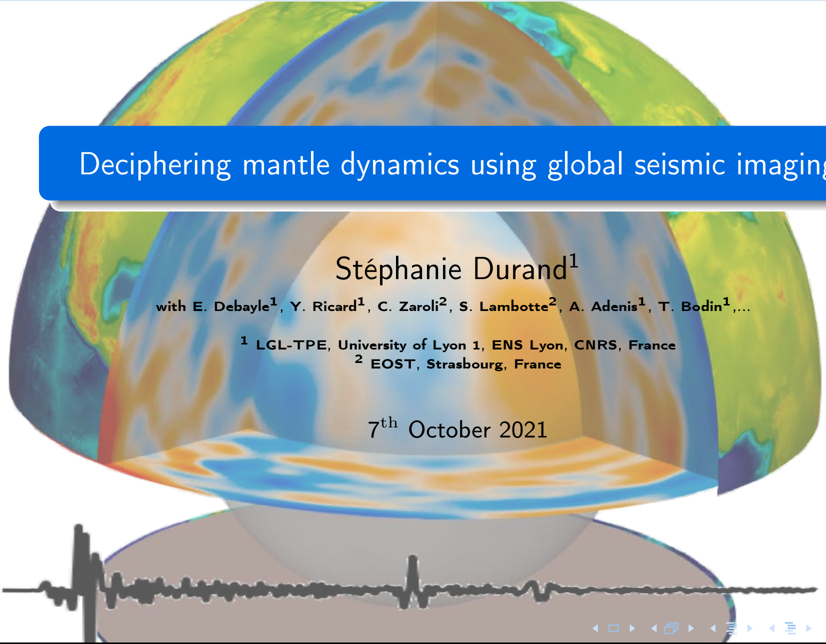


Deciphering mantle dynamics using global seismic imaging

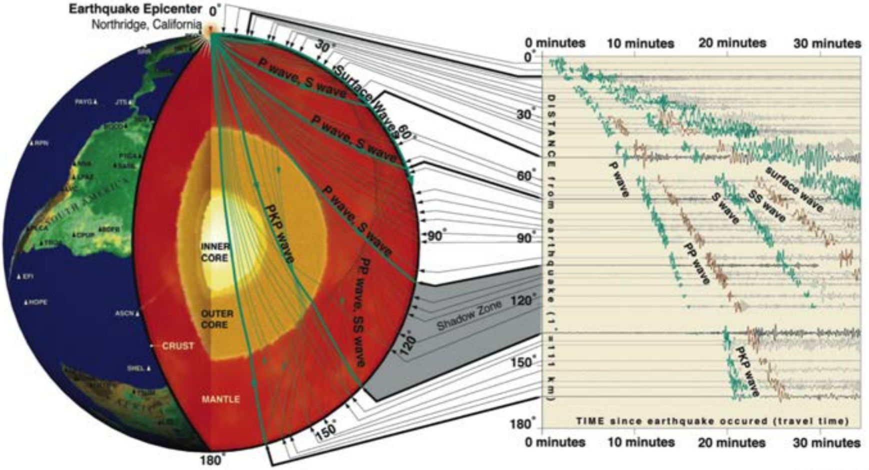
Stéphanie Durand[1]

with E. Debayle[1], Y. Ricard[1], C. Zaroli[2], S. Lambotte[2], A. Adenis[1], T. Bodin[1],...

[1] LGL-TPE, University of Lyon 1, ENS Lyon, CNRS, France
[2] EOST, Strasbourg, France

7$^{\text{th}}$ October 2021

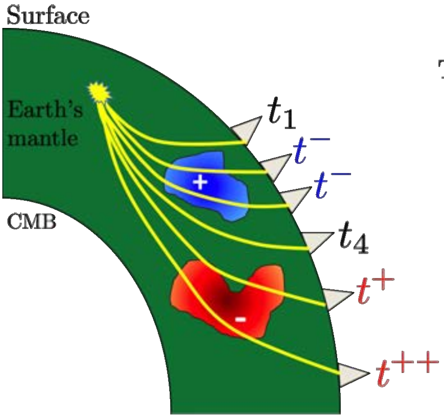
How to study the deep Earth ?



Tomography principle

Hypothesis

Homogeneous Earth's mantle



Observations

Travel time anomalies

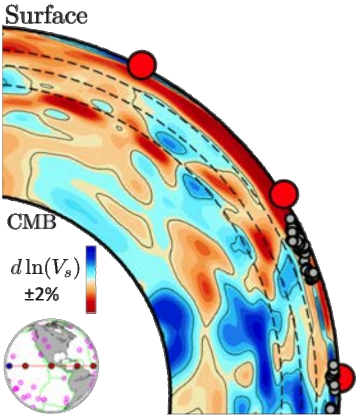
Tomographic inversion

3D model of seismic velocities of the Earth's mantle

Tomography principle

Hypothesis

Homogeneous Earth's mantle



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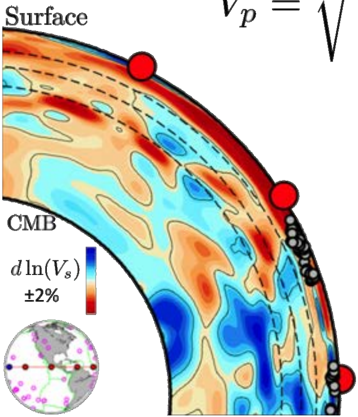


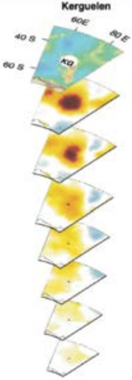
$$V_p = \sqrt{\frac{\kappa + 4/3\mu}{\rho}} \quad V_s = \sqrt{\frac{\mu}{\rho}}$$

$$\kappa = f(T, P, \chi, ...)$$
$$\mu = f(T, P, \chi, ...)$$

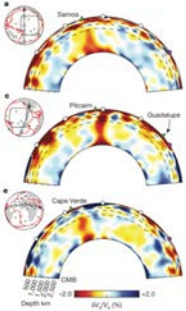
Interpretation in terms of density, thermal or compositional heterogeneities

Ricard et al. [2005], Matas & Bukowinski [2007]

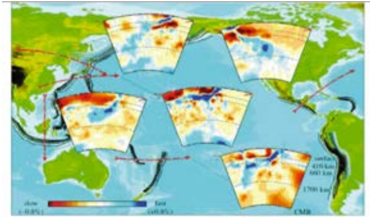
Imaging slabs, plumes...



