Structure anisotrope et dynamique du manteau à l’échelle continentale

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Avec la participation de:
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S waveform tomography

- Depth of continental roots
- Chemical and/or thermal nature of cratonic roots
- Nature of anisotropy observed in the upper mantle under continents
- Nature of the “LAB”
- Lithosphere and asthenosphere:
  - comparison between ocean basins/stable continents
Approach

• Seismic waveform tomography
  - Isotropic
  - Anisotropic
  - Anelastic

• SKS splitting observations

• Global scale/Continental scale (north America)
Types of anisotropy

- General anisotropic model: 21 independent elements of the elastic tensor $c_{ijkl}$

- Long period waveforms sensitive to a subset, to first order (13) of which only a small number can be resolved
  - Radial anisotropy
  - Azimuthal anisotropy
• **Radial anisotropy**
  - A,C,F,L,N (Love, 1911)
  - Long period S waveforms can only resolve
    - $L = \rho V_{sv}^2$
    - $N = \rho V_{sh}^2$
    - $\Rightarrow \xi = \left(\frac{V_{sh}}{V_{sv}}\right)^2$
    - $\forall \Delta \ln \xi = 2(\Delta \ln V_{sh} - \Delta \ln V_{sv})$

• **Azimuthal anisotropy**
  - Terms in $2\psi$ and $4\psi$ (8 of them)
  - Resolve Gc and Gs (2 of 6 terms in $2\psi$)
• Radial anisotropy only:
  - Vertical axis of symmetry
  - Love/Rayleigh wave discrepancy

• Azimuthal anisotropy only
  - Horizontal symmetry axis

• Vectorial tomography: Combination radial/azimuthal (Montagner and Nataf, 1986):
  - Vs isotropic, $\xi$, two angles of orientation of symmetry axis
  - Radial anisotropy with arbitrary axis orientation (cf olivine crystals oriented in “flow”)
Vectorial tomography
Montagner and Nataf (1986)

\[ \delta \omega(\theta, \phi) = \int \left[ \delta A_0(r, \theta, \phi) + \delta A_1(r, \theta, \phi) \cos 2\Psi_0 + \delta A_2(r, \theta, \phi) \sin 2\Psi_0 + \delta A_3(r, \theta, \phi) \cos 4\Psi_0 + \delta A_4(r, \theta, \phi) \sin 4\Psi_0 \right] r^2 \, dr \]

Azimuthal anisotropy

Radial anisotropy
Vectorial tomography

Orthotropic medium: hexagonal symmetry with inclined symmetry axis

$$(A_R, C_R, F_R, L_R, N_R, B_R, G_R, H_R, E_R) \quad \rightarrow \quad (A_0, C_0, F_0, L_0, N_0, \Psi, \Theta)$$

Axis of symmetry
Montagner, 2002

\[ \xi = (V_{sh}/V_{sv})^2 \]
SKS splitting observations
SKS Splitting Observations

Interpreted in terms of a model of a layer of anisotropy with a horizontal symmetry axis

\[ \Delta t = \text{time shift between fast and slow waves} \]

\[ \Psi_0 = \text{Direction of fast velocity axis} \]

Montagner et al. (2000) show how to relate surface wave anisotropy and shear wave splitting

Huang et al., 2000
Waveform Inversion Methodology:
- Non-linear Asymptotic Coupling Theory (NACT); 3 component waveforms
- Extension to anisotropic inversion
- Iterative inversion for elastic and anelastic structure
- Fundamental and overtone surface waves
- Body waves
Depth = 140 km

- **SH**: horizontally polarized S waves
- **SV**: vertically polarized S waves
- **hybrid**: both

**Diagram:**
- SIO: SB4L18
- Caltech: S20RTS
- BRK: SAW24B16
- HRV: S362D1
Ecström and Dziewonski, 1998
Elastic models: correlation with SAW24B16

(a) Global

- S20A_SV
- S20RTS
- S20A_SH
- S362D1

(b) Continent

- S20A_SV
- S20RTS
- S20A_SH
- S362D1
“SH models”

Gung et al., Nature 2003

“SV models”
Transverse isotropy
(referred to anisotropic PREM)

\[ \xi = (V_{sh}/V_{sv})^2 \]

Average PREM removed

Continental lithosphere: temperature/compositional effects
3D temperature variations based on inversion of long period seismic waveforms
Depth profiles of temperature under oceans and continents

Cammarano and Romanowicz, PNAS, 2007
Depth profiles of temperature under oceans and continents

Cammarano and Romanowicz, PNAS, 2007

Compositional signature emerges beneath cratons
Continental scale, isotropic, radial and azimuthal Anisotropy

Extension to waveform inversion of Montagner’s “vectorial tomography”
Predictions from surface wave inversion

SKS splitting measurements

Montagner et al. 2000
Australia

Predicted from Surface wave model

SKS Splitting measurements

Simons et al., 2005
Models based on surface waves or SKS splitting observations

Limitations:

- lack horizontal and vertical resolution
- limited to either radial or azimuthal anisotropy

High resolution upper mantle 3D model with increased lateral and vertical resolution including both radial and azimuthal anisotropy
Overtones

By including overtones, we can see into the transition zone and the top of the lower mantle.

