Seismological imaging of the mantle: state of the art and open problems

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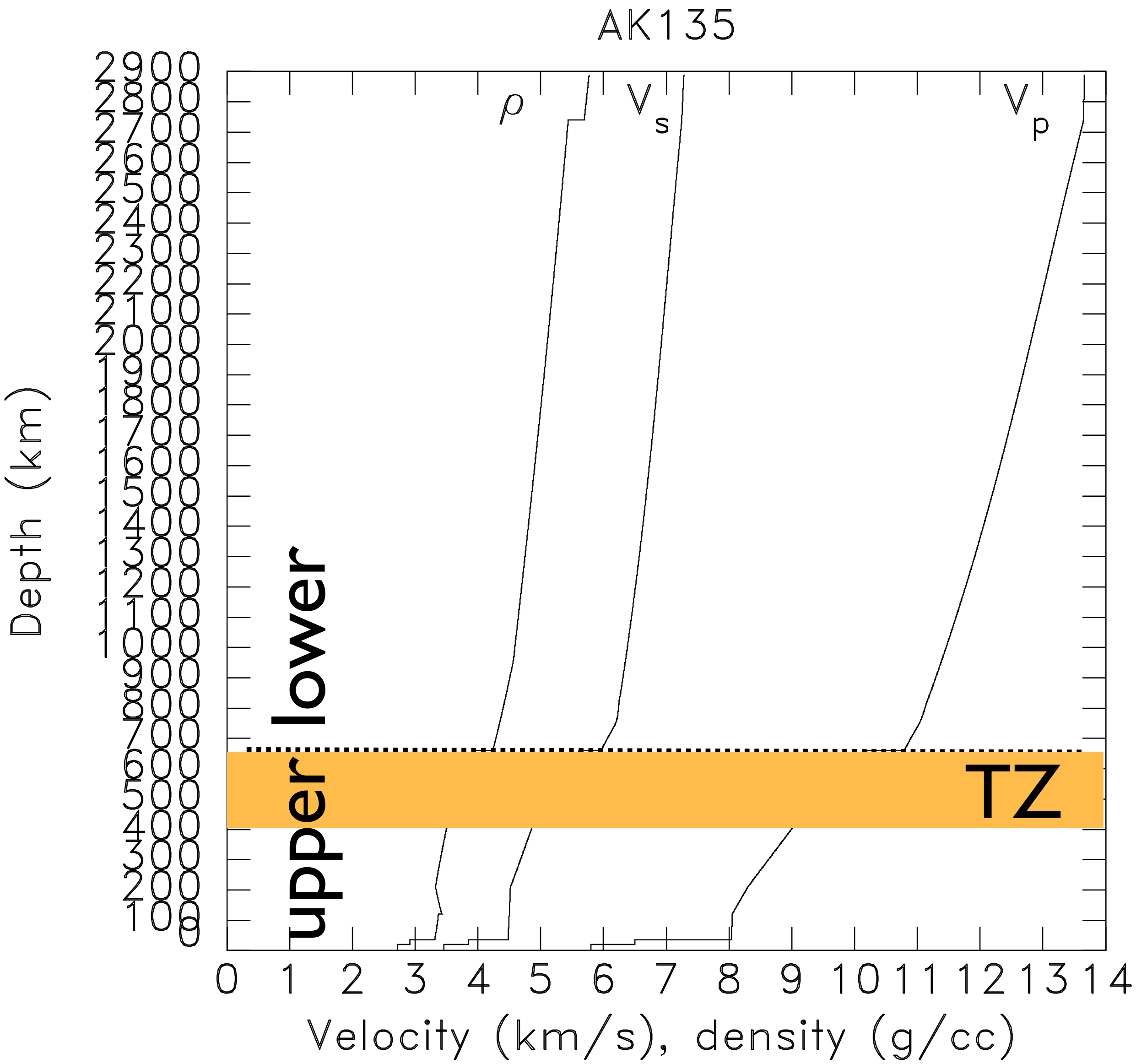
The Mantle

- ~2900 km deep
- Rocky, silicate part of differentiated Earth
- Cooled on top in oceanic regions, heated within and at the base
- Portions both rigid (lithosphere) and weak (asthenosphere)

Radial seismic structure

- By inversion of travel times of global data
- Discontinuities at Moho, 410, 660, core
- Upper, lower and transition zone divisions



Discontinuities

- Transition zone (410 & 660): mineralogical

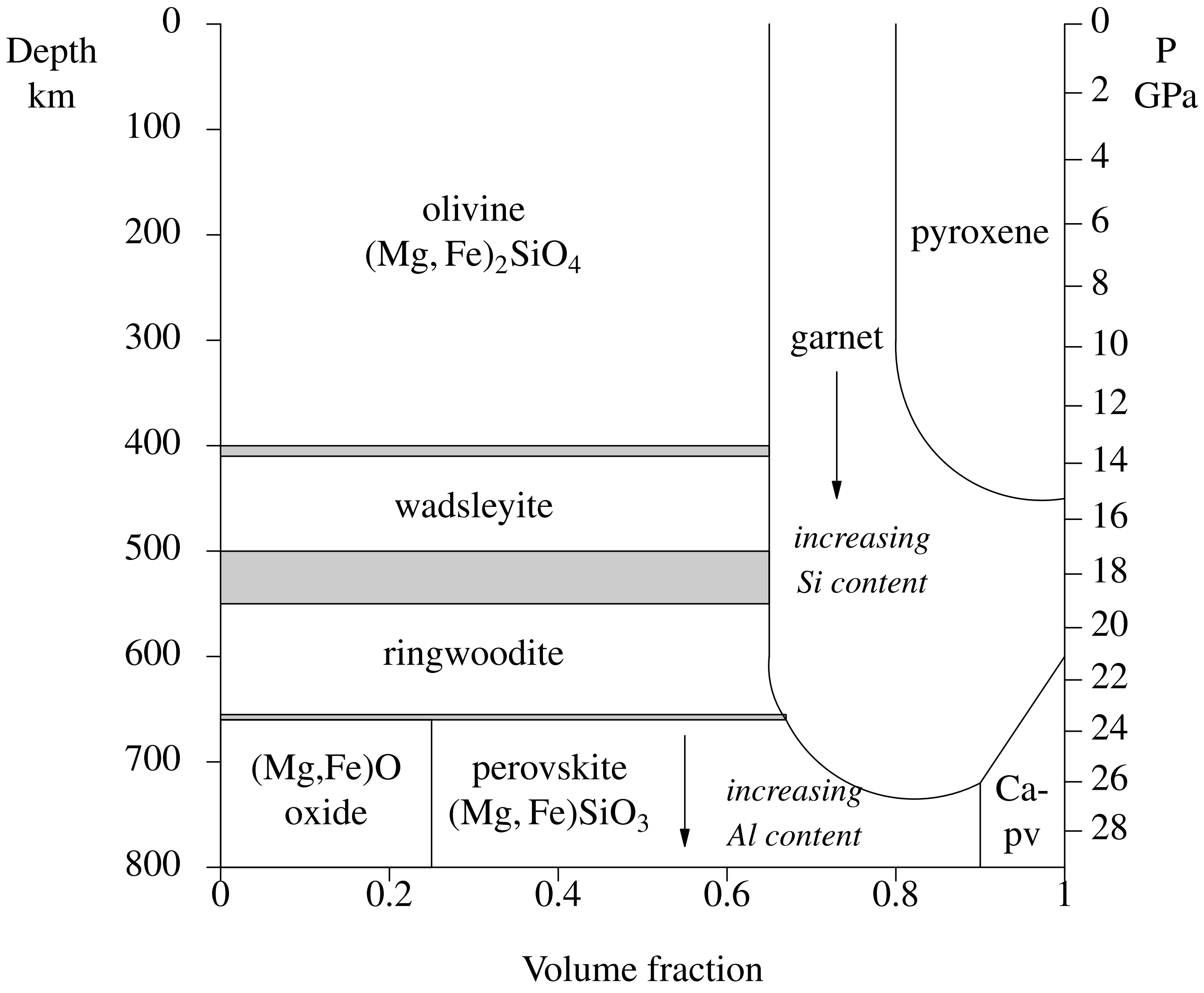
  410 - olivine → wadsleyite (Mg_2SiO_4 polymorphs)

  660 - ringwoodite → periclase + perovskite ($Mg_2SiO_4 \rightarrow MgO + MgSiO_3$)
- Core compositional: solid silicate / liquid iron
- Moho: likely to be multiple causes

Moho

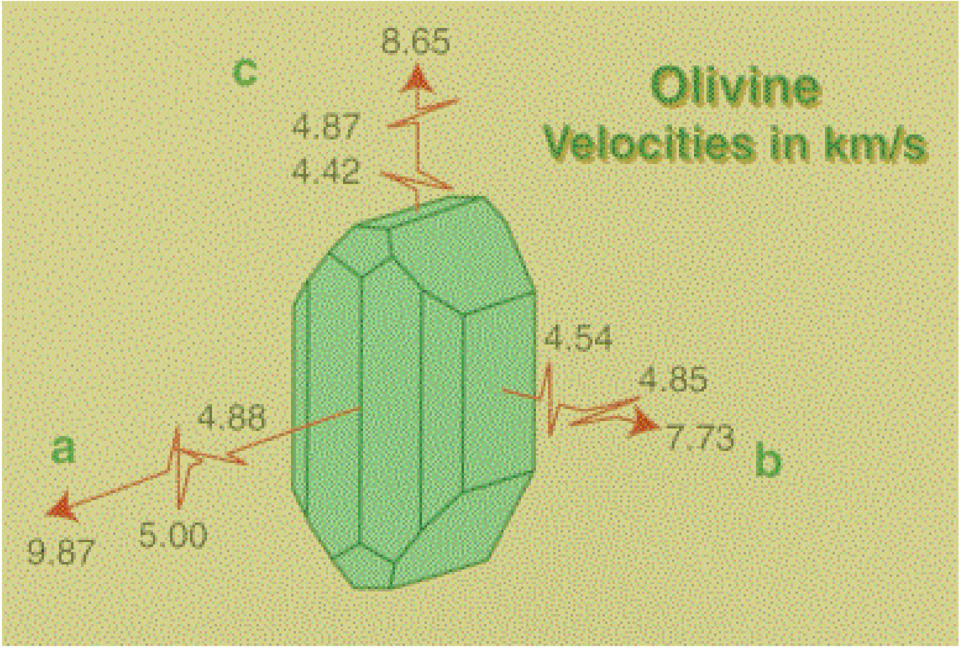
- After Andrea Mohorovičić, Croatian seismologist
- Defined by increase in P speeds to above 7.6 km/s in the crust, marks crust-mantle boundary, but within the lithosphere (except for zero-age crust)
- Proposed origins: compositional boundary, phase transition.