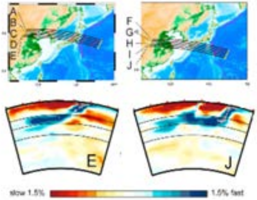
Montelli et al. [2004]



French & Romanowicz [2015]

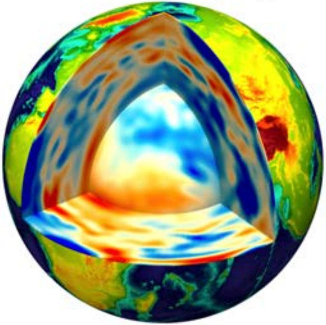


Karason & van der Hilst [2001]



Fukao & Obayashi [2013]

Model (m)



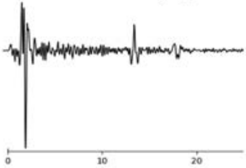
Forward problem

$$d = g(m) + \epsilon$$

Inverse problem

$$m = \ldots \, ?$$

Data (d)

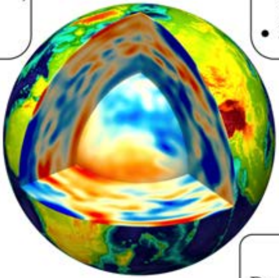


PARAMETRIZATION

- Spherical harmonics, spherical splines, radial splines,
- Velocity, anisotropy

SEISMIC DATA

- Normal modes, surface waves and body waves
- Measurements or waveforms



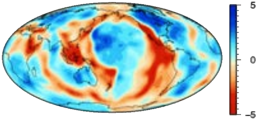
REGULARIZATION

Damping parameter

THEORY

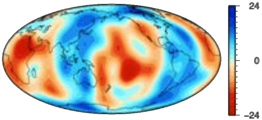
Ray theory or finite frequency kernels

SURFACE WAVE
Fundamental mode
40 s



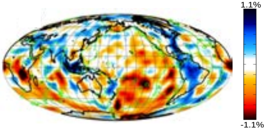
Upper mantle
Wavelengths ≈ 1900 km
Durand et al. [2015]

NORMAL MODE
$_2S_{15}$



Whole mantle
Wavelengths ≈ 4500 km
Koelemeijer et al. [2013]

BODY WAVES

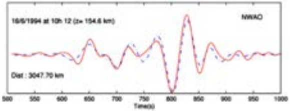


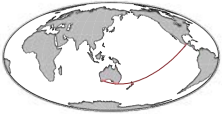
Lower mantle
Wavelengths ≈ 2000 km
Zaroli et al. [2013]

Joint inversion toward a 3D elastic model of the Earth's mantle

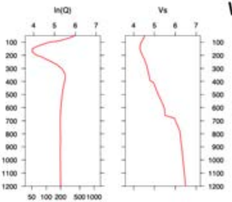
Rayleigh phase velocities (40-360 s)

1) Automated waveform inversion **(Cara and Lévêque, 1987 ; Debayle and Ricard 2012).**
Rayleigh waveforms, period range : 50 -250 s



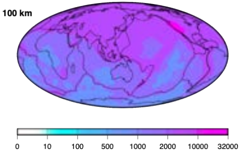


$Q_s(z)$



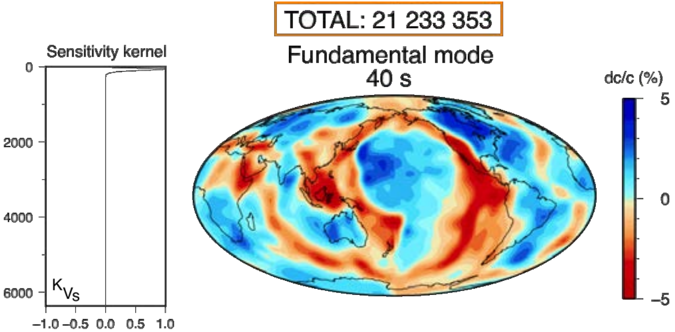
$V_s(z)$

2) Application to a massive dataset **(Debayle and Ricard, 2012)**



Rayleigh phase velocities (40-360 s)

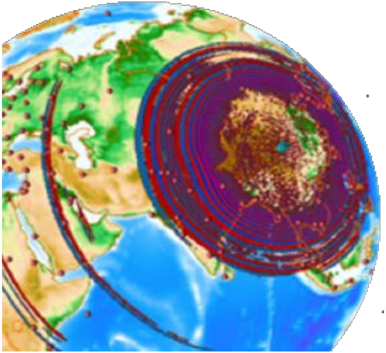
534,359 sets of dispersion curves
From fundamental mode up to the 5th overtone
Phase velocity and errors at 60 periods

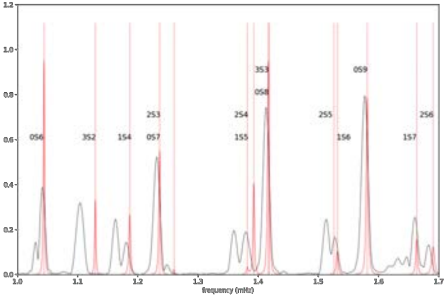


Largest dataset of Rayleigh wave phase velocity measurements with their errors **(Durand et al. [2015])**

