Constraints on the presence of post-perovskite in Earth's lowermost mantle from tomographic-geodynamic model comparisons

British Seismology Meeting – Reading Town Hall – 7th April 2017

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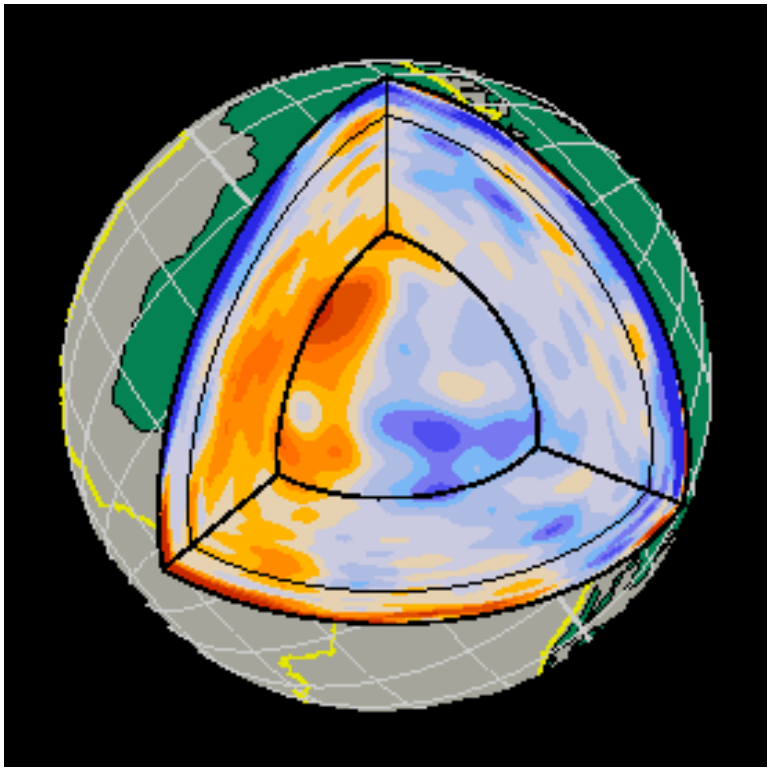
Bernhard Schuberth, Rhodri Davies
Arwen Deuss, Jeroen Ritsema

How to interpret seismic tomography?

Structures



Seismology: $d\ln V_S$, $d\ln V_P$, $d\ln V_C$

Courtesy of John Woodhouse

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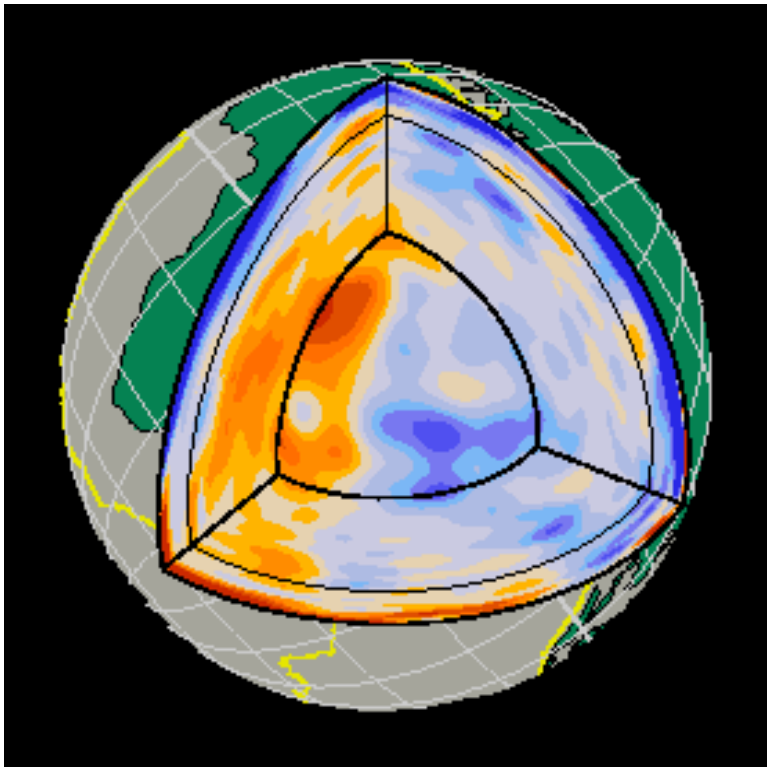

$$V_P = \sqrt{\left(K + {}^{4}\!/_{3}\,\mu\right)/\rho}$$

$$V_S = \sqrt{\mu/\rho}$$

$$V_C = \sqrt{K/\rho}$$

K:	bulk modulus
μ:	shear modulus
ρ:	density
$dlnV_X$:	variations with respect to radial average

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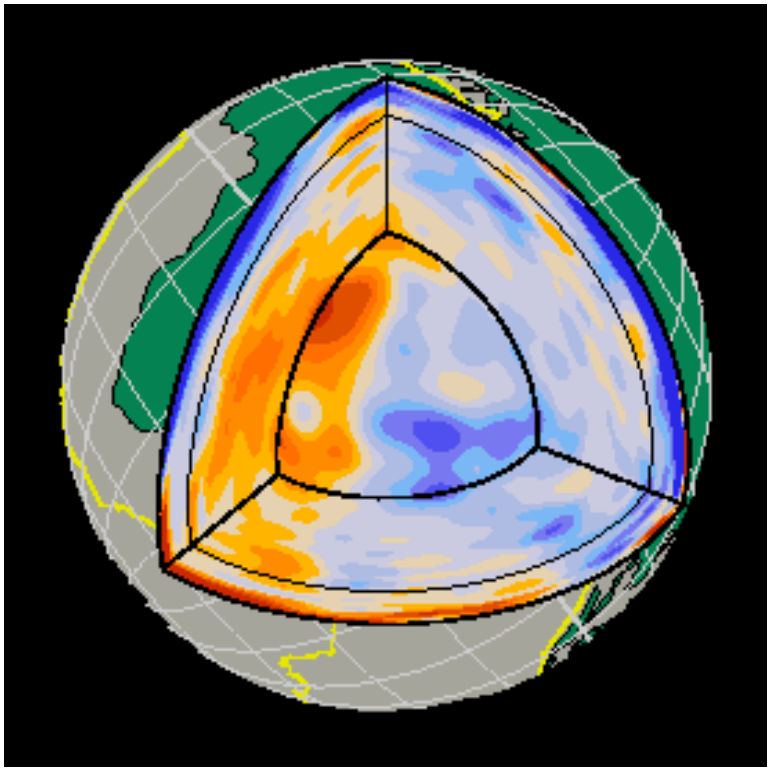
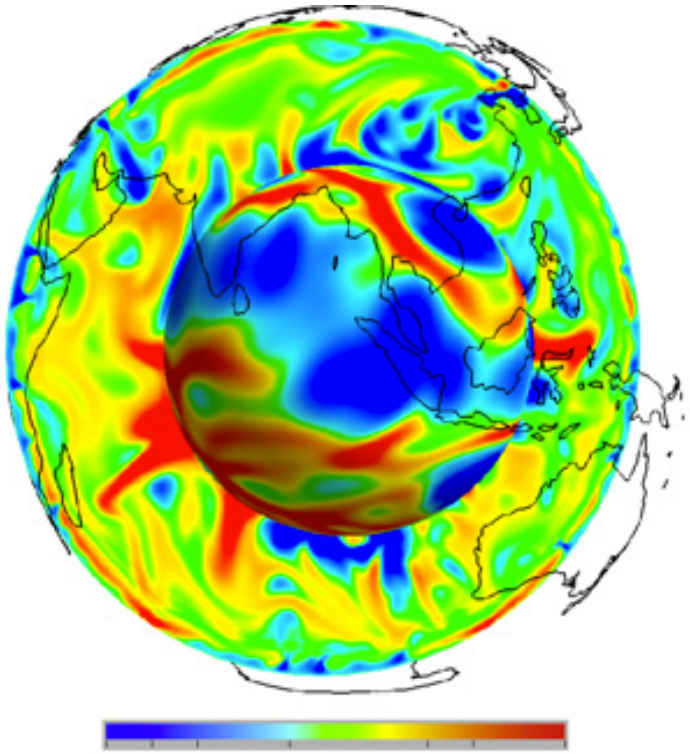


Physical processes



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Davies et al., 2012

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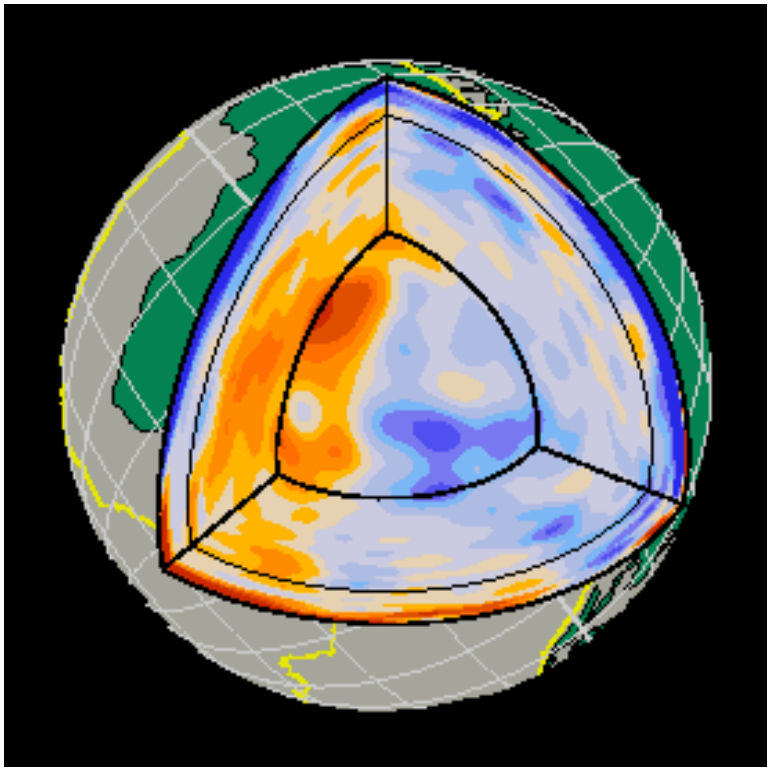

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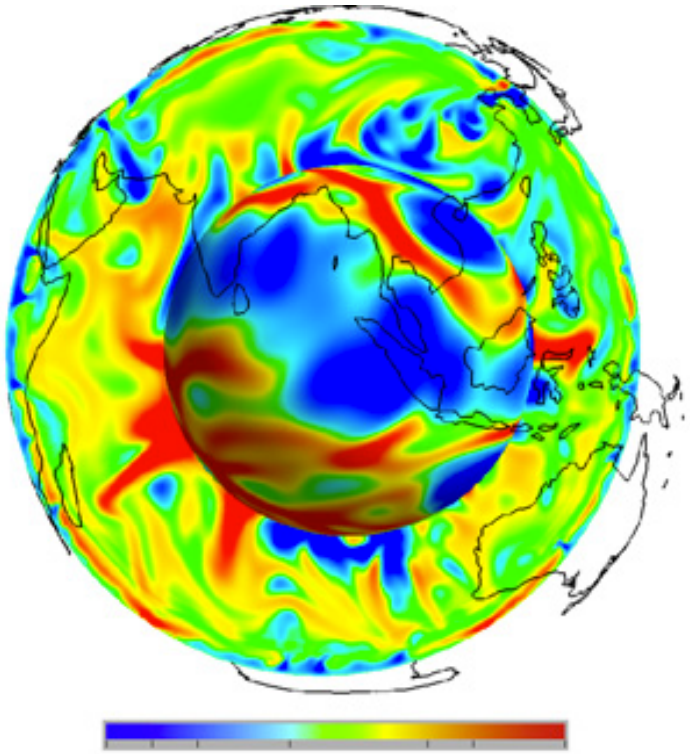


Seismology: $dlnV_S$, $dlnV_P$, $dlnV_C$

Geodynamics: dT, dX

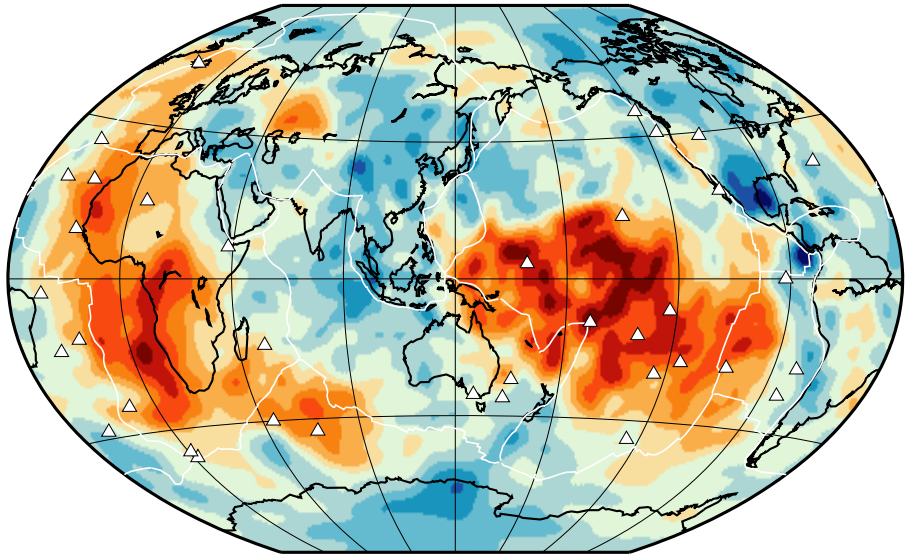
Compare structures and properties

Courtesy of John Woodhouse

Davies et al., 2012

Cause of seismic velocity variations

S40RTS @ 2850 km (± 2.4 %)



Typical structure of the lowermost mantle

Ritsema et al., 2011

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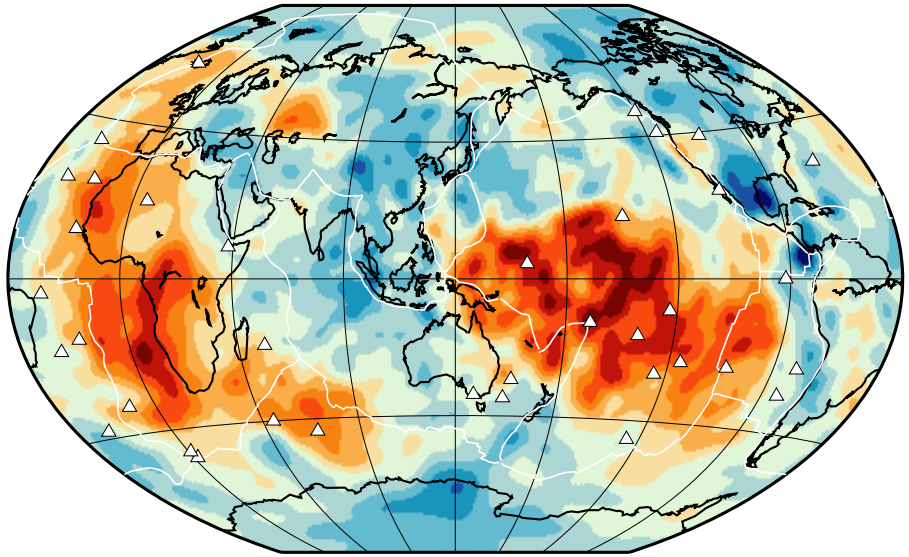

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Interpreted as:

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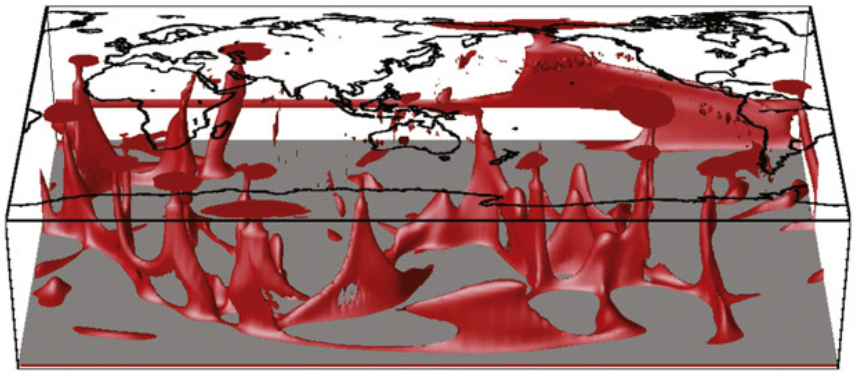
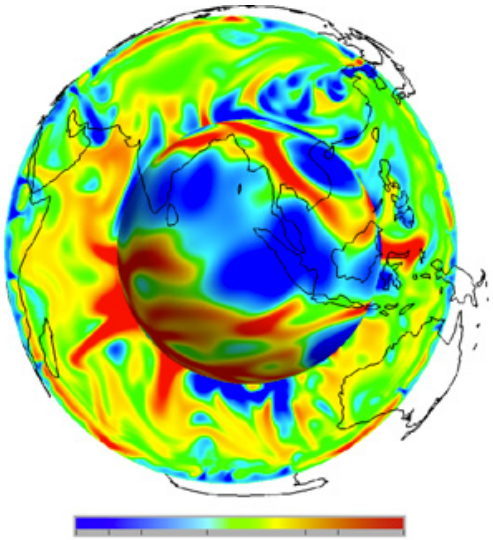
- Chemical piles?

