# Structure anisotrope et dynamique du manteau à l'échelle continentale

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*Avec la participation de:*
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# S waveform tomography

- Depth of continental roots
- Chemical and/or thermal nature of cratonic roots
- Nature of anisotropy observed in the upper mantle under continents
- Nature of the "LAB"
- Lithosphere and asthenosphere:
  - comparison between ocean basins/stable continents

# Approach

- Seismic waveform tomography
  - Isotropic
  - Anisotropic
  - Anelastic
- SKS splitting observations
- Global scale/Continental scale (north America)

# Types of anisotropy

- General anisotropic model: 21 independent elements of the elastic tensor $c_{ijkl}$

- Long period waveforms sensitive to a subset, to first order (13) of which only a small number can be resolved

  - Radial anisotropy
  - Azimuthal anisotropy

- Radial anisotropy
  - A,C,F,L,N (Love, 1911)
  - Long period S waveforms can only resolve
    - $L = \rho V_{sv}^2$
    - $N = \rho V_{sh}^2$
    - => $\xi = (V_{sh}/V_{sv})^2$

    $\forall \delta \ln \xi = 2(\delta \ln V_{sh} - \delta \ln V_{sv})$

- Azimuthal anisotropy
  - Terms in $2\psi$ and $4\psi$ (8 of them)
  - Resolve Gc and Gs (2 of 6 terms in $2\psi$)

- Radial anisotropy only:
  - Vertical axis of symmetry
  - Love/Rayleigh wave discrepancy

- Azimuthal anisotropy only
  - Horizontal symmetry axis

- Vectorial tomography: Combination radial/azimuthal (*Montagner and Nataf, 1986*):
  - Vs isotropic, $\xi$, two angles of orientation of symmetry axis
  - Radial anisotropy with arbitrary axis orientation (cf olivine crystals oriented in "flow")

# Vectorial tomography

Montagner and Nataf (1986)

$$\delta\omega(\theta,\phi) = \int [\delta A_0(r,\theta,\phi) + \delta A_1(r,\theta,\phi)\cos 2\Psi_0 + \delta A_2(r,\theta,\phi)\sin 2\Psi_0 + \delta A_3(r,\theta,\phi)\cos 4\Psi_0 + \delta A_4(r,\theta,\phi)\sin 4\Psi_0]\, r^2\, dr$$

B,G,H

E

Azimuthal anisotropy

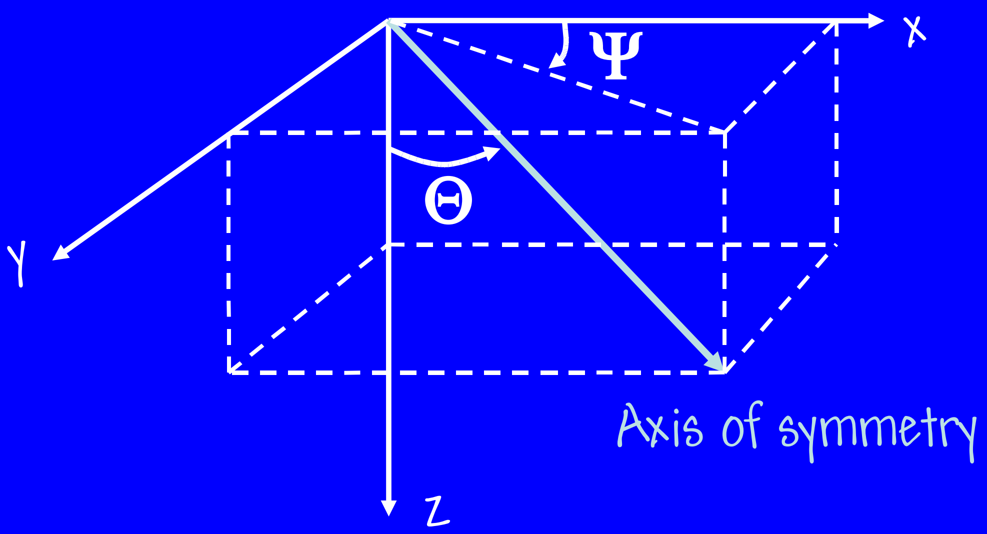
A,C,F,L,N

Radial anisotropy

# Vectorial tomography

Orthotropic medium: hexagonal symmetry with inclined symmetry axis

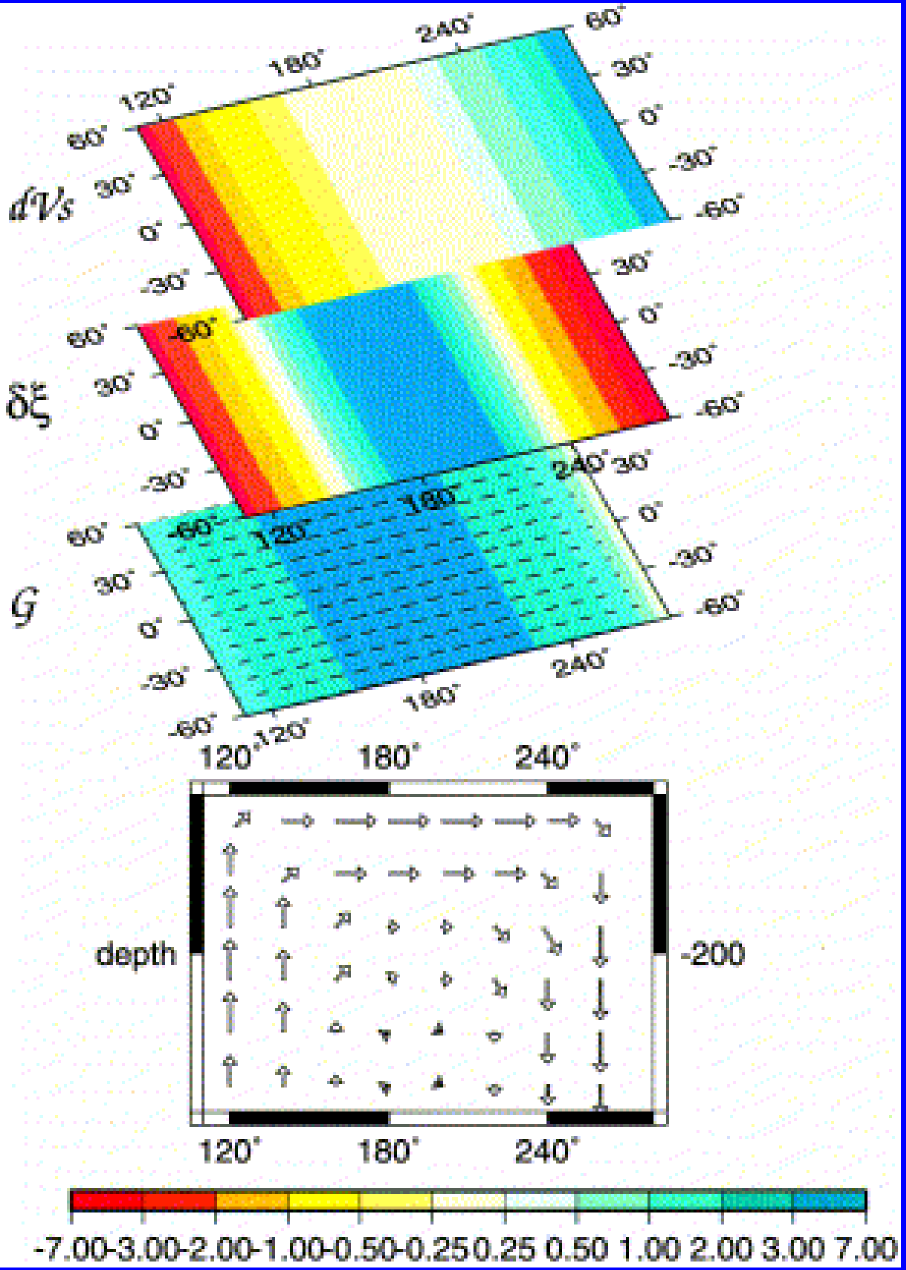
$$(A_R, C_R, F_R, L_R, N_R, B_R, G_R, H_R, E_R) \longleftrightarrow (A_0, C_0, F_0, L_0, N_0, \Psi, \Theta)$$



Isotropic velocity →

Radial Anisotropy →

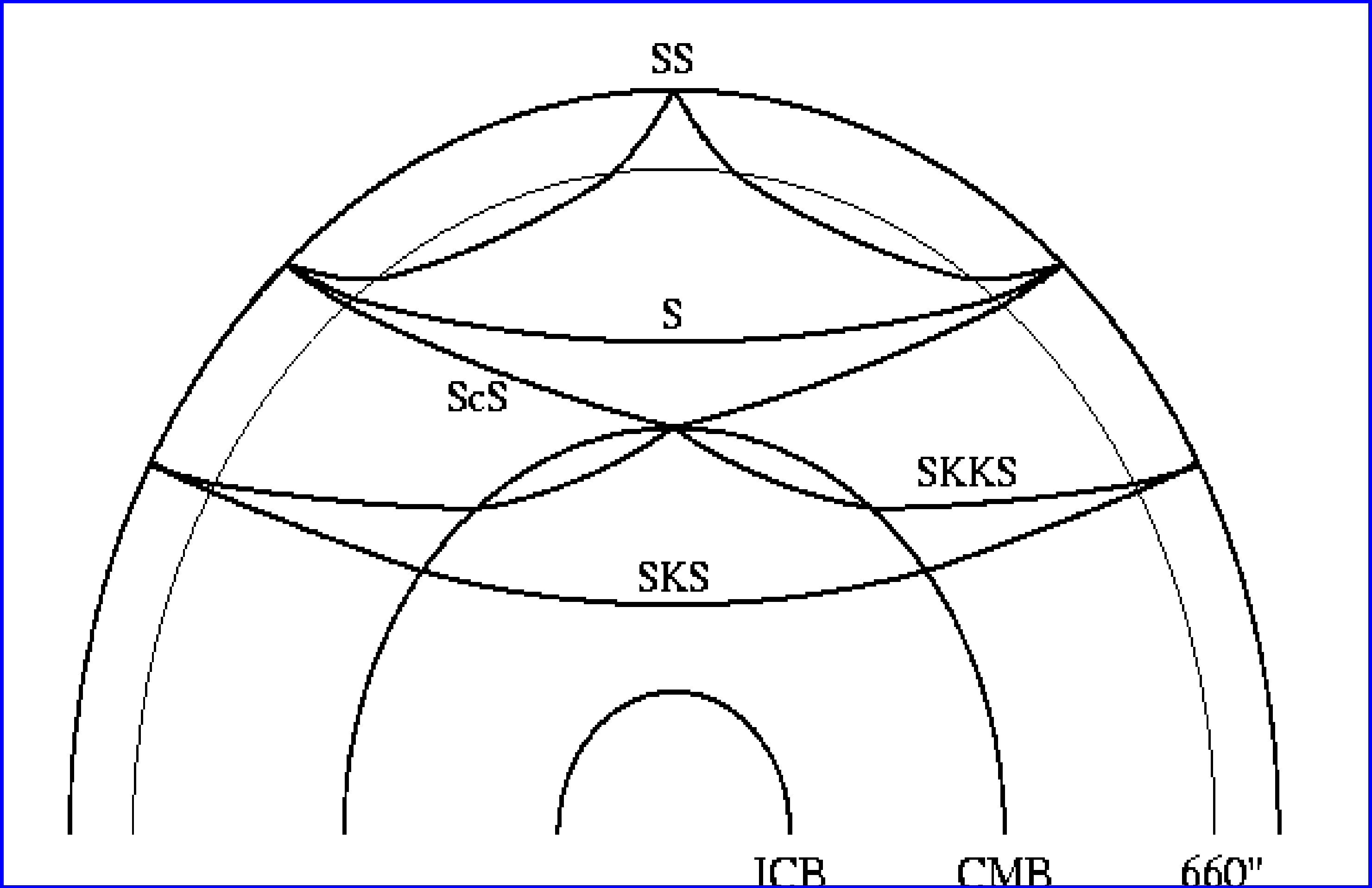
Azimuthal anisotropy →



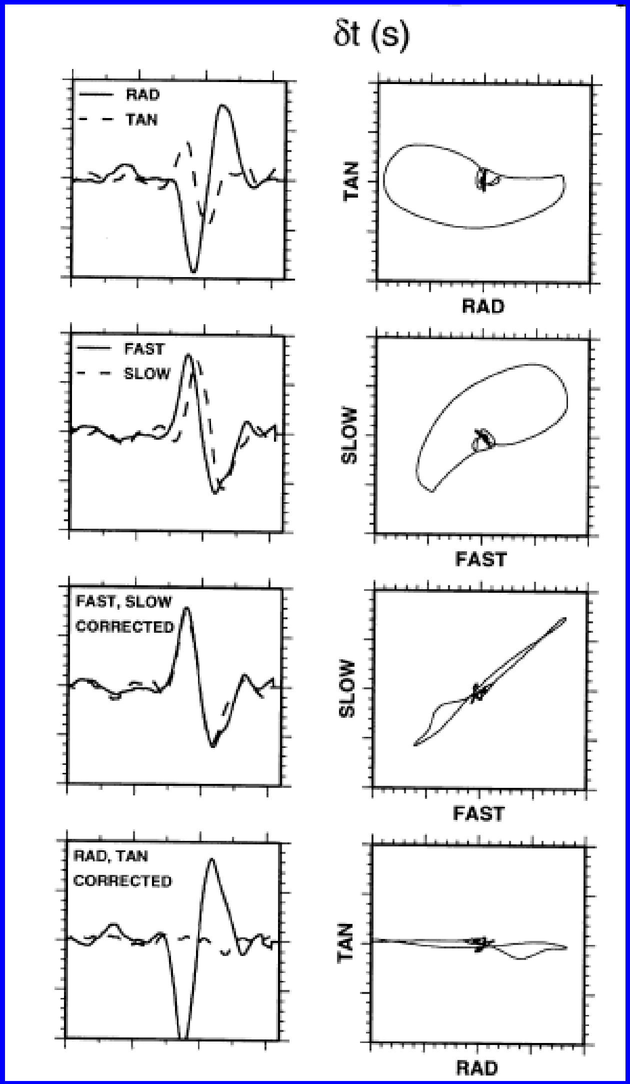

$\xi = (Vsh/Vsv)^2$

*Montagner, 2002*

# SKS splitting observations



# SKS Splitting Observations




*Huang et al., 2000*

Interpreted in terms of a model of a layer of anisotropy with a horizontal symmetry axis

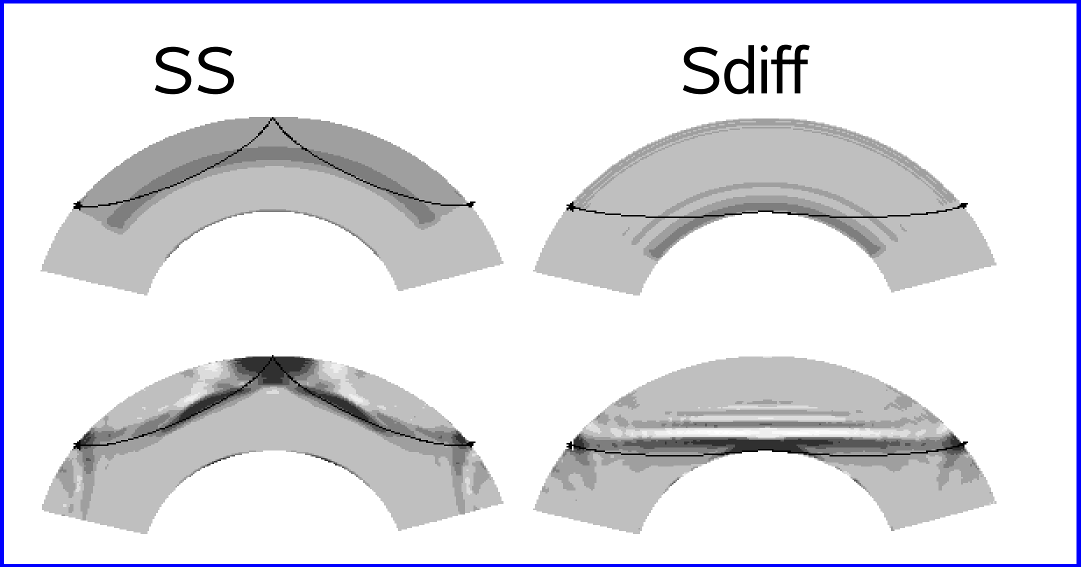
$\Delta t$ = time shift between fast and slow waves

$\Psi_0$ = Direction of fast velocity axis

Montagner et al. (2000) show how to relate surface wave anisotropy and shear wave splitting

# Waveform Inversion Methodology:

- Non-linear Asymptotic Coupling Theory (NACT); 3 component waveforms

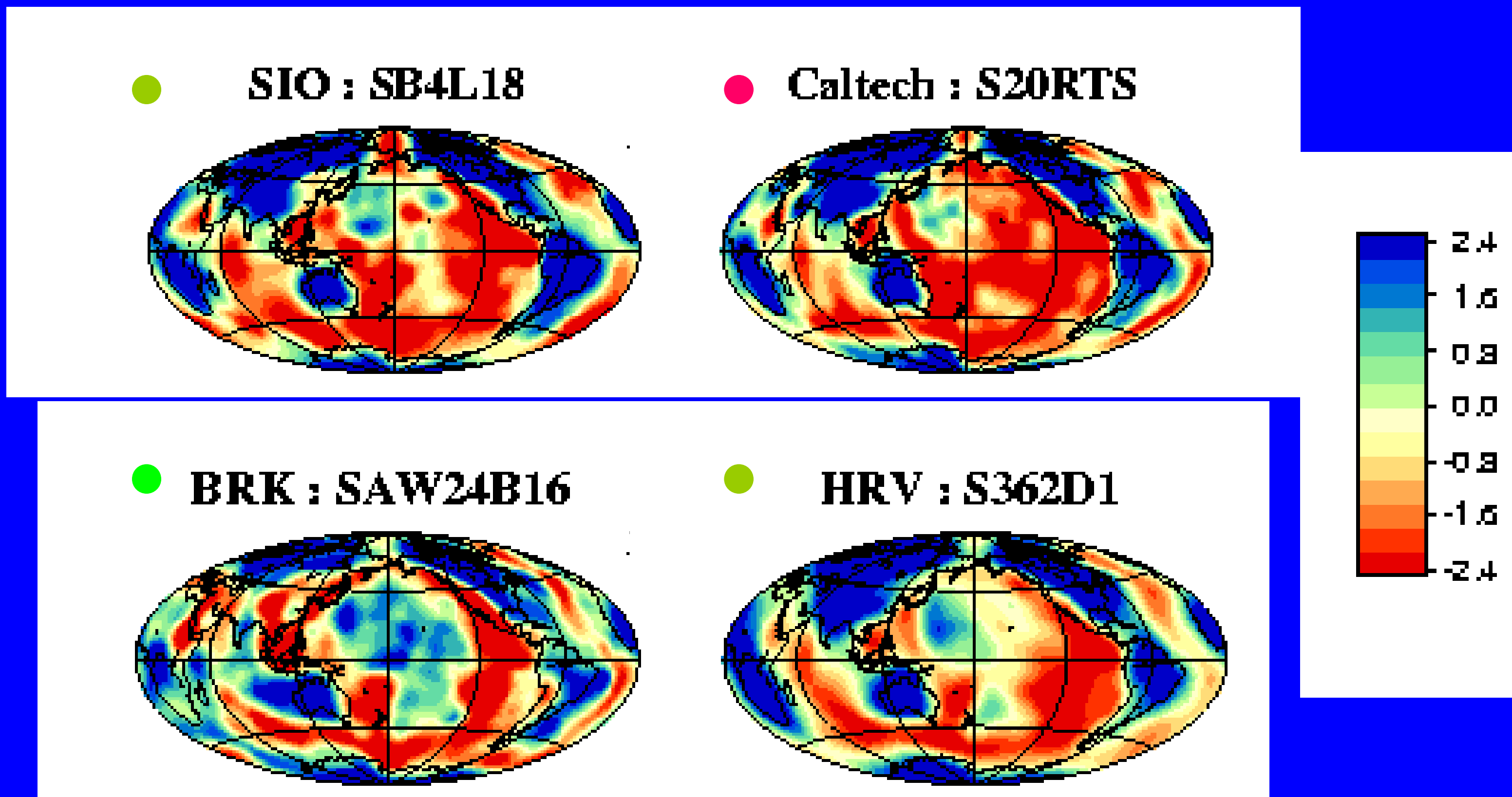



PAVA

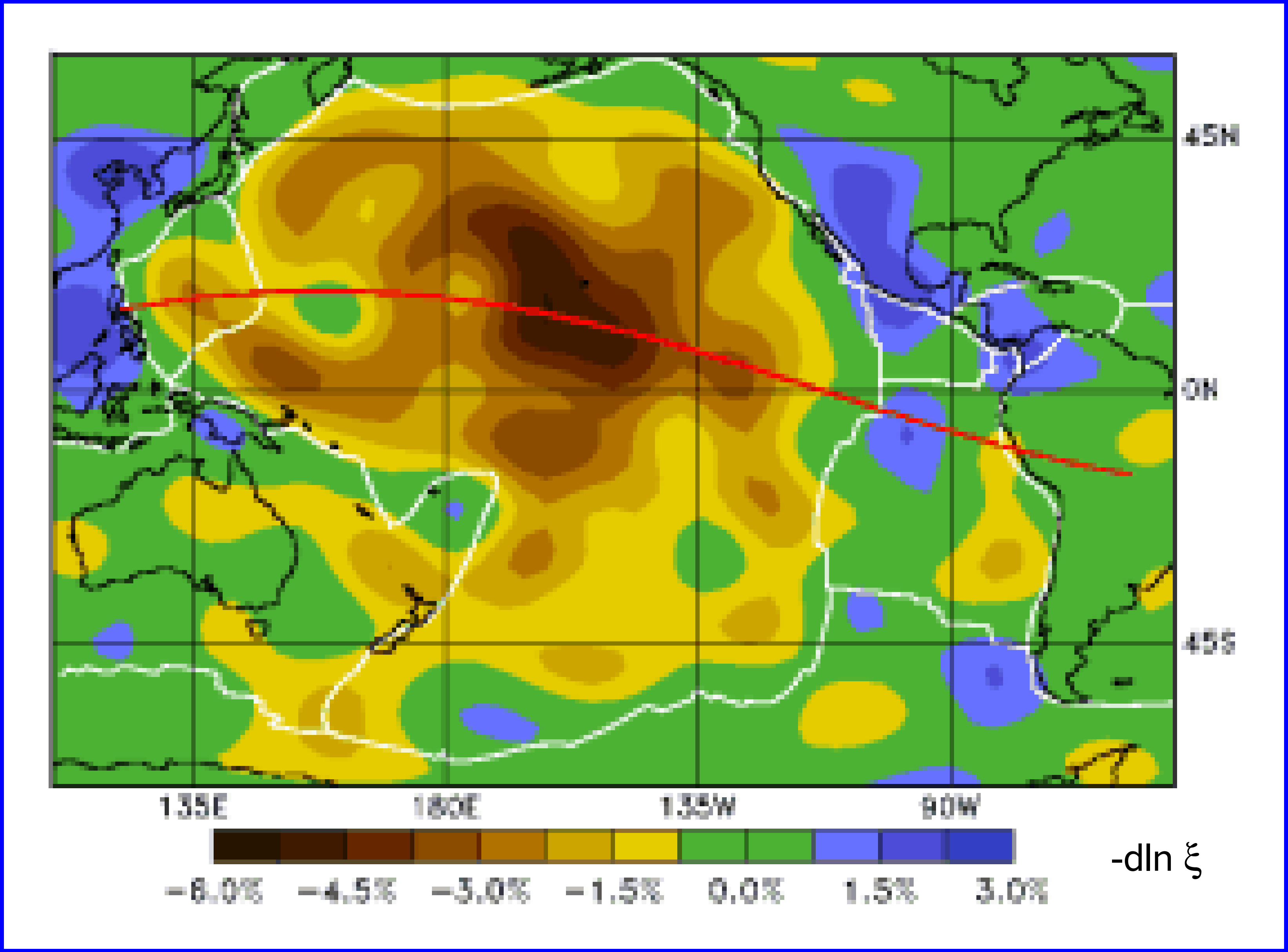
NACT

- extension to anisotropic inversion
- iterative inversion for elastic and anelastic structure
- Fundamental and overtone surface waves
- Body waves

