Anisotropic Imaging of the Mantle
Oceanic and Continental Lithosphere-Asthenosphere Boundary

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OUTLINE

- Structure of a plate? of a continent?
- Seismic Anisotropy: many processes, different interpretations
- Scientific Issues: 3D- anisotropic structure of the Earth

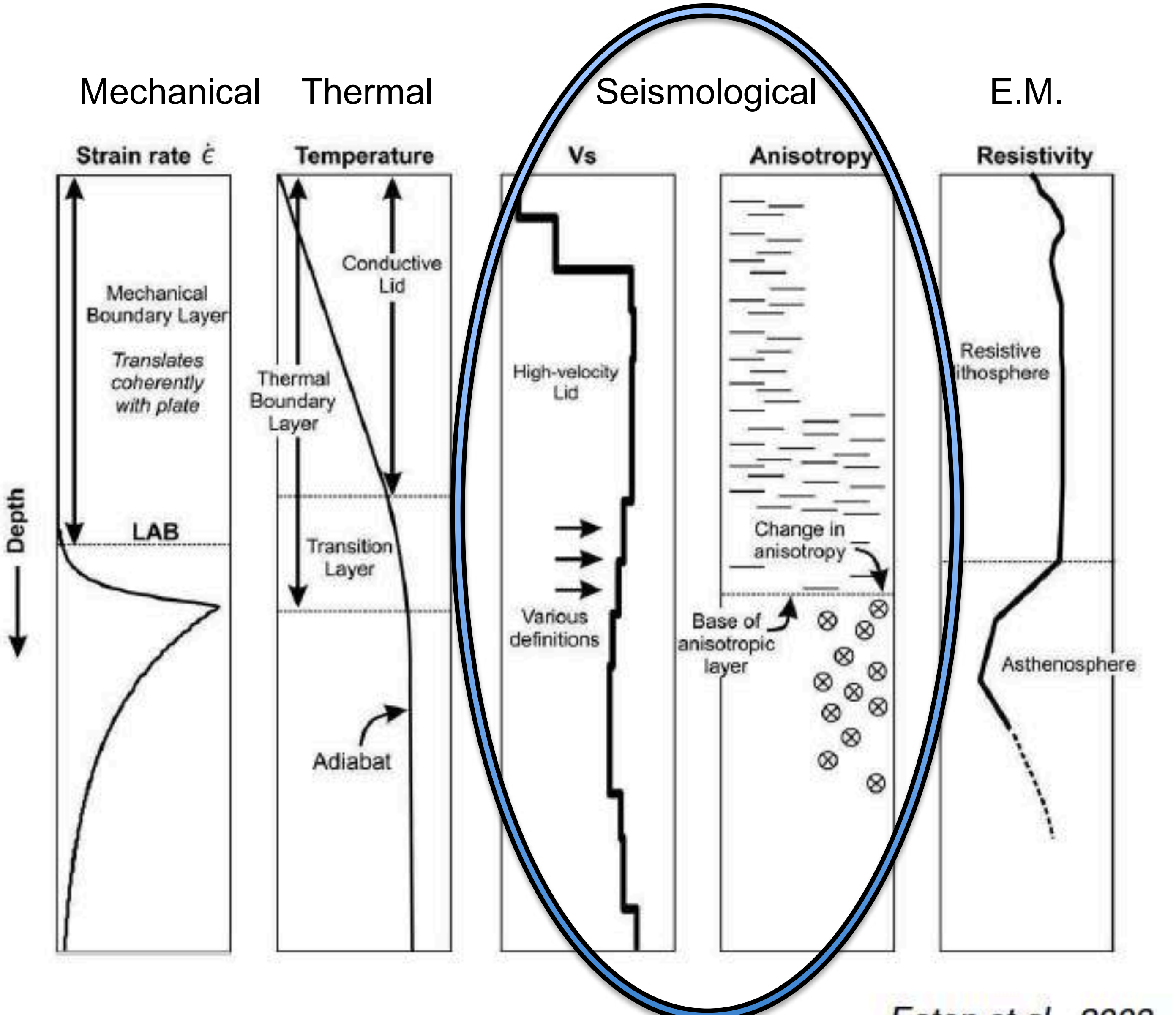
  Lithosphere- Asthenosphere Boundary

  -Oceans

  - Continent (Indian continent)

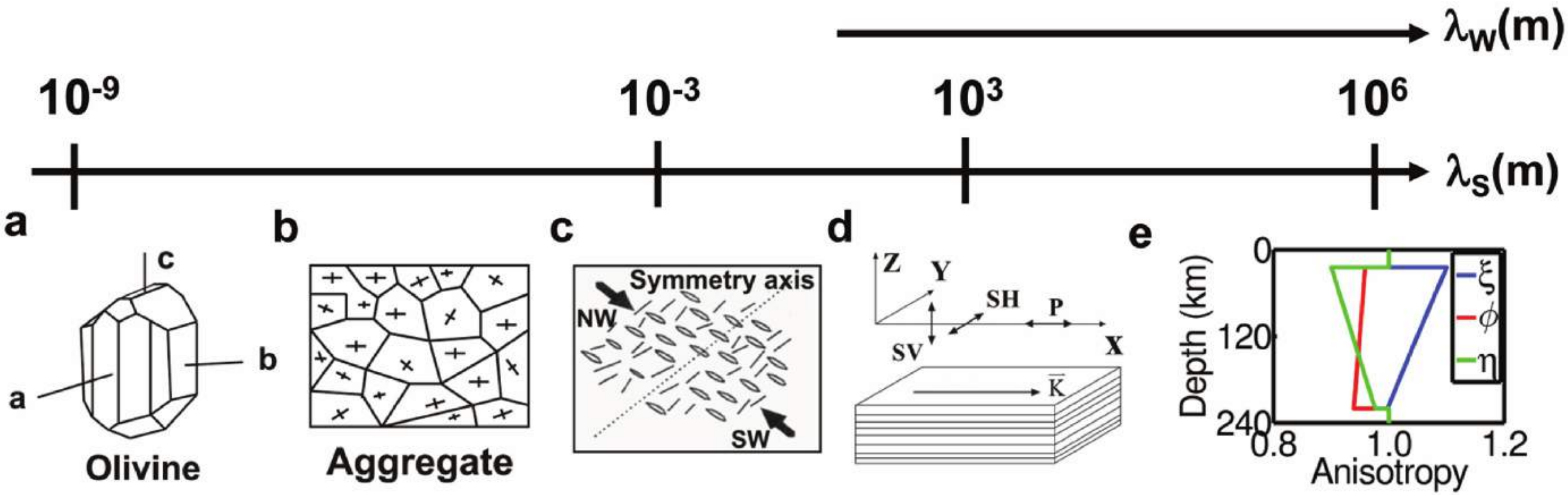
  (- Mantle transition zones: 410-1000km)

L.A.B.: Lithosphere-Asthenosphere Boundary
(many different approaches and definitions)



Eaton et al., 2008

Seismic Anisotropy at all scales



PREM

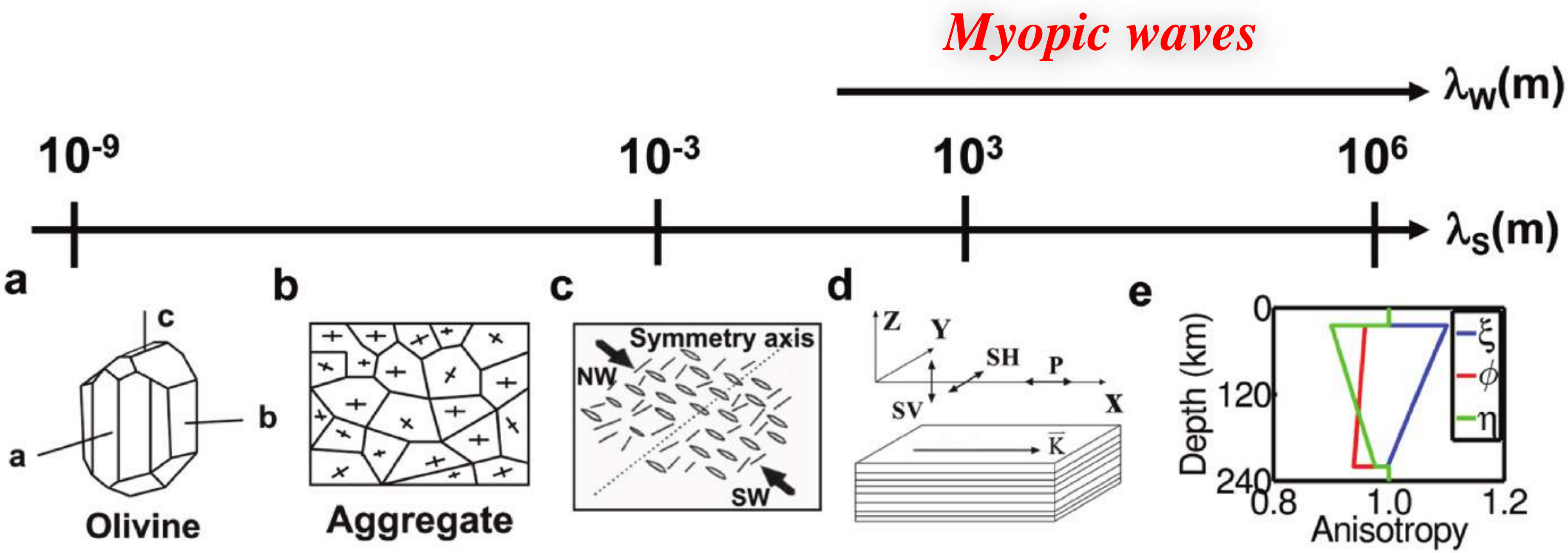
PREM: radial anisotropy: up to 10%

λ_W seismic wavelength

λ_S spatial scale

(Wang et al., 2013)

Seismic Anisotropy at all scales



Intrinsic **Extrinsic** PREM

Observed (apparent) anisotropy

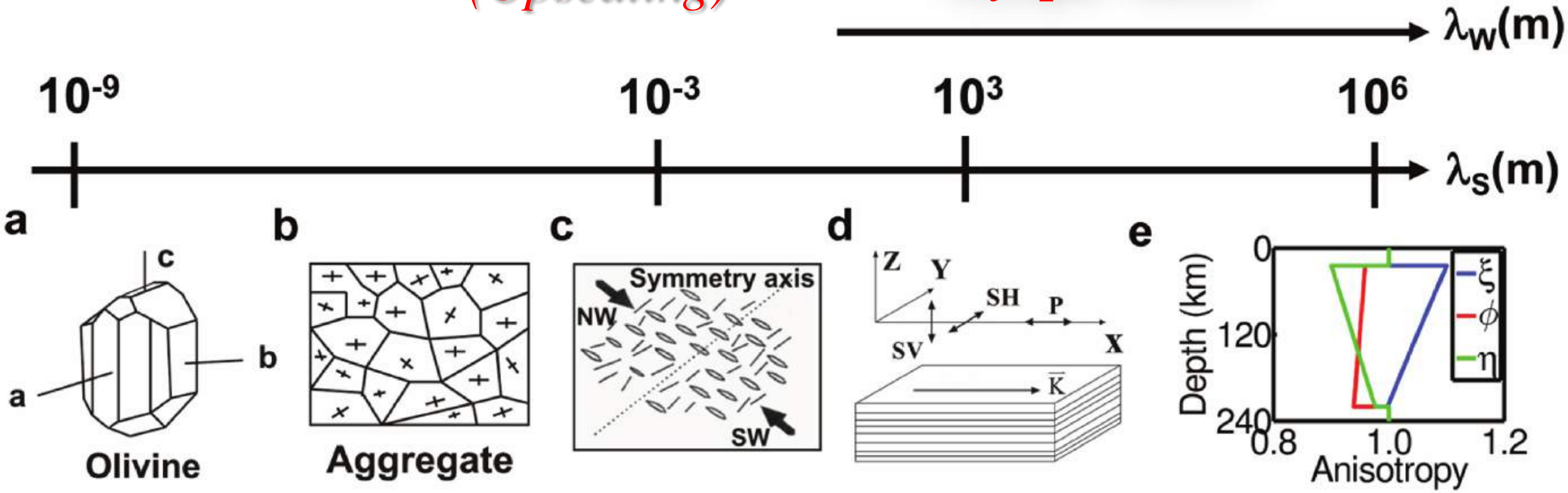
Intrinsic versus Extrinsic anisotropy

$\alpha = p\alpha^{int} + (1-p)\,\alpha^{ext}$

Seismic Anisotropy at all scales

(Upscaling)

Myopic waves



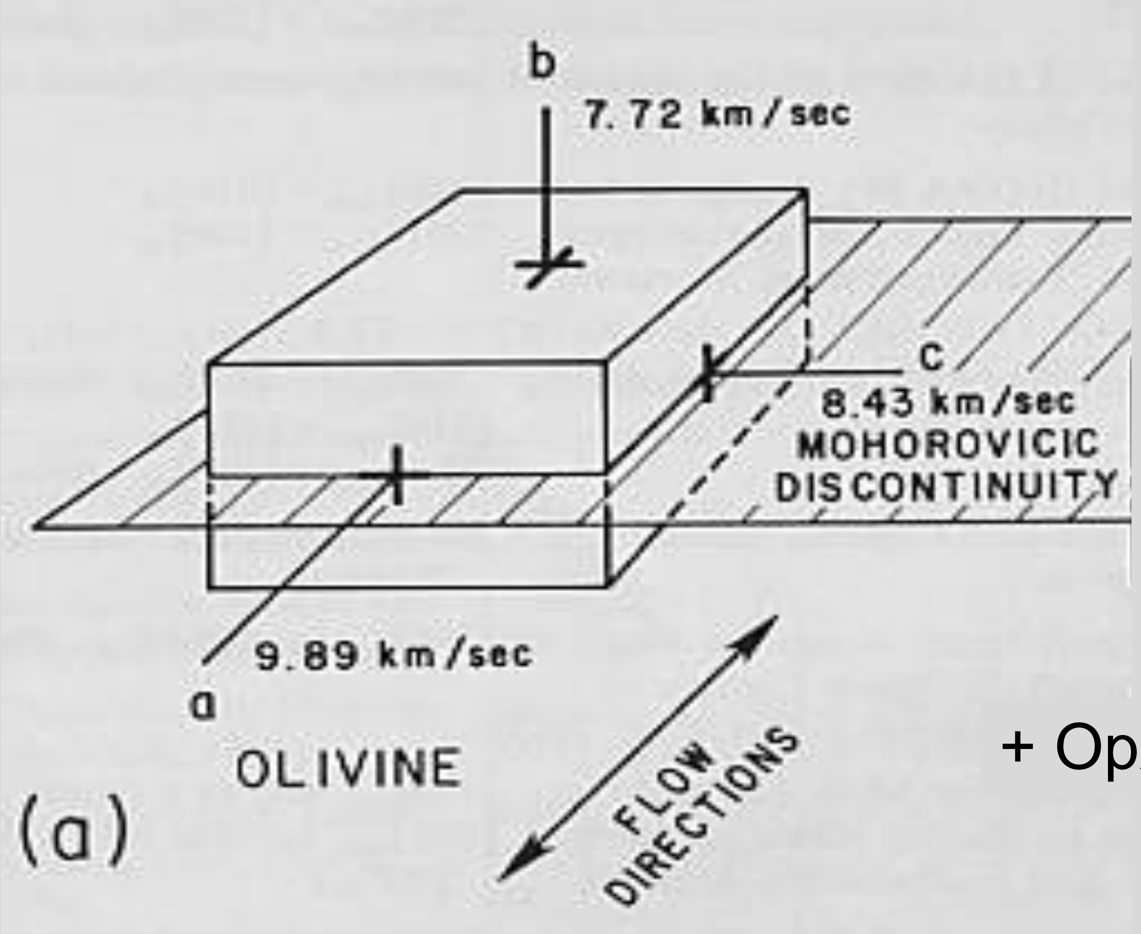
Mineralogical composition

Melt

Mapping convection

(Downscaling)

C.P.O./L.P.O. : Crystal/Lattice Preferred Orientation (strain field)



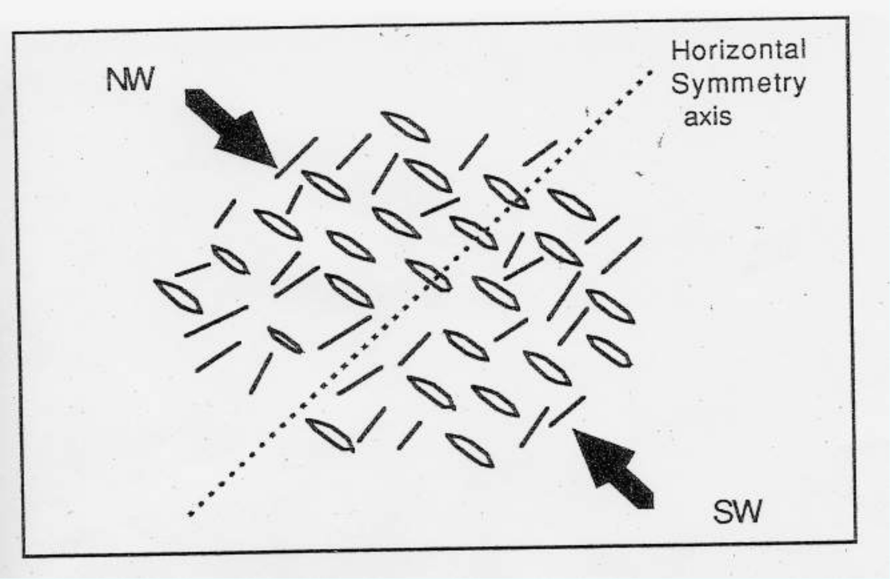
+ Opx, Cpx, Gt

→ ***Mapping of convection***

Christensen and Lundquist, 1982

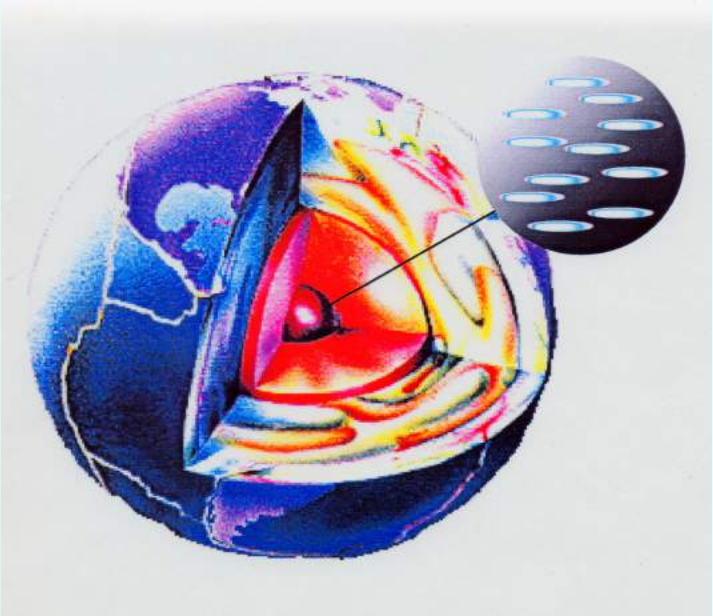
Other effects: Cracks, fluid inclusions-S.P.O.: (shape preferred orientation-stress field)

Crust (+lithosphere, asthenosphere)



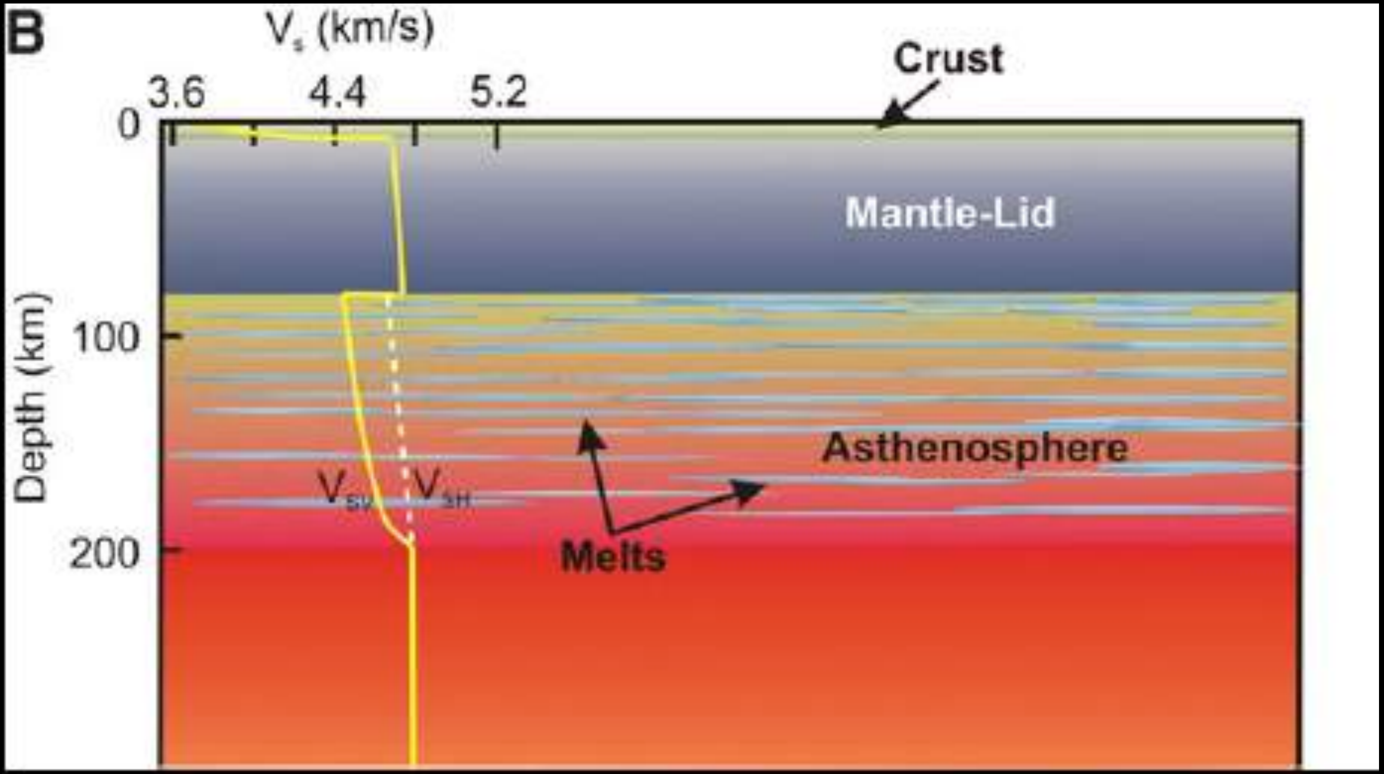
(Babuska and Cara, 1991)

Inner core



(Singh et al., 2001)

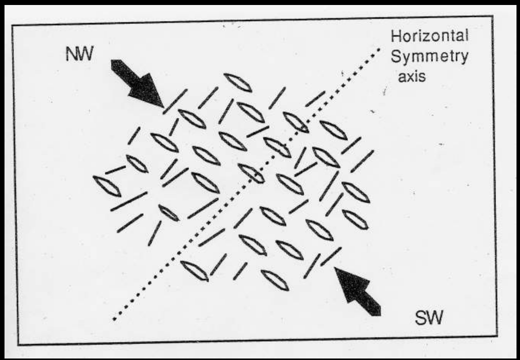
FINE LAYERING: Stratification Anisotropy Mille-feuilles model (partial melting)