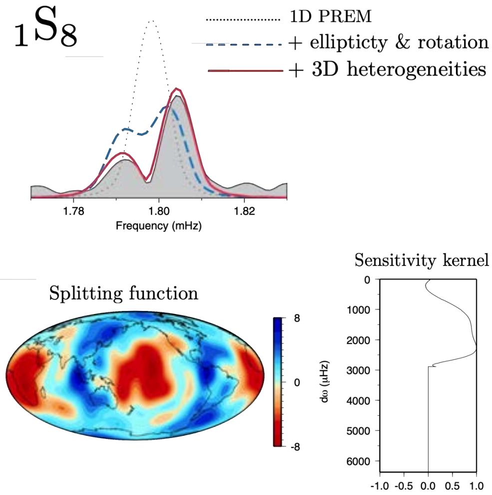
Normal modes

50hr long vertical component seismogram of the Sumatra EQ recorded at the GEOSCOPE station CAN (Canberra, Australia)





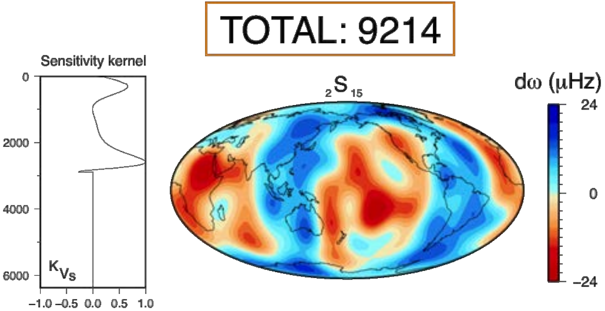
Normal modes



Splitting coefficients of spheroidal modes

Up to the degree 8, for 158 spheroidal modes

Koelemeijer et al. [2013], Deuss et al. [2013], Masters et al. [2000], Resovsky & Ritzwoller [1999], Smith & Masters [1989]



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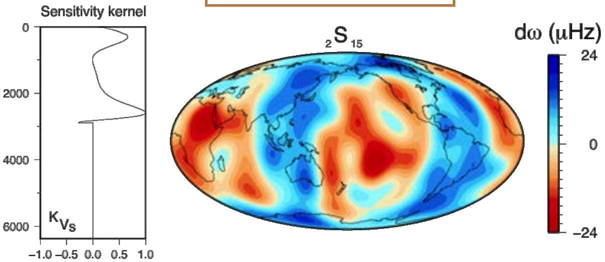
Up to the degree 8, for 158 spheroidal modes

Koelemeijer et al. [2013], Deuss et al. [2013], Masters et al. [2000], Resovsky & Ritzwoller [1999], Smith & Masters [1989]

TOTAL: 9214

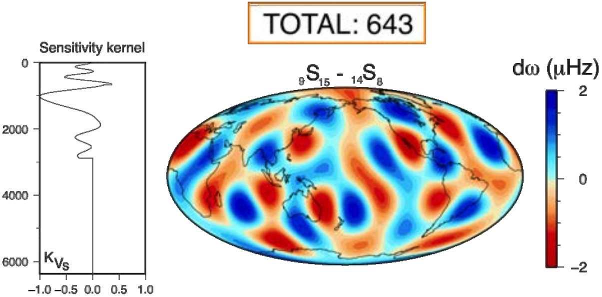


But they ONLY constrain the EVEN degrees of the spherical harmonic decomposition of the mantle structure

Coupling coefficients of spheroidal modes

Up to the degree 8, for 26 spheroidal modes

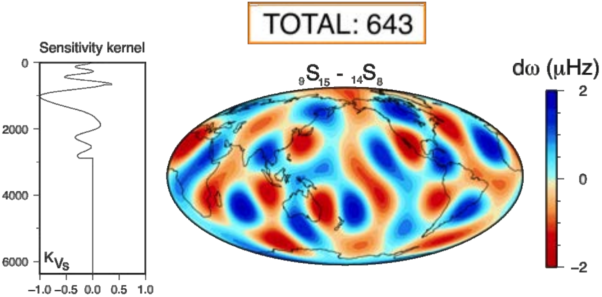
Deuss et al. [2013], Resovsky & Ritzwoller [1999]



Coupling coefficients of spheroidal modes

Up to the degree 8, for 26 spheroidal modes

Deuss et al. [2013], Resovsky & Ritzwoller [1999]

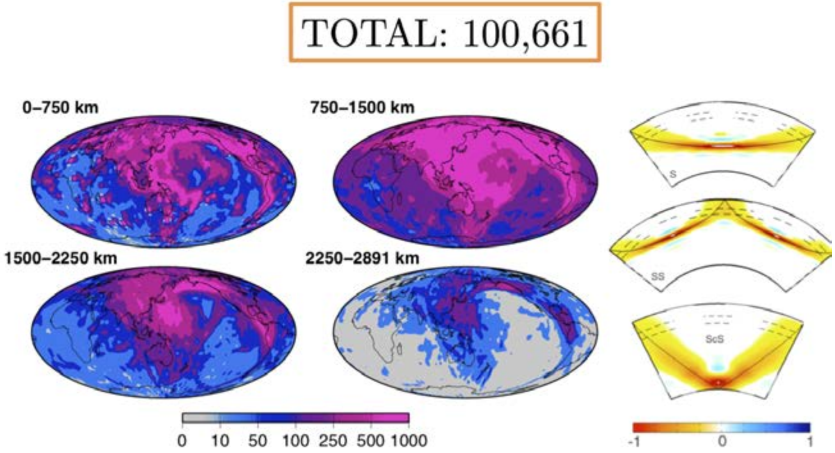


They can constrain BOTH the EVEN and ODD degrees of the spherical harmonic decomposition of the mantle structure
The FIRST tomographic model to include data on the coupling of normal modes

S, SS and ScS travel times

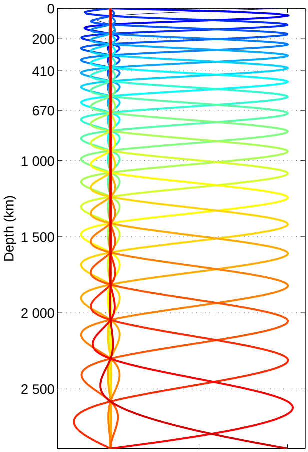
47,007 S, 42,174 SS and 11,480 ScS measured at 34 s