# Depth = 140 km

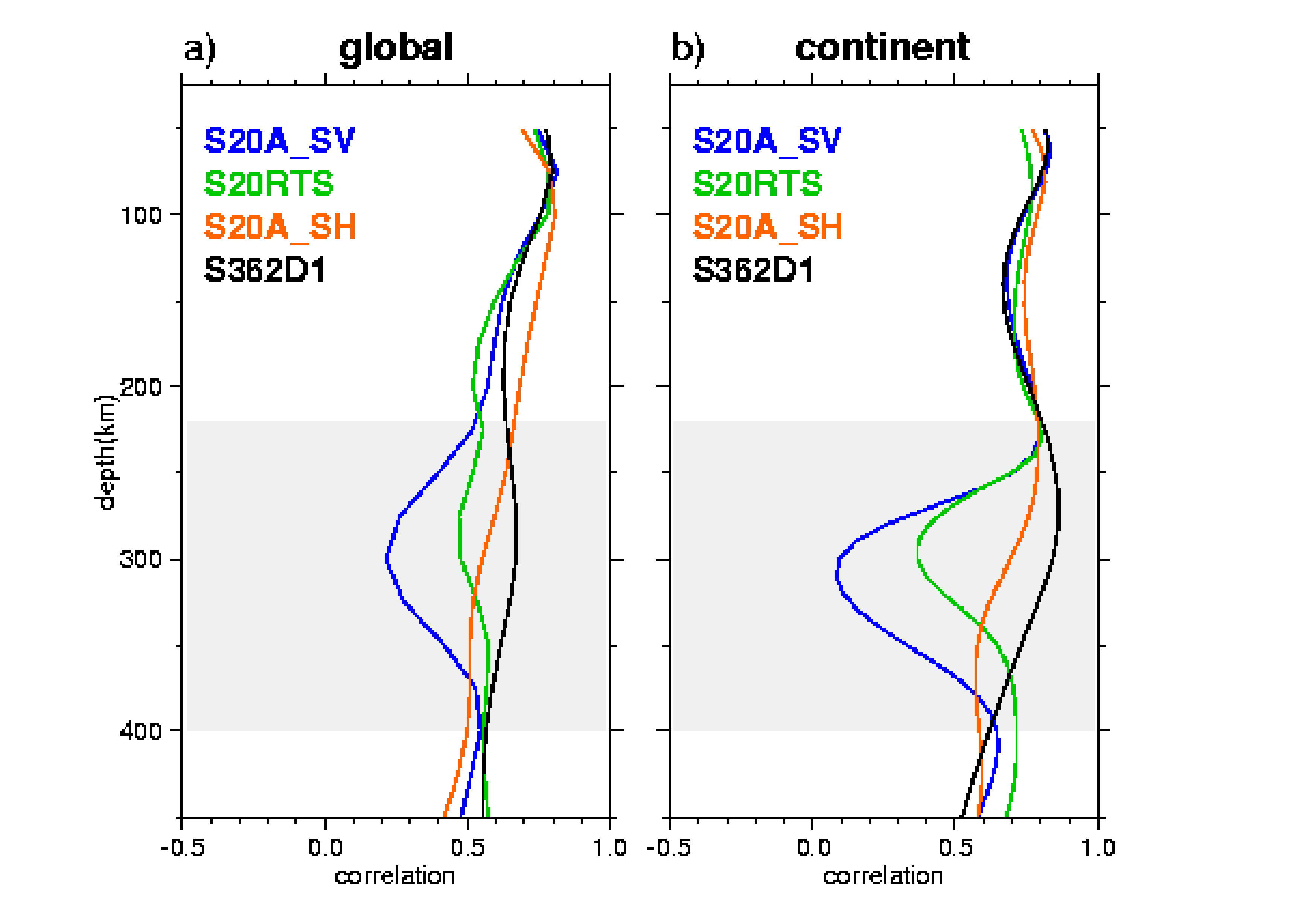



- "SH": horizontally polarized S waves
- "SV": vertically polarized S waves
- "hybrid": both

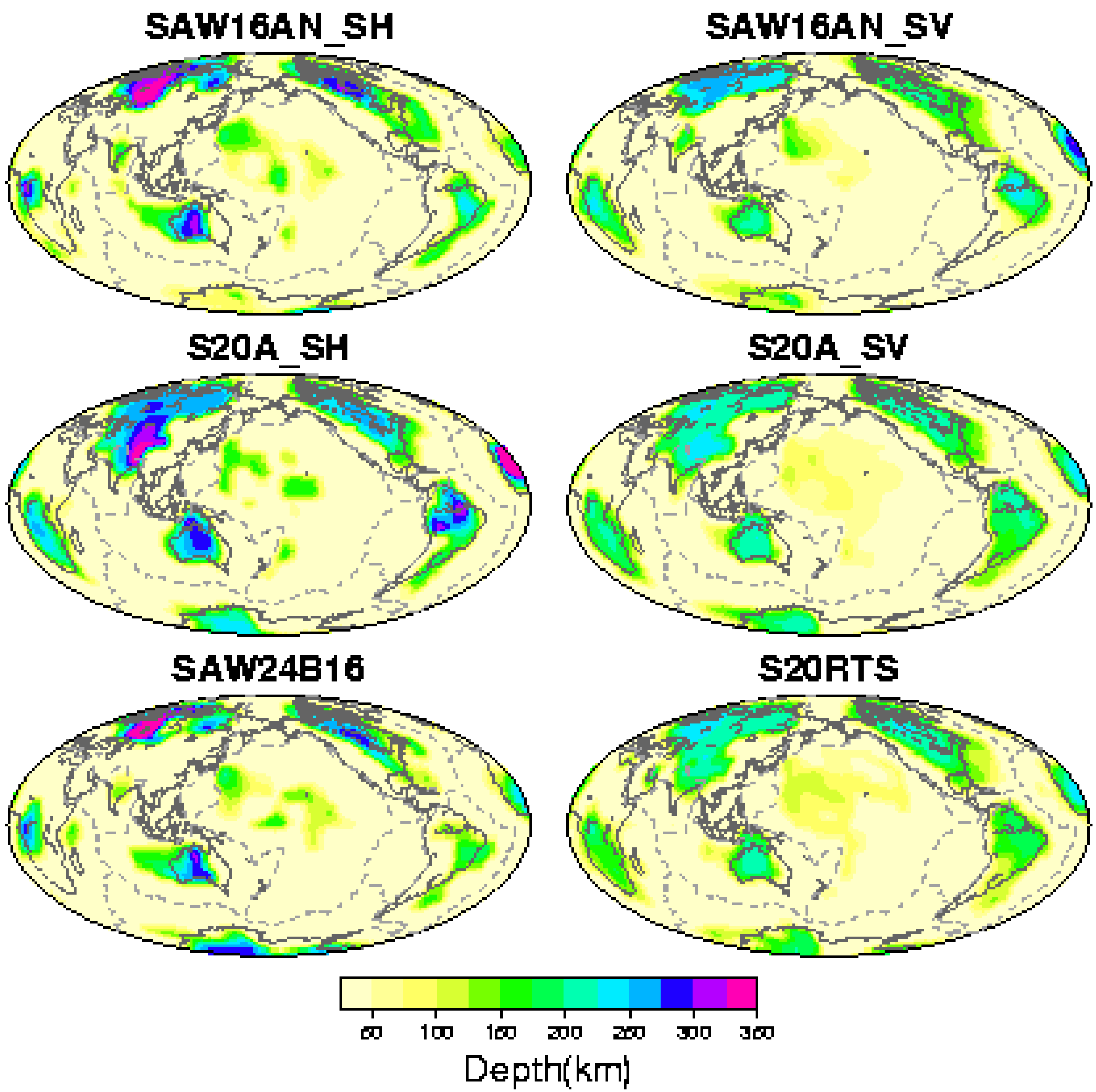



*Ekström and Dziewonski, 1998*

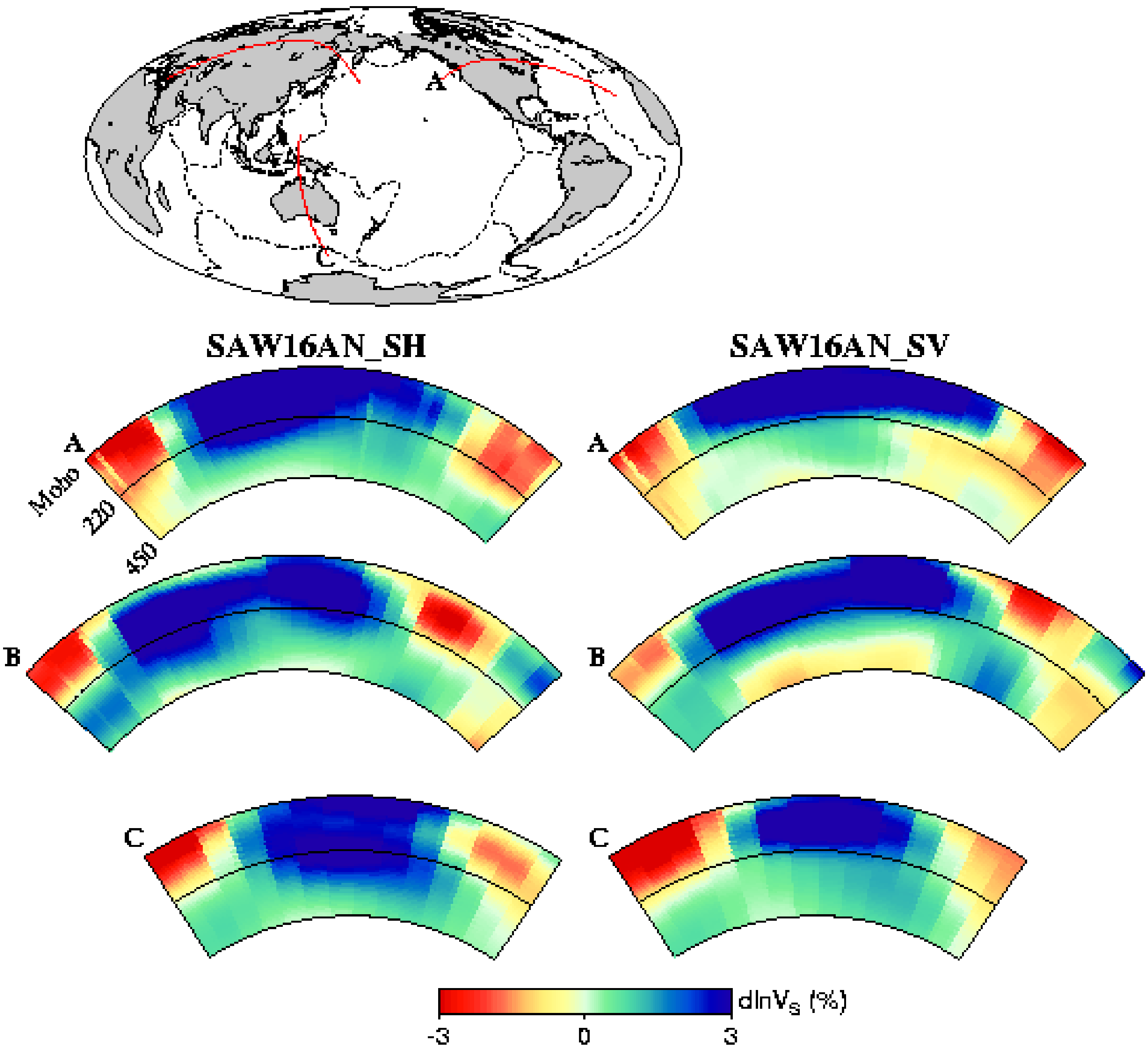
# Elastic models: correlation with SAW24B16



“SH models” “SV models”




Gung et al., Nature 2003



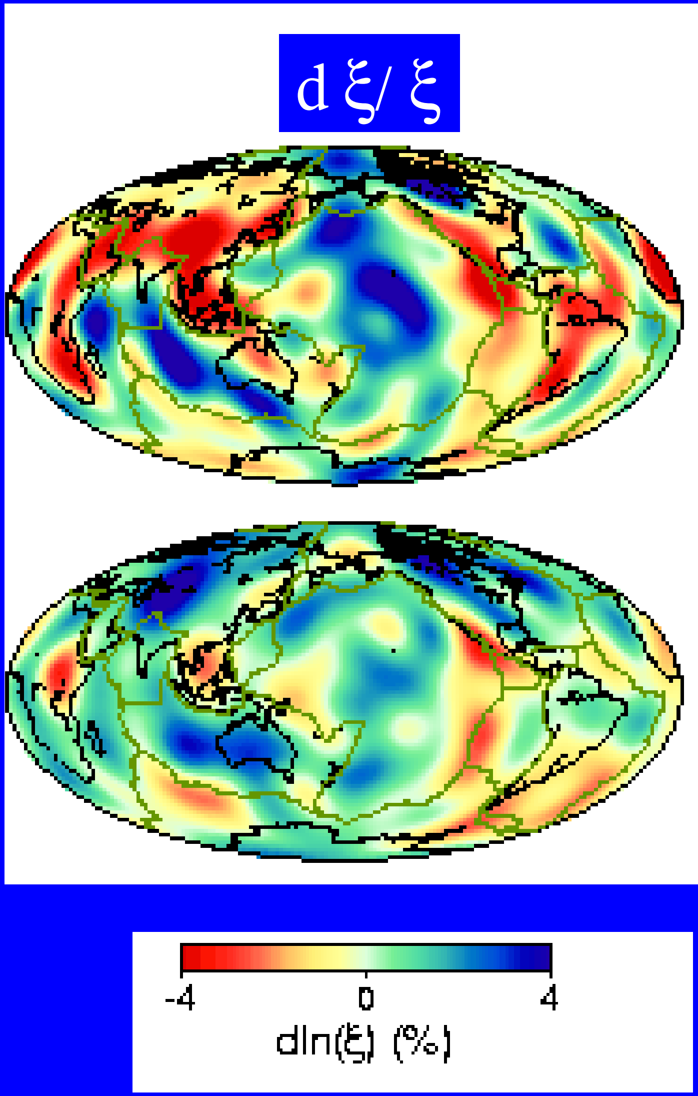
A
C
SAW16AN_SH
SAW16AN_SV
A
Moho
220
450
B
C
A
B
C
dlnV$_S$ (%)
-3
0
3