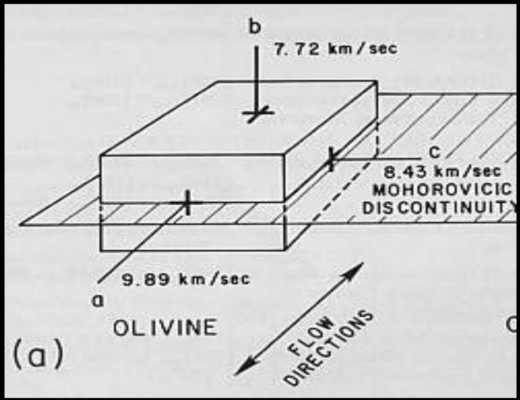


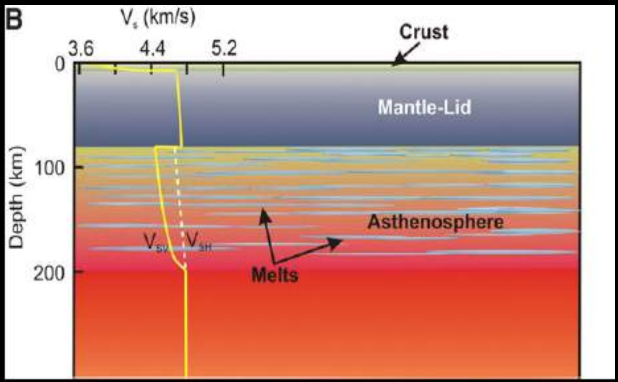
Radial anisotropy (Kawakatsu et al. 2009)
V.T.I. Vertical Transversely Isotropic medium: 5 parameters
($A=\rho V_{PH}^2$, $C=\rho V_{PV}^2$, F, $L= V_{SV}^2$, $N= V_{SH}^2$)

Different processes in different layers

-S.P.O. (stress) -C.P.O.(strain) Fine Layering







- *Mineralogy, water and fluid content*
- *Present day tectonic, geodynamic processes*
- *Past processes (frozen anisotropy)*
- *(Monitoring of stress and strain fields)*

Separation of the different kinds of anisotropy in different layers => Different interpretations
(Stratification of anisotropy in the crust & mantle)

Effect of anisotropy on the phase of surface waves

4th-order Elastic tensor: C_{ijkl}
Effect on phase velocity V

$$\frac{\delta V}{V} = \frac{\int_\Omega \varepsilon_{ij}^* \, \delta C_{ijkl} \, \varepsilon_{kl} \, d\Omega}{\int_\Omega \rho_0 \, u_r^* \, u_r \, d\Omega}$$

ε strain tensor, u displacement, δC_{ijkl} elastic tensor perturbation,

V phase velocity (V_R Rayleigh; V_L Love)

Phase velocity pertubation $\delta V(T,\theta,\phi,\Psi)$ at point r (θ,ϕ)
(Smith & Dahlen, 1973; Montagner & Nataf, 1986)

Ψ Azimuth (angle between North and wave vector)

$$\delta V(T,\theta,\phi,\Psi)/V = \alpha_0(T,\theta,\phi) + \alpha_1(T,\theta,\phi)\cos 2\Psi + \alpha_2(T,\theta,\phi)\sin 2\Psi + \alpha_3(T,\theta,\phi)\cos 4\Psi + \alpha_4(T,\theta,\phi)\sin 4\Psi$$

Sensitivity Kernels of 0-Ψ, 2-Ψ, 4-Ψ azimuthal terms

•C_{ijkl} 21 elastic moduli

•$\alpha_0 = 0\text{-}\psi$ term: 5 parameters A, C, F, L, N (PREM)

VTI Model (transverse isotropy with vertical symmetry axis)

•Best resolved parameters from surface waves (among 13 parameters when including azimuthal anisotropy $2\psi-$, $4\psi-$ terms)

$L = \rho V_{SV}^2$ Isotropic part of V_{SV}

$\xi = N/L = (V_{SH}/V_{SV})^2$ Radial Anisotropy

G, Ψ_G Azimuthal Anisotropy of V_{SV}, also related to SKS splitting (when horizontal symmetry axis, vertical propagation, Montagner et al., 2000)

•Body waves (Crampin, 1984)

$$\rho V_{SV}^2 = L + G_c \cos 2\Psi + G_s \sin 2\Psi$$

$$\rho V_{SH}^2 = N - E_c \cos 4\Psi - E_s \sin 4\Psi$$

Geodynamic Interpretation: CPO

Horizontal maps of anisotropic parameters

Tomographies of:

-S- Velocity

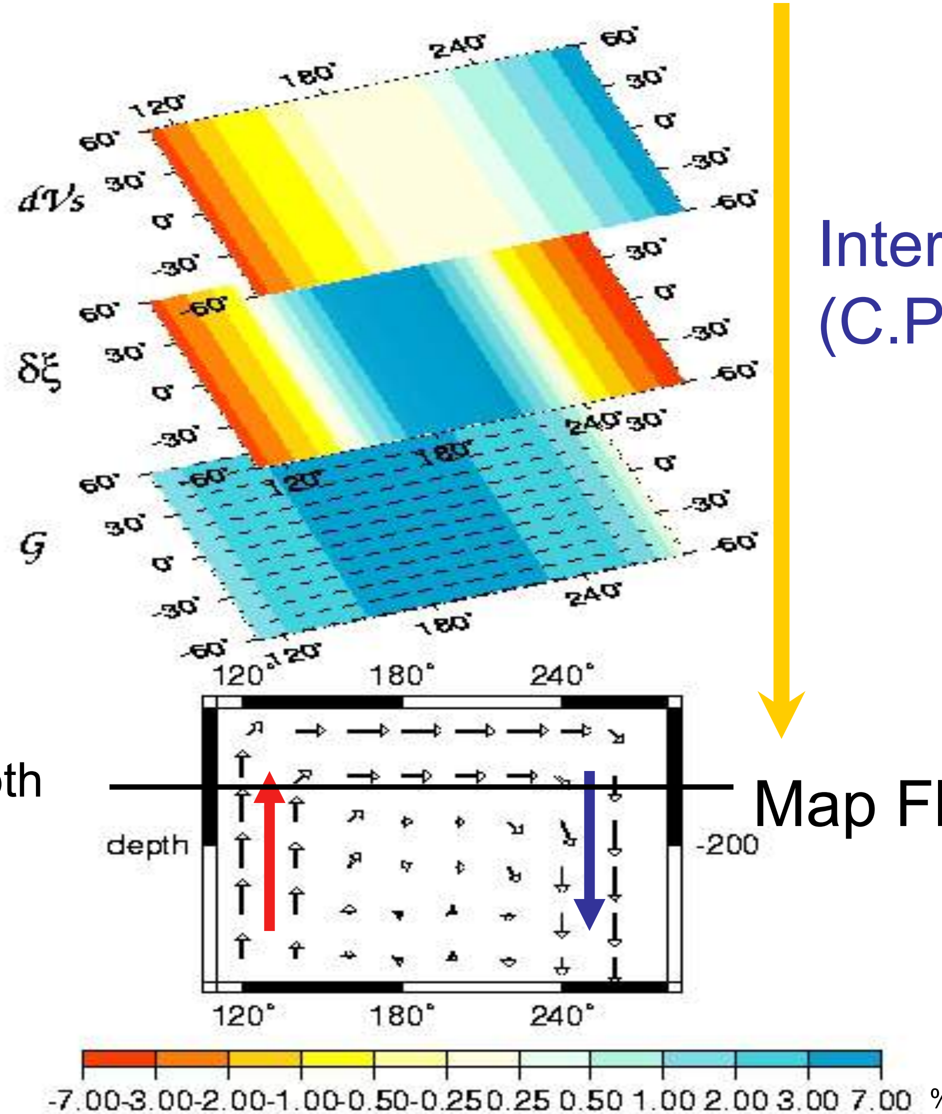
-Radial Anisotropy

$\delta\xi = (V_{SH}^2 - V_{SV}^2)/V_{SV}^2$

-Azimuthal Anisotropy

$V_{SV} \approx V_{SV0} + {}^1/_2 G\cos(2(\Psi - \Psi_G))$

At a given depth



Interpretation (C.P.O.)

Map Flow

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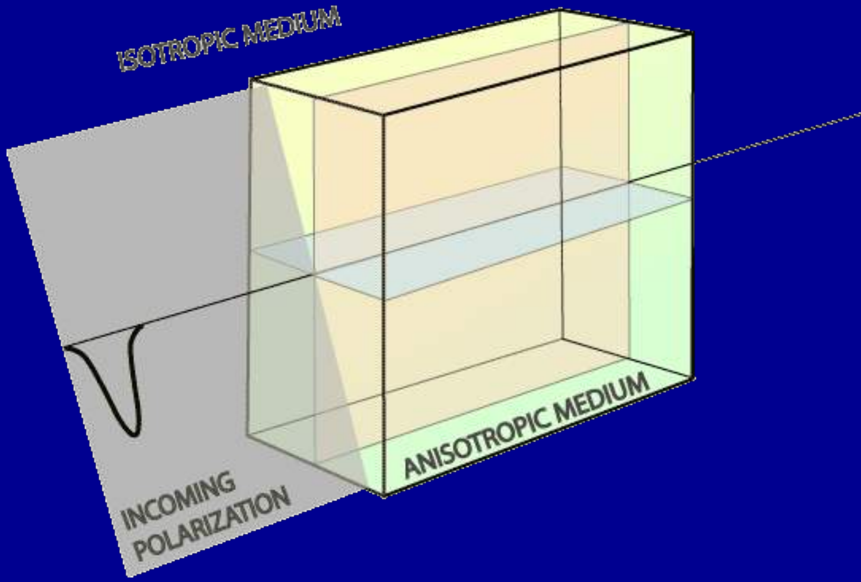
Different kinds of seismic data

Body waves:

P-wave azimuthal variations

S-wave splitting, SKS



Animation courtesy of Ed Garnero

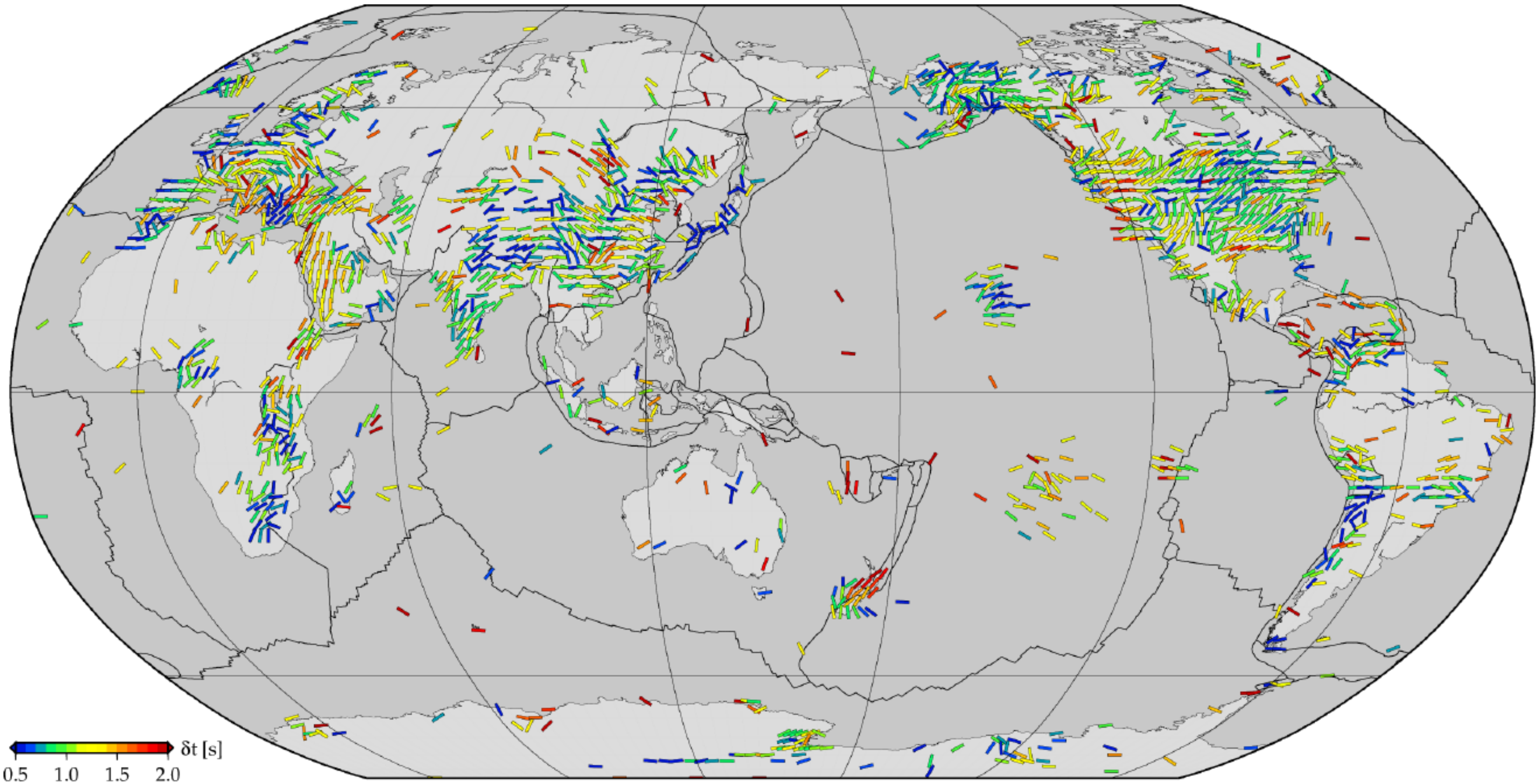
Surface waves:

-discrepancy Rayleigh-Love (polarization anisotropy)

-Azimuthal variations of phase (or group) velocities

- Effect on amplitudes

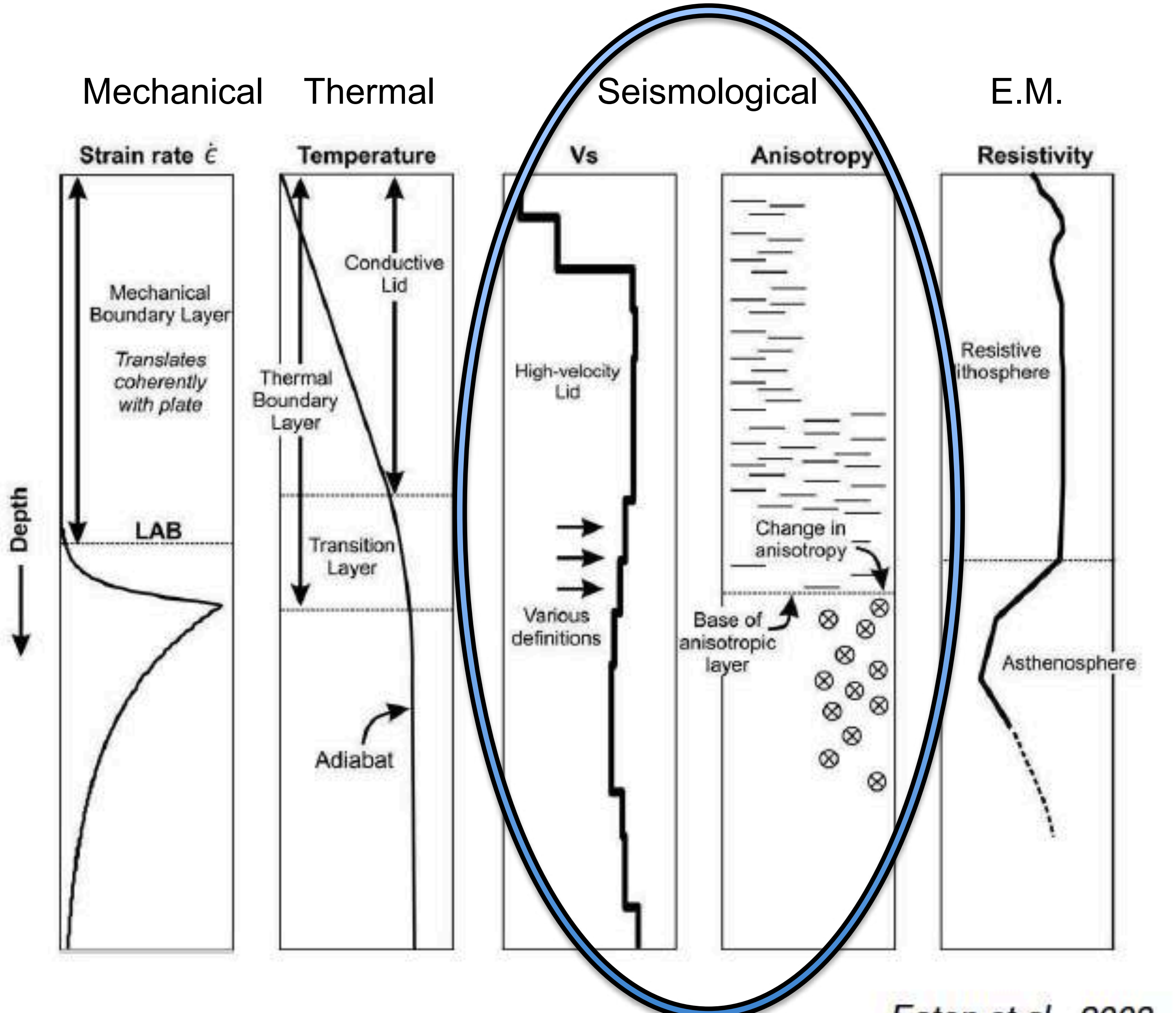
S-wave splitting: Updated SKS database (Becker, 2020)



Savage, 1999; Fouch, 2006;
Wüstefeld et al., 2009;
Becker et al., 2012; …

⇨ Surface waves

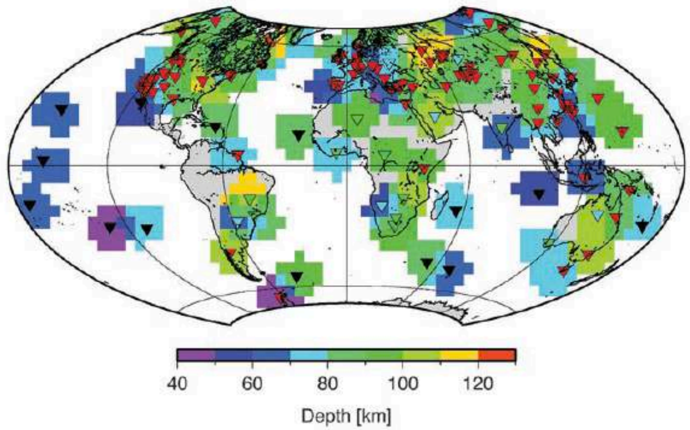
L.A.B.: Lithosphere-Asthenosphere Boundary
(many different approaches and definitions)



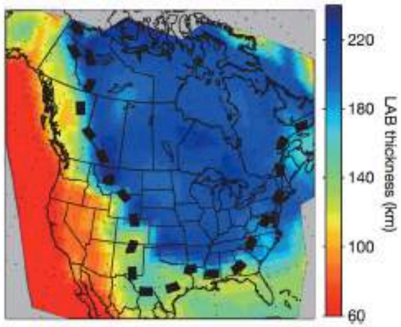
Eaton et al., 2008

LAB : from seismic data

Receiver functions ~100-120km

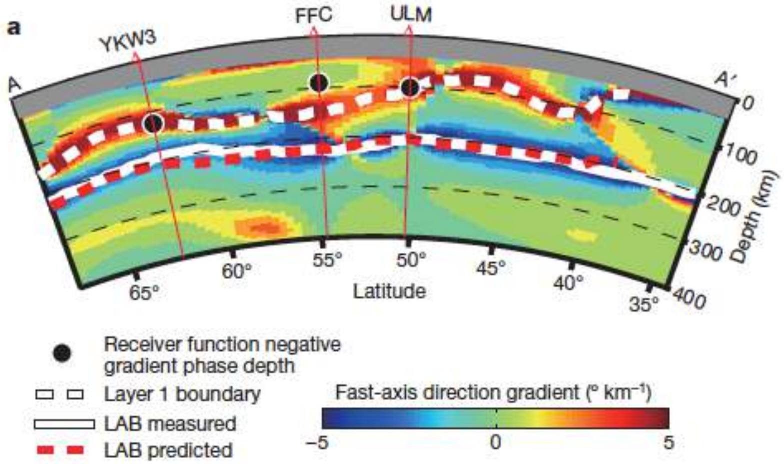


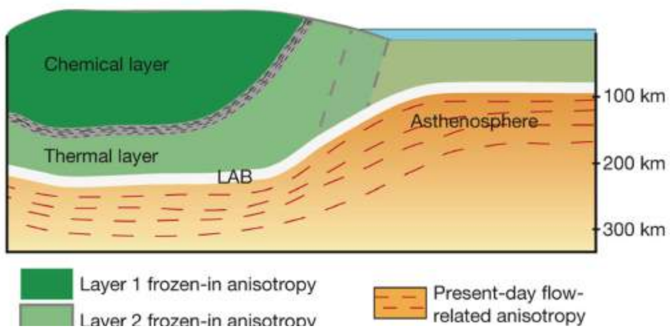
Surface waves ~200-250km



+SKS *Yuan & Romanowicz, 2010*

Structure of continents from seismic anisotropy

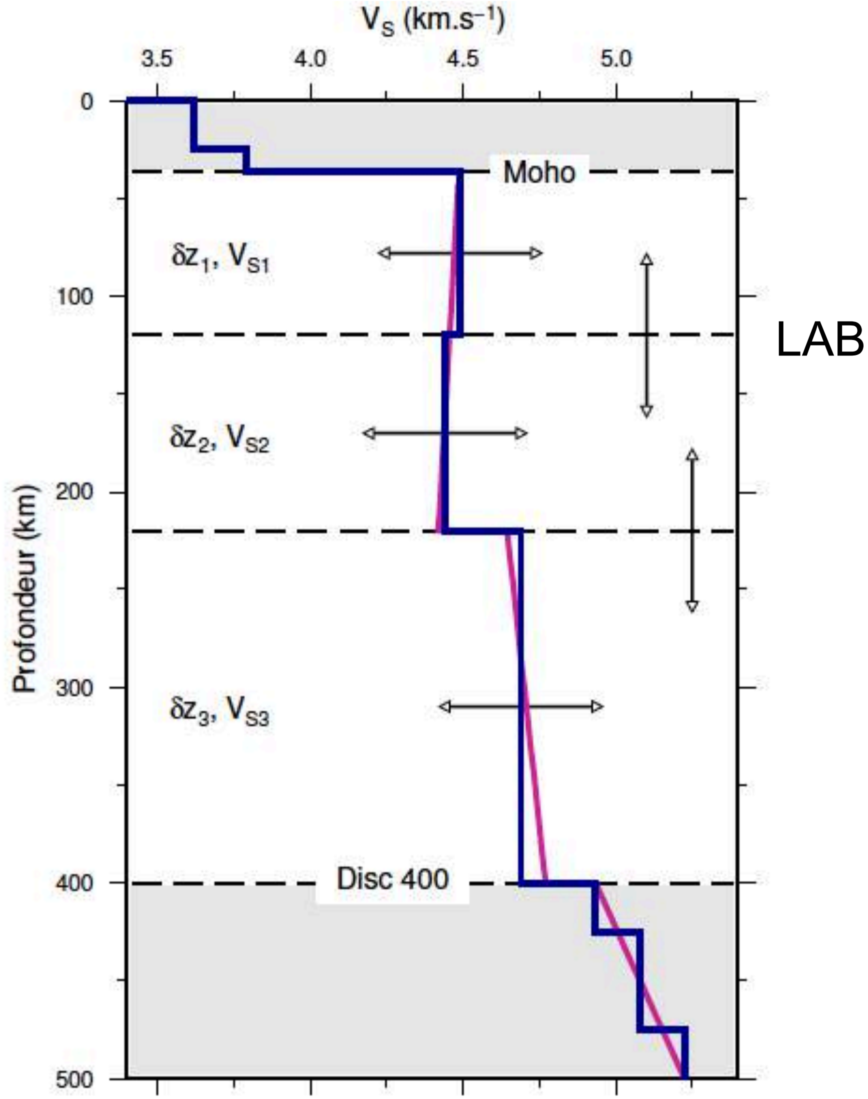




Mid-lithospheric Discontinuity (Yuan & Romanowicz, 2010)