Zaroli et al. [2013]



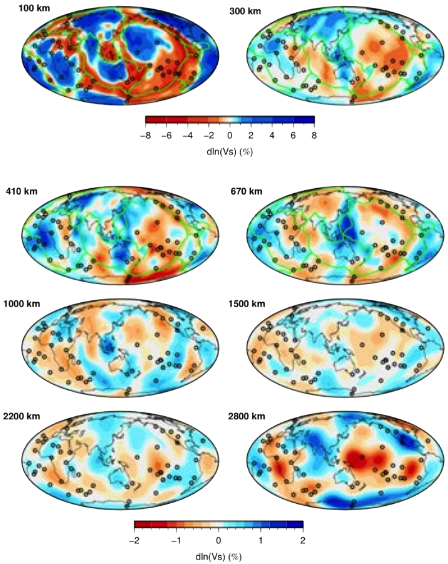
Parametrization

- Model parameters : V_S assuming an *a priori* correlation with V_P and ρ
  $d\ln(\rho) = 0.2\, d\ln(V_S)$
  $d\ln(V_P) = 0.55\, d\ln(V_S)$
- Lateral parameterization : spherical harmonics up to degree 40/20/8
- Radial parametrization : spline functions



Ritsema et al. [2011]

SEISGLOB1 : a pure Sv model based on normal modes and surface waves



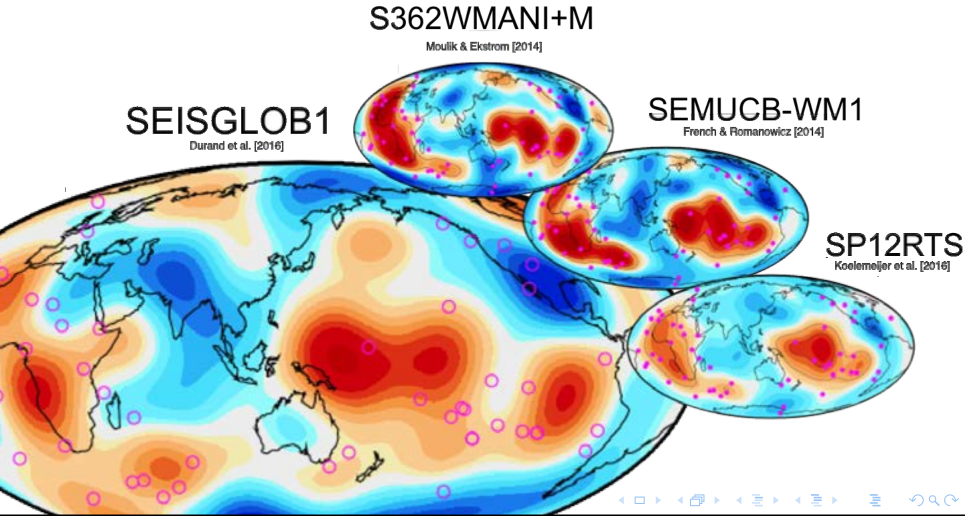
Durand et al. [2016]

Imprint of tectonics

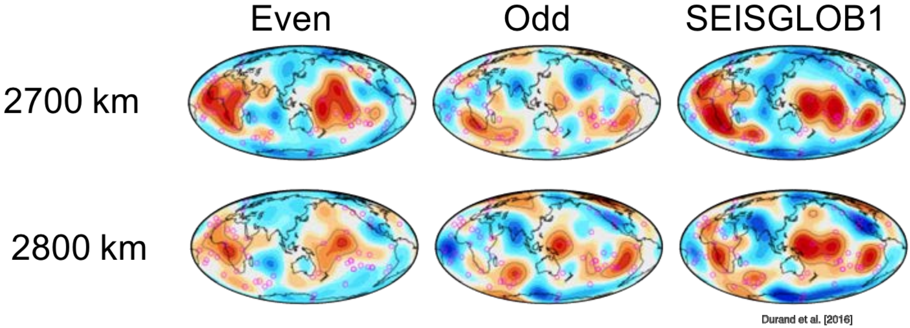
Subducted slabs

LLSVPs

A new large scale pattern at 2800 km depth

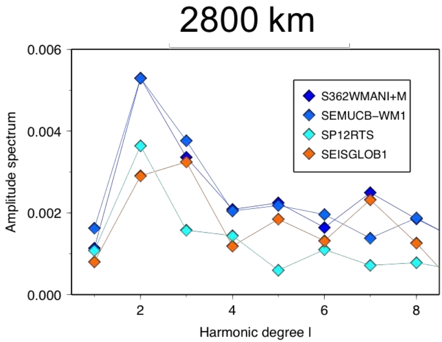


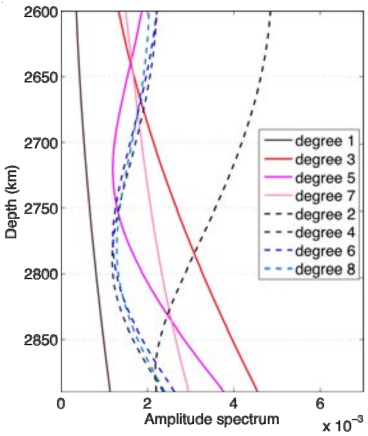
Stronger odd degrees



Decrease of the degree 2 throught the D".
The complexity comes from odd degrees and thus from the normal mode coupling data.