# Transverse isotropy
(referred to anisotropic PREM)

$\xi = (Vsh/Vsv)^2$

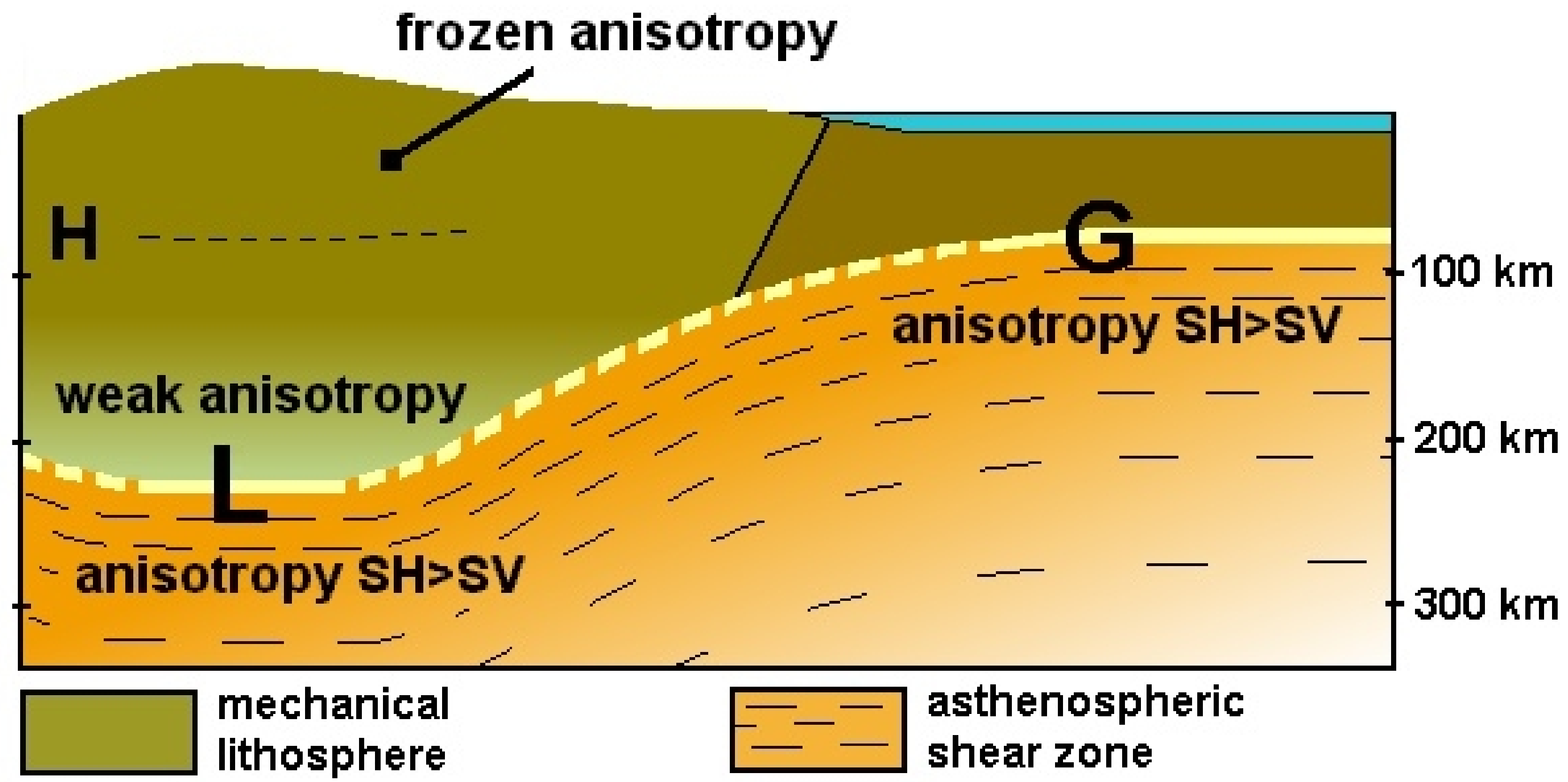
175 km

300 km



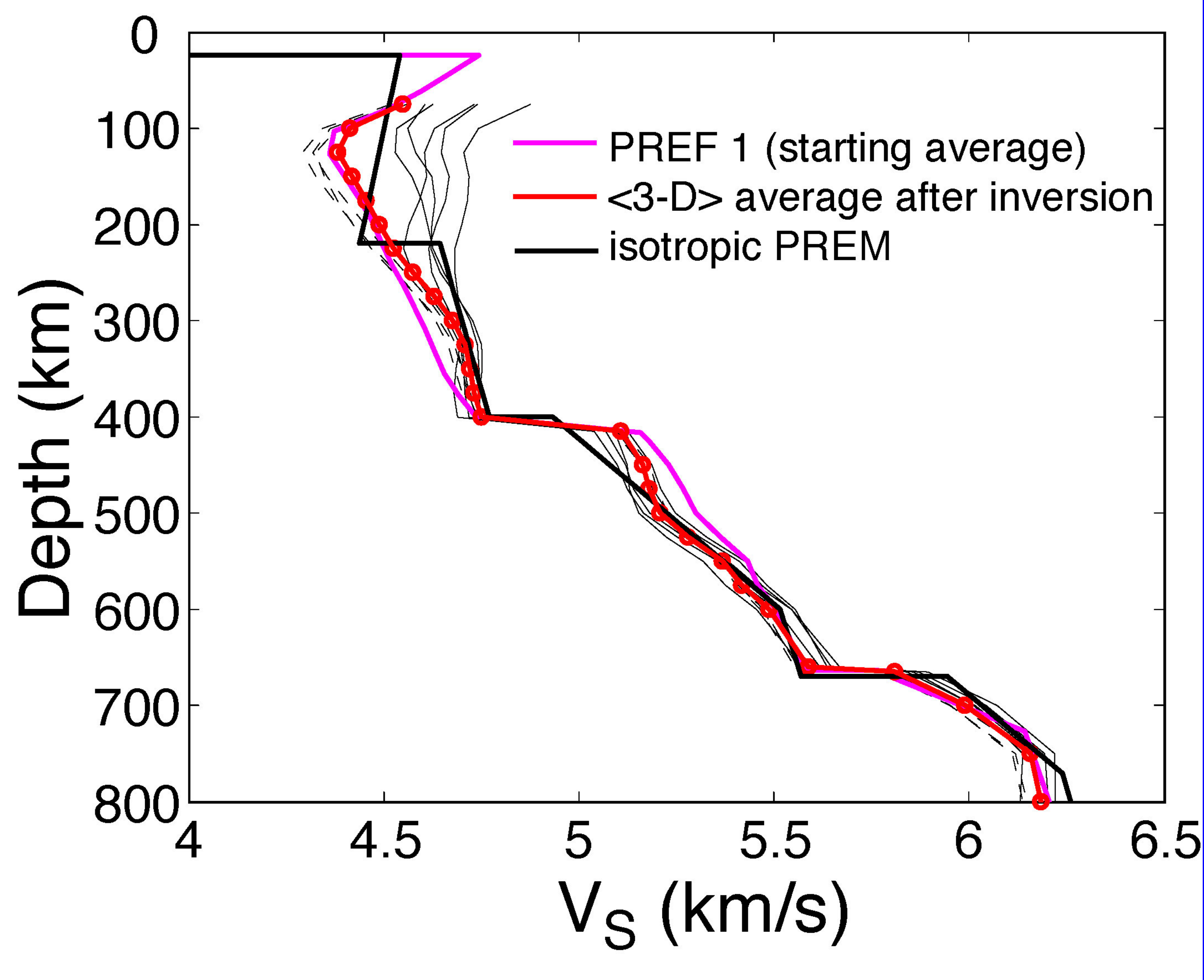

Average PREM removed

*Gung, Panning and Romanowicz, Nature, 2003*




*Gung et al., 2003*

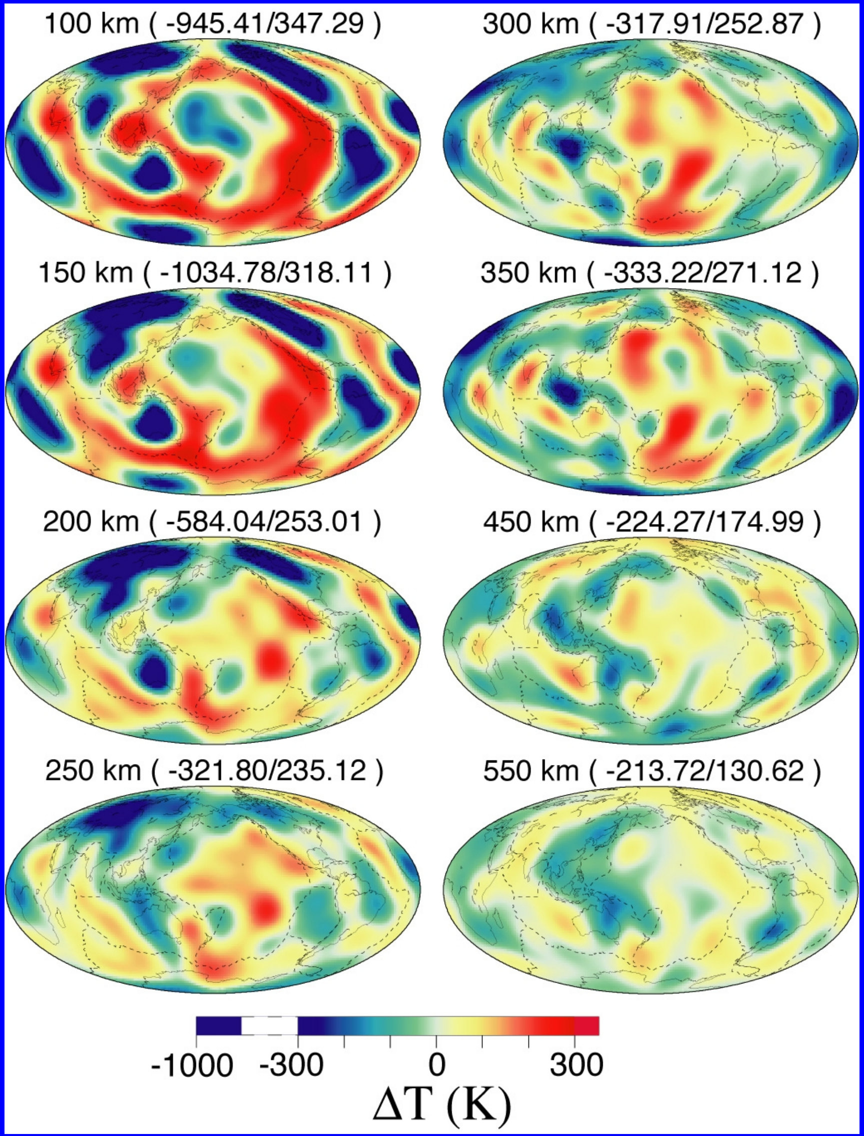
# Continental lithosphere: temperature/compositional effects




UC Berkeley
Global Seismology Group

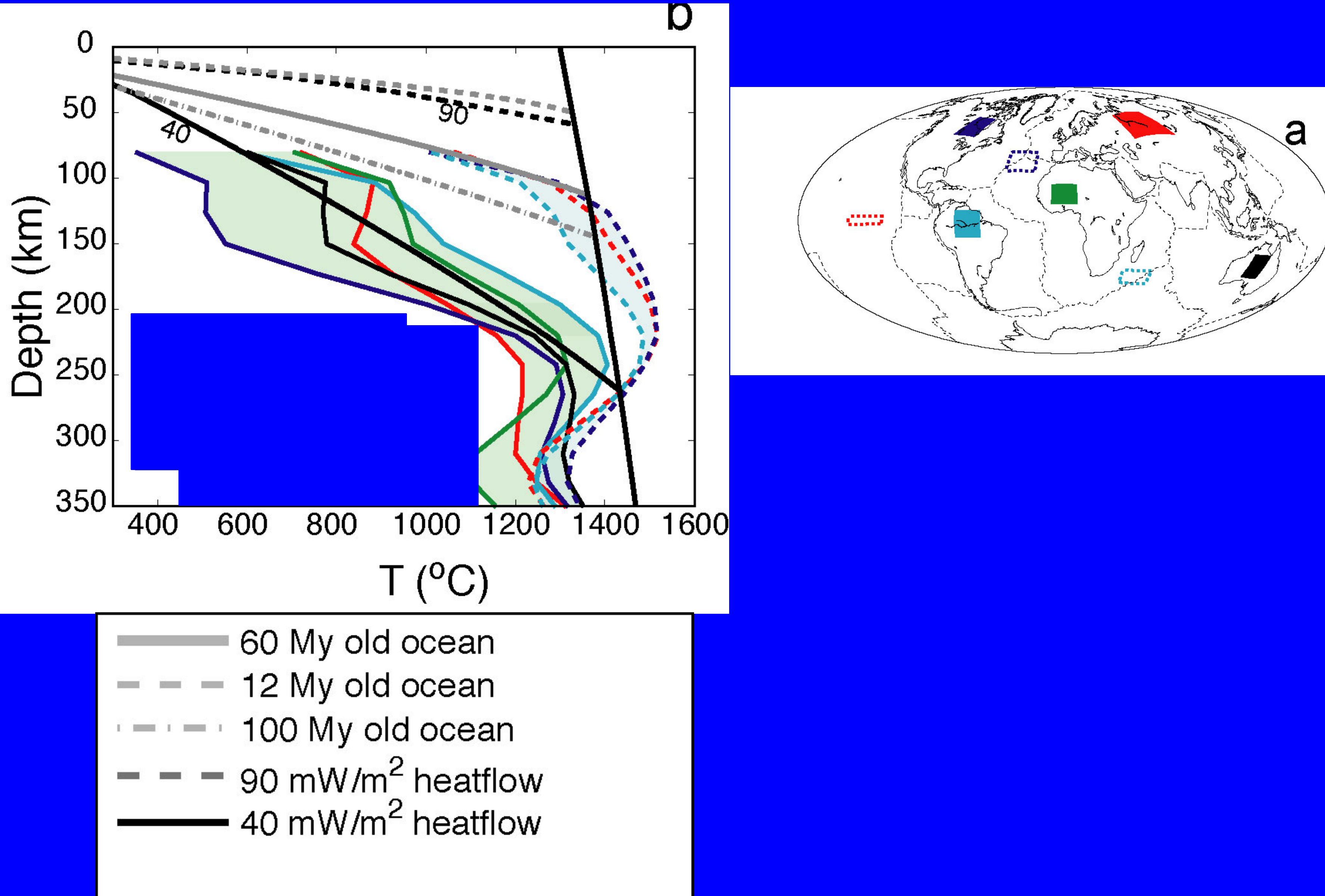
*Cammarano and Romanowicz, PNAS 2007*

# 3D temperature variations based on inversion of long period seismic waveforms



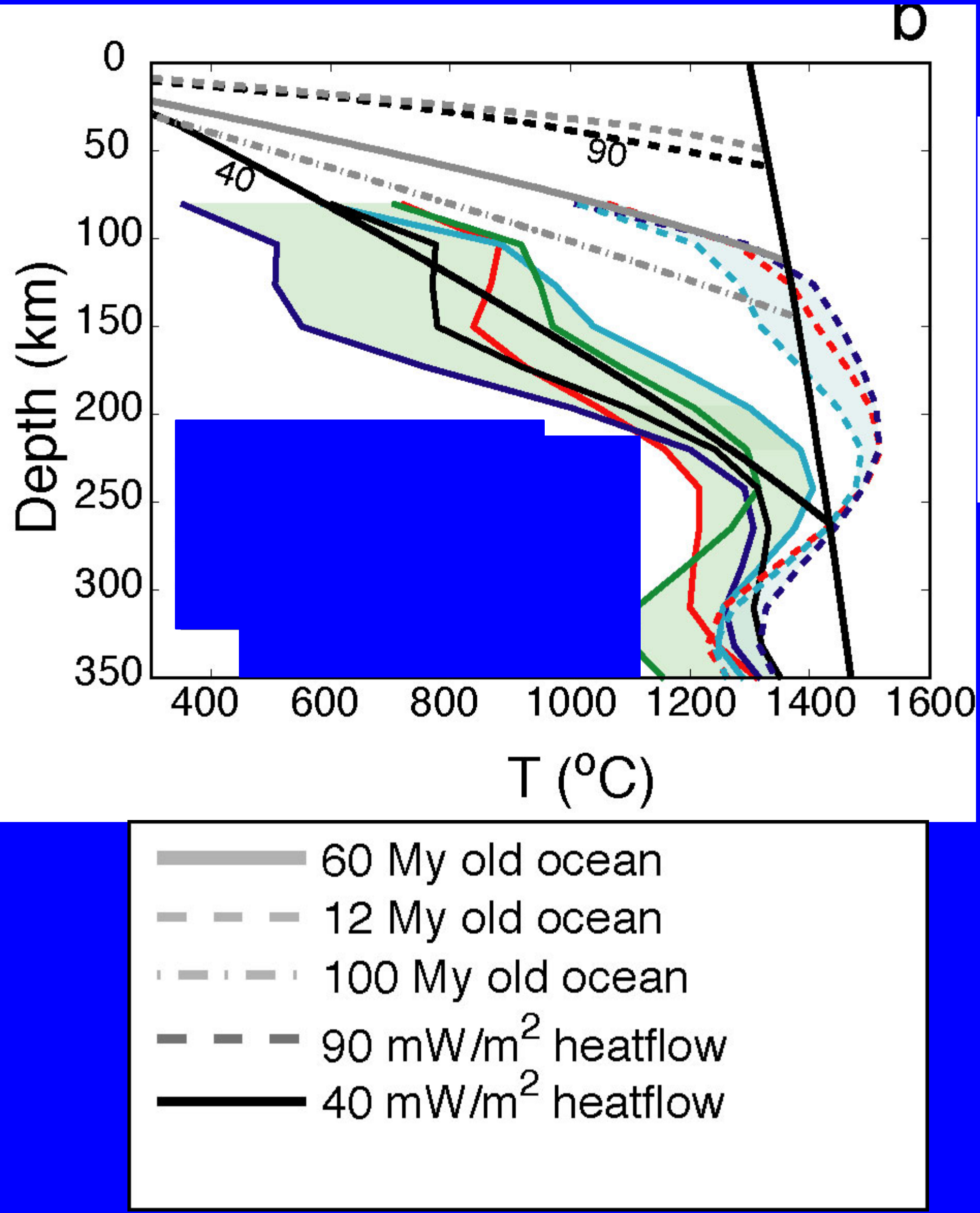

*Cammarano and Romanowicz, PNAS, 2007*

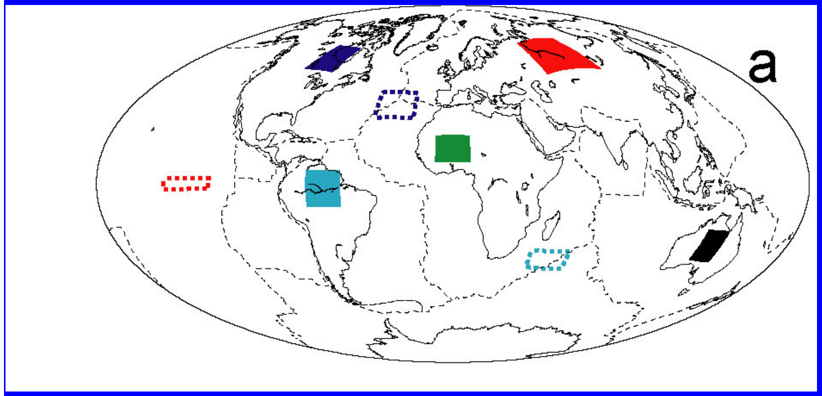
# Depth profiles of temperature under oceans and continents




*Cammarano and Romanowicz, PNAS, 2007*

# Depth profiles of temperature under oceans and continents



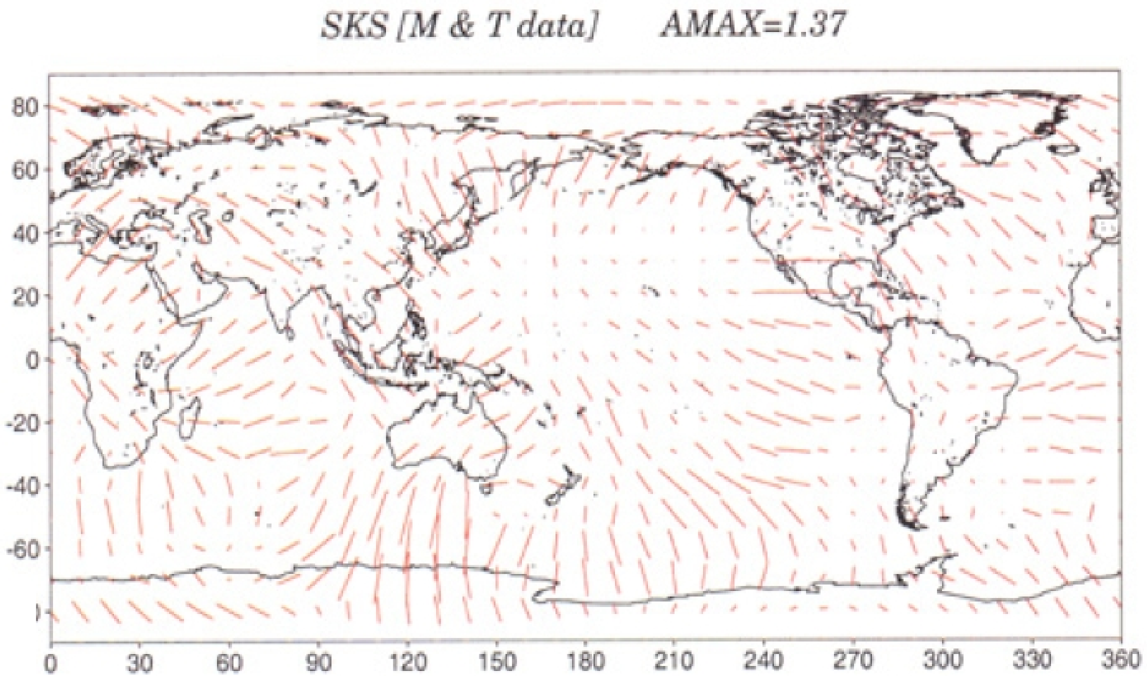




**Compositional signature emerges beneath cratons**

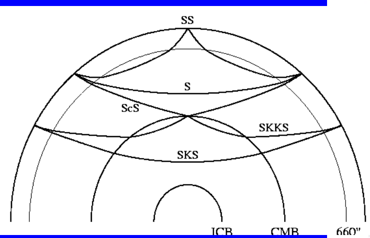
*Cammarano and Romanowicz, PNAS, 2007*

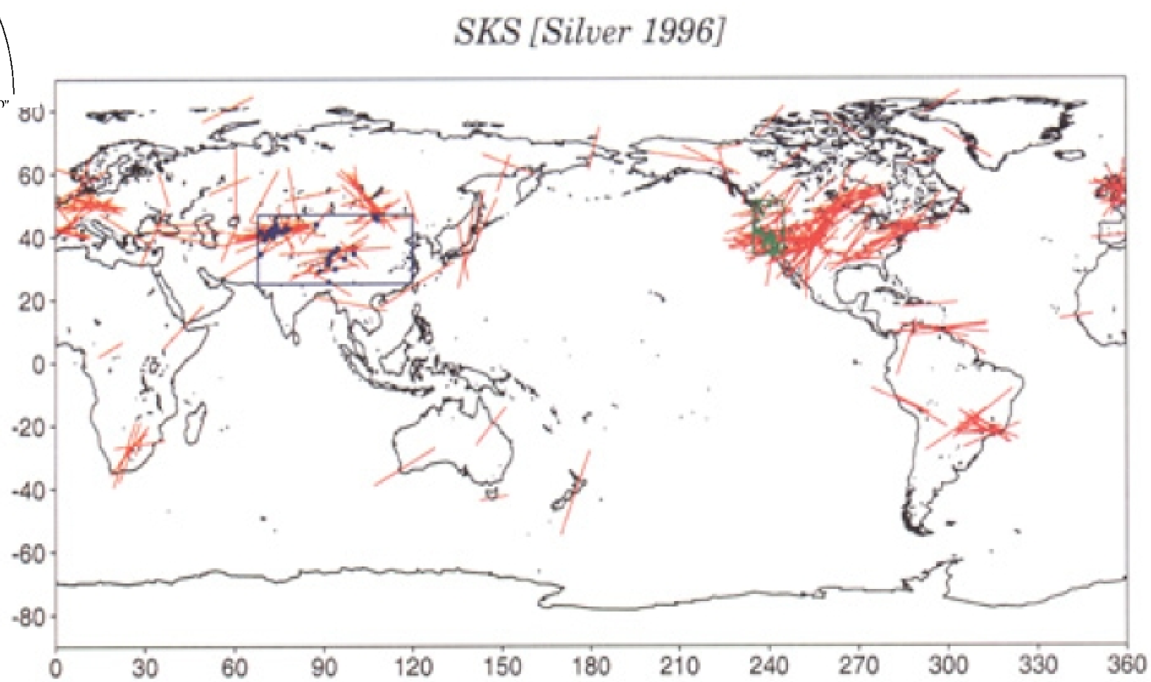
# Continental scale, isotropic, radial and azimuthal Anisotropy

Extension to waveform inversion of Montagner's "vectorial tomography"