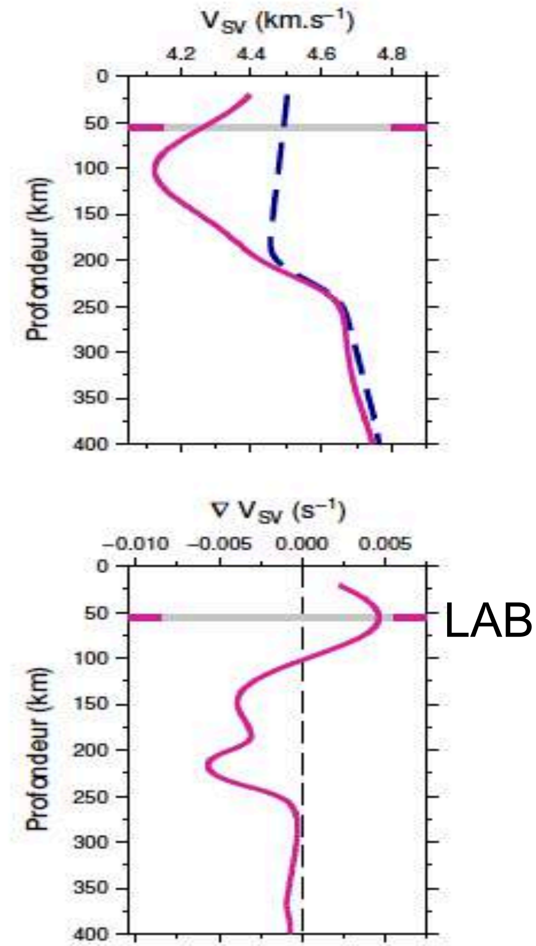
From Surface wave dispersion

Statistical Monte-Carlo Approach

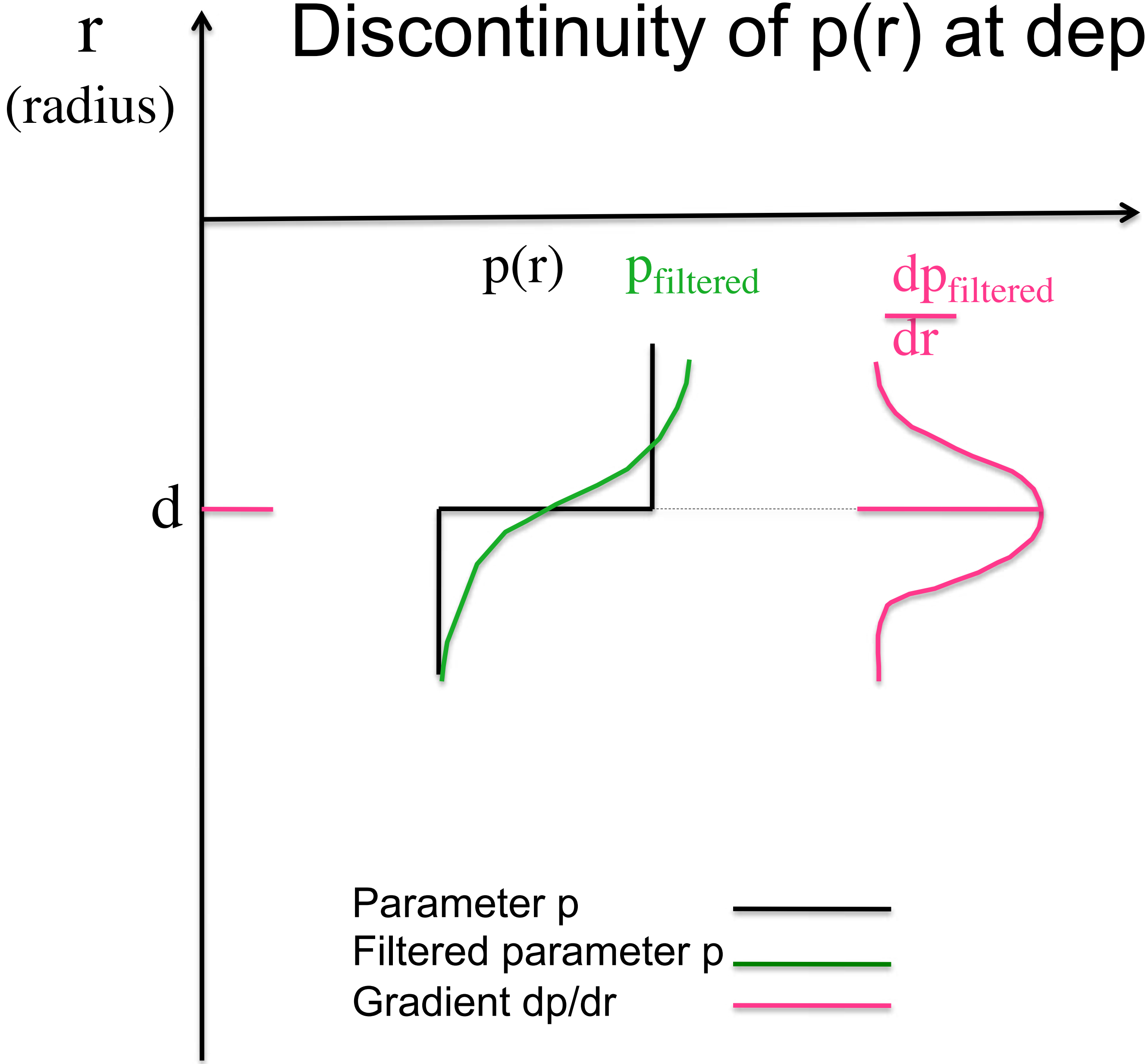


First order Perturbation theory

Proxy from parameter Vsv

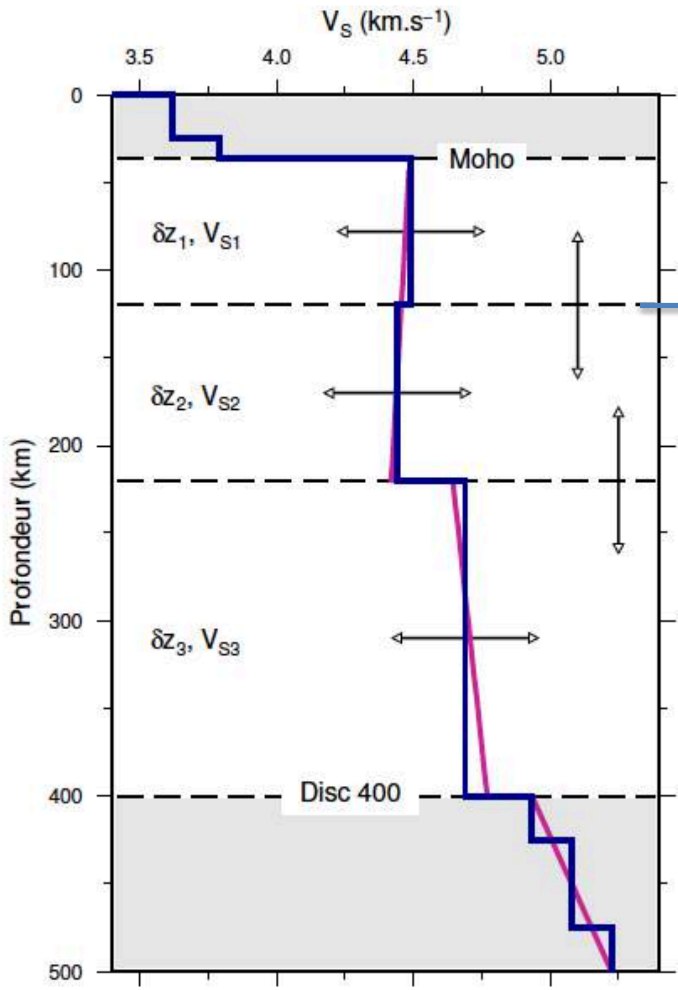


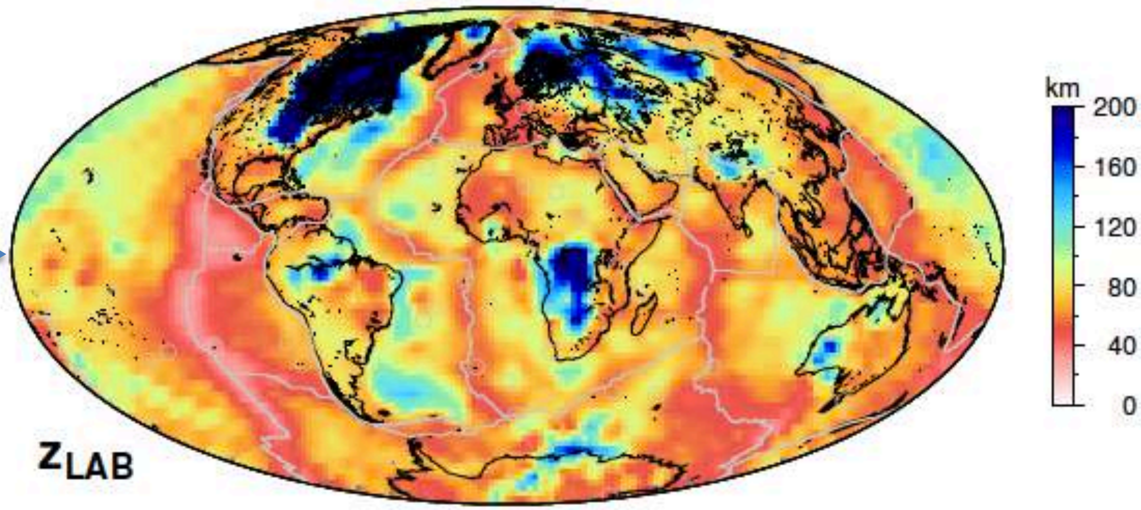
Discontinuity of p(r) at depth d



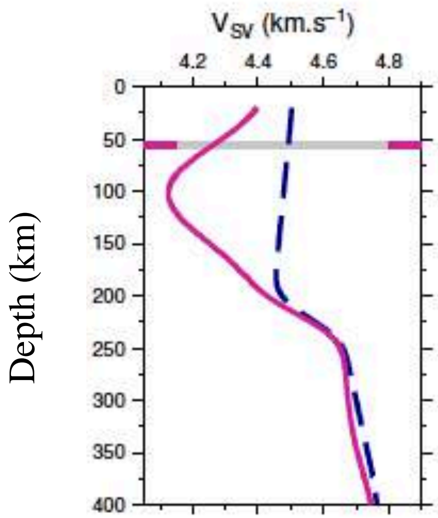
LAB: Statistical M.C. Isotropic Inversion

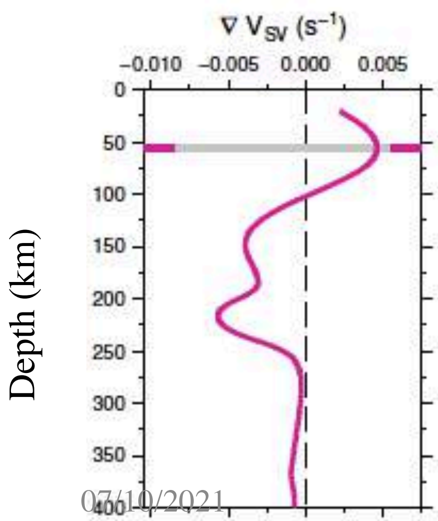
Data: C_R, C_L, U_R, U_L [30-300s], Parameters: 3Vs, 2 δz

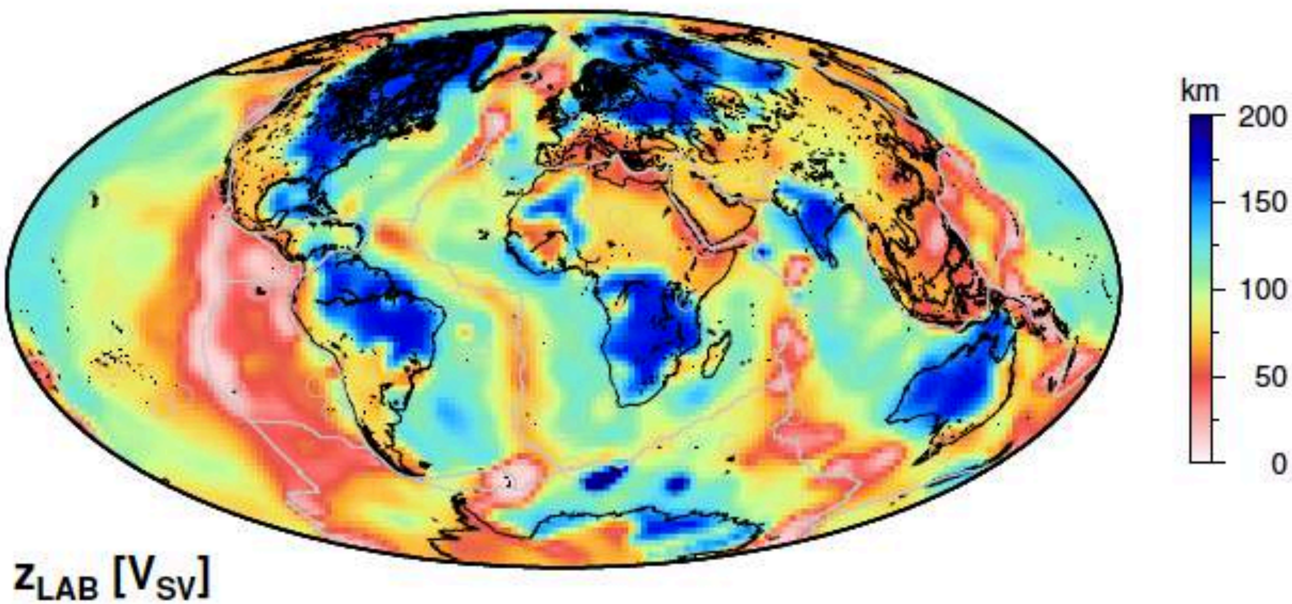




LAB from the gradient of V_{SV} parameter

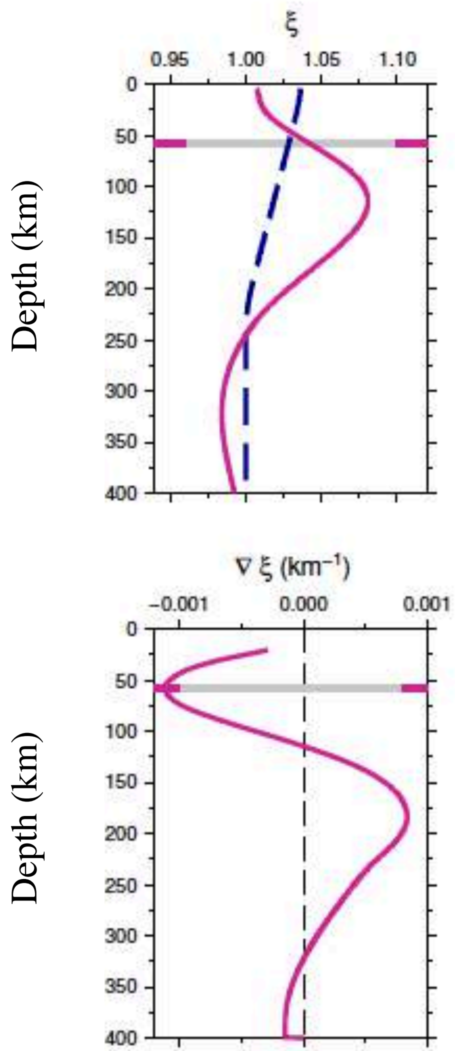


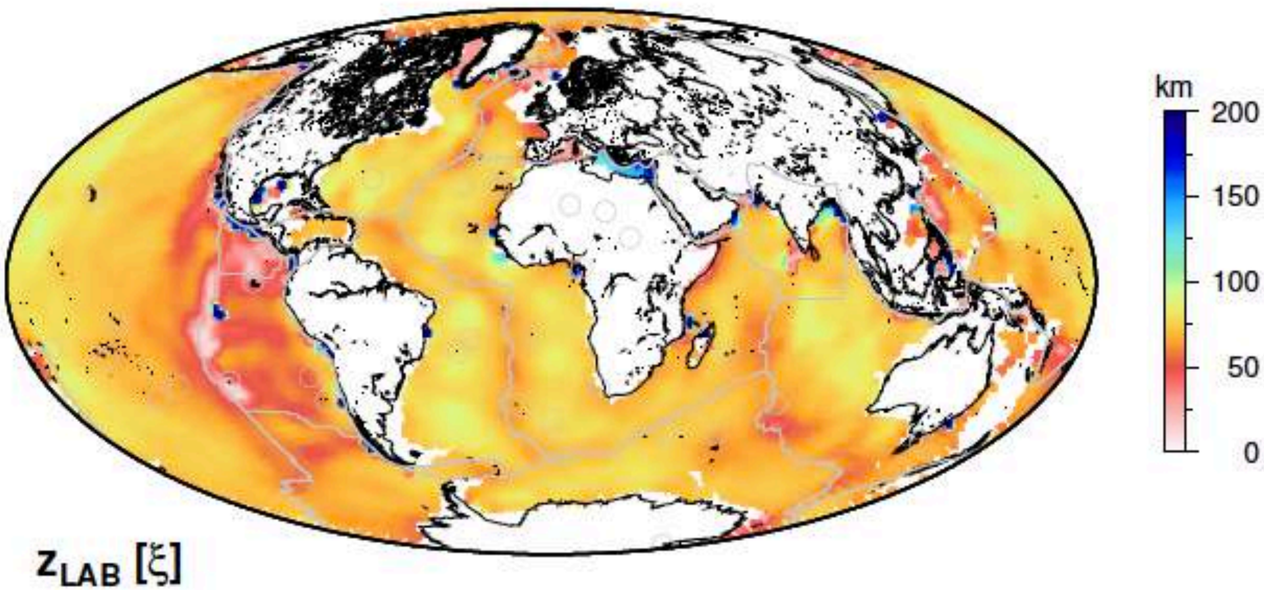




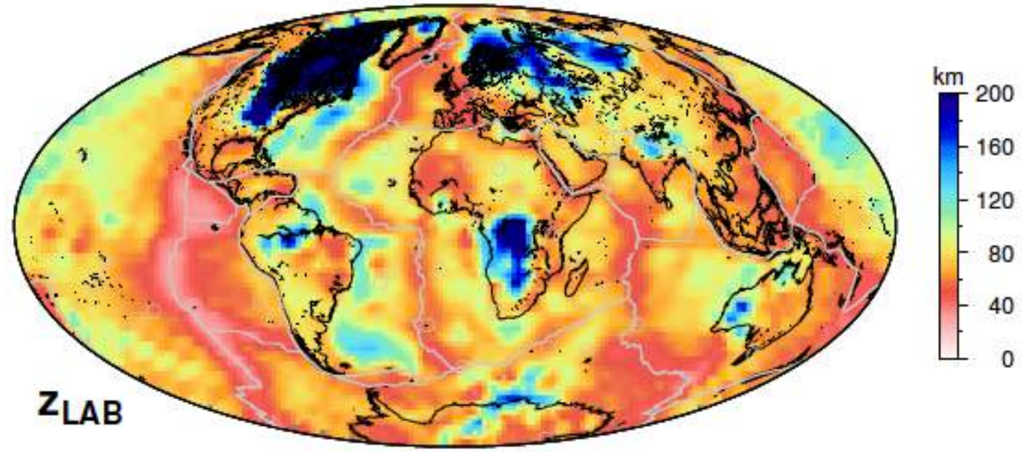
LAB from the gradient of ξ parameter (only oceans)

Radial anisotropy $\xi = (V_{SH}/V_{SV})^2$

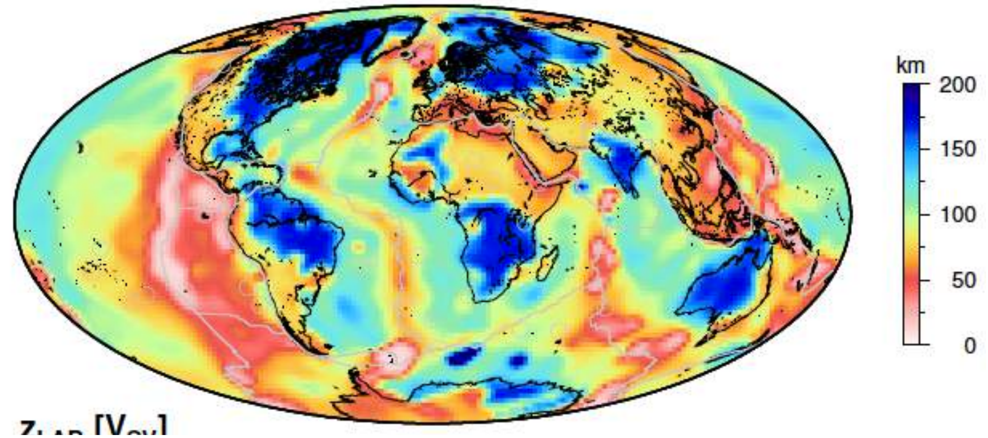




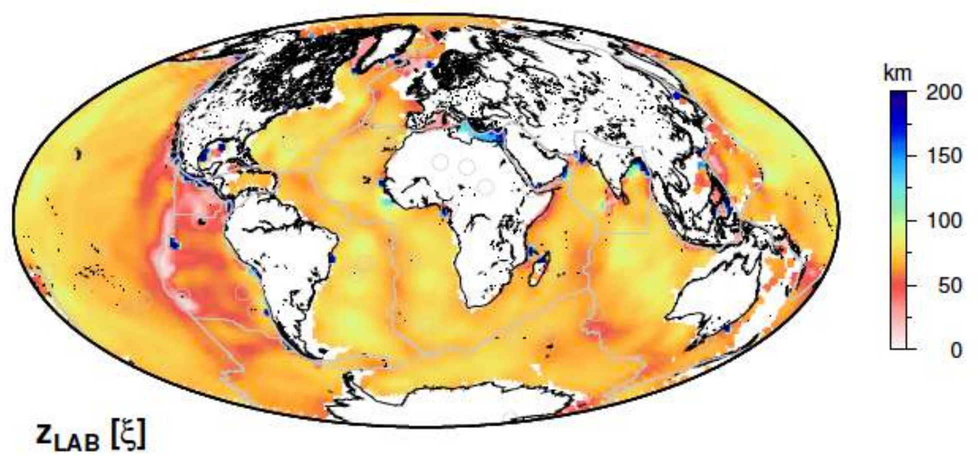
Statistical MC **Isotropic** Inversion



Vsv proxy (**Anisotropic** Perturbation Theory)

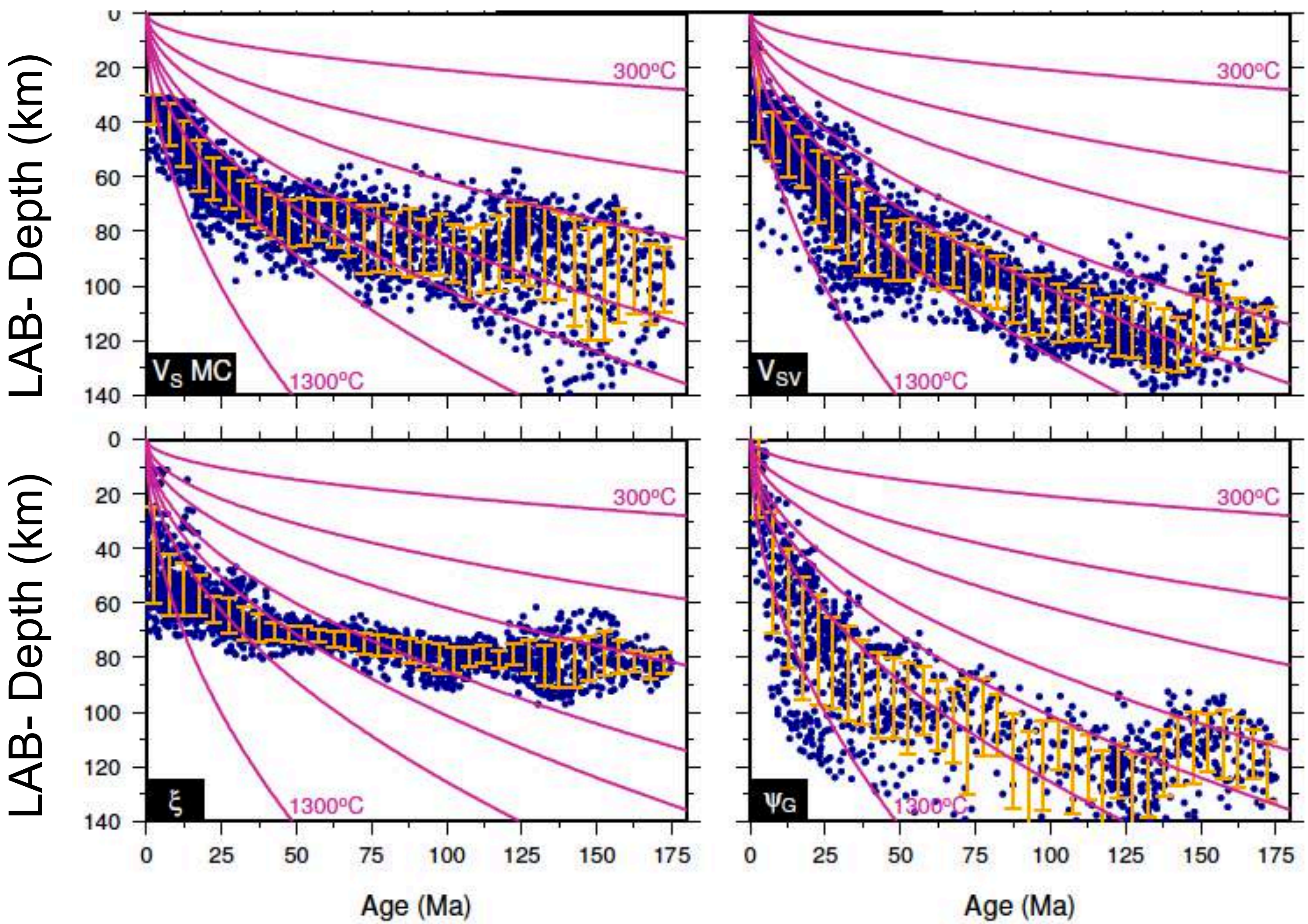


ξ proxy (**Anisotropic** Perturbation Theory)



