What does Seismic Anisotropy tell us about the Lithosphere-Asthenosphere Boundary?

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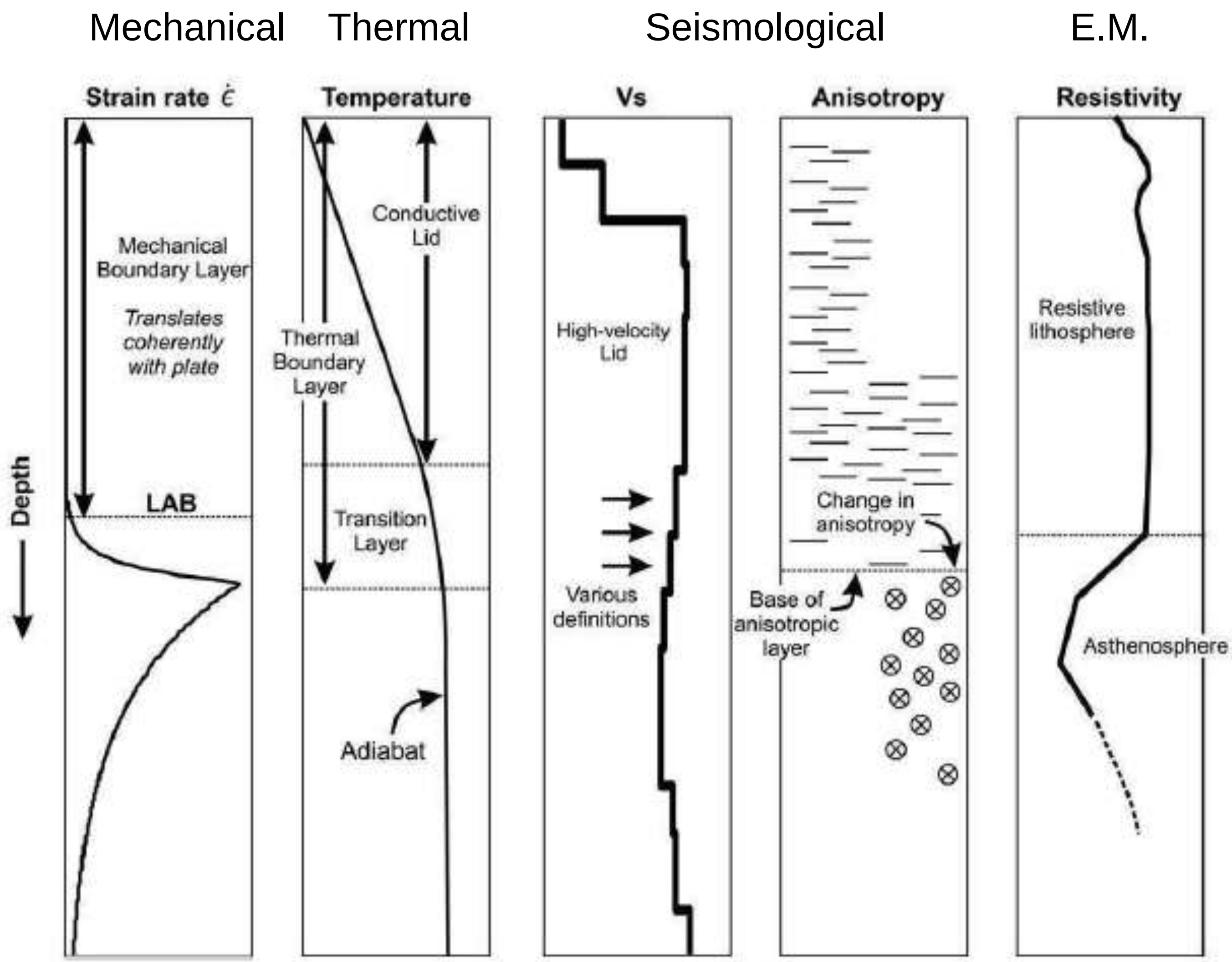
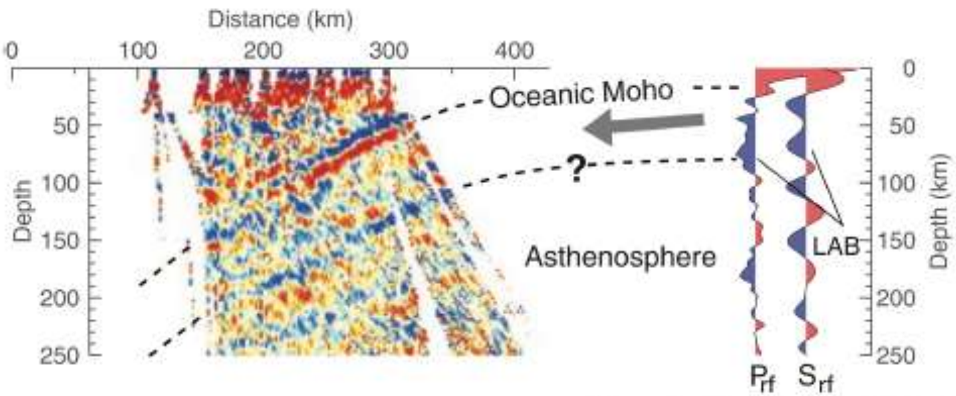
L.A.B.: Lithosphere-Asthenosphere Boundary
(many different approaches and definitions)



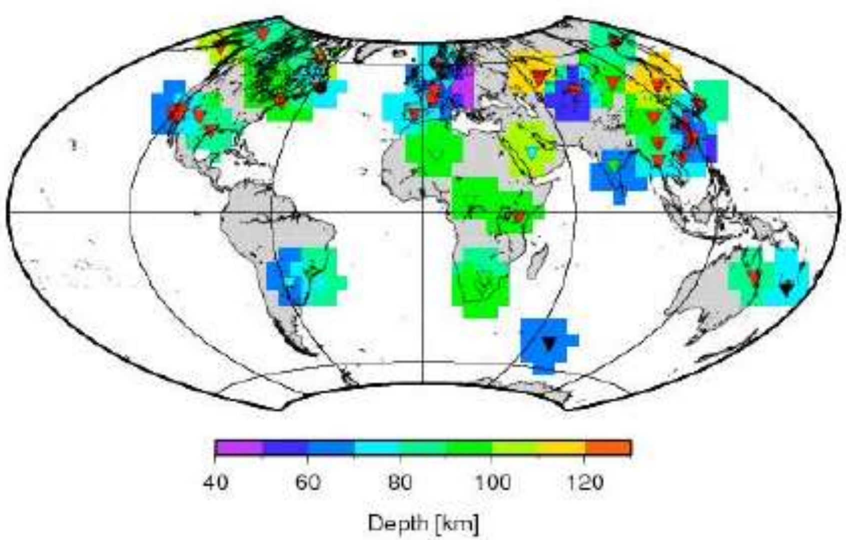
Eaton et al., 2008

LAB : from seismic data

Receiver functions

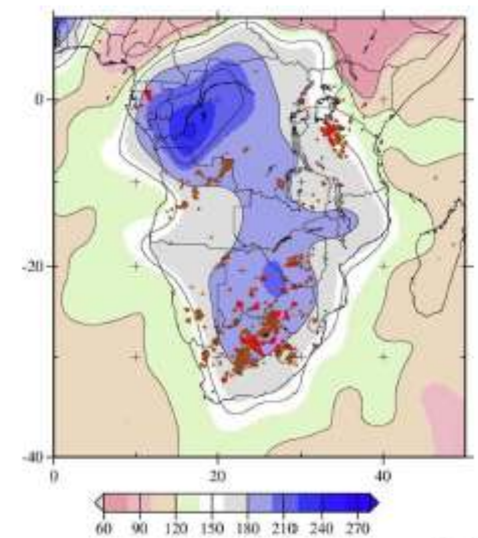


Kawakatsu et al., 2009

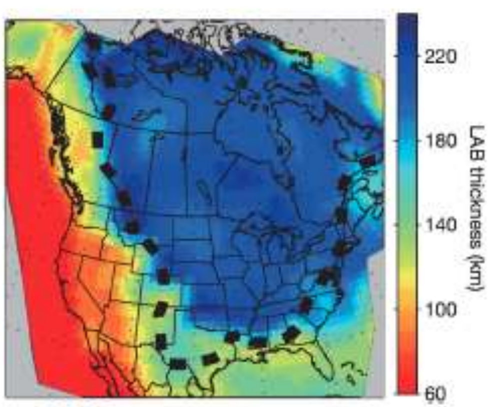


Rychert & Shearer, 2009

Surface waves

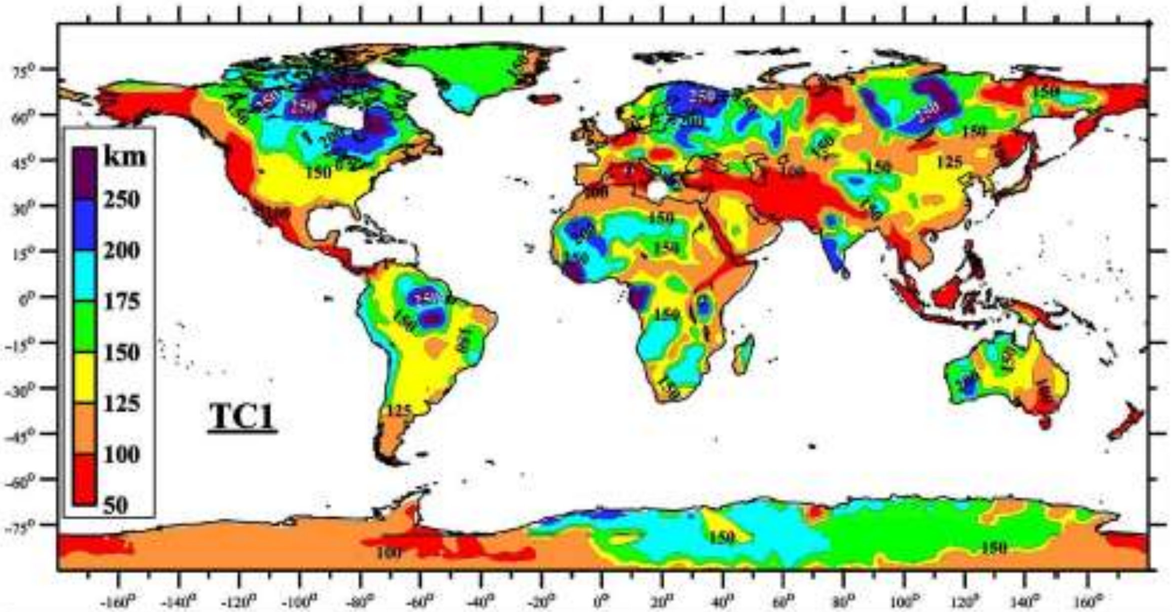


Fishwick, 2010



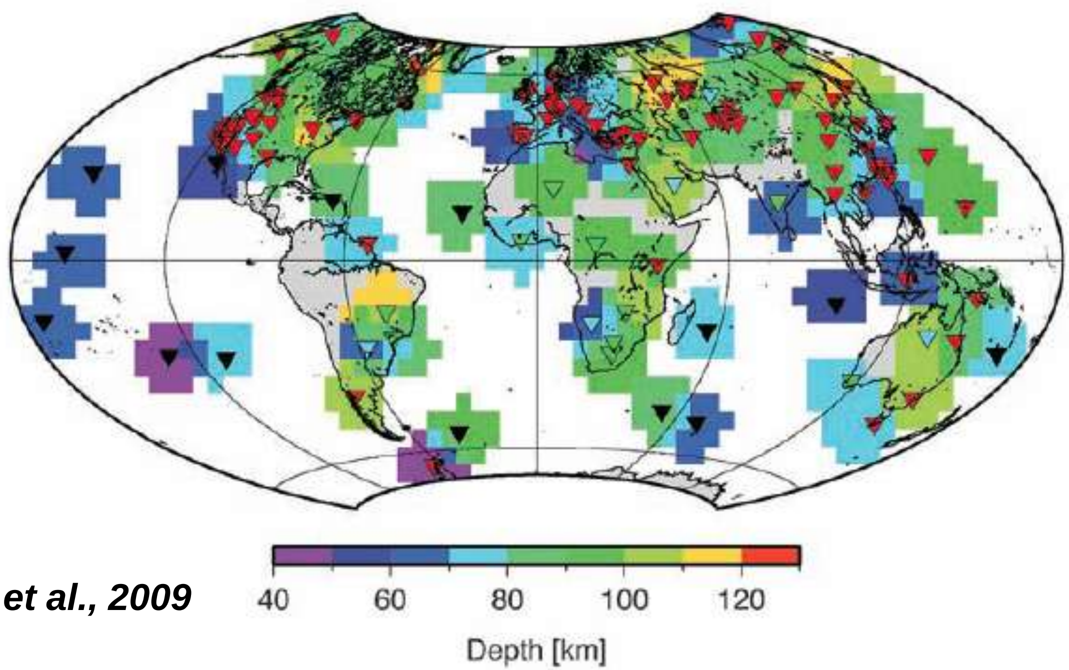
+SKS

Yuan & Romanowicz, 2010



Artemieva, 2006

Global scale

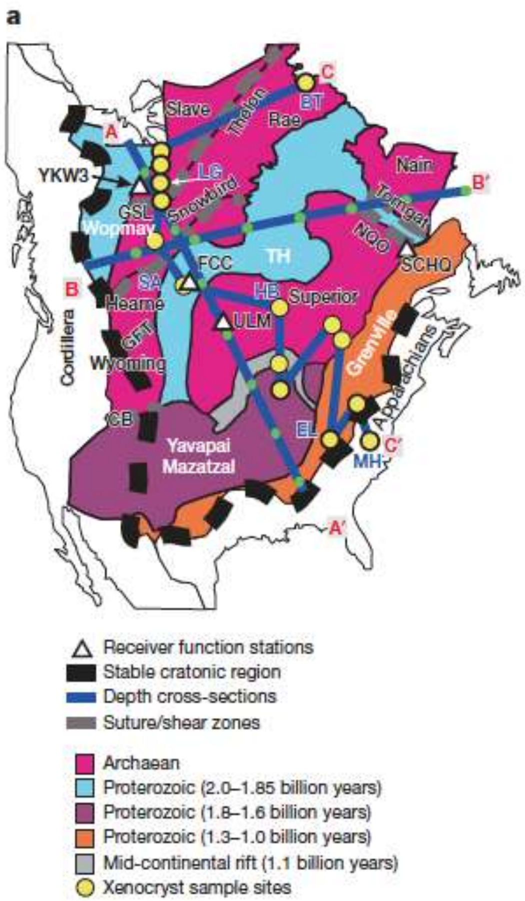


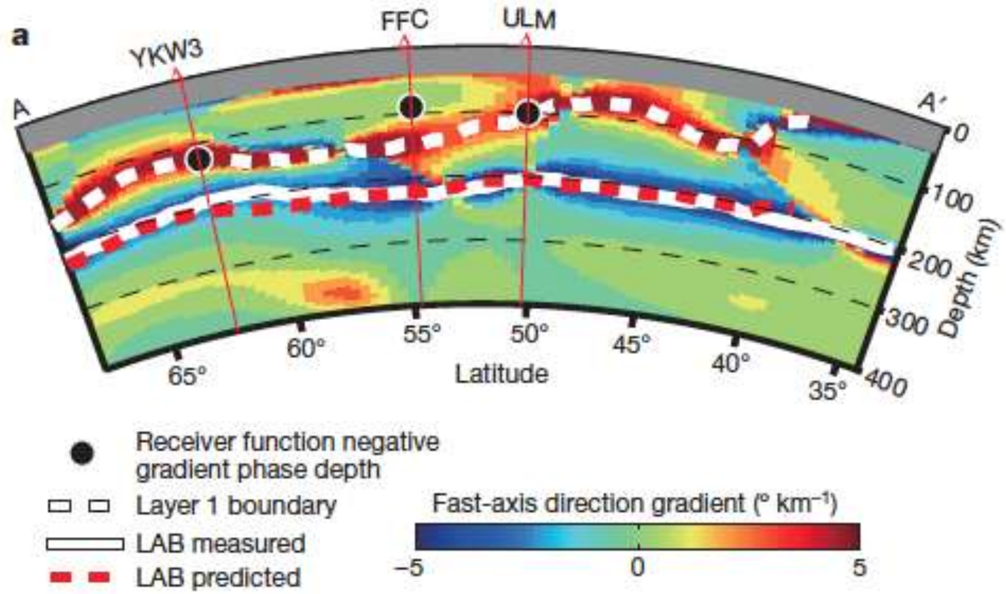
Rychert et al., 2009

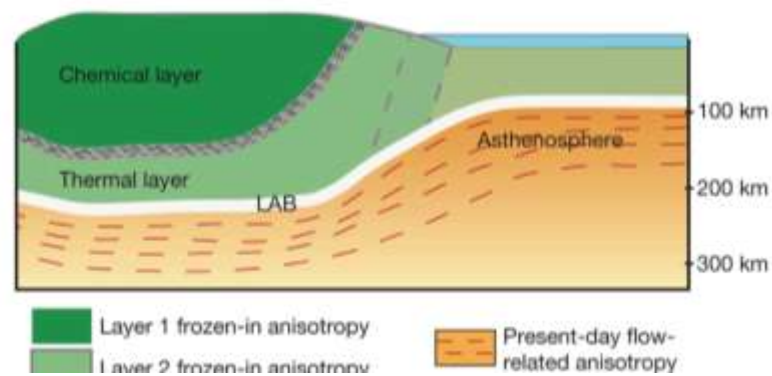
-Much discrepancy
Between different
Estimates
-Global tomographies
give 200-250km depth
for continental roots