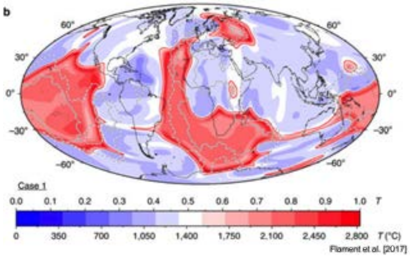
Stronger odd degrees

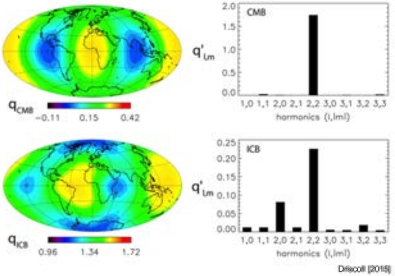




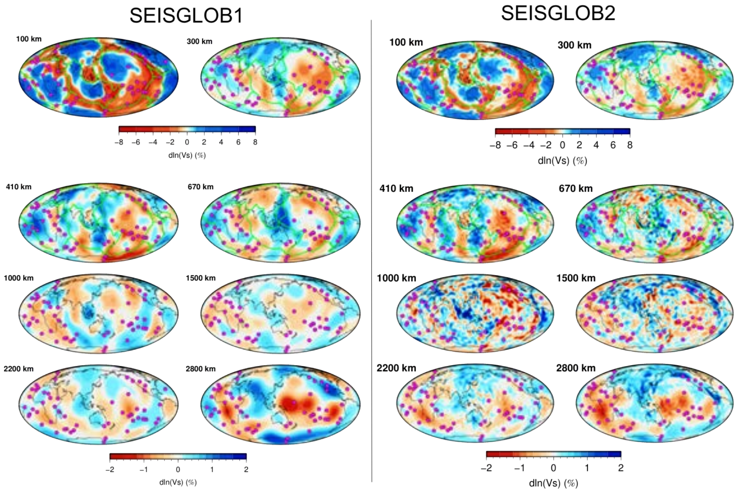
Durand et al. [2016]

It can tell us something about mantle and core dynamics





SEISGLOB2 : a S model based on normal modes, surface wave and body waves



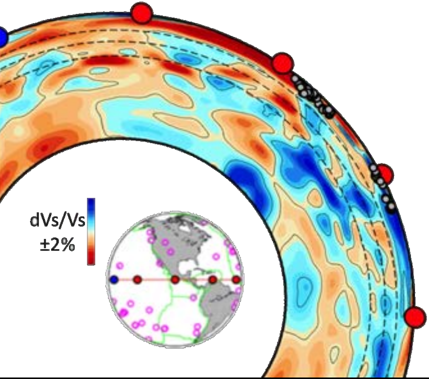
Durand et al. [2017]

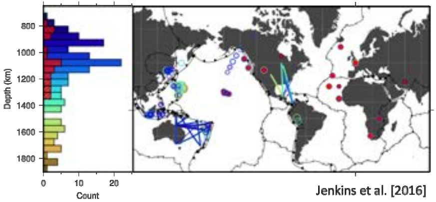
Surface tectonics

Subducted slabs

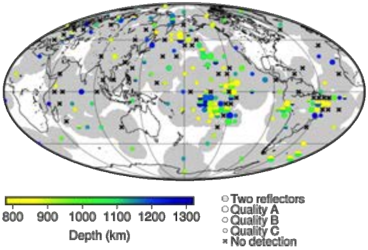
LLSVPs

There is a "change" at ≈ 1000 km depth



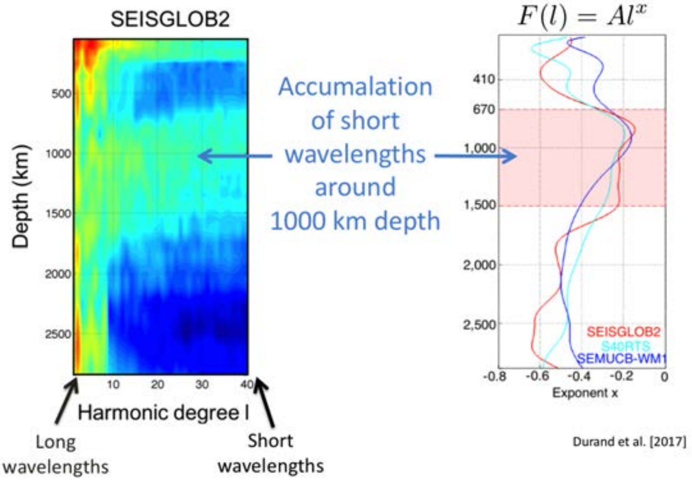


Jenkins et al. [2016]



Waszek et al. [2018]

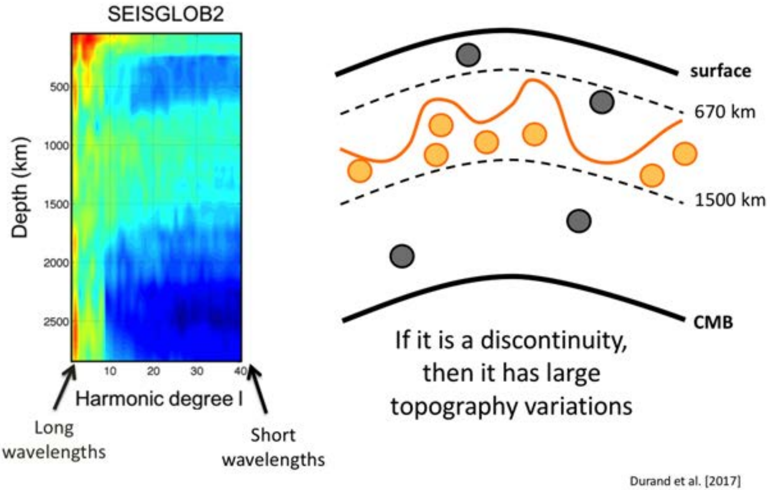
Is it a global feature ?