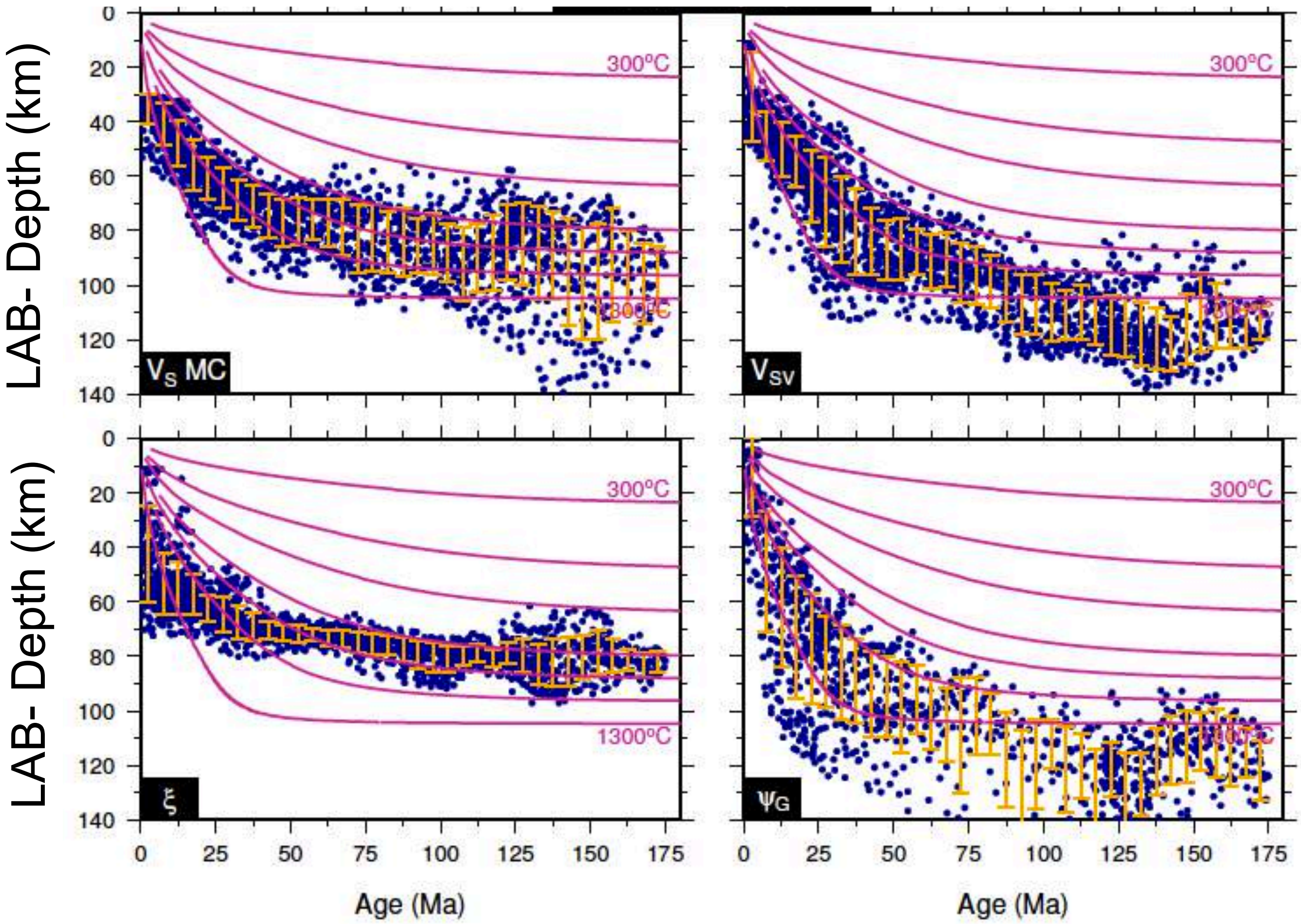
Age Variation of LAB depth in oceanic regions

Compared with Half Space Cooling model



Age Variation of LAB depth in oceanic regions

Compared with Plate model (McK)



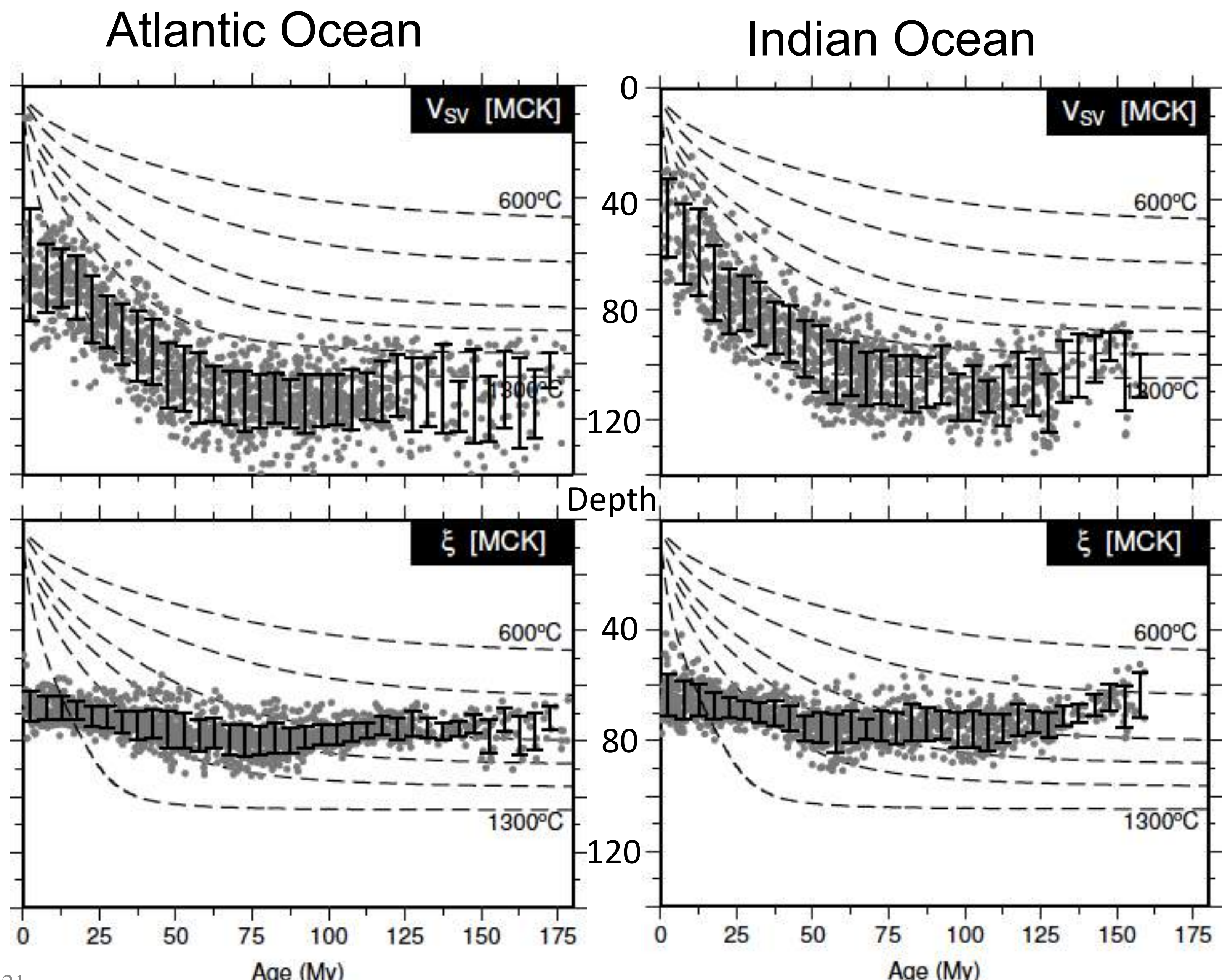
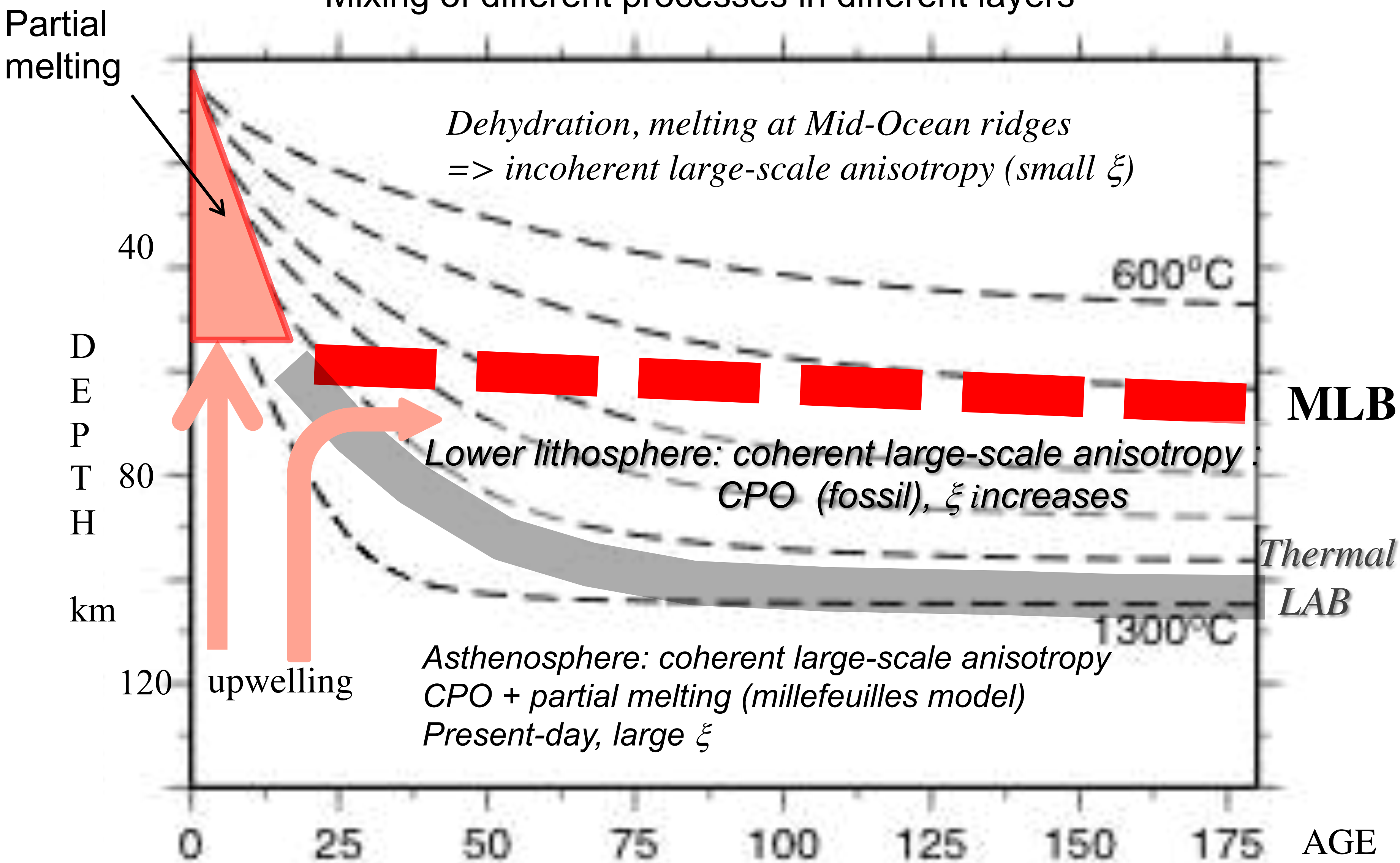


Plate Model McK

Mixing of different processes in different layers



MLB: Mid-Lithospheric Boundary – Gutenberg Discontinuity

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See also Schmerr, 2012; Beghein et al., 2014, …

New Discontinuity within the lithosphere

-LAB topography derived from surface wave data on a global scale

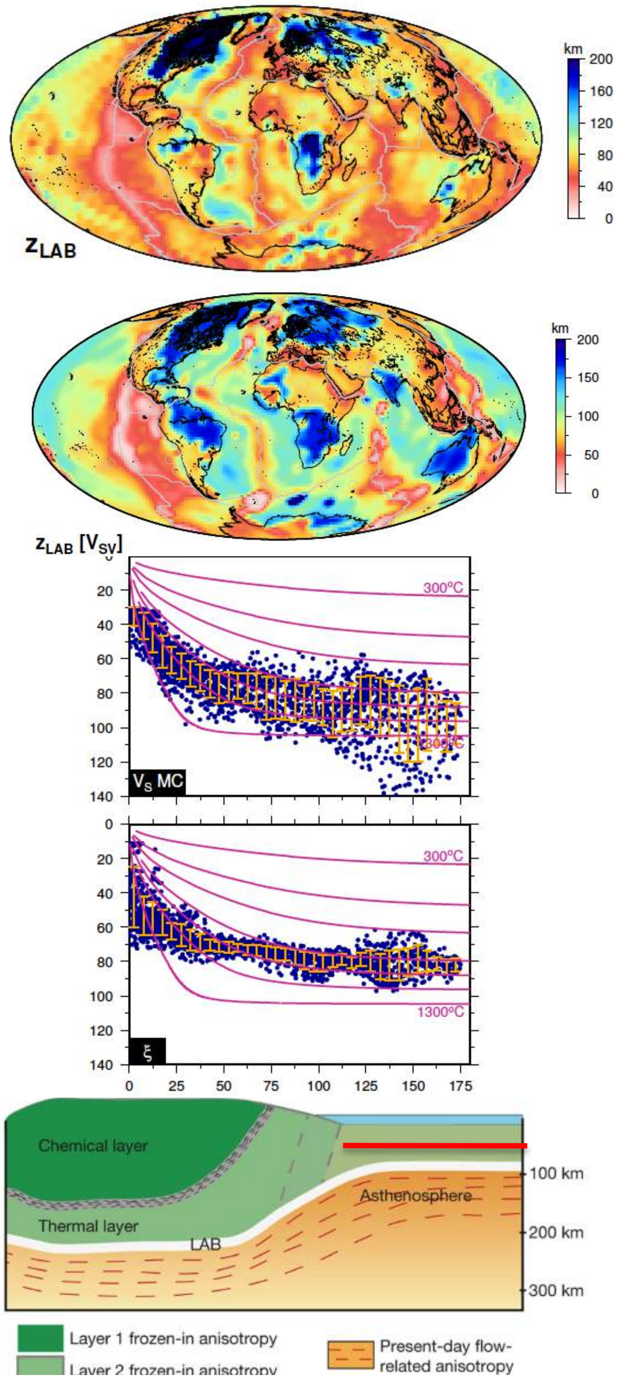
-The ocean lithosphere not so simple!

- For oceans, the model of formation of lithosphere must be revisited in view of results from radial and azimuthal anisotropies.

-Existence of a strong gradient of ξ between 60-80km (related to dehydration boundary layer?)

Mid-Lithospheric Boundary

CONTINENTS?

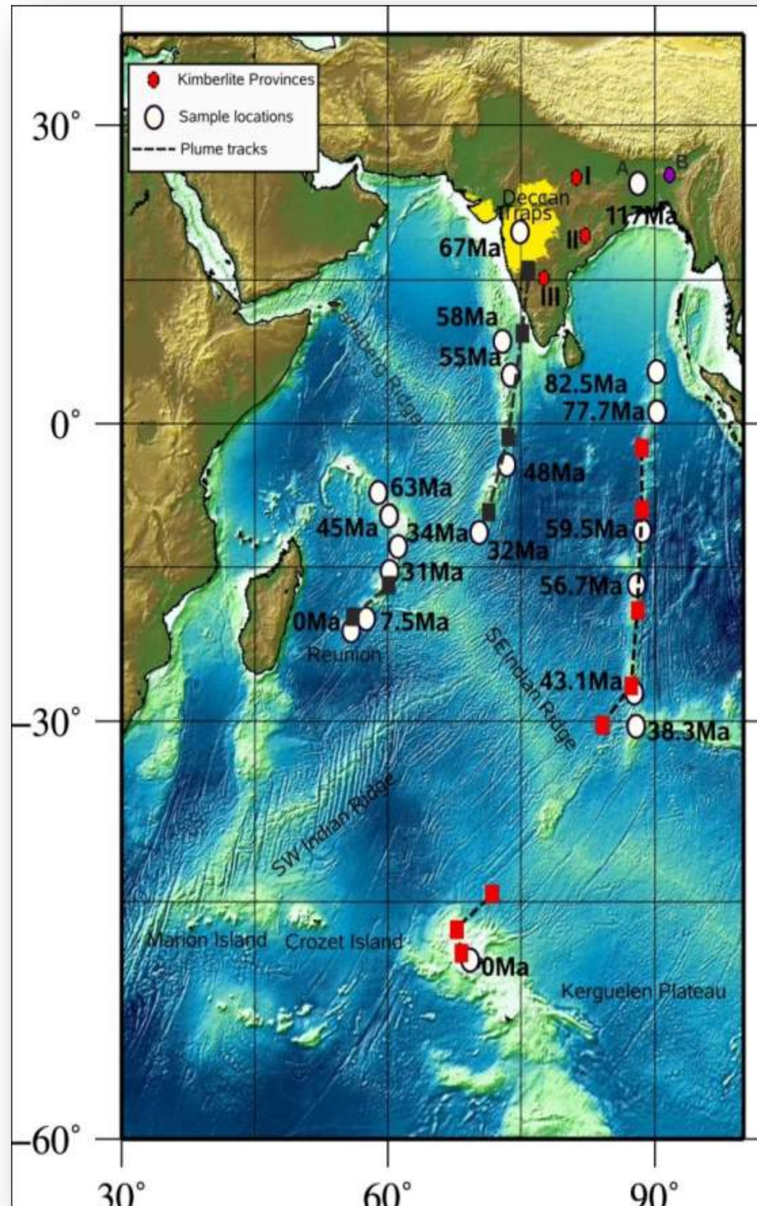


Yuan and Romanowicz, 2010

Indian Continent

Motivation and Scientific Challenges

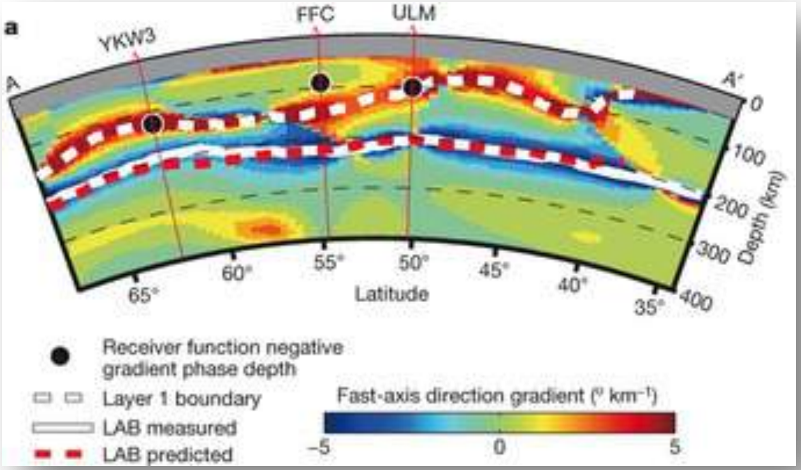
- Indian continent is **unique** in many respects.
- Indian plate moved at exceptionally high speeds of 18-20 cm/yr after its breakup from Gondwanaland ~65 Myr. Ago
- Five cratons of various extension,
- Ravaged by hotspots and experienced large scale magmatism.
- Deccan, Rajmahal volcanic trapps
- Interaction with plumes (*La Réunion, Marion, Crozet and Kerguelen*) ?



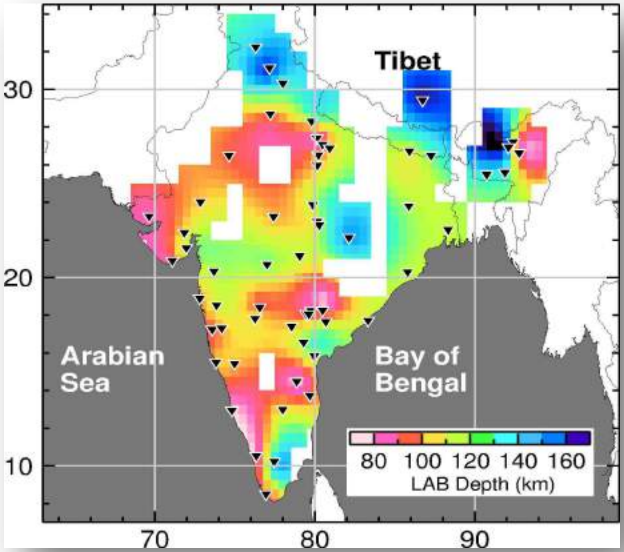
Scientific Challenges – Debate on Indian LAB

- **Super mobility** due to a thin seismic lithosphere (~80-100km)) (Kumar et al., Nature, 2007)?
- In total disagreement with common consensus on cratons:

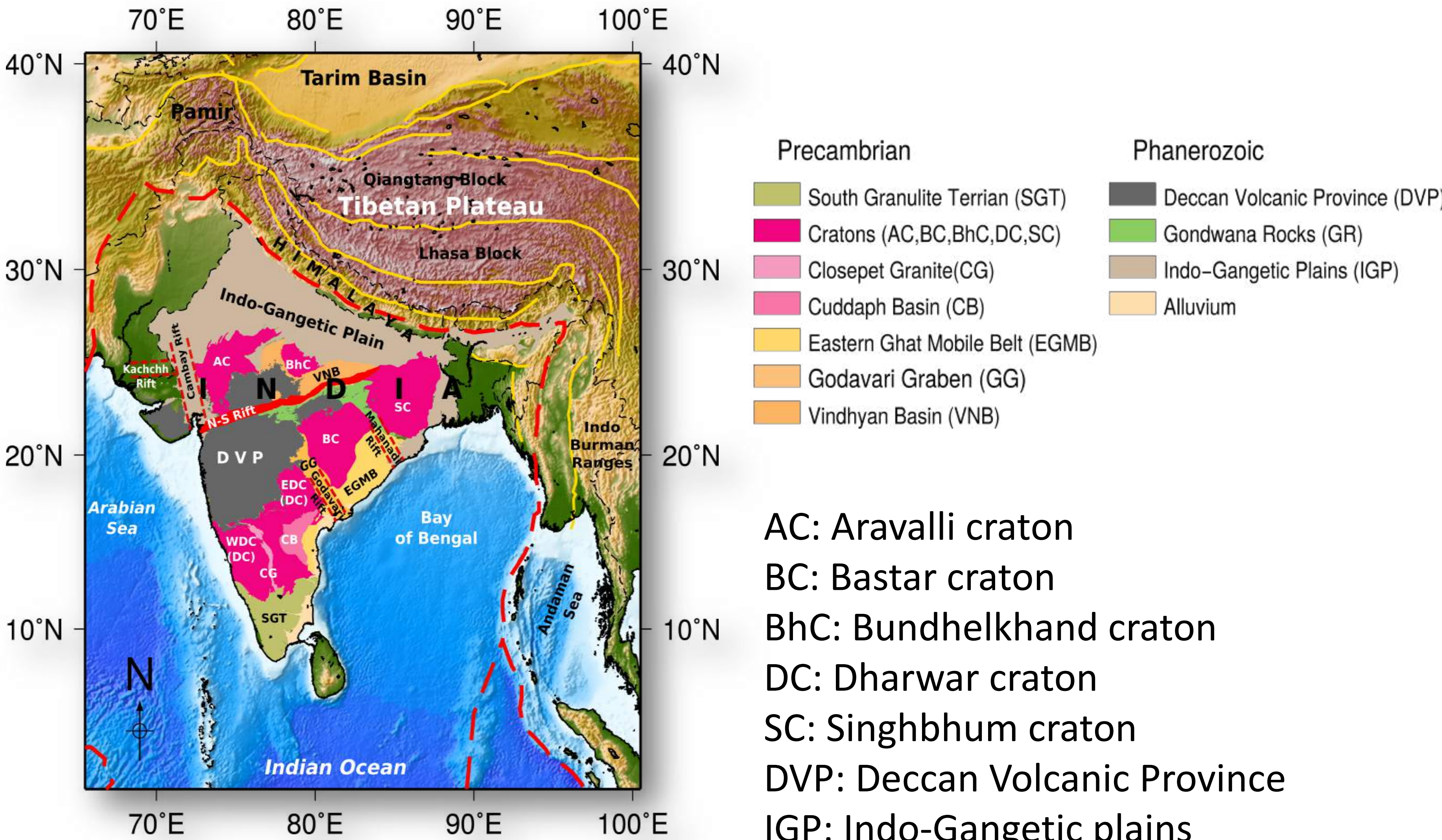
  North America (~200-250km) [Yuan and Romanowicz, 2010, …]: stratification.
- Is the seismic discontinuity at **~100 km** depth related to MLB, unrelated to LAB?
- Evidence for postcollisional flexuring of the Indian plate with a wavelength of ~1000 km [Kumar et al., 2013]
- **=> Large topography** on the LAB (Lithosphere-Asthenosphere Boundary)?
- Deep structure of the Indian continent.