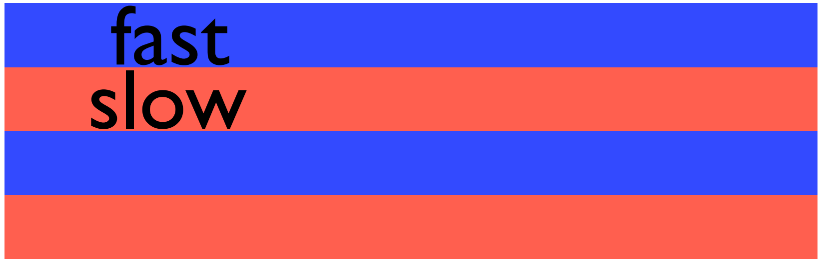
Mantle mineralogy



Anisotropy

- Wave speeds depend on direction
- Depends on medium’s properties:
  - Mineralogy - minerals intrinsically anisotropic
  - Fabric - layering or preferred orientation in even isotropic medium leads to anisotropy





P-speeds vary with direction

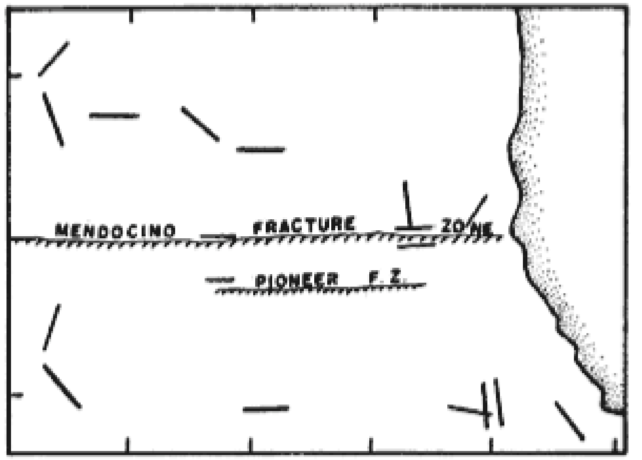
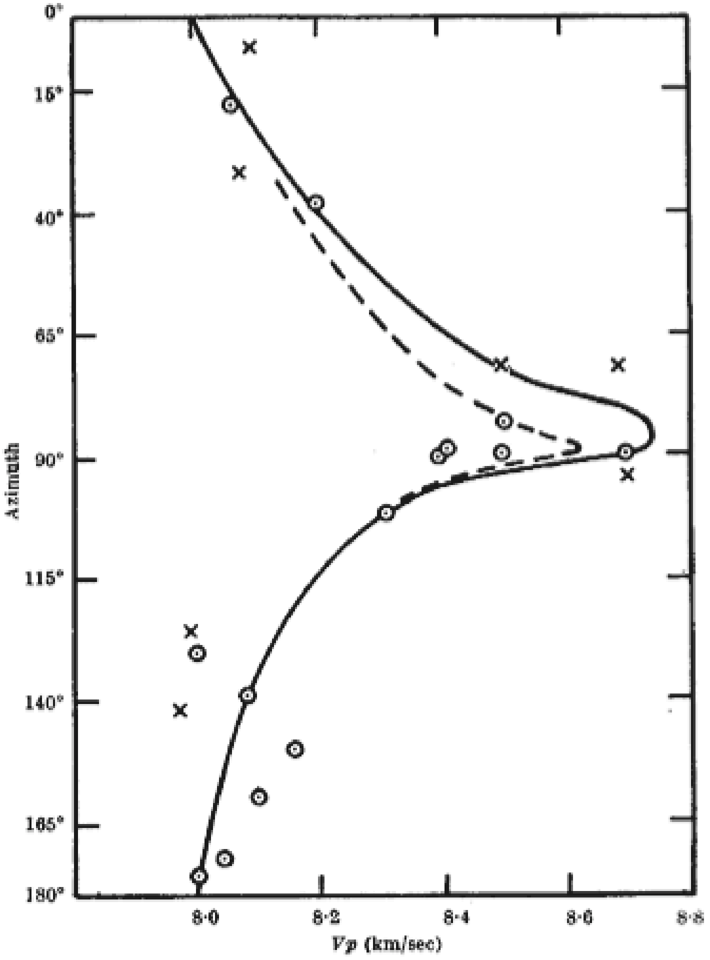
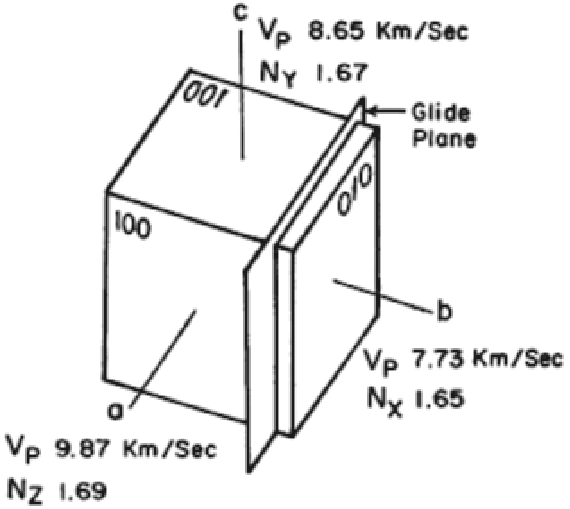


Fig. 2. Location of seismic refraction profiles in Raitt's study of Mendocino fracture zone area off California

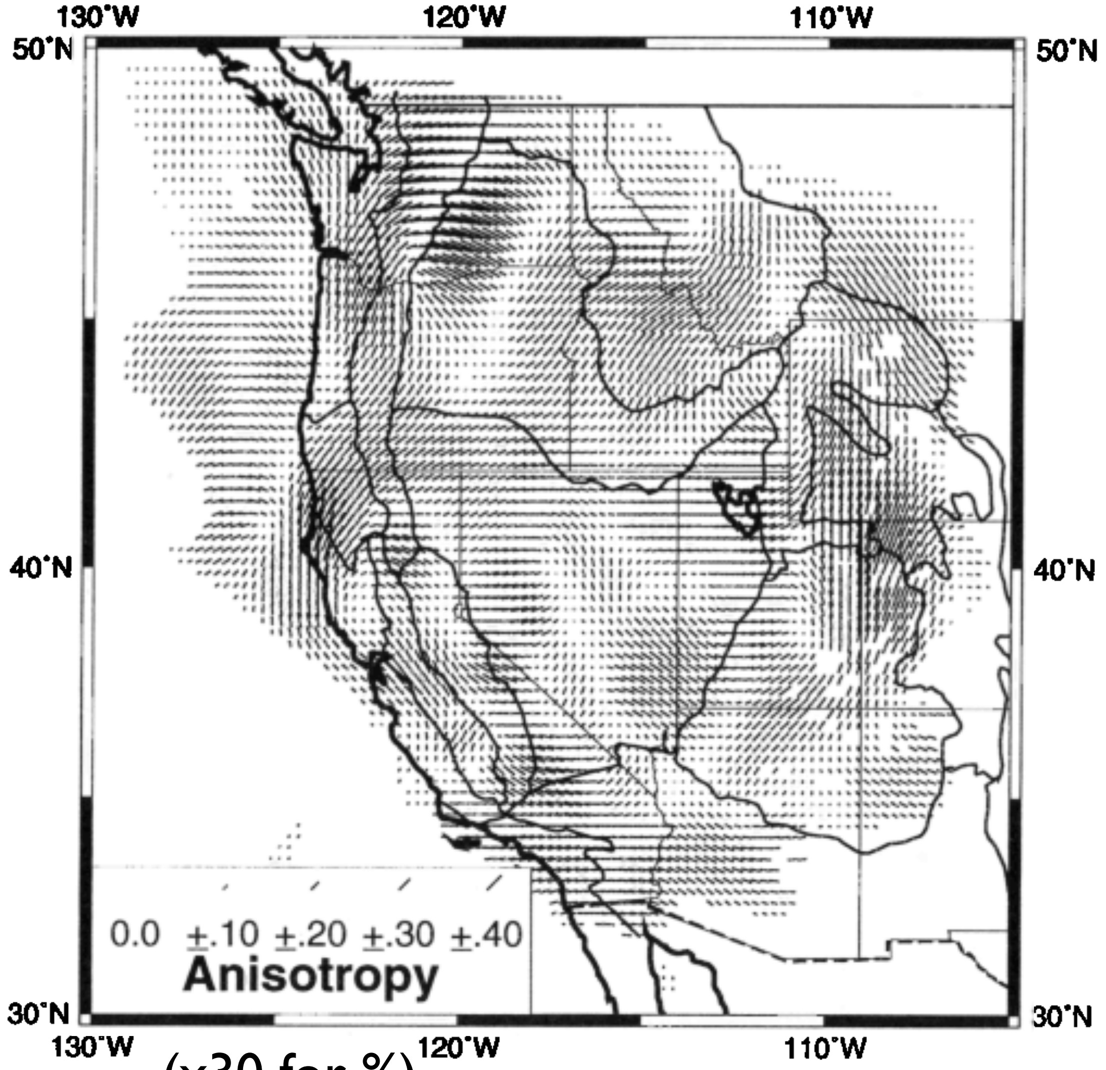


- Hess (1964) showed Pn speeds maximum in E-W direction
- Parallel to fracture zones (or seafloor age gradient)



(Actually, wrong conclusion! Thought that glide plane // fracture zone, so a+c directions fast)

Continental Pn anisotropy



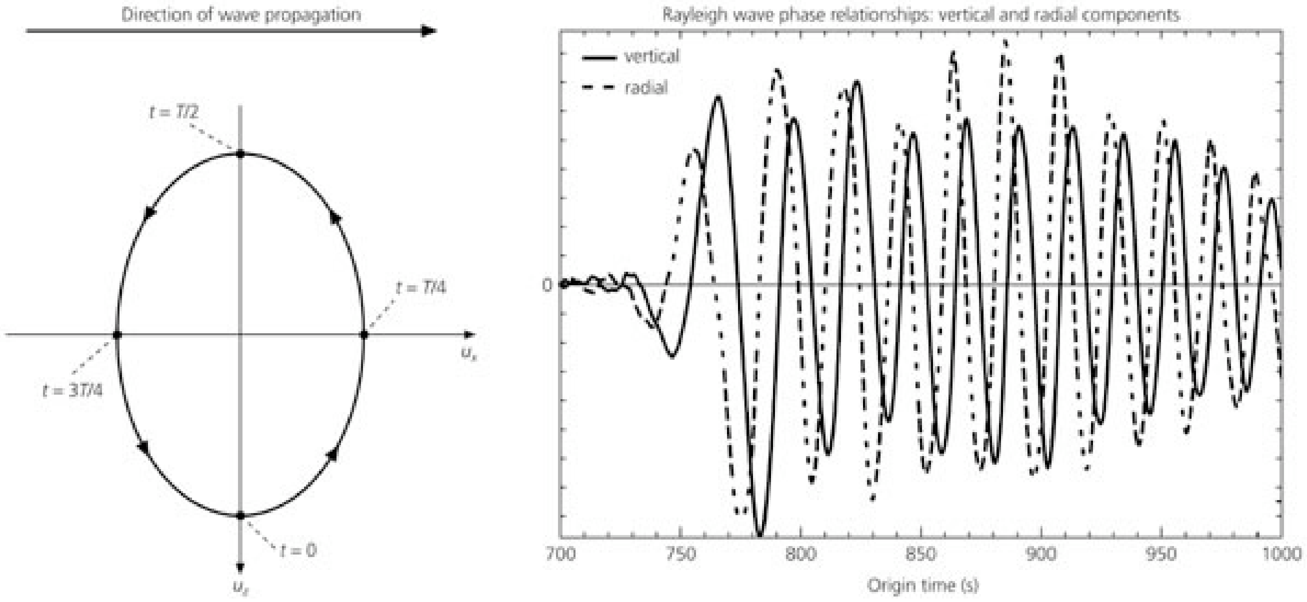
(x30 for %)

(Hearn 1996)

- Pn anisotropy varies substantially in strength and orientation
- Fabric at base of Moho

Azimuthal surface wave anisotropy

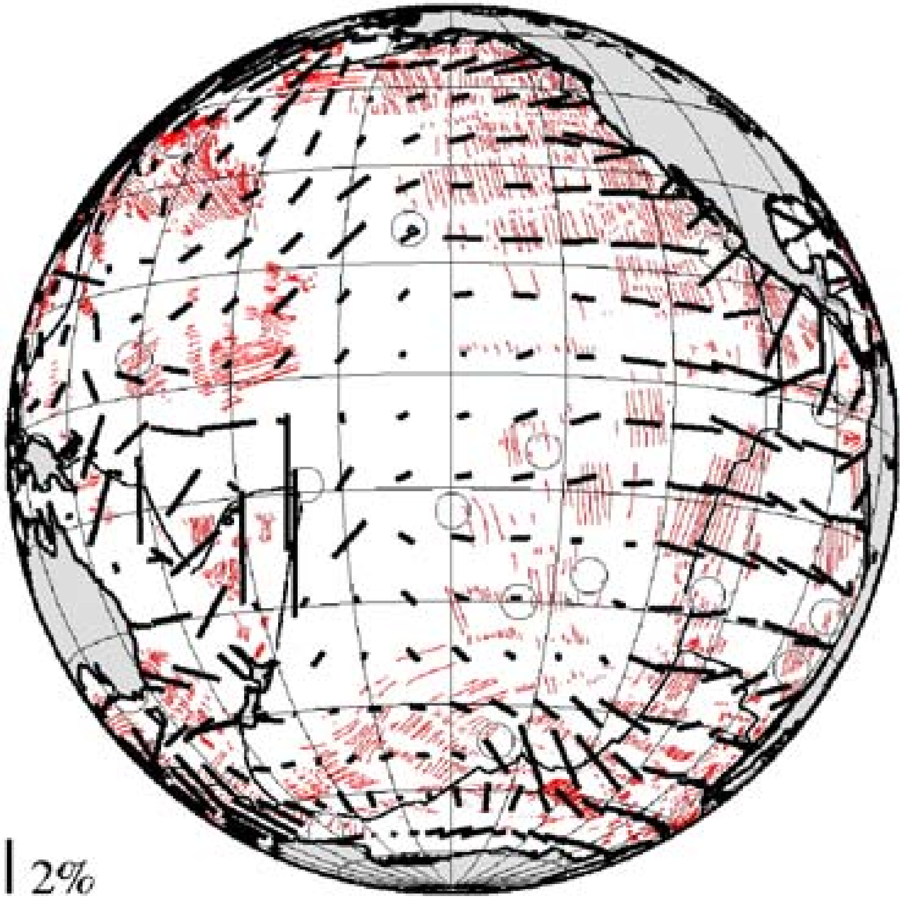
Figure 2.7-6: Horizontal and vertical Rayleigh wave motions.



