Oceanic and continental plates as seen by seismic anisotropy

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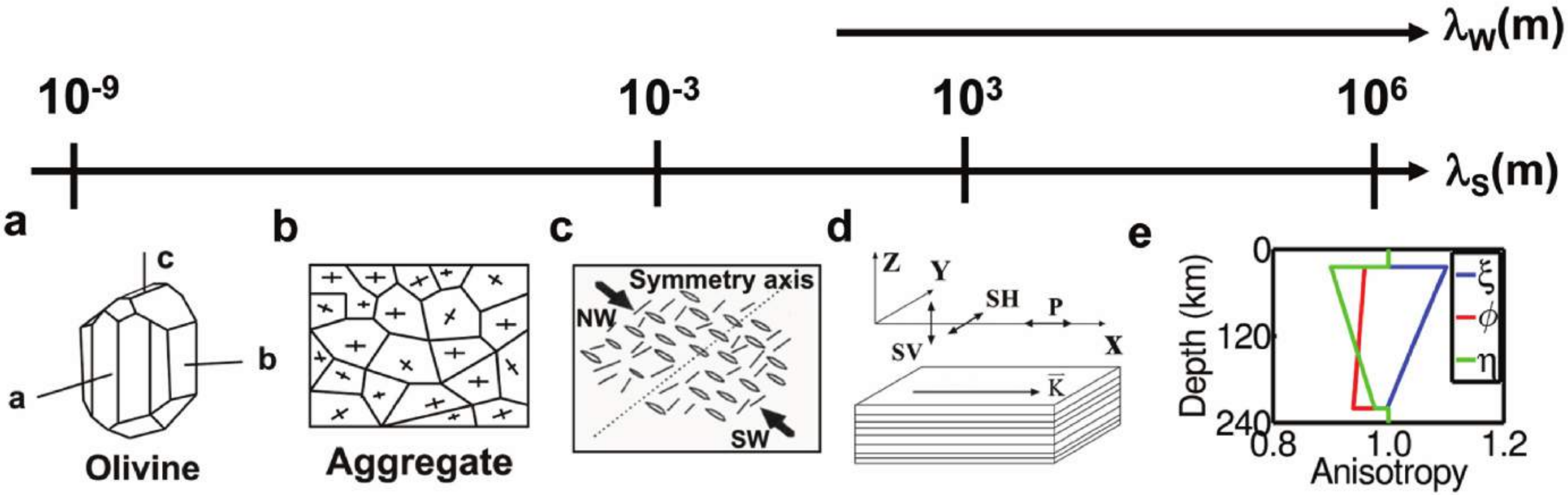
OUTLINE

- What is a plate? Role of continents?
  Surface manifestation of mantle convection,
  role of mantle plumes, slabs?
- Seismic Anisotropy: many processes, different interpretations
- 3D- anisotropic structure of the Earth
  Lithosphere- Asthenosphere Boundary (LAB)
    - Oceans (Burgos et al., 2014)
    - Continents: Indian Continent (Maurya et al., 2016)

Seismic Anisotropy at all scales



PREM

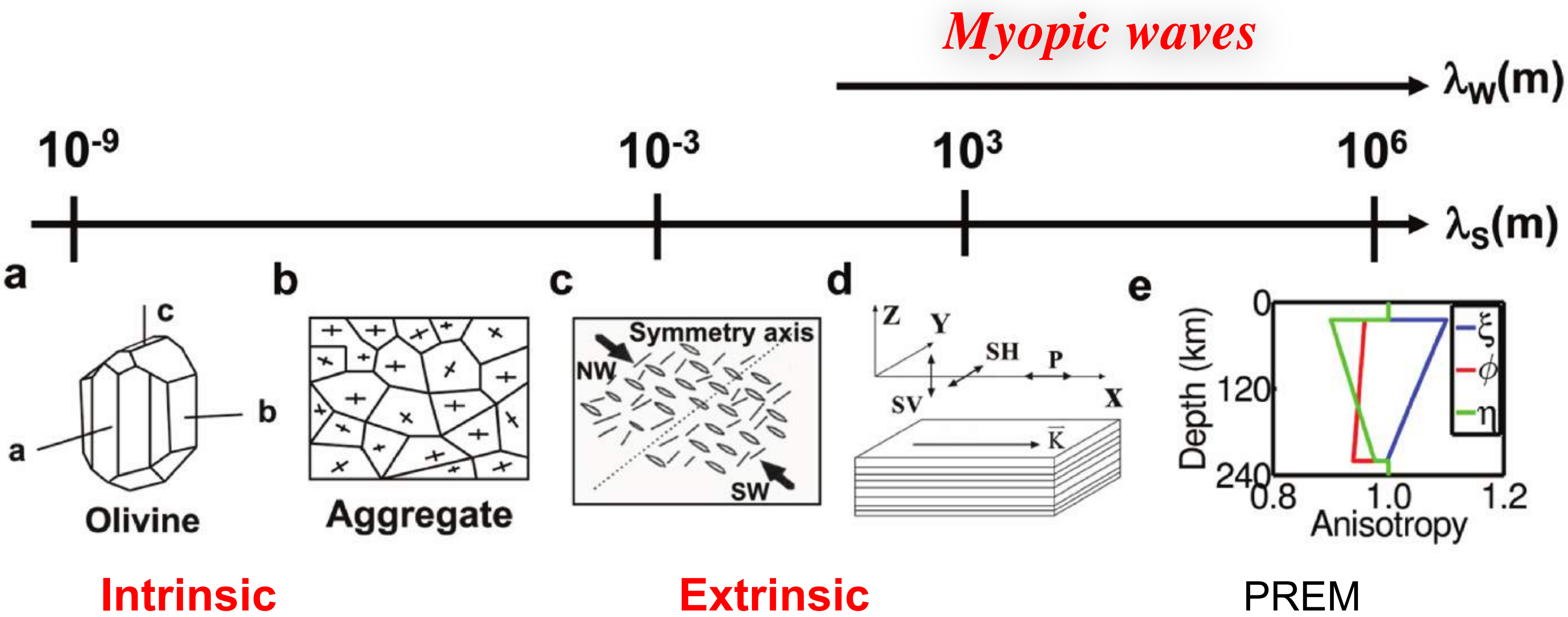
PREM: radial anisotropy: up to 10%

λ_W seismic wavelength

λ_S spatial scale

(Wang et al., 2013)

Seismic Anisotropy at all scales

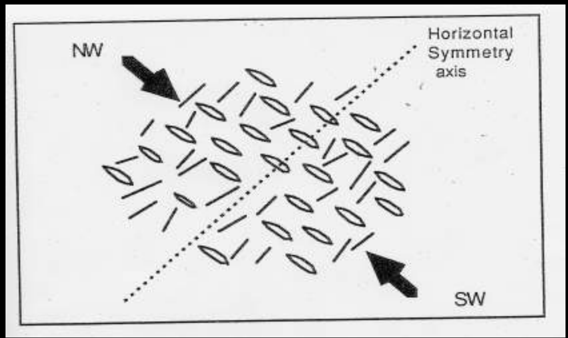


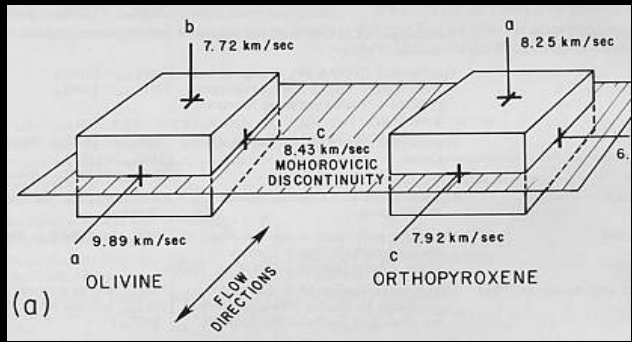
Observed (apparent) anisotropy

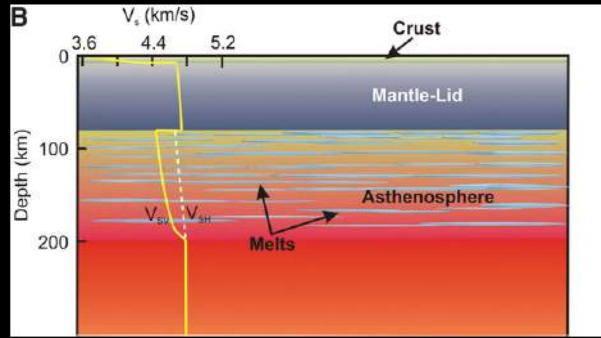
Intrinsic versus Extrinsic anisotropy

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

Different processes in different layers
-S.P.O. (stress) -L.P.O.(strain) Fine Layering







- *Mineralogy, Water and fluid content, layering*
- *Present day tectonics, geodynamic processes*
- *Mantle Convection*
- *Past processes (frozen anisotropy)*

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

Effect on eigenfrequency ω_k for multiplet k={n,l,m} (Rayleigh's principle)

$$\frac{\delta\omega_k}{\omega_k} = \frac{\int_\Omega \varepsilon_{ij}^* \, \delta\mathcal{C}_{ijkl} \, \varepsilon_{kl} \, d\Omega}{\int_\Omega \rho_0 \, u_r^* \, u_r \, d\Omega} = \left.\frac{\delta V}{V}\right|_k$$

ε strain tensor, u displacement, $\delta\mathcal{C}_{ijkl}$ elastic tensor perturbation,

V phase velocity (V_R Rayleigh; V_L Love)

Phase velocity pertubation $\boldsymbol{\delta V(T,\theta,\phi,\Psi)}$ at point r (θ,ϕ)

(Smith & Dahlen, 1973; Montagner & Nataf, 1986)

ΨAzimuth (angle between North and wave vector)

Azimuthal Terms: ***0-ψ, 2-ψ, 4-ψ***

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

- *Cijkl 21 elastic moduli*
- α_0 *= 0-ψ 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 2ψ−, 4ψ− terms)*

$L = \rho V_{SV}^2$ *Isotropic part of* V_{SV} *or* $\mu_{iso} \approx (2L+N)/3$

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

G, Ψ_G ***Azimuthal Anisotropy*** *of* V_{SV} *, also related to SKS splitting*

Geodynamic Interpretation: LPO

Tomographies of:

-S- Velocity

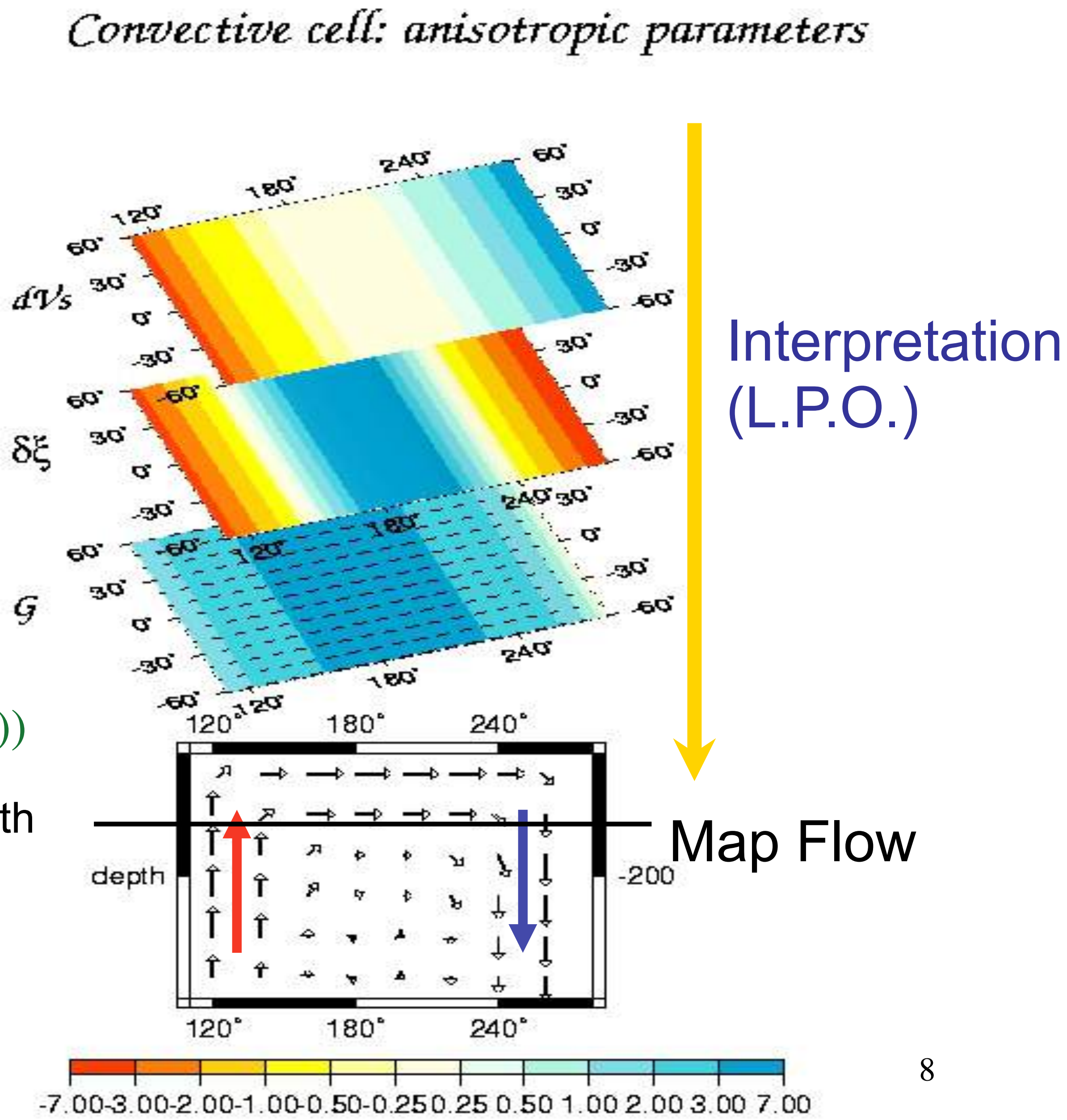
-Radial Anisotropy

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

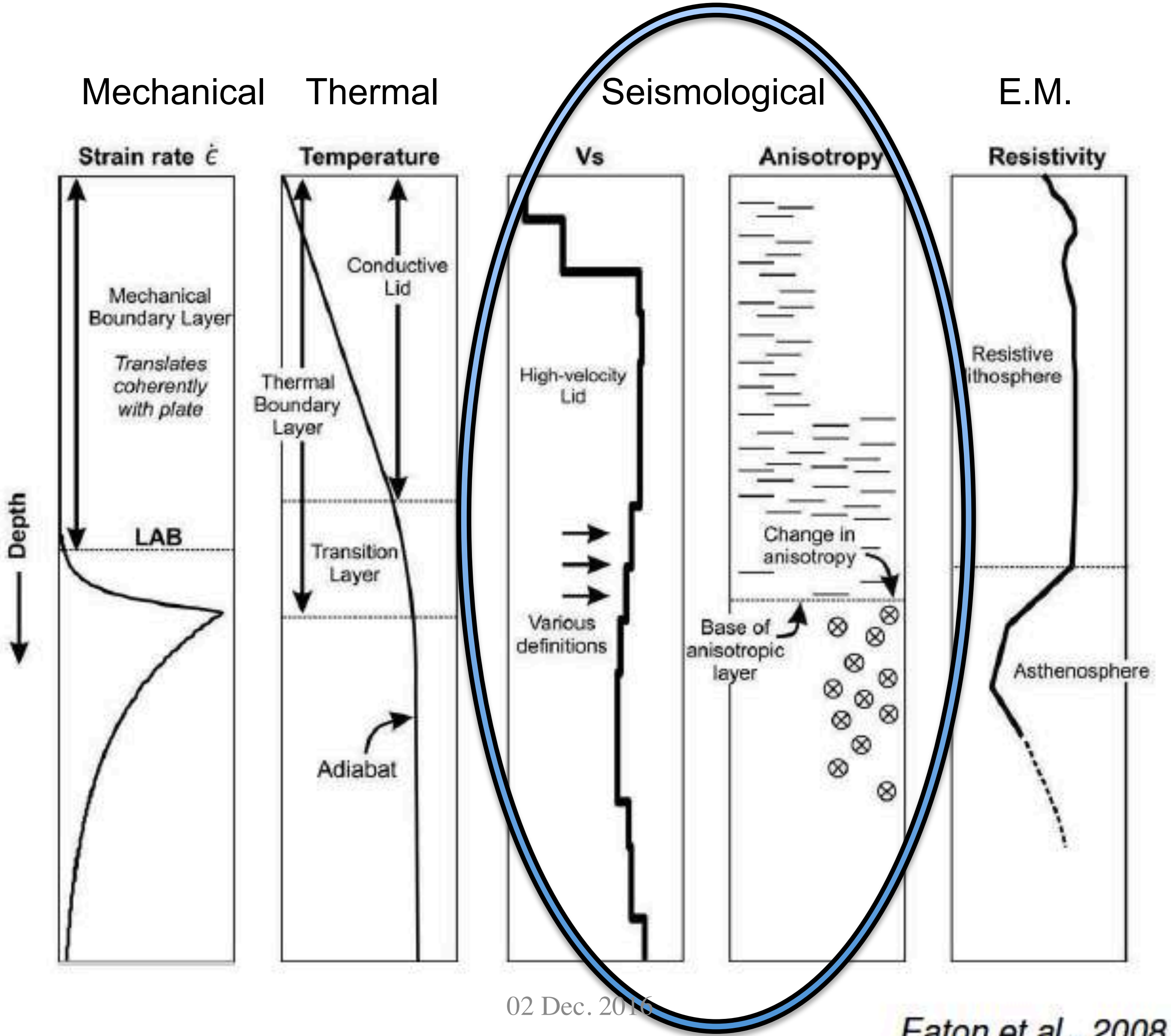
-Azimuthal Anisotropy

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

At a given depth



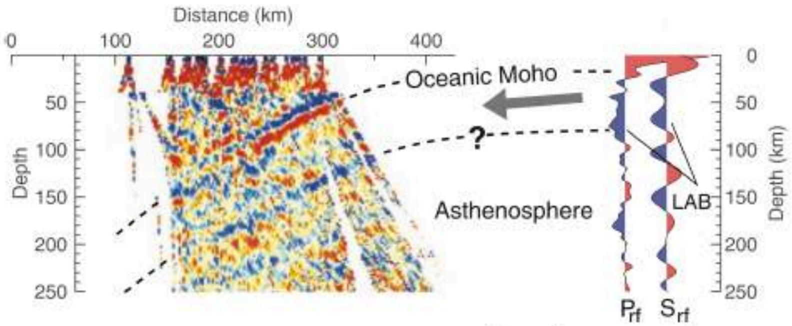
L.A.B.: Lithosphere-Asthenosphere Boundary
(many different approaches and definitions)