Predictions from surface wave inversion



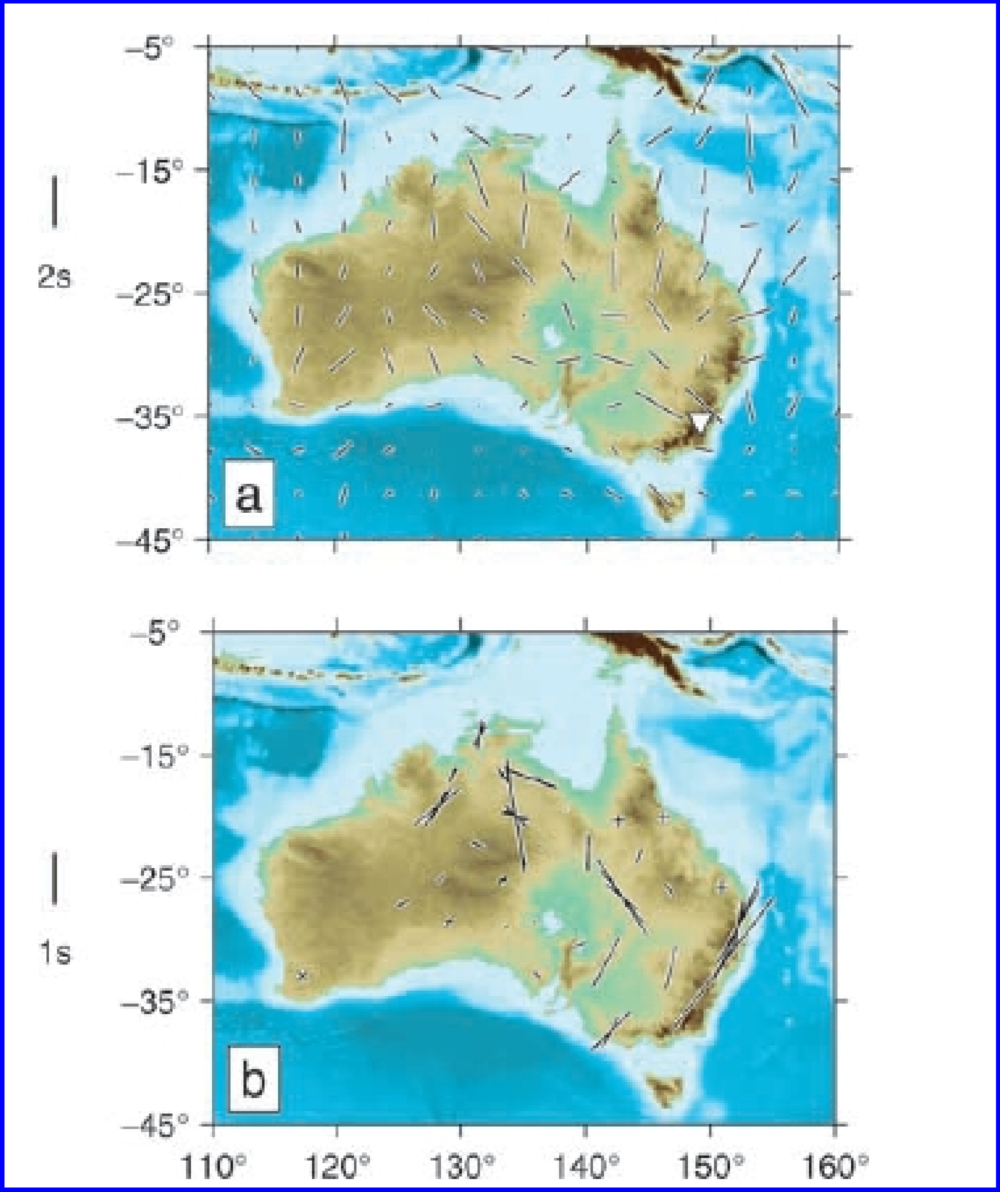

SKS splitting measurements

*Montagner et al. 2000*

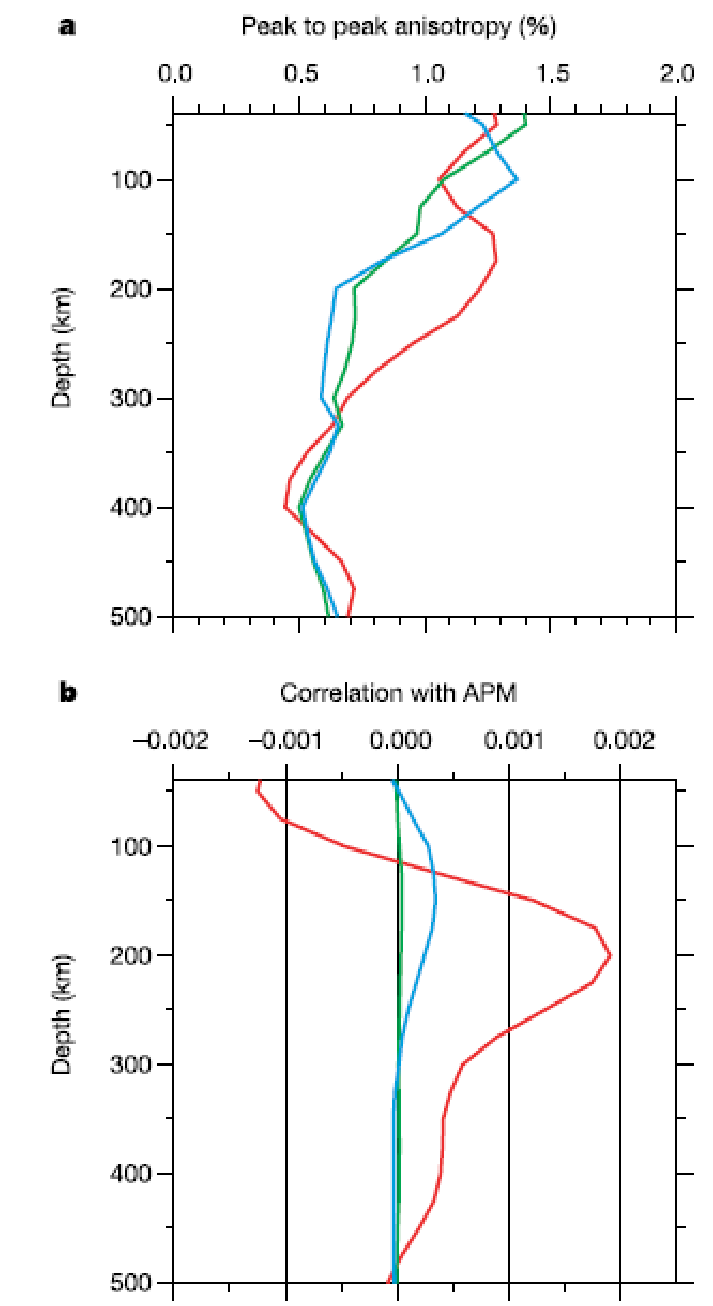
# Australia

Predicted from Surface wave model

SKS Splitting measurements




*Simons et al., 2005*




Oceans

Australia

Other continents

*Debayle et al.,Nature, 2005,*

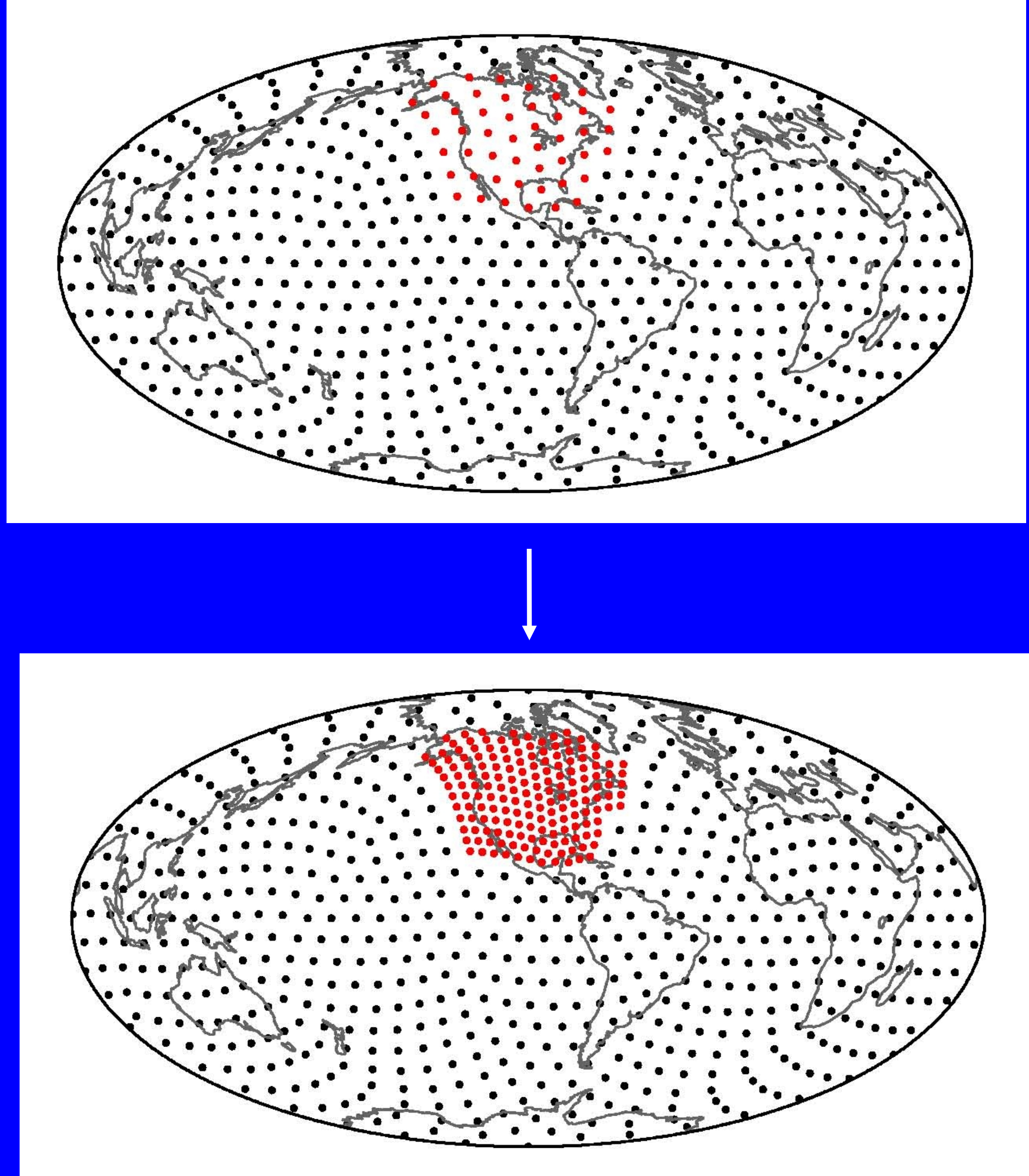
# Models based on surface waves or SKS splitting observations

Limitations:

→ lack horizontal and vertical resolution

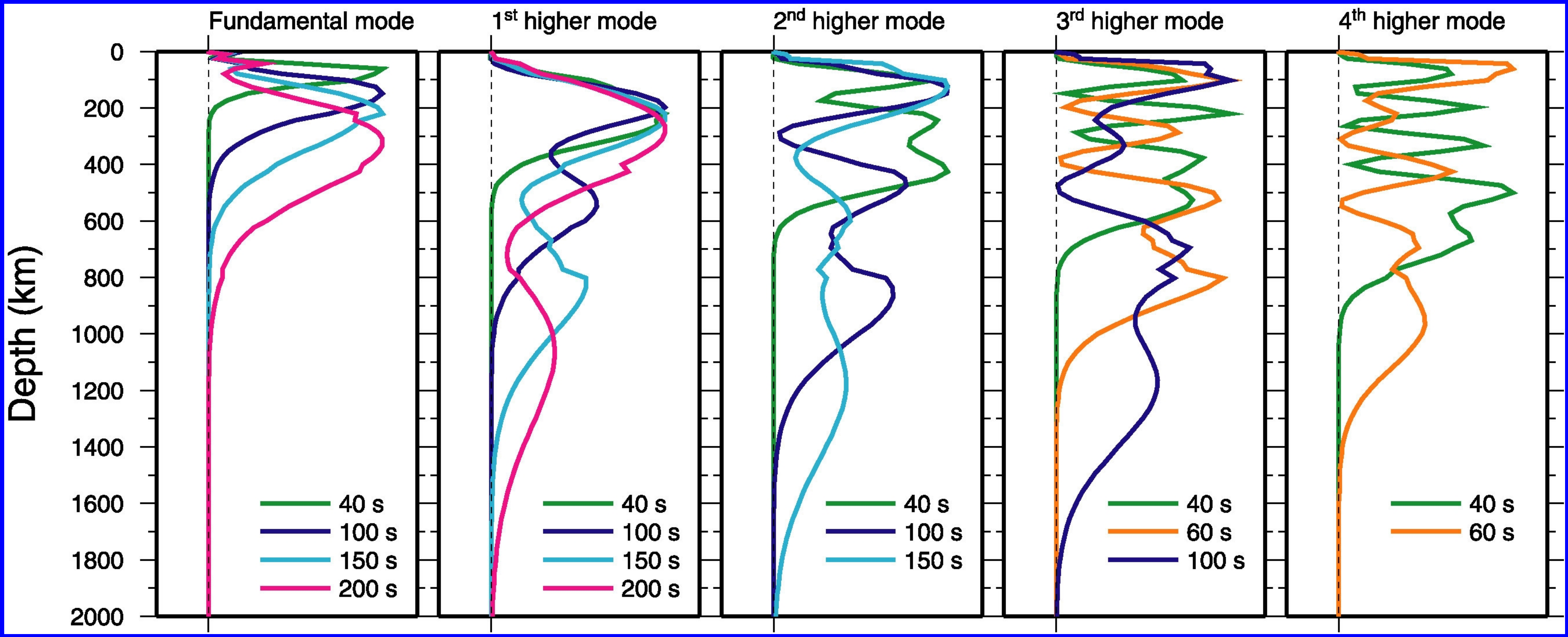
→ limited to either radial or azimuthal anisotropy

High resolution upper mantle 3D model
with increased lateral and vertical resolution including both radial and azimuthal anisotropy



# Overtones

By including overtones, we can see into the transition zone and the top of the lower mantle.