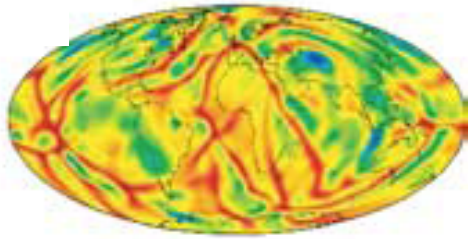
Ritsema et al., 2011

Thermal and thermochemical convection

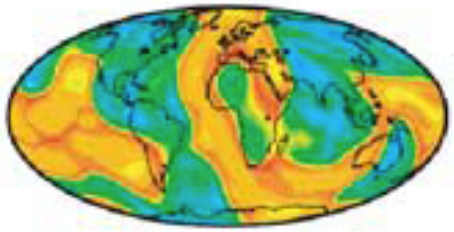


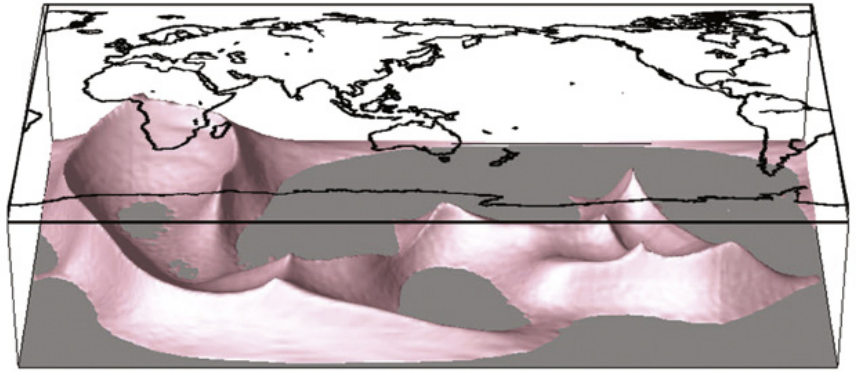


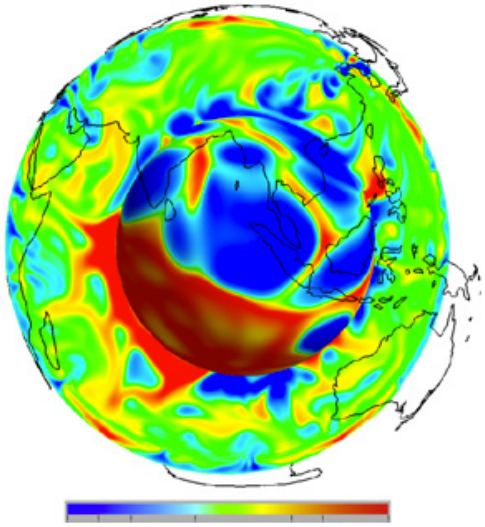
Thermal



Thermochemical







McNamara & Zhong, 2005, Lassak et al., 2010, Davies et al., 2012

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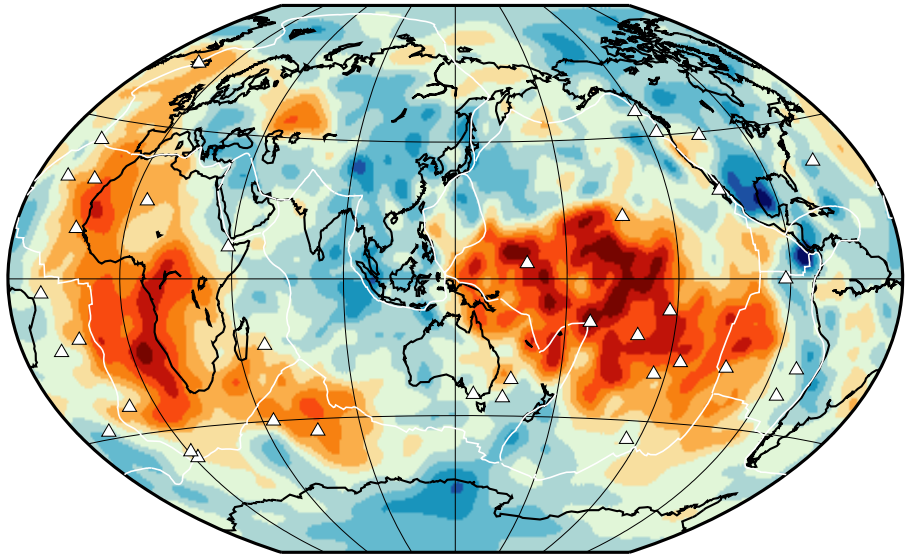

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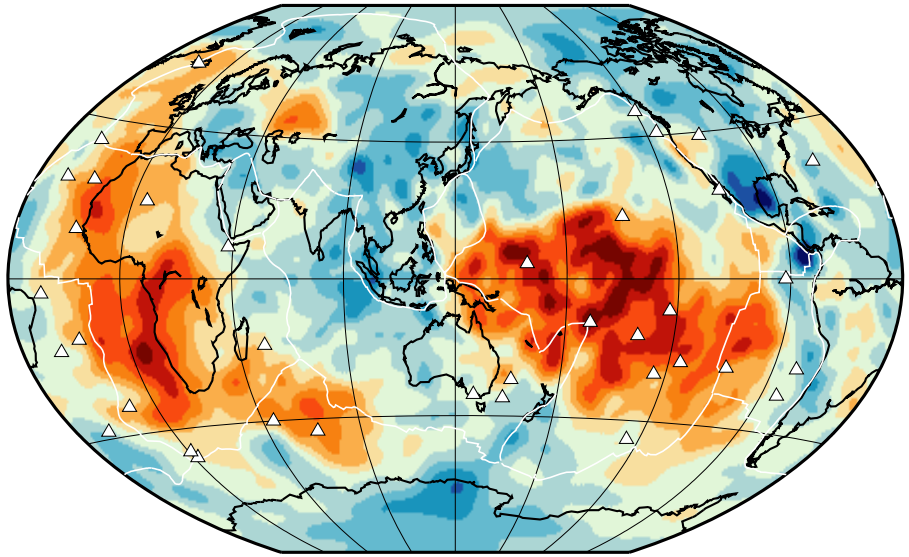

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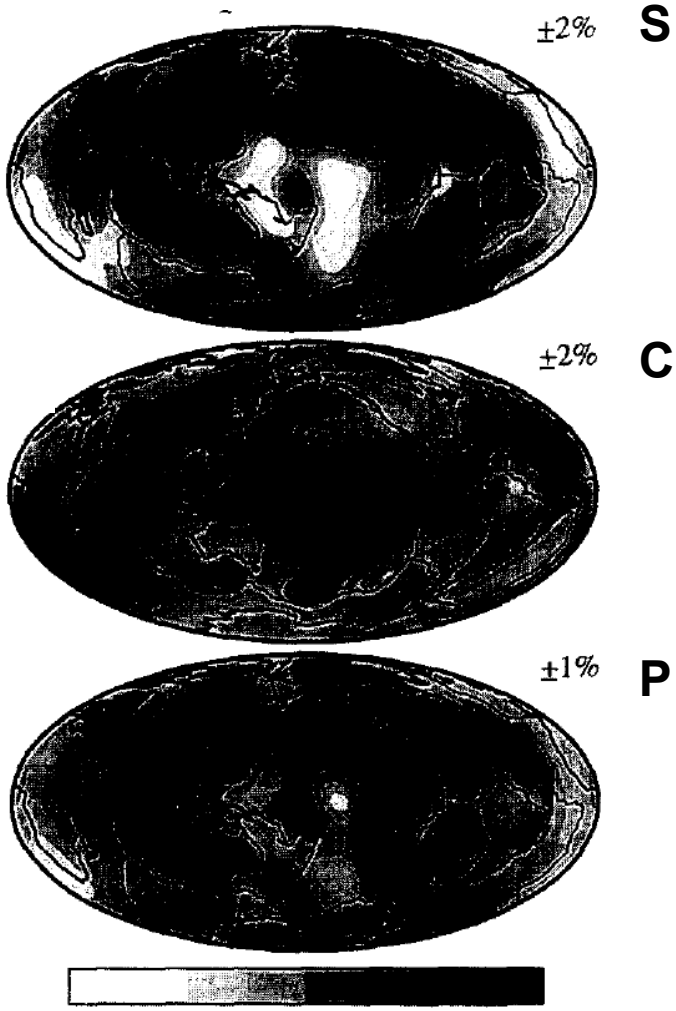
➔ Ratios / correlation of seismic velocities

