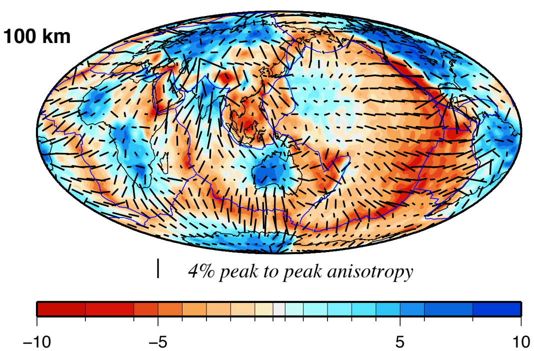
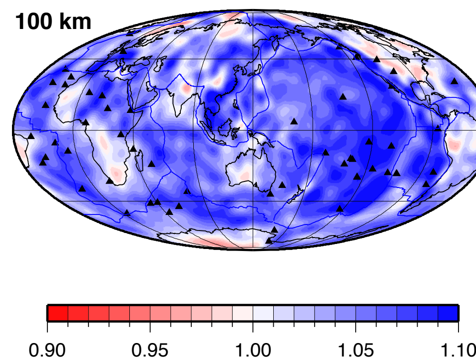
Anisotropy (and seismic attenuation) in the upper mantle from surface waves

Eric Debayle[1], Alice Adenis[1], Stéphanie Durand[1,3],Fabien Dubuffet[1], Yanick Ricard[1], Tak Ho[2] and Keith Priestley[2]

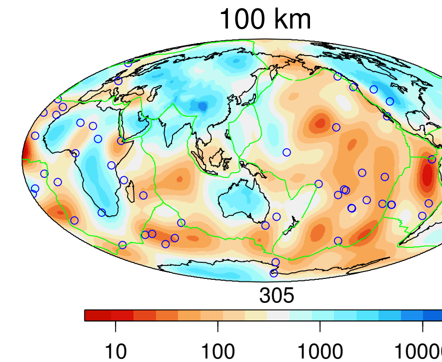
S velocity and azimuthal anisotropy



Radial anisotropy



S Quality factor model

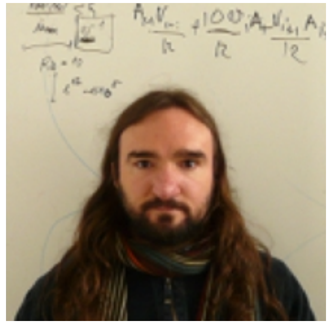


[1]Laboratoire de Géologie de Lyon : Terre, Planètes et Environnement, Université Claude Bernard, ENS de Lyon and CNRS
[2]Department of Earth Sciences, Bullard Laboratories, University of Cambridge
[3]Geophysics group, University of Münster

Laboratoire de Géologie de Lyon
Terre Planètes Environnement

- Laboratoire de Géologie de Lyon : Terre, Planètes et Environnement, Université Claude Bernard, ENS de Lyon and CNRS
- Geophysics group, University of Münster

Alice Adenis (Q)



Fabien Dubuffet(Sv)

Yanick Ricard (Sv)

Stéphanie Durand (Sv)

cnrs dépasser les frontières

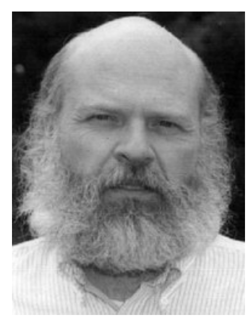
OSU Lyon 1

Laboratoire de Géologie de Lyon
Terre Planètes Environnement

GEOPHYSIK
WWU MÜNSTER

- Department of Earth Sciences, Bullard Laboratories, University of Cambridge

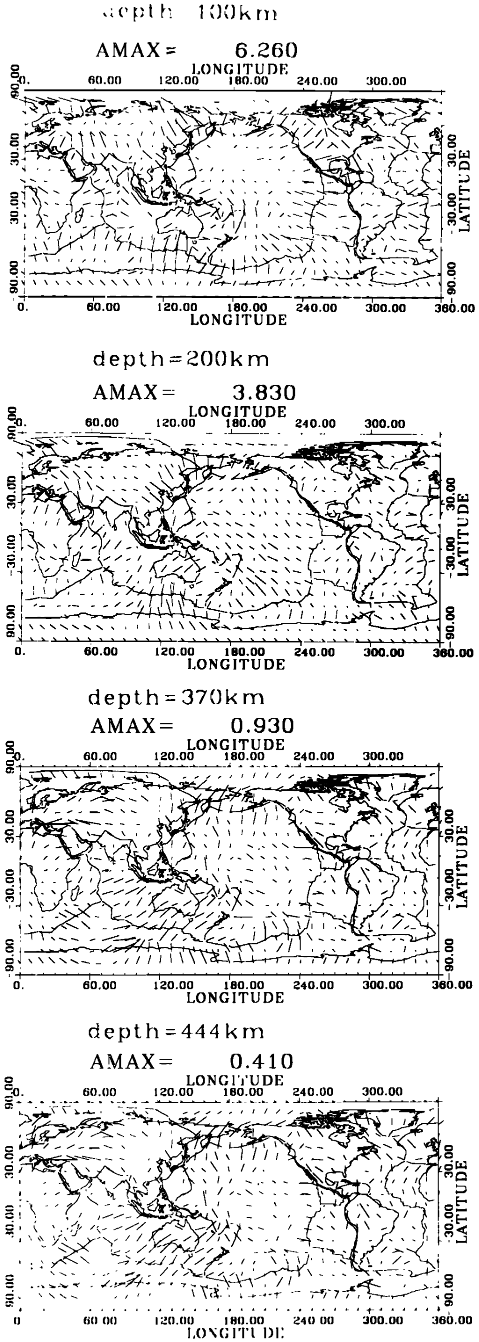
Tak Ho (Sh,ξ)



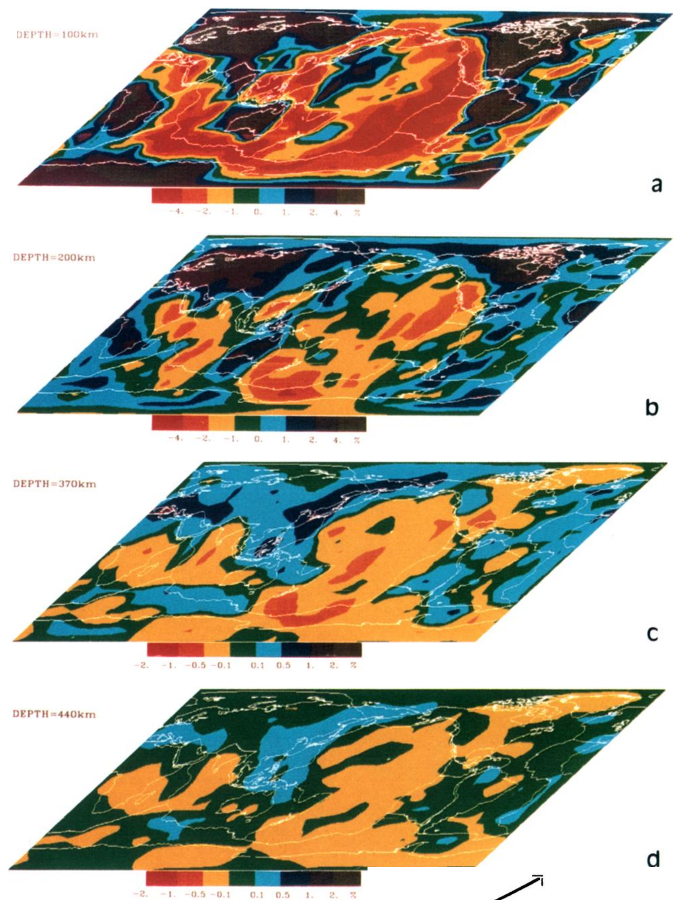
Keith Priestley (Sh,ξ)

UNIVERSITY OF CAMBRIDGE

Vsv azimuthal anisotropy

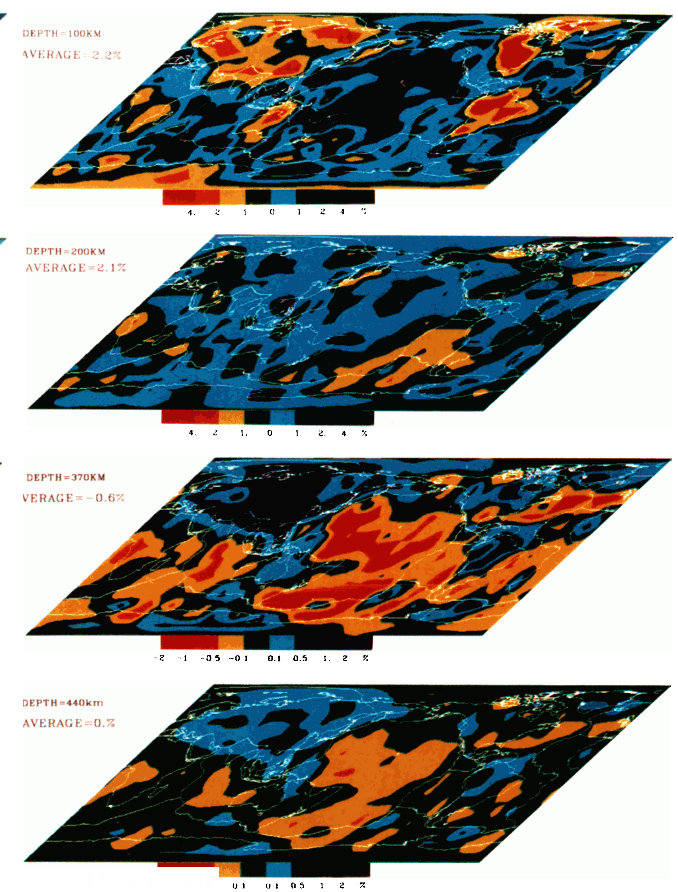


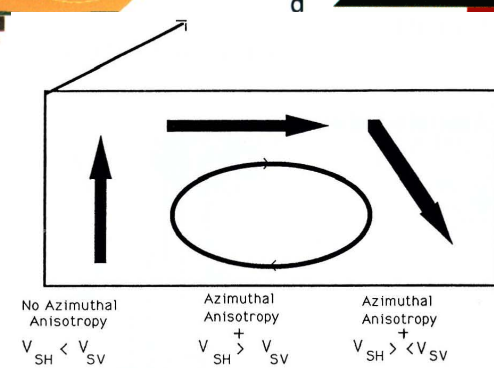
Vsv heterogeneities



Radial anisotropy

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

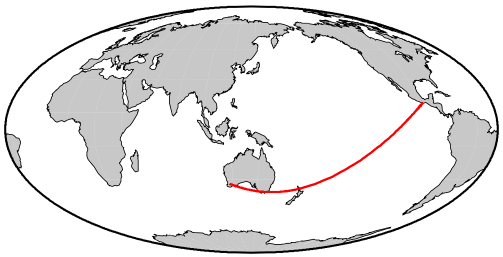


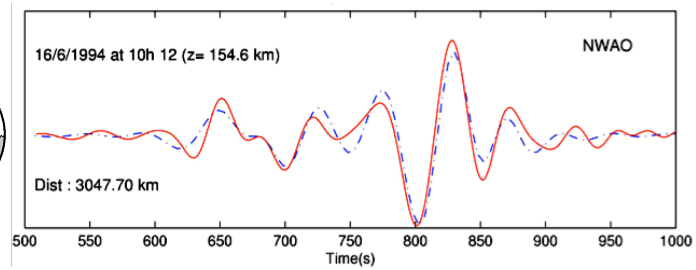


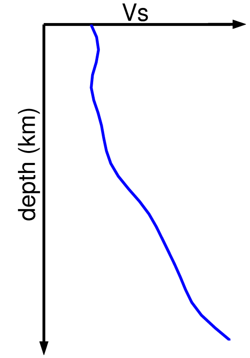
Montagner and Tanimoto , JGR 1991; Montagner, Rev. Geophys., 1994

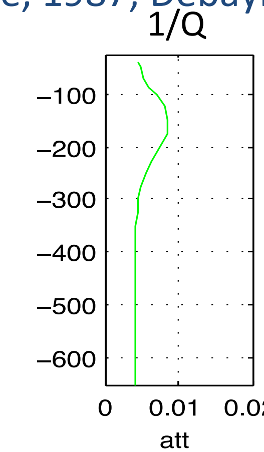
Building seismic models :

1) Automated waveform inversion applied to millions of waveforms (Cara and Lévêque, 1987; Debayle and Ricard 2012, 2016). Period range : 50 -250 s



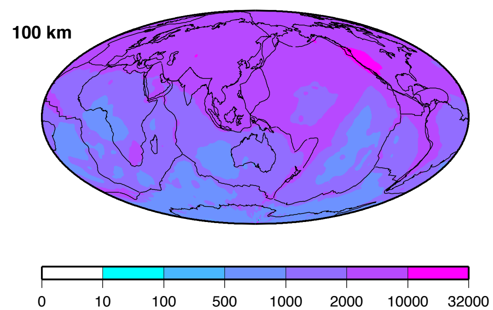




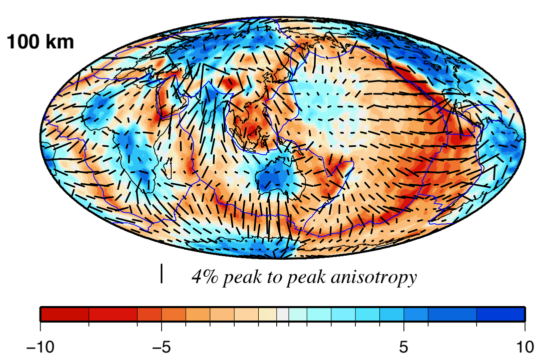


2) Tomographic inversion (Debayle and Sambridge 2004).

