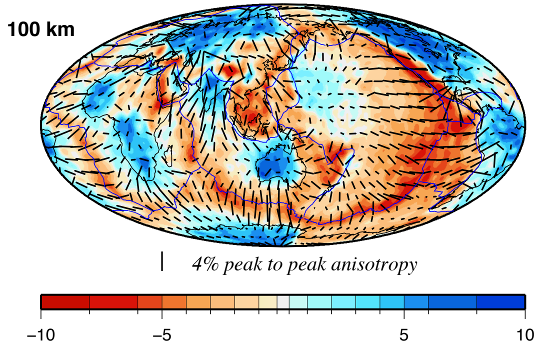
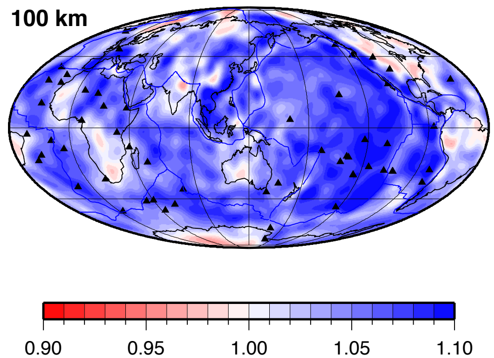
Global imaging of the lithosphere-asthenosphere system

Eric Debayle, Yanick Ricard, Stéphanie Durand and Thomas Bodin

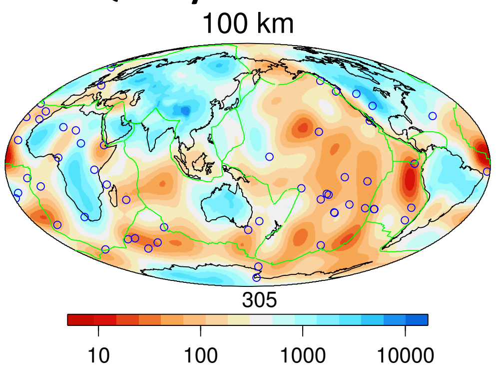
S velocity and azimuthal anisotropy



Radial anisotropy



S Quality factor model



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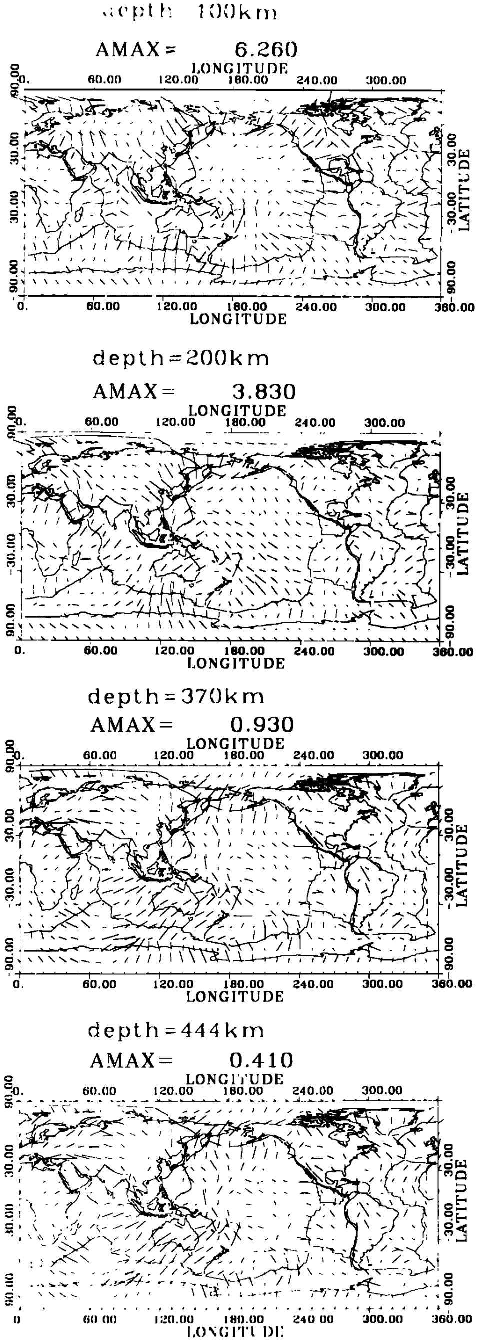
Laboratoire de Géologie de Lyon
Terre Planètes Environnement

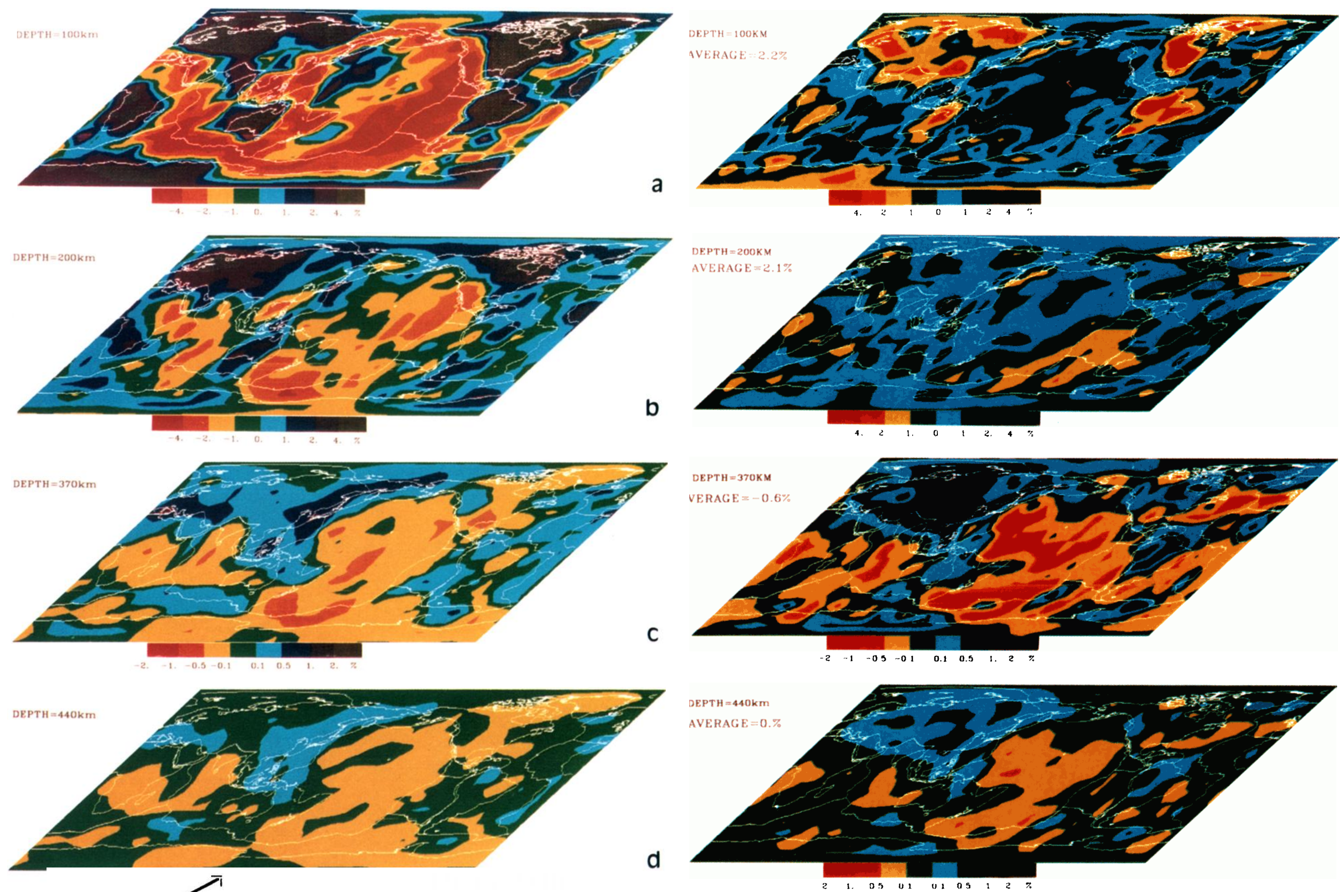
Vsv azimuthal anisotropy

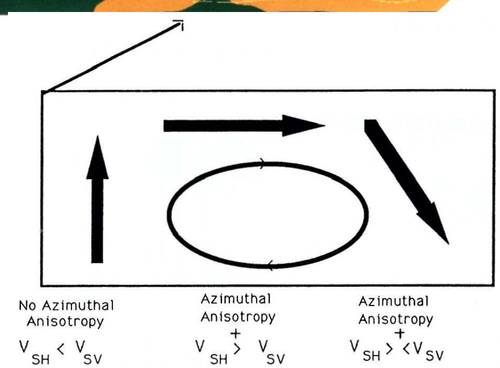


Vsv heterogeneities

Radial anisotropy

$\xi = (Vsh/Vsv)^2$



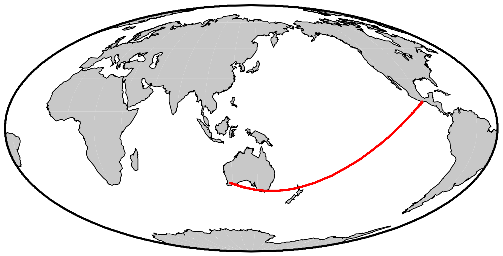


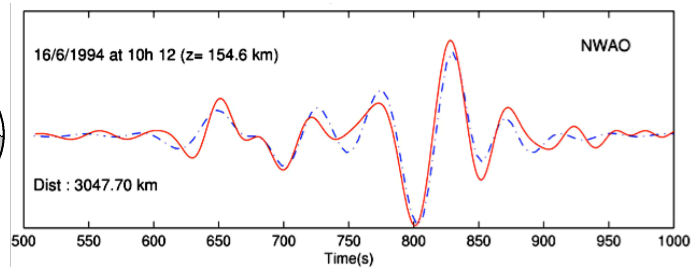
Early global models of Vsv, azimuthal and radial anisotropy and their interpretation in terms of flow.

