MYRES 2004

Seismic Constraints on Boundary Layers

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Outline

Seismic constraints:

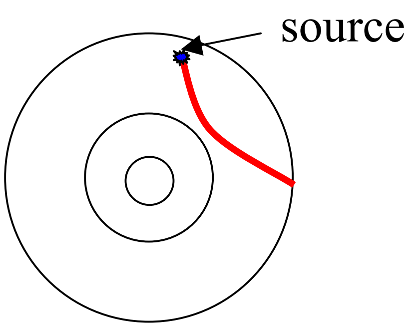
- what can we resolve?
- how can we detect seismic structures?
- how well can we resolve these structures? (resolution issues)

Boundary layers in the mantle:

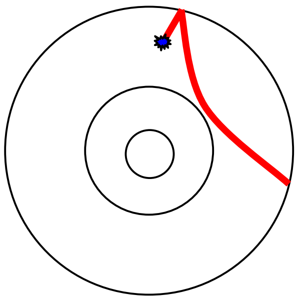
- core-mantle boundary
- D”
- mantle transition zone (660-410)
- upper mantle discontinuities
- other discontinuities in the mantle?

Overview - seismic phases:

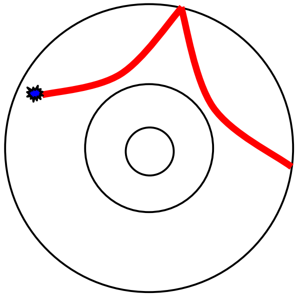
Direct waves: travel through layers without reflection (e.g. P, S)



Depth phases: travel first to the surface, then through layers (with or without reflections), e.g. sS, pP, sP



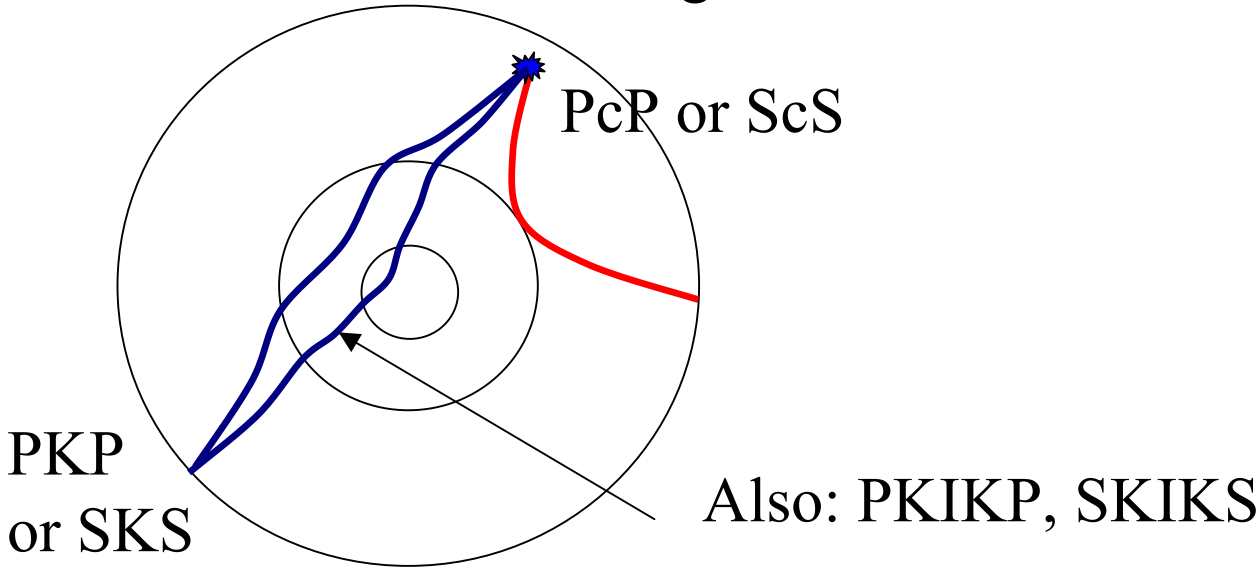
Multiples: wave that arrives at surface, reflects and travels through Earth again, (SS, PP, PPP etc)



Overview - seismic phases:

Names of phases: Different layers of the Earth are denoted by different letters:

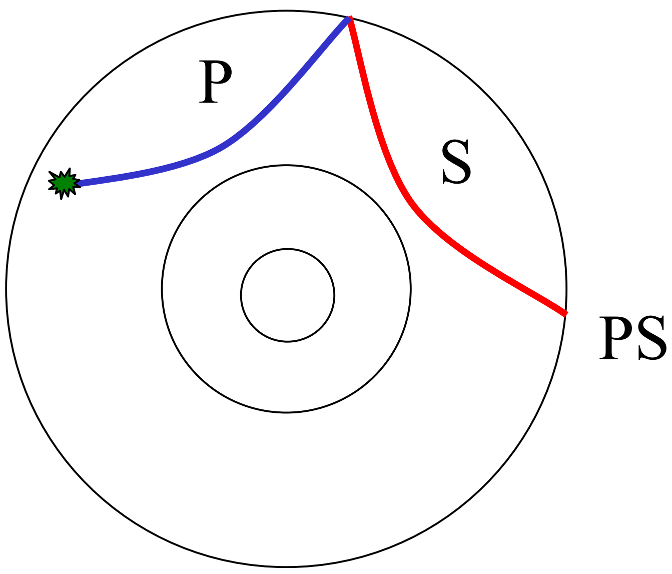
K - transmission through core (P-waves)
c - reflection from core-mantle boundary (CMB) – P and S
I - transmission through inner core (P-wave)
i - reflection from inner core boundary (ICB) – P and S
J - transmission of S-wave through inner core



Overview - seismic phases:

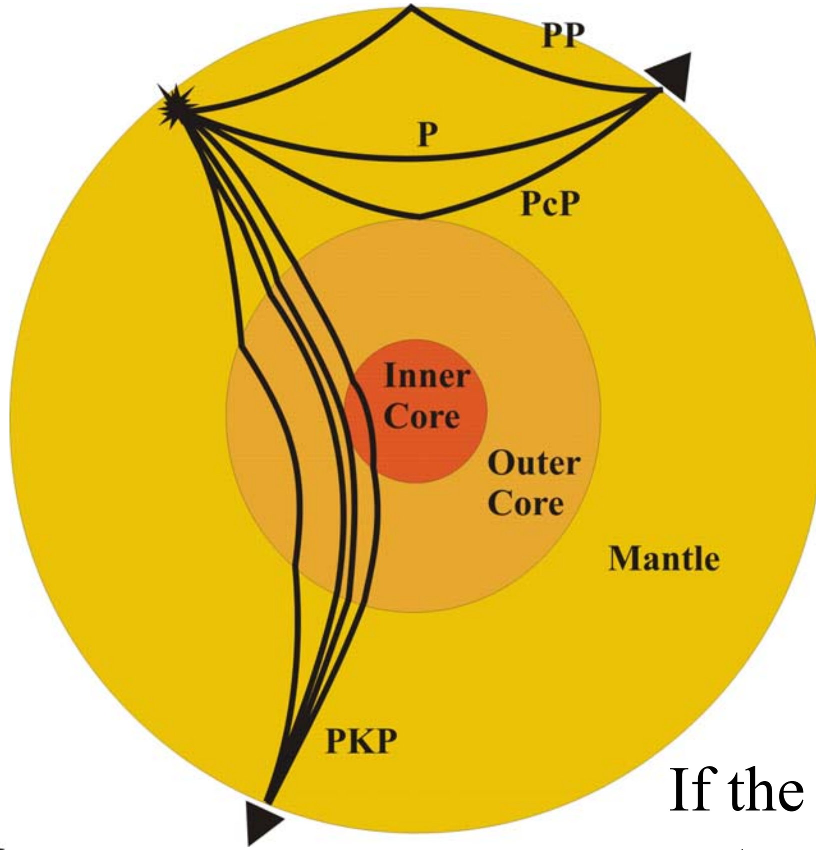
And then there are conversions between P and S!

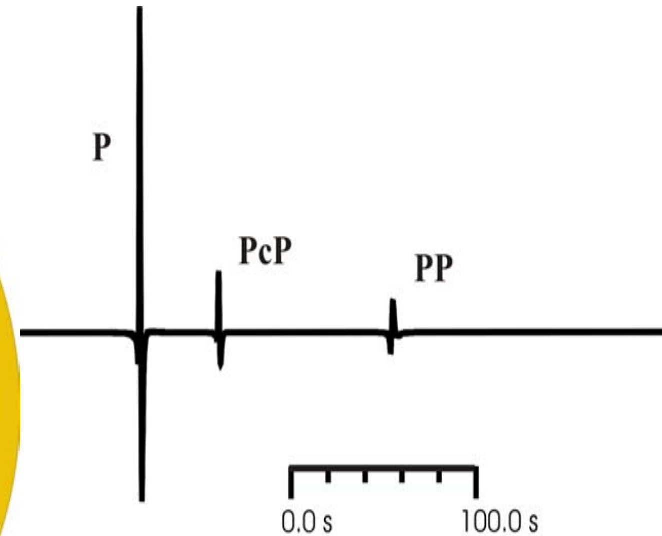
For example: PS starts as P-wave, reflects at surface and converts to S wave and second leg travel through the Earth as S wave.

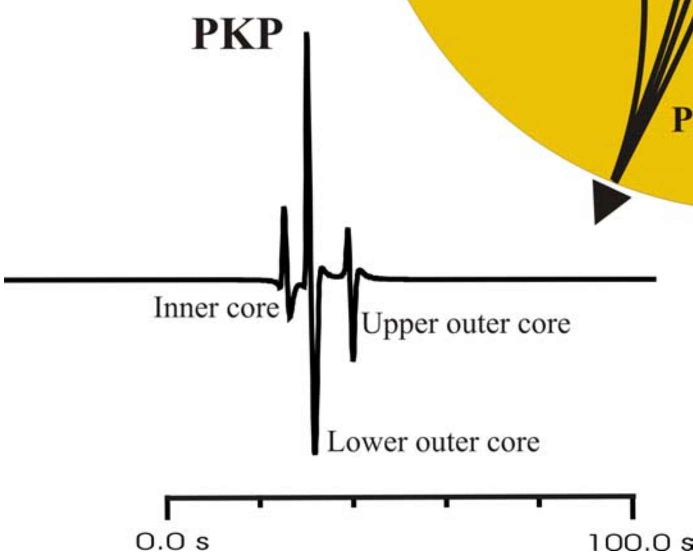


Combination with depth phases and core phases, other multiples etc are possible…

A simple Earth





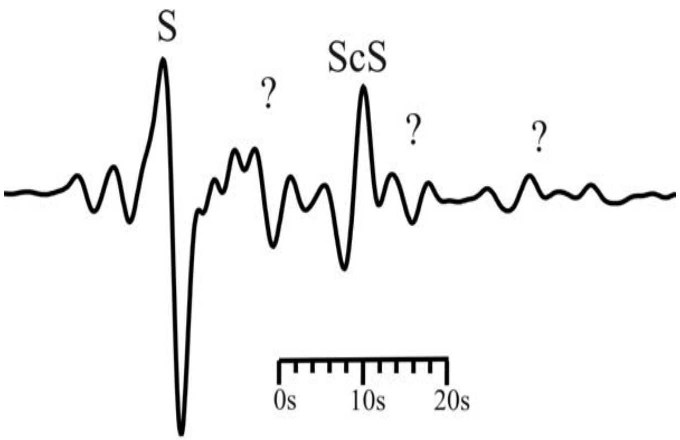


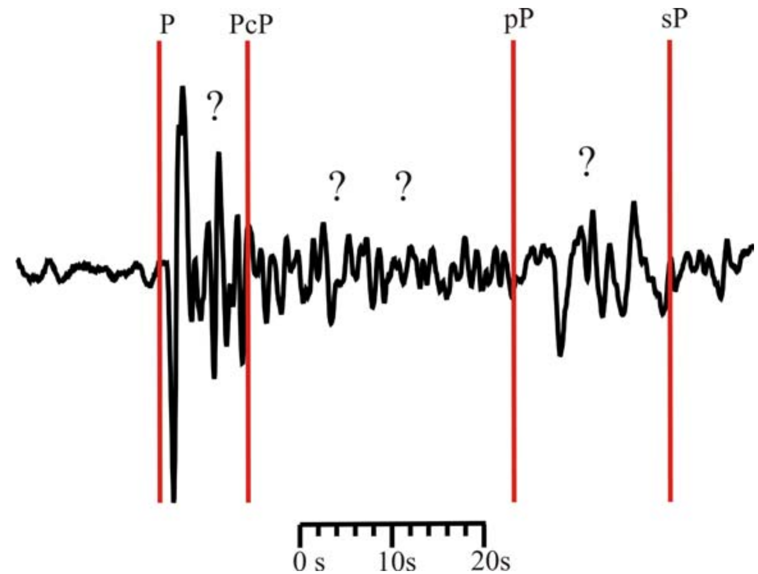
If the Earth only had mantle, outer and inner core (no other layers):