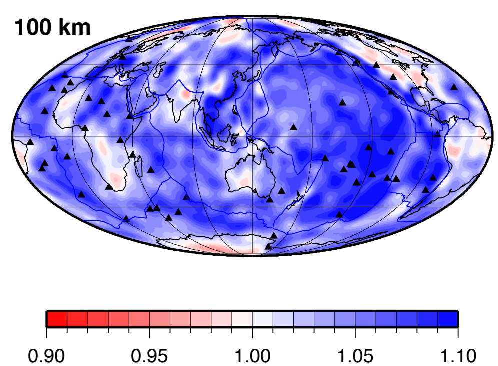
Ray density map



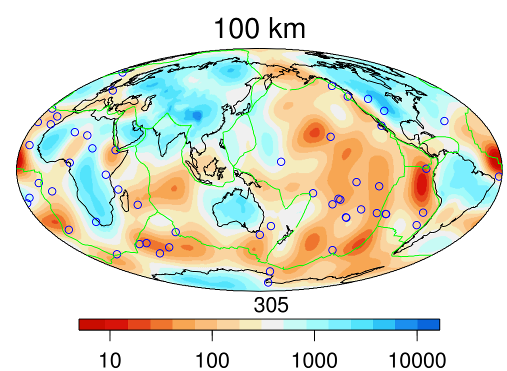
Sv velocity and azimuthal anisotropy



Radial anisotropy



S Quality factor model



3D2016_03Sv : an automatically updated Sv-wave model of the upper mantle

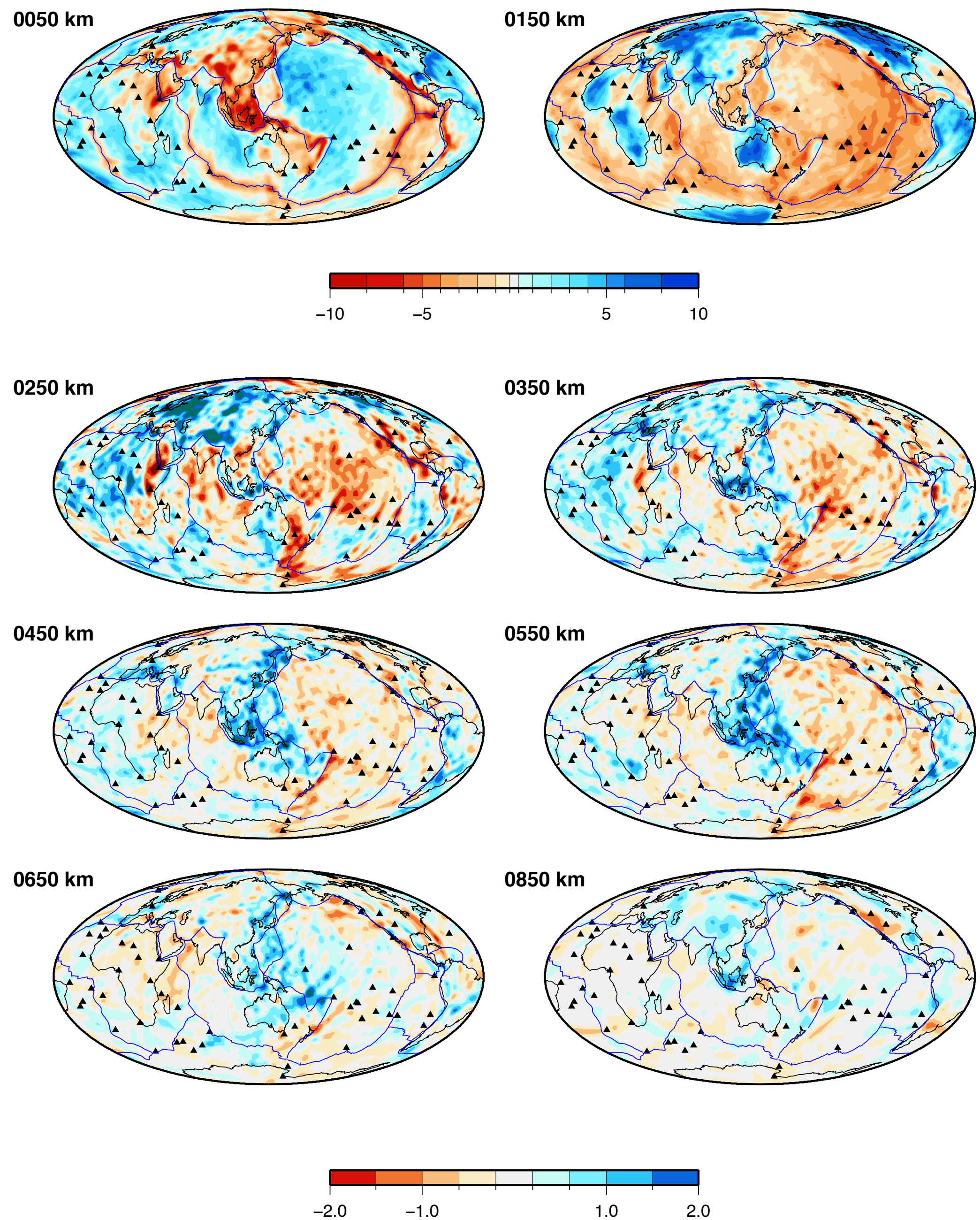
(Debayle et al., GRL, 2016)

- 3D2016_03SV : SV-wave model updated up to March 2016
- 1,391,400 Rayleigh waveforms
- Includes azimuthal anisotropy
- Updated every three months following publication of the CMT catalog
- Updated model available at :

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

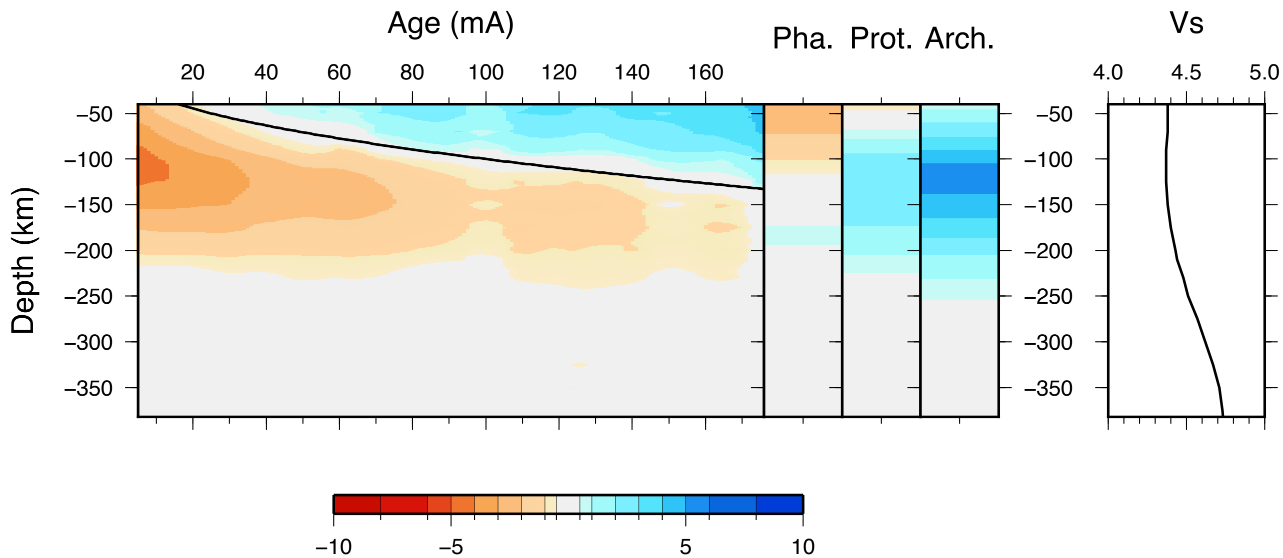
Or as a IRIS data product at

http://ds.iris.edu/ds/products/emc-3d2016_03sv/

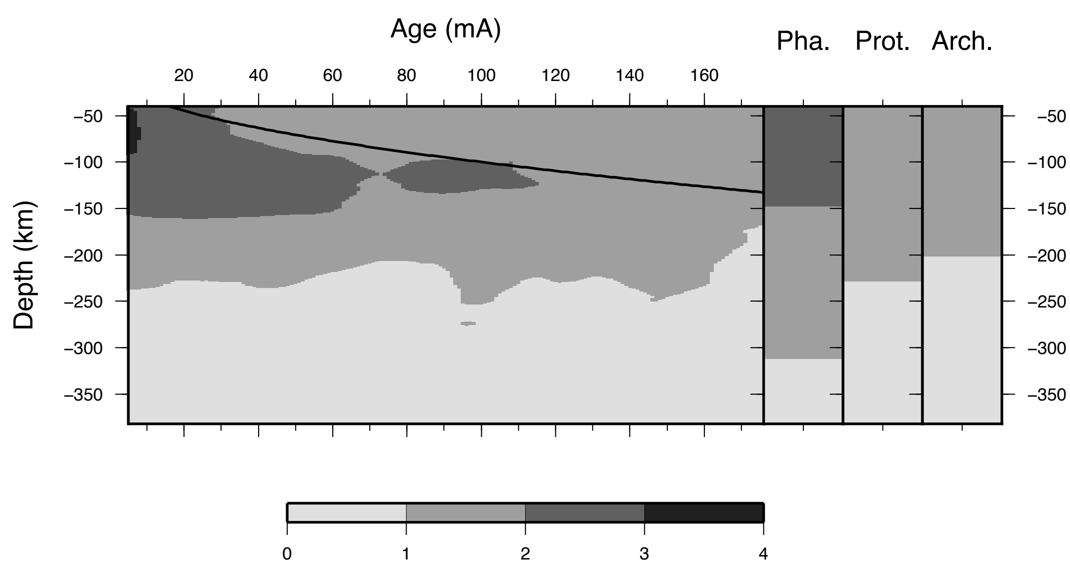


3D2016_03Sv : cross-sections with respect to age

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

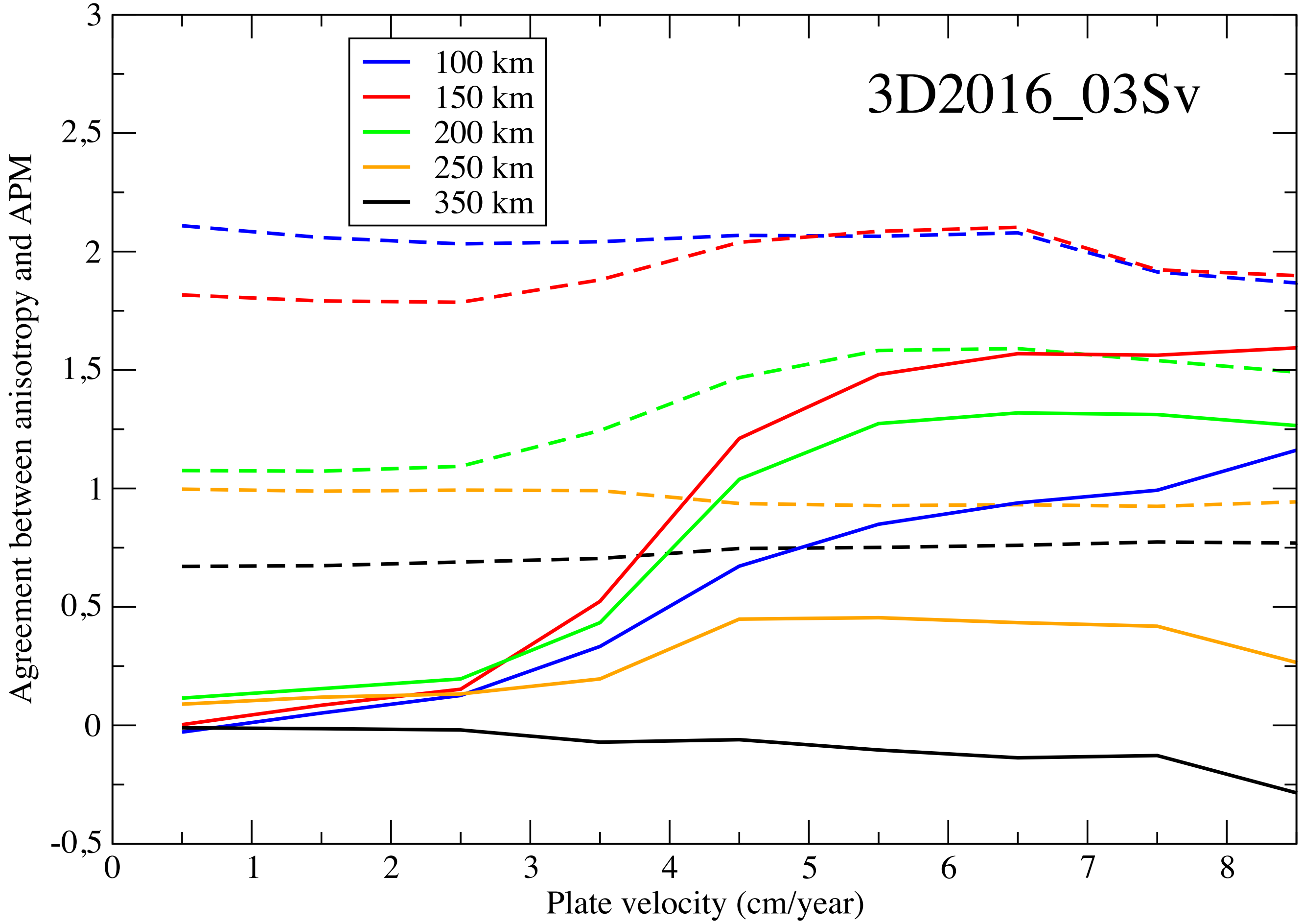


Strength of azimuthal anisotropy (Debayle et al., 2016) :