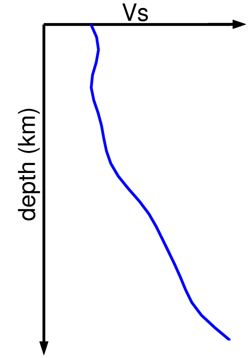
Montagner and Tanimoto , JGR 1991; Montagner, Rev. Geophys., 1994

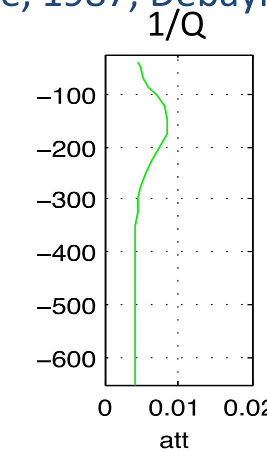
Building seismic models in two steps :

1) Automated waveform inversion applied to millions of waveforms (Cara and Lévêque, 1987; Debayle and Ricard 2012). Period range : 50 -250 s



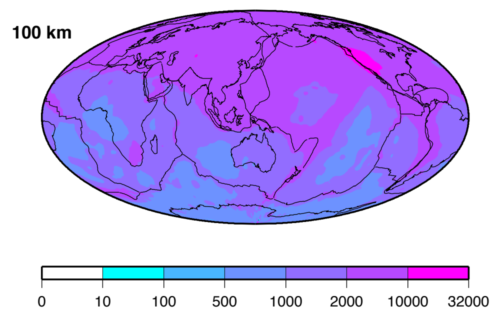




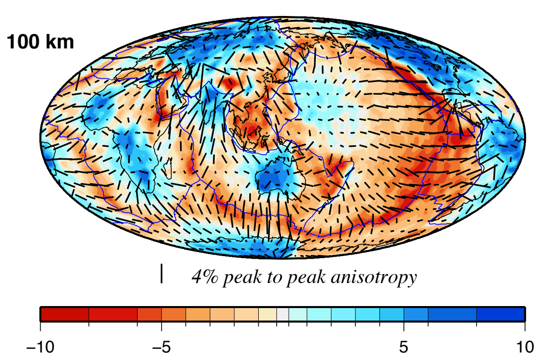


2) Tomographic inversion (Debayle and Sambridge 2004).

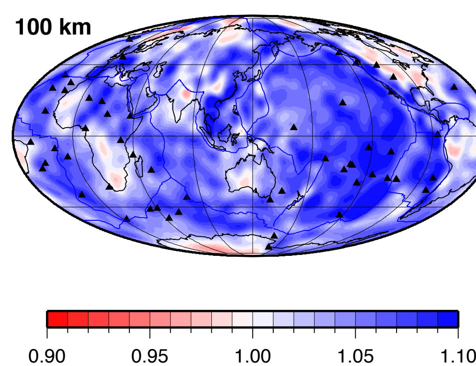
Ray density map



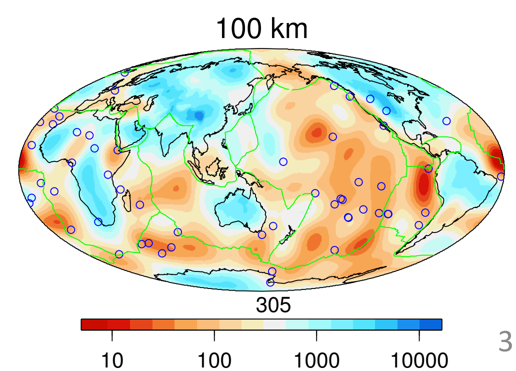
Sv velocity and azimuthal anisotropy



Radial anisotropy



S Quality factor model



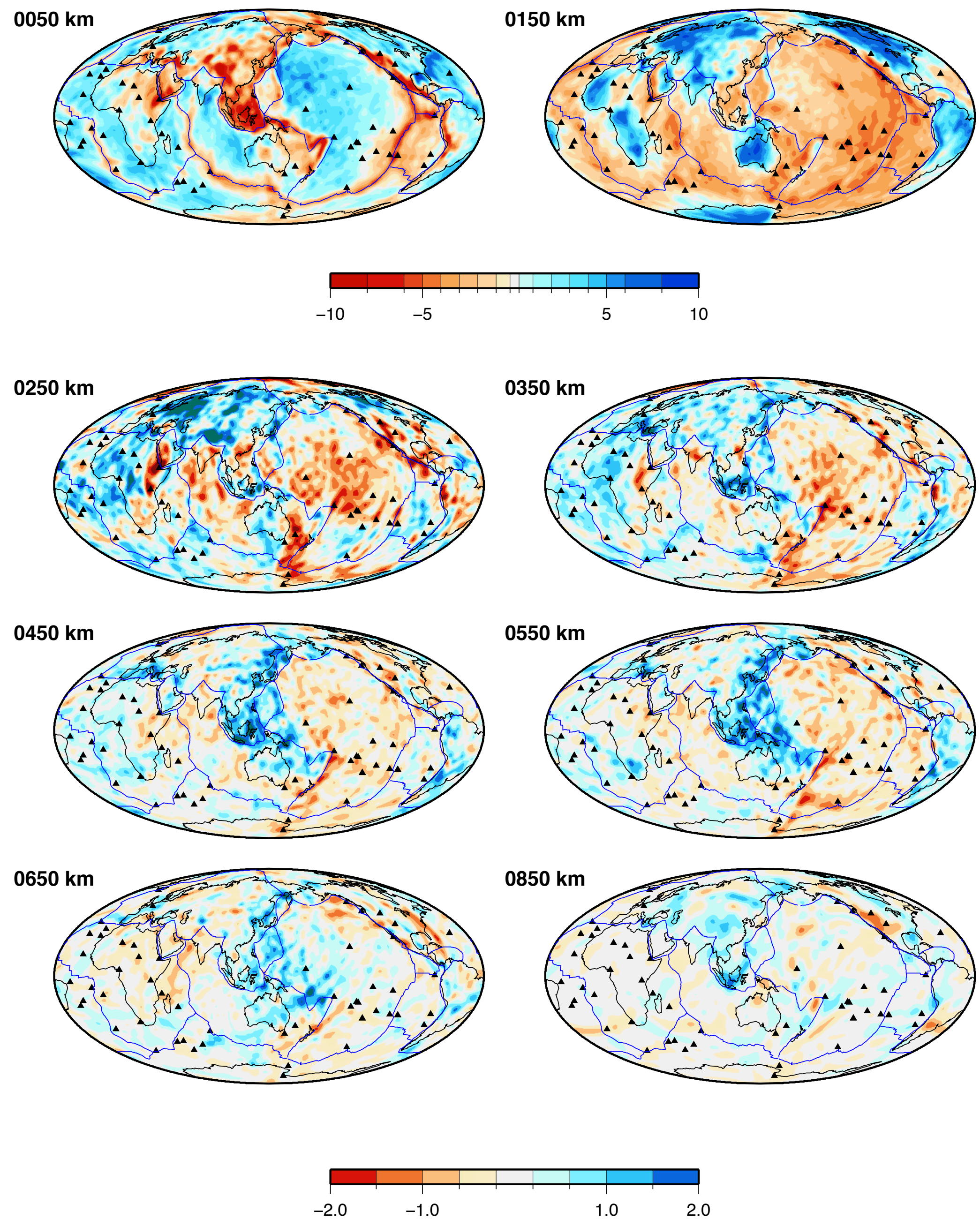
3D2018_08Sv : an automatically updated Sv-wave model of the upper mantle

(Debayle et al., GRL, 2016)

- 3D2018_08SV : SV-wave model updated up to August 2018
- 1,600,492 Rayleigh waveforms
- Includes azimuthal anisotropy
- Updated on a regular basis following publication of the CMT catalog
- Updated model available at :