Layering in the lithosphere in NA [Yuan and Romanowicz, 2010]



Study Area: geological signature

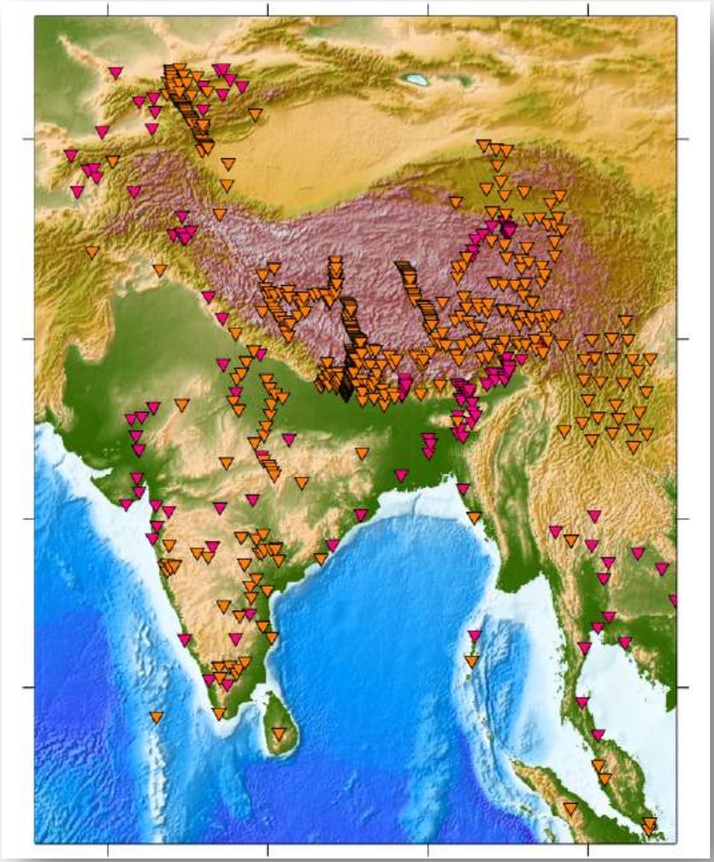


AC: Aravalli craton
BC: Bastar craton
BhC: Bundhelkhand craton
DC: Dharwar craton
SC: Singhbhum craton
DVP: Deccan Volcanic Province
IGP: Indo-Gangetic plains

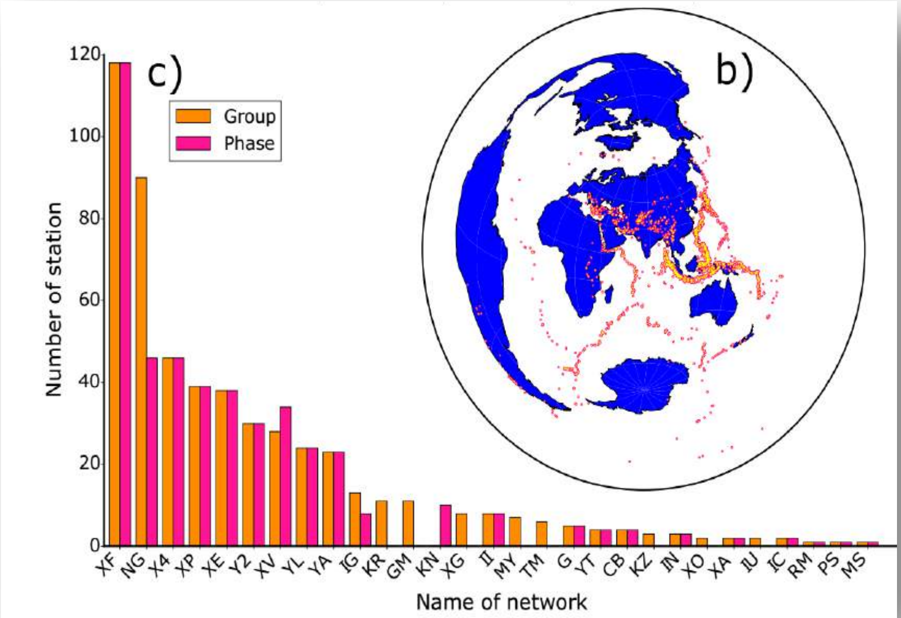
Maurya et al., 2016

Unique Dataset

Stations

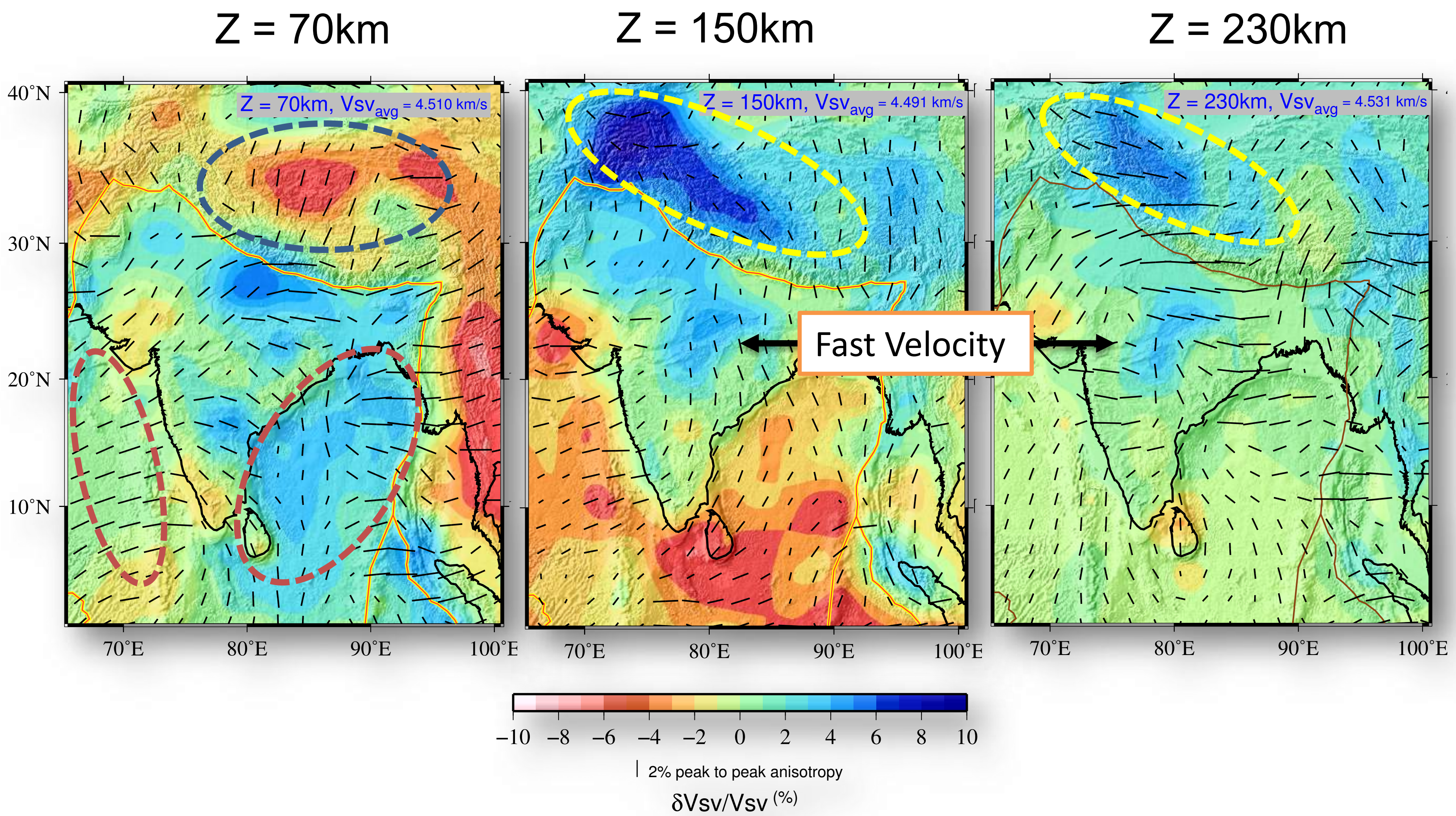


Earthquakes

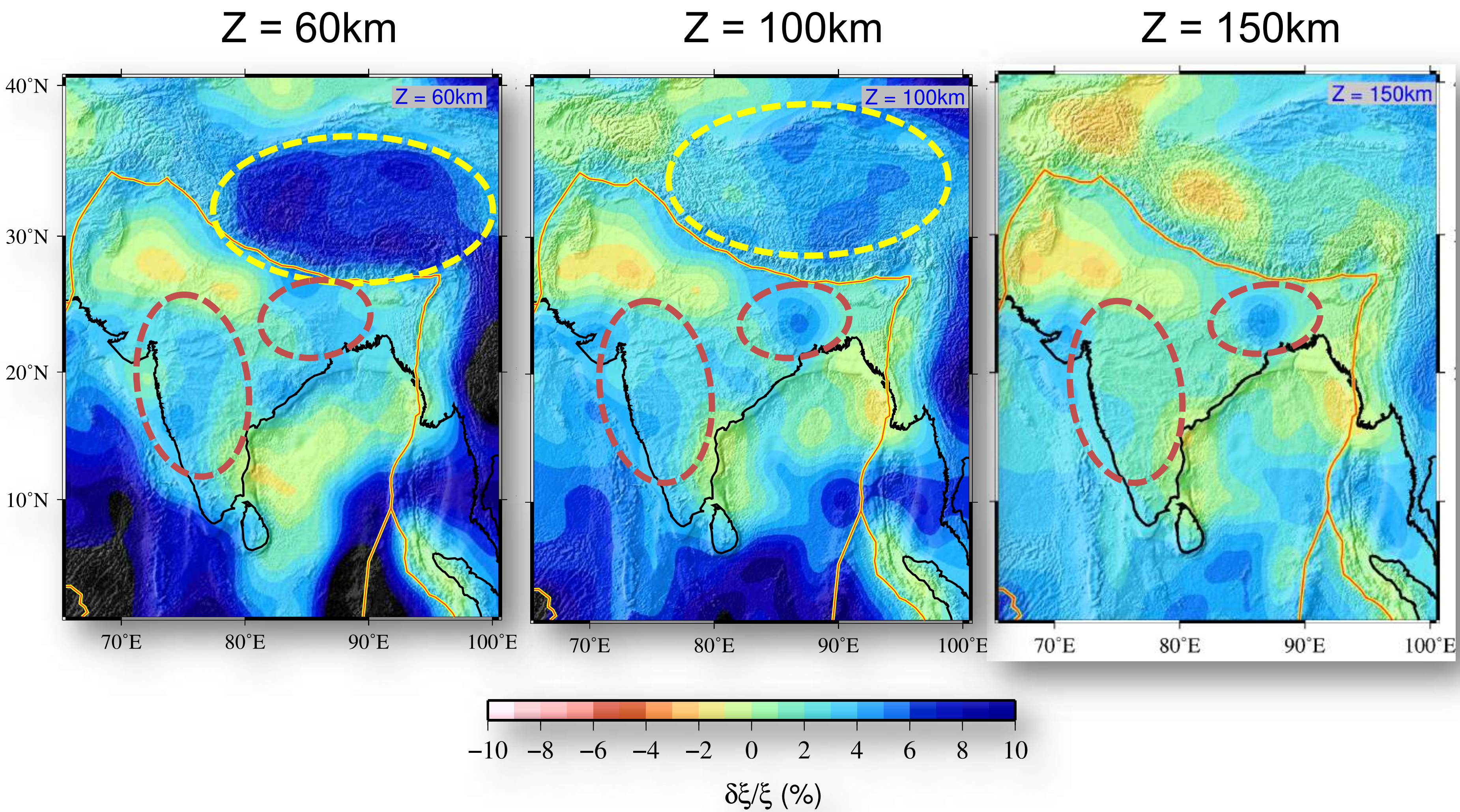


- 29 Seismic broadband Networks (**global and regional**)
- Over 550 seismic stations
- Earthquakes of magnitude >5.5
- Surface wave data in the period range of 10-400s.

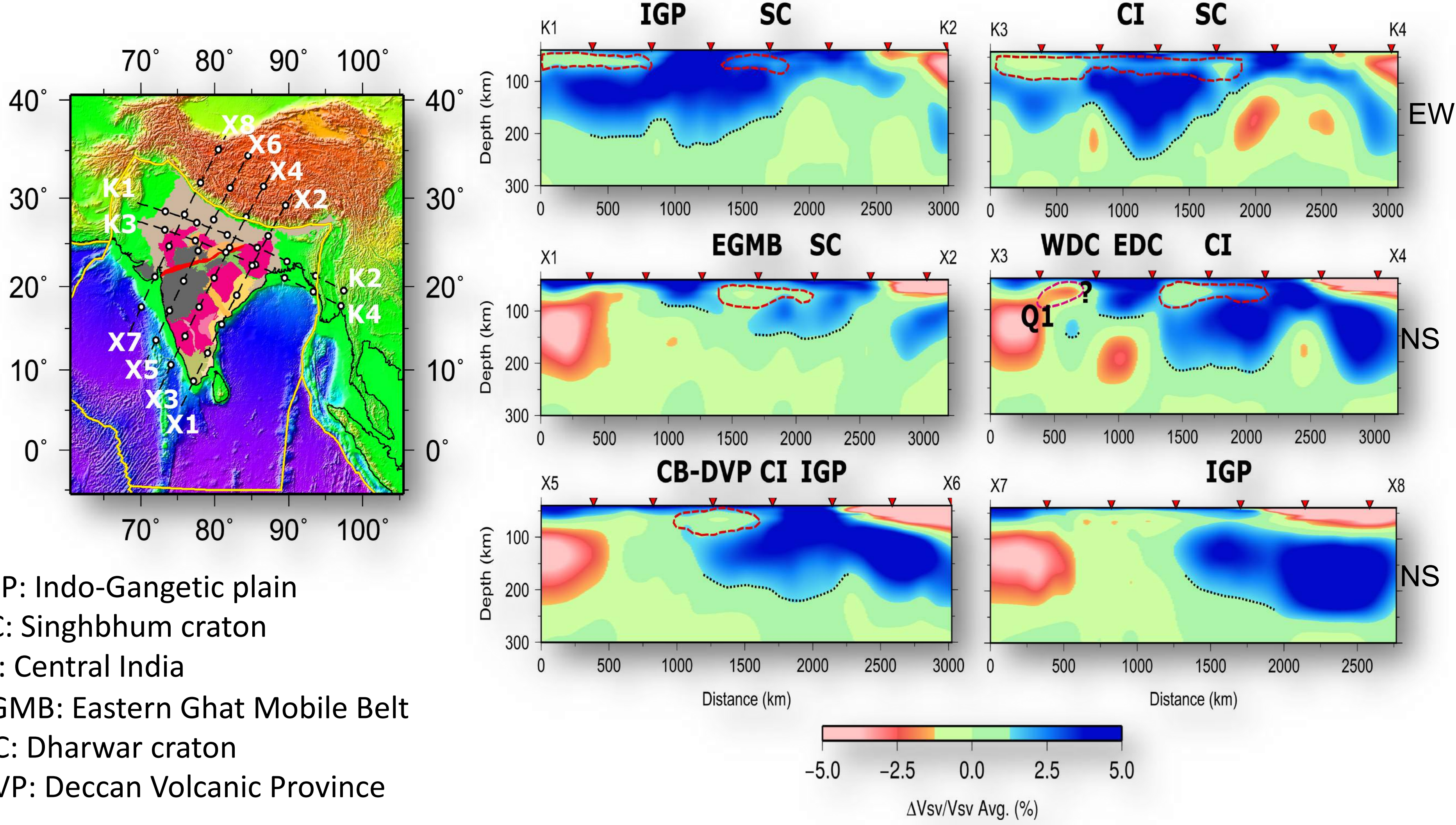
3-D tomography model of the Indian continent
Velocity and Azimuthal Anisotropy



3-D tomography model of the Indian continent
Radial Anisotropy ξ (Rayleigh – Love inversion)

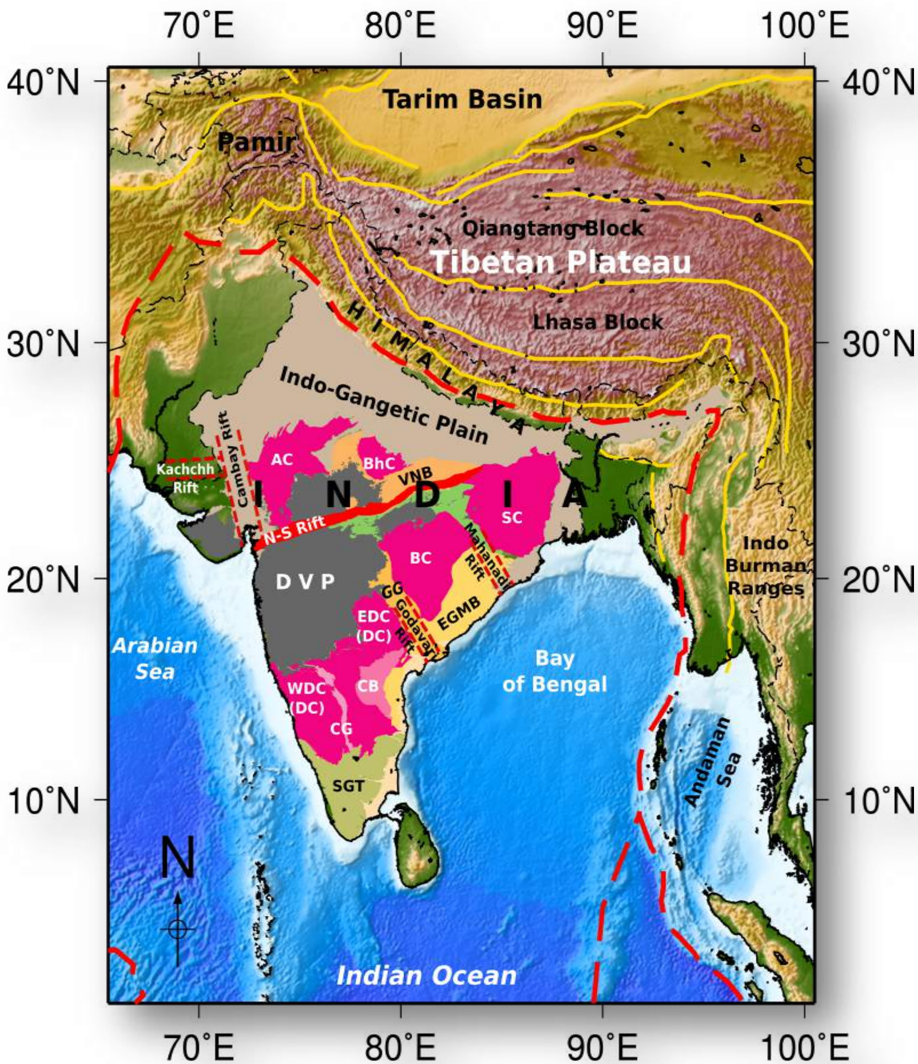


3D-Perturbation model



IGP: Indo-Gangetic plain
SC: Singhbhum craton
CI: Central India
EGMB: Eastern Ghat Mobile Belt
DC: Dharwar craton
DVP: Deccan Volcanic Province

Study Area: geological signature



Precambrian	Phanerozoic
South Granulite Terrian (SGT)	Deccan Volcanic Province (DVP)
Cratons (AC,BC,BhC,DC,SC)	Gondwana Rocks (GR)
Closepet Granite(CG)	Indo–Gangetic Plains (IGP)
Cuddaph Basin (CB)	Alluvium
Eastern Ghat Mobile Belt (EGMB)	
Godavari Graben (GG)	
Vindhyan Basin (VNB)	