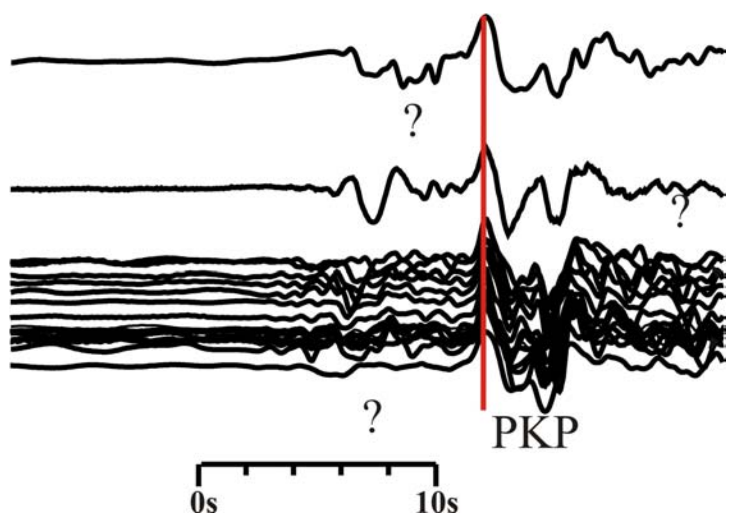
(higher order multiples and depth phases not shown)

A not quite so simple Earth

Real seismograms show that the Earth is more complex:

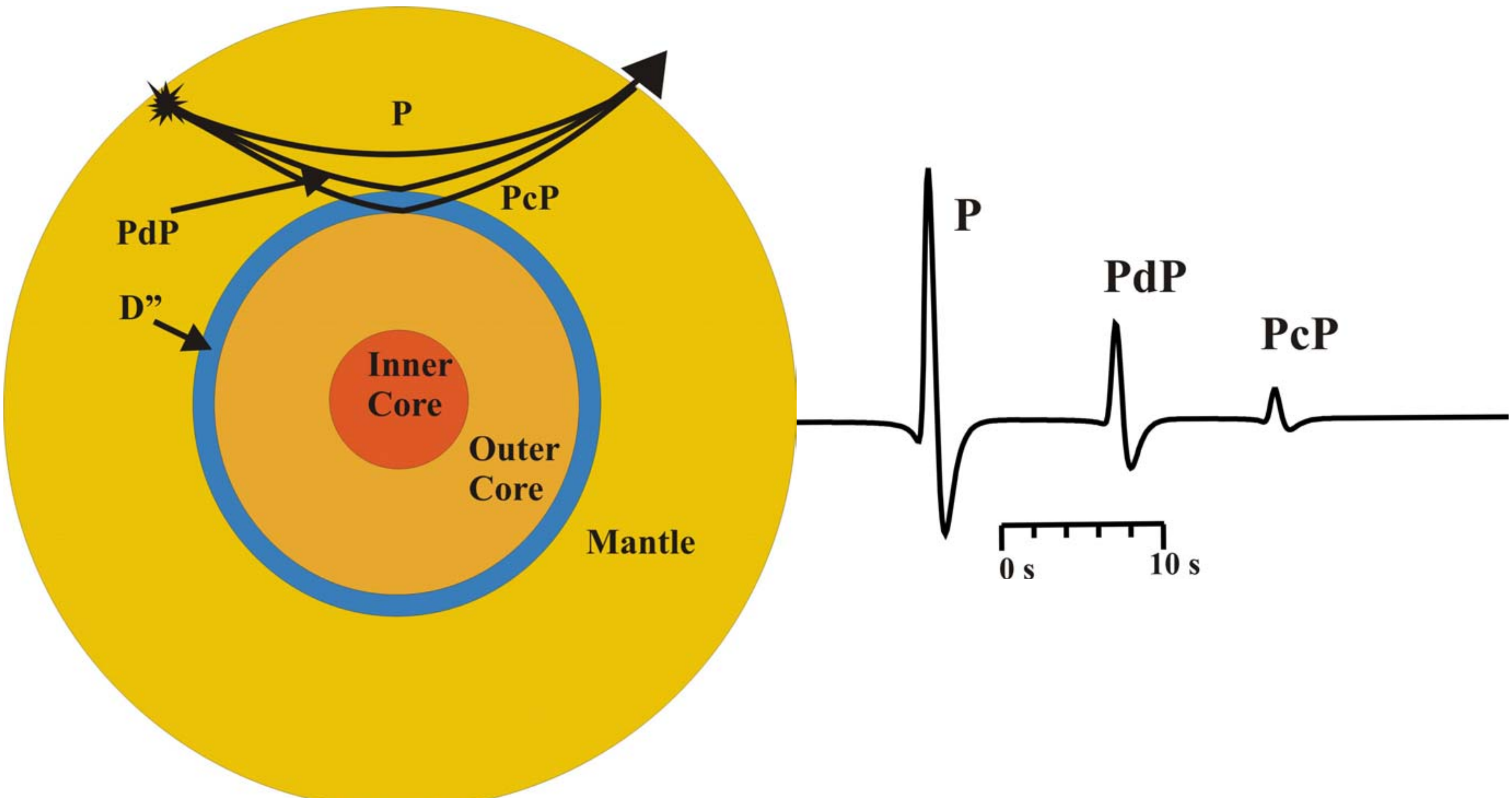






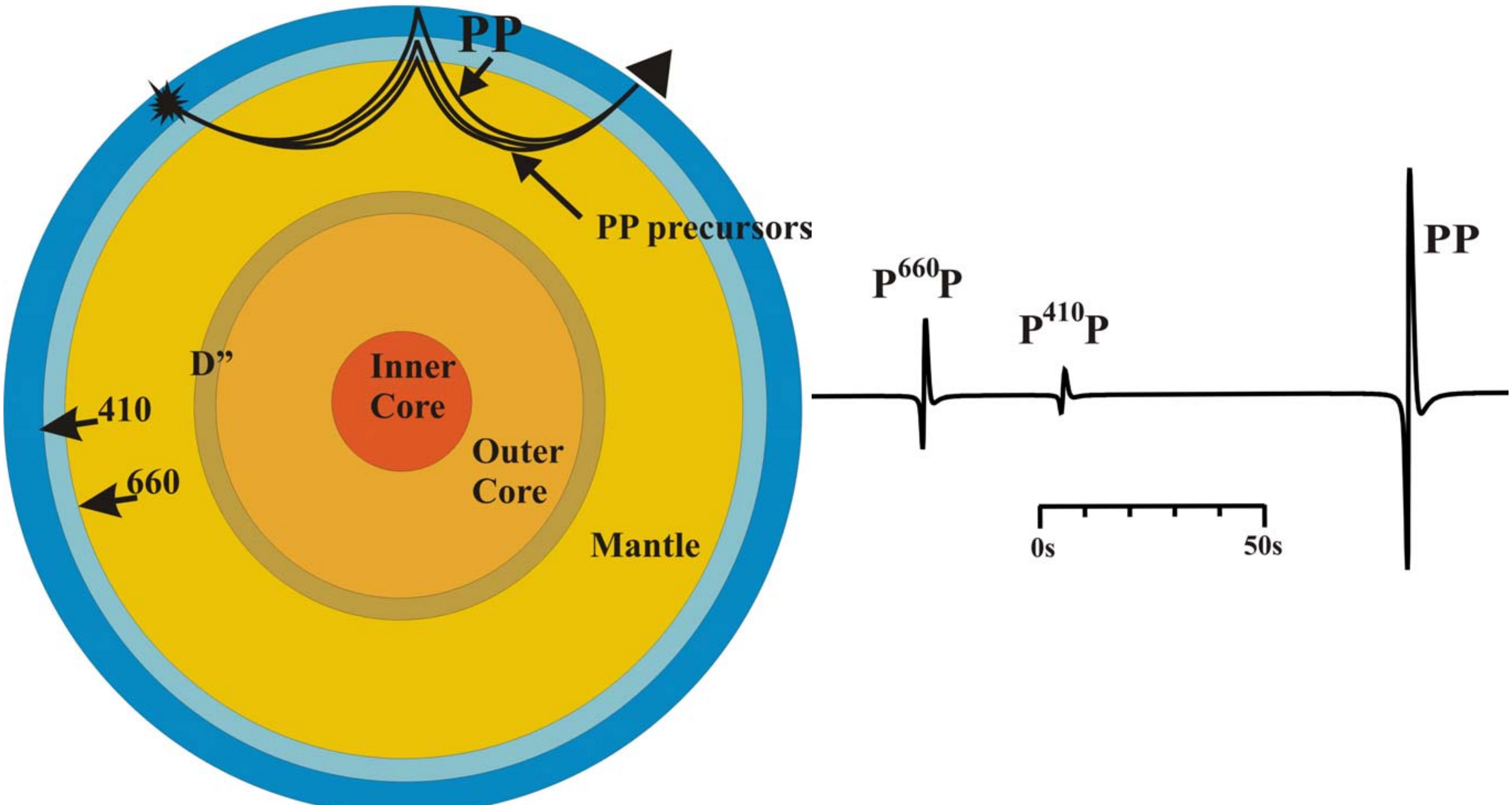
More layers in our simple Earth

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



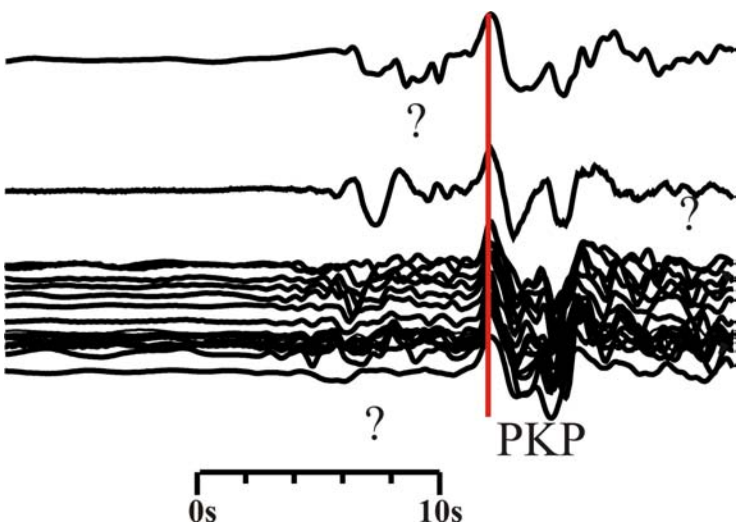
More layers in our simple Earth

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



More structure in our simple Earth

Small scattering objects in the Earth's mantle cause seismic waves to leave their paths, which is otherwise given by Snell's law (i.e., refraction angle is given by the ratio of velocities above and below the discontinuity).
Waves arrive as 'scattered waves'.