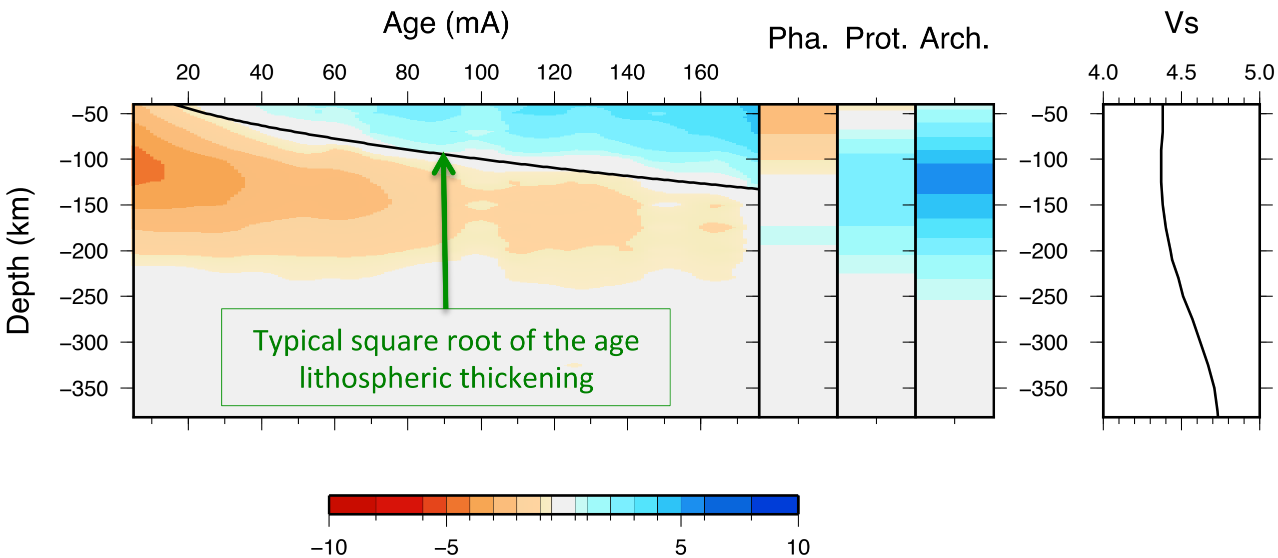
http://perso.ens-lyon.fr/eric.debayle/

Or as a IRIS data product at
https://ds.iris.edu/ds/products/emc-3d2018_08sv/

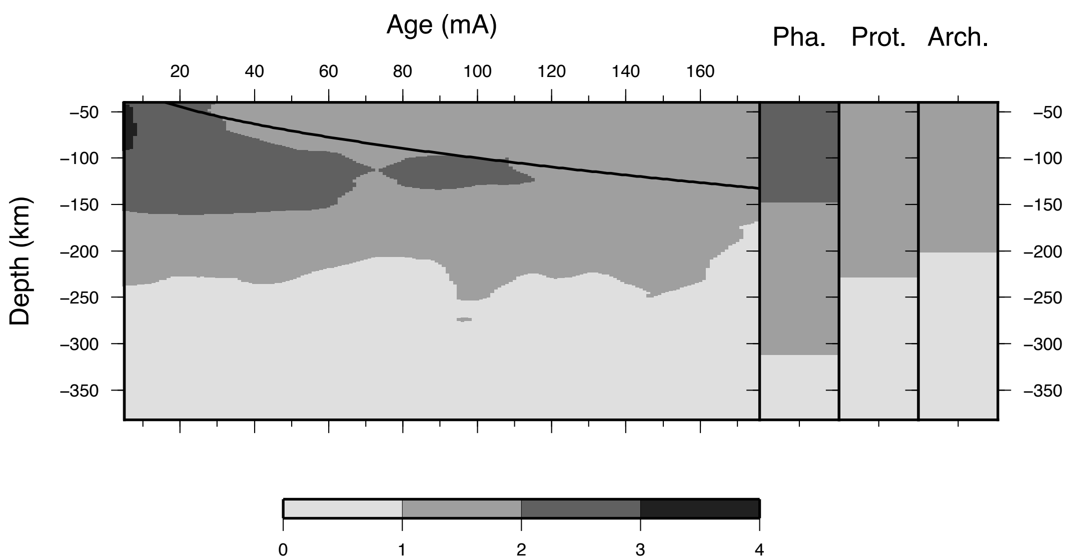


3D2016_03Sv : cross-sections with respect to age

SV-wave heterogeneities in 3D2016_03Sv (Debayle et al., 2016) :



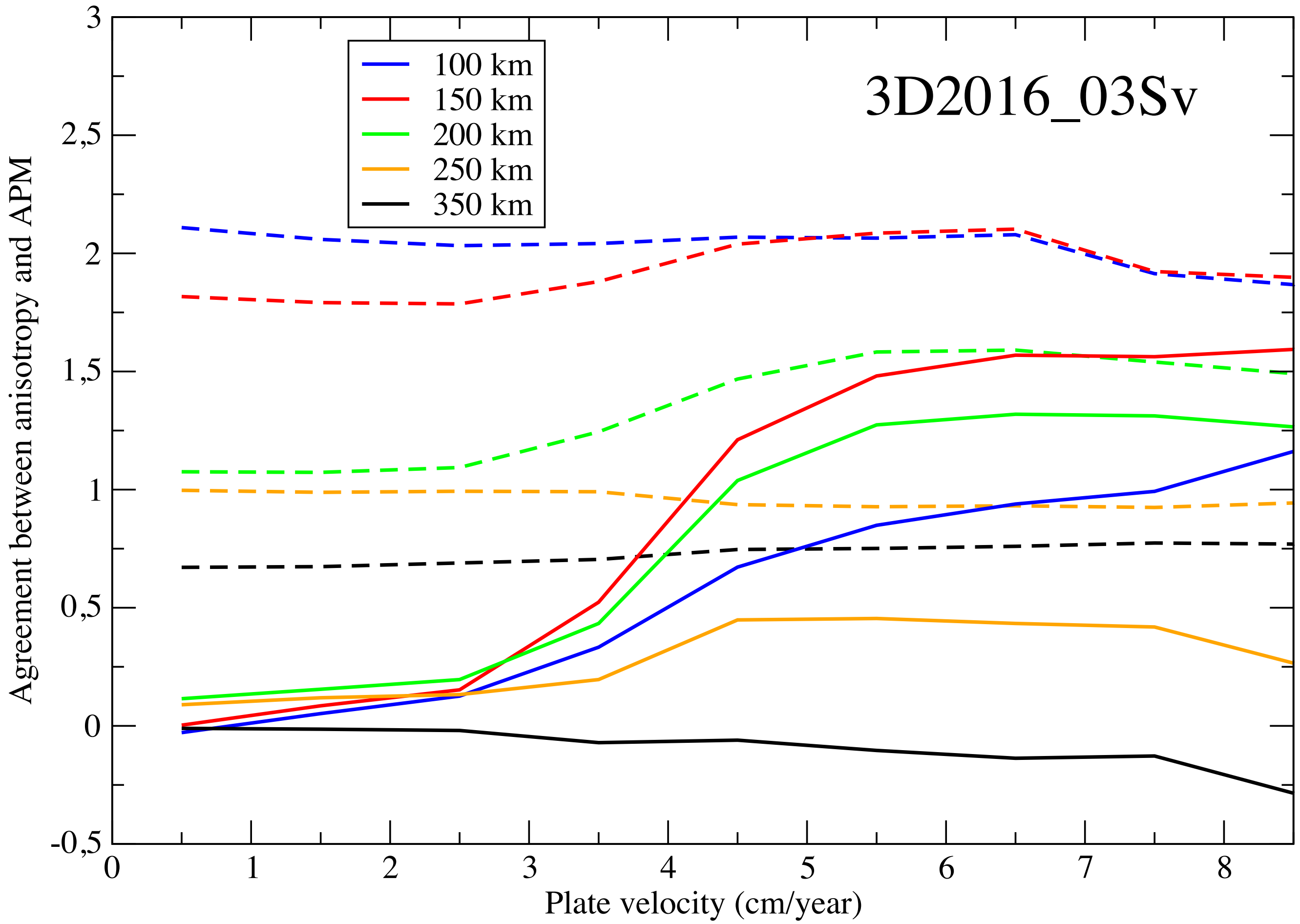
Strength of azimuthal anisotropy (Debayle et al., 2016) :



In average, azimuthal anisotropy does not extend deeper beneath continents than beneath oceans.

Azimuthal Anisotropy versus plate velocity

Dashed lines : strength of anisotropy; Solid lines : anisotropy projected on APM



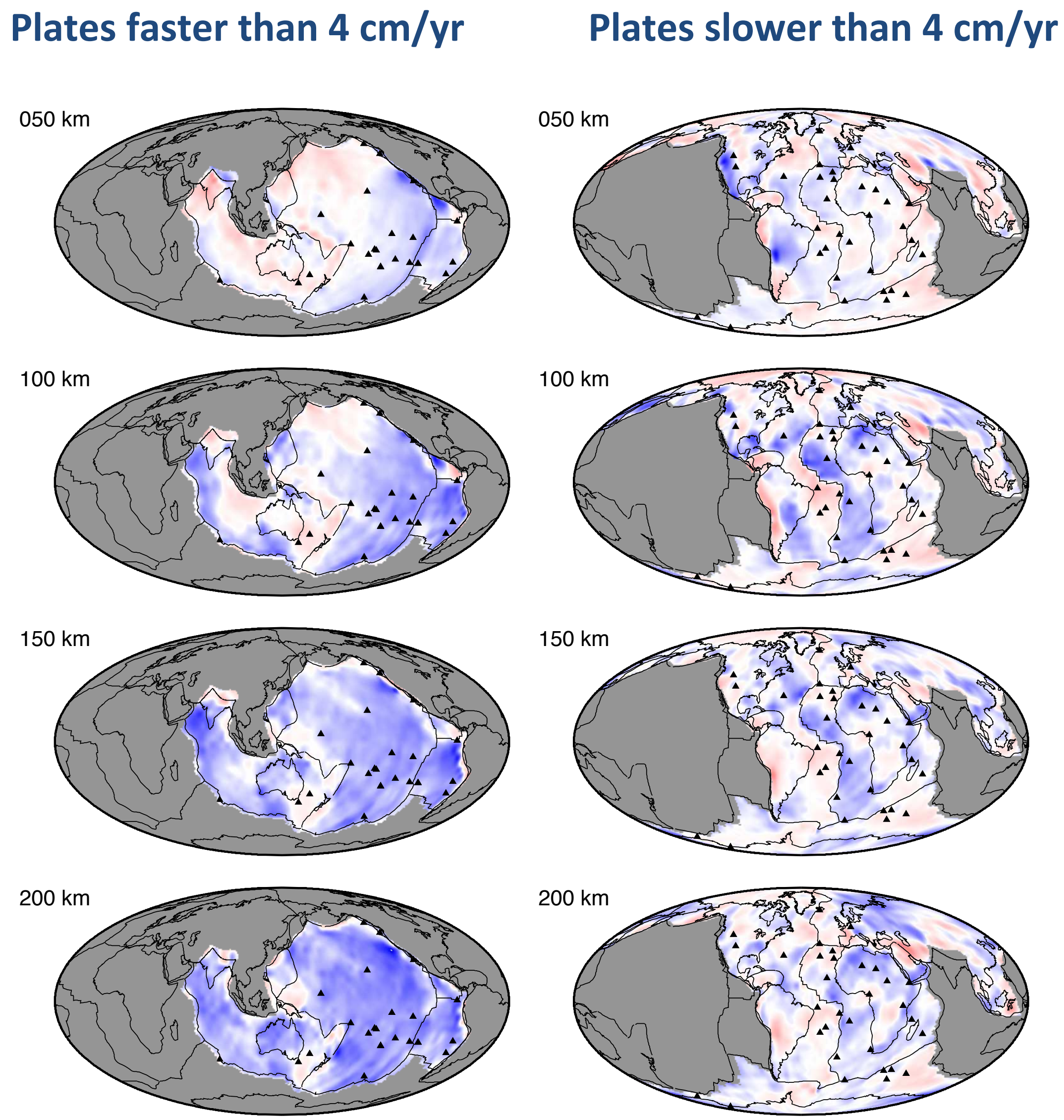
"only plates moving faster than about 4 cm/year can produce sufficient shearing at their base to organize the asthenospheric anisotropy at the scale of the entire tectonic plates"

Debayle and Ricard, EPSL, 2013

Agreement between anisotropy and APM (50-200 km)

$$G.\cos(2\theta)$$

- *G* : anisotropy strength
- θ : angular difference between APM and fast anisotropic direction
- Blue : strong agreement, θ <45 °, G large.
- red: poor agreement, θ >45 °, G large.