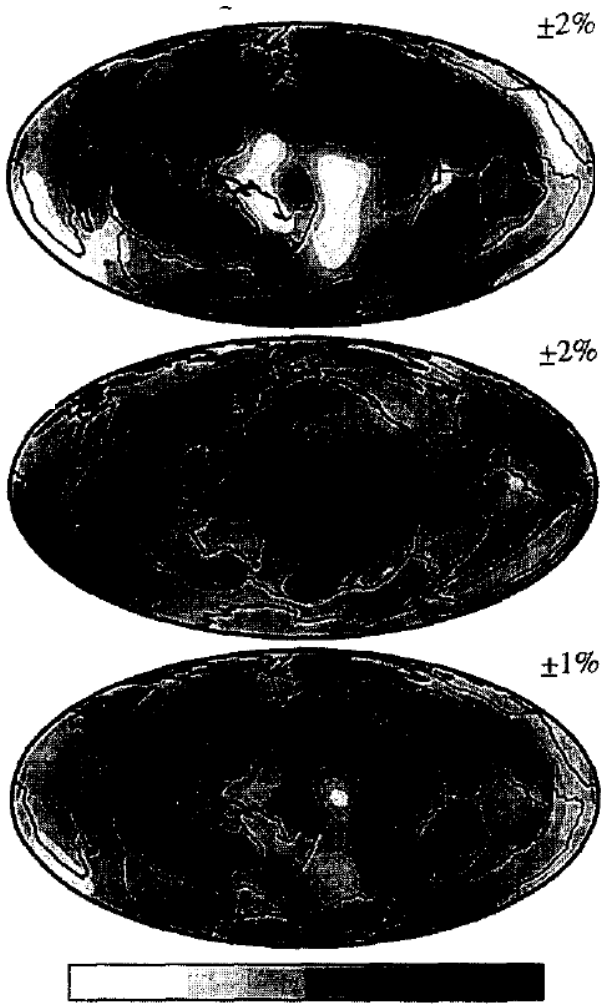
Cause of seismic velocity variations

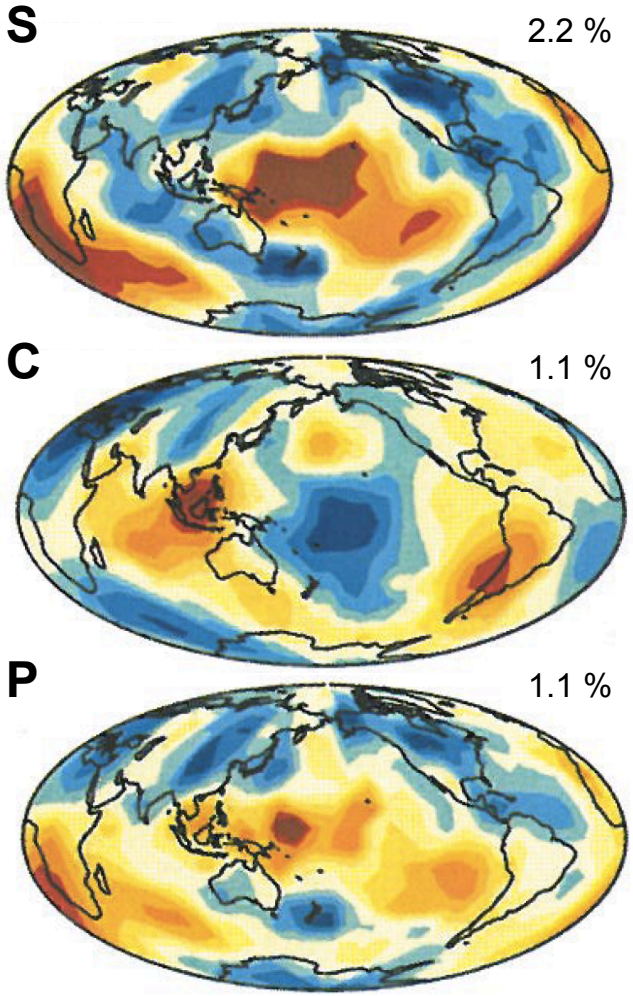


Su & Dziewonski, 1997

Obtained from ~ 4.5 million ISC traveltimes & 50.000 waveforms

Cause of seismic velocity variations

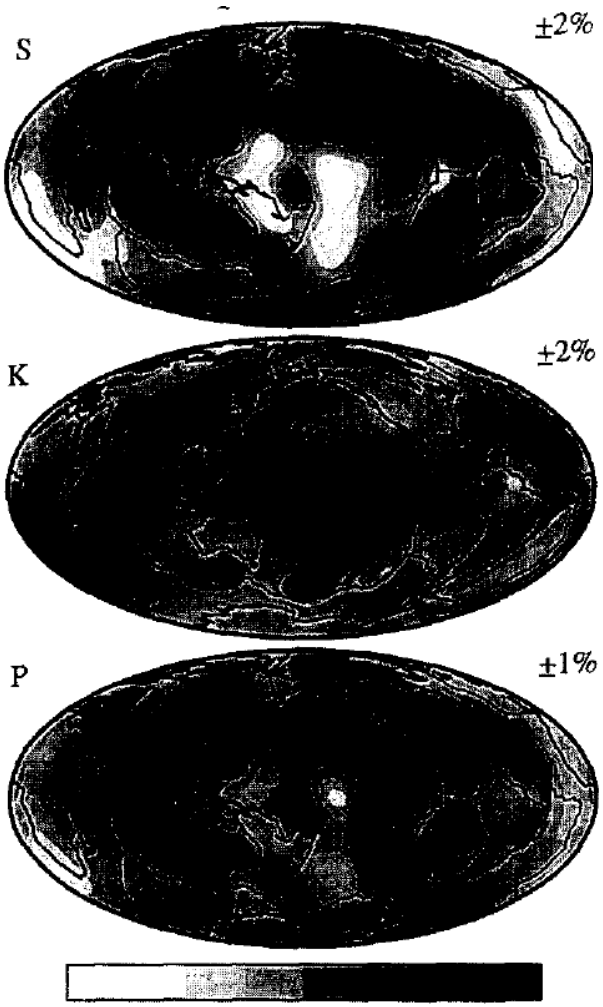


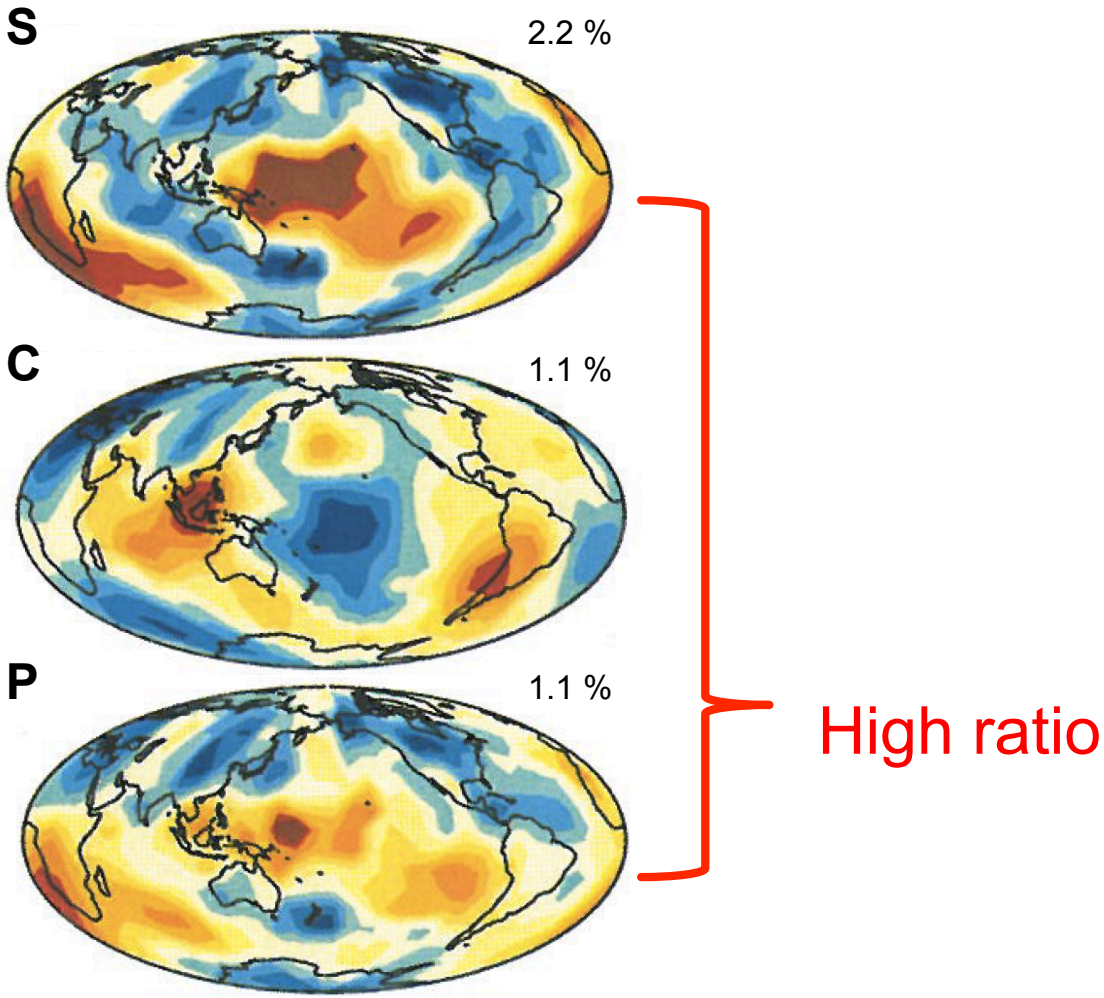


Su & Dziewonski, 1997

Masters et al., 2000

Cause of seismic velocity variations





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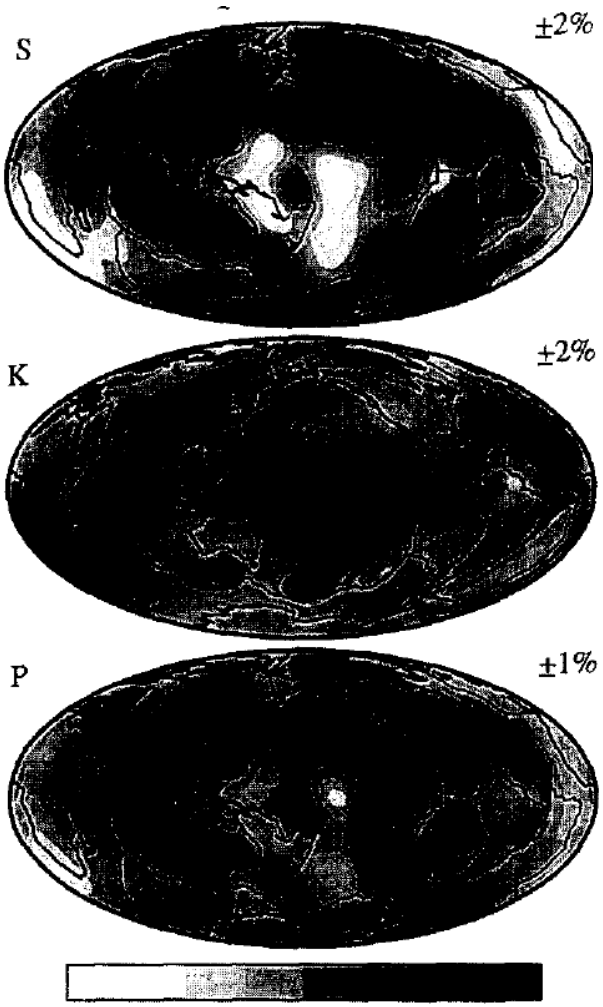

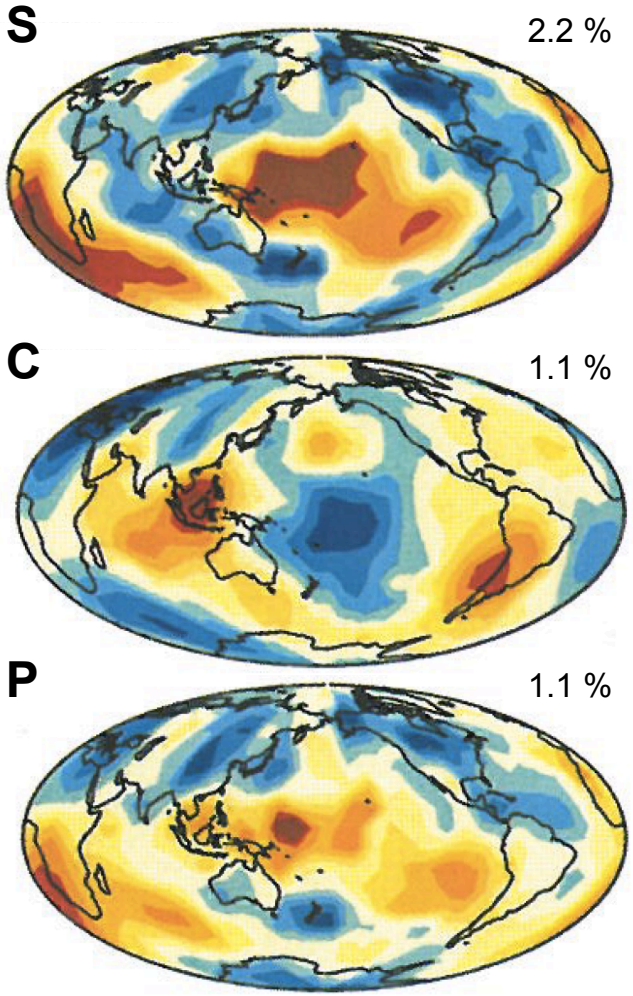

Negative correlation

High ratio

Su & Dziewonski, 1997

Masters et al., 2000

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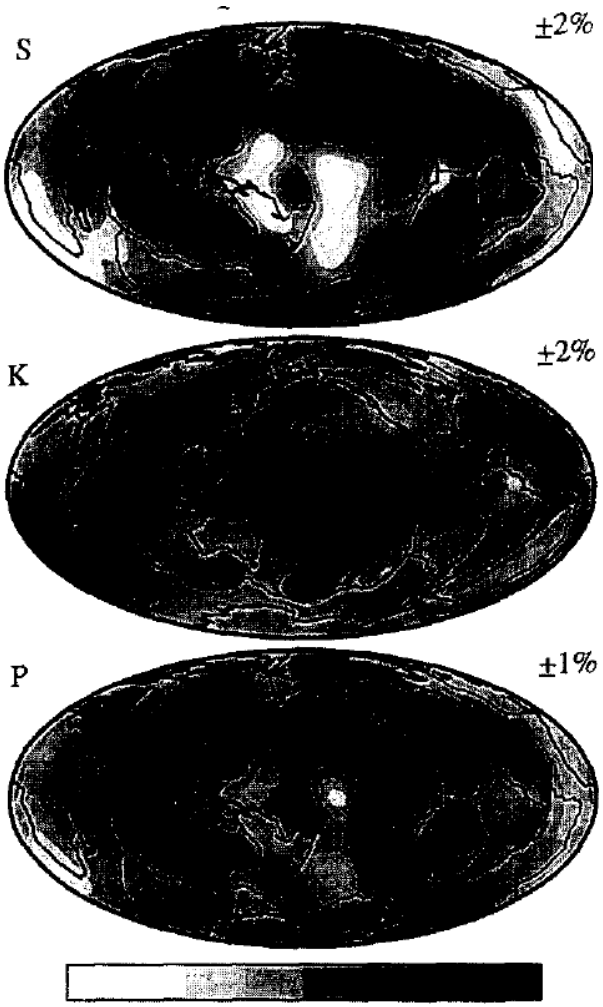

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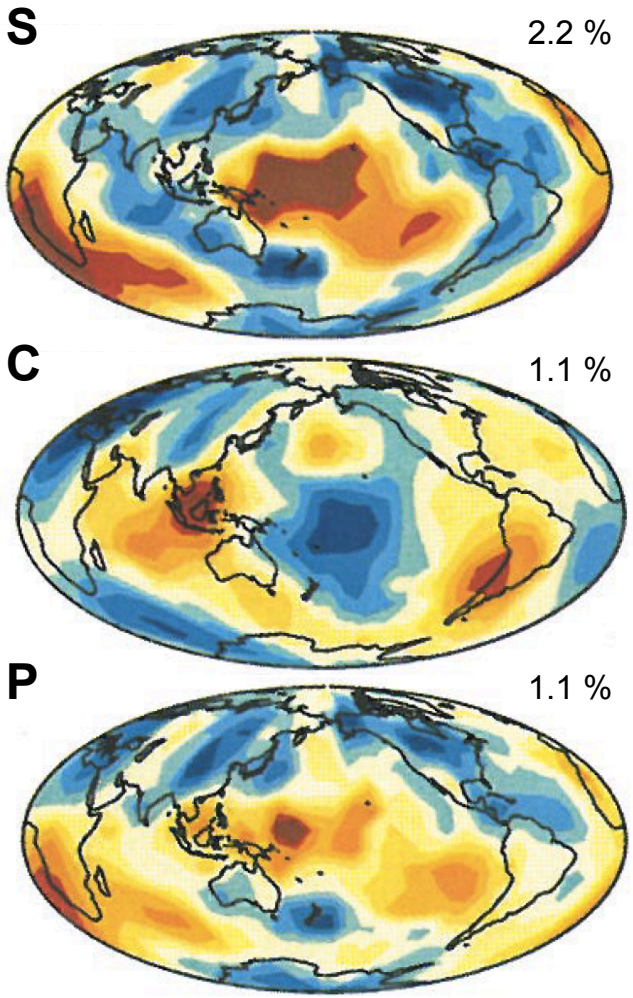

Masters et al., 2000

Negative correlation

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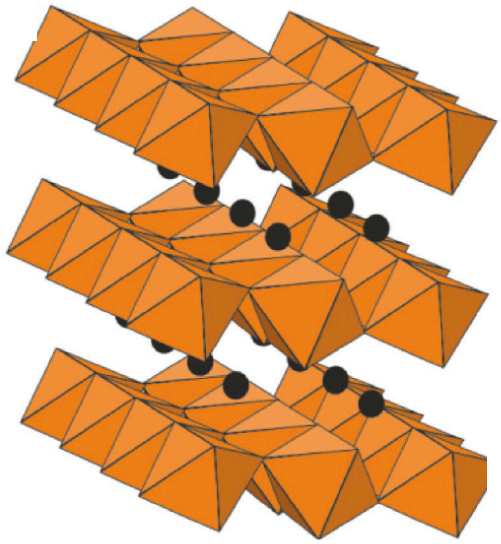
Due to large-scale chemical heterogeneity?

Post-perovskite as alternative explanation

- Lower mantle phase transition, denser than perovskite (Pv)
- pPv has higher V_S and lower V_P than Pv ➔ higher ratio



Cobden et al., 2014

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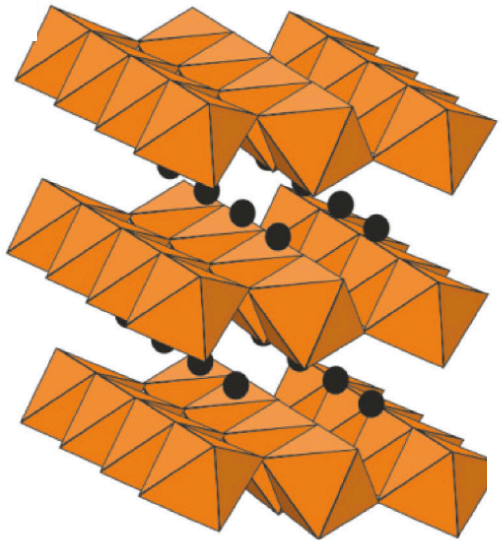

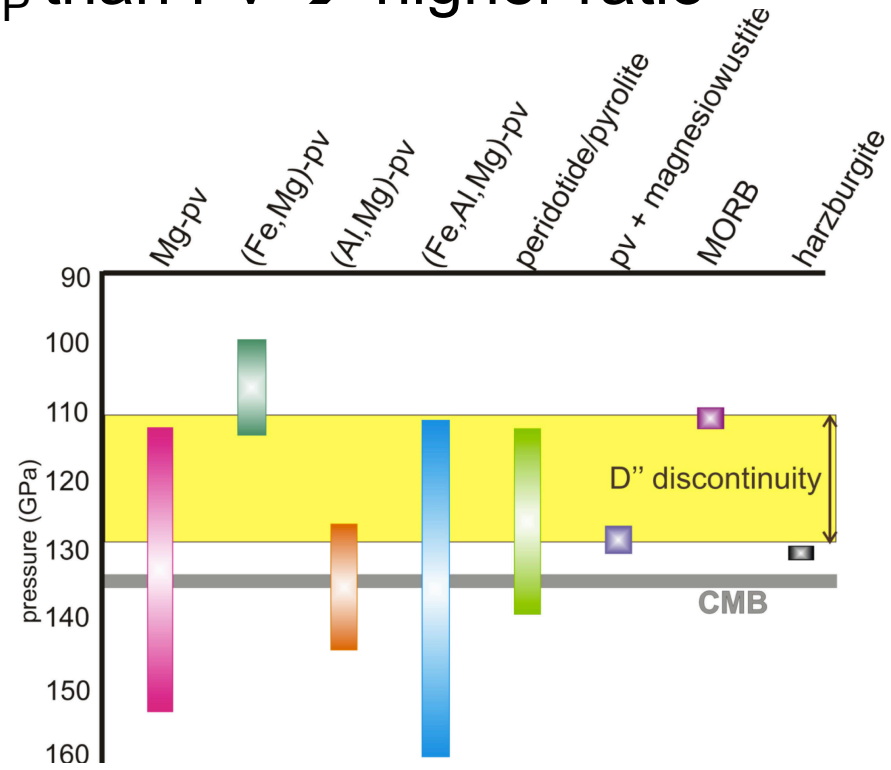

But:

- Stability of pPv?
- Occurrence wide-spread?

Cobden et al., 2014

Our approach

We investigate:

- Influence of post-perovskite on global tomography?
- pPv feasible explanation for the high S/P ratio and negative S-C correlation in the lower mantle?
- Useful for distinguishing thermal and thermochemical convection?