Azimuthal Anisotropy versus plate velocity

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



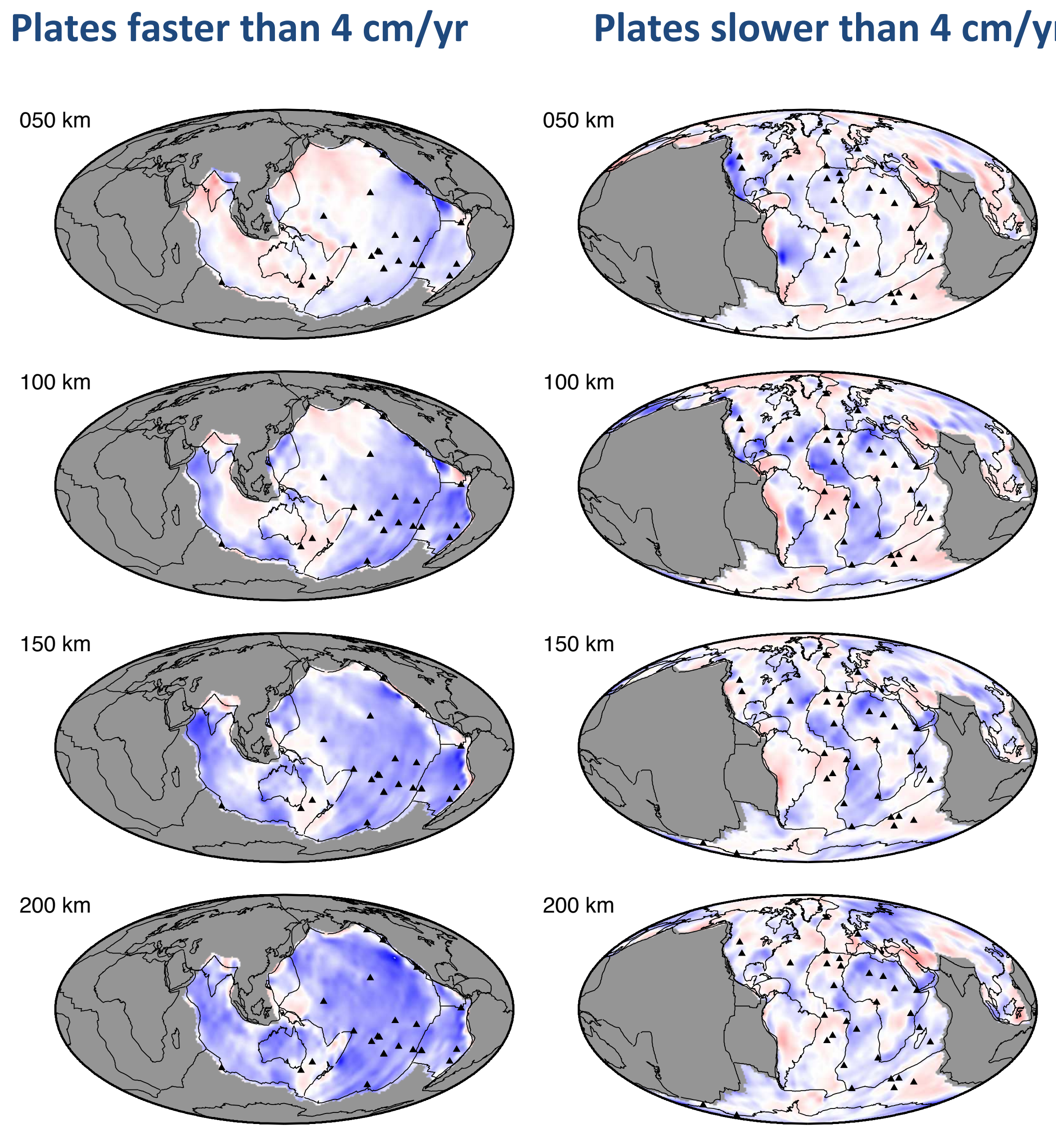
"only plates moving faster than about 4 cm/year can produce sufficient shearing at their base to organize the asthenospheric anisotropy at the scale of the entire tectonic plates"

Debayle and Ricard, EPSL, 2013

Agreement between anisotropy and APM (50-200 km)

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

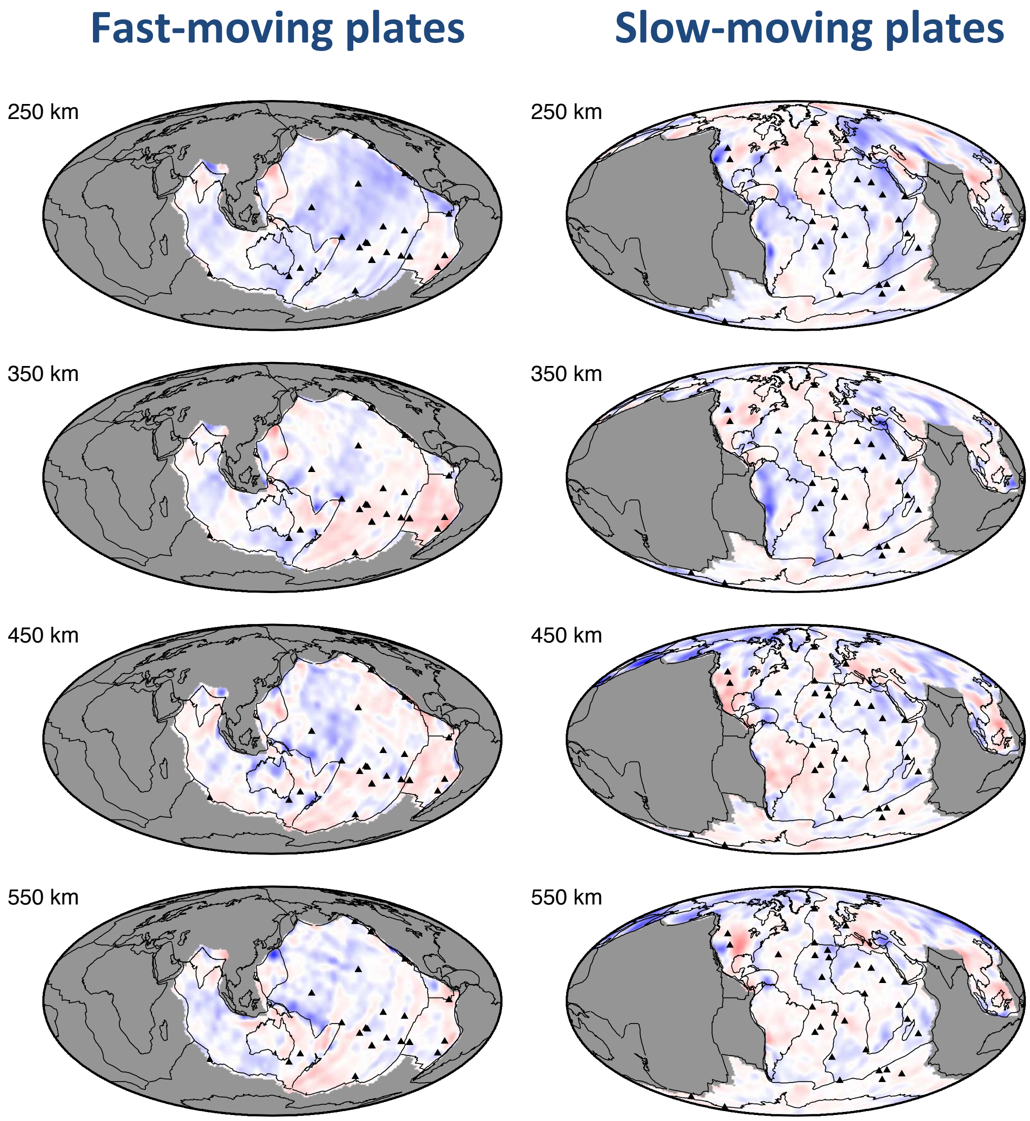
- *G* : anisotropy strength
- θ : angular difference between APM and fast anisotropic direction
- Blue : strong agreement, θ <45 °, G large.
- red: poor agreement, θ >45 °, G large.



Agreement between anisotropy and APM (250-550 km)

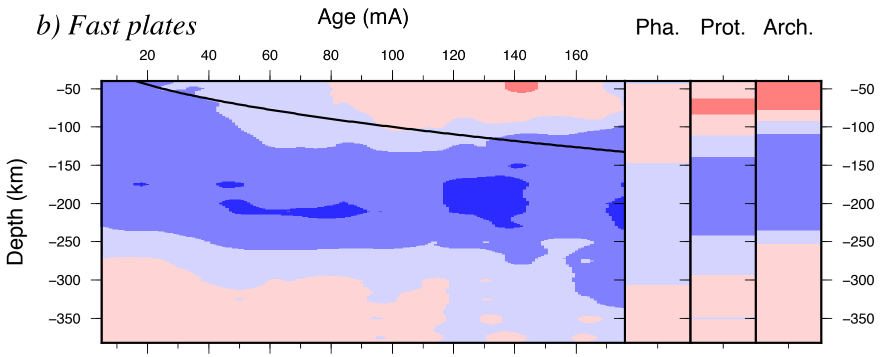
$$G.\cos(2\theta)$$

- *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.

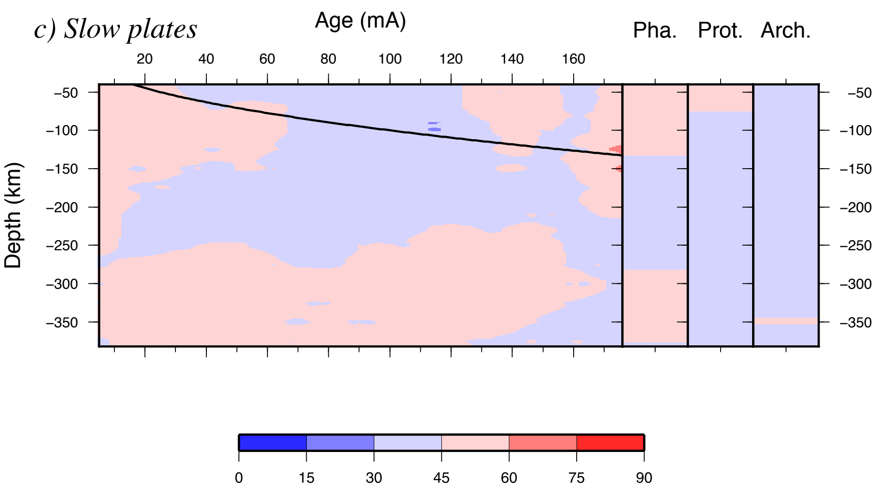


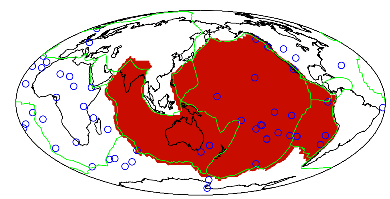
Angular difference between anisotropy directions and APM

Fast-moving plates



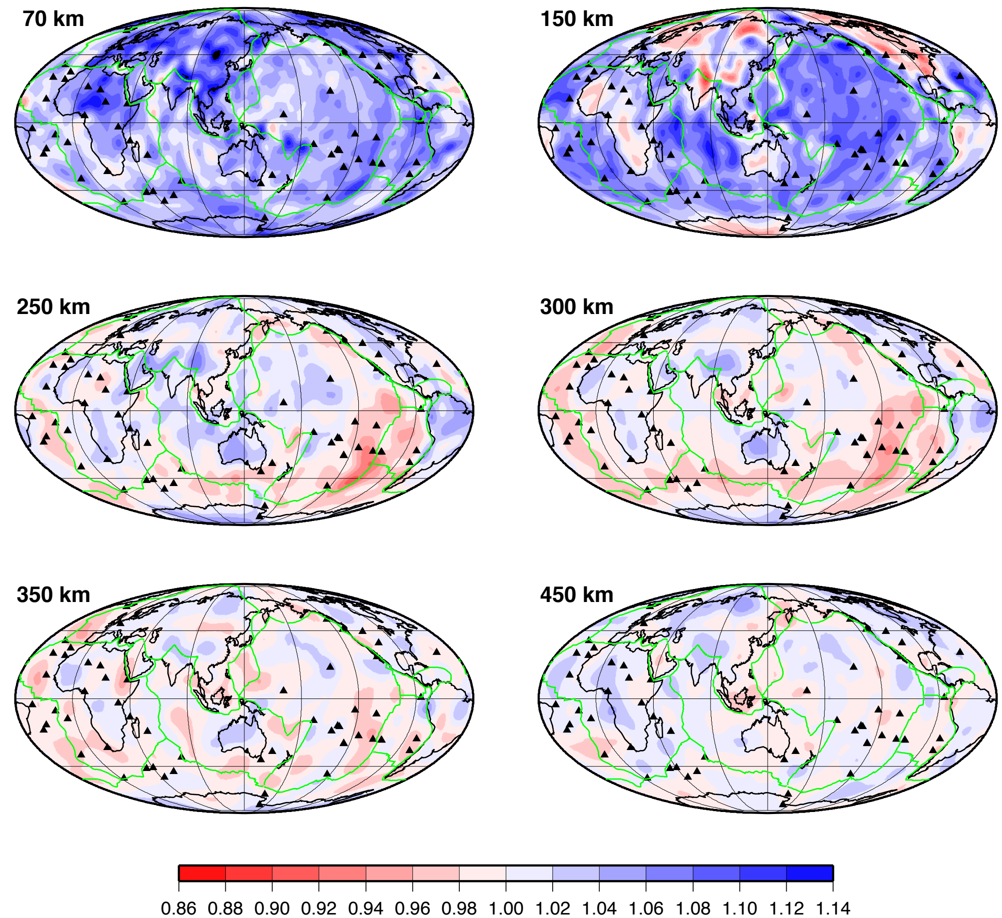
Slow-moving plates



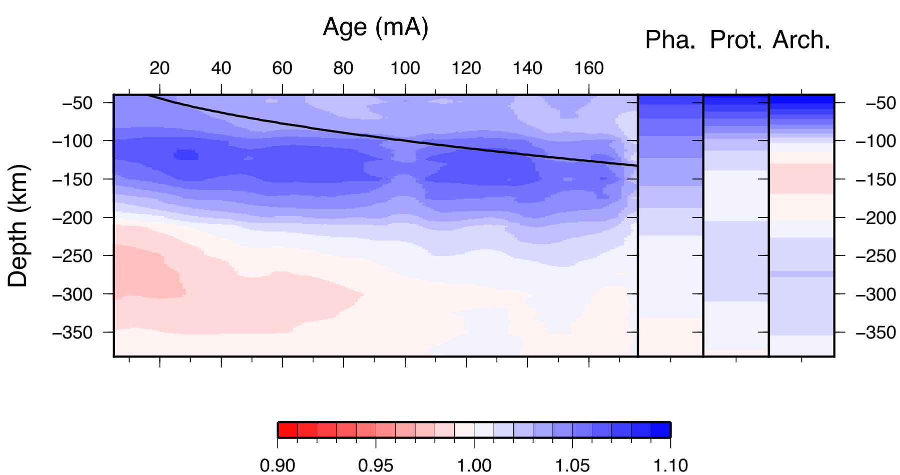


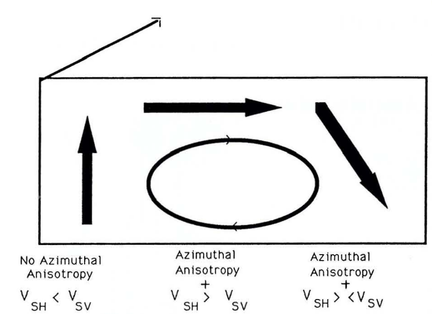
Radial anisotropy model
$\xi = (Vsh/Vsv)^2$
(Ho et al., in prep.)