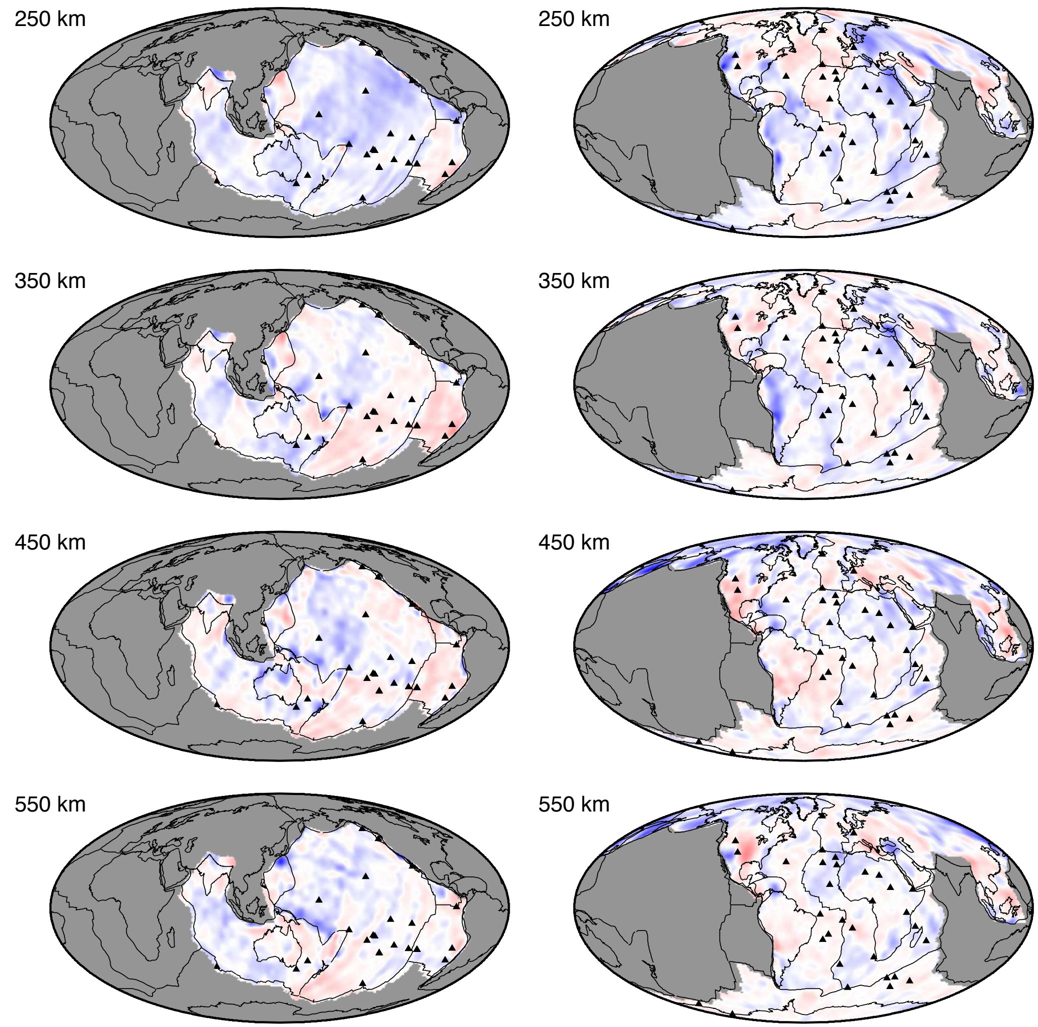


Agreement between anisotropy and APM (250-550 km)

$$G.\cos(2\theta)$$

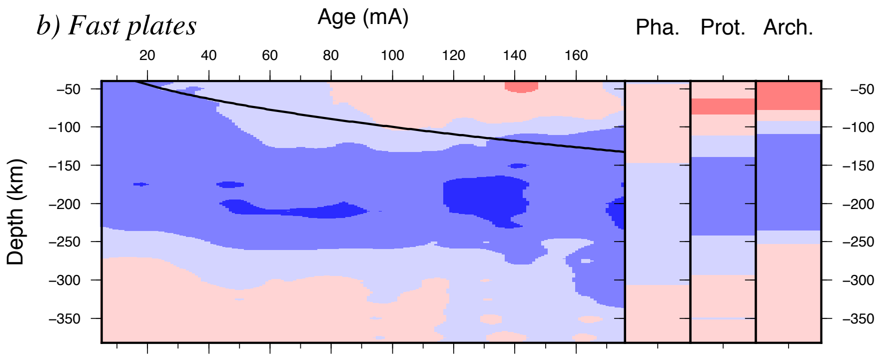
- *G* : anisotropy strength
- θ : angular difference between APM and fast anisotropic direction
- Blue : strong agreement, θ <45 °, G large.
- red: poor agreement, θ >45 °, G large.

Fast-moving plates **Slow-moving plates**

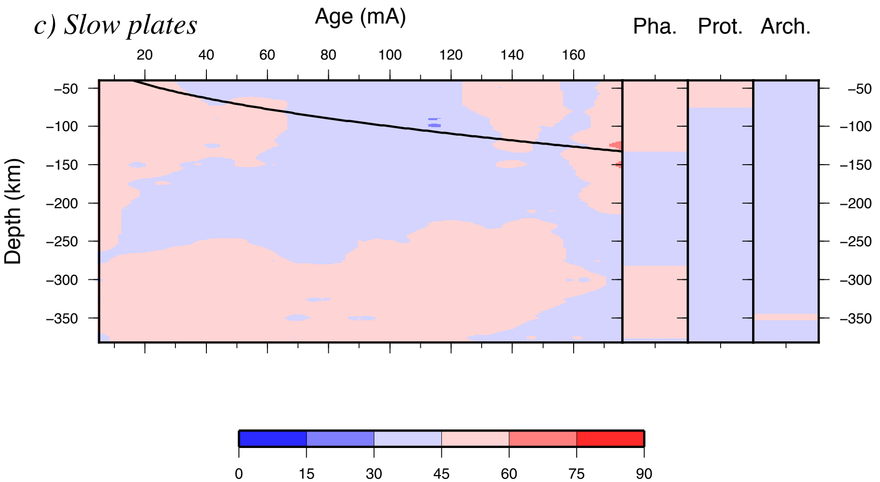


Angular difference between anisotropy directions and APM

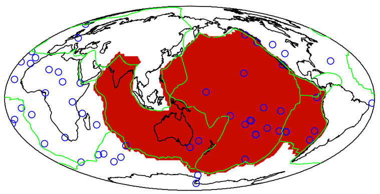
Fast-moving plates



Slow-moving plates

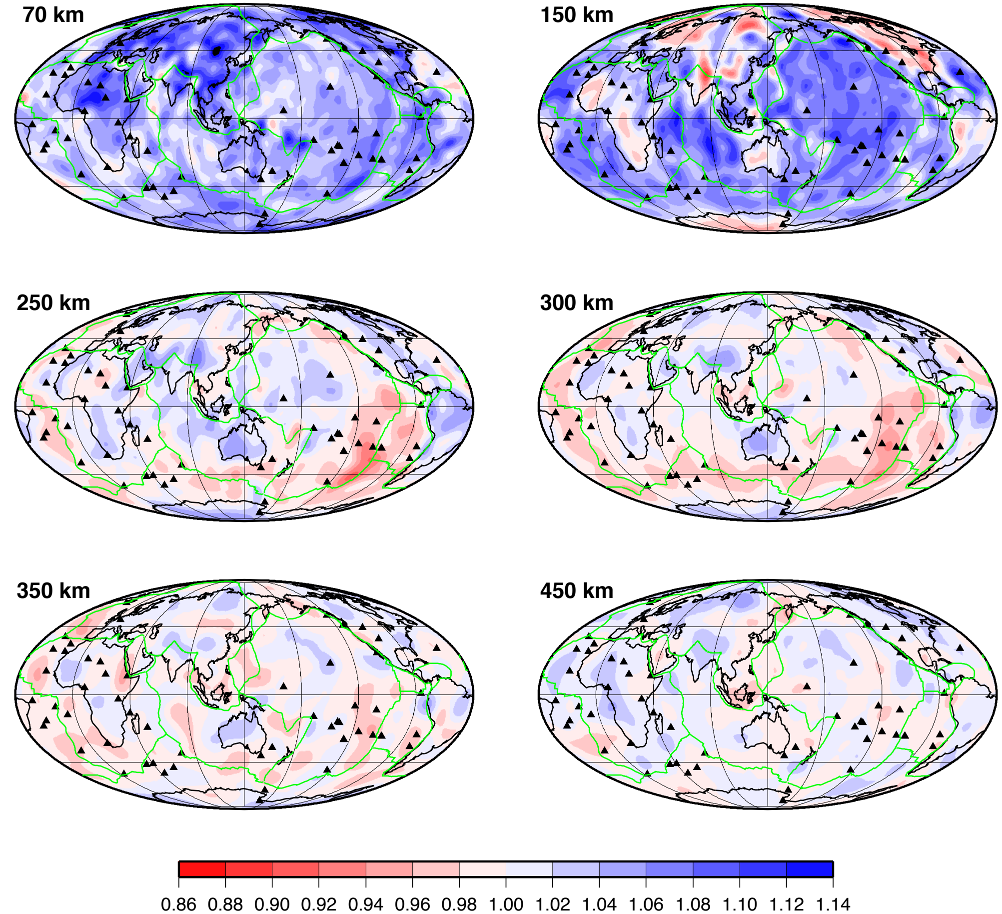


Angle in degree between fast anisotropy and plate motion



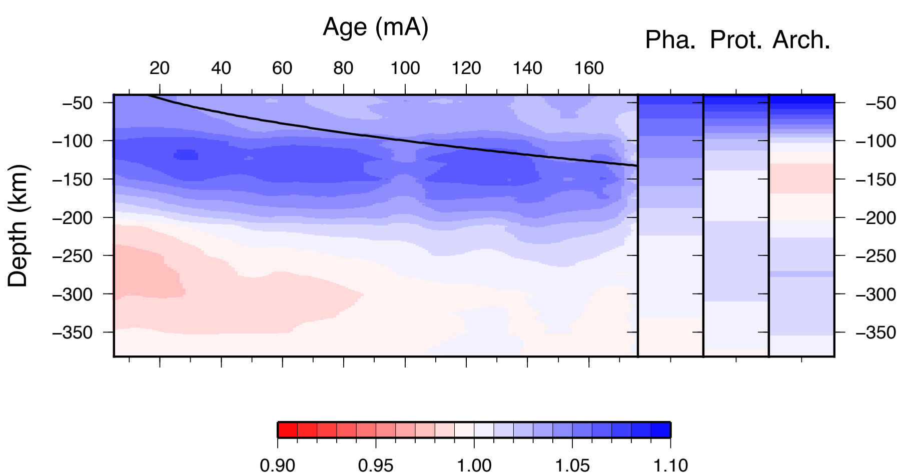
Small angular difference between, azimuthal anisotropy and APM for fast-moving plates (> 4cm/yr, in red on the map).