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Mantle dynamics

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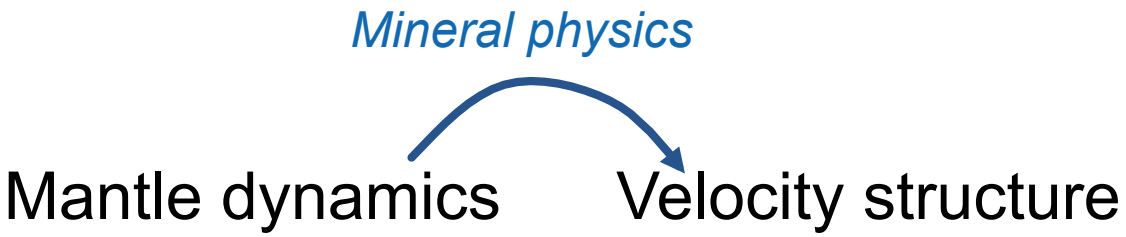

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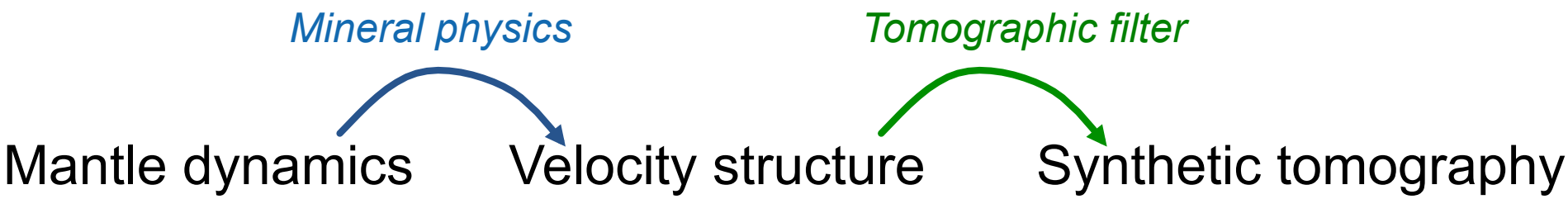

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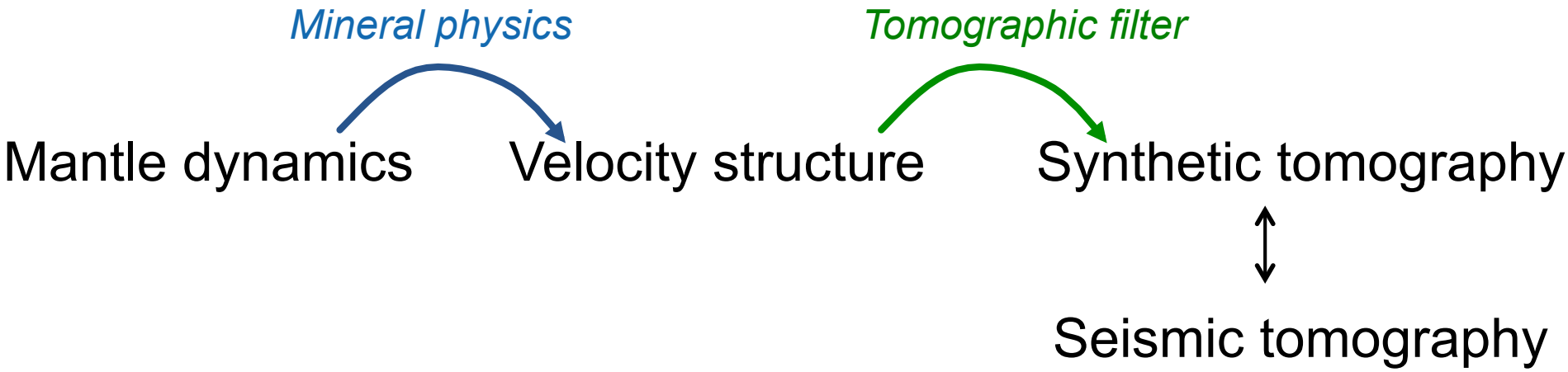
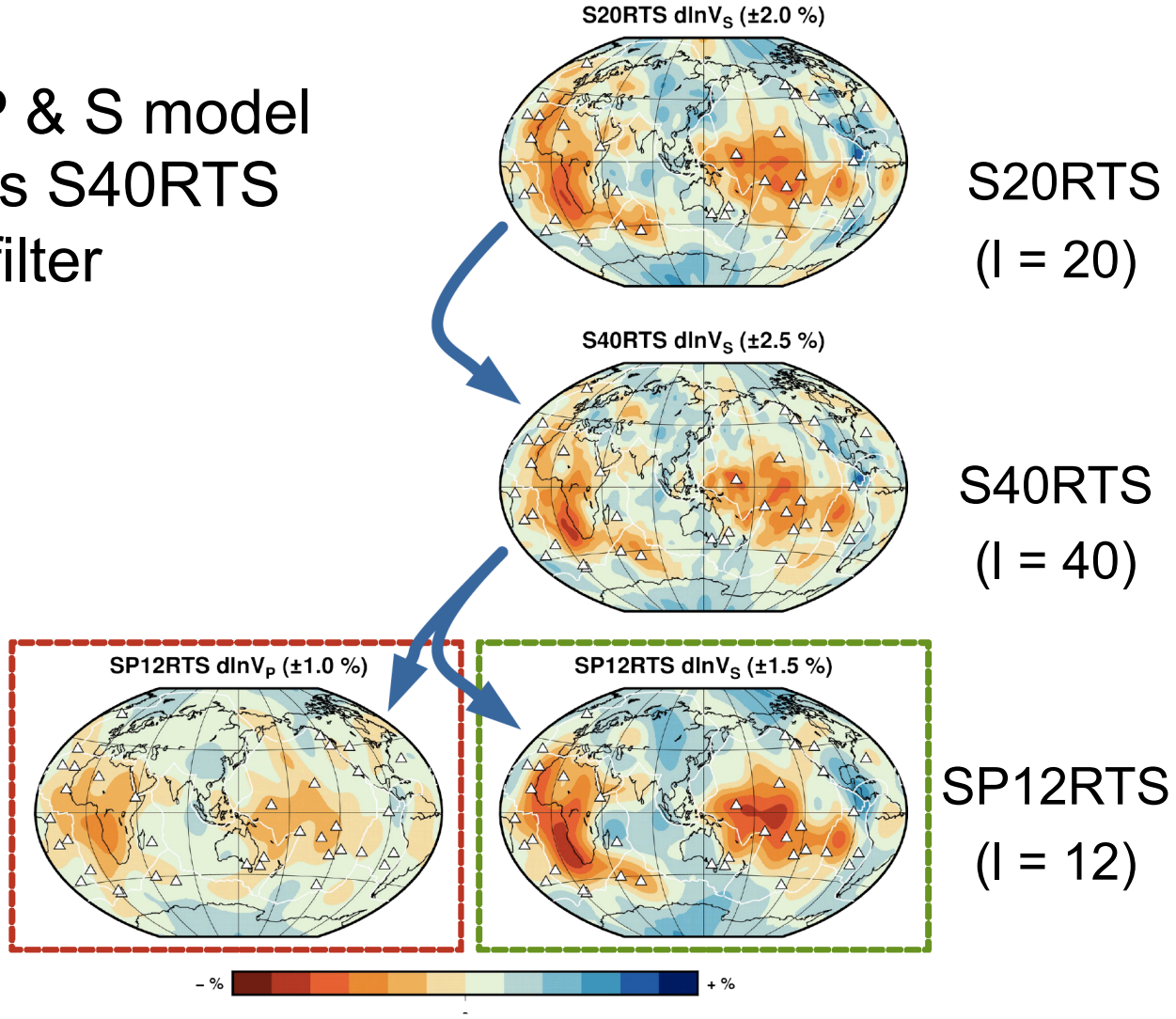


Model SP12RTS

- Long-wavelength P & S model
- Same framework as S40RTS
- Joint tomographic filter

➔ Crucial for studying ratios and correlations!



S20RTS
(l = 20)

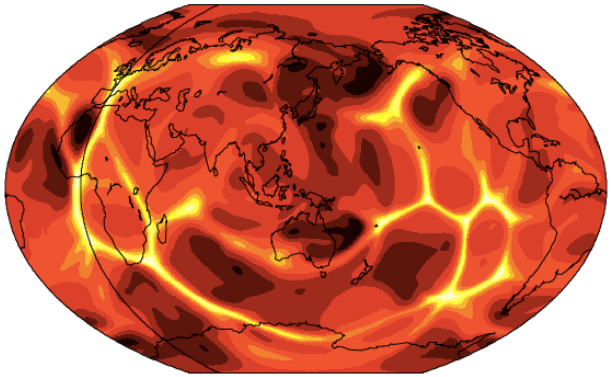
S40RTS
(l = 40)

SP12RTS
(l = 12)

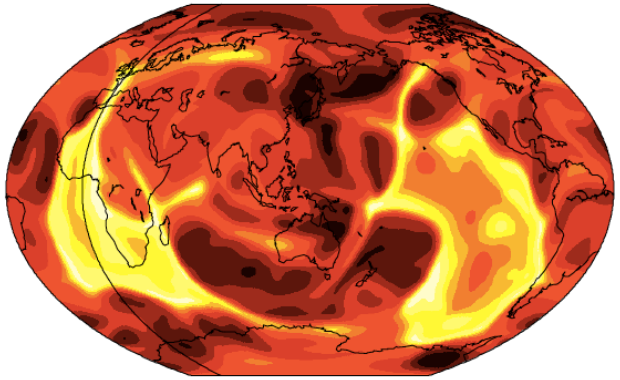
Ritsema et al., 1999
Ritsema et al., 2011
Koelemeijer et al., 2016

Geodynamic models

Isochemical



Thermochemical



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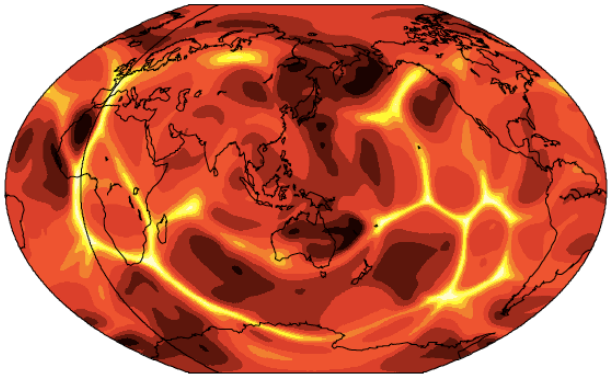

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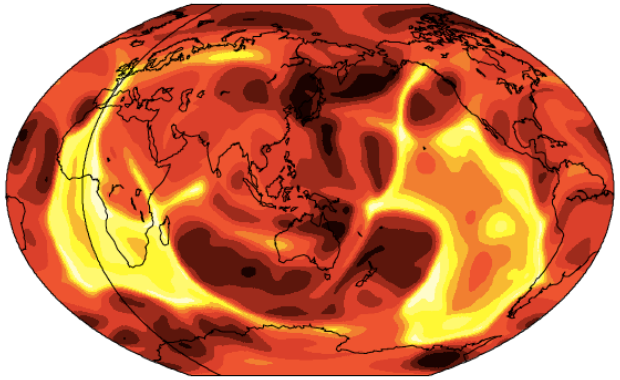
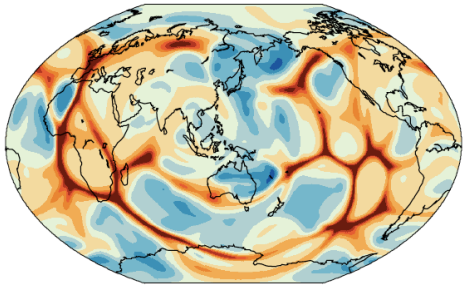
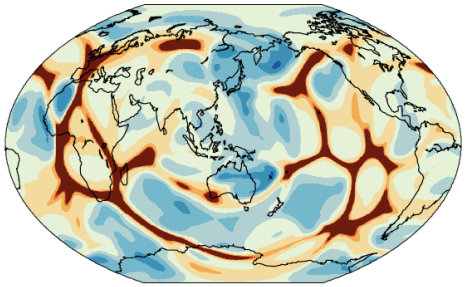


TH-PY



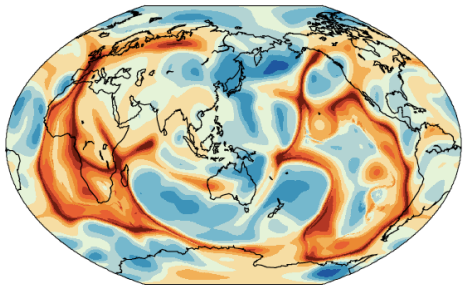
Pyrolite

TH-PY-pPv



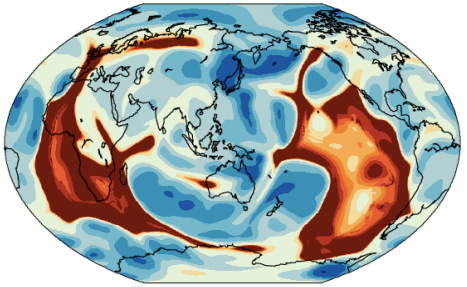
Pyrolite + pPv

TC-PYBA



Pyrolite+basalt

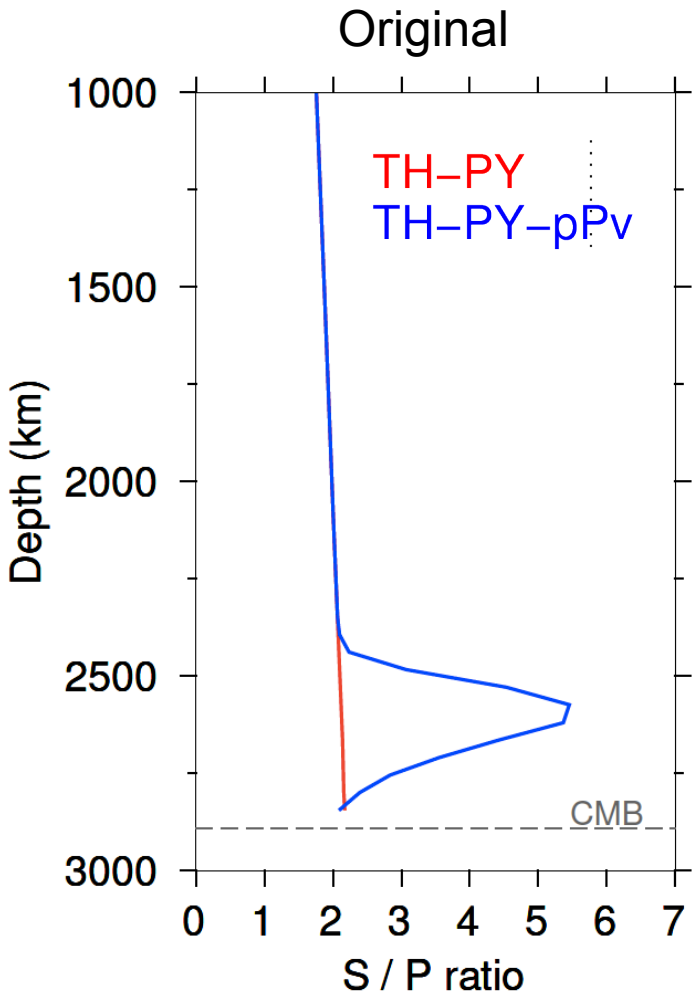
TC-PYBA-pPv



Pyrolite+basalt+pPv

$dlnV_S$ (±2%) @ 2650 km depth

Effects of tomographic filtering: ratio



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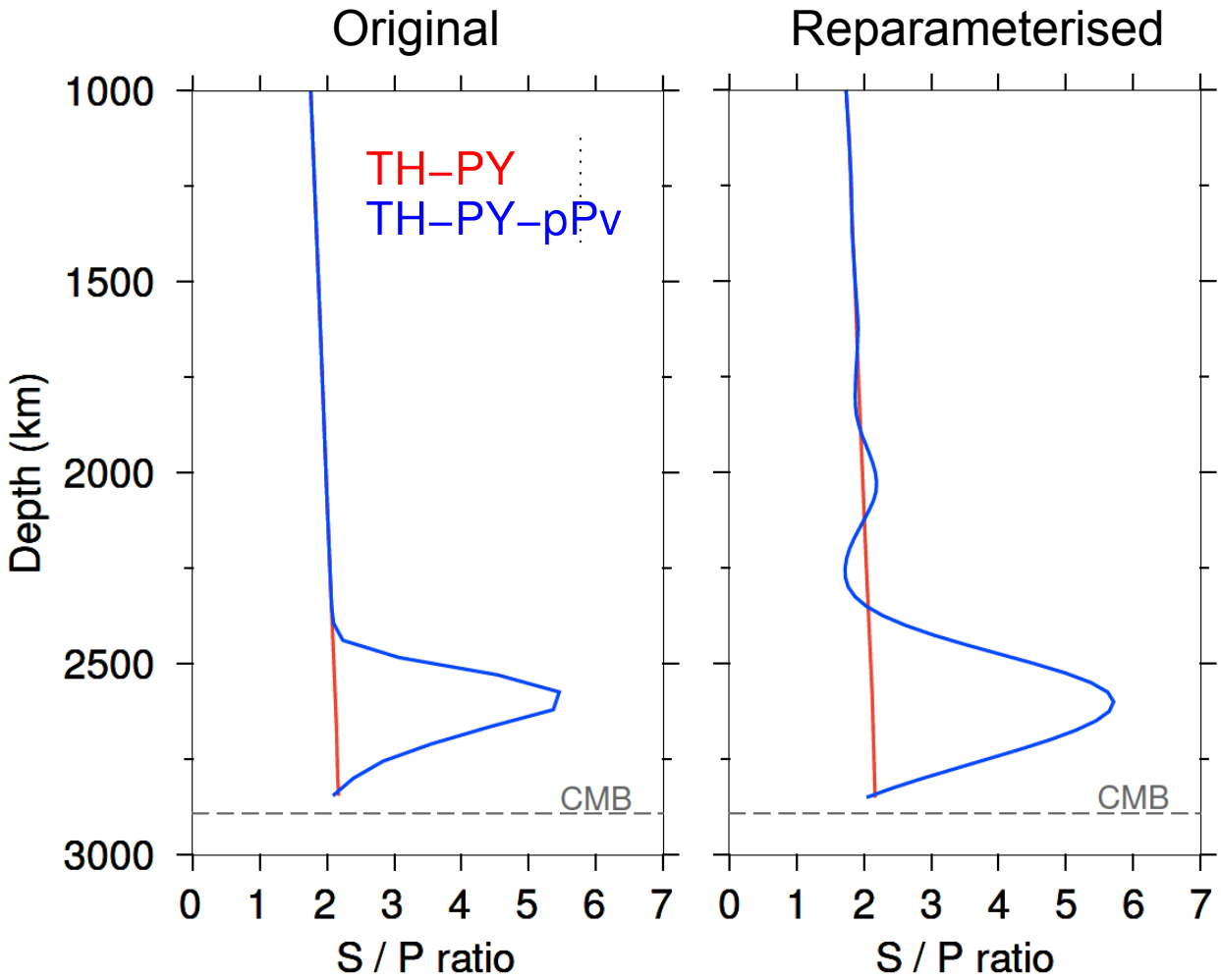