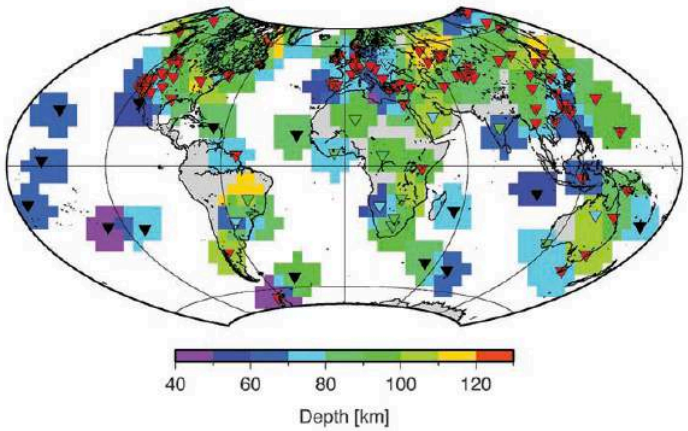
Eaton et al., 2008

LAB : from seismic data

Receiver functions

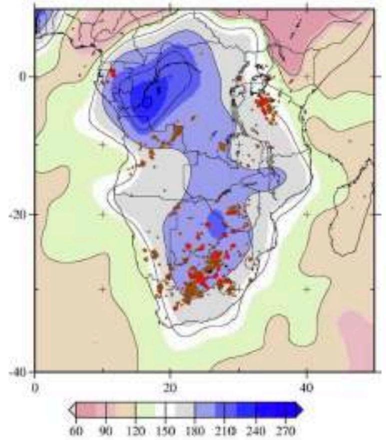


Kawakatsu et al., 2009

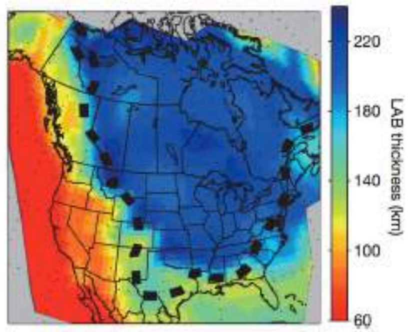


Rychert & Shearer, 2009

Surface waves



Fishwick, 2010



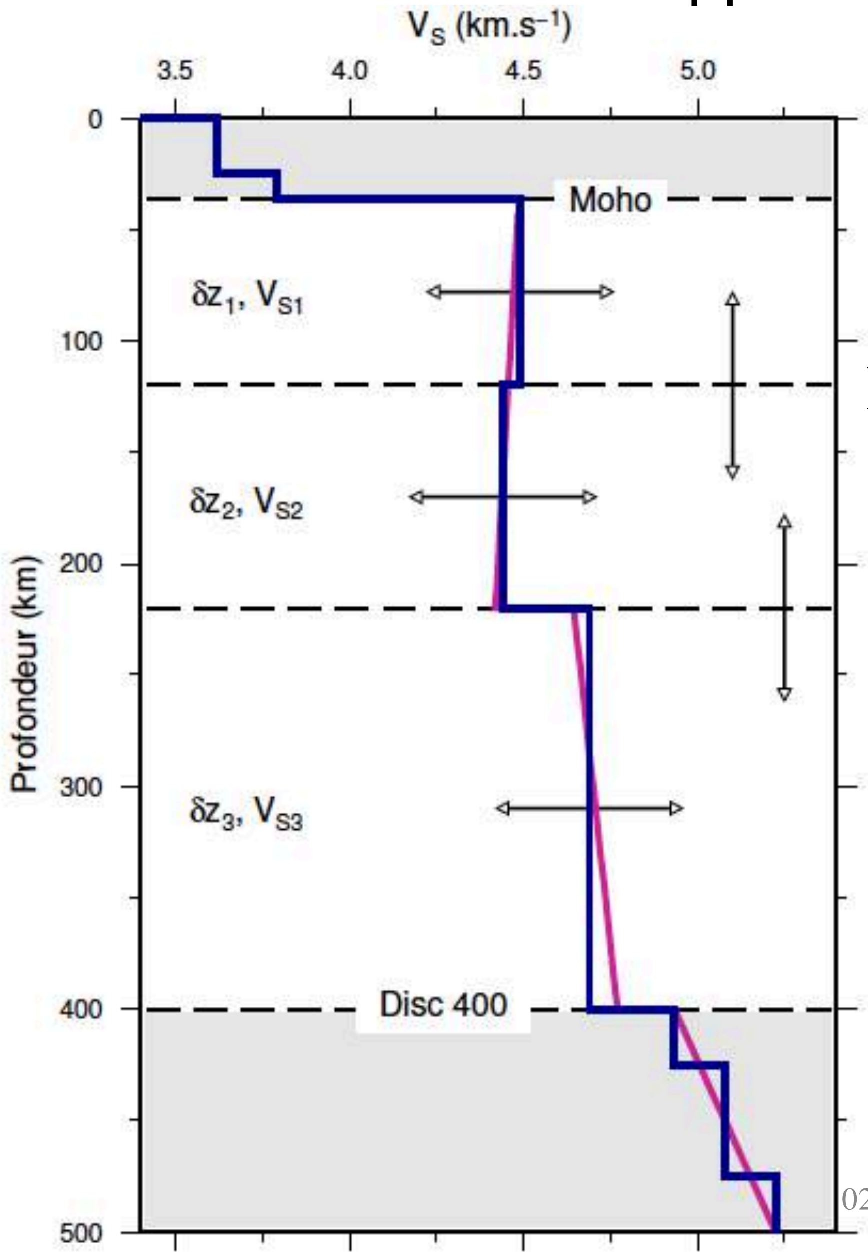
+SKS *Yuan & Romanowicz, 2010*

Much discrepancy between different estimates:
Global surface wave tomographies give 200-250km depth for continental roots

Mid-lithospheric Discontinuity (Yuan & Romanowicz, 2010)

From Surface wave dispersion

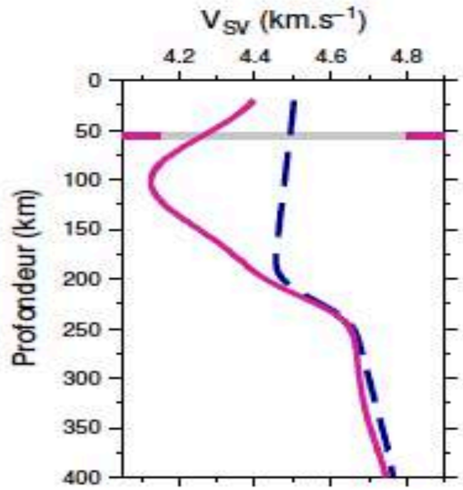
Statistical Monte-Carlo Approach

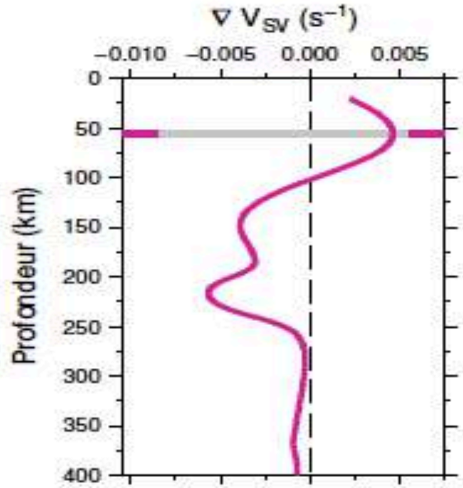


LAB

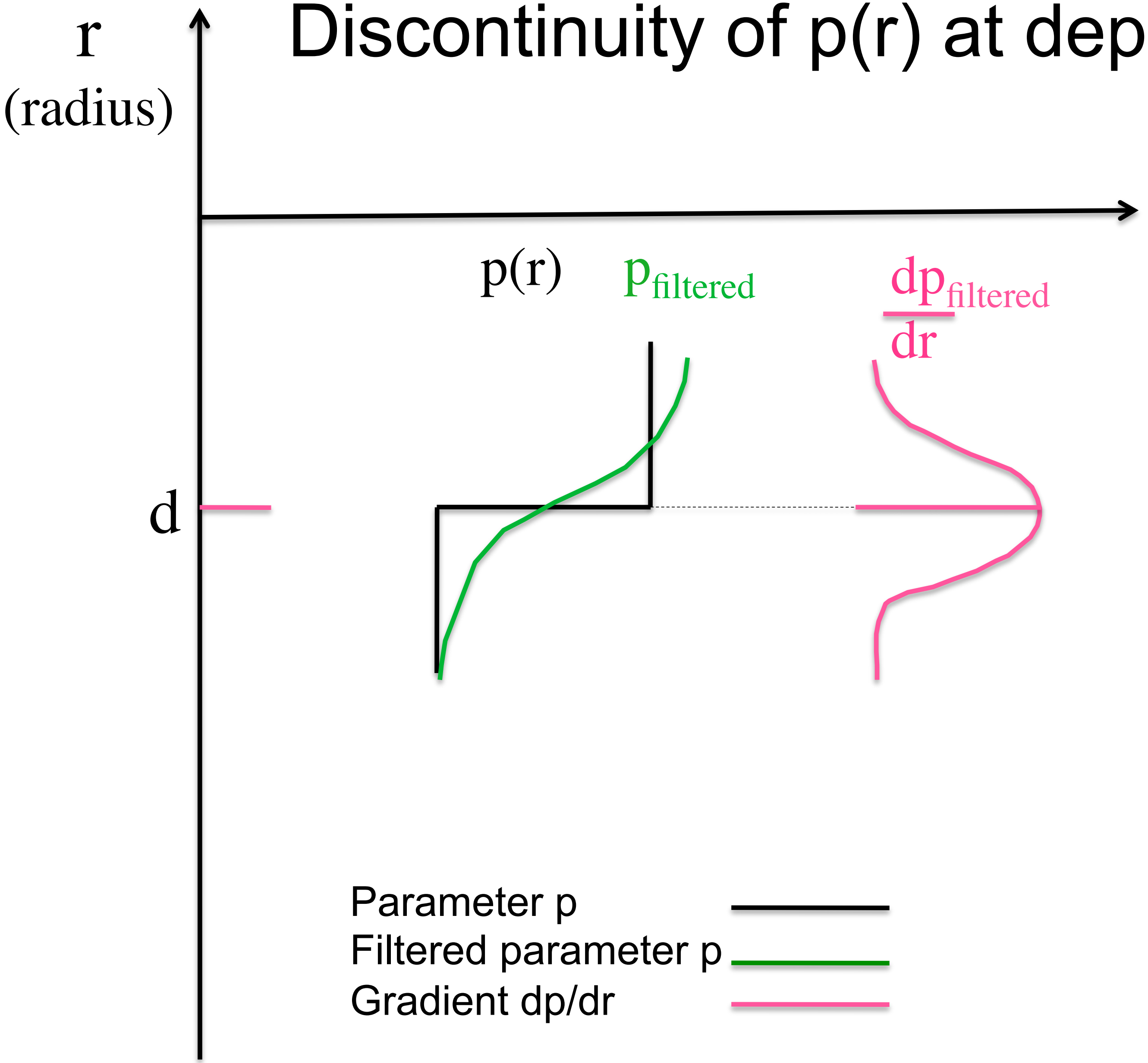
First order Perturbation theory

Proxy from parameter Vsv





Discontinuity of p(r) at depth d

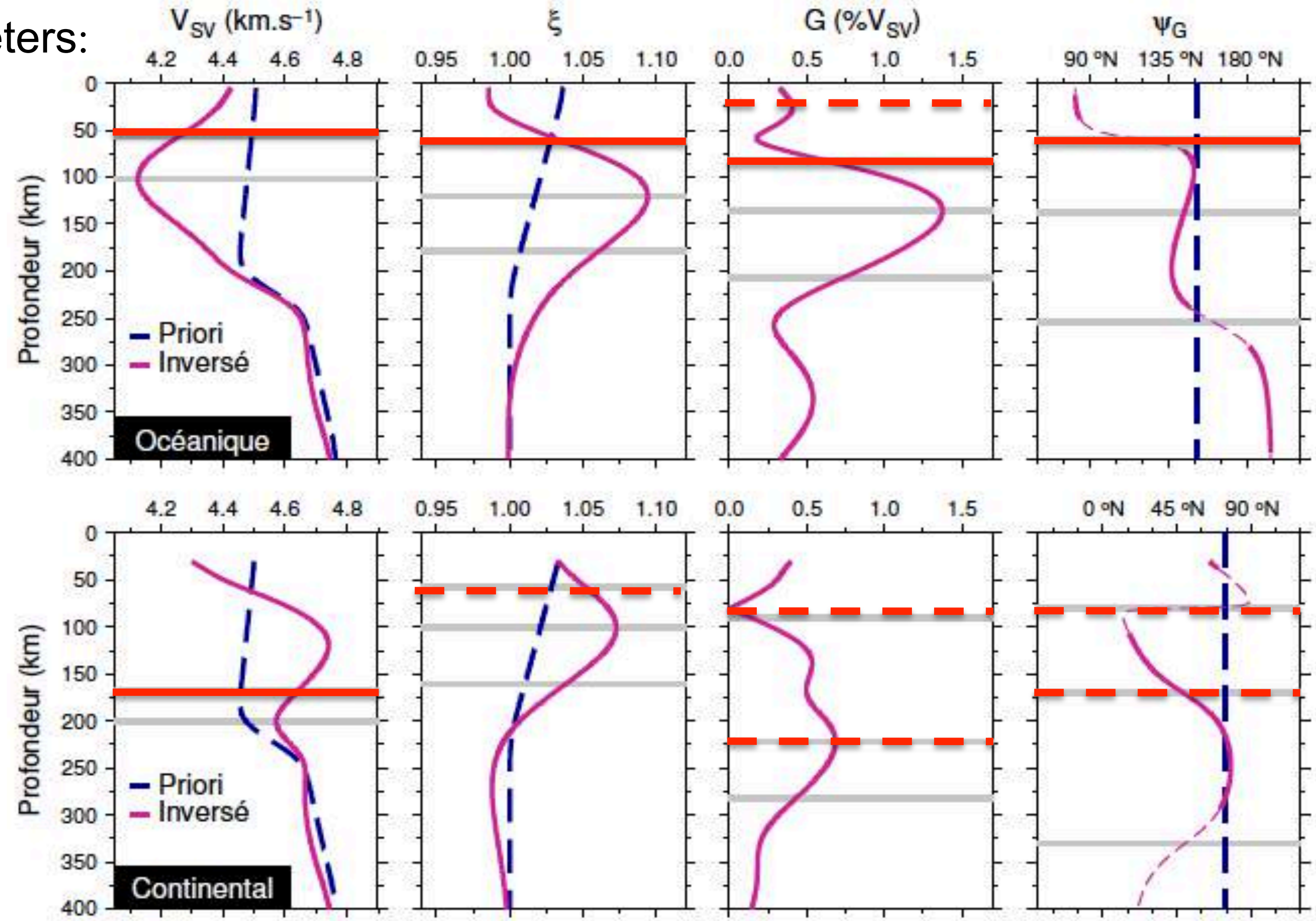


Other proxies from parameters obtained from anisotropy tomographic models

Well resolved parameters:
V_{SV} S-wave velocity
ξ, radial anisotropy
G, Ψ_G S-wave azimuthal anisotropy

Oceanic profile
λ=35°, ϕ=-35°

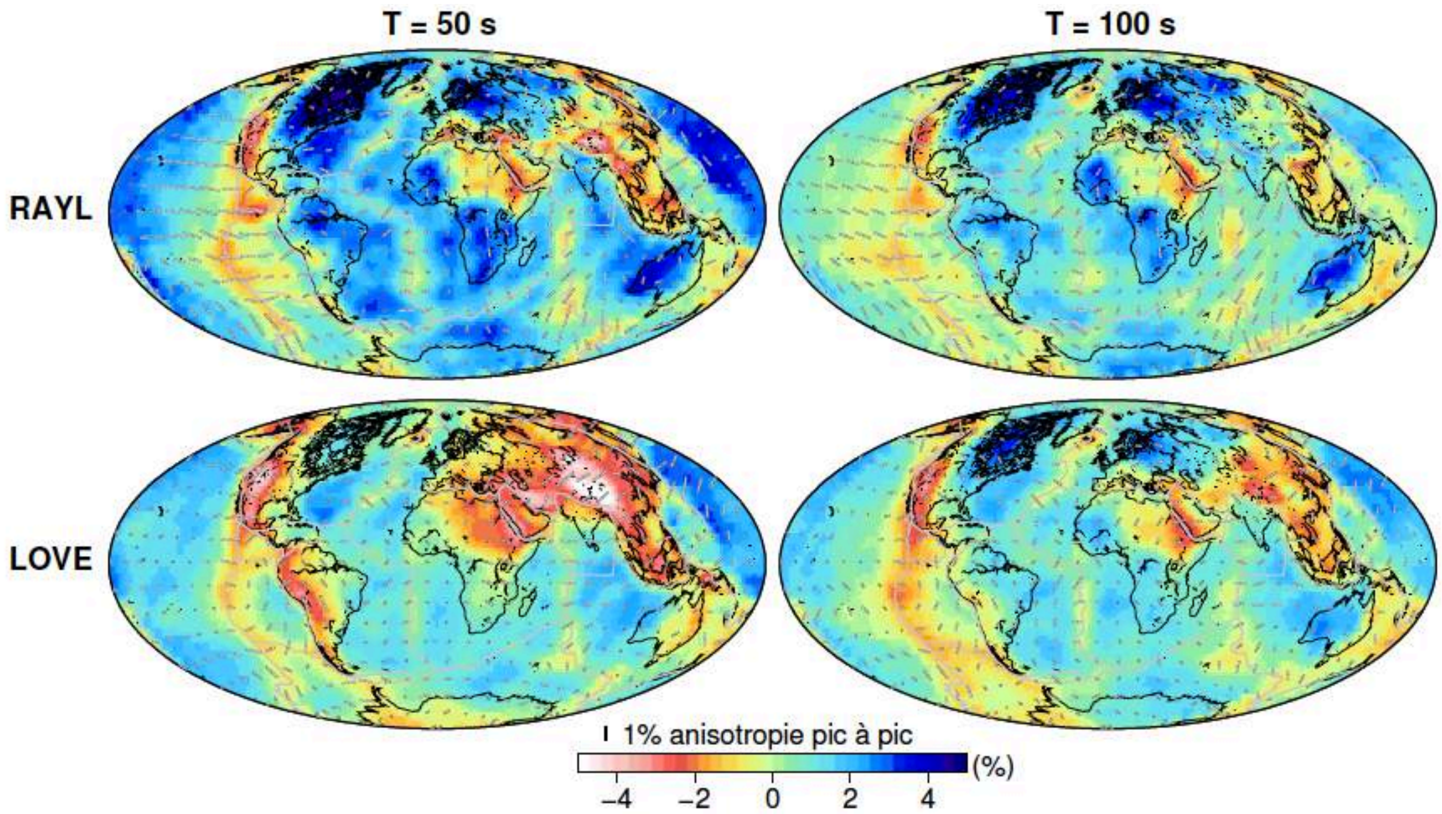
Continental profile
λ=63°, ϕ=-96°



Collection of surface wave dispersion data (IPGP, Harvard, Utrecht, Boulder)

