Seismic Anisotropy

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OUTLINE

- Seismic Anisotropy: many processes
- Seismic Data: Body waves, Surface waves
- Scientific Issues:

  3D- anisotropic structure of the Earth

  - Upper mantle – LAB

    Oceans- continents

  - Intrinsic versus extrinsic anisotropy and attenuation

  (-Transition zones: 410-900km)

Seismic Anisotropy is present at all scales Not a second order effect

-From microscopic scale up to macroscopic scale

-Efficient mechanisms of alignment of minerals in the crust and upper mantle:

C.P.O./ L.P.O.: Crystal/Lattice Preferred Orientation;
S.P.O.: Shape preferred orientation;
FINE LAYERING

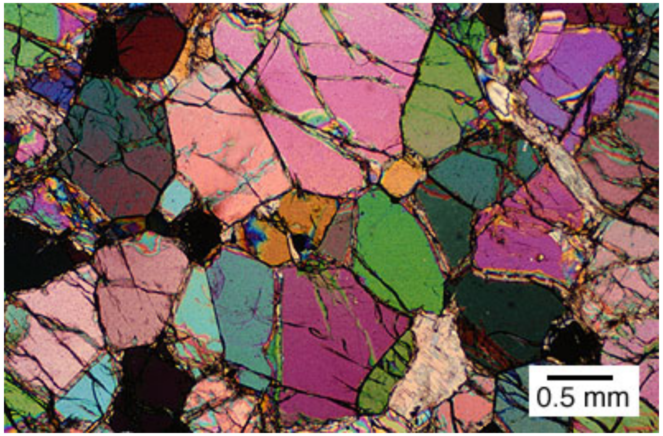
ANISOTROPY is the Rule not the Exception

Apparent (observed) anisotropy:
NON UNIQUE INTERPRETATION
in different depth ranges of the Earth

To explain seismic data:
heterogeneities isotropic / anisotropic, anelasticity

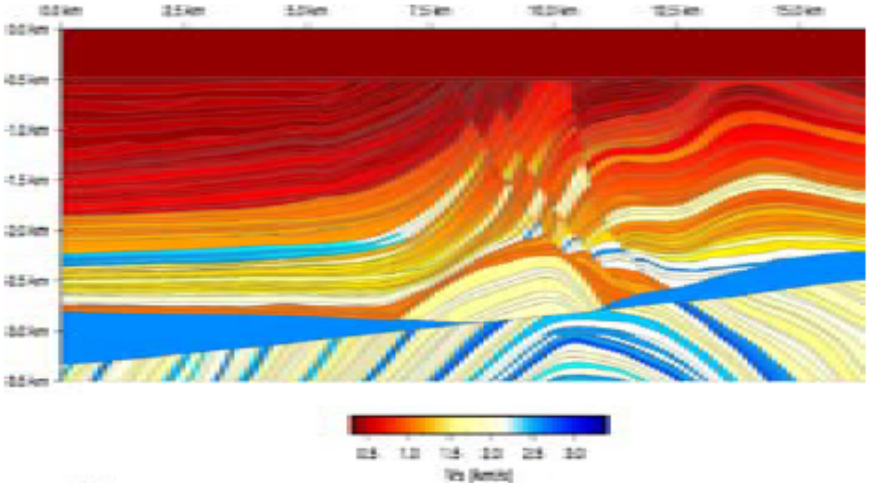
Confusion: Heterogeneity ≠ Anisotropy

-Homogeneous, anisotropic
(Olivine aggregates)



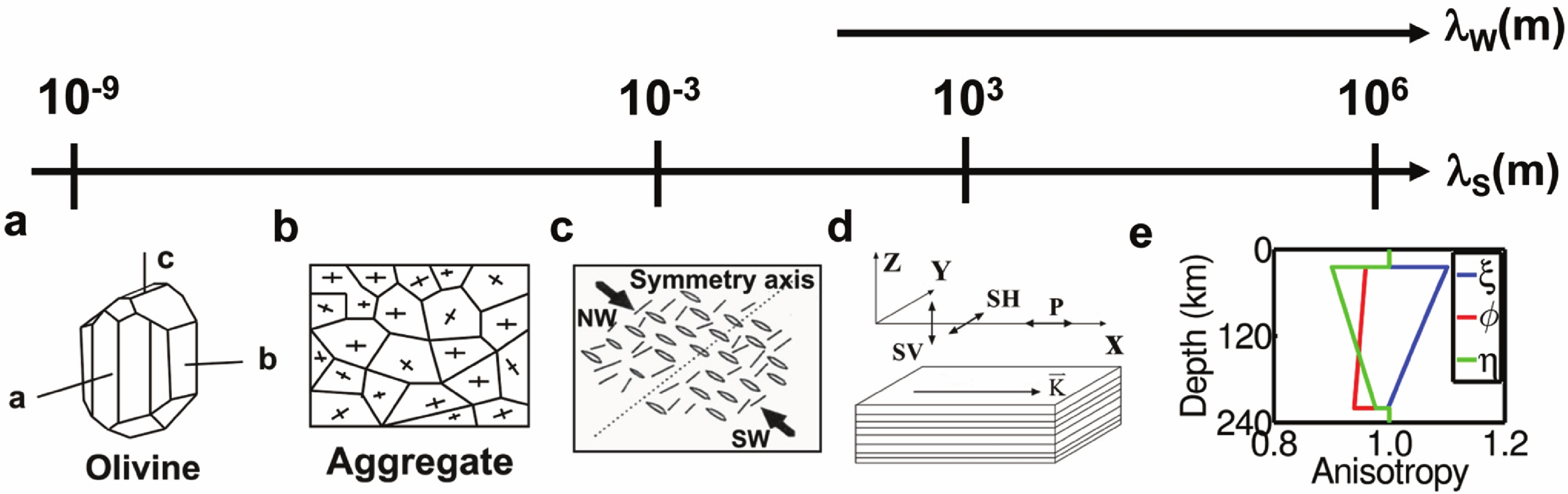
-Heterogeneous, isotropic

Marmousi



Solid Earth: heterogeneous + anisotropic + anelastic

Seismic Anisotropy at all scales



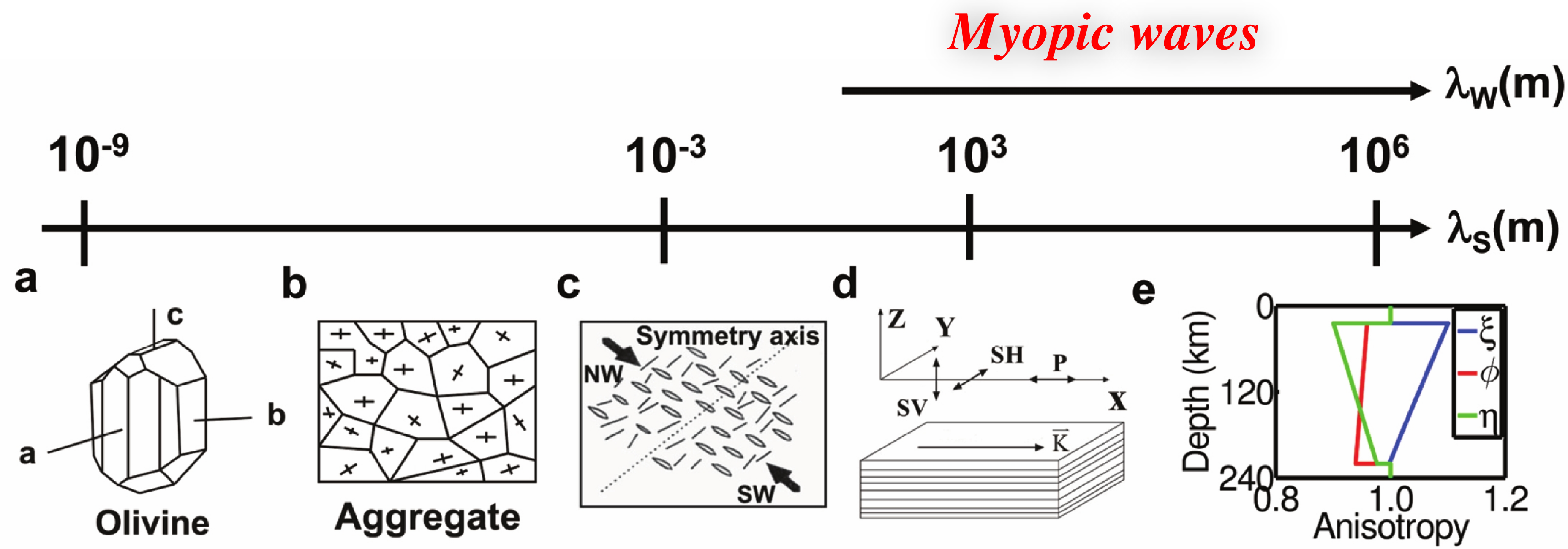
PREM

PREM: radial anisotropy: up to 10%

λ_W seismic wavelength
λ_S spatial scale

(Wang et al., 2013)

Seismic Anisotropy at all scales



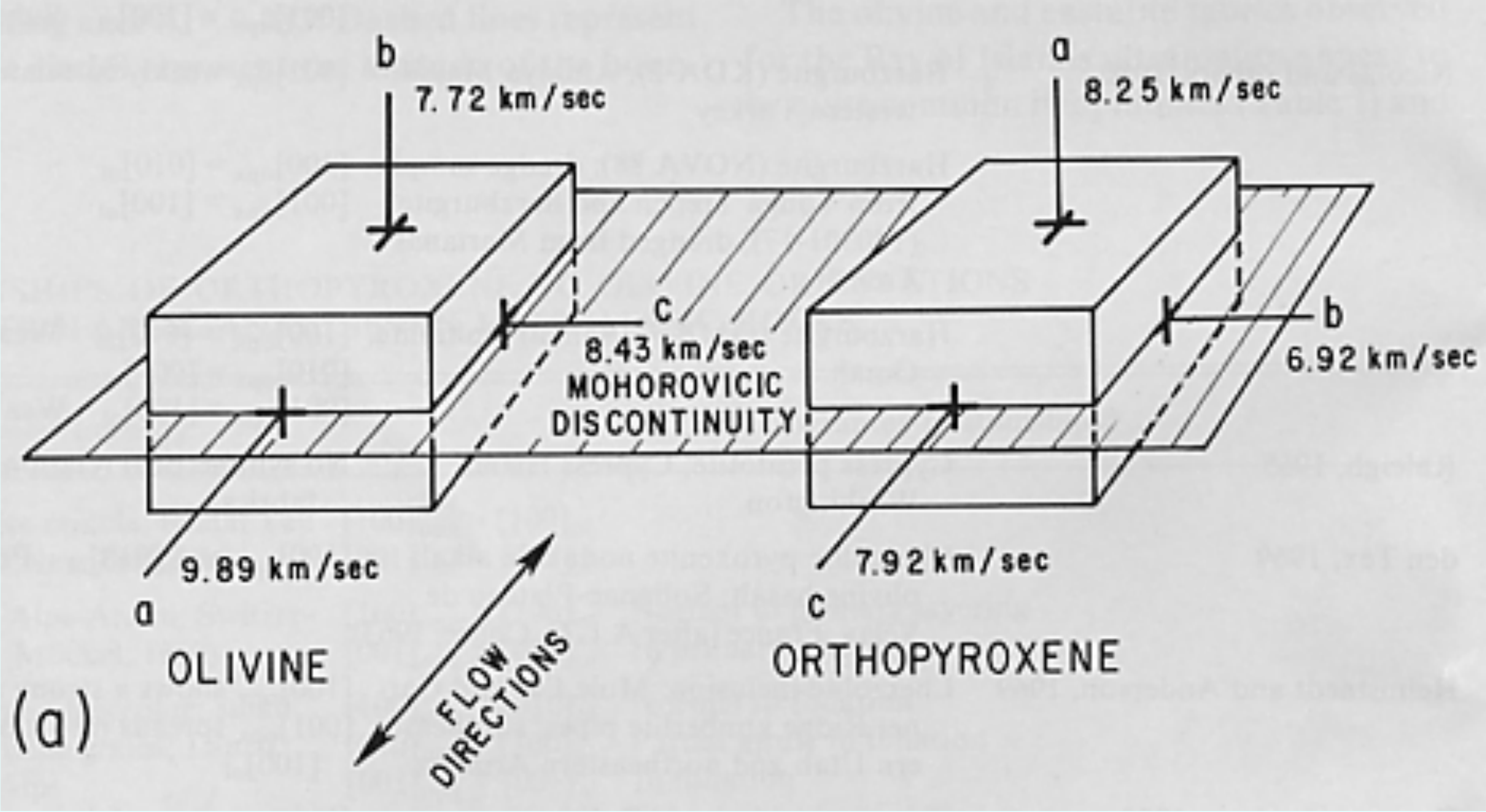
Intrinsic **Extrinsic** PREM

Observed (apparent) anisotropy

Intrinsic versus Extrinsic anisotropy

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

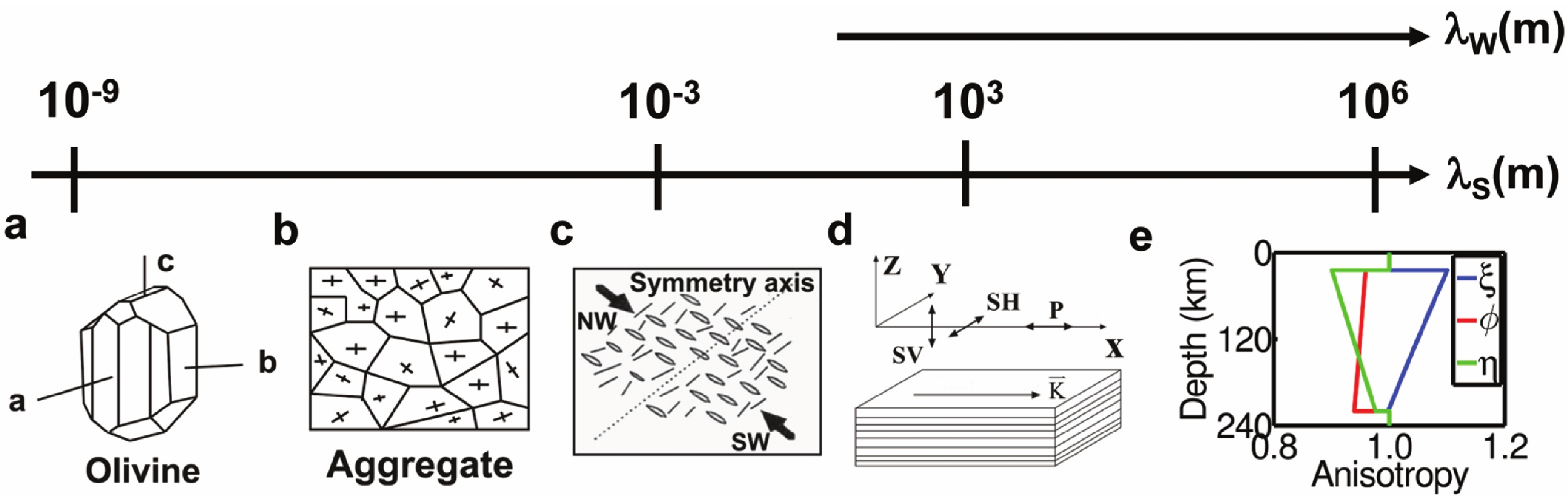
C.P.O. : Crystal Preferred Orientation
(strain field)



→ ***Mapping of convection***

Christensen and Lundquist, 1982

Seismic Anisotropy at all scales



PREM

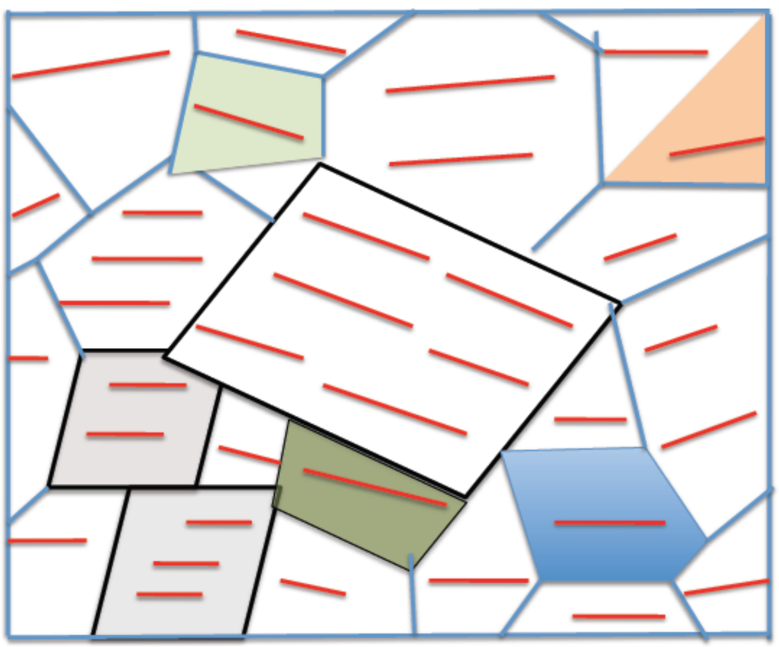
PREM: radial anisotropy: up to 10%

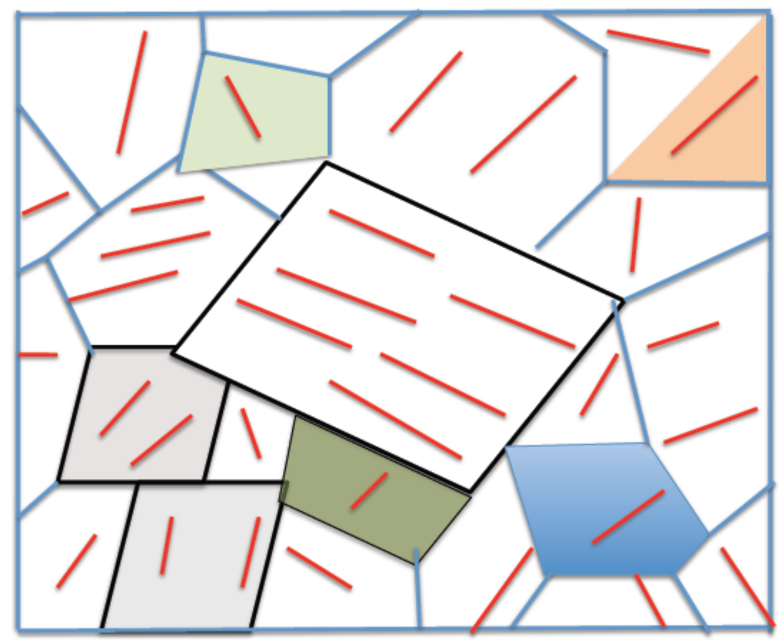
λ_W seismic wavelength
λ_S spatial scale

(Wang et al., 2013)

Coherent Strain field
(preferred orientation)
Large-scale Seismic anisotropy ≠ 0

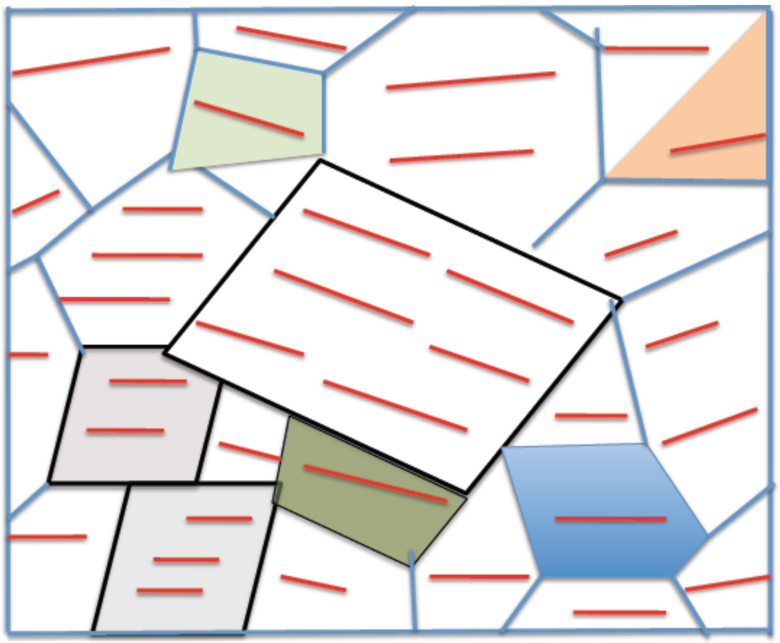
Incoherent Strain field
(random orientation)
Large-scale Seismic anisotropy ≈ 0





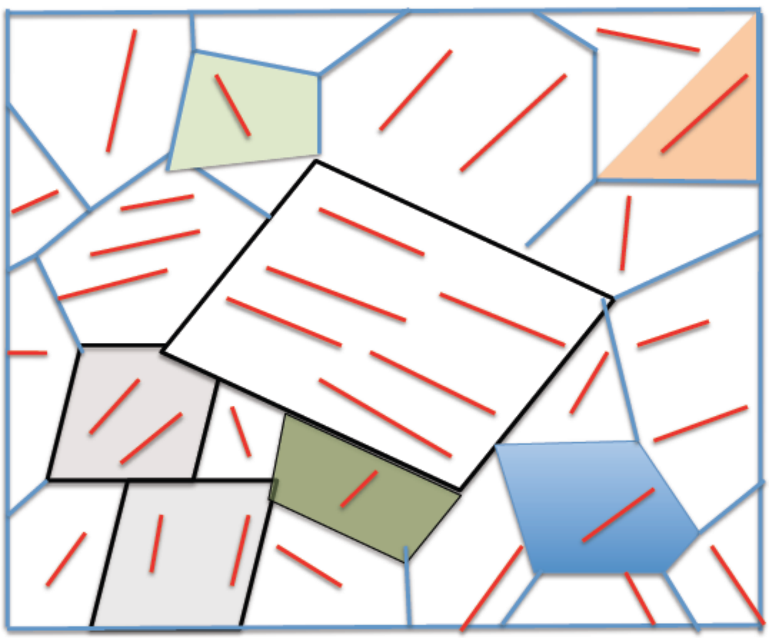
Coherent Strain field

Large-scale Seismic anisotropy ≠ 0



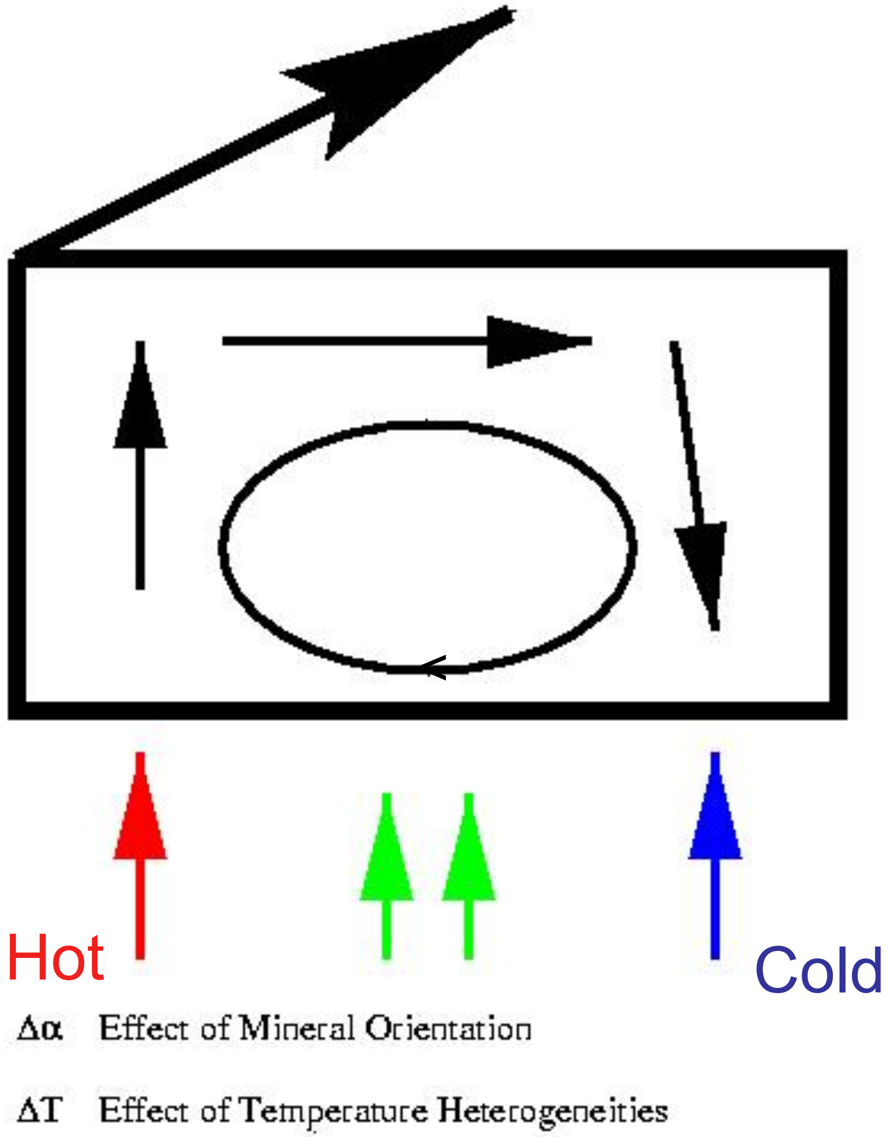
Incoherent Strain field

Large-scale Seismic anisotropy ≈ 0



Inner Organization

Anisotropy: Not a second order effect

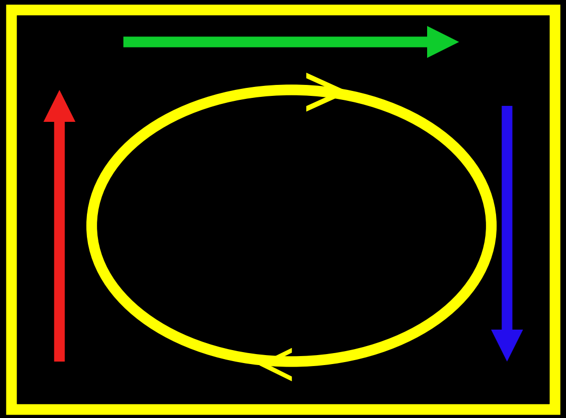


Montagner & Guillot, 2002

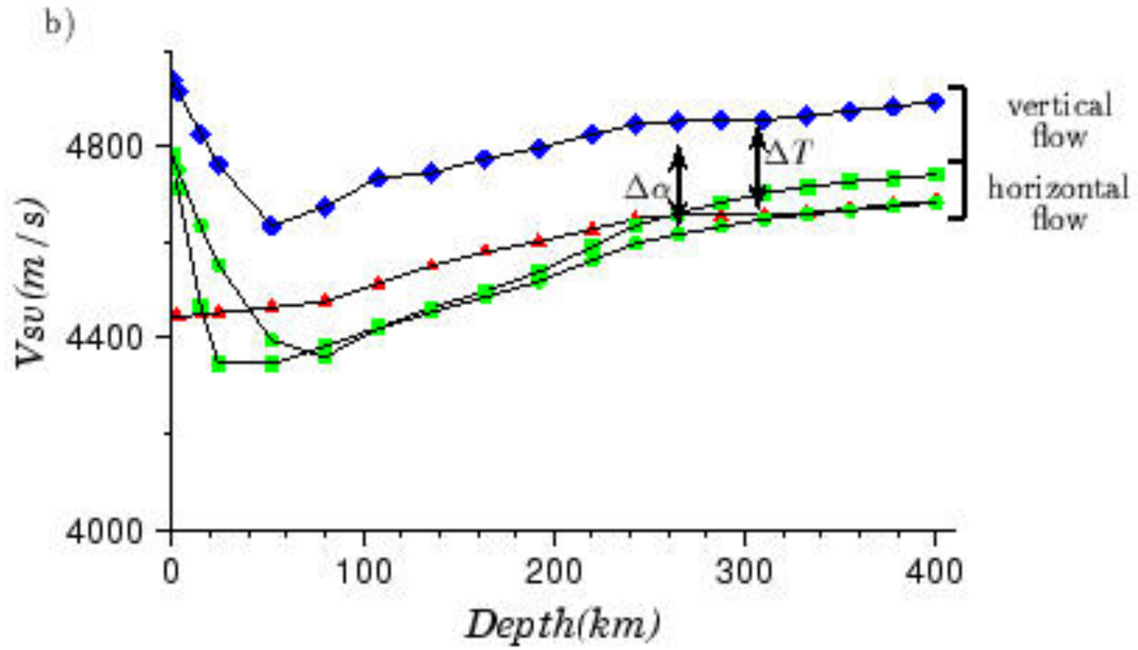
$\Delta\alpha$: Anisotropy Effect (CPO)

ΔT:Temperature Effect

$$\Delta\alpha \approx \Delta T$$



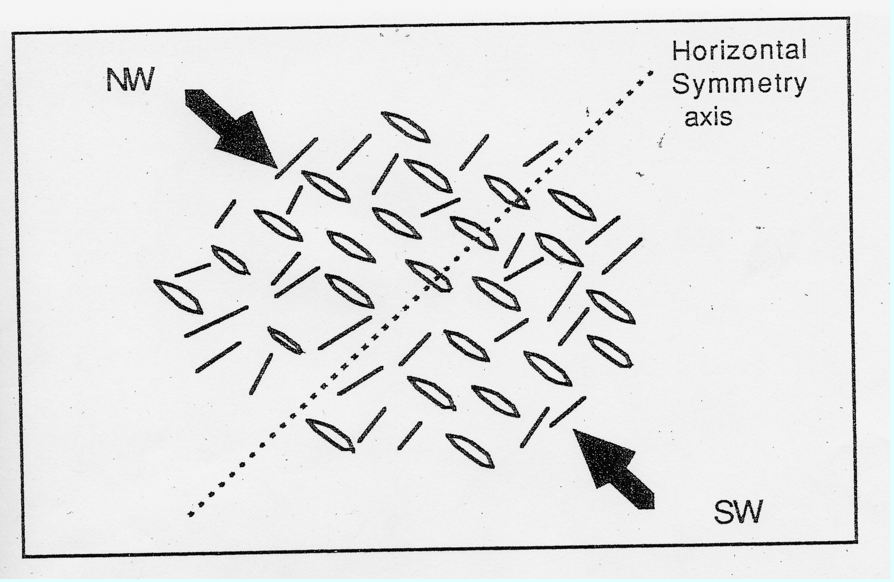
Olivine (60%) +Opx (40%)



Montagner & Guillot, 2002

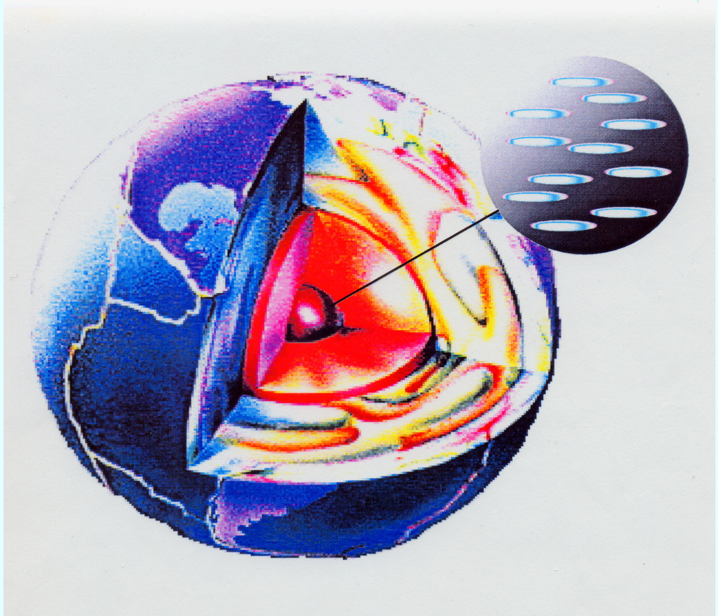
Other effects: Cracks, fluid inclusions-S.P.O.: (shape preferred orientation-stress field)

Crust (+lithosphere, asthenosphere)