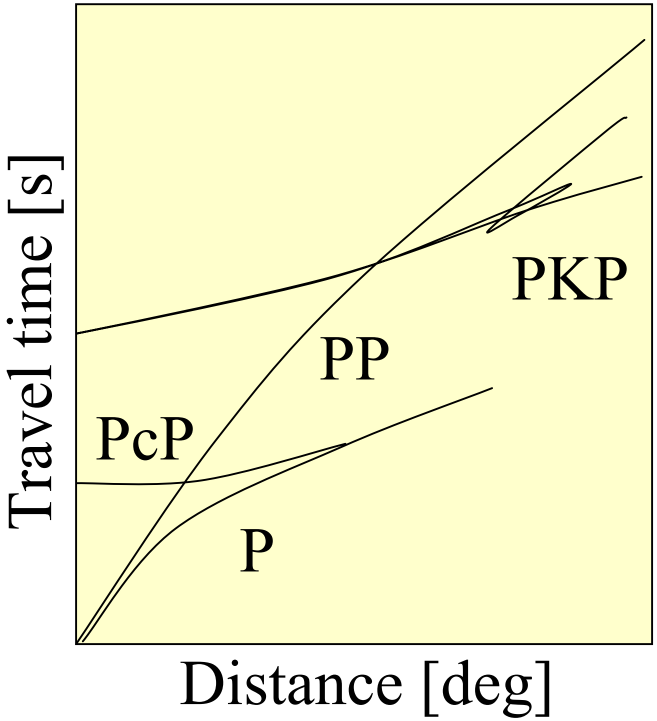
Hot abyssal layer or Stealth Layer (L. Kellogg et al., 1999) – hypothetical layer in the mid-mantle – would produce additional arrivals in seismograms

Any additional structure would give a new signal in seismogram

Ways to analyse data

- Waveform modelling
- Travel times (raytracing)
- Global stacking
- Differential travel times
- Array seismology

Can either concentrate on arrival times or waveforms or both



Travel times studies rely on 'Travel time curves'

Analysing Data

- Waveform modelling – looking at a wave that arrives at station. if not the same as predicted by Earth model: change model, compare waveforms again …

- Travel times/differential travel times – additional arrivals in seismograms. Arrival time can give indication of depth and place of structure

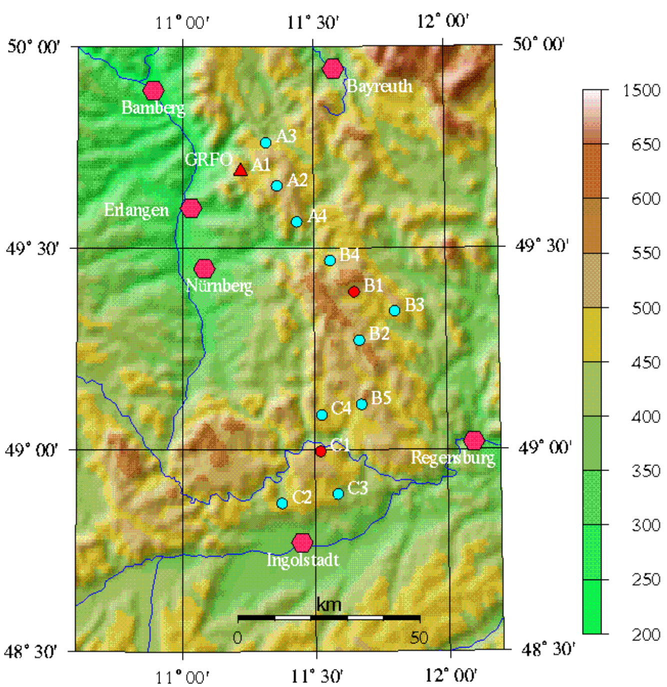
  Travel time of known phases – can give indication of velocities on path (Tomography)

- Global stacking – search for global differences in reflections or presence or absence of waves.

Analysing Data

- Array seismology Arrays allow to use directional information to identify waves.

important parameters:
(horizontal) slowness and back-azimuth



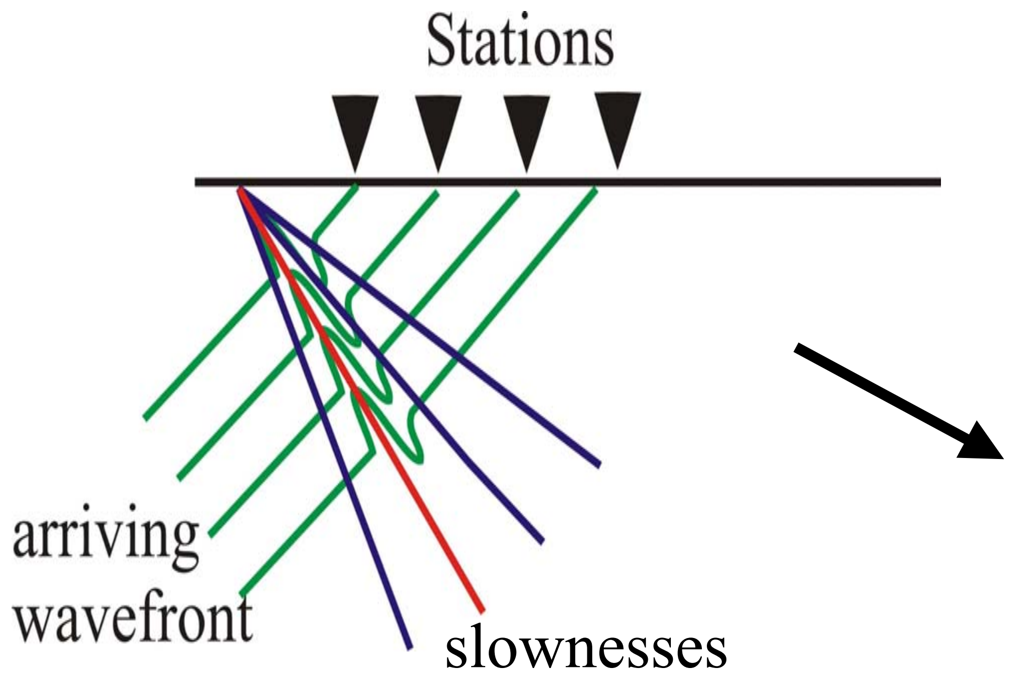
Gräfenberg array

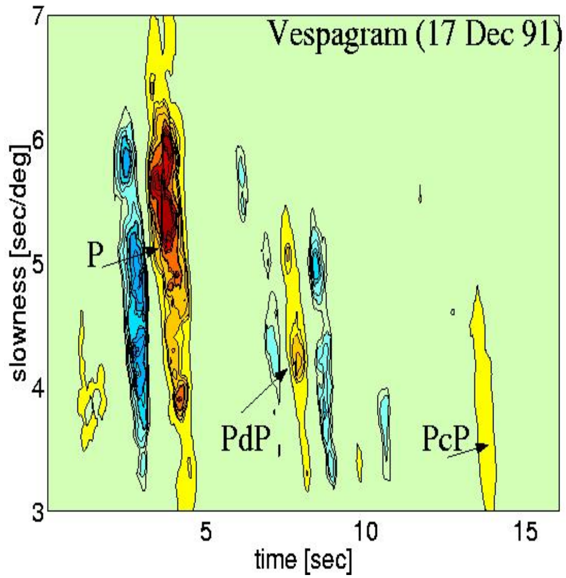
slowness: $\vec{u}$ direction of wave propagation modulus is reciprocal of wave speed

back-azimuth: angle in horizontal plane measured at receiver w.r.t North

Array seismology methods

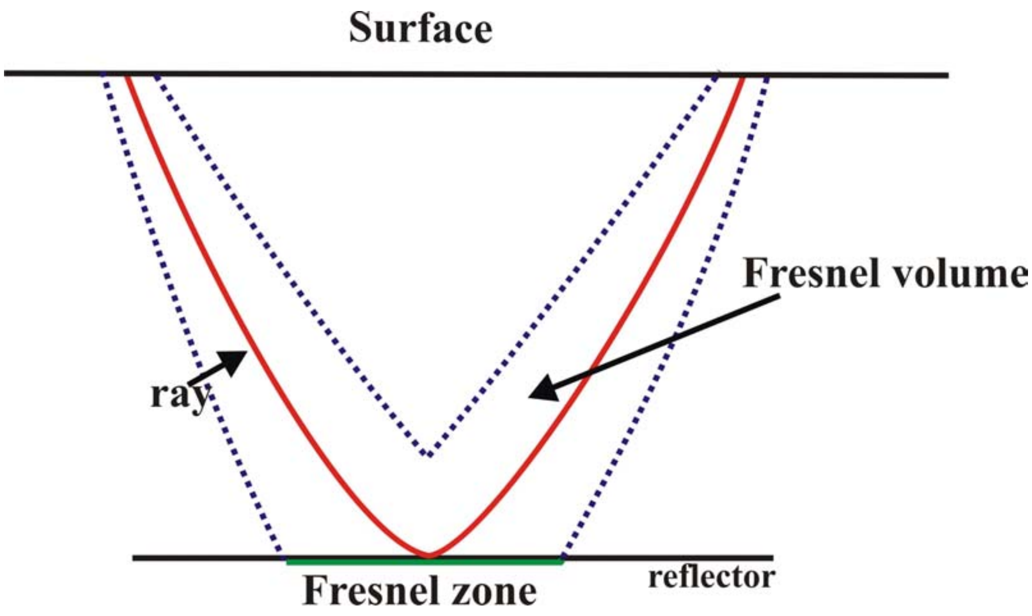
All methods are based on shifting and summing traces

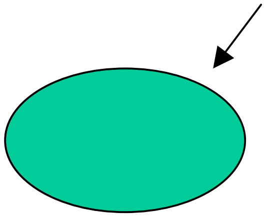




vespagram
slowness or backazimuth versus time

Resolution – Fresnel zone





view from top

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

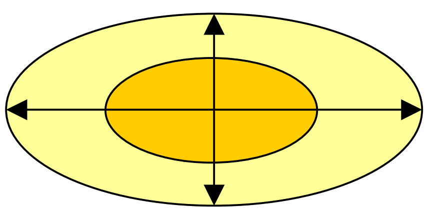
Size of Fresnel zone depends on: frequency, depth of reflector, and seismic velocity ($\Rightarrow$ wavelength).

Resolution – Fresnel Zone

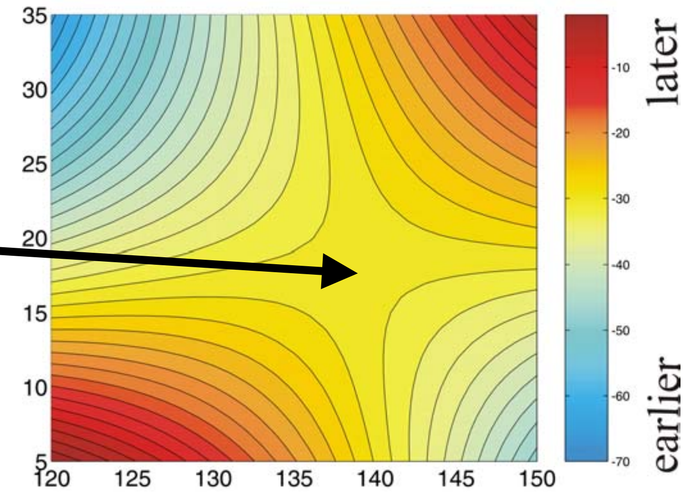
What does that mean? If we deal with a strictly layered (1D) Earth our resolution is only as good as the size of the Fresnel zone!

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

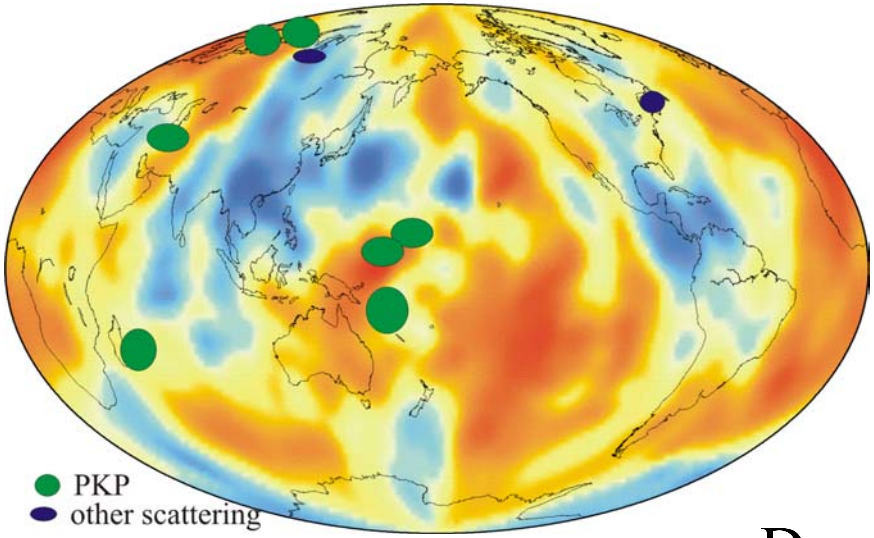
(1 degree ~60km at the CMB)



But PP precursors have a different Fresnel zone:



Resolution – what can we resolve?