- Surface wave (Rayleigh) motion elliptical in vertical plane; anisotropy in vertical/horizontal speeds distorts ellipse
- Invertible for anisotropy

Surface wave anisotropy

(Maggi et al. 2006)

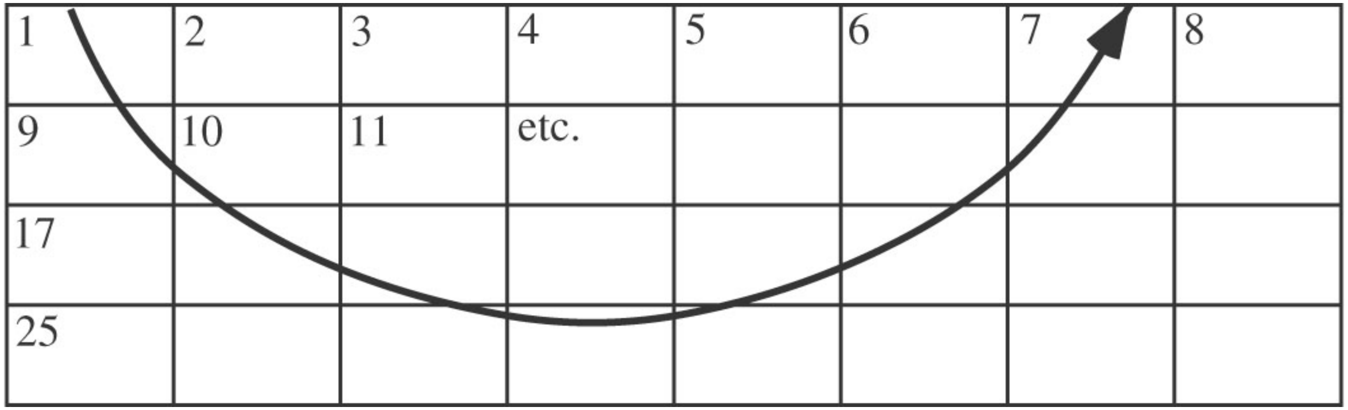


- Maggi et al. find fast directions // seafloor age gradients
- 3-4% maximum anisotropy

Imaging methods

- Tomography - 2- or 3-D maps of wave speed variations from a reference; travel time based (body waves) or waveform based (surface waves); qualitative
- Record sections - 1- and 2-D maps of discontinuity variations in space or slowness; quantitative
- Anisotropy - directional dependence of wave speeds, polarization; spatial and depth variation of shear wave birefringence (splitting); quantitative

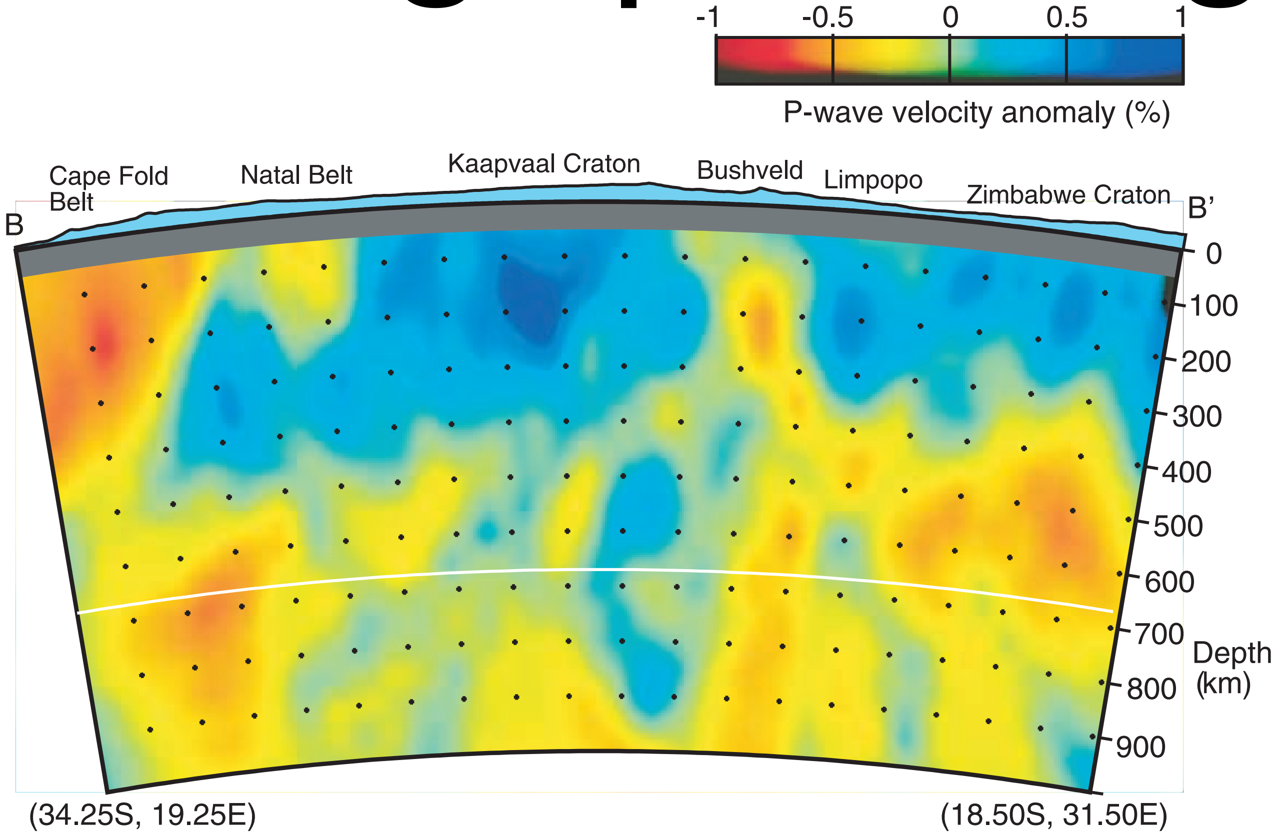
Tomography (body wave)



(Shearer 2009)

- Travel time difference from reference 1-D model proportionally smeared into each box based on path length
- Each box's anomaly obtained from least squares fit to all arrival time data
- Yields image of velocity perturbations

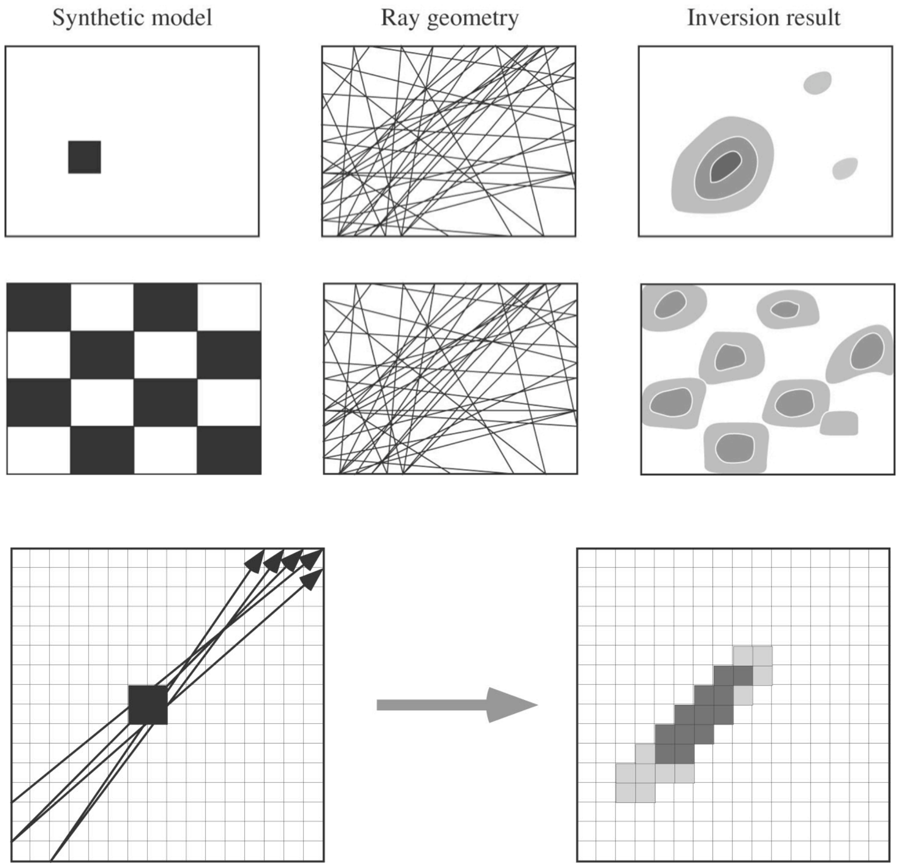
Tomographic image



(James et al. 2004)

- Shows fast (blue) cratonic roots down to >300 km
- Blotchy and streaked

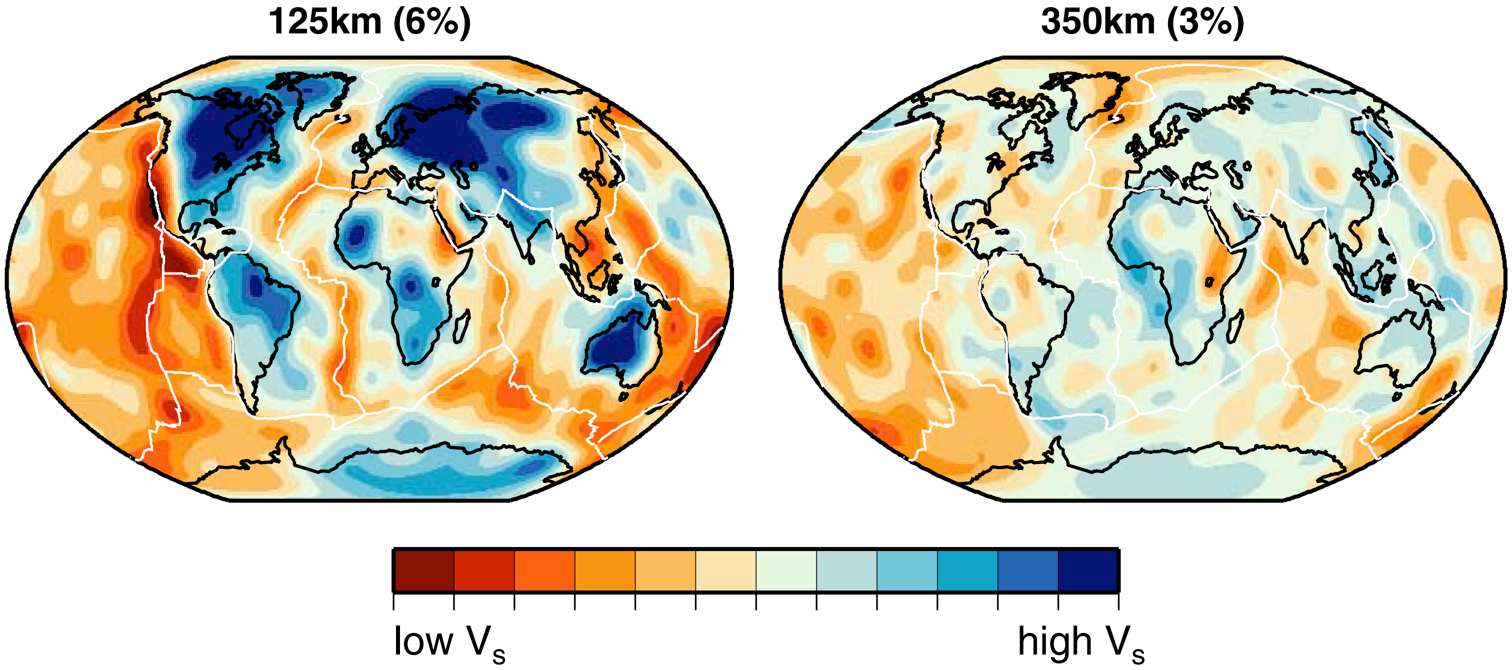
Tomographic skepticism



(Shearer 2009)