-Ocean-Continent

Structure of continents from seismic anisotropy





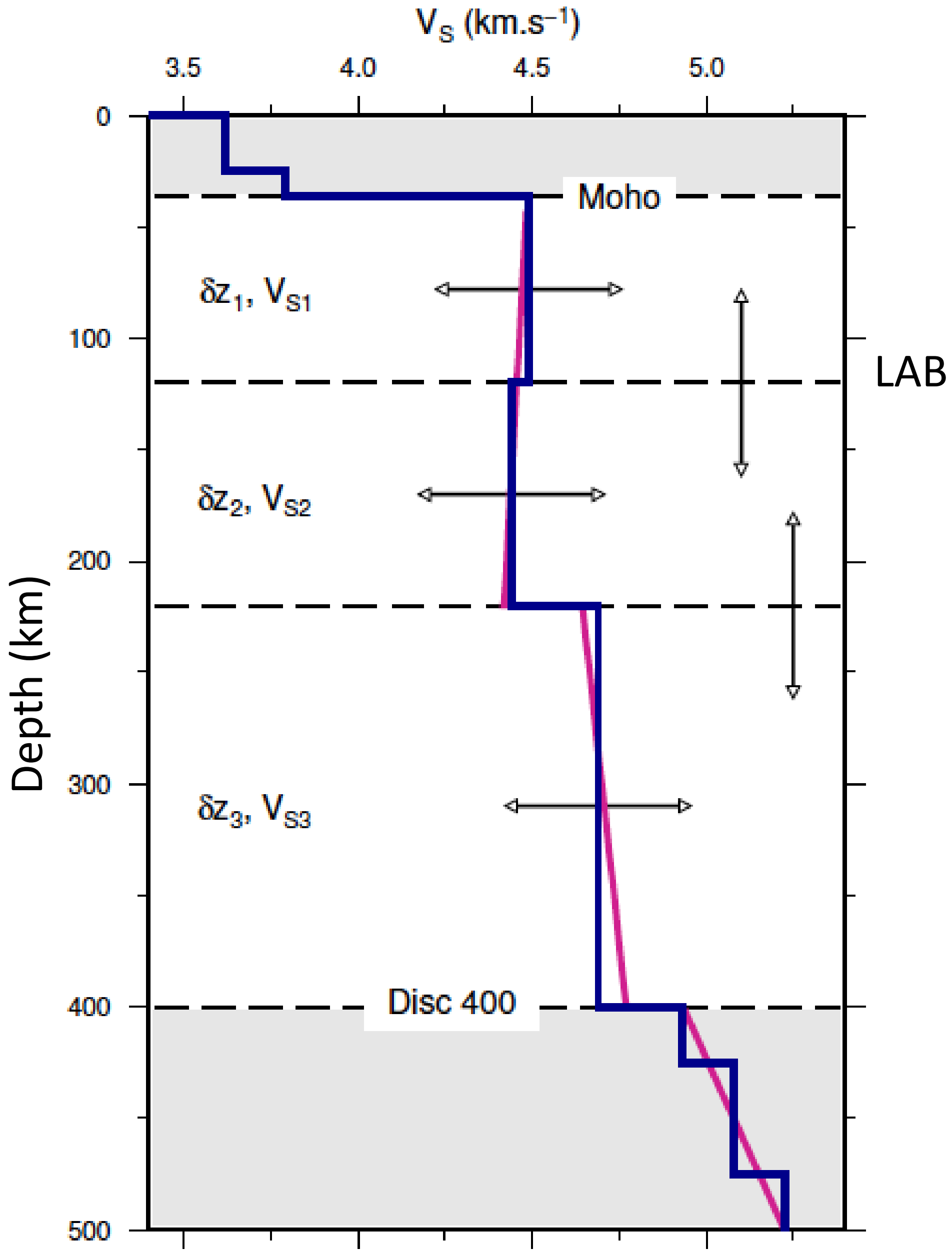


Mid-Lithospheric Boundary

Yuan and Romanowicz, 2010

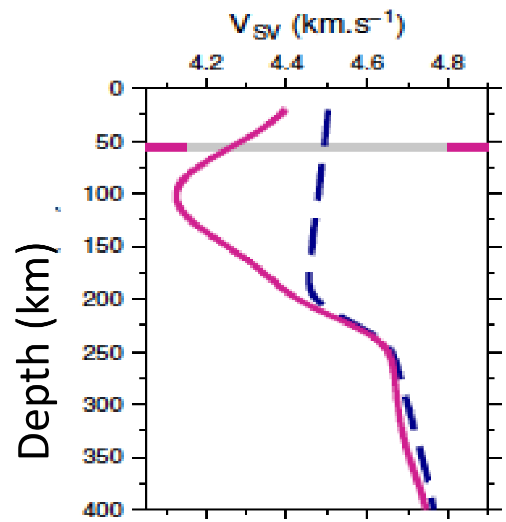
From Surface wave dispersion

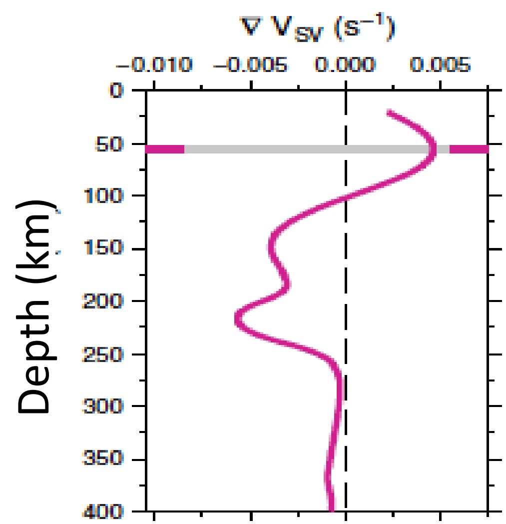
Statistical Monte-Carlo Approach



First order Perturbation theory
(from phase velocity inversion)

Proxy from parameter Vsv



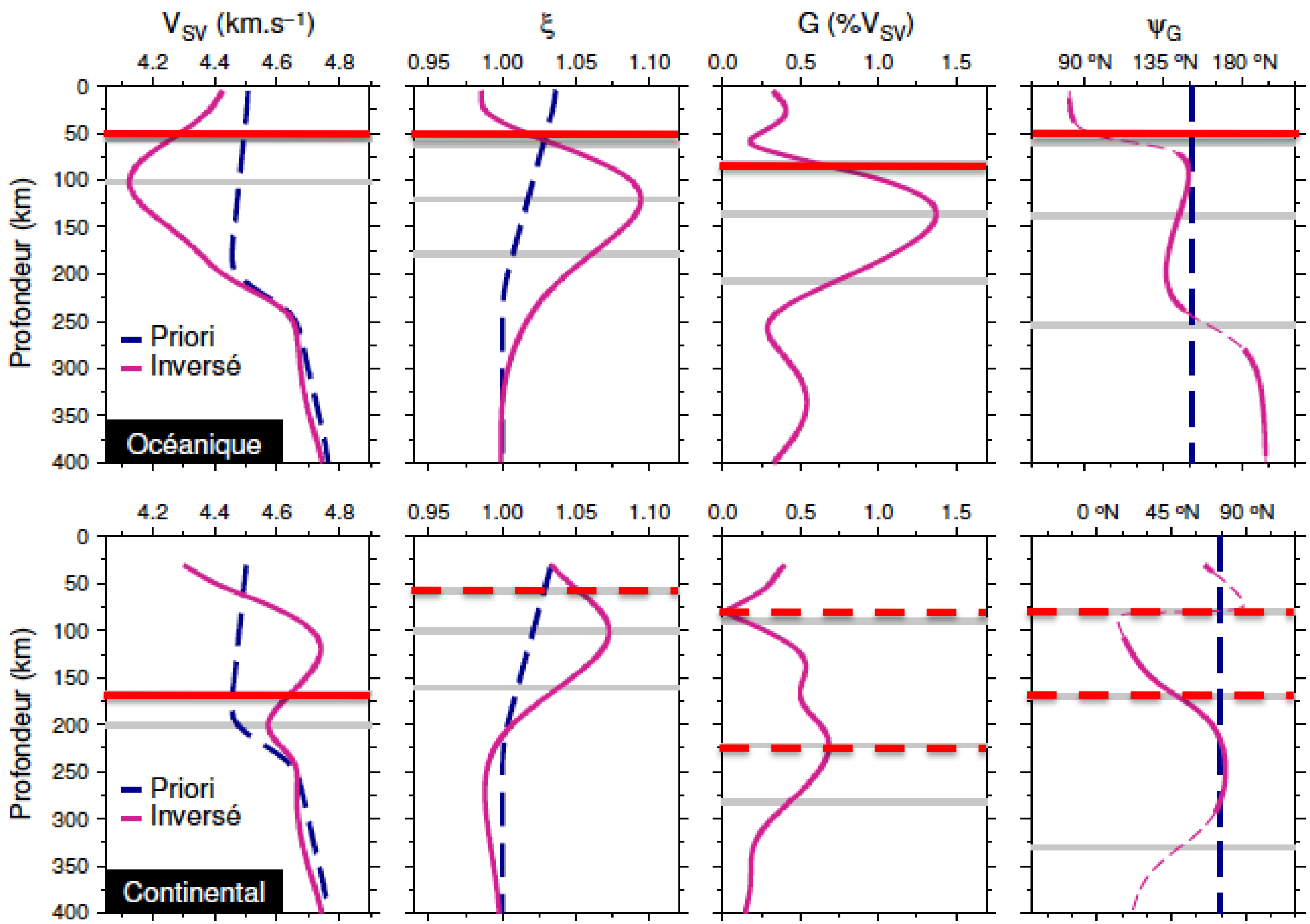


Proxies from other parameters: Seismic Anisotropy?

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°



Seismic Anisotropy at all scales

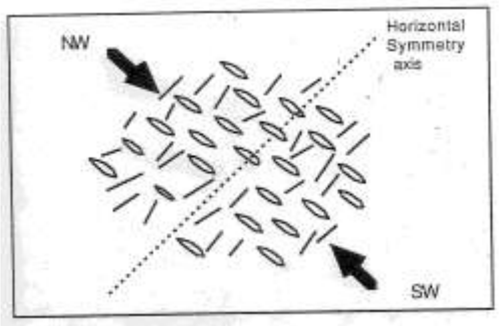
-From microscopic scale up to macroscopic scale

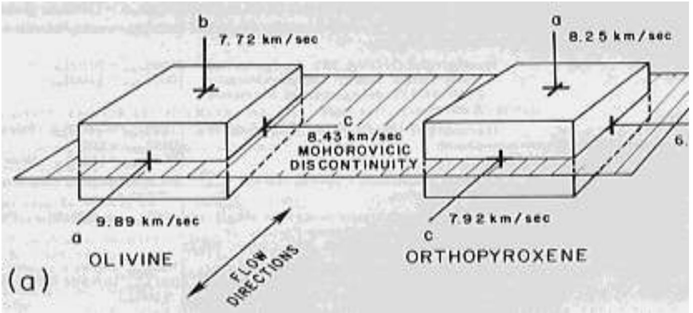
-Efficient mechanisms of alignment of minerals in the crust and upper mantle:
(L.P.O.: Lattice preferred orientation of minerals;
S.P.O.: Shape preferred orientation: fluid inclusions, cracks…
Fine Layering)

ANISOTROPY is the Rule not the Exception

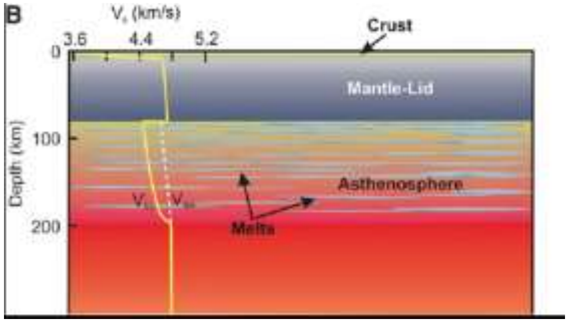
Apparent (observed) anisotropy:
NON UNIQUE INTERPRETATION
in different depth ranges of the Earth

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





Christensen and Lundquist (1982)



Kawakatsu et al. (2009)

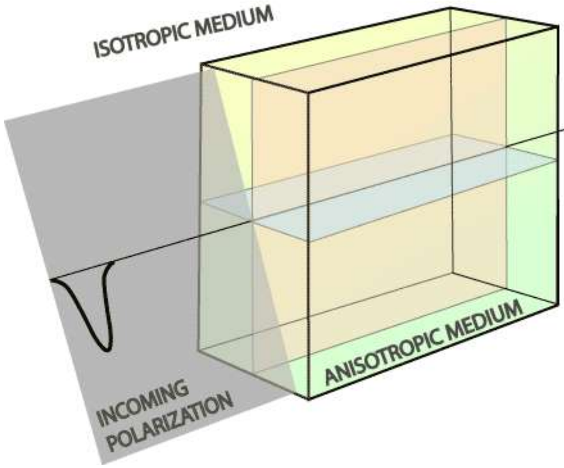
- *Mineralogy, Water and fluid content*
- *Present day tectonic, geodynamic processes*
- *Past processes (frozen anisotropy)*

Separation of the different kinds of anisotropy in different layers => Different interpretations

Stratification of anisotropy in the crust & mantle
Above, below the LAB?

Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting
(birefringence)



•Surface waves (Rayleigh and Love):

-Rayleigh-Love discrepancy
(VTI model: radial anisotropy)
-Azimuthal variations of phase or group velocities

Courtesy of Ed. Garnero

-Amplitude effects: Quasi-Rayleigh, Quasi-Love
polarization anomalies

Effect of anisotropy on the phase of surface waves

Effect on eigenfrequency ω_k (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 (21 elastic moduli), V phase velocity

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)

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

•*Cijkl 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}*

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

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

•*Body waves (Crampin, 1984)*

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

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

Proxies from other parameters: Seismic Anisotropy

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Oceanic profile
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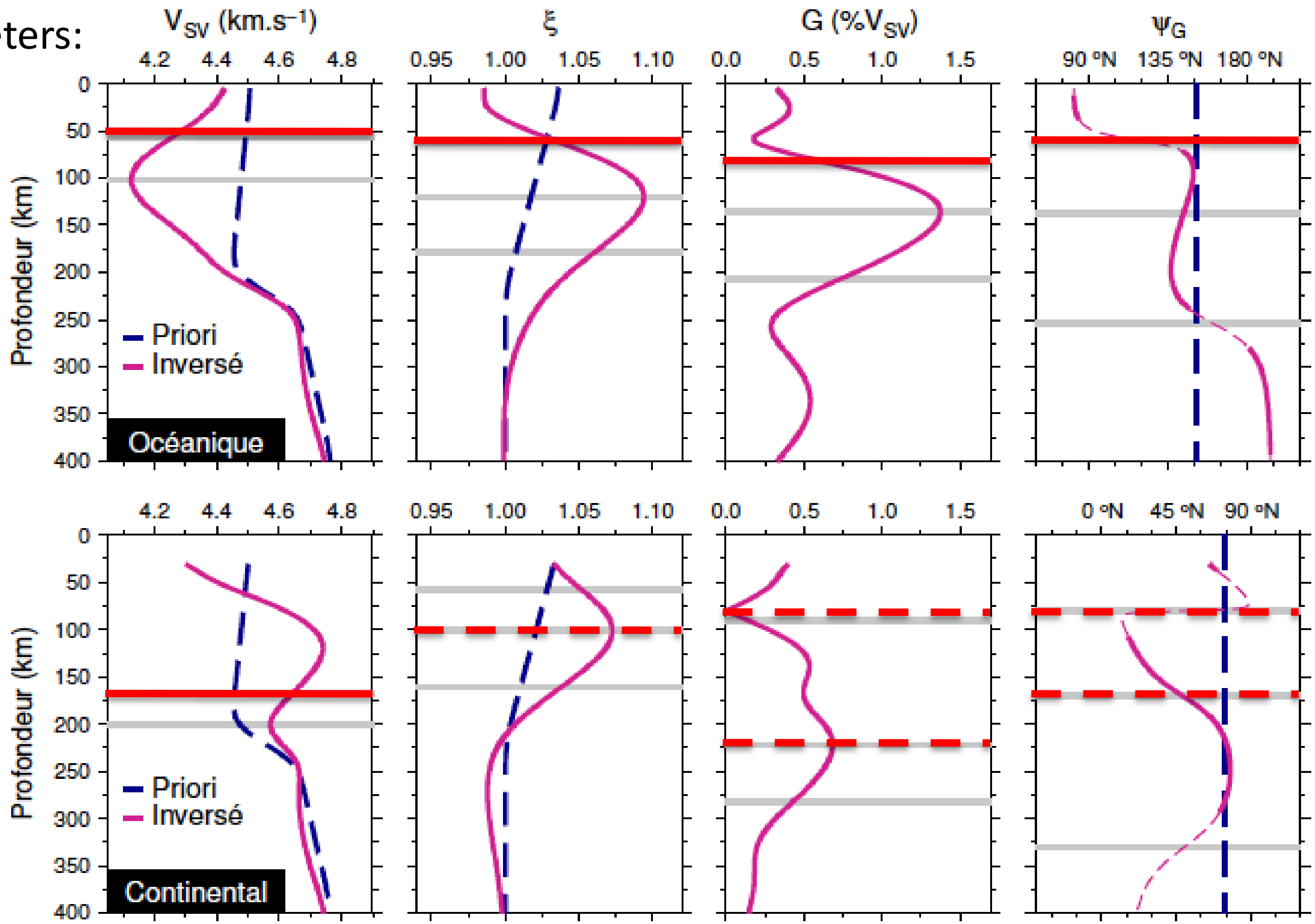


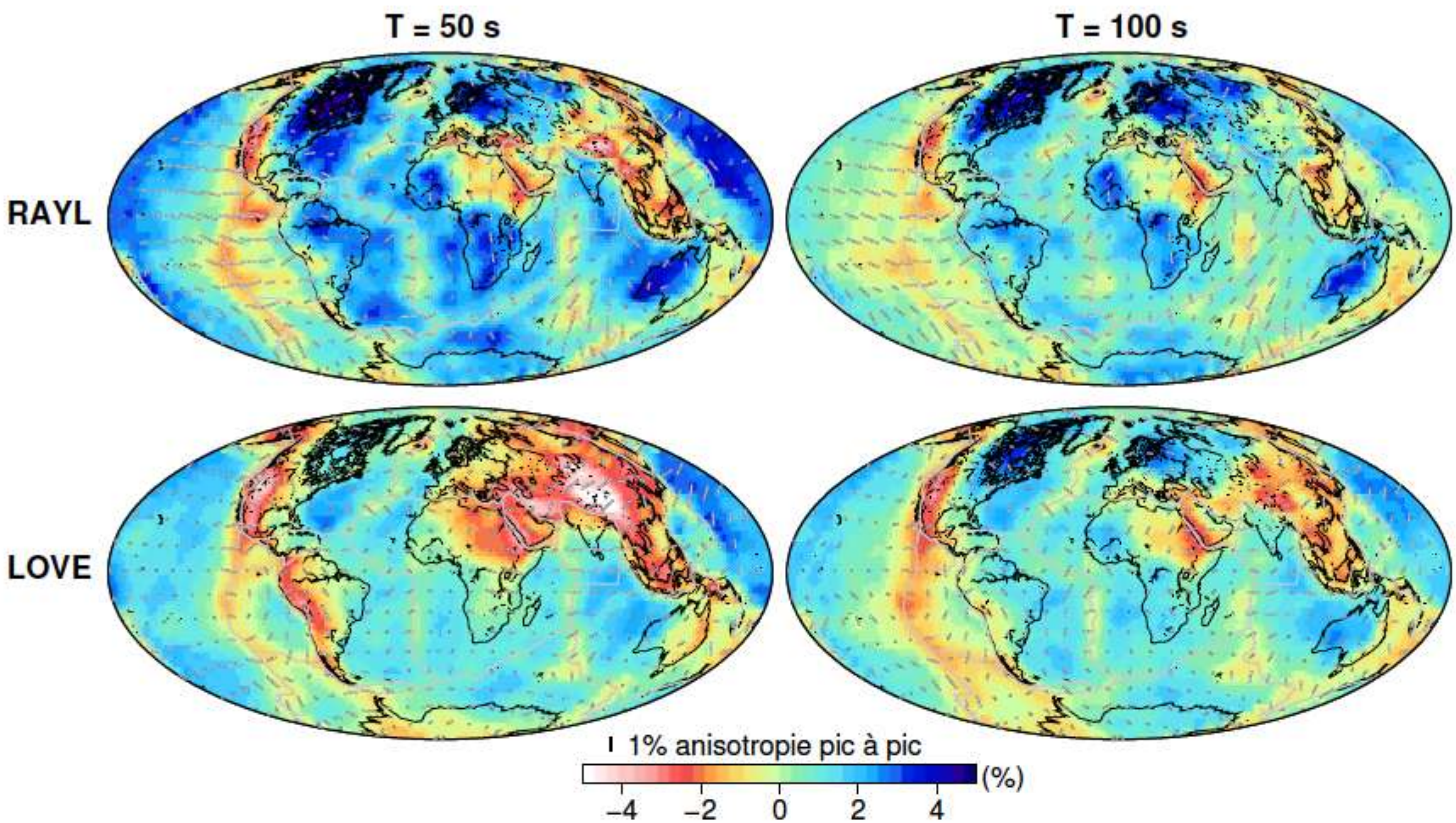
Data collection

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, θ, ϕ, ψ)

