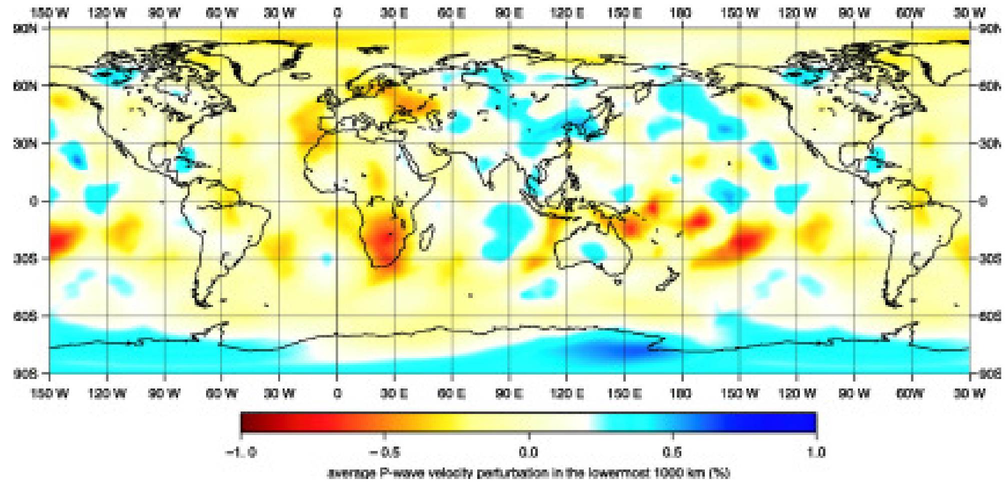
upwellings (?) and
downwellings (?)
visible



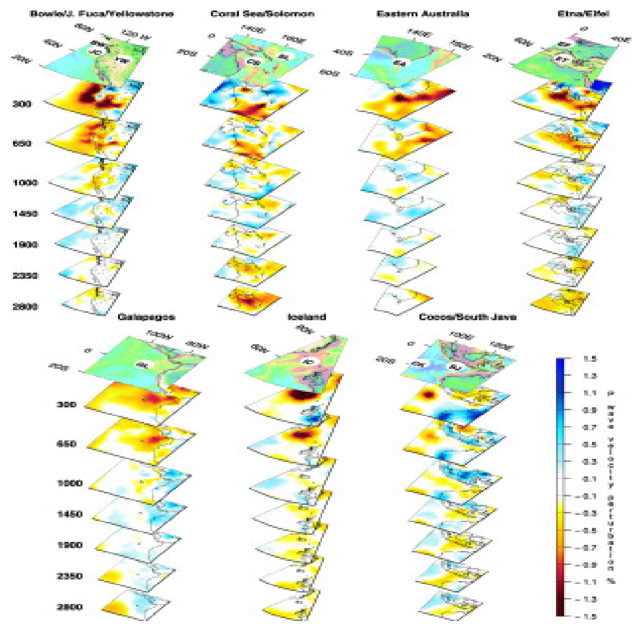


deep slabs/plumes





R Montelli et al. 2004



Seismic tomography records variations in P-wave velocity, which correlate with the temperatures of matter in Earth's interior.

- Slower P waves, indicating warmer-than-average matter
- Average-speed P waves, indicating average-temperature matter
- Faster P waves, indicating cooler-than-average matter
- No data

van der Hilst et al 1997

So, have we solved the style of mantle convection??

wavespeed variations

Seismic shear wave velocities as a function of depth in the mantle at long wavelength

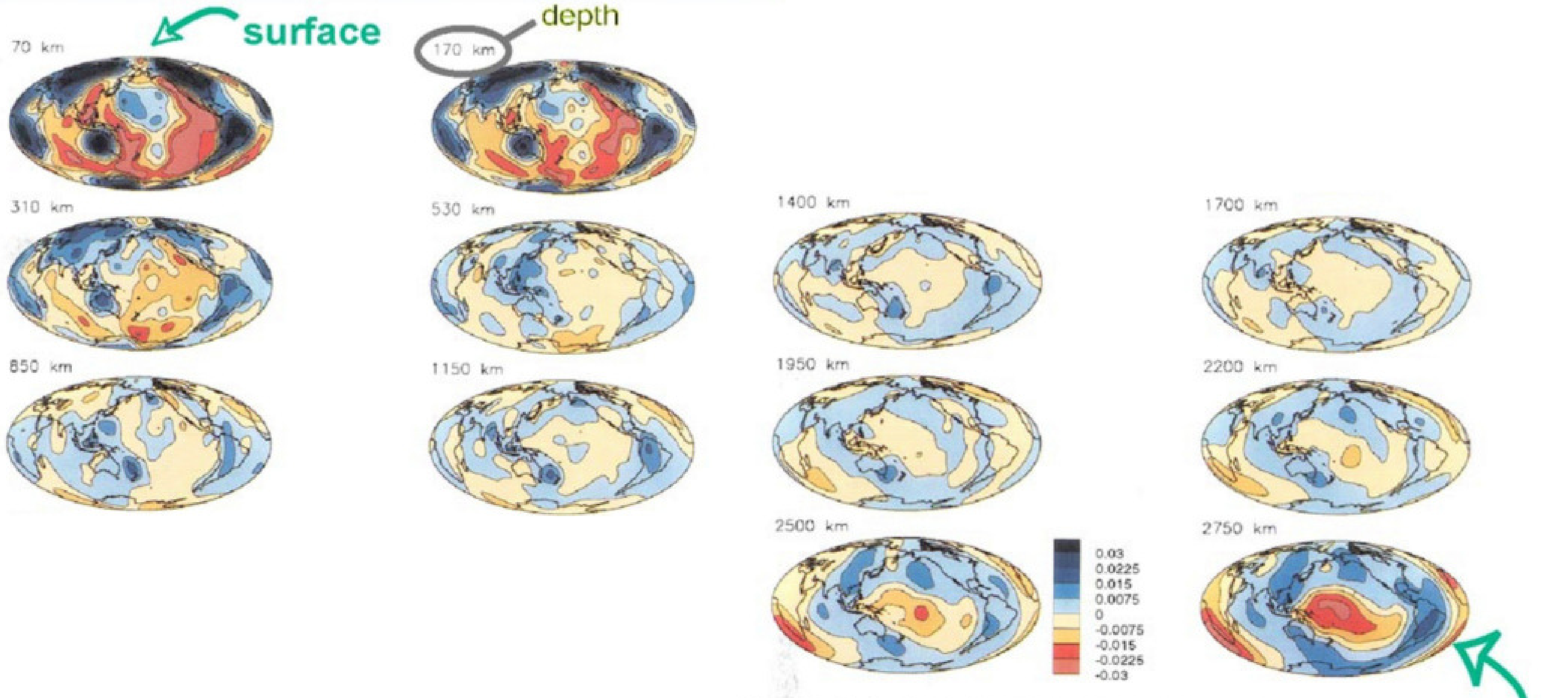
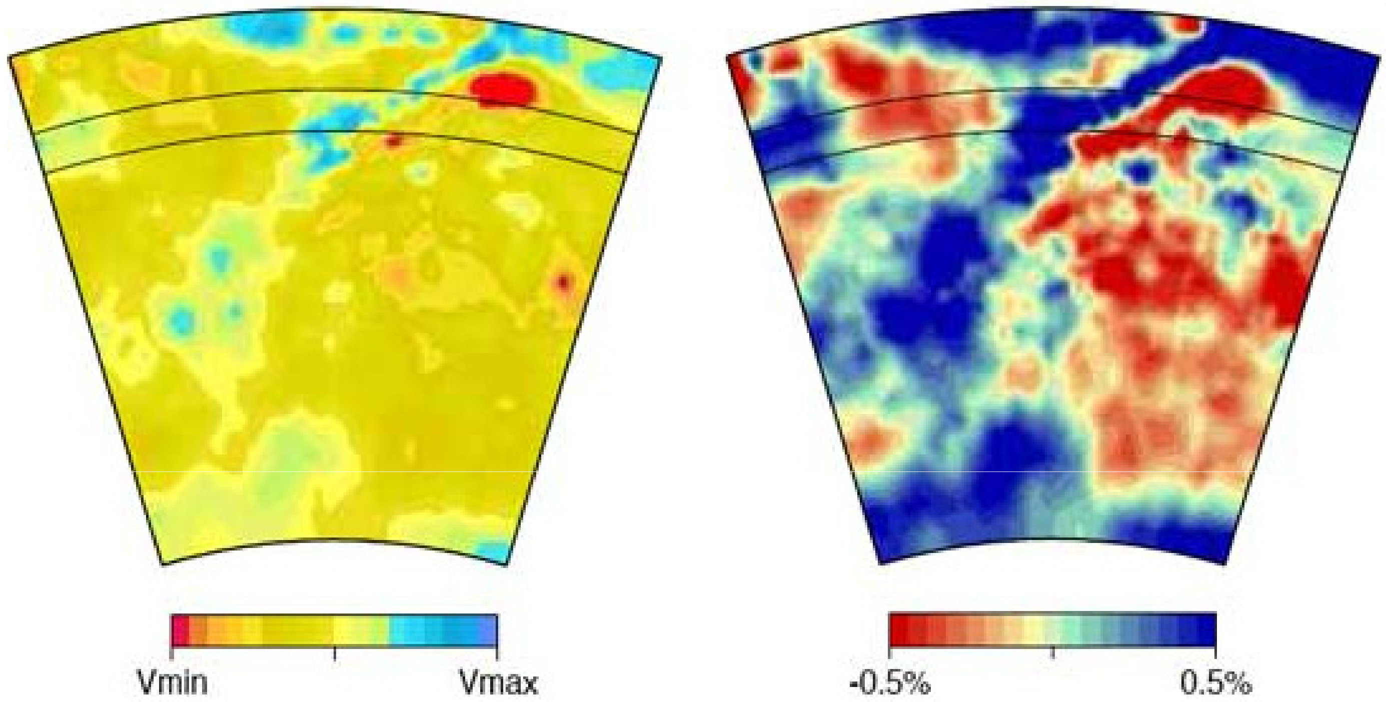


Figure 13. Twelve depth slices of model S16B30. Contoured values are shear velocity perturbation relative to the global model average at a given depth.

UC San Diego model
Masters et al., 1996

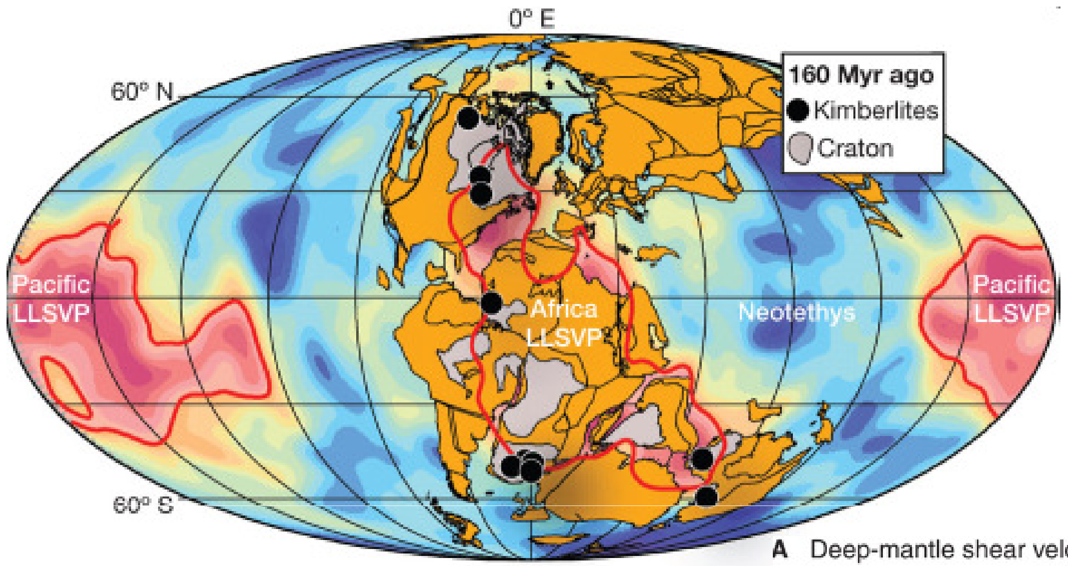
deep slabs?



Ricard et al. 2005

slab under Japan with two different colour scales

Deep mantle structures

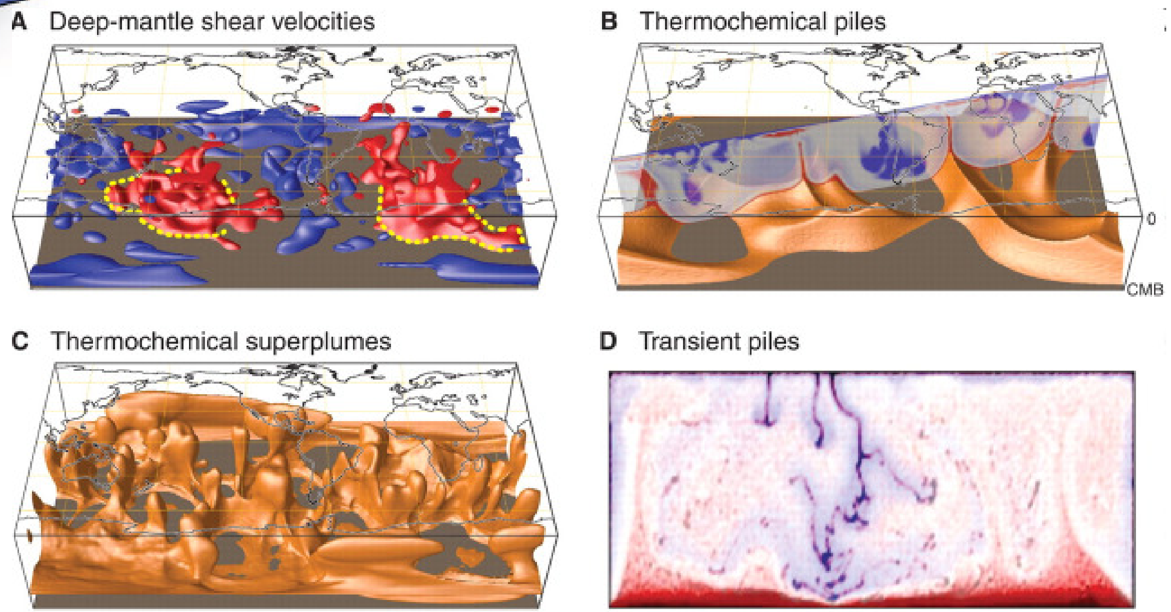


LLSVP
sharp edges? flat tops?
chemical origin?
density/velocity difference?

some information from
seismic observations

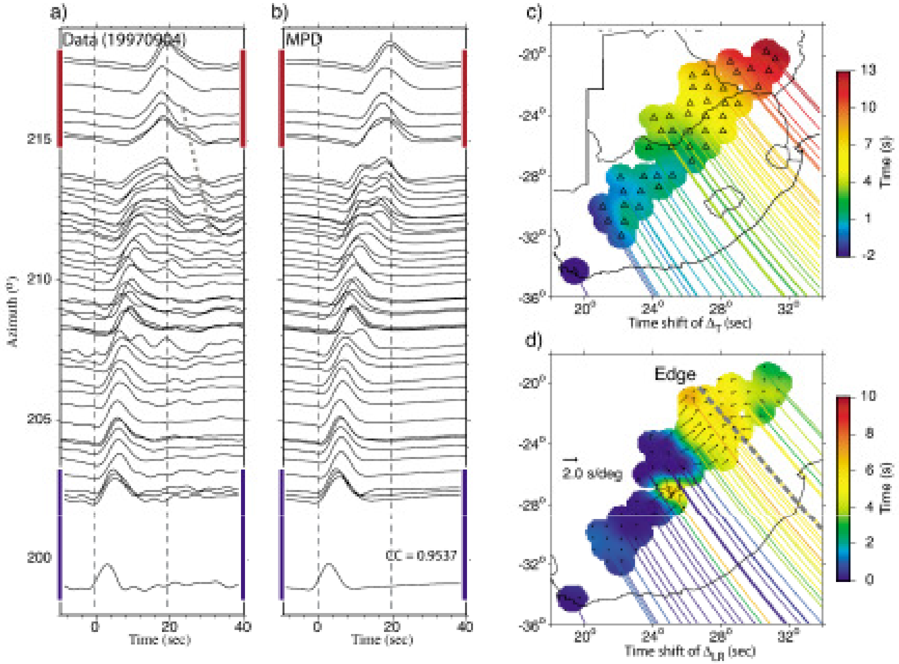
Torsvik et al, 2010

also Burke and Torsvik, 2004
etc

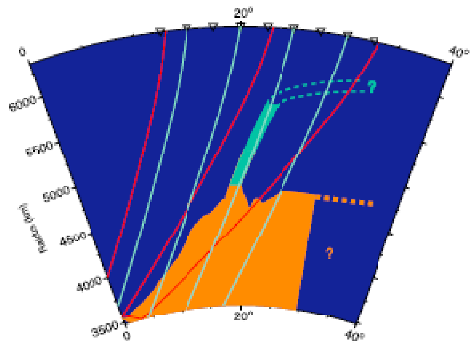


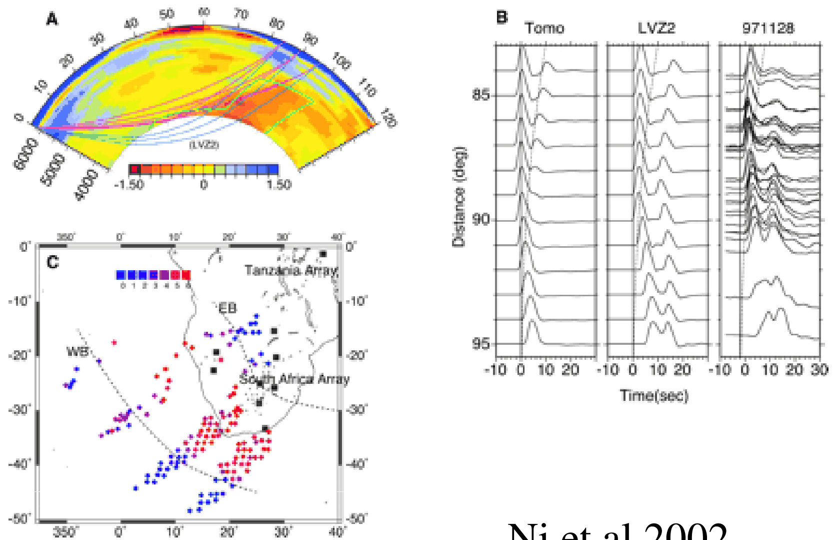
Garnero and McNamara, 2008

Observations: low velocity zones



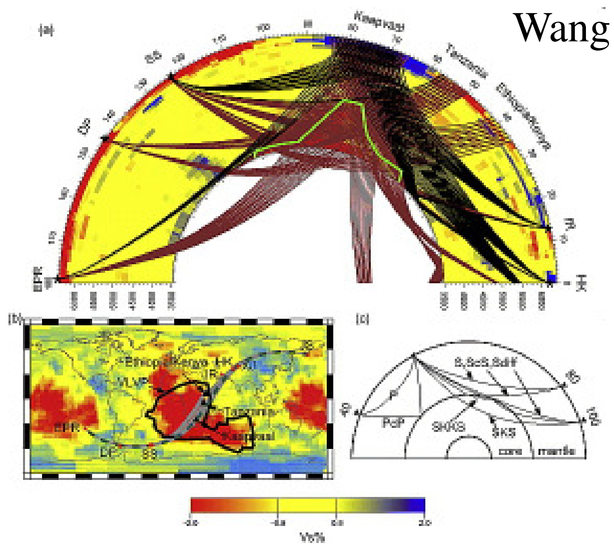
Sun et al 2010





Ni et al 2002

Wang and Wen 2007



Tomography

Tomography tells us about faster/slower regions in the Earth compared to a 1D starting model