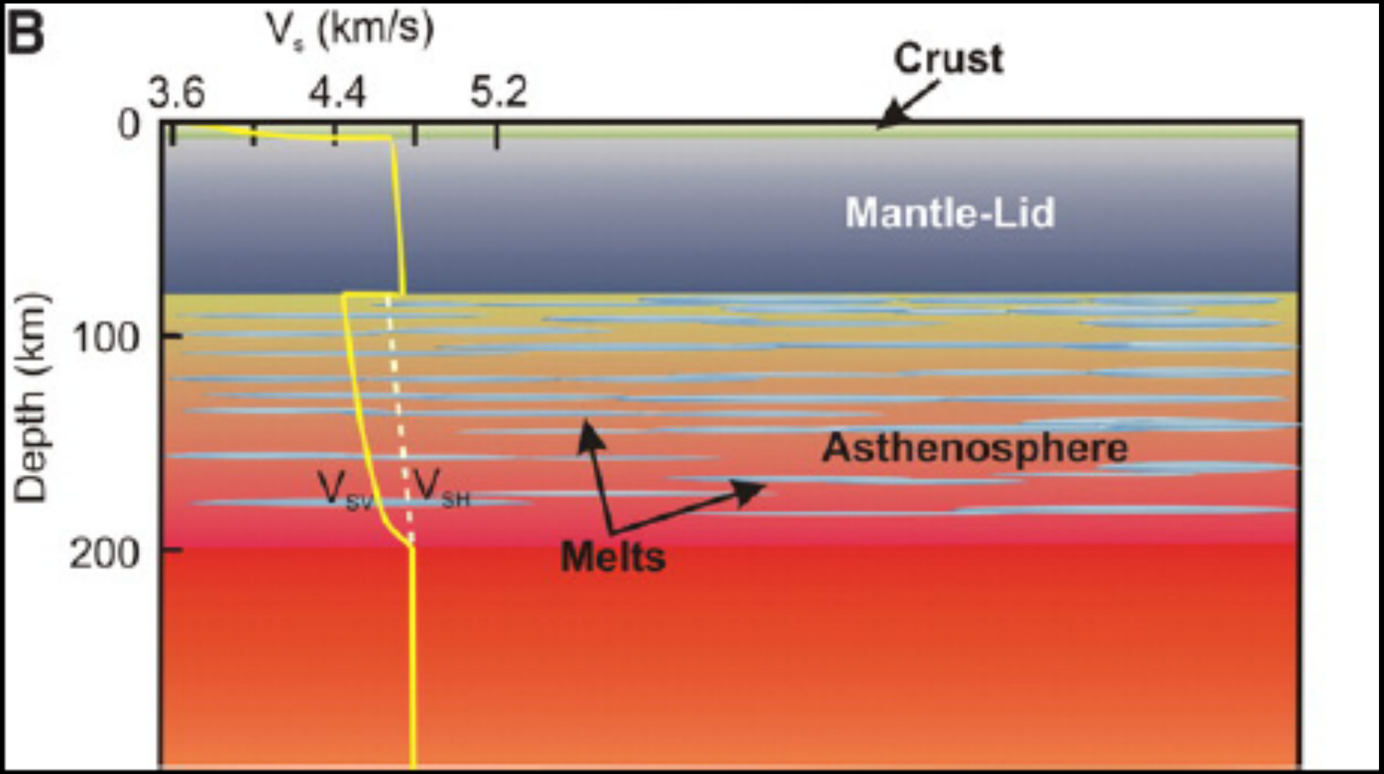
(Babuska and Cara, 1991)

Inner core



(Singh et al., 2001)

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



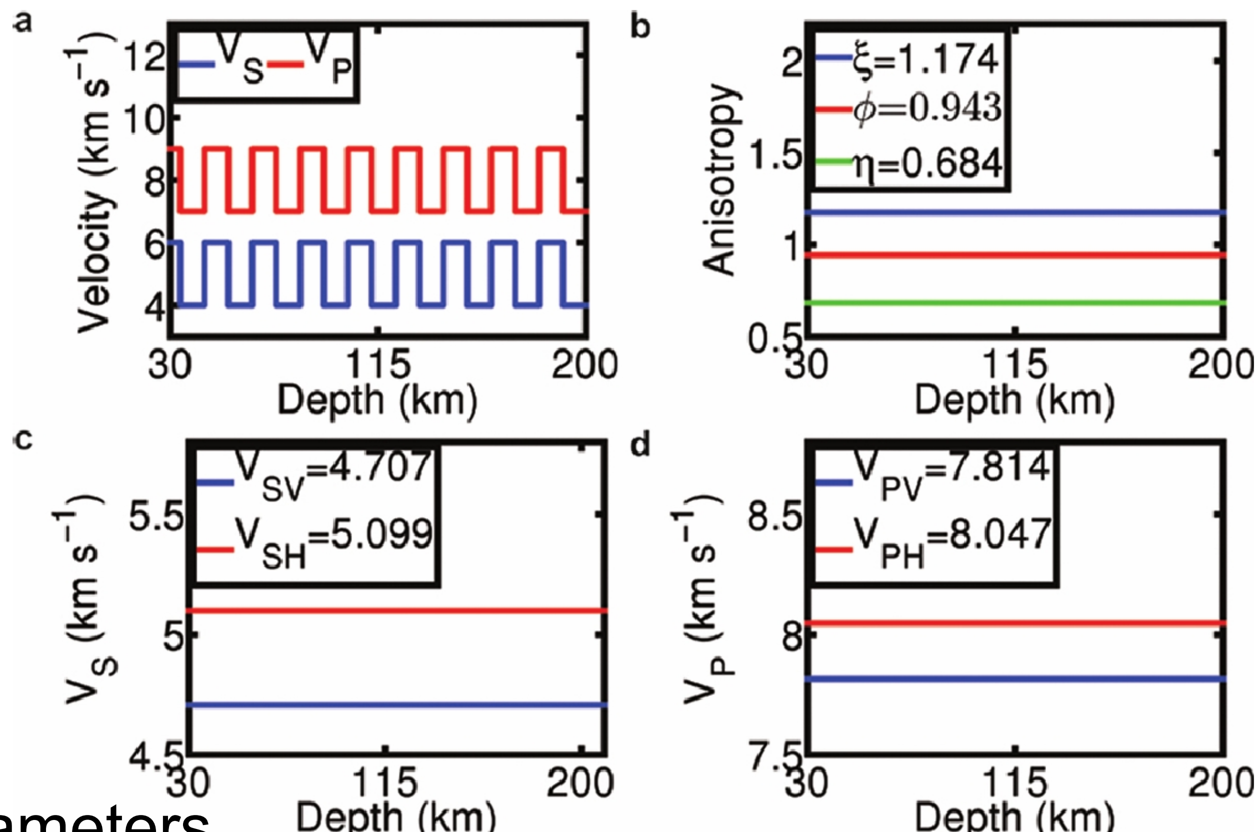
→ *Radial anisotropy (Kawakatsu et al. 2009)*
V.T.I. Vertical Transversely Isotropic medium: 5 parameters
($A=\rho V_{PH}^2$, $C=\rho V_{PV}^2$, F, $L= V_{SV}^2$, $N= V_{SH}^2$)

Effective medium theory: Stratified medium (Fine Layering)

Backus (1962) => Homogenization technique (Capdeville et al., 2008…)

PITL:
Periodic,
Isotropic
Two-Layered
Medium

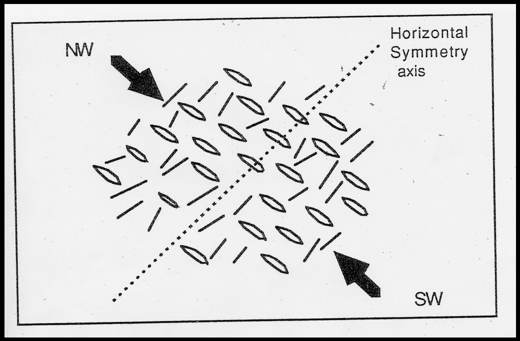
$L^{-1}=\langle\mu^{-1}\rangle$ (V_{SV})
$N=\langle\mu\rangle$ (V_{SH})
$\xi = N/L$, $\phi = C/A$,
$\eta = F/(A-2L)$

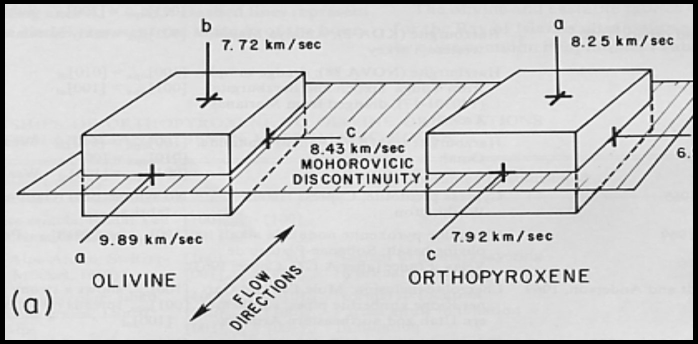


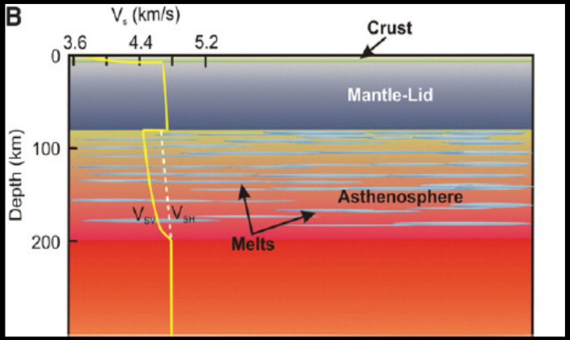
5 independent parameters
V_{s1}, V_{p1}, V_{s2}, V_{p2}, p_1 (respective Thickness of layers): V.T.I.

Wang et al. (2013)

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





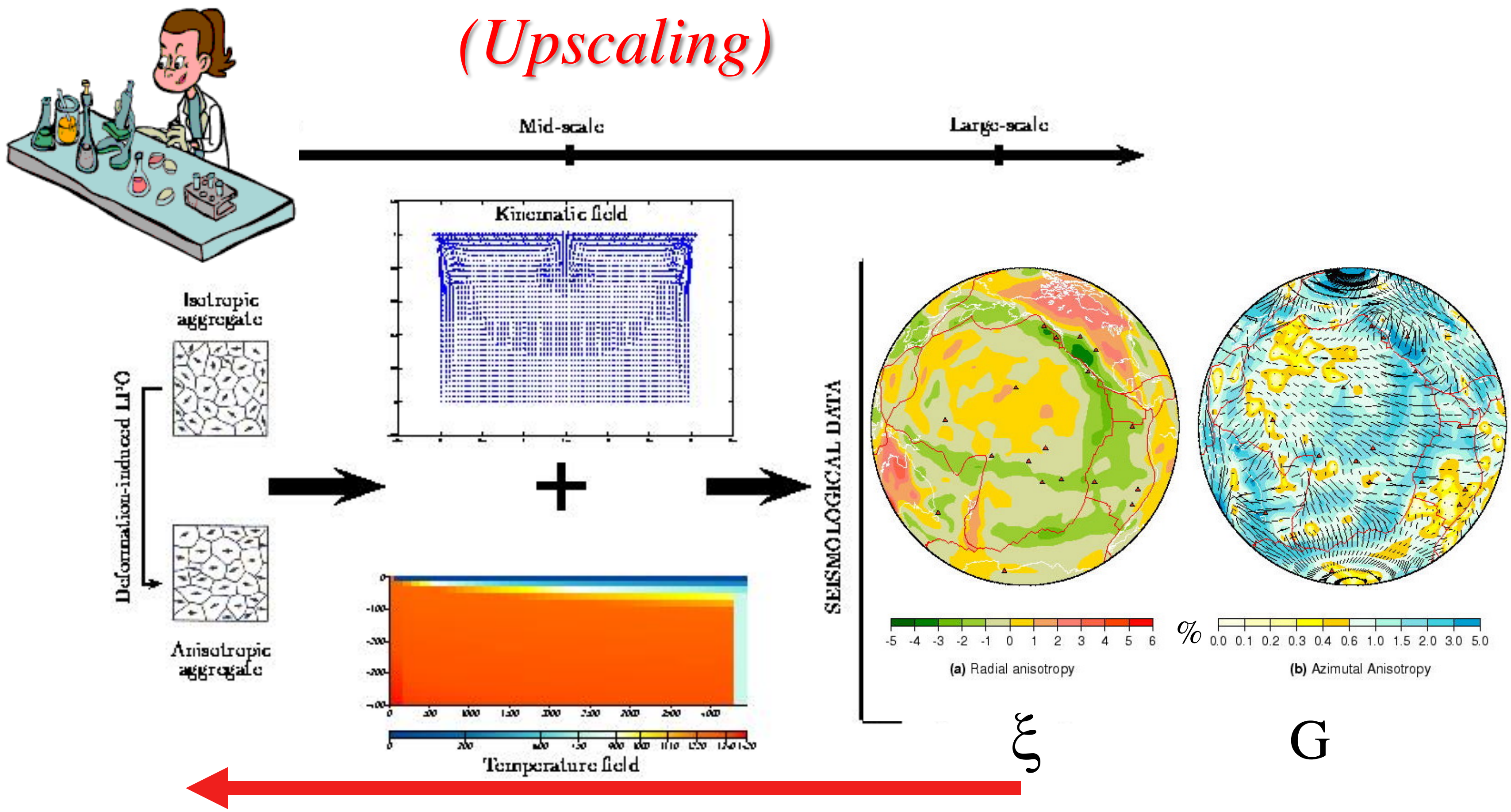


- *Mineralogy, Water and fluid content*
- *Present day tectonic, geodynamic processes*
- *Past processes (frozen anisotropy)*
- *Monitoring of stress and strain fields*

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

Micro CPO (strain) Macro

(Upscaling)



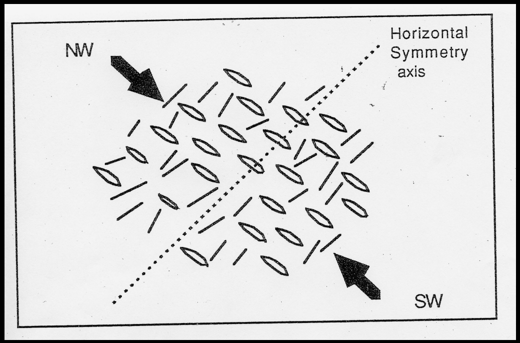
Mineralogical composition

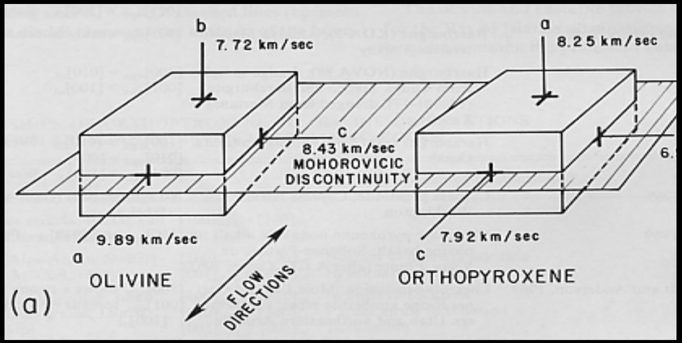
Mapping convection

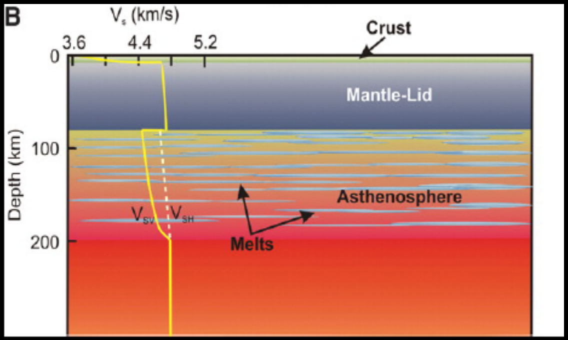
(Downscaling)

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)*

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

DATA?

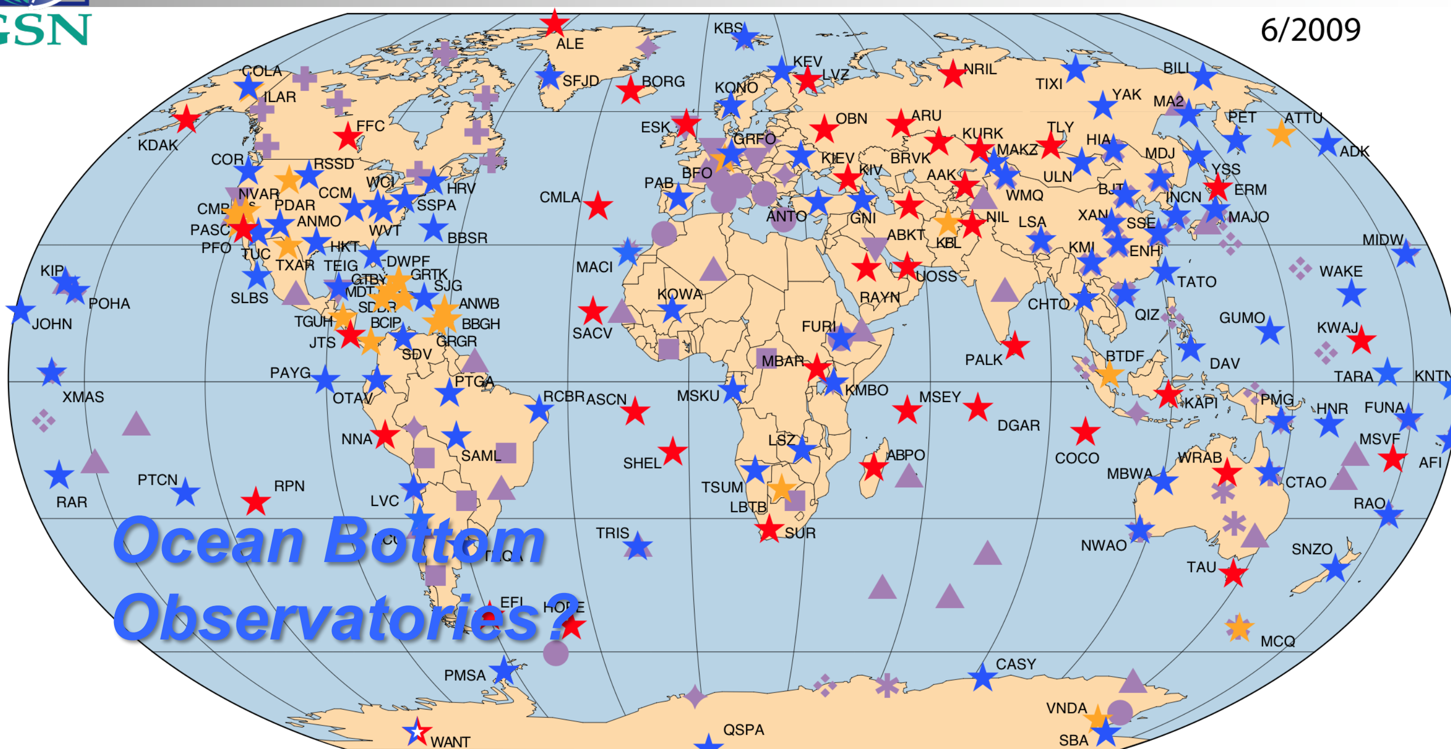
Broadband Seismic Data

GLOBAL SEISMOGRAPHIC NETWORK

FEDERATION OF BROADBAND DIGITAL SEISMIC NETWORKS (FDSN)

GSN

6/2009

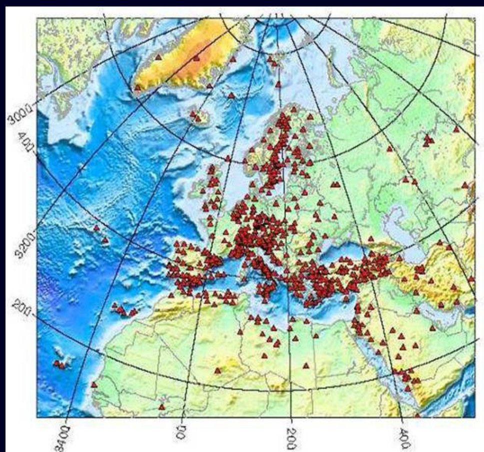


IRIS / IDA Stations | IRIS / USGS Stations | Affiliate Stations

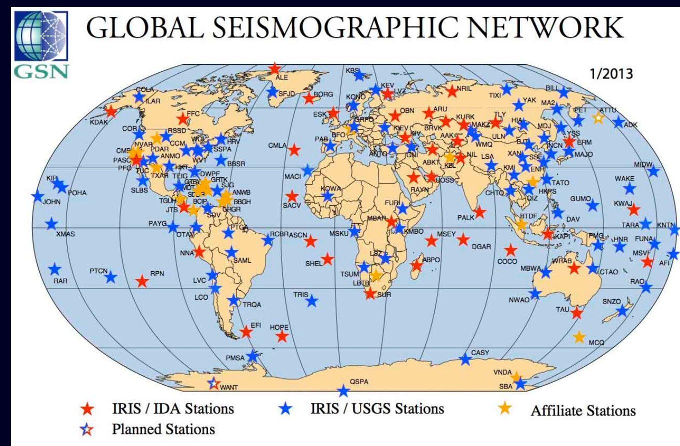
Planned Stations

Australia | Canada | France | Germany | Italy | Japan | U.S. | China | Spain | Other

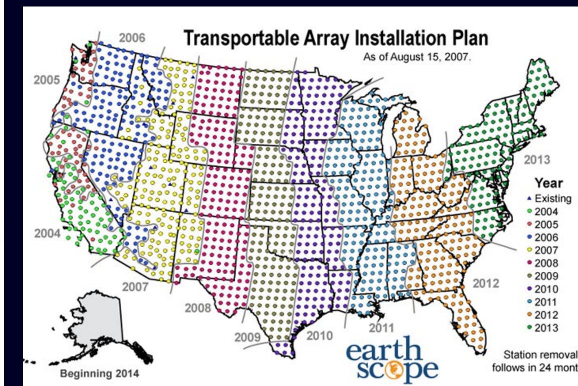
Data in Global & Regional Seismology



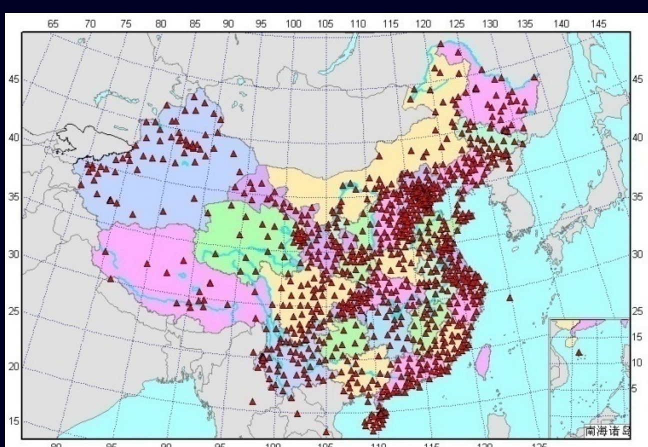
[www.geo.uib.no]



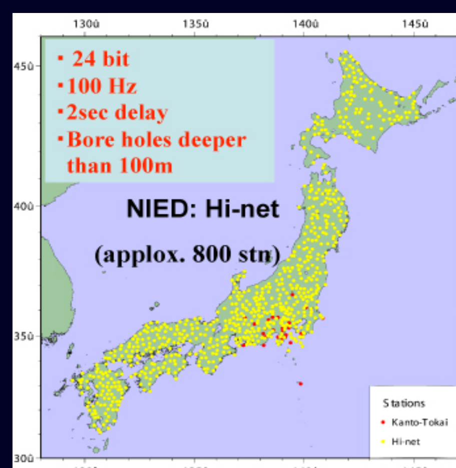
[www.iris.edu]



[web.mst.edu]



[data.earthquake.cn]

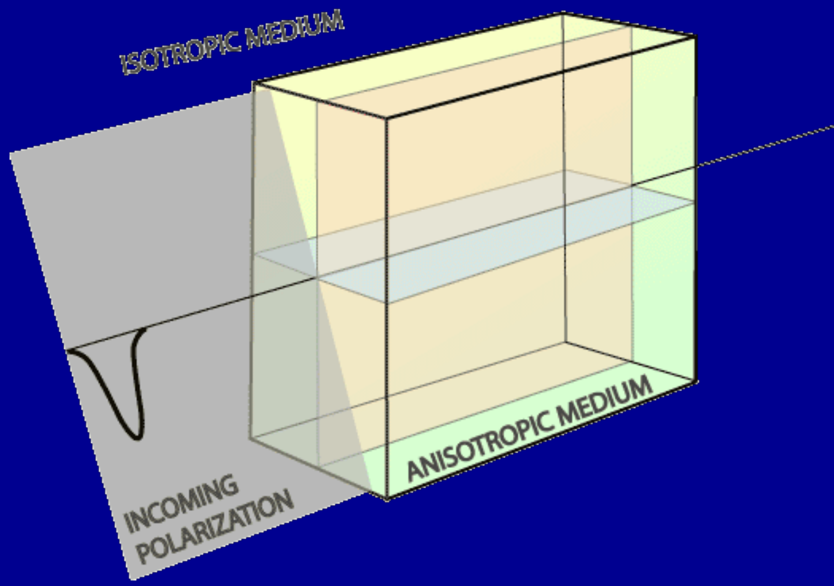


[drh.edm.bosai.go.jp]

Barruol et al., 2013

Different kinds of seismic data

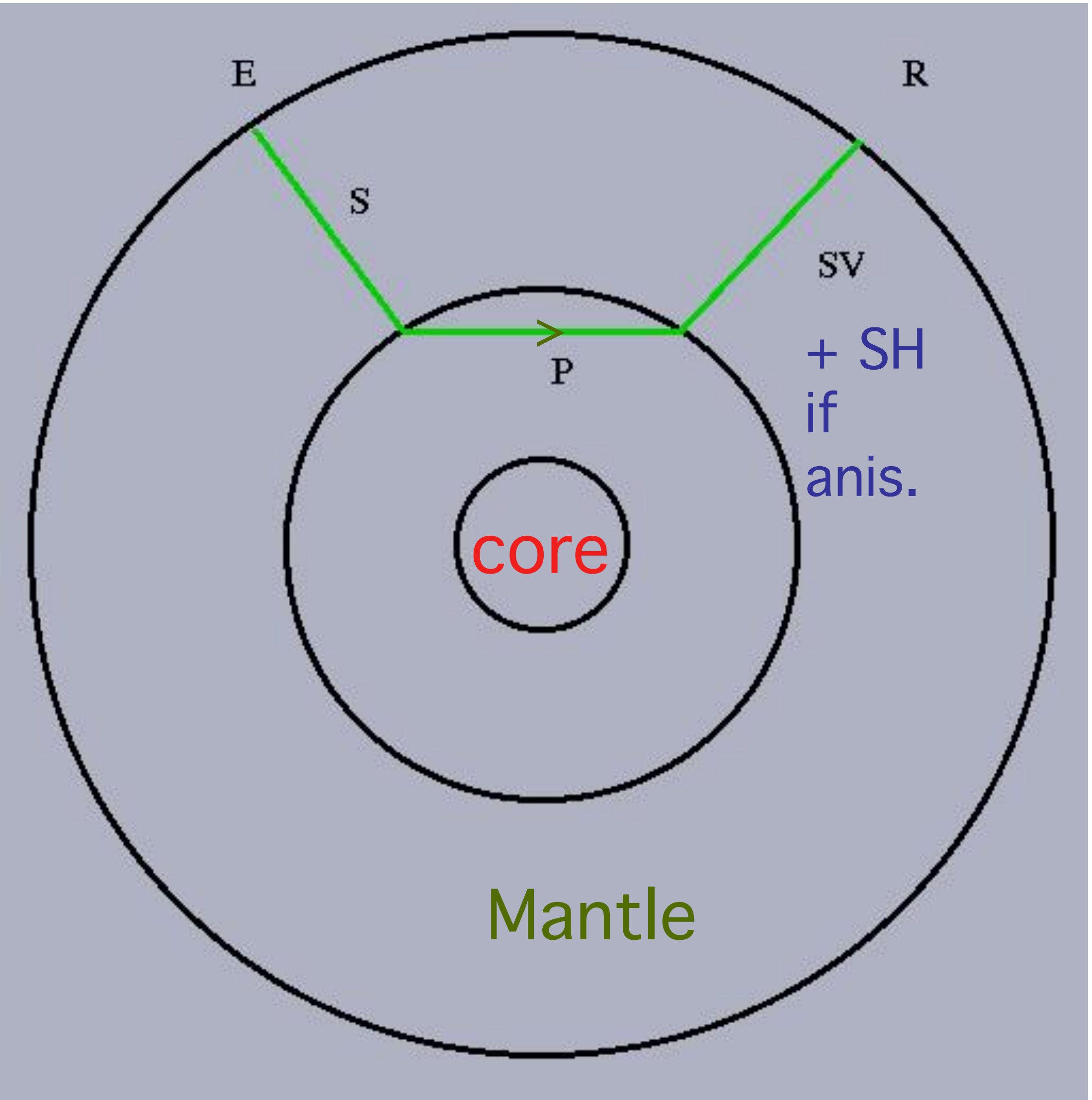
Body waves:
P-wave azimuthal variations
S-wave splitting, SKS

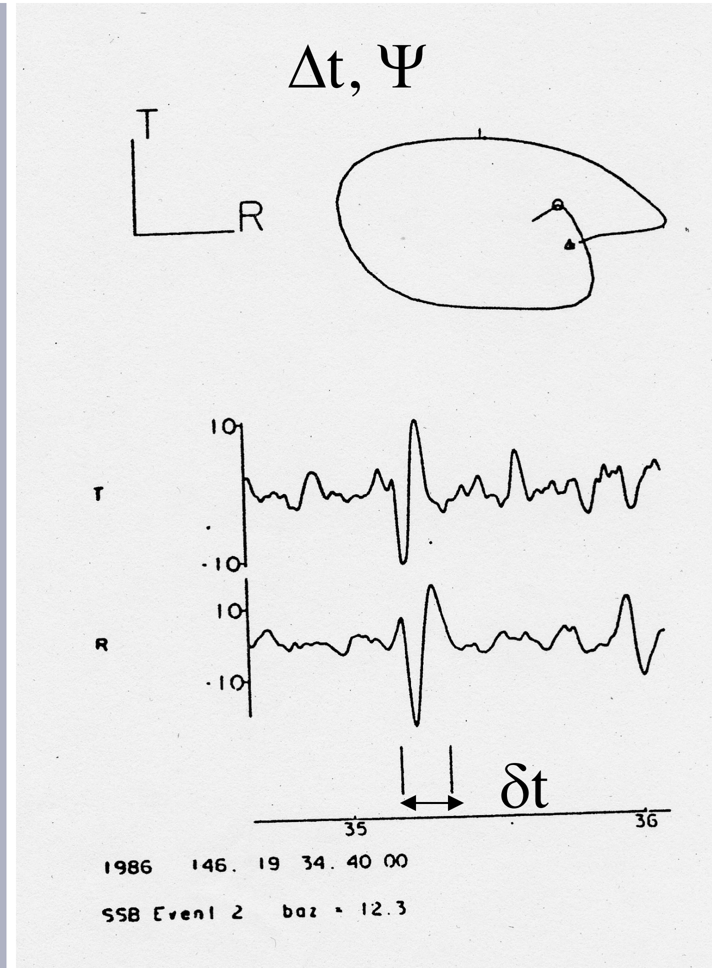


Animation courtesy of Ed Garnero

Surface waves:
-discrepancy Rayleigh-Love (polarization anisotropy)
-Azimuthal variations of phase (or group) velocities
- Effect on amplitudes

SKS- Splitting



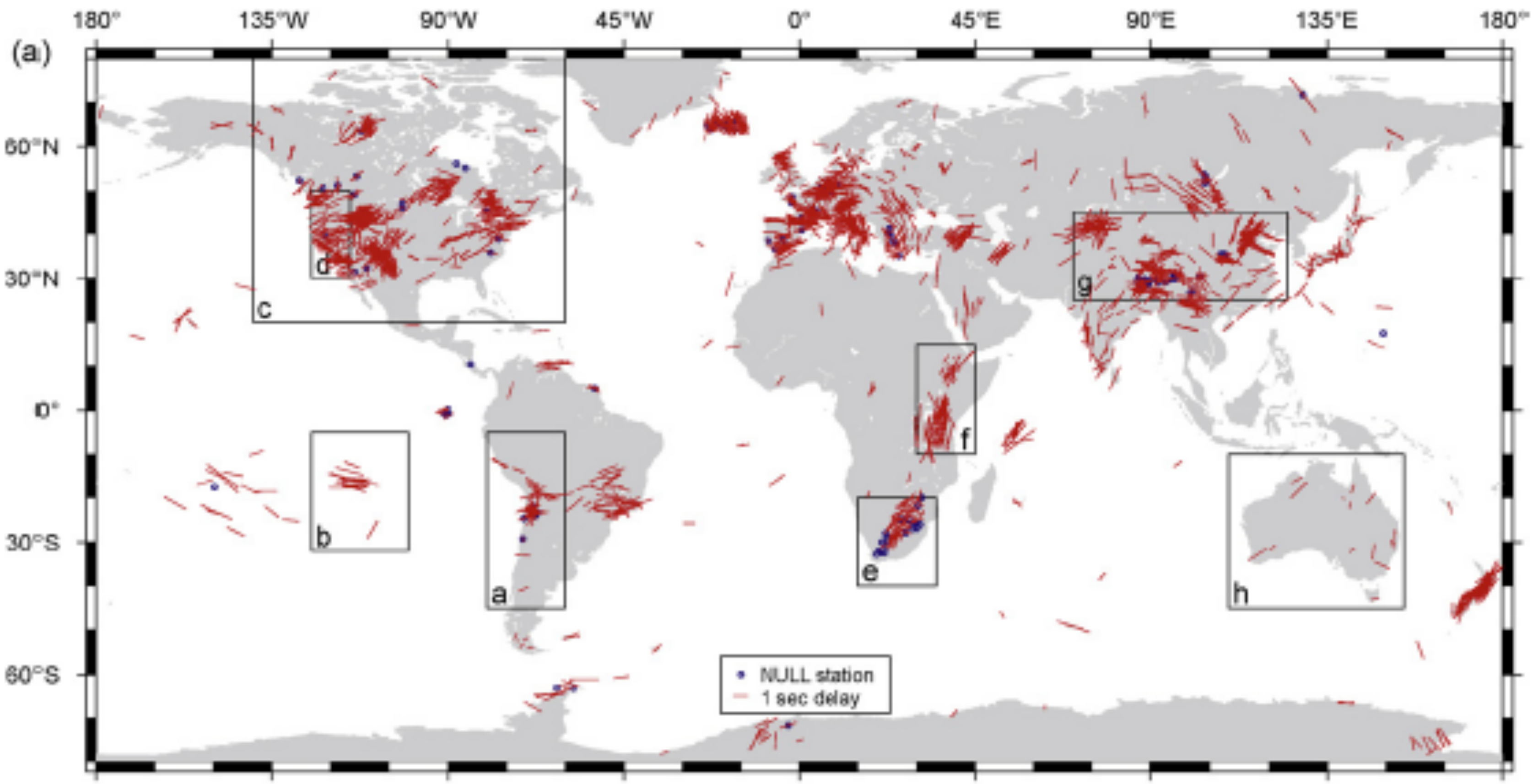


T

R

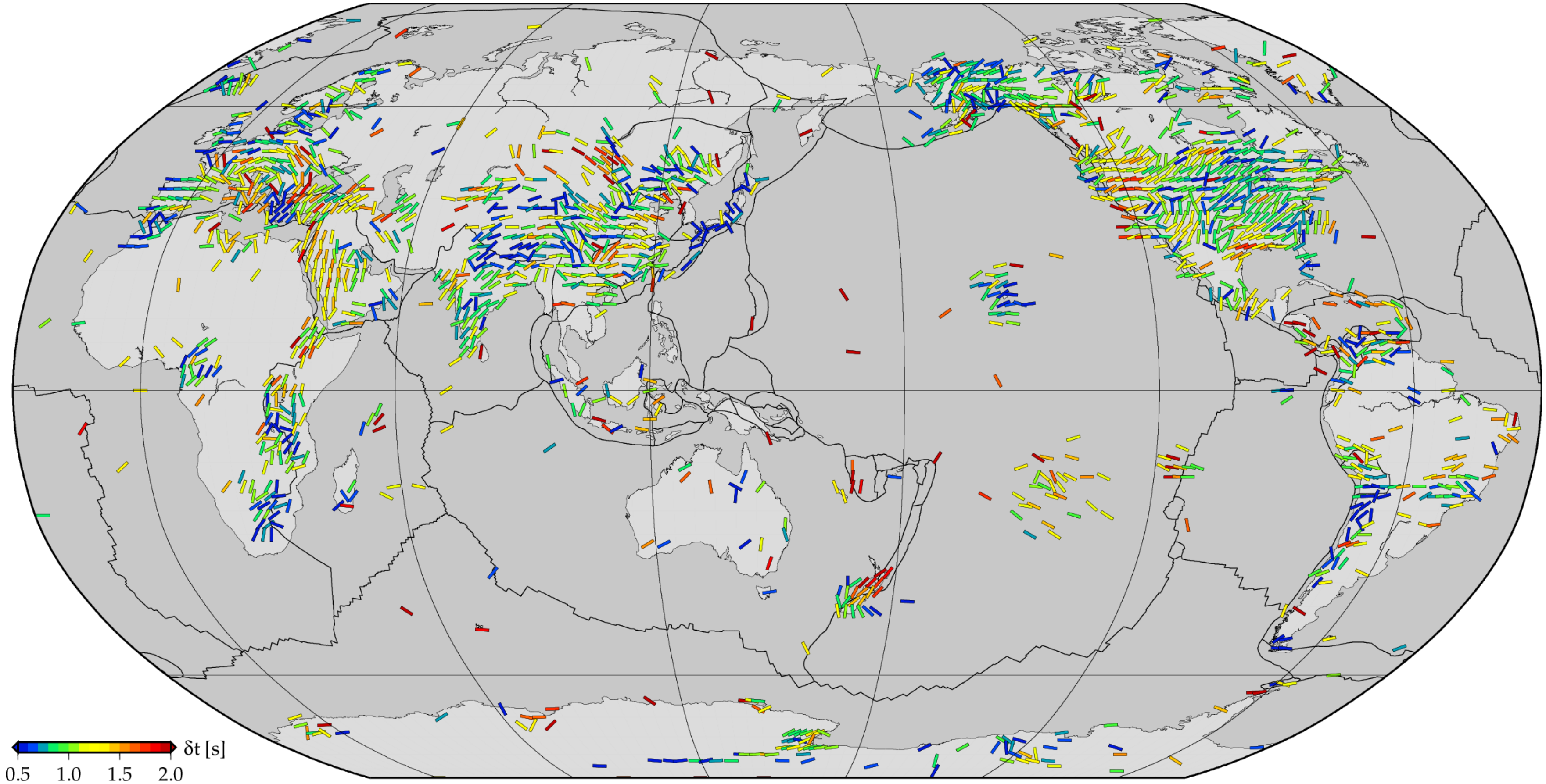
Vinnik et al., 1989
Silver et al., ….