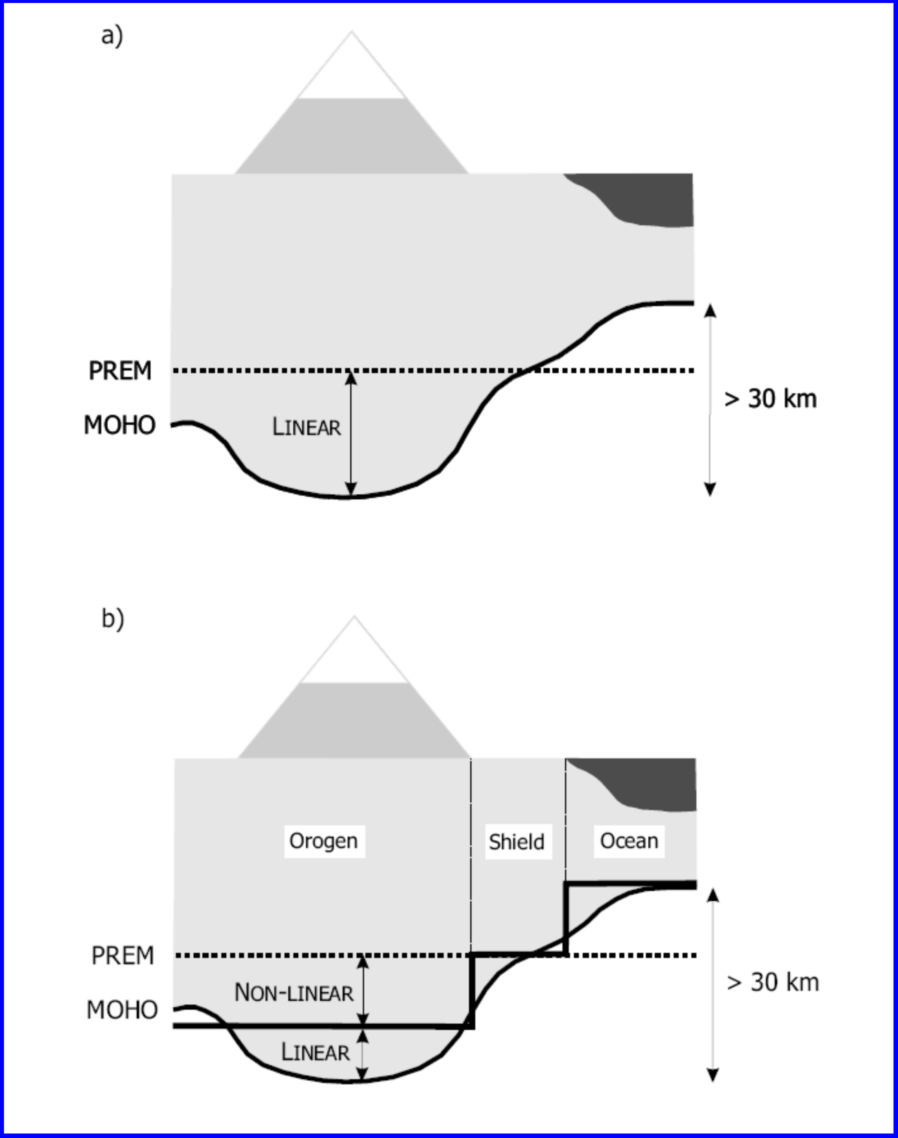

*after Ritsema et al, 2004*

# Crustal corrections

Linear

v/s

Non-linear

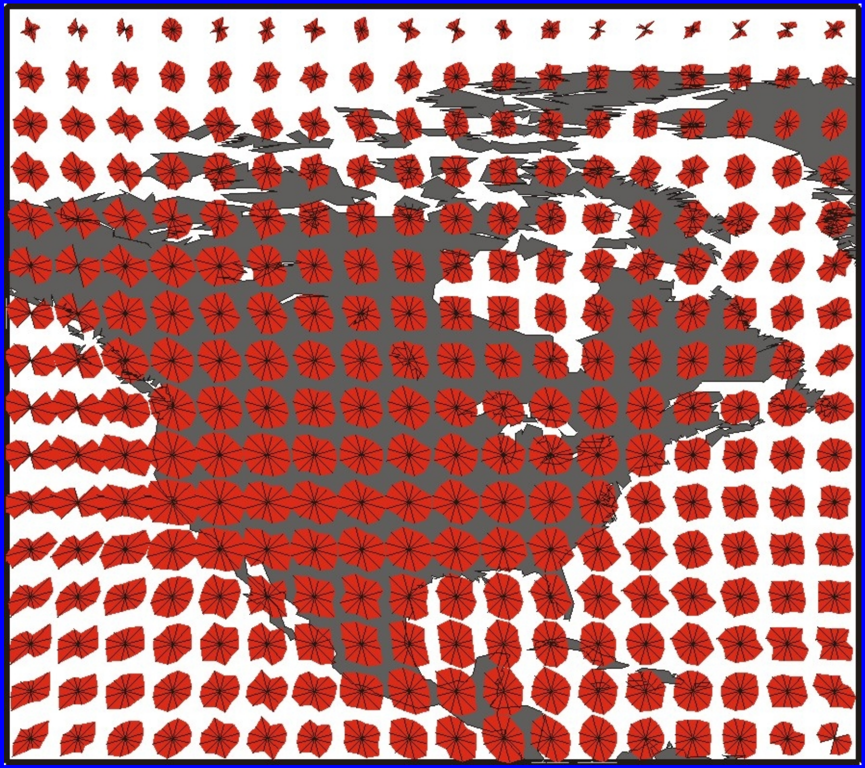



*Marone and Romanowicz, 20*

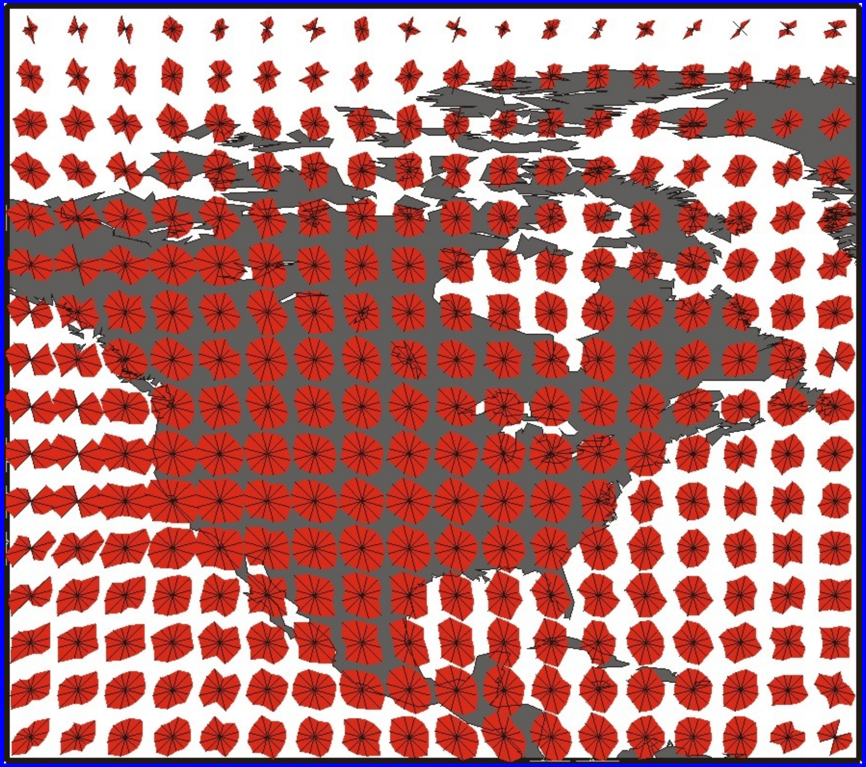
# Azimuthal coverage

Fundamental and higher modes

Z component



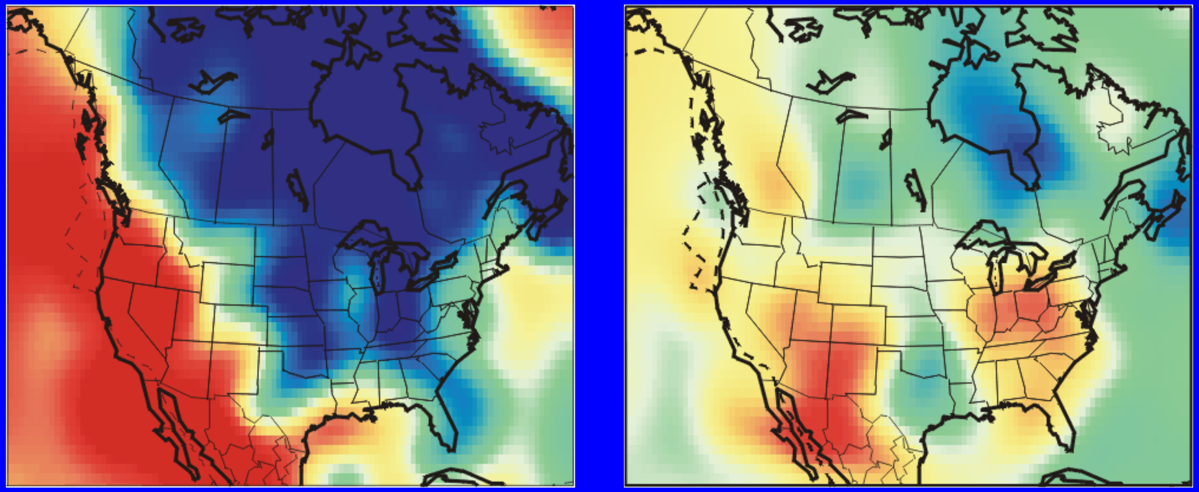
T component

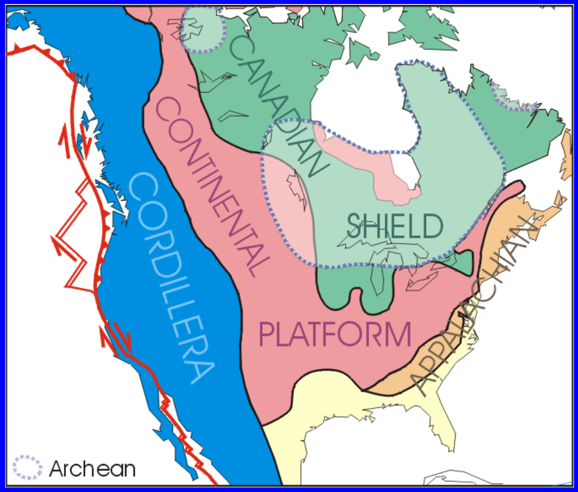


# Isotropic S-velocity

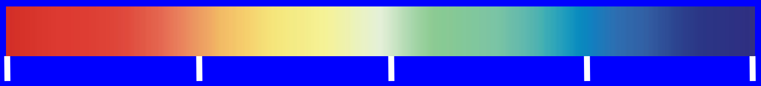
150 km

250 km





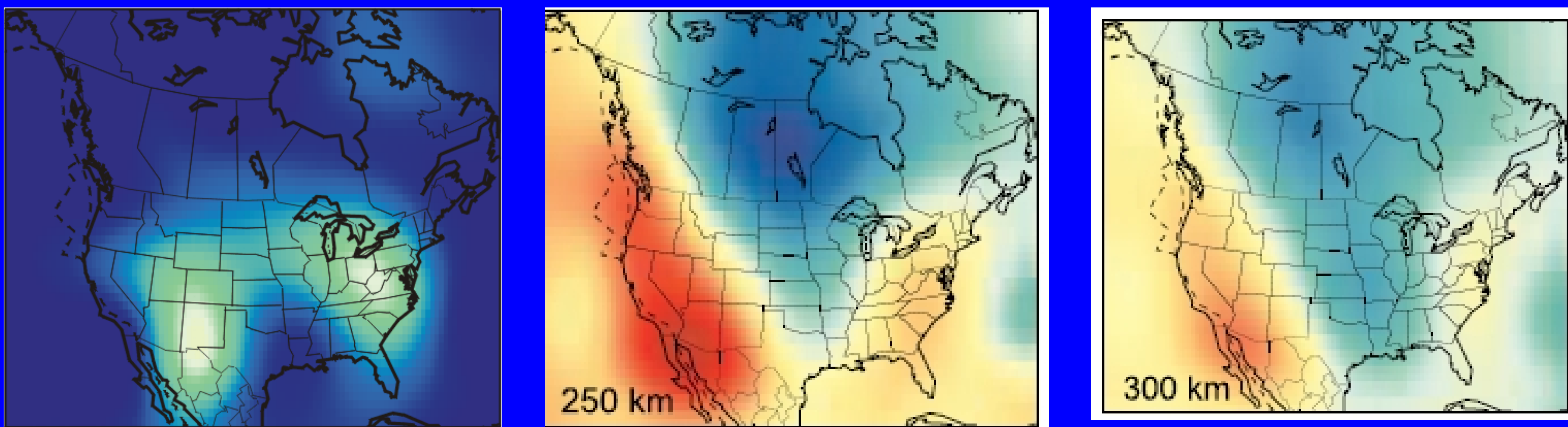

After Bally et al., 1989



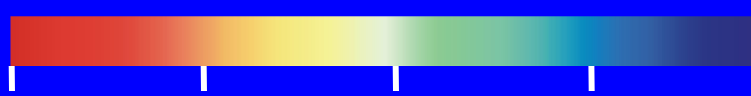

dln $V_s$ (%)

# Anisotropic parameter $\xi = (V_{SH}/V_{SV})^2$

150 km    250 km    300 km




$V_{SV} > V_{SH}$

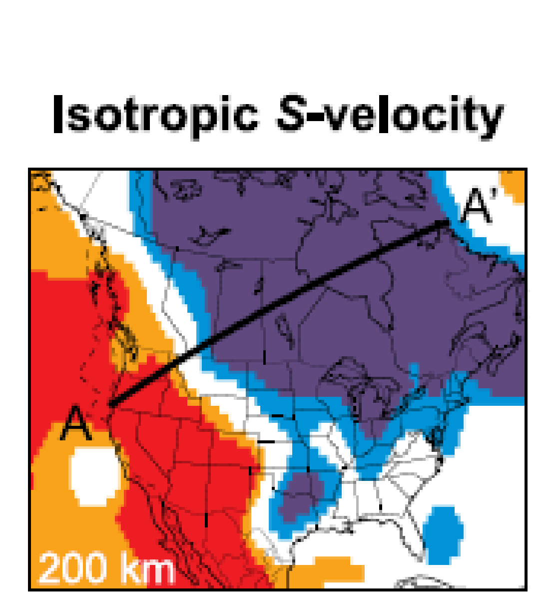


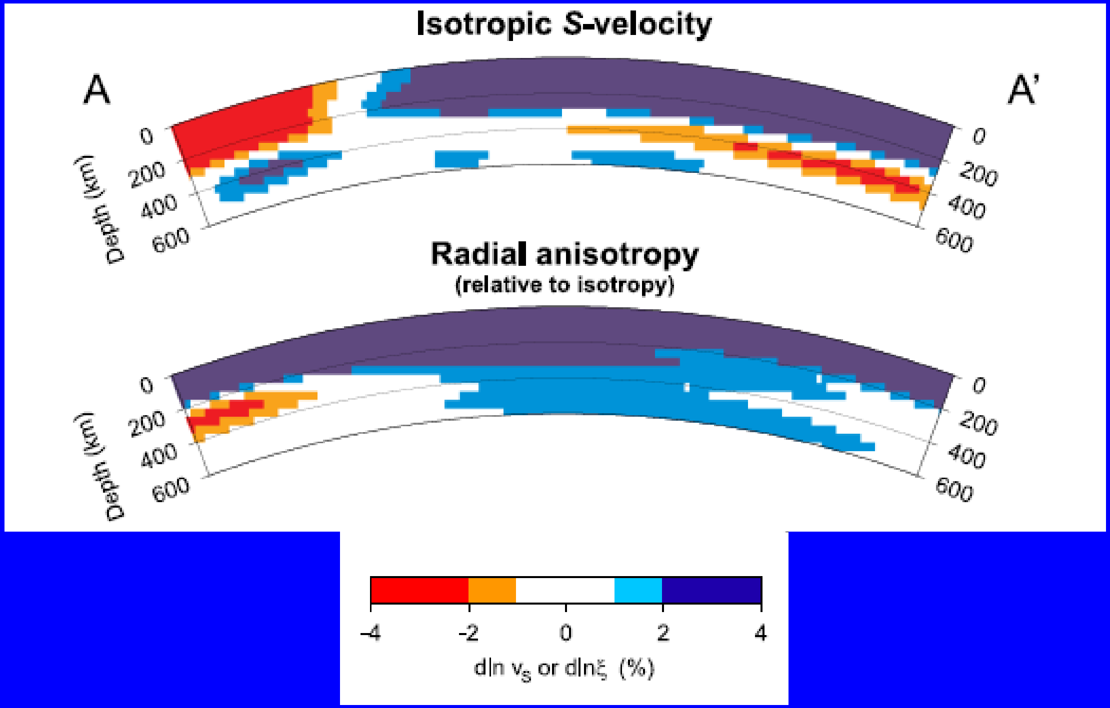
-4    -2    0    2    4

$V_{SH} > V_{SV}$

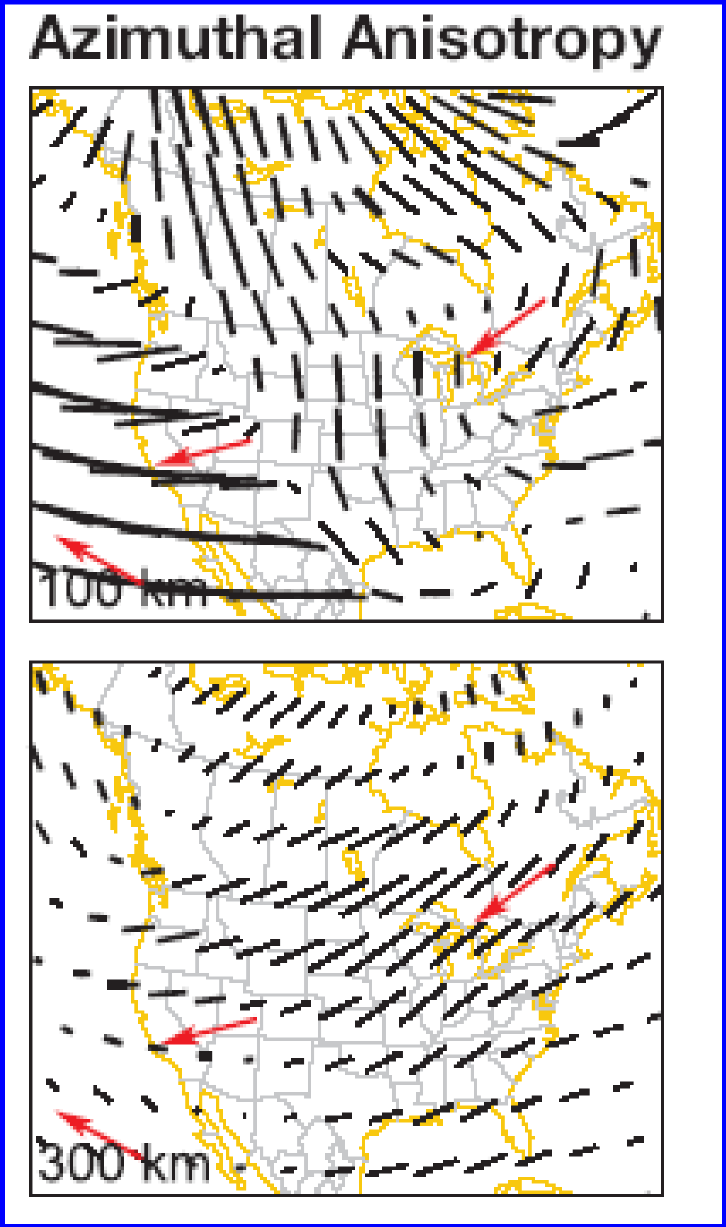
dln $\xi$ (%)

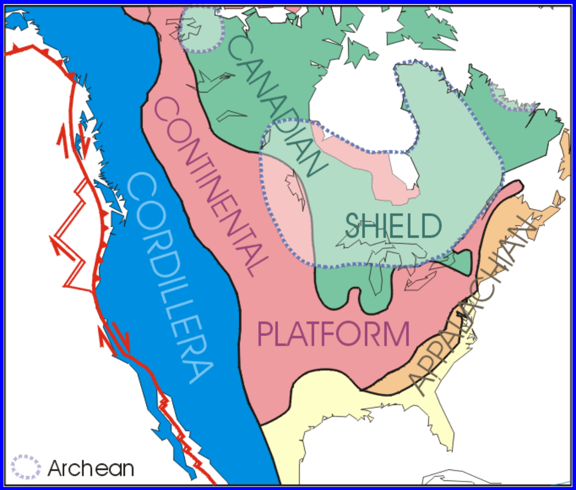
*Marone and Romanowicz, GJI,2007*



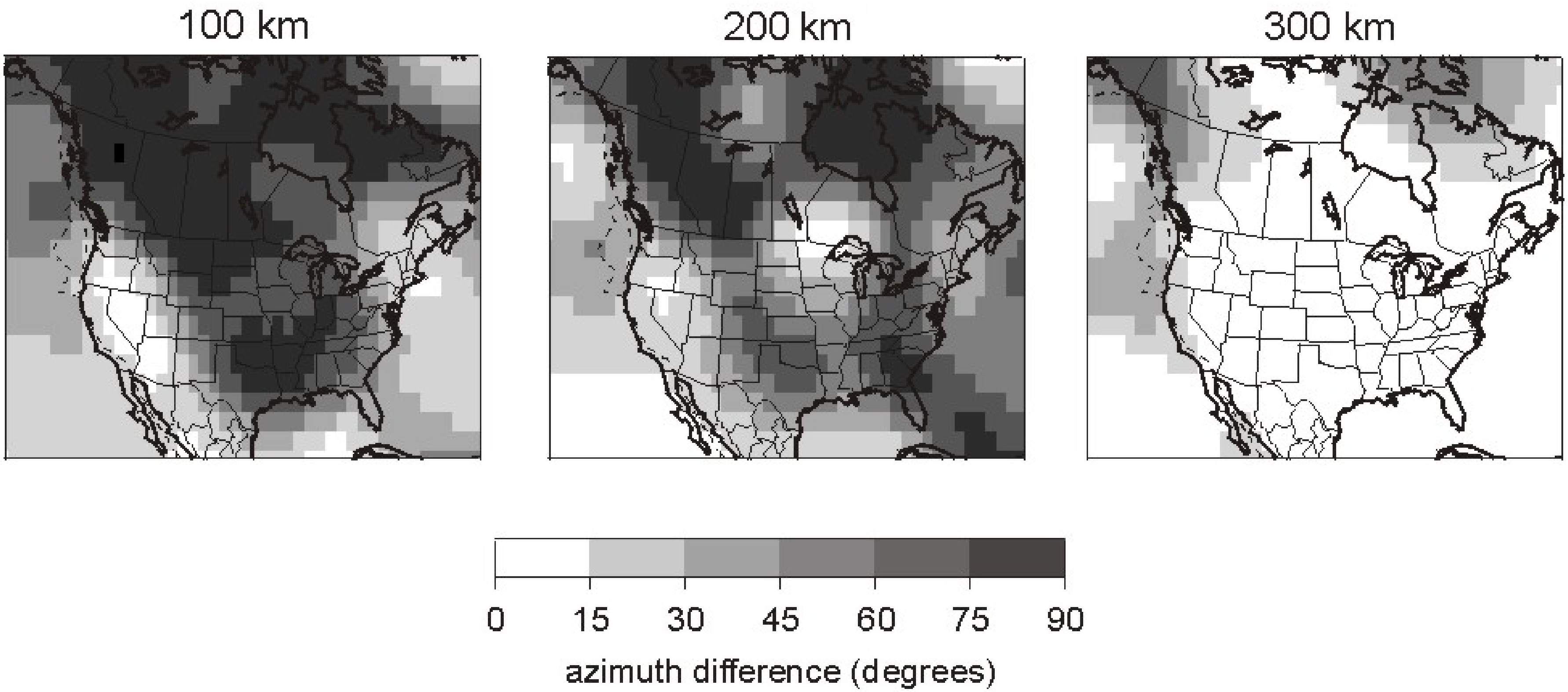

*Marone et al., GJI, in press*

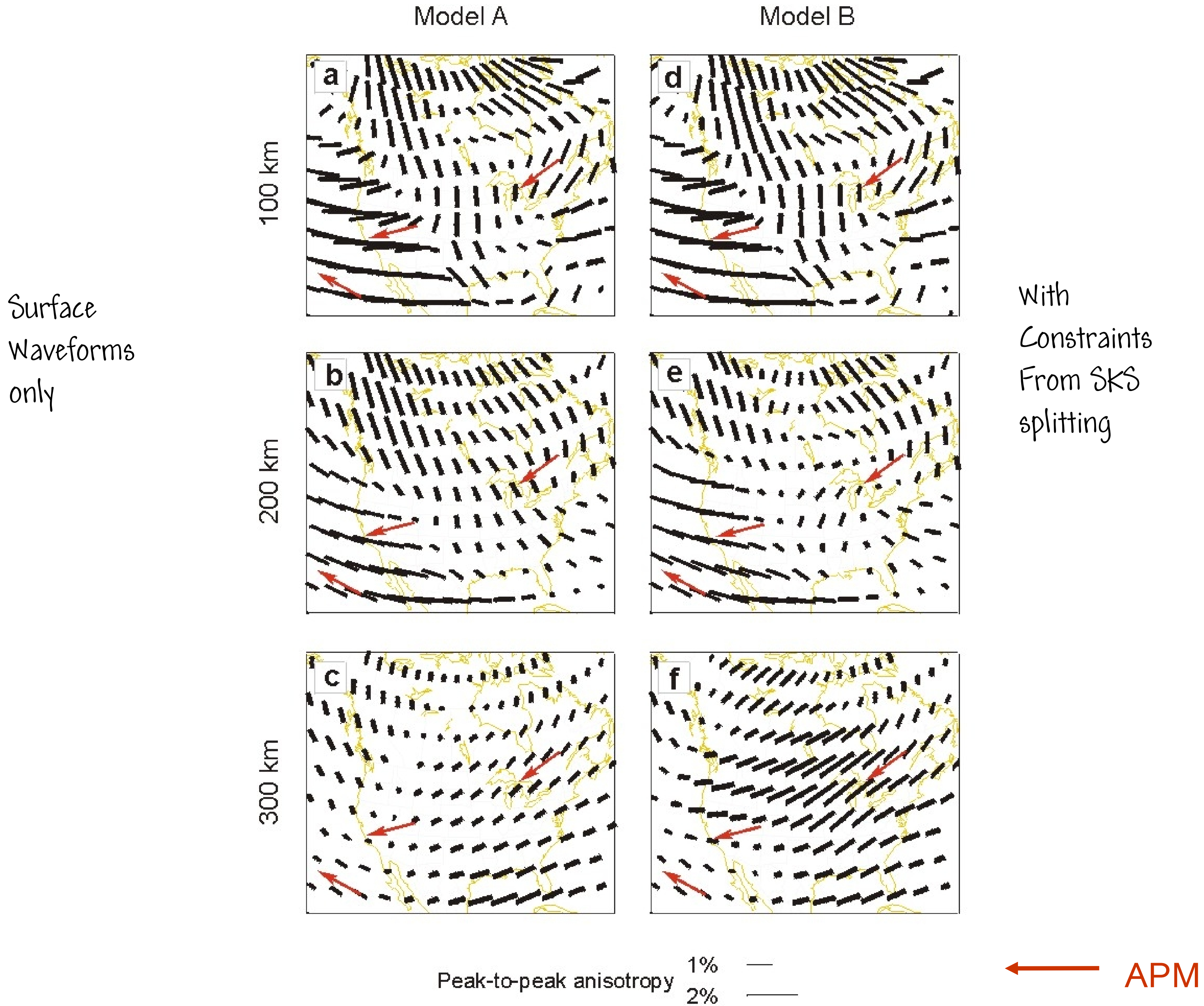



*Marone and Romanowicz, 2007*

# Difference between directions of fast velocity and absolute plate motion





Model A
Model B
a
b
c
d
e
f
100 km
200 km
300 km
Surface Waveforms only
With Constraints From SKS splitting
Peak-to-peak anisotropy
1%
2%
APM