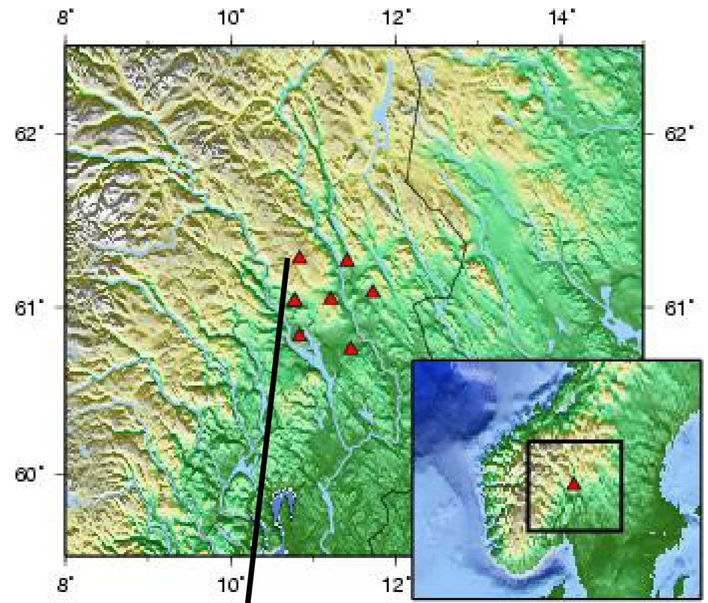
ray coverage is important

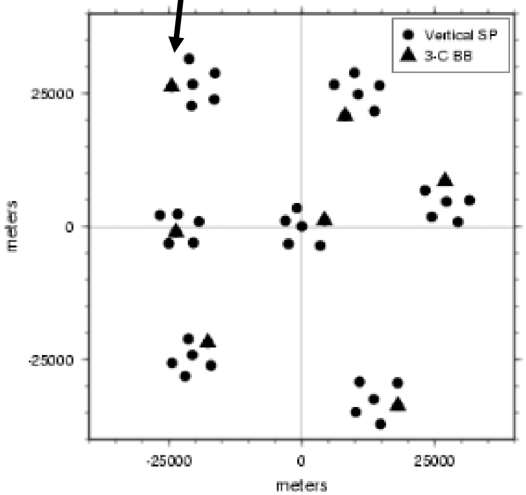
Tomography is constantly improved

Scientists need to be critical when interpreting tomography pictures…

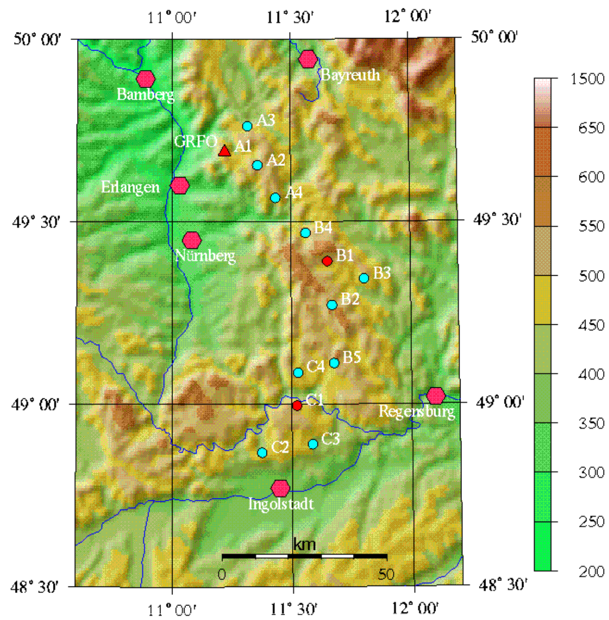
Arrays

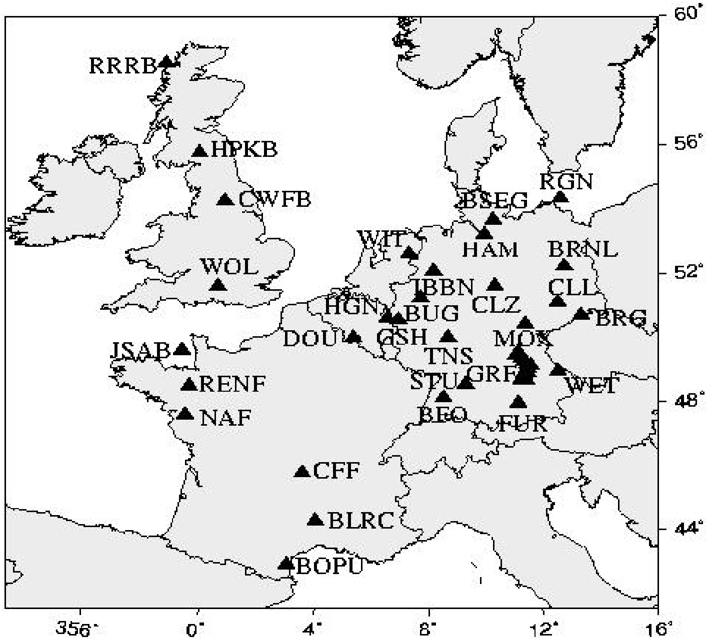
NORSAR





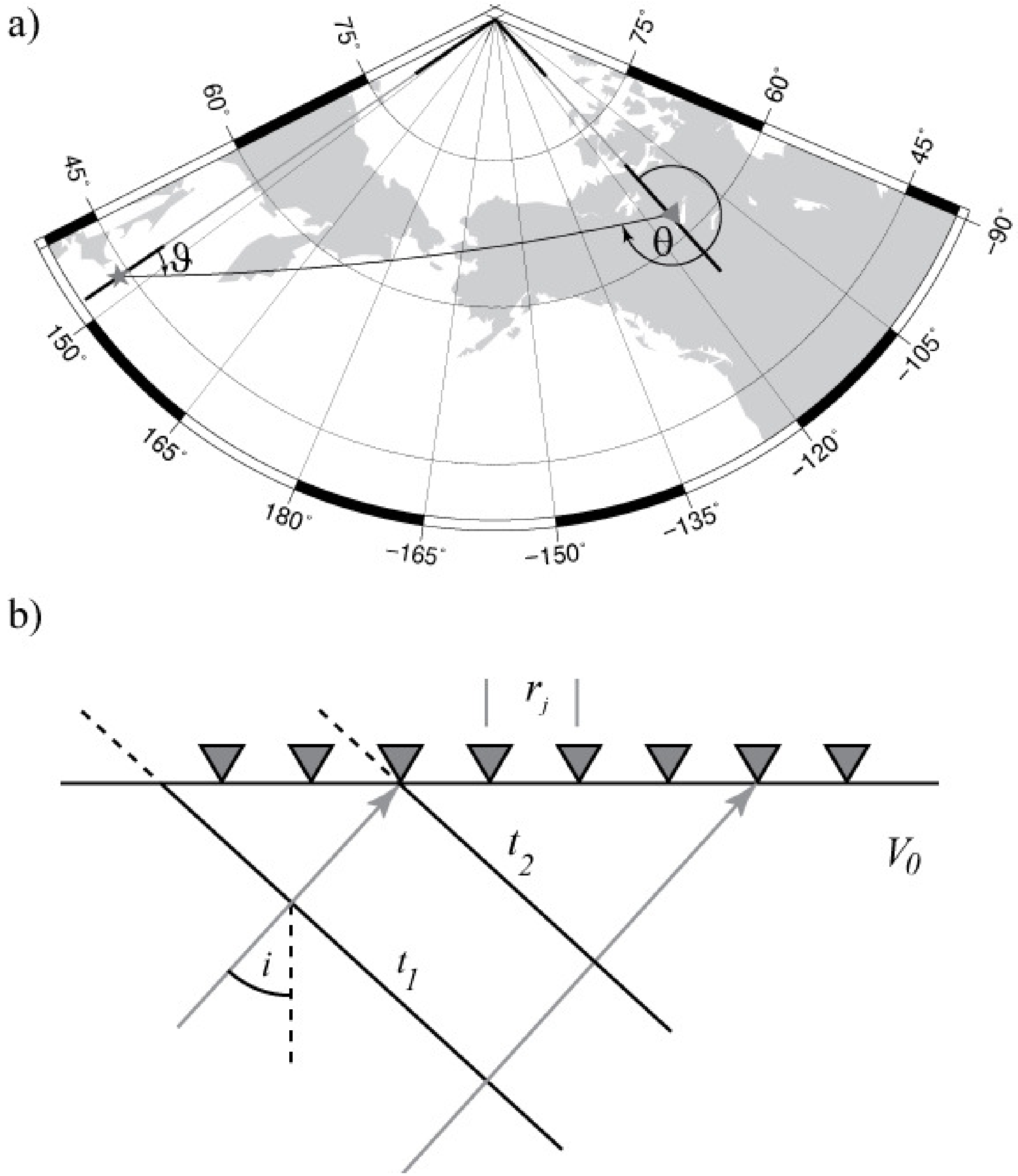
GRF





European Stations (GRSN, Spiced, etc)

Slowness u and backazimuth baz



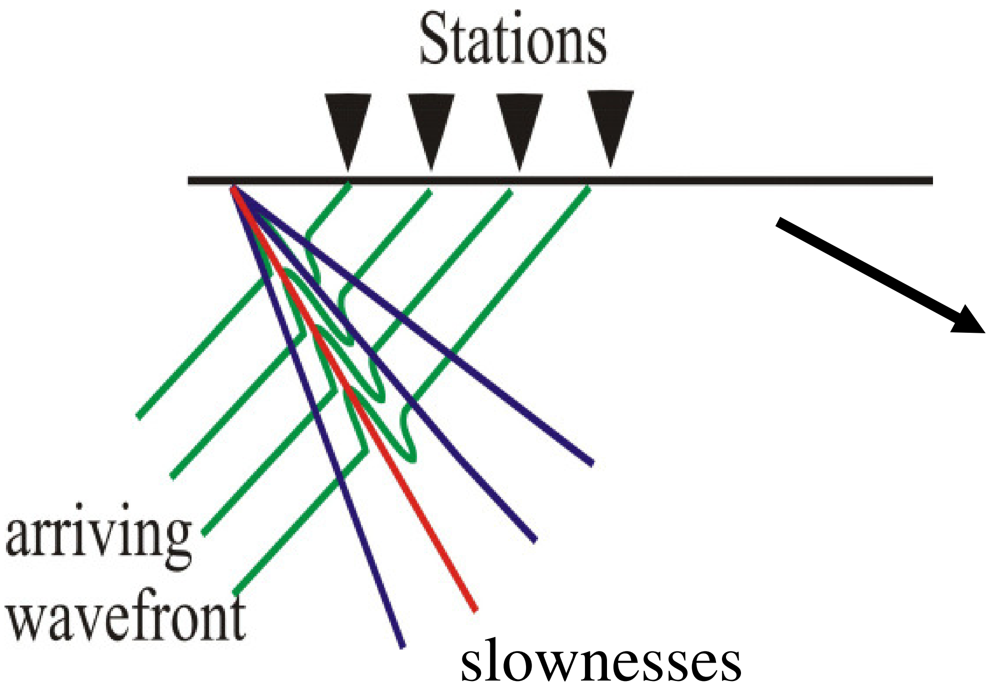
backazimuth: angle from North to gcp clockwise at the receiver

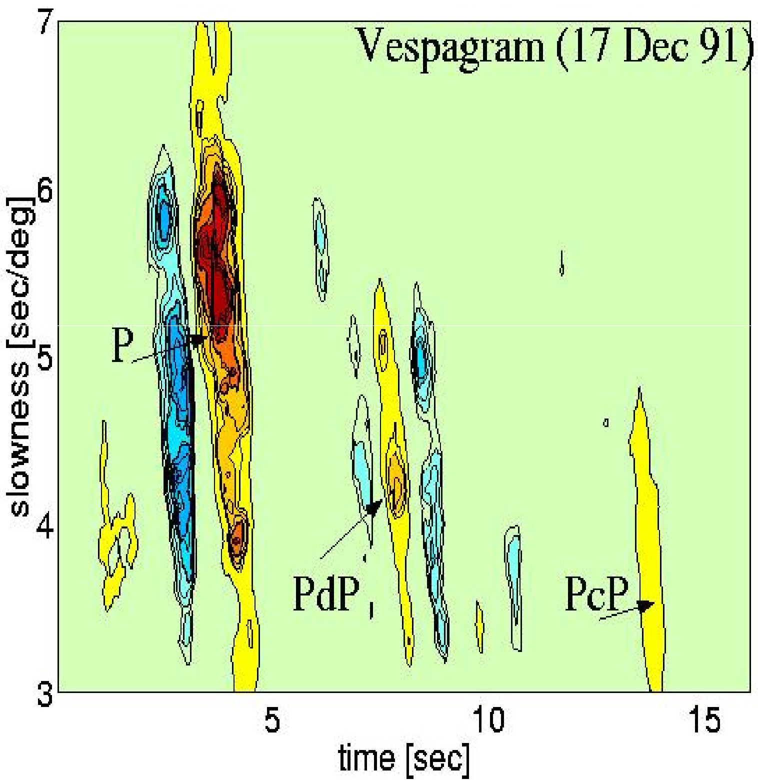
slowness: related to angle of incidence at the array

Array seismology methods

All array methods are based on shifting and summing traces.

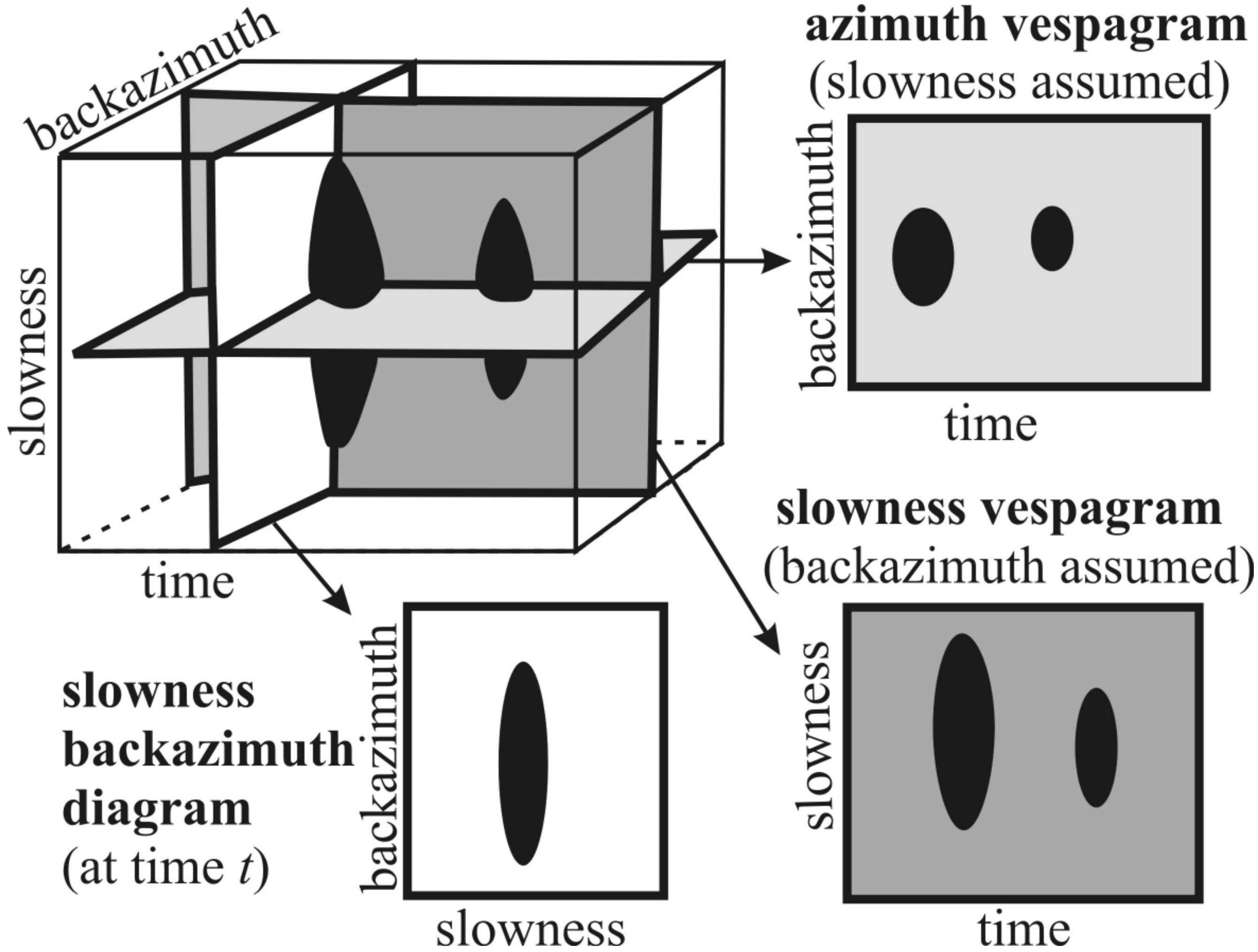
For a range of slowness values:





vespagram
slowness or backazimuth
versus time

Array seismology methods

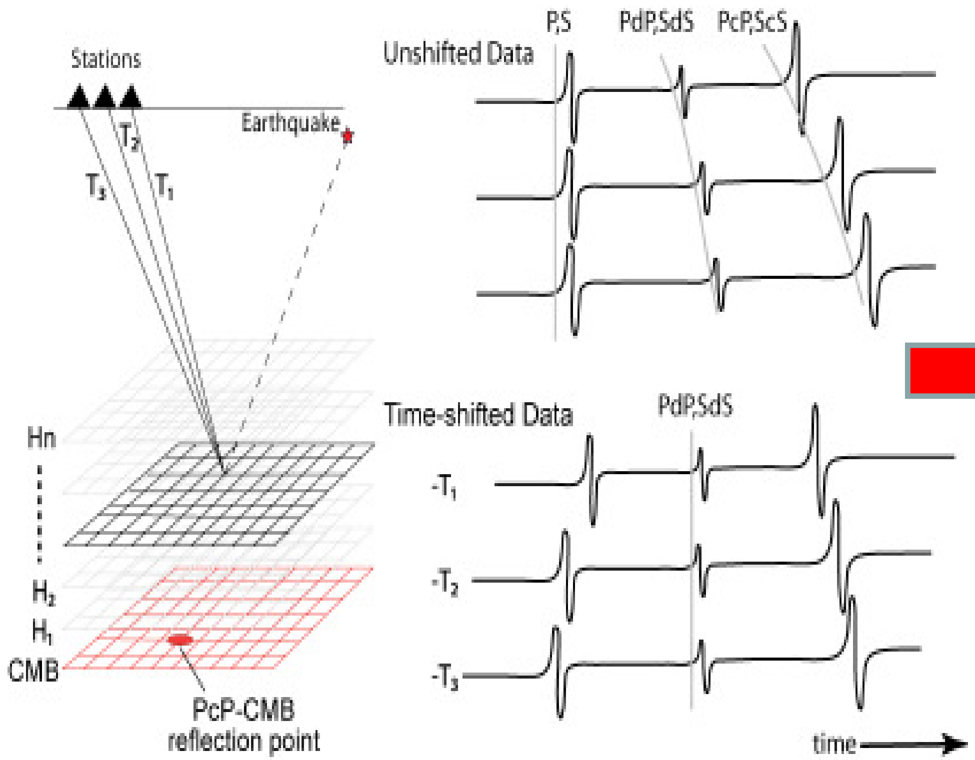


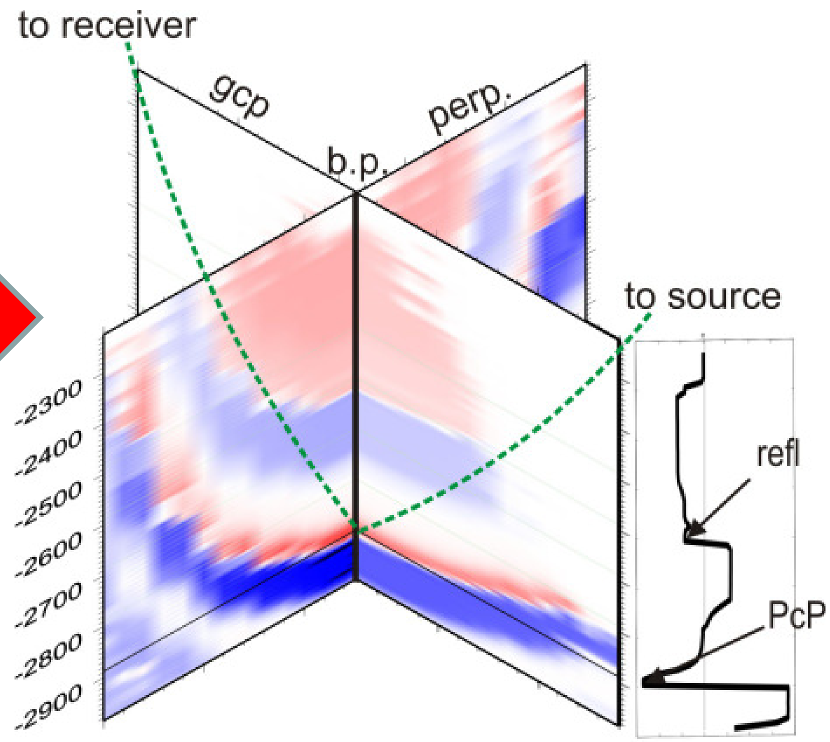
Thomas 2008

Array methods

Migration

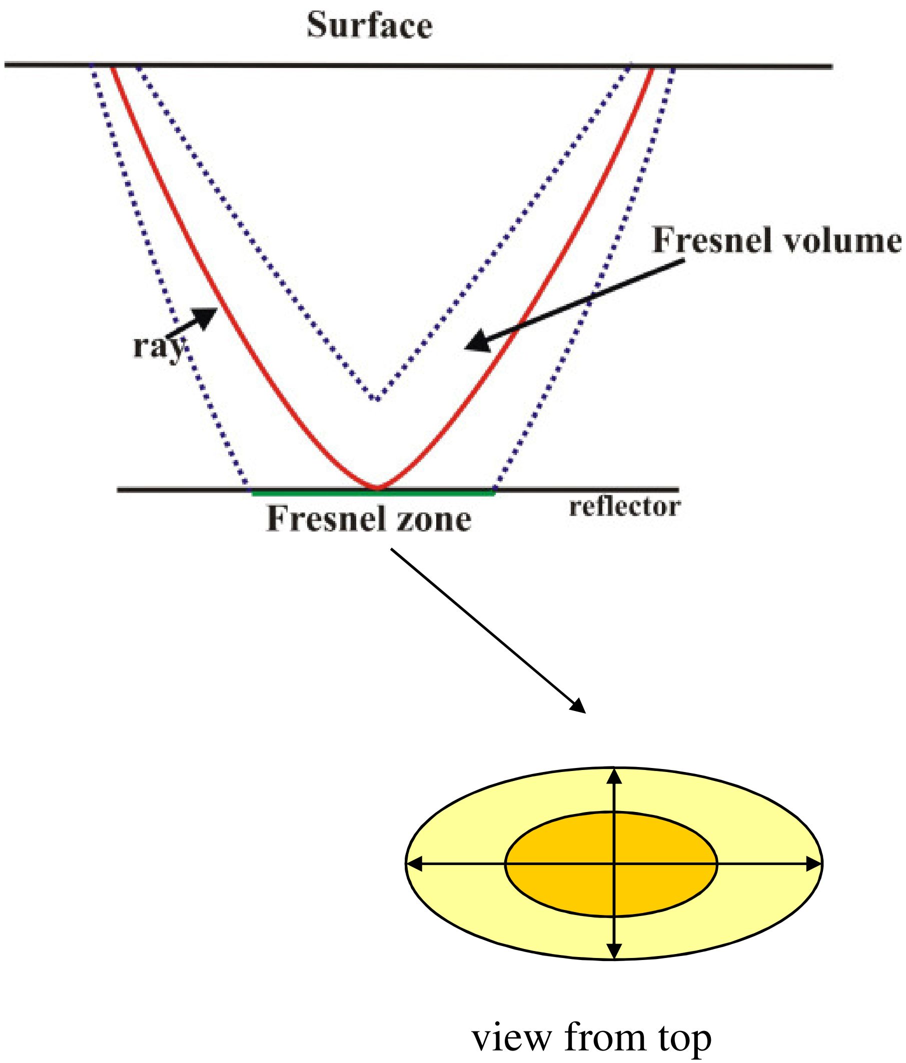
- calculates delay times from point at depth.
- shifts traces back with these delay times
- stacks traces
- 3D grids with appropriate spacing





Ampl. at b.p.

Resolution – Fresnel zone



Volume around ray contributes to signal: Fresnel volume.
At reflector this volume (in 1D) is the Fresnel zone.

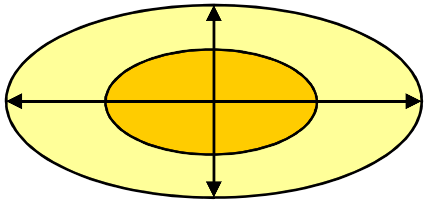
Size of Fresnel zone depends on: frequency, depth of reflector, and seismic velocity ($\Rightarrow$ wavelength).

Resolution – Fresnel Zone

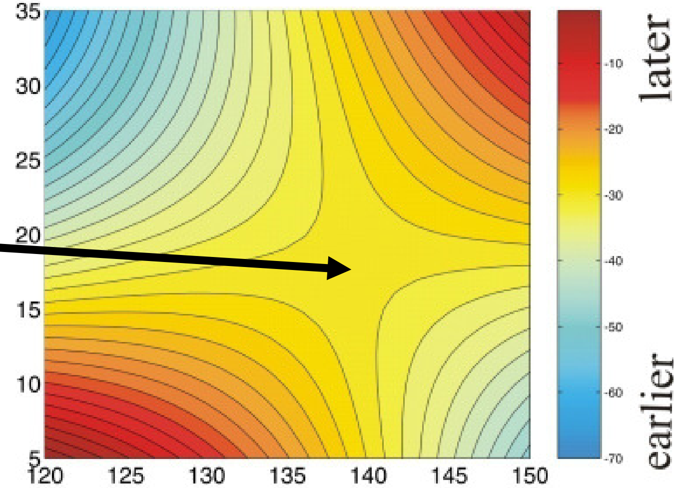
What does that mean? If we deal with a strictly layered (1D) Earth our resolution is only as good as the size of the Fresnel zone!

e.g.: P-waves reflected at D": 2 x 4 degrees (1Hz)
S-waves reflected at D": 3.5 x 7 degrees (6 s)

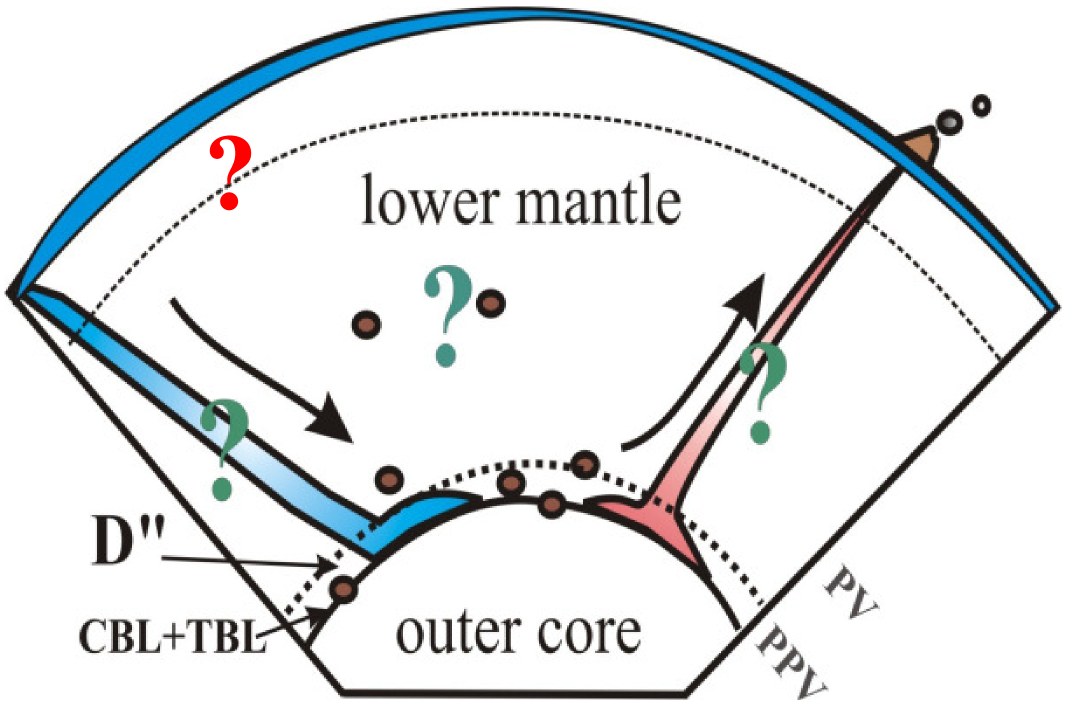
(1 degree ~60km at the CMB)



PP precursors have a very different Fresnel zone:



Why the mid- and lower mantle ?