Rayleigh phase velocity and azimuthal anisotropy



Second step: Inversion at depth

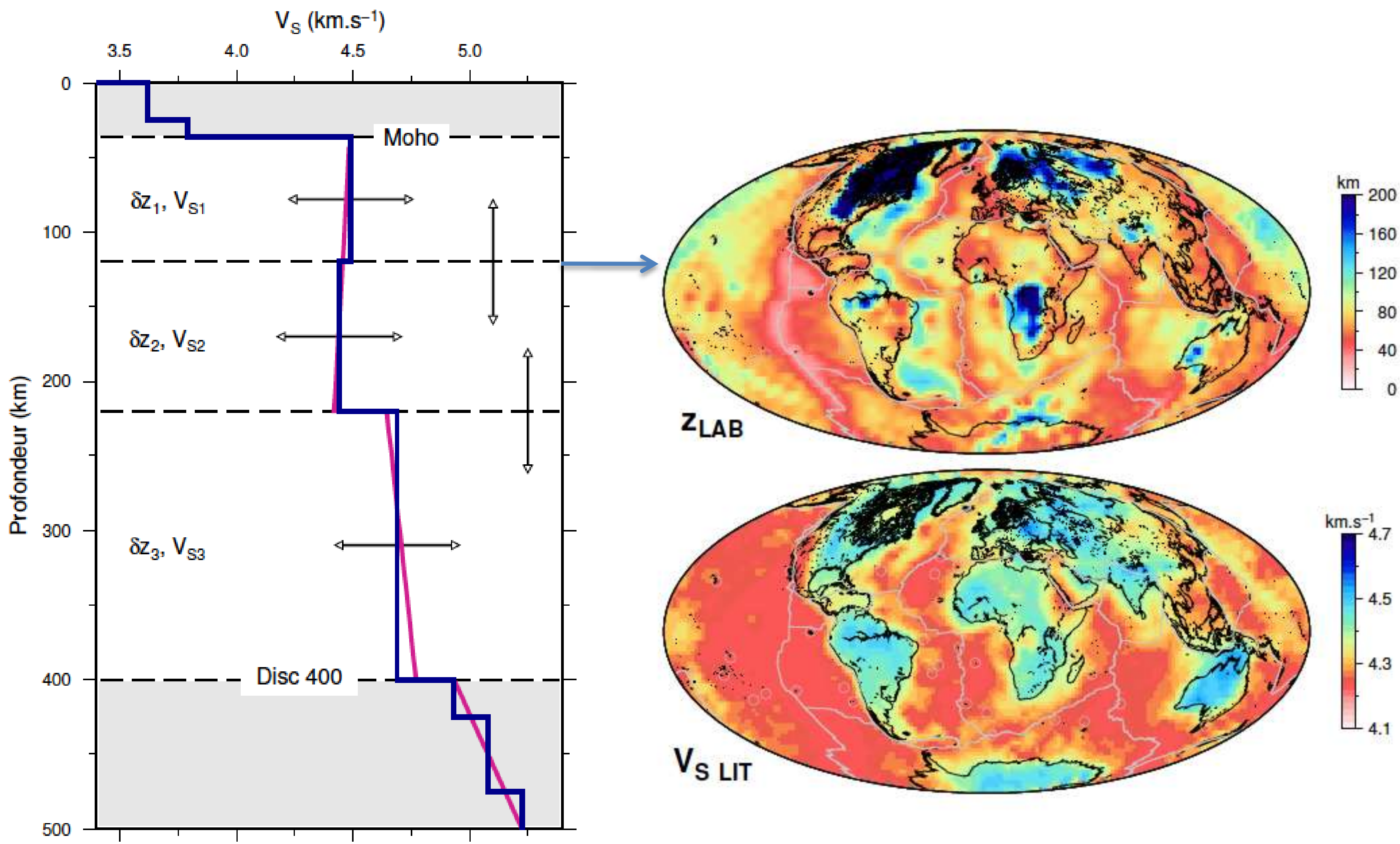
Statistical Monte-Carlo Inversion

First order Perturbation

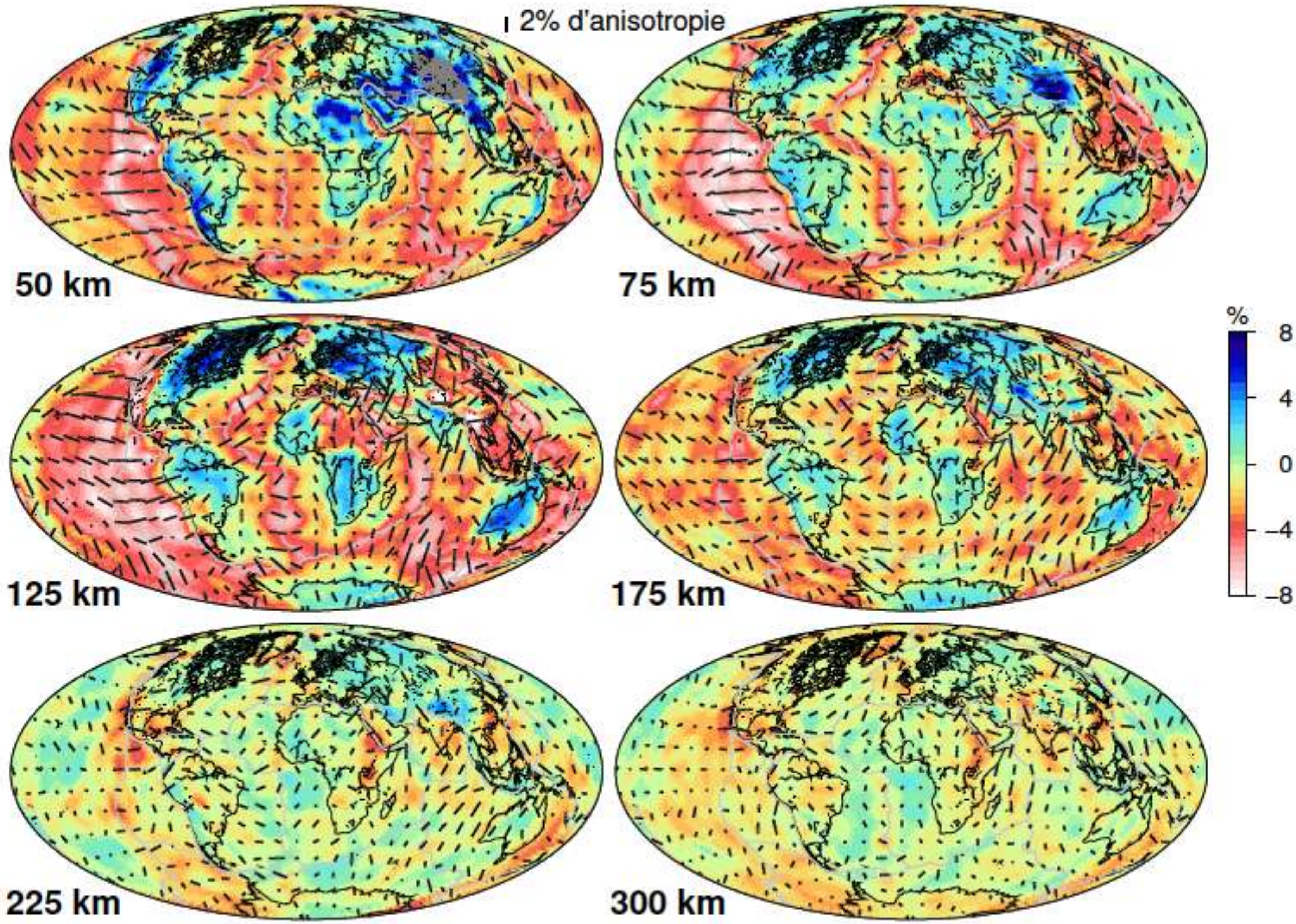
Th

LAB: Statistical M.C. 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)



Proxies obtained from anisotropic tomographic models

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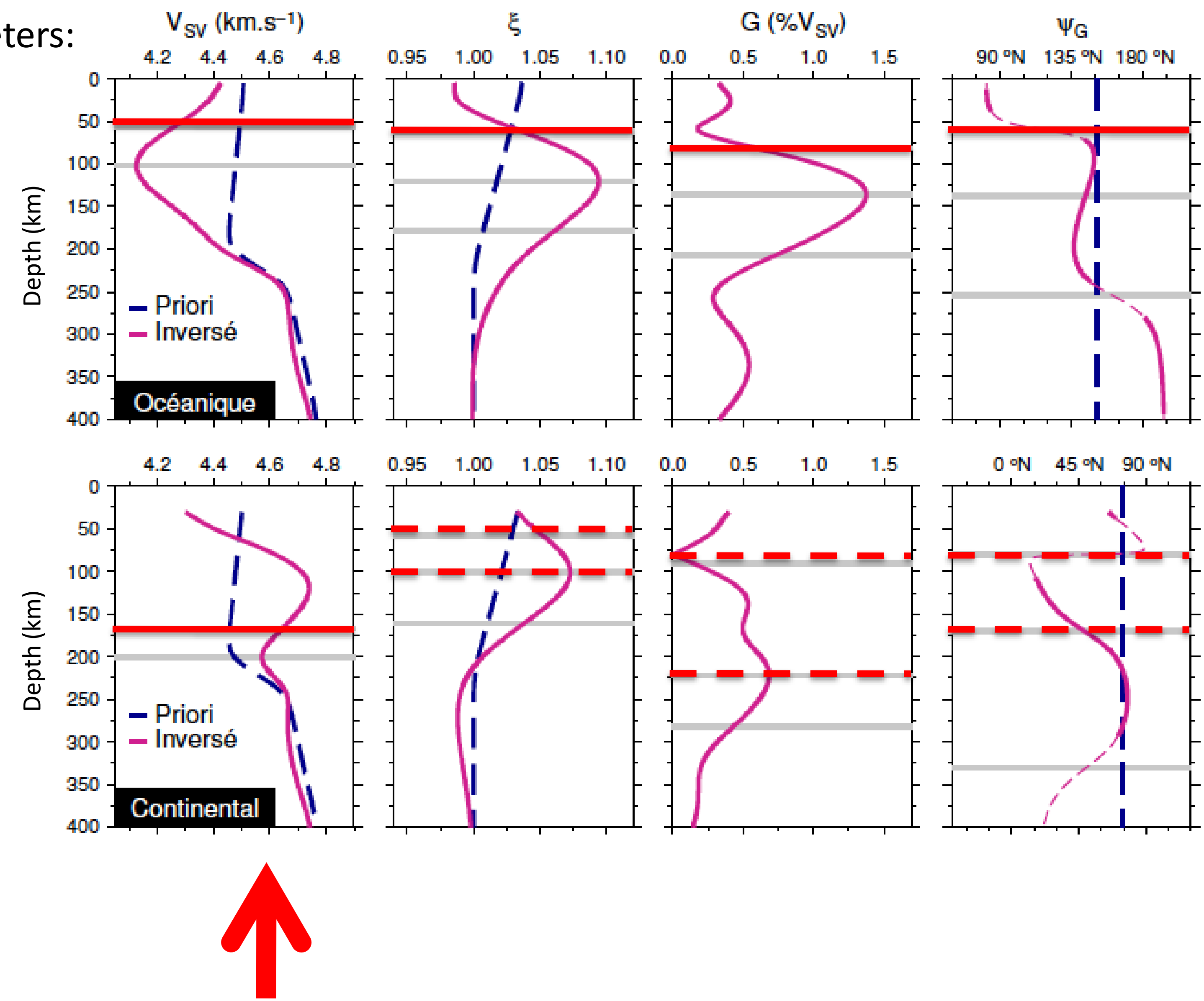
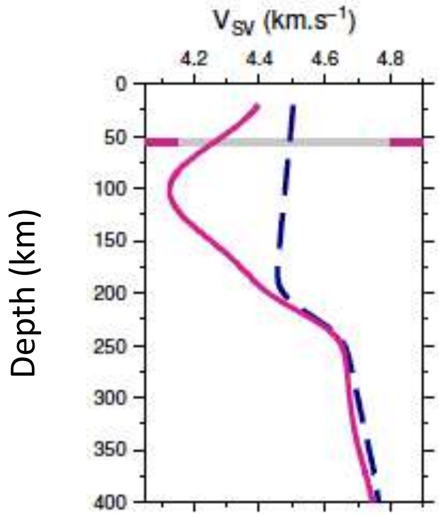
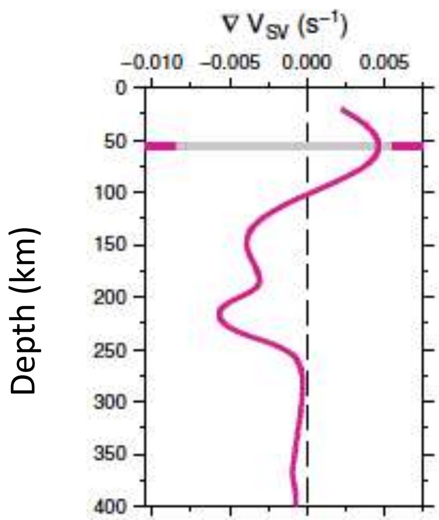
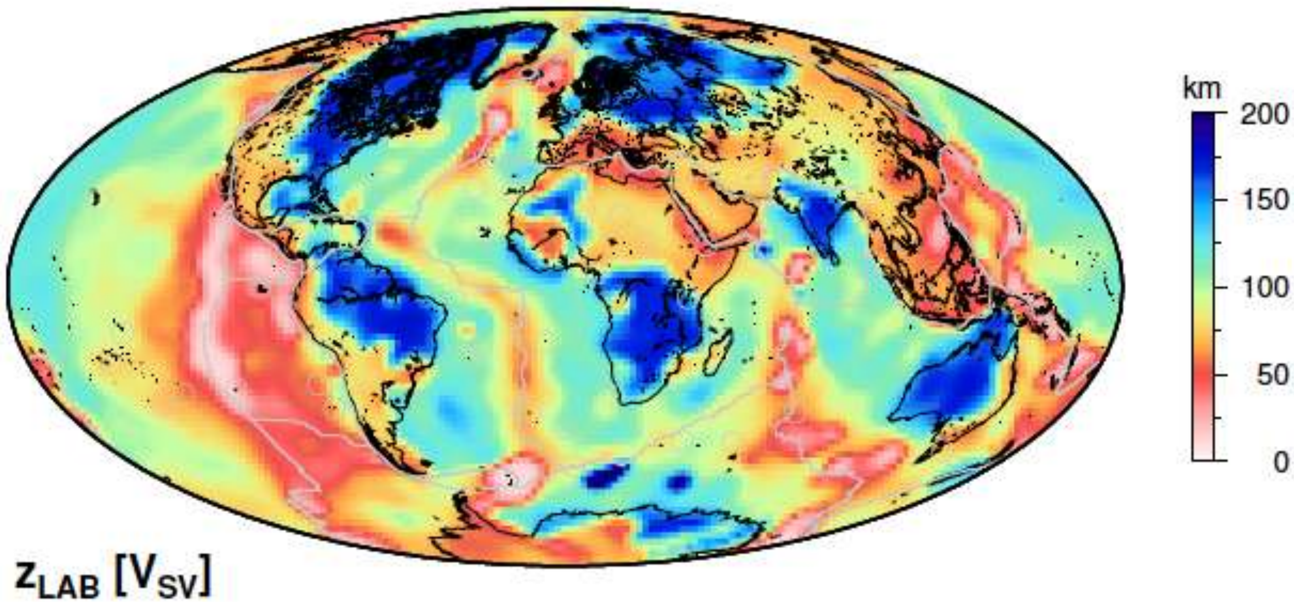