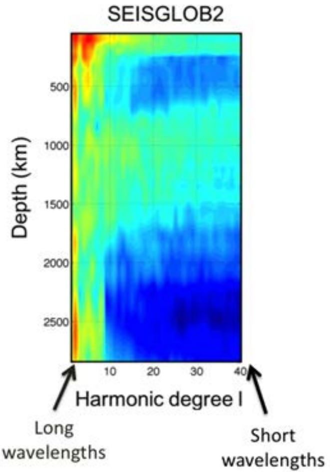
Durand et al. [2017]

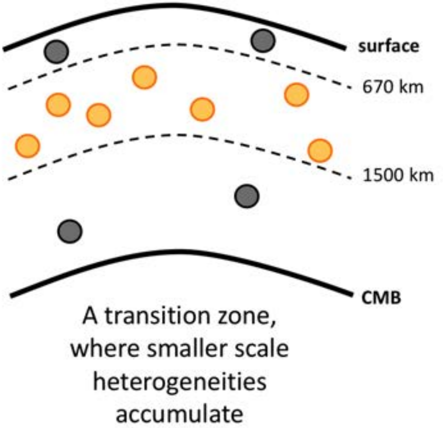
Is it a discontinuity or a “transition” zone ?

Is it a discontinuity or a "transition" zone ?



Is it a discontinuity or a "transition" zone ?

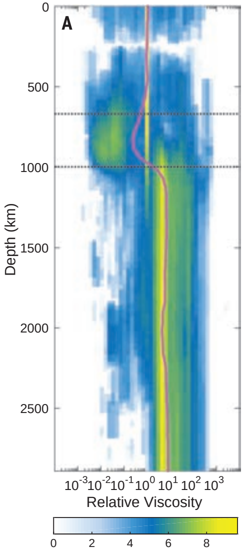


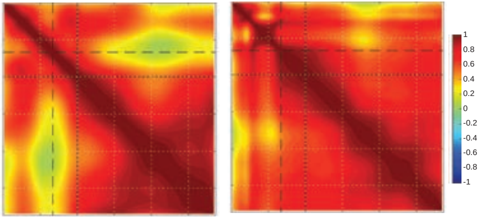


Durand et al. [2017]

What could be the origin ? A viscosity jump...

What could be the origin ? A viscosity jump...



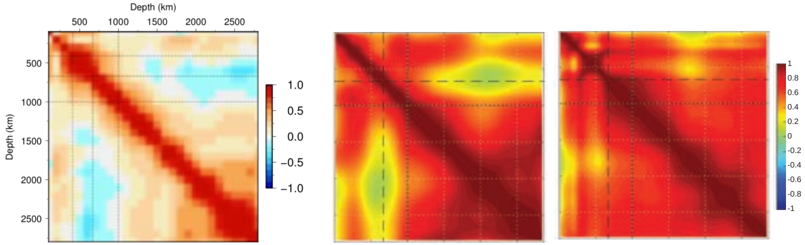


Geodynamic model with viscosity jump at 1,000 km depth

Geodynamic model with a lower viscosity jump at 670 km depth

Rudolph et al. [2015]

What could be the origin ? A viscosity jump...



SEISGLOB2

Durand et al. [2017]

Geodynamic model with viscosity jump at 1,000 km depth

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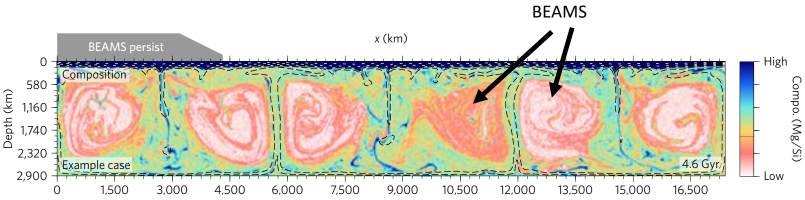


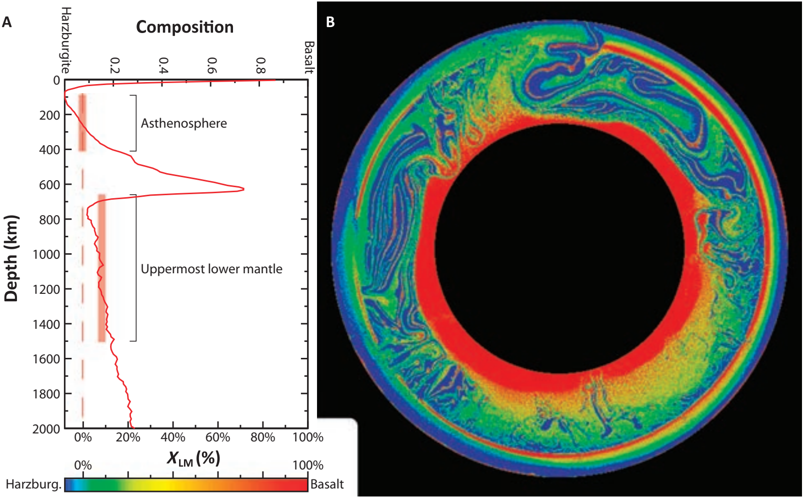
Ballmer et al. [2017]

BEAMS = Bridgmanite Enriched Ancient Mantle Structures

SiO_2 – enriched regions, highly viscous

What could be the origin ? Chemical layering...

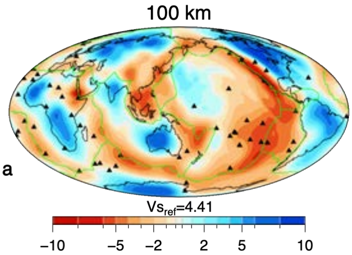
What could be the origin ? Chemical layering...



Ballmer et al. [2015]

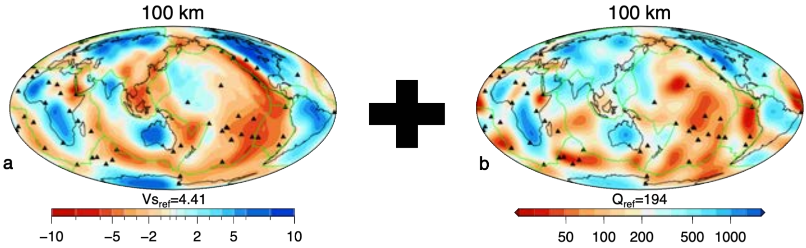
Imaging attenuation

Imaging attenuation



Velocity alone cannot discriminate thermal or compositional effects...