- 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





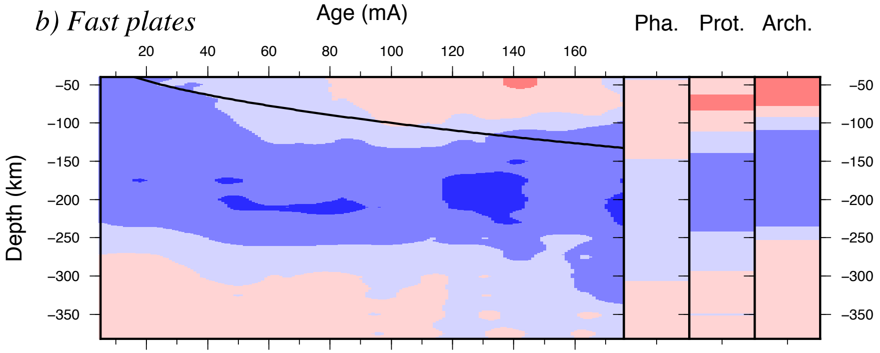
Ho et al., in prep

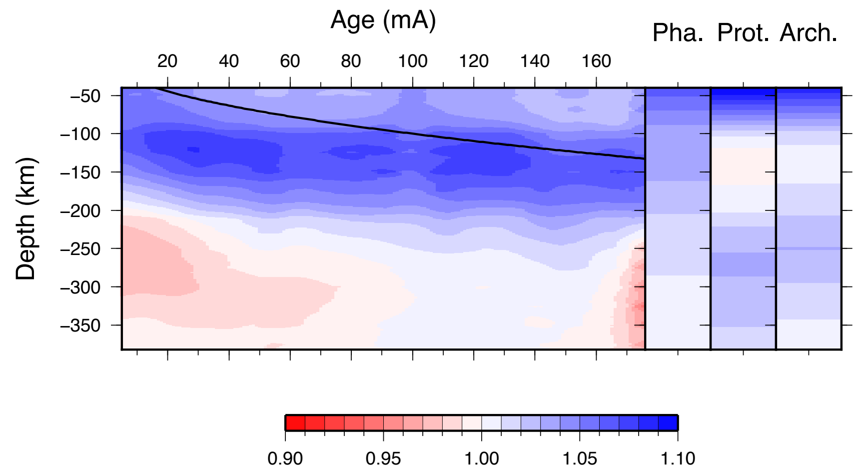
Azimuthal and radial anisotropy versus age

Azimuthal anisotropy (angular difference between anisotropy directions and APM)

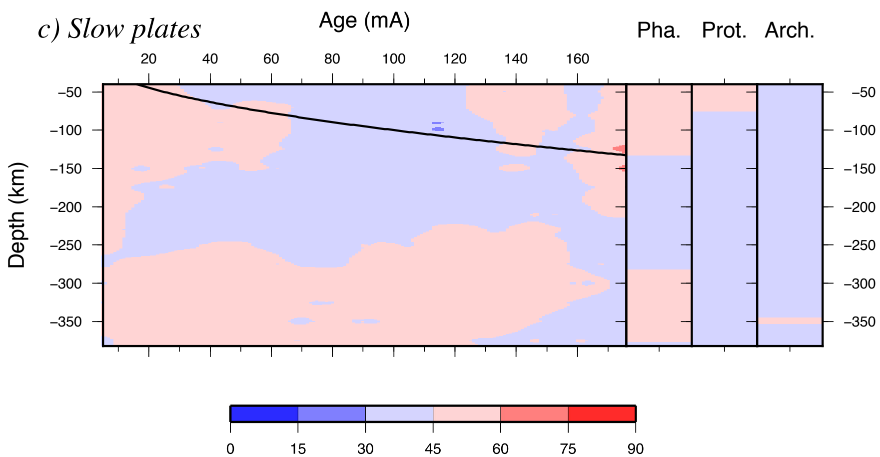
Radial anisotropy
$\xi = (Vsh/Vsv)^2$

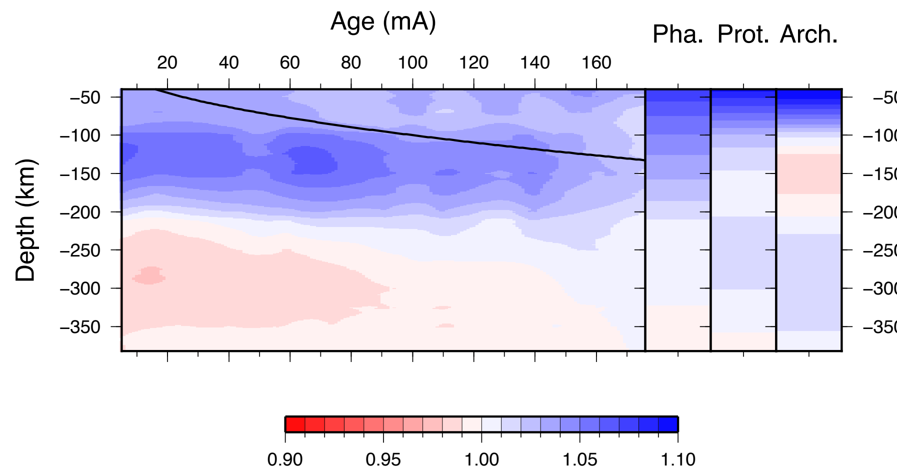
Fast-moving plates



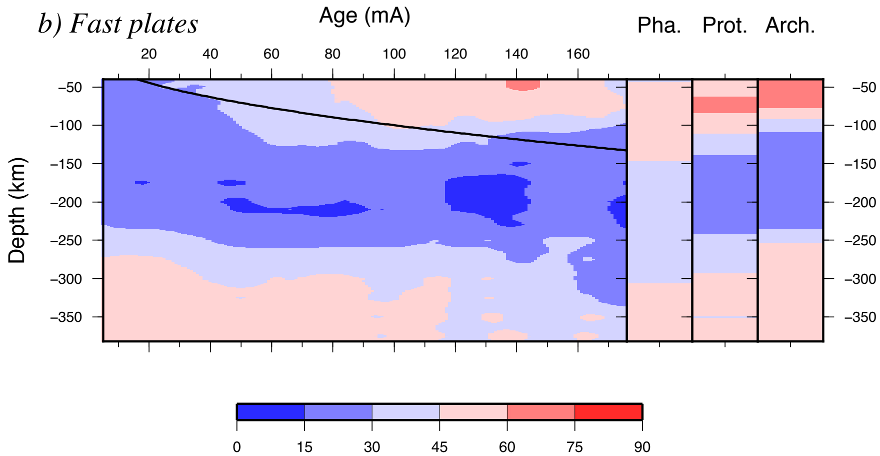


Slow-moving plates

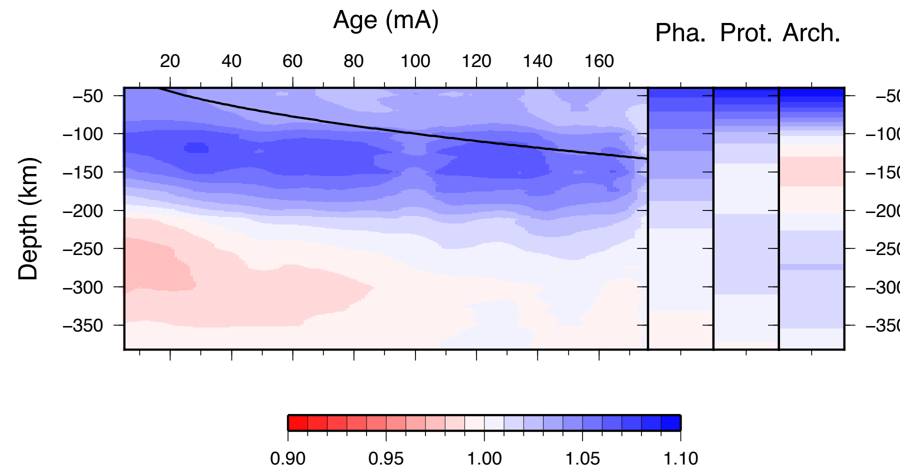




Azimuthal anisotropy



Radial anisotropy



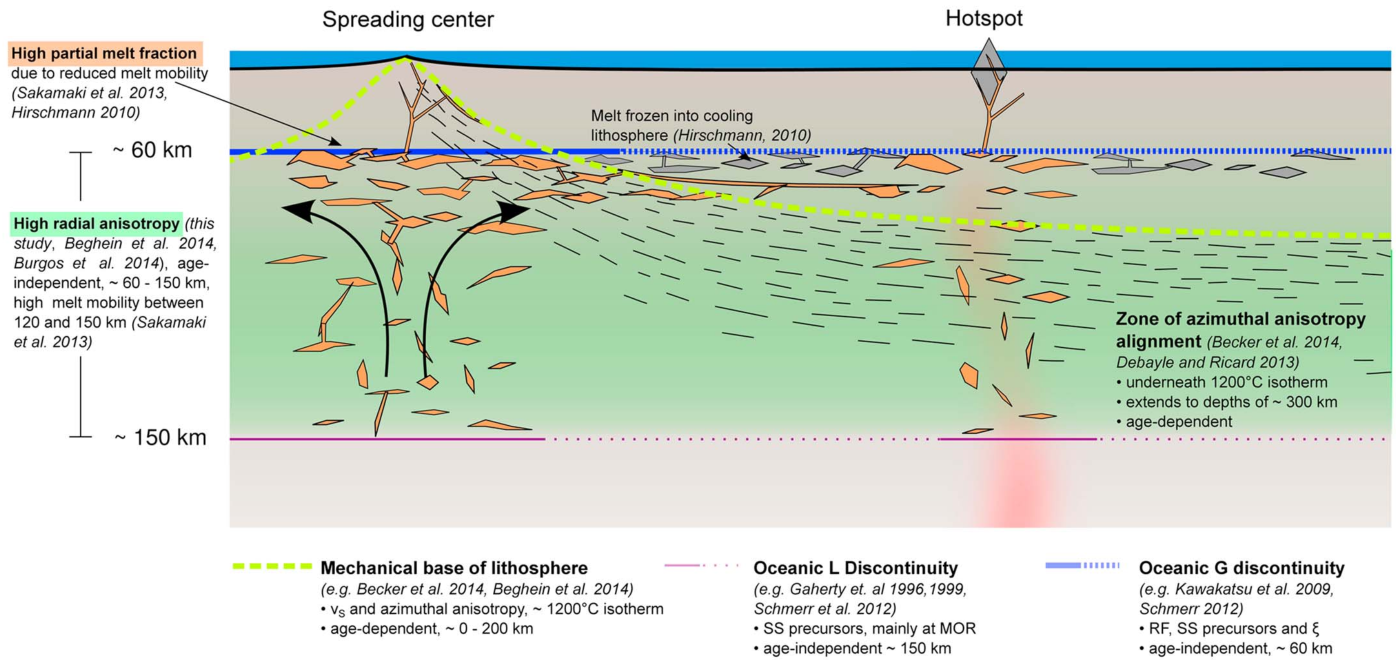
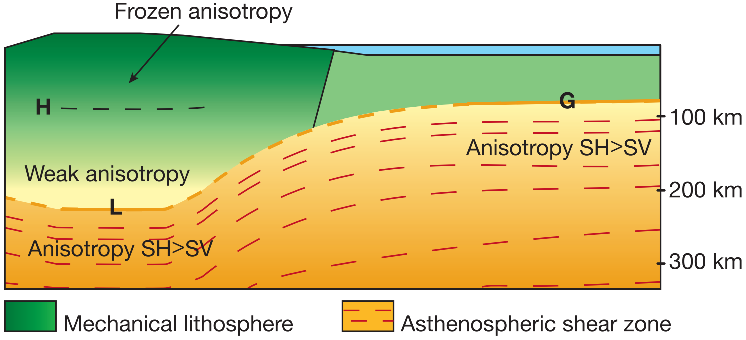


Figure 4. Conceptual model of anisotropy and upper mantle seismic discontinuities in the lithosphere-asthenosphere system.

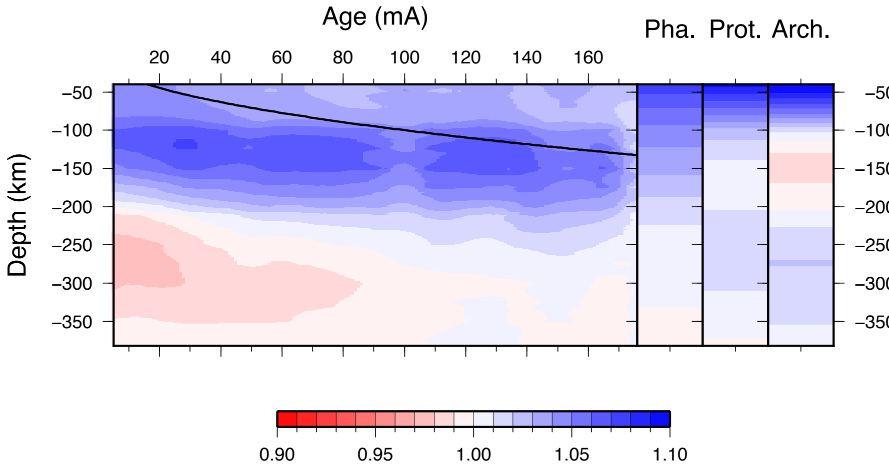
Auer et al., GRL, 2015

Depth extent of Anisotropy

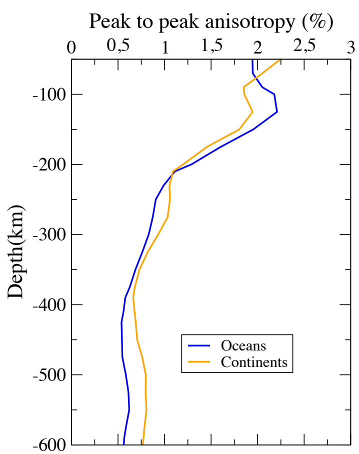
Gung and Romanowicz, 2003 (from radial anisotropy)



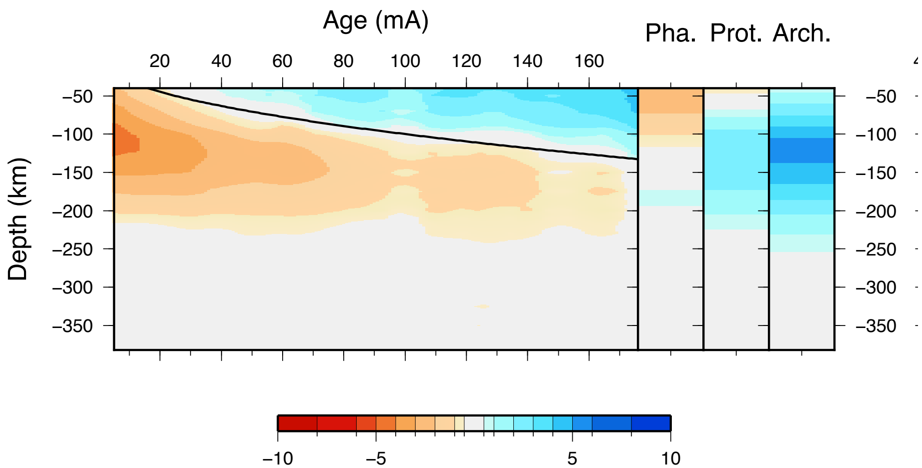
Radial anisotropy ($\xi=(Vsh/Vsv)^2$) (Ho et al., in prep)



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.