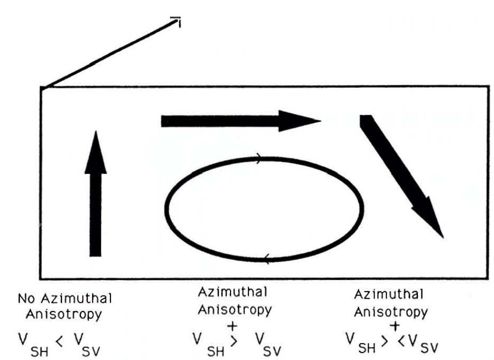
Radial anisotropy model
$\xi = (Vsh/Vsv)^2$



- 400,000 Love and Rayleigh waves inverted to produce Sh and Sv models with same coverage
- Crustal corrections with Crust 1
- Fundamental and overtones up to the fifth, period range 50-250 s

ξ versus age





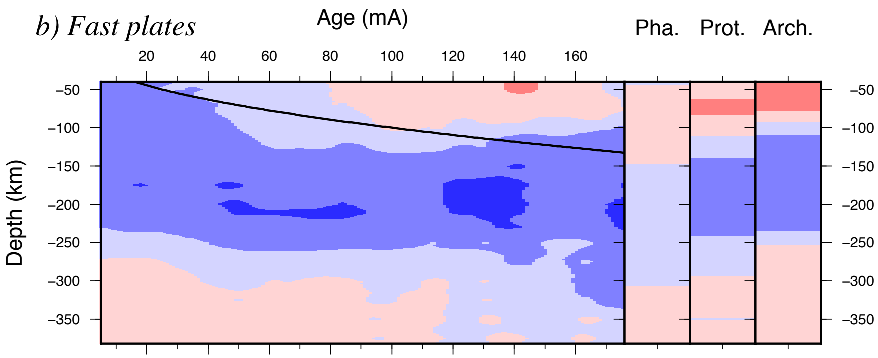
Ho et al., in prep.

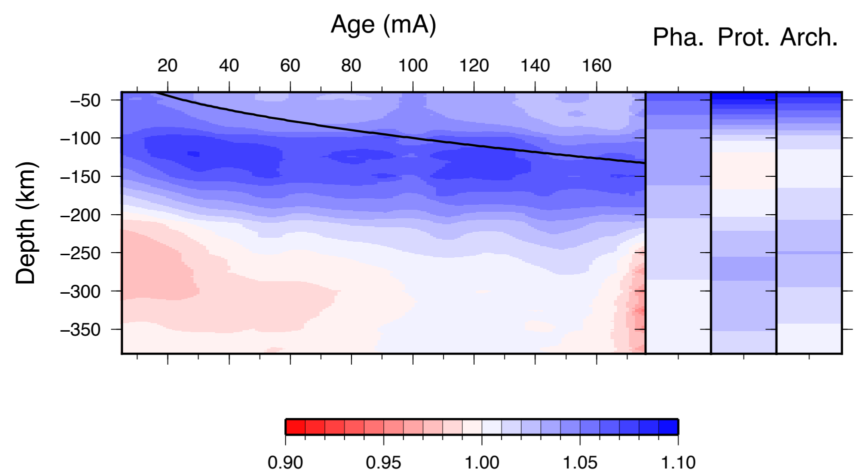
Azimuthal and radial anisotropy versus age

Azimuthal anisotropy (angular difference between anisotropy directions and APM)

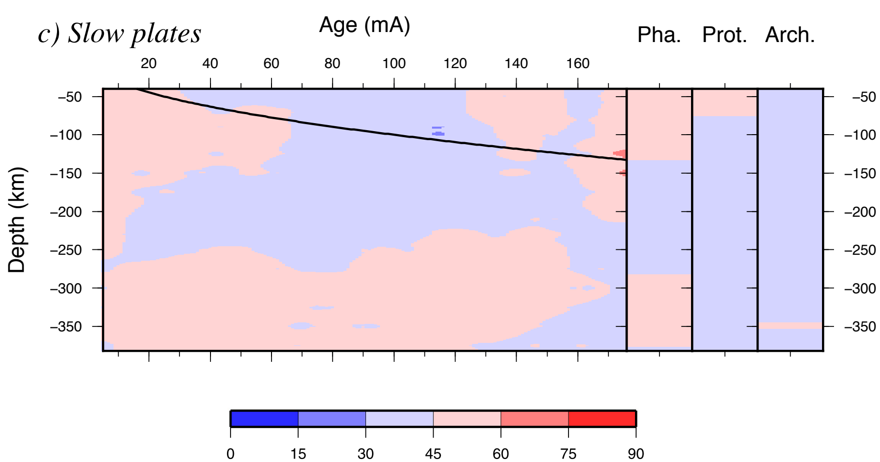
Radial anisotropy
$\xi = (Vsh/Vsv)^2$

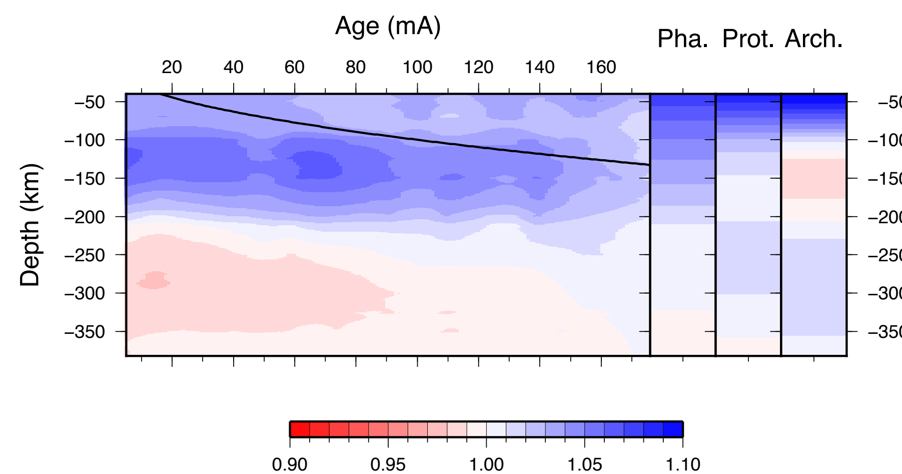
Fast-moving plates





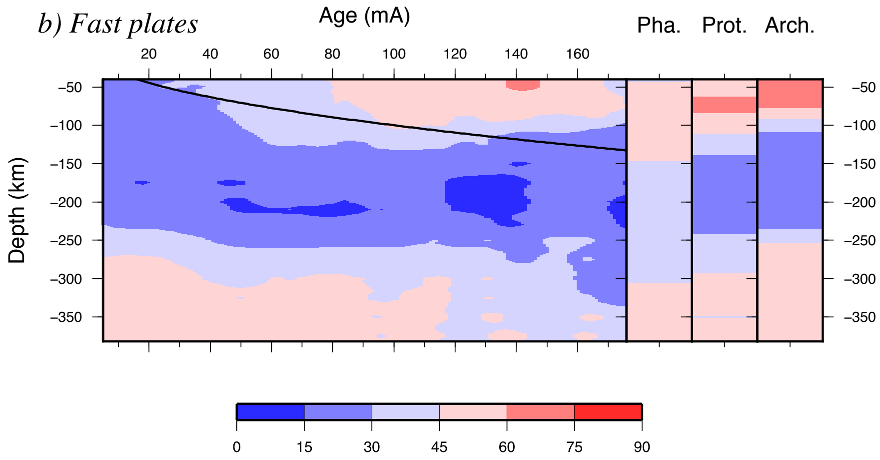
Slow-moving plates



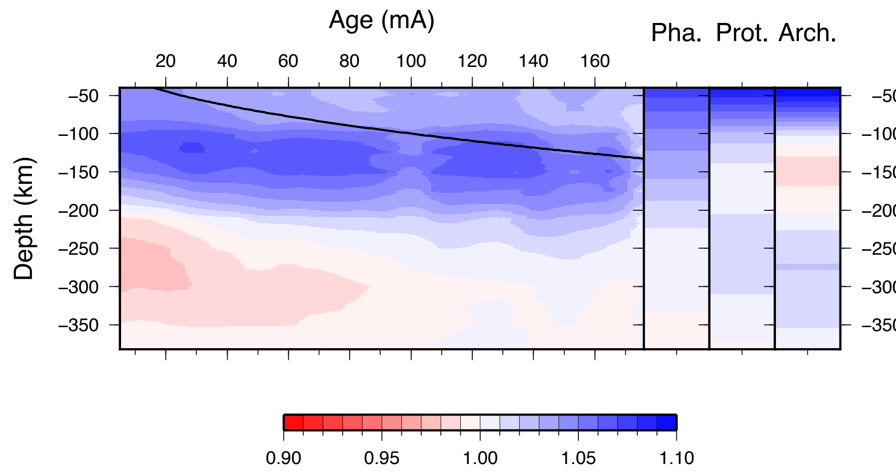


Azimuthal anisotropy seems to deepen in the asthenosphere with the square root of the age, this is less clear for radial anisotropy.