First step: Regionalization =>local dispersion velocity $V(T, \theta, \phi, \psi)$

Rayleigh phase velocity and azimuthal anisotropy



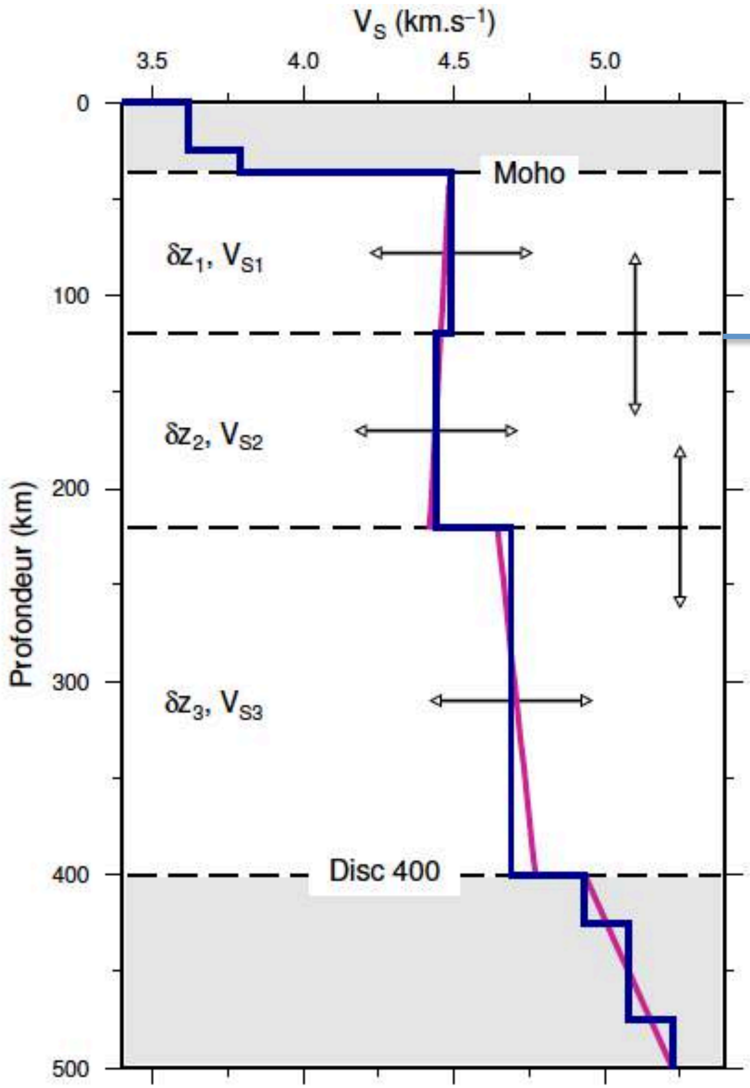
Second step: Inversion at depth

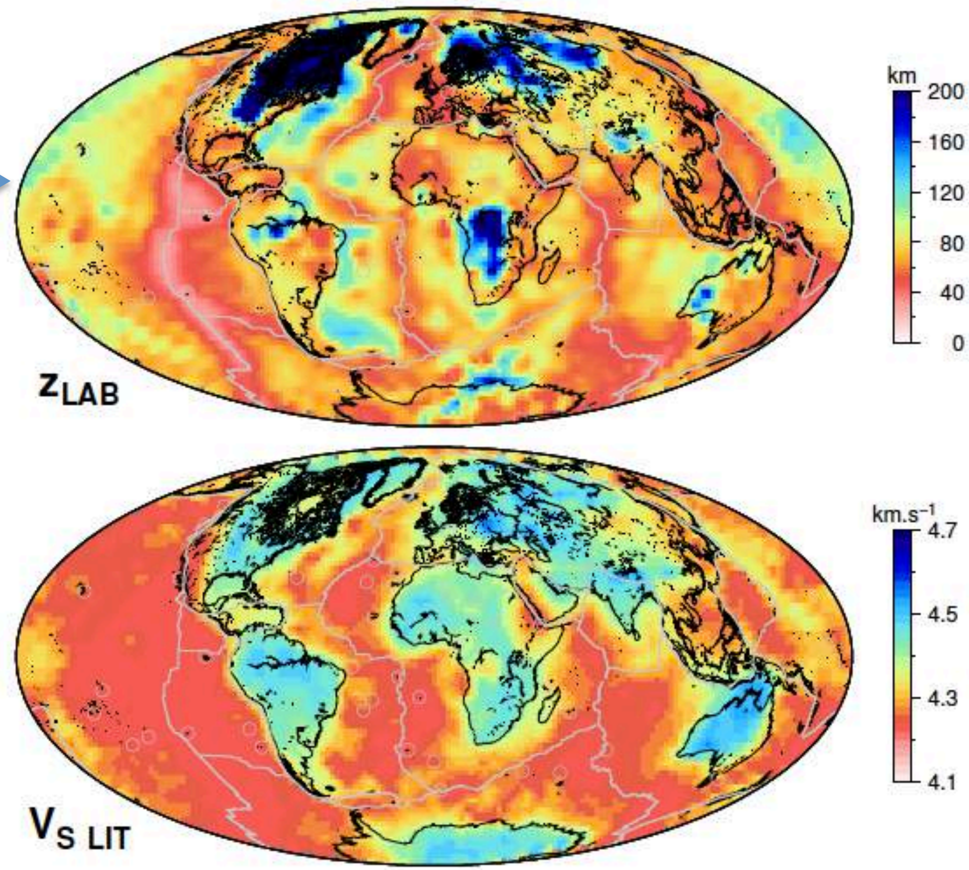
Statistical Monte-Carlo Inversion

First order Perturbation Theory

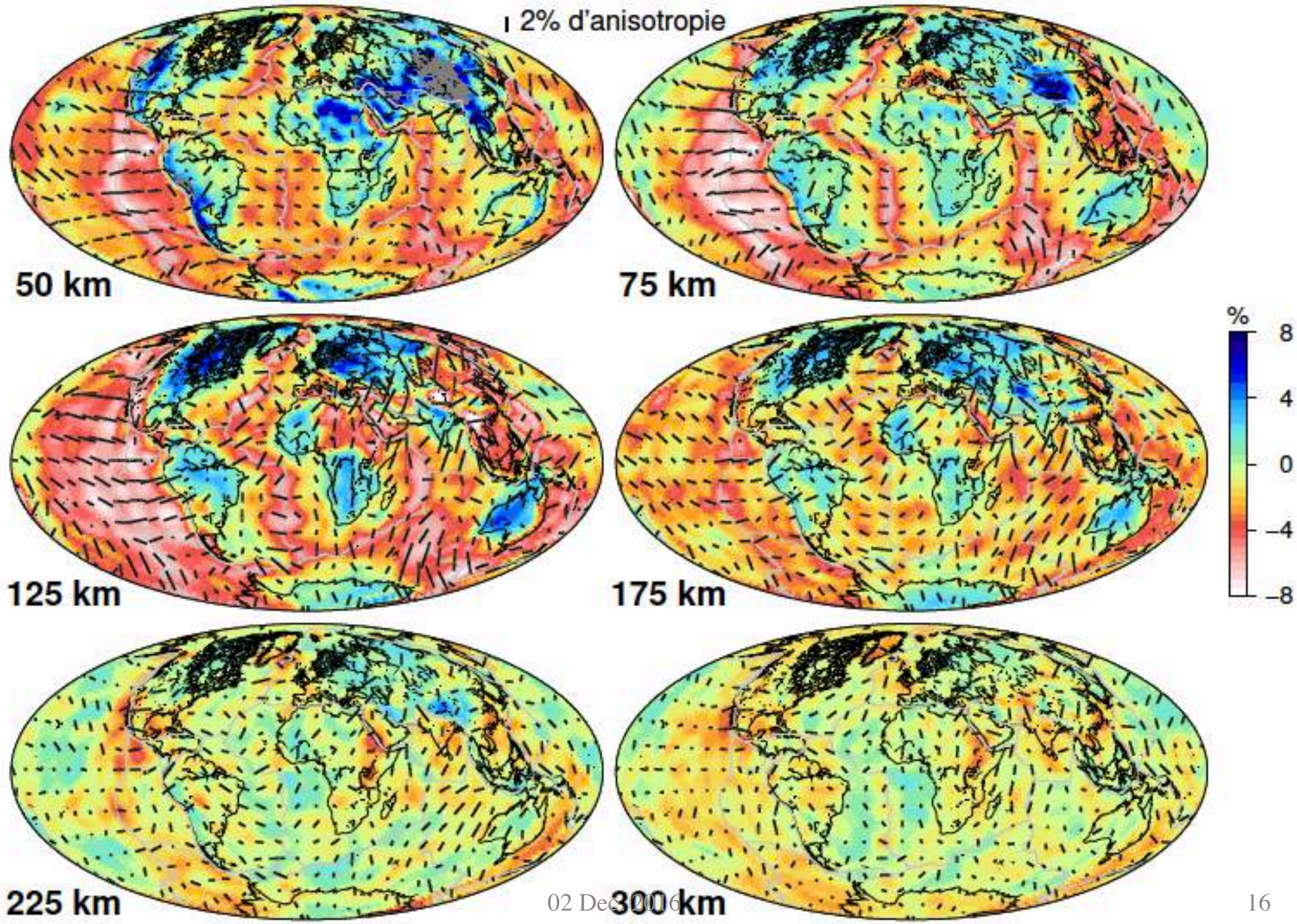
LAB: Statistical M.C. Isotropic Inversion

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

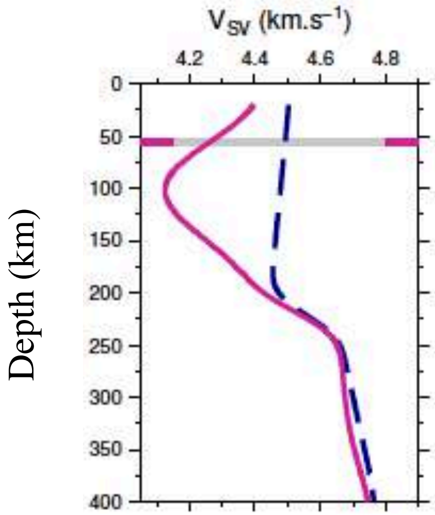


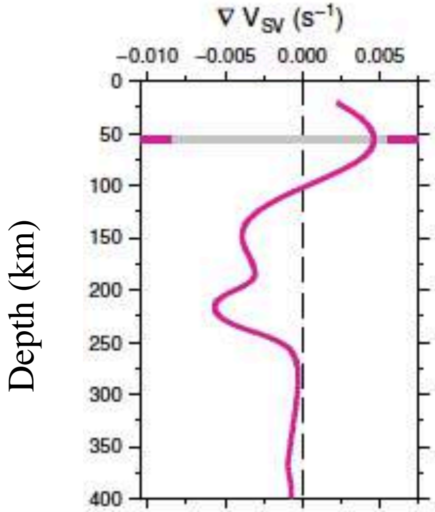


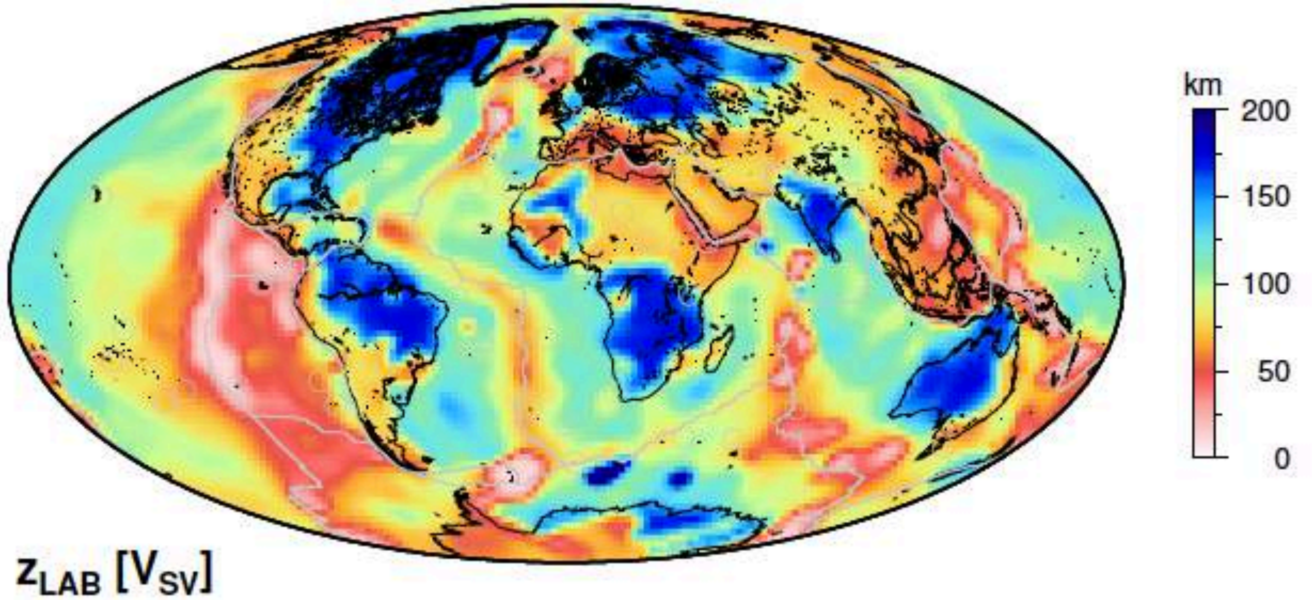
First order perturbation Theory => depth distribution of Vsv, G (and ξ)



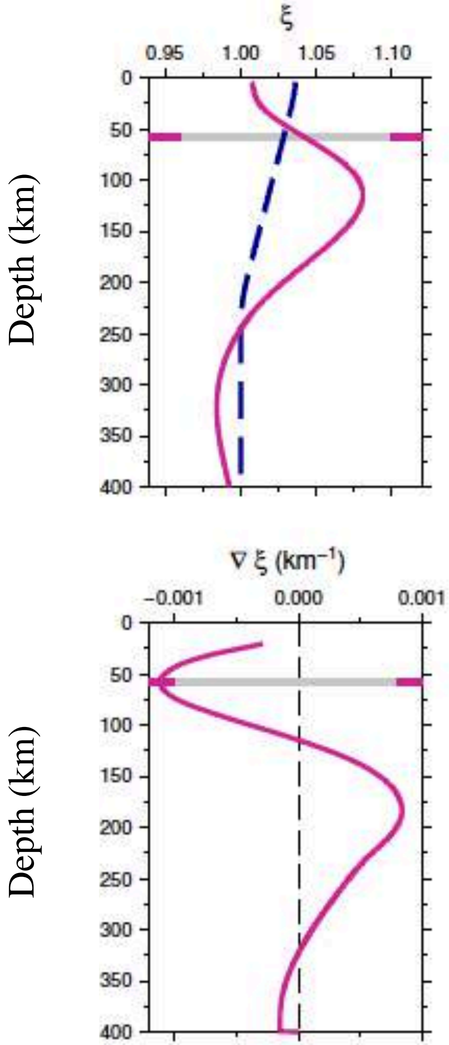
LAB from the gradient of VSV parameter

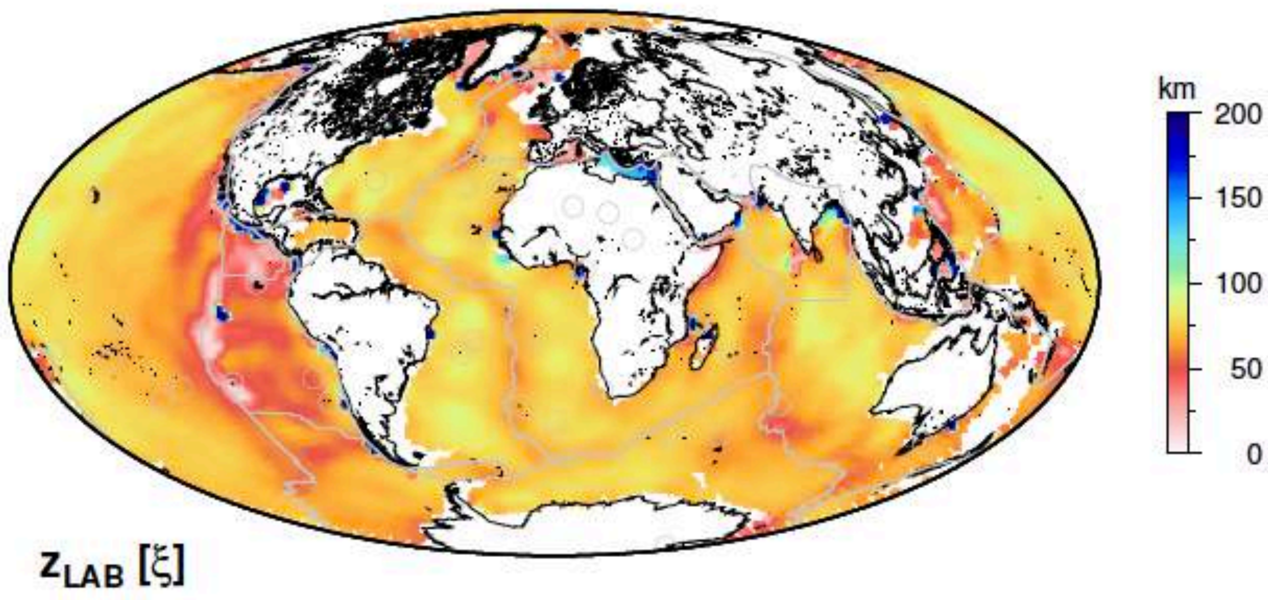




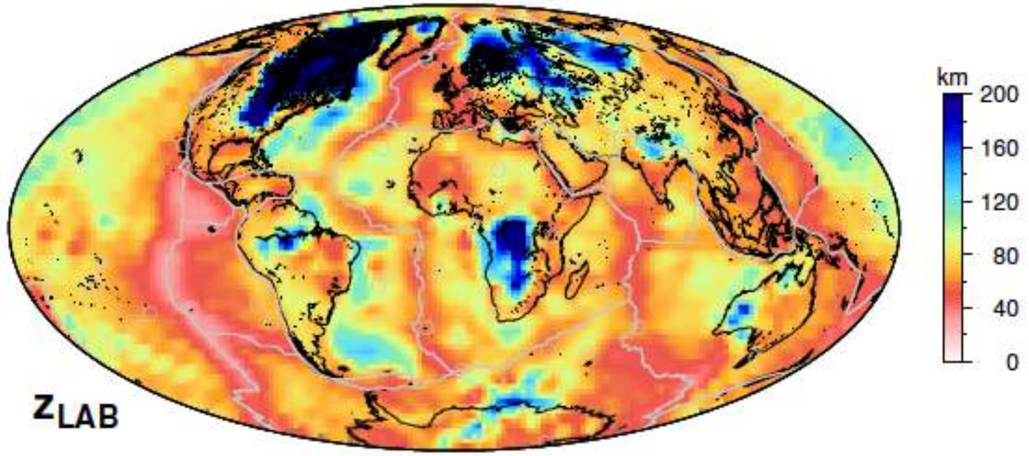


LAB from the gradient of ξ parameter (only oceans)
Radial anisotropy $\xi = (V_{SH}/V_{SV})^2$