•Insight into mantle processes

•Constraints on mineralogy

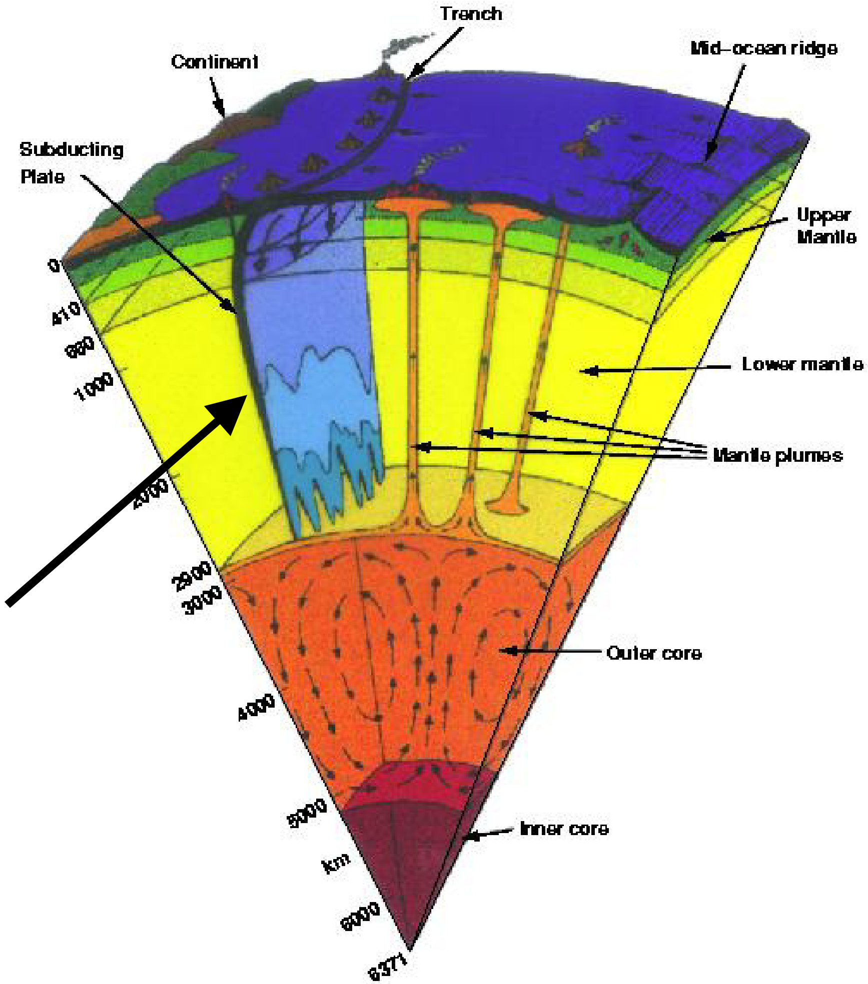
•How far do slabs reach?

•Can we determine temperature/composition of slabs

•Are lowermost mantle structures related to deep subduction?

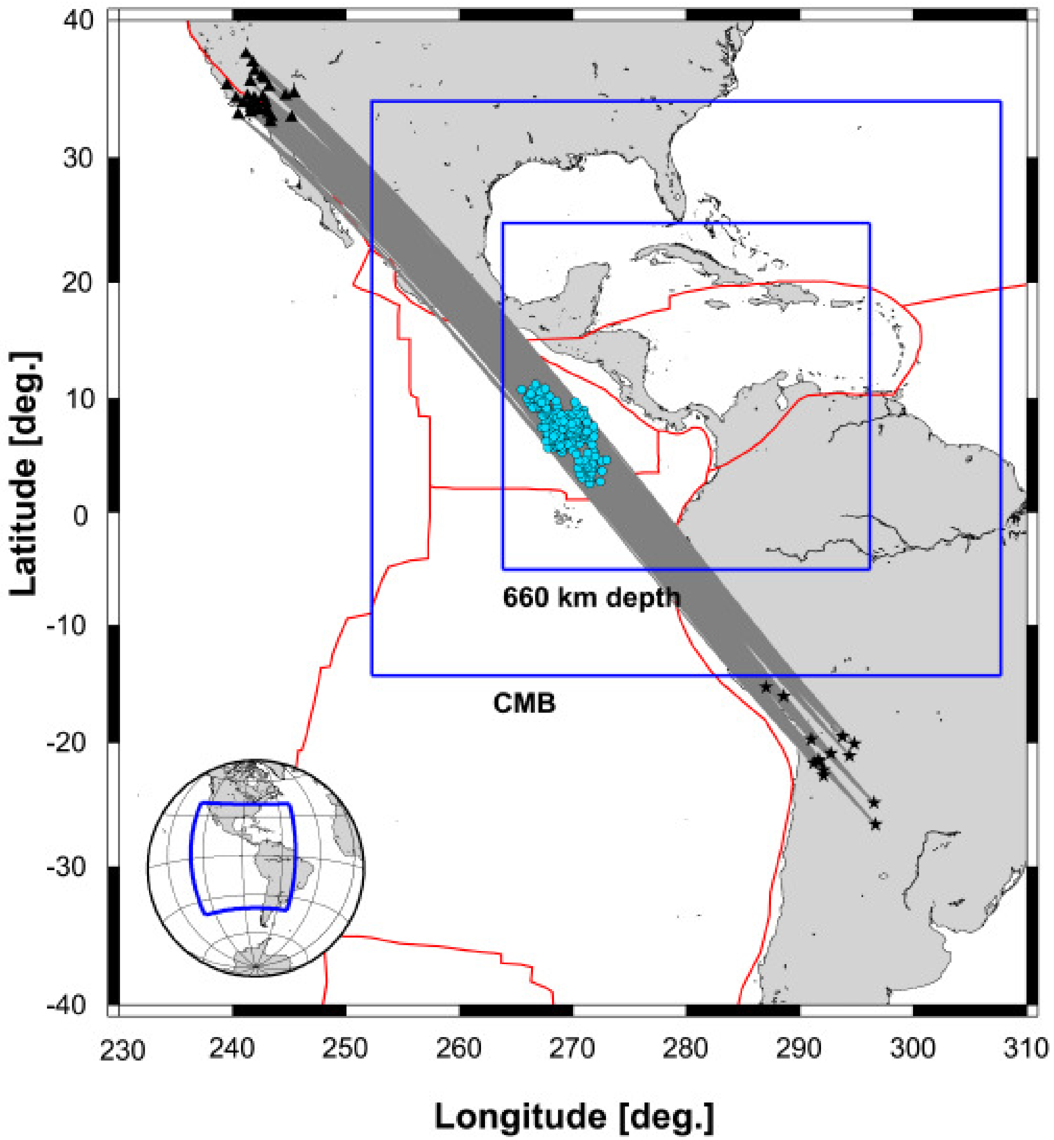
•What are causes for lowermost mantle structures

Examples

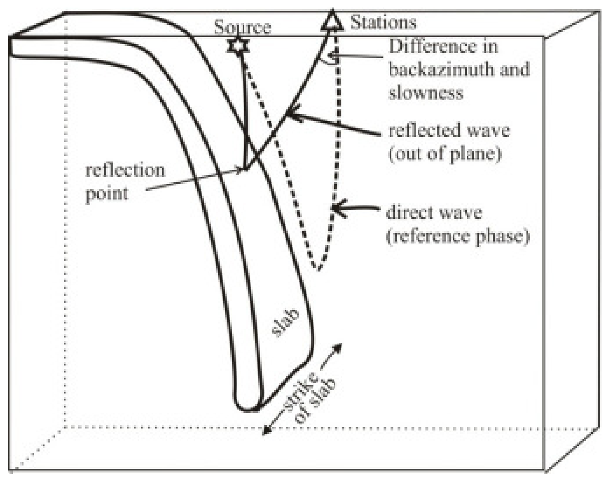


1) How deep do slabs go?

1) Lower mantle slabs



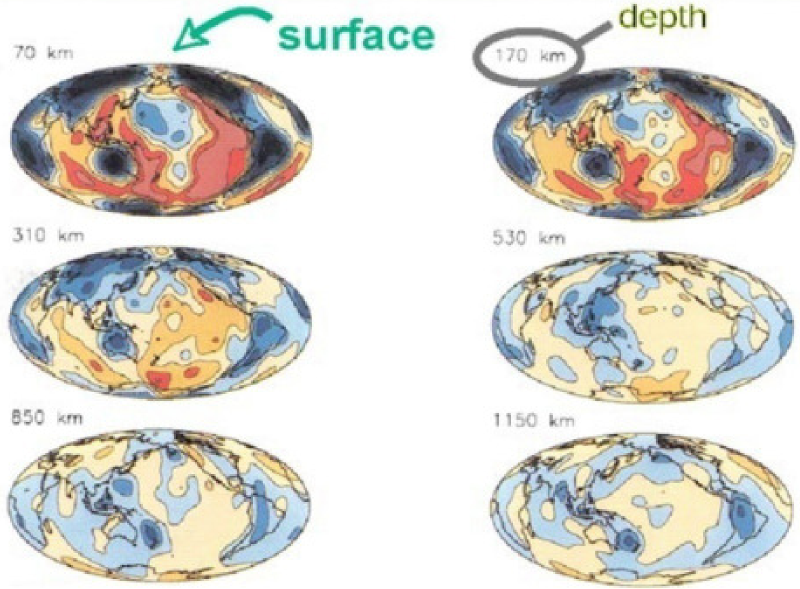
Are slabs and D" discontinuities connected? Do slabs enter the lower mantle and how far do they extend?



Kito, Thomas, Rietbrock, Garnero, Nippress, Heath, 2008

Tomography (Masters)

Seismic shear wave velocities as a function of depth in the mantle at long wavelength



Strongest signals in

- **Upper mantle**
- **Lowermost mantle**

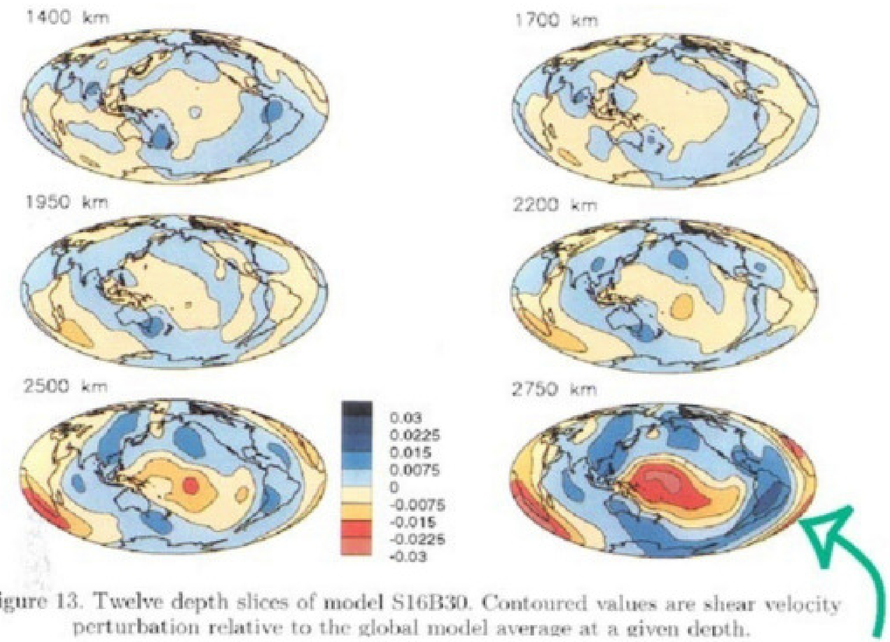
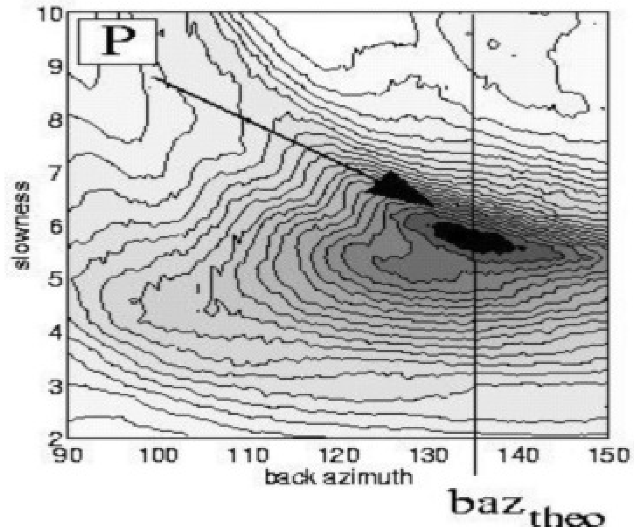
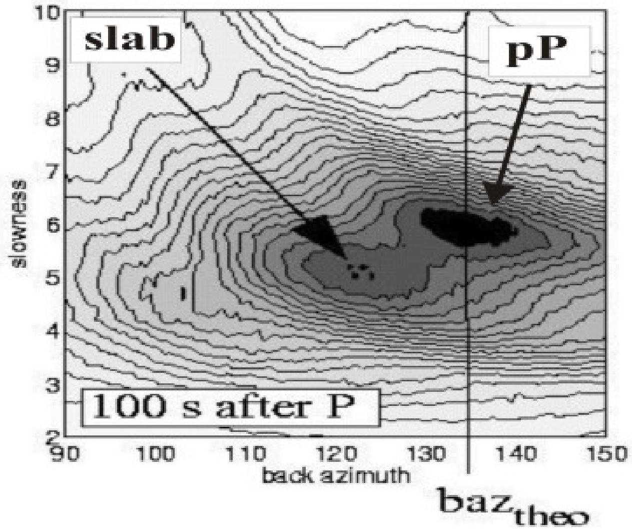


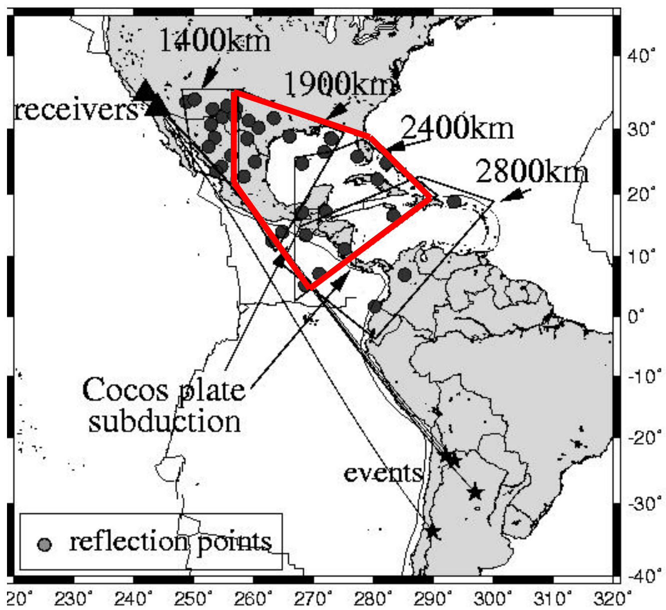
Figure 13. Twelve depth slices of model S16B30. Contoured values are shear velocity perturbation relative to the global model average at a given depth.

UC San Diego model
Masters et al., 1996

Mid-mantle slabs





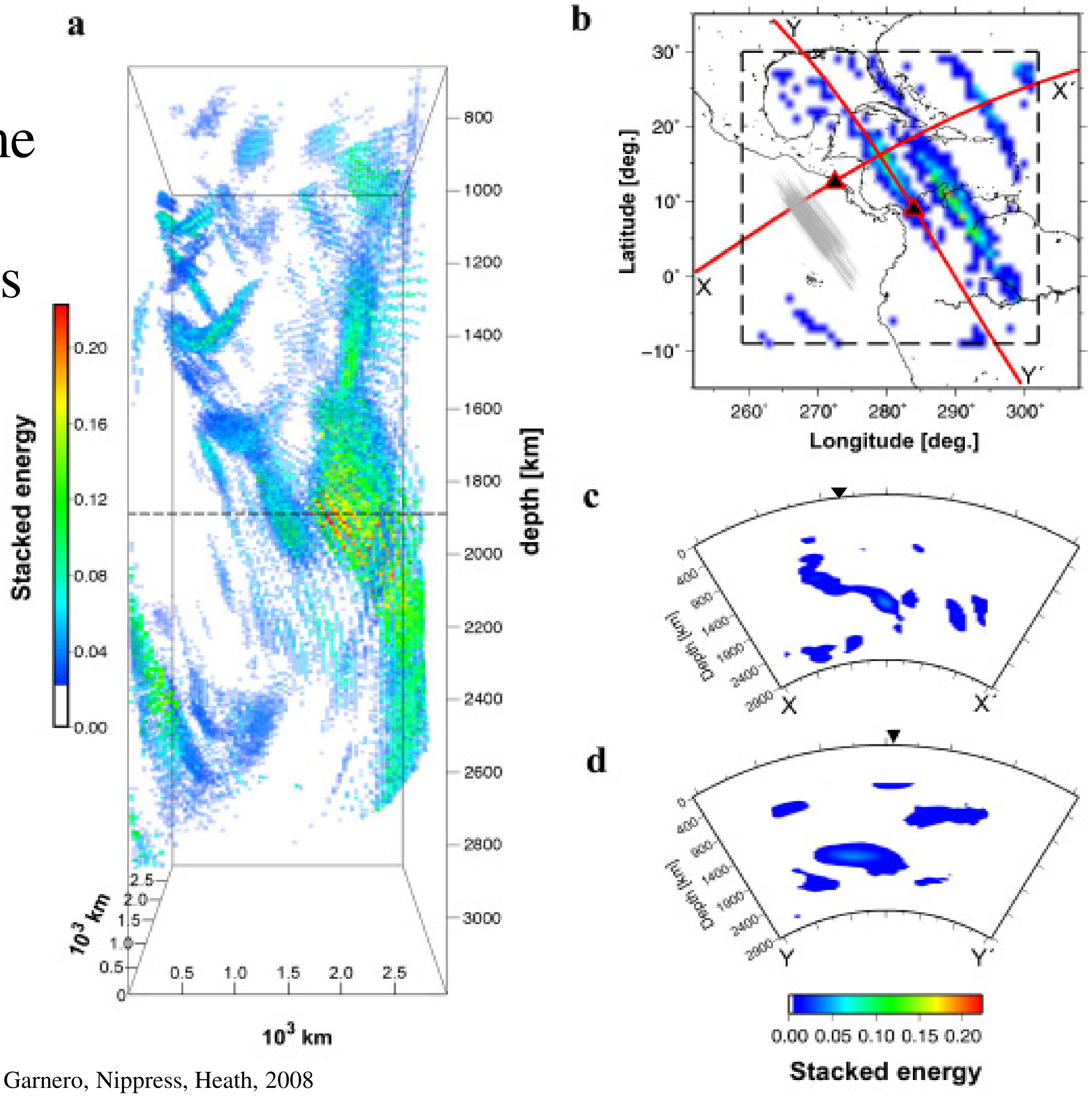


Out-of-plane reflections visible in South-American earthquakes recorded in N.America

Wallace and Thomas

Migration

3D volume of reflections



Cut through 1880km depth

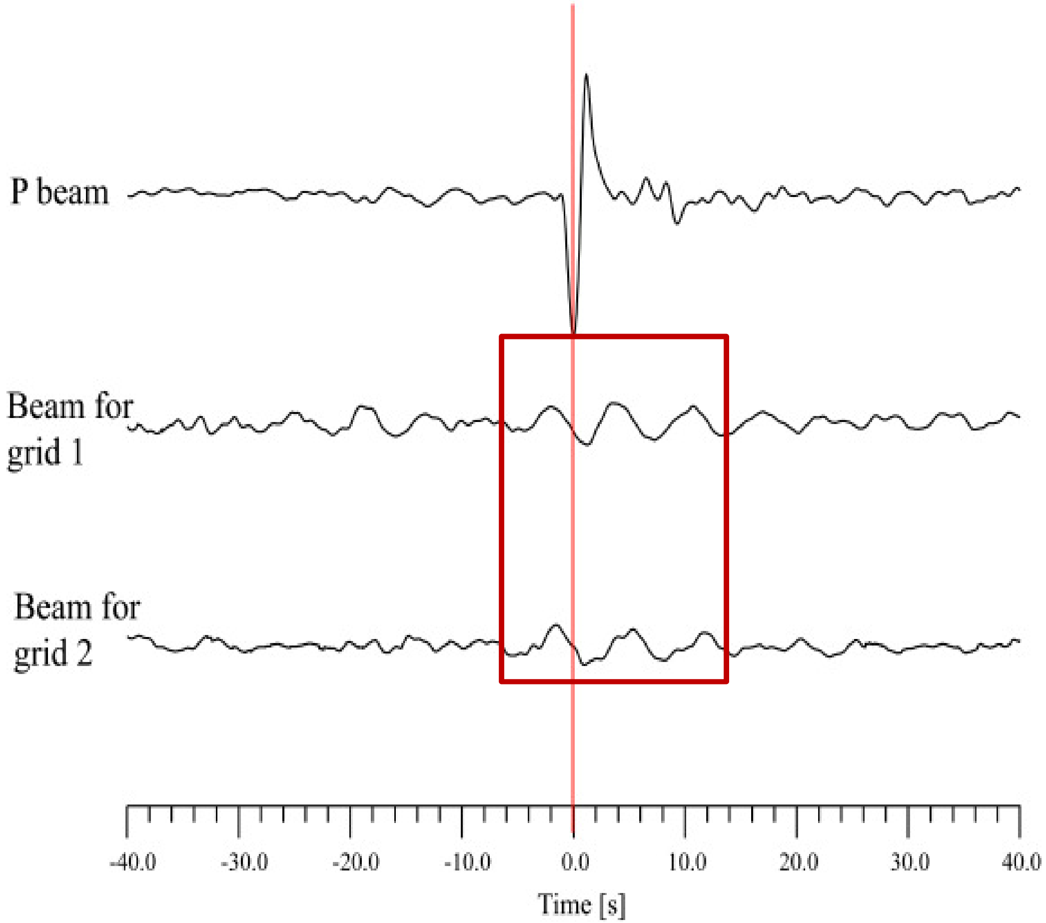
Cross sections

Perp. to gcp

Parallel to gcp

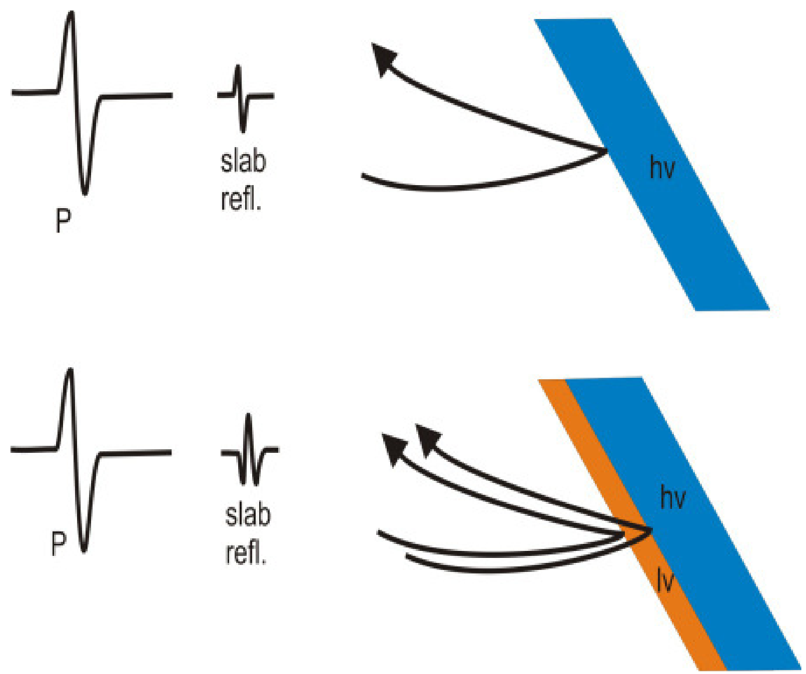
Kito, Thomas, Rietbrock, Garnero, Nippress, Heath, 2008