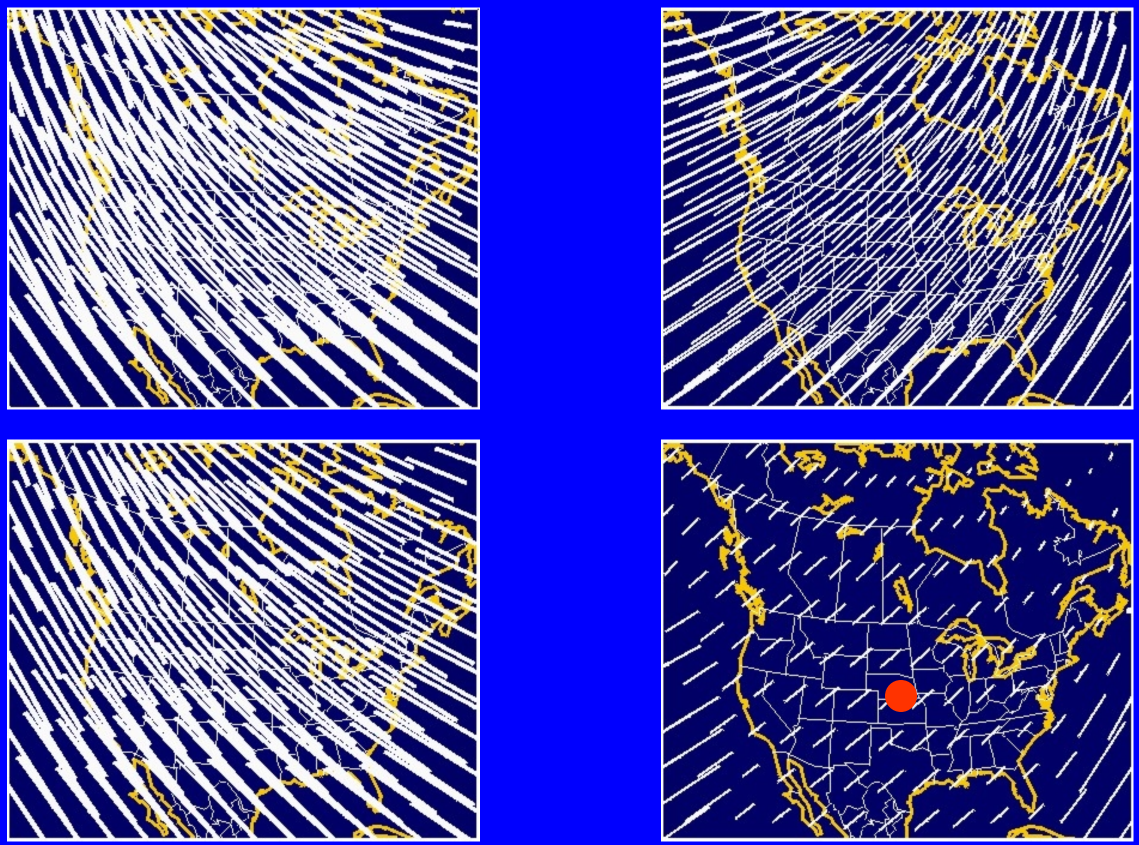
# Azimuthal anisotropy

## Resolution

100 km | 300 km

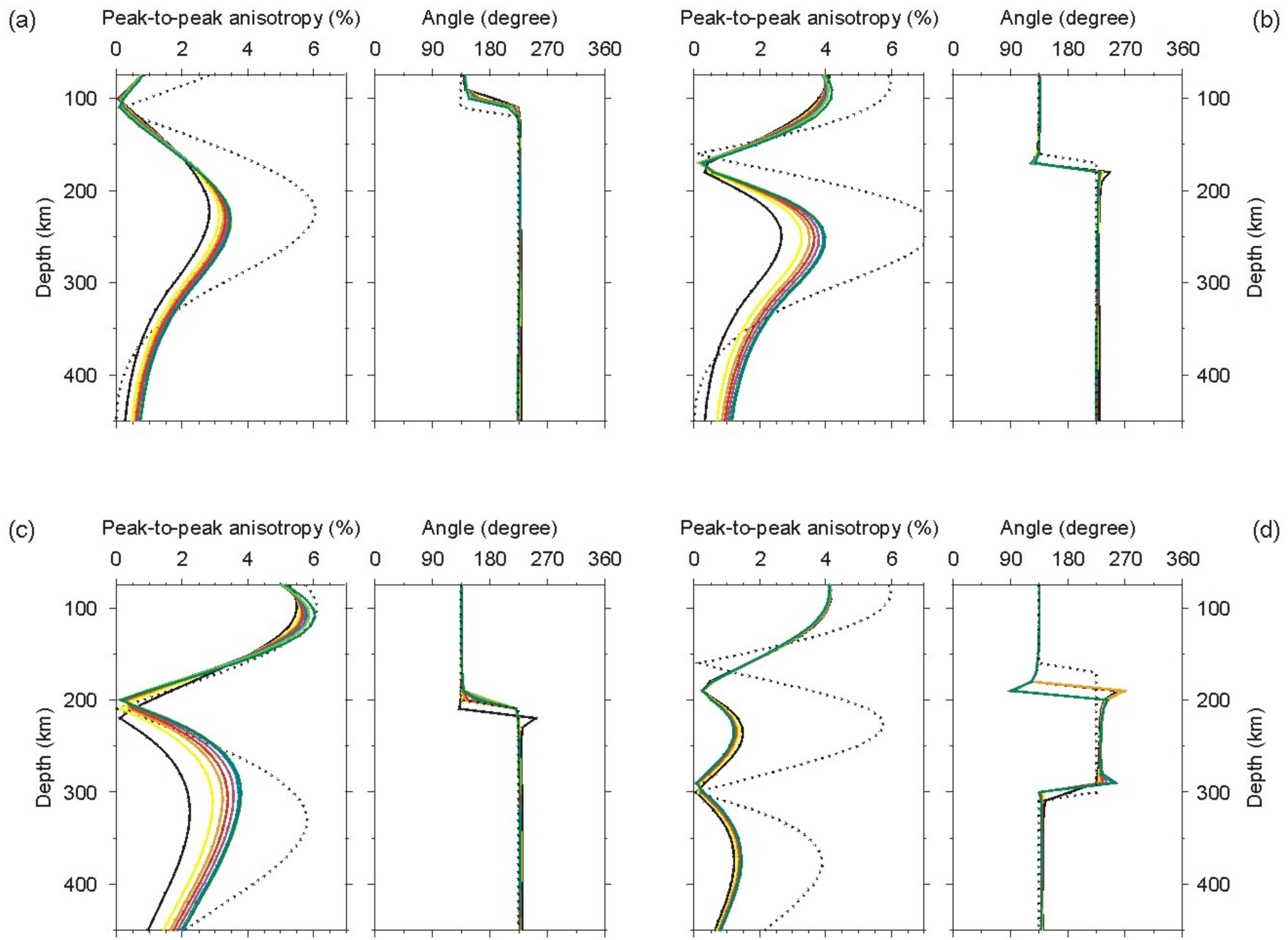
Input

Output

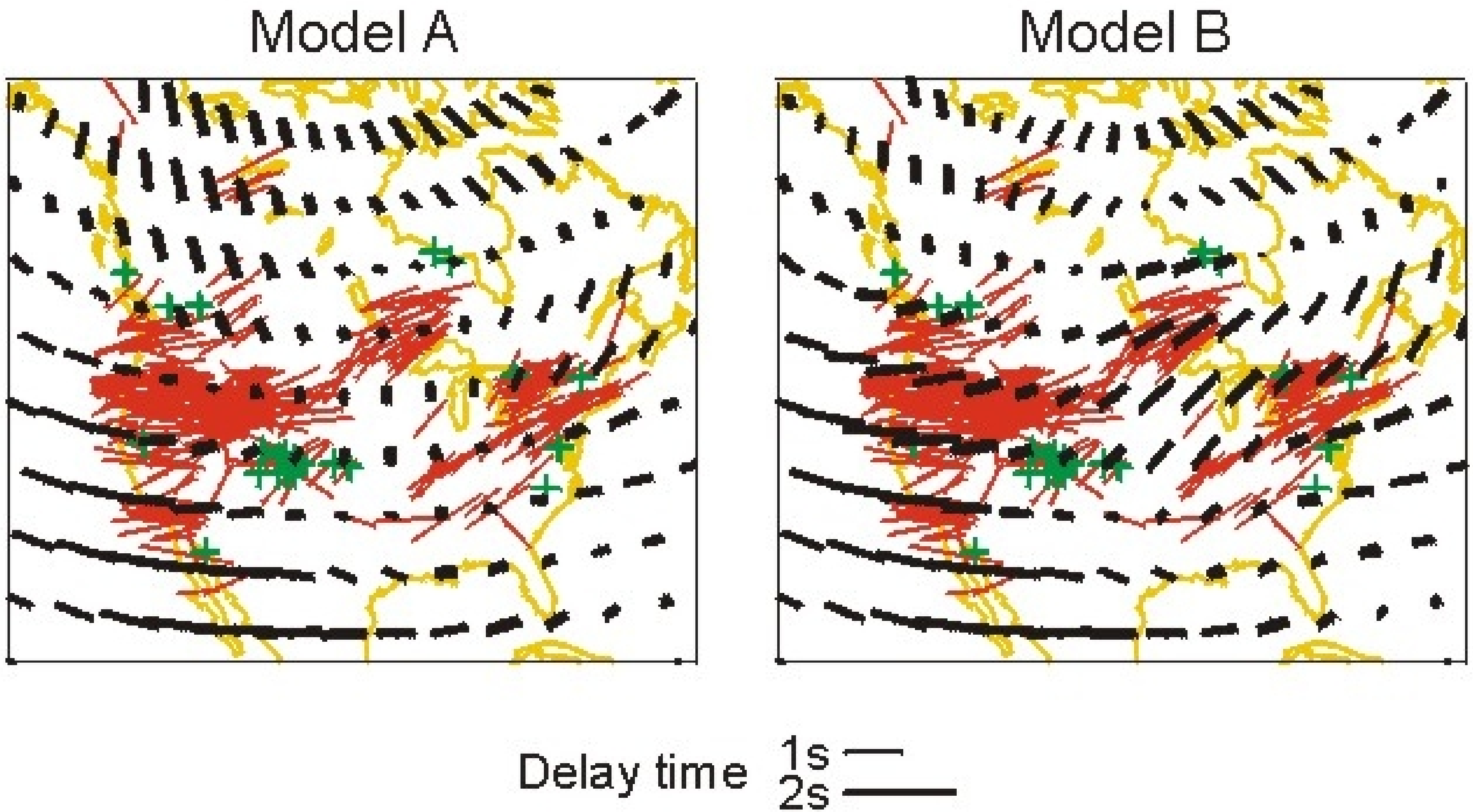


2% peak-to-peak anisotropy

# Synthetic test inversions

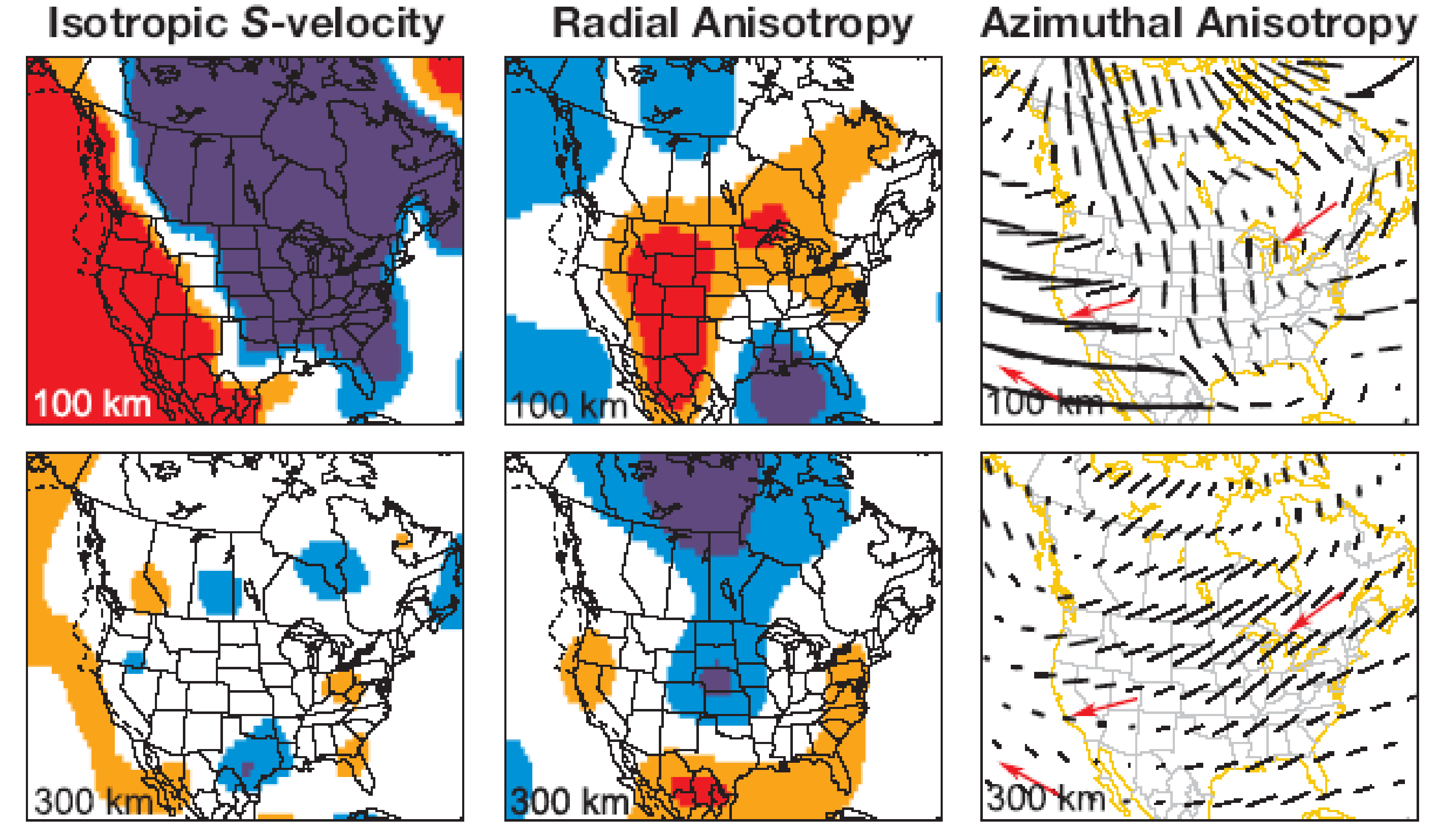


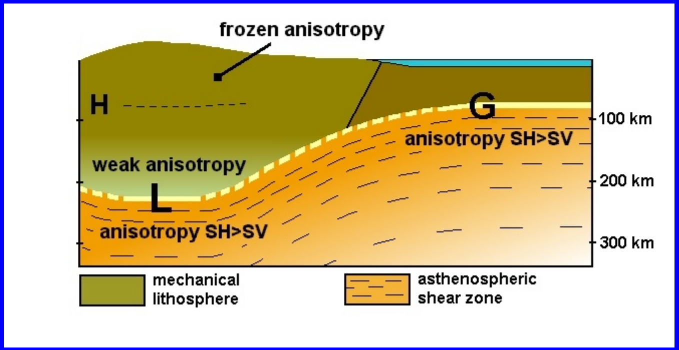
# Comparison with SKS splitting measurements



# Variance Reduction

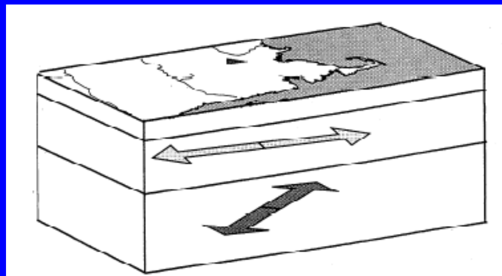
| Model name | Waveform data | SKS splitting data |
|---|---|---|
| Model A | 0.7091 | 0.10 |
| Model B | 0.7087 | 0.51 |