AC: Aravalli craton
BC: Bastar craton
BhC: Bundhelkhand craton
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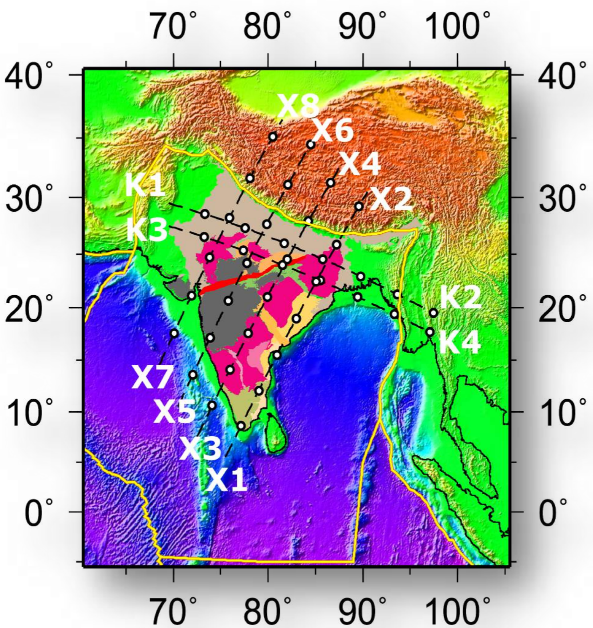
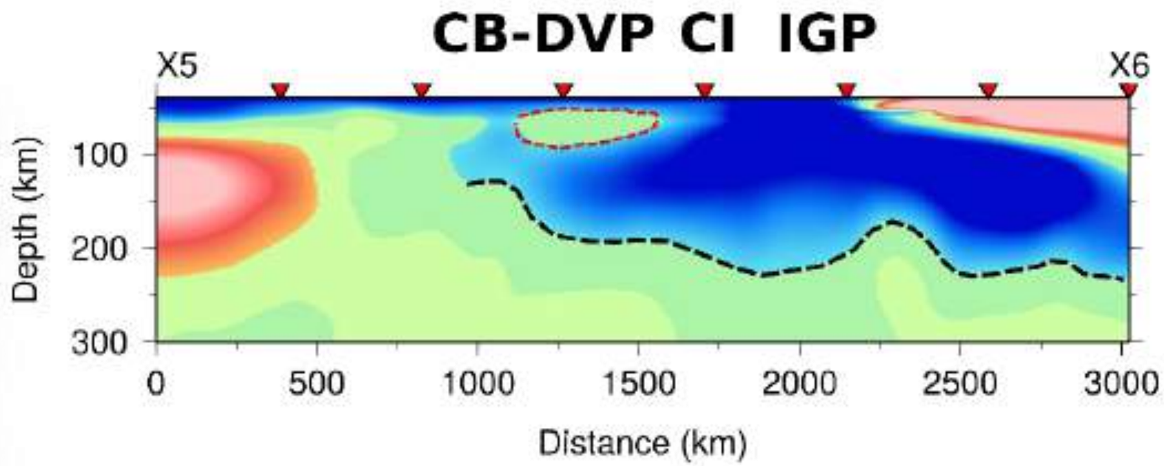
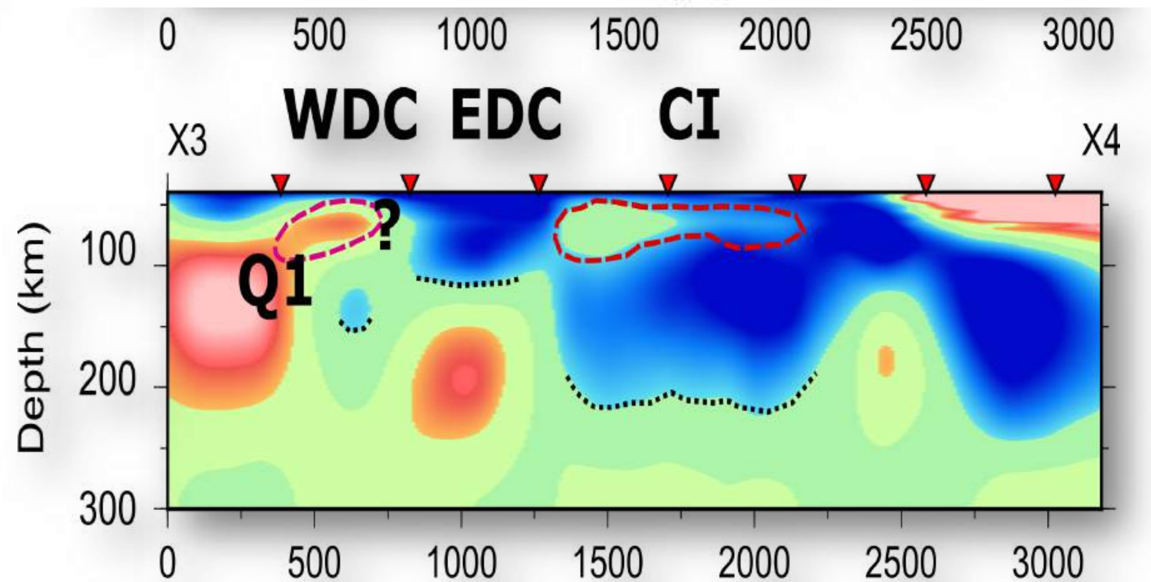
Maurya et al., 2016

3D-Perturbation model -NS





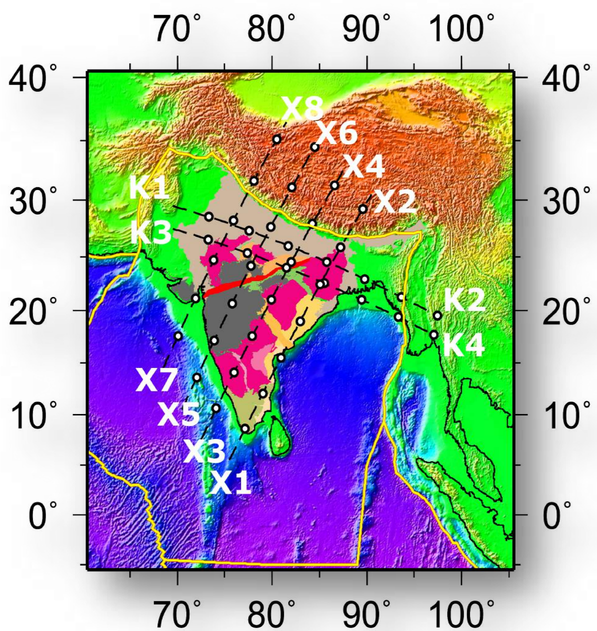


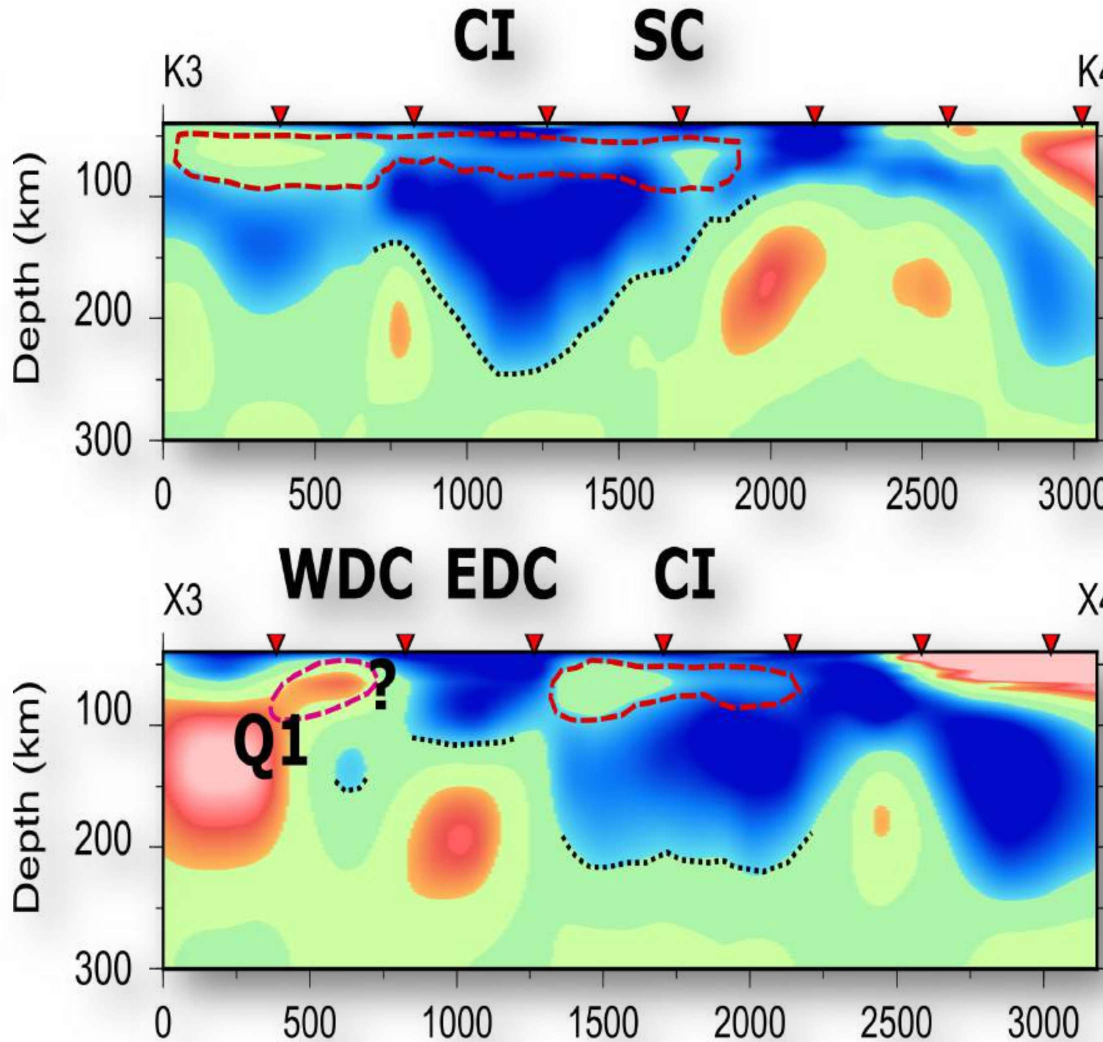
DVP: Low velocity zone
Remnant of hotspot birth

IGP: Indo-Gangetic plain
CI: Central India
WDC, EDC: West, East Dharwar craton
DVP: Deccan Volcanic Province

MLB-ML-LVZ: Mid-lithospheric low velocity zone

3D-Perturbation model: Indian Keel

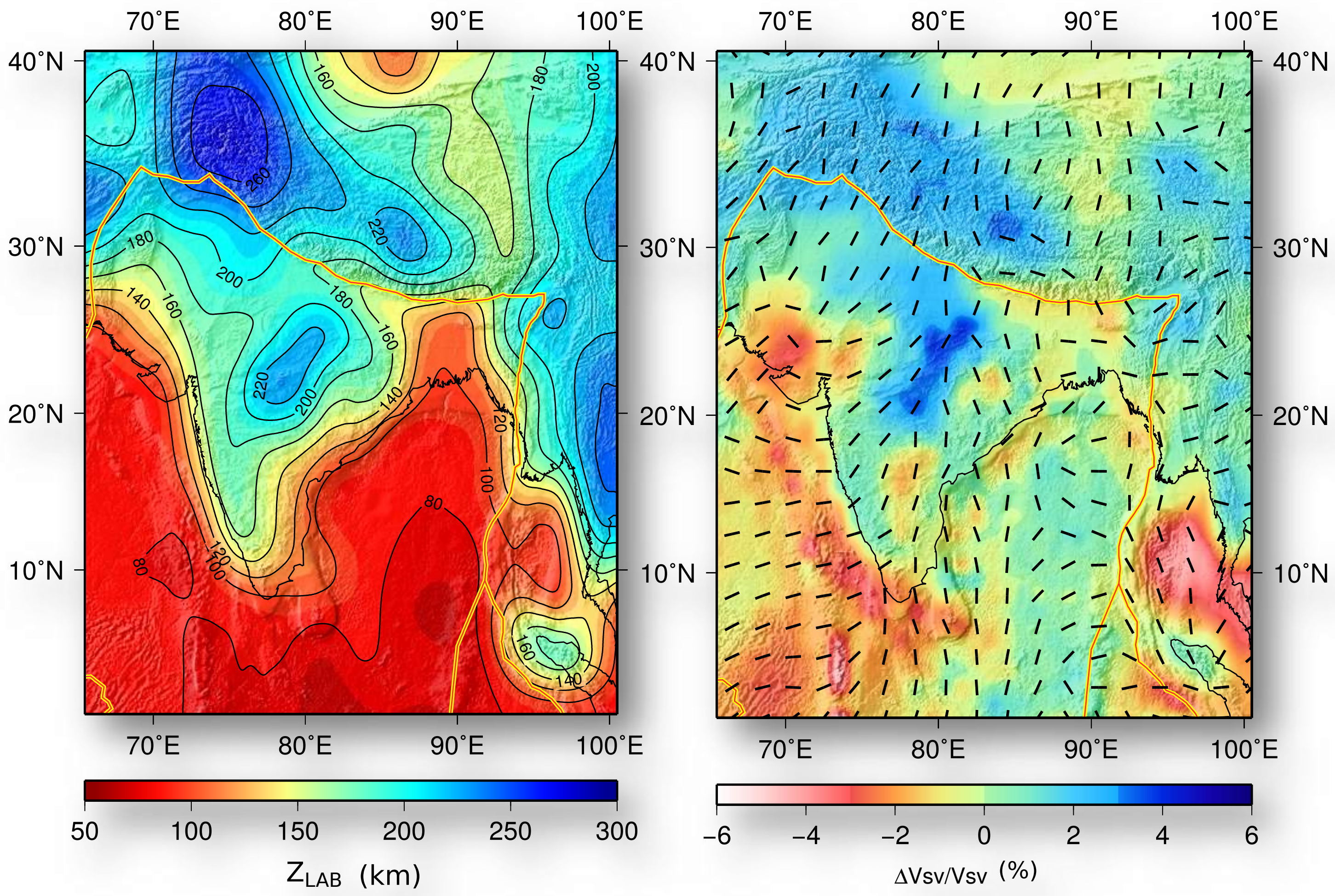




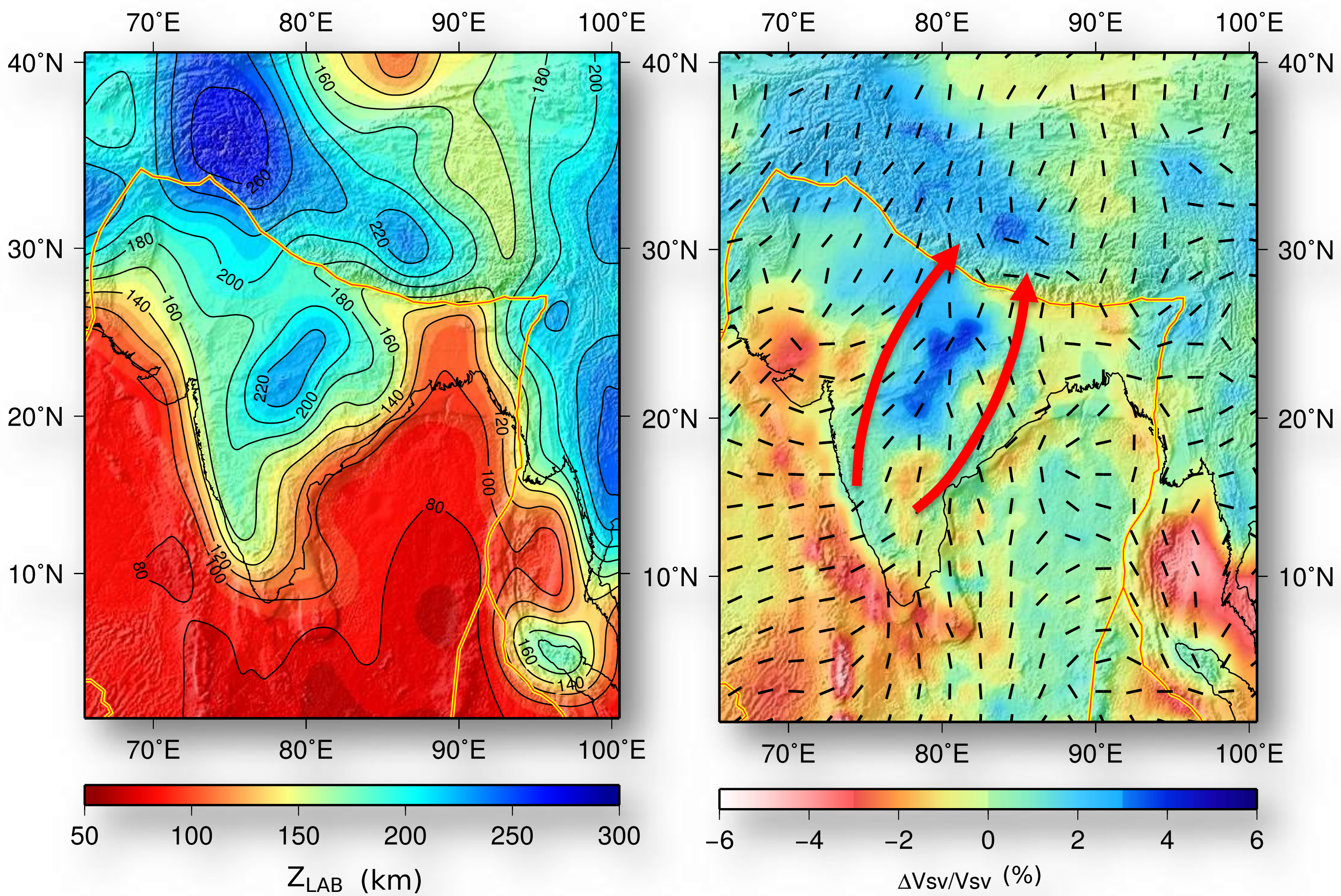
IGP: Indo-Gangetic plain
CI: Central India
SC: Singhbum craton
WDC, EDC: West, East Dharwar craton

MLB-ML-LVZ: Mid-lithospheric low velocity zone

Indian Plate LAB
(Lithosphere-Asthenosphere Boundary)



Indian Plate LAB: Keel

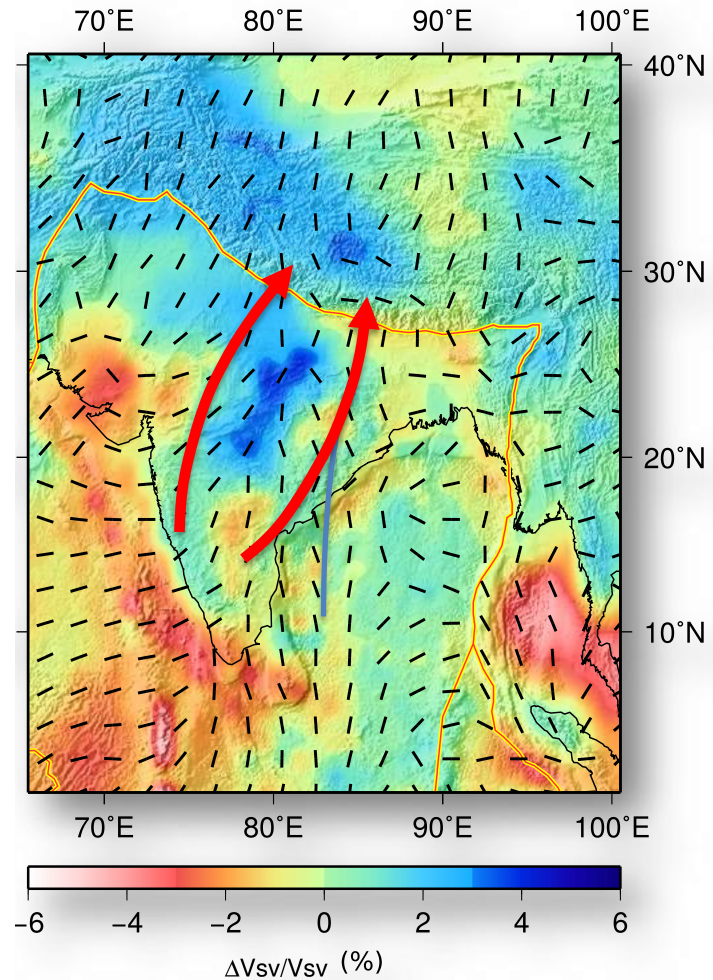


Geodynamic Role?

Plume influence?

Indian Plate LAB: Keel

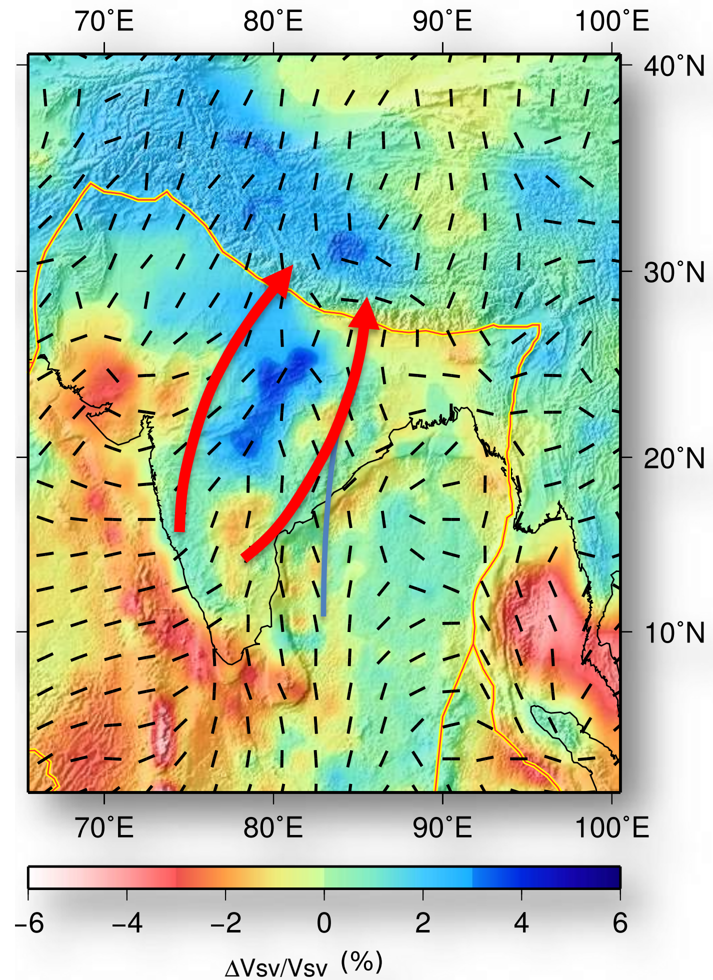
- Prominent cratonic keel present in the center of the Indian continent.
- Shape and orientation of the keel along to the direction of the plate motion.

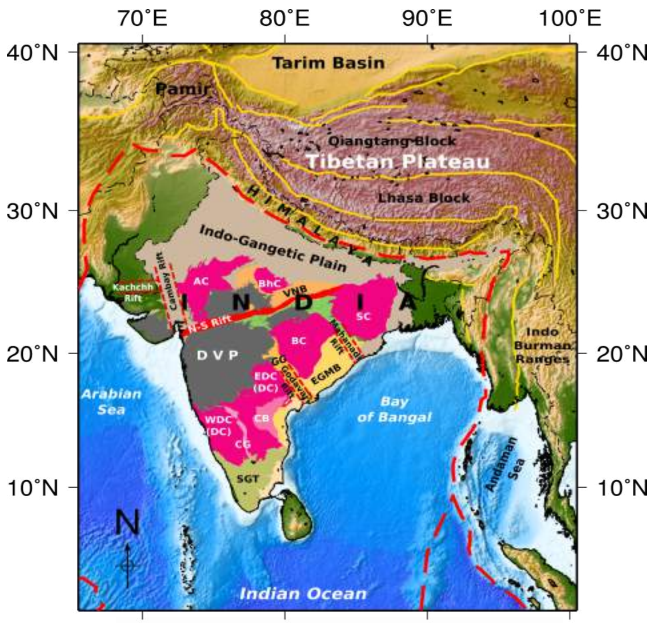


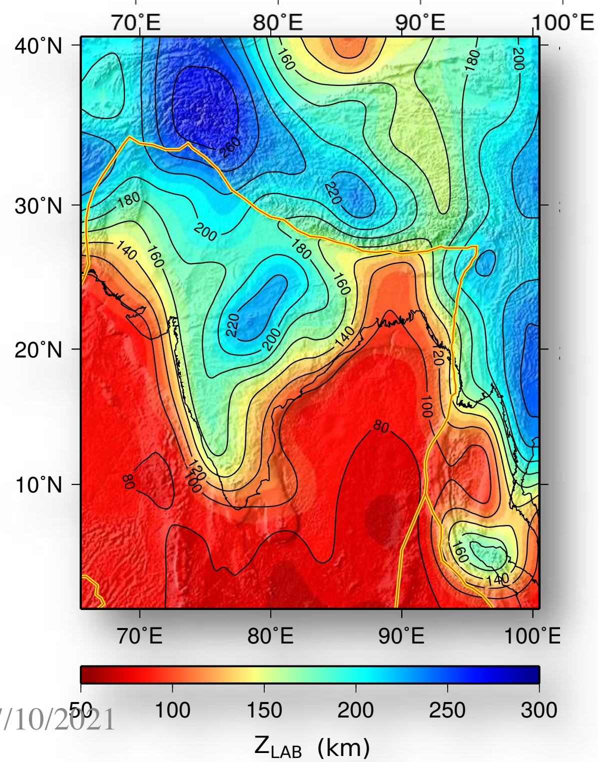
Indian Plate LAB: Keel

➢ Geodynamic Role of the keel:
- Aligned with plate motion
- Might fix the direction of motion

➢ Plume influence:
fast plate velocities might be due to La Réunion plume







Structure of the Indian continent

- Large variability of craton thicknesses

- MLB (ML-LVZ): low velocity zone
- MLB: Change in azimuthal anisotropy
- MLB not present in all blocks

-DVP (Deccan Volcanic Province)
 MLB: memory of La Réunion Hotspot birth

- Indian Keel: geodynamic role? (laboratory experiments)

Oceanic plates and Continents

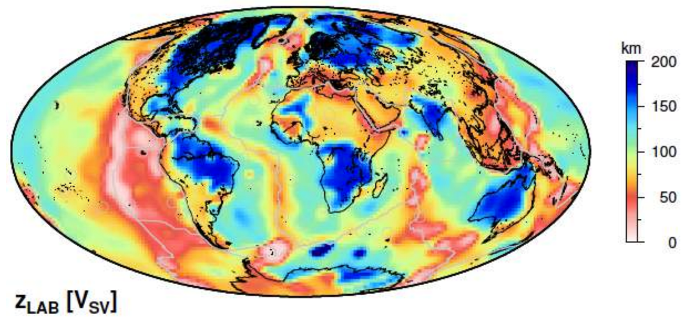
- LAB topography derived from surface wave data on a global scale and regional scale (India)

- For continents: Large variability of craton thickness Stratification: MLB- ML-LVZ, low velocity zone (not present in all cratonic blocks). Relationship with MLB?