Waveforms



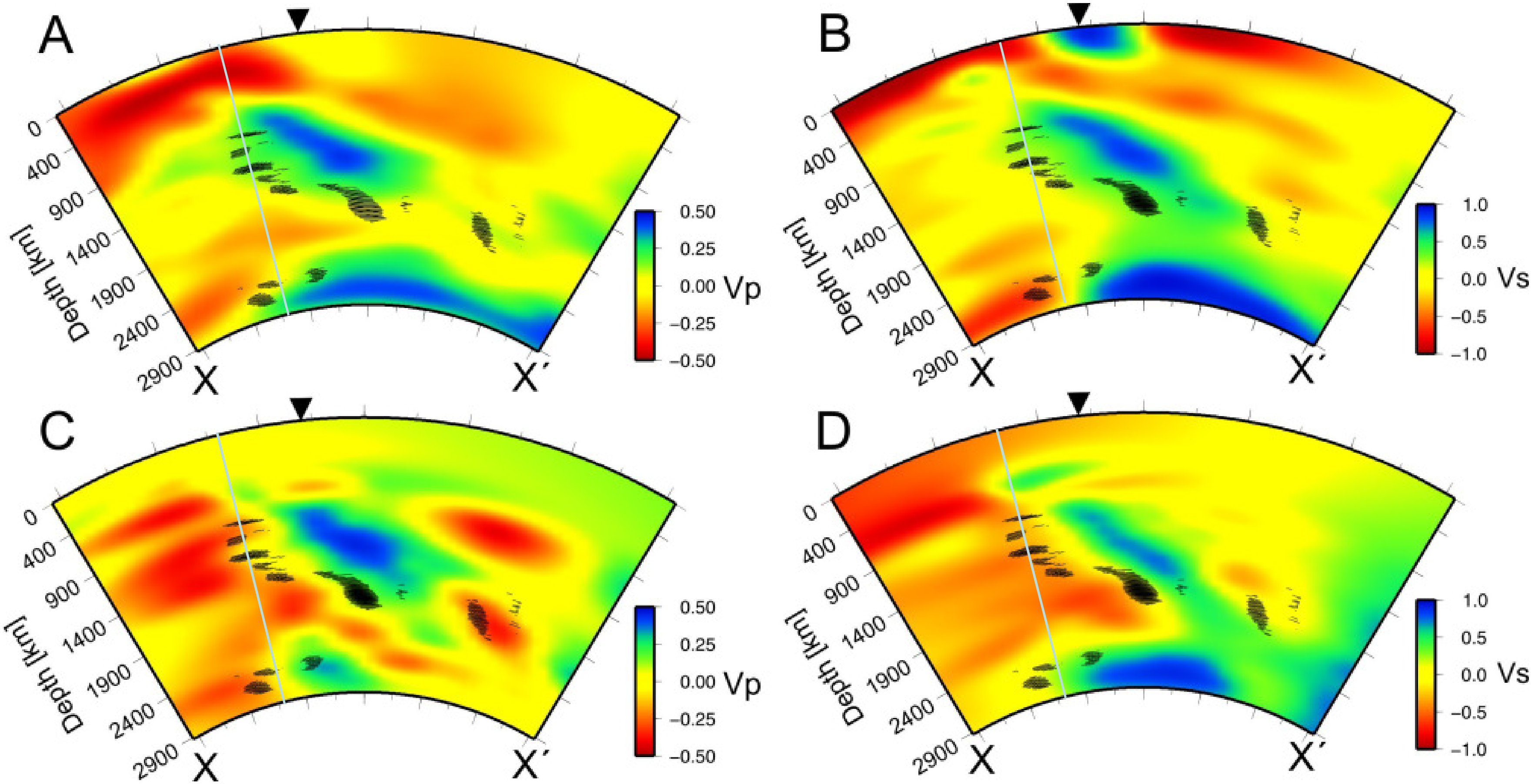
longer wavelet than P (more swings)

can be generated by high-vel. or low-vel. lamella



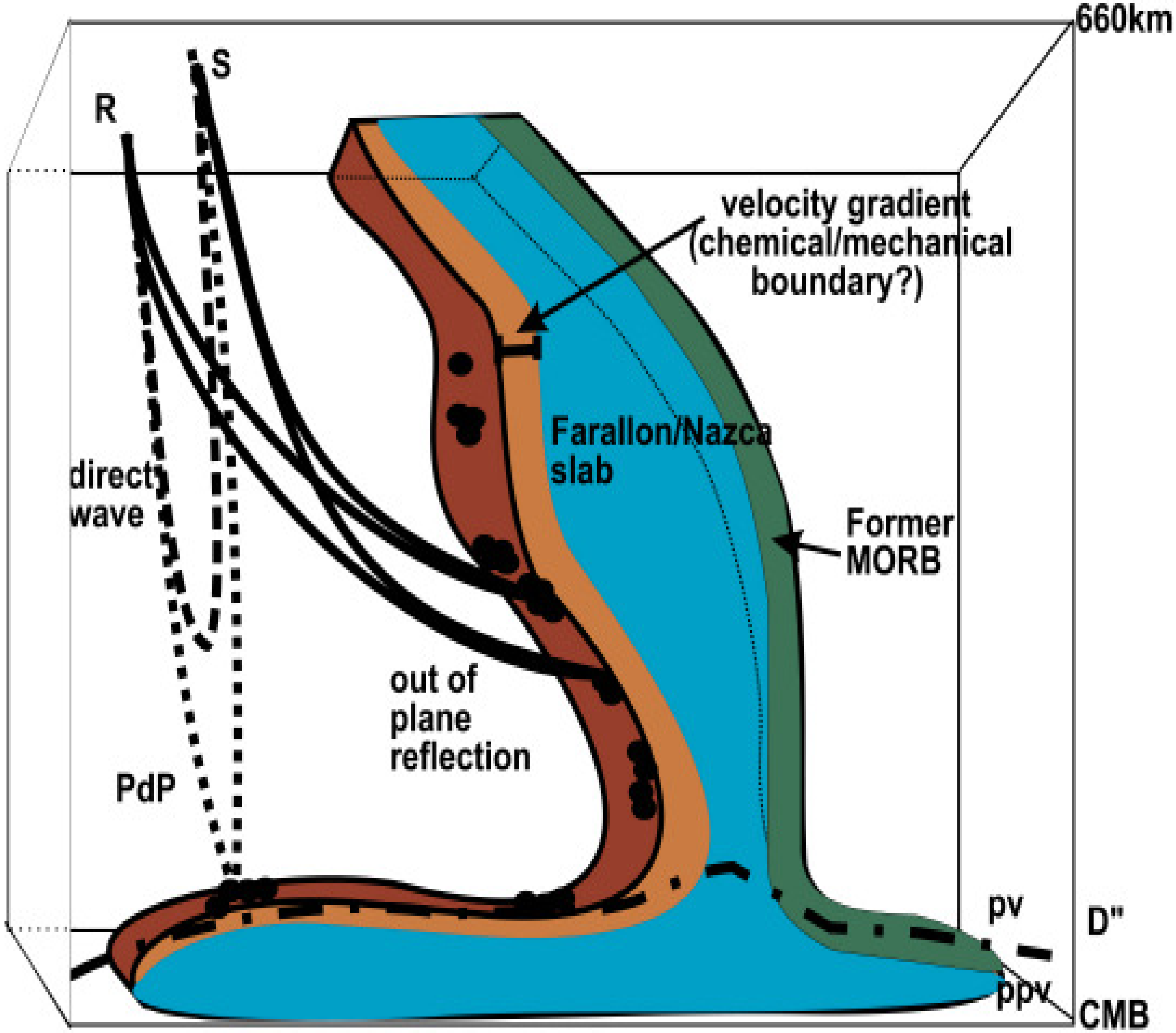
Kito, Thomas, Rietbrock, Garnero, Nippress, Heath, 2008

Slab reflections



Kito, Thomas, Rietbrock, Garnero, Nippress, Heath, 2008

Interpretation



Kito, Thomas, Rietbrock, Garnero, Nippress, Heath, 2008

Entrained astenosphere including anisotropy in low-viscosity layer
(Phipps-Morgan et al. 2007)

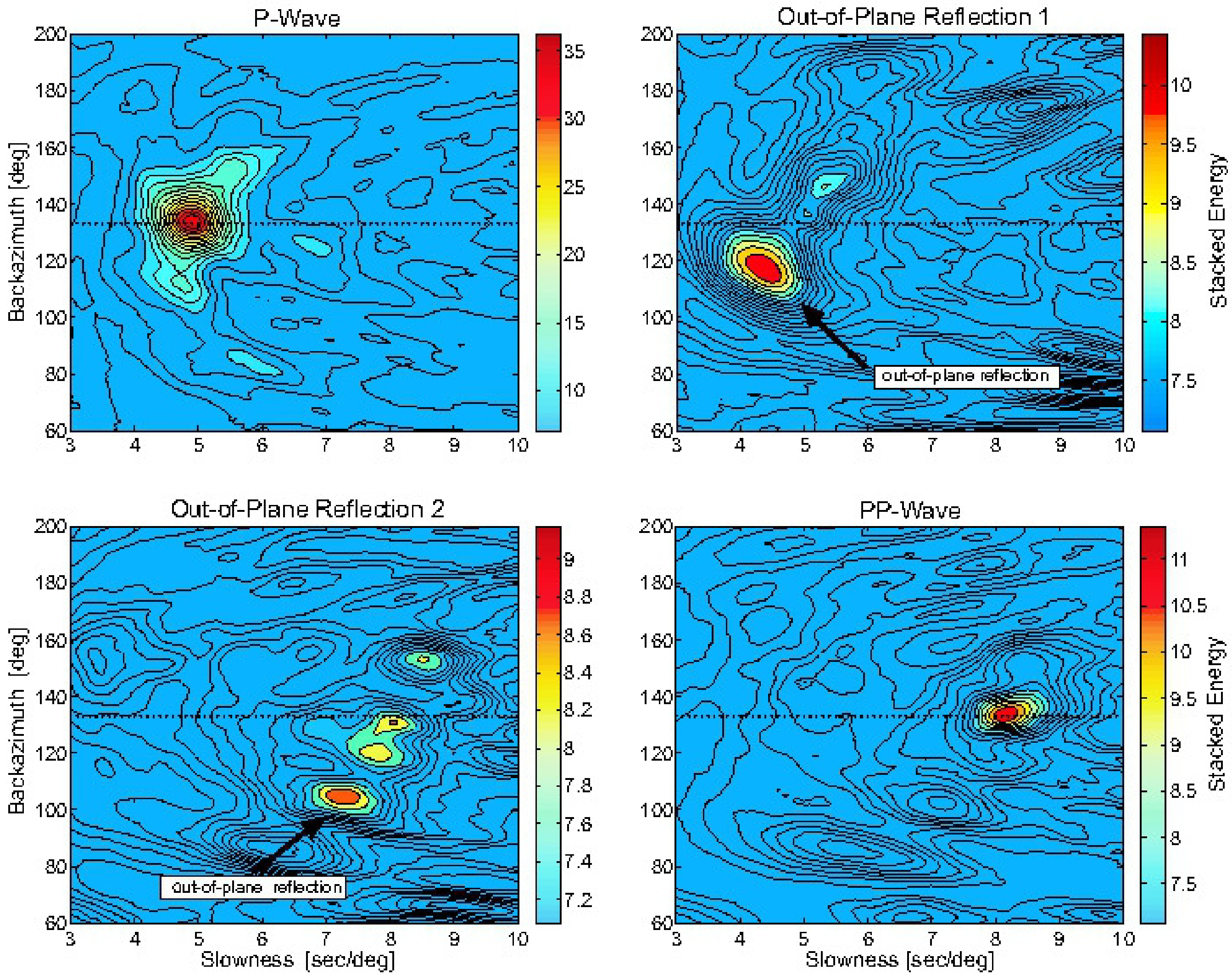
Anisotropy through Deformation
(e.g., McNamara et al. 2003)

Chemically distinct material (Gutenberg D.)
(e.g. Gaherty et al., 1999)

Other possibilities?

D" observations seem to be connected to deep slab

...taking it further



out-of plane reflections:

polarities?
waveforms?
locations?

can they tell us about:
temperature?
mineralogy?
internal structure of the slab?

Schumacher and Thomas, in prep.

Aims

Try to quantify impedance contrast of deep structures

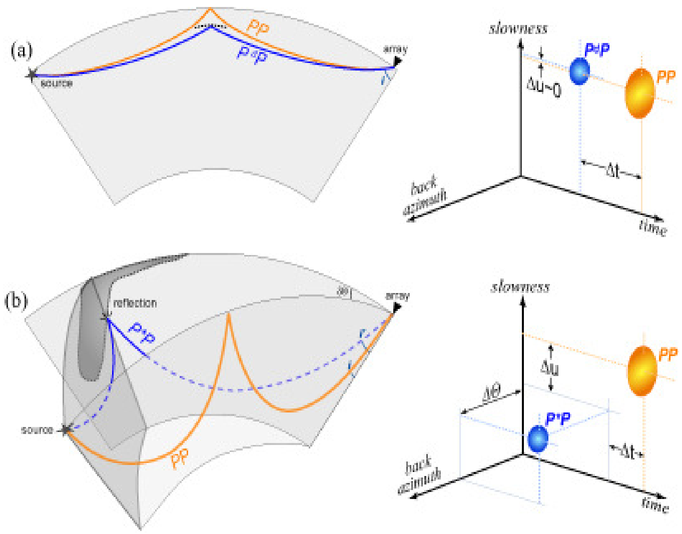
polarity/ waveforms etc of reflections

extent of deep structures? Differences in different regions?

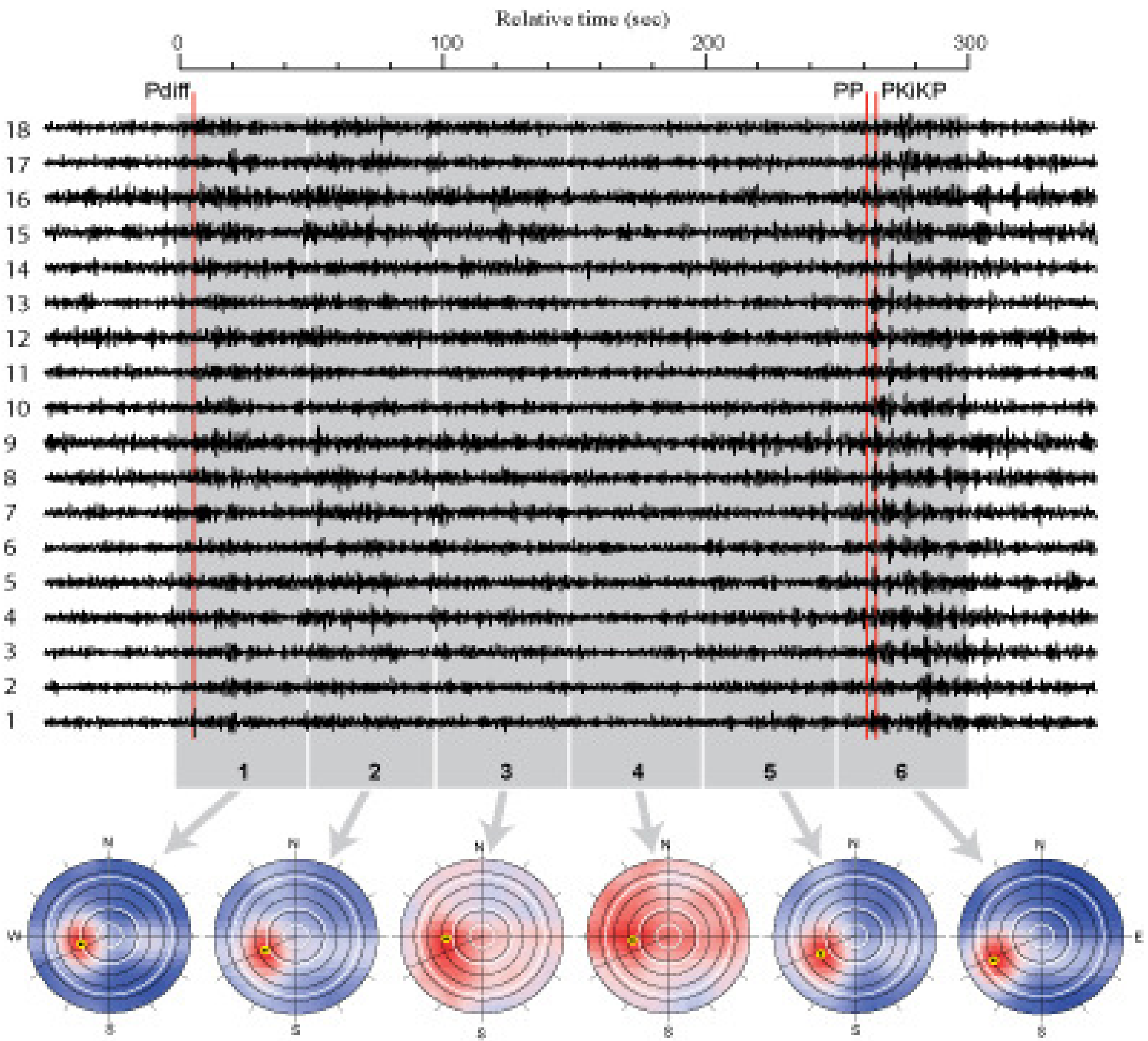
Is it possible to determine shape of subduction?

Can we see both sides of the slab, do they produce different signatures in reflected waves?

Second example (Rost et al 2008)

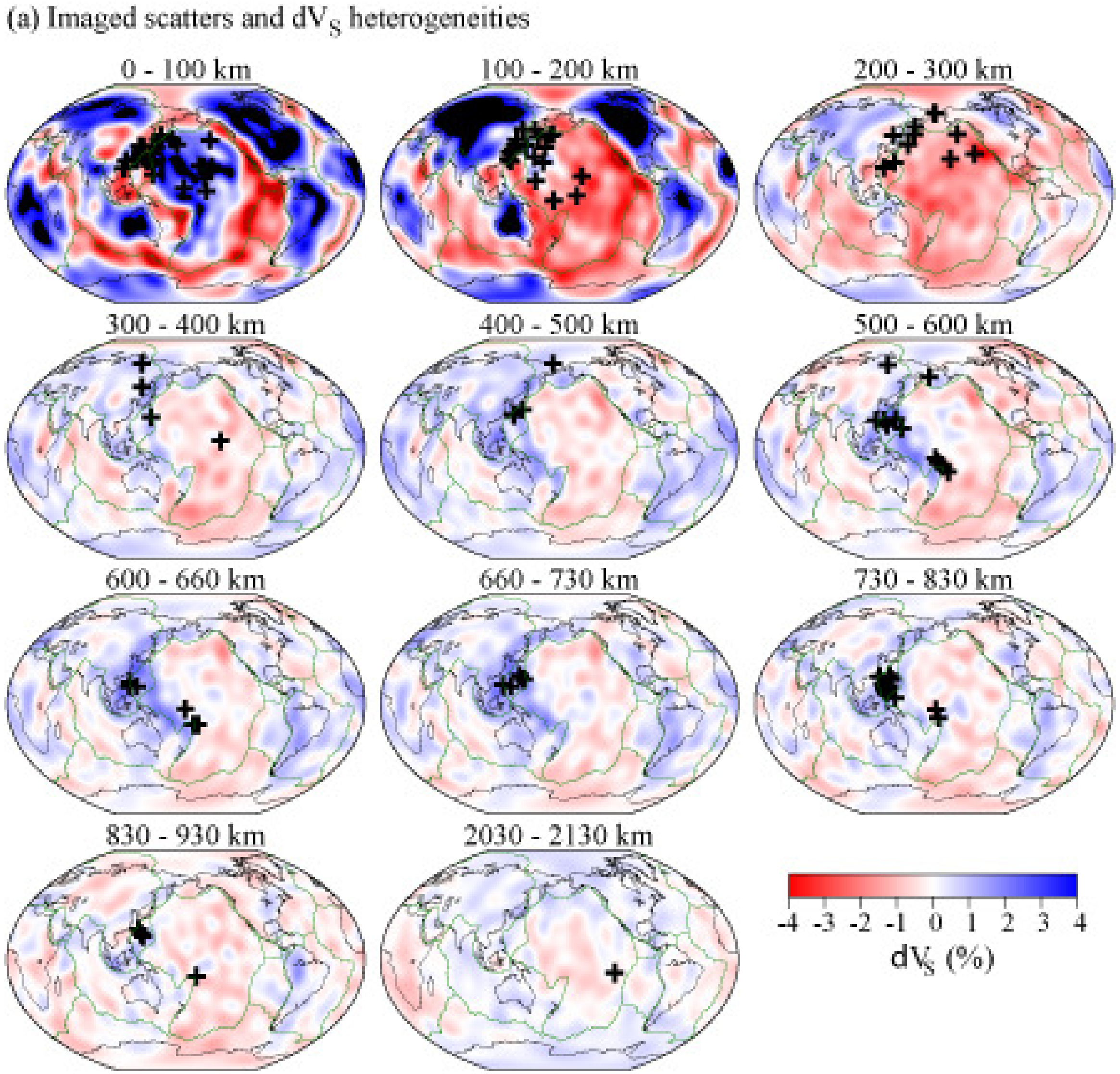


out-of plane PP precursors are detected and mapped using slowness, backazimuth and travel time information



Rost et al., 2008

Second example (Rost et al 2008)



Reflections arrive from high-velocity regions in the mid- and lower mantle

Rost et al., 2008

Summary Part 1

Array analysis and migration are powerful tools to detect structures/slabs in the deep mantle.

Mid-mantle slab reflections can be detected almost continuously from 660 km to the CMB under Caribbean.

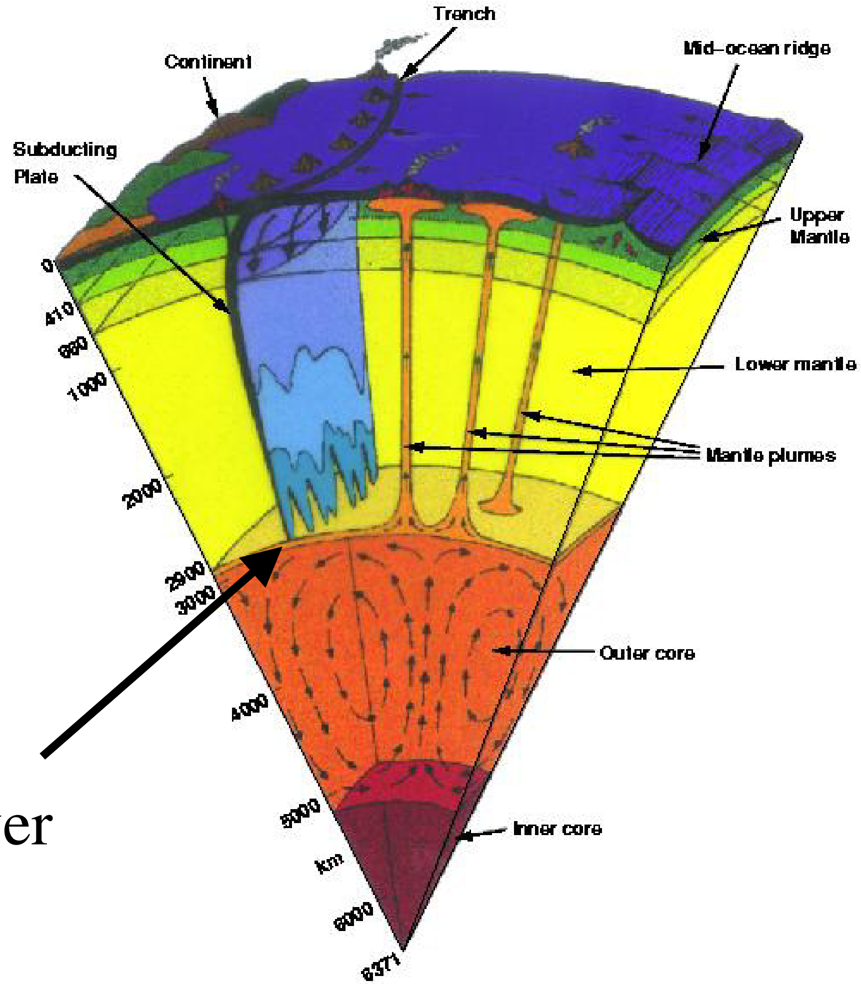
Indications of a sharp underside reflector at lithosphere in the Caribbean. => Mechanical or chemical boundary.