S-wave splitting



Savage, 1999; Fouch, 2006;
Wüstefeld et al., 2009;

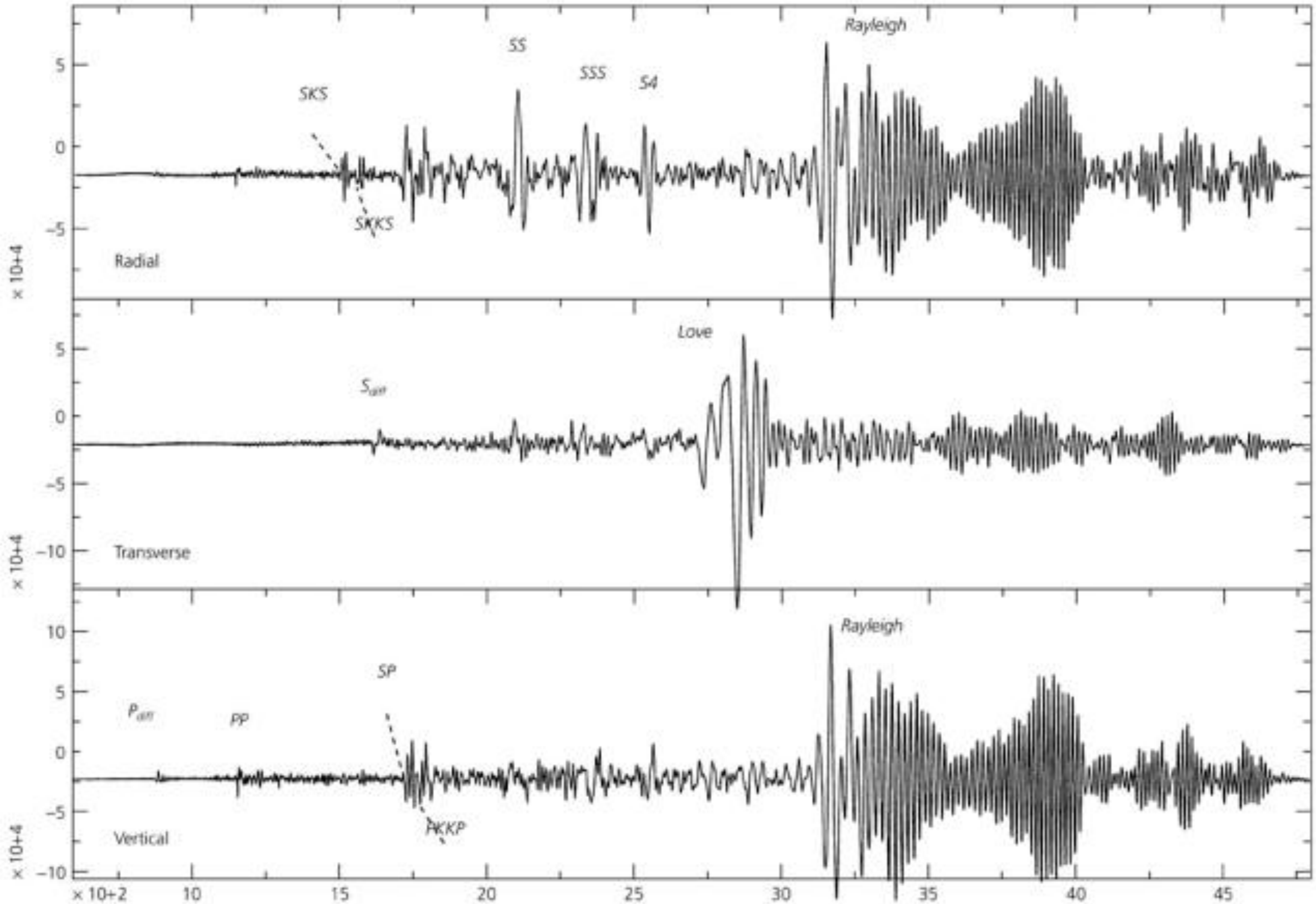
S-wave splitting: Updated SKS database (Becker, 2020)



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

⇨ Surface waves

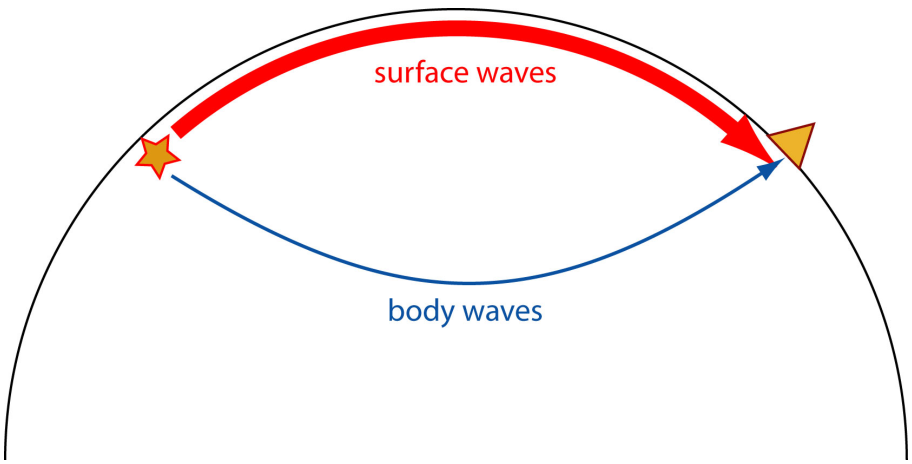
Figure 2.7-1: Seismograms recorded at a distance of 110°, showing surface waves.

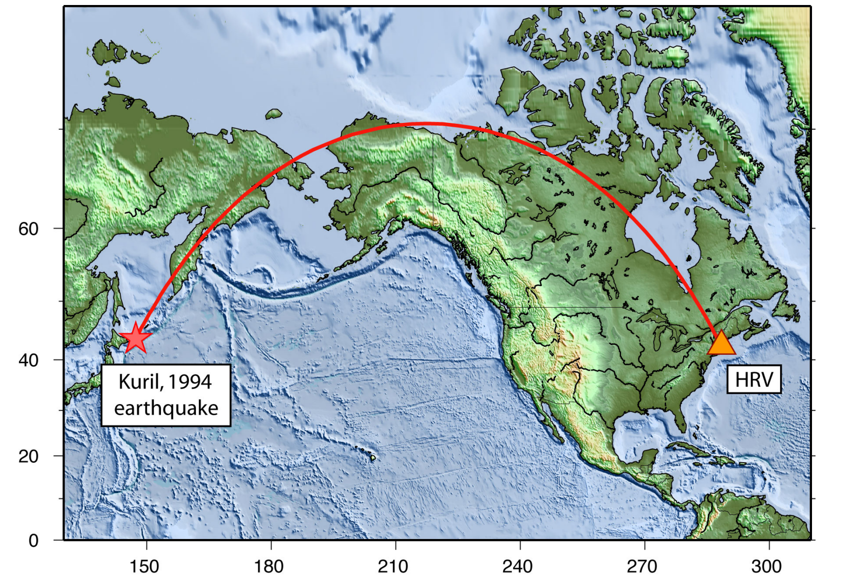


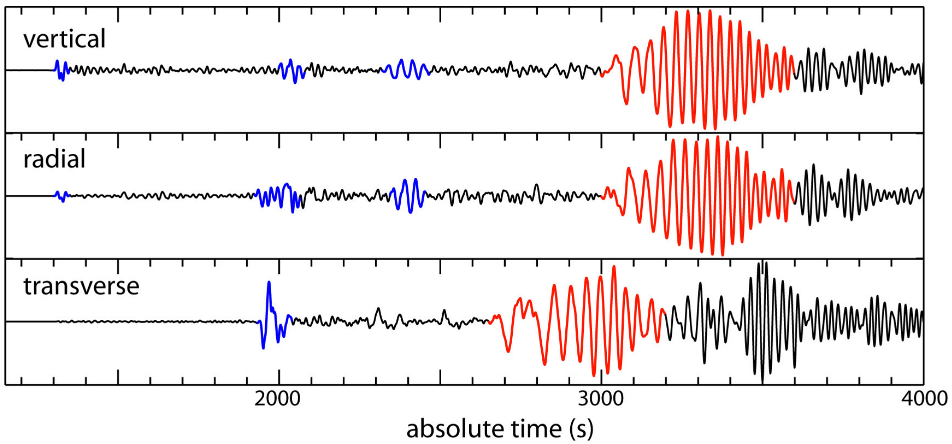
Stein & Wysession, 2009
Barbara

surface-wave tomography

Seismic data





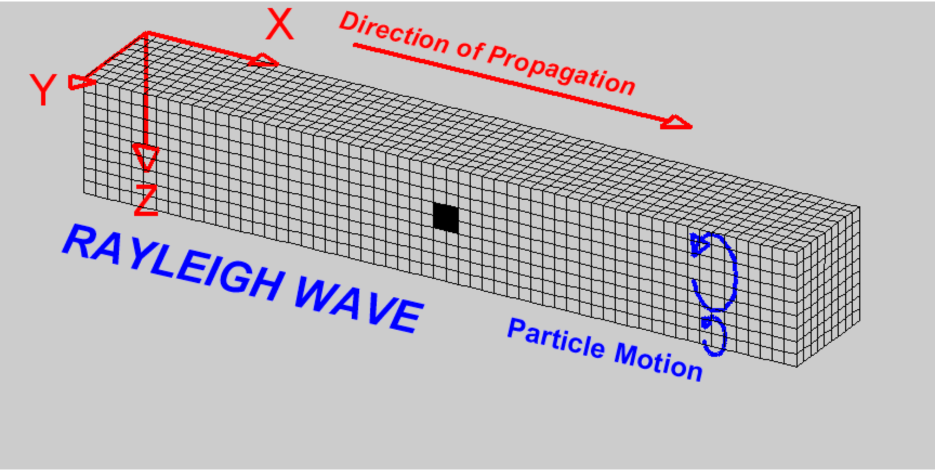


Body waves sample deep parts of the Earth

Surface waves sample the crust and upper mantle

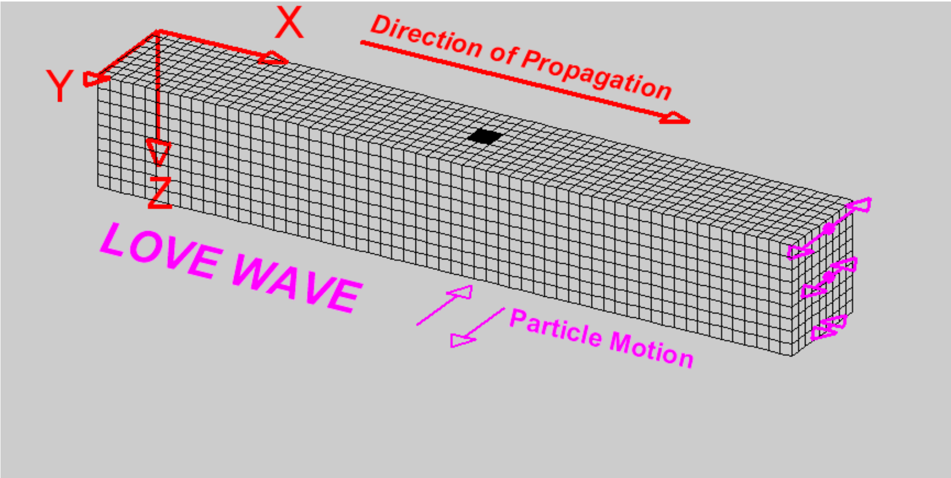
Surface waves

Rayleigh waves



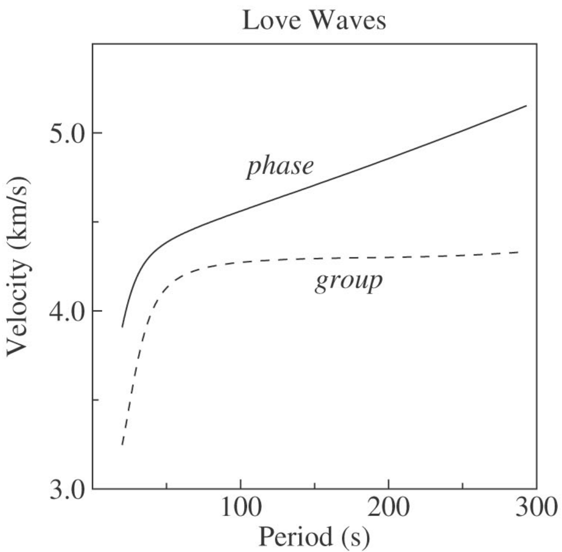
P-SV Spheroidal modes

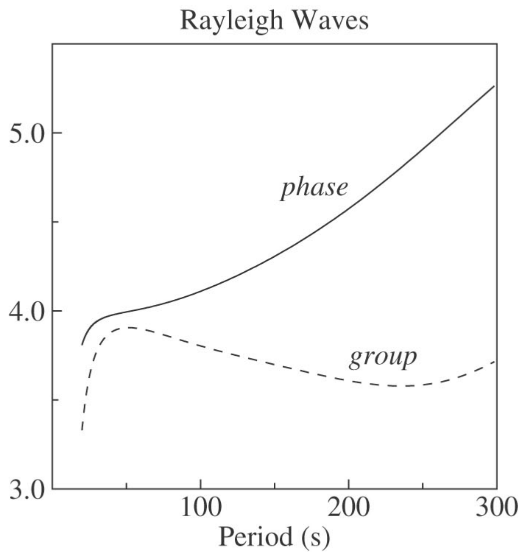
Love waves



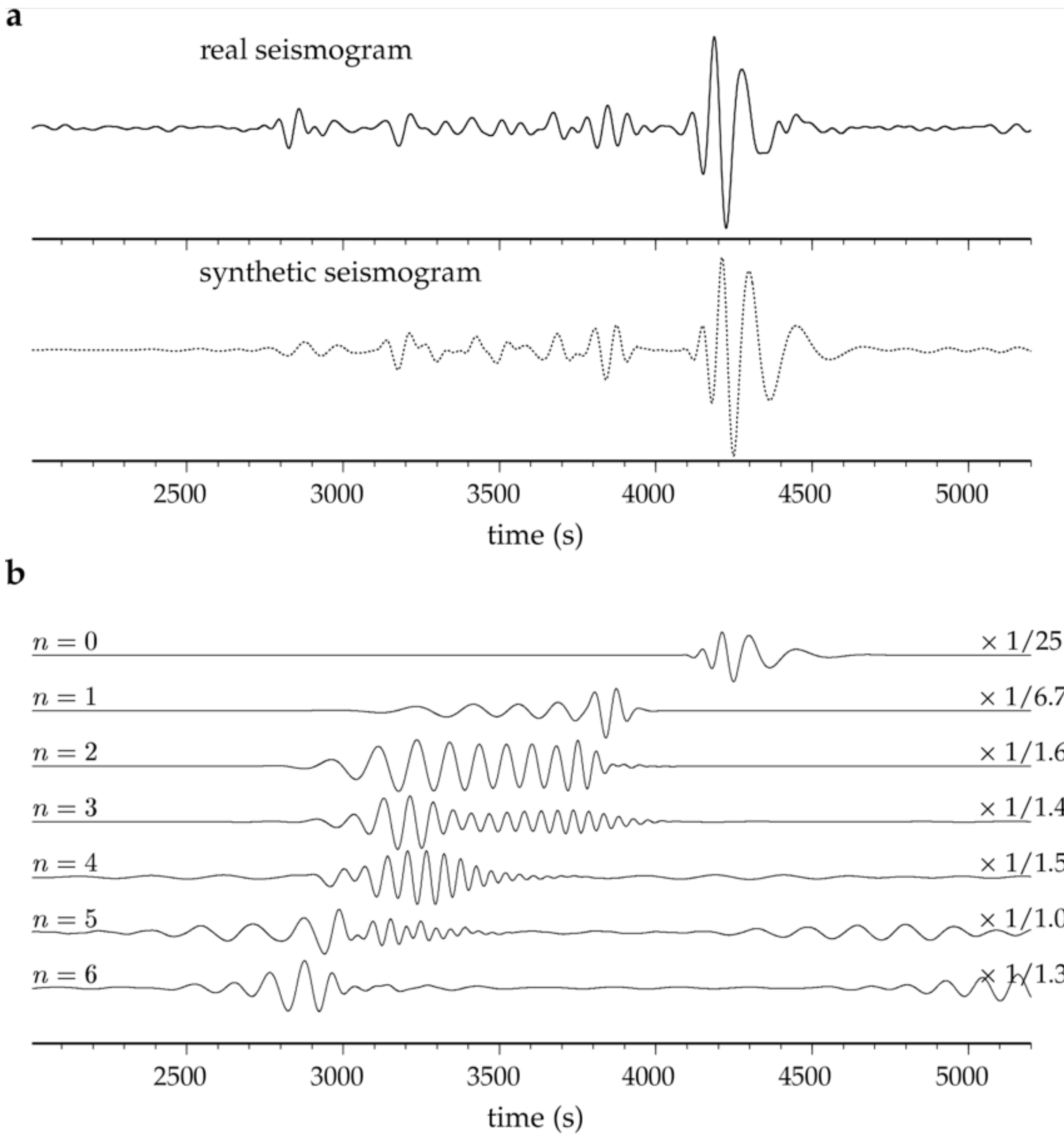
SH Toroidal modes

Surface waves are dispersive.





Example of seismogram (Rayleigh wave)



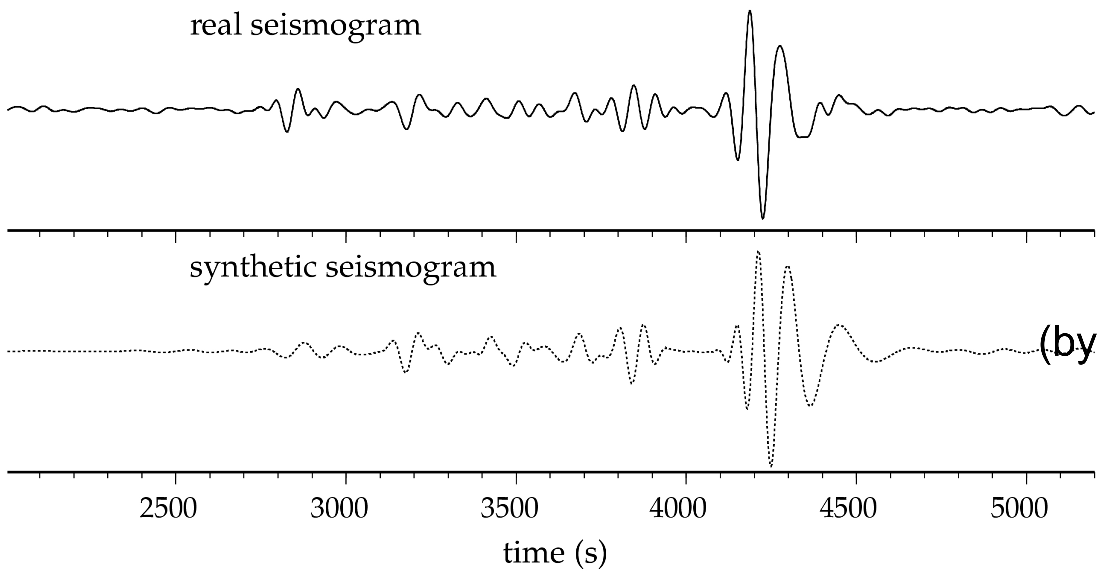
*Synthetic seismogram by **normal mode summation***

Fundamental mode

Higher modes

Beucler, 2003

3-component Seismogram Inversion



(by normal mode summation)

Different approaches:

-***Phase information***: measurement of **phase and group velocity dispersion curves of fundamental and higher modes** along paths; regionalization + inversion at depth (classical technique)

-***Waveform inversion*** => Adjoint Tomography, …

Seismic Anisotropy?

Anisotropic Tomographic Technique

- Forward Problem: Theory **d=g(m)**

d data space: observables + C_d

SEISMIC DATA: SEISMOGRAMS

m model parameter space + C_m

- Reference Earth model m_0:

$d_0 = g(m_0)$

- Kernels $\partial g/\partial m$

- Inverse Problem: $\mathbf{m-m_0 = \tilde{g}^{-1} (d-d_0)}$

Barbara (next week)

Effect of anisotropy on the phase of surface waves

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

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

ε strain tensor, u displacement, 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

13 parameters, functions of C_{ijkl} (3x3x3x3) ⇔ c_{pq} (6x6)

Constant term (0 Ψ-azimuthal term: α_0)

$$A = \rho V_{PH}^2 = \frac{3}{8}(C_{11} + C_{22}) + \frac{1}{4}C_{12} + \frac{1}{2}C_{66}$$

$$C = \rho V_{PV}^2 = C_{33}$$

$$F = \frac{1}{2}(C_{13} + C_{23})$$

$$L = \rho V_{SV}^2 = \frac{1}{2}(C_{44} + C_{55})$$

$$N = \rho V_{SH}^2 = \frac{1}{8}(C_{11} + C_{22}) - \frac{1}{4}C_{12} + \frac{1}{2}C_{66}$$

Equivalent V.T.I (Transversely Isotropic medium with vertical symmetry axis): 5 parameters

2 Ψ-azimuthal term:

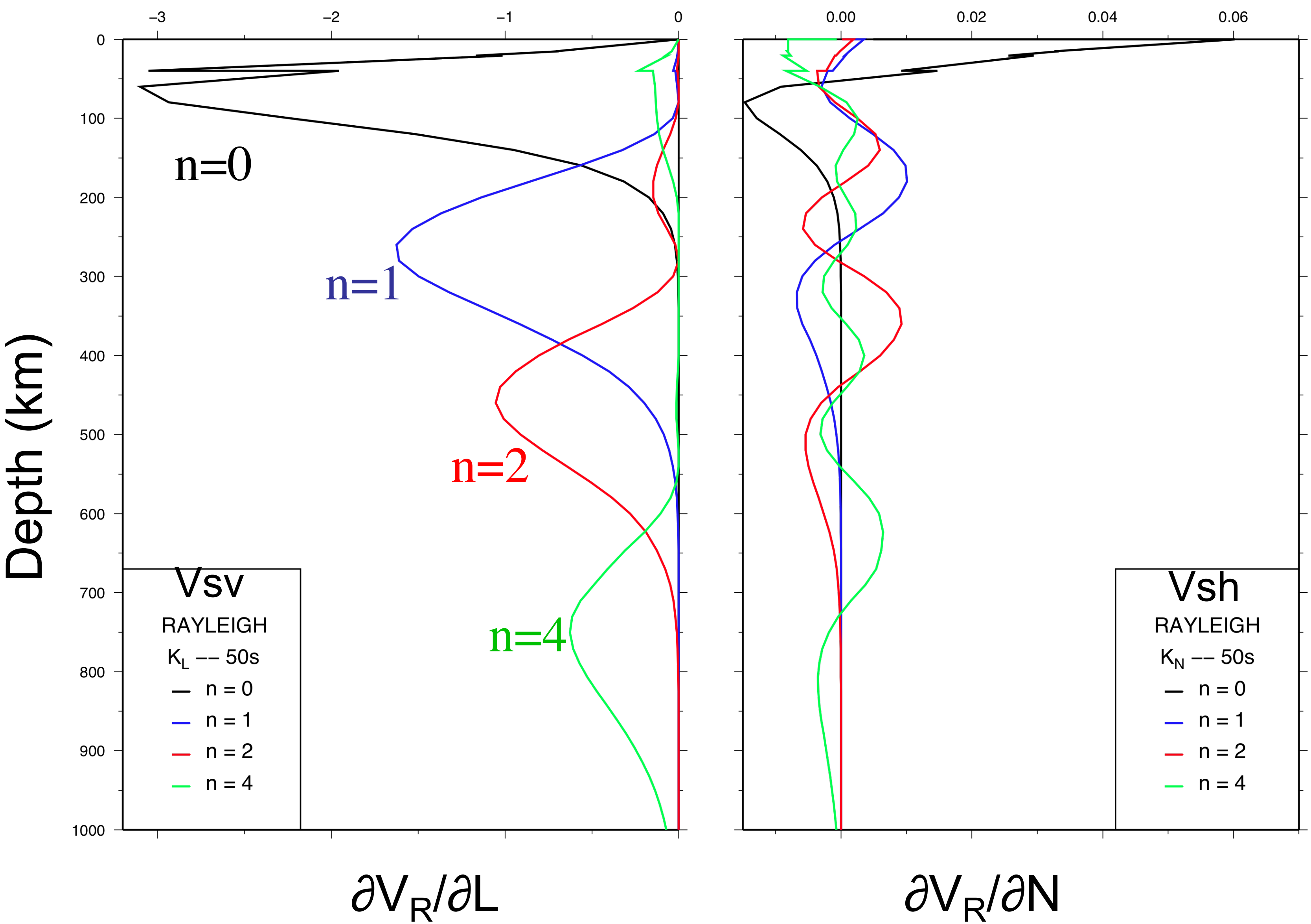
$\alpha_1 \cos 2\Psi$	$\alpha_2 \sin 2\Psi$
$B_c = \frac{1}{2}(C_{11} - C_{22})$	$B_s = C_{16} + C_{26}$
$G_c = \frac{1}{2}(C_{55} - C_{44})$	$G_s = C_{54}$
$H_c = \frac{1}{2}(C_{13} - C_{23})$	$H_s = C_{36}$

4 Ψ-azimuthal term:

$\alpha_3 \cos 4\Psi$	$\alpha_4 \sin 4\Psi$
$E_c = \frac{1}{8}(C_{11} + C_{22}) - \frac{1}{4}C_{12} - \frac{1}{2}C_{66}$	$E_s = \frac{1}{2}(C_{16} - C_{26})$

Azimuthal terms: 8 parameters

Fundamental - Higher modes: Depth Sensitivity Kernels
Rayleigh waves



•*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* $2\psi-$, $4\psi-$ *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: LPO

Tomographies of:

-S- Velocity

-Radial Anisotropy

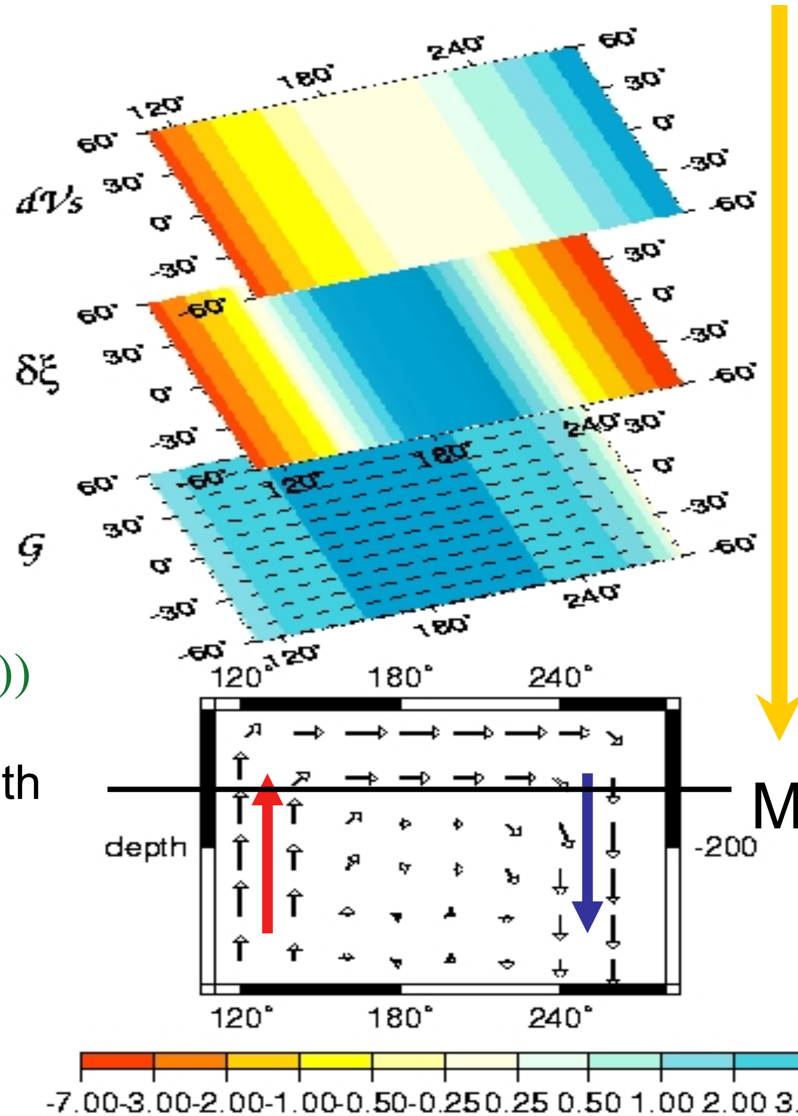
$\delta\xi = (V_{SH}^2 - V_{SV}^2)/V_{SV}^2$

-Azimuthal Anisotropy

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

At a given depth

Convective cell: anisotropic parameters



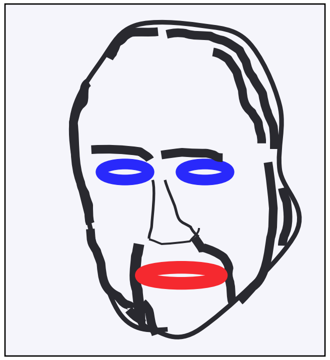
Interpretation (C.P.O.)