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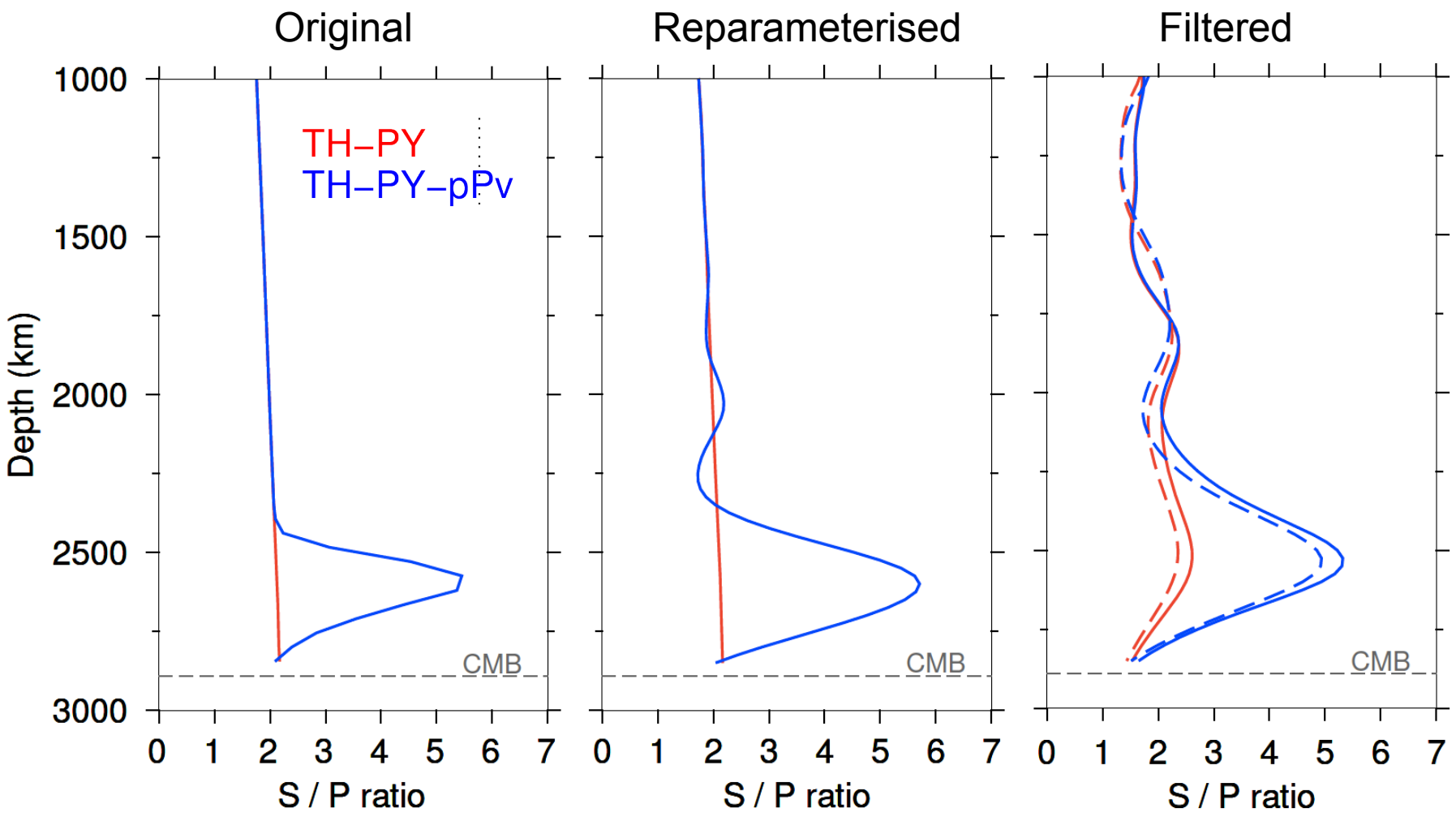

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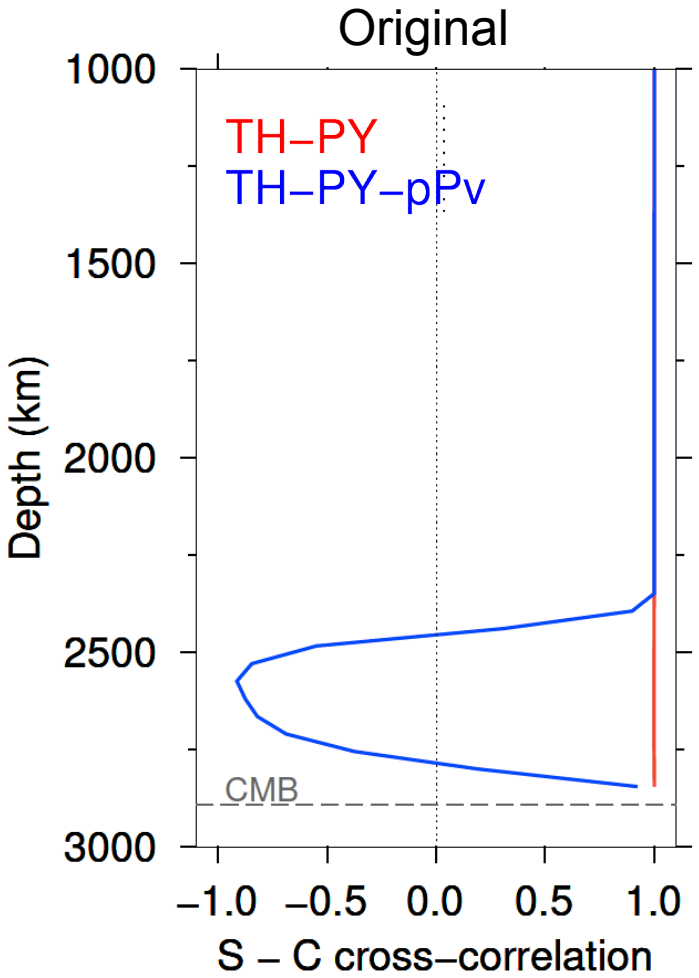

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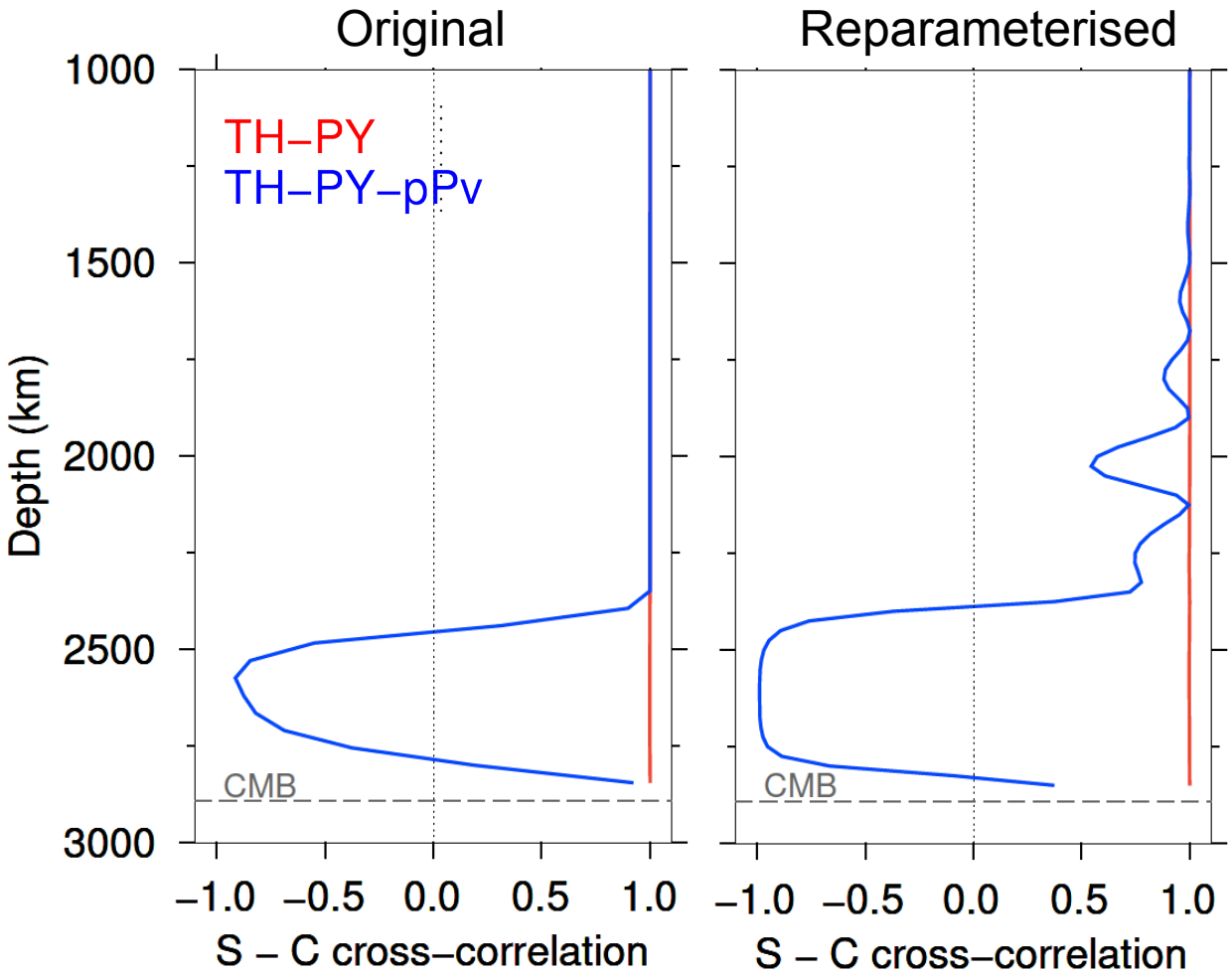

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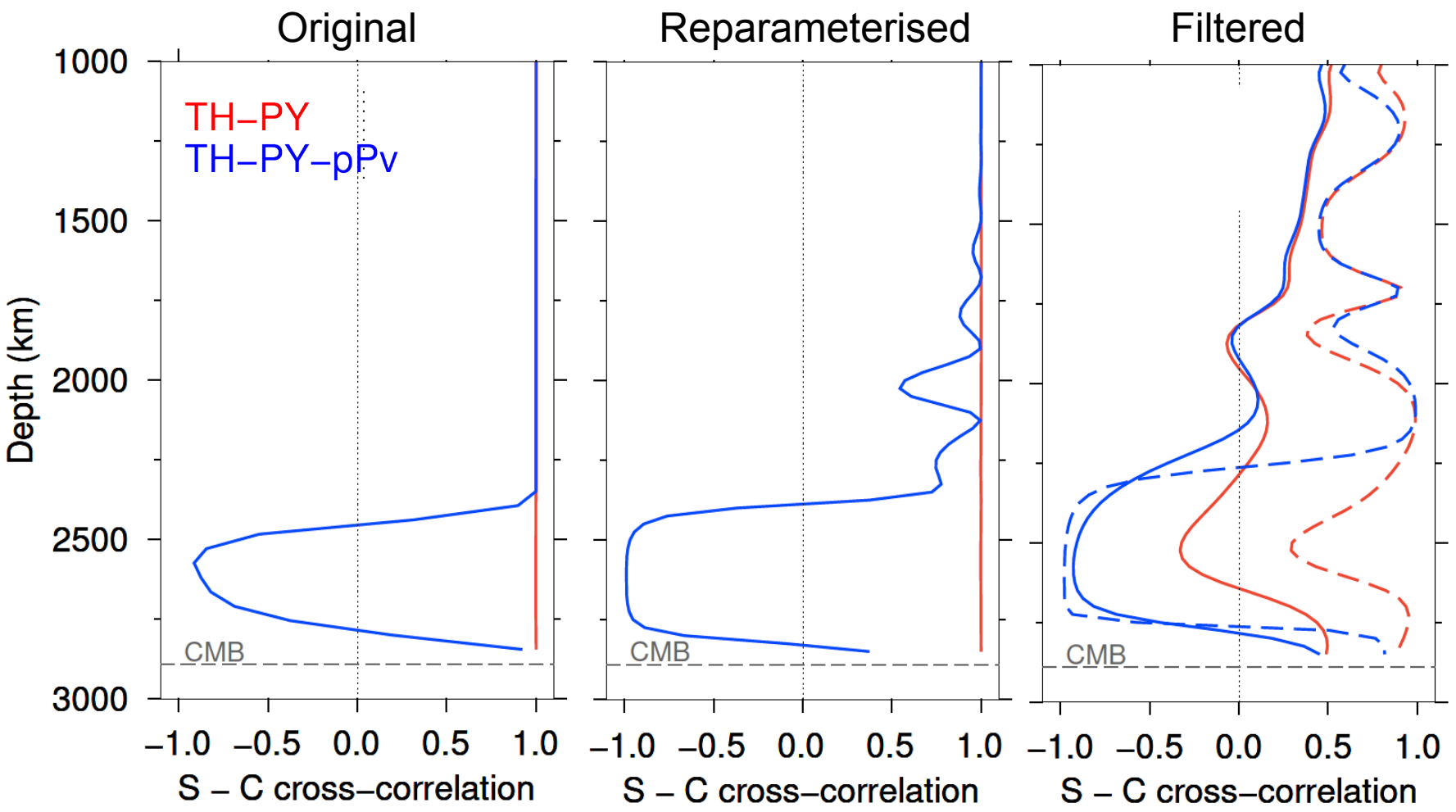
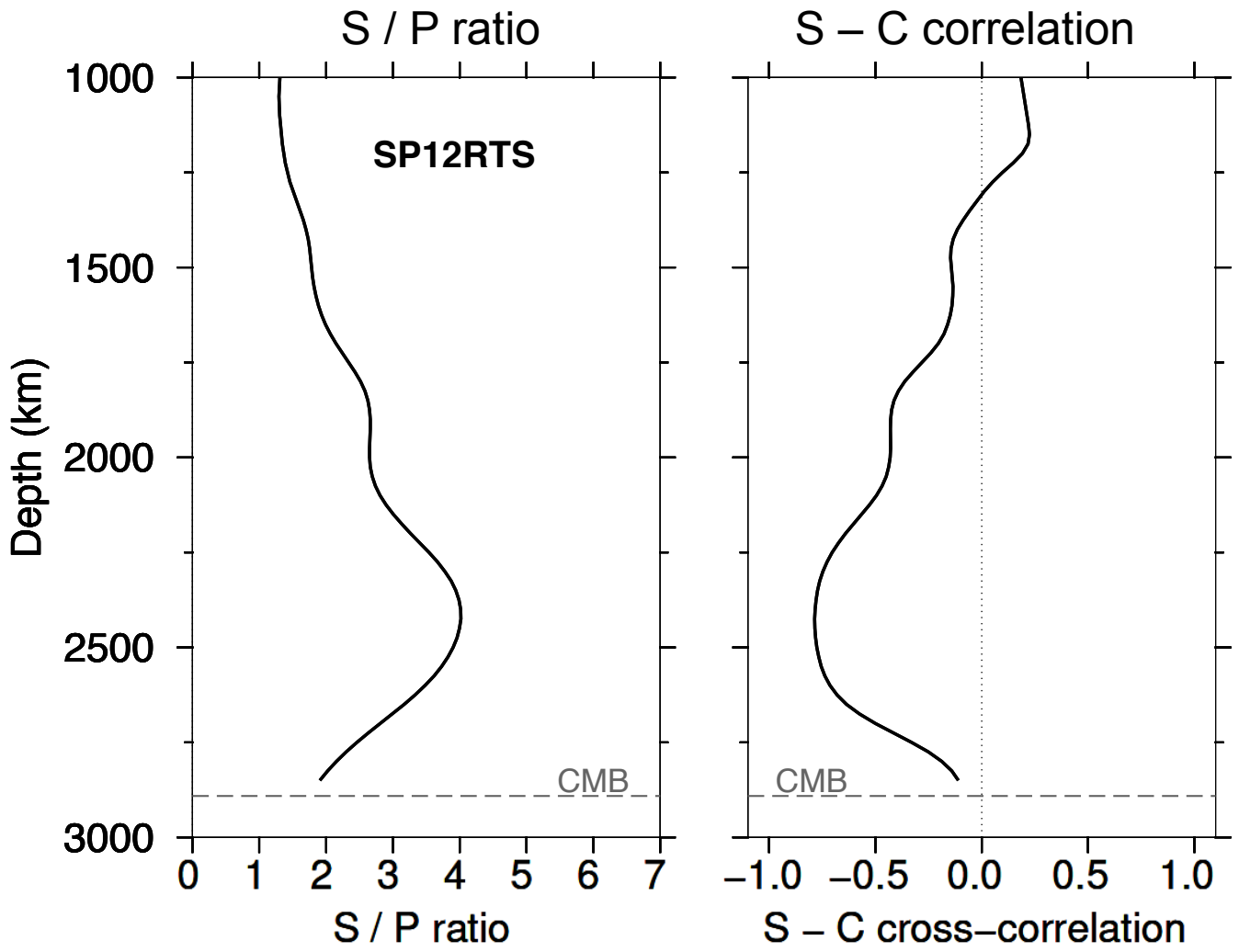