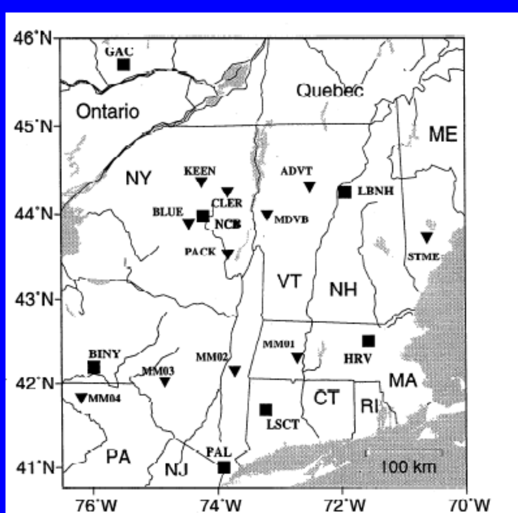

*Marone and Romanowicz, 2007*

# Evidence for two layers of anisotropy in North- Eastern US

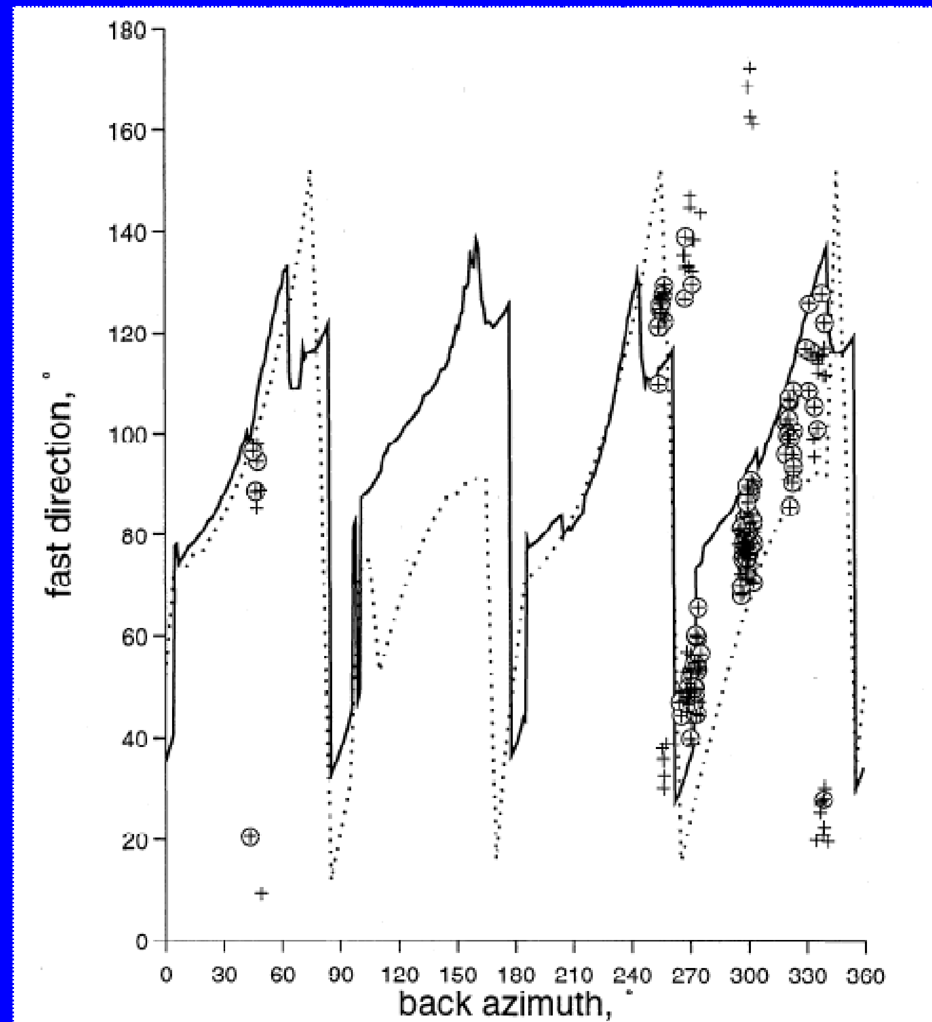


hexagonal

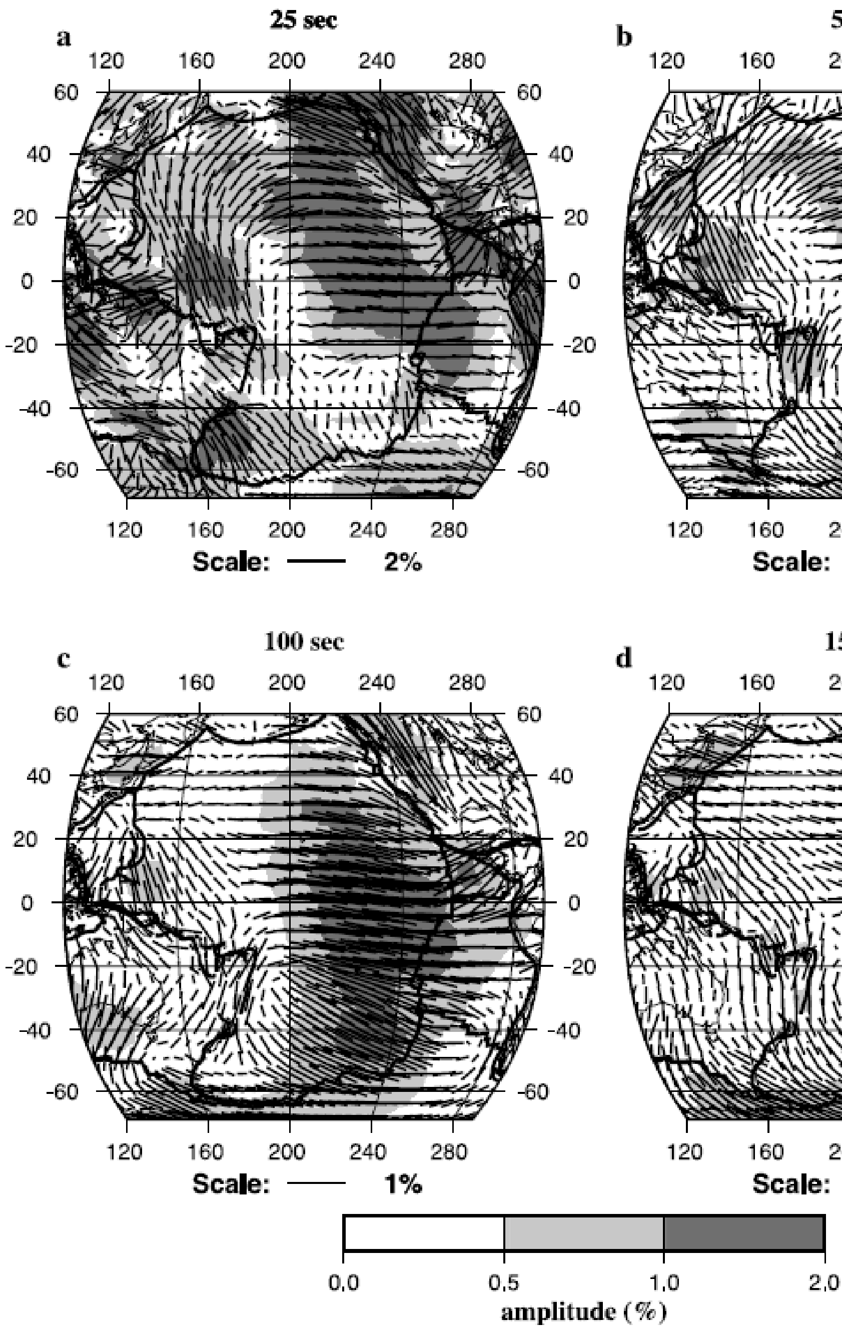
orthorombic



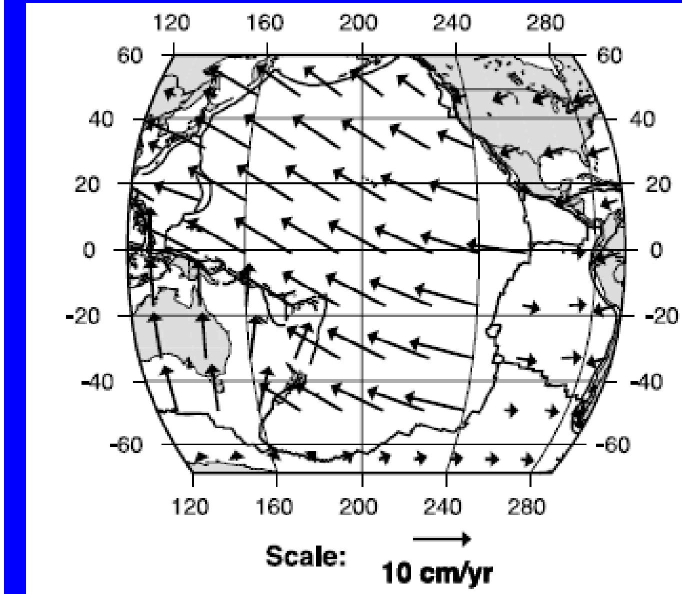

Variation of splitting time with azimuth



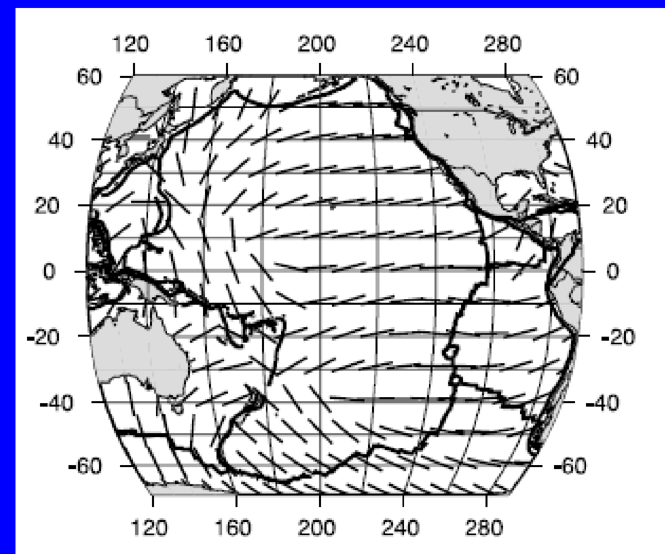

*Levin et al. 2000*




Current APM

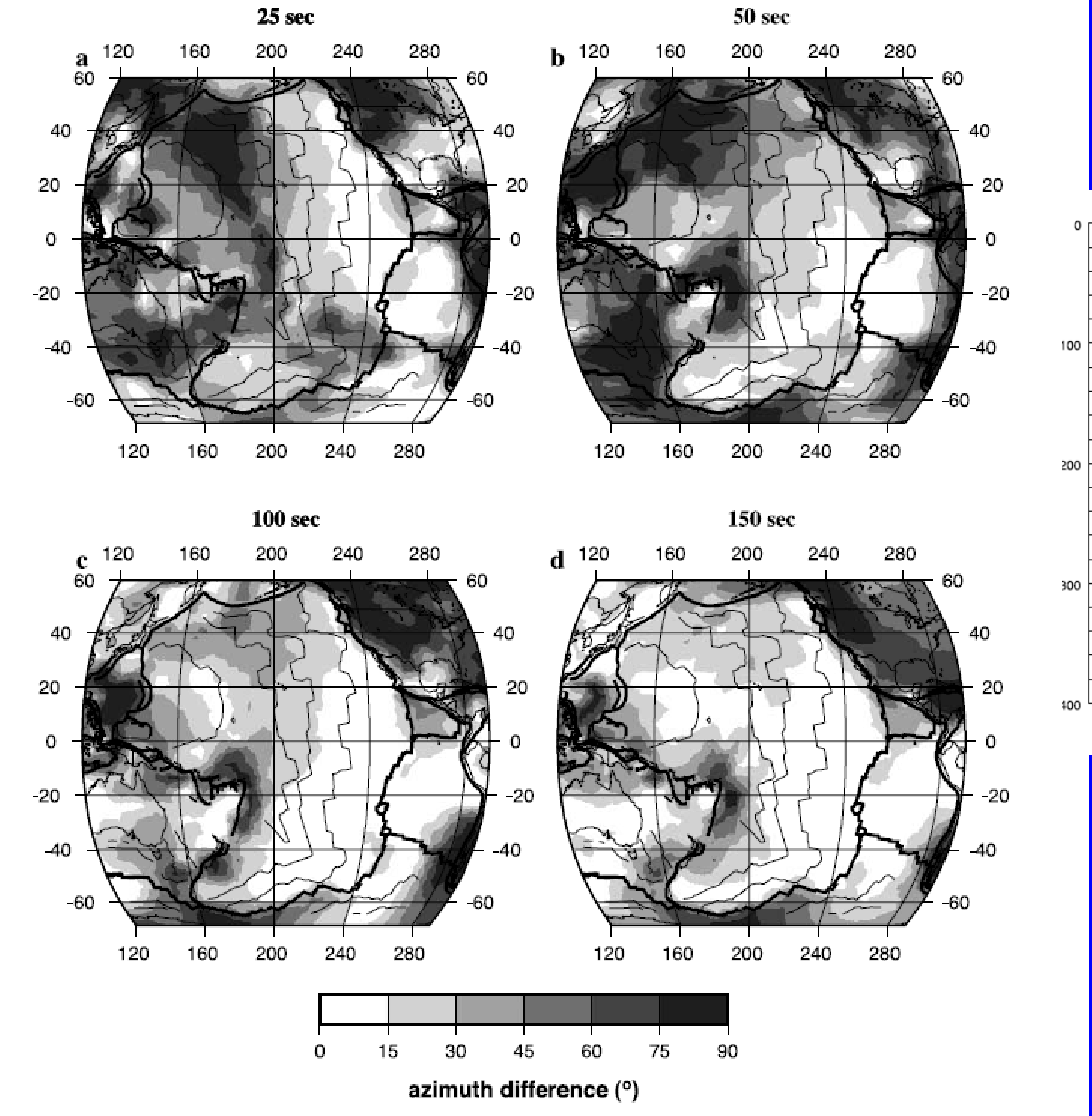


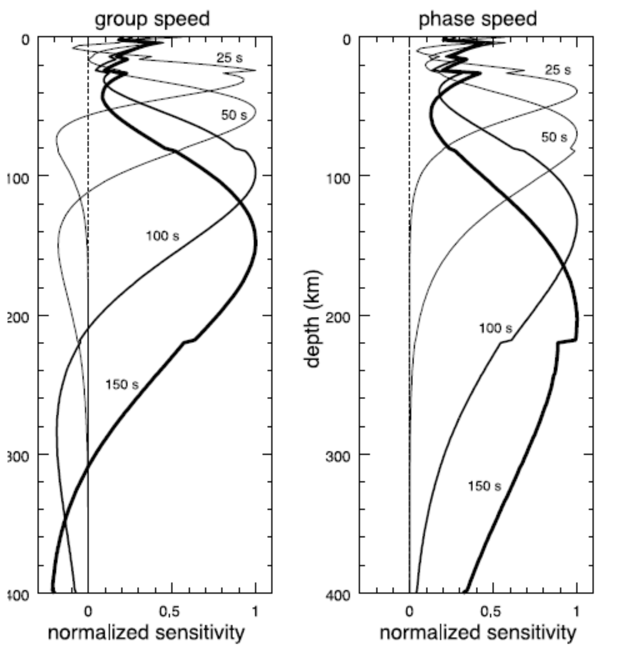

Paleo-spreading dir.



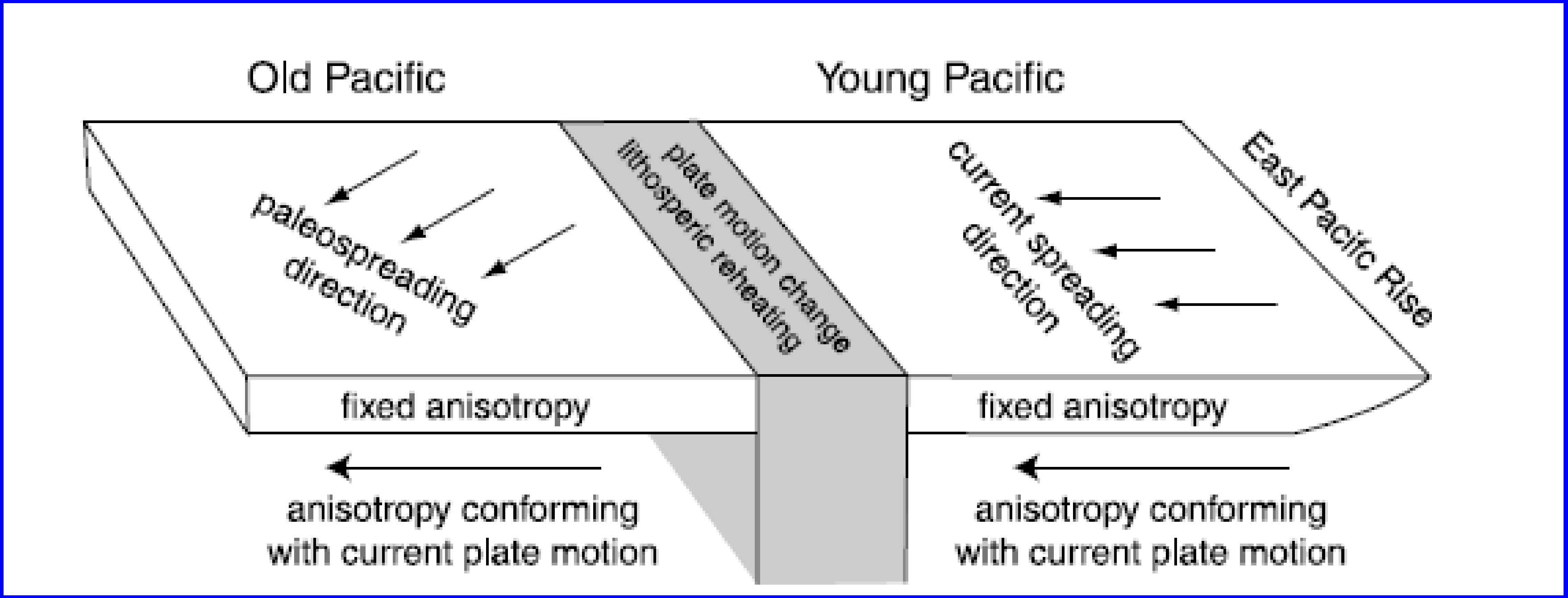
Smith et al., 2004

# Azimuth difference between fast direction of anisotropy and APM




Smith et al., 2004

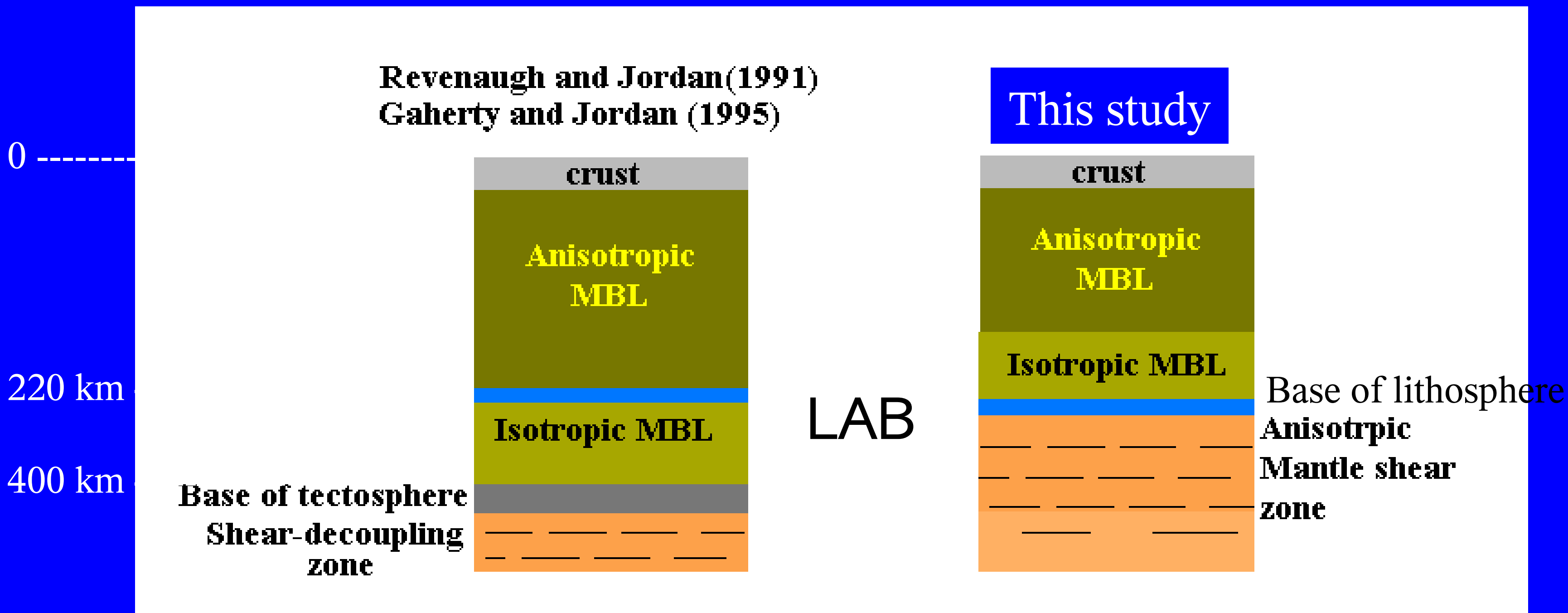



Smith et al., 2004

# Conclusions: anisotropy

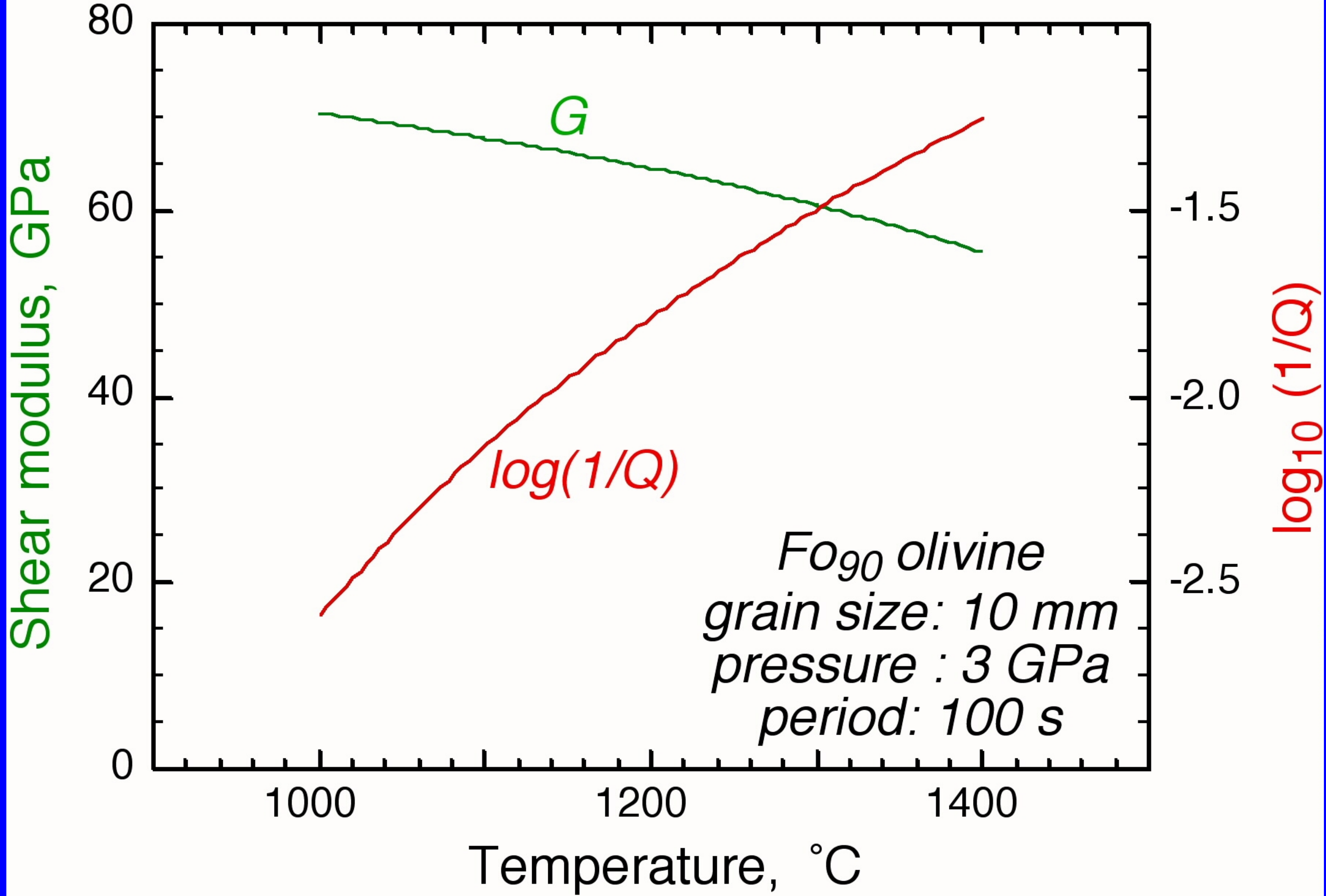
- Surface waves alone lose resolution in anisotropy at depths greater than 200km
  - *fail to recover the full amplitude of azimuthal anisotropy*
- SKS splitting data alone integrate over whole upper mantle but do not have depth resolution
- Combining the two improves depth resolutions and leads to 3D structure compatible with both datasets.
- Anisotropic tomography aloows us to image two" layers" of anisotropy worldwide, one in the lithosphere and the other in the asthenosphere, of different orientations, separated by an undulating LAB, deeper under continents than under ocean basins

- The continental lithosphere, as defined seismically is no thicker than 200-250 km, in agreement with other geophysical data (heat flow, kimberlites)
- The LAB is an anisotropic boundary with fossil anisotropy above, APS oriented anisotropy below
- Dislocation creep is likely active at asthenospheric depths.