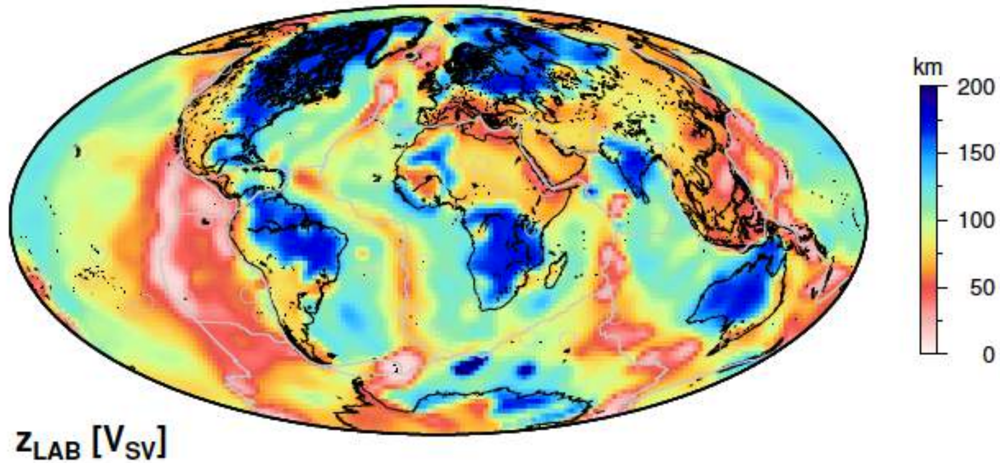




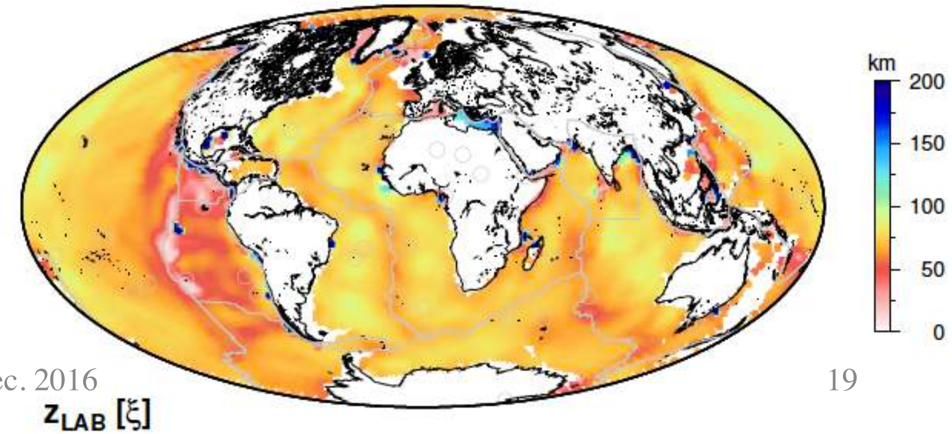
Statistical MC Isotropic Inversion



Vsv proxy (1st order Perturbation Theory)

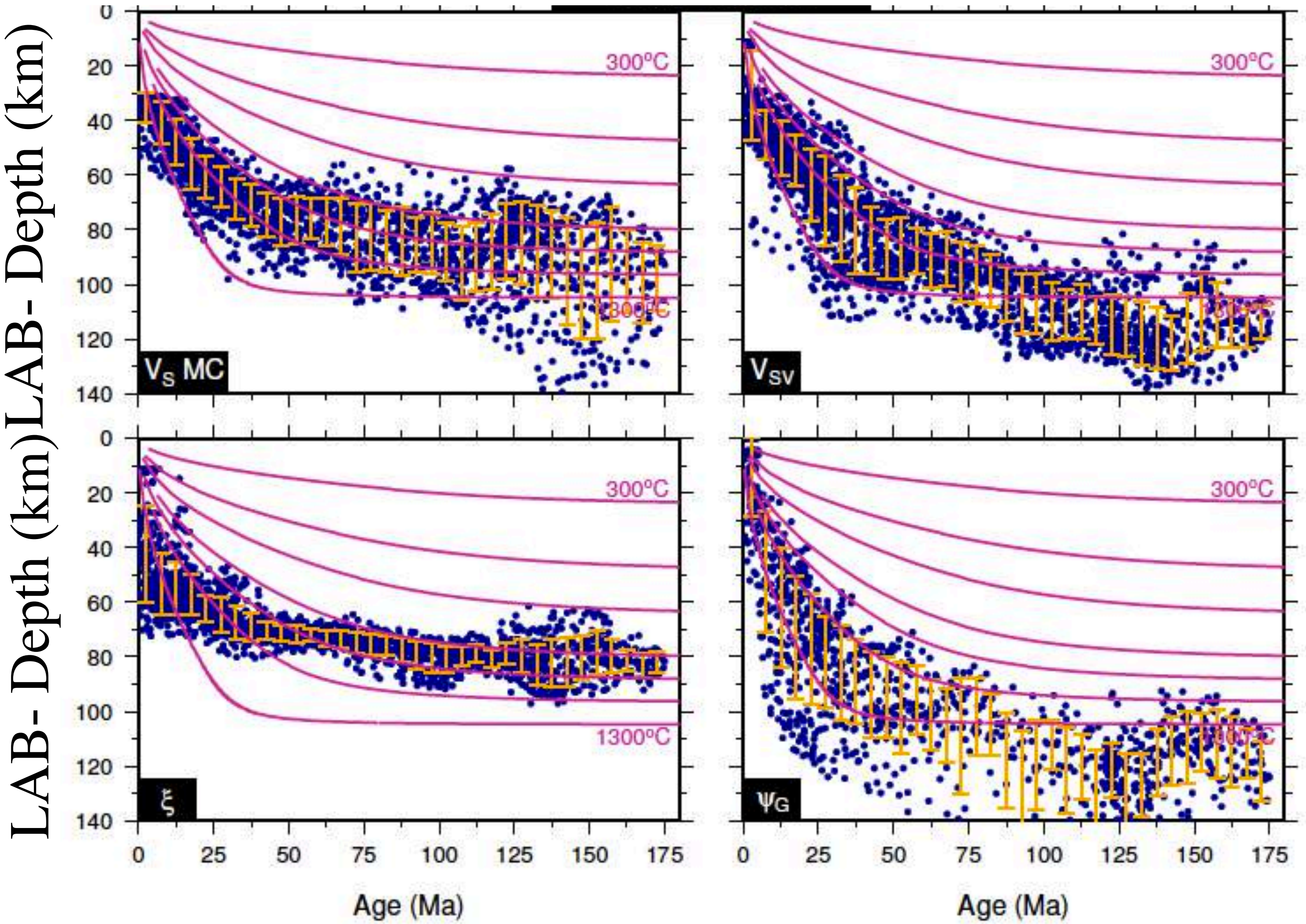


ξ proxy (1st order Perturbation Theory)



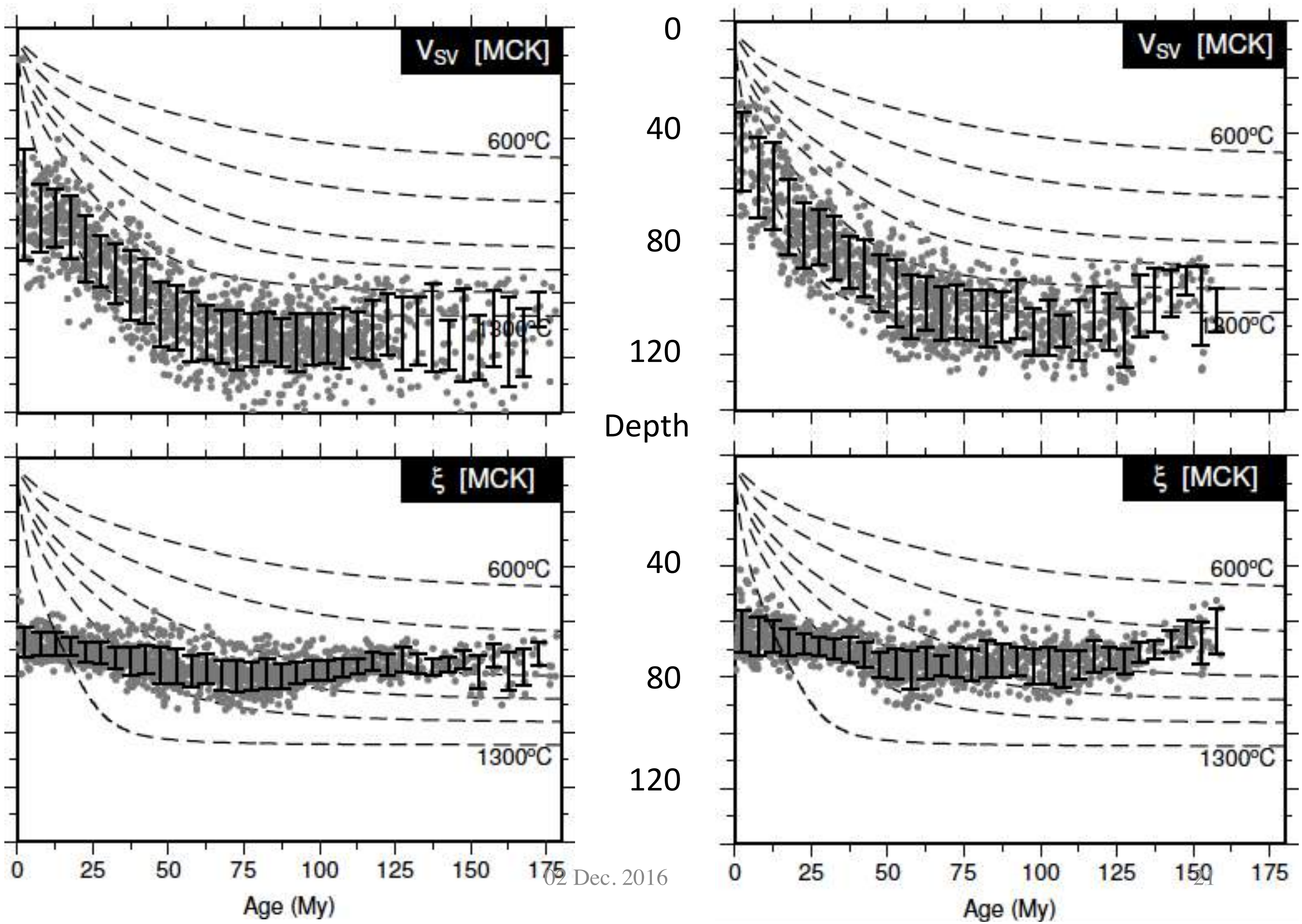
Age Variation of LAB depth in oceanic regions

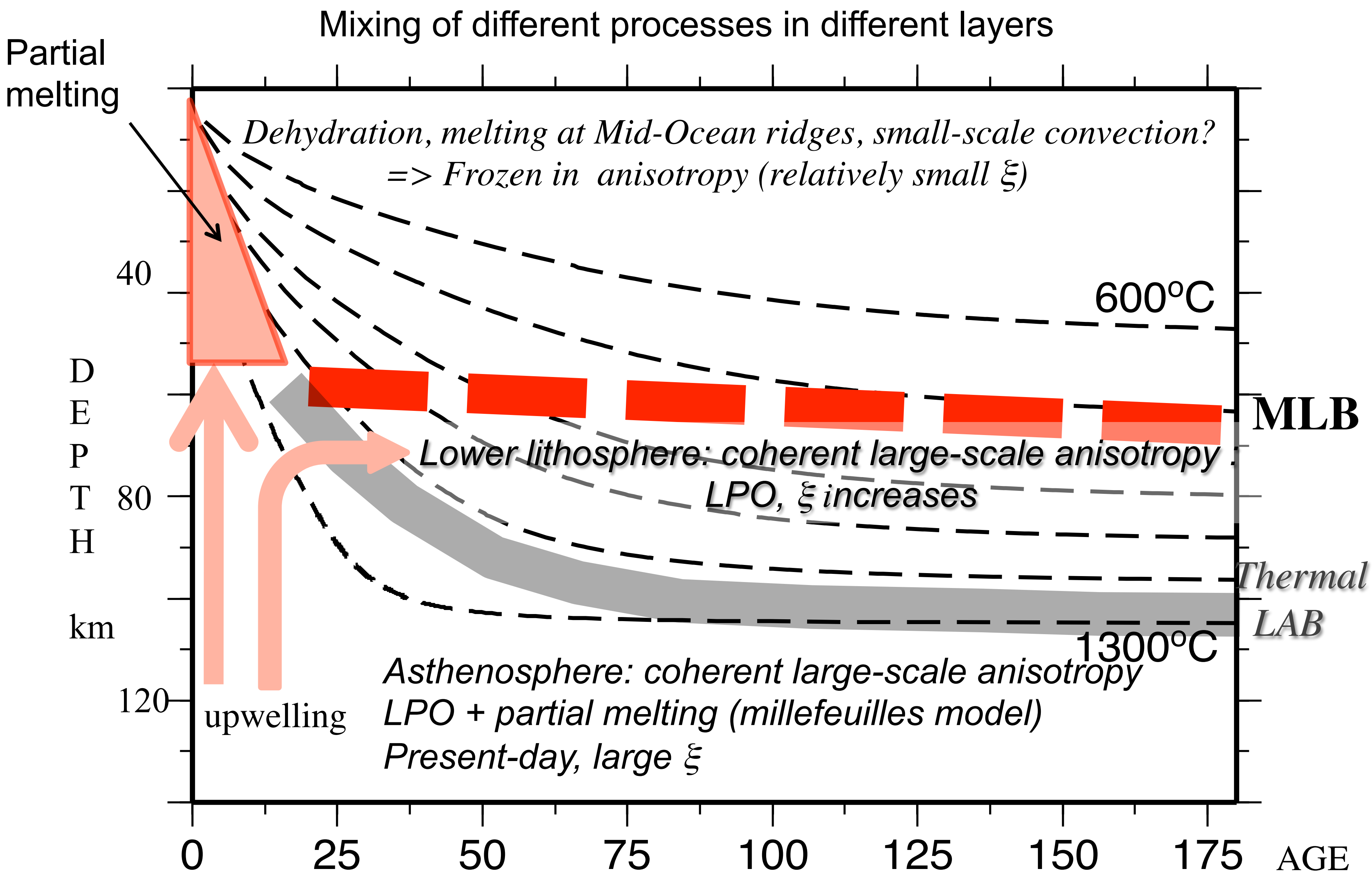
Compared with Plate model



Atlantic Ocean

Indian Ocean





MLB: Mid-Lithospheric Boundary

New Discontinuity within the lithosphere

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

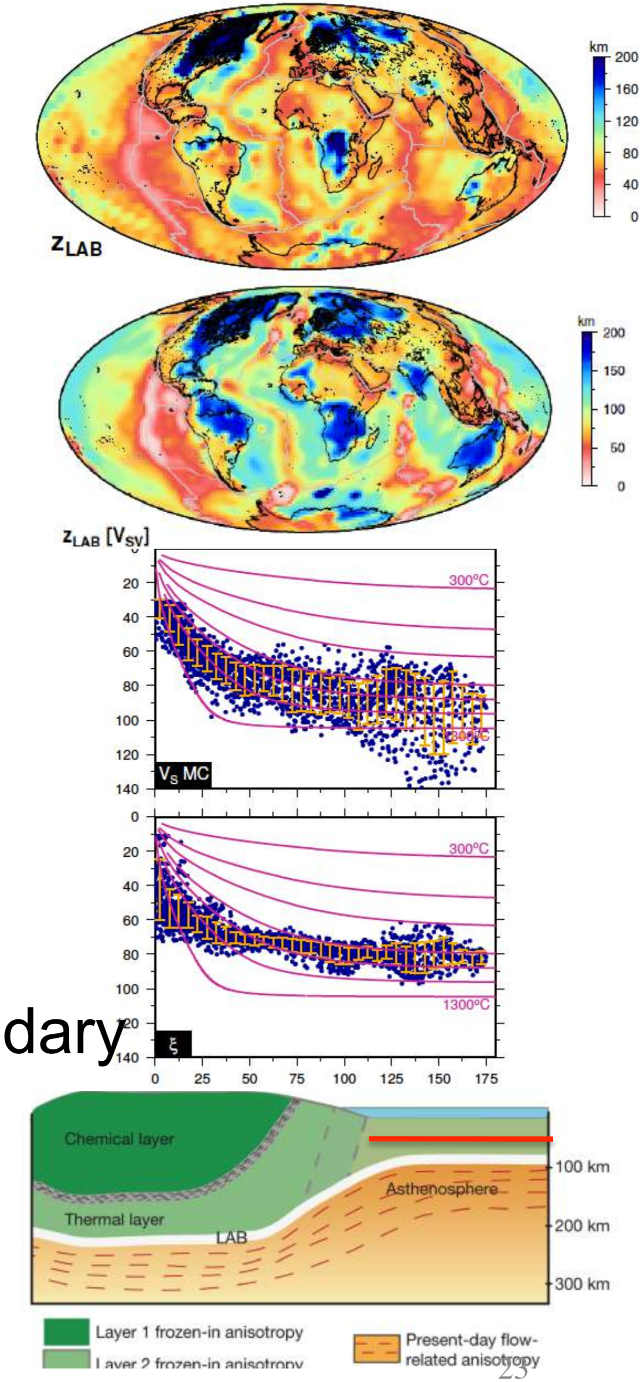
-The ocean lithosphere not so simple!

- 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 (plate; related to dehydration boundary layer?)

Mid-Lithospheric Boundary

CONTINENTS?