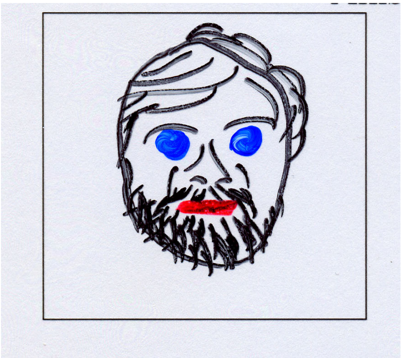
Map Flow

Imaging of famous geophysicists

Imaging of famous geophysicists

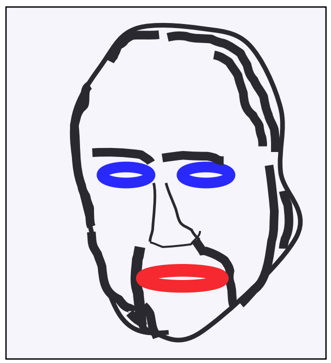
Anisotropic Imaging

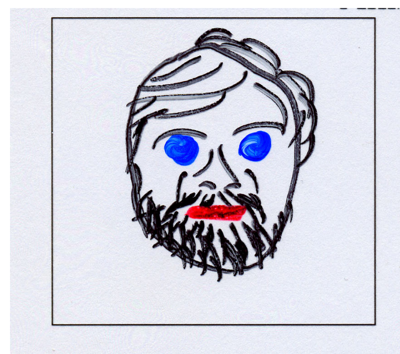




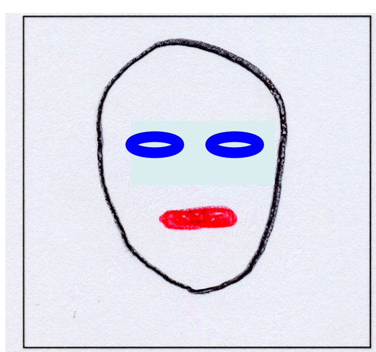
Imaging of famous geophysicists

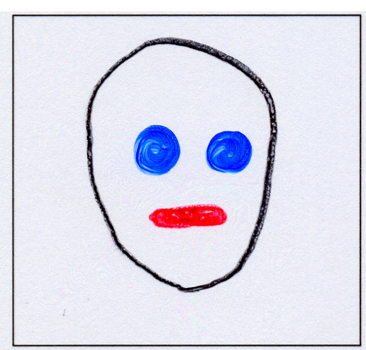
Anisotropic Imaging





Isotropic Imaging





Examples of applications of seismic anisotropy to geodynamic processes

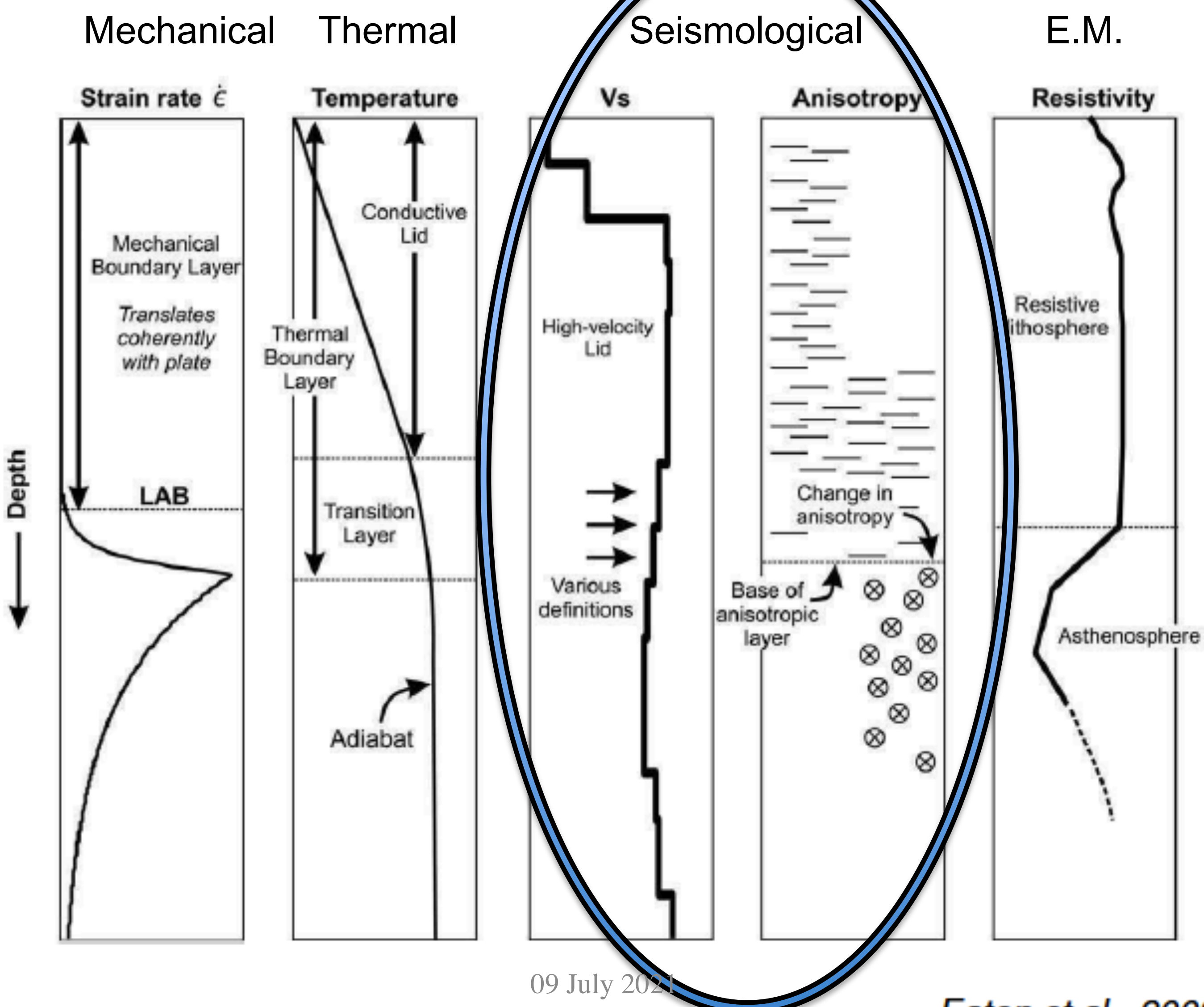
•Mapping of mantle convection (global scale)

•**Mapping of the LAB** (Lithosphere- Asthenosphere Boundary) Lithosphere roots (oceans- continents)

•Intrinsic versus Extrinsic anisotropy and attenuation

•Mantle Transition Zones (410-1000km depth range)

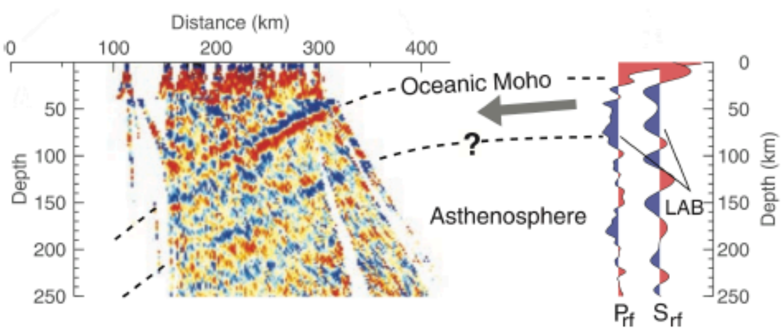
L.A.B.: Lithosphere-Asthenosphere Boundary
(many different approaches and definitions)



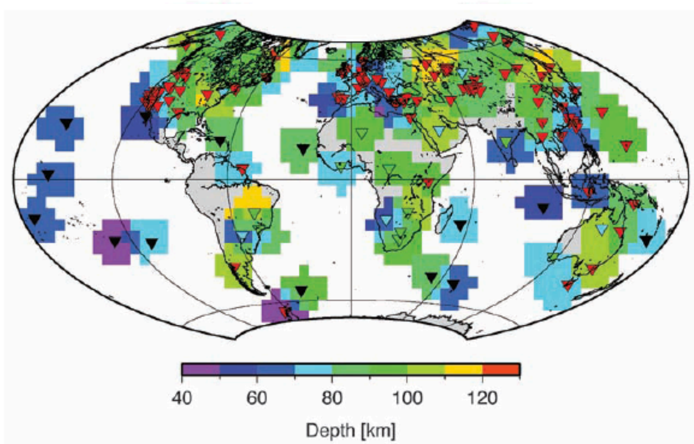
Eaton et al., 2008

LAB : from seismic data

Receiver functions

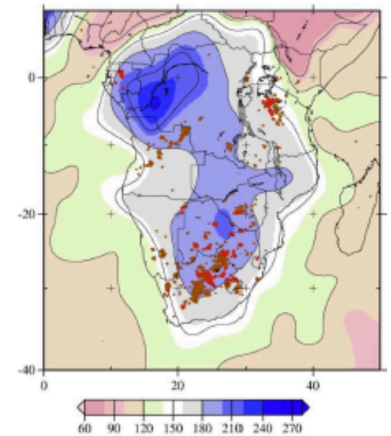


Kawakatsu et al., 2009

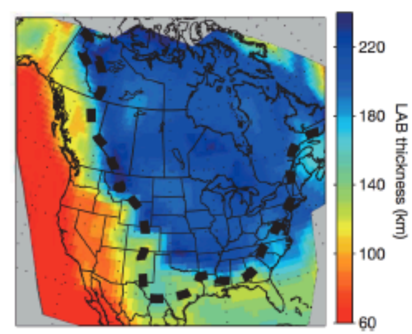


Rychert & Shearer, 2009

Surface waves



Fishwick, 2010



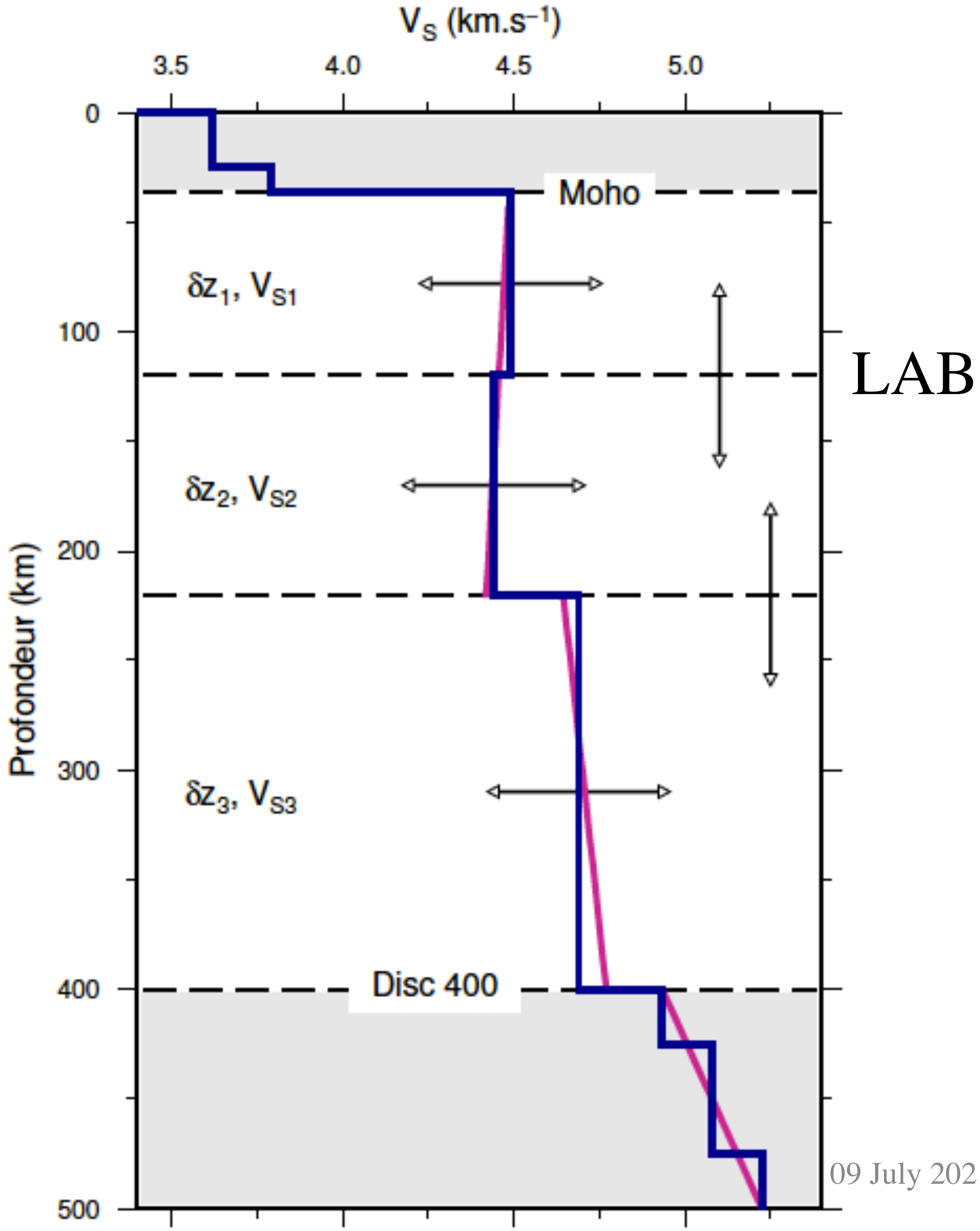
+SKS *Yuan & Romanowicz, 2010*

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

Mid-lithospheric Discontinuity (Yuan & Romanowicz, 2010)

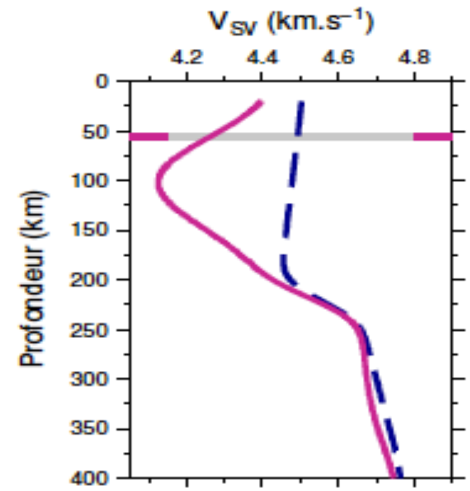
From Surface wave dispersion

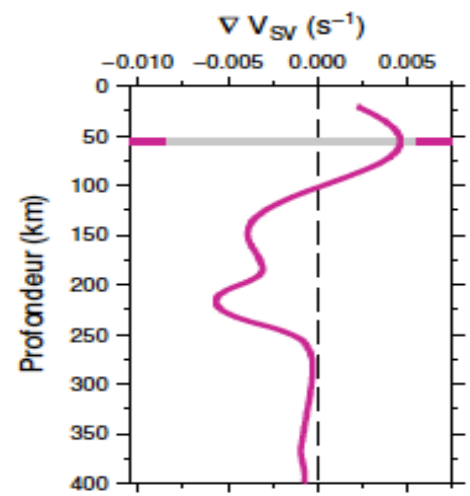
Statistical Monte-Carlo Approach



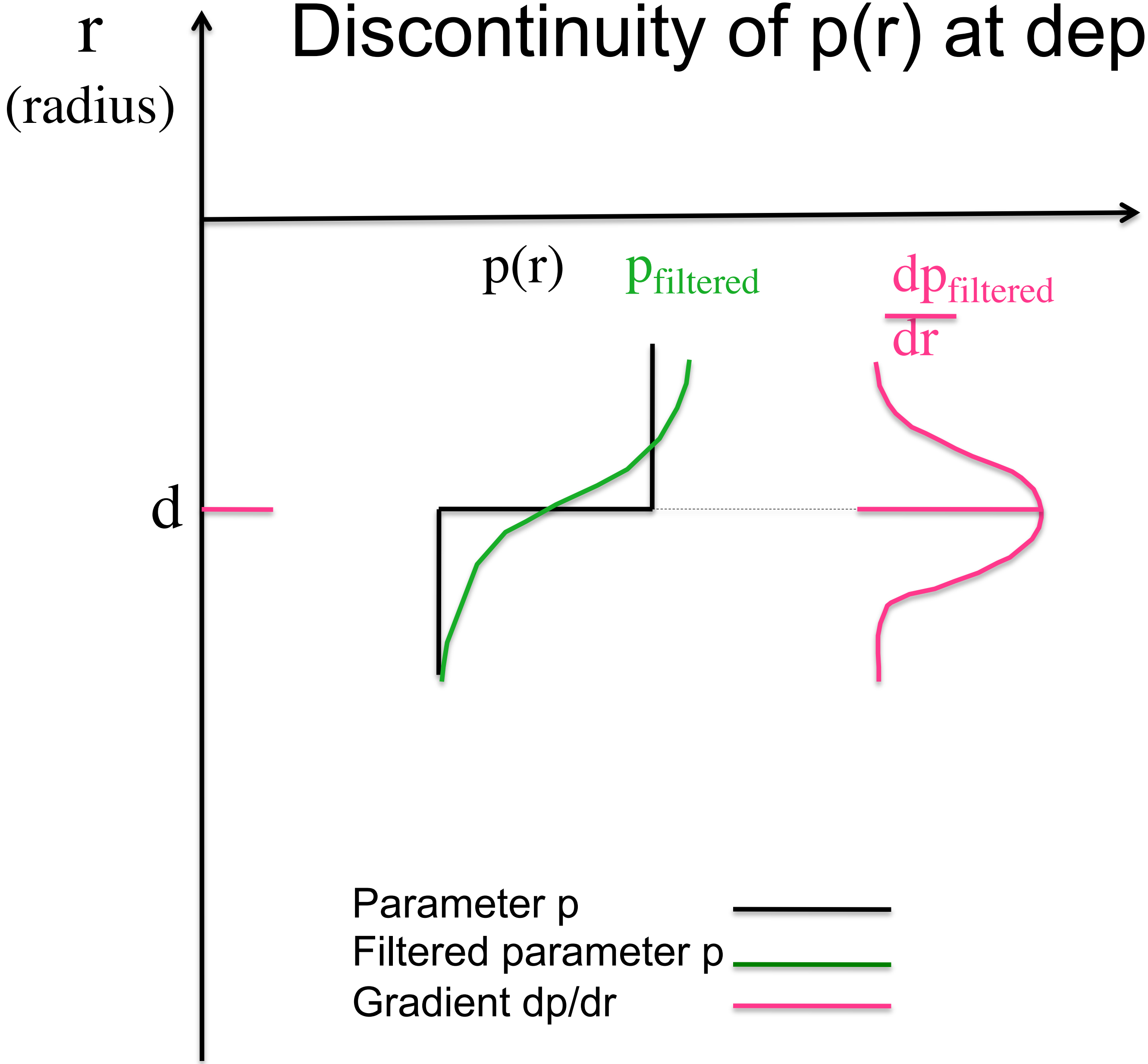
First order Perturbation theory

Proxy from parameter Vsv





Discontinuity of p(r) at depth d

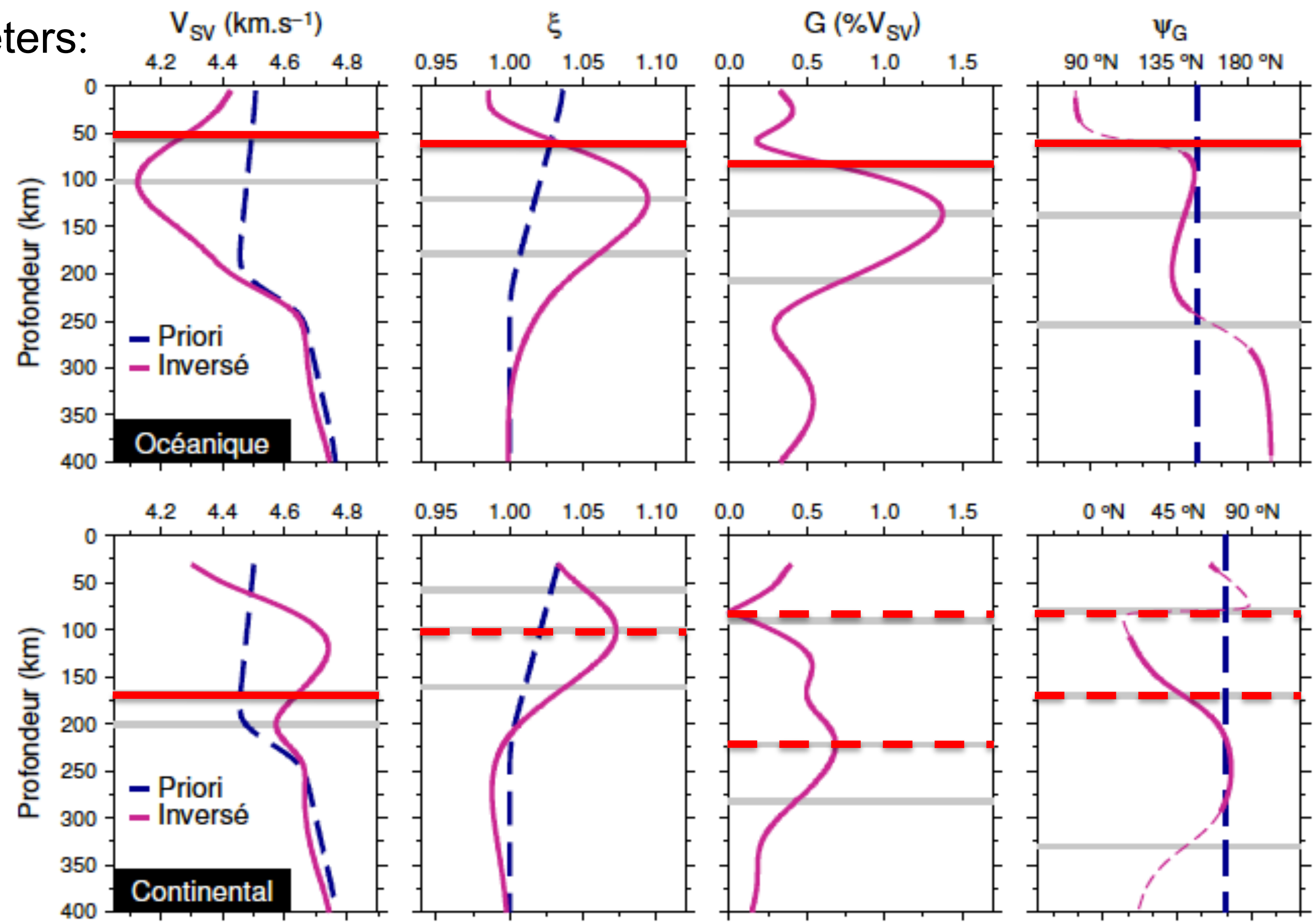


Other proxies from parameters obtained from anisotropy tomographic models

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

Oceanic profile
$\lambda=35^o$, $\phi=-35^o$

Continental profile
$\lambda=63^o$, $\phi=-96^o$



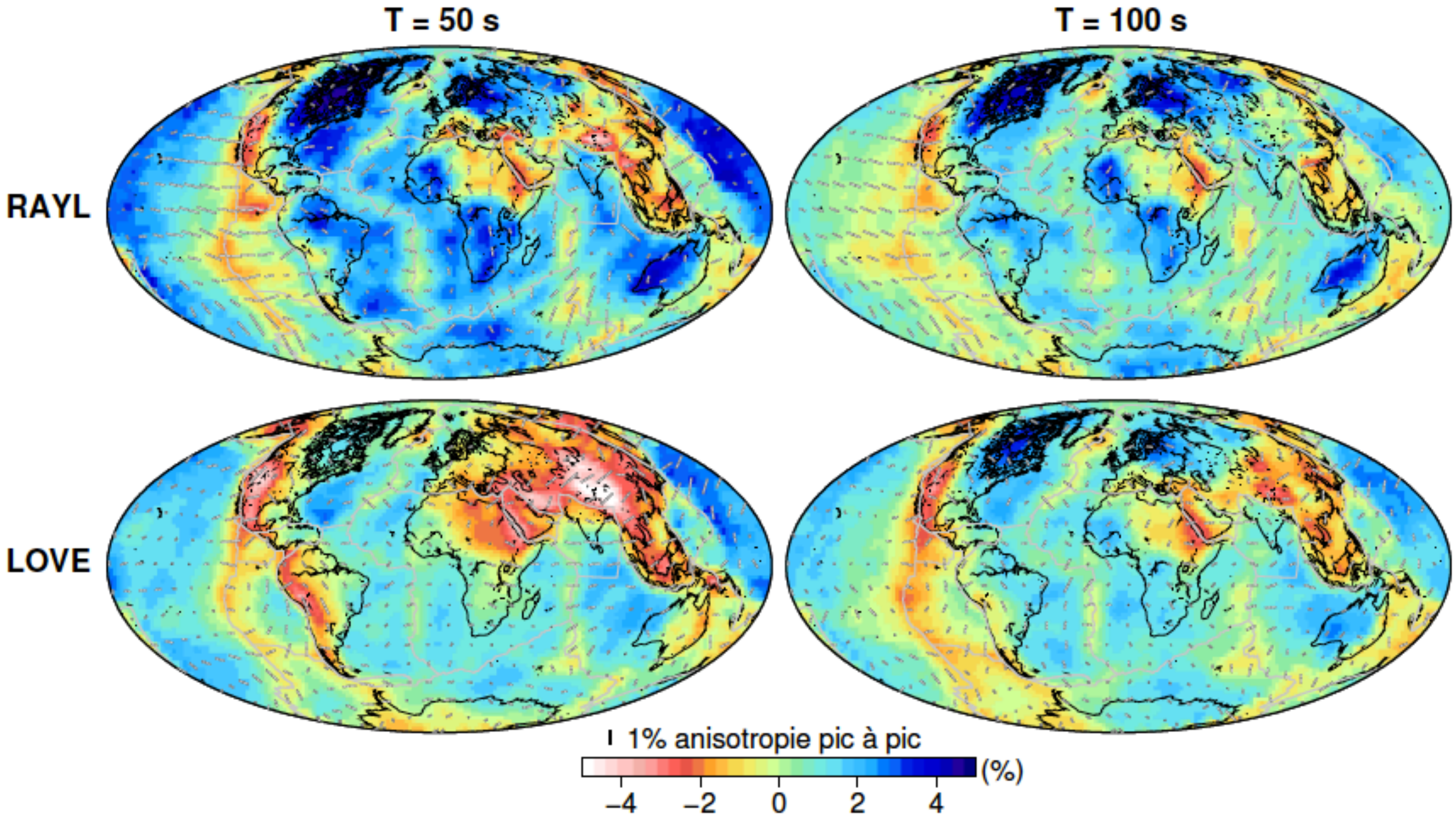
Data collection

Phase and group velocity dispersion curves
Rayleigh and Love waves,
Fundamental and higher modes (n={0,6})

IPGP(1)	44 - 315	9292†	-	-
UTRECHT(2)	35 - 175	63628	35 - 176	45179
HARVARD(3)	35 - 150	37738	35 - 150	23227
BOULDER(4)	16 - 200	76580	16 - 150	47021
TOTAL	-	187238	-	115427

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

Rayleigh phase velocity and azimuthal anisotropy



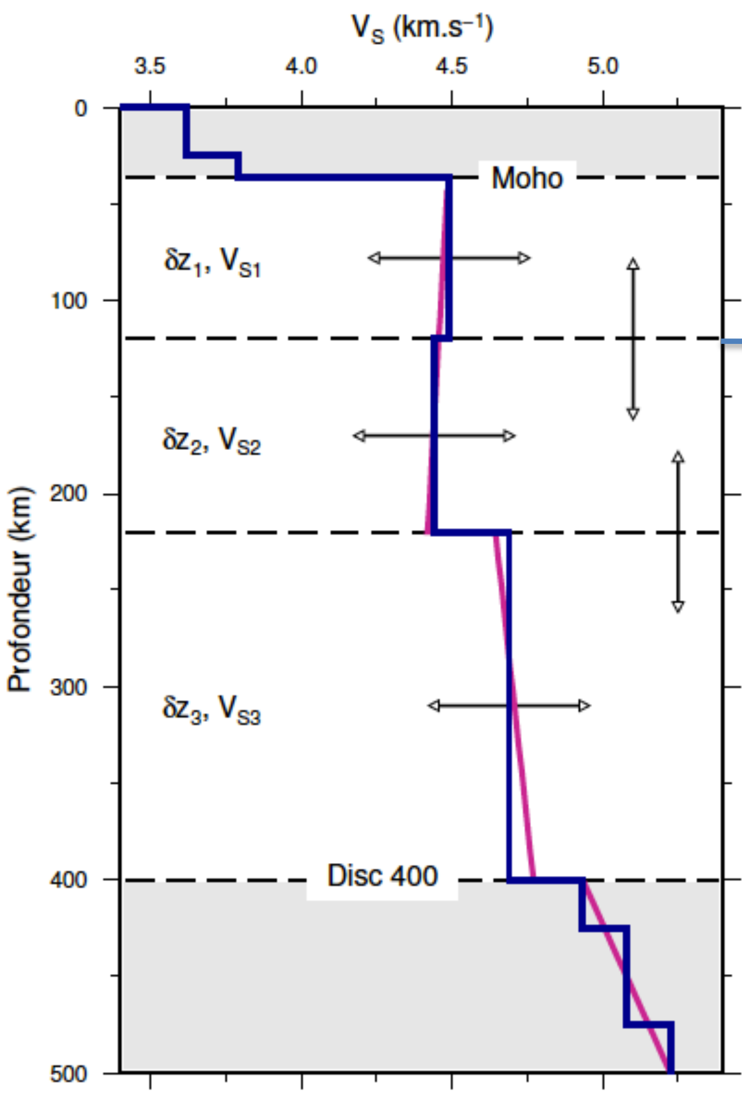
Second step: Inversion at depth

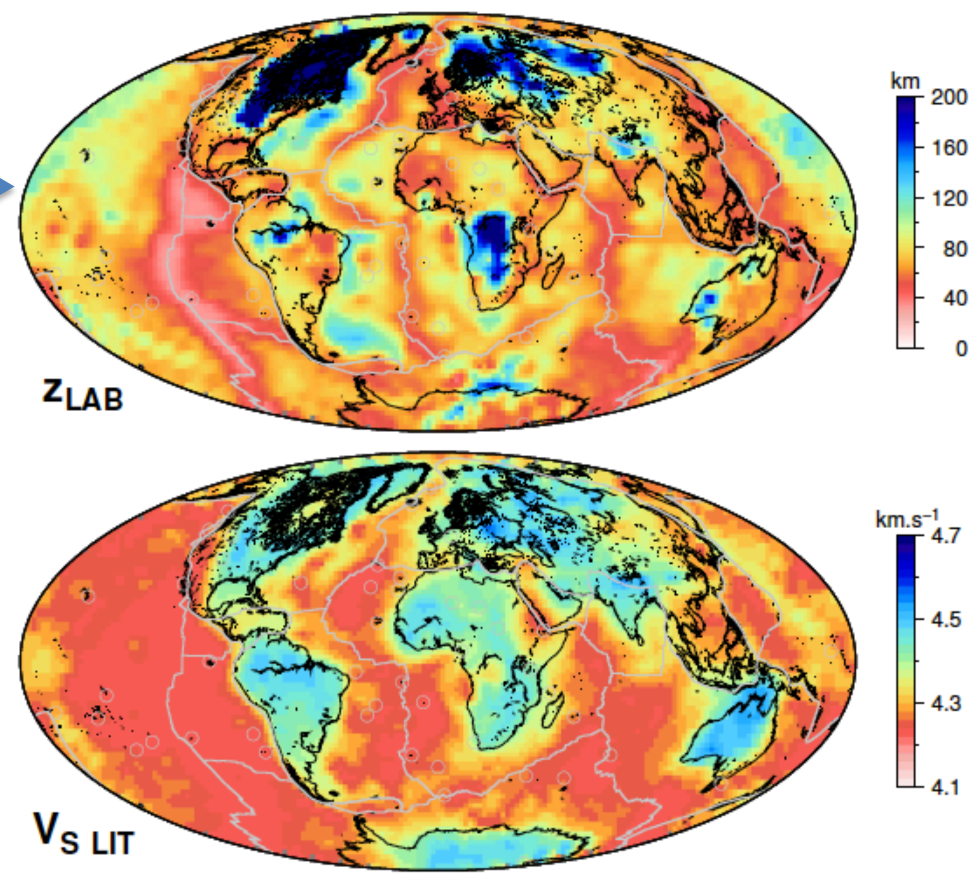
Statistical Monte-Carlo Inversion

First order Perturbation Theory

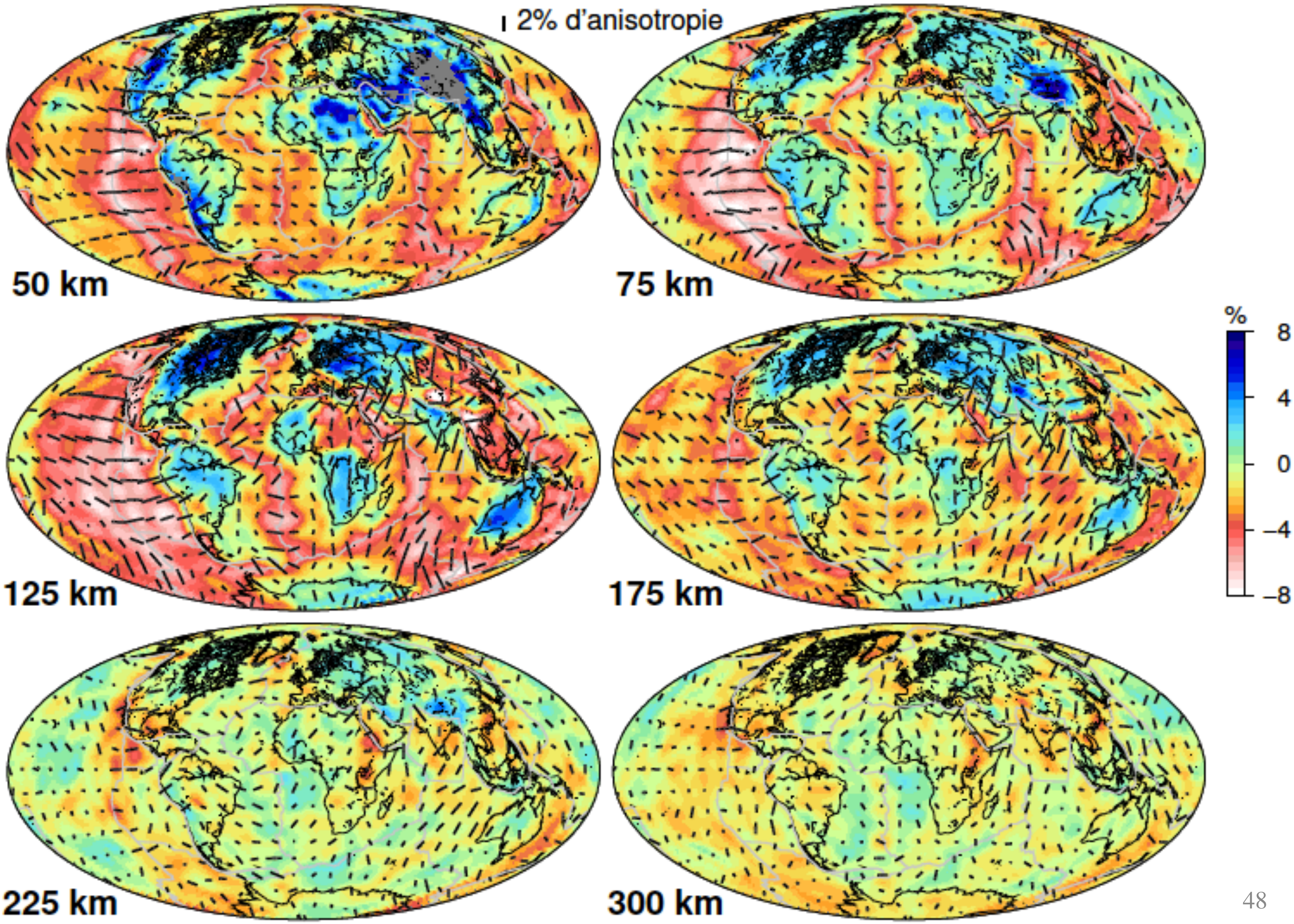
LAB: Statistical M.C. Isotropic Inversion