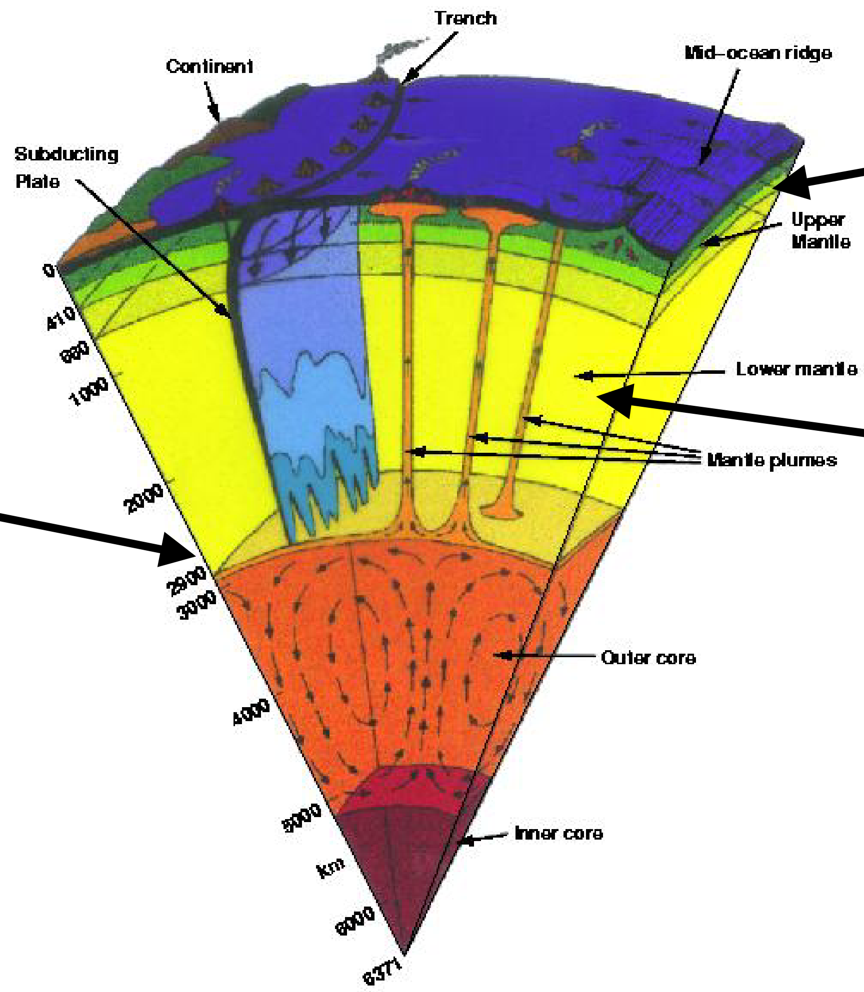


Does that mean we don’t see scattering in all other places? NO

Does it mean we haven’t been able to look in other places? YES

We need suitable source receiver combinations to study different structures. This is not always possible for all the regions of the Earth!

Boundary layers in the mantle



2) Transition zone

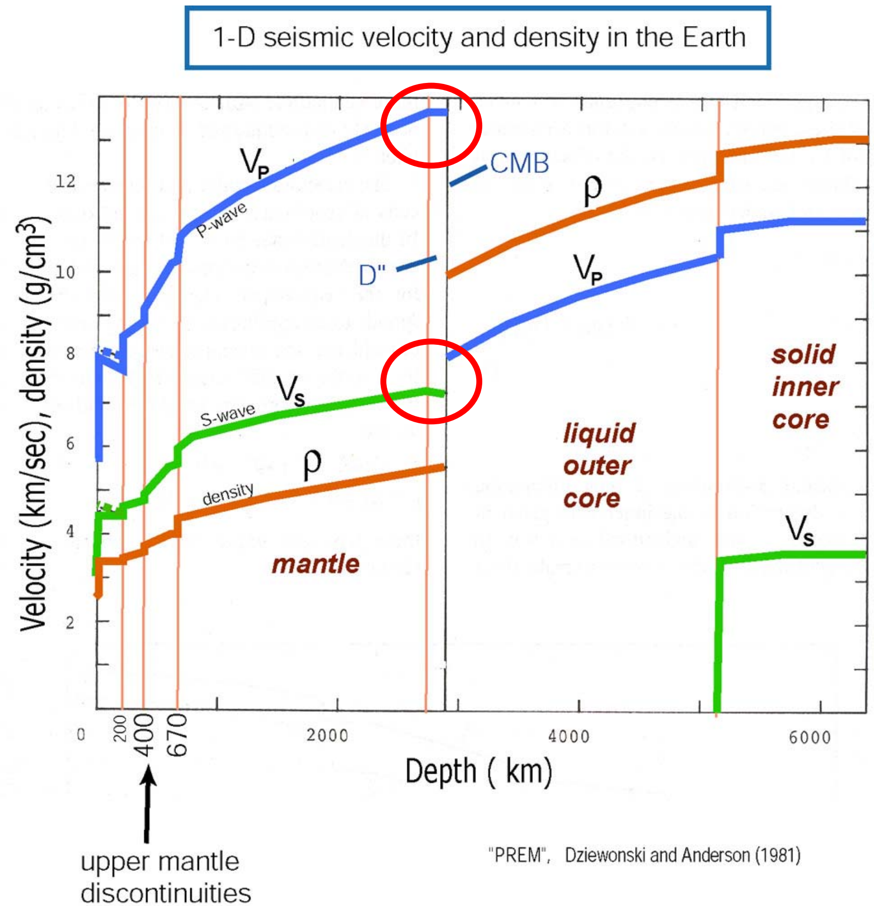
3) possible mid-mantle reflectors?

1) D” region

after Strohbach

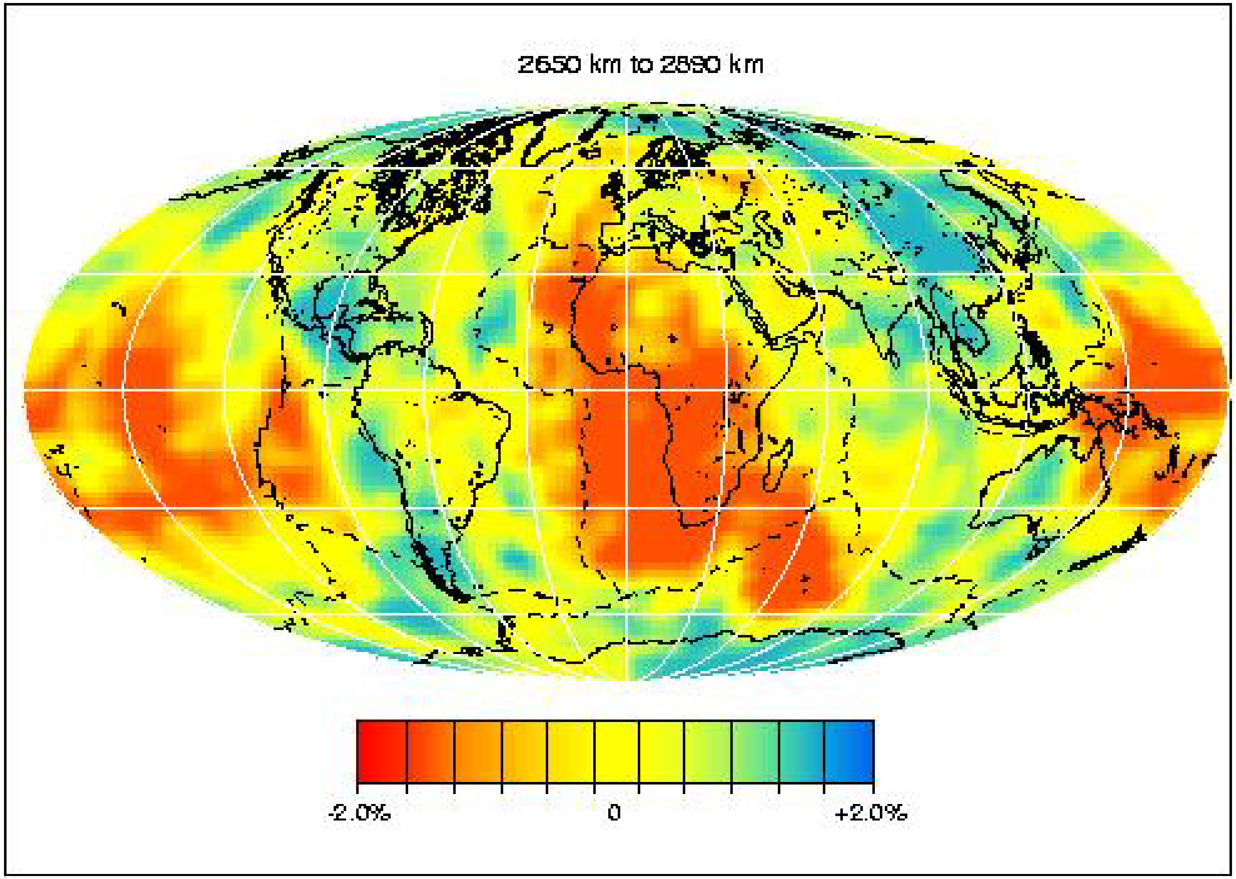
D” region

For a long time it has been recognised that the D” region in the Earth’s mantle is different from the rest of the lower mantle



e.g. Earth models such as JB, PREM, IASPEI91 etc contain a region of different velocity gradients in D”.