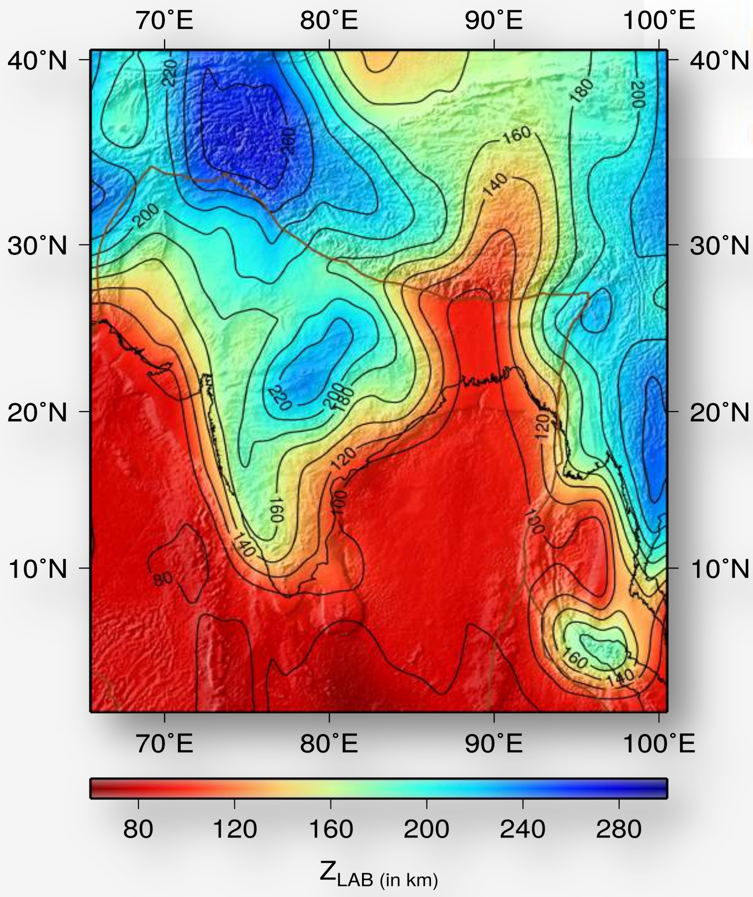


Yuan and Romanowicz, 2010

Deep Structure of the Indian Continent

1: IPG-Paris, France (J.-P. Montagner)

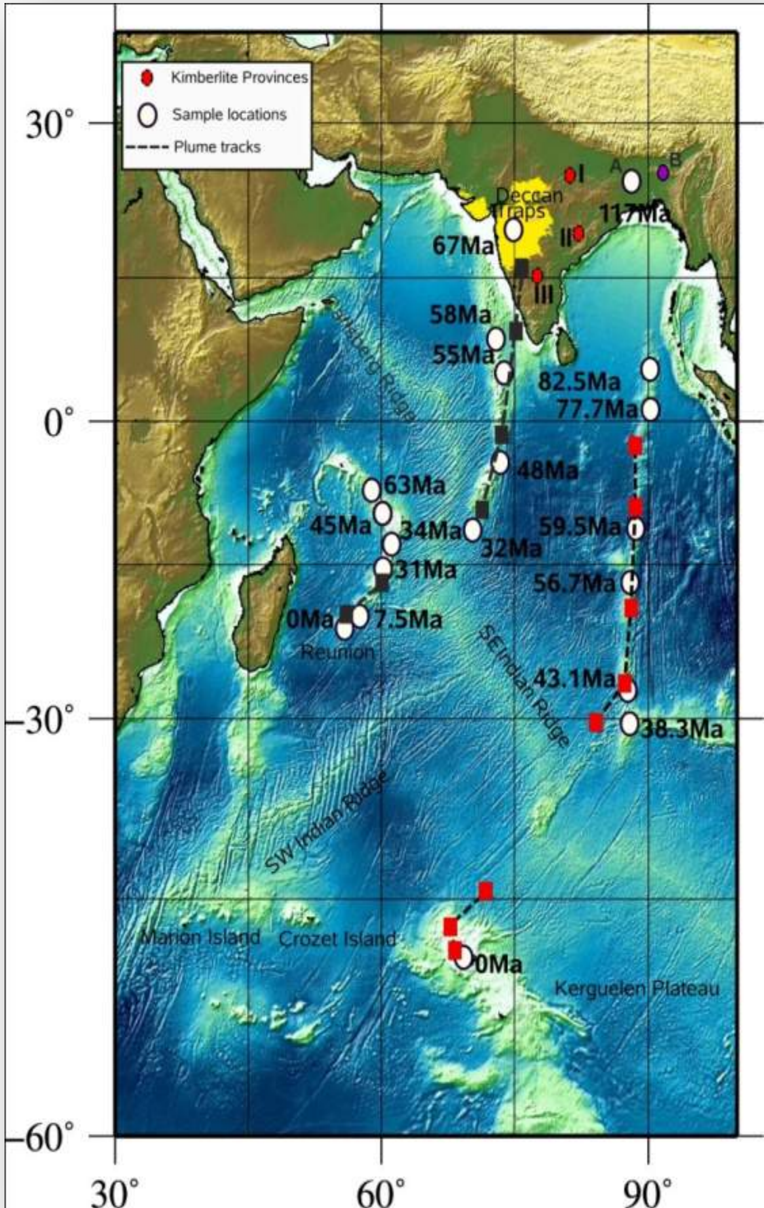
2: NGRI-Hyderabad, India (Ravi Kumar)



Satish Maurya
IPG-Paris

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 (Paleomagnetic data).
- Ravaged by hotspots and experienced large scale magmatism.
- Five cratons. Indian continental lithosphere might be underlain by an anomalously hot sub-lithospheric mantle
- Interaction with plumes (*Réunion, Marion, Crozet and Kerguelen*)



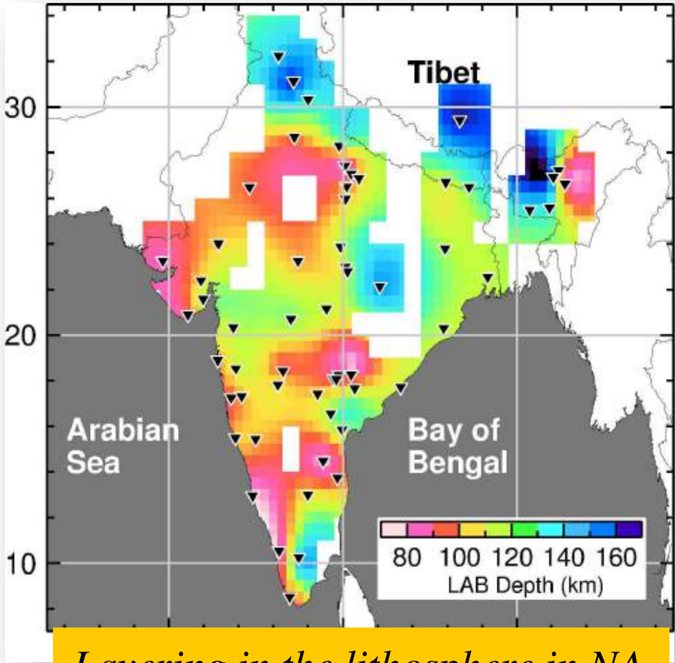
Scientific Challenges – Debate on Indian LAB

- **Super mobility** due to a thin seismic lithosphere (~100km) **[Kumar et al., 2007** & **Negi et al., 1986]** - in total disagreement with common consensus on cratons.

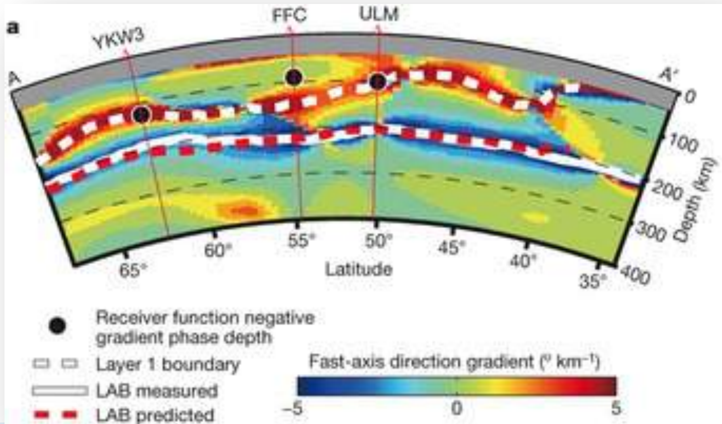
- Pressure-Temperature studies on mantle xenoliths reveal a thick lithosphere that is **~230 km** at ~1100 Ma. underneath **Dharwar Craton** **[Griffin et al., 2008]**.

- **~175 km** at ~ 65 Ma underneath **Bastar craton** **[Babu et al. 2009]**.

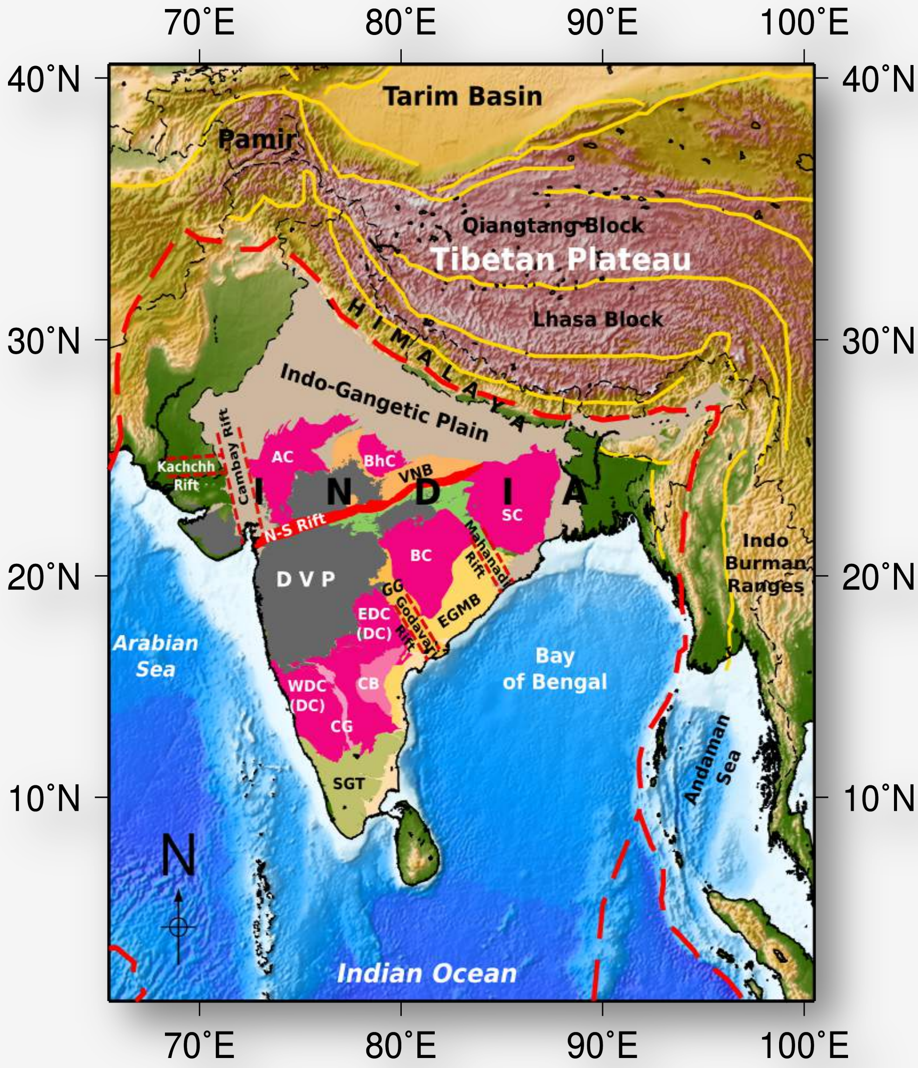
- Evidence for postcollisional flexuring of the Indian plate with a wavelength of ~1000 km



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



Study Area



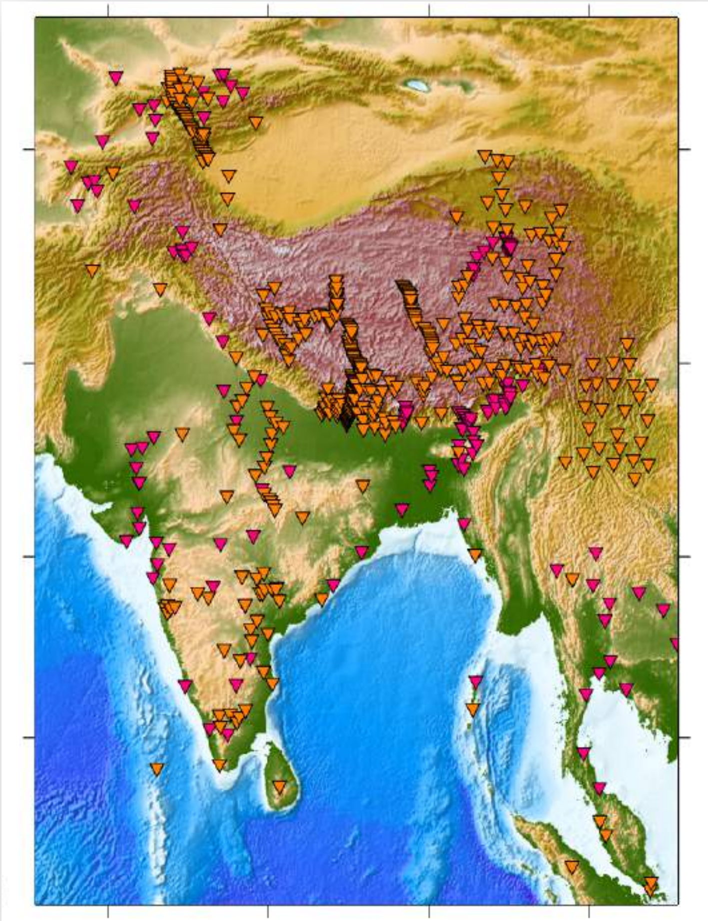
Precambrian	Phanerozoic
South Granulite Terrian (SGT)	Deccan Volcanic Province (DVP)
Cratons (AC,BC,BhC,DC,SC)	Gondwana Rocks (GR)
Closepet Granite(CG)	Indo-Gangetic Plains (IGP)
Cuddaph Basin (CB)	Alluvium
Eastern Ghat Mobile Belt (EGMB)	
Godavari Graben (GG)	
Vindhyan Basin (VNB)	

AC: Aravalli craton
BC: Bastar craton
BhC: Bundhelkhand craton
DC: Dharwar craton
SC: Singhbhum craton