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

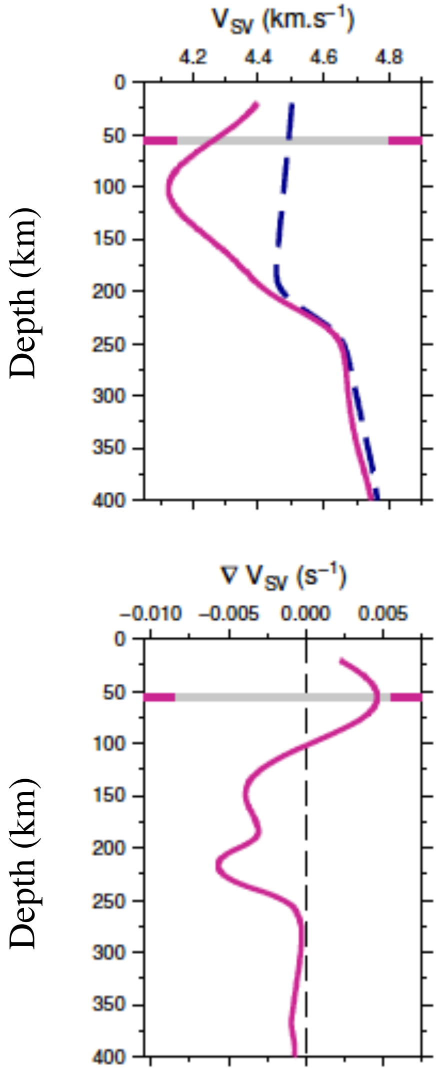


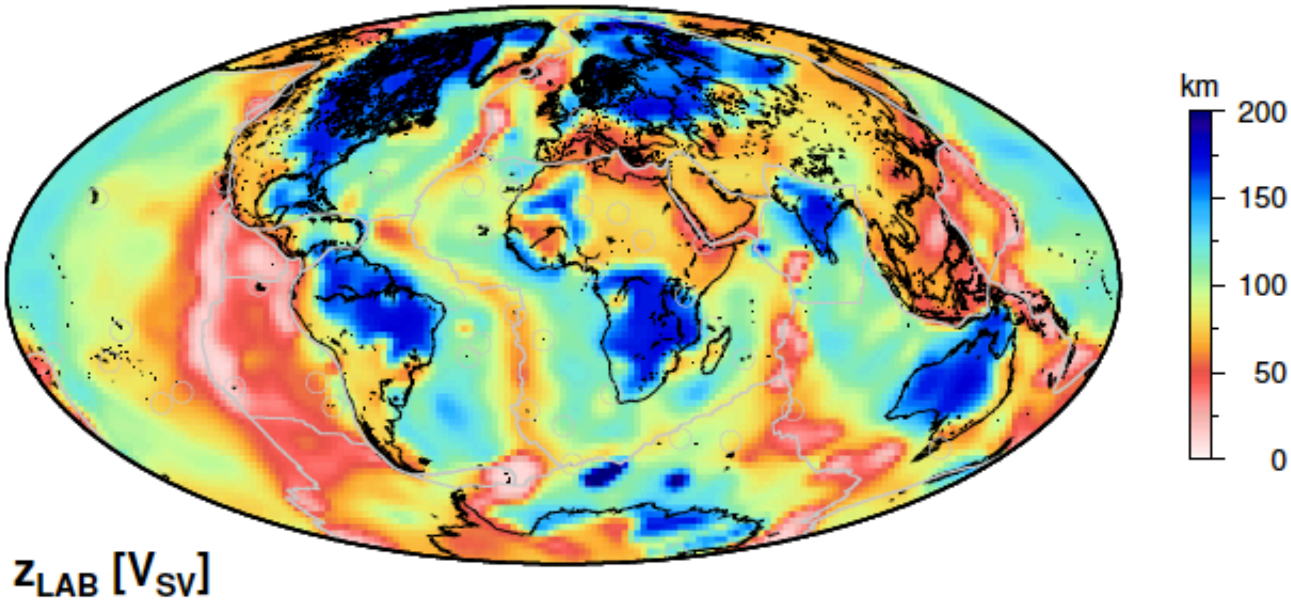


First order perturbation Theory => depth distribution of Vsv, G (and ξ)

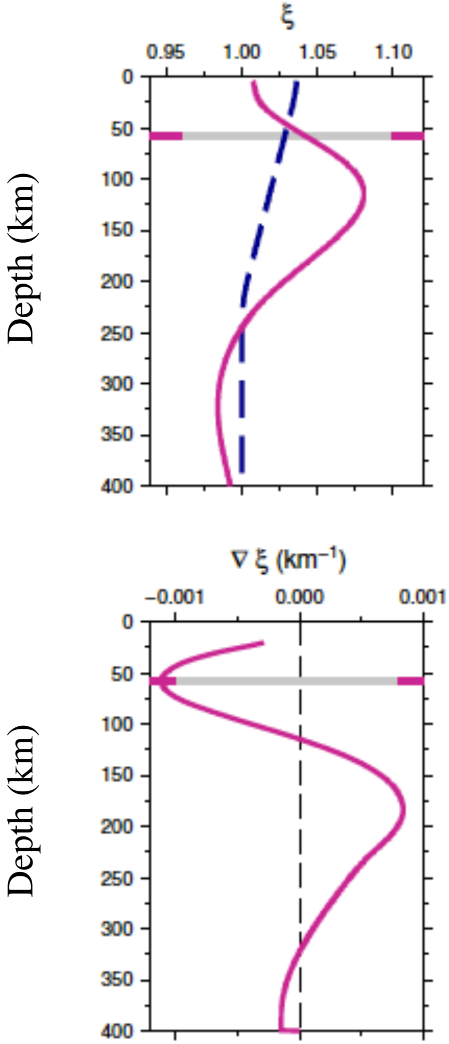


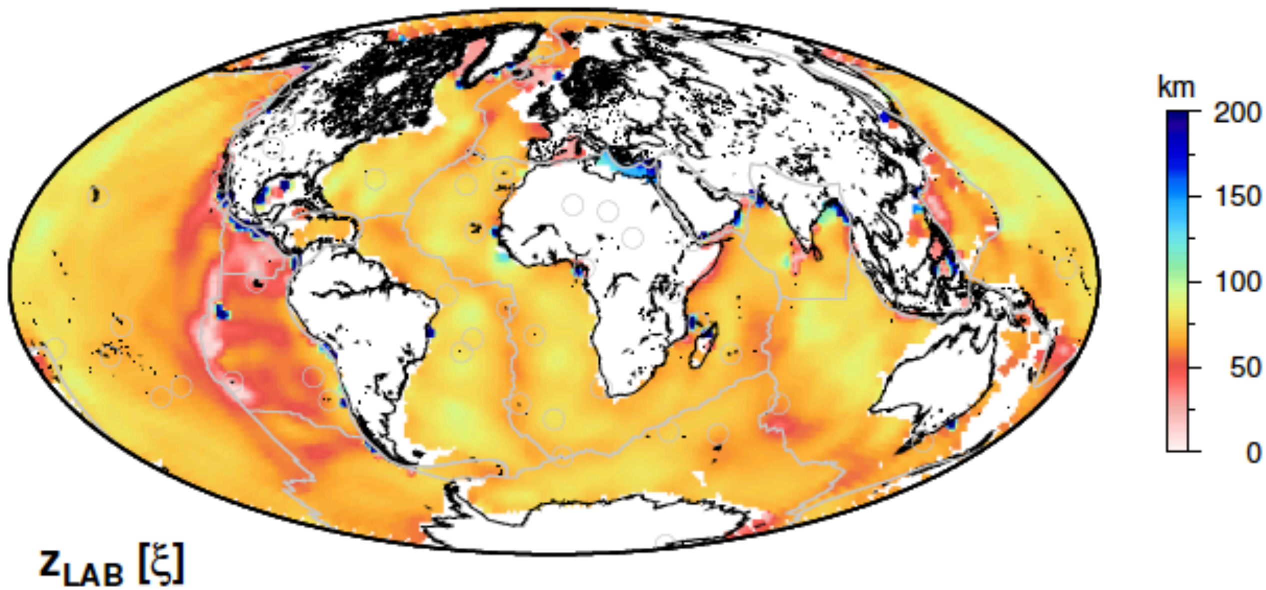
LAB from the gradient of VSV parameter



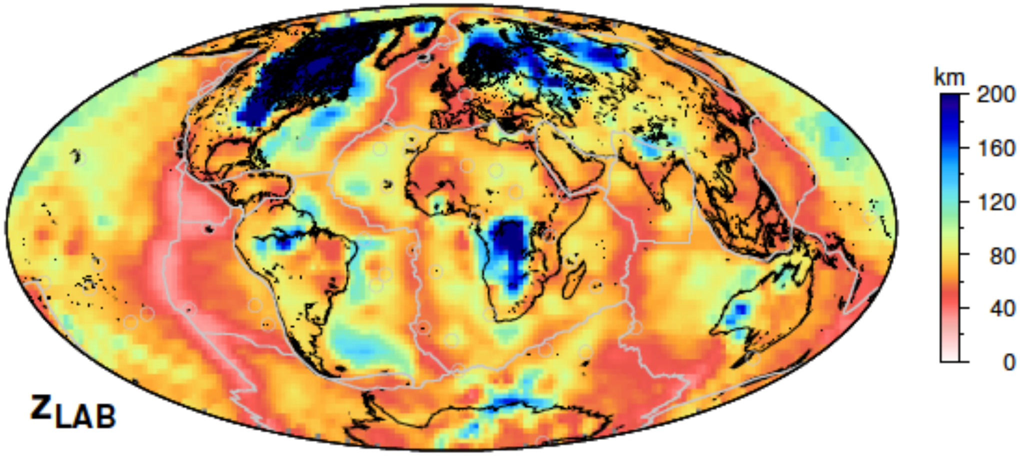


LAB from the gradient of ξ parameter (only oceans)
Radial anisotropy $\xi = (V_{SH}/V_{SV})^2$

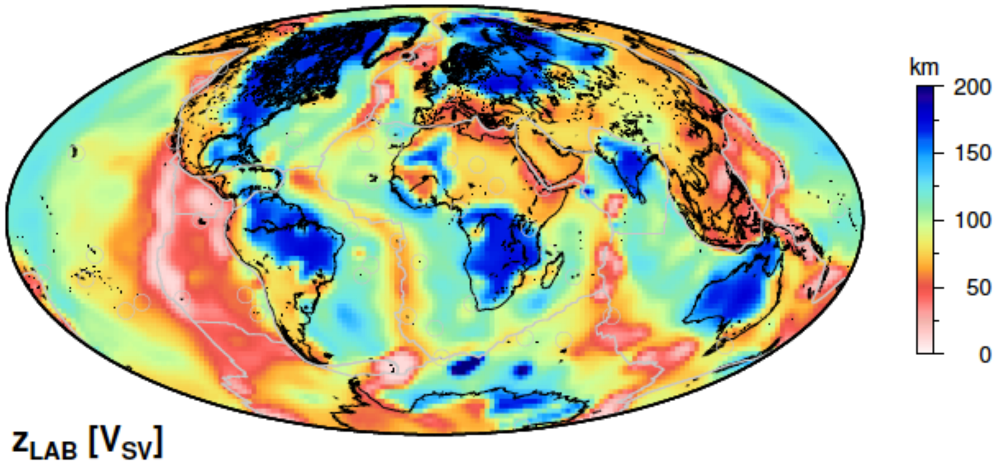




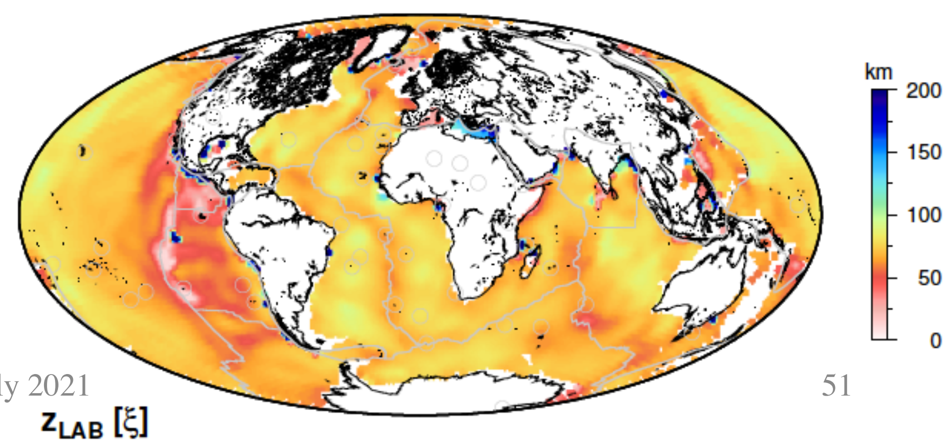
Statistical MC Isotropic Inversion



Vsv proxy (1st order Perturbation Theory)

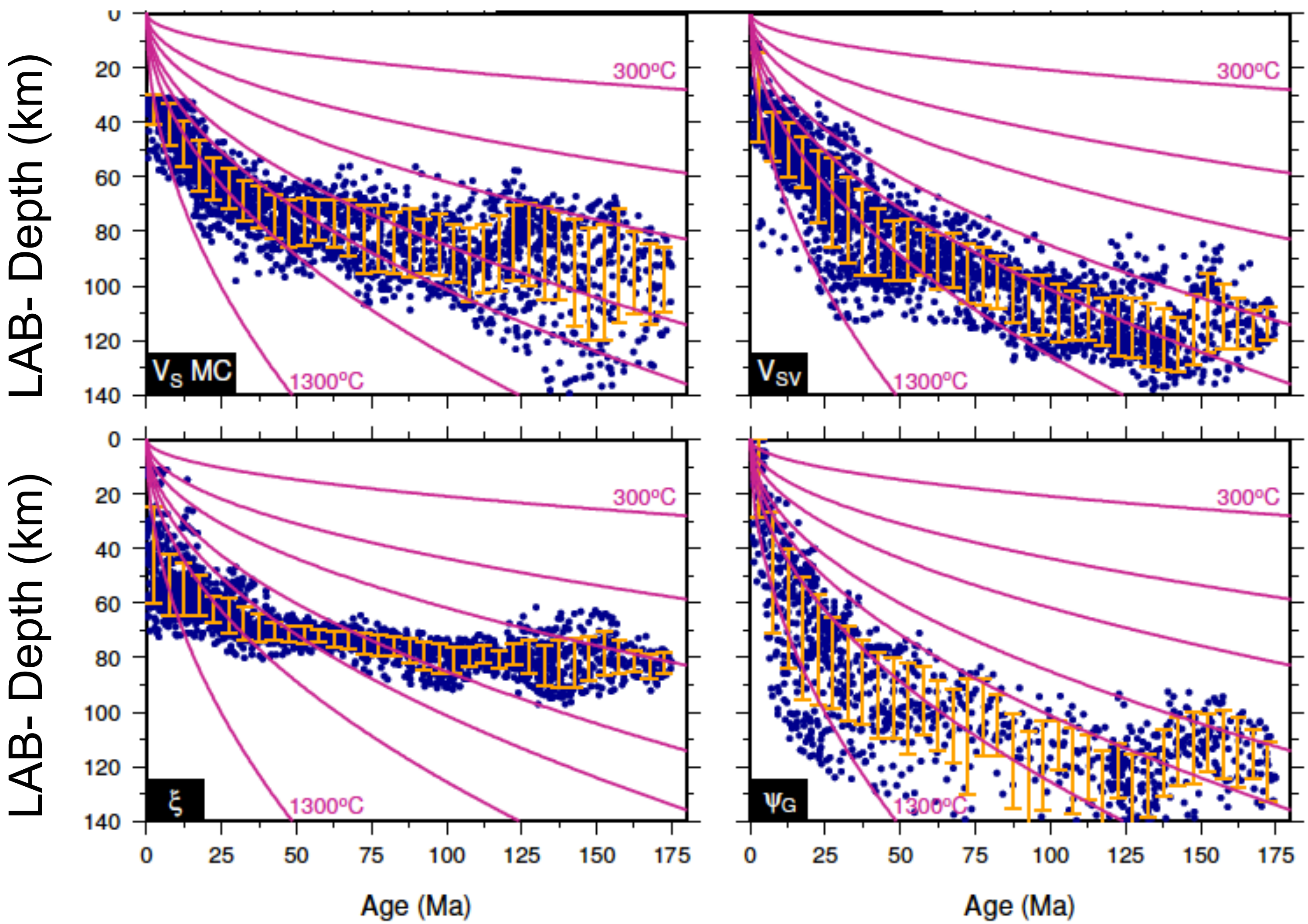


ξ proxy (1st order Perturbation Theory)



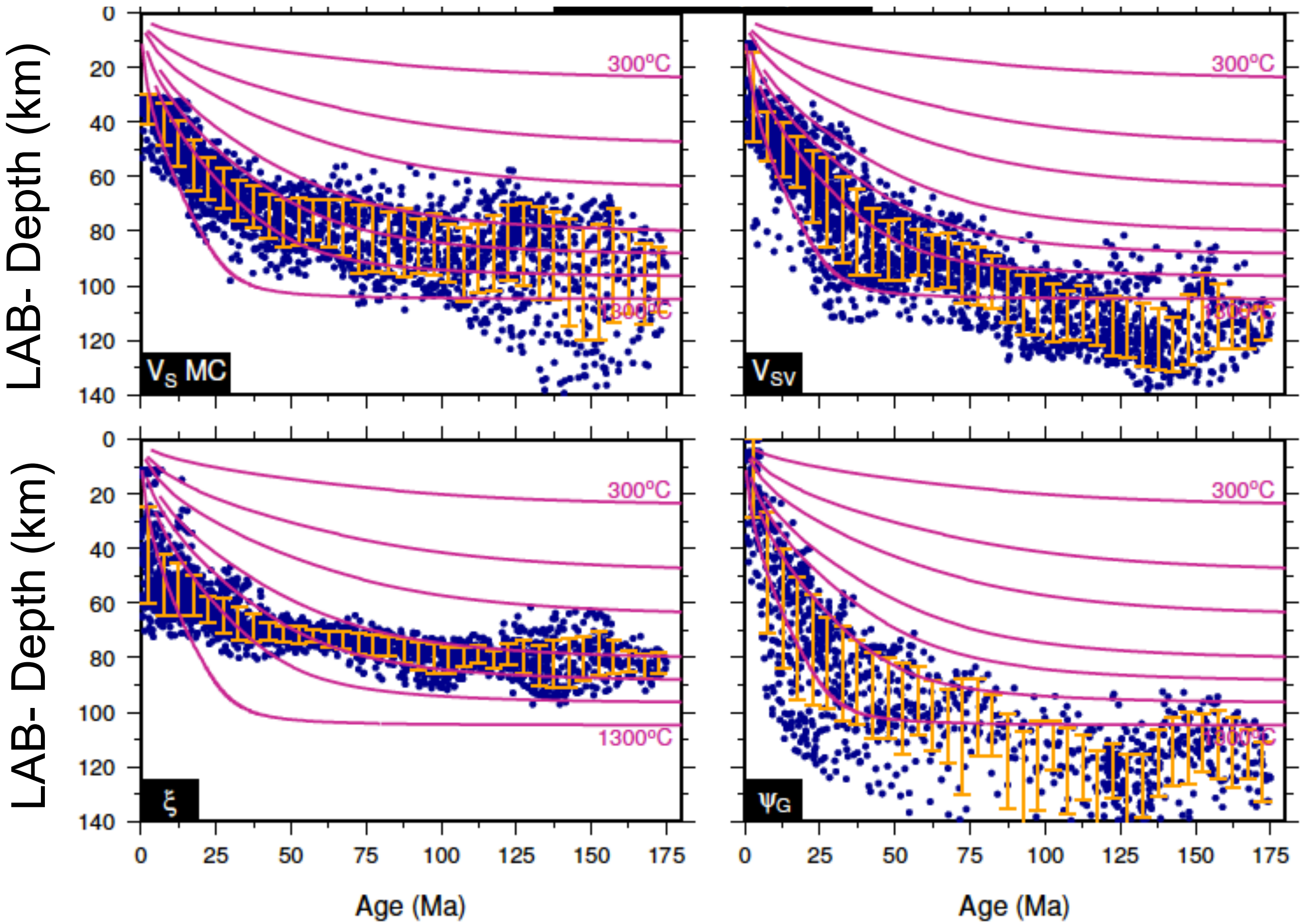
Age Variation of LAB depth in oceanic regions

Compared with Half Space Cooling model



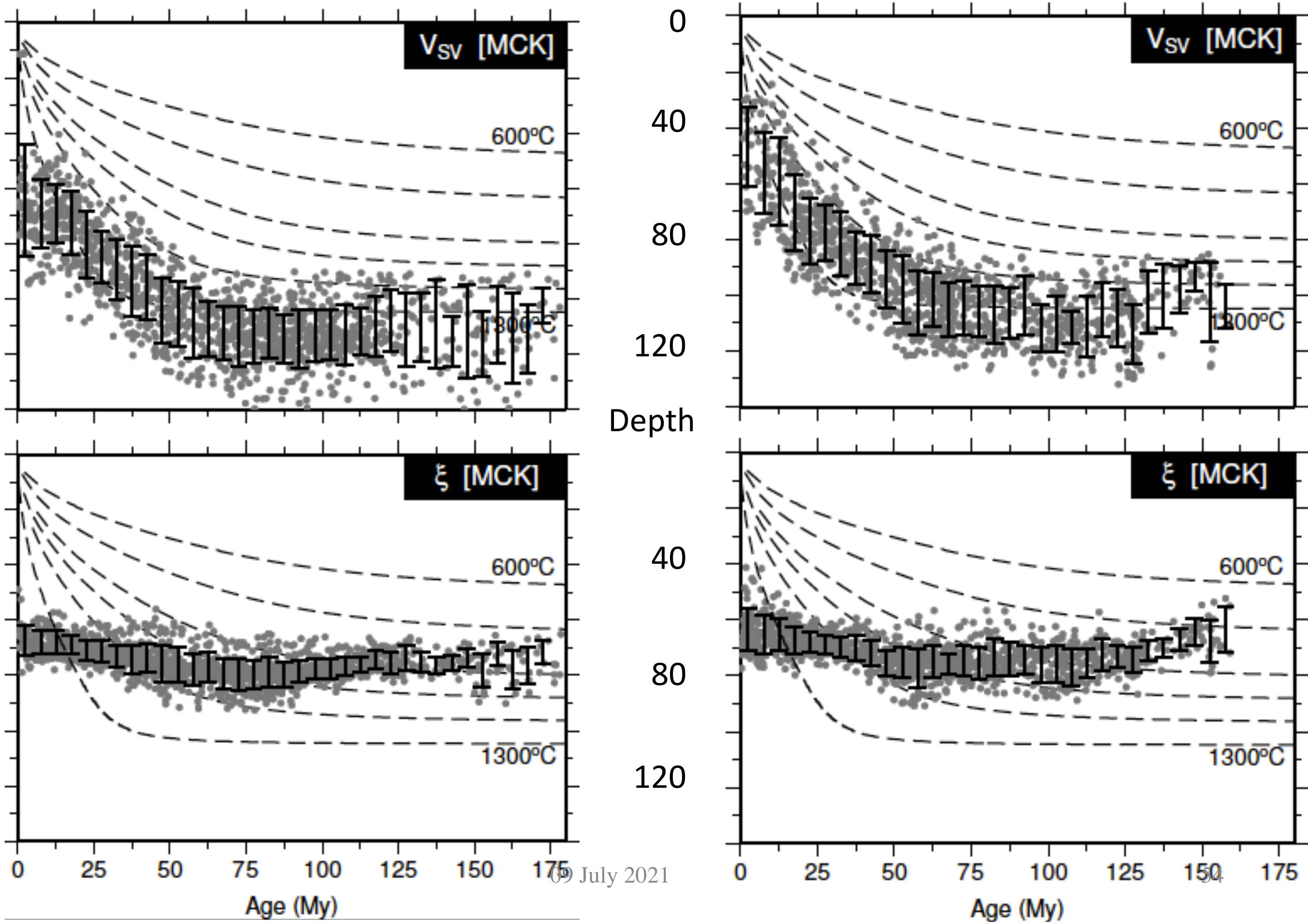
Age Variation of LAB depth in oceanic regions

Compared with Plate model

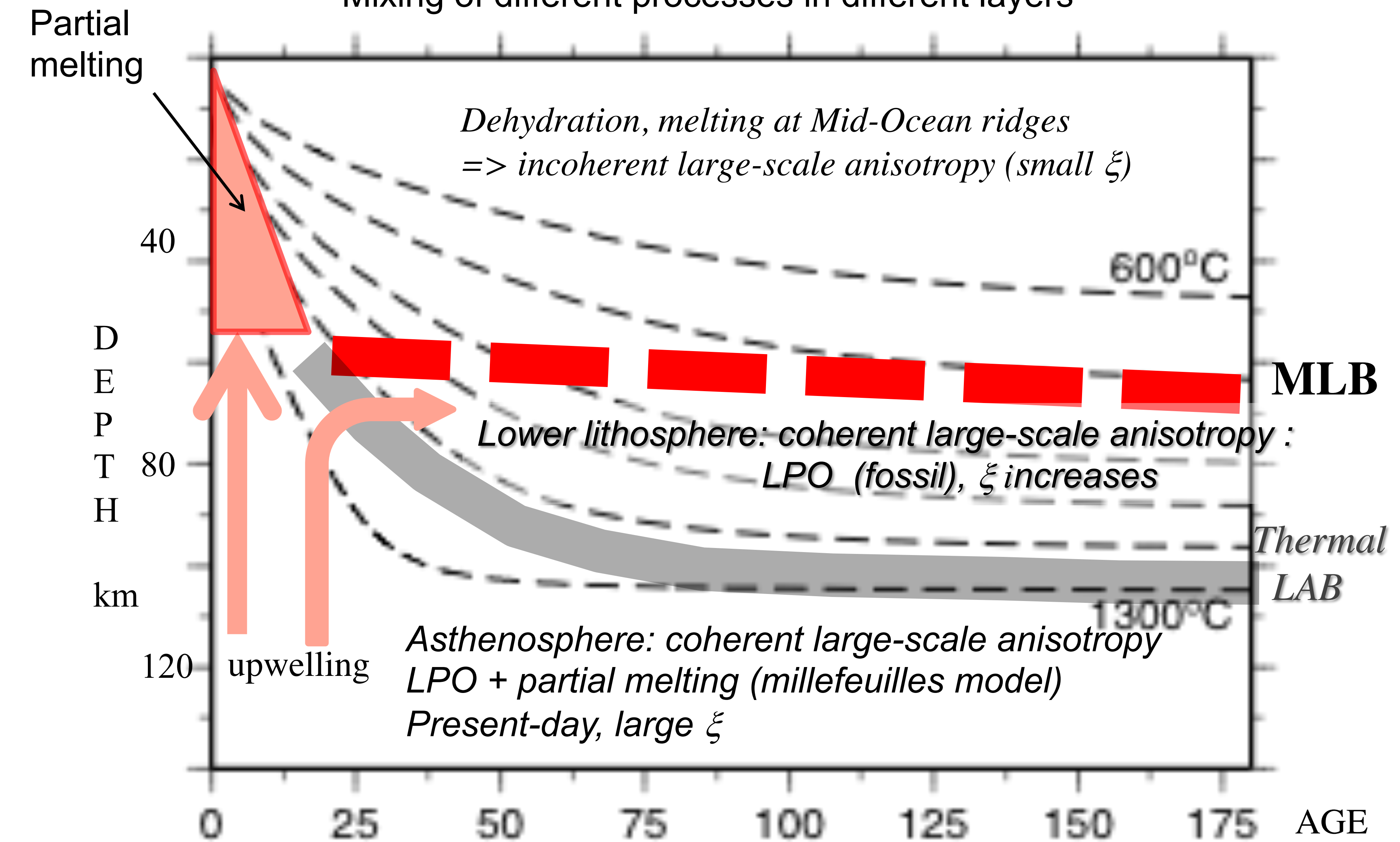


Atlantic Ocean

Indian Ocean

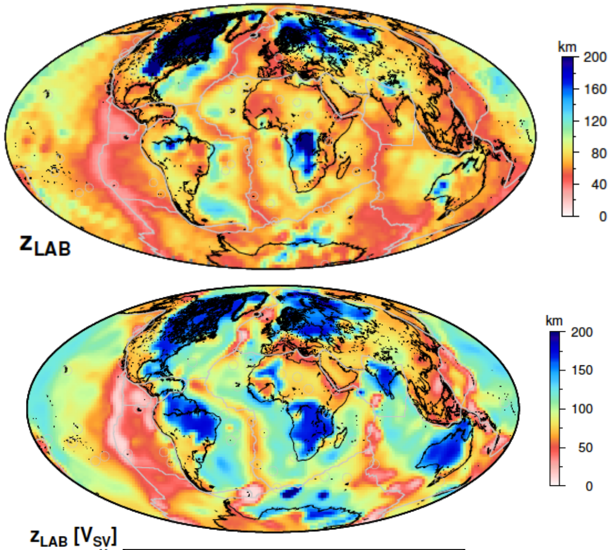


Mixing of different processes in different layers



MLB: Mid-Lithospheric Boundary

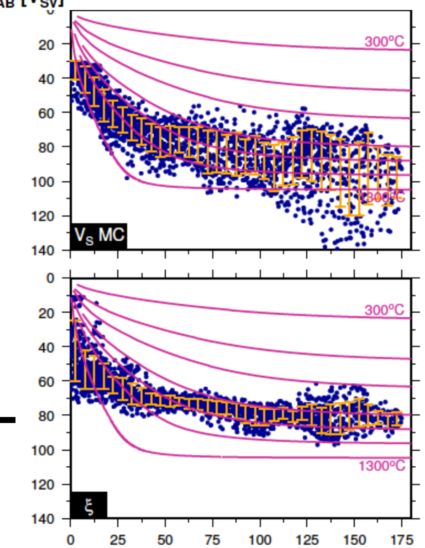
New Discontinuity within the lithosphere



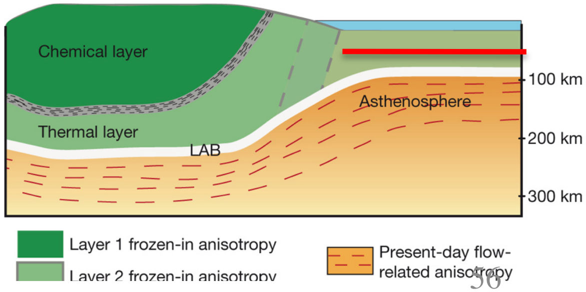
-LAB topography derived from surface wave data on a global scale

-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 (related to dehydration boundary layer?)
Mid-Lithospheric Boundary

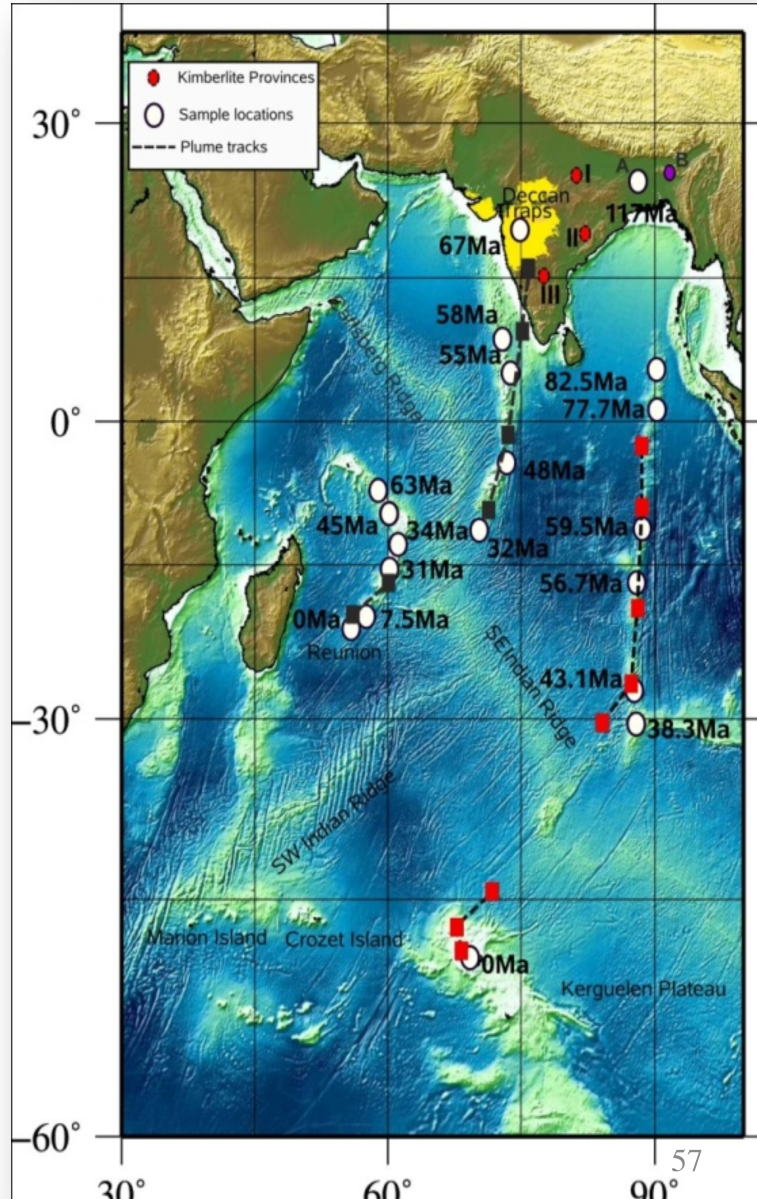


CONTINENTS?