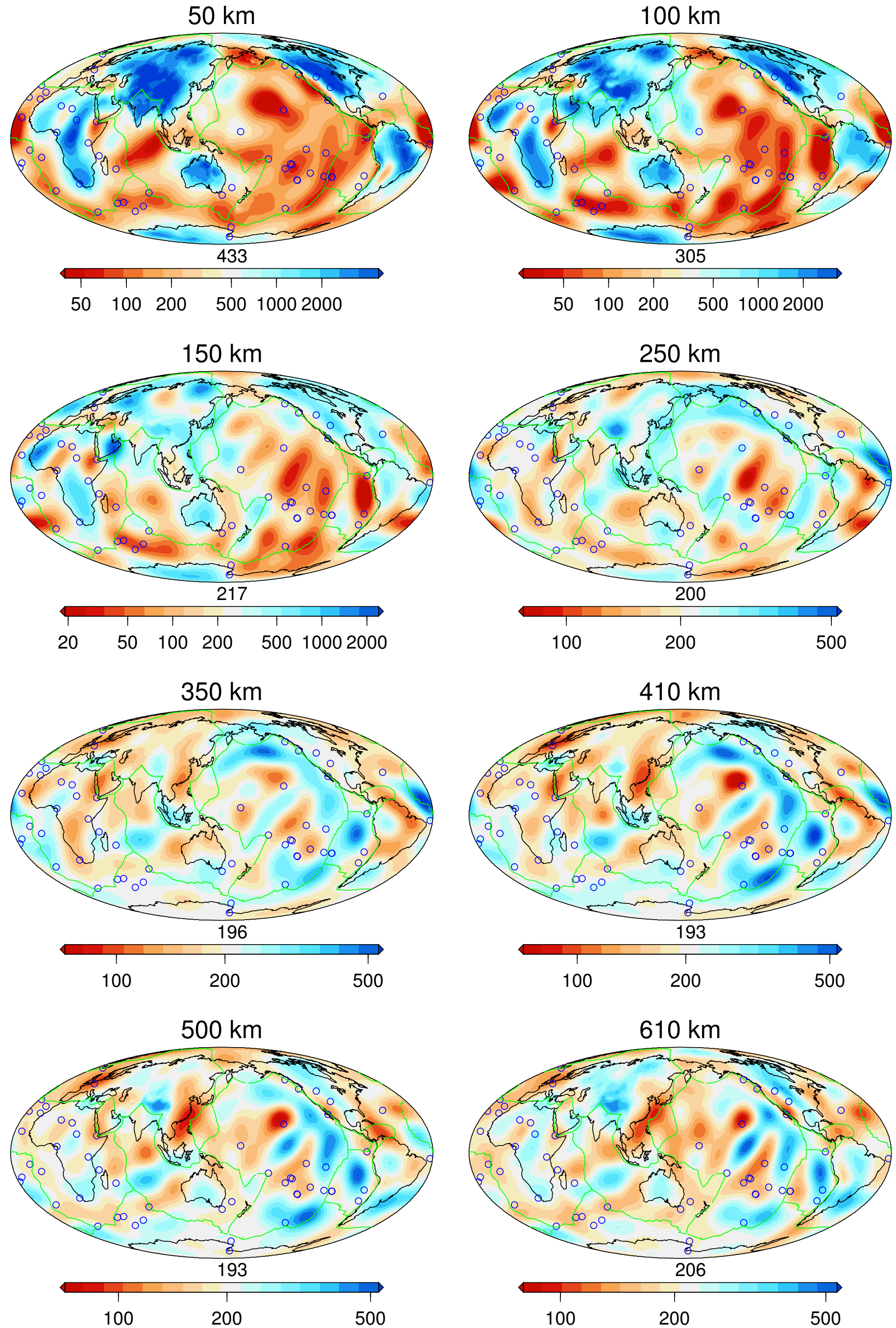
- Shape preferred orientation may explain the "flat" radial anisotropy beneath oceans.

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

S Quality factor model QsADR17

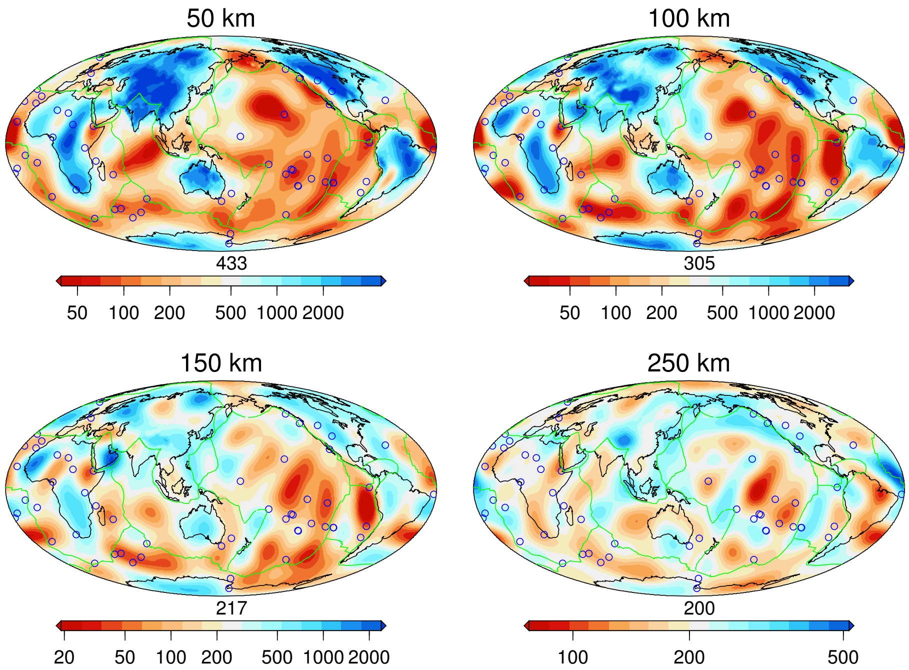
Adenis et al., in prep

- 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

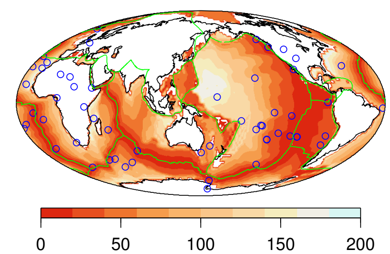


Adenis et al., in prep

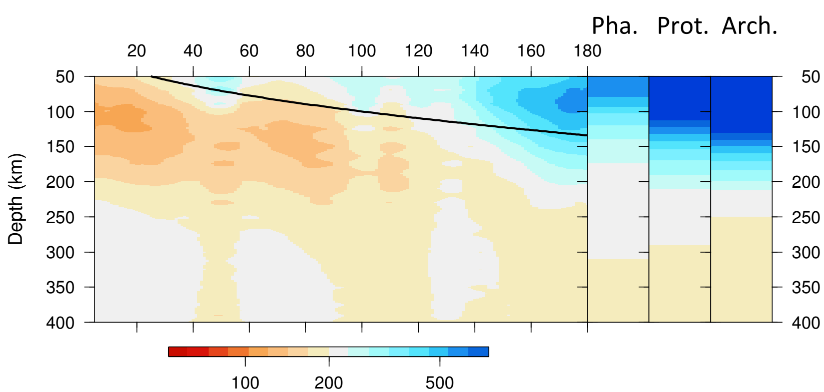
Quality factor model QsADR17



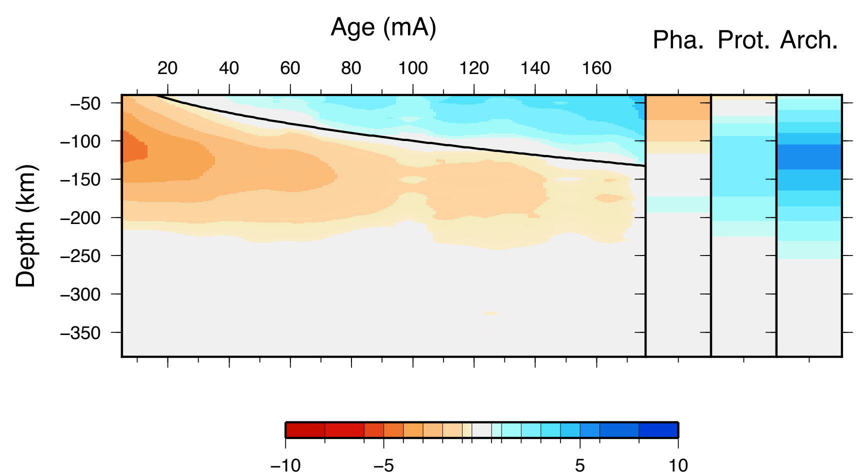
Age map



Q versus age

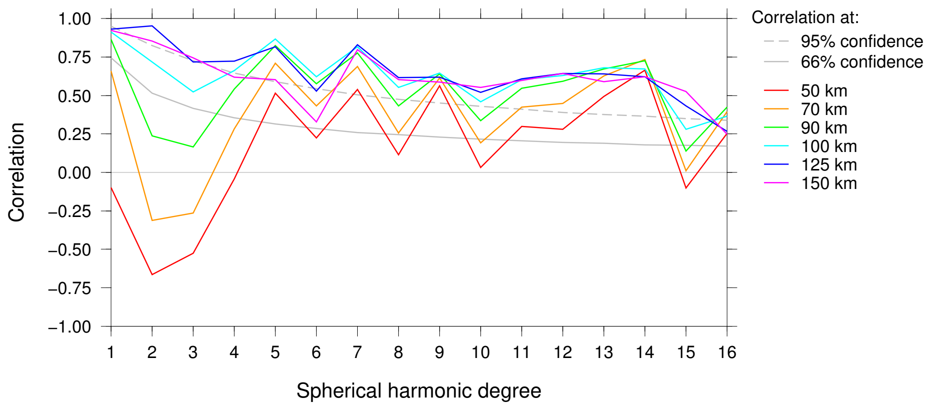


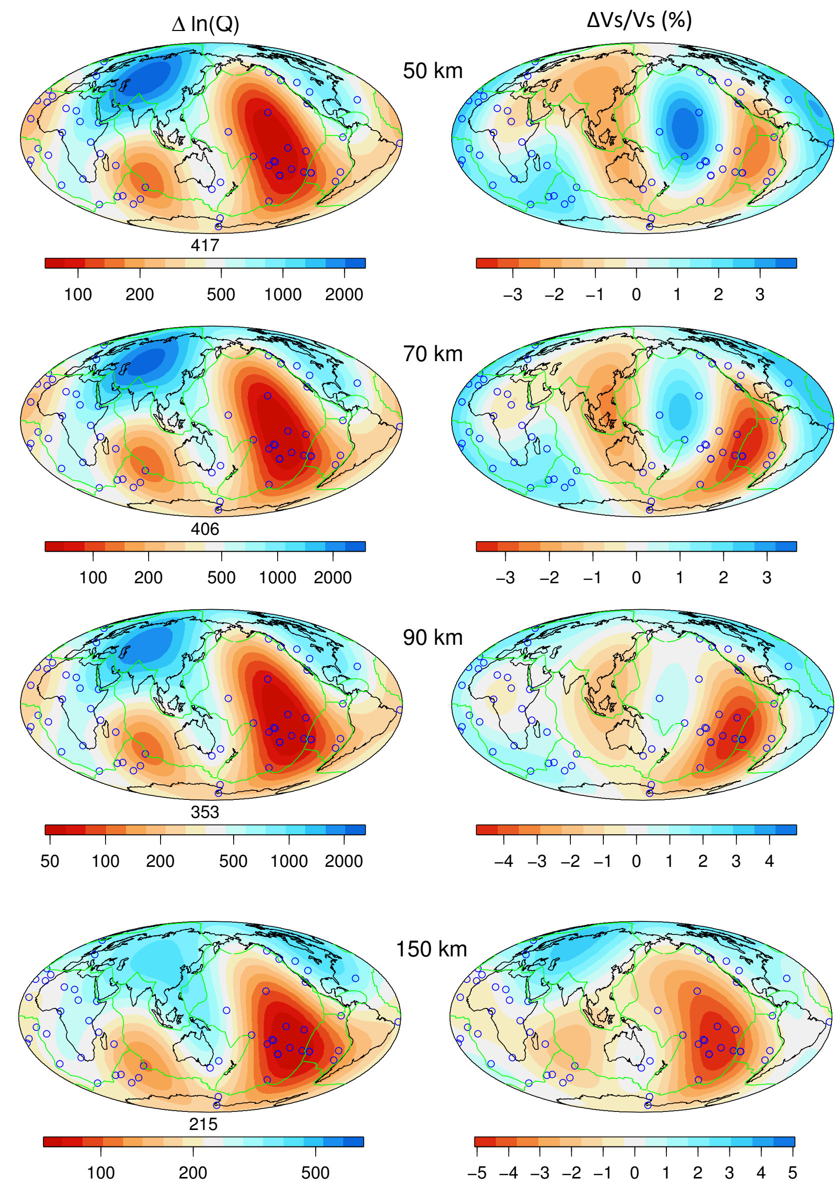
Vs versus age (3D2016_03Sv)



Adenis et al., in prep

Correlation between QsADR17 and S velocity (3D2016_07Sv)