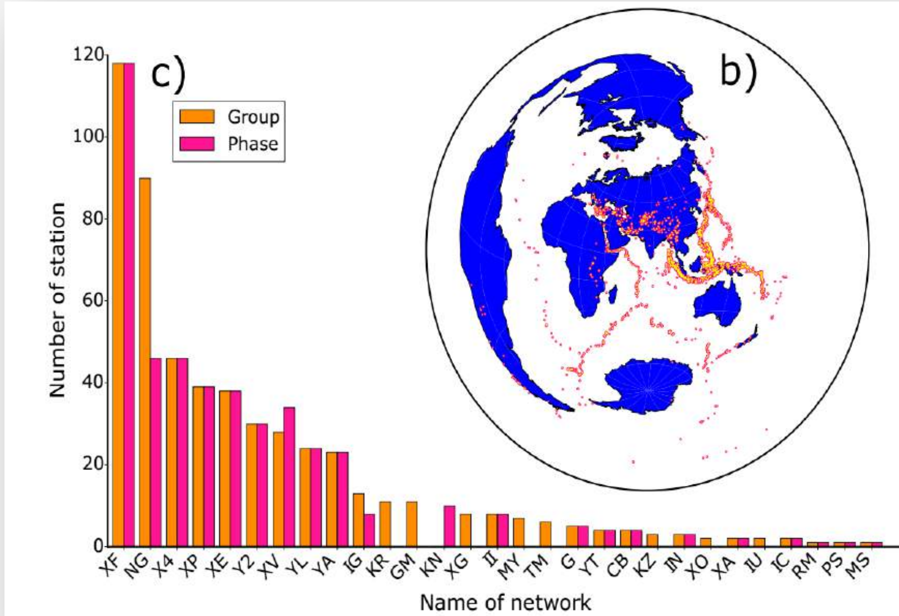
Maurya et al., 2016

Data

Stations

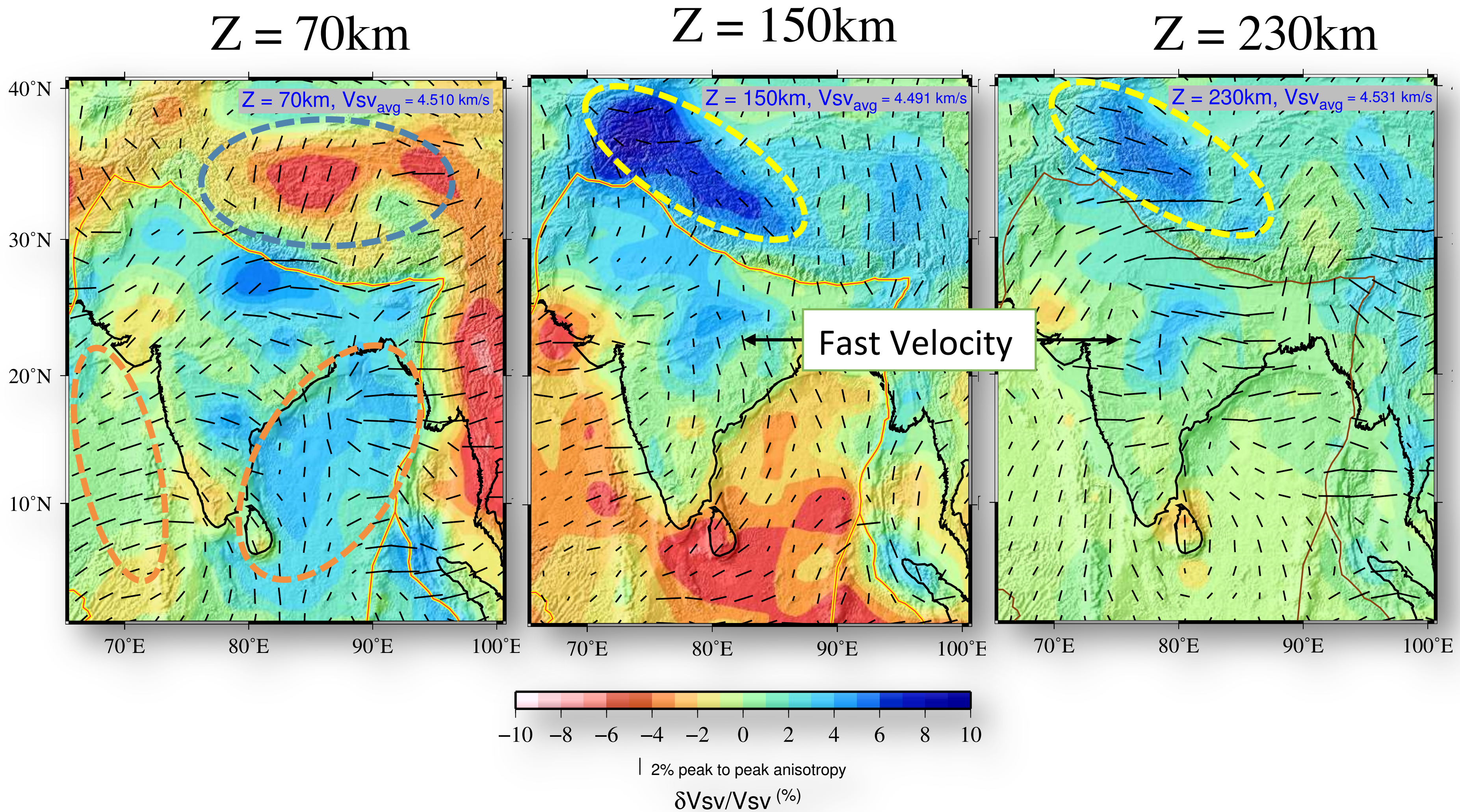


Earthquakes

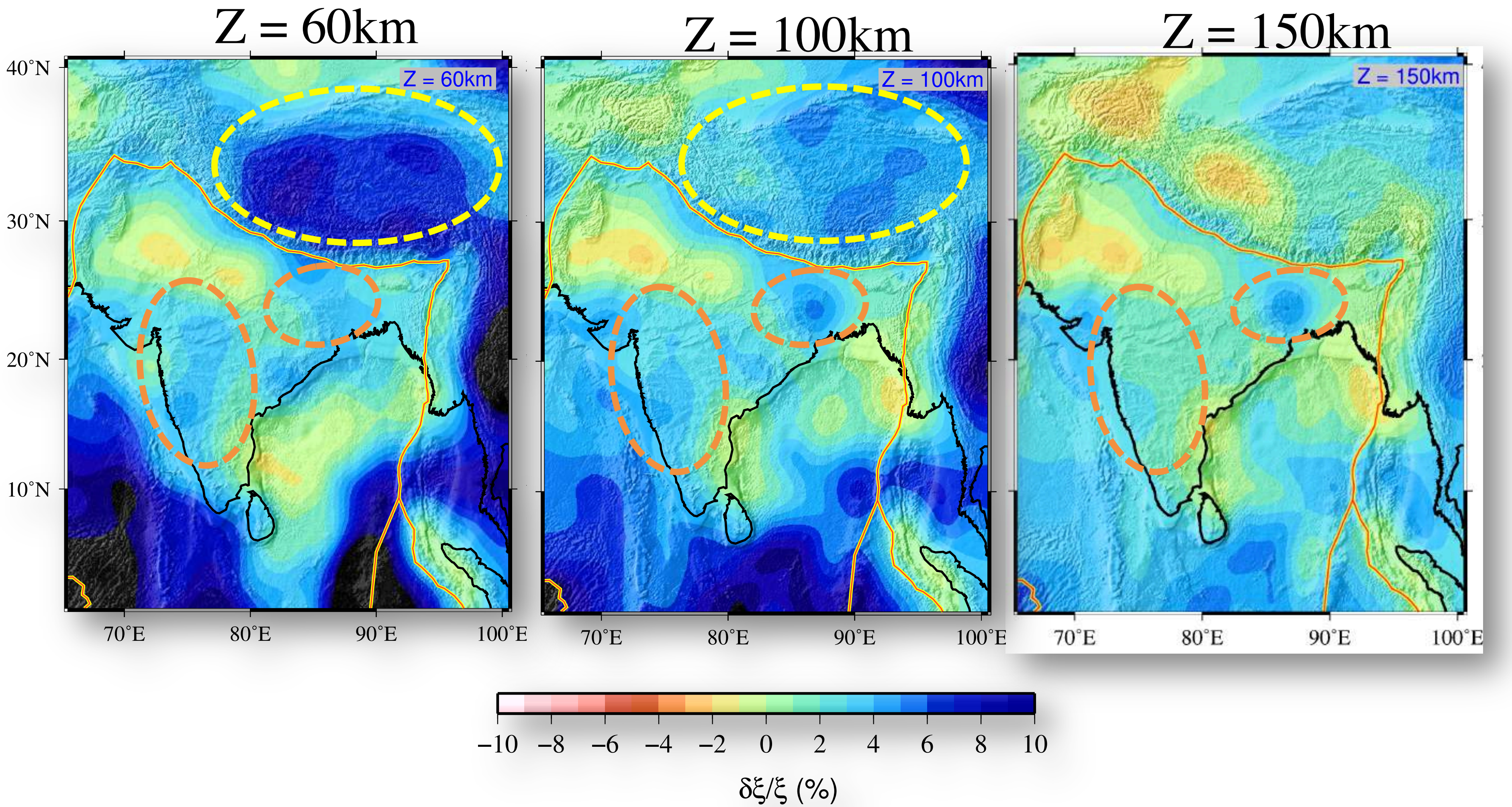


- 29 Seismic broadband Networks (**global and regional**)
- Over 550 seismic stations
- Earthquakes of magnitude >5.5
- Surface wave data in the period range of 10-400s.

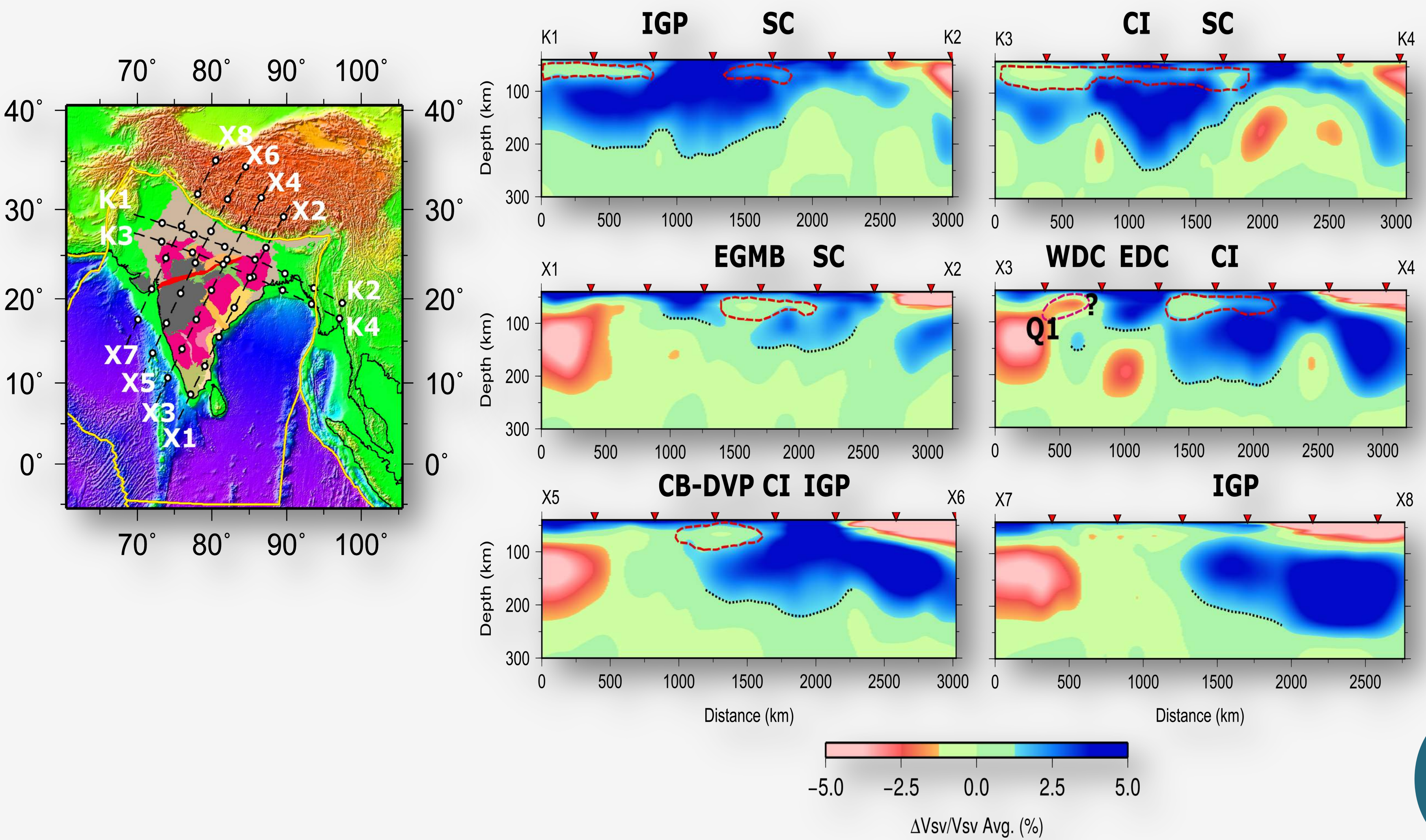
3-D tomography model of the Indian continent
Velocity and Azimuthal Anisotropy



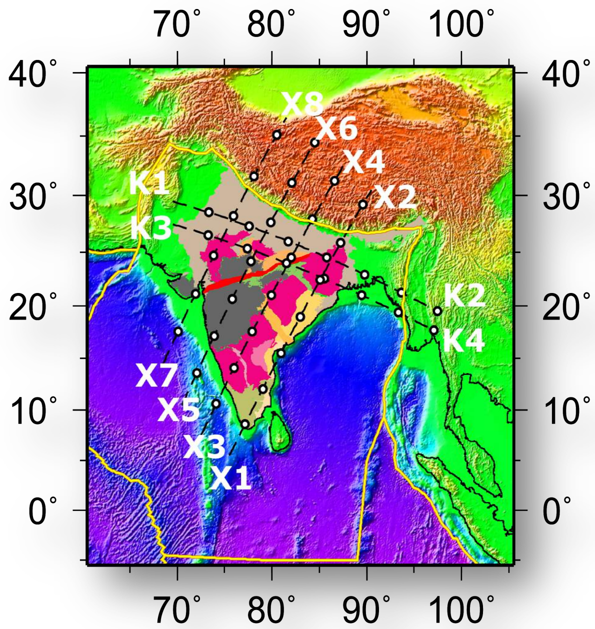
3-D tomography model of the Indian continent
Radial Anisotropy ξ