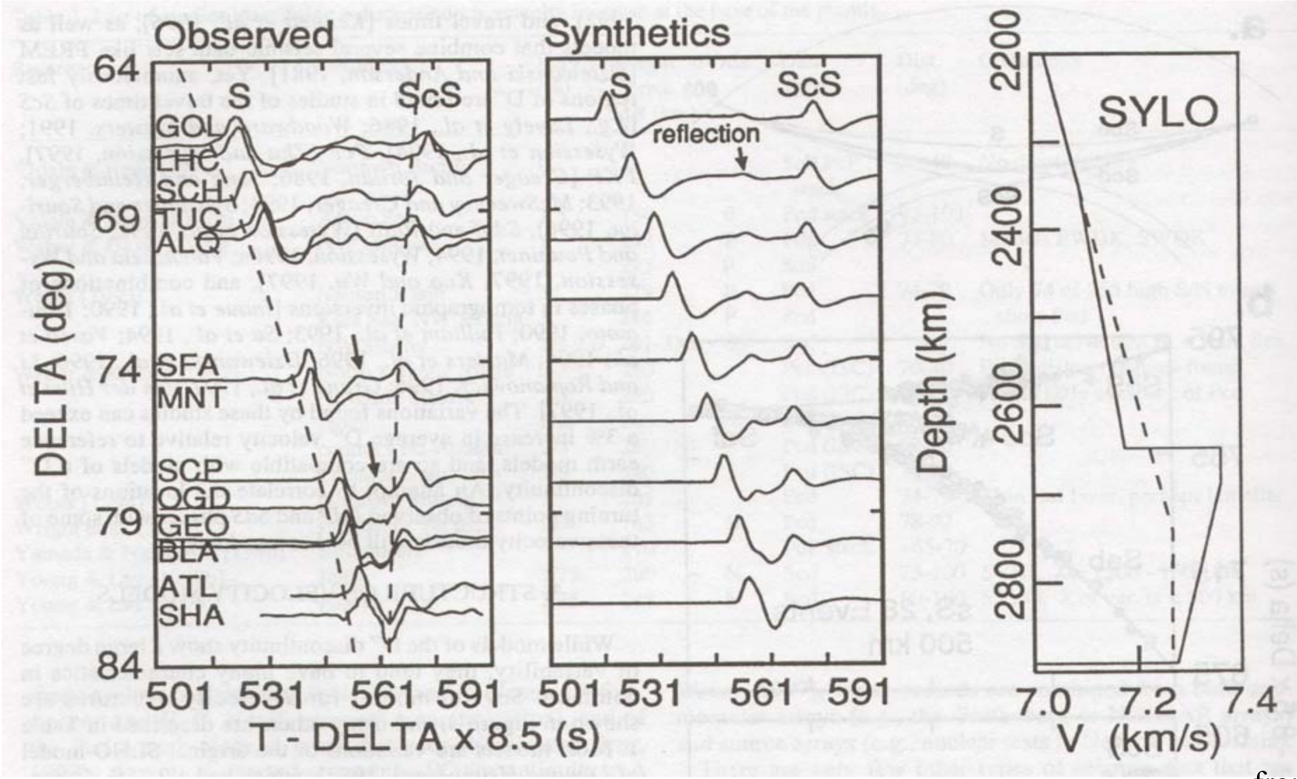
Tomography in the lowermost mantle



from Grand et al 1997

fast velocities around Pacific,
slow velocities under Africa, Mid-Pacific

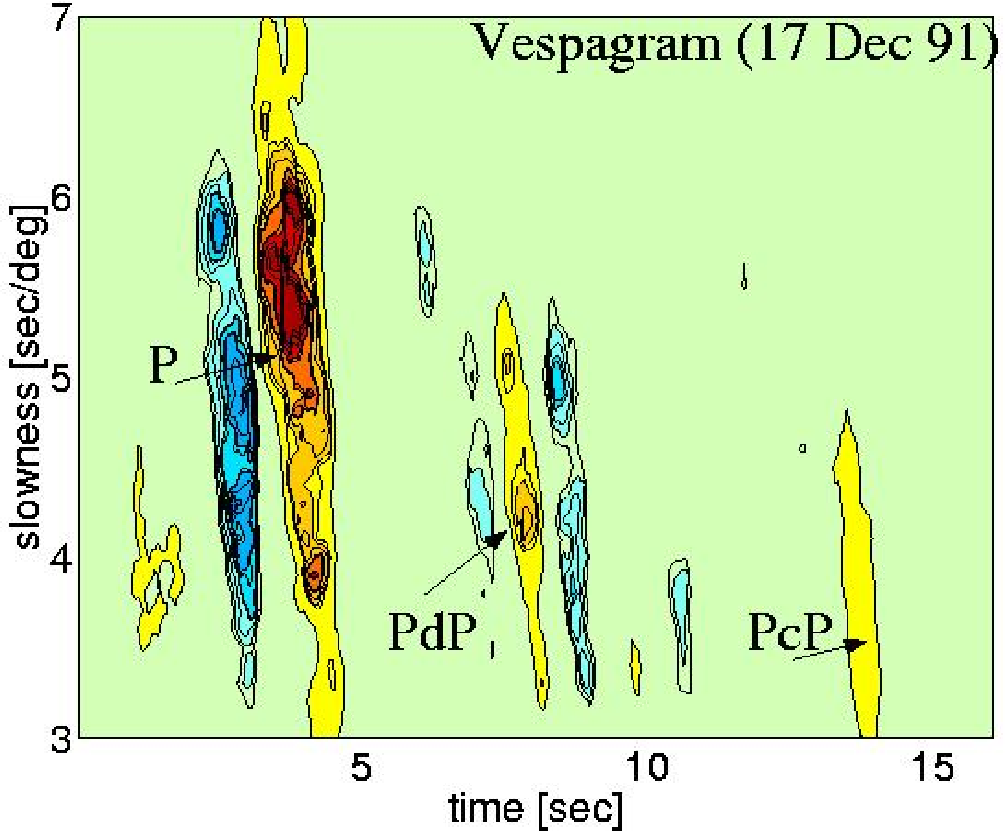
D'' discontinuity

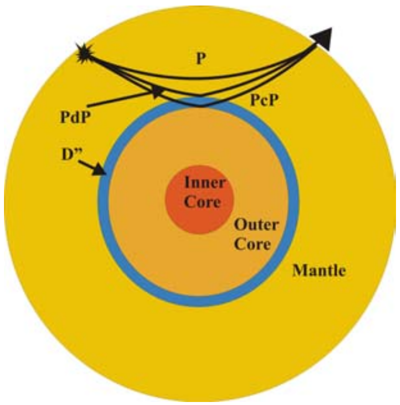


from Wysession et al 1998

Observations like these showed a discontinuity that can explain additional arrivals between S and ScS
(the first observation was by Lay and Helmberger, 1983
and many more followed)

D" discontinuity

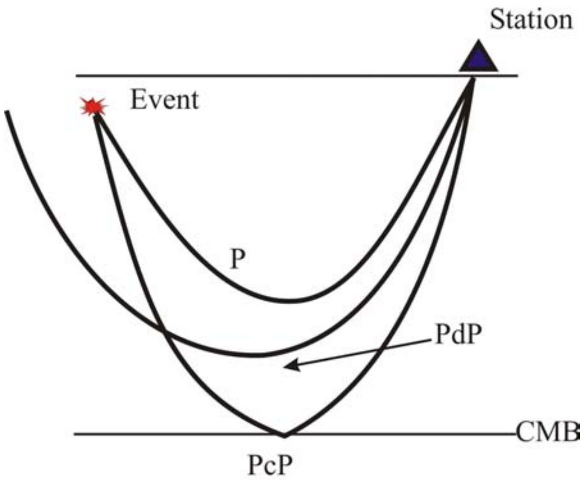




Using arrays we can use slowness information to detect coherent arrivals less ambiguously.

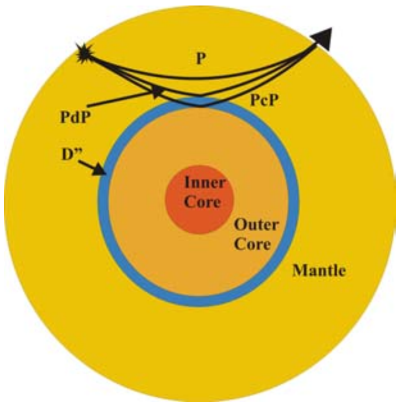
But how do we know it's a wave that's reflected in the lowermost mantle?

D” discontinuity

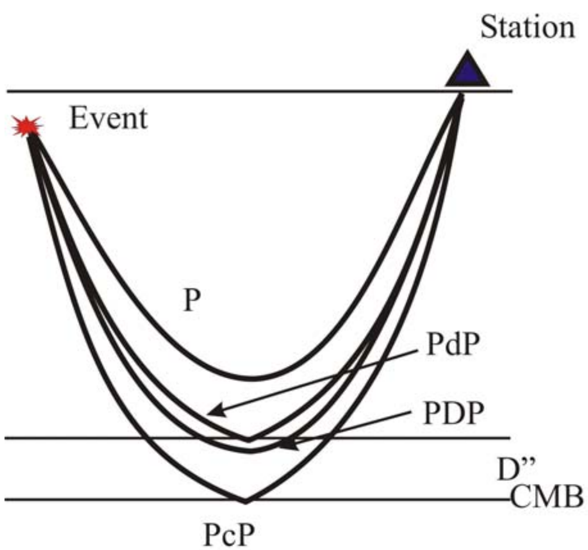


Raypaths

The slowness gives the angle of incidence at the array. Shooting a ray back with this angle gives the endpoint of the ray – should be the same place as P and PcP…

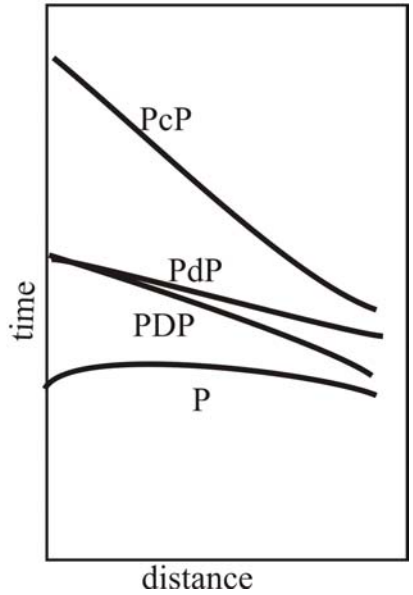


To make the rays end at the same point we need a reflector in the lowermost mantle



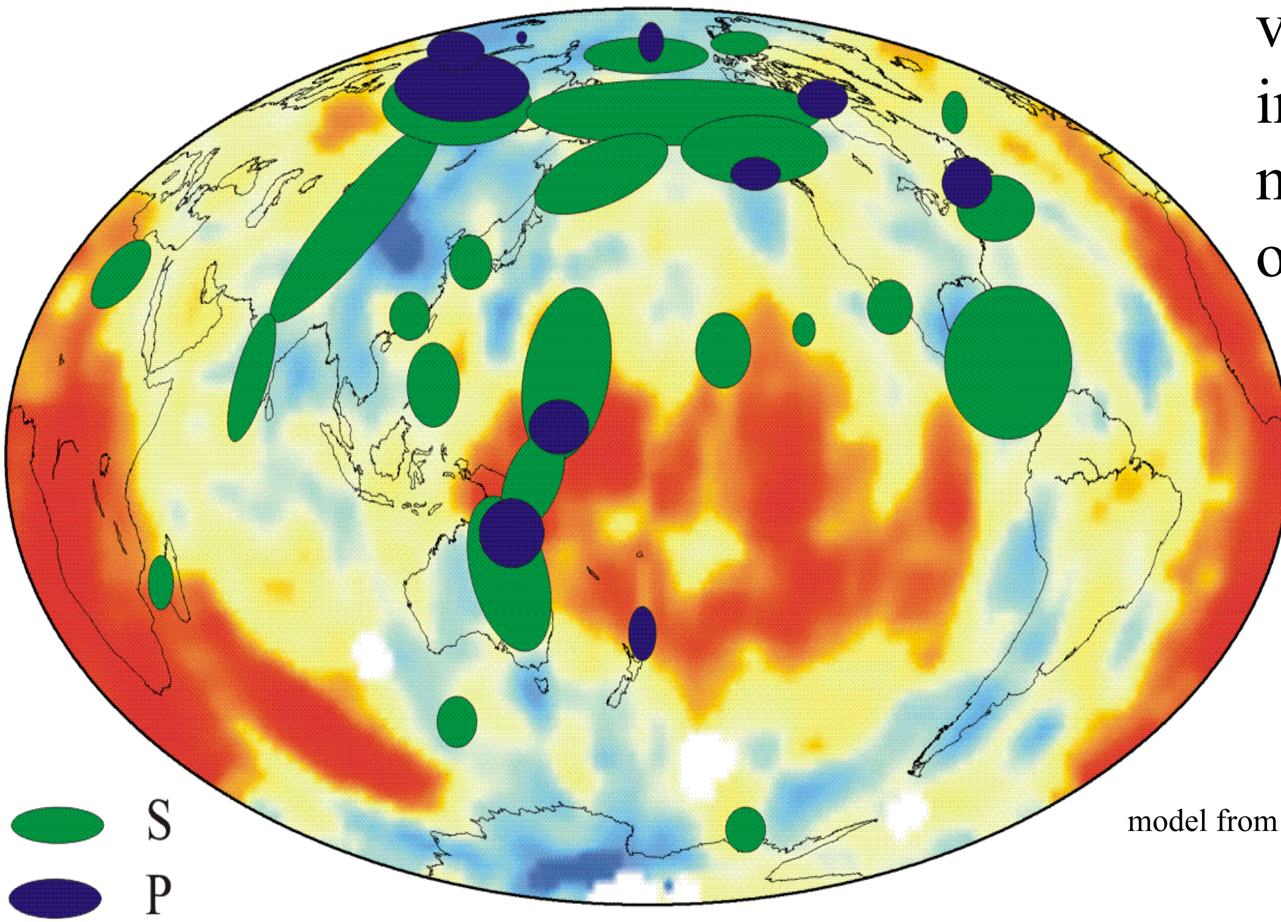
Raypaths

Travel-time curve



D" discontinuity

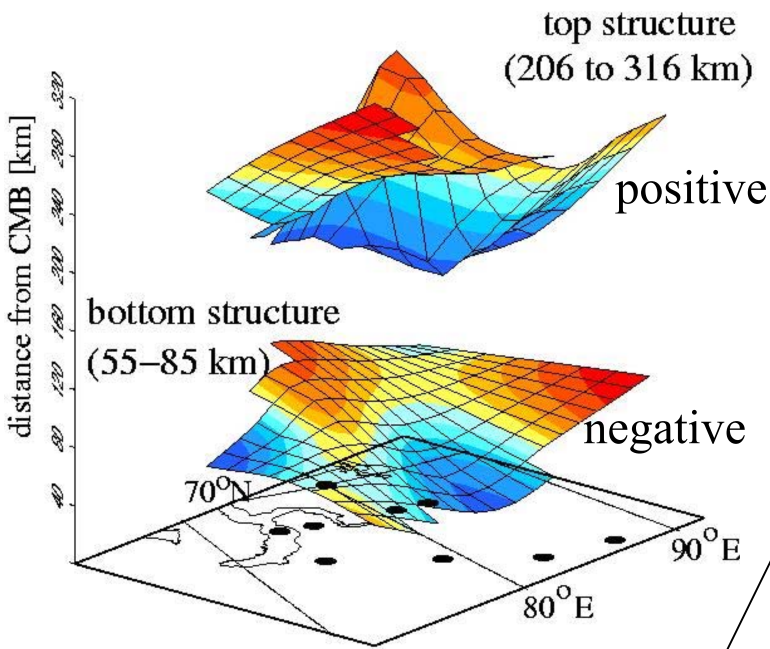
velocity increases in S- and P-wave models but not observed globally



model from Grand et al 1997

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, and many more.