Azimuthal anisotropy



Radial anisotropy



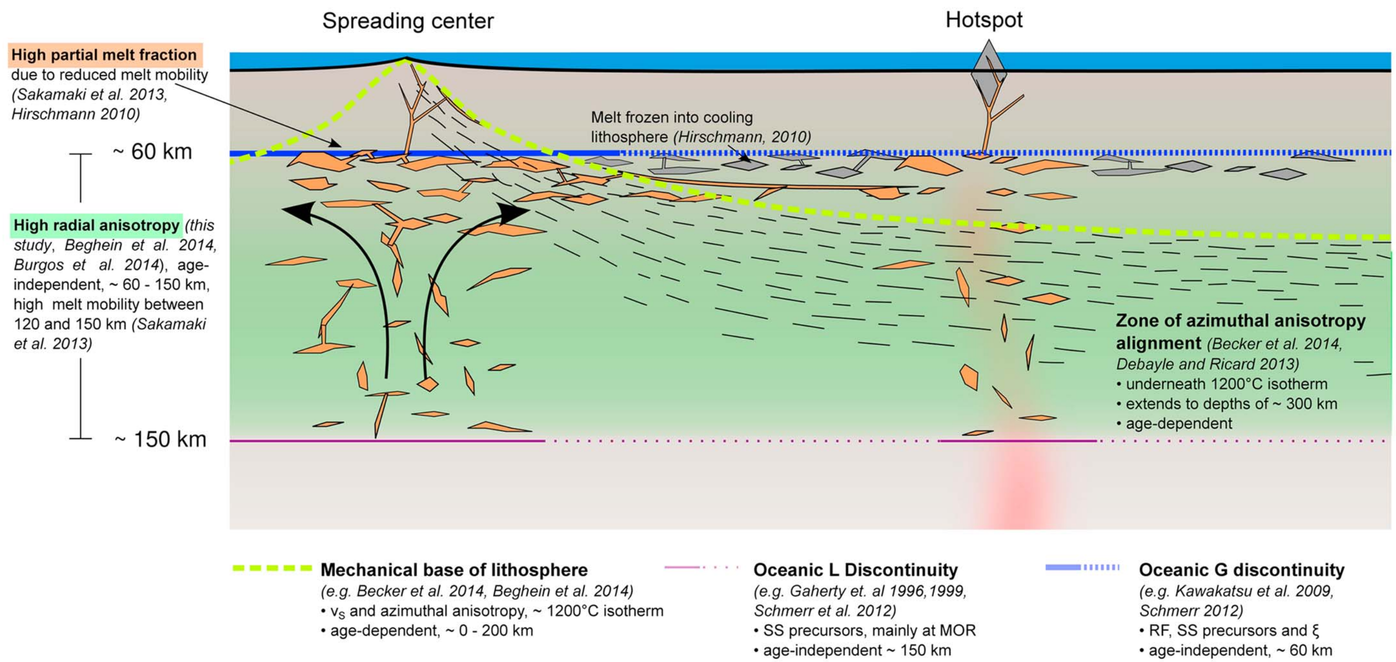


Figure 4. Conceptual model of anisotropy and upper mantle seismic discontinuities in the lithosphere-asthenosphere system.

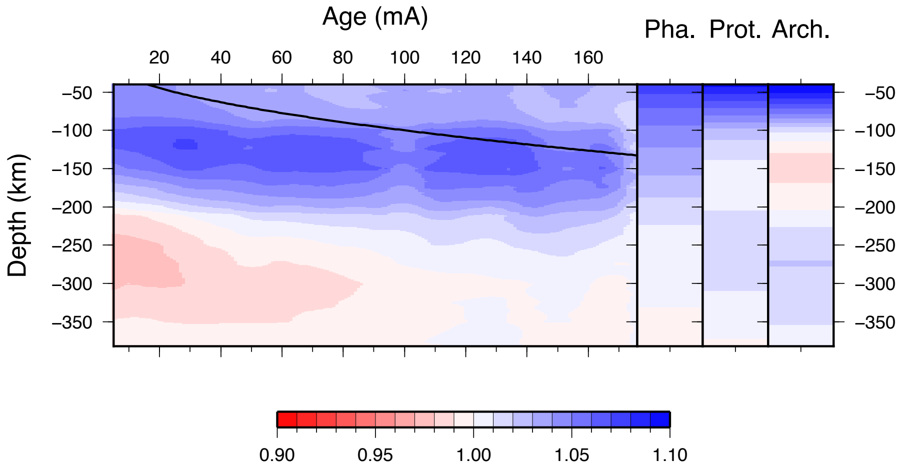
This cartoon by Auer et al., (2015) may explain why azimuthal anisotropy deepens with the square root of the age and not radial anisotropy.

Auer et al., GRL, 2015

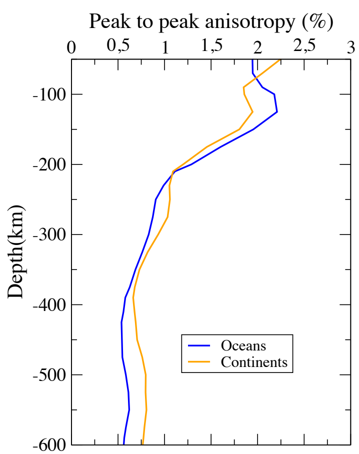
Depth extent of Anisotropy

Radial anisotropy extends deeper beneath continents than beneath oceans, but we find no such difference for azimuthal anisotropy (figure below), suggesting that beneath most continents, the alignment of olivine crystal is preferentially horizontal and azimuthally random at large scale.

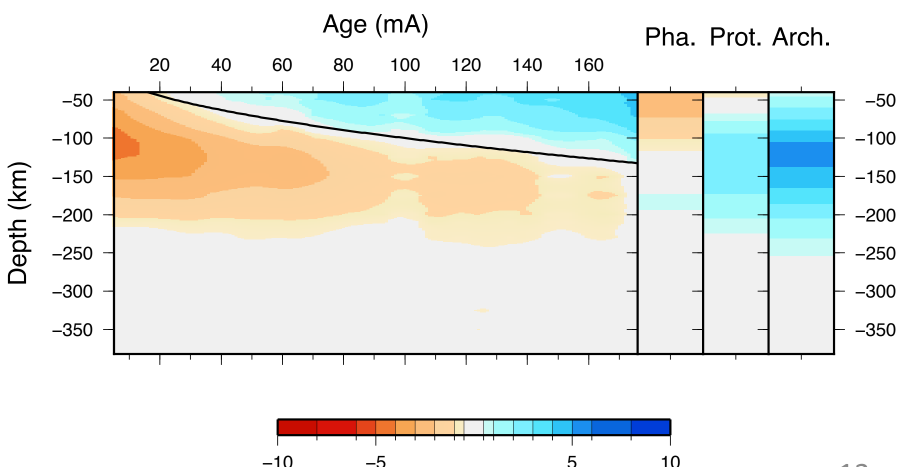
Radial anisotropy ($\xi=(Vsh/Vsv)^2$)
(Ho et al., in prep.)



Azimuthal anisotropy
(Debayle, et al., 2016)



Sv heterogeneities
(Debayle & Ricard 2012; Debayle et al., 2016)



Summary anisotropy :

- Radial anisotropy extends deeper (down to 350 km depth) beneath continents than beneath oceans.
  - ➢ Between 200 and 350 km, anisotropic crystals may be predominantly oriented in the horizontal plane (producing SH-waves faster than SV-waves).

- There is no ocean/continent difference in the depth extent of azimuthal anisotropy which extends down to about 200 km.
  - ➢ Between 200 and 350 km, anisotropic crystals may be be predominantly oriented in the horizontal plane but azimuthally random at very large scale (producing no significant azimuthal anisotropy).

  - ➢ This is consistent with the idea that *"only plates faster than 4 cm/year organize the anisotropy at very large scale"* , as most continents excepted India and Australia are located on plates slower than 4 cm/year.

- Shape preferred orientation may explain the "flat" radial anisotropy beneath oceans.

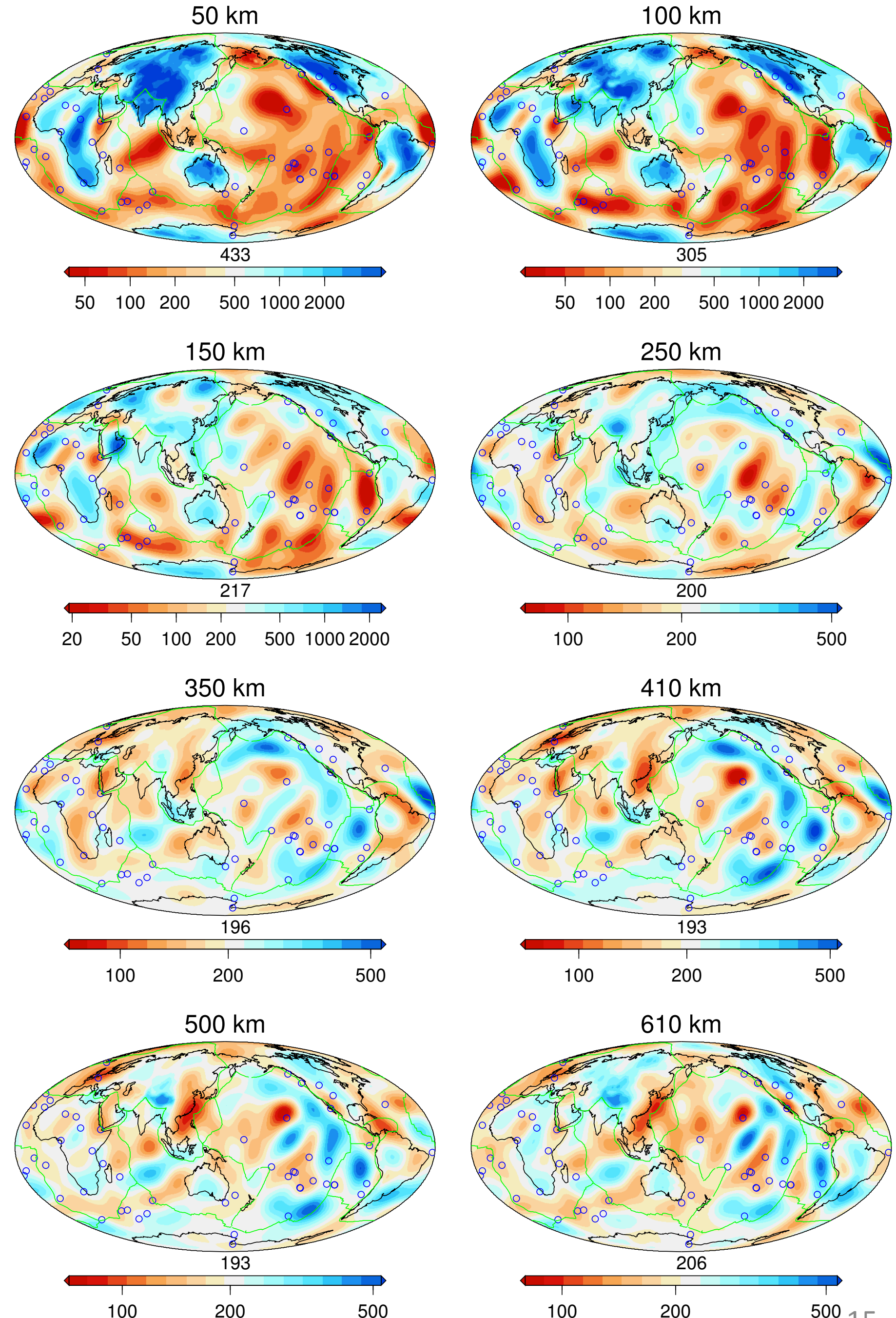
- Radial anisotropy suggests broad regions of vertical flow beneath mid ocean ridges between 200 and 250 km depths.