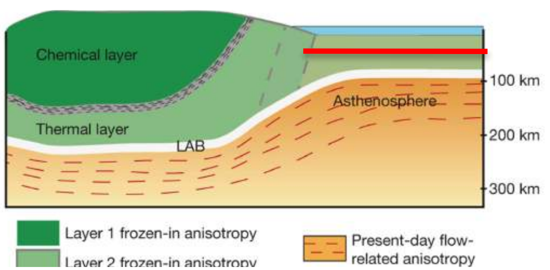
- The model of formation of lithosphere must be revisited in view of results from radial and azimuthal anisotropies in oceans and continents.

- Role of the Indian Keel

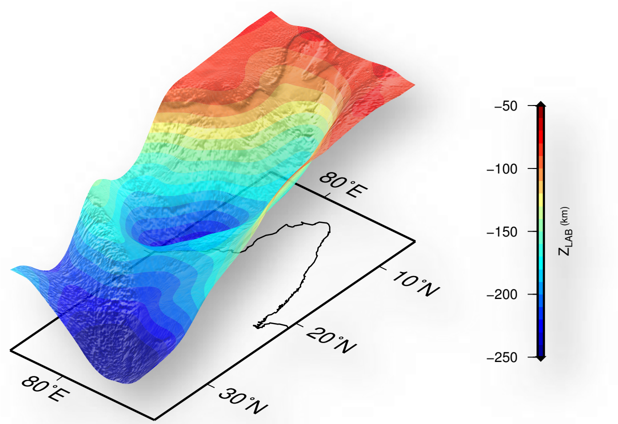
- Role of mantle upwellings in plate motion which might be as important as subducting slabs



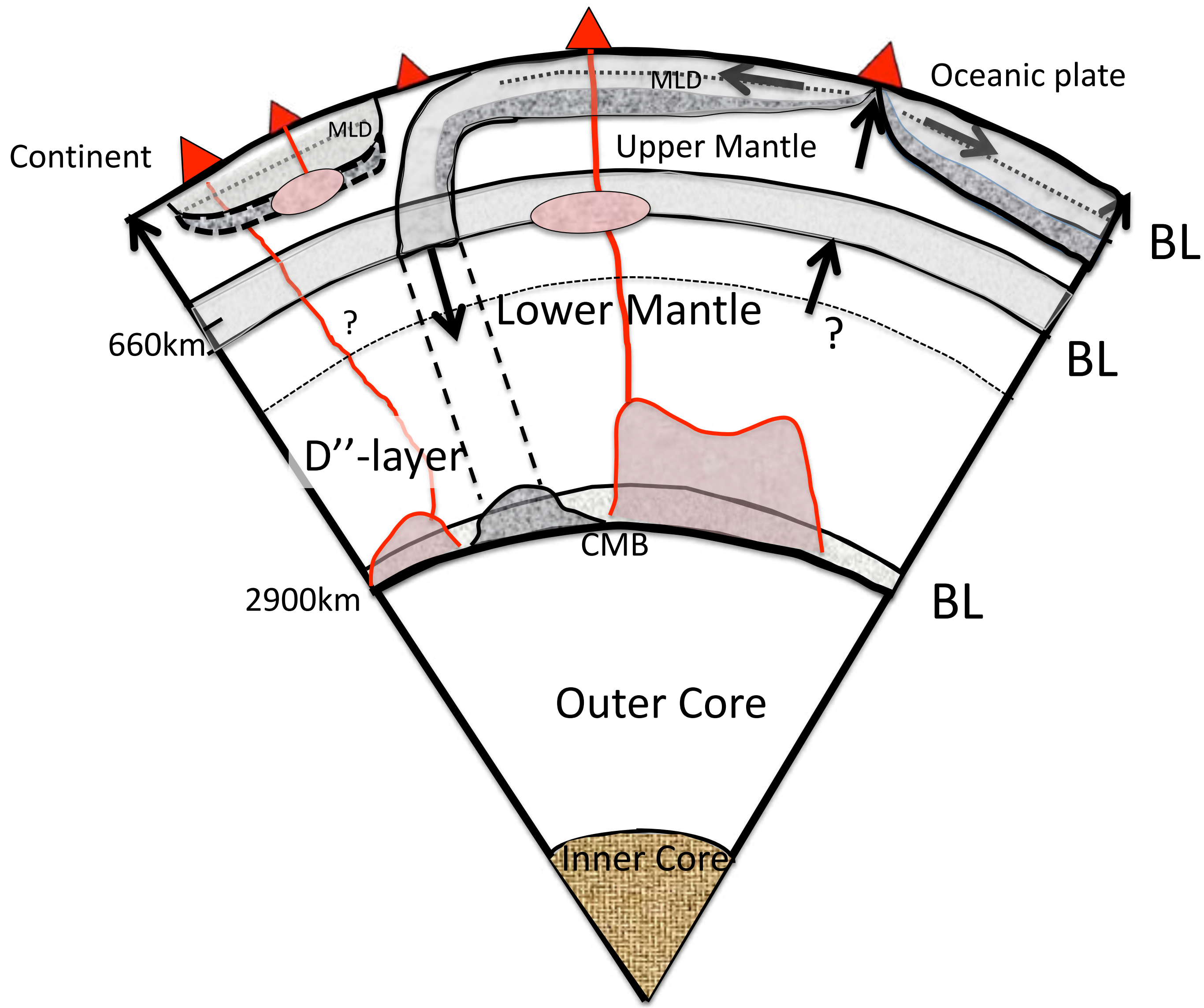
Burgos et al., 2014



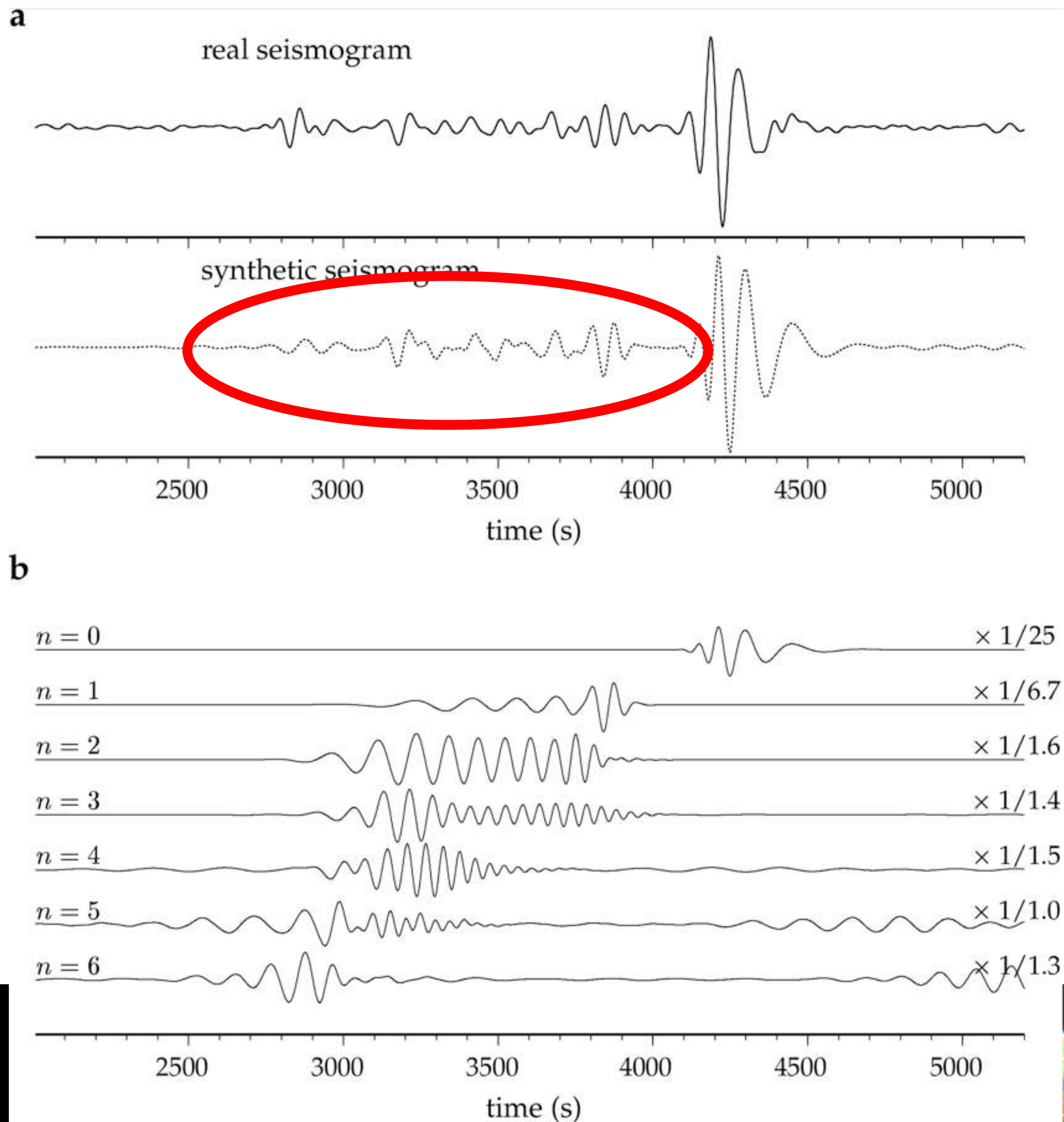
Yuan & Romanowicz, 2010



Evidence of Anisotropy in different depth ranges



Deep structure of Mantle transition zone from surface wave higher modes

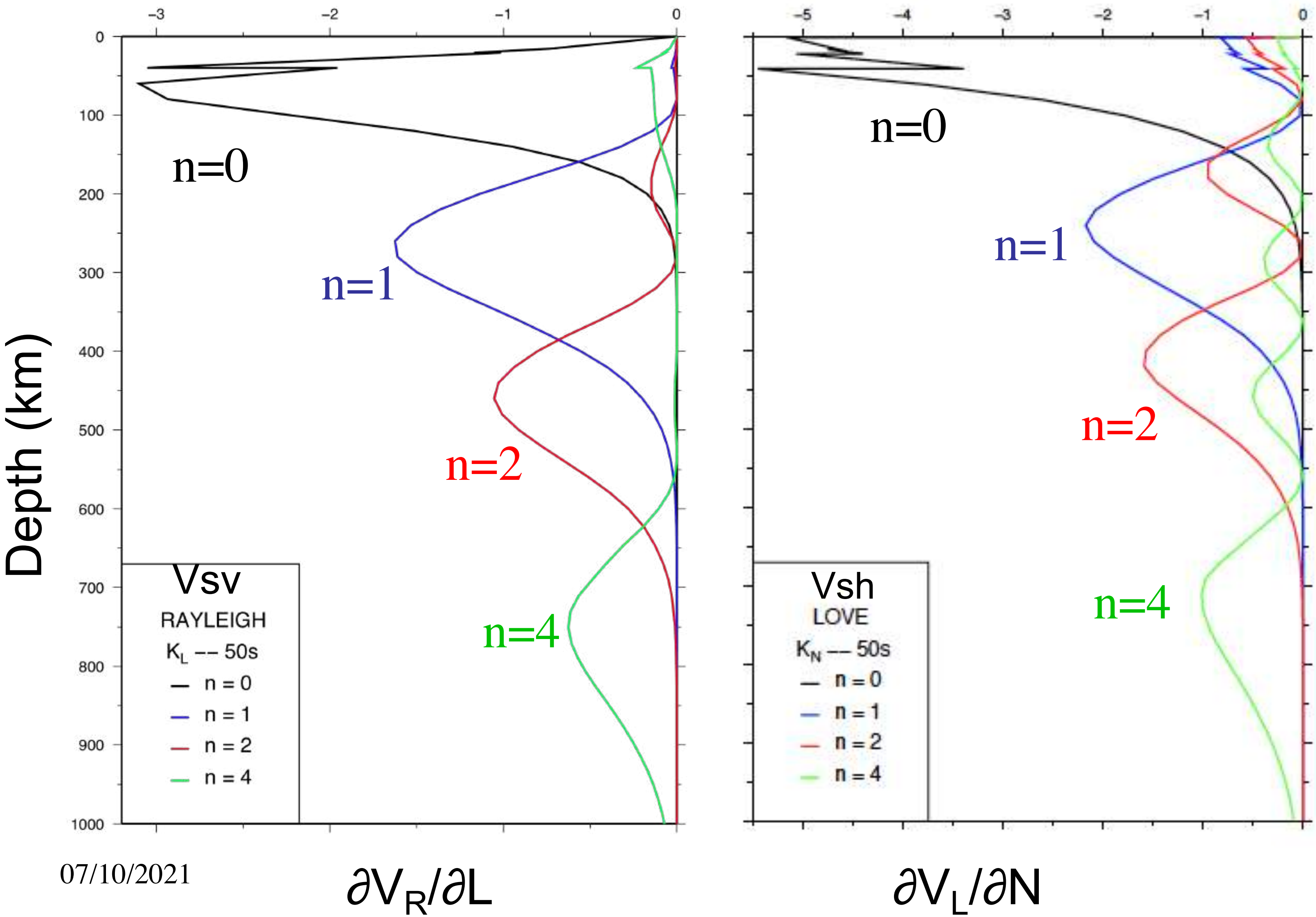


Synthetic seismogram
By normal mode
summation

Fundamental mode

Higher modes

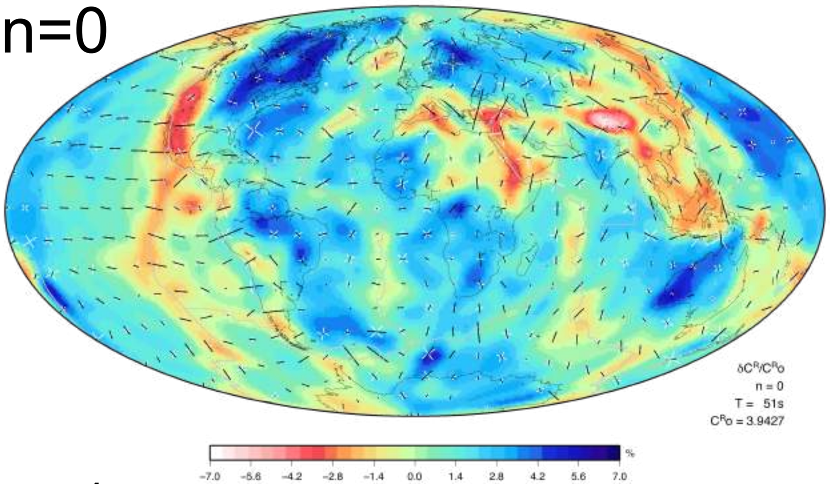
Fundamental - Higher modes: Depth Sensitivity Kernels
Rayleigh and Love waves



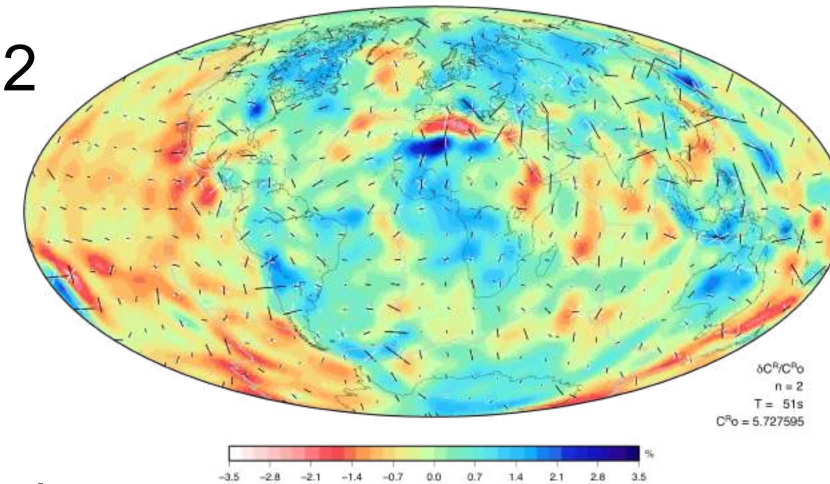
07/10/2021

Rayleigh wave phase velocity distribution for different higher modes (T=51s)