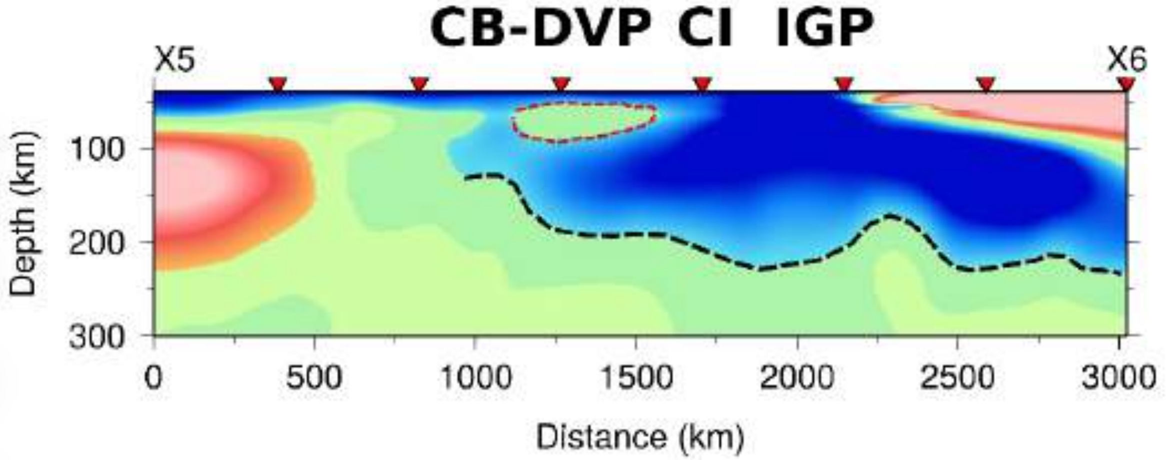
3D-Perturbation model

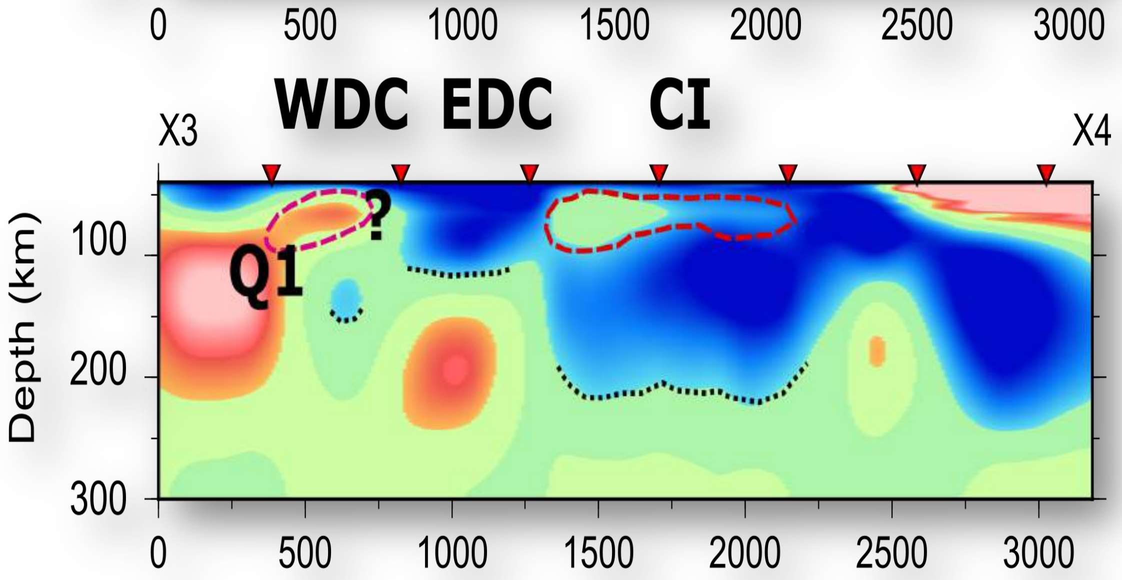


3D-Perturbation model



DVP: Low velocity zone
Remnant of hotspot birth

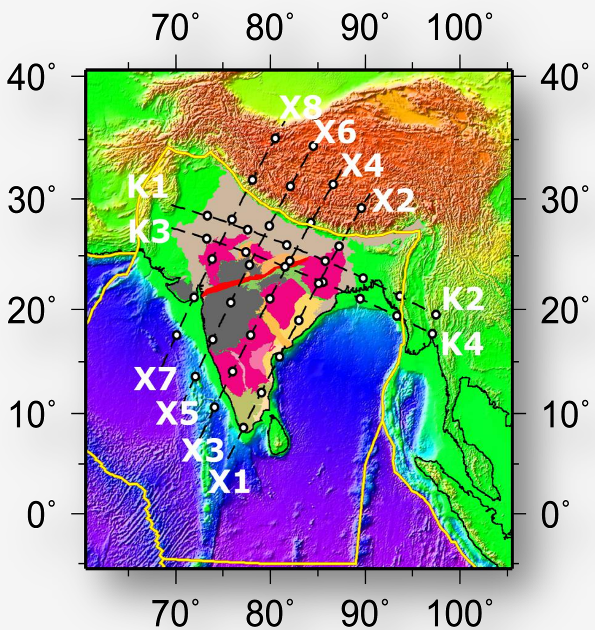


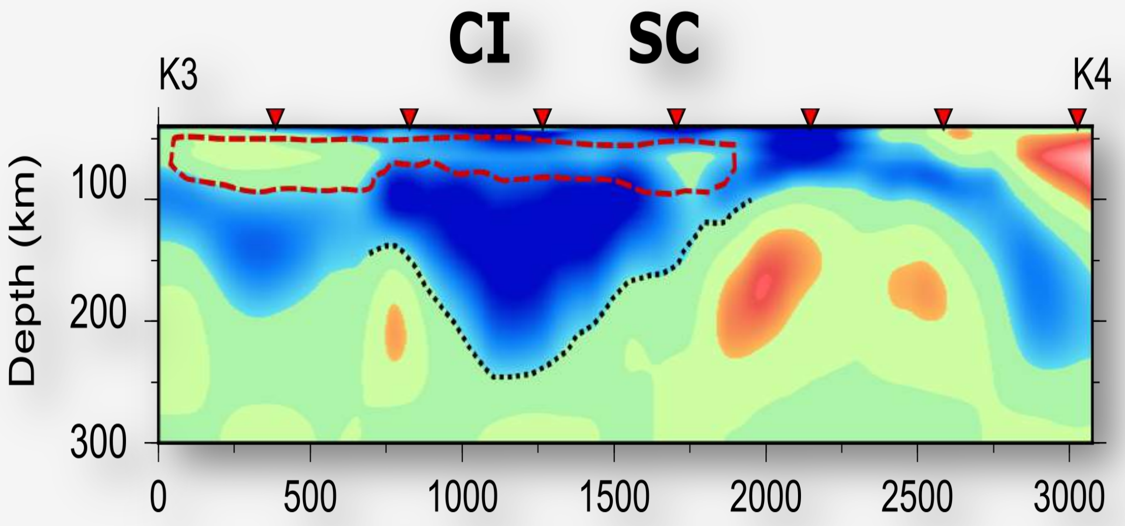


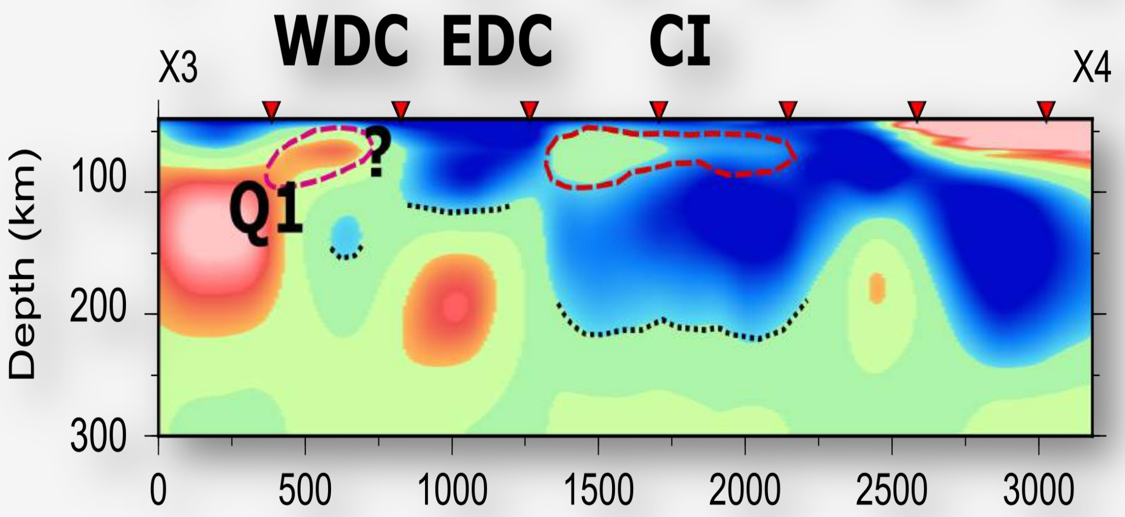
MLB: Mid-lithospheric low velocity zone

3D-Perturbation model

Indian Keel



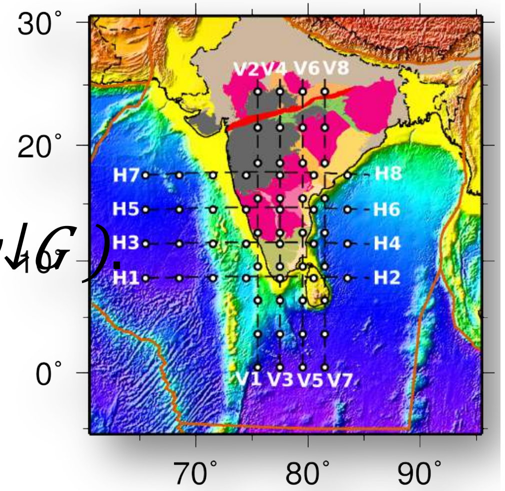


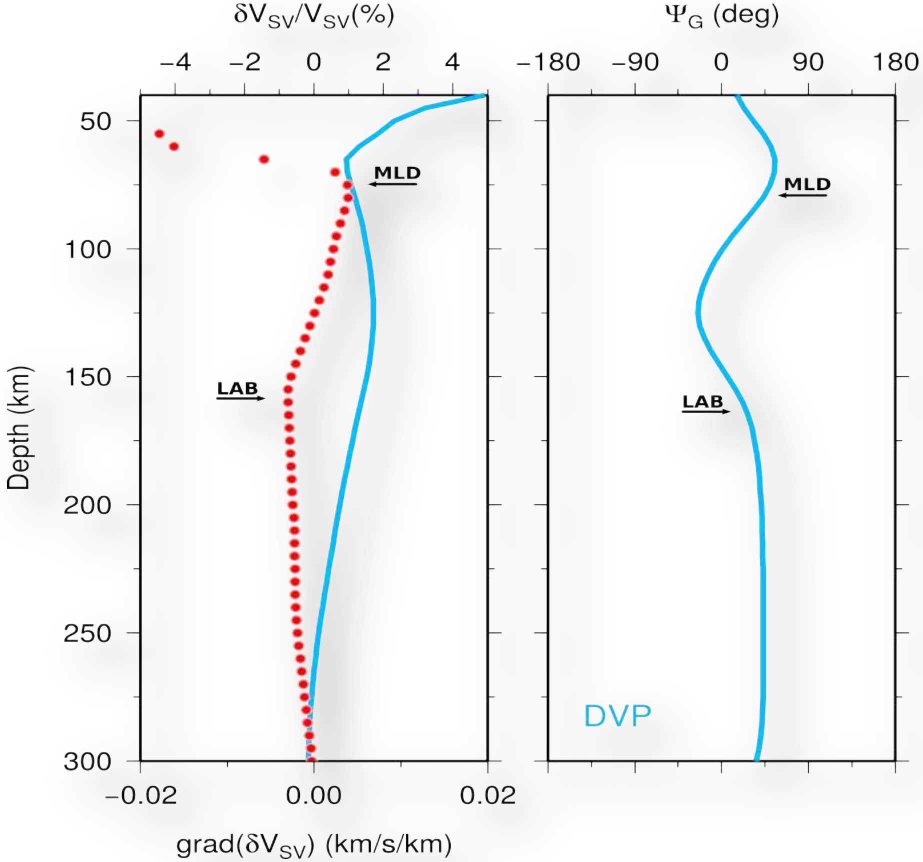


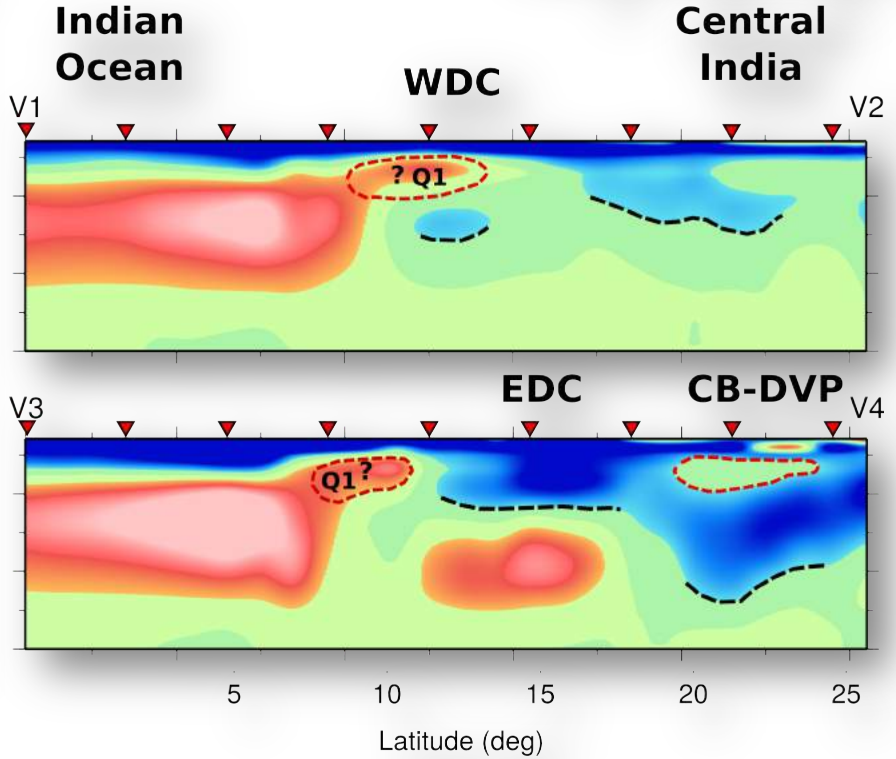
MLB: Mid-lithospheric low velocity zone

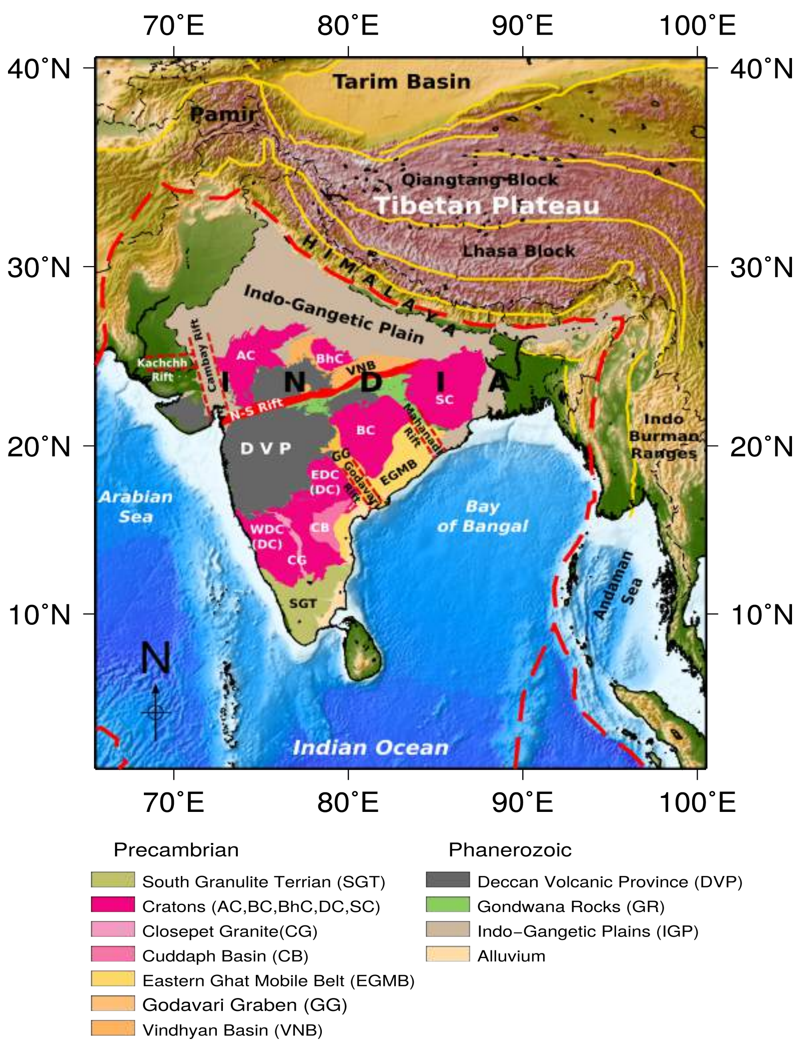
Discussion: Central India (CI)

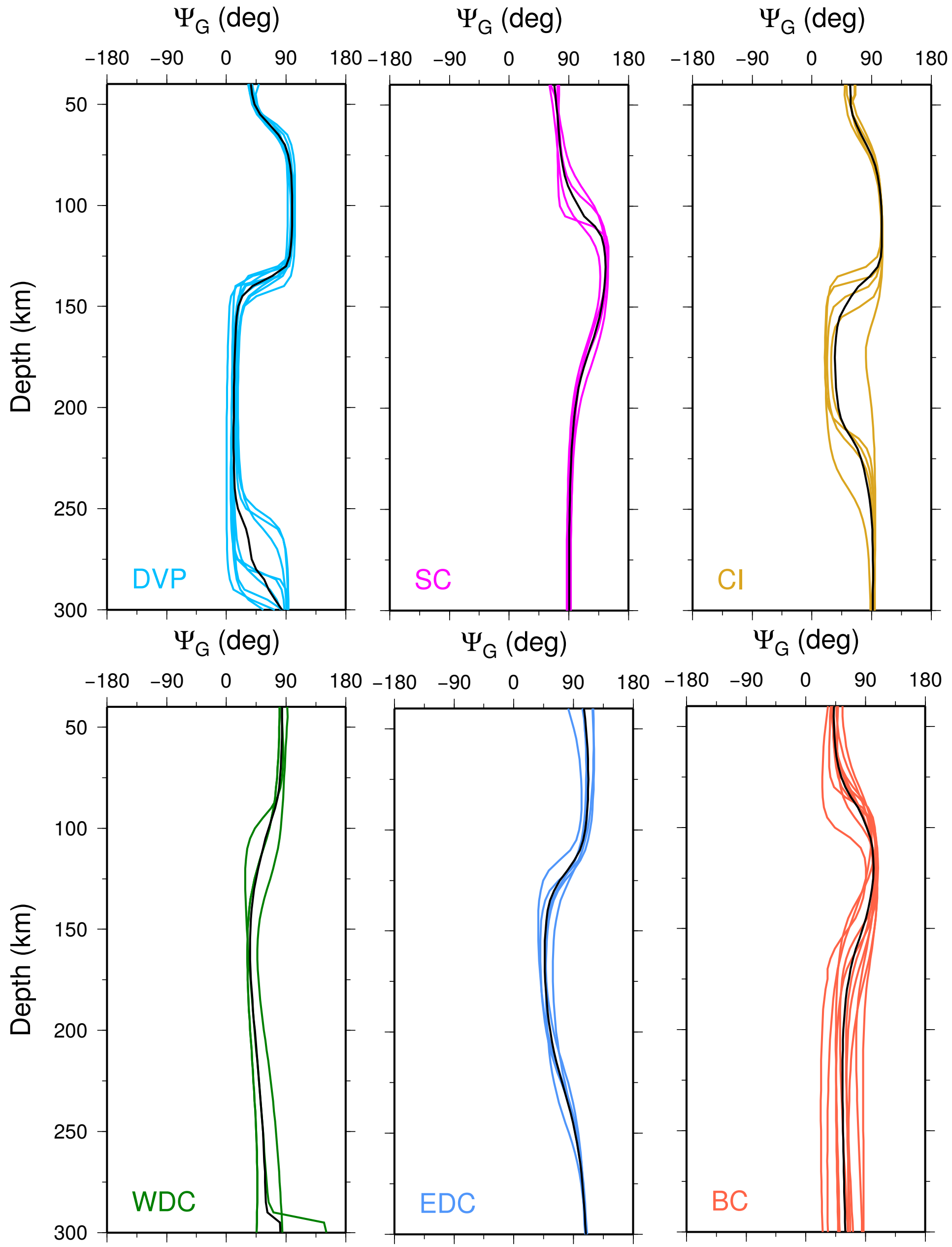
- Small velocity drop beneath DVP.
- Good agreement in both parameters (V_{SV}, ψ_G).
- Slow velocity present in the lithosphere.

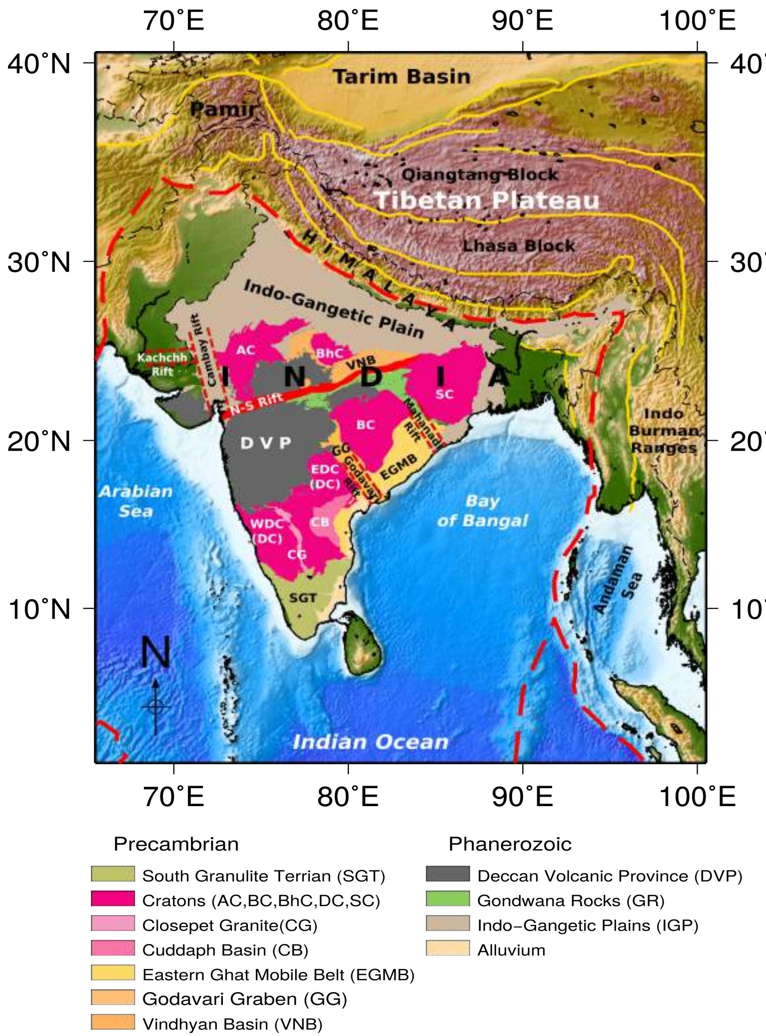




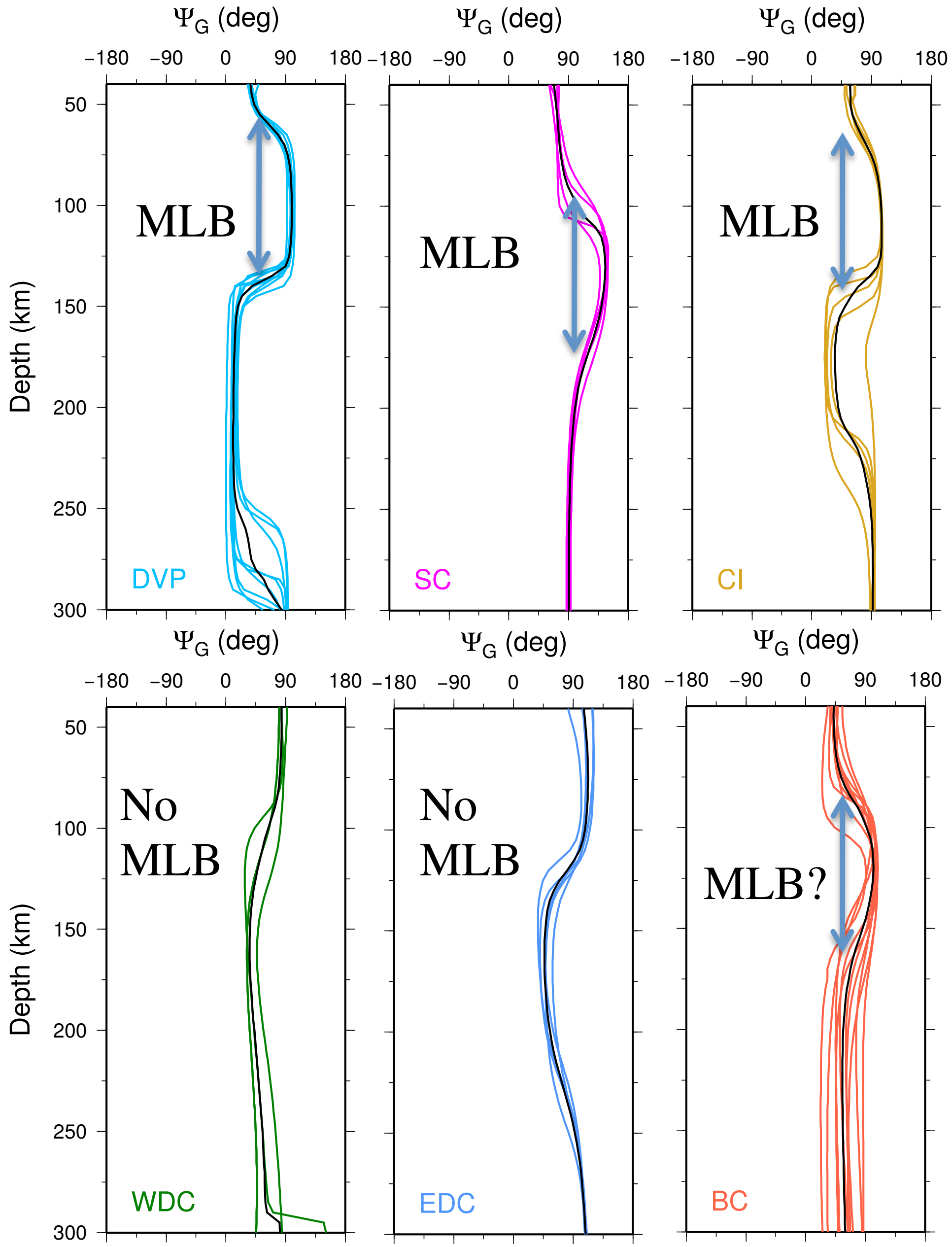



70˚E
80˚E
90˚E
100˚E
40˚N
30˚N
20˚N
10˚N
Tarim Basin
Pamir
Qiangtang Block
Tibetan Plateau
Lhasa Block
H I M A L A Y A
Indo-Gangetic Plain
Kachchh Rift
Cambay Rift
AC
BhC
VNB
I N D I A
N-S Rift
SC
D V P
BC
Mahanadi Rift
GG
Godavari Rift
EDC (DC)
EGMB
WDC (DC)
CB
CG
SGT
Indo Burman Ranges
Arabian Sea
Bay of Bangal
Andaman Sea
Indian Ocean
N
Precambrian
South Granulite Terrian (SGT)
Cratons (AC,BC,BhC,DC,SC)
Closepet Granite(CG)
Cuddaph Basin (CB)
Eastern Ghat Mobile Belt (EGMB)
Godavari Graben (GG)
Vindhyan Basin (VNB)
Phanerozoic
Deccan Volcanic Province (DVP)
Gondwana Rocks (GR)
Indo-Gangetic Plains (IGP)
Alluvium