After Ritsema et al, 2004
Crustal corrections

Linear v/s Non-linear

Marone and Romanowicz, 2007
Azimuthal coverage

Fundamental and higher modes

Z component

T component
Isotropic $S$-velocity

After Bally et al., 1989
Anisotropic parameter $\xi = (v_{SH}/v_{SV})^2$

Marone and Romanowicz, GJI, 2007
Difference between directions of fast velocity and absolute plate motion
Surface Waveforms only

Peak-to-peak anisotropy: 1%, 2%

Model A

Model B

With Constraints From SKS splitting

APM
Azimuthal anisotropy

Resolution

Input

Output

100 km

300 km

2% peak-to-peak anisotropy
Synthetic test inversions
Comparison with SKS splitting measurements

Model A

Model B

Delay time $\frac{1}{2}s$
Variance Reduction

<table>
<thead>
<tr>
<th>Model name</th>
<th>Waveform data</th>
<th>SKS splitting data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td>0.7091</td>
<td>0.10</td>
</tr>
<tr>
<td>Model B</td>
<td>0.7087</td>
<td>0.51</td>
</tr>
</tbody>
</table>
Evidence for two layers of anisotropy in North-Eastern US

Variation of splitting time with azimuth

hexagonal orthorombic

Levin et al., 2000
Smith et al., 2004

Current APM

Paleo-spreading dir.
Azimuth difference between fast direction of anisotropy and APM

Smith et al., 2004
Conclusions: anisotropy

- Surface waves alone lose resolution in anisotropy at depths greater than 200km, fail to recover the full amplitude of azimuthal anisotropy.

- SKS splitting data alone integrate over whole upper mantle but do not have depth resolution.

- Combining the two improves depth resolutions and leads to 3D structure compatible with both datasets.

- Anisotropic tomography allows us to image two “layers” of anisotropy worldwide, one in the lithosphere and the other in the asthenosphere, of different orientations, separated by an undulating LAB, deeper under continents than under ocean basins.
• The continental lithosphere, as defined seismically is no thicker than 200–250 km, in agreement with other geophysical data (heat flow, kimberlites)

• The LAB is an anisotropic boundary with fossil anisotropy above, APS oriented anisotropy below

• Dislocation creep is likely active at asthenospheric depths.
This study

Revenaugh and Jordan (1991)
Gaherty and Jordan (1995)

crust

Anisotropic MBL

Isotropic MBL

Base of tectosphere

Shear-decoupling zone

LAB

crust

Anisotropic MBL

Isotropic MBL

Base of lithosphere

Anisotropic Mantle shear zone
Attenuation tomography of the upper mantle
Motivation for seismic Q tomography:

Faul and Jackson, 2005

\[ G \]

\[ \log(1/Q) \]

Fo\textsubscript{90} olivine

- grain size: 10 mm
- pressure: 3 GPa
- period: 100 s

Faul and Jackson, 2005
Anelastic attenuation: QRLW8

Gung and Romanowicz, 2004
$Q^{-1}$: Centered on Africa

- 140 km (45%)
- 210 km (54%)
- 300 km (48%)
- 400 km (49%)
- 500 km (42%)
- 600 km (39%)

$\text{dln}(1/Q)(\%)$
QRLW8

500 km (42 %)

Hotspot distribution

Weighted by buoyancy flux
Hawaii
Anisotropy versus attenuation
Central Pacific
African “superplume”
Conclusions

• African and Pacific superplumes are the roots of upwellings that “rise” through the lower-mantle and through the transition zone, into the asthenosphere, where the flow spreads laterally towards mid-ocean ridges, feeding hotspots and lubricating plate motions.

• “hot” asthenosphere
Perspectives

• Mode asymptotics are fast, there is still a lot we can learn about the earth from them.

• To obtain higher resolution images of the earth, we need to move towards numerical methods such as SEM.

• Work towards this goal step by step
  - Start at low frequencies
  - Separate forward/inverse parts of the problem

• Model parametrization