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*) ?

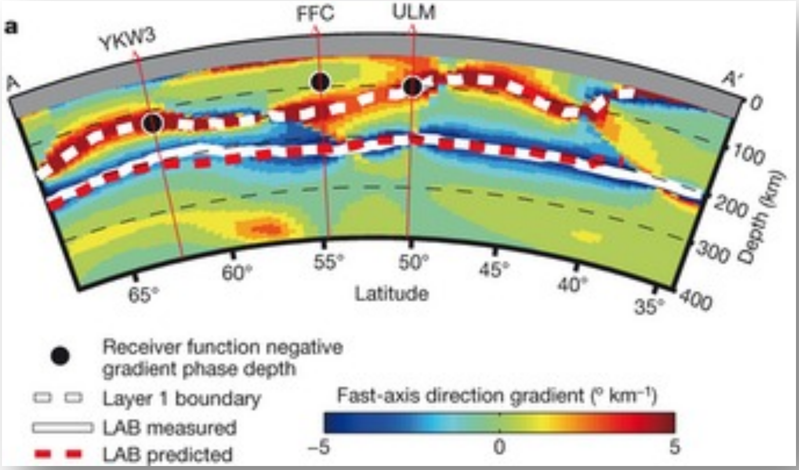


Scientific Challenges – Debate on Indian LAB

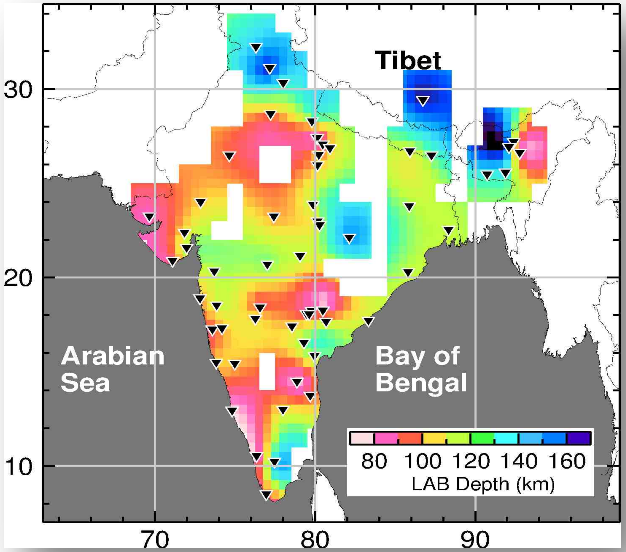
- **Super mobility** due to a thin seismic lithosphere (~80-100km)) (Kumar et al., Nature, 2007)?
- In total disagreement with common consensus on cratons:

North America (~200-250km) [Yuan and Romanowicz, 2010, …]: stratification.

- Is the seismic discontinuity at **~100 km** depth 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.

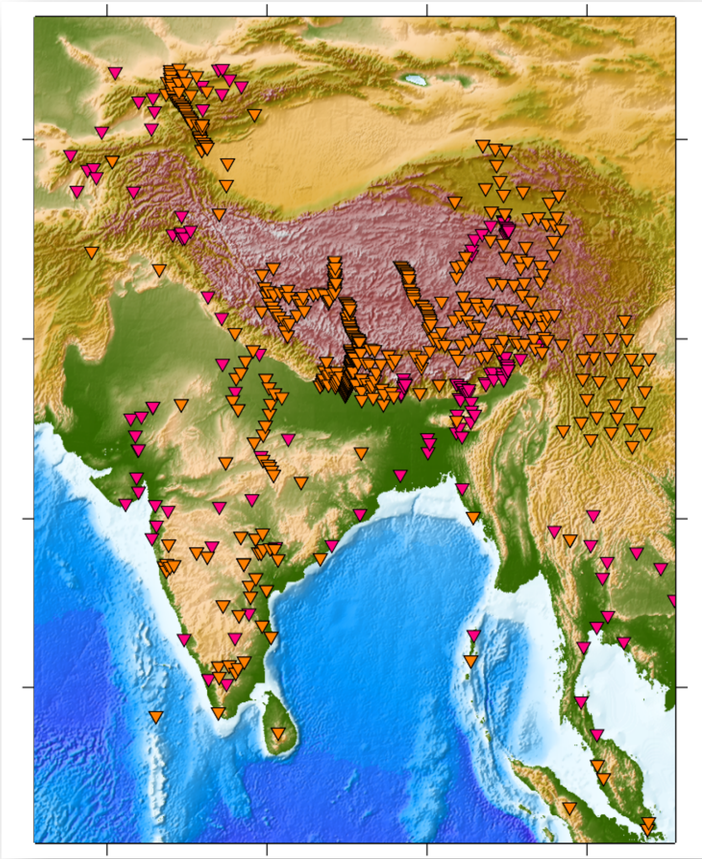


Layering in the lithosphere in NA [Yuan and Romanowicz, 2010]

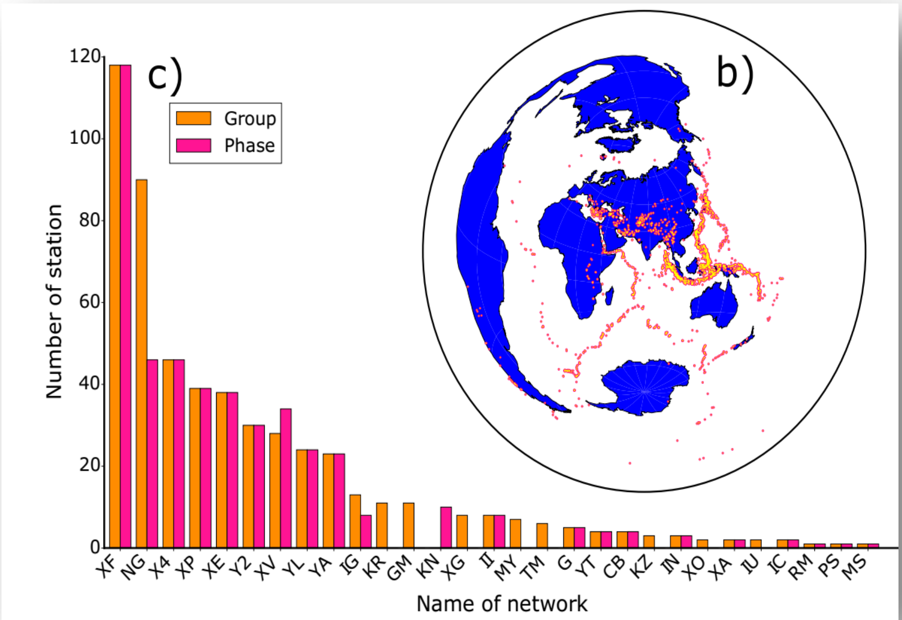


Unique Dataset

Stations

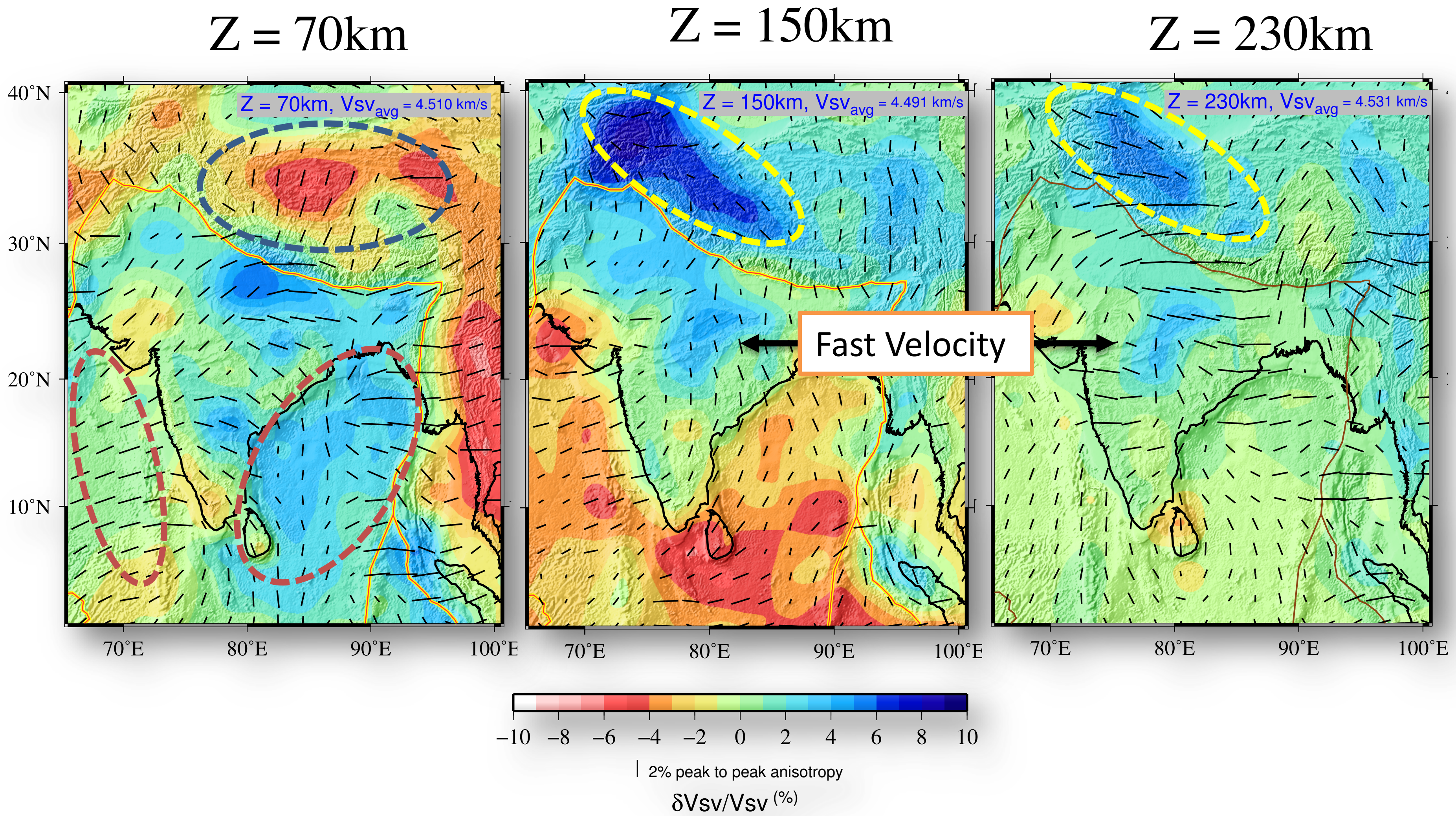


Earthquakes

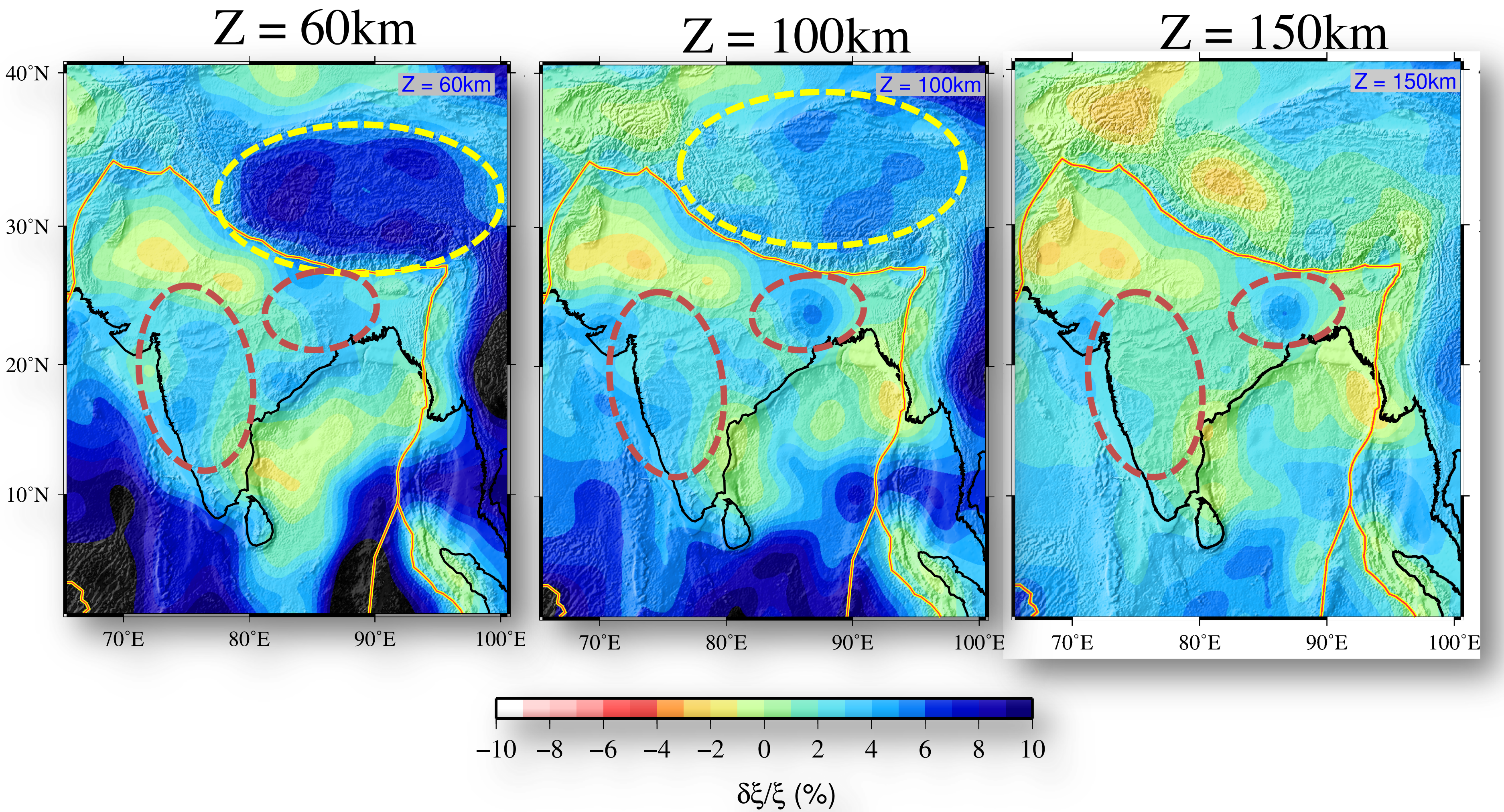


- 29 Seismic broadband Networks (**global and regional**)
- Over 550 seismic stations
- Earthquakes of magnitude >5.5
- Surface wave data in the period range of 10-400s.

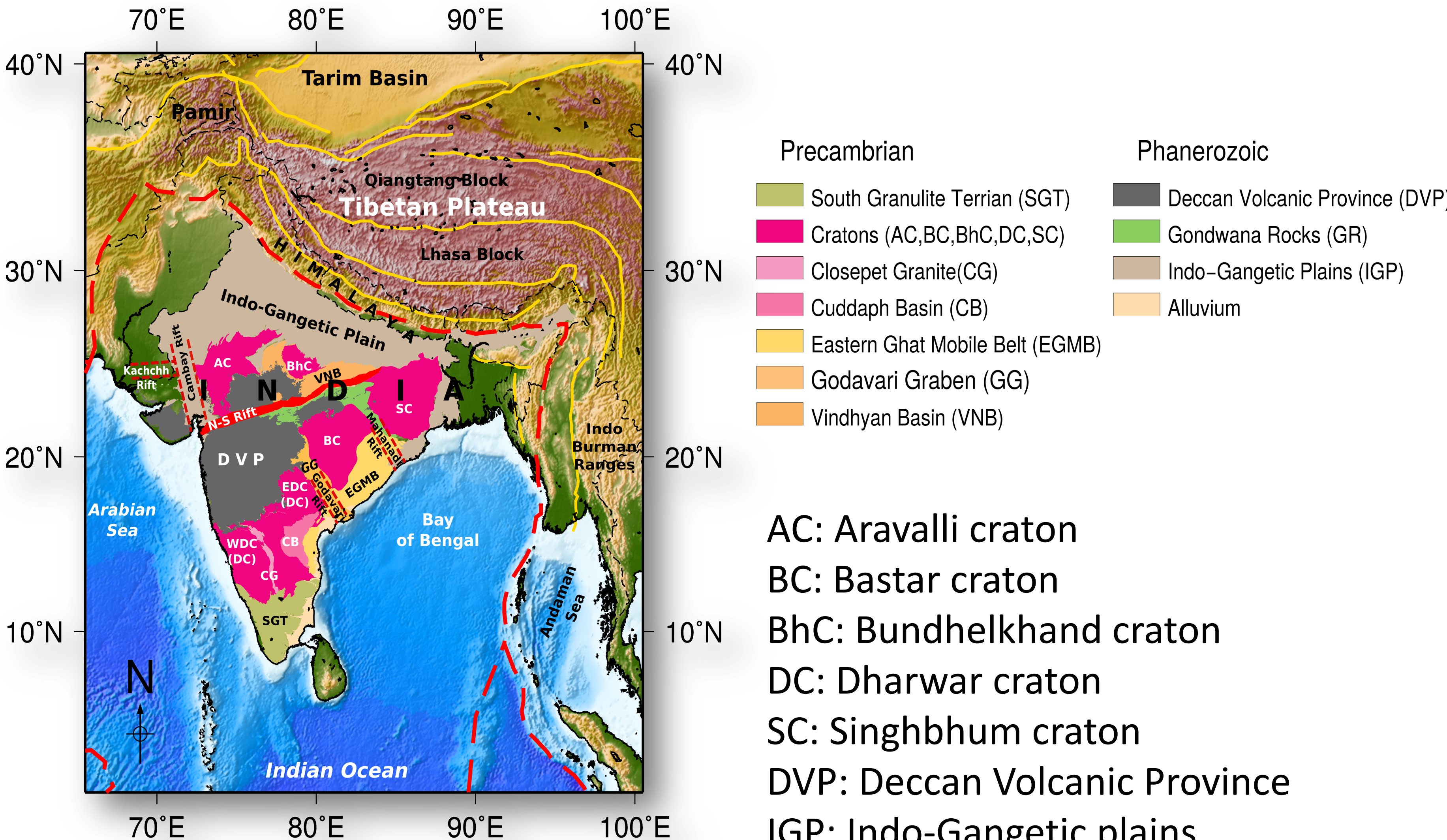
3-D tomography model of the Indian continent
Velocity and Azimuthal Anisotropy



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



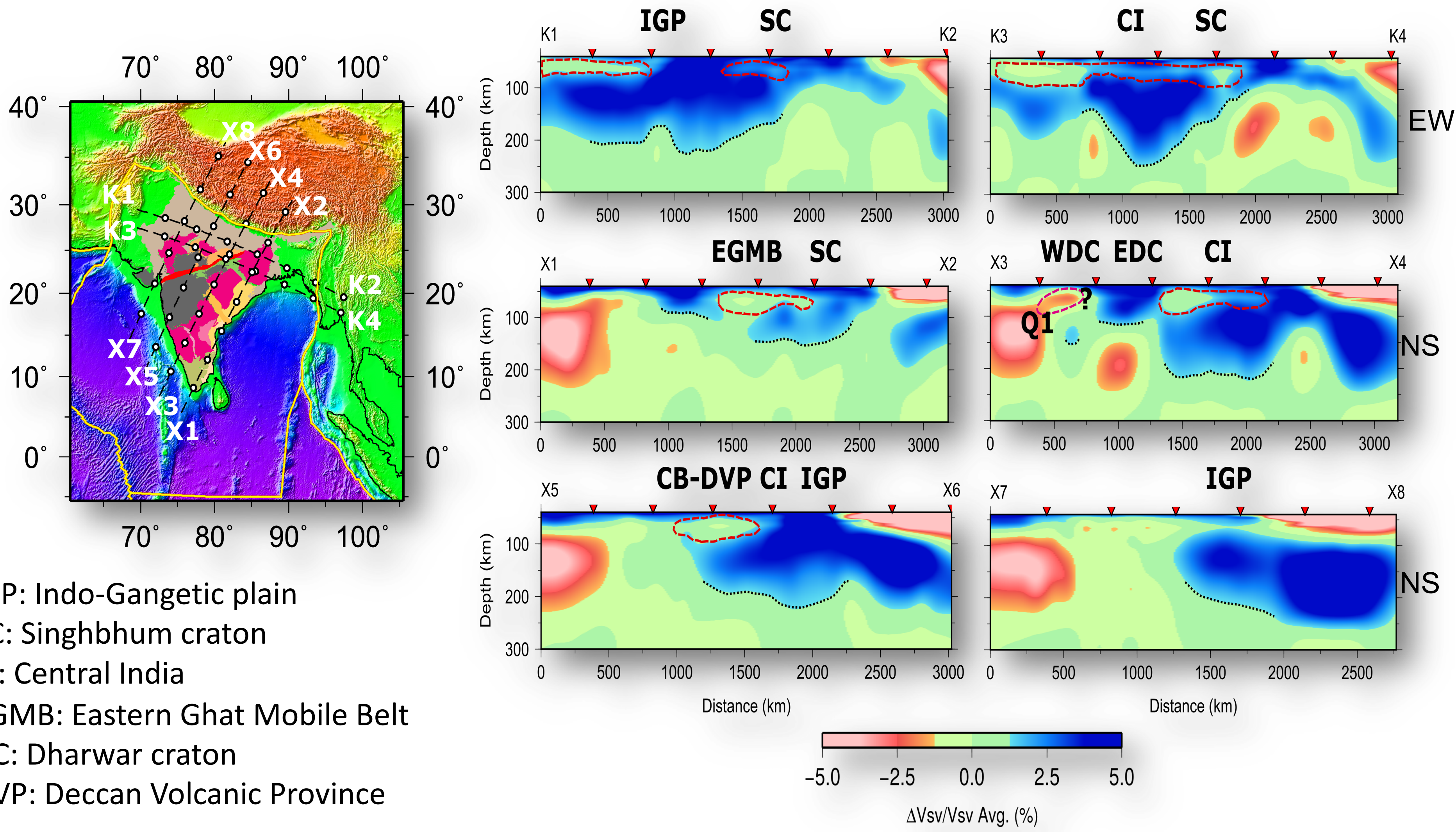
Study Area: geological signature



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

3D-Perturbation model



IGP: Indo-Gangetic plain

SC: Singhbhum craton

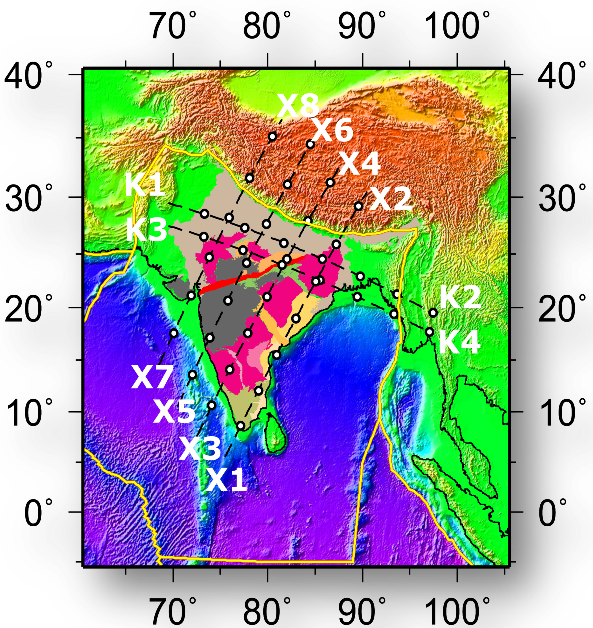
CI: Central India

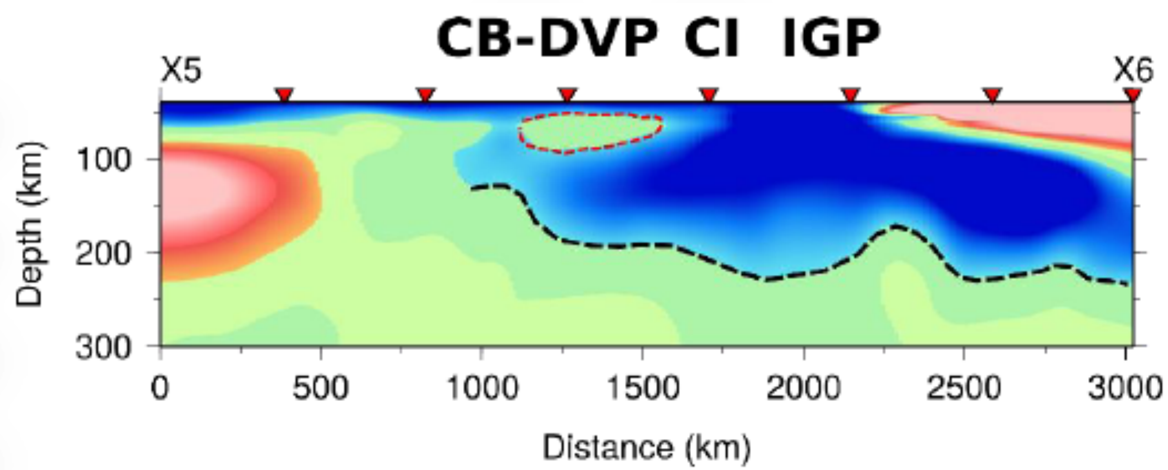
EGMB: Eastern Ghat Mobile Belt

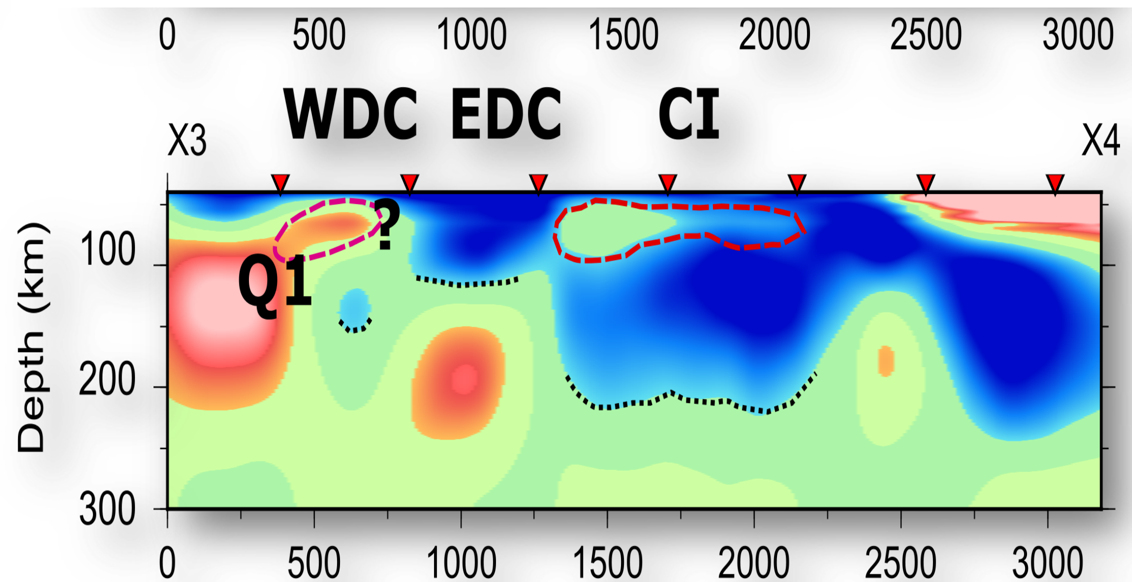
DC: Dharwar craton

DVP: Deccan Volcanic Province

3D-Perturbation model -NS





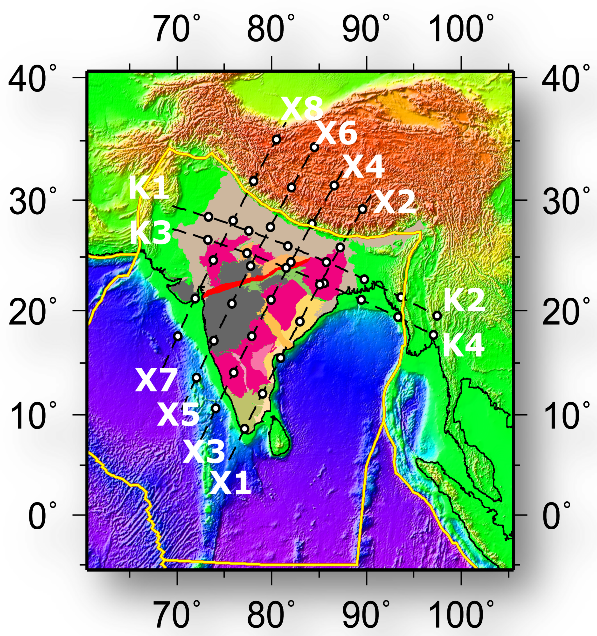


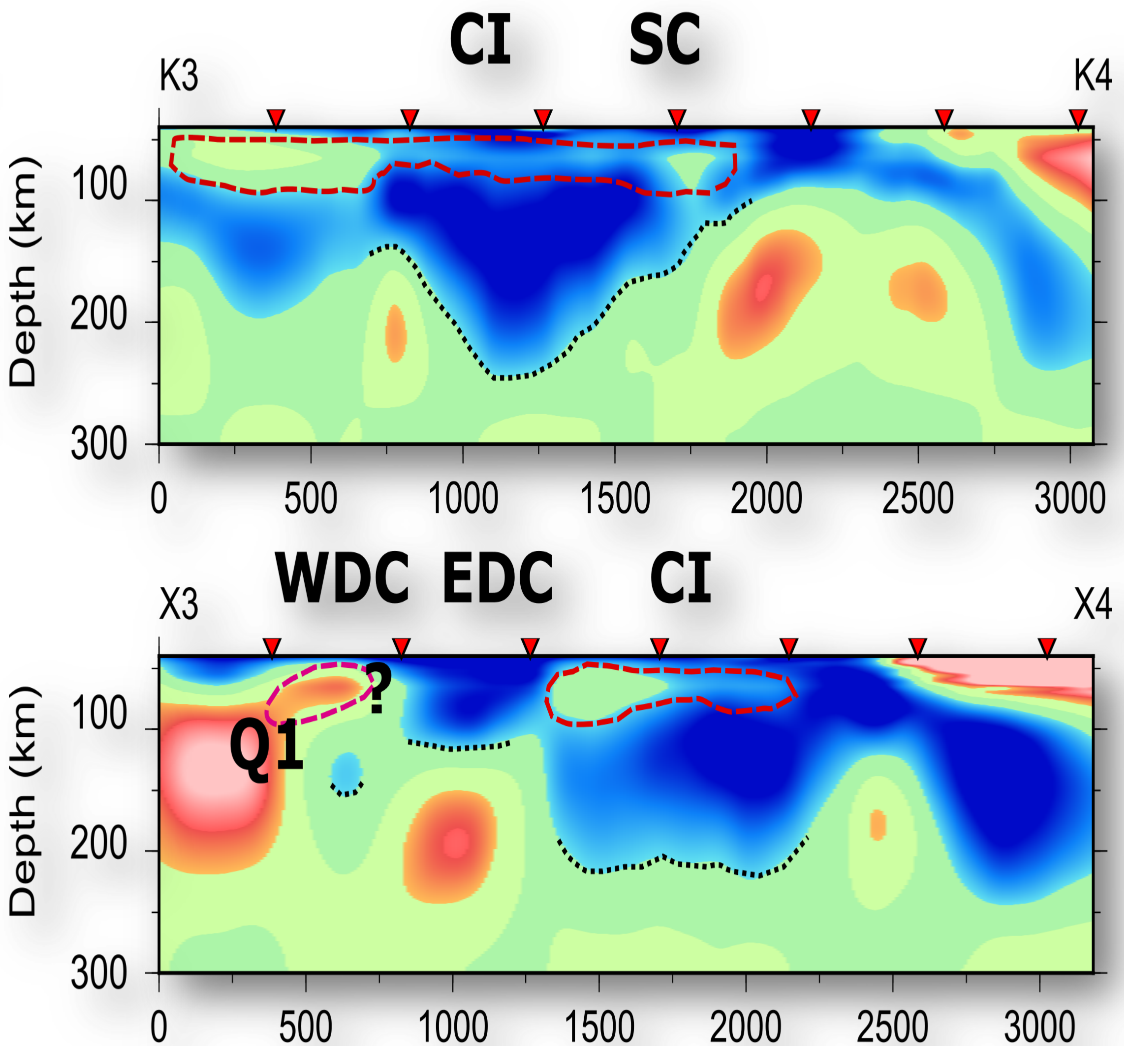
DVP: Low velocity zone
Remnant of hotspot birth