Detections from the Mariana slab reach to about 950 km depth

Out-of plane reflections from Aleutian slab observed

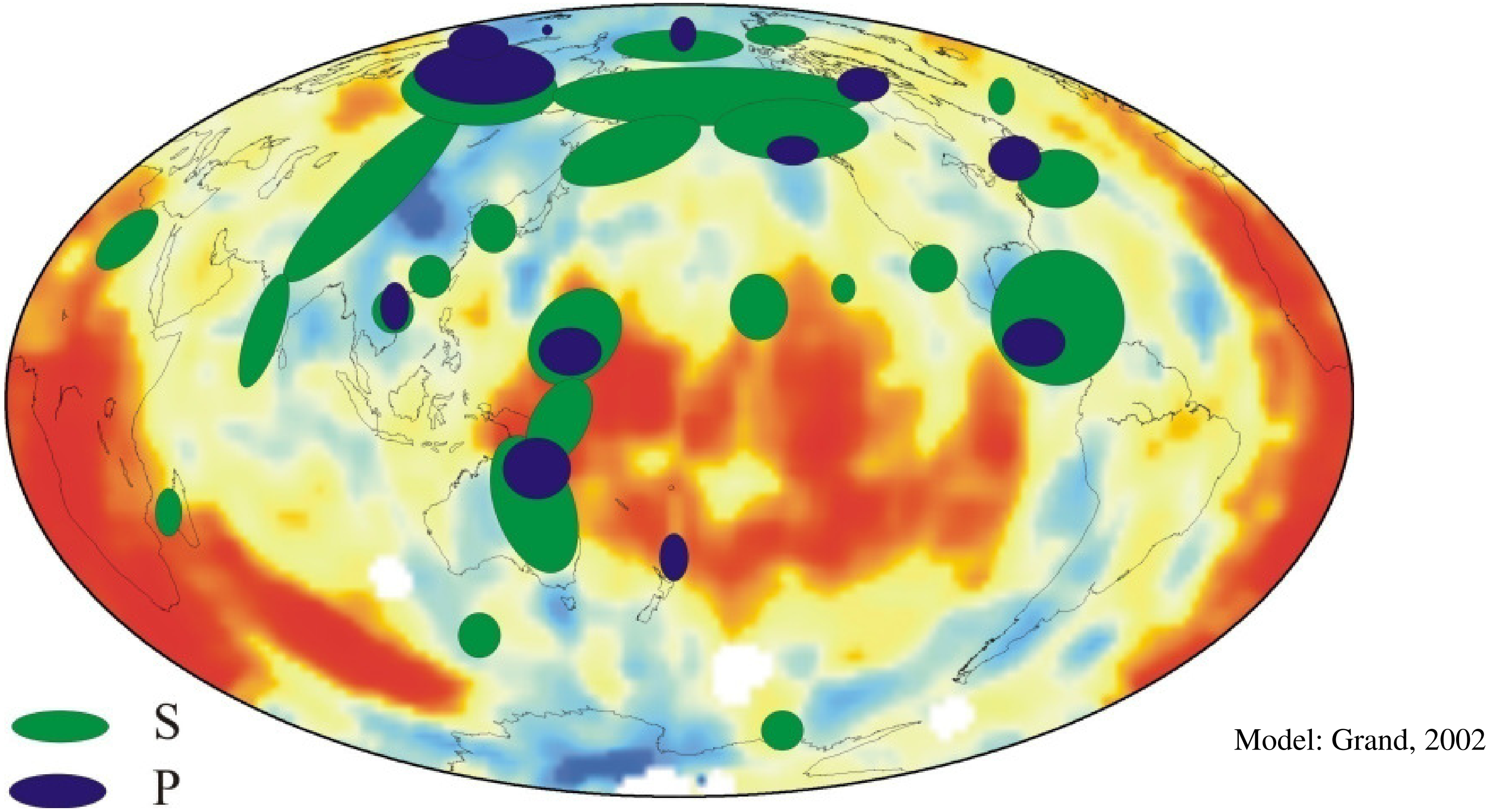
D" reflections seem to be related to deep subduction beneath Caribbean

Examples



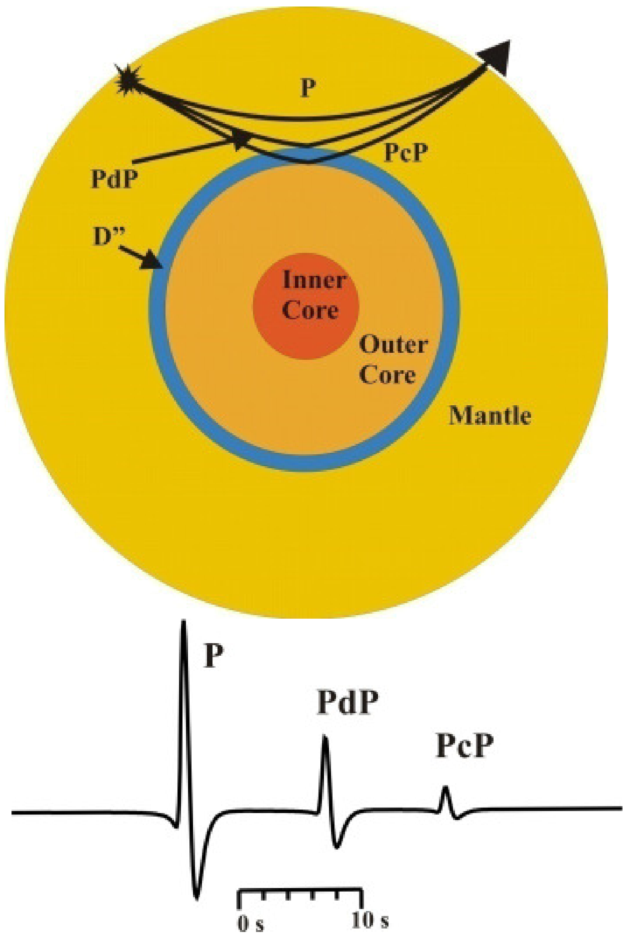
2) The D" layer
and CMB

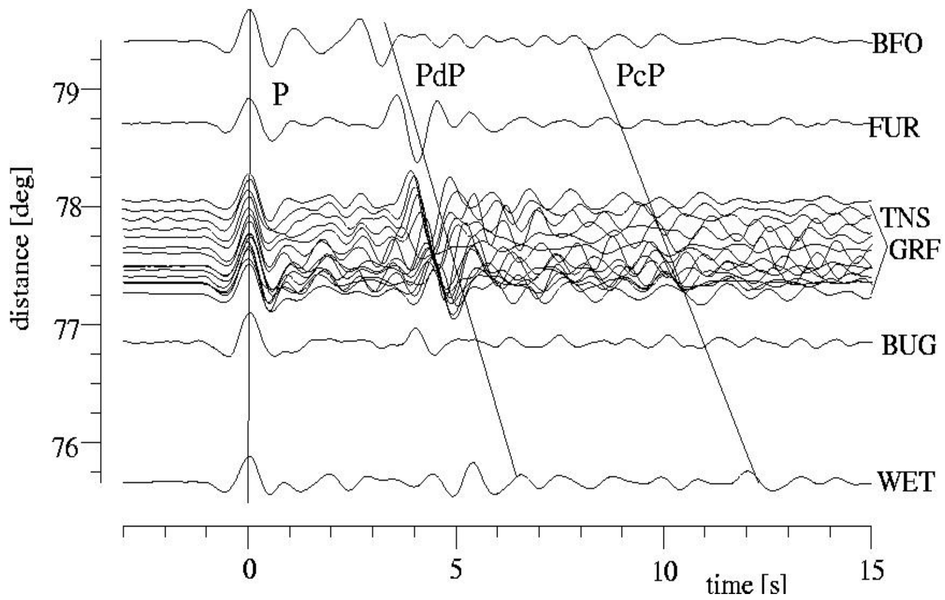
D” discontinuity studies



Data from: Lay and Helmberger, 1983, Weber and co-workers, 1990s, Kendall and co-wokers, Scherbaum et al, 1997, Lay and co-workers, Houard and Nataf 1990s, Wysession et al., 1998, Kito et al, and many more.

Reflections from D"





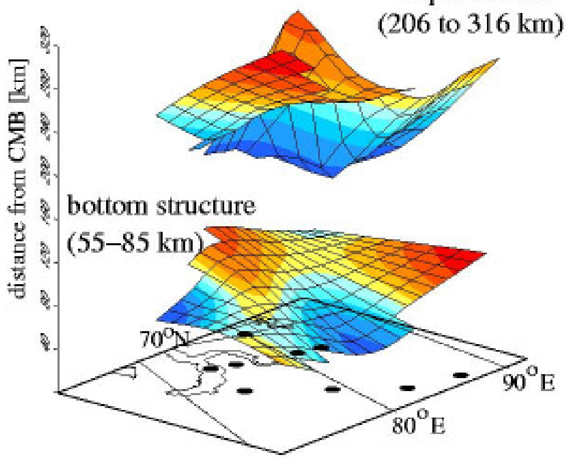
Seismic reflection from D" in P- and S-waves are observed.

Thomas and Weber 1997

Observations 1

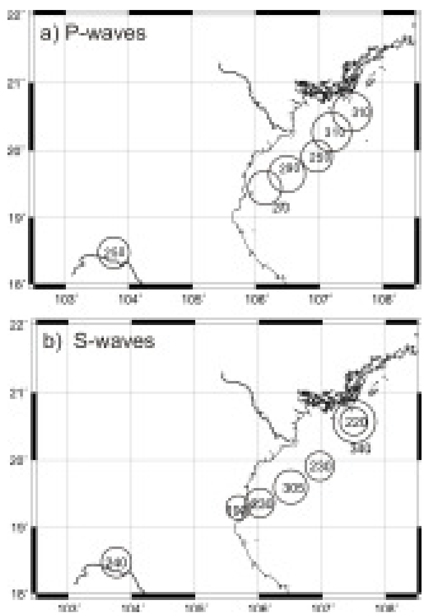
Eurasia

S-Waves



from
Thomas, Kendall, Lowman 2004

SE Asia



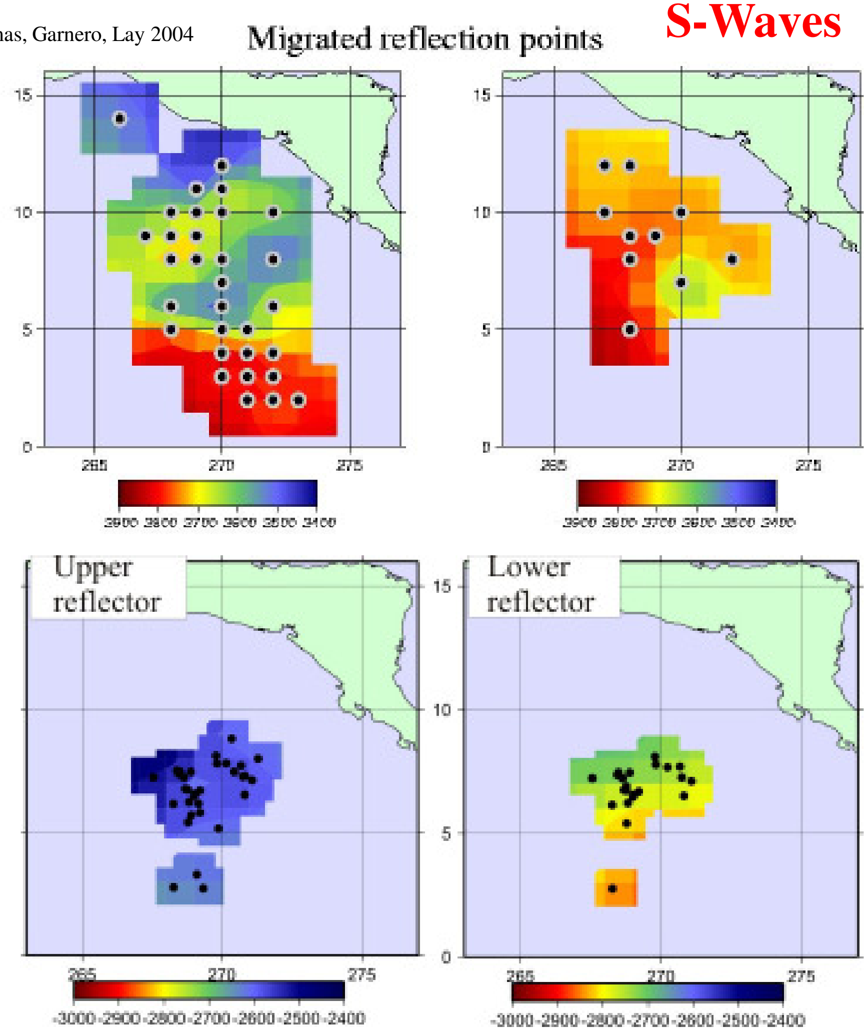
from Chaloner,
Thomas,
Rietbrock, 2009

up to two reflectors found with P- and S-waves beneath:
Caribbean
SE Asia
Eurasia

Caribbean

S-Waves

Thomas, Garnero, Lay 2004



P-Waves

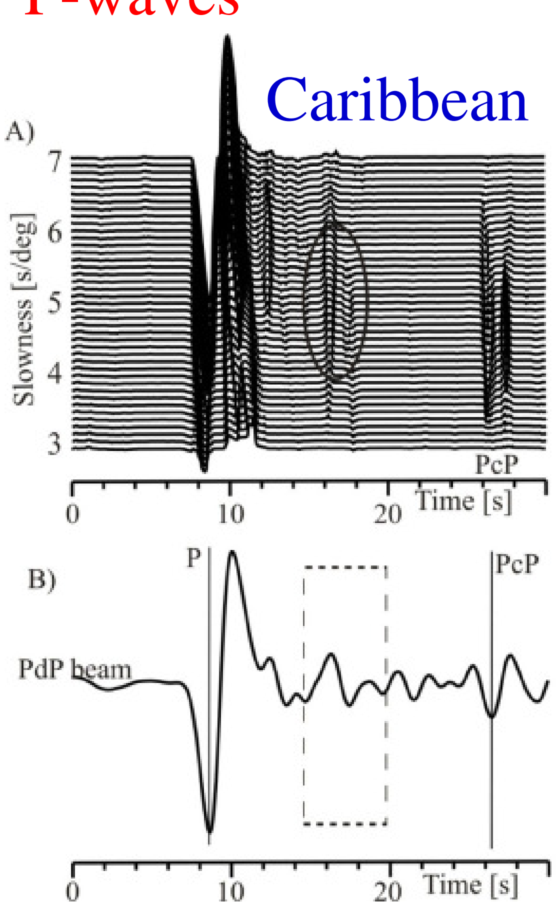
2 reflectors under Caribbean also observed by e.g., Hutko et al. 2006, van der Hilst et al. 2007

Kito, Rost, Thomas, Garnero, 2007

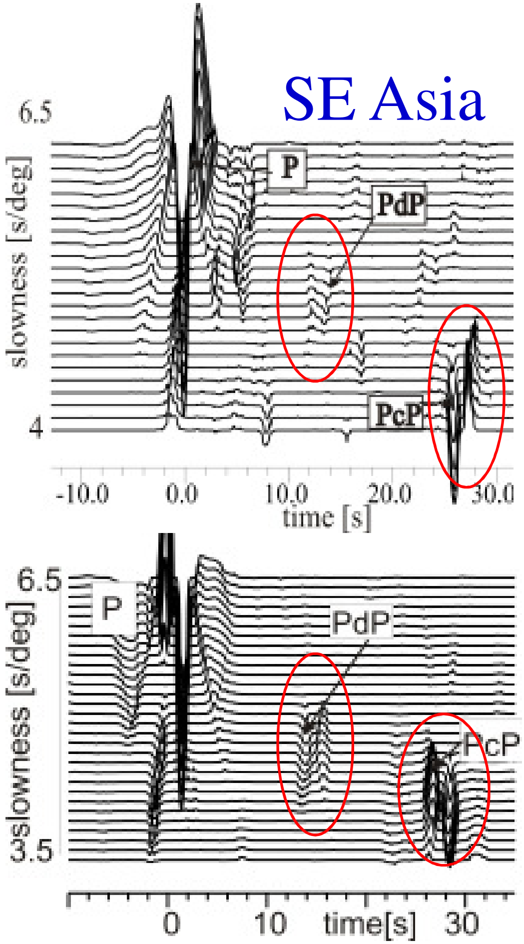
Observations 2

P-waves

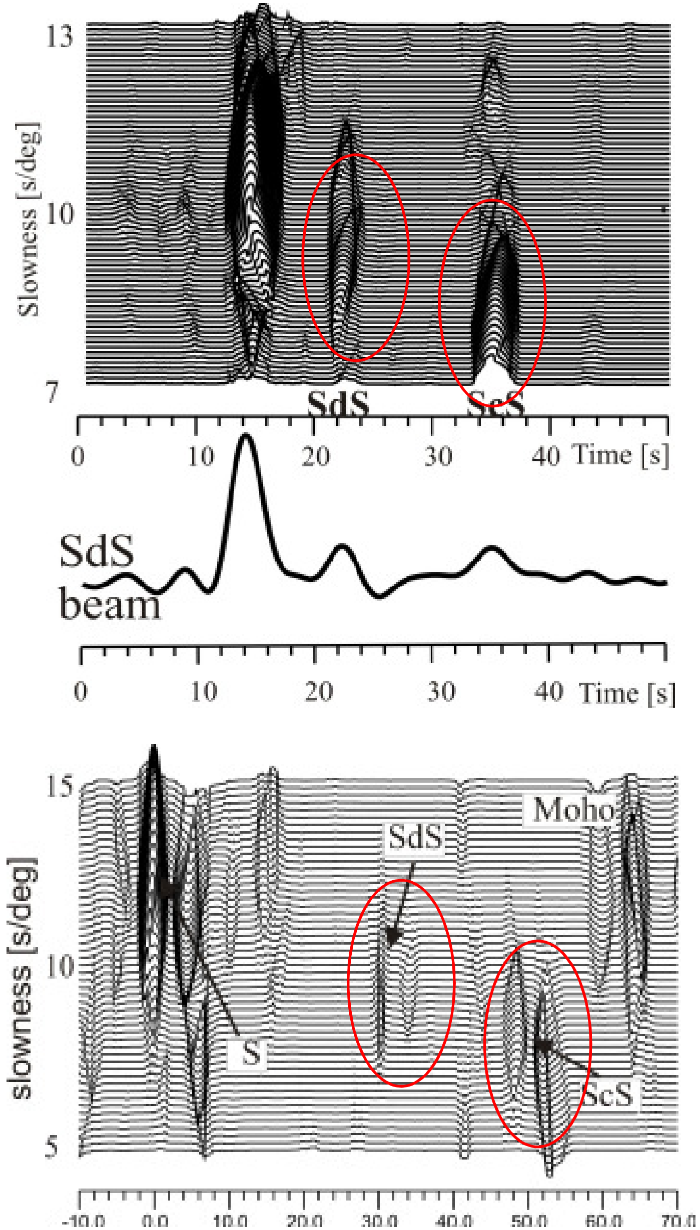
Caribbean



SE Asia



S-waves Caribbean



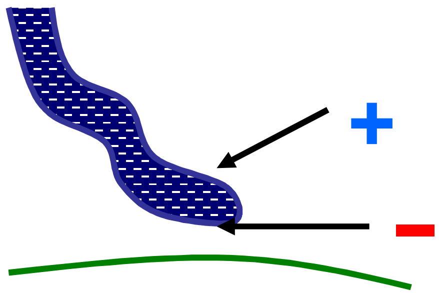
SE Asia

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

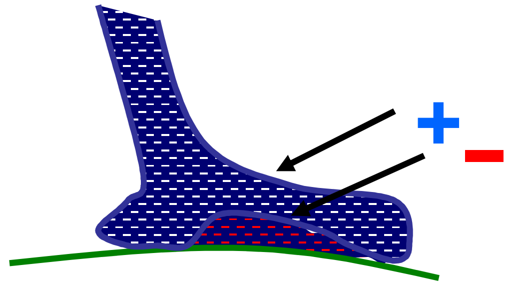
Kito, Rost,, Thomas, Garnero, 2007

Chaloner, Thomas, Rietbrock, 2009

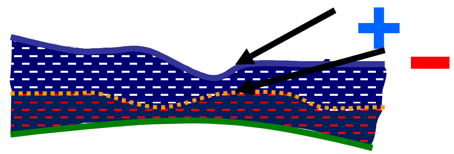
Possible explanations



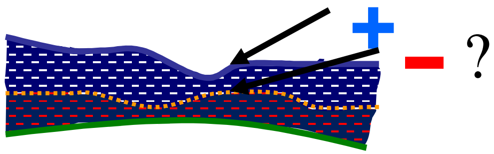
Top and bottom of a slab
e.g. Thomas et al. 2004



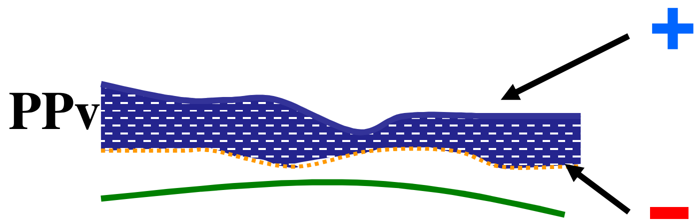
Birth of an upwelling
e.g. Tan et al. 2002



Thermo-chemical boundary layer with internal low-velocity zone *e.g. Lay et al. 2004*



Change of anisotropy with depth

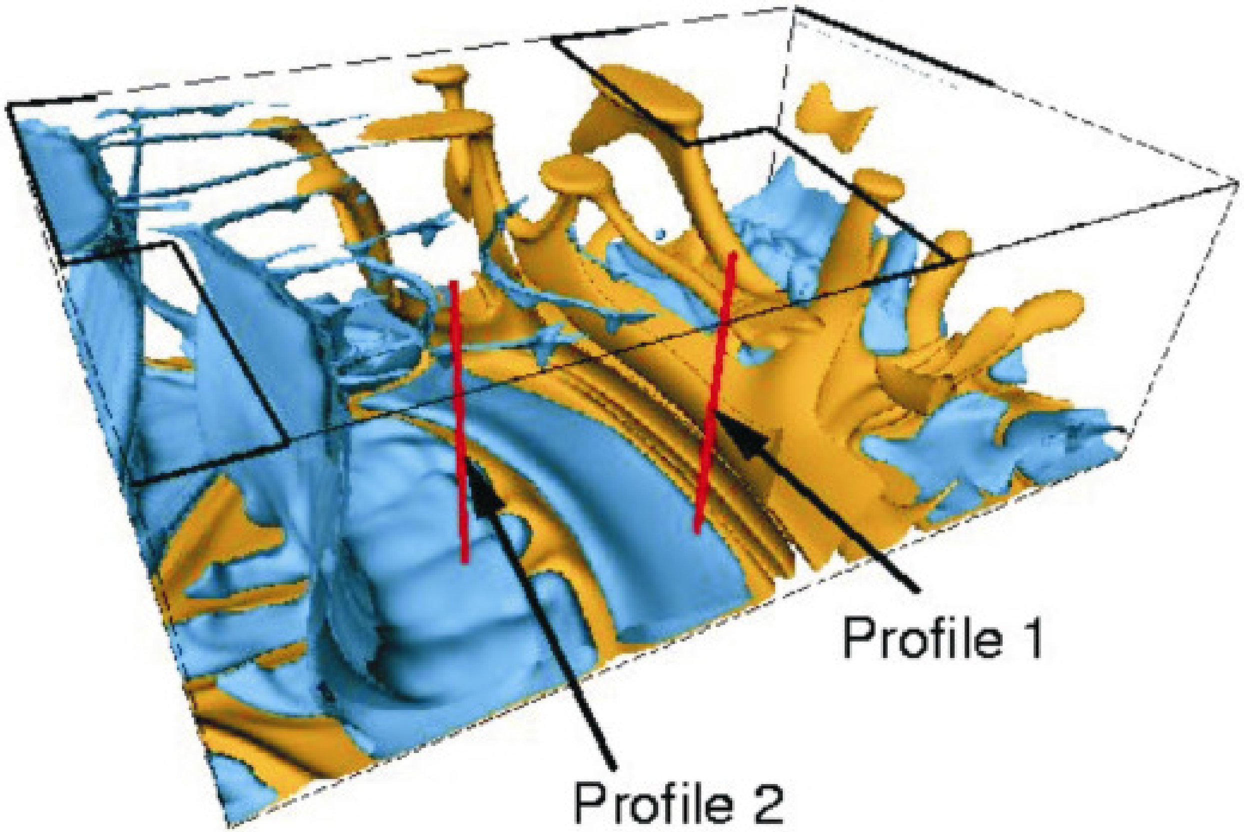


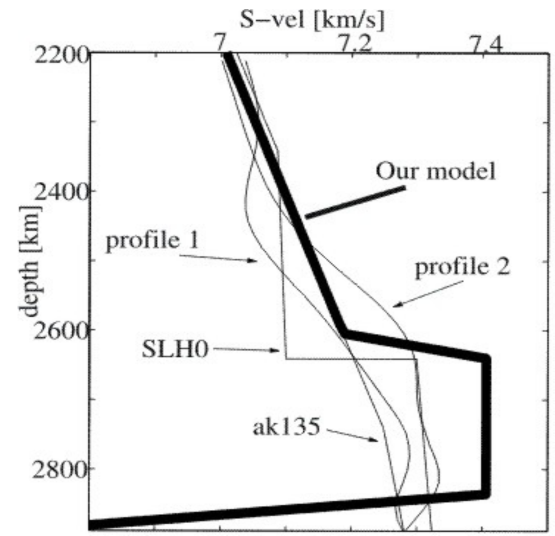
Post-perovskite transition stability field
e.g. Hernlund et al. 2005

others??