Tomographic-geodynamic model comparison



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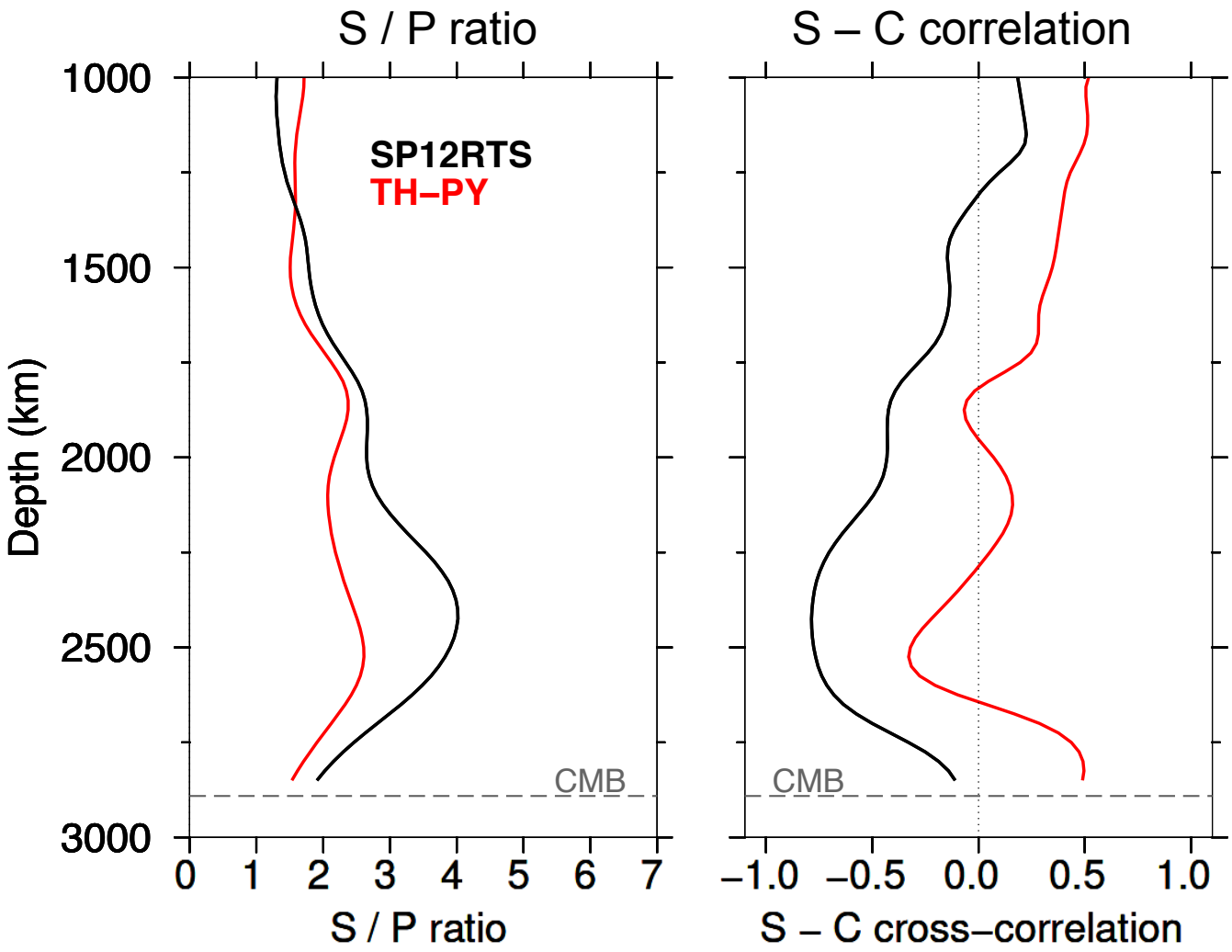

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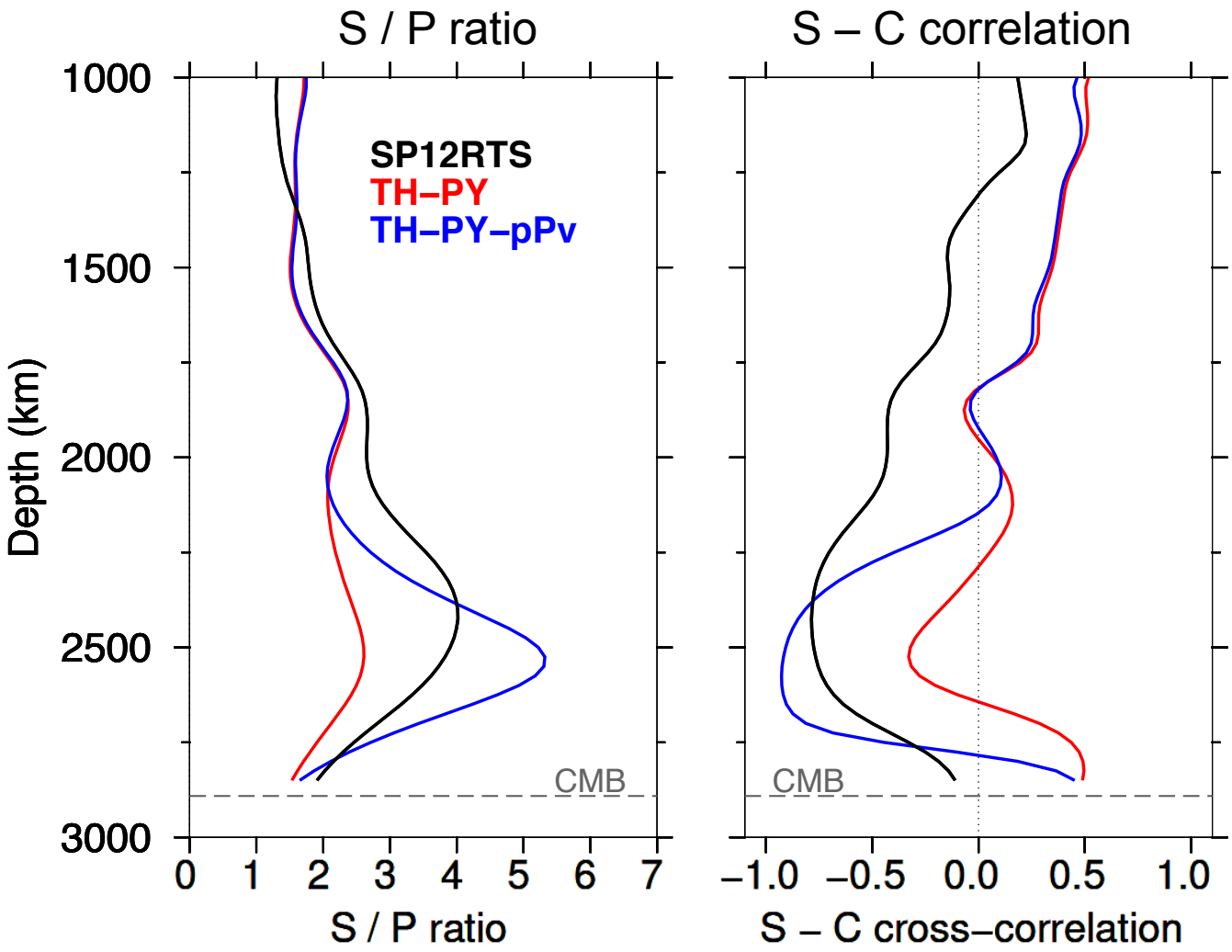

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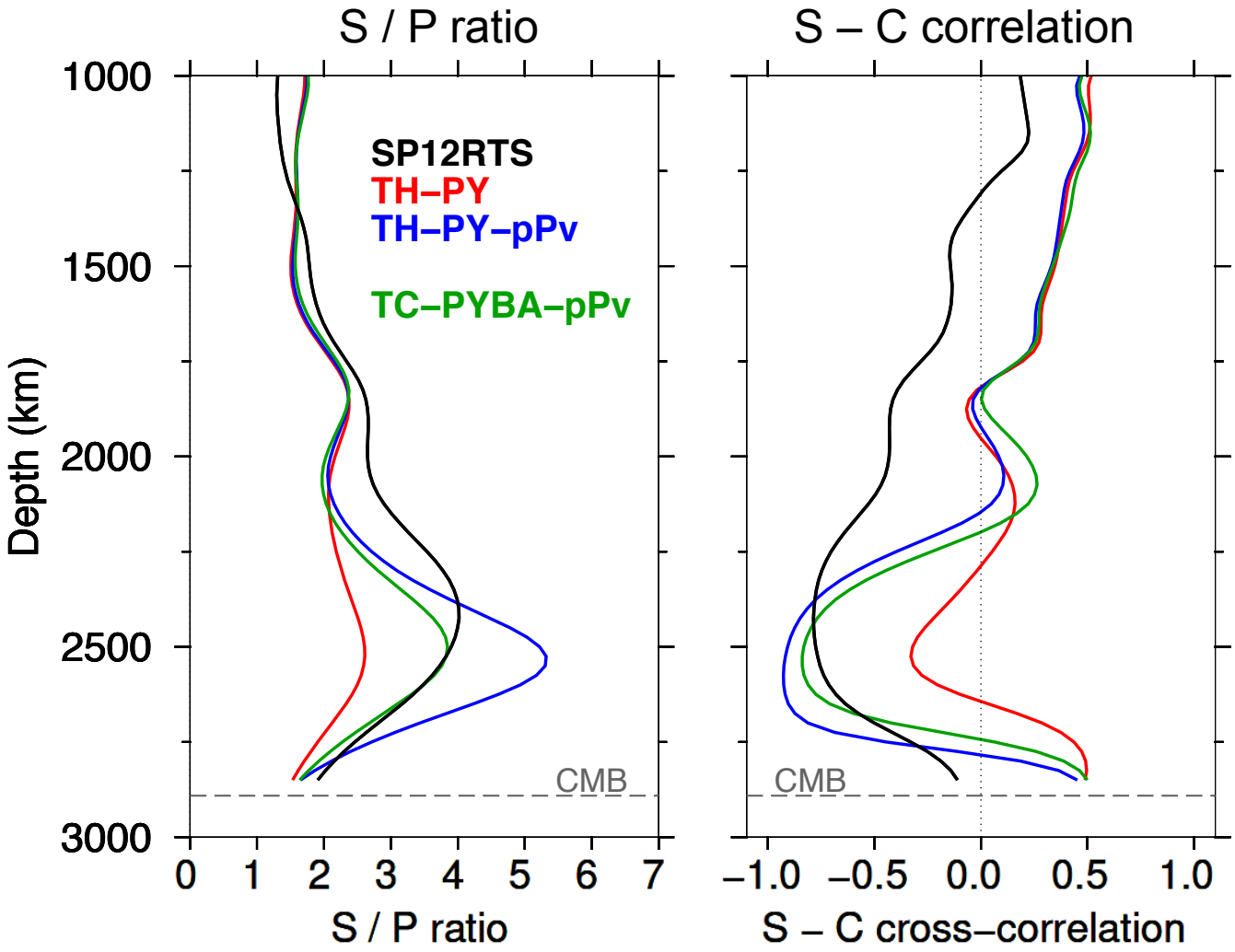
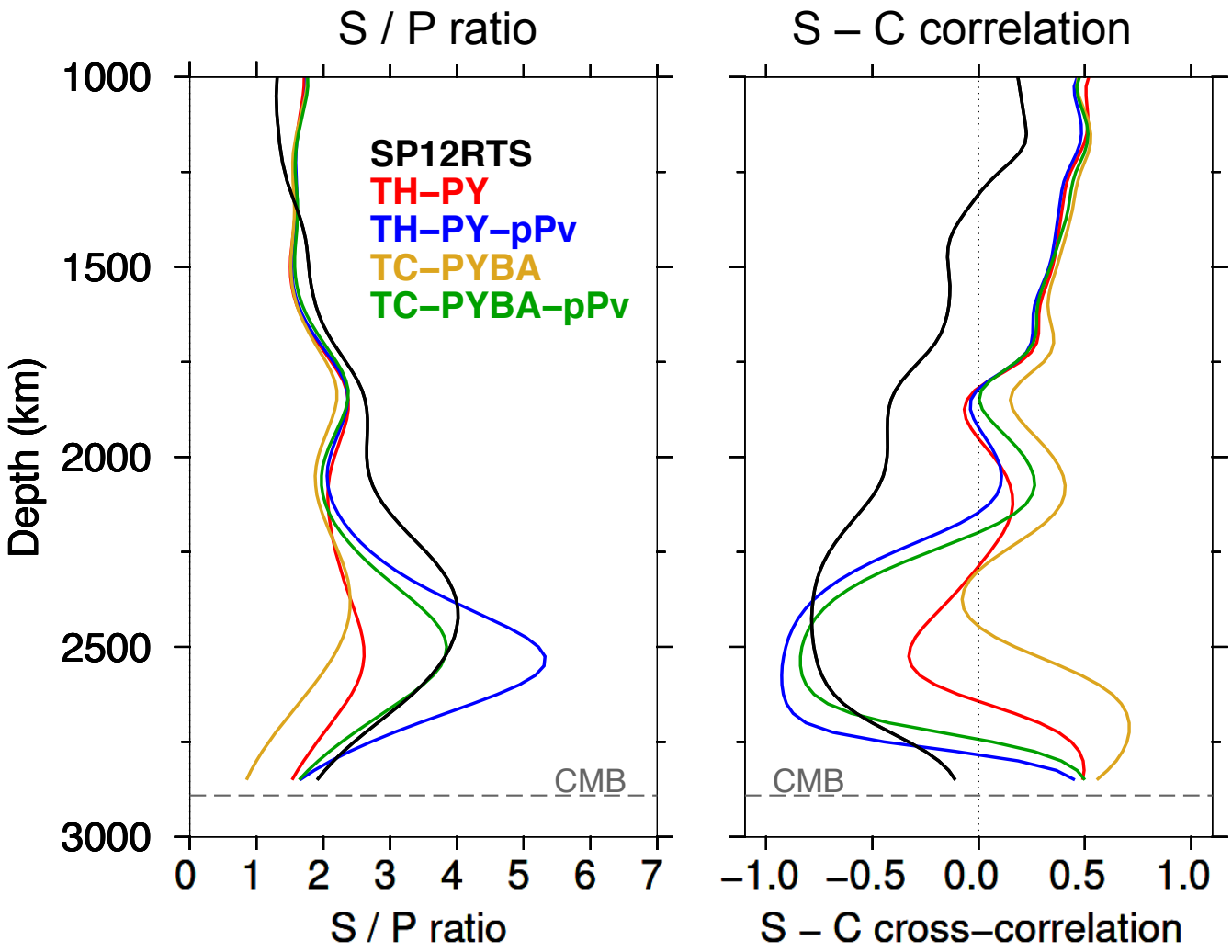
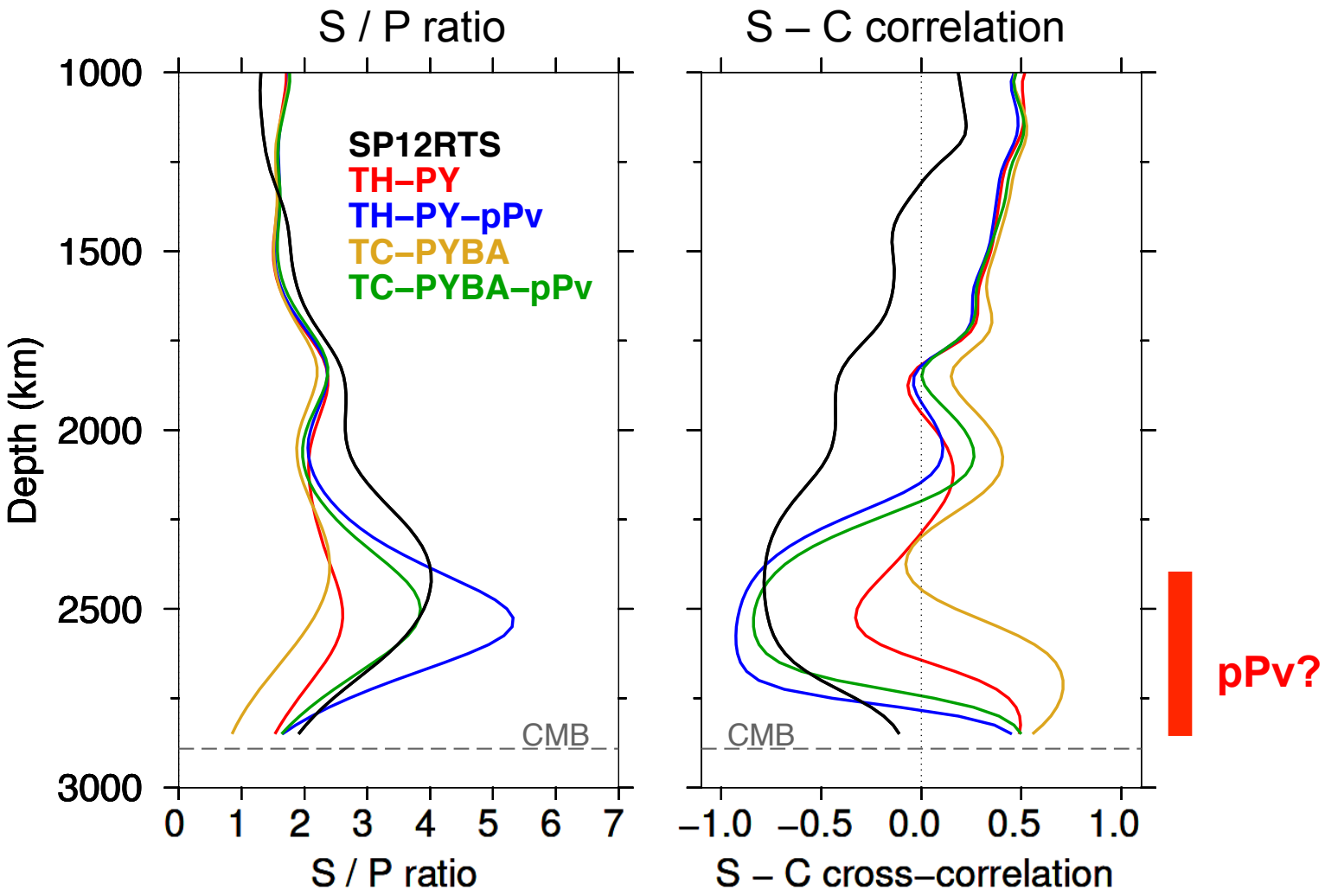