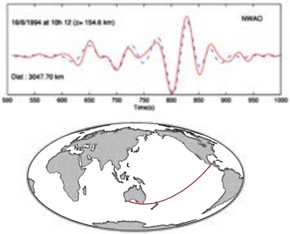
Imaging attenuation



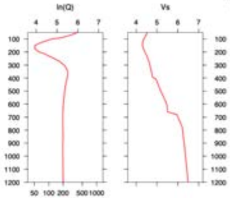
There is a need of new observations (Q_s) !

Waveform inversion

1) Automated waveform inversion **(Cara and Lévêque, 1987 ; Debayle and Ricard 2012).**
Rayleigh waveforms, period range : 50 -250 s

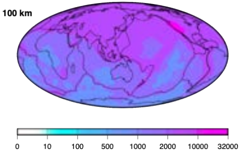


$Q_s(z)$

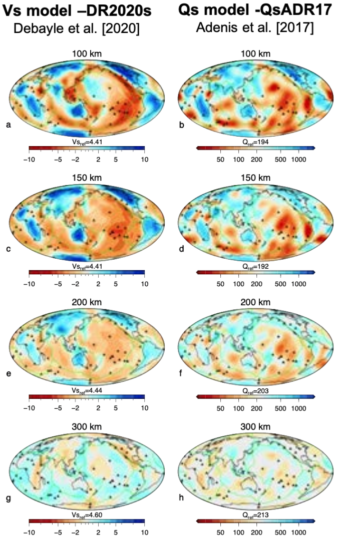


$V_s(z)$

2) Application to a massive dataset **(Debayle and Ricard, 2012)**



Global S-wave attenuation and velocity models



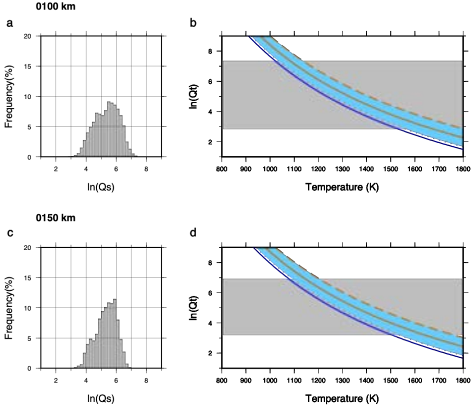
- Based on the same dataset : fundamental and higher modes global dataset (372,629 Rayleigh waveforms).
- Inverted using the same approach with the same horizontal and vertical smoothing
- Specific treatment for Qs : Focusing/defocusing effects accounted for, specific model for source excitation and careful data selection

Joint interpretation of DR2012 & QsADR2017

Experimental results from Jackson et al. [2002]

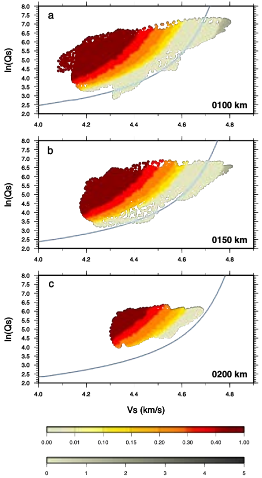
$$Q_t^{-1} = A\left[\frac{1}{d f_0}\left(\frac{C}{C_r}\right)^r \exp\left(-\frac{E+PV}{RT}\right)\right]^\alpha$$

- $A = 750\ s^{-\alpha}\ \mu m^\alpha$
- $E = 424$ kJ mol^{-1}
- $V = 6.10^{-6}\ m^3\ mol^{-1}$
- $\alpha = 0.26$
- $\frac{1}{f_0} = 100$ s (oscillation period)
- $d = 1 - 100$ mm (grain size)
- Water effect (after Behn et al. [2009])

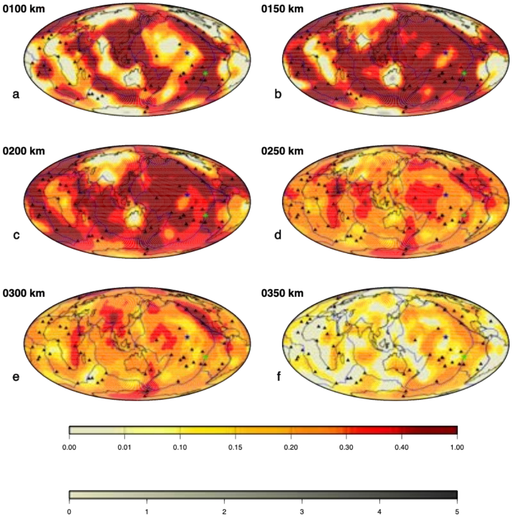


Joint interpretation of DR2012 & QsADR2017

- Knowing Q_s and temperature T we can predict V_s for each T (or Q_s) (blue curve).
- We assume a pyrolitic mantle, we use PerpleX to predict Vs (Connolly, 2005), and we correct for the effect of Q_s on V_s (Karato, 1993).
- Then we can add our data (V_s and Q_s at each geographical point on each map) (dots from red to grey)
- The blue curve does not explain all the data, we can shift it to the left by adding melt, which reduces velocities (Chantel et al., 2016)



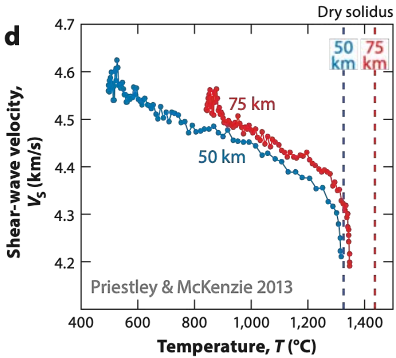
There is melt !