D” discontinuity – fine-scale

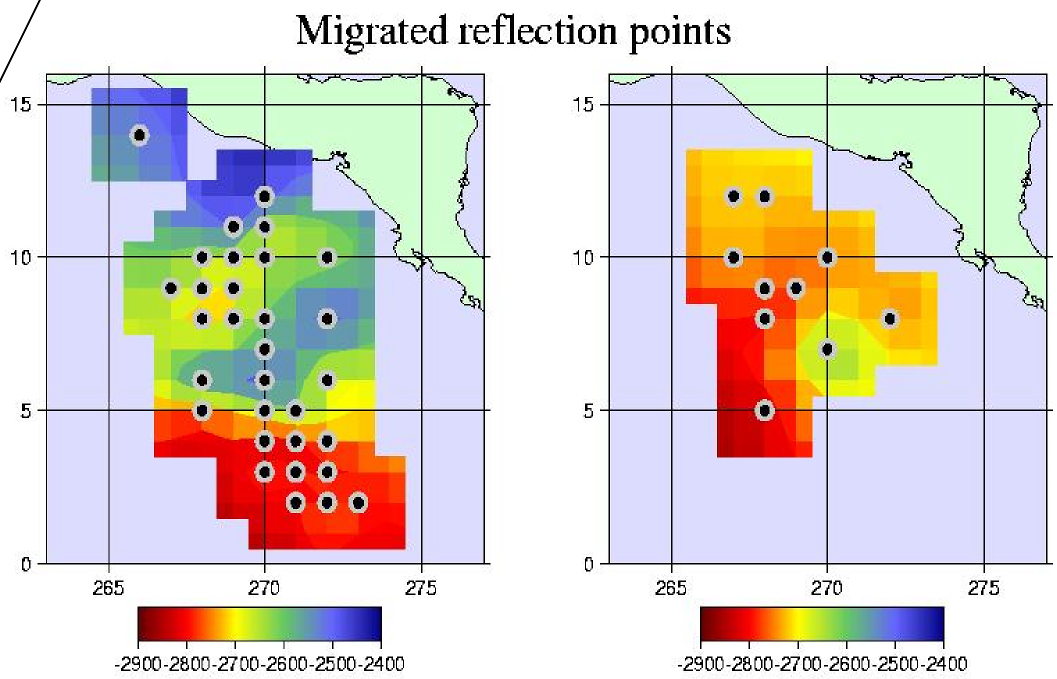


under Eurasia

under Caribbean

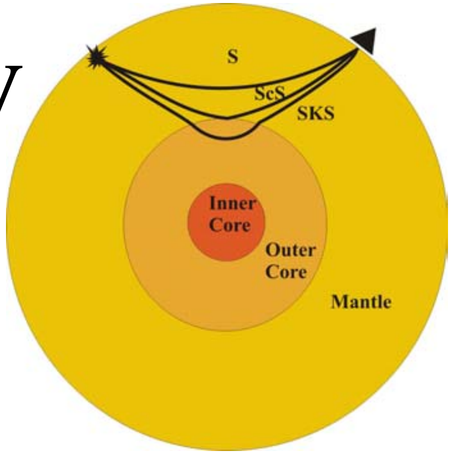
upper (positive) reflector

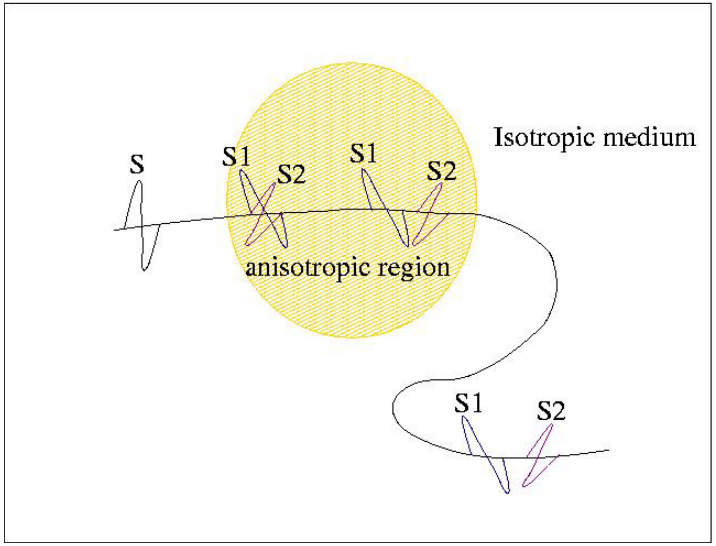
lower (negative) reflector



These results have been obtained using array methods, especially migration

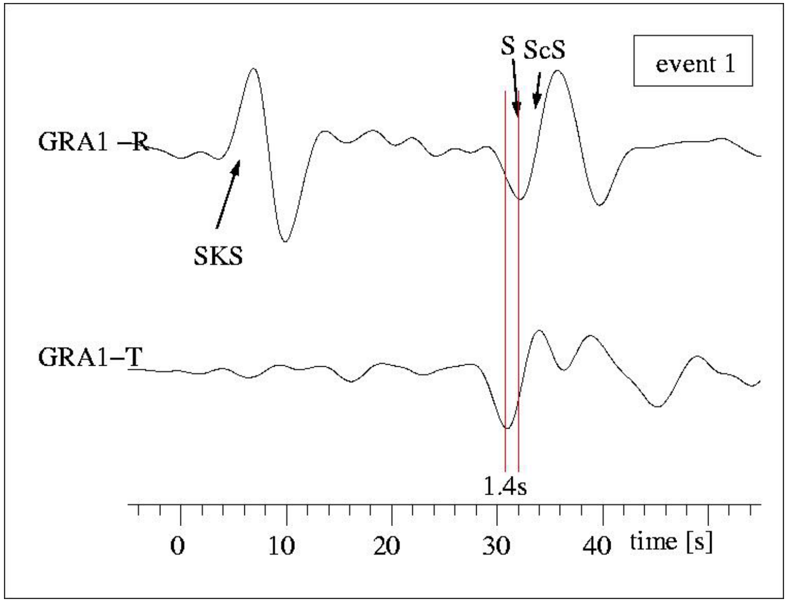
Other D" features - anisotropy





In anisotropic region S wave splits in fast and slow component.

For layered medium this would produce a time delay between radial and transverse components in a seismogram.

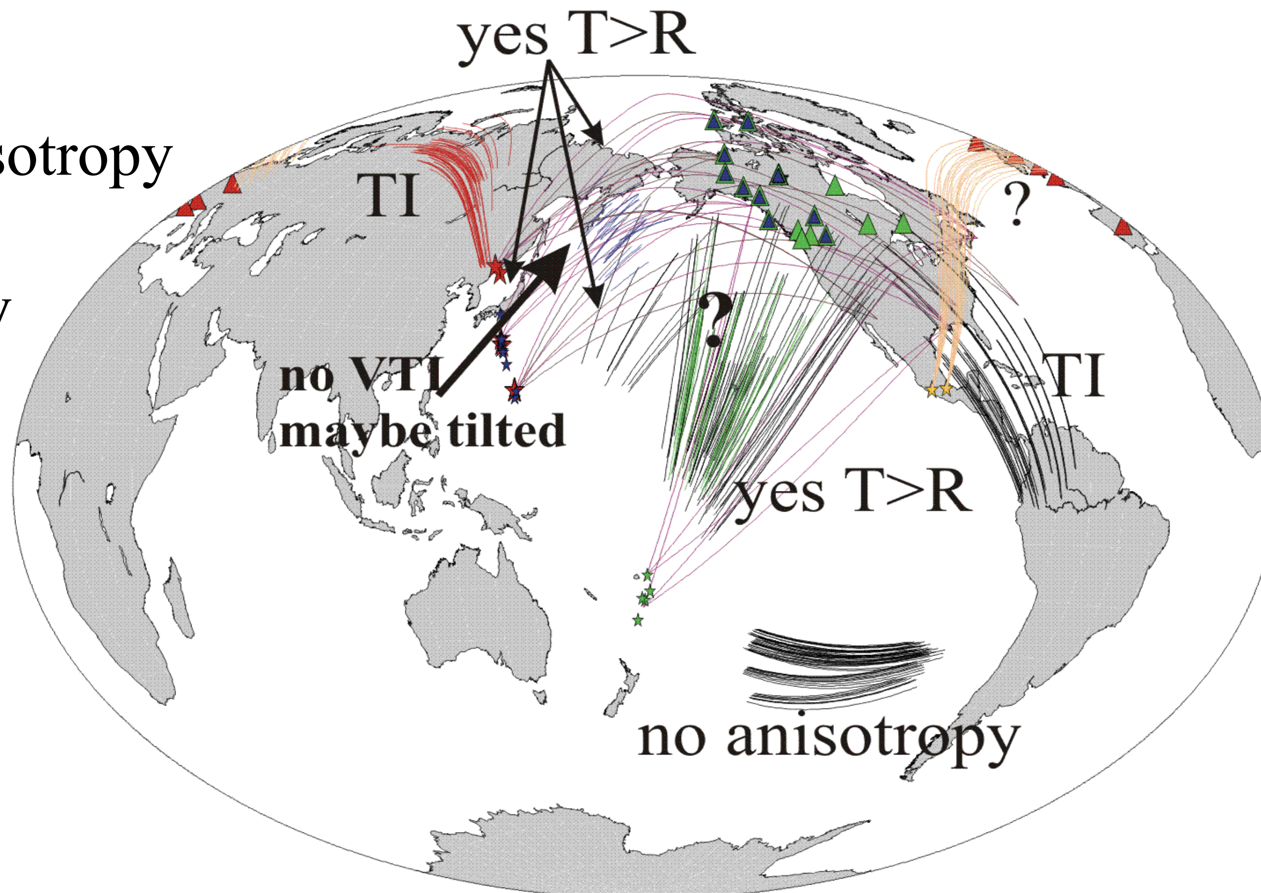


Other D" features - anisotropy

(V)TI:
(vertical) transverse isotropy
(vertical symmetry axis - e.g. horizontally layered medium)

under Central Pacific:
azimuthal anisotropy and not clear

under South Pacific:
no anisotropy observed



Data from: Lay and co-workers, Garnero and co-workers, Kendall and Silver 1998, Thomas and Kendall, 2002, Heesom 2001, Fouch et al 2001, etc.