- Smearing of anomalies reduces apparent strength
- Illumination in restricted angular range leads to streaking along path

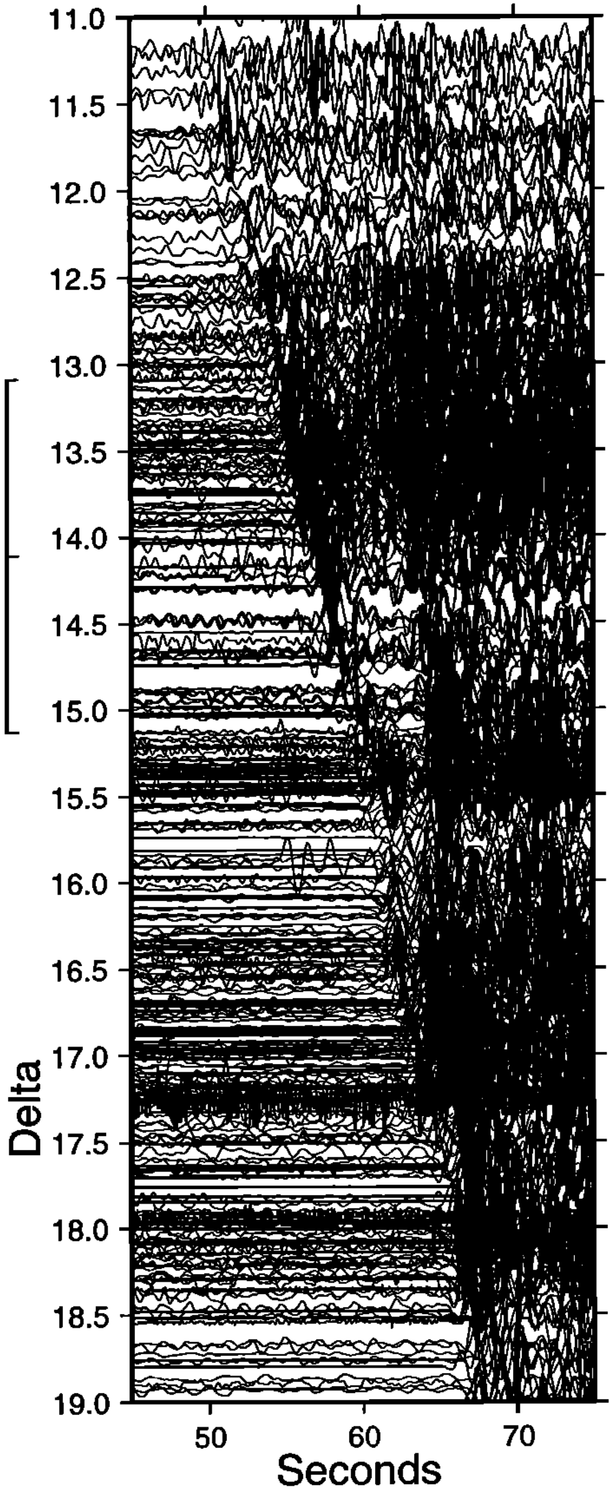
Tomography (surface wave)



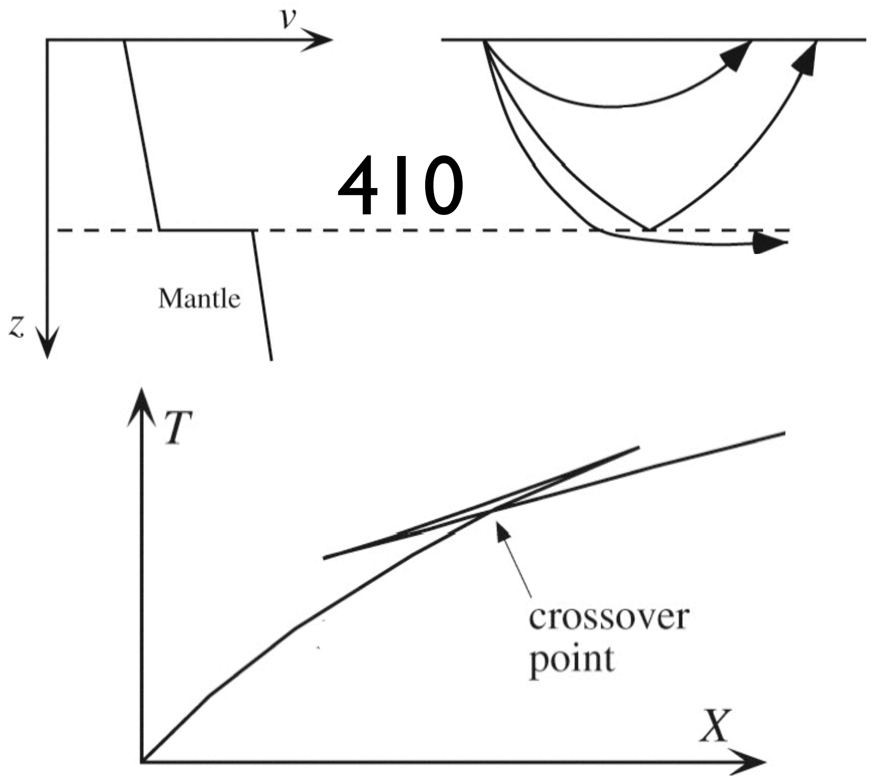
(Ritsema et al. 2004)

- Surface waves yield uniform coverage in the upper mantle (body waves restricted to near stations)
- Show cratonic roots under continents extend <350 km -- and only under continents!

Record sections (seismograms)

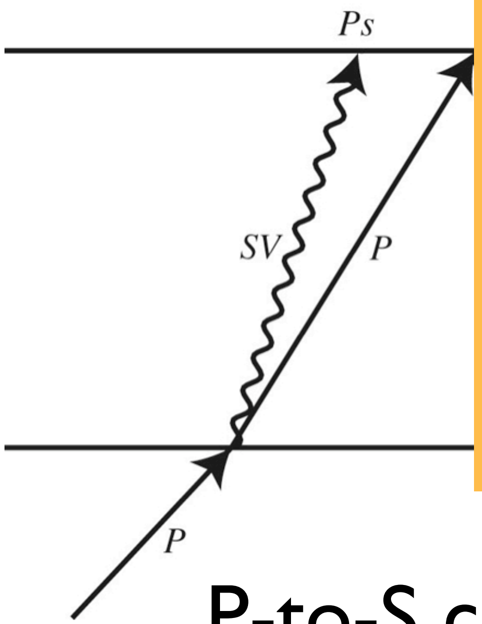


(Melbourne and Helmberger, 1998)



- 3% P speed jump at 410 and 14 km 3.5% gradient

Record sections (receiver functions)

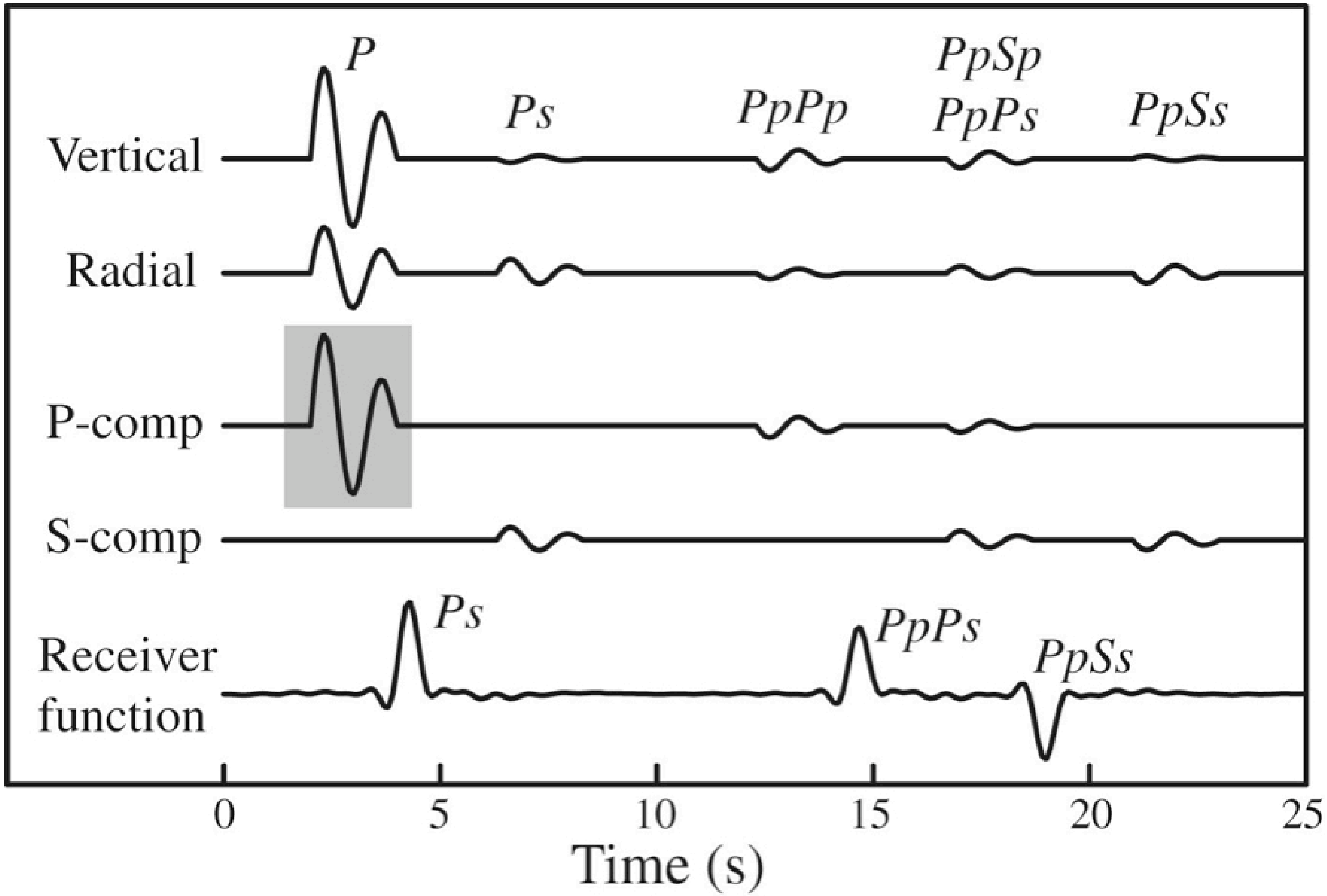


(Shearer 2009)