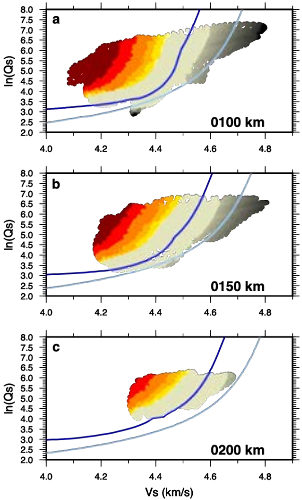


Melt content at each depth in %

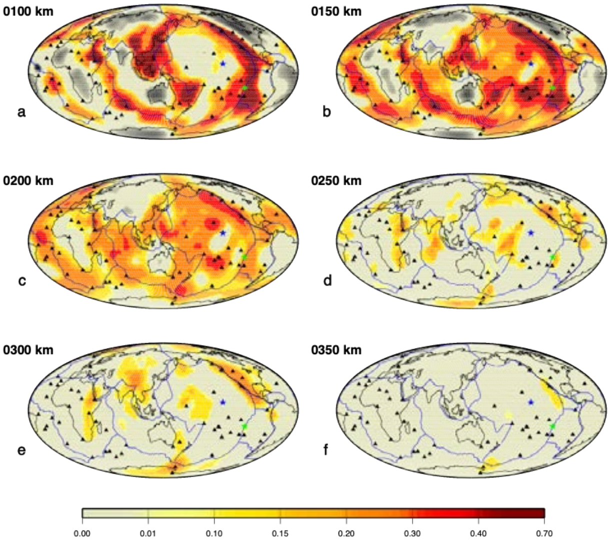
Misfit in %

Temperature dependent anelastic model (Yamauchi & Takei, 2016 ; Takei, 2017)

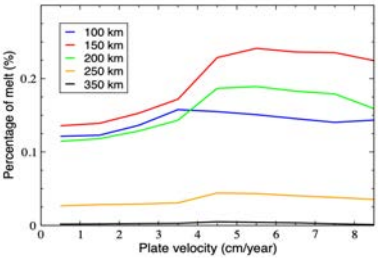




Temperature dependent anelastic model (Yamauchi & Takei, 2016 ; Takei, 2017)



Consequences on plate motions



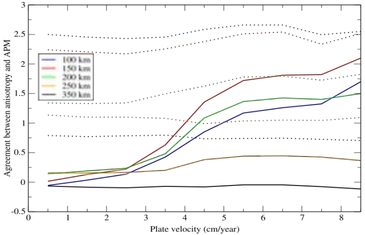
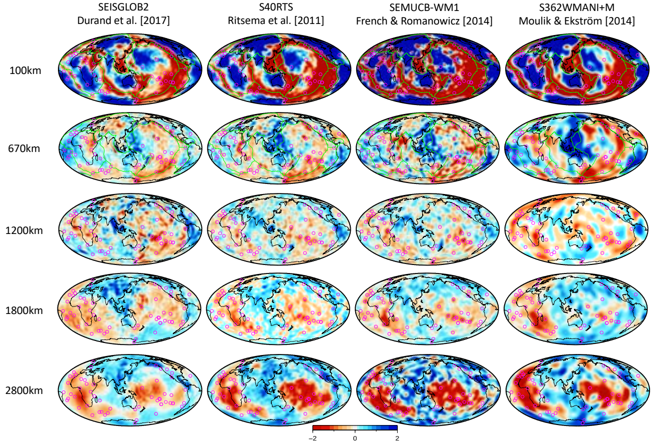


Plate-scale crystal alignment beneath plates moving faster than 4 cm/year is associated with a greater amount of melt.
This requires either that melt facilitates deformation or that deformation favours melt retention in the LVZ, or both


FUTURE
FUTURE
FUTURE
FUTURE

Toward a 3D Reference Earth Model

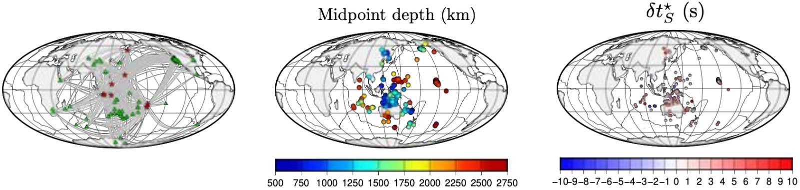
There is currently an initiative on building a 3D Reference Earth Model, REM, **(R. Moulik, V. Lekič, B. Romanowicz, A. Dziewonski)**



J. Ritsema & V. Lekič [2021]

New attenuation measurements

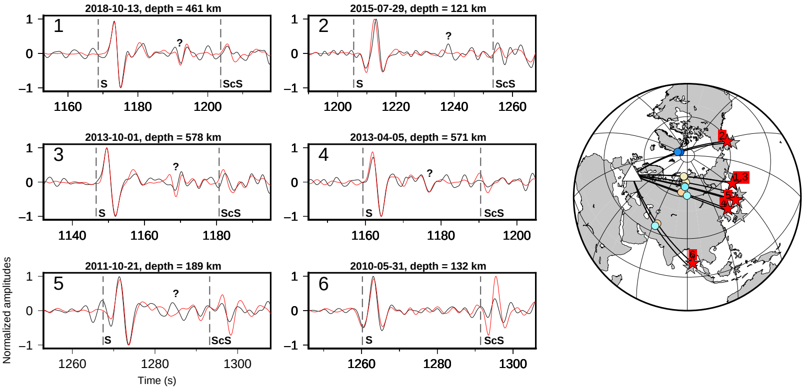
We are now measuring the differential attenuation between an observed and a 3D synthetic seismogram **(Durand et al. *in prep*)**



The aim is to extend the attenuation model to the lower mantle.

New data to study the deep Earth

It is based on the fact that $\frac{a_T}{\Omega_Z} = 2c$ **(Fichtner & Igel, 2009)**. Can we get velocity measurement directly without any inversion ? (See R. Abreu's poster)



Abreu et al. *in prep*.