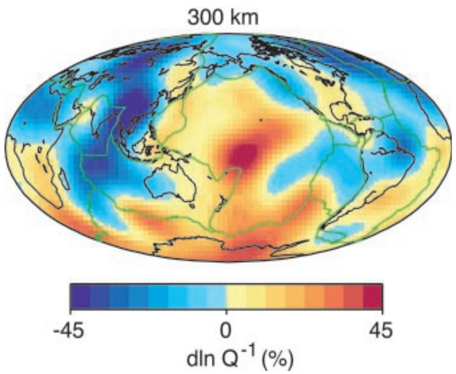


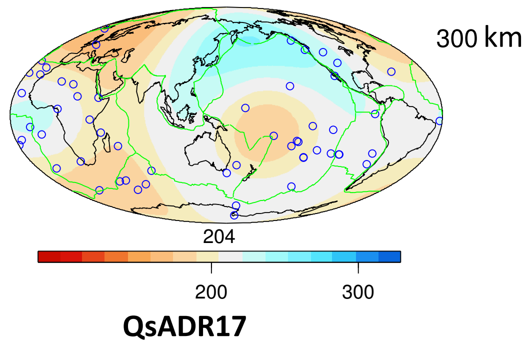
Adenis et al., in prep

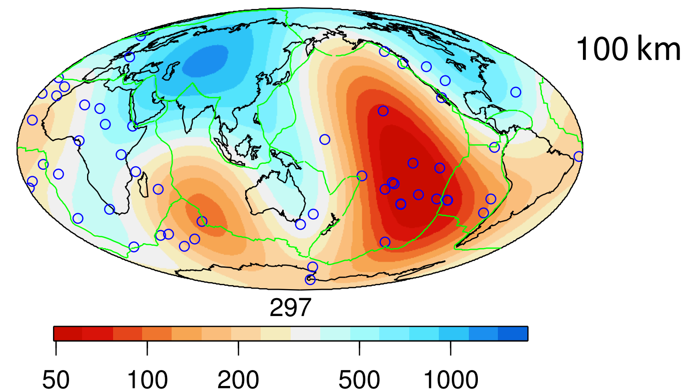
Attenuation and radial anisotropy in the Pacific Ocean

Attenuation :

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

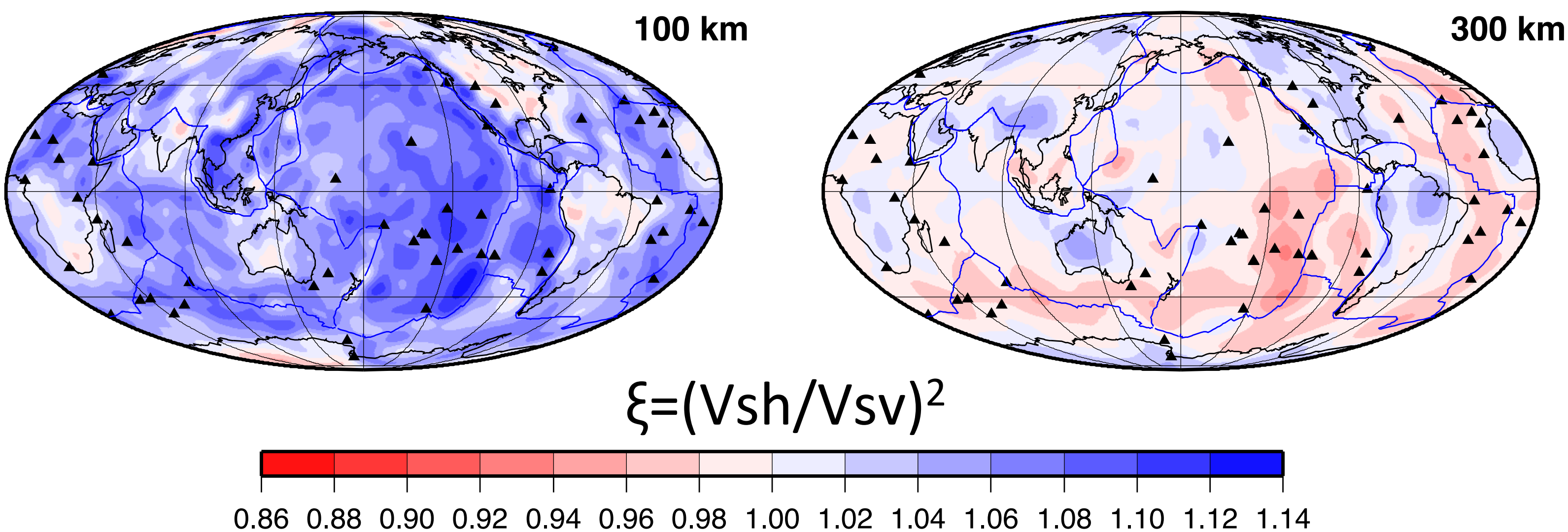






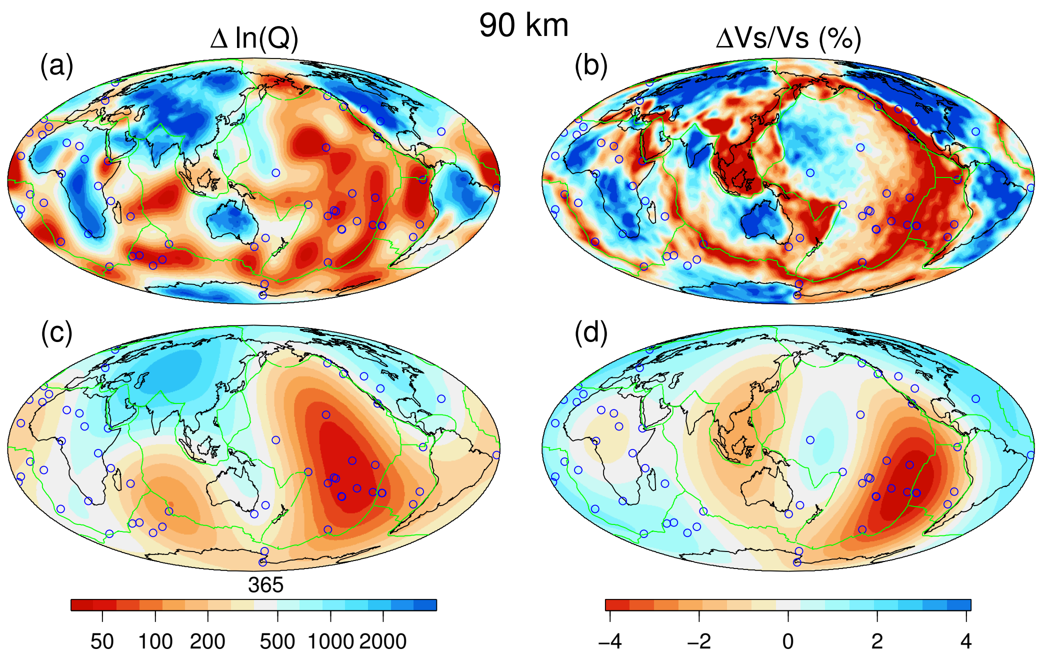
Thermal upwelling deflected horizontally beneath the lithosphere?

Radial anisotropy : Ho, Priestley and Debayle, to be submitted, 2016



Regions of reduced velocities and moderate or weak attenuation?

- If a significant amount of melt is present, it may reduce velocity without affecting attenuation (e.g. 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.

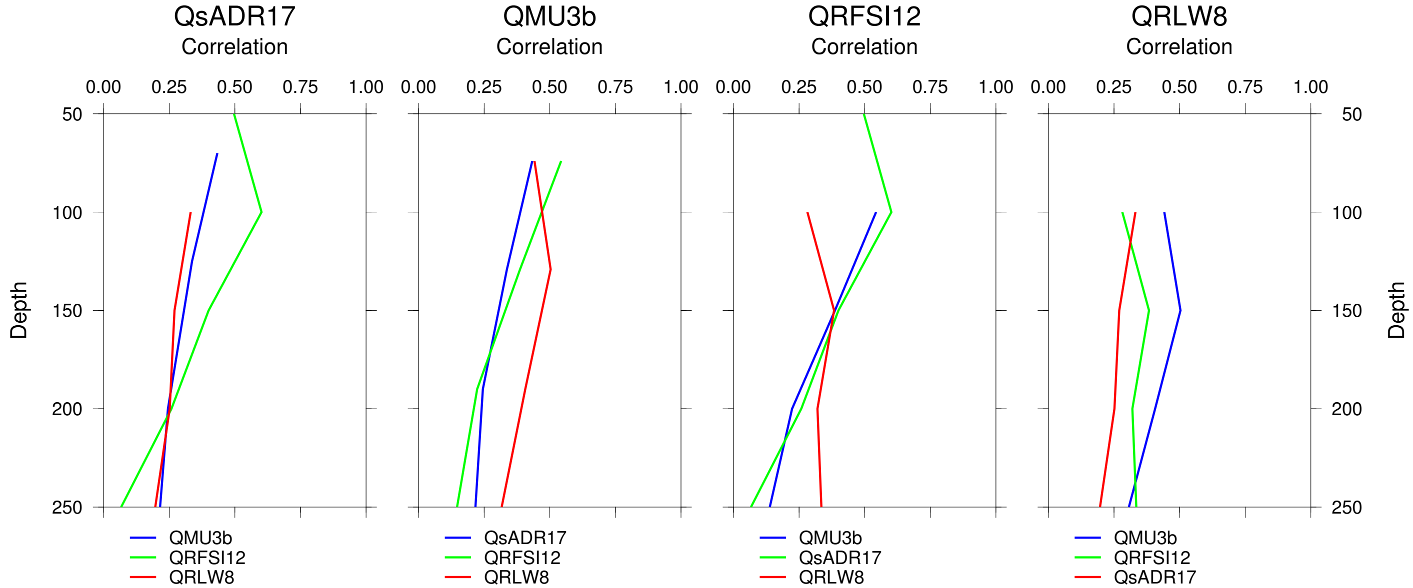


Summary attenuation :

- 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 EP,R as observed at a more local scale after the MELT experiment (Yang et al., 2007; Forsyth, et al., 1998).