P-to-S conversion at layer boundary produces later arrival following P

Reverberations (colored) a nuisance because they hide Ps from deeper layers

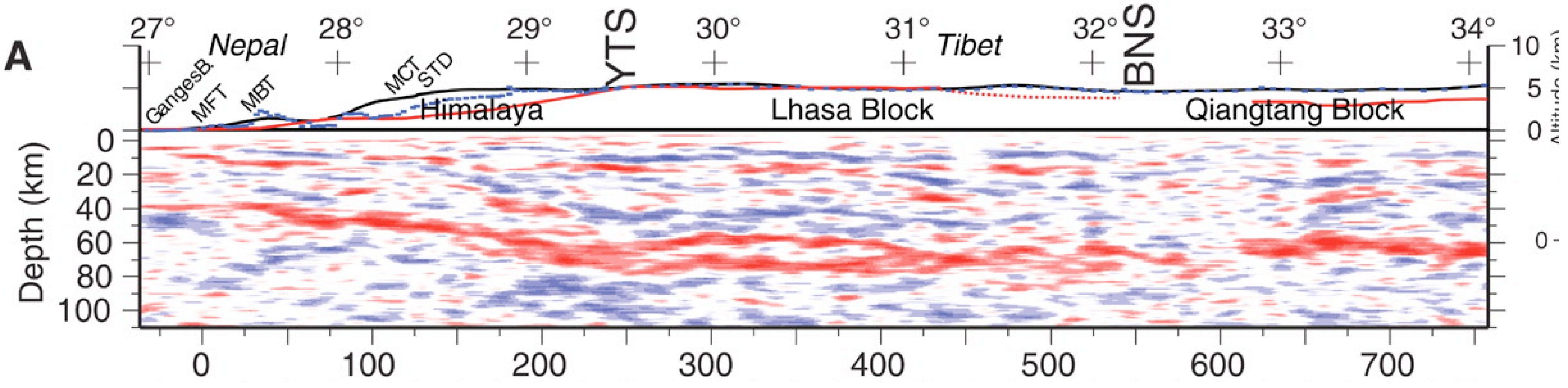
Receiver functions



(Shearer 2009)

Deconvolution of direct P wave from radial component of motion gives receiver function

Receiver functions



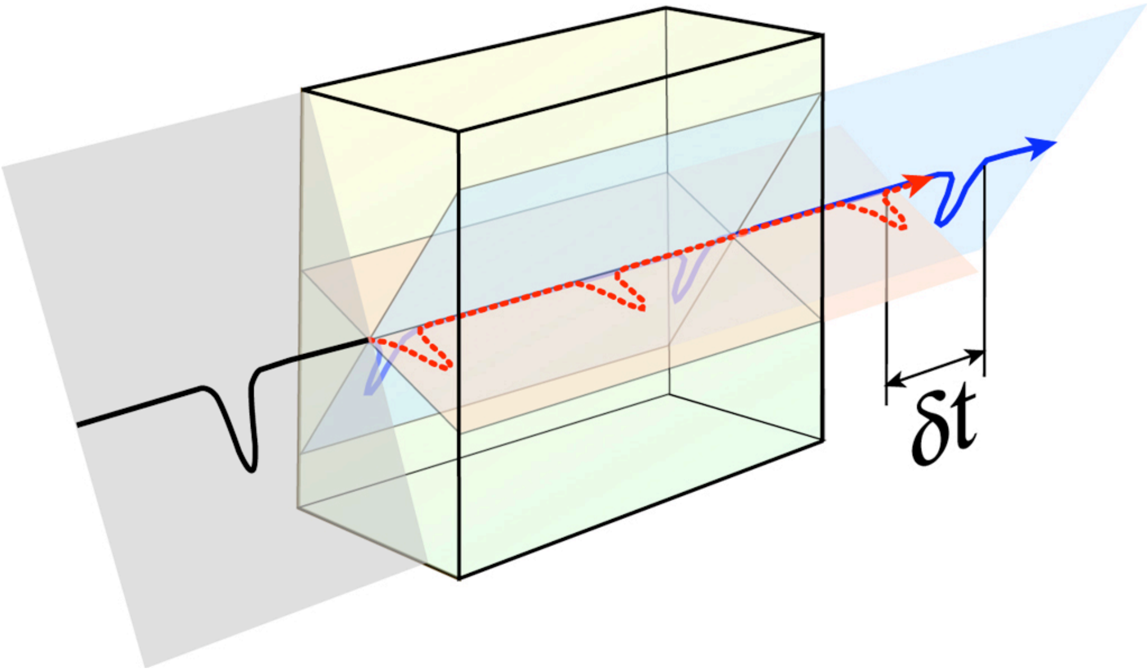
(Nabelek et al. 2009)

N-S transect across Himalayan front of RFs recorded at different stations yields composite image of Moho

Shear-wave splitting

- Incoming shear wave components resolved onto symmetry axes of medium
- Directional dependent wave speeds lead to fast and slow arrivals
- Measure lag δt and angle of fast polarization from North
- dt gives strength, angle gives orientation

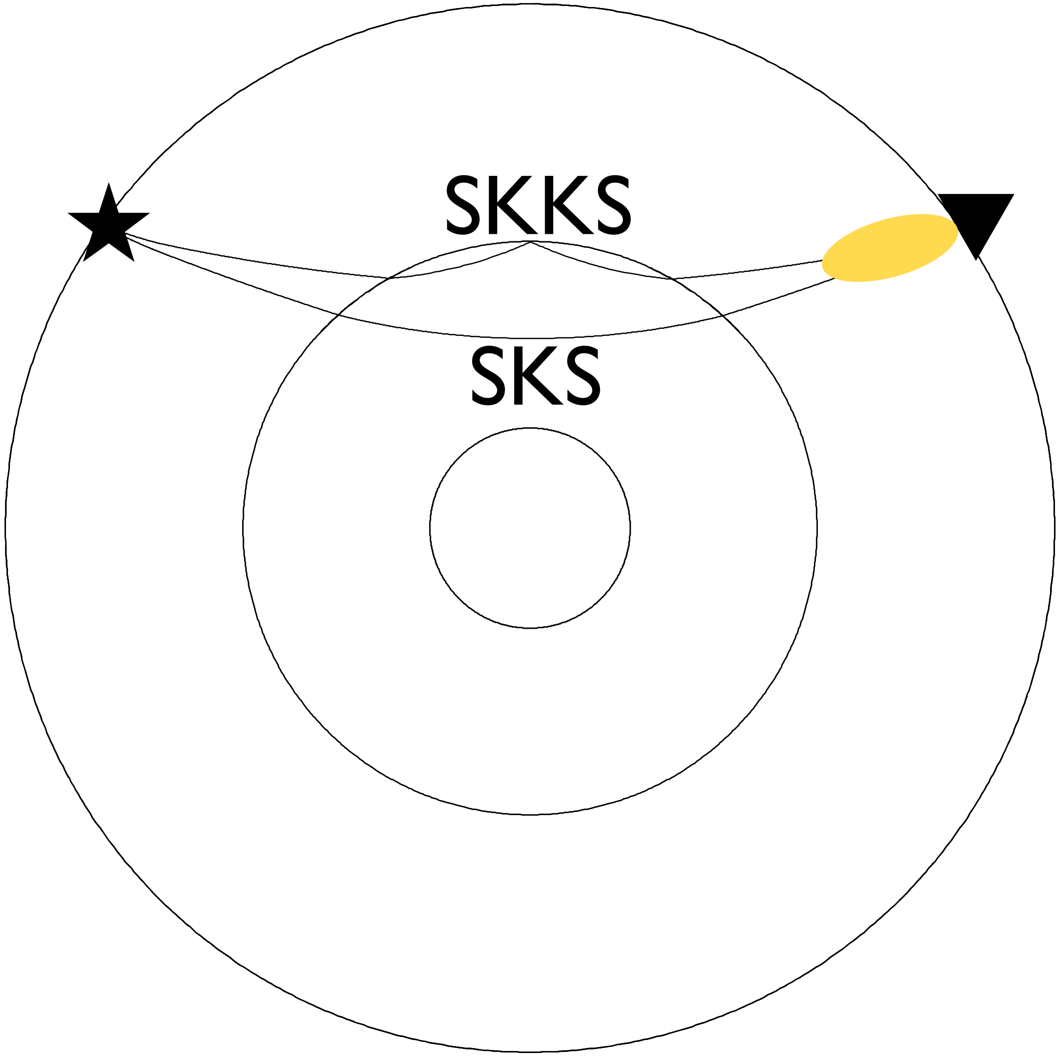
Shear wave splitting in anisotropic media



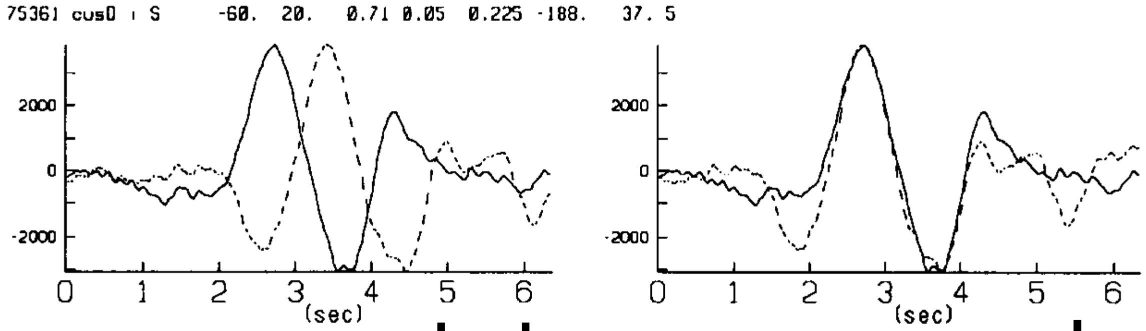
(http://garnero.asu.edu)

SKS/SKKS - splitting workhorse

- P wave in core, S wave in mantle
- S polarized in diametral plane by conversion at core/mantle boundary; known
- Fabric/ orientation probe on upwards path