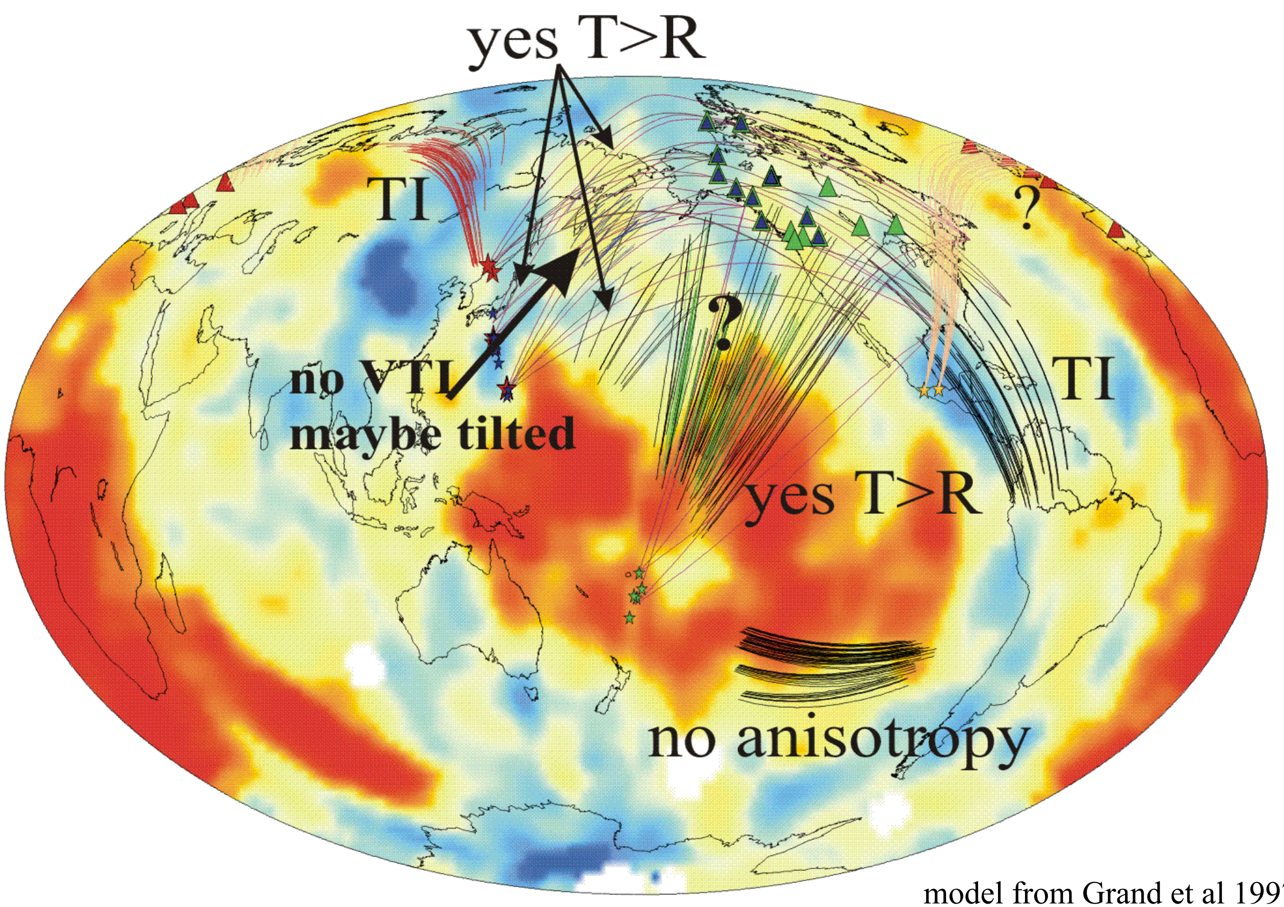
Other D” features – anisotropy

circum Pacific:
mostly VTI

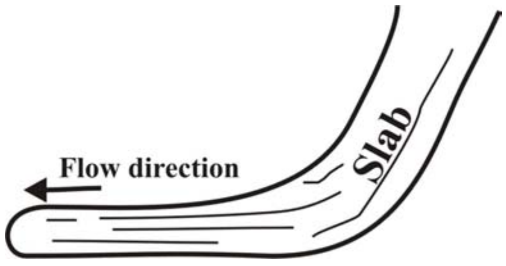
strong in regions with high velocities

weak anisotropy in regions with moderate velocity decrease

intermittent azimuthal anisotropy below Central Pacific

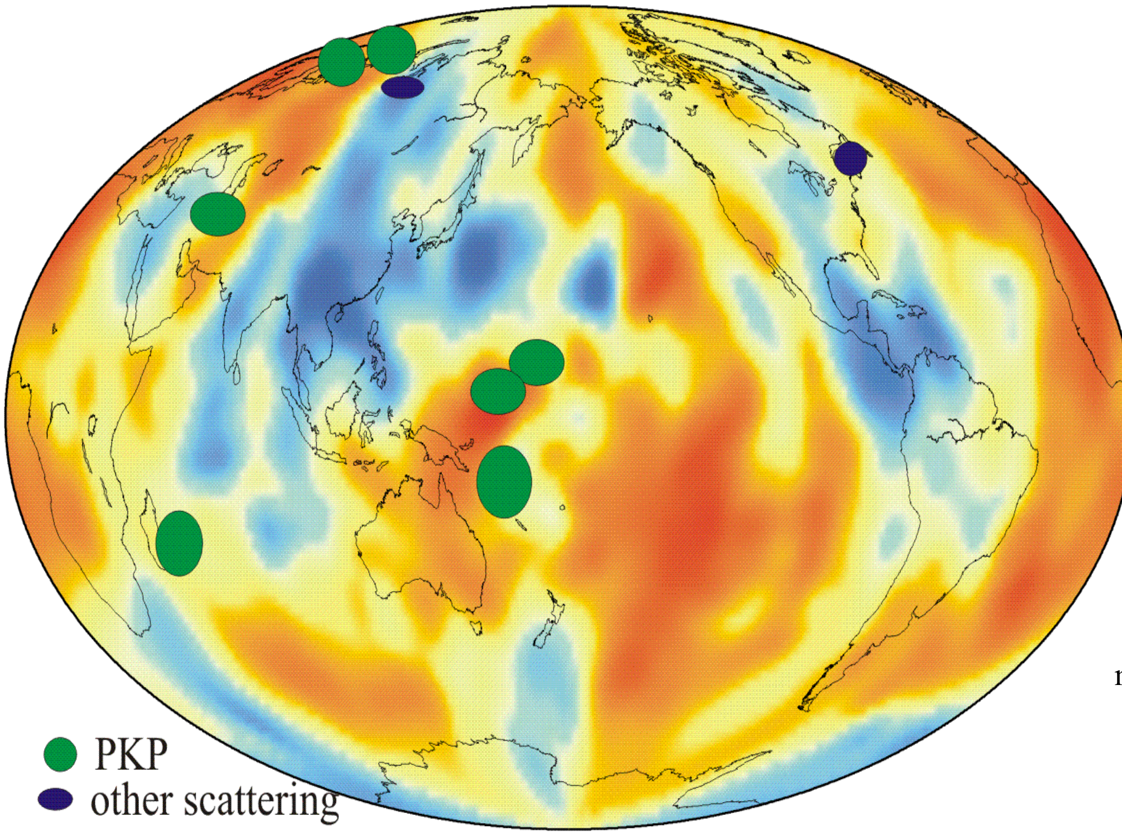


model from Grand et al 1997



Explanation could be slab in D”.
(for example: sheared zones of partial melt)

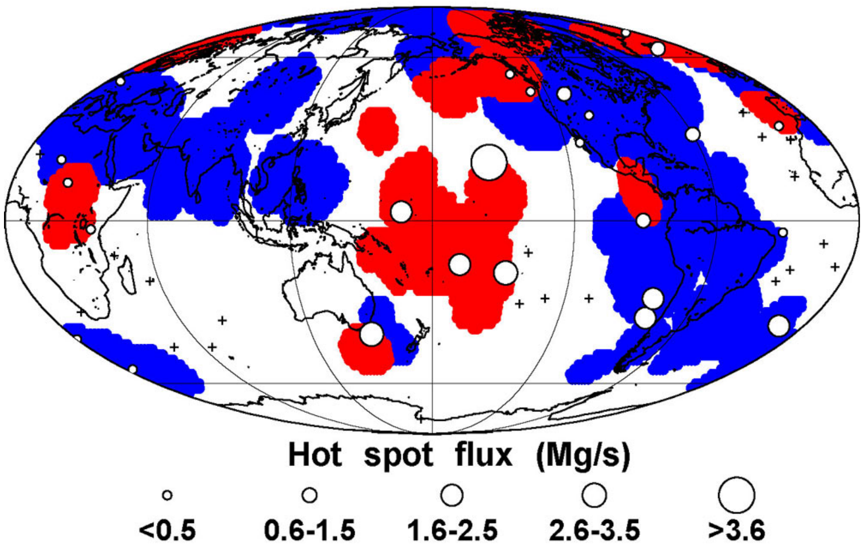
Other D” features – scatterers



model from Karason & van der Hilst, 2001

PKP-data from Wen and Helmberger (1998), Thomas et al. (1999), Vidale and Hedlin (1998), Haddon and co-workers (1970s), Doornbos and co-workers (1970s), etc
other scatterers (D” phases): Freybourger et al. 2001, Braňa and Helffrich (2003), Wallace and Thomas (2003)

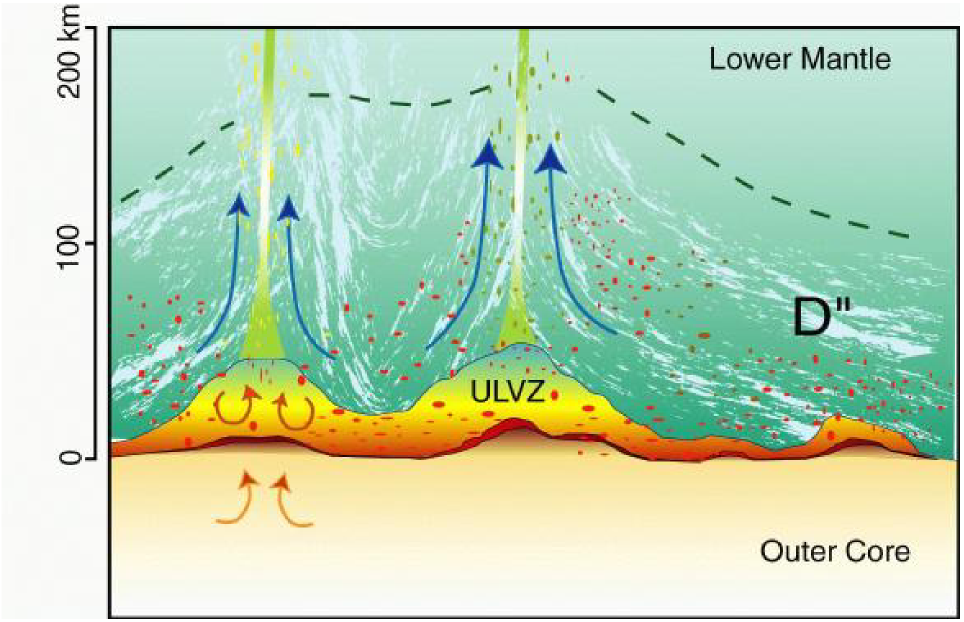
Other D” features – ULVZ



red: regions with ULVZ
blue: regions with no indication for ULVZ

Correlation with hotspots?

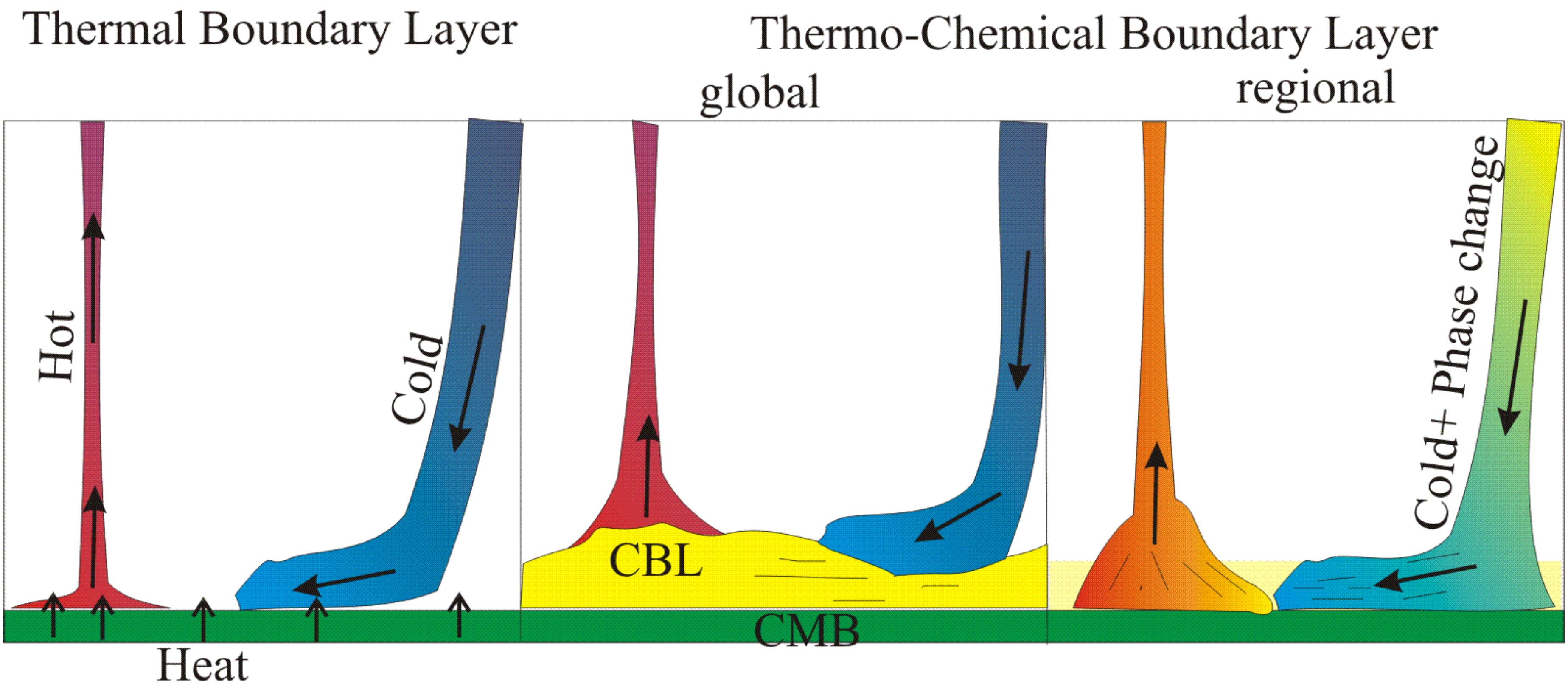
from Garnero, 2000



from Garnero, 2000

What is D”