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

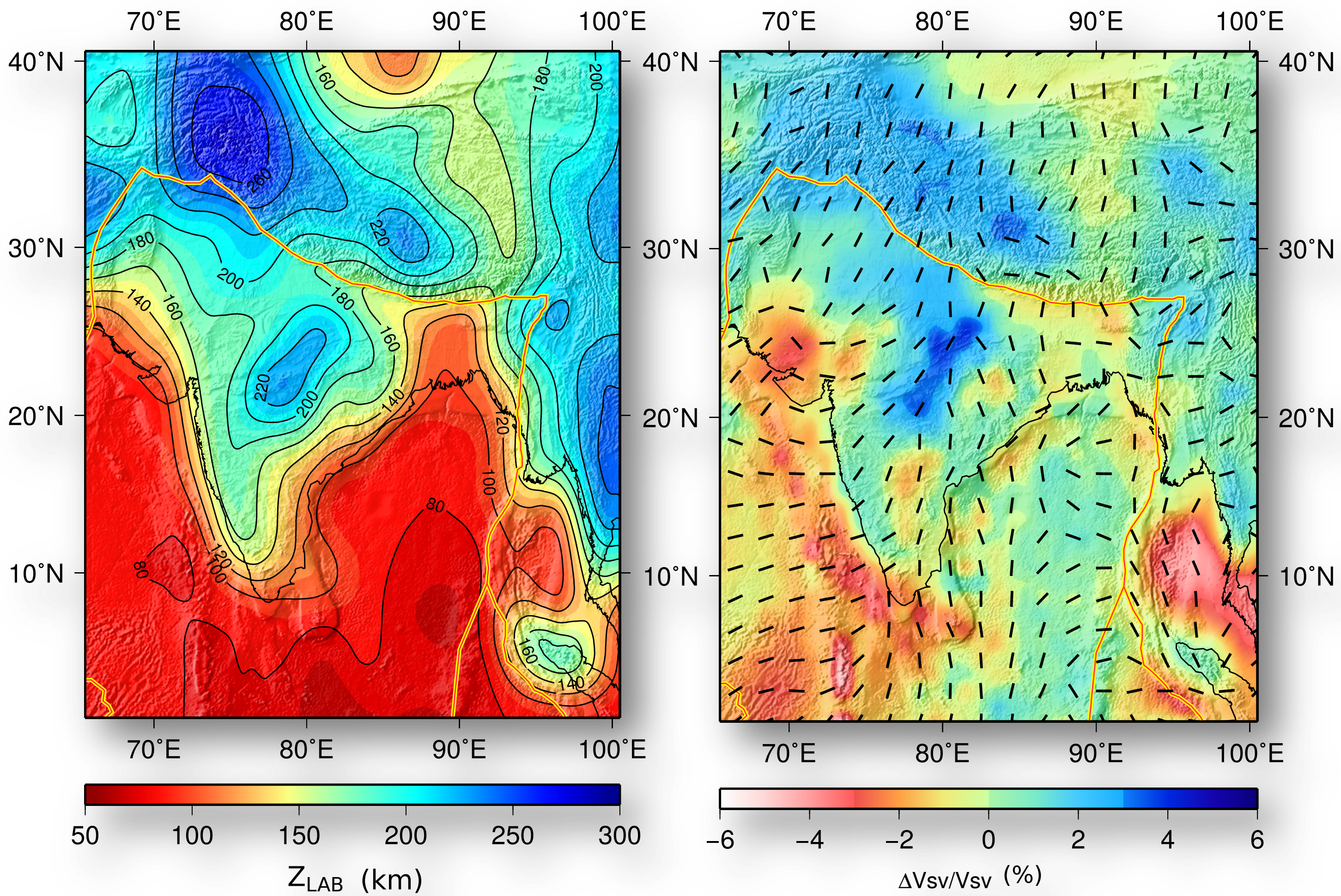




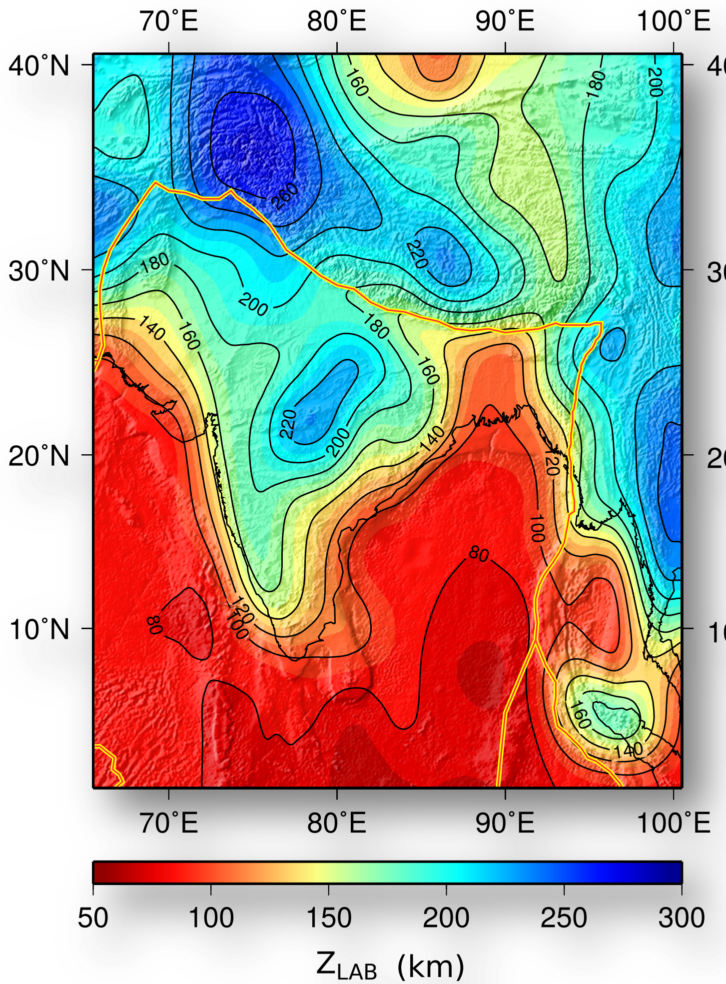
IGP: Indo-Gangetic plain
CI: Central India
SC: Singhbum craton
WDC, EDC: West, East Dharwar craton

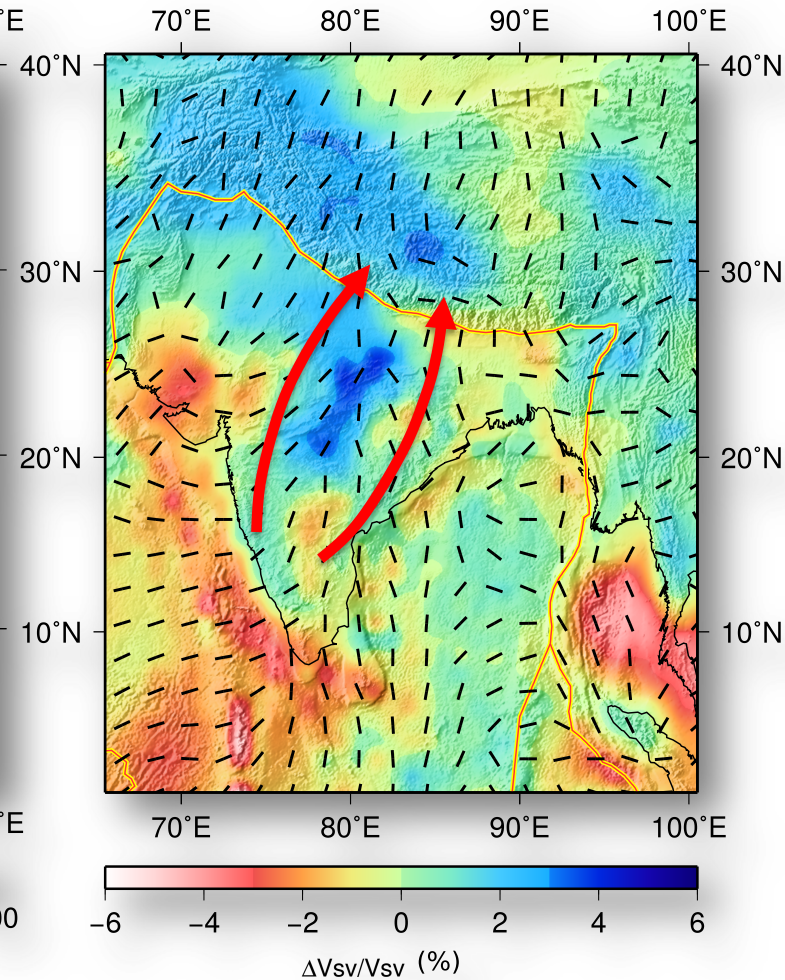
MLB-ML-LVZ: Mid-lithospheric low velocity zone

Indian Plate LAB
(Lithosphere-Asthenosphere Boundary)



Indian Plate LAB: Keel

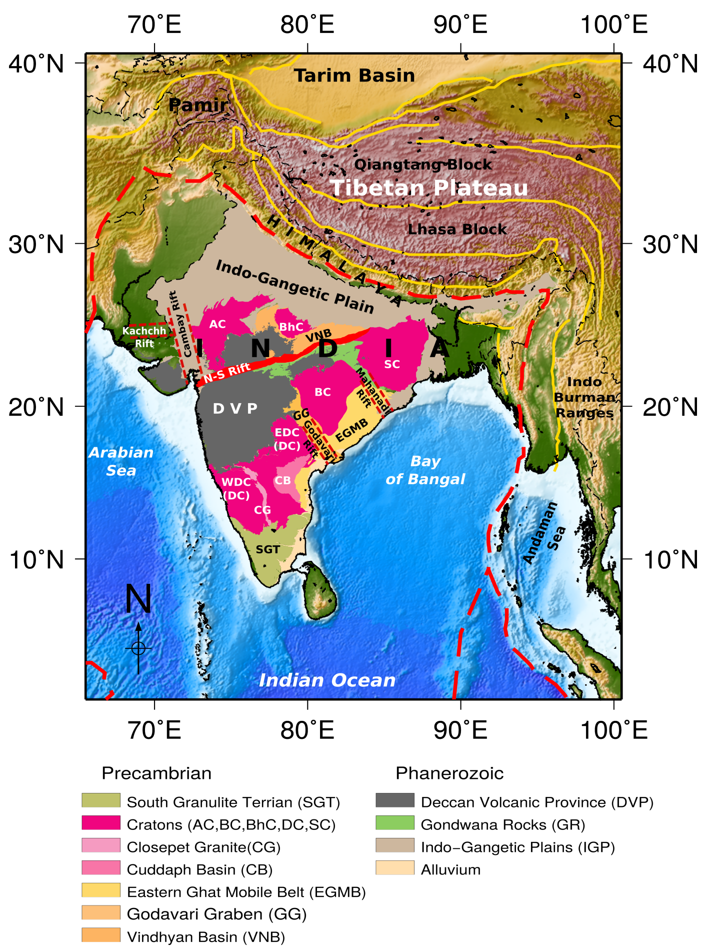


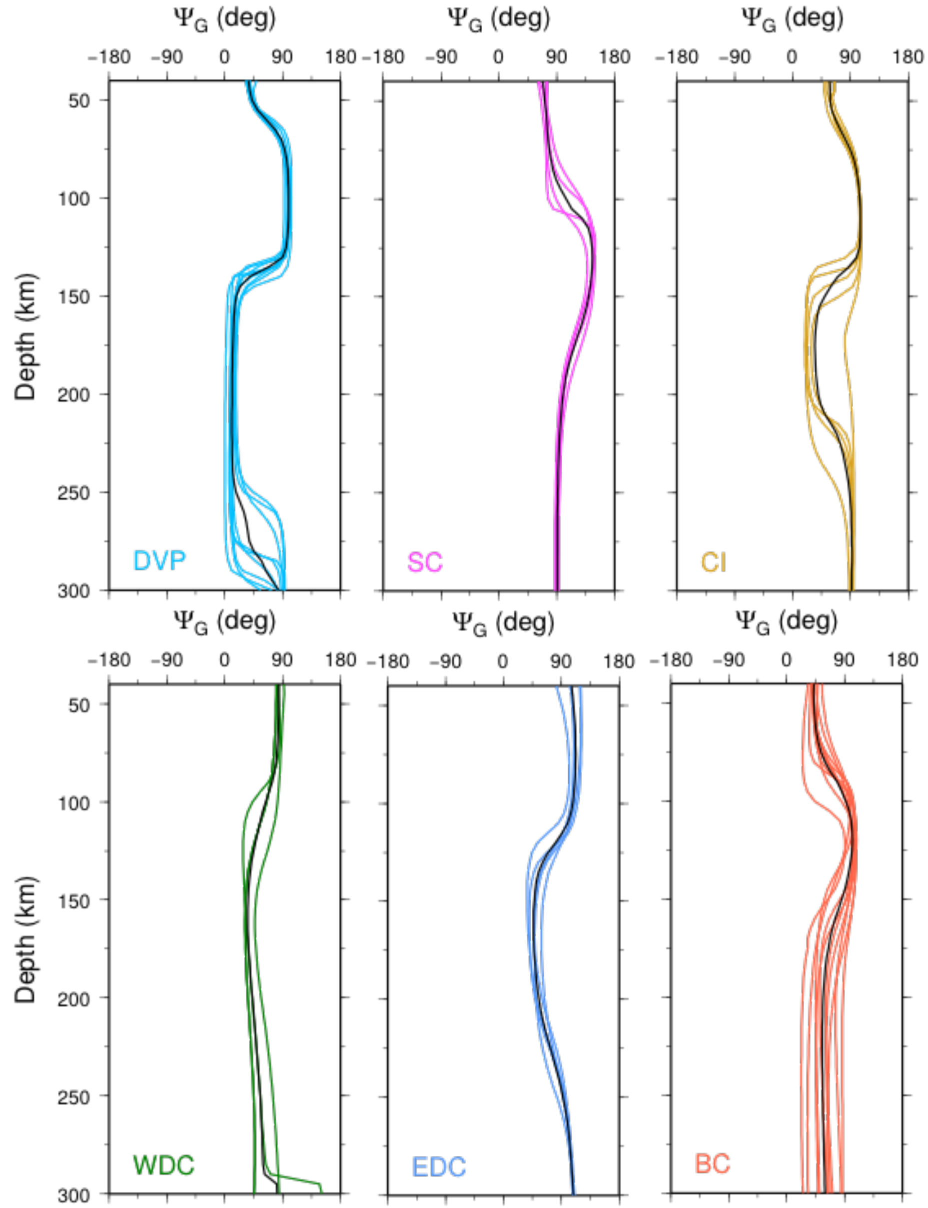


Geodynamic Role?

Plume influence?

Azimuthal anisotropy

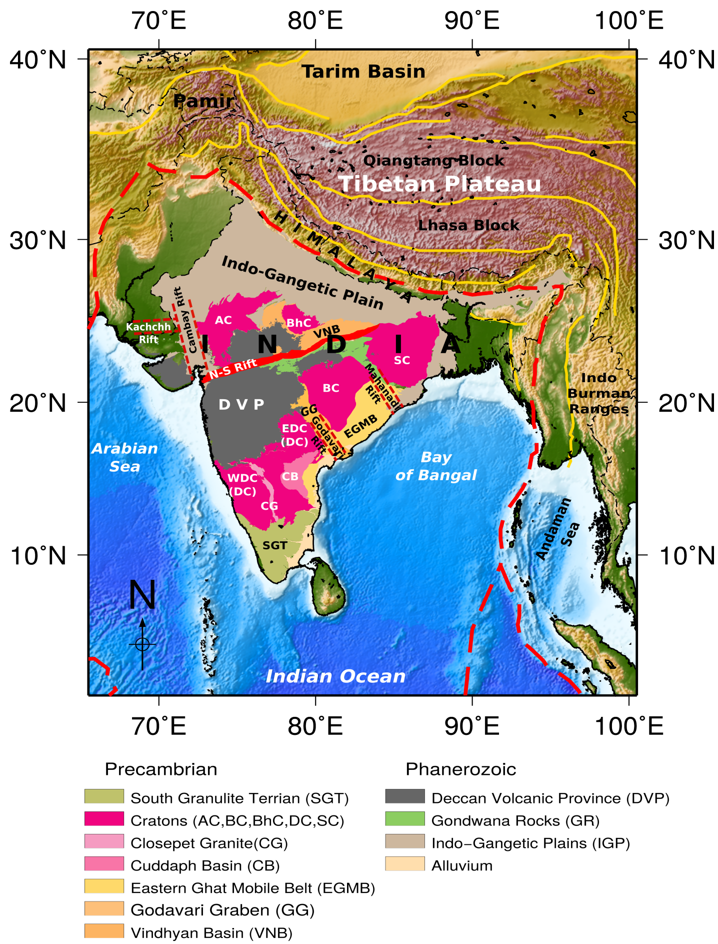


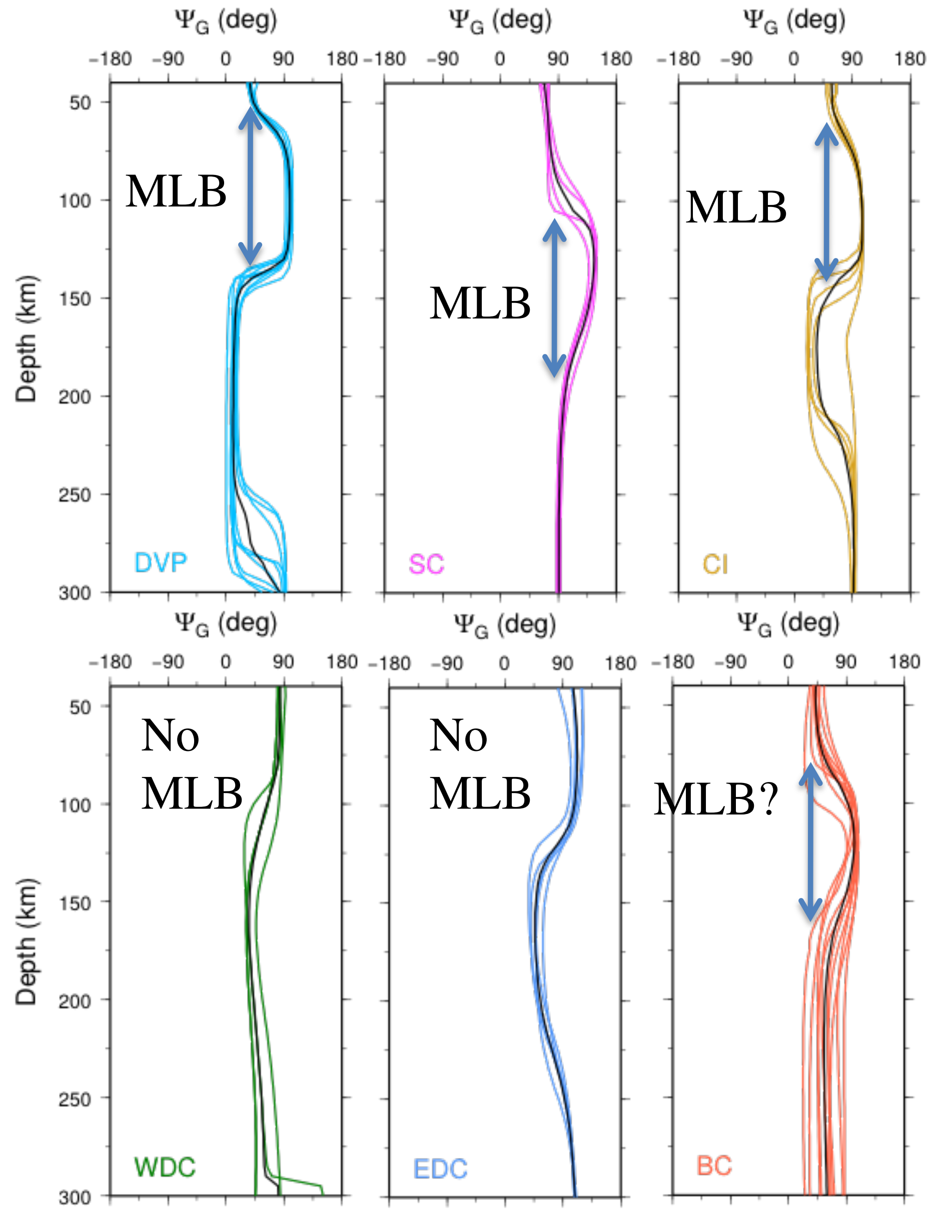


DVP: Deccan Volcanic Province
SC: Singhbhum craton
CI: Central India

WDC, EDC: West, East Dharwar craton
BC: Bastar craton

Azimuthal anisotropy





MLB = ML-LVZ

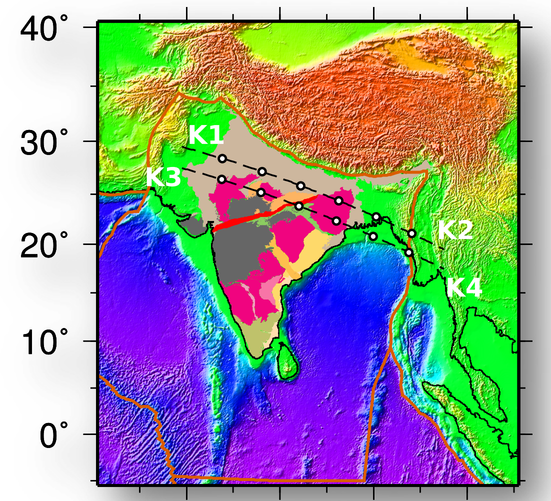
2 different orientations of Ψ_G

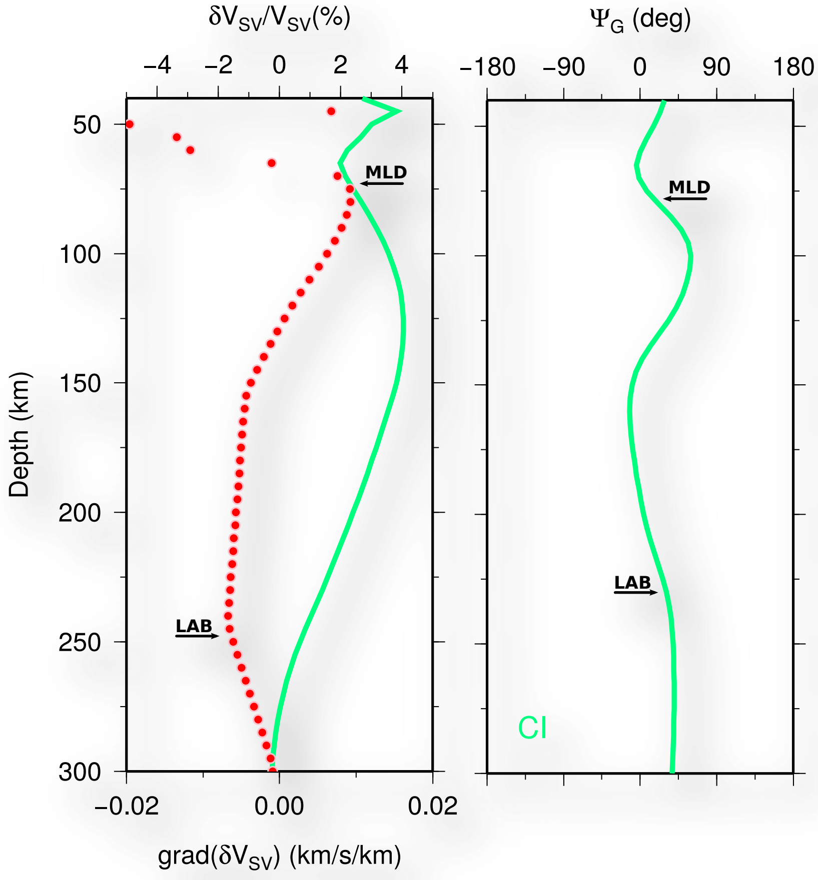
90-120°

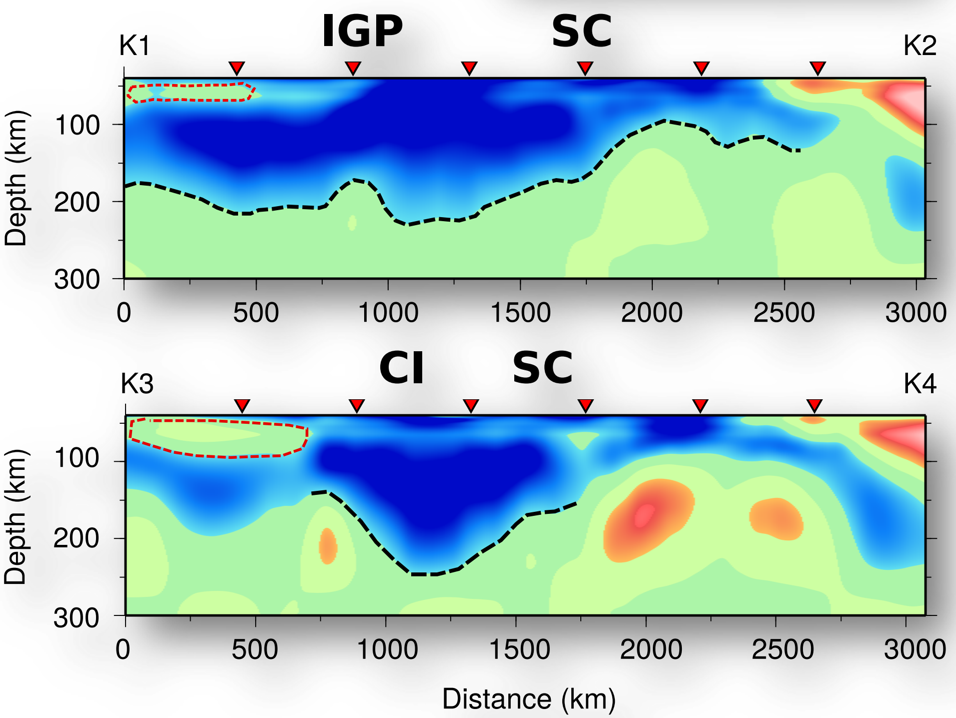
10-40° : **Indian plate motion**

Discussion: Indian 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.



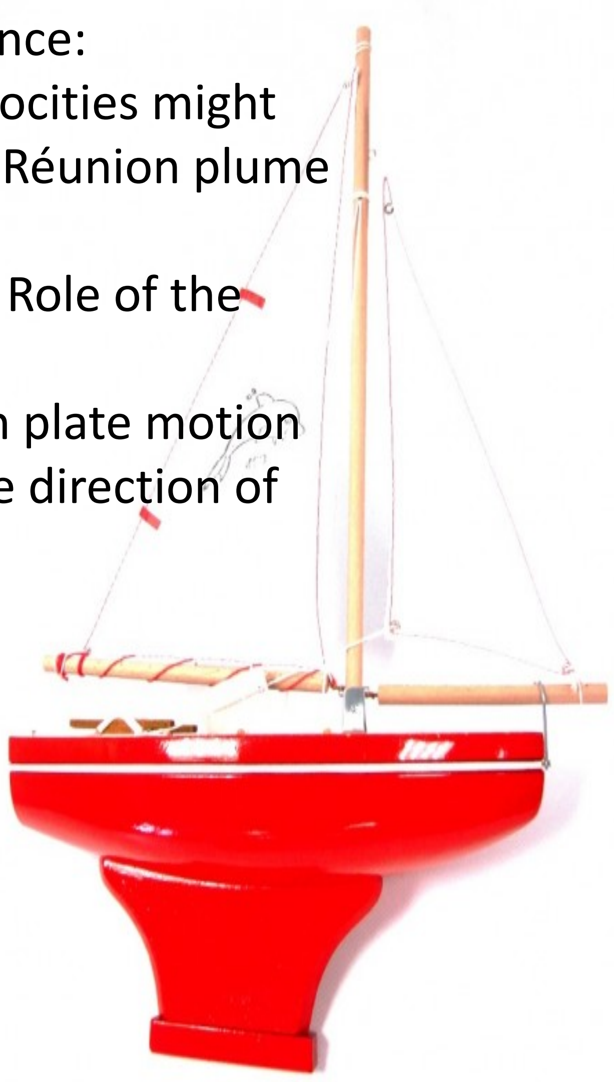


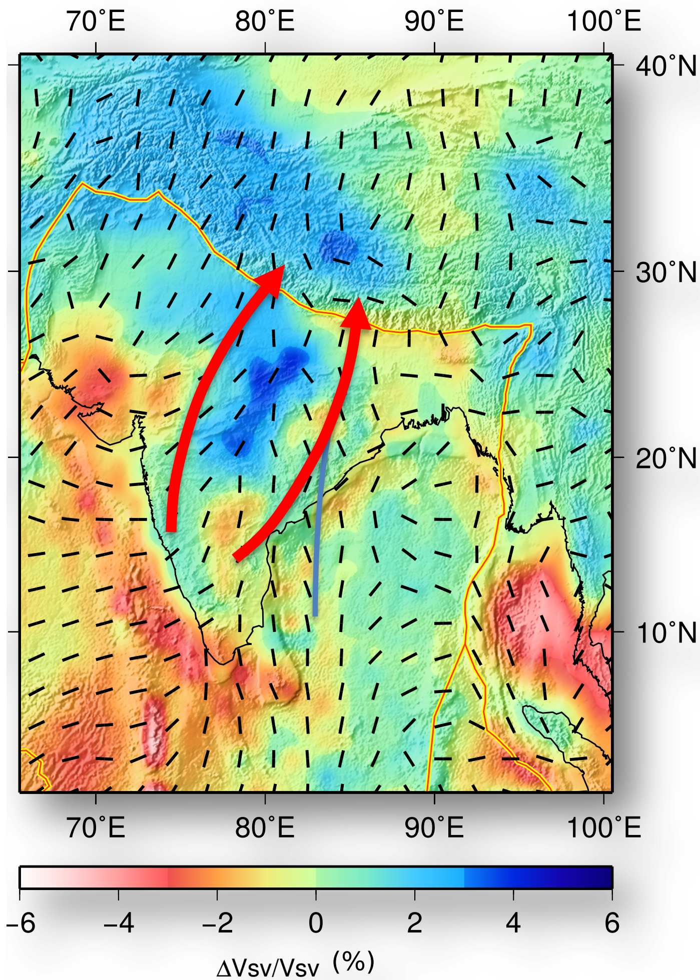


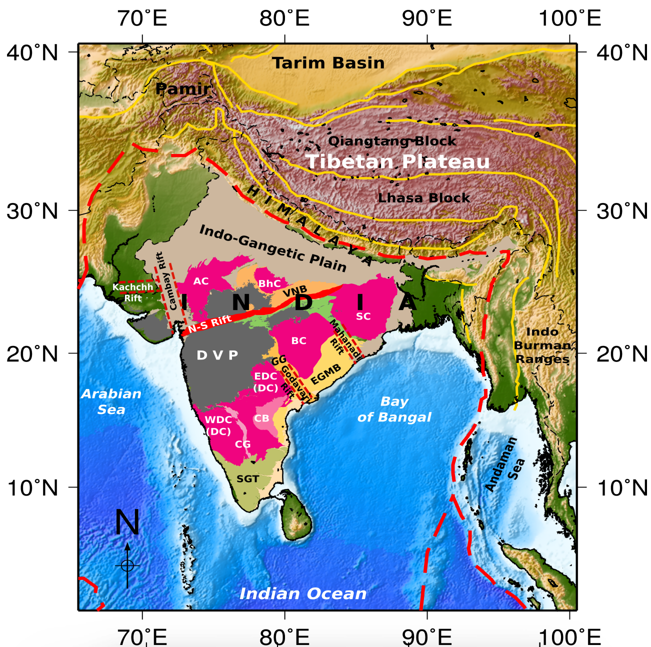
Indian Plate LAB: Keel

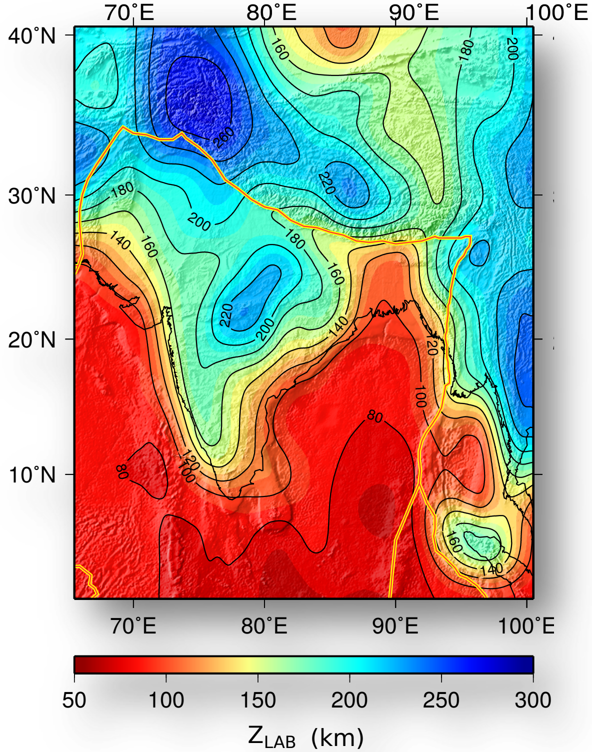
Plume influence:
fast plate velocities might be due to La Réunion plume

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









- 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)

Continental plates

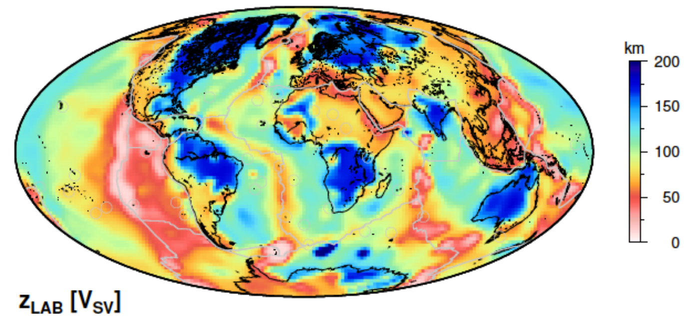
- ➢ LAB topography derived from surface wave data on a global scale and regional scale (India)

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

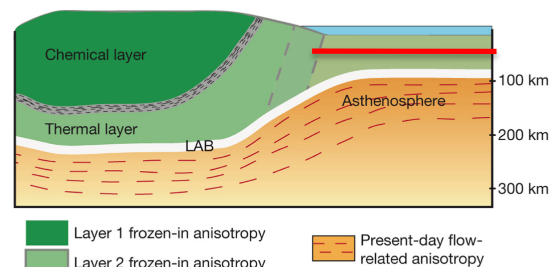
- ➢The model of fomation of lithosphere must be revisited in view of results from radial and azimuthal anisotropies in oceans and continents.