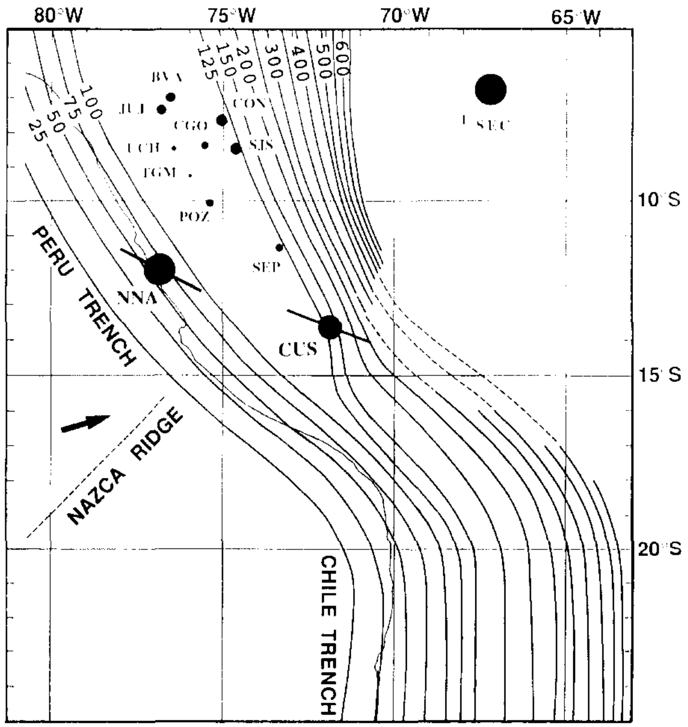
What splitting looks like



as recorded

restored

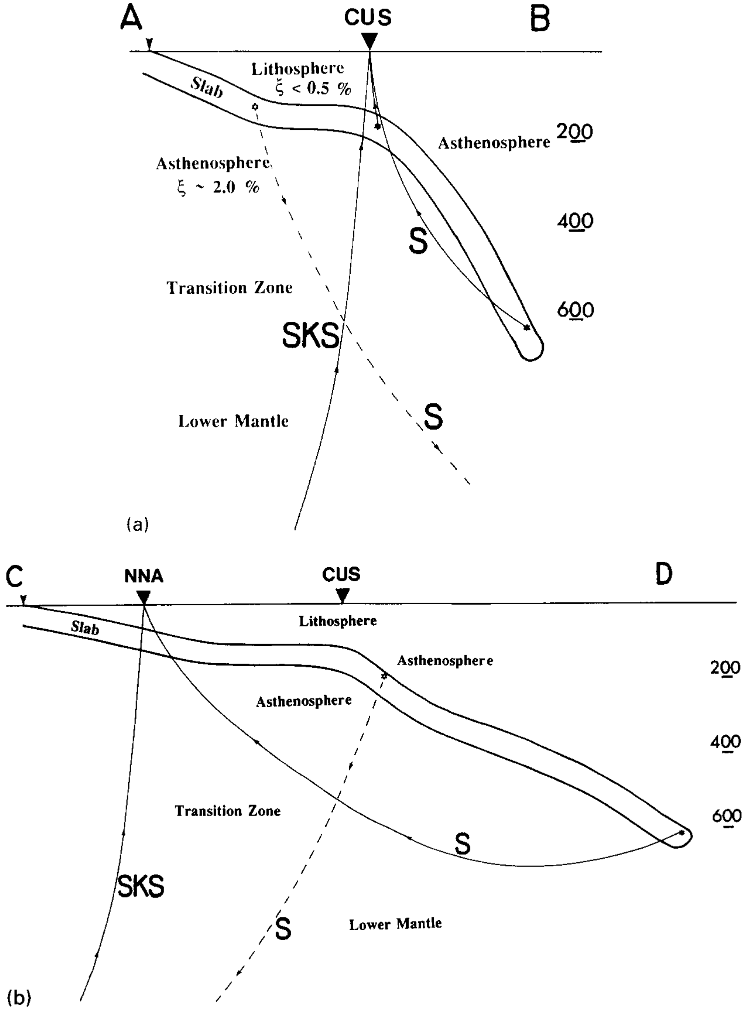
Slow and fast polarization traces



(Kaneshima & Silver, 1995)

- Bar shows fast polarization direction
- Circle diameter represents delay (bar length can, too; nonstandard)

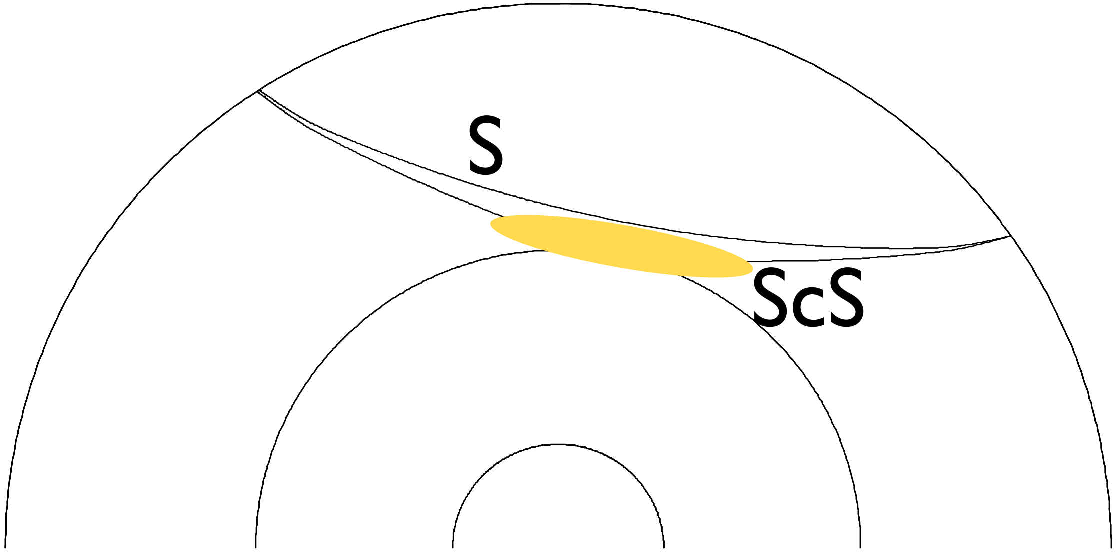
Localizing anisotropy



(Kaneshima & Silver, 1995)

- SKS splitting compared with local S events
- Same delay times measured within uncertainty
- anisotropy must be in common part of path: upper mantle

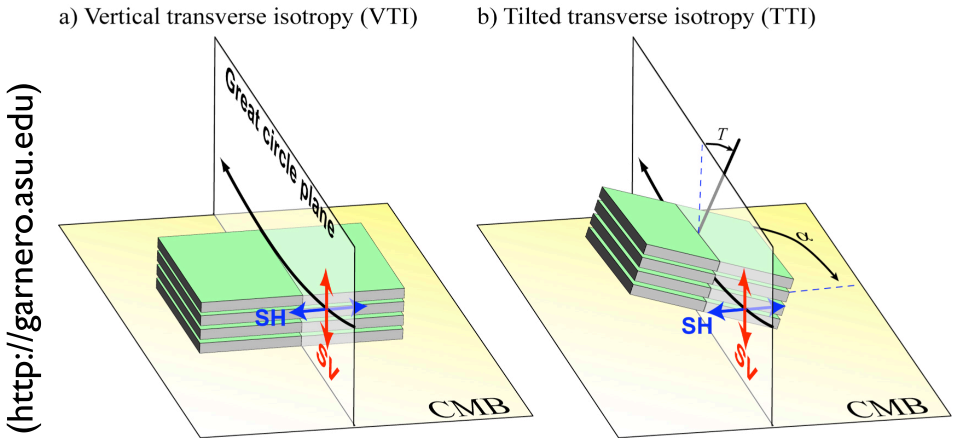
Deep mantle anisotropy



- Different splitting of S and ScS attributed to path difference in base of mantle

- Anisotropy significant

- Flow texture or melt orientation


a) Vertical transverse isotropy (VTI)

b) Tilted transverse isotropy (TTI)

(http://garnero.asu.edu)

Lithosphere - asthenosphere boundary

- Mechanical definition: part of the solid Earth with long-term strength
- Strength a rheological property, but in situ samples unavailable
- Proxies used:
  - shear wave speed
  - flexural parameters (thickness)

Strength formulation

$$\dot{\varepsilon} = A \left[\frac{\sigma}{\sigma_0}\right]^n \left[\frac{d_0}{d}\right]^m \exp\left[-\frac{E^* + PV^*}{RT}\right]$$

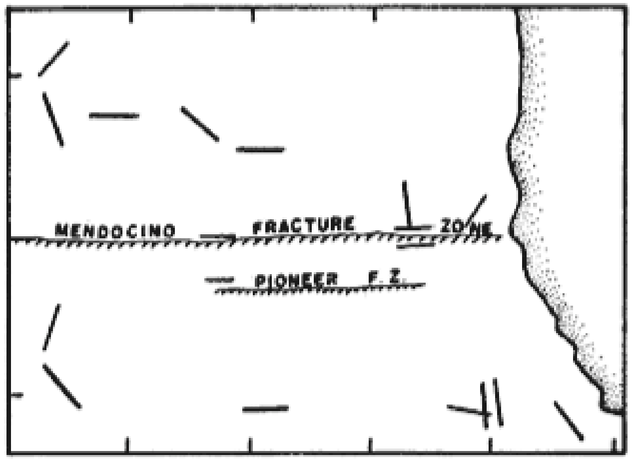
$\dot{\varepsilon}$	strain rate
A	process constant
σ, σ_0	stress and reference
d, d_0	grain size and reference
E^*	activation energy
V^*	activation volume
m, n	exponents
R	gas constant
T	temperature
P	pressure

- Power law dependence on stress, grain size
- Exponential dependence on temperature

Consequences

- LAB likely to be approximated by an isotherm if all other factors same
- LAB likely to vary with composition (A dependence), history (d dependence), deformation intensity (σ dependence)

LAB observations: Pn



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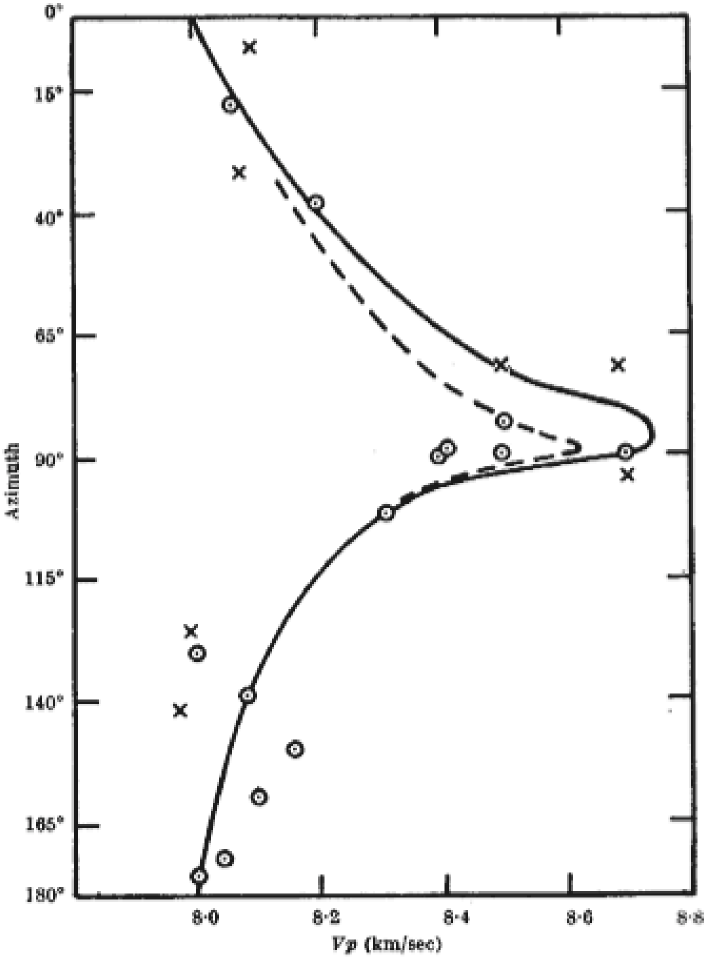
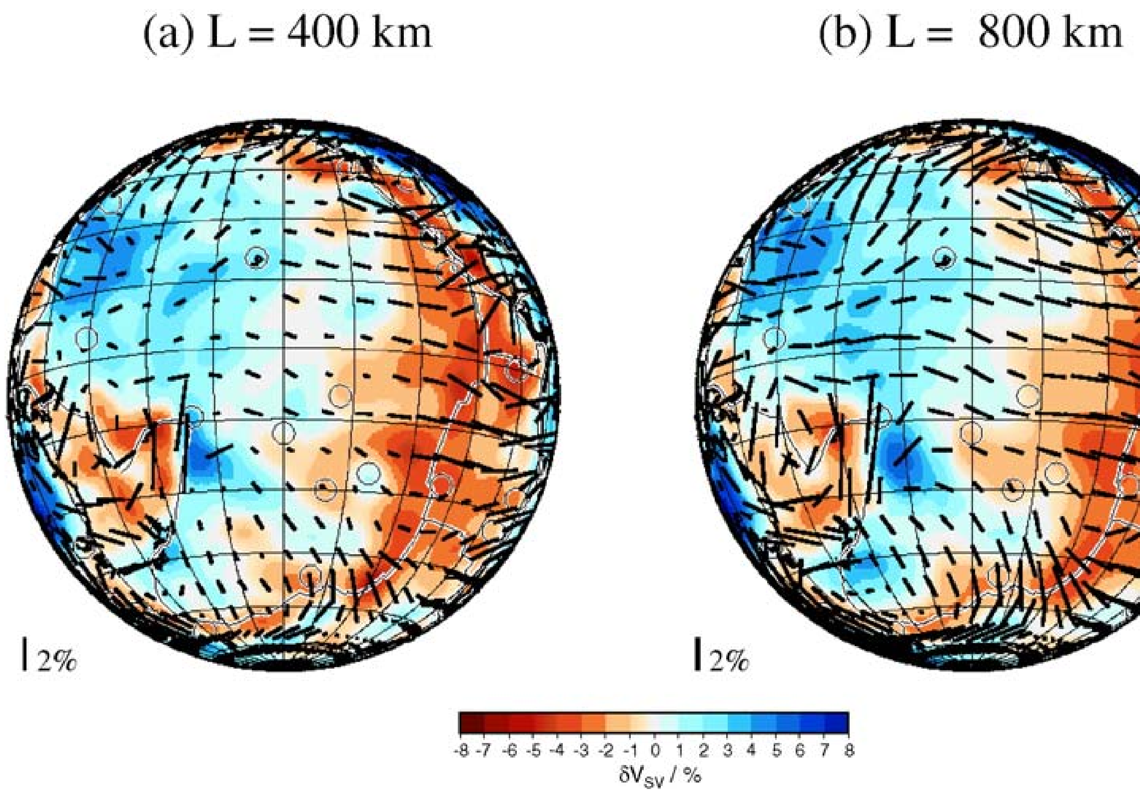