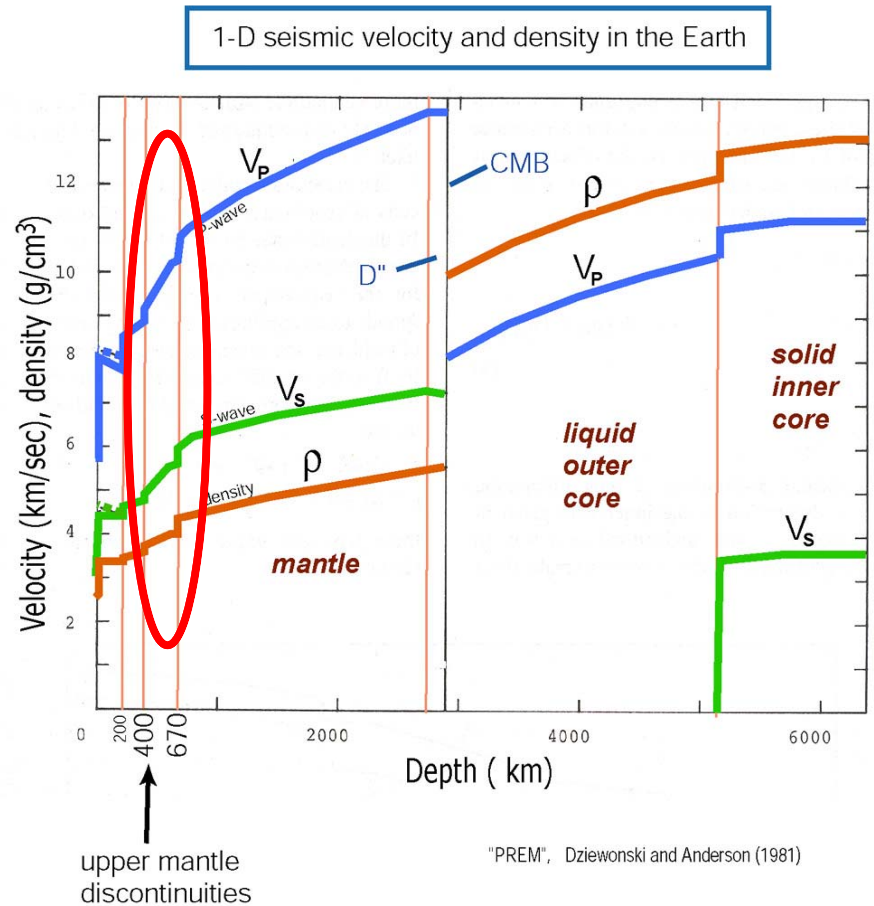
As the lower boundary layer in the Earth’s mantle, D” could be:



thermal transition zone, chemical reaction zone, chemically distinct layer, resting place of slabs, origin of plumes, mineral phase change

Mantle Transition Zone

Upper mantle transition zone: 410 to 670 km
marked by discontinuities in seismic velocity.



Detection of 410 km and 670 km discontinuity. (olivin-spinel-perovskite)

In some areas, detection of 520 km discontinuity. Not globally detected yet.

Seismic Structure of TZ

410 km: P-vel. increase 5-6% S-vel. increase 4-7%
first order discontinuity sharp: 2-4km beneath oceans
35 km beneath continents
recently: complex: gradient and sharp transition
α to β sp exothermic with positive Clapeyron slope 3MPa/K

520 km: Controversial discussion of existence
artefact? There in some regions, absent in others?
few seismological observations
contrasts $\Delta vp = 1\%$ $\Delta vs = 0.8\text{-}1.5\%$ $\Delta\rho = 2.5\text{-}3\%$
base of garnet layer?

Seismic Structure of TZ

670 km: maybe barrier to convection?

increase in velocity and density: 6-11%

could be explained by phase change or change in chemical composition.

if chemical: either: Fe content or Al content

γ-sp to pv and mw same T, P range as gt to pv

=> discontinuity complex

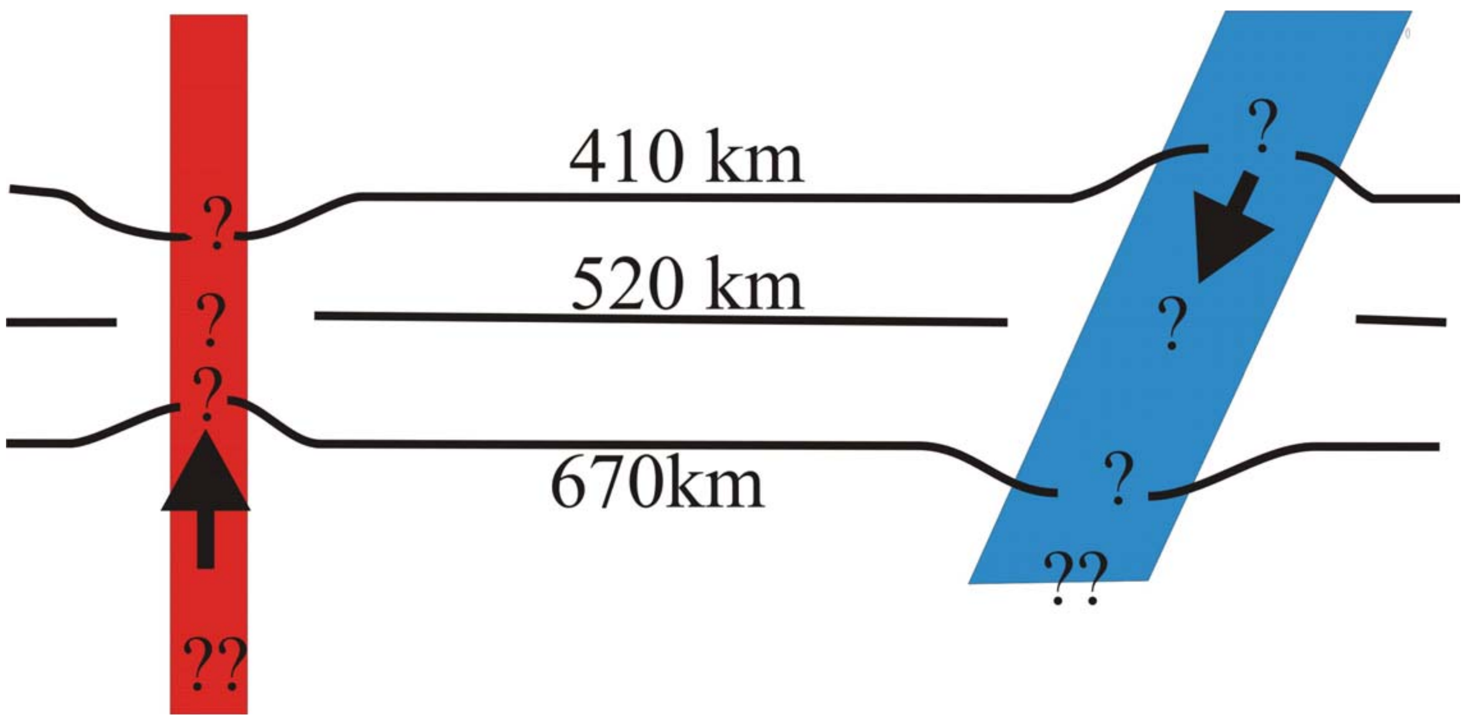
P'P' observations => <4km but long period P-SV conversions: 20-30 km

Clapeyron slope negative, endothermic, depression of 670 disc.

may hinder convection

Seismic structure of TZ

We expect the discontinuities to deflect in the regions of hot upwellings and cold downwellings



Observations of TZ discontinuities

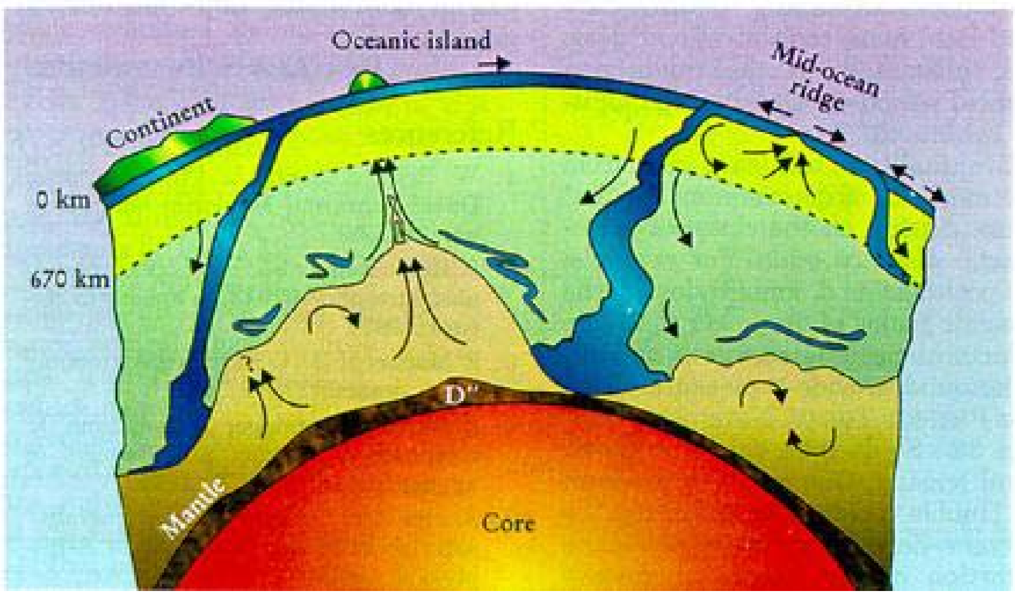
670 km: variation of depth of 30 to 40 km (using different seismological methods and phases)
P670P is not observed but S670S is: velocity jump across 670 must be smaller than in global models (Estabrook and Kind, 1996)
=> $\Delta vp=2\%$, $\Delta vs=4.8\%$, $\Delta\rho=5.2\%$ (Shearer and Flanagan, 1999)
(PREM: $\Delta vp=4.6\%$, $\Delta vs=6.5\%$, $\Delta\rho=9.3\%$)

410 km: sharp discontinuity with moderate variation (e.g. Benz and Vidale 1993, Vinnik 1997 and many others)
but up to 70 km elevated in subduction zones (Collier et al 2001).

520 km: observed in a few regions, not in others,
splitting of the discontinuity? (Deuss and Woodhouse 2001, Rost 2000)

Other boundaries in the mid-mantle?

Other layers in the mid-mantle have been proposed, at 900 km,
1200 km,
one of the most recent one was the Stealth layer (HAL, Kellogg layer)



from Kellogg et al. 1999

enriched layer in lower mantle (from 1500 km to CMB); topography; density contrast +1% more than adiabatic; velocity contrast (S) –5%?

Other boundaries in the mid-mantle?

How can they be observed?

Deeper layers, if they are bound by seismic discontinuities or fairly strong gradients, should be visible through seismic reflections or conversions of phases (P to S etc)

Have they been observed?

Some observation of deeper reflectors (900, 1200 km etc) have been reported in localised places.
The Stealth layer has not really been observed yet.

What can they be and what do they explain (should they be there..)?

Stealth layer:
Could explain the difference of MORB and OIB, could reconcile the observed discrepancy in observed heat flux and heat production in MORB regions.

Conclusions

•Seismology (especially array seismology) helps to detect structure in the Earth that can give information on processes. Resolution issues have to be kept in mind.

•D" layer shows small- and large-scale structure and seems to be consistent with thermo-chemical layer, possibly including slab graveyards, plume origins

•Mantle transition zone shows difference in thickness but more studies are needed to have a more global picture.

•Additional layers (Stealth layer, other mantle transition zones) have not been observed globally with seismological methods.