- ➢Role of the Indian Keel

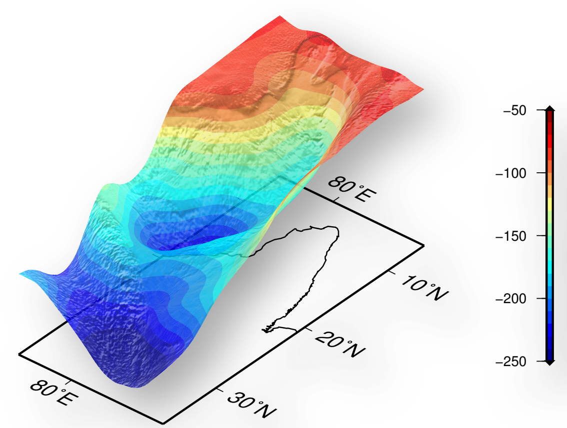
- ➢Role of mantle upwellings in plate motion which might be as important as subducting slabs



Burgos et al., 2014

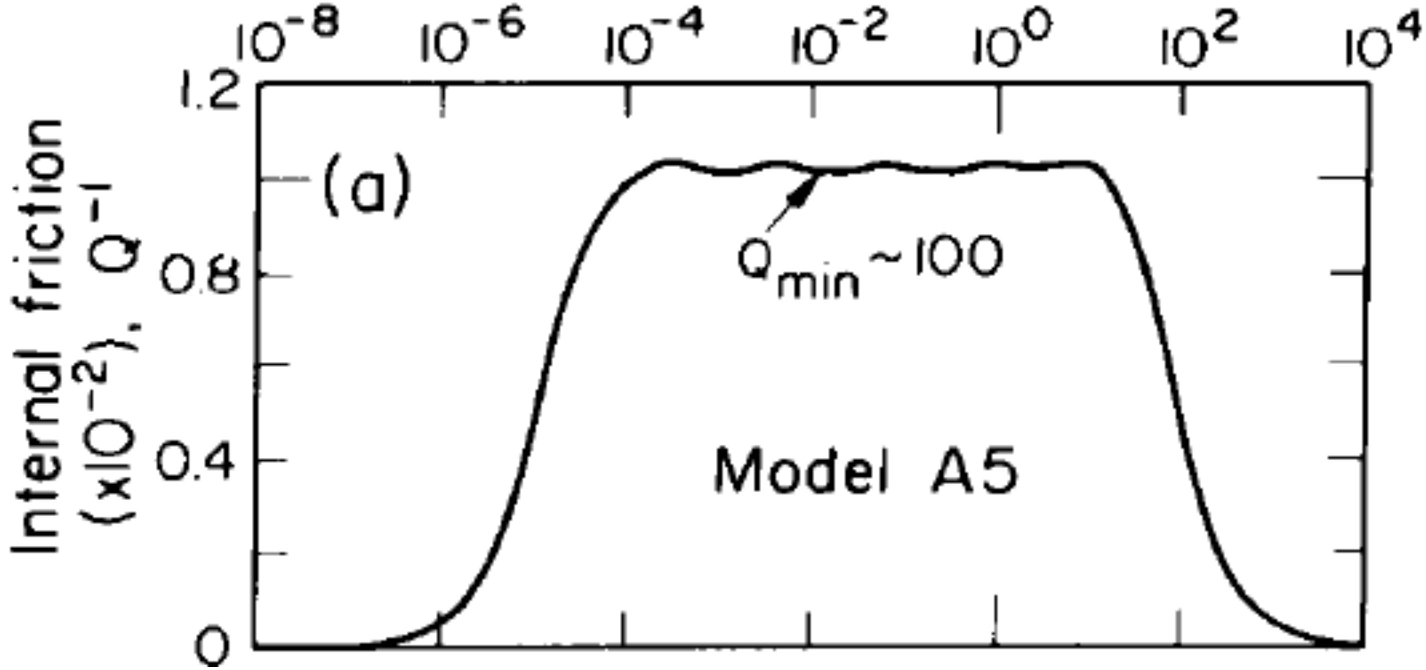


Yuan & Romanowicz, 2010



Anisotropy and extrinsic Anelasticity (Q factor or Q^{-1} attenuation)

Knopoff, 1964: Q? no frequency dependence



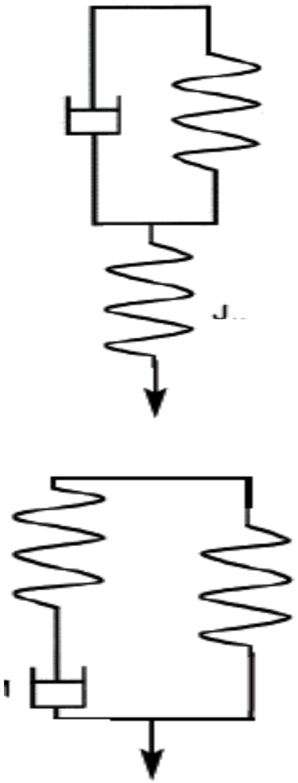
Frequency (Hz)

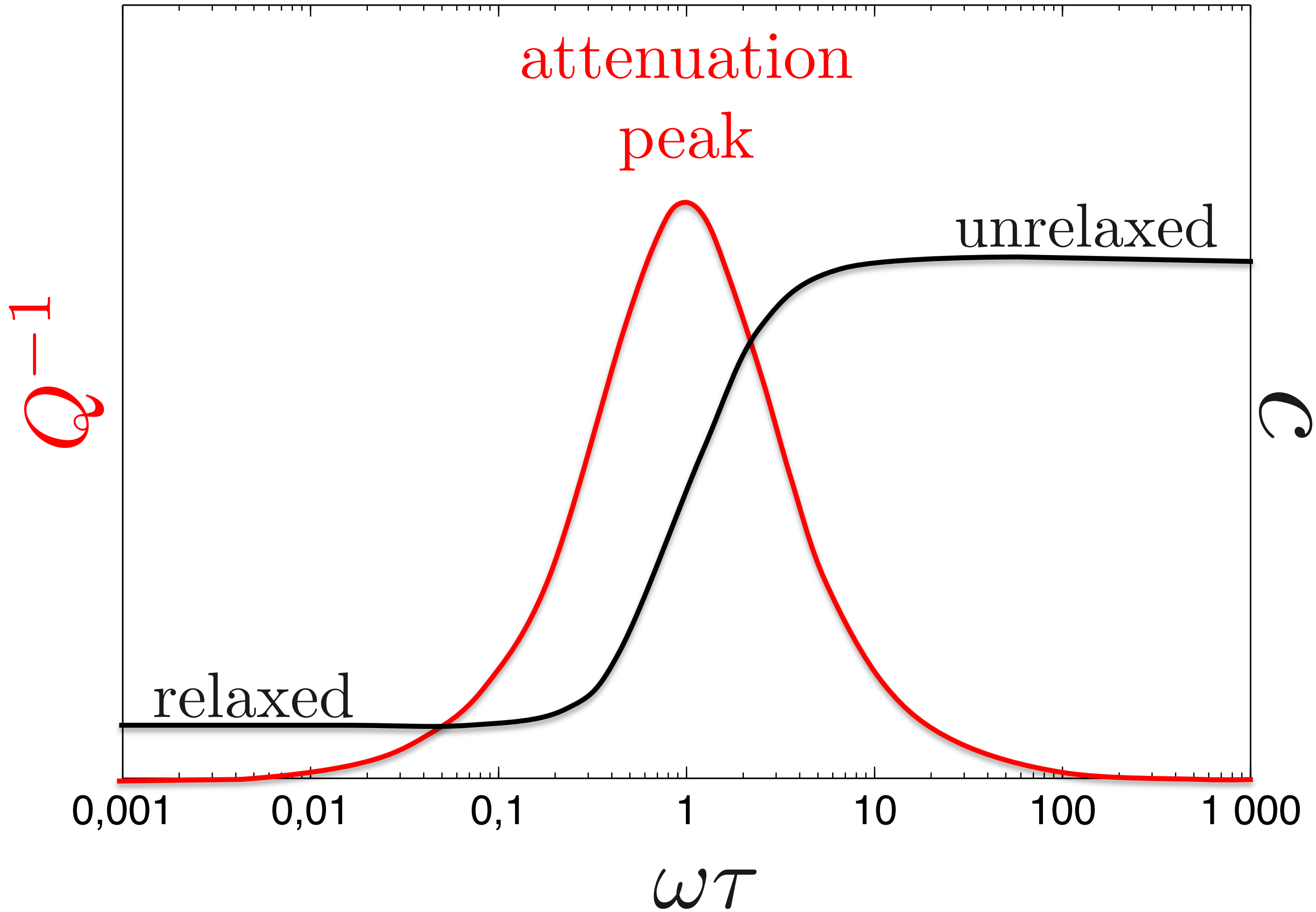
Liu et al., 1976

$$Q \sim \omega^{\alpha}$$

$-0.3 \leq \alpha \leq 0$ (Lekic et al., 2009)

Standard Linear Solid: τ relaxation time





Anisotropy and Anelasticity (Q factor or Q^{-1} attenuation)

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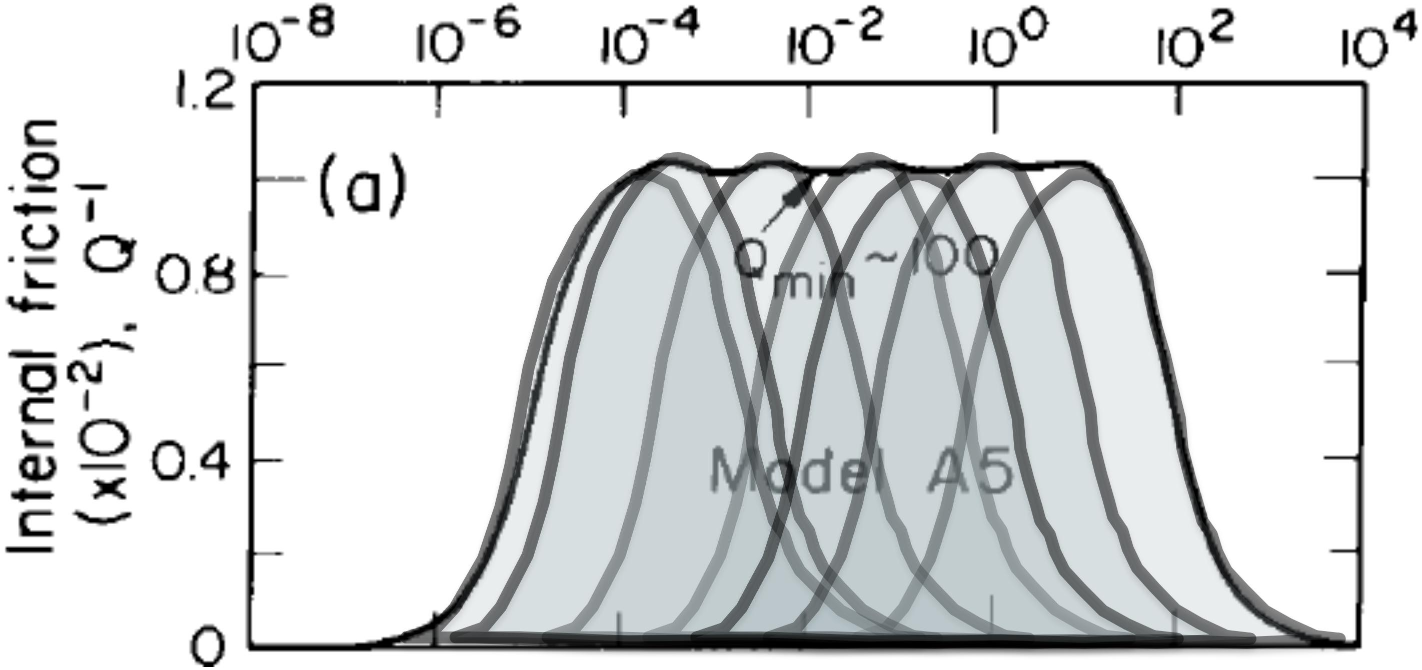


Frequency (Hz)

Liu et al., 1976

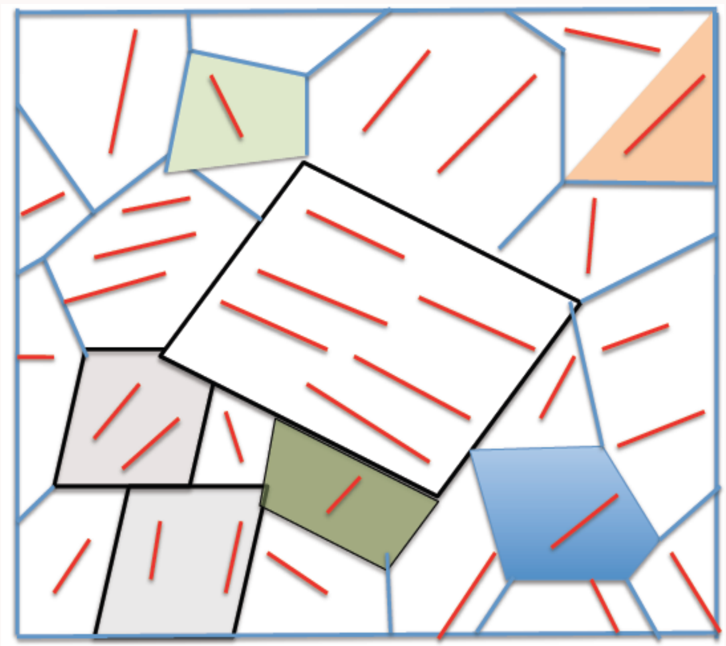
$$Q \sim \omega^{\alpha}$$

$-0.3 \leq \alpha \leq 0$ (Lekic et al., 2009)

Anisotropy and Anelasticity

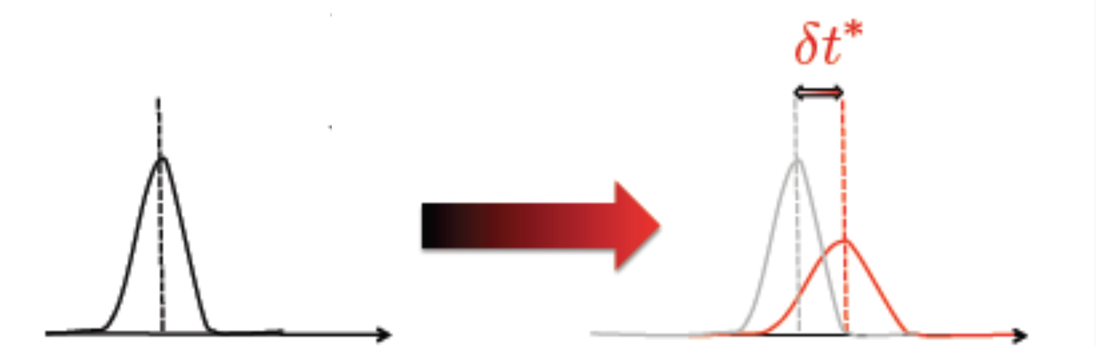
Incoherent Strain field

⇩

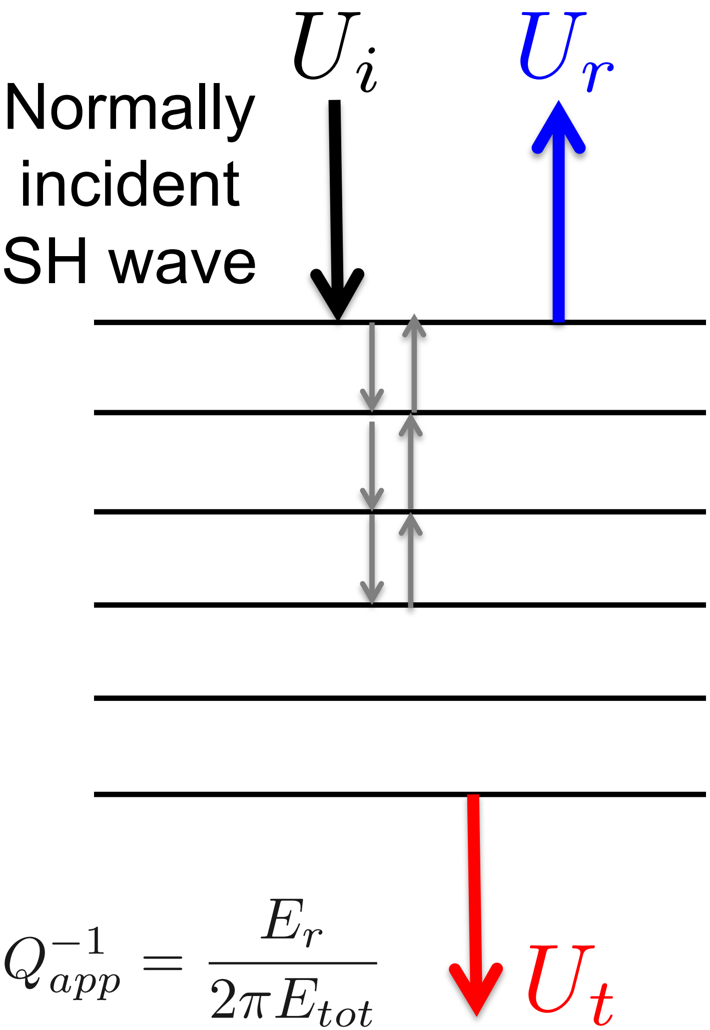


Large-scale Seismic anisotropy ≈ 0

But extrinsic (scattering) attenuation



1D-Layered medium



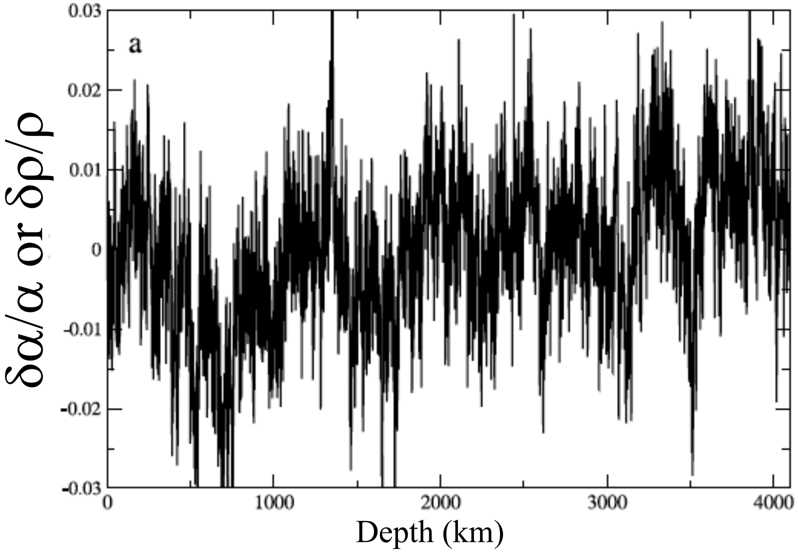
$$Q_{app}^{-1} = \frac{E_r}{2\pi E_{tot}}$$

Random orientation of fast axis

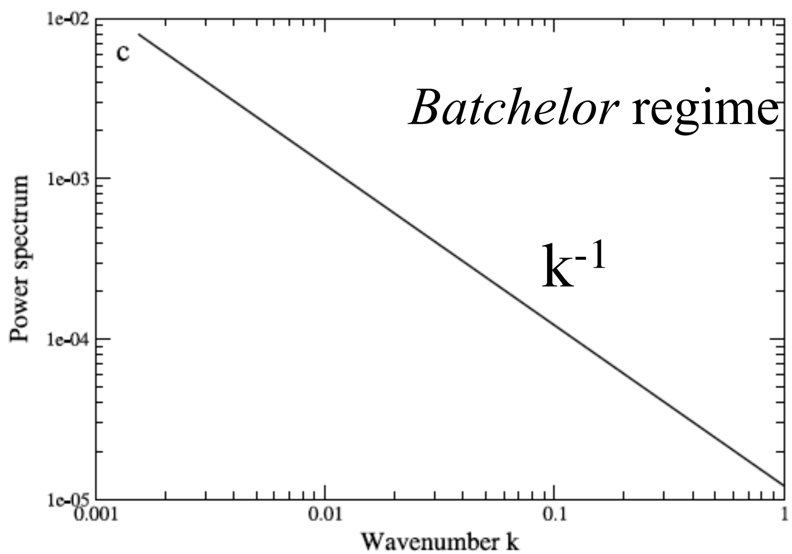
-Exact numerical solution: Thomson- Haskell (*Aki & Richard*, 1980)

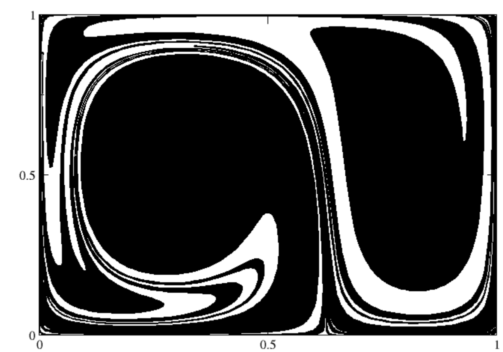
- Approximated analytical solution: equivalent medium (*Backus*,1962, *O'Doherty & Anstey*, 1971, *Capdeville & Marigo*, 2007)

Anisotropy and Attenuation



Different kinds
Of heterogeneities
$\delta\alpha/\alpha$, or $\delta\mu/\mu$, or $\delta\rho/\rho$

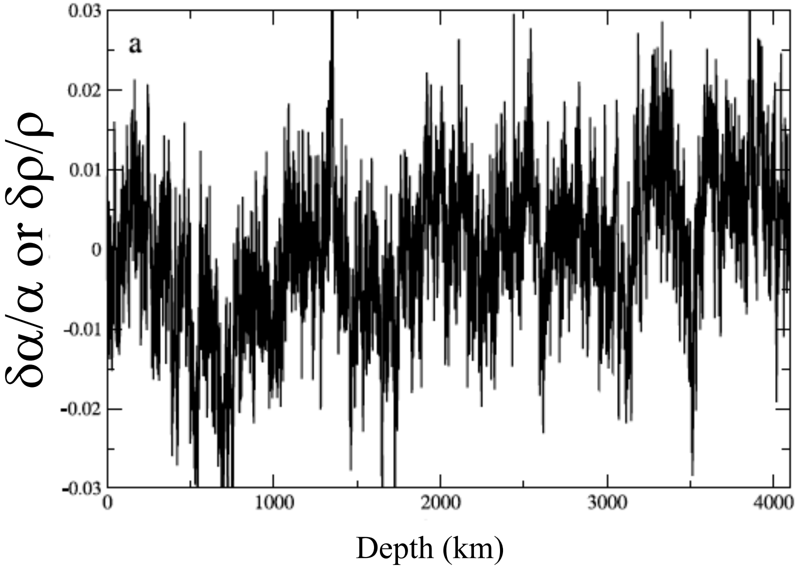


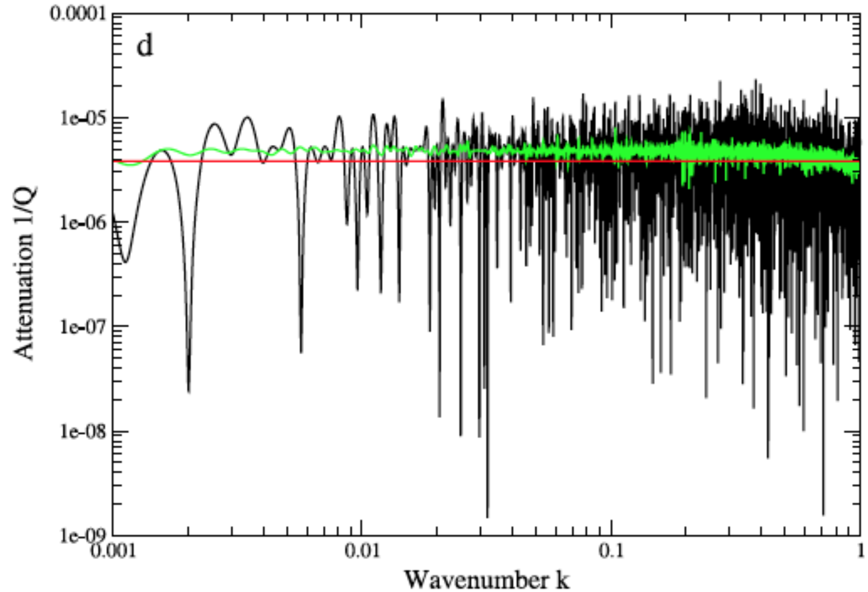


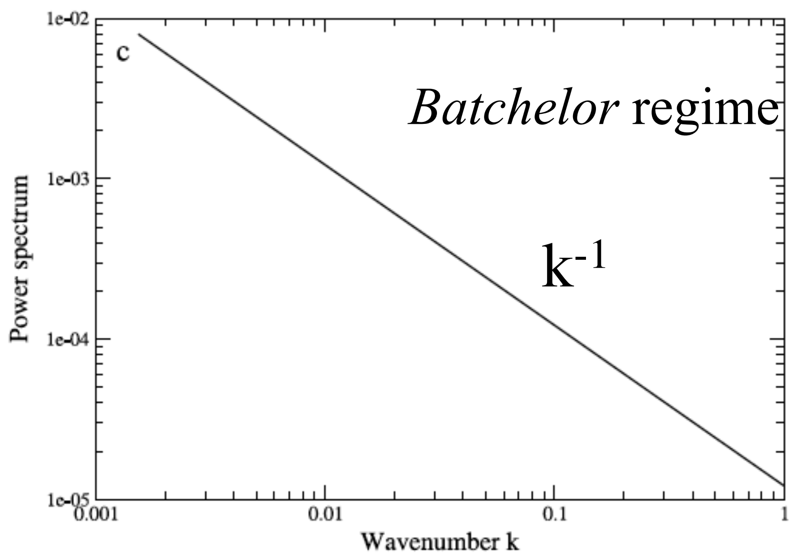
Example of mixing

Ricard et al. (2014)
Alder et al., 2017

Anisotropy and Attenuation





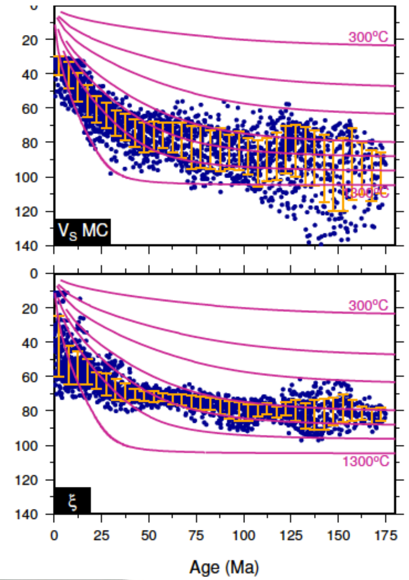


Q is frequency independent

~6-9% amplitude of $\delta\alpha/\alpha$, $\delta\mu/\mu$, $\delta\rho/\rho$

Ricard et al. (2014)

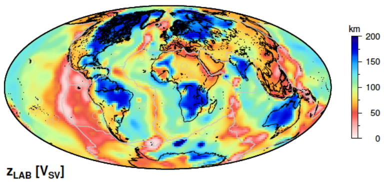
Conclusions



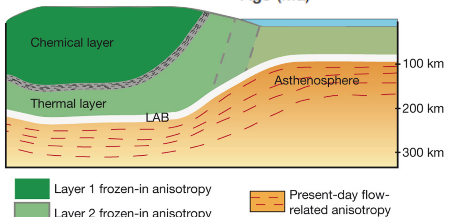
- Seismic Anisotropy can be mapped in different depth ranges

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

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



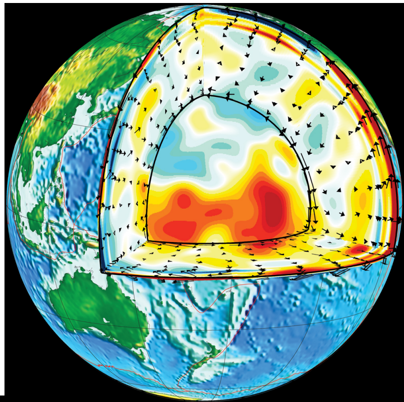
- New findings from anisotropy : MLB

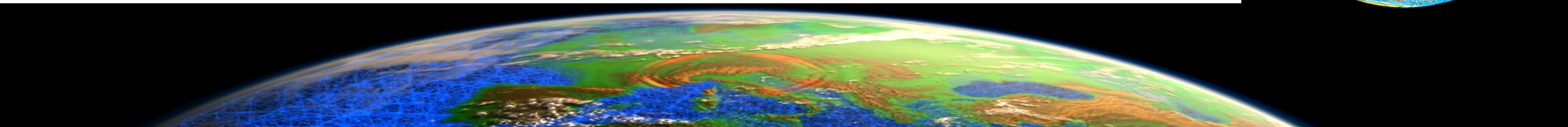


Yuan and Romanowicz, 2010

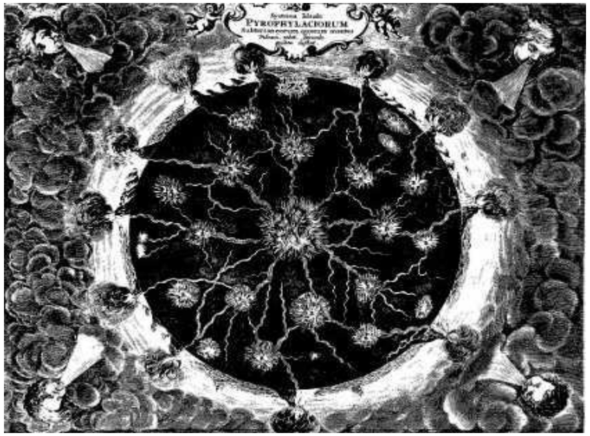
- Attenuation (extrinsic) correlated with anisotropy

-New tools, numerical techniques and approaches are necessary in order to separate different causes of anisotropy and to model strain and stress fields





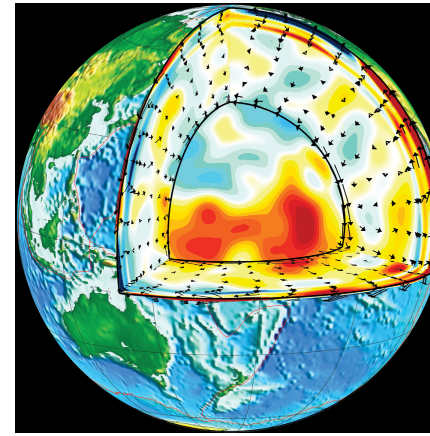
Messages of ancestors/grand-parents to kids



Athanasius Kircher, 1678

The Earth is a fascinating object

Our vision completely changed during the last centuries



- Earth science is an object-oriented discipline
- 15 orders of magnitude: upscaling-downscaling
- The fundamental laws of physics cannot explain most geological objects

- Seismic Anisotropy is a good example:
- **Intrinsic** anisotropy (CPO microscopic)<=>**Extrinsic** anisotropy (geometry, larger scale)
- Interpretation of seismic anisotropy (and attenuation) is non-unique

- Anisotropy mapped in different depth ranges => Dream: $C_{ijkl}(r,\theta,\phi)$, $Q_{ijkl}(r,\theta,\phi)$, $\eta_{ijkl}(r,\theta,\phi)$
- Multidisciplinary approach: Imaging + evolution of geological objects