- Widely observed arrival
- Fabric in oceanic lithosphere below Moho (top of mantle)

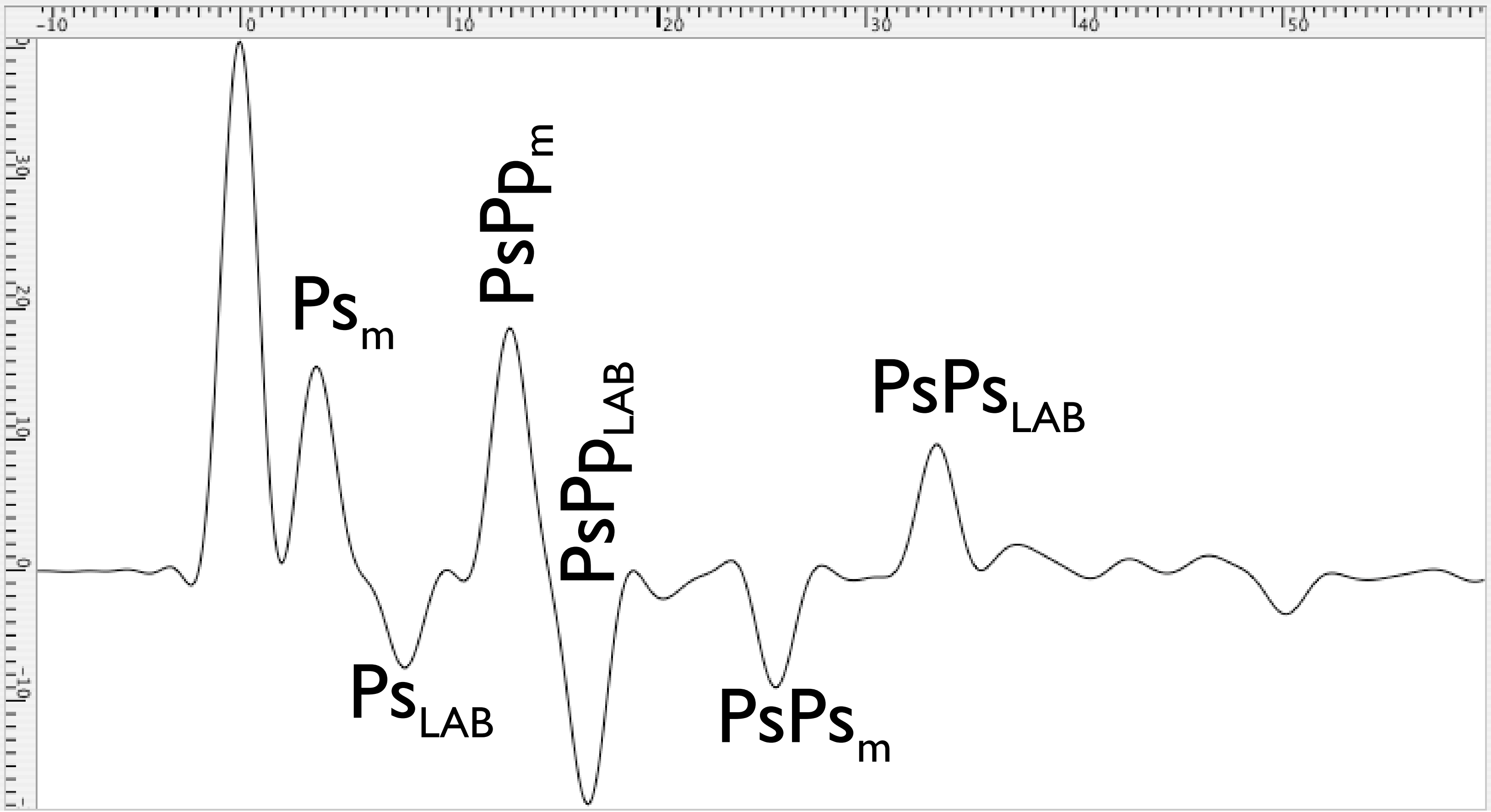
Shallow mantle anisotropy



(Maggi et al. 2006)

- Strongest near ridges, wanes with age
- Destruction of fabric or interference with secondary fabric?

LAB observations

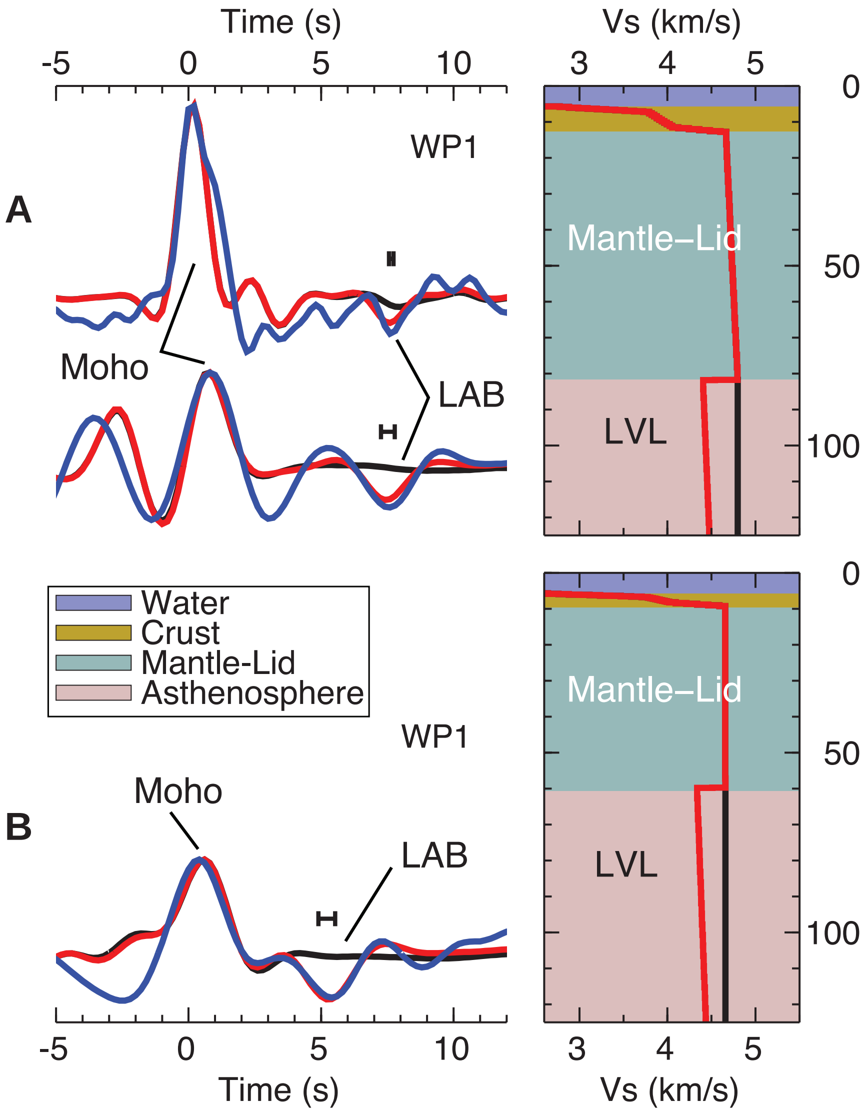


- Hard to see seismologically with receiver function analysis of P arrivals (PRFs): interference with Moho +/- reverberations

S receiver functions

- Incoming S wave converts to P
- Sp arrives before S -- no complications from reverberations (but later arrivals like SpPp, SpSp ... yes)

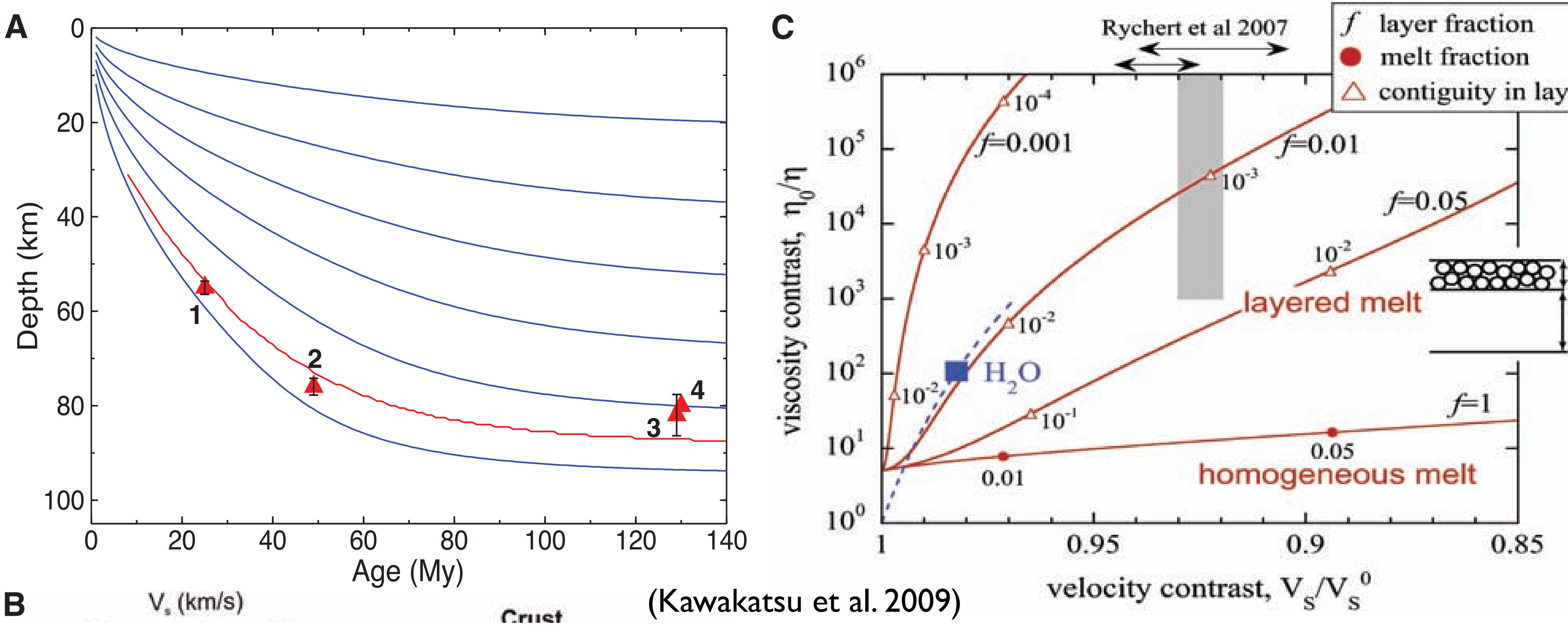
Ocean bottom borehole SRFs



- SRFs on Philippine Plate and Pacific Plate
- LAB at 82 +/- 4 km
- 7-8% S wave drop

(Kawakatsu et al. 2009)