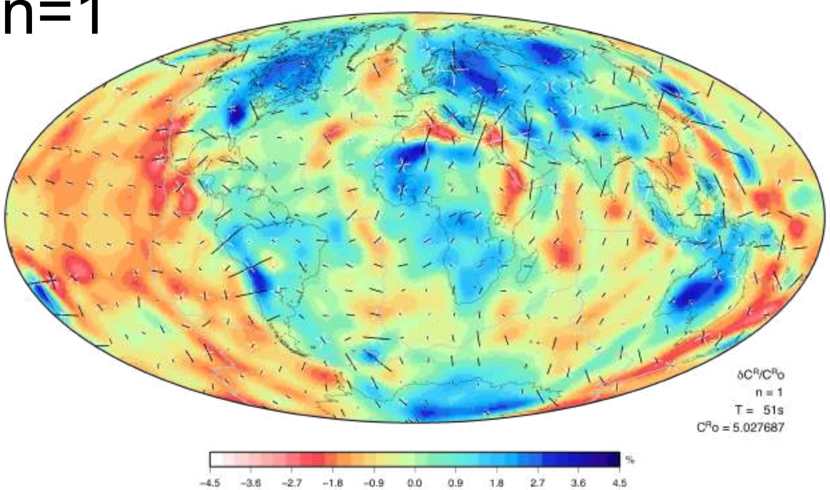
n=0



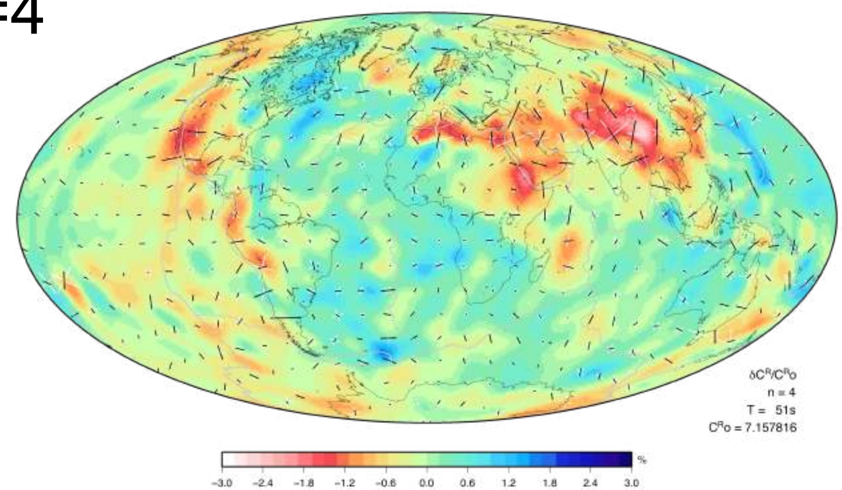
n=2

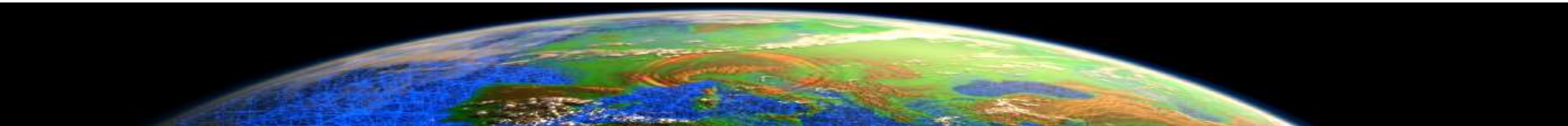


n=1



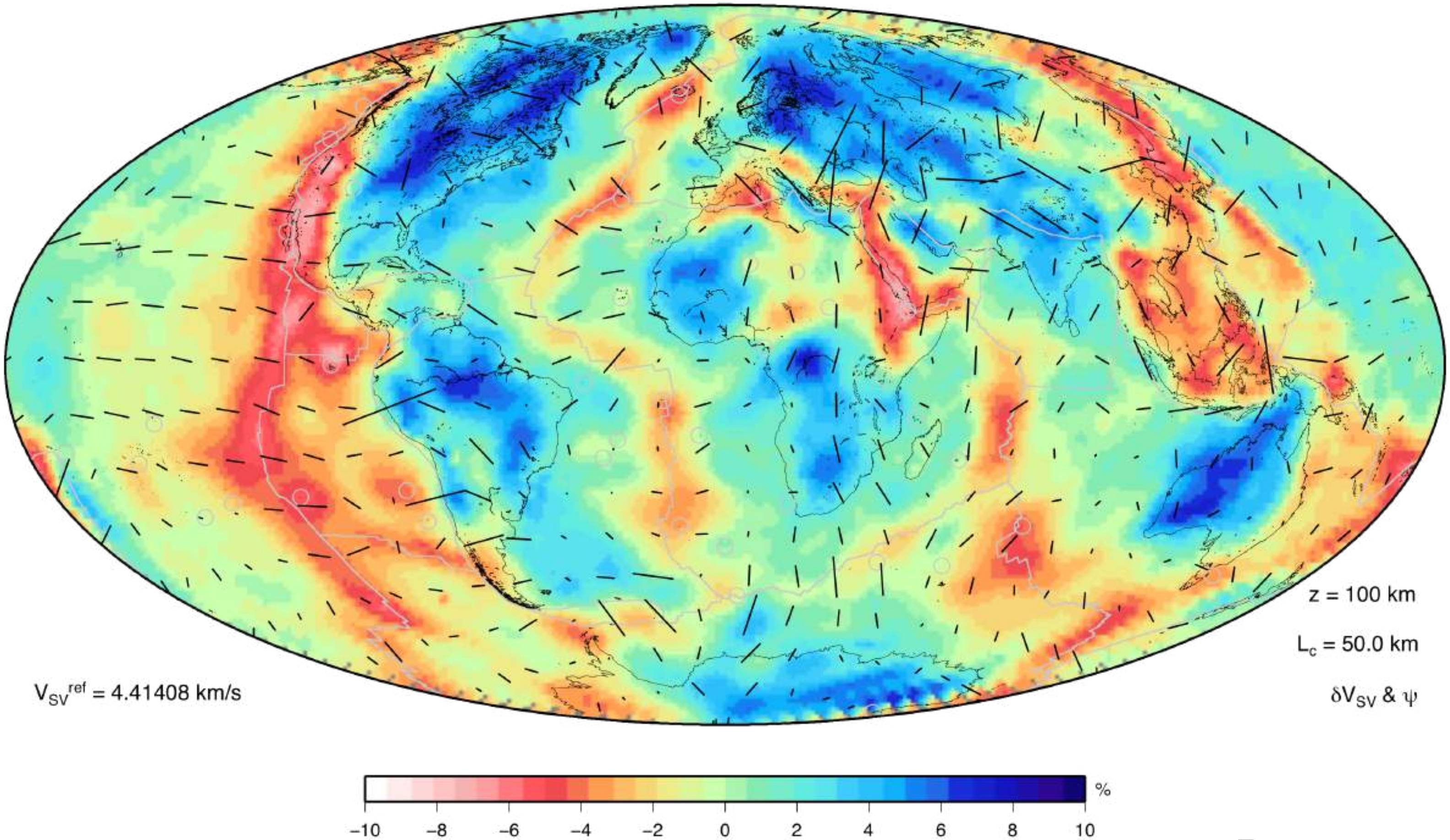
n=4



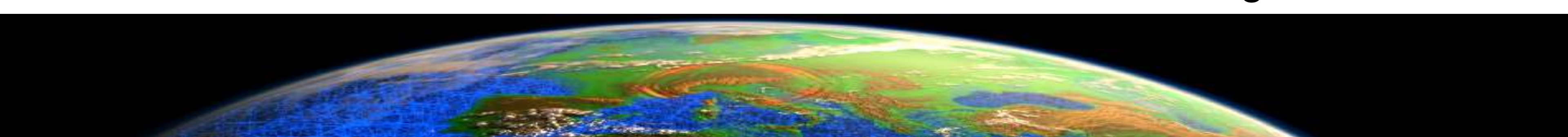


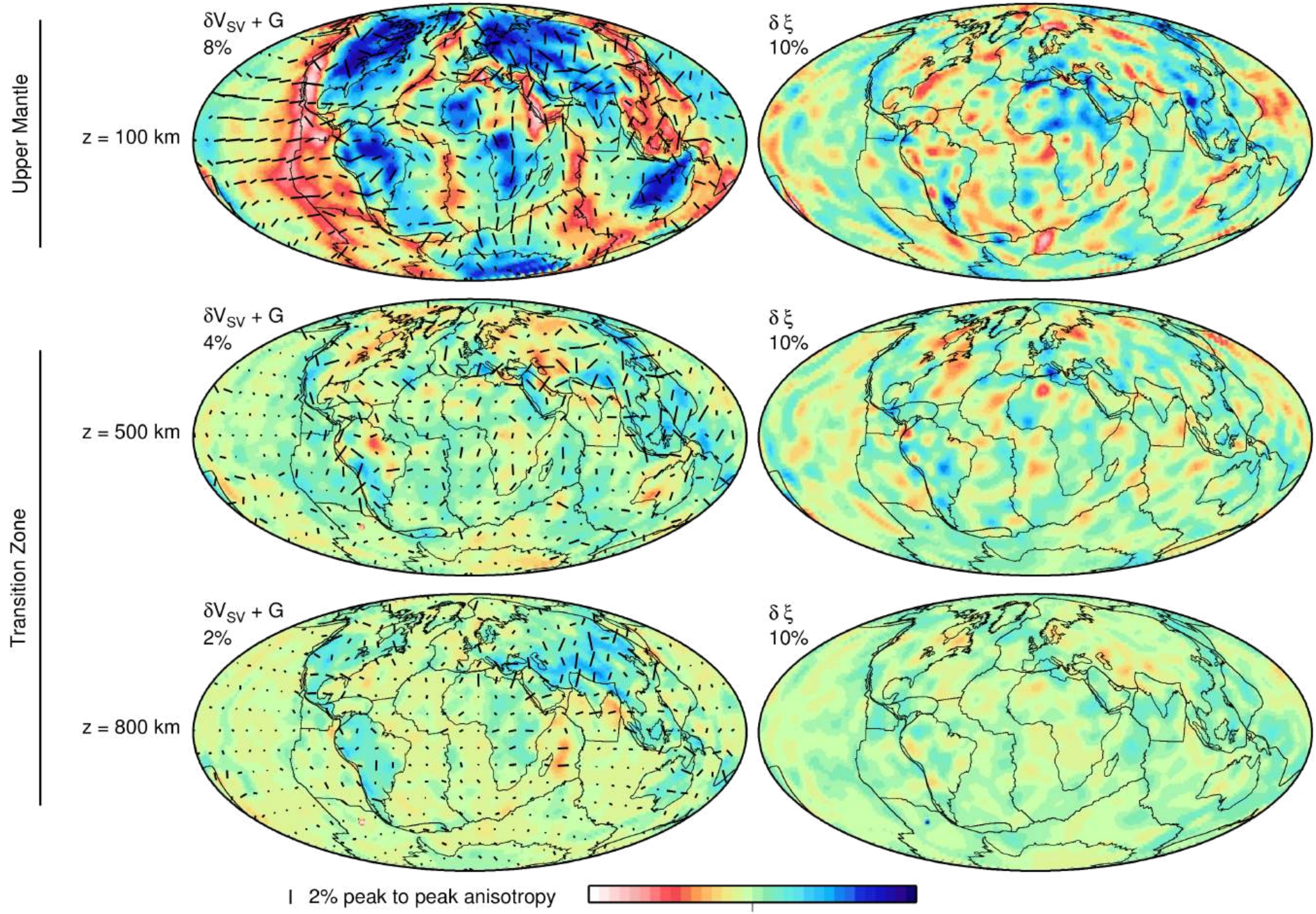
3D anisotropic model (radial + azimuthal anisotropy) in the upper 1500km of the mantle from the inversion of fundamental and higher modes (n={0,6})

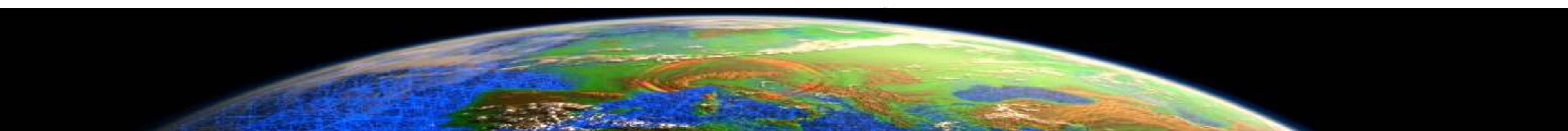
Depth=100km



Burgos et al., 2014



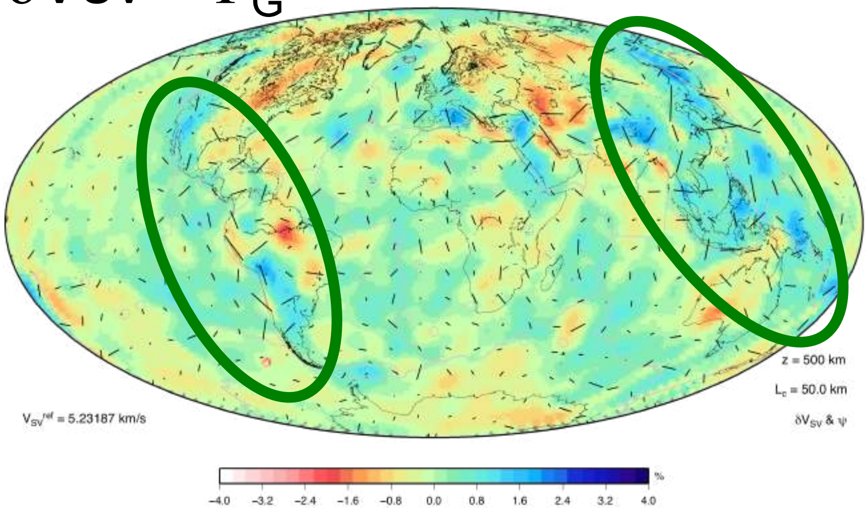

Upper Mantle
Transition Zone
z = 100 km
z = 500 km
z = 800 km
δV_{SV} + G
8%
δV_{SV} + G
4%
δV_{SV} + G
2%
δ ξ
10%
δ ξ
10%
δ ξ
10%
2% peak to peak anisotropy



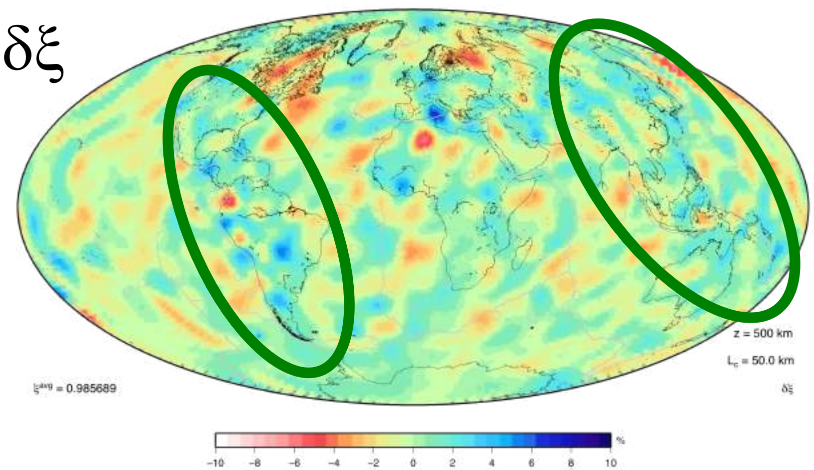
3D anisotropic model (radial + azimuthal anisotropy) in the upper 1500km of the mantle from the inversion of fundamental and higher modes (n={0,6})

Depth=500km

$\delta Vsv + \Psi_G$

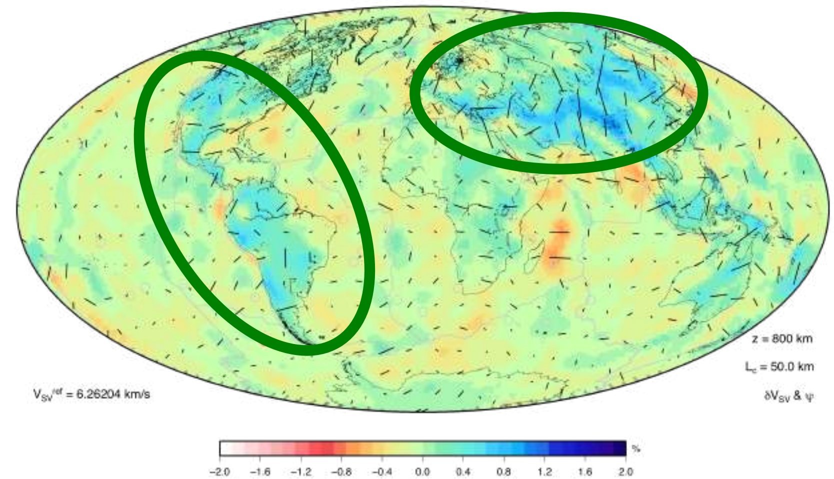


$\delta\xi$

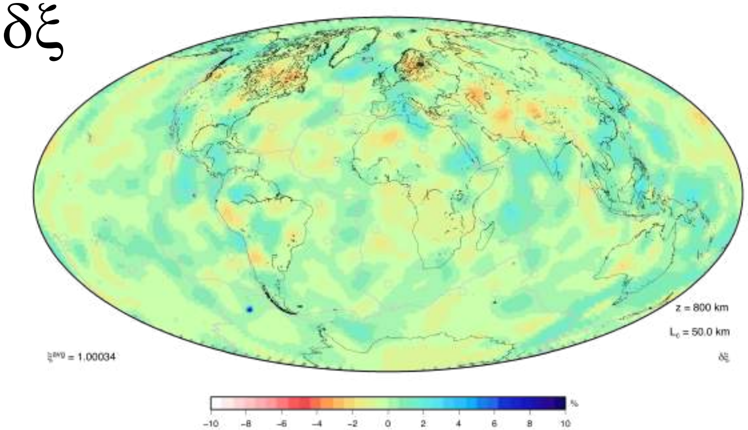


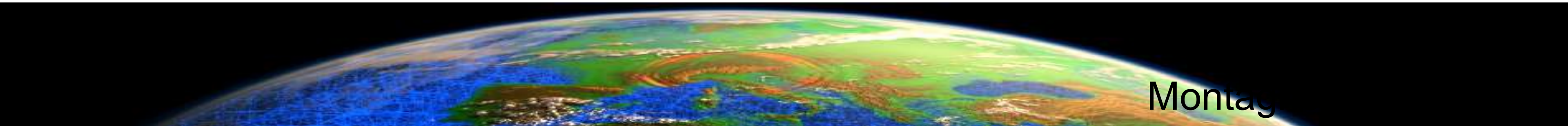
Depth=800km

$\delta Vsv + \Psi_G$



$\delta\xi$

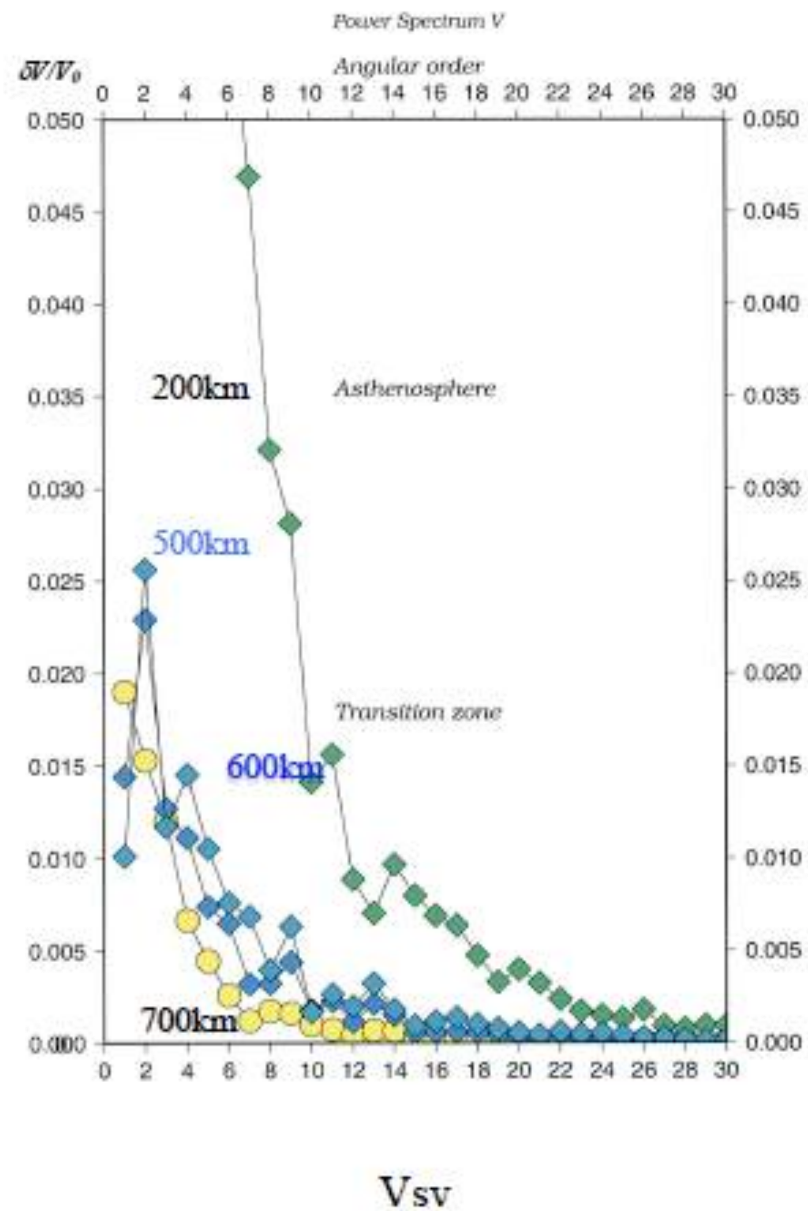


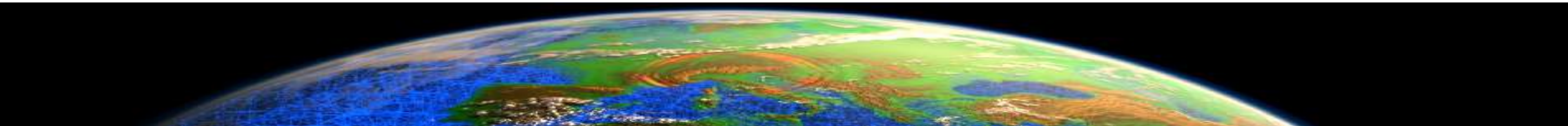


Power spectrum
of Vs velocity

Predominance
of degree 2
At 500 and 600km

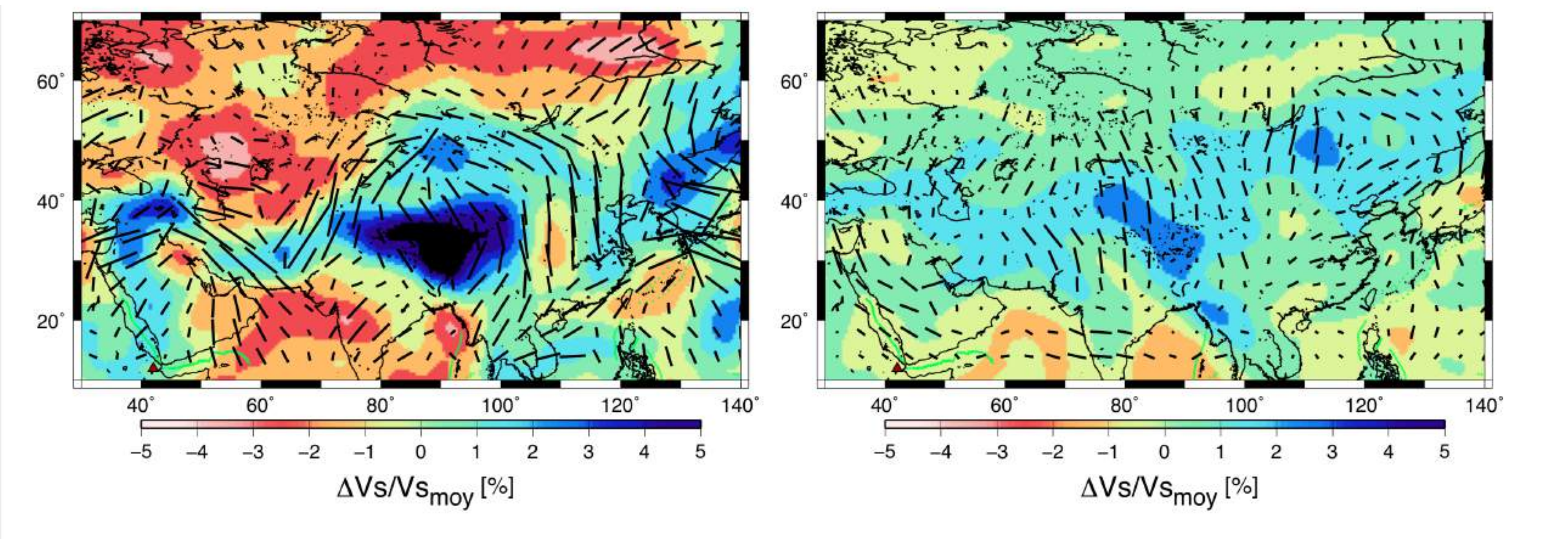
Degree 1 at 700km



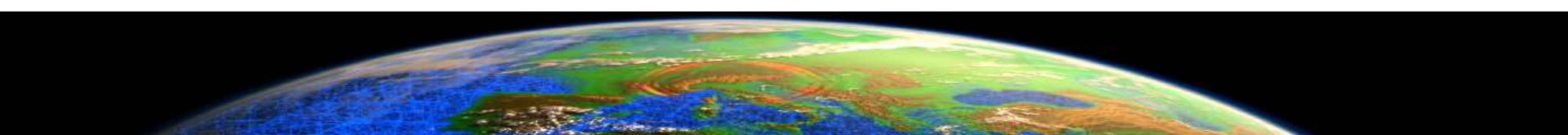


Change of orientation of azimuthal anisotropy beneath Eurasia between 500km and 800km

Depth=500km $\delta Vsv + \Psi_G$ Depth=800km



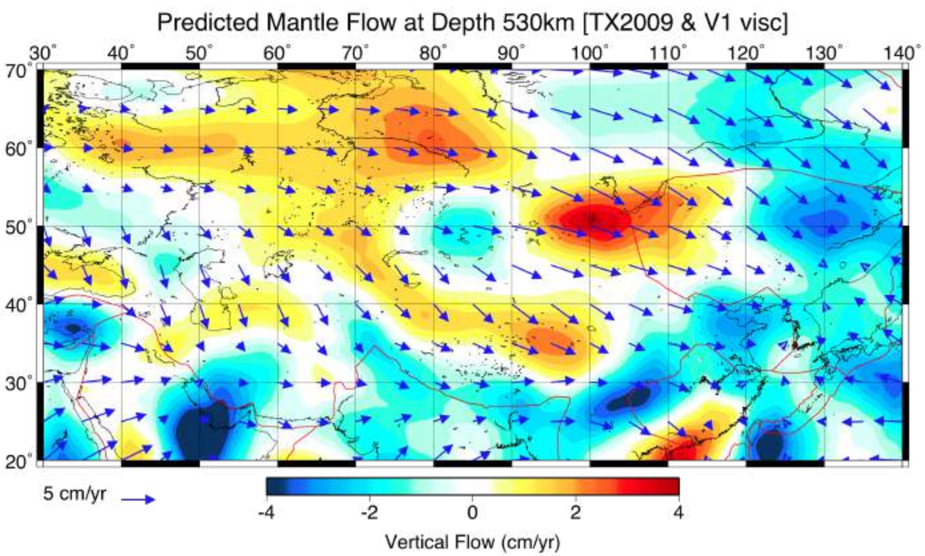
Interaction between Tethys and Izanagi subducting slabs

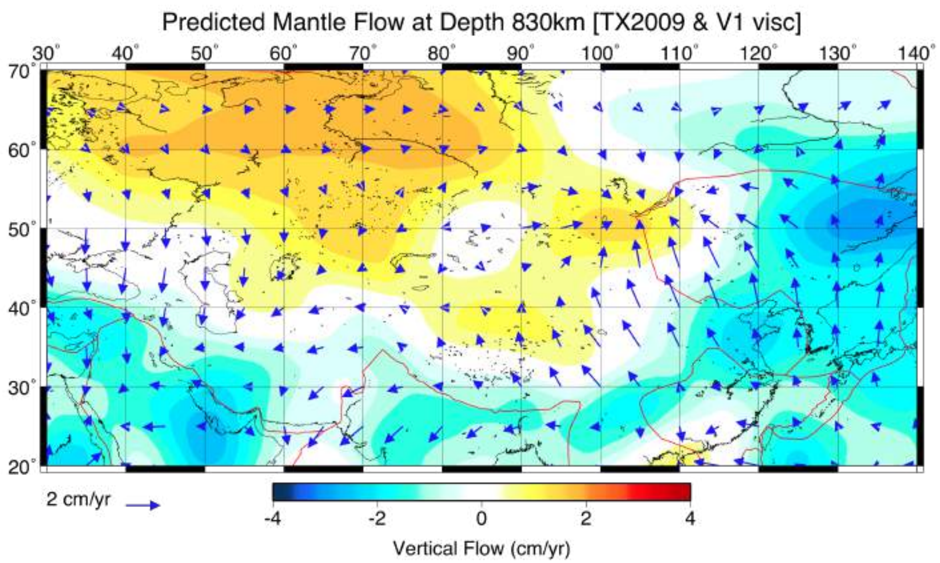


Mantle flow derived from geodynamic modeling

Depth=530km

Depth=830km

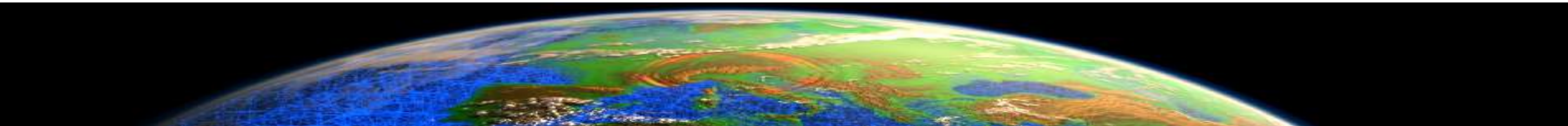




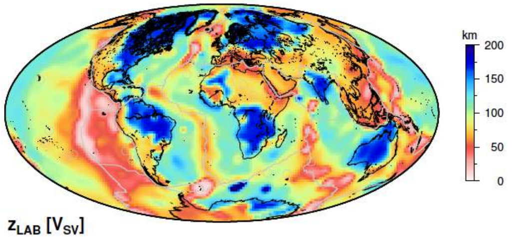
(Forte, Simmons, … 2009)

- Change of flow between upper and lower transition zones

- Mechanisms of CPO still uncertain

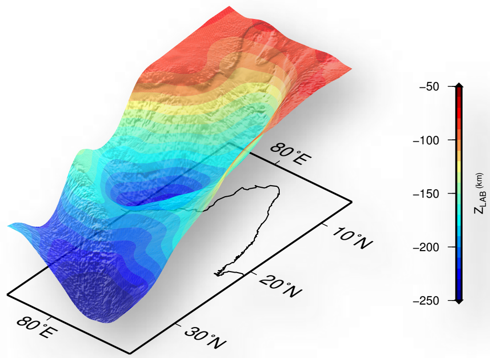


Conclusions



- Seismic Anisotropy can be mapped in different depth ranges

- Interpretation of seismic anisotropy is non-unique (intrinsic C.P.O. versus extrinsic anisotropy)



- Seismic anisotropy enables to gain insight into oceanic and continental structures (MLD, LAB)

- Seismic anisotropy detected in the mantle transition zone, but not everywhere (subduction zones, Eurasia).