After Garnero 2005/ Thomas et al. 2004

Top and Bottom of a slab?

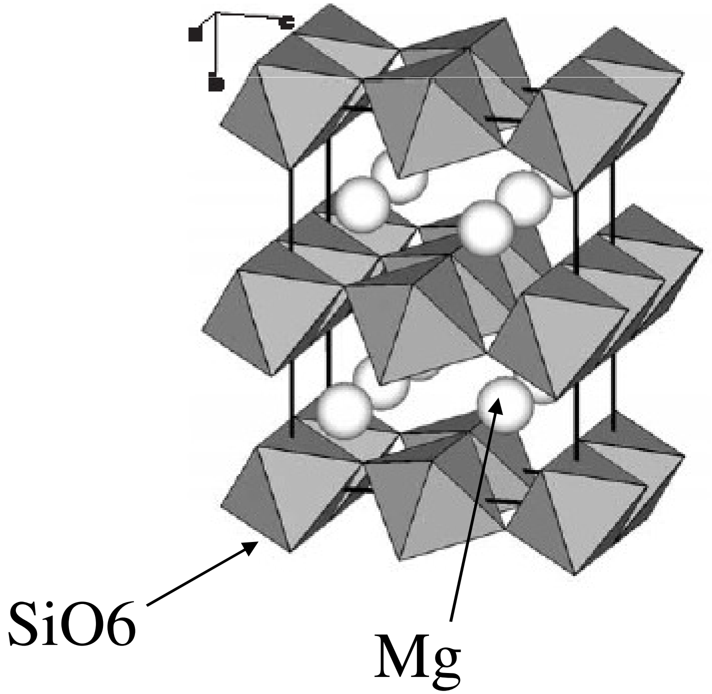




from Thomas, Kendall and Lowman 2004

Post-perovskite?

Recent studies show post-perovskite phase at >125 GPa and 2500K
density increase 1-1.2%

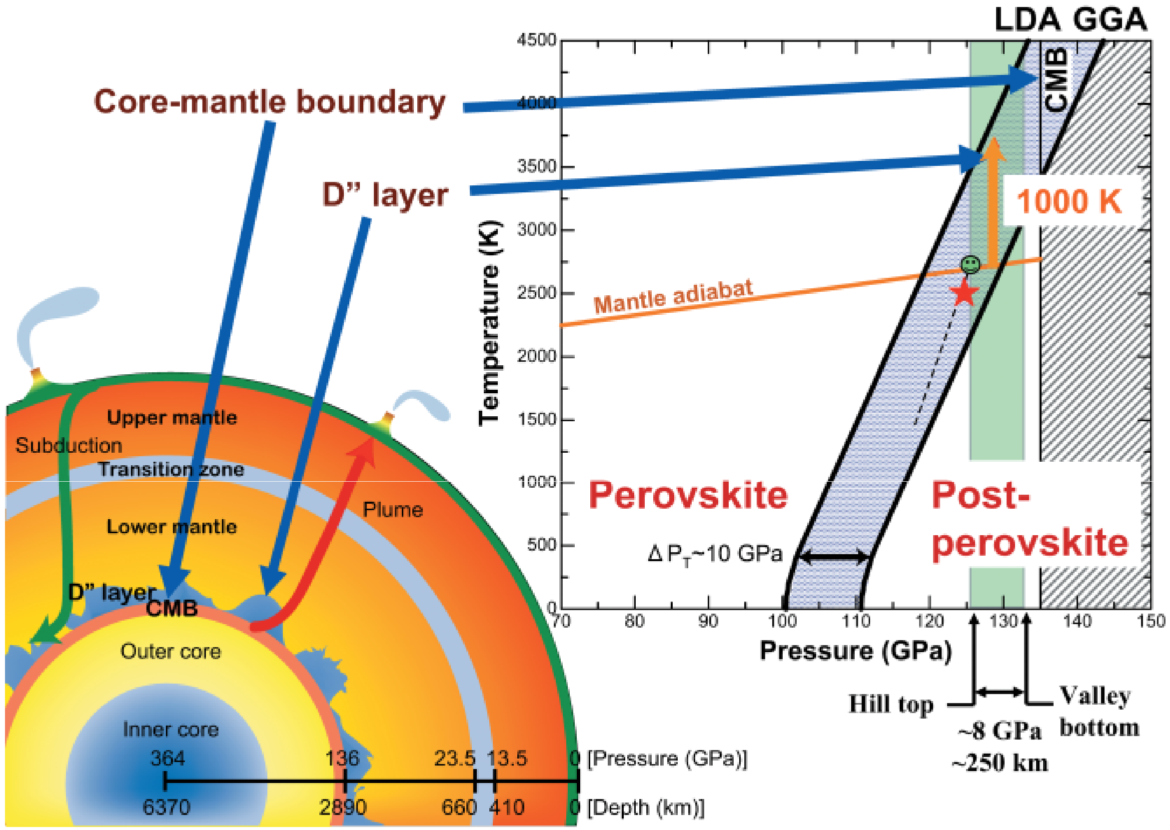


Crystal structure in
different directions:
layered structure = anisotropy?!

Clapeyron slope not well
defined but positive
(6-9MPa/K)

from Oganov and Ono, 2004

D" and ppv



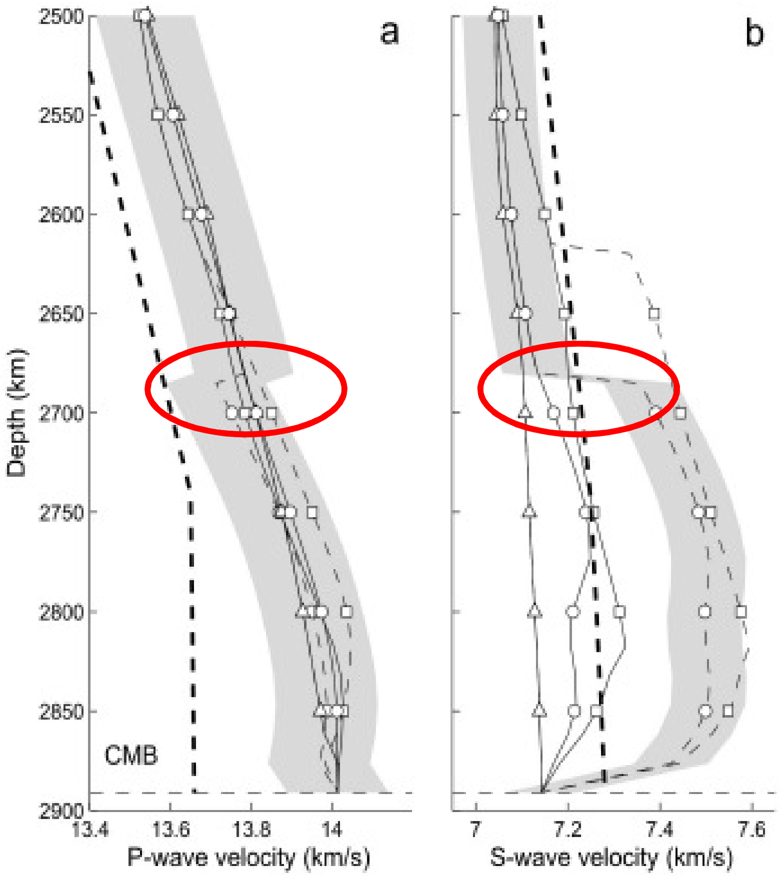
from : R. Wentzcovitch, T. Tsuchiya, J. Tsuchiya, K. Umemoto, AGU monograph, 2007

mineral phase change at high P/T

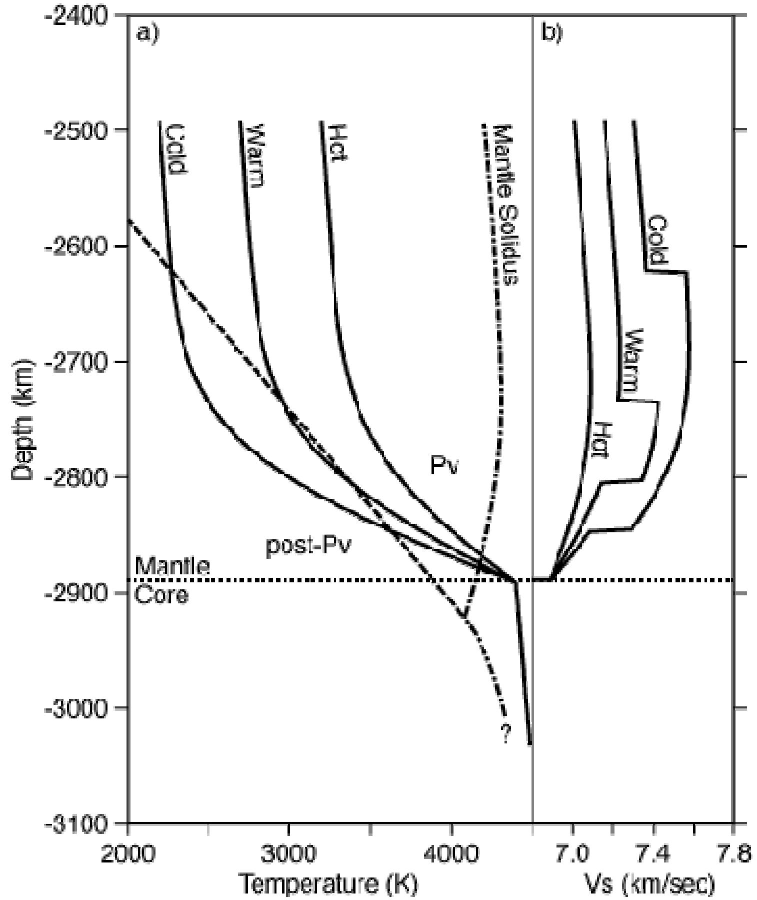
causes density jump and velocity jump

could explain:
discontinuity in D"
anisotropy
ulvz
...

Phase transition



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

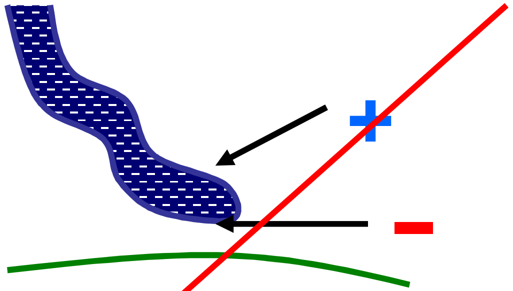


from Hernlund, Thomas and Tackley, 2005

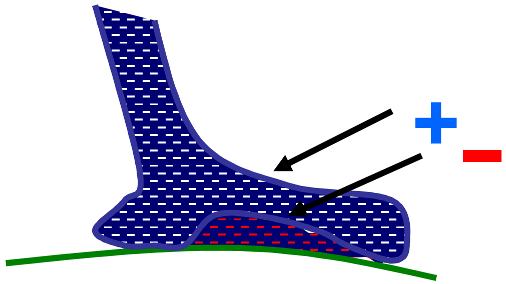
double crossing model explains two discontinuities and topography

=> agreement with observations beneath Caribbean and SE Asia

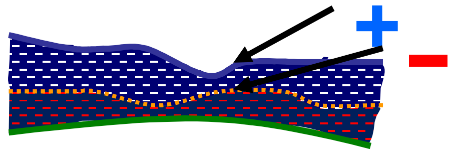
Some hypotheses



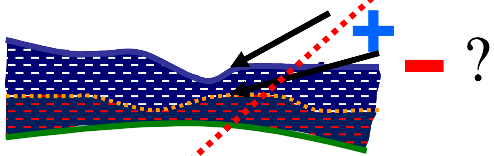
Top and Bottom of a (purely thermal) slab
e.g. Thomas et al. 2004



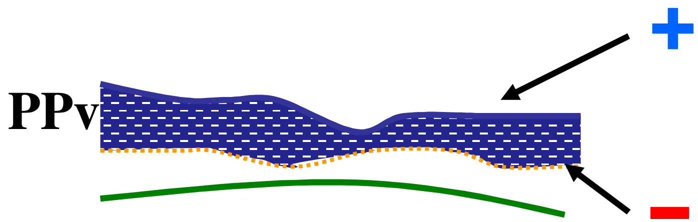
Birth of an upwelling
e.g. Tan et al. 2002



Thermo-chemical boundary layer with internal low-velocity zone *e.g. Lay et al. 2004*



Change of anisotropy with depth



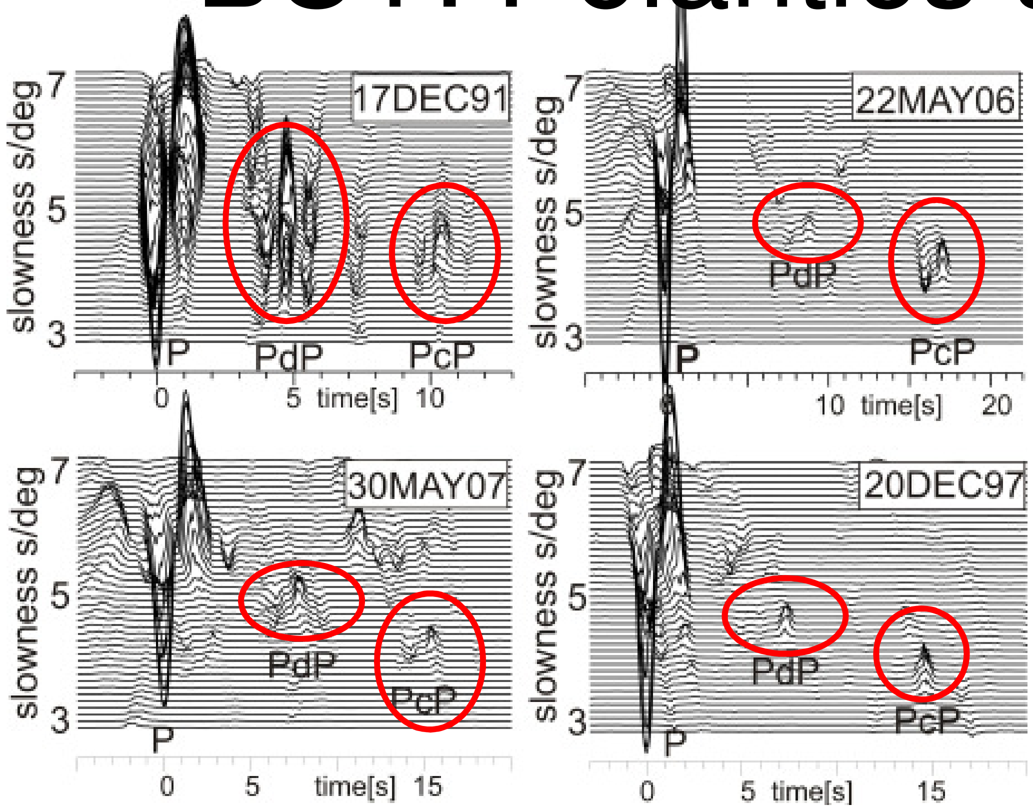
Post-perovskite transition stability field
e.g. Hernlund et al. 2005

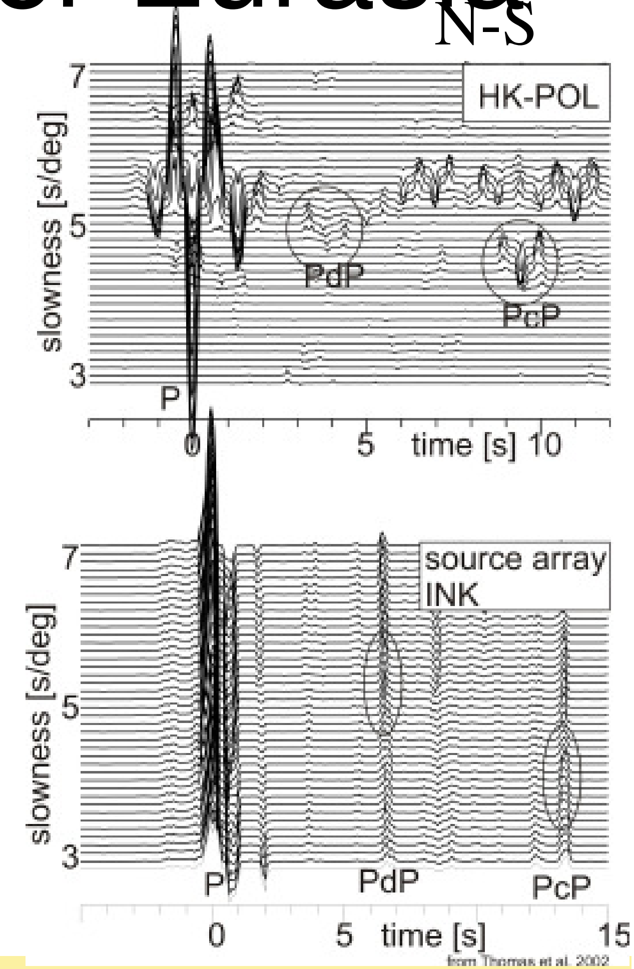
others??

After Garnero 2005/ Thomas et al 2004

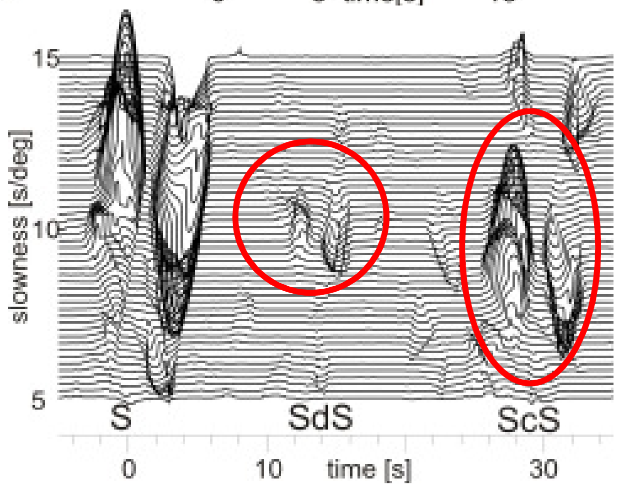
BUT: Polarities under Eurasia

N-S





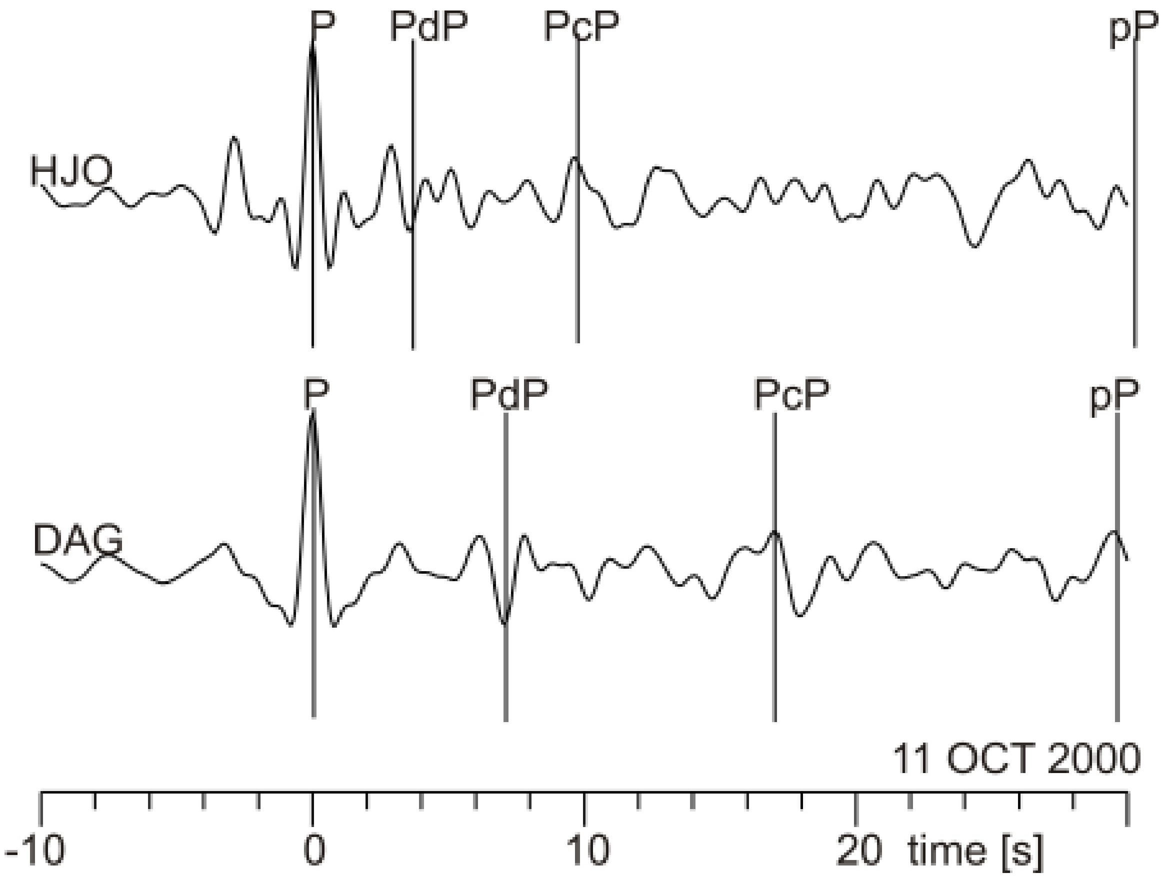
E-W



Thomas, Wookey, Brodholt, Fieseler, 2011

Under Eurasia:
PdP polarity is same as PcP, P polarity
positive contrast?

45 degree path

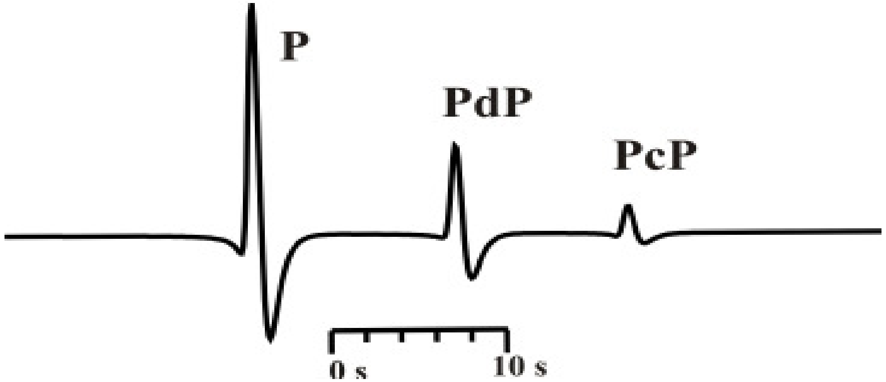


PdP seems to have negative polarity for a path 45 degrees to slab flow direction

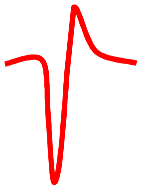
Thomas, Wookey, Brodholt, Fieseler,subm. 2011

Observations 3

Caribbean /S.E. Asia

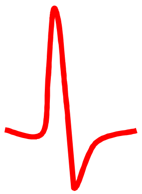


P reflection



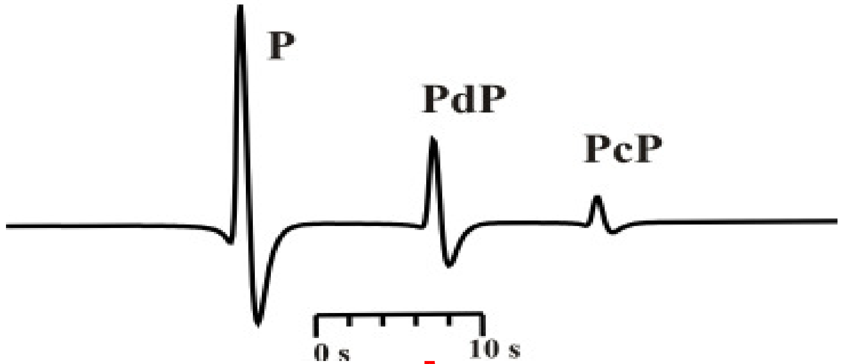
neg. impedance

S reflection

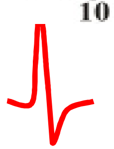


pos. impedance

Eurasia

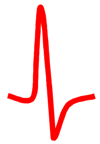


P reflection
P reflection



pos. impedance

S reflection
S reflection



pos. impedance

for 2 perpendicular crossing paths

P reflection

neg. impedance

for a 45 degrees path

Difference?