Correlation between recent Q models



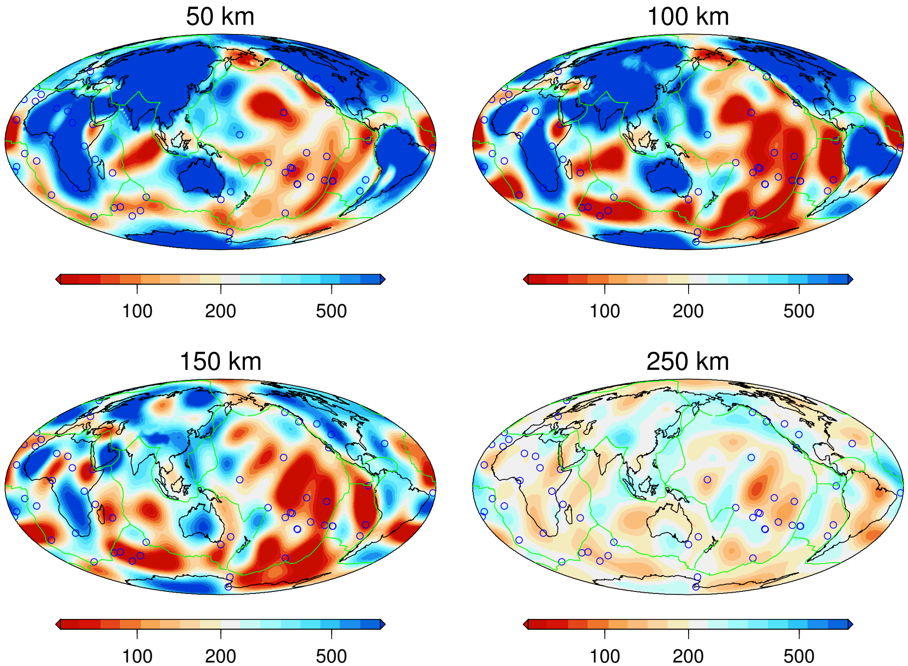
QsADR17 : this study

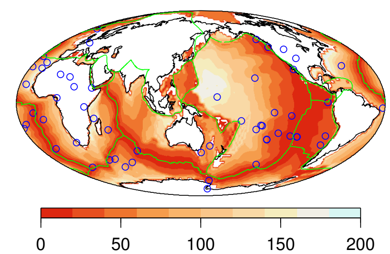
QMU3B : Selby and Woodhouse, JGR, 2002

QRFSI12 : Dalton et al., JGR, 2008

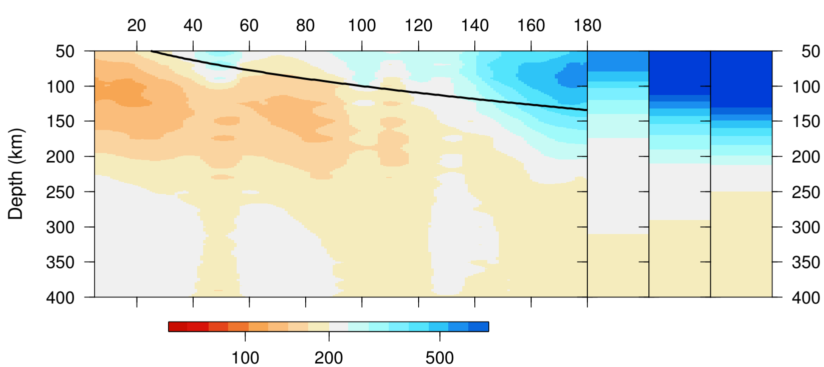
QRLW8 : Gung and Romanowicz, GJI, 2004

Quality factor model QsADR17

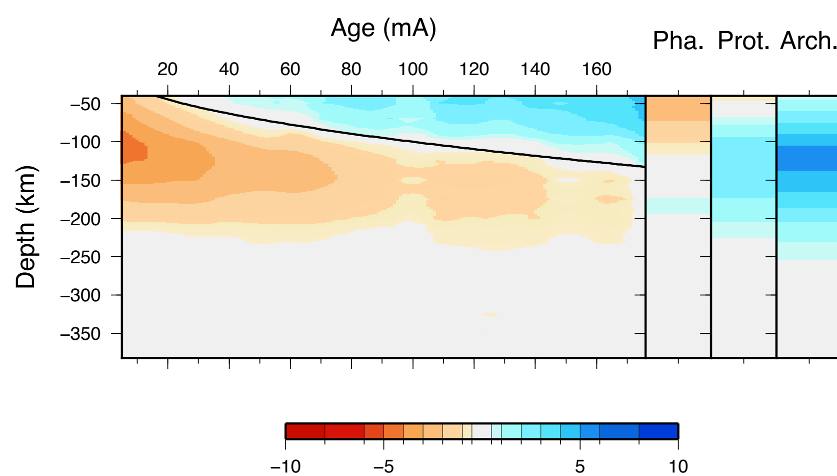




Q versus age

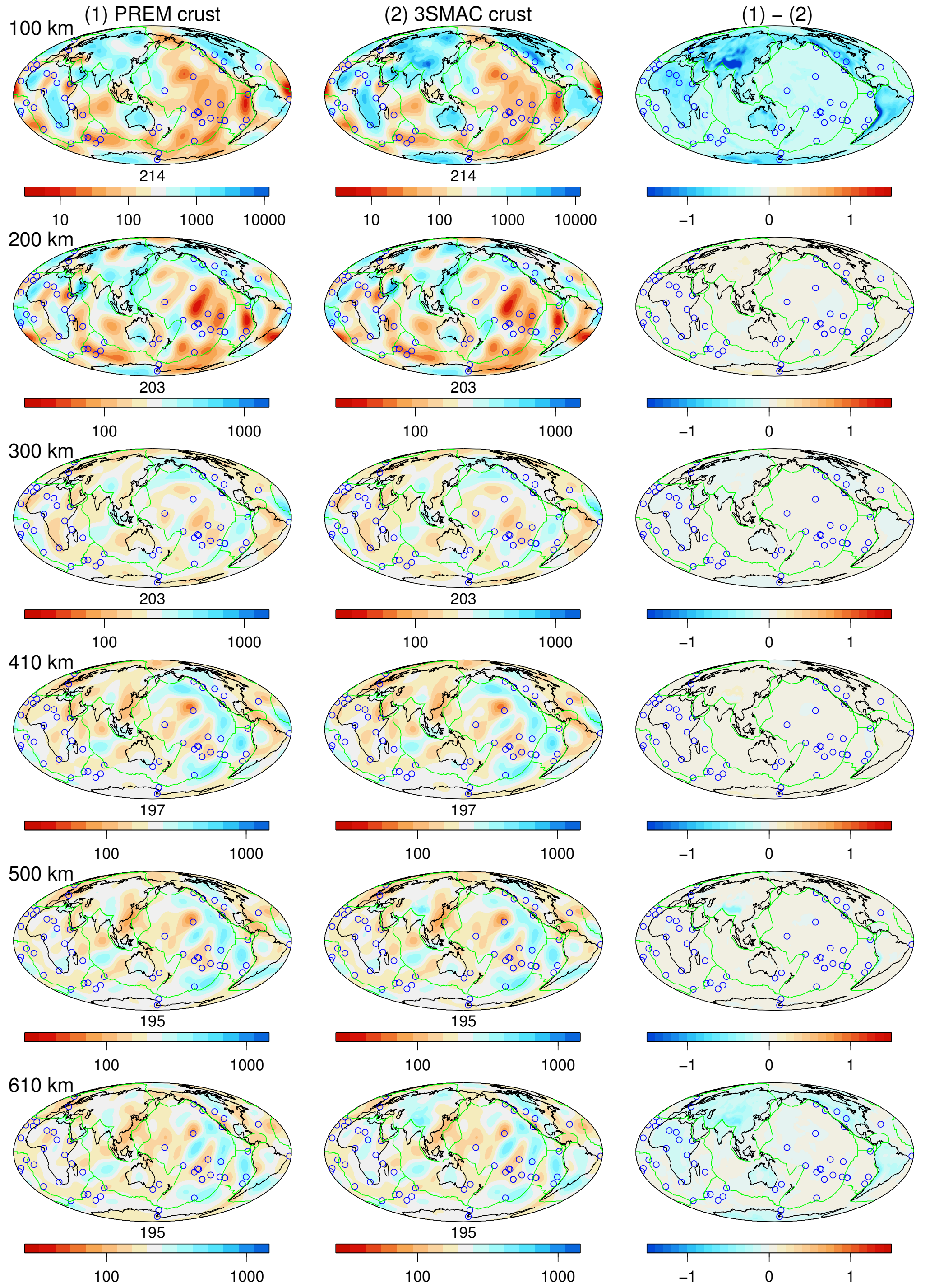


Vs versus age

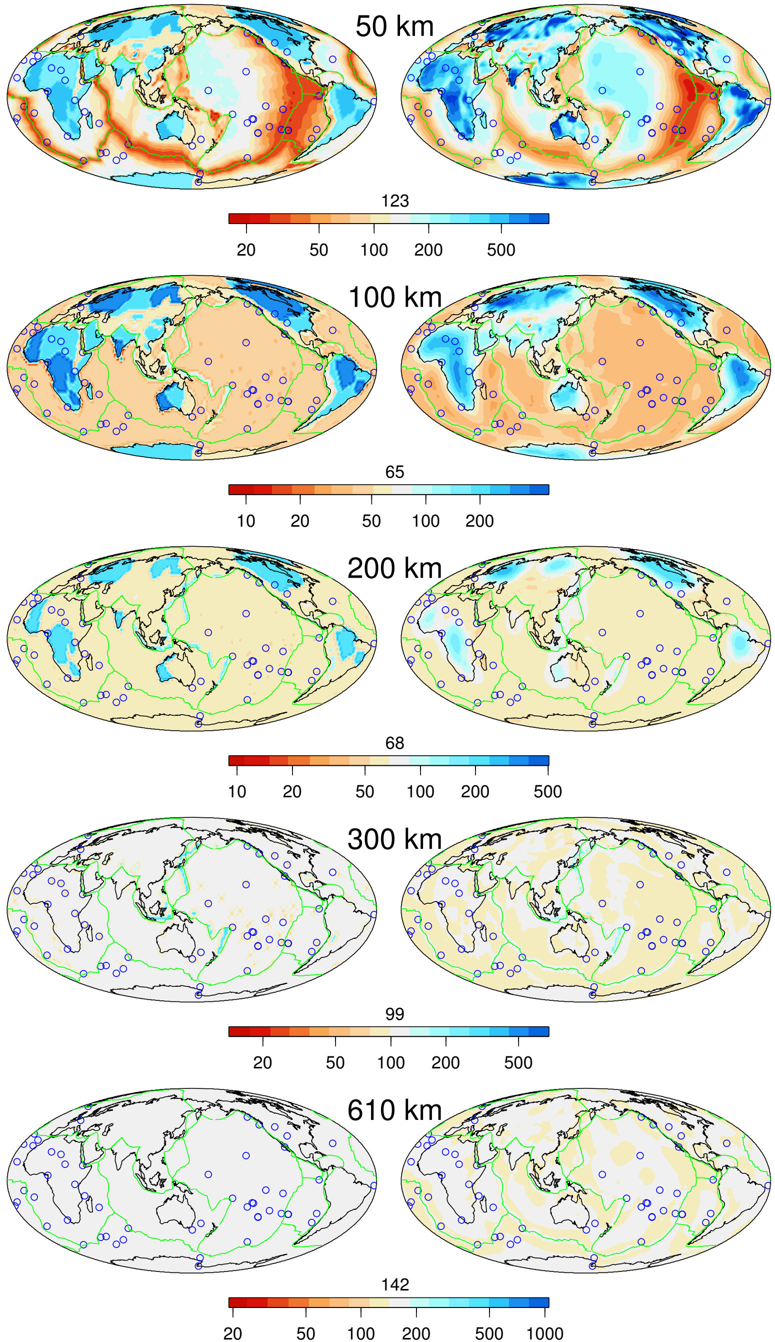


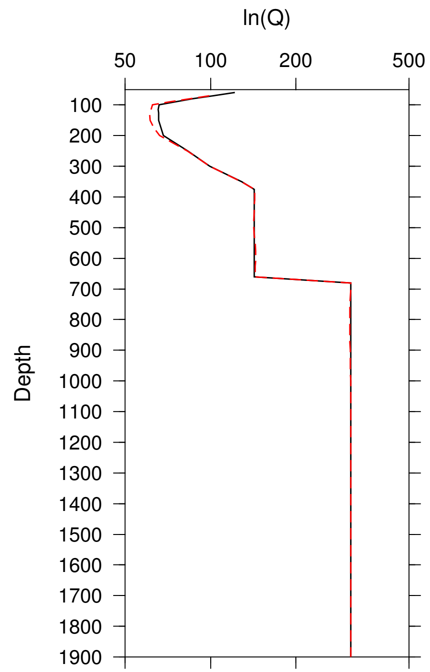
Adenis et al., in prep

Crustal effect on Q

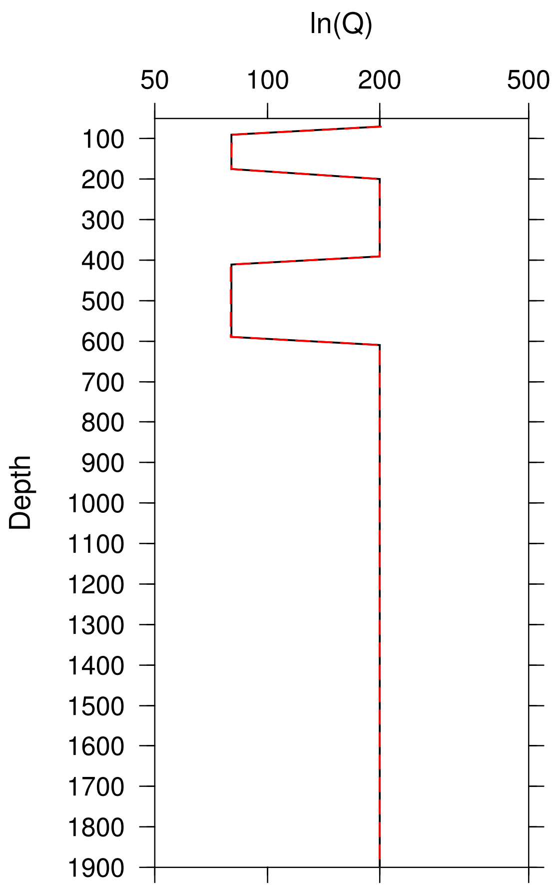


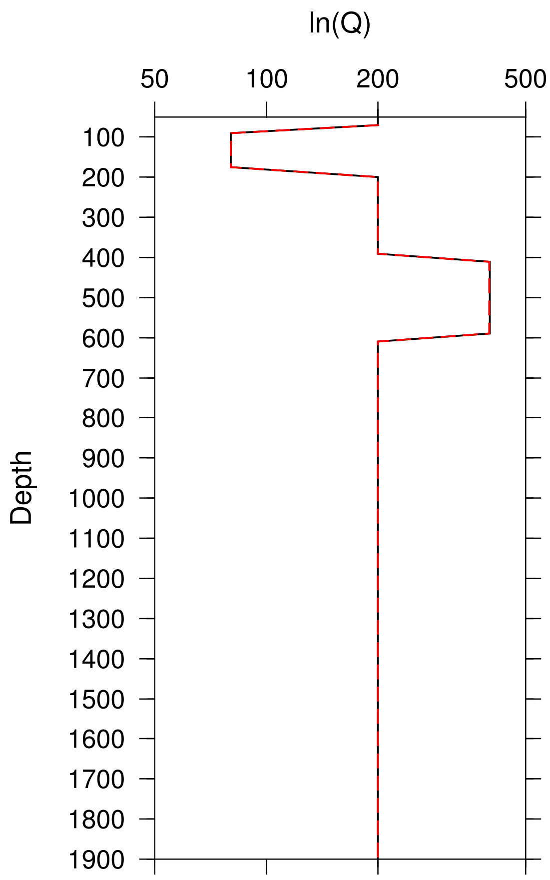
Synthetic tests for attenuation



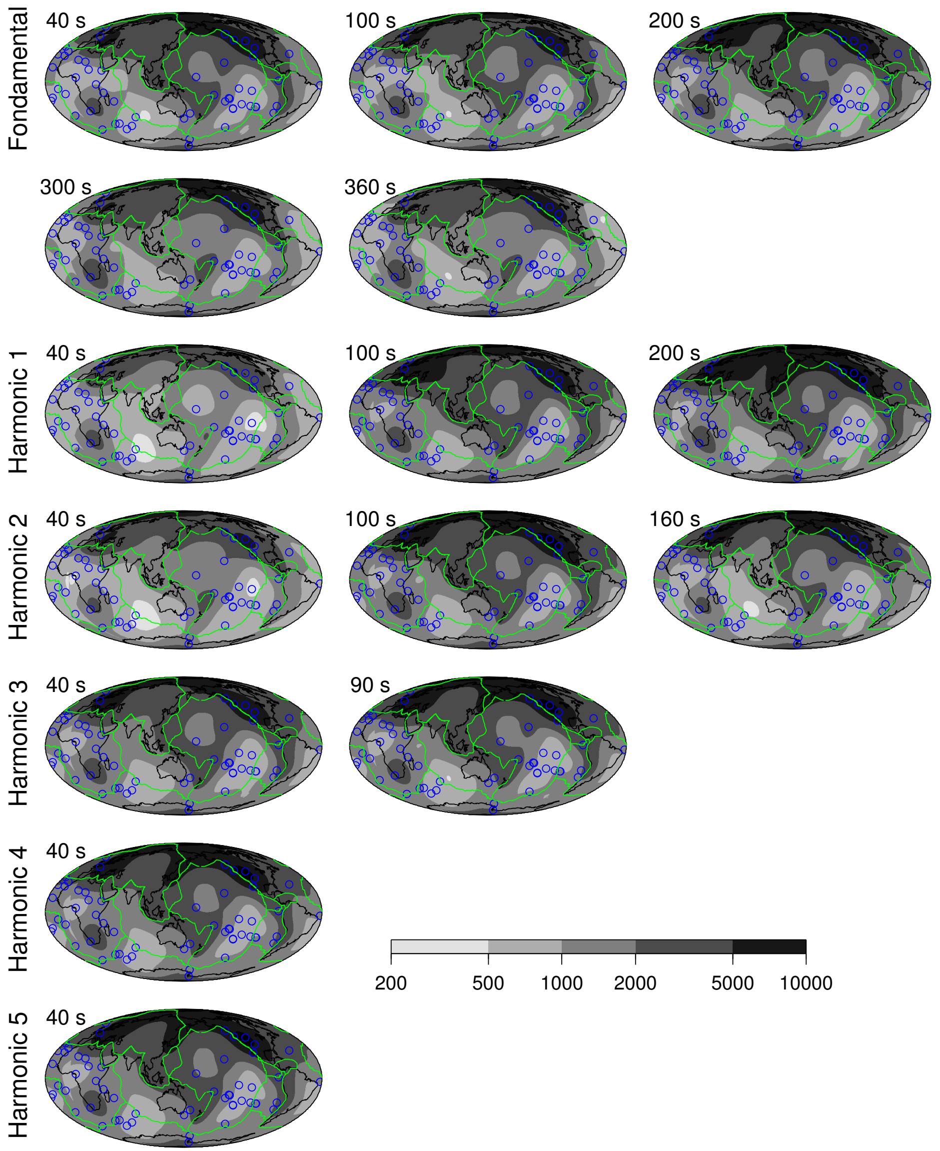


Synthetic tests for attenuation



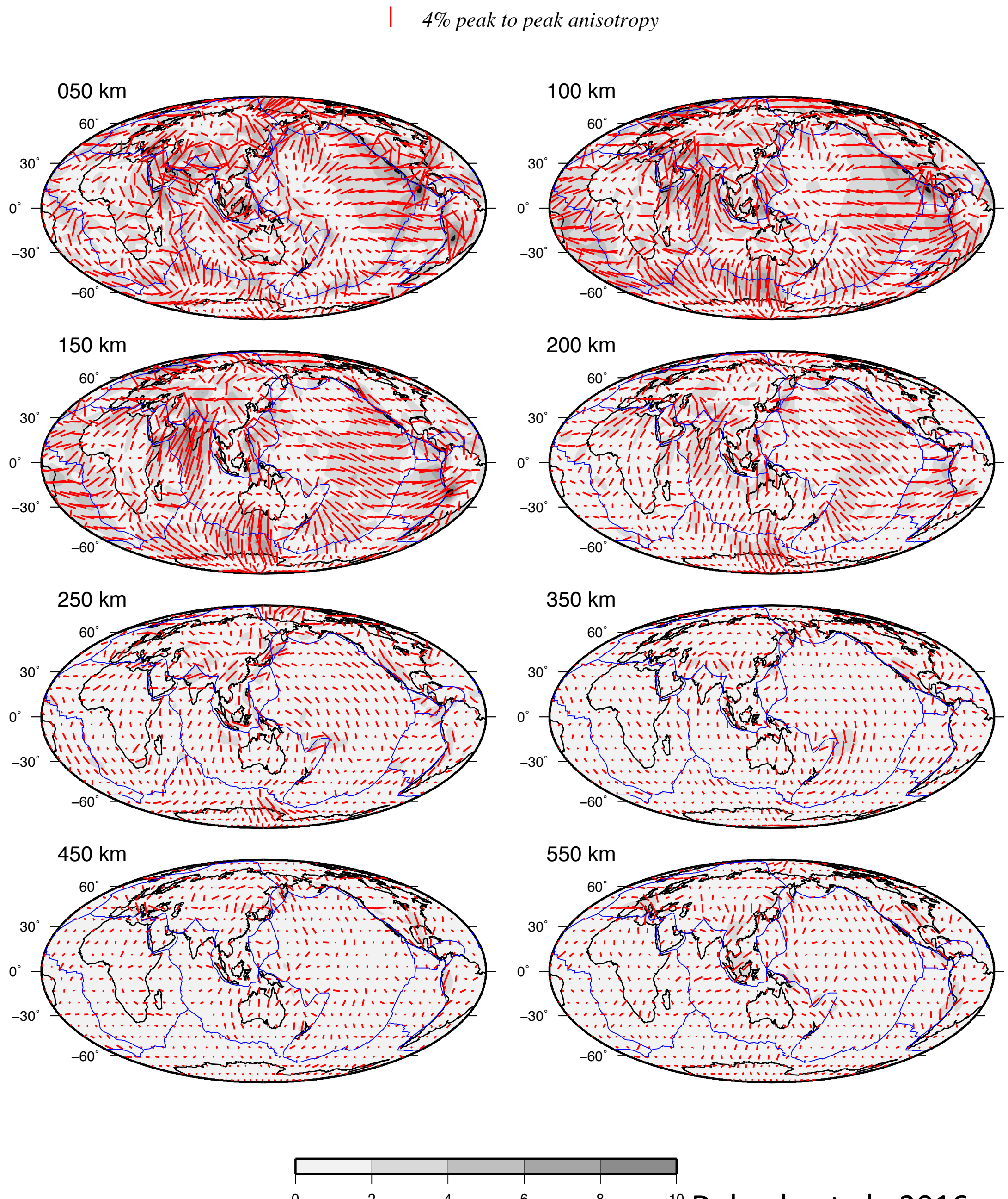