- **More information on our Vs models in : Debayle & Ricard, EPSL 2013; Debayle et al., GRL 2017**

S Quality factor model QsADR17

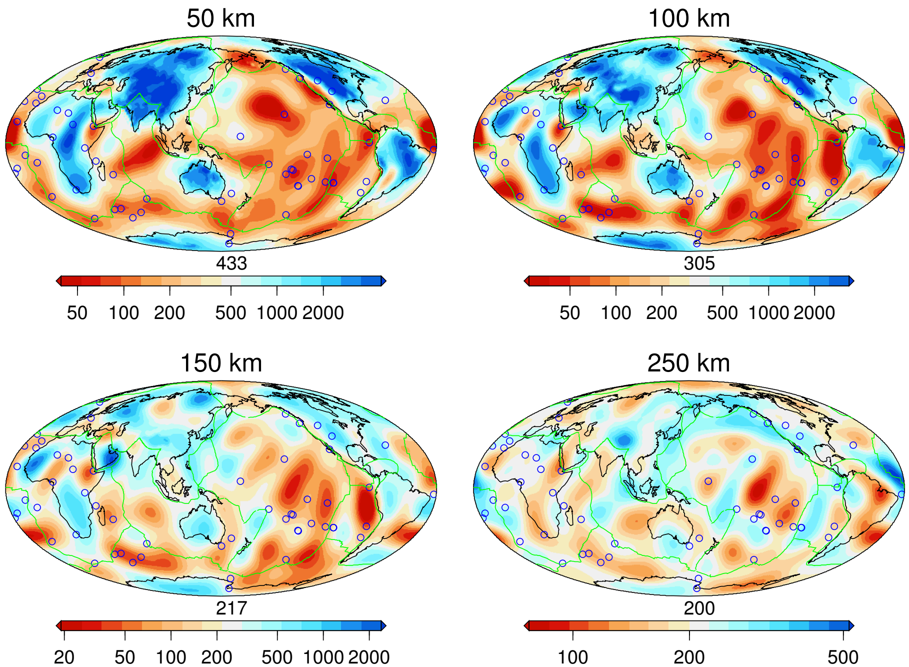
Adenis et al., GRL, 2017

- Based on Debayle and Ricard, (2012) fundamental and higher modes global dataset.
- Inversion of ln (Q_s) at different depths
- Focussing/defocussing effects accounted for using Woodhouse and Wong (1986)
- Specific model for source excitation
- Careful data selection :
  - Data close to a node in the radiation pattern rejected.
  - Data likely to have instrument or M_0 problems rejected
  - Outliers rejected
- About 40,000 paths kept for inversion



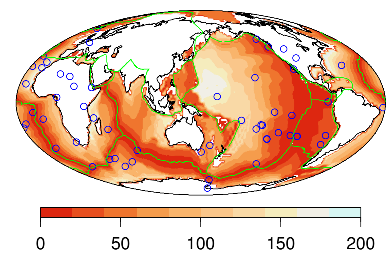
Adenis et al.,GRL 2017

Quality factor model QsADR17

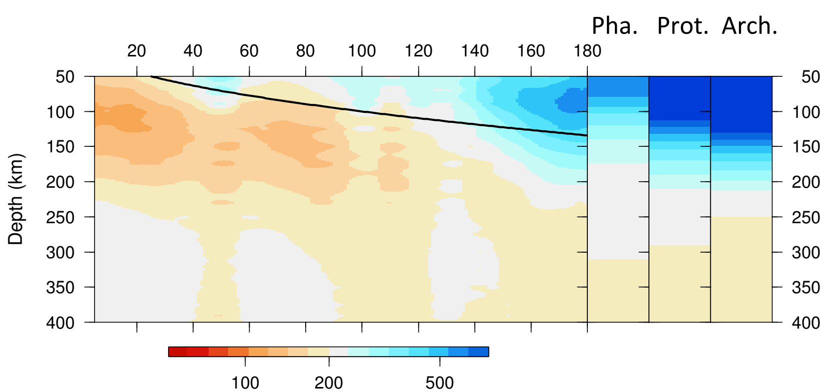


Notice the age dependence of Vs and Q_s on the cross section versus age at the bottom

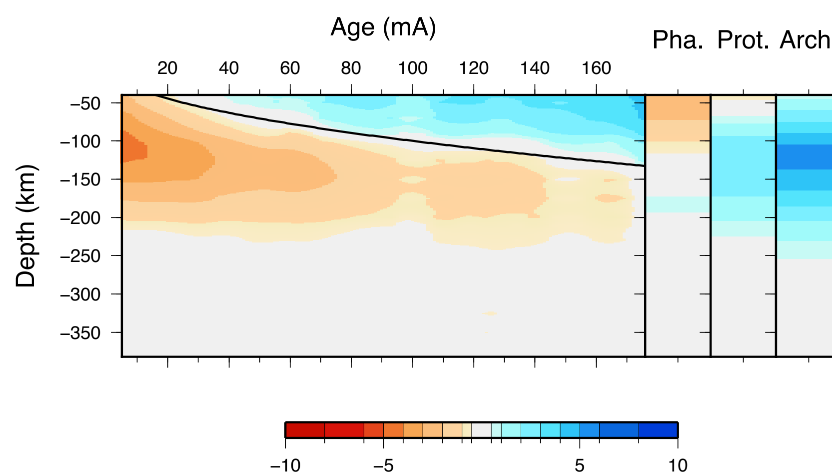
Age map



Q versus age

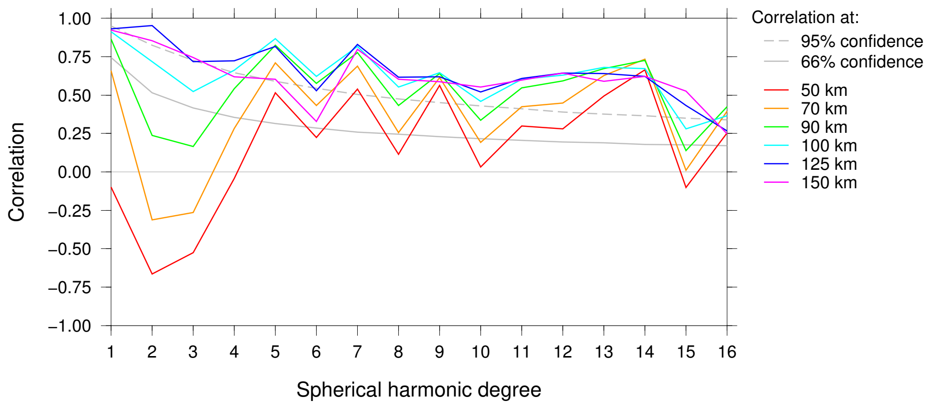


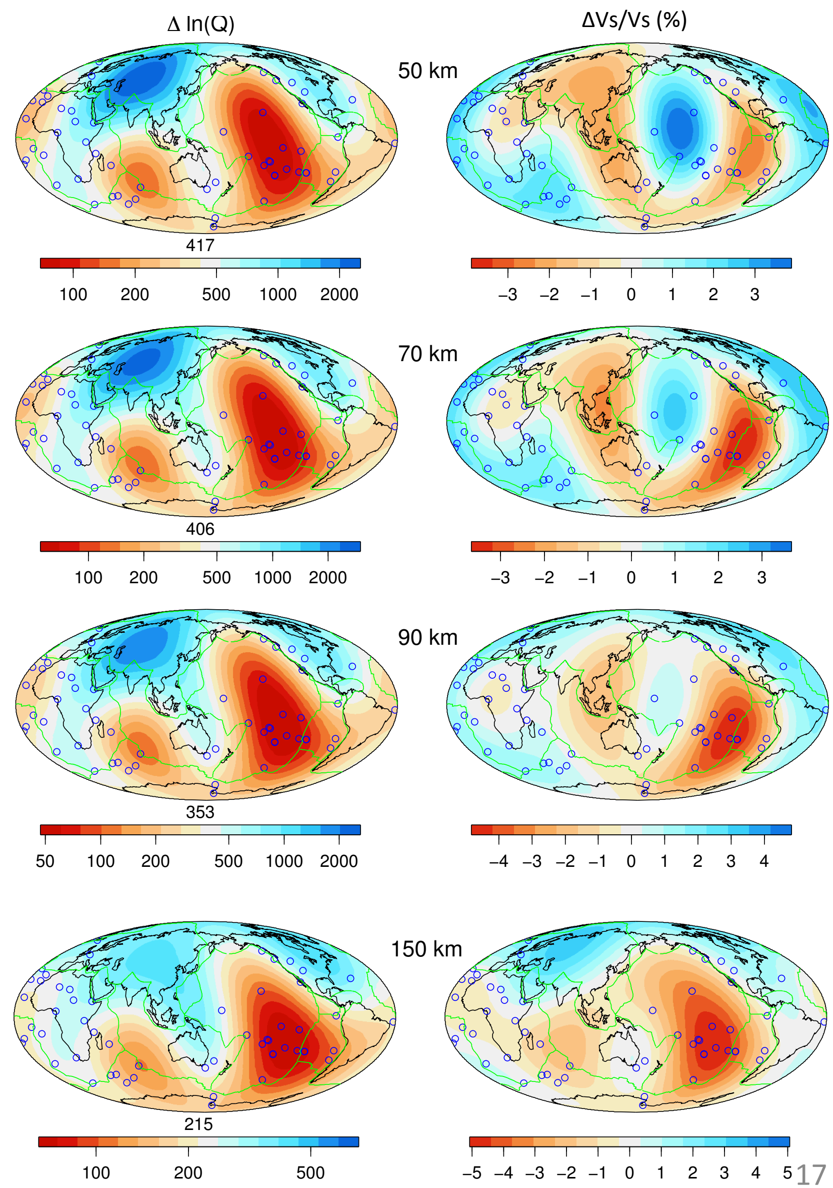
Vs versus age (3D2018_08Sv)