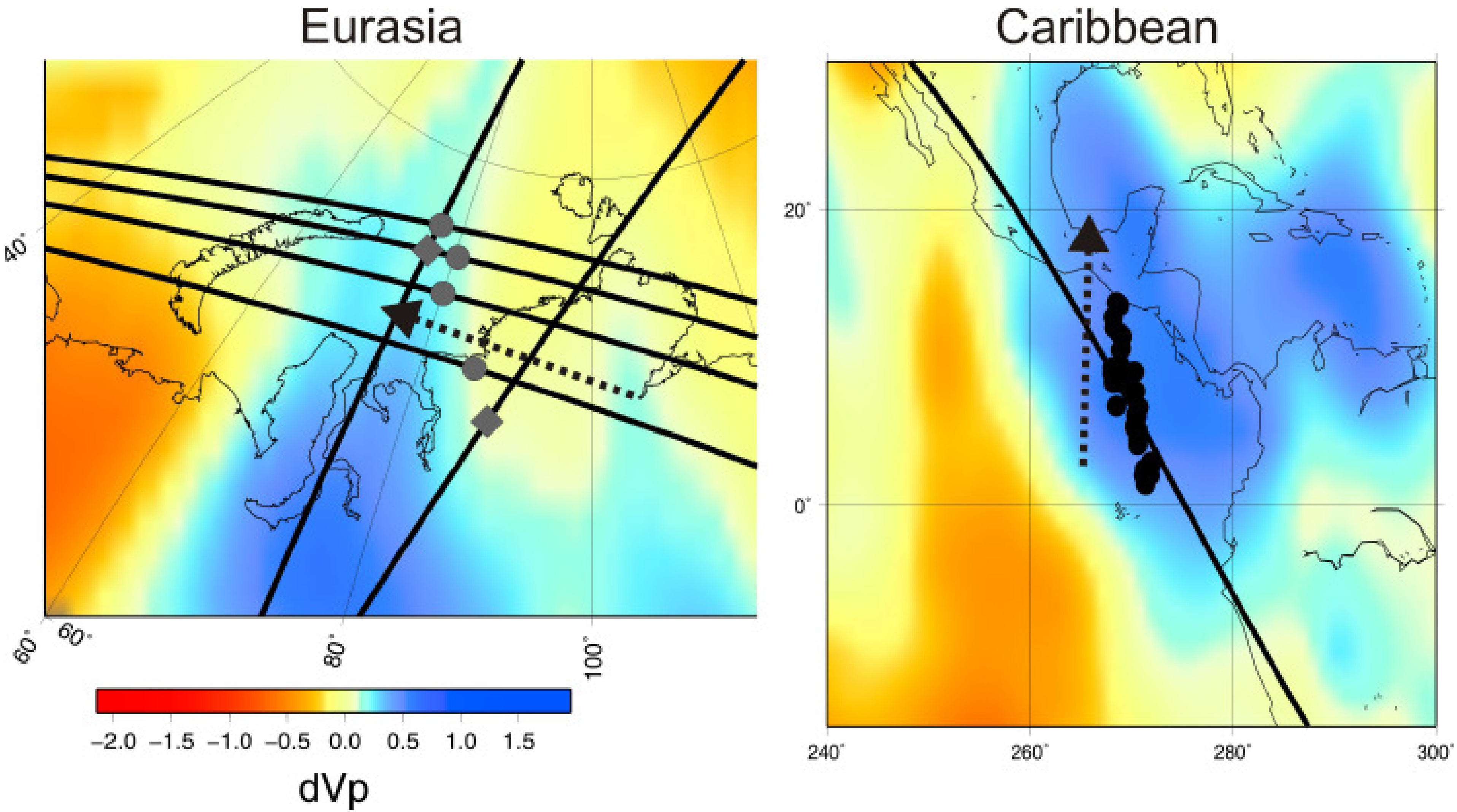
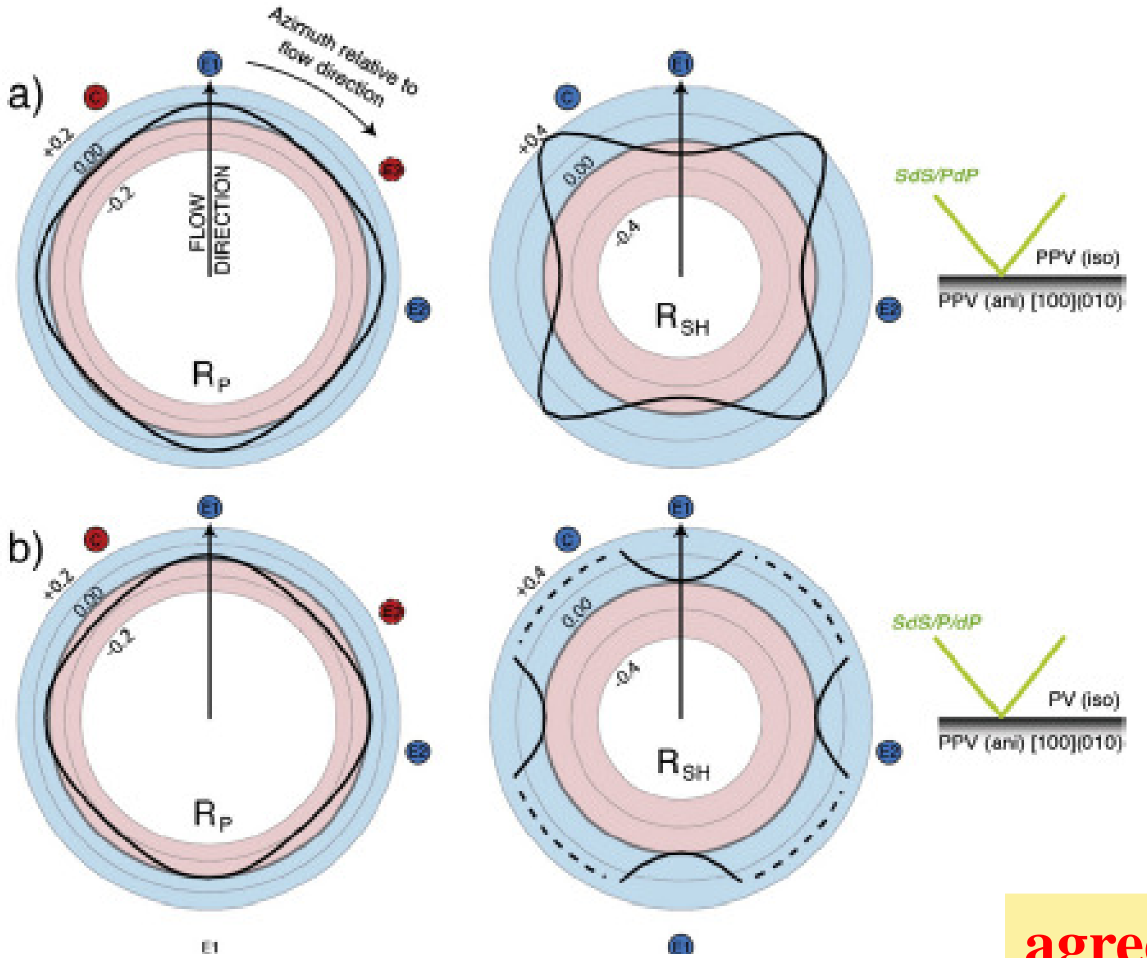


plate motion 80-100 Ma ago

Thomas, Wookey, Brodholt; Fieseler, 2011

Anisotropy to the rescue



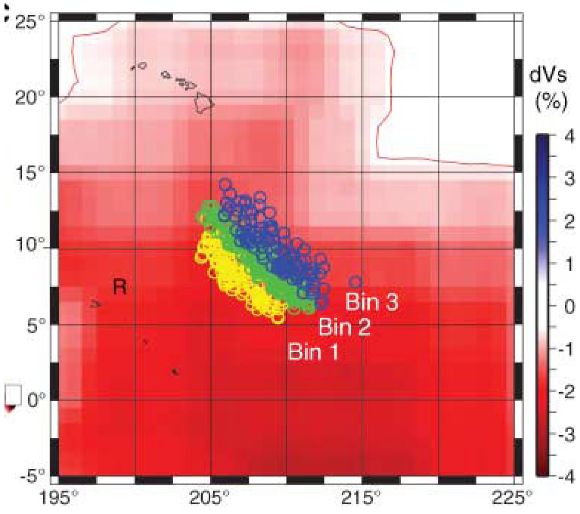
calculated reflectivity

along alignment direction and perpendicular:
positive P-wave contrast
negative S-wave contrast

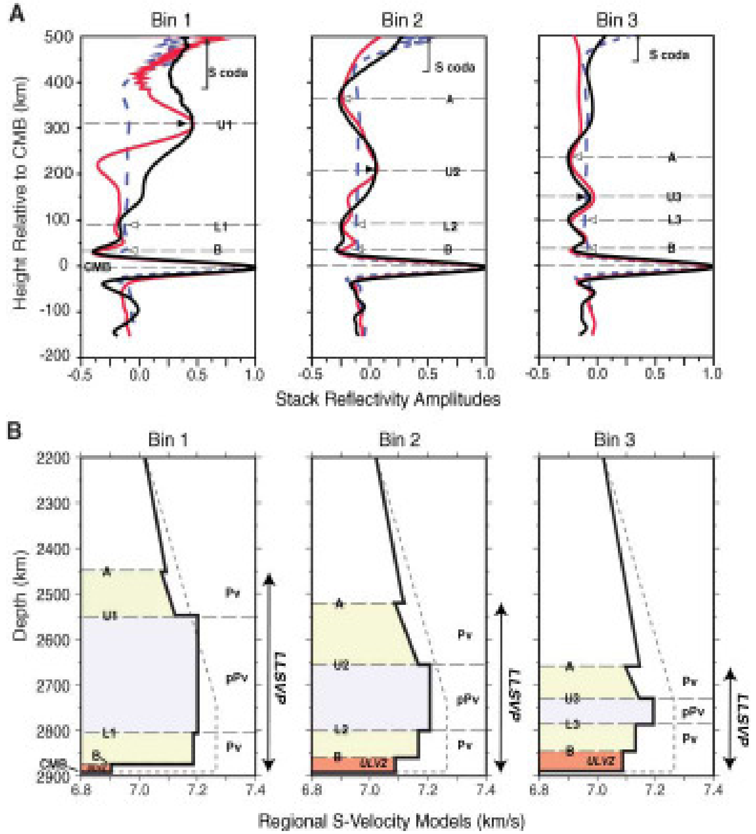
45 deg: neg. P and pos. S contrast

agreement with observations beneath Eurasia <u>and</u> Caribbean

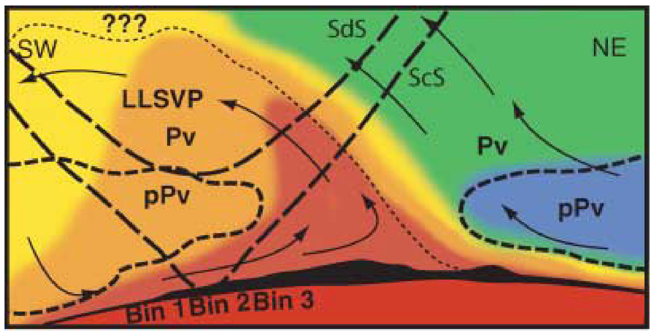
Low-velocity regions (Central Pacific)



S-reflections show strong variation in reflectors with decreasing thickness towards edge.



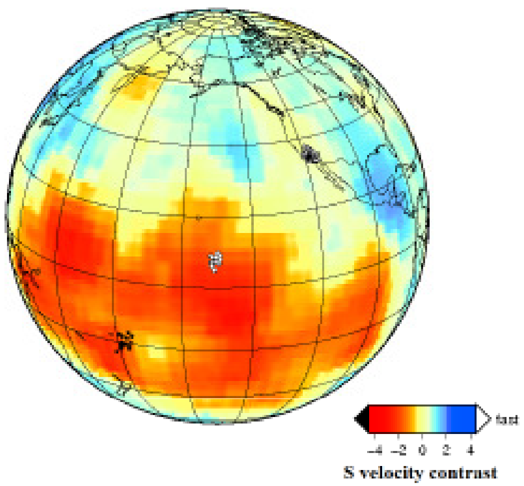
Ohta et al., 2008

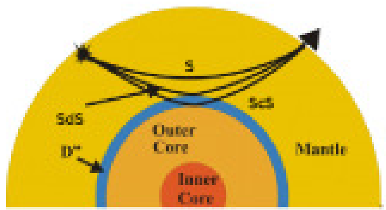


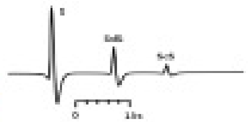
Lay et al., 2006

Lay et al. (2006): double crossing observed and additional two reflectors (A and B).
Pyrolite mantle and MORB ppv transition? (Ohta et al., 2008)
Or top/bottom of LLSVP and ulvz. (Lay et al., 2006)

Low velocity region (again)



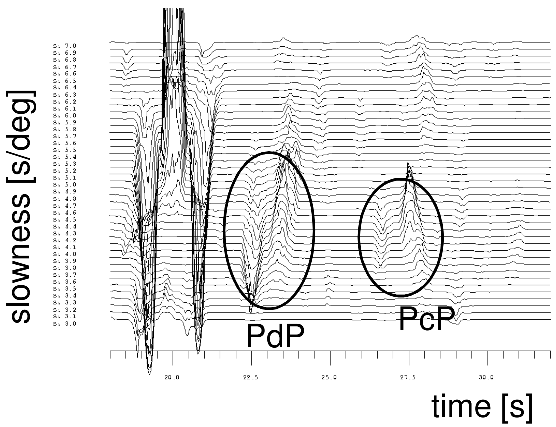


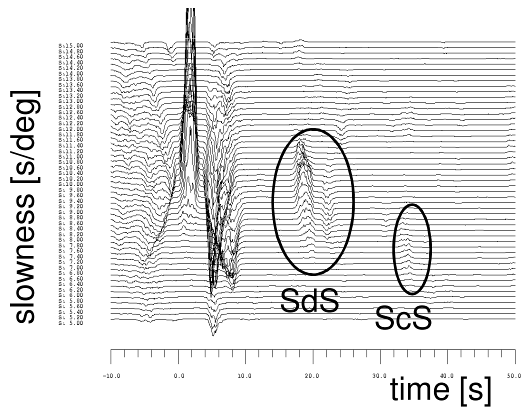


P and S-wave reflections at structures in the D" region

Fiji events recorded at CI and Anza stations (California). Reflection points are in the Pacific.

(Region of Avants et al. 2006, Lay et al., 2006)



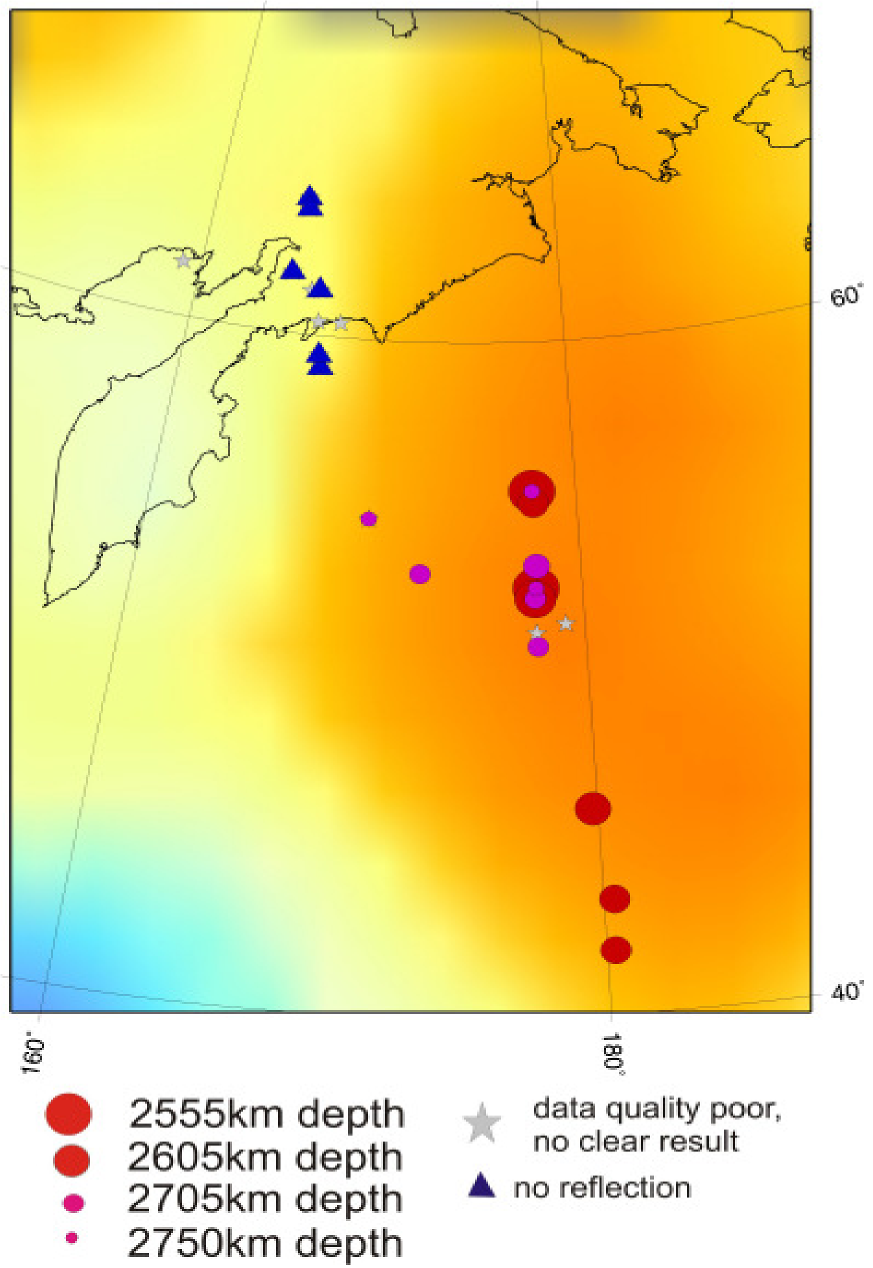


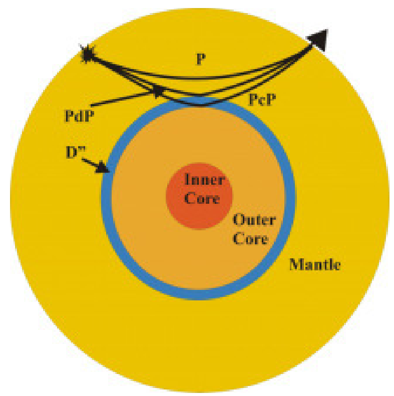
Examples for PdP and SdS

Casal-Berbel & Thomas, in prep

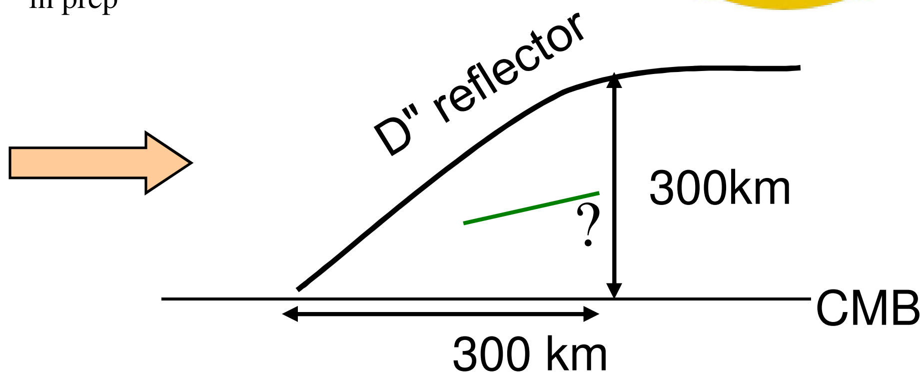
using same data but vespagrams and slowness-backazimuth analysis:

Low-velocity zone





Hempel, Thomas, Caracas, Coltice, in prep

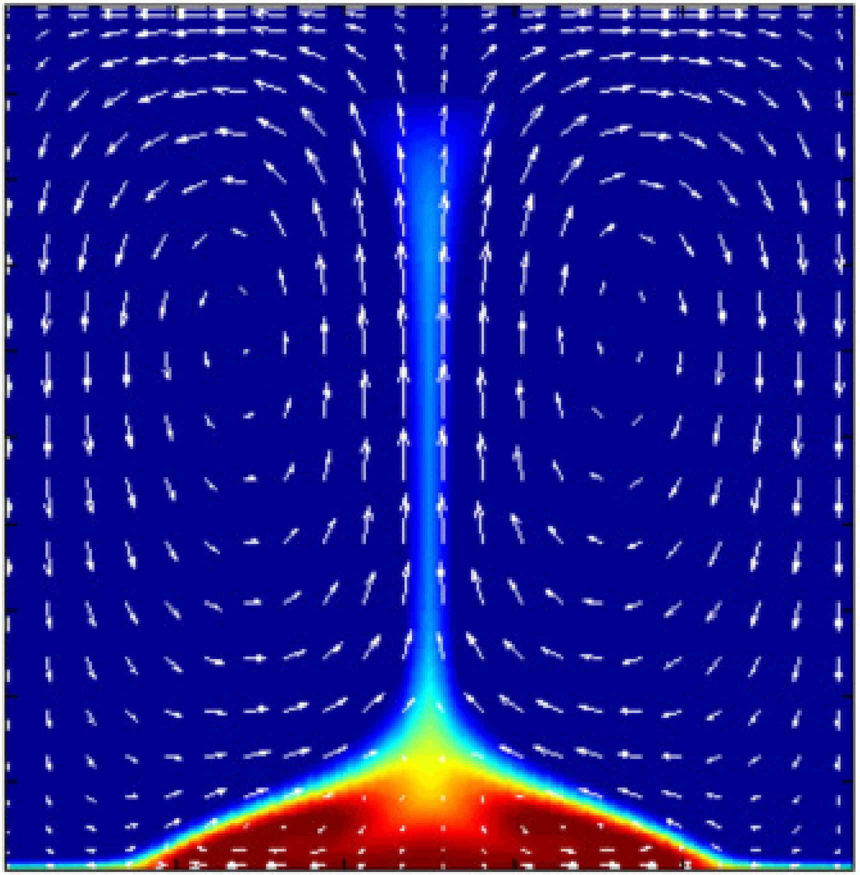


observations:

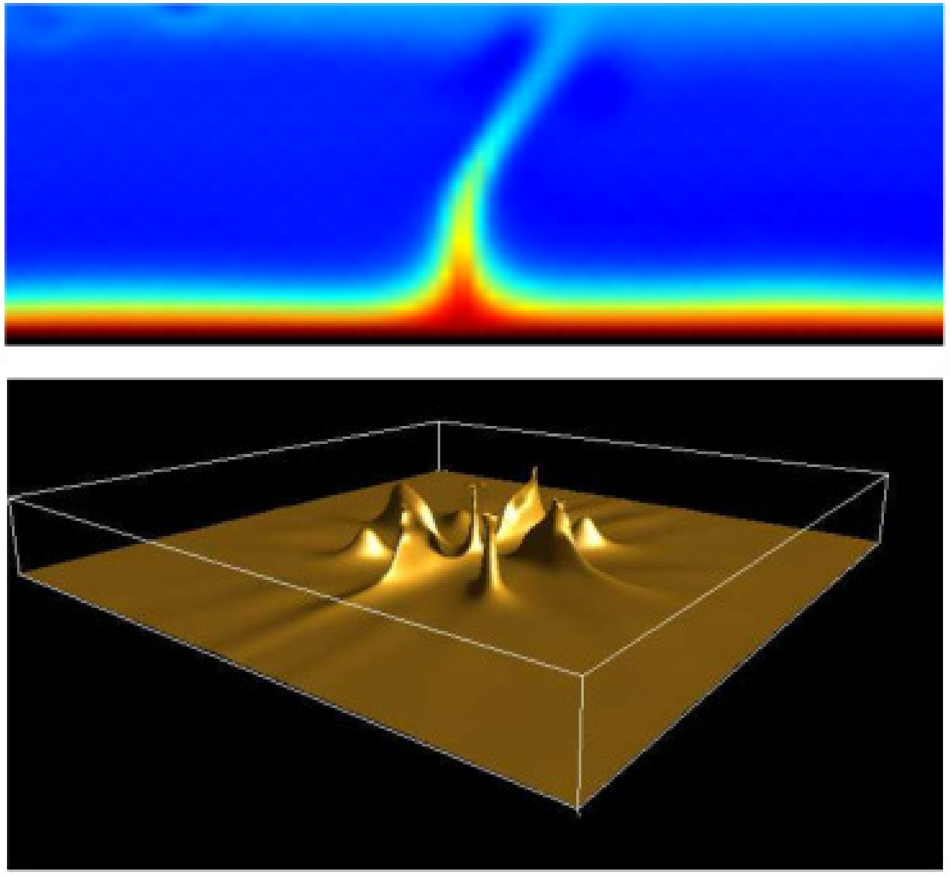
- low-velocity region,
- top reflector 40-90 km sharp
- 2nd reflector possible
- positive contrast for top reflector(?)
- steep sides

see also poster by Hempel et al for more information

Dynamical interpretation



Thermo-chemical convection, weakly temperature-dependent viscosity

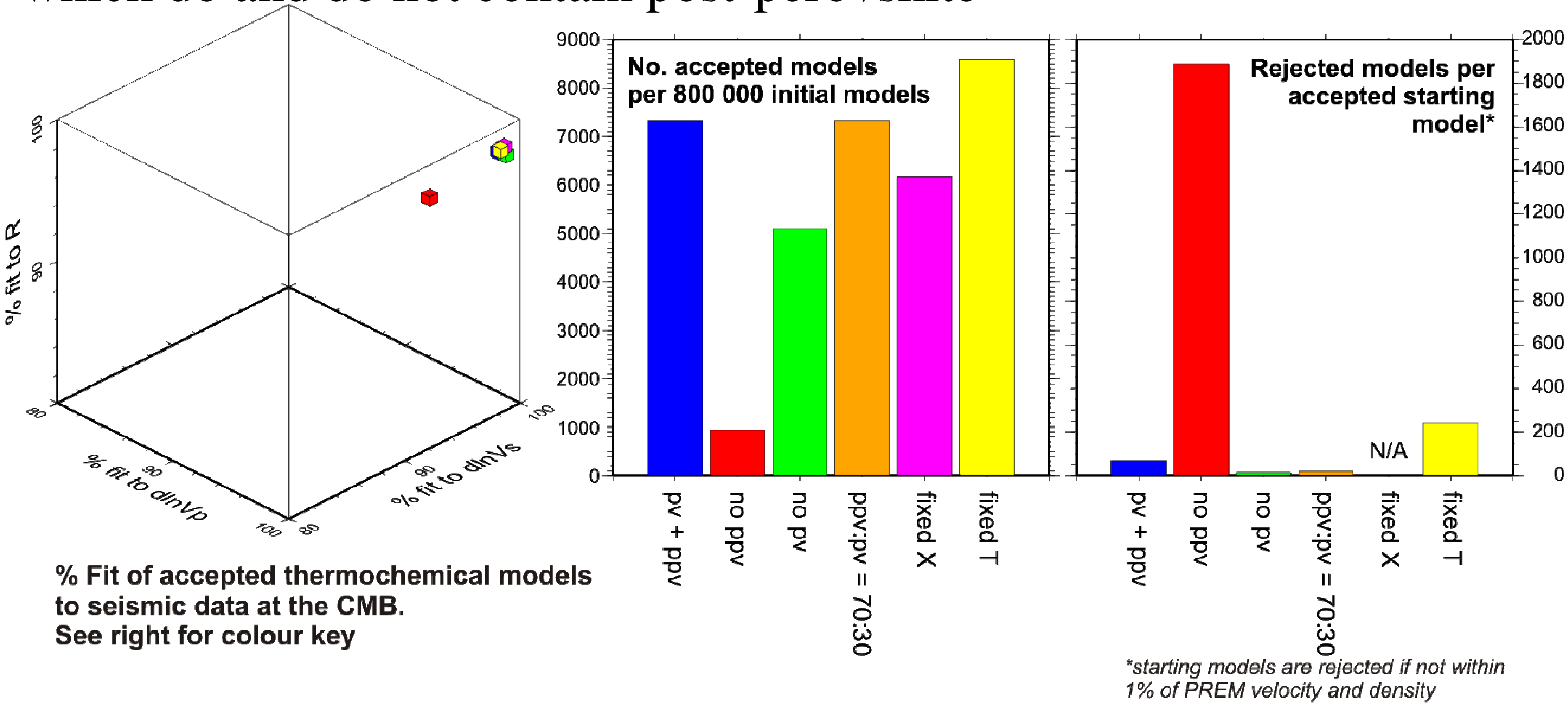


Temperature- and pressure-dependent viscosity

pictures courtesy of Ulli Hansen

Possible scenarios for lower mantle

statistical comparison of the relative fit to seismic data of mantle models which do and do not contain post-perovskite

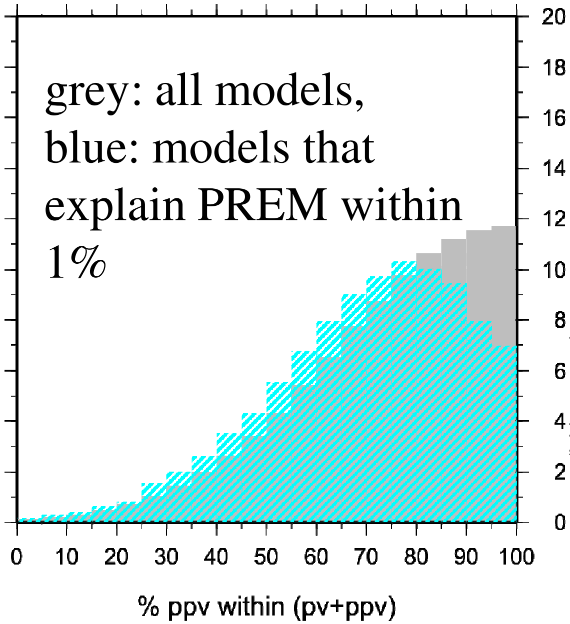


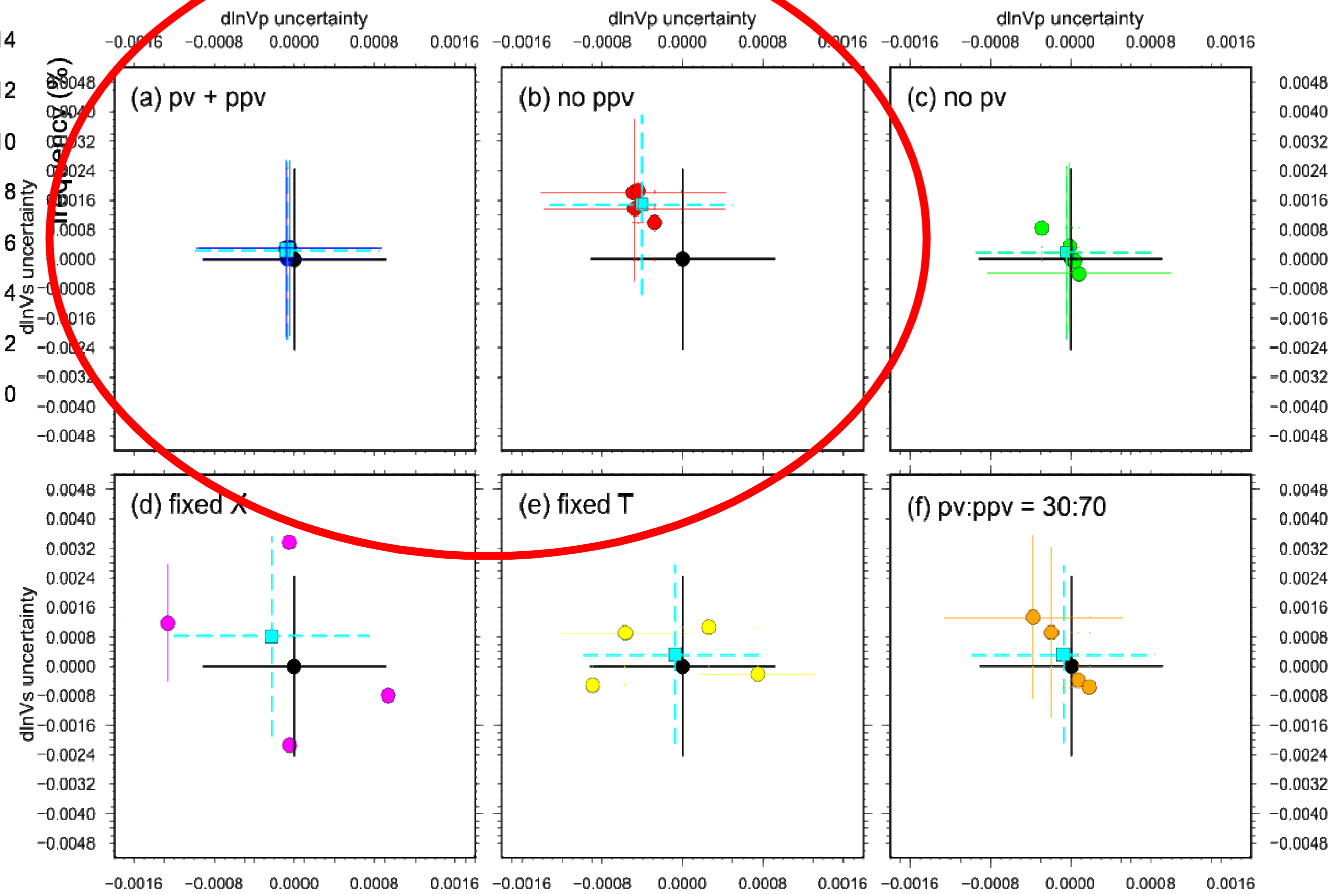
% Fit of accepted thermochemical models to seismic data at the CMB. See right for colour key

Cobden et al, 2011

Difficult to distinguish between different scenarios on this evidence alone, although stastically "no post-perovskite" (red) has the worst fit to the data

Possibilities for lvz



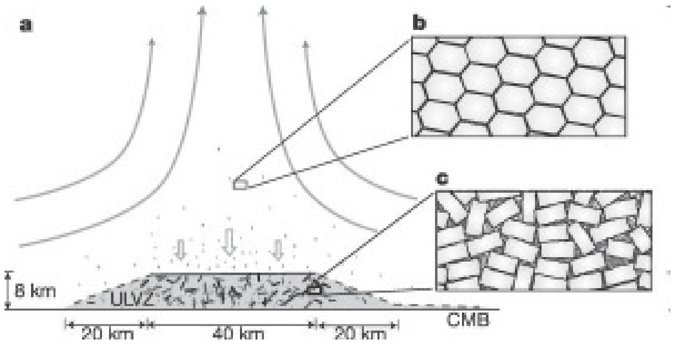


distributions of the seismic uncertainties within the accepted models.

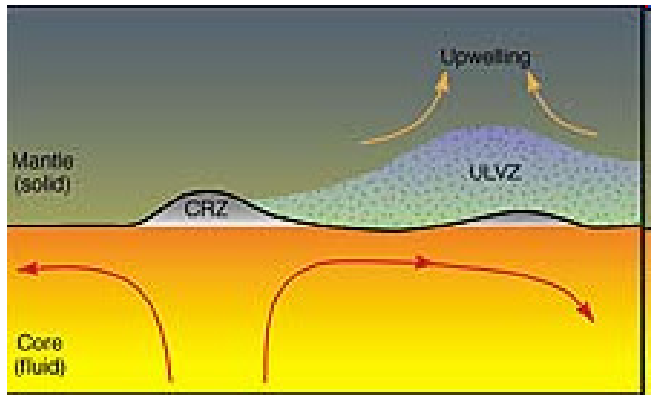
Cobden et al, 2011

Statistically, a mixture of pv and ppv explains the observations (PREM) and double crossing of pv-ppv-pv not global feature

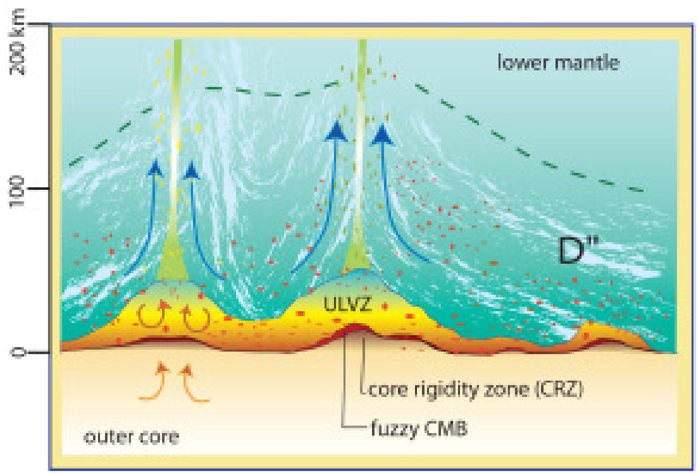
ultra-low velocity zones



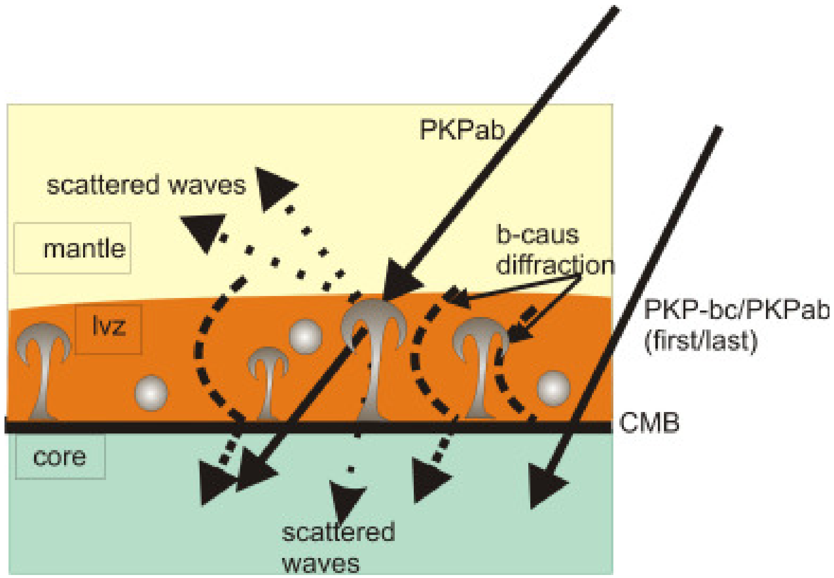
Rost et al., 2005



Rost and Revenaugh



garnero.asu.edu



Thomas et al., 2009

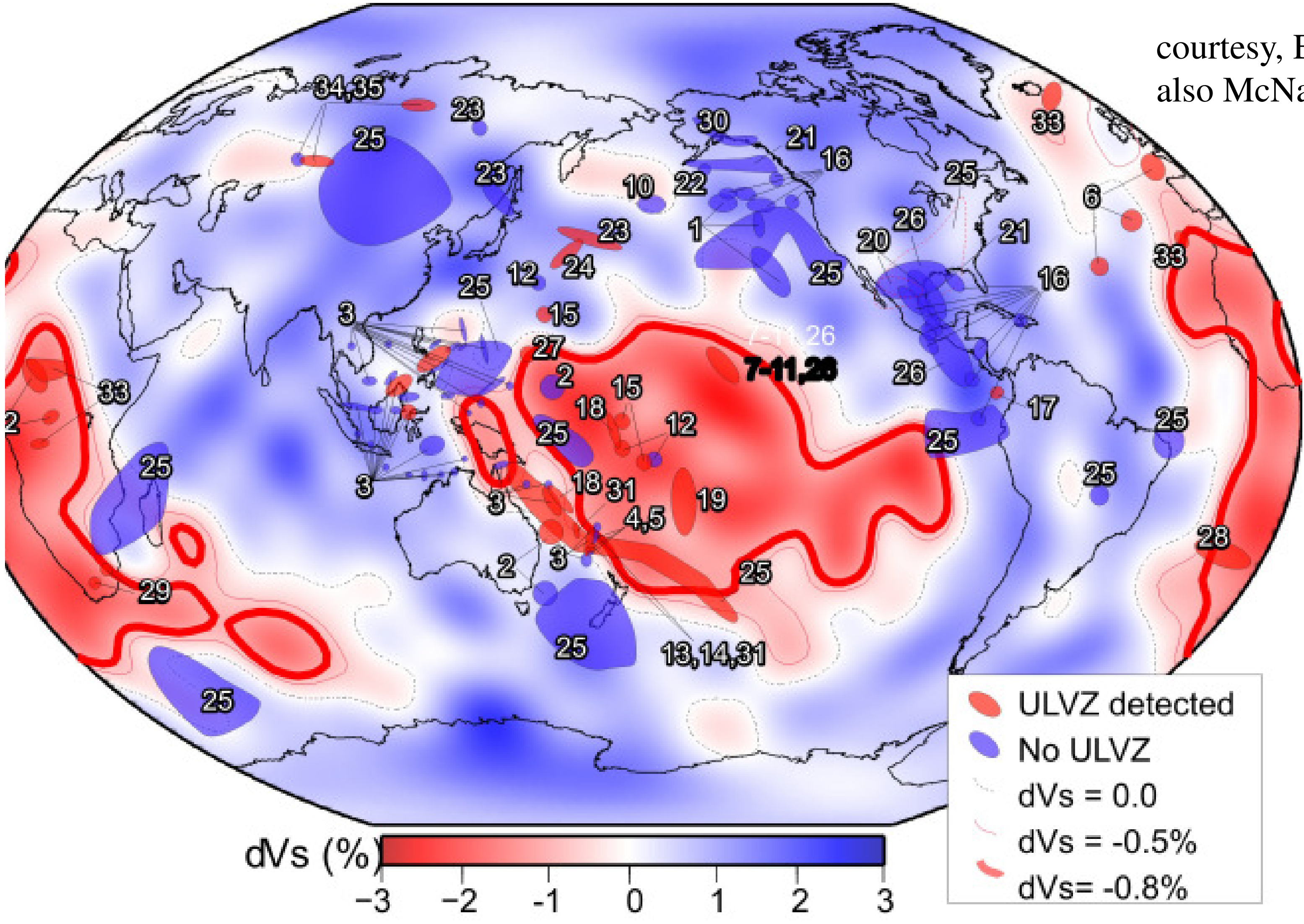
ulvz

core rigidity zones

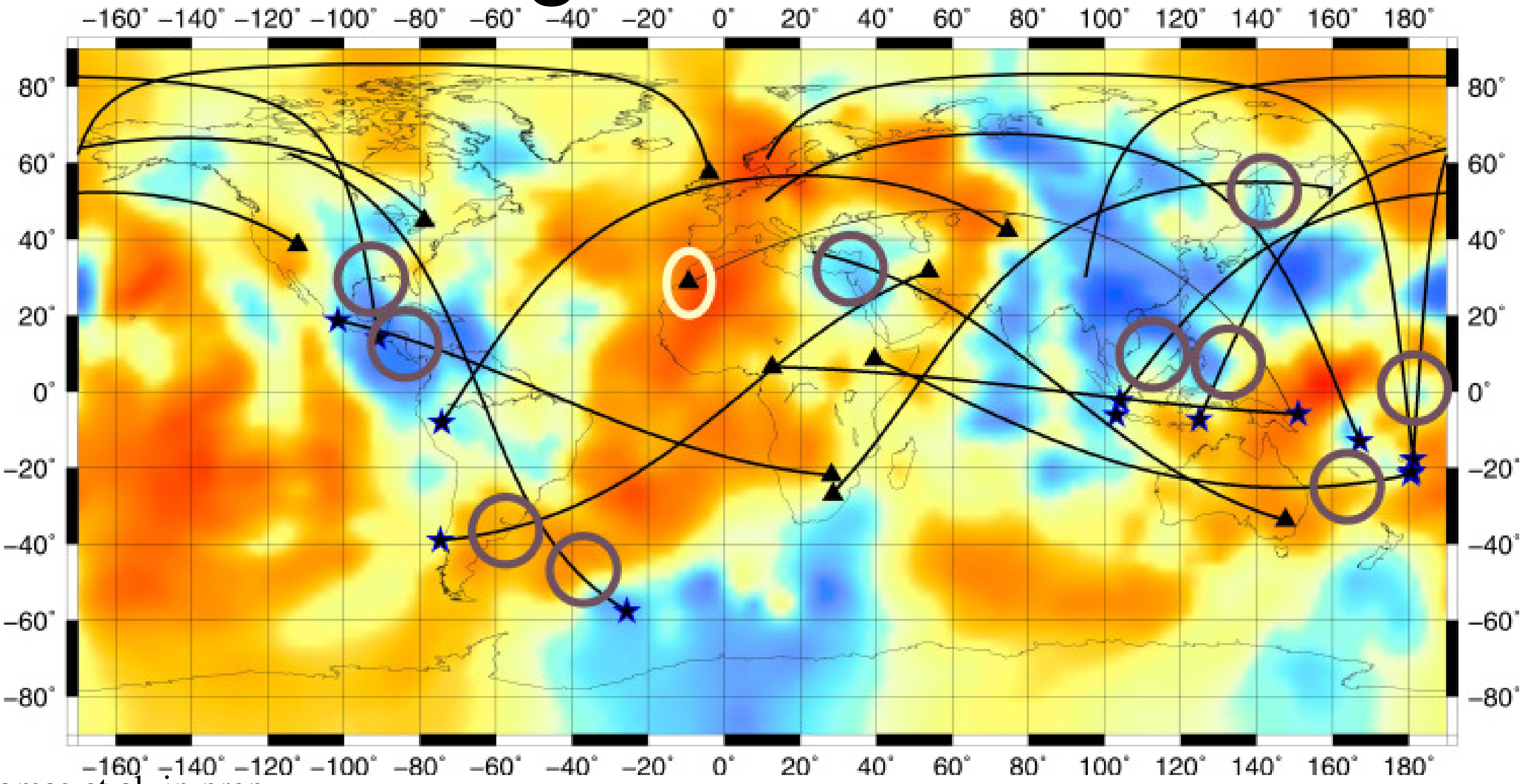
near margins of low-velocity regions

ulvz

courtesy, Ed Garnero,
also McNamara et al. 2010



scattering in the mantle …



Thomas et al, in prep.

Scattering observations: Haddon and Cleary (72), Doornbos (78), Husebye (72), Wen and Helmberger (98), Hedlin and co-workers (97,98), Thomas and co-workers (99, 09), Cao and Romanowicz 06, Vanacore et al. 09, and several others

Conclusions (D")

High-velocity regions

P-wave velocity contrast for Eurasia differs from Caribbean / SE Asia; S-wave velocity contrast is positive in both cases.

Possible Explanation*:*

A phase transition to post-perovskite (ppv) with 12% alignment of the ppv (different path with respect to direction of the slab)

Low-velocity regions

Sharp velocity contrast, steep sides and positive S (P) wave contrast up to 4 reflectors observed.

Possible explanation*:*

(Thermal or) thermo-chemical convection. Phase change? More data needed!

ultra-low velocity zones

observed in many regions but also "absence" of ulvz. Linked to convection in low velocity regions? Mechanisms? Link to scattering? (e.g. Bower et al. 2011, Wicks et al., 2010, Labrosse et al., 2007, Mao et al., 2006)