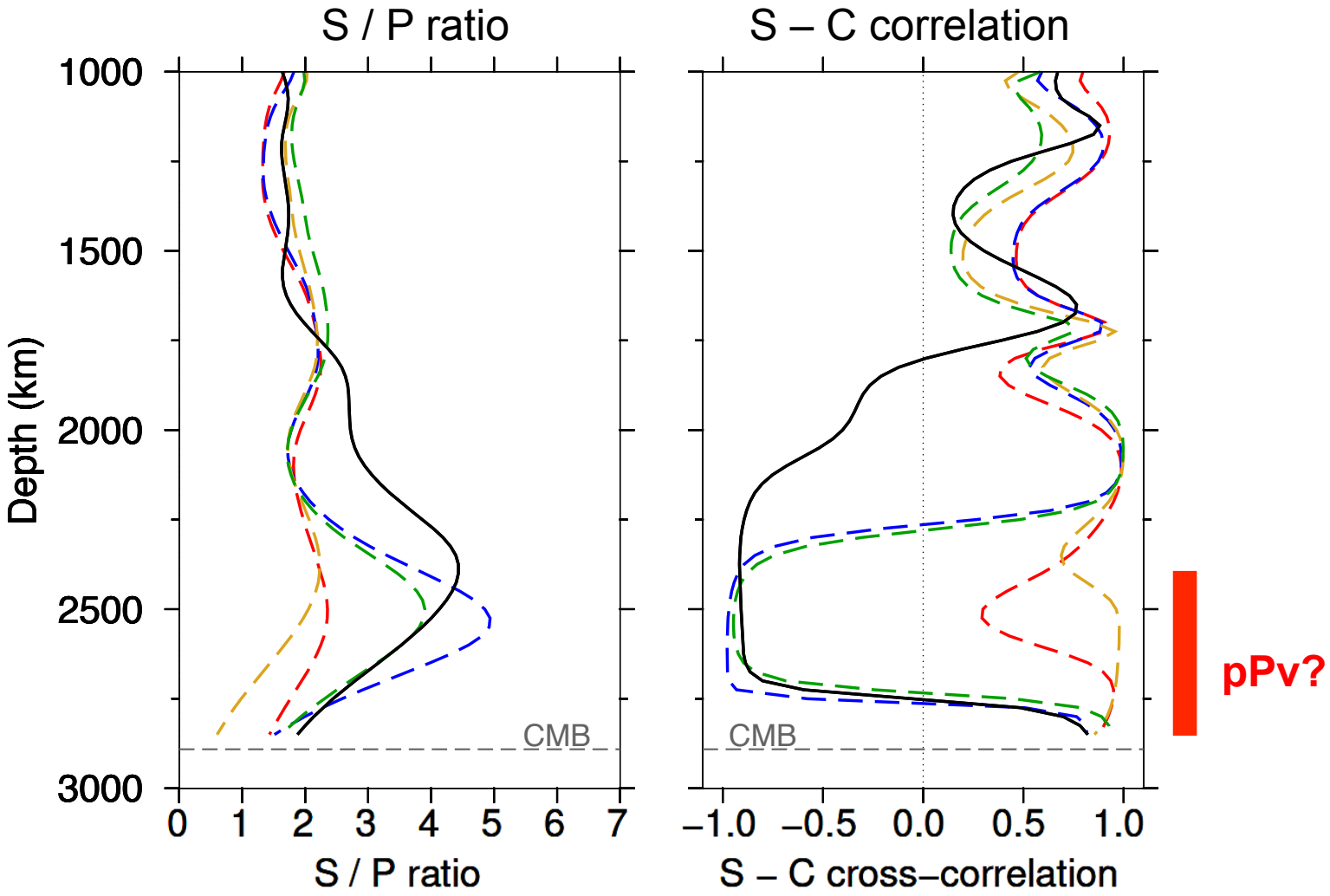
Tomographic-geodynamic model comparison



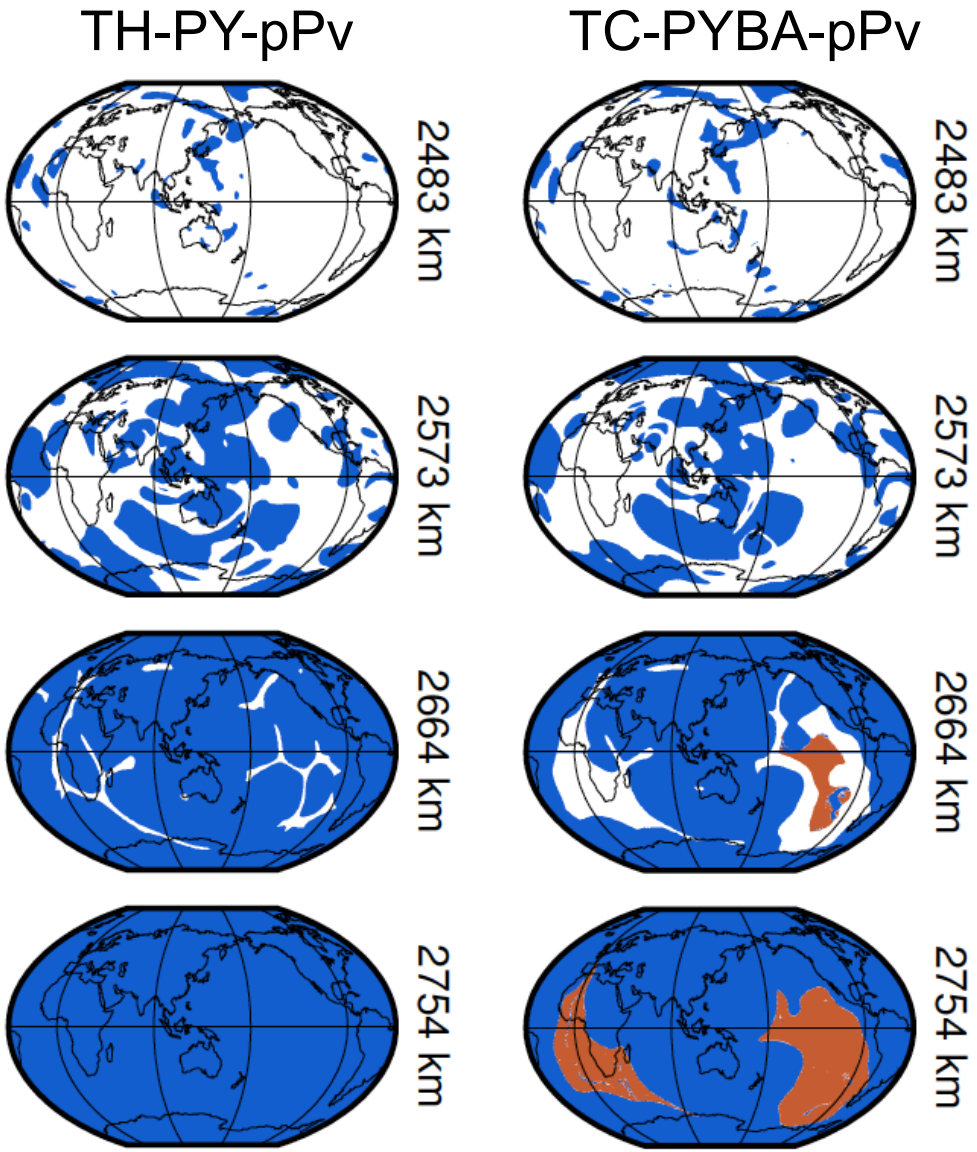
Tomographic-geodynamic model comparison



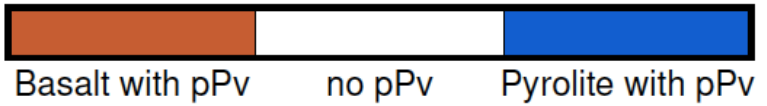
Tomographic-geodynamic model comparison l=2



Occurrence of pPv in geodynamic models



- Total amount of pPv is similar in TH and TC models
- Below 2750 km, pPv is everywhere
- pPv also occurs in the LLSVPs

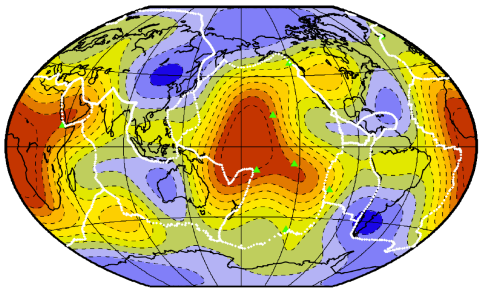


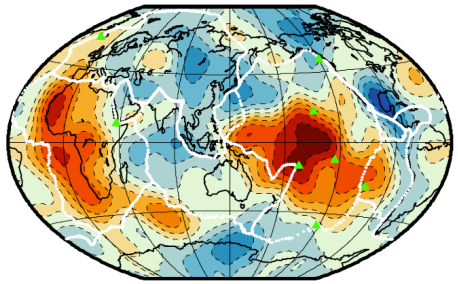
Summary

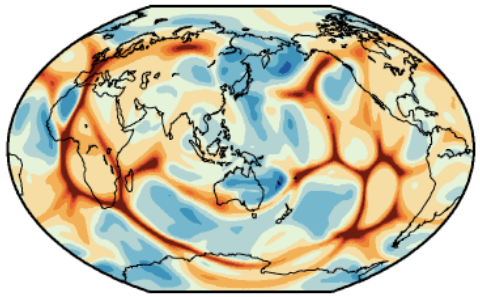
Tomographic-geodynamic model comparisons indicate:

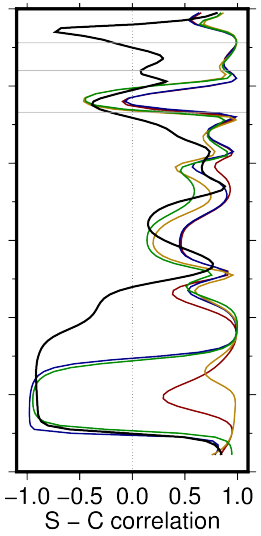
- pPv explains many characteristics of global tomography
- Implies presence of pPv inside the LLSVPs
- Possible depth offset between clusters lost in filtering
- Older results can be explained by data weighting

High S/P ratio and negative S-C correlation do not uniquely point to chemical variations









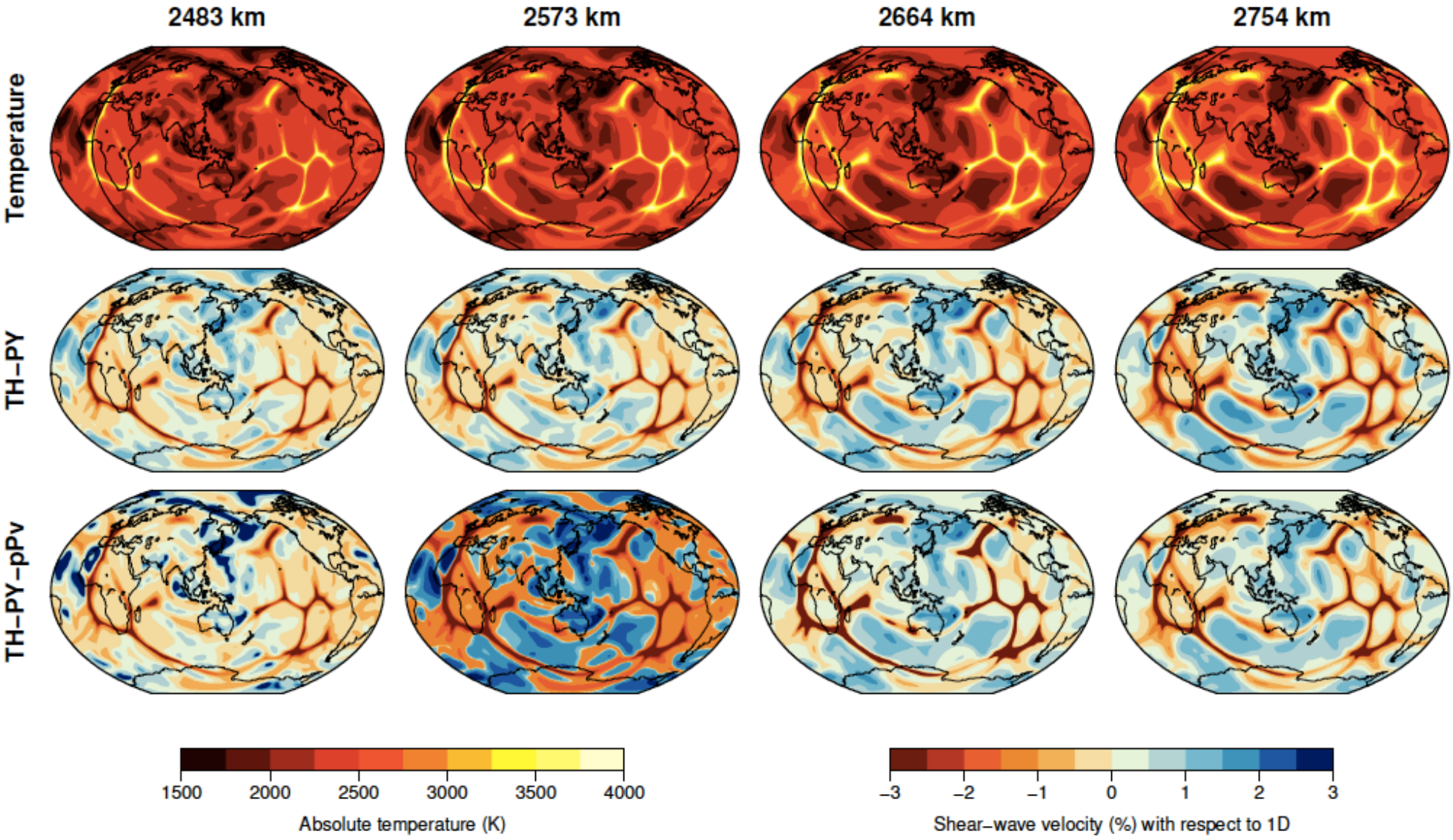
Thank you for your attention

Model SP12RTS (with plotting scripts / codes) available on:
www.earth.ox.ac.uk/~univ4152/downloads_sp12rts.html