SRF results under oceans

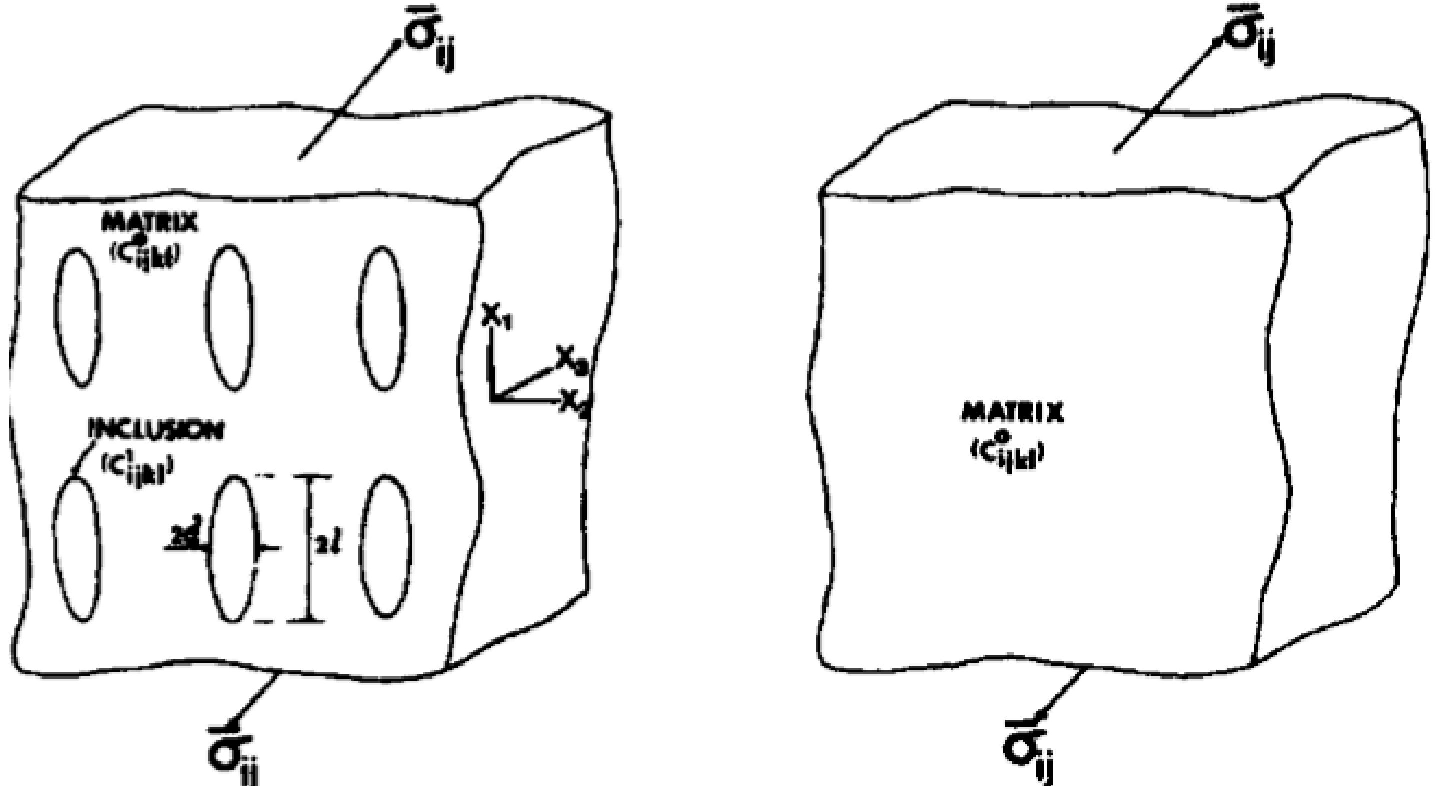


(Kawakatsu et al. 2009)

Age-LAB depth consistent with constant-T plate base

Expect melt tubes with 0.5-5% melt; but not damp melting

Inclusion anisotropy

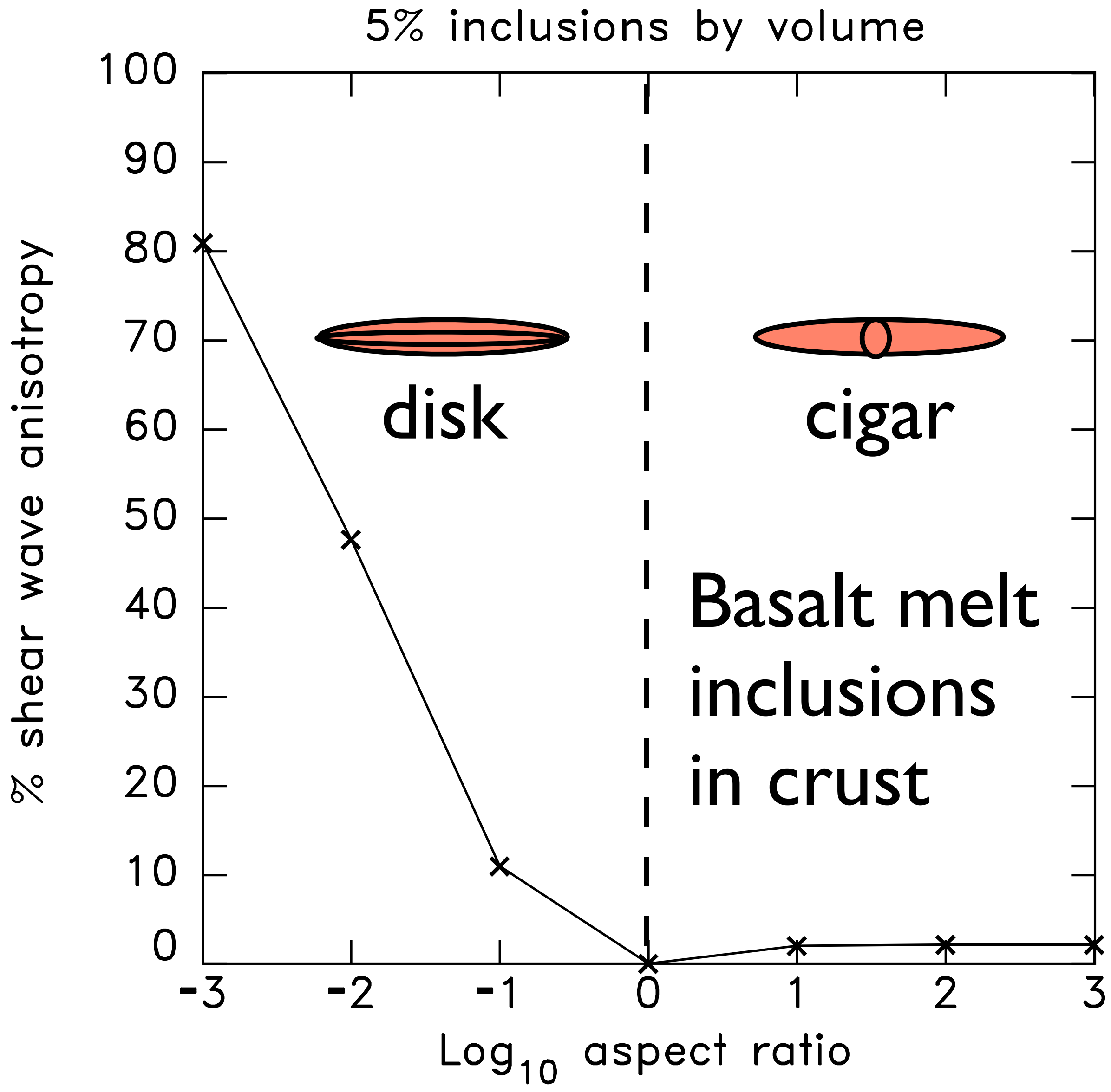


(Tandon & Weng 1984)

- Shaped inclusions embedded in a material yield anisotropy: e.g. melt veins, dyke sheets, tension gashes

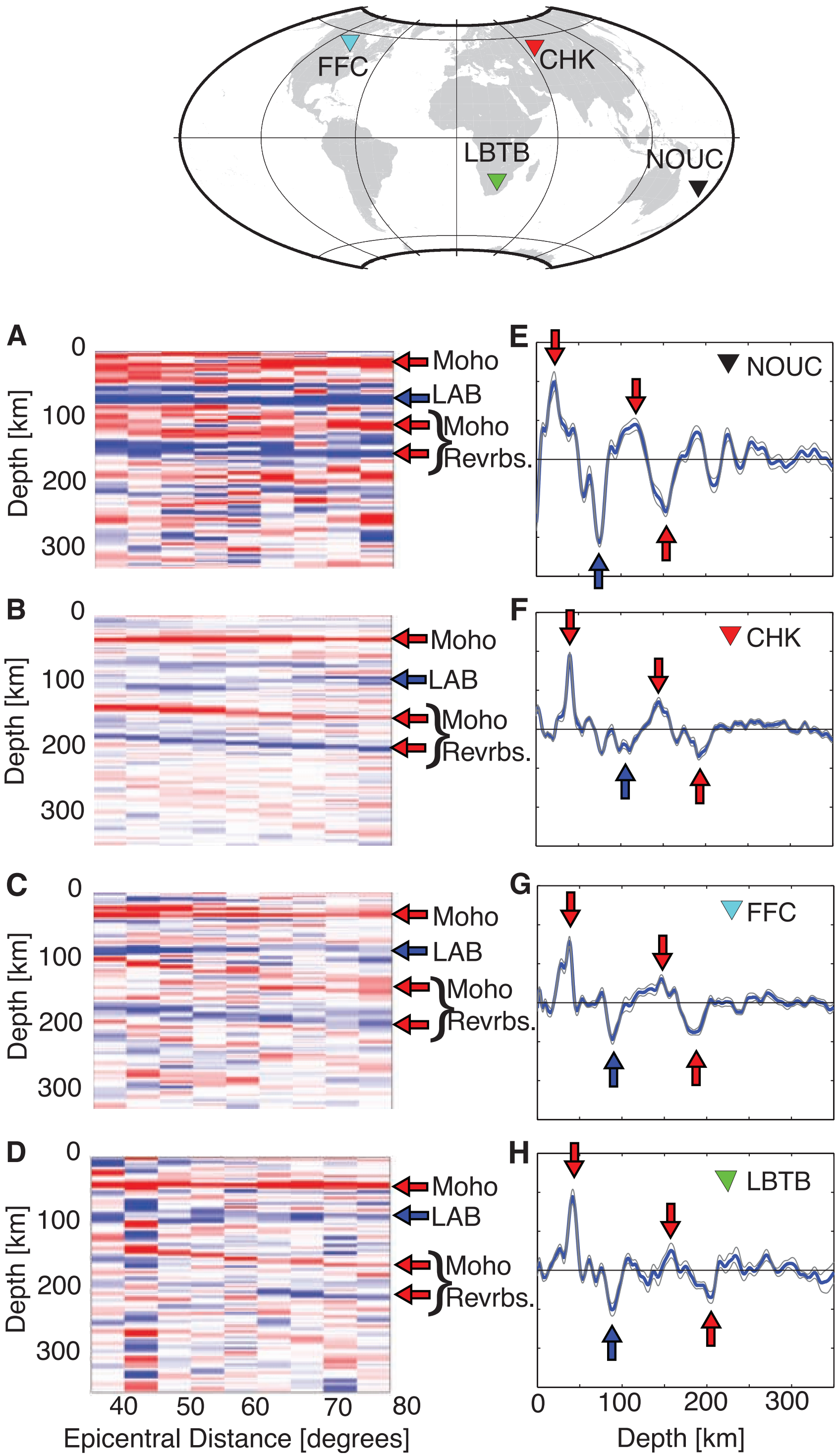
- Depend on aspect ratio and concentration

Shape control of anisotropy



- Disks more effective than cigars at given volume fraction
- Melt sheets, joints → anisotropy
- Melt tendrils → no effect

Subcontinental LAB



- PRF study 6 +/- 0.3% S drop at LAB
- LAB 82 +/- 6 km Pz platforms
- LAB 95 +/- 4 km Pc shields
- No Moho-LAB corelation

(Rychert and Shearer 2009)

Questions

- LAB = top of low velocity zone (LVZ)?
- Does the fabric implied by Pn anisotropy extend down from the Moho to the LAB?

  ... if so, is the LAB a fabric change?
- Is the nature of the LAB under continents same as under oceans?