0
220 km
400 km
Revenaugh and Jordan(1991)
Gaherty and Jordan (1995)
crust
Anisotropic
MBL
Isotropic MBL
Base of tectosphere
Shear-decoupling
zone
LAB
This study
crust
Anisotropic
MBL
Isotropic MBL
Base of lithosphere
Anisotrpic
Mantle shear
zone

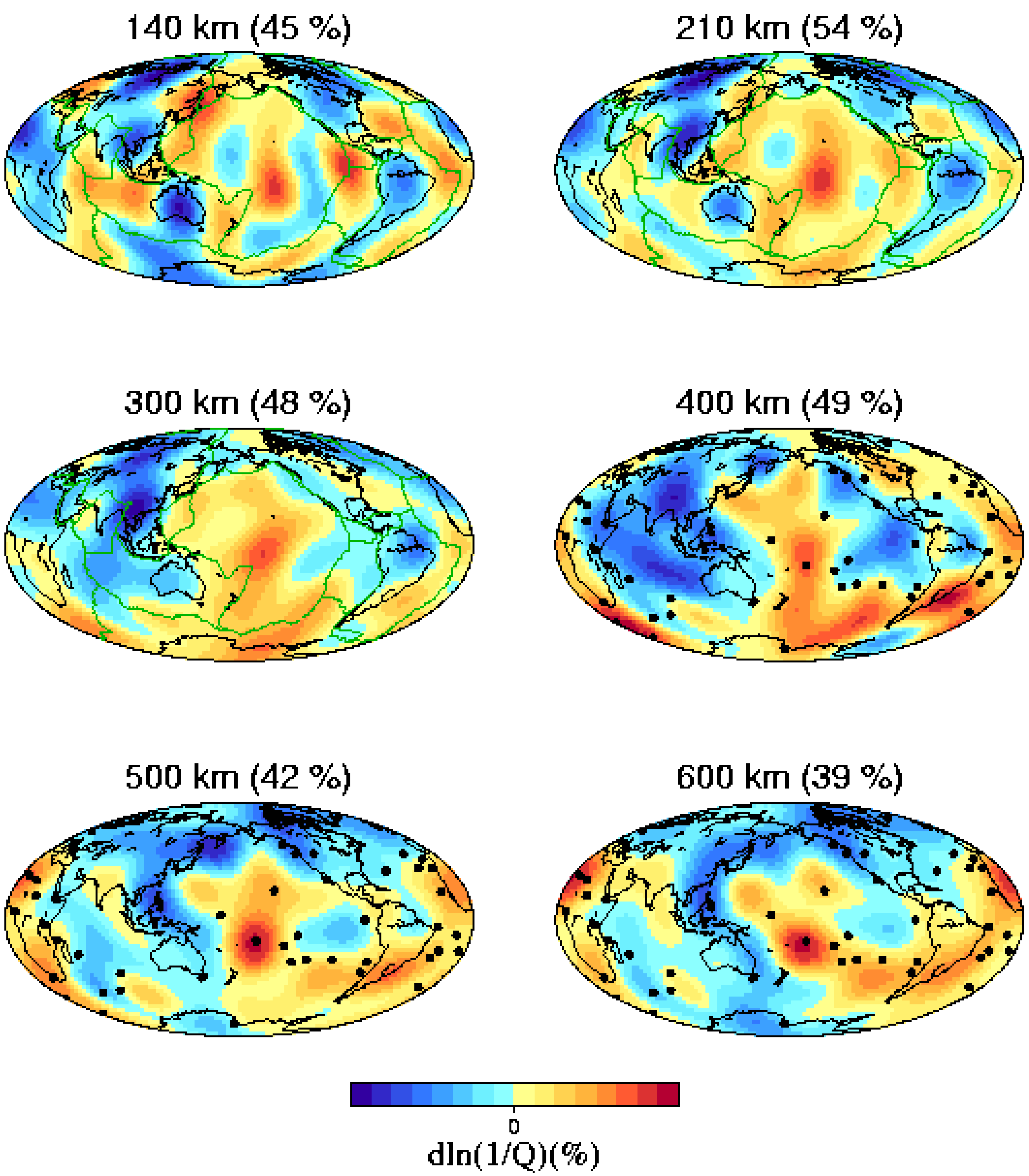
# Attenuation tomography of the upper mantle

# Motivation for seismic Q tomography:



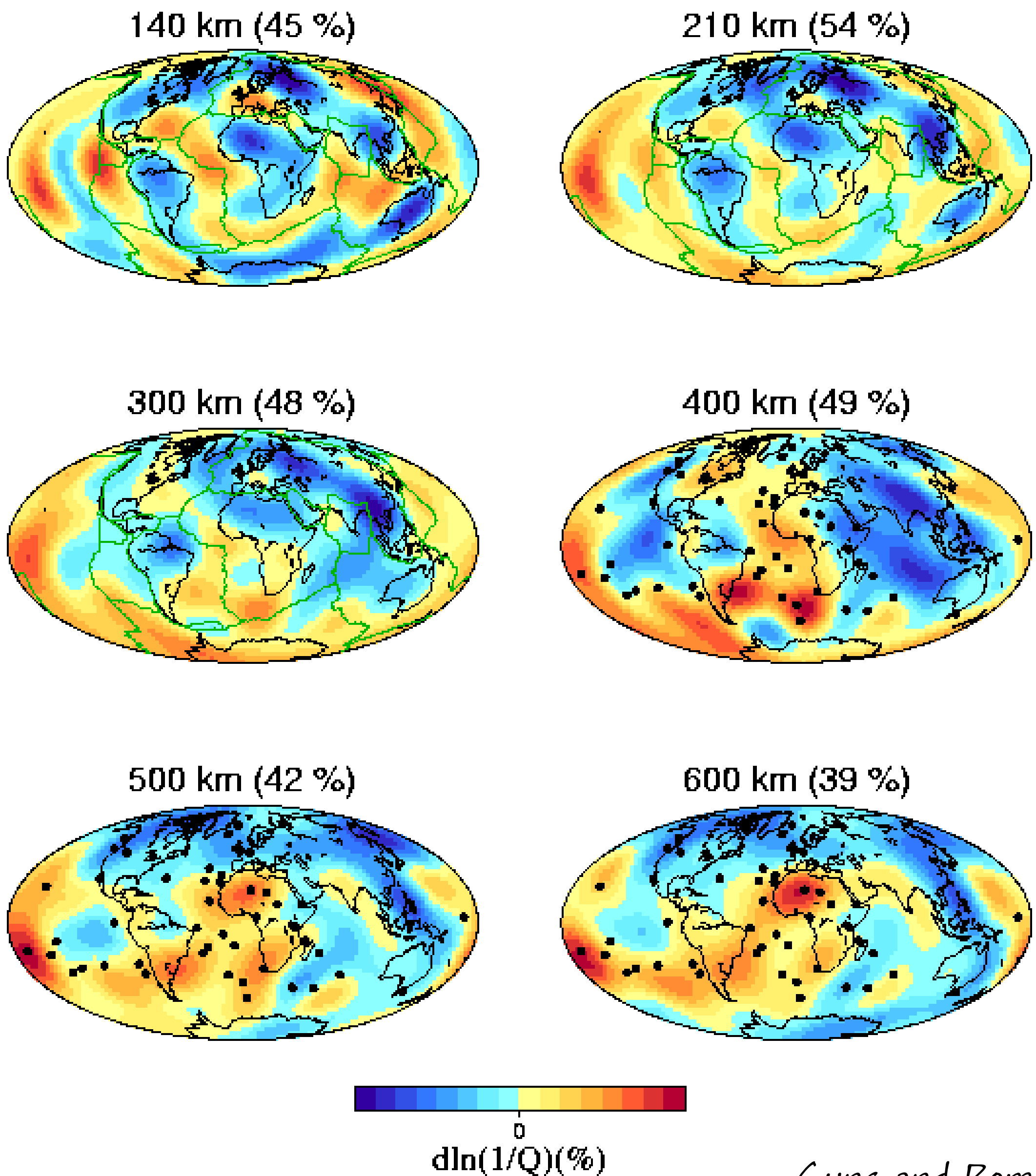

*Faul and Jackson, 2005*

# Anelastic attenuation: QRLW8



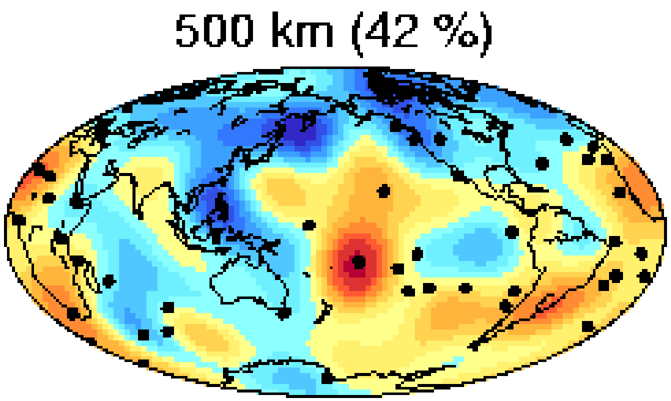

Gung and Romanowicz, 2004

# $Q^{-1}$: Centered on Africa

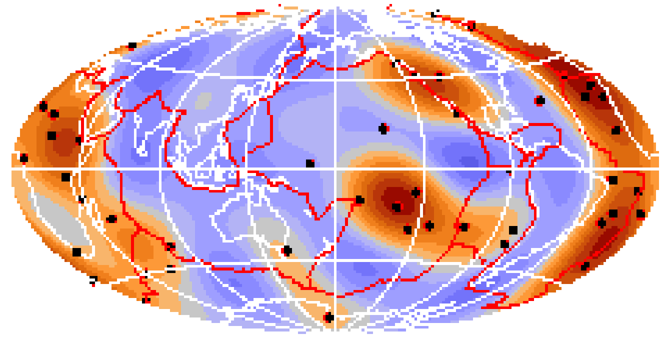



Gung and Romanowicz, 2004

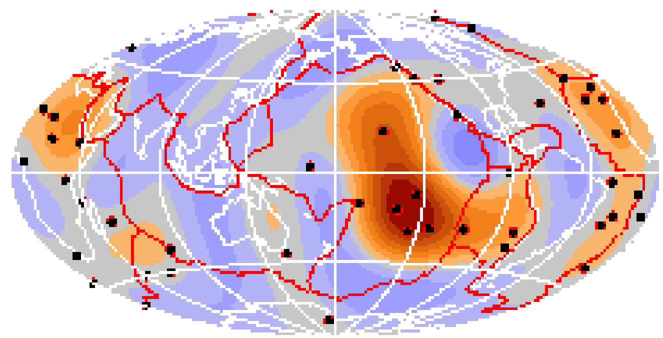
## QRLW8

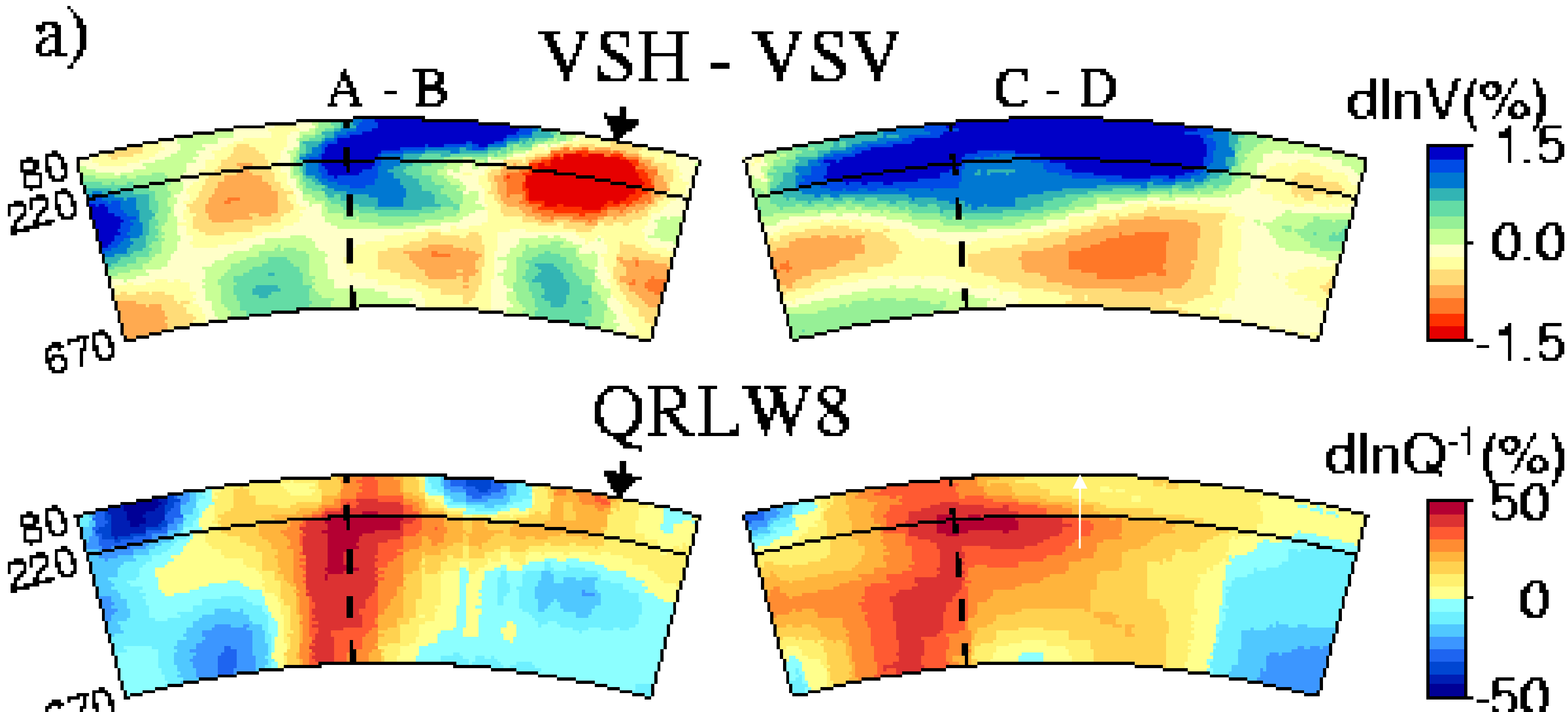



## Hotspot distribution

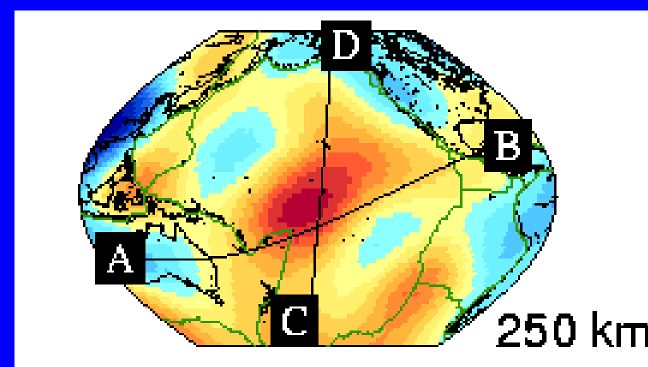


## Weighted by buoyancy flux

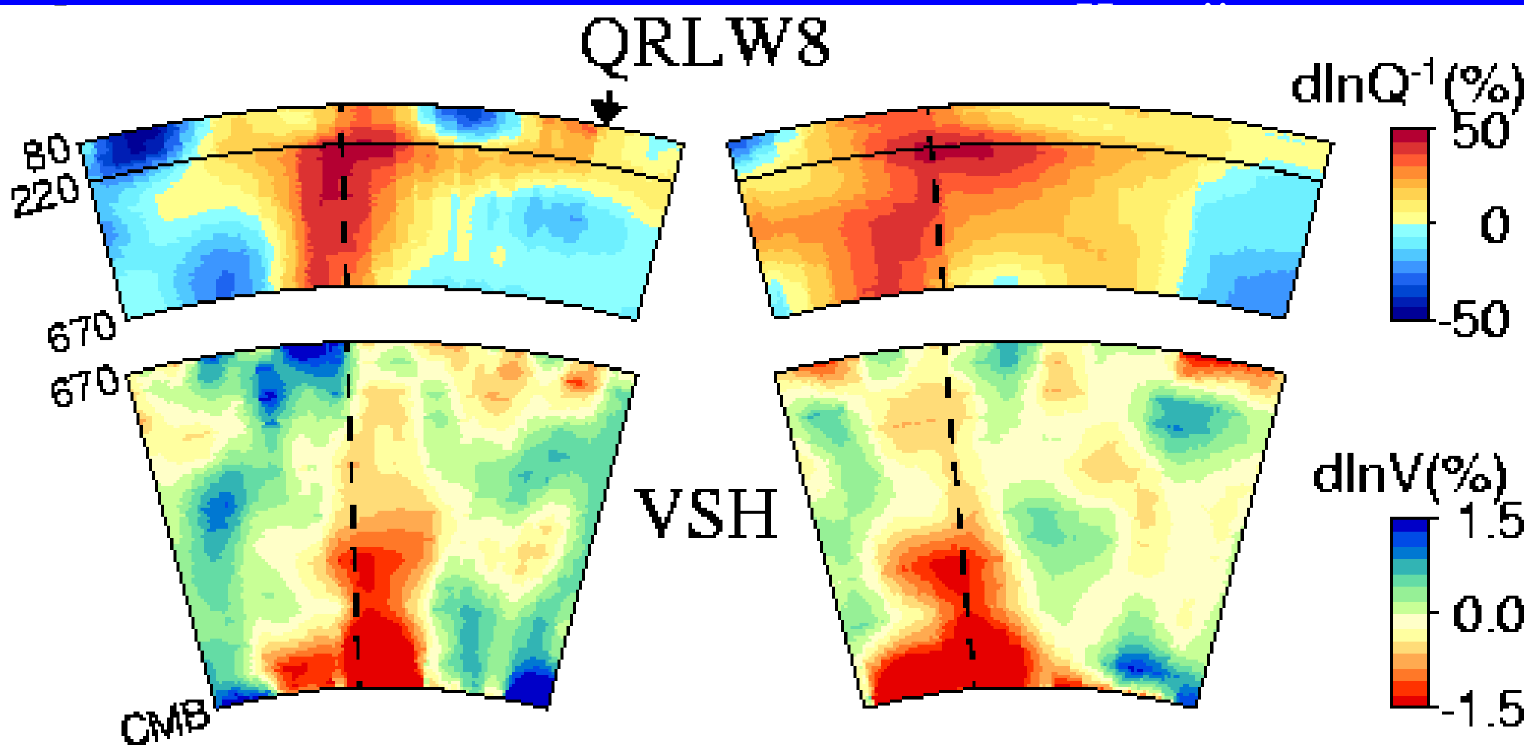




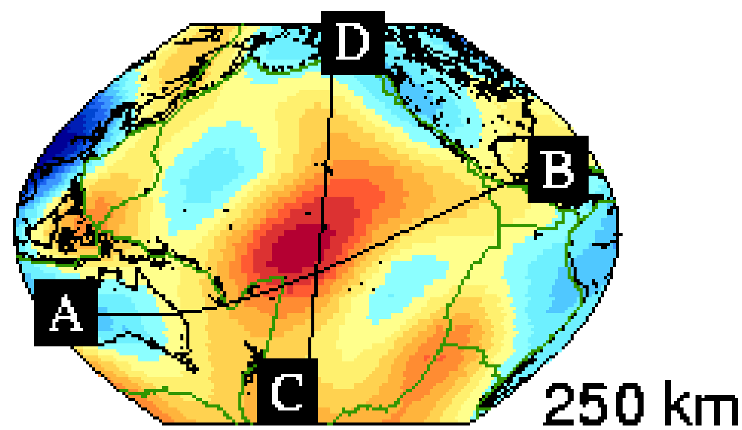

Central Pacific

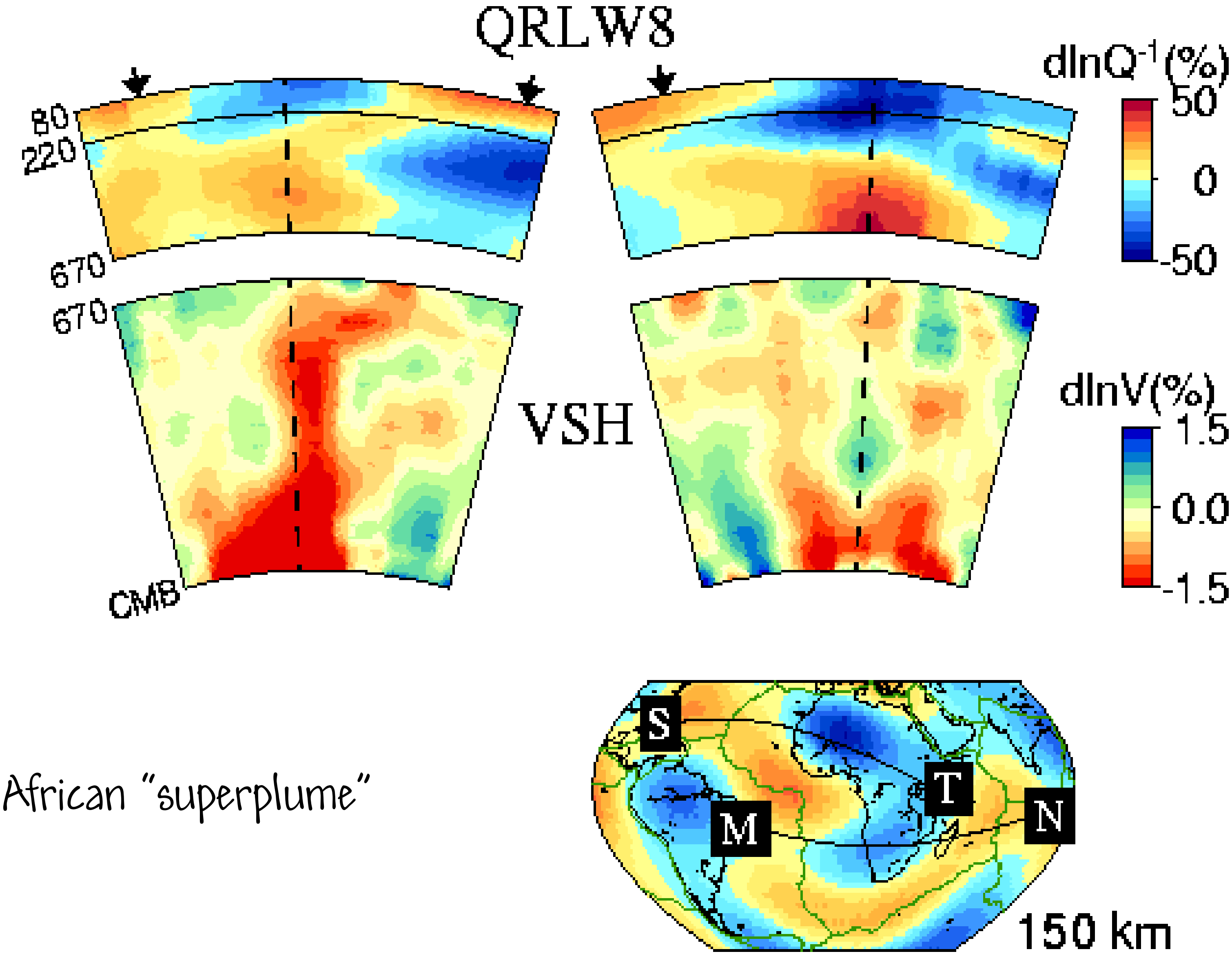


AB CD




Pacific Superplume






African "superplume"

# Conclusions Q

- African and Pacific superplumes are the roots of upwellings that "rise" through the lower-mantle and through the transition zone, into the asthenosphere, where the flow spreads laterally towards mid-ocean ridges, feeding hotspots and lubricating plate motions.

- "hot" asthenosphere

# Perspectives

- Mode asymptotics are fast, there is still a lot we can learn about the earth from them
- To obtain higher resolution images of the earth, we need to move towards numerical methods such as SEM.
- Work towards this goal step by step
  - Start at low frequencies
  - Separate forward/inverse parts of the problem
- Model parametrization