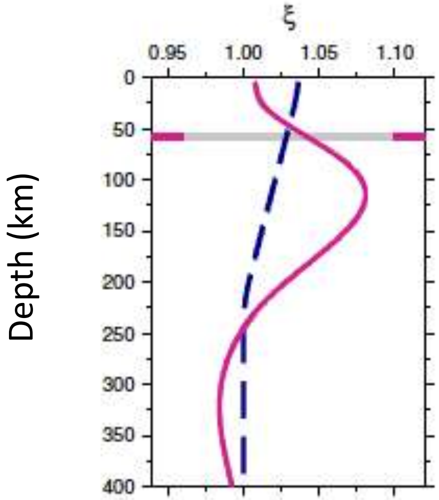
LAB from the gradient of VSV parameter

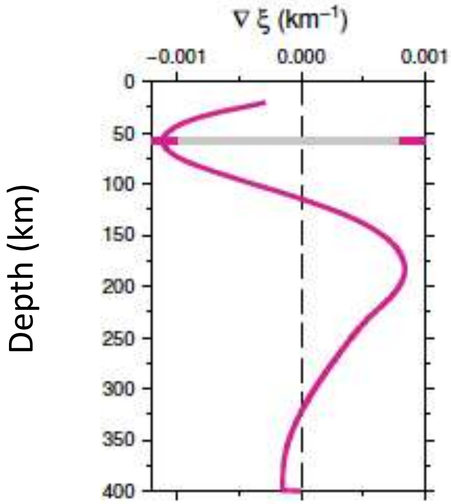


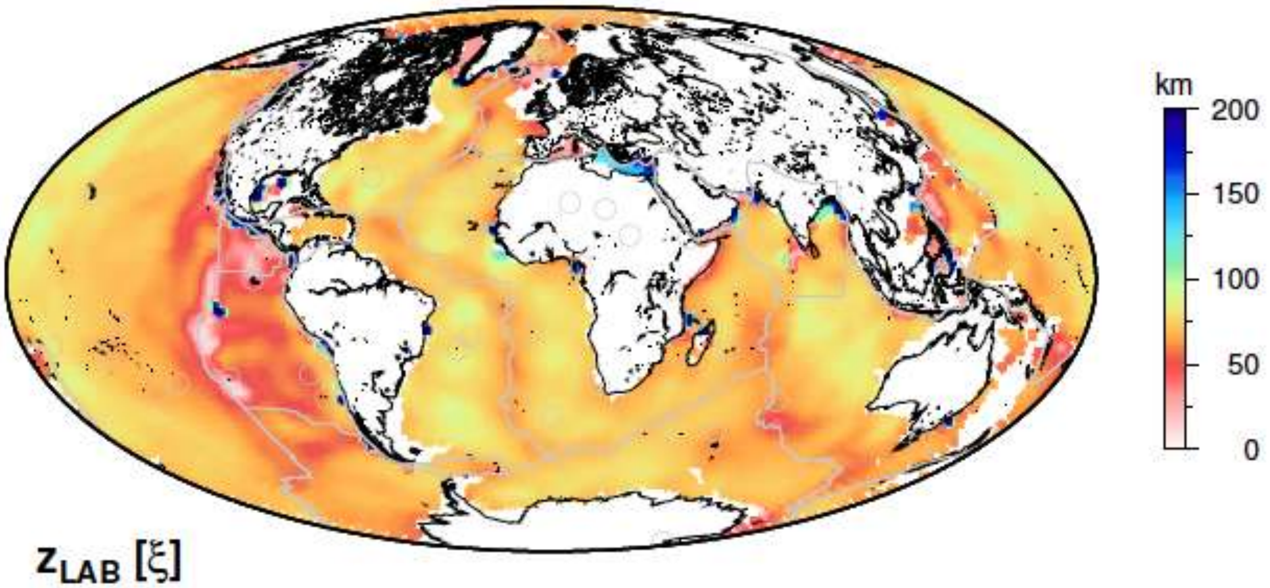




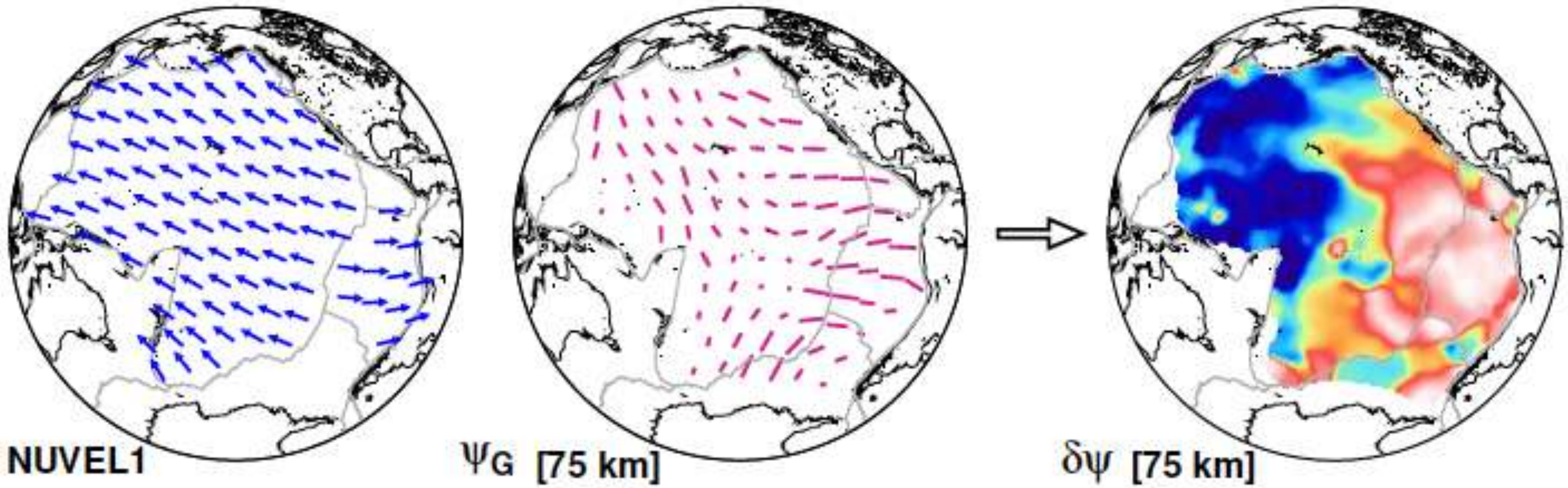
LAB from the gradient of ξ parameter (only oceans)
Radial anisotropy $\xi = (V_{SH}/V_{SV})^2$



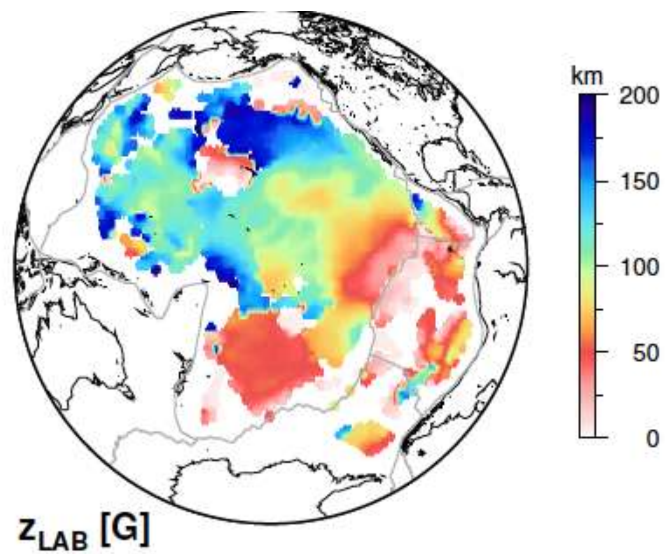




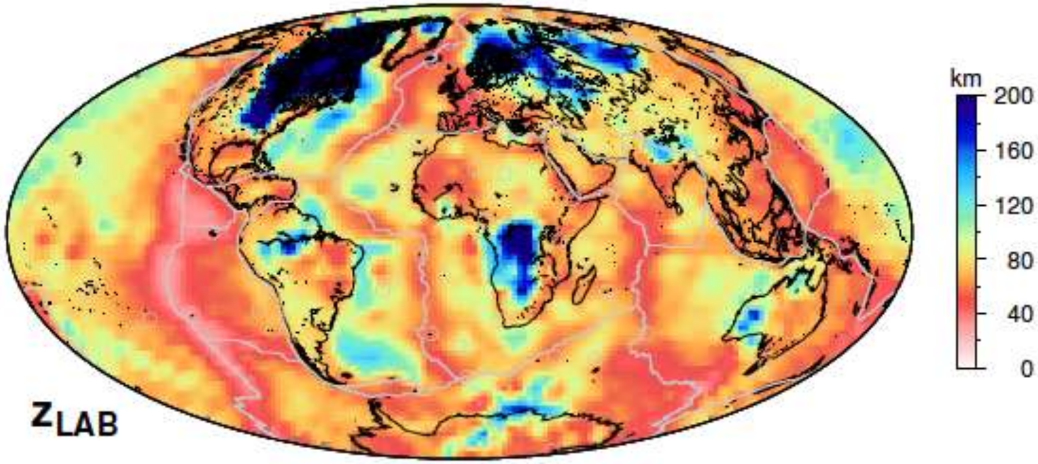
LAB from the change of orientation of azimuthal anisotropy Ψ_G



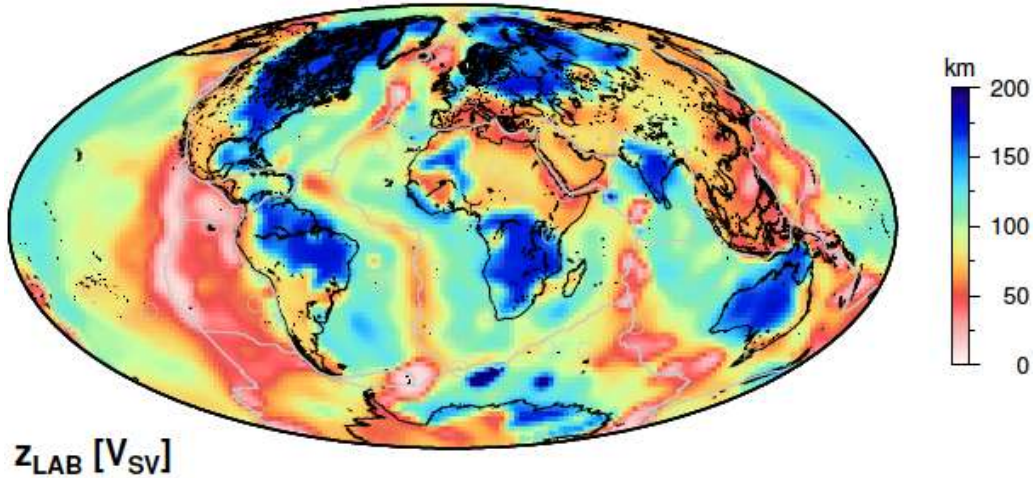
Correlation between plate motion given by NUVEL-1 and the orientation Ψ_G of fast axis of SV-wave azimuthal anisotropy G



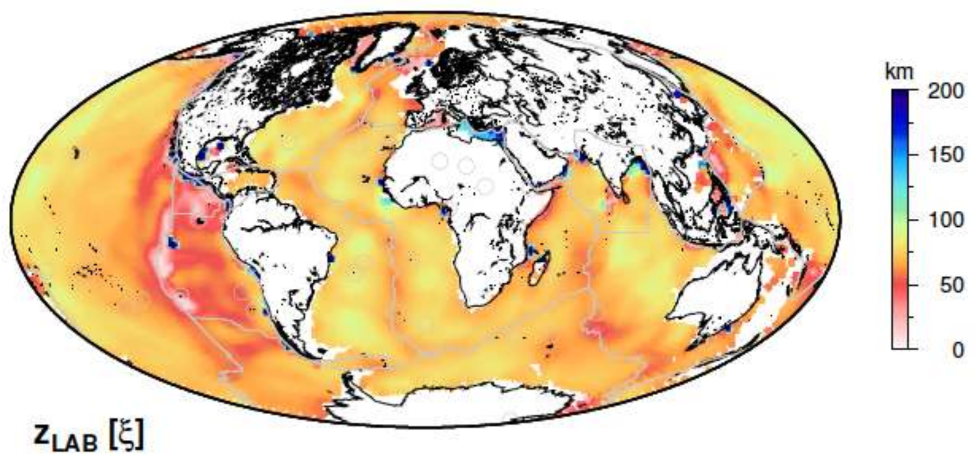
Vs Statistical MC Inversion



Vsv proxy (1st order Perturbation Theory)

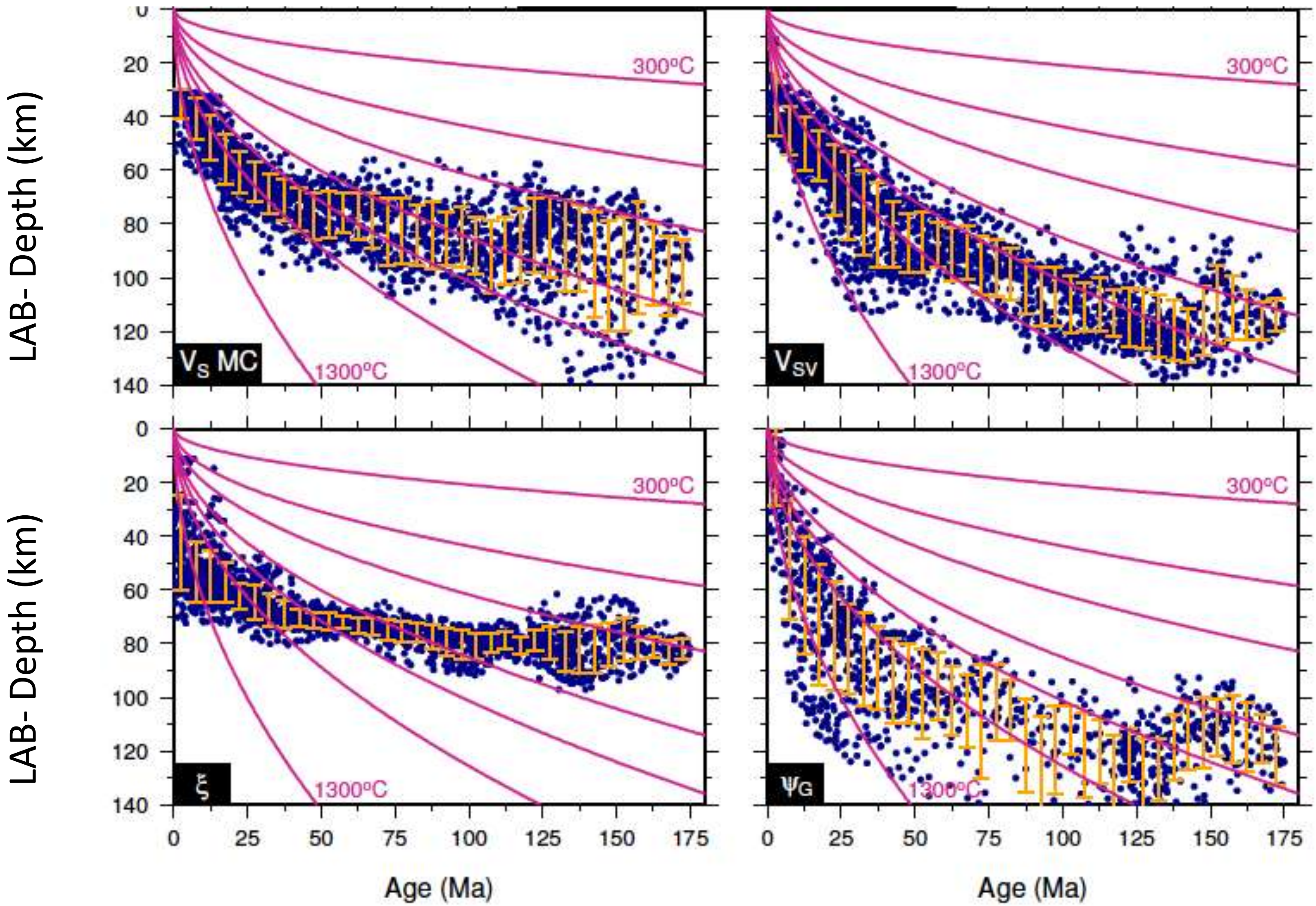


ξ proxy (1st order Perturbation Theory)



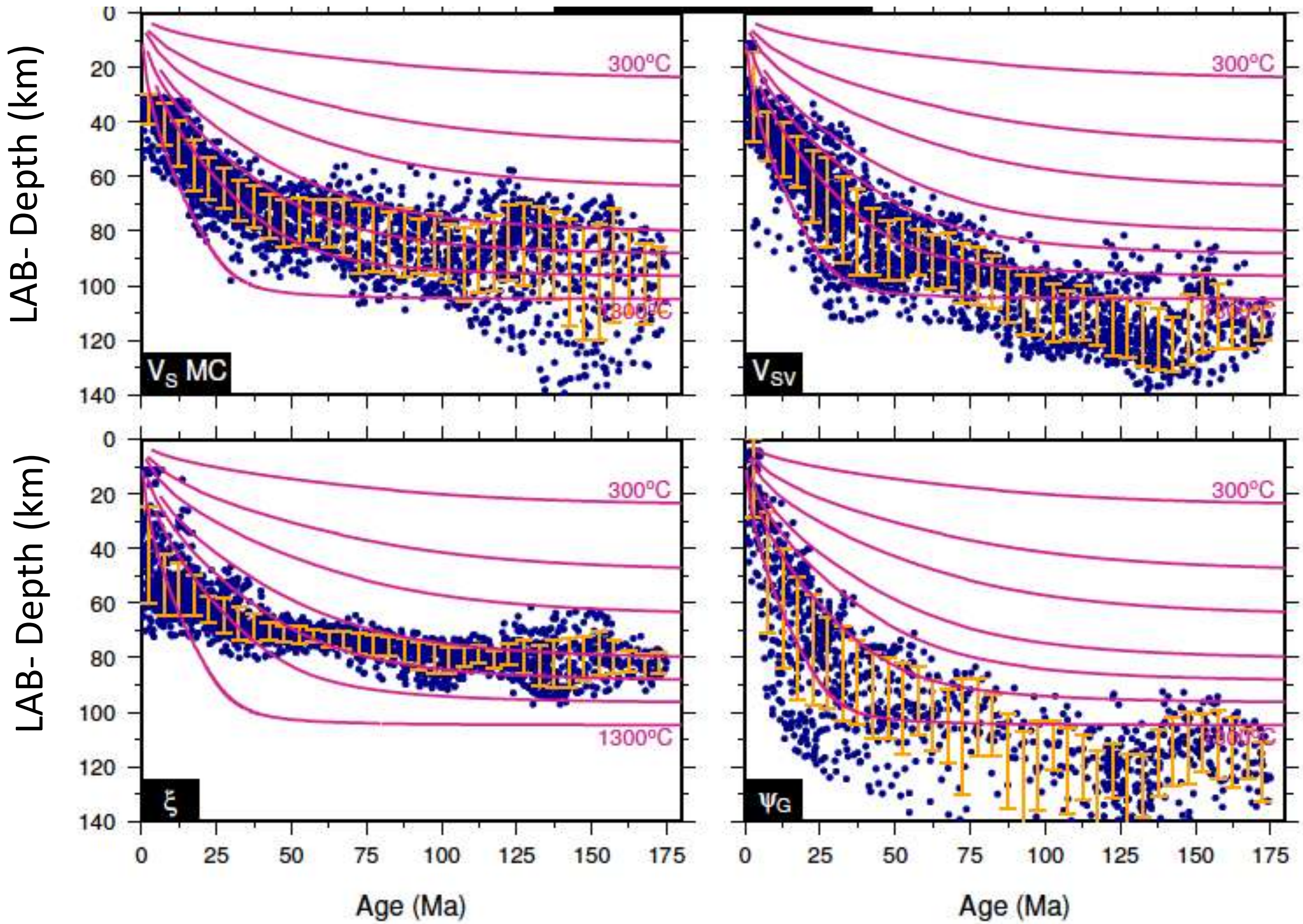
Age Variation of LAB depth in oceanic regions

Compared with Half Space Cooling model

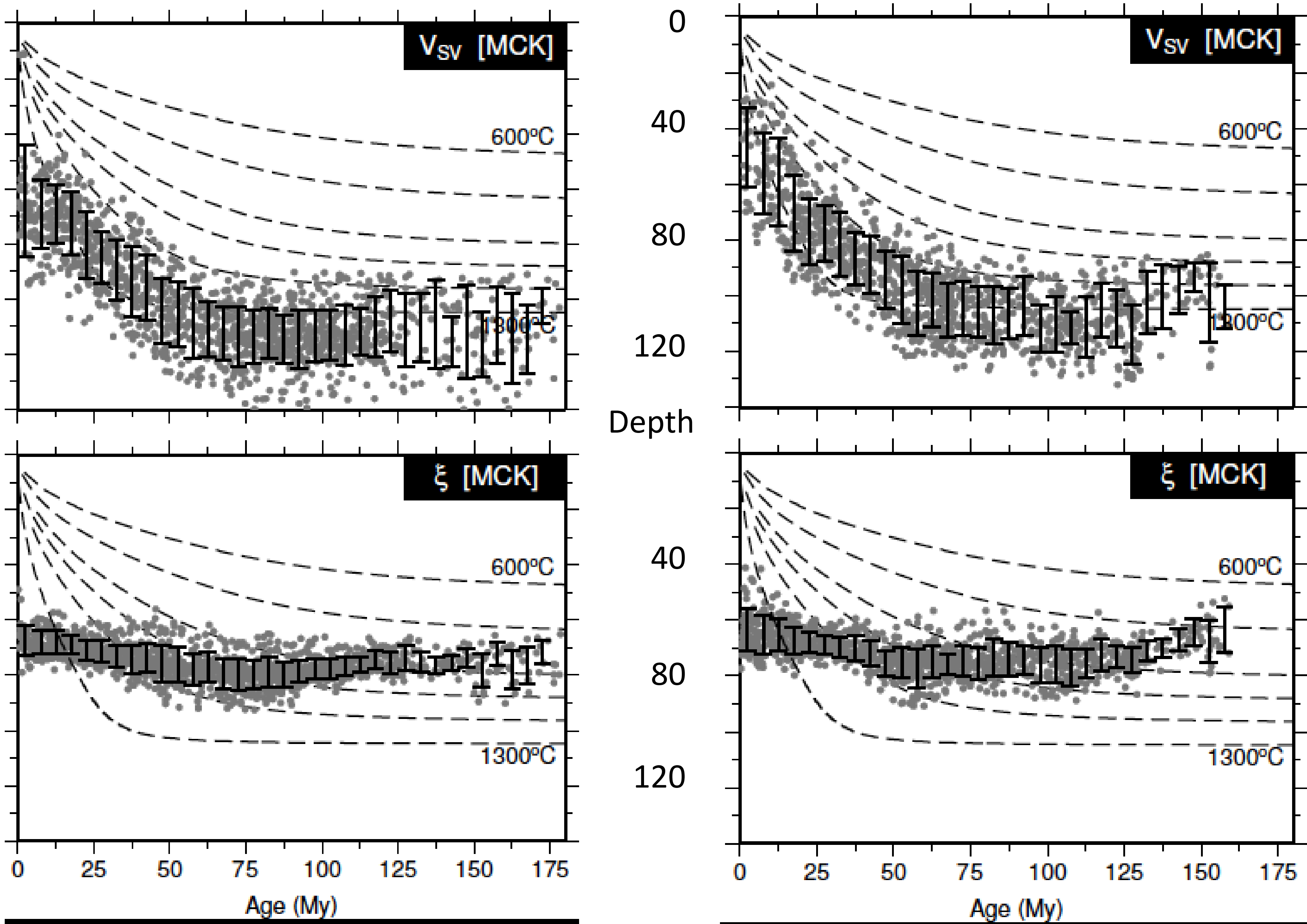


Age Variation of LAB depth in oceanic regions

Compared with plate model (McKenzie et al., 2005)
Pacific plate

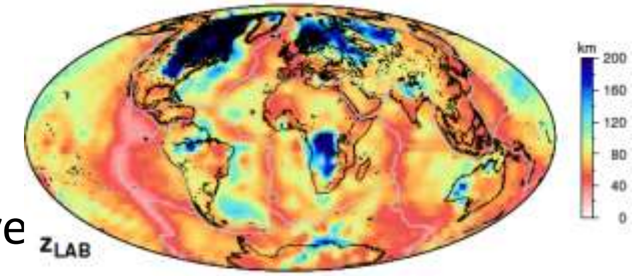


Atlantic Ocean Indian Ocean

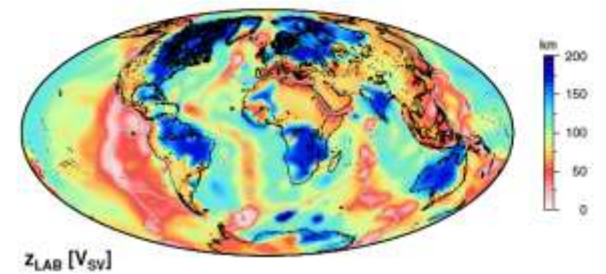


First Conclusions

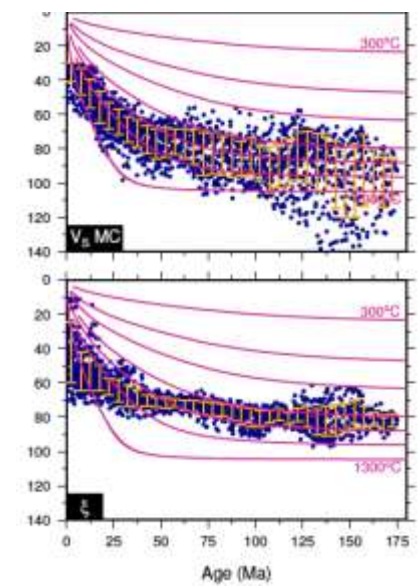
-LAB topography derived from surface wave data with 2 different inversion techniques (Monte-Carlo, 1st order perturbation theory) and for different proxies (S-wave velocity, radial anisotropy, azimuthal anisotropy)



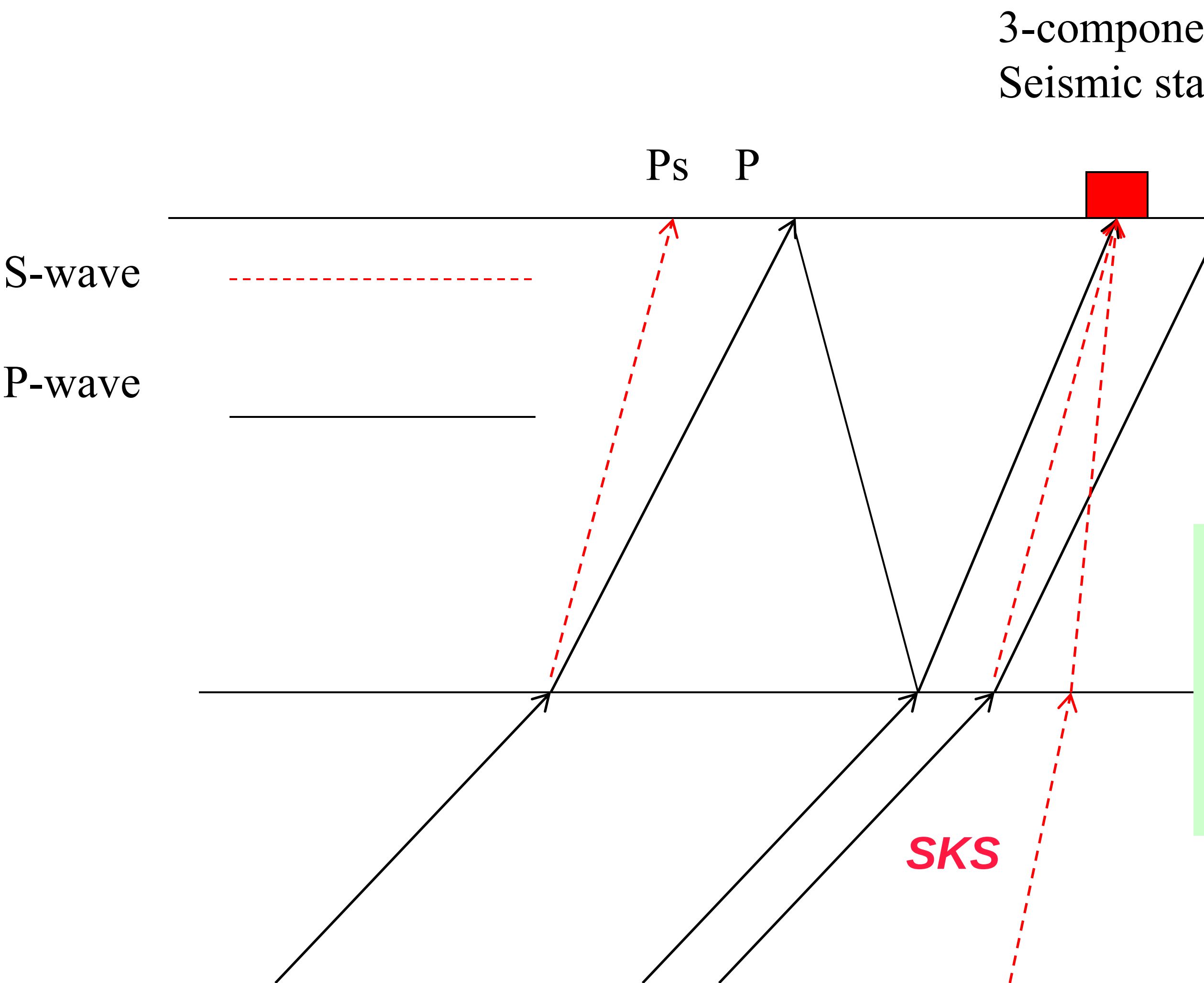
-Lateral variations of LAB (except from ξ) are similar but not their absolute values.



- For oceans, half-space cooling model does not work, plate model works slightly better, but the model of formation of lithosphere should be revisited in view of results from radial and azimuthal anisotropies.

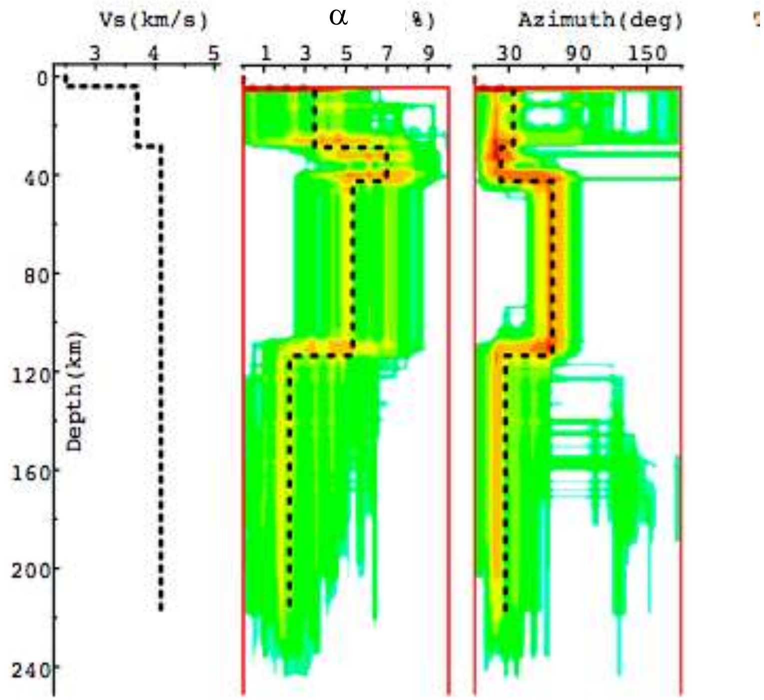


Simultaneous inversion of SKS and receiver functions: AFAR (Horn of Africa)



$P \longrightarrow S_V$ if isotropic medium

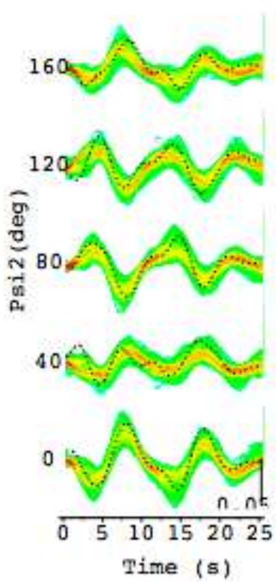
$P \longrightarrow S_V + S_H$ if anisotropic medium



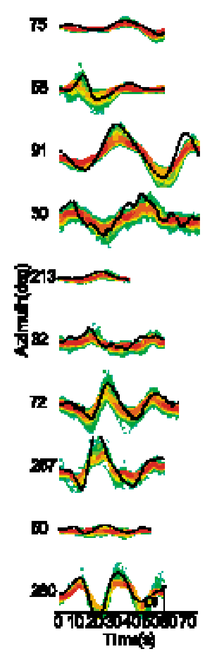
Geoscope
ATD Station
(Djibouti)

Receiver functions (RF)
+
SKS

RF



SKS

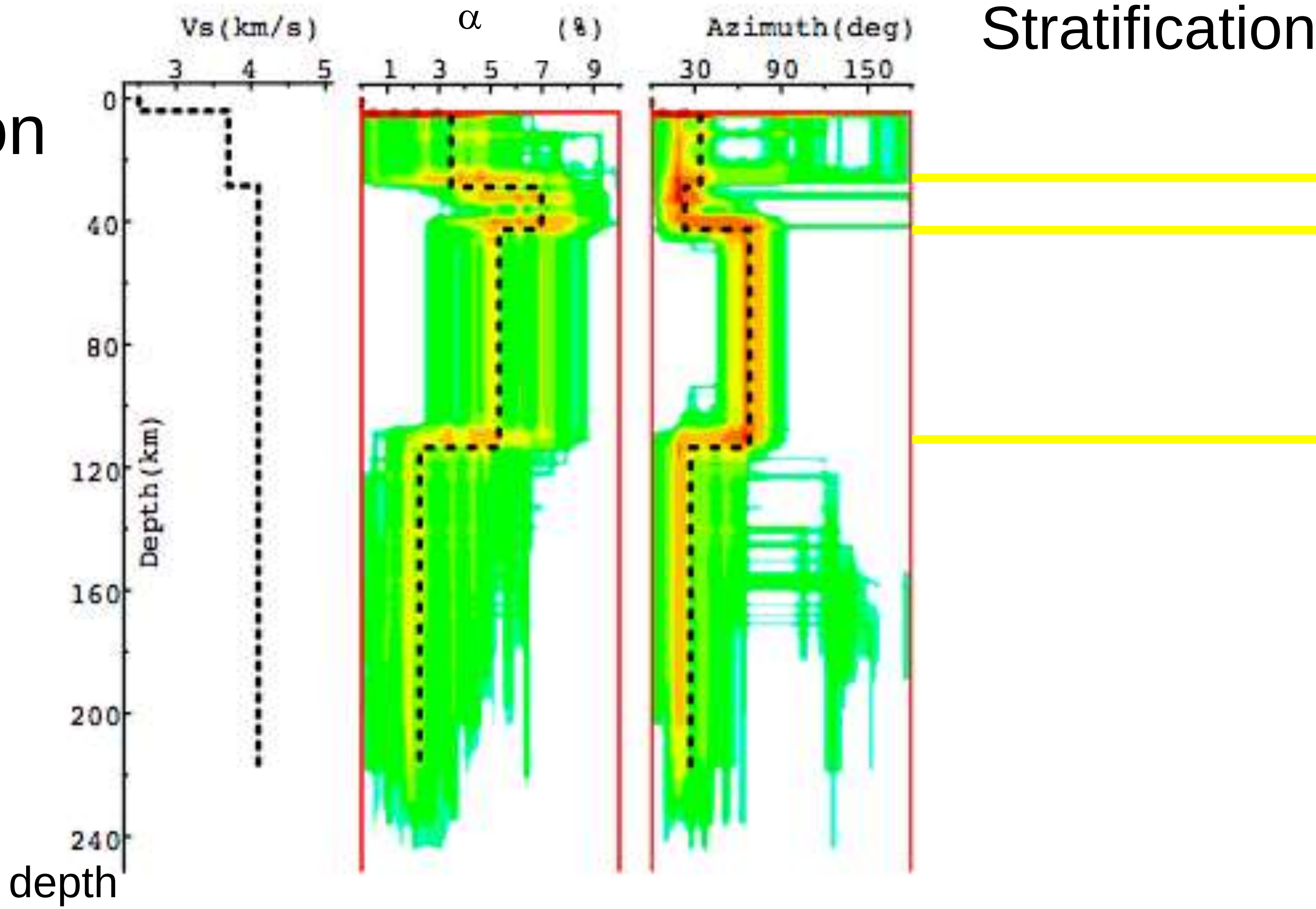


Good Azimuthal Coverage

Obrebski et al., 2010

Simultaneous inversion of SKS and receiver functions

ATD
Station

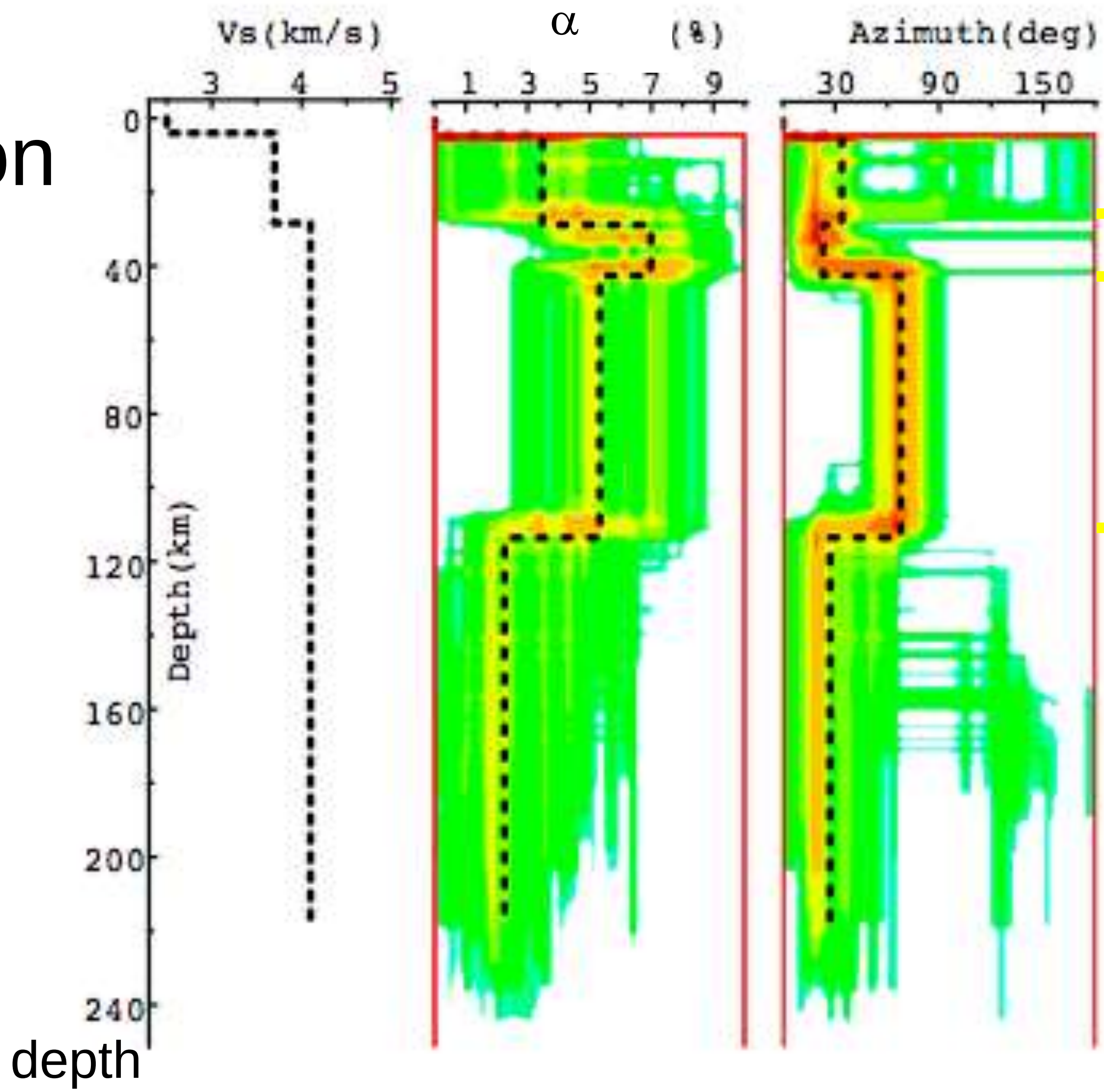


Stratification

Obrebski et al., 2010

Simultaneous inversion of SKS and receiver functions

ATD Station



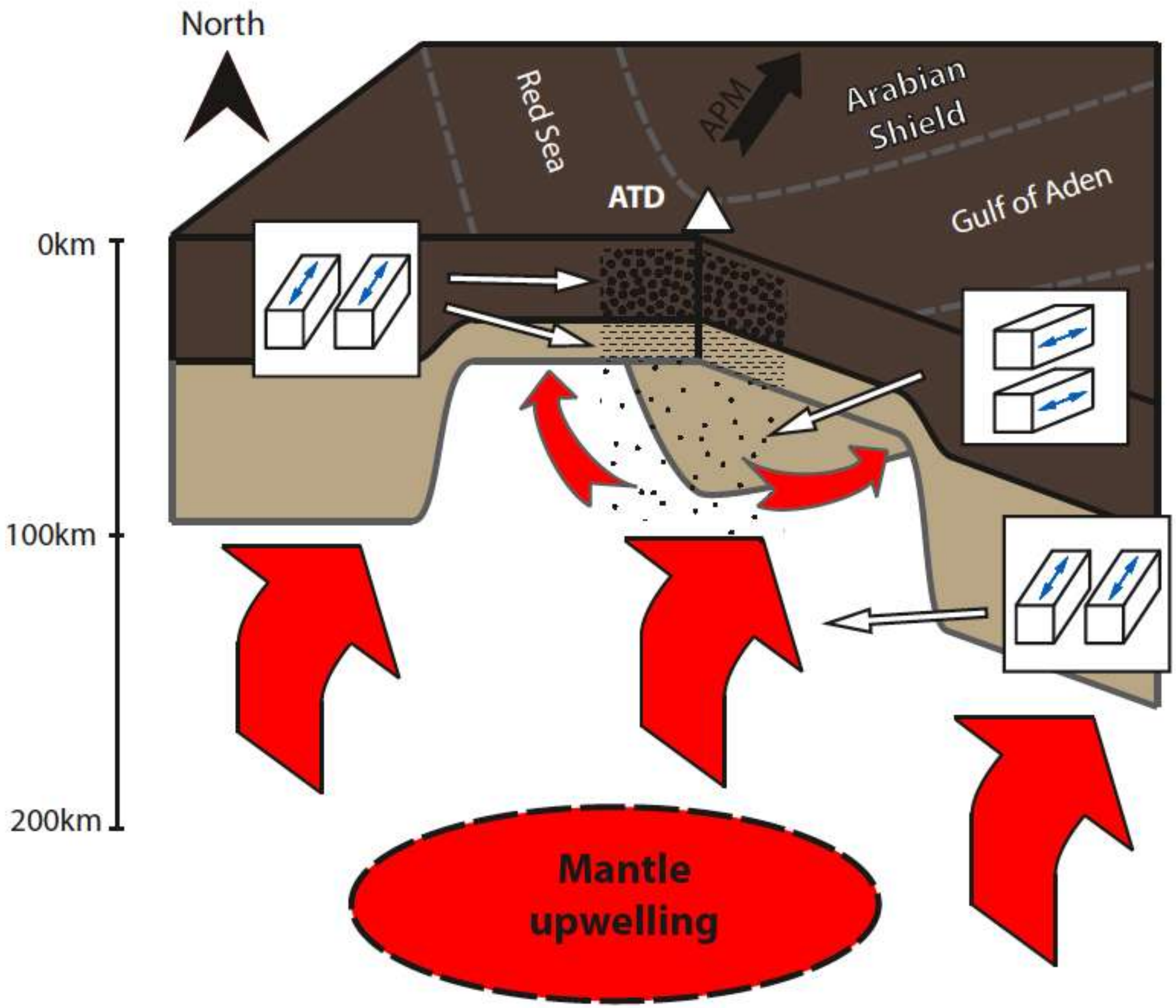
Stratification

Small anisotropy

Coherent anisotropy: SPO

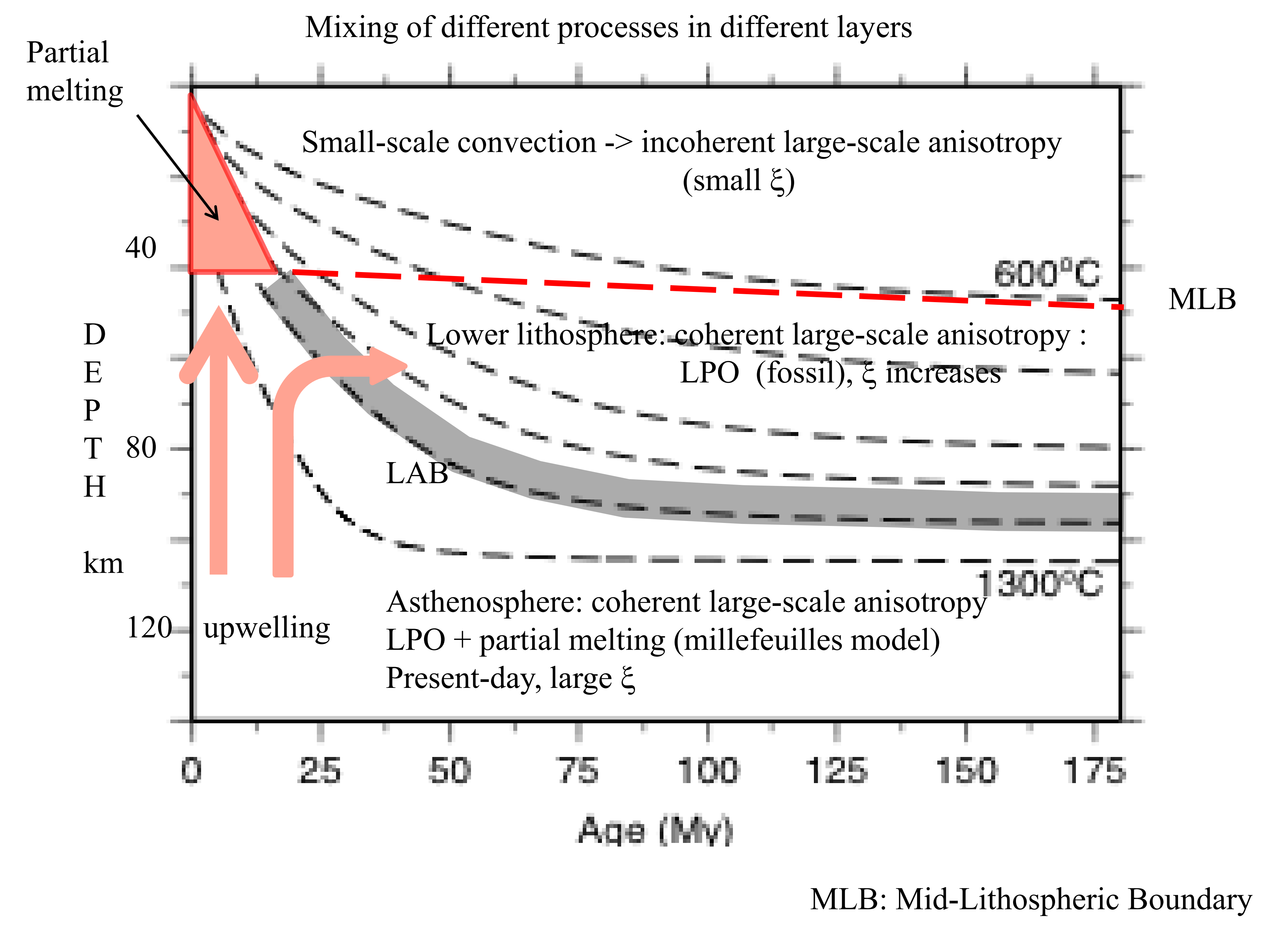
Coherent anisotropy: LPO

Obrebski et al., 2010



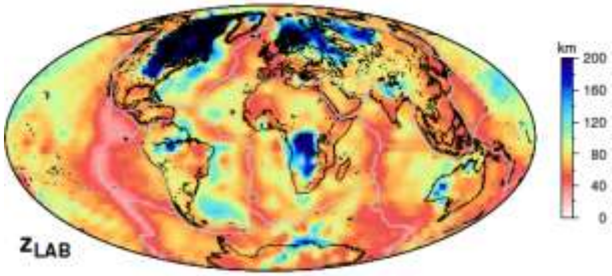
Tentative tectonic model to explain the stratification of anisotropy around Afar.

Obrebski et al., 2010


Mixing of different processes in different layers
Partial melting
Small-scale convection -> incoherent large-scale anisotropy (small ξ)
600°C
MLB
Lower lithosphere: coherent large-scale anisotropy : LPO (fossil), ξ increases
LAB
1300°C
Asthenosphere: coherent large-scale anisotropy
LPO + partial melting (millefeuilles model)
Present-day, large ξ
upwelling
DEPTH km
40
80
120
0
25
50
75
100
125
150
175
Age (My)
MLB: Mid-Lithospheric Boundary

Conclusions

-LAB topography derived from surface wave data
with 2 different inversion techniques (Monte-Carlo, 1st order perturbation theory) and for different proxies (S-wave velocity, radial anisotropy, azimuthal anisotropy).



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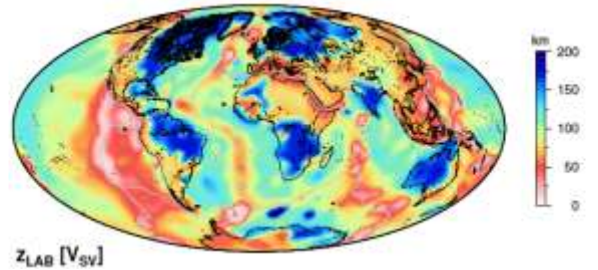
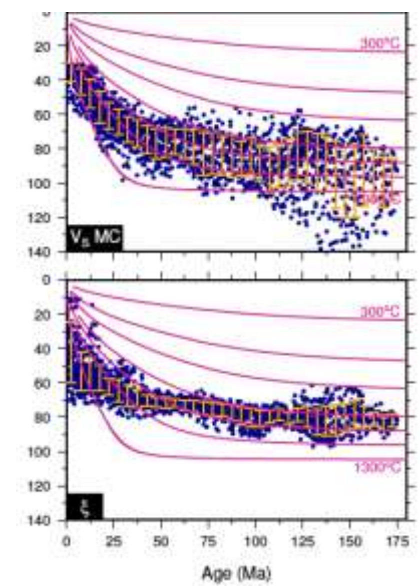


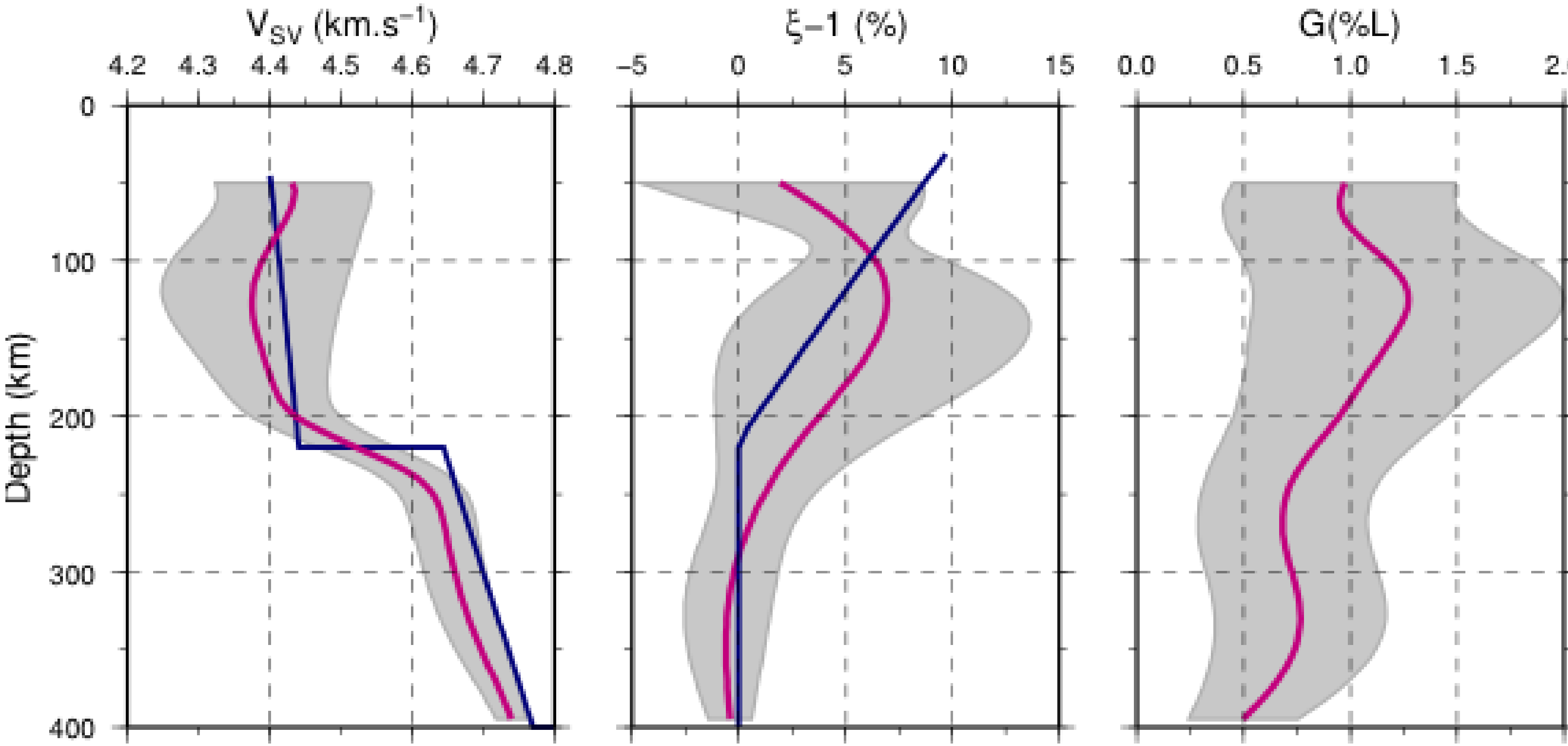
- For oceans, half-space cooling model does not work, plate model works slightly better, but the model of formation of lithosphere should be revisited in view of results from radial and azimuthal anisotropies.

- For oceans **mid-lithospheric discontinuity** derived from ξ.

- LAB in continents is more difficult to investigate (need to jointly use surface wave and SKS data).



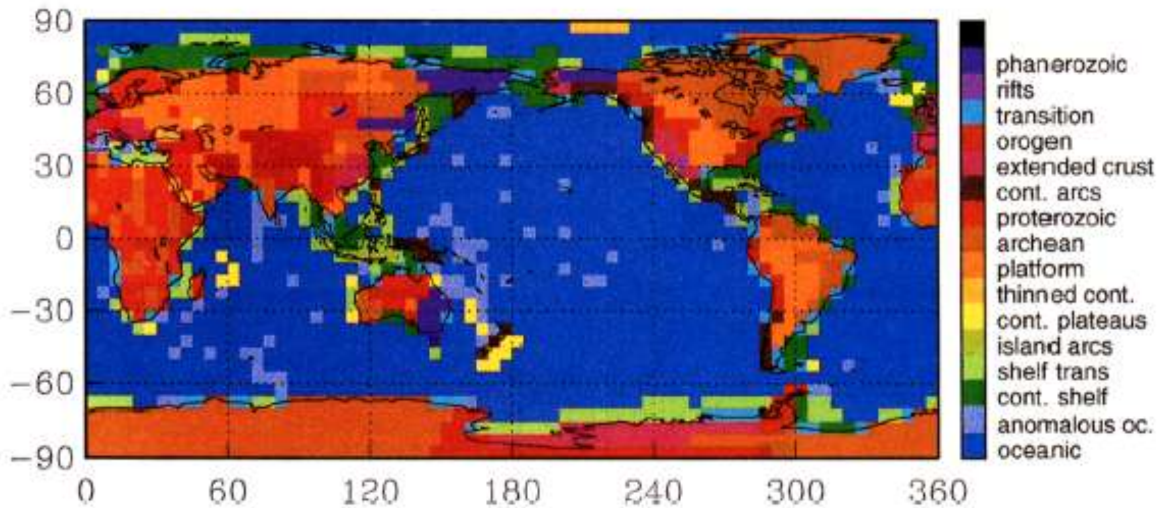
Average seismic parameters below oceans



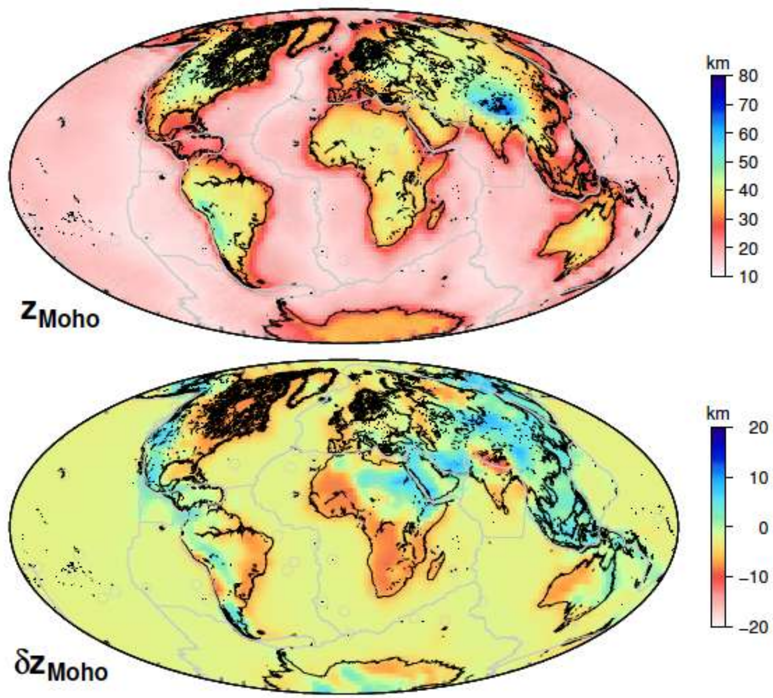
Crustal model:

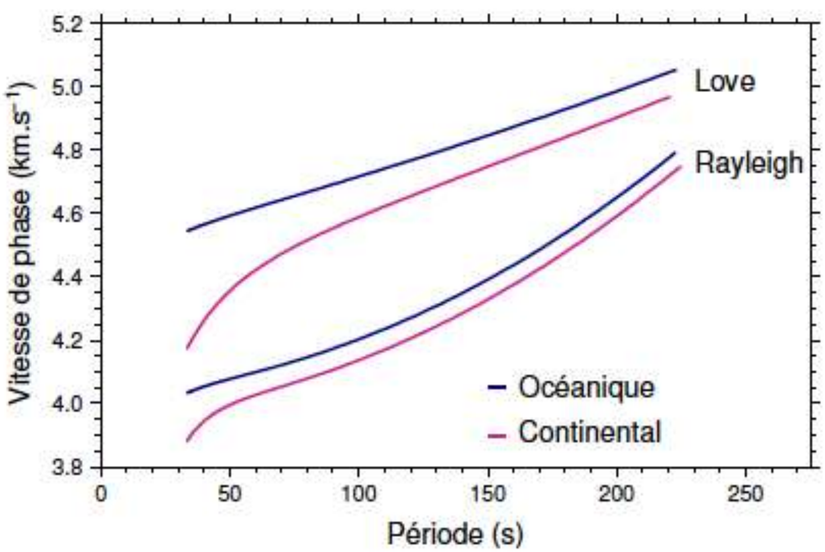
Improvement of the crust2.0 Model (Bassin et al., 2000)

Joint Monte-Carlo inversion of Rayleigh, Love phase, group velocity dispersion curves: d=[C_R C_L U_R U_L]



Mooney et al., 1998; Bassin et al., 2000

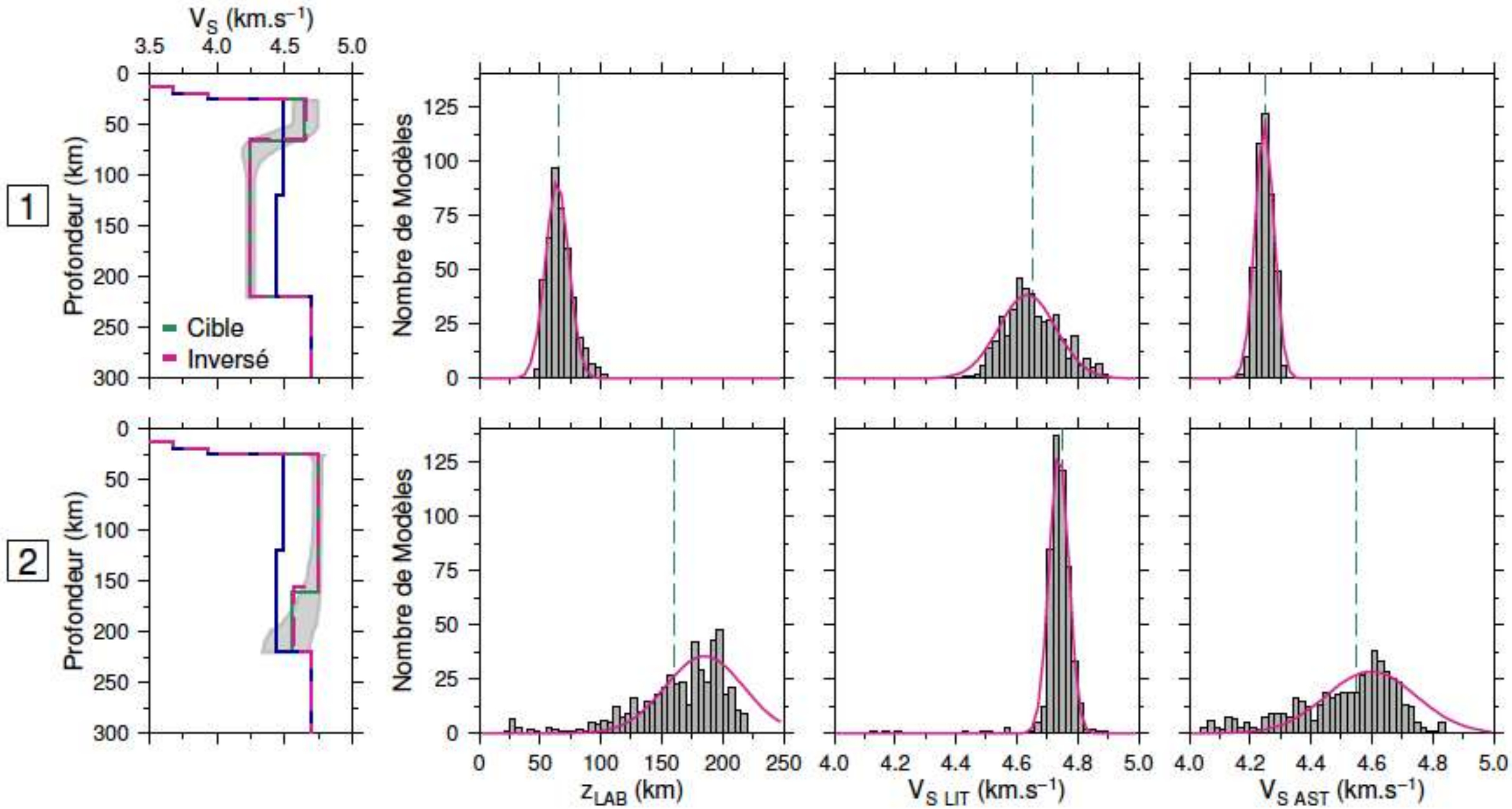




Sensitivity of surface waves to the LAB
Red: starting model,
Grey Monte-Carlo Inversion

OCEAN

CONTINENT



Méthode du rejet

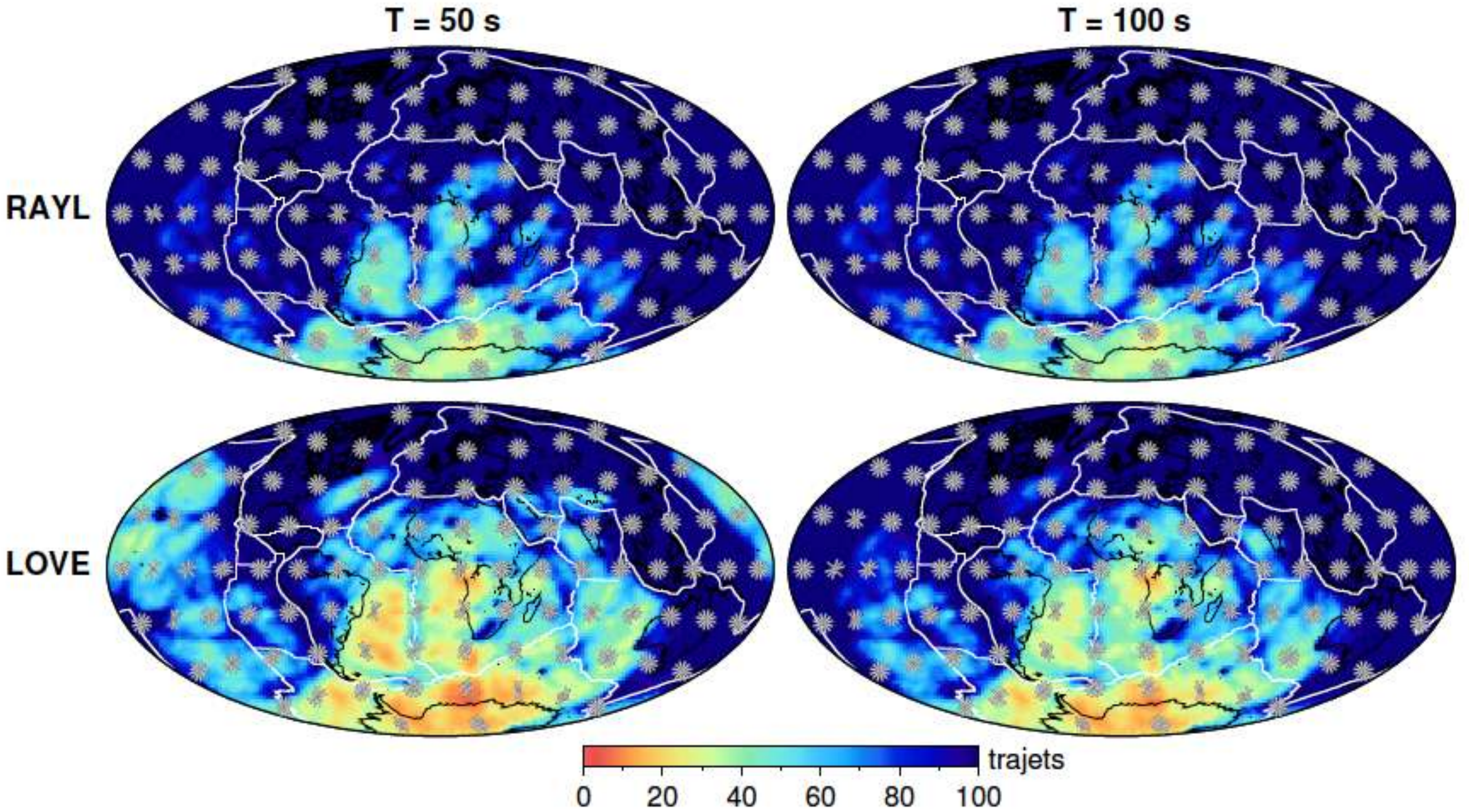
Paramètres : 2 V_S, 1 δz

1 Océanique : $\delta z_{LAB} \sim 5$ km

2 Continental : $\delta z_{LAB} \sim 35$ km

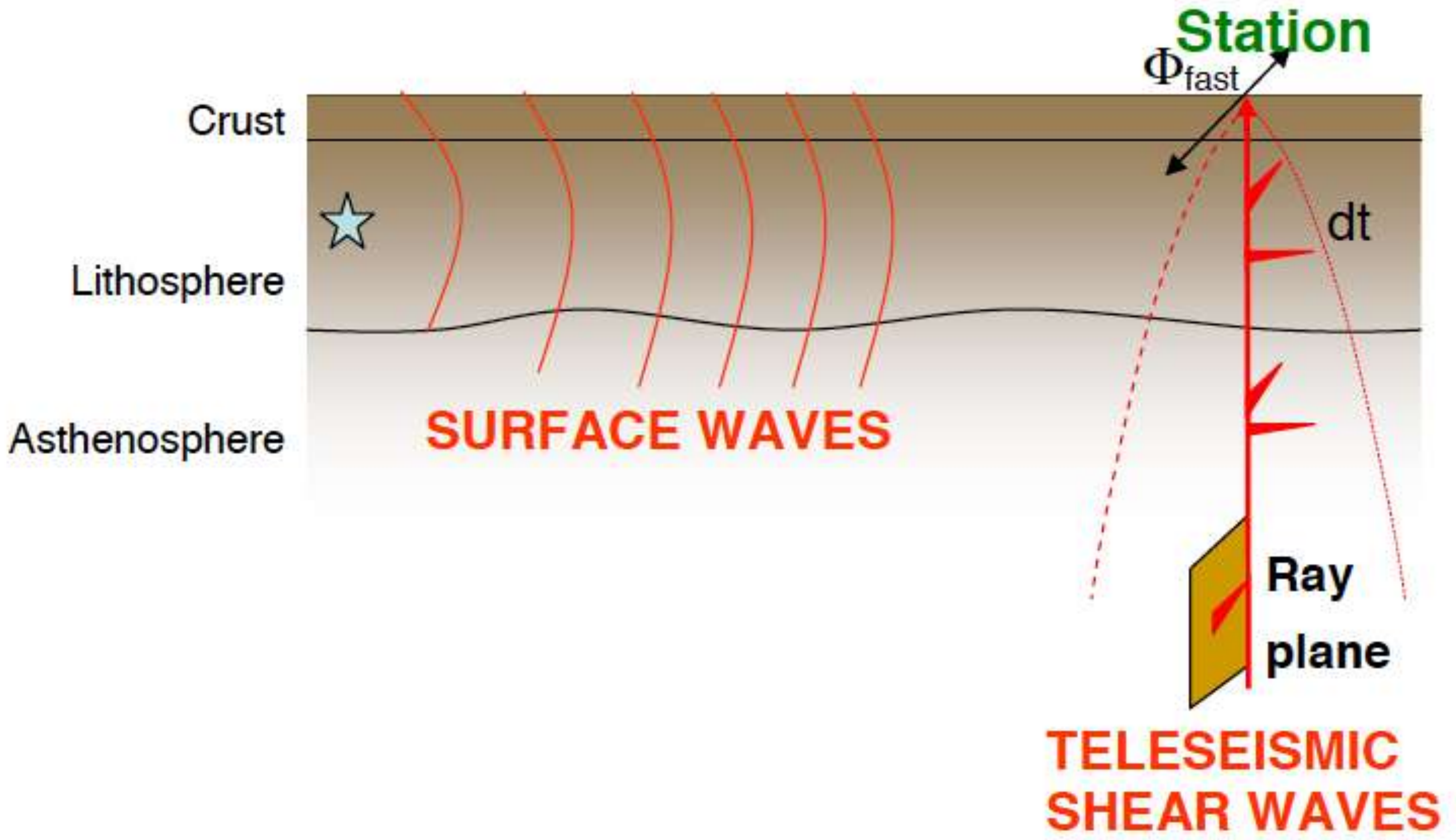
Path and azimuthal coverages of the merged dataset

Rayleigh, Love: C_R, C_L, U_R, U_L



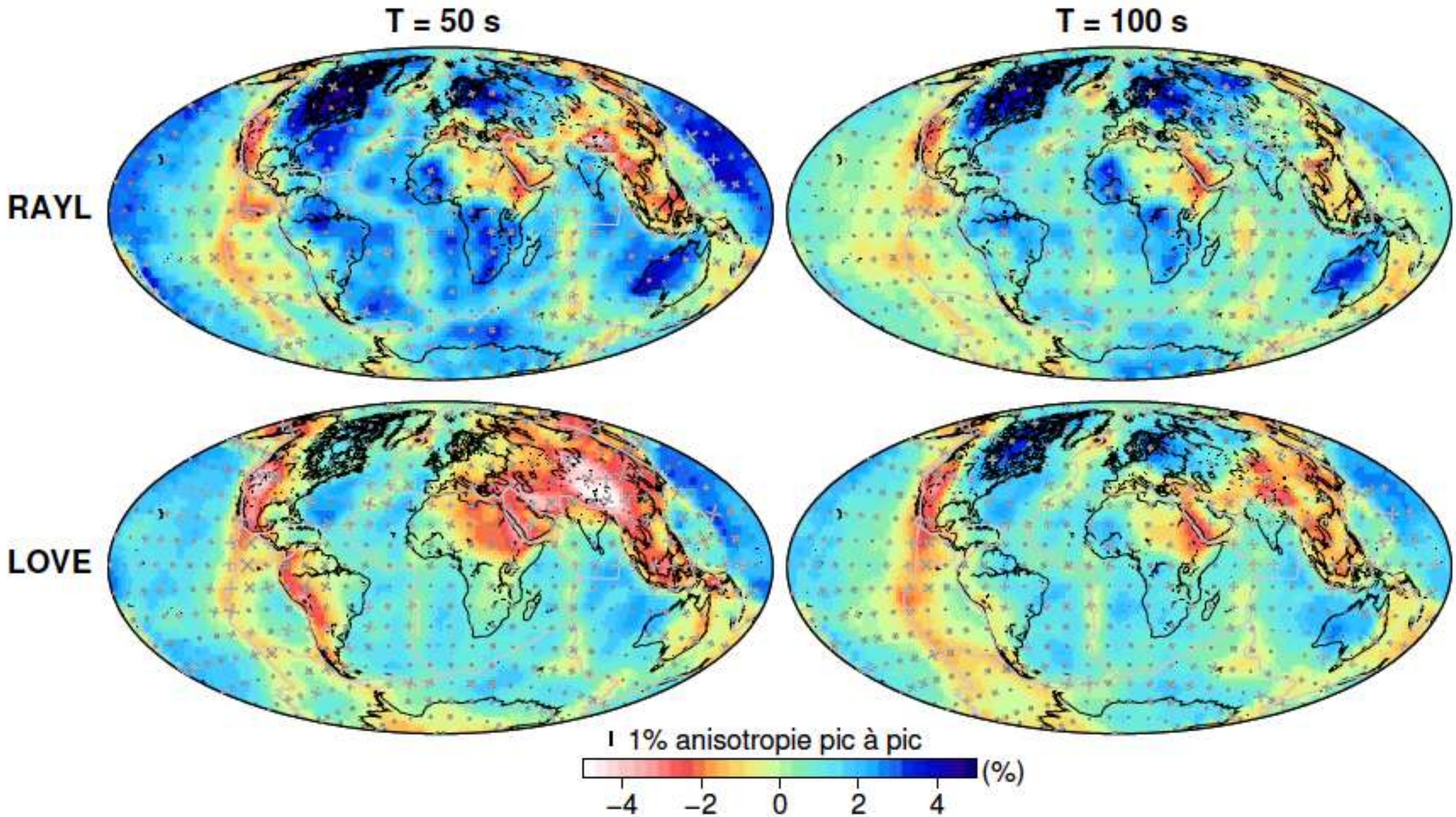
Continental LAB: more complex

Joint anisotropic inversion of body wave and surface wave data

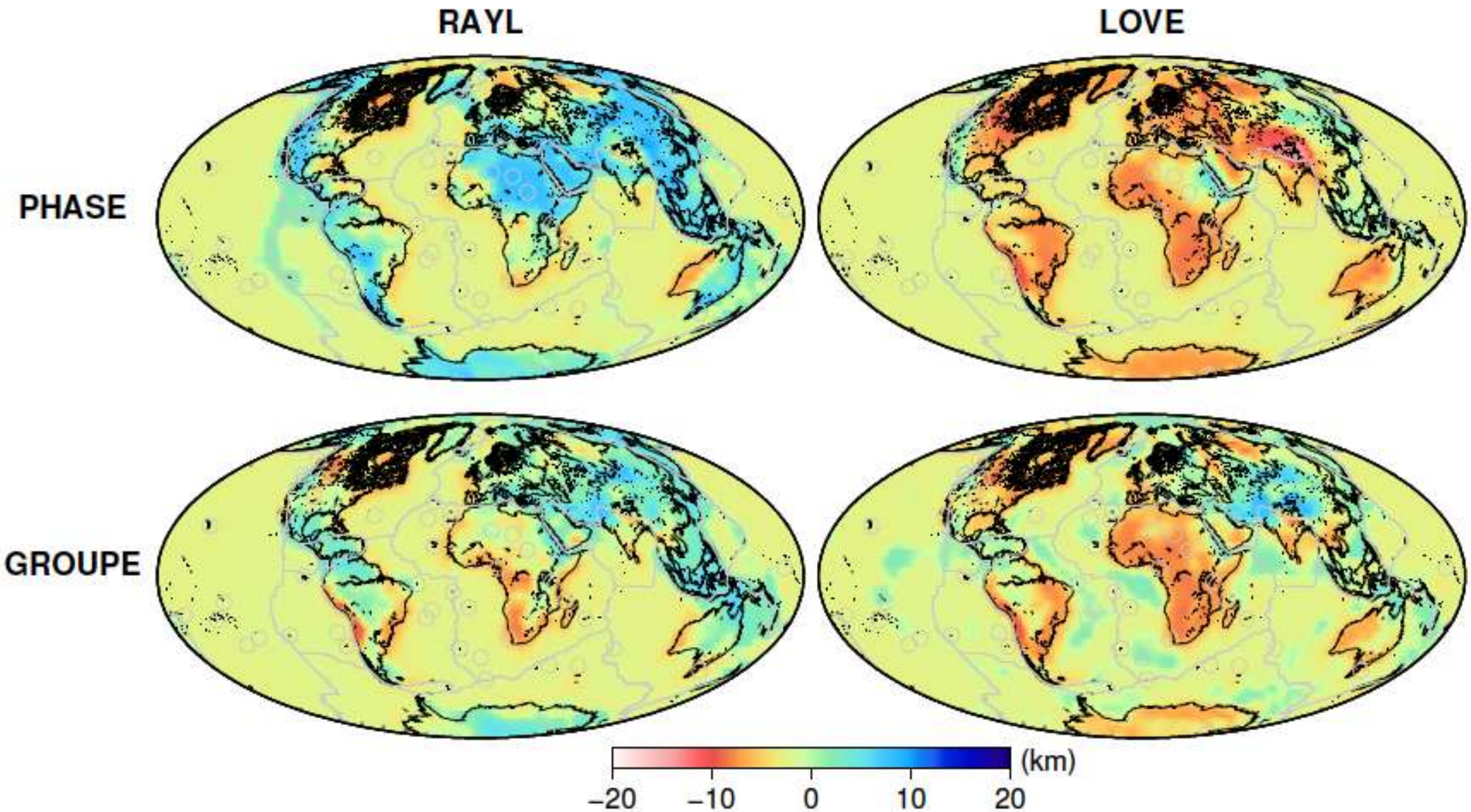


Wuestefeld et al., 2009
For SKS and S.W. Montagner et al., 2000

Cartes des vitesses de phase 0ψ+4ψ



Inversion des données séparées



Inversion Monte-Carlo

Paramètres : 3 V_S, 1 δz.
Données : C_R, C_L, U_R, U_L [20-50s].

Différentes méthodes de Monte-Carlo.

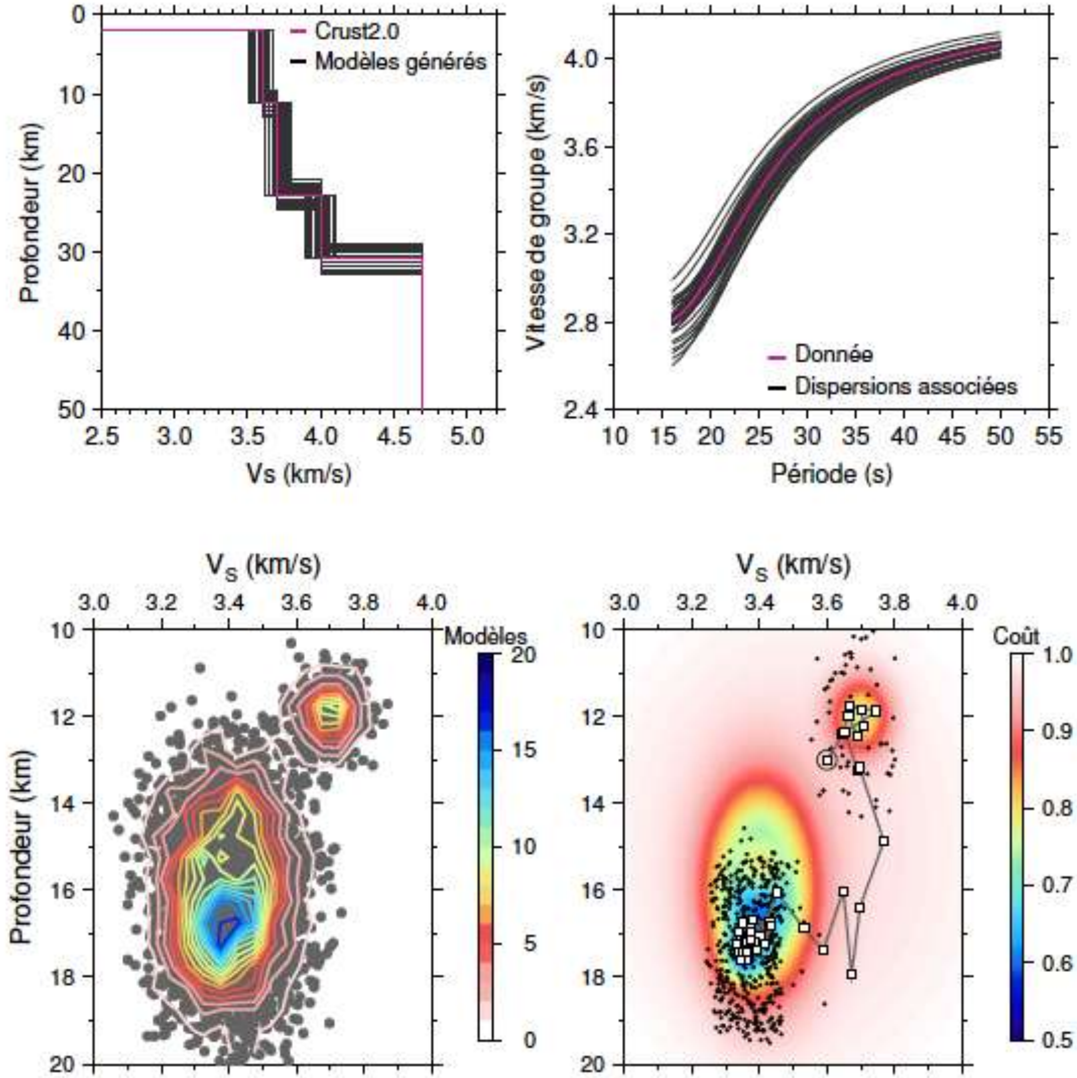
Fonction coût :

$$s_i = \sum_k^n \frac{(d_k^i - d_k)^2}{\sigma_k}$$

Probabilité d'acceptation :

$$P_i = \begin{cases} \exp\left(\frac{-(s_i - s_j)}{T_i}\right) & s_i \geq s_j \\ 1 & \text{pour } s_i < s_j \end{cases}$$

Routine de calcul de dispersion très rapide (*Herrmann, 1996*).

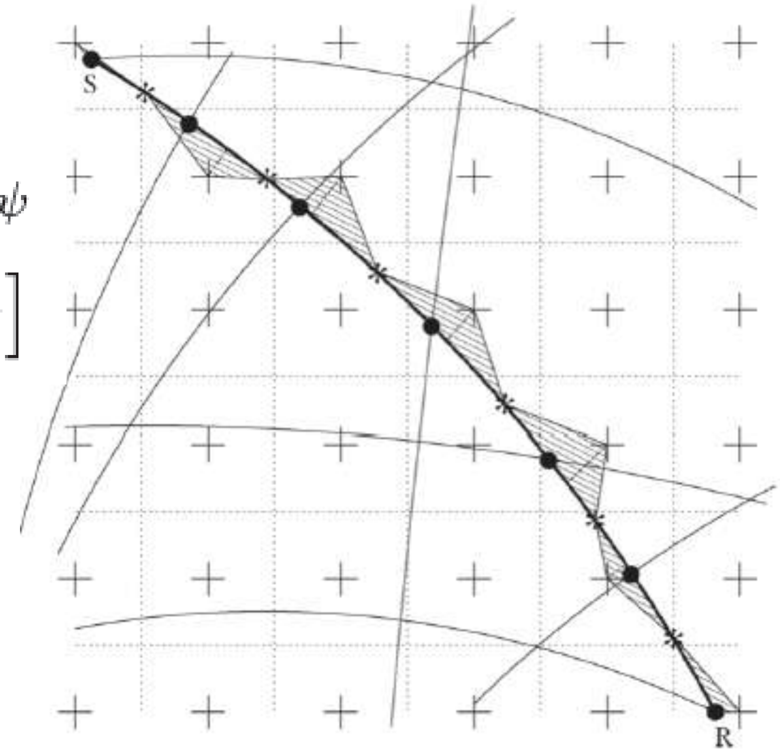


Méthode du Rejet

Recuit Simulé

$$\frac{\Delta}{C(T,\mathrm{trajet})} = \int_S^R \frac{ds}{C(T,\theta,\phi)}$$

$$C(T,\psi) = C_i(T)\Big[1 + \alpha_1(T)\cos 2\psi + \alpha_2(T)\sin 2\psi$$
$$+\alpha_3(T)\cos 4\psi + \alpha_4(T)\sin 4\psi\Big]$$



Beucler, 2002

Inversion en profondeur

Paramétrisation complètement anisotrope du manteau supérieur.
13 paramètres : $[\rho, A, L, \xi, \phi, \eta, B_c, B_s, E_c, E_s, G_c, G_s, H_c, H_s]$.

Données : C_R, α_R^*, C_L, α_L^* [35-300s].

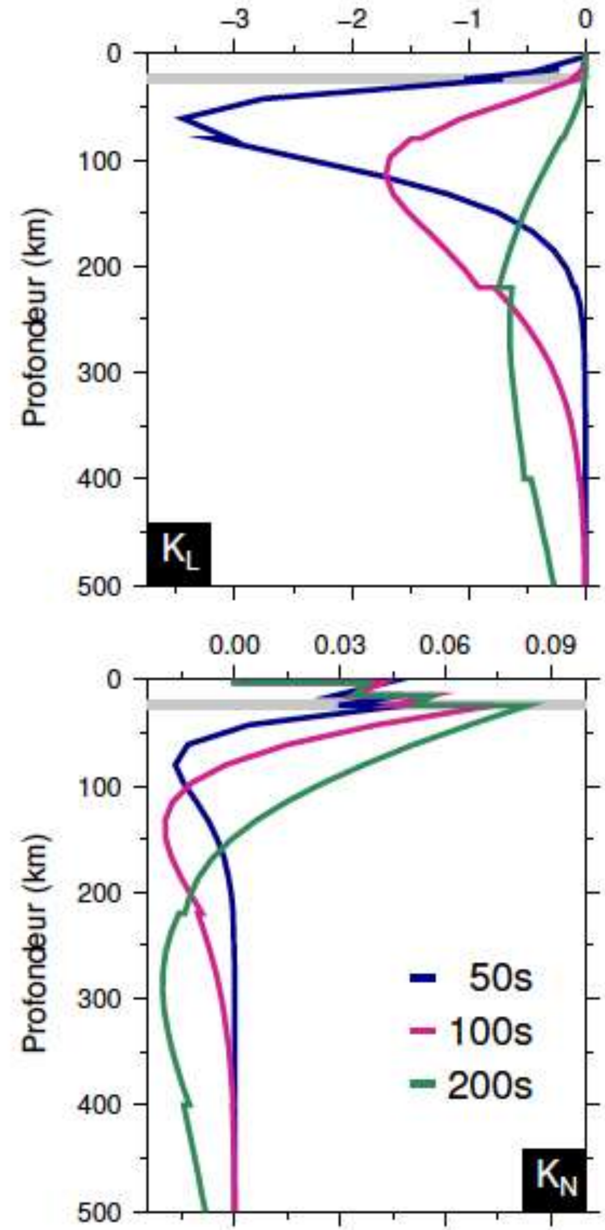
Inversion moindres carrés, théorie de la perturbation au 1er ordre.

$$\delta C_R|_{k,\psi} = \int_\Omega \Bigg[\frac{\partial C_R}{\partial A}\bigg|_k (\delta A + B_c \cos 2\psi + B_s \sin 2\psi + E_c \cos 4\psi + E_s \sin 4\psi) + \frac{\partial C_R}{\partial C}\bigg|_k \delta C + \frac{\partial C_R}{\partial F}\bigg|_k (\delta F + H_c \cos 2\psi + H_s \sin 2\psi) + \frac{\partial C_R}{\partial L}\bigg|_k (\delta L + G_c \cos 2\psi + G_s \sin 2\psi)\Bigg] d_\Omega / \Delta_\Omega$$

$$\delta C_L|_{k,\psi} = \int_\Omega \Bigg[\frac{\partial C_L}{\partial L}\bigg|_k (\delta L - G_c \cos 2\psi - G_s \sin 2\psi) + \frac{\partial C_L}{\partial N}\bigg|_k (\delta N - E_c \cos 4\psi - E_s \sin 4\psi)\Bigg] d_\Omega / \Delta_\Omega$$

(code modifié de *Montagner, 1986*)

Paramètres résolus : V_{SV}, ξ, G_c, G_s.

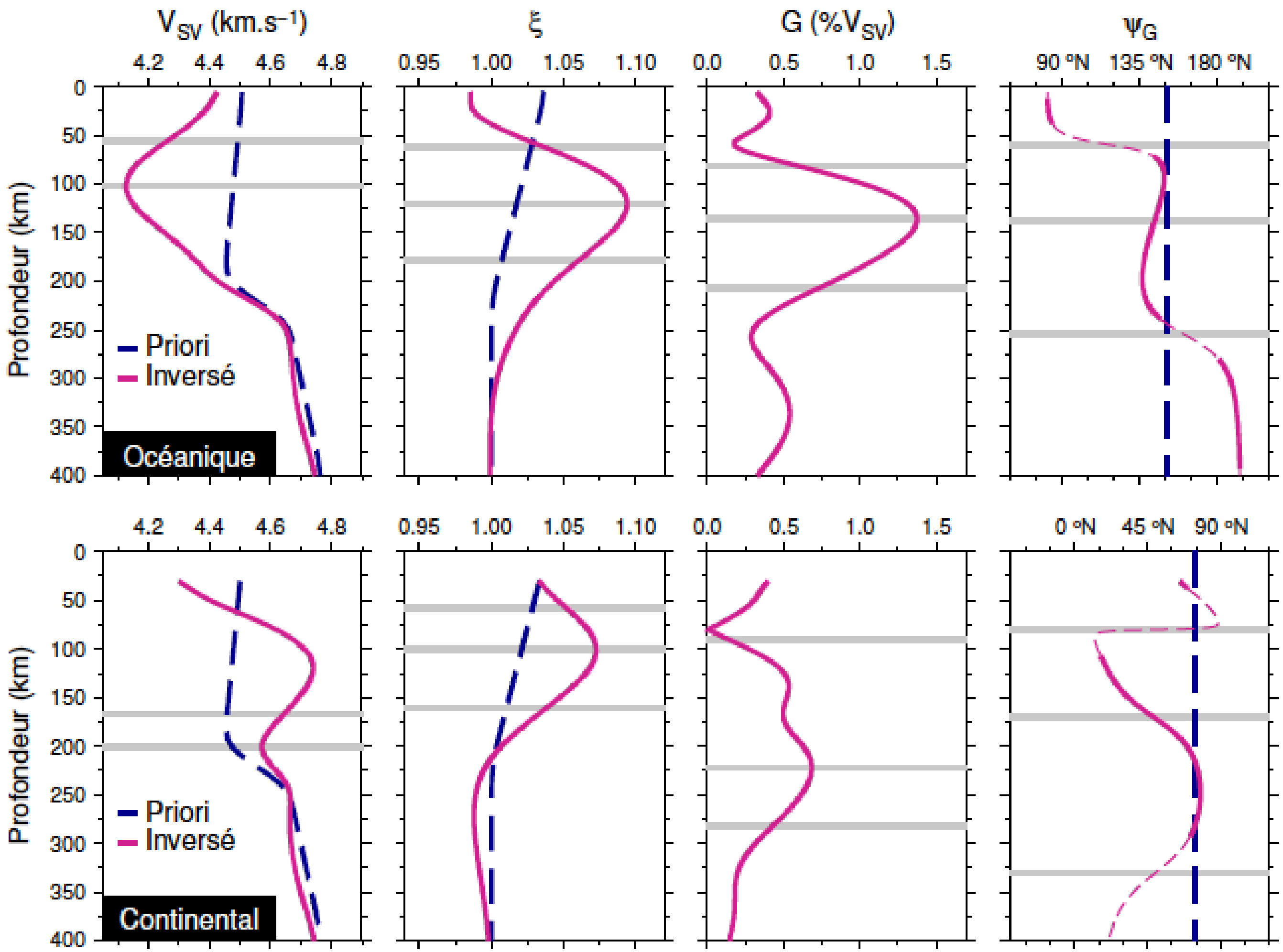


Paramètres du modèle tomographique

Paramètres résolus :
V_{SV}, ξ, G_c, G_s.

Profil océanique
($\lambda = 35^o$, $\phi = -35^o$).

Profil continental
($\lambda = 63^o$, $\phi = -96^o$).

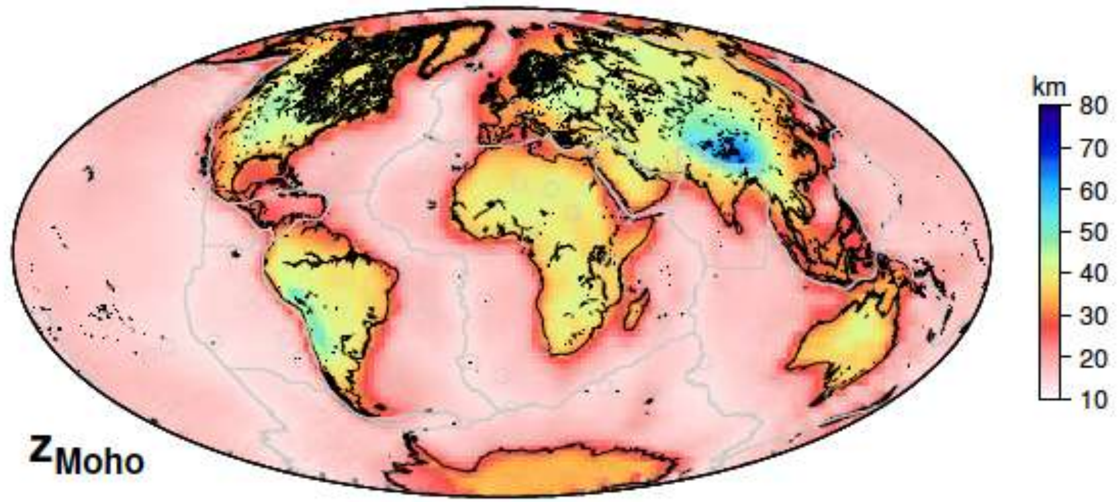


CRUSTAL MODEL

Joint M.C. inversion

d=[C_R C_L U_R U_L]

~25% variance reduction
wrt *a priori* Crust2.0



δz_{Moho}: difference between
Our model and crust2.0