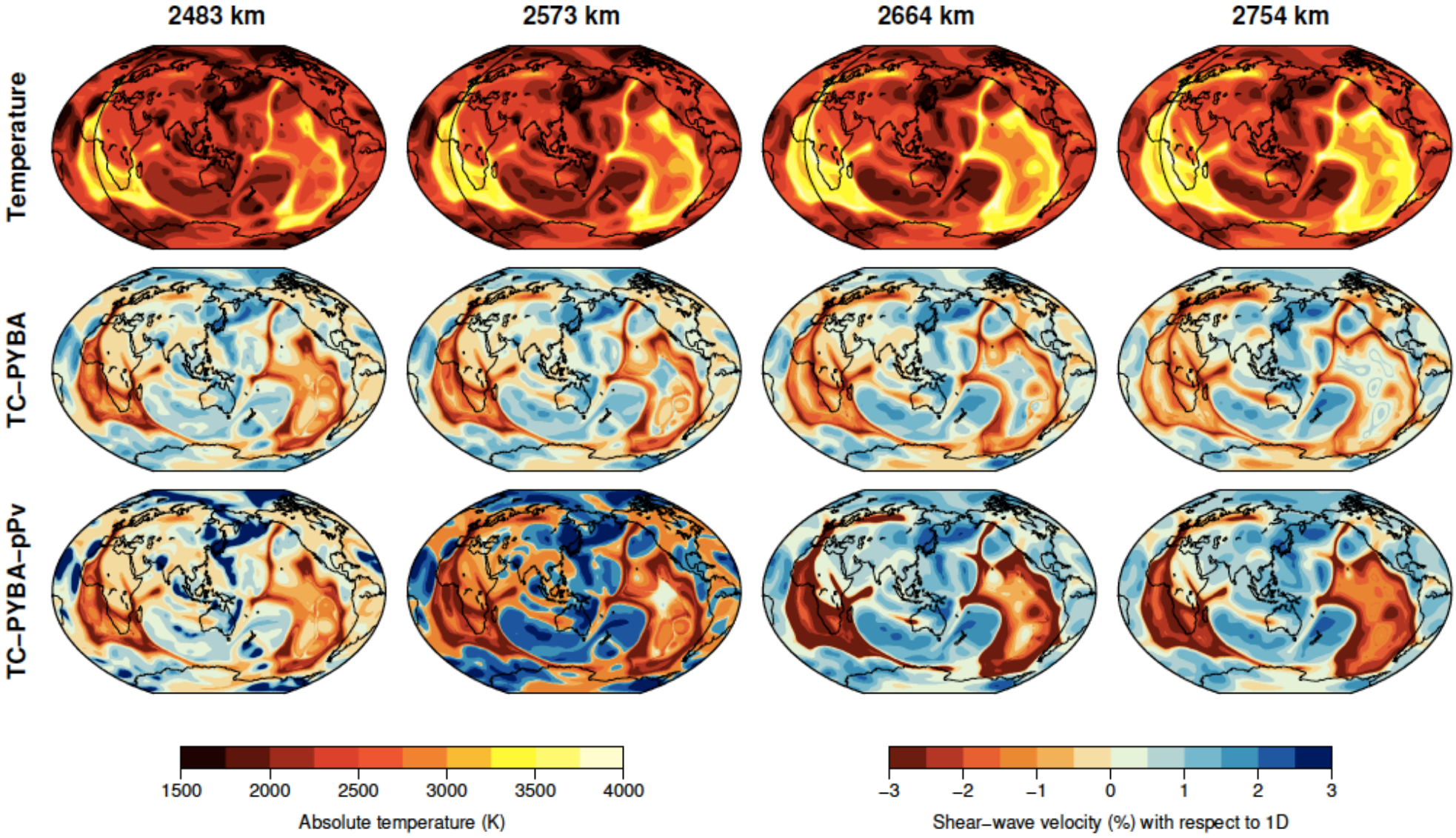
Get in touch if you want to use the tomographic filter

Extra slides: Geodynamic comparisons

Geodynamic models: isochemical (TH)

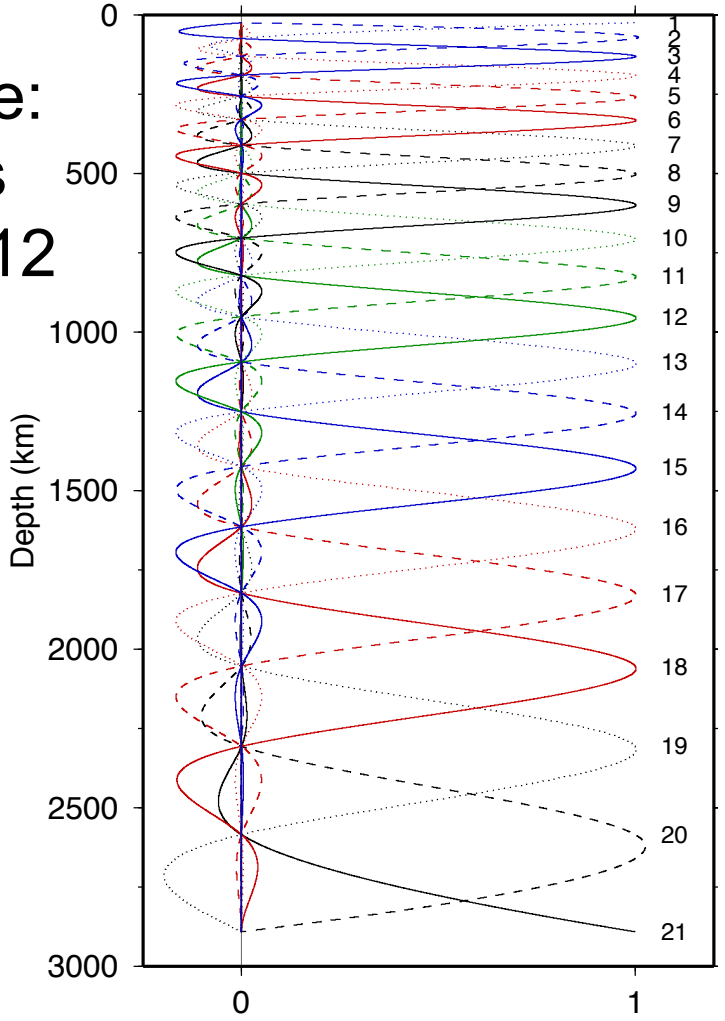


Geodynamic models: thermochemical (TC)



Reparameterisation

- Reparametrise model to be the same:
- Depth parameterized with 21 splines
- Lateral spherical harmonics up to l=12
  - ~ 1600 km @ the surface
  - ~ 900 km @ the CMB
- Tends to broaden structures and reduce amplitudes



Tomographic filtering: resolution operator

$$m = \begin{pmatrix} S \\ P \end{pmatrix}$$

$$m_{out} = R \cdot m_{in}$$

$$R = G^t \cdot G$$

m: model describes both $dlnV_S$ and $dlnV_P$

R: resolution operator of seismic inversion

G: operator of seismic forward problem

G^t: generalised inverse

m_{in}: synthetic input model

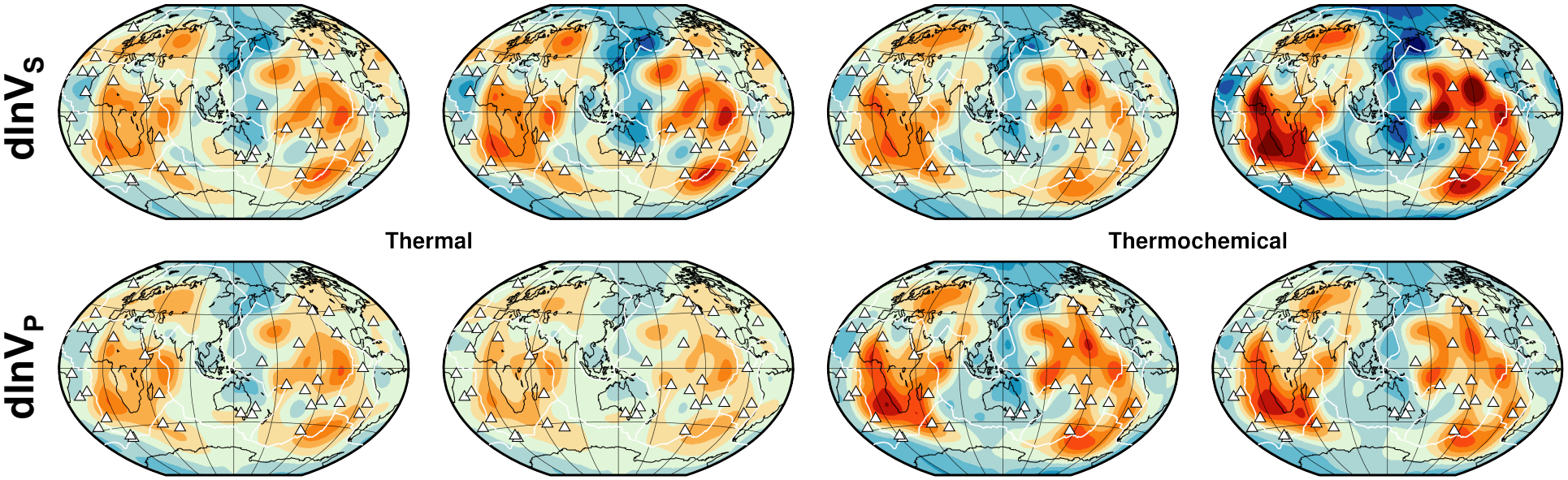
m_{out}: filtered output model

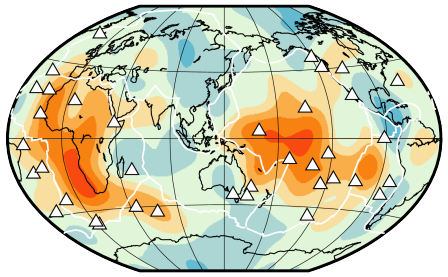
$$\begin{pmatrix} S_{out} \\ P_{out} \end{pmatrix} = \begin{pmatrix} R_{SS} & R_{SP} \\ R_{PS} & R_{PP} \end{pmatrix} \cdot \begin{pmatrix} S_{in} \\ P_{in} \end{pmatrix}$$

- Reduces amplitudes further
- plus vertical and horizontal smearing

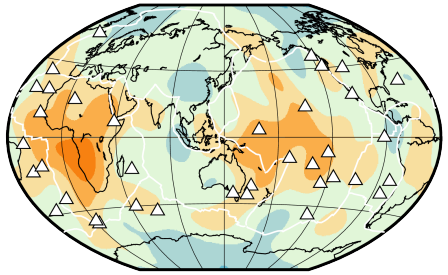
Cross terms are non-zero:
leakage from $dlnV_S$ to $dlnV_P$ and vice versa

Tomographic-geodynamic model comparisons





SP12RTS dlnV$_S$ (±2%)

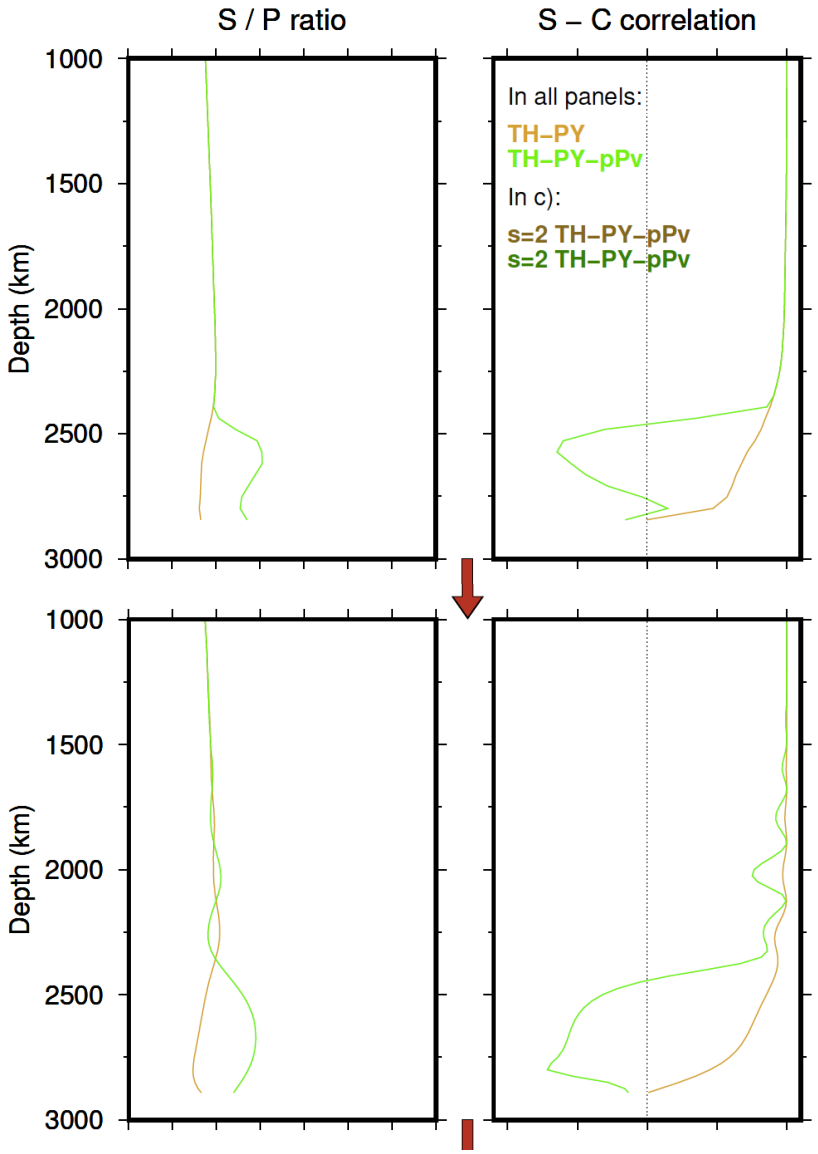


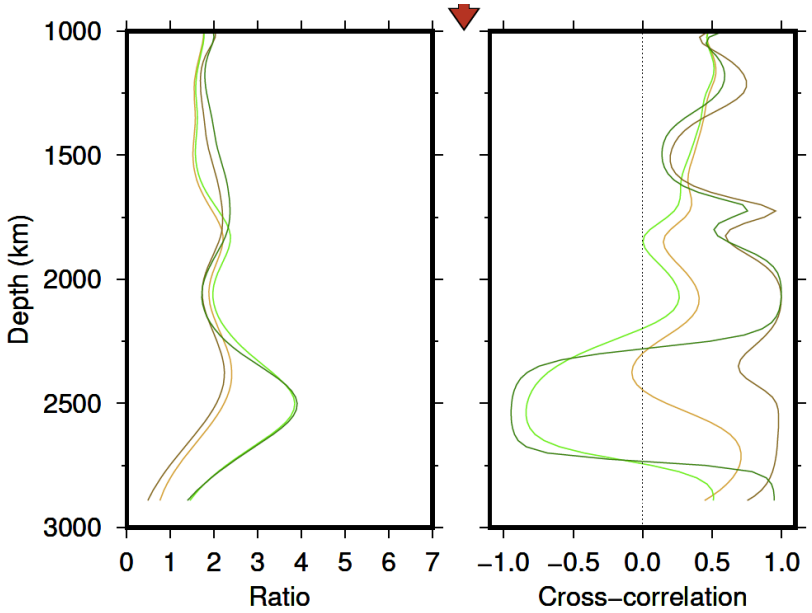
SP12RTS dlnV$_P$ (±1%)