Adenis et al., GRL 2017

Correlation between QsADR17 and S velocity (3D2016_07Sv)





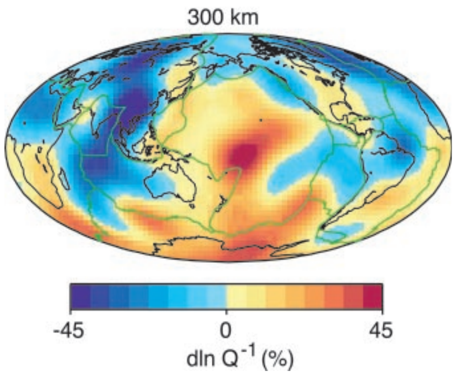
The figure shows an anti-correlation between Vs and Qs at depths <70 km for spherical harmonic degrees smaller than 4.This can be seen on the Qs and Vs maps where we filtered out degrees >4.

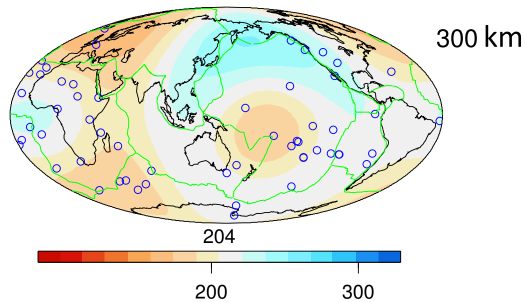
Adenis et al., GRL 2017

Attenuation and radial anisotropy in the Pacific Ocean

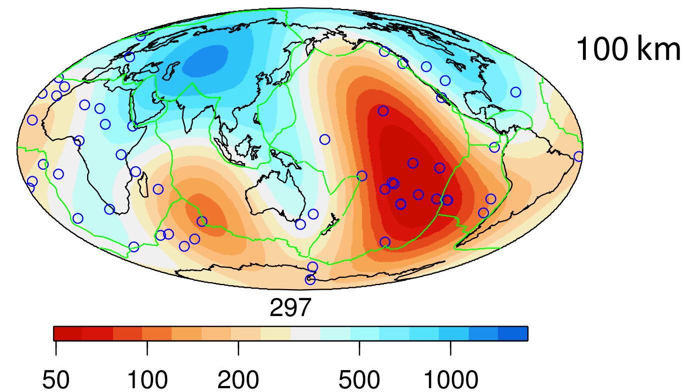
Attenuation :

A strong attenuation was previously observed by
Rommanowicz & Gung (2002) in the Pacific asthenosphere:



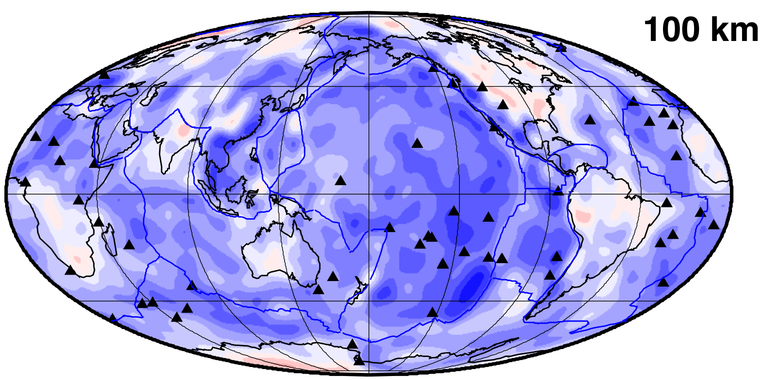


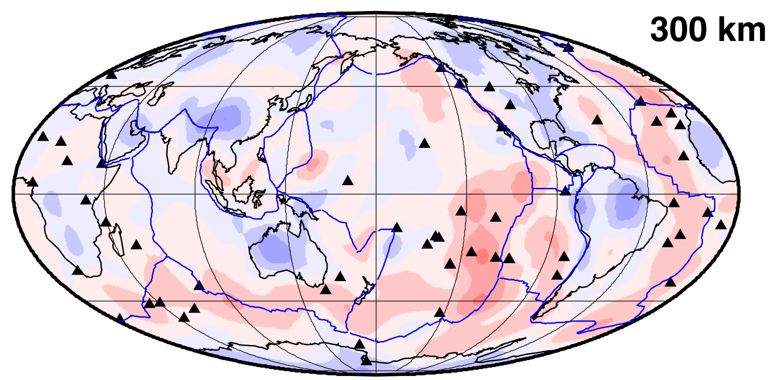
QsADR17



Thermal upwelling deflected horizontally beneath the lithosphere? Would also explain radial anisotropy (Sh>Sv : horizontal flow at 100 km; Sh<Sv : vertical flow at 300 km)

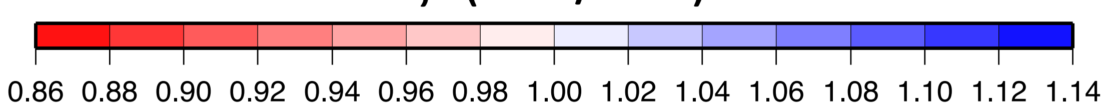
Radial anisotropy :





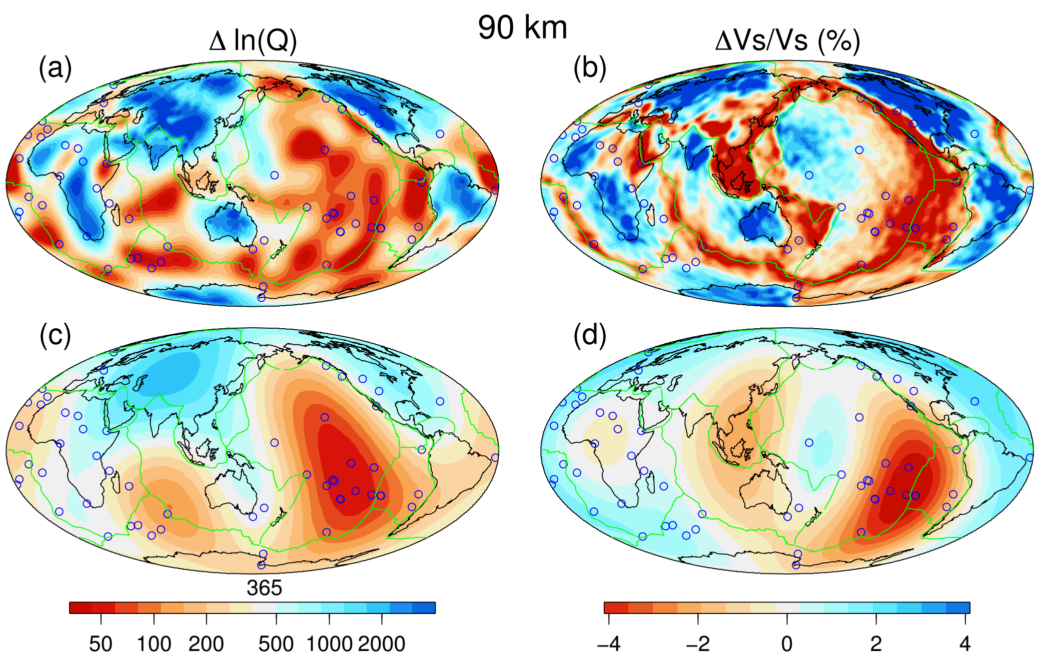
$$\xi=(Vsh/Vsv)^2$$

Ho et al., in prep.



Regions of reduced velocities and moderate or weak attenuation?

- If a small amount of melt is present, it may reduce velocity without affecting attenuation (e.g. Hammond and Humphreys, 2000; Shito et al., 2006) :
    - Proposed by Yang et al., 2007 and Forsyth et al., 1998 to explain portions of the East Pacific Rise covered by the MELT experiment.



Adenis et al., GRL 2017

Summary attenuation :

- The broad attenuation anomaly in the central Pacific could result from several thermal upwelling deflected horizontally in the Pacific asthenosphere.
  - ➢ Compatible with the strong radial anisotropy with Sh waves faster than Sv waves observed between 100 and 200 km in the same region.

- Partial melt may provide an explanation for some regions where low velocities are associated with moderate or high Q, if it has a stronger effect on seismic velocities than on attenuation (Shito, 2006) :
  - ➢ May work for Indonesia and eastern Asia.
  - ➢ May explain observations beneath the EPR as observed at a more local scale after the MELT experiment (Yang et al., 2007; Forsyth, et al., 1998).

- The simultaneous interpretation of global 3D shear attenuation and velocity models has a great potential to decipher the effect of temperature, melt and composition on seismic observables.

- **More information on our Q models in : Adenis et al. GJI, 2017 and Adenis et al. GRL, 2017**