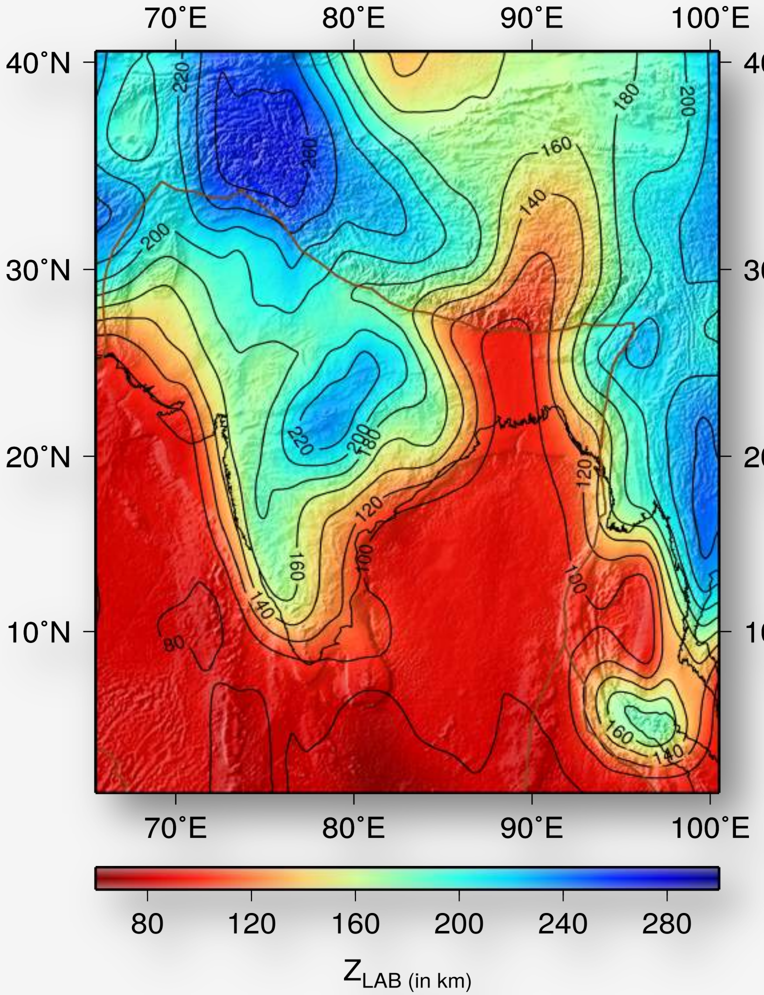

Ψ_G (deg)
−180 −90 0 90 180
Depth (km)
50
100
150
200
250
300
DVP
SC
CI
WDC
EDC
BC

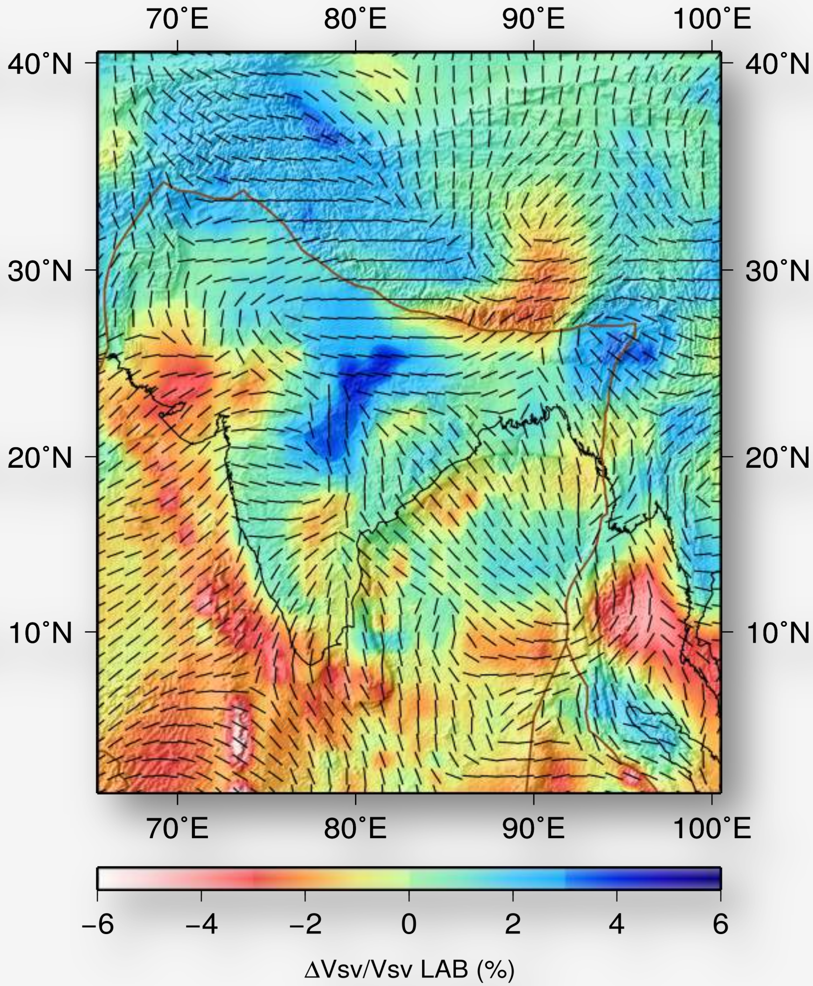

Tarim Basin
Pamir
Qiangtang Block
Tibetan Plateau
Lhasa Block
Indo-Gangetic Plain
INDIA
DVP
Arabian Sea
Bay of Bangal
Indian Ocean
Indo Burman Ranges
Andaman Sea
Precambrian
South Granulite Terrian (SGT)
Cratons (AC,BC,BhC,DC,SC)
Closepet Granite(CG)
Cuddaph Basin (CB)
Eastern Ghat Mobile Belt (EGMB)
Godavari Graben (GG)
Vindhyan Basin (VNB)
Phanerozoic
Deccan Volcanic Province (DVP)
Gondwana Rocks (GR)
Indo–Gangetic Plains (IGP)
Alluvium

MLB = ML-LVZ


Ψ_G (deg)
Depth (km)
MLB
DVP
MLB
SC
MLB
CI
No MLB
WDC
No MLB
EDC
MLB?
BC

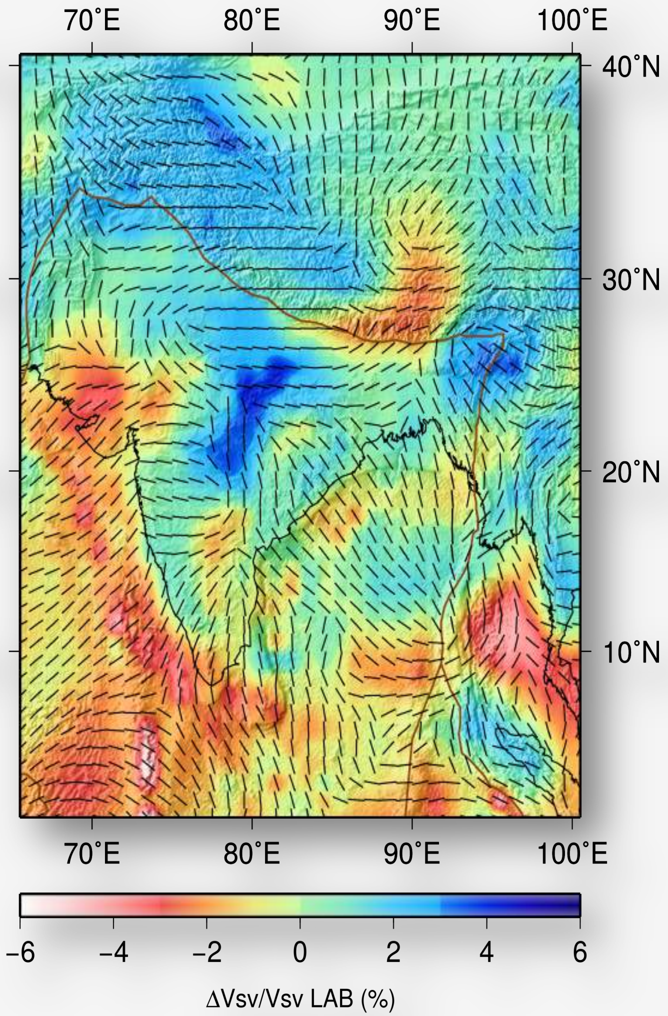
Indian Plate LAB (Lithosphere-Asthenosphere Boundary)



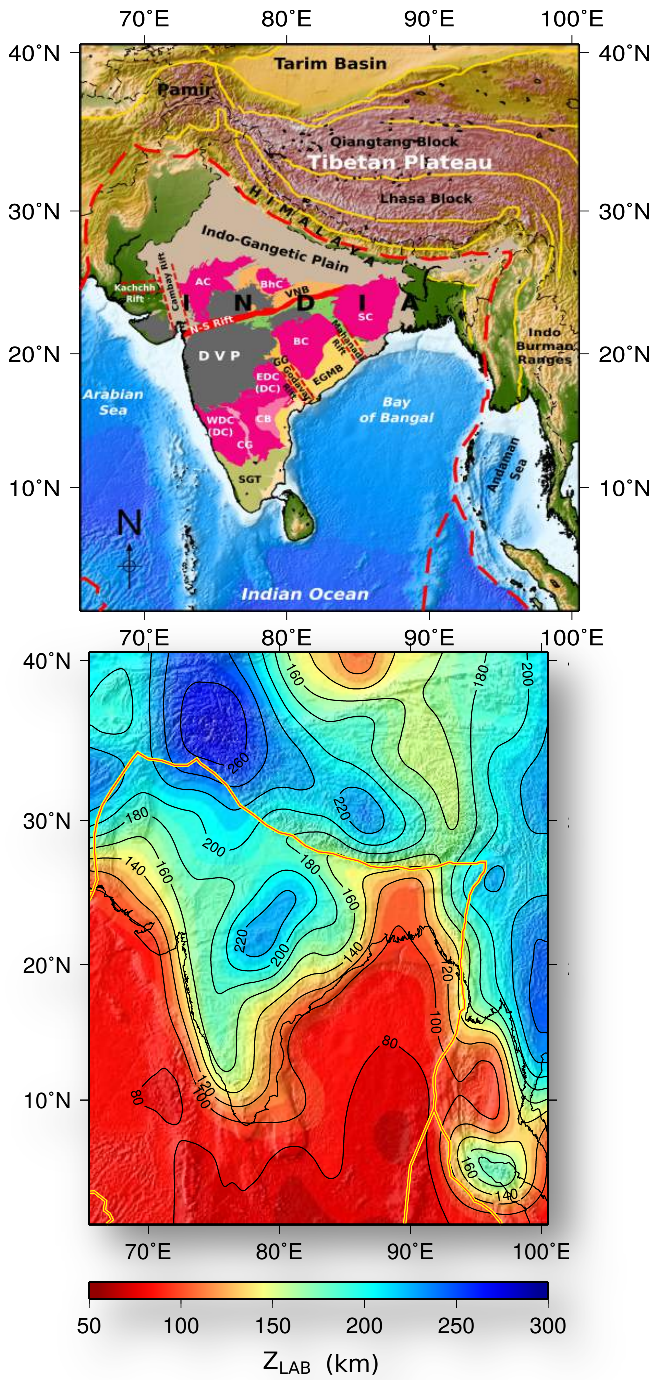


Indian Plate LAB: Keel

LAB (in km)



Geodynamic Role?
Plume influence?



- 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?

-Continents much more complicated than oceans

Conclusions

- Seismic Anisotropy can be mapped in different depth ranges

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

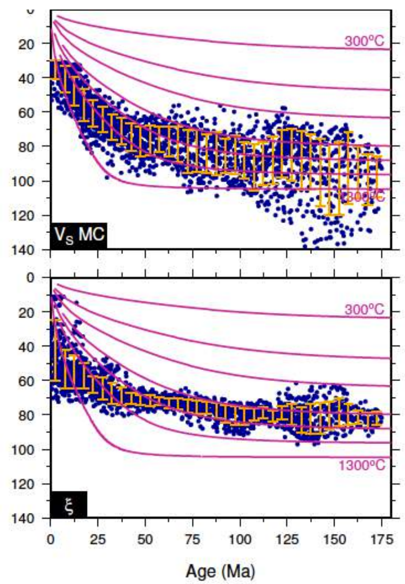
- Imaging of geological objects such as LAB (Lithosphere-Asthenosphere Boundary)

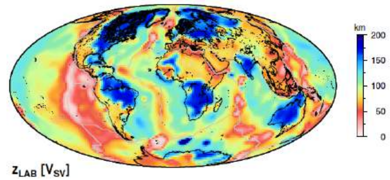
- New findings from anisotropy :

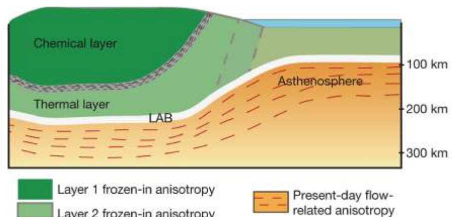
Oceans: MLB

Continents: variable thickness, Mid-LVZ
Keel

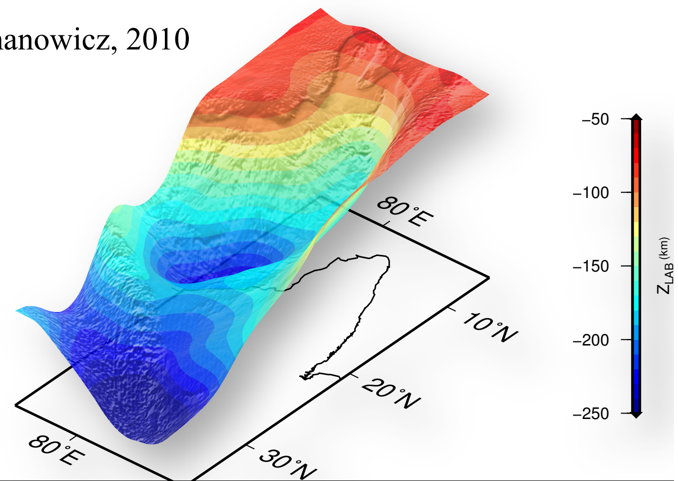
-

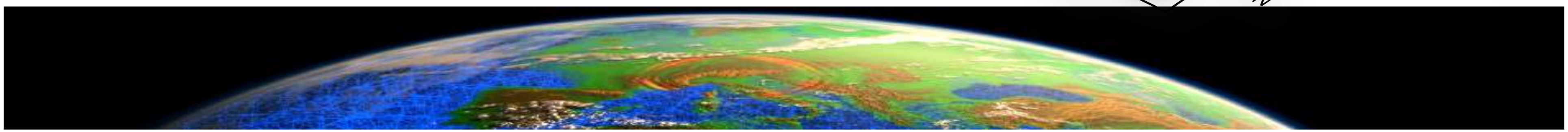






Yuan and Romanowicz, 2010





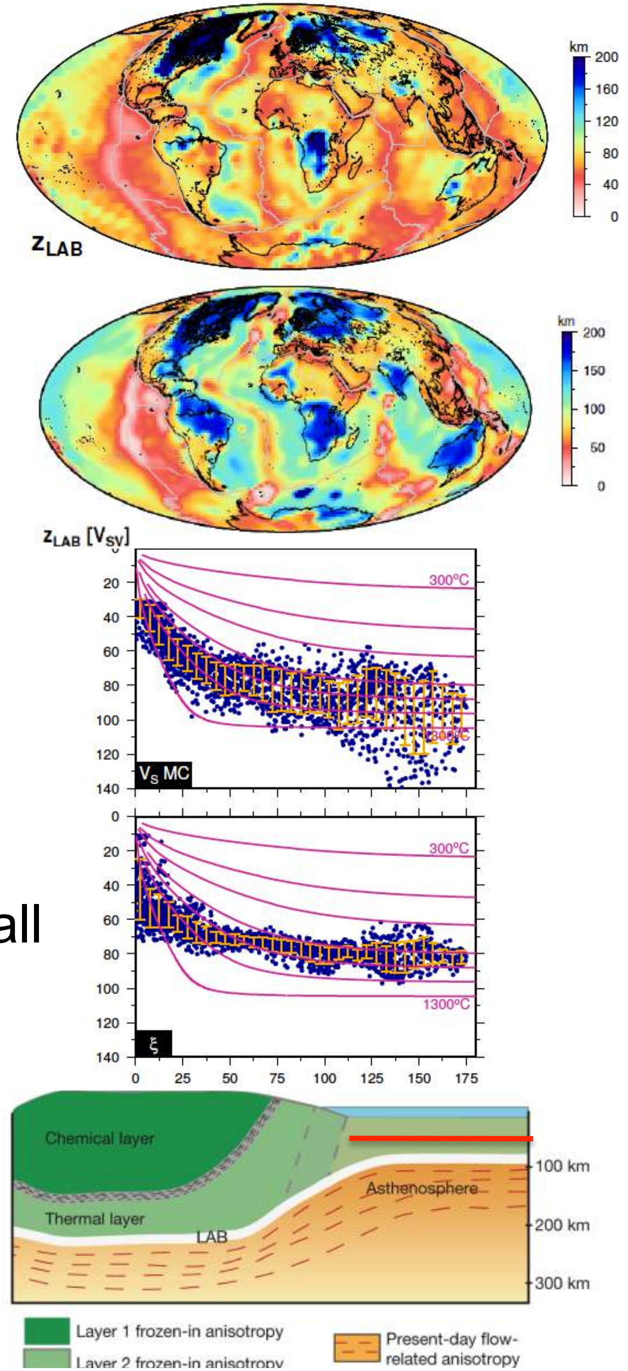
Oceanic and Continental plates

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

- For oceans: The ocean lithosphere not so simple! Stratification, existence of a Mid-Lithospheric Discontinuity (MLD: strong gradient of ξ between 60-80km)

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

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



Yuan and Romanowicz, 2010

3-D Indian LAB model