Ray density for attenuation



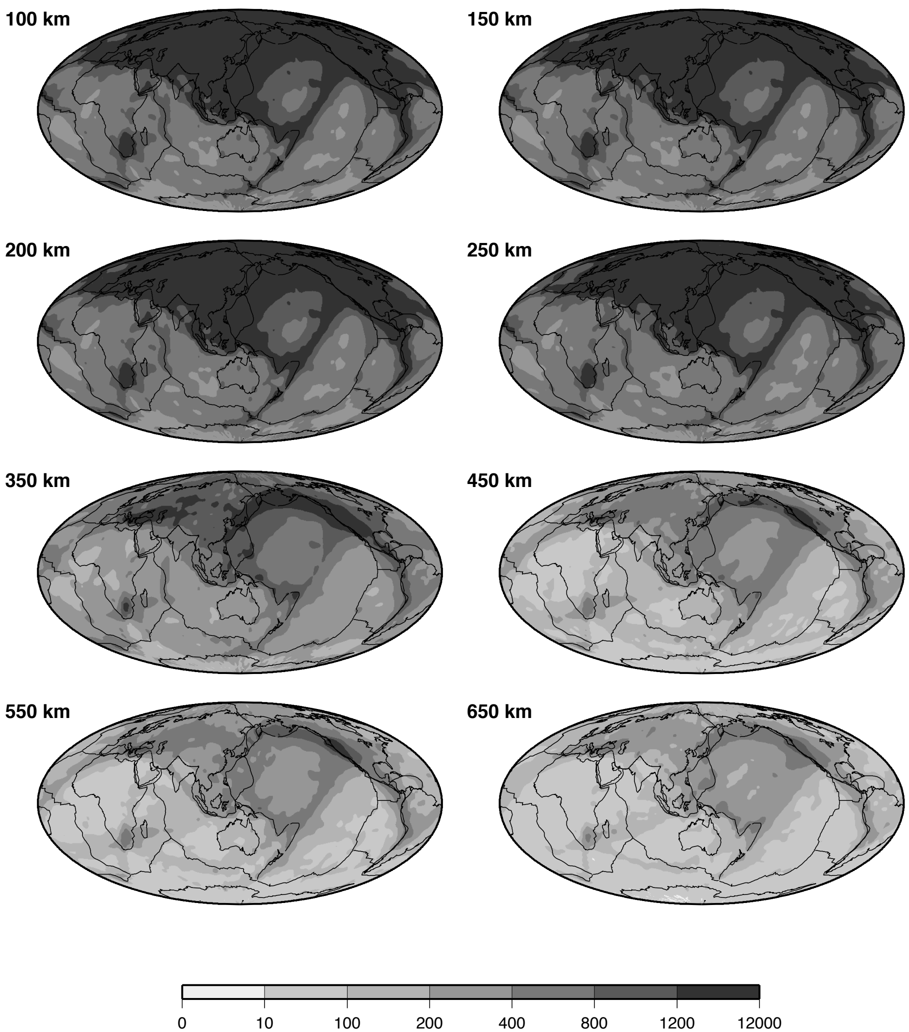
Azimuthal anisotropy maps

- Strongest anisotropy in the uppermost 200 km
- Perpendicular to ridge axis beneath oceanic regions
- Complex beneath continents
- Pattern robust with respect to changes in horizontal smoothing

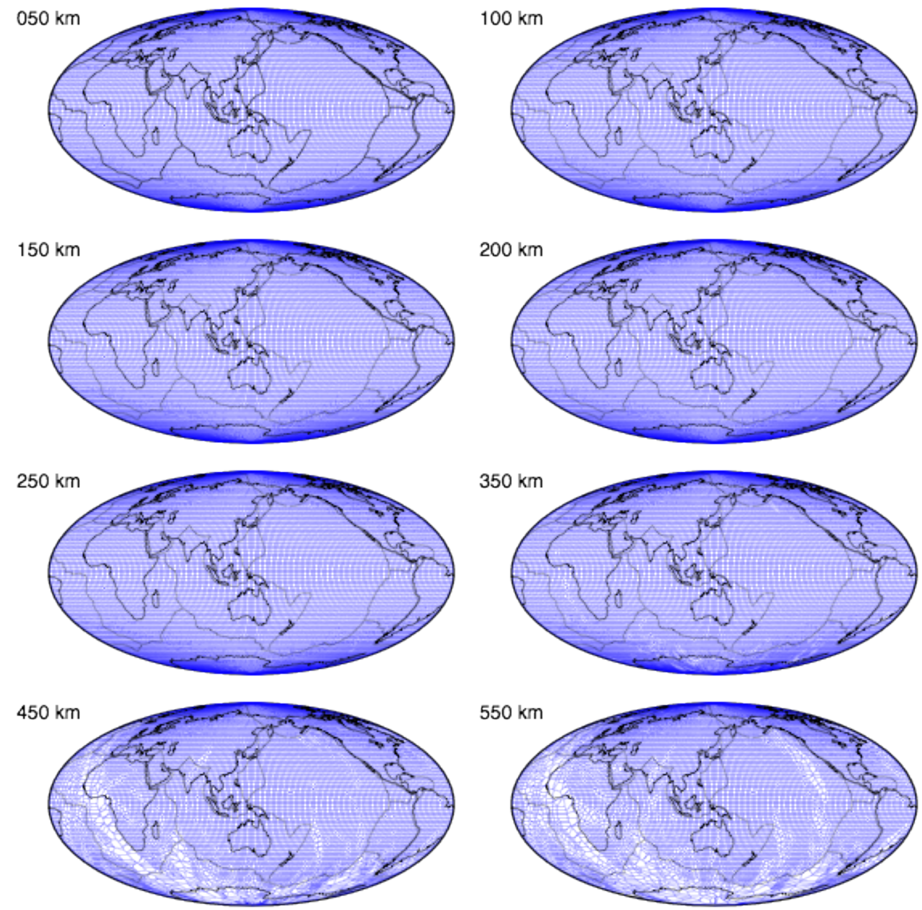


Debayle et al., 2016

Ray density maps
(typical of modern global tomography)

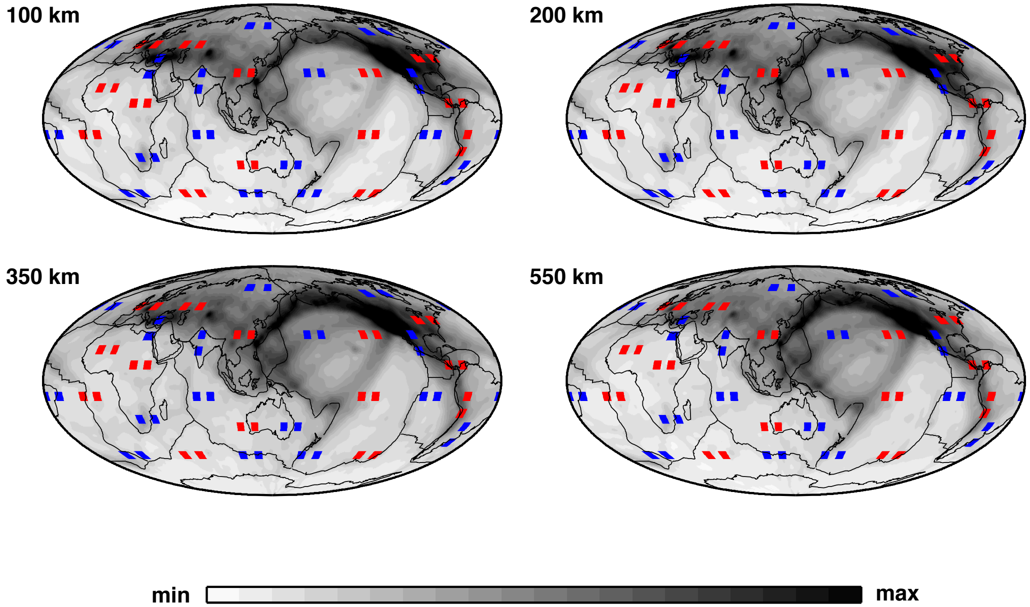


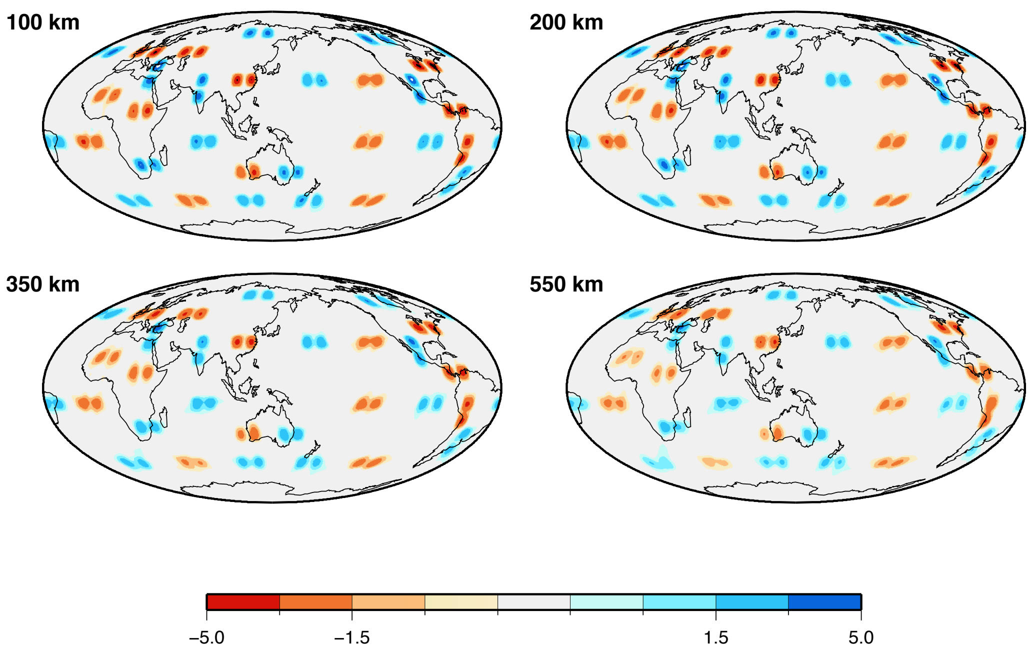
Azimuthal distribution of rays
(Voronoi diagrams after
Debayle and Sambridge, JGR, 2004)



Each Voronoi cell is the smallest for which we are sure that our azimuthal coverage allows us to resolve the cos(2), sin(2) azimuthal variation of SV waves

Debayle et al., 2016





Debayle et al., 2016