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

Jean-Paul Montagner\(^{(1)}\), Gael Burgos \(^{(1)}\), Eric Beucler \(^{(2)}\), Antoine Mocquet\(^{(2)}\) and Yann Capdeville\(^{(2)}\), Mathias Obrebski\(^{(1,3)}\), Lev Vinnik\(^{(4)}\)…..

1- Laboratoire Sismologie, I.P.G., Paris, France
2- L.P.G., University of Nantes, Nantes, France
3- LDEO, New-York, U.S.A.
4- I.P.E., Moscow, Russia
L.A.B.: Lithosphere-Asthenosphere Boundary (many different approaches and definitions)

Eaton et al., 2008
LAB: from seismic data

Receiver functions

Surface waves

Kawakatsu et al., 2009

Fishwick, 2010

Rychert & Shearer, 2009

Yuan & Romanowicz, 2010
- Much discrepancy between different estimates

- Global tomographies give 200-250 km 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 $V_{sv}$

Depth (km)
Proxies from other parameters: Seismic Anisotropy?

Well resolved parameters:
\( V_{SV} \) S-wave velocity
\( \xi \), radial anisotropy
\( G, \Psi_G \) S-wave azimuthal anisotropy

Oceanic profile
\( \lambda=35^\circ, \phi=-35^\circ \)

Continental profile
\( \lambda=63^\circ, \phi=-96^\circ \)
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
Separation of the different kinds of anisotropy in different layers => Different interpretations

- 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
  - Amplitude effects: Quasi-Rayleigh, Quasi-Love polarization anomalies
Effect of anisotropy on the phase of surface waves

Effect on eigenfrequency $\omega_k$ (Rayleigh’s principle)

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

$\varepsilon$ strain tensor, $u$ displacement, $\delta C_{ijkl}$ elastic tensor perturbation (21 elastic moduli), $V$ phase velocity

**Phase velocity perturbation** $\delta V(T, \theta, \phi, \Psi)$ at point $r (\theta, \phi)$

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

$\Psi$ Azimuth (angle between North and wave vector)

$$\frac{\delta V(T, \theta, \phi, \Psi)}{V} = \alpha_0(T, \theta, \phi) + \alpha_1(T, \theta, \phi)\cos 2\Psi + \alpha_2(T, \theta, \phi)\sin 2\Psi + \alpha_3(T, \theta, \phi)\cos 4\Psi + \alpha_4(T, \theta, \phi)\sin 4\Psi$$
• Cijkl 21 elastic moduli

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

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)

\[ L = \rho V_{SV}^2 \quad \text{Isotropic part of } V_{SV} \]

\[ \frac{N}{L} = \xi = (V_{SH}/V_{SV})^2 \text{ Radial Anisotropy} \]

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

• 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

Well resolved parameters:

- $V_{SV}$ S-wave velocity
- $\xi$, radial anisotropy
- $G$, $\Psi_G$ S-wave azimuthal anisotropy

Oceanic profile

$\lambda=35^\circ$, $\phi=-35^\circ$

Continental profile

$\lambda=63^\circ$, $\phi=-96^\circ$
Data collection

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency Range (Hz)</th>
<th>Dispersion Rate (s/km)</th>
<th>Phase Velocity (km/s)</th>
<th>Group Velocity (km/s)</th>
<th>Total Count</th>
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</thead>
<tbody>
<tr>
<td>IPGP(1)</td>
<td>44 - 315</td>
<td>9292†</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UTRECHT(2)</td>
<td>35 - 175</td>
<td>63628</td>
<td>35 - 176</td>
<td>45179</td>
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<tr>
<td>HARVARD(3)</td>
<td>35 - 150</td>
<td>37738</td>
<td>35 - 150</td>
<td>23227</td>
<td></td>
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<tr>
<td>BOULDER(4)</td>
<td>16 - 200</td>
<td>76580</td>
<td>16 - 150</td>
<td>47021</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>-</td>
<td>187238</td>
<td>-</td>
<td>115427</td>
<td></td>
</tr>
</tbody>
</table>
First step: Regionalization $\Rightarrow$ local dispersion velocity $V(T, \theta, \phi, \psi)$

Rayleigh phase velocity and azimuthal anisotropy

Second step: Inversion at depth

Statistical Monte-Carlo Inversion $\quad$ First order Perturbation Theory
LAB: Statistical M.C. Inversion

Data: $C_R$, $C_L$, $U_R$, $U_L$ [30-300s], Parameters: 3Vs, 2 $\delta z$
First order perturbation Theory $\Rightarrow$ depth distribution of Vsv, G (and $\xi$)
Proxies obtained from anisotropic tomographic models

Well resolved parameters:
- $V_{SV}$ S-wave velocity
- $\xi$, radial anisotropy
- $G$, $\Psi_G$ S-wave azimuthal anisotropy

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

Continental profile
- $\lambda=63^\circ$, $\phi=-96^\circ$
LAB from the gradient of VSV parameter
LAB from the gradient of $\xi$ parameter (only oceans)
Radial anisotropy $\xi = (V_{SH}/V_{SV})^2$
LAB from the change of orientation of azimuthal anisotropy $\Psi_G$

Correlation between plate motion given by NUVEL-1 and the orientation $\Psi_G$ 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

![Graph showing LAB depth against age for different regions and comparisons with Half Space Cooling model.](image-url)
Age Variation of LAB depth in oceanic regions

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

Pacific plate
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 $\zeta$) 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)

3-component Seismic station

P-s  P

S-wave

P-wave

S-wave

P-wave

P→$S_V$ if isotropic medium
P→$S_V + S_H$ if anisotropic medium
Geoscope
ATD Station
(Djibouti)

Receiver functions (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
Small-scale convection -> incoherent large-scale anisotropy
(small $\xi$)

Asthenosphere: coherent large-scale anisotropy
LPO + partial melting (millefeuilles model)
Present-day, large $\xi$

Lower lithosphere: coherent large-scale anisotropy:
LPO (fossil), $\xi$ increases

Partial melting

Mixing of different processes in different layers

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).

- Lateral variations of LAB (except from \( \xi \)) 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.

- For oceans **mid-lithospheric discontinuity** derived from \( \xi \).

- 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:
\[ d = [C_R \ C_L \ U_R \ U_L] \]
Sensitivity of surface waves to the LAB Red: starting model, Grey Monte-Carlo Inversion

Méthode du rejet
Paramètres : 2 $V_S$, 1 $\delta z$

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: $C_R, C_L, U_R, U_L$
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 $0\psi + 4\psi$

$T = 50\ s$

$T = 100\ s$

RAYL

LOVE

1\% anisotropie pic à pic (%)

-4  -2  0  2  4
Inversion des données séparées

RAYL

LOVE

PHASE

GROUPE

(km)
Inversion Monte-Carlo

Paramètres : 3 $V_S$, 1 $\delta z$.
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).
\[
\frac{\Delta}{C(T, \text{trait})} = \int_S^R \frac{ds}{C(T, \theta, \phi)}
\]

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

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 : \(c_R, \alpha_R^*, c_L, \alpha_L^* [35-300s]\).

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

\[
\delta C_R|_{k, \psi} = \int_{\Omega} \left[ \frac{\partial C_R}{\partial A} \right]_k (\delta A + B_c \cos 2\psi + B_s \sin 2\psi + \delta F + H_c \cos 2\psi + H_s \sin 2\psi) + \frac{\partial C_R}{\partial C} \delta C + \frac{\partial C_R}{\partial F} \delta F + H_c \cos 2\psi + H_s \sin 2\psi)
\]

\[
\delta C_L|_{k, \psi} = \int_{\Omega} \left[ \frac{\partial C_L}{\partial L} \right]_k (\delta L + G_c \cos 2\psi + G_s \sin 2\psi) + \frac{\partial C_L}{\partial L} \delta L + G_c \cos 2\psi + G_s \sin 2\psi)
\]

\[
\delta C_L|_{k, \psi} = \int_{\Omega} \left[ \frac{\partial C_L}{\partial N} \right]_k (\delta N - E_c \cos 4\psi + E_s \sin 4\psi)
\]

(code modifié de Montagner, 1986)

Paramètres résolus : \(V_{SV}, \xi, G_c, G_s\).
Paramètres du modèle tomographique

Paramètres résolus : $V_{SV}$, $\xi$, $G_c$, $G_s$.

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

Profil continental ($\lambda = 63^\circ$, $\phi = -96^\circ$).
Joint M.C. inversion
\[ d = [C_R \ C_L \ U_R \ U_L] \]

\( \sim 25\% \) variance reduction
wrt \( a \ priori \) Crust2.0

\( \delta z_{\text{Moho}} \): difference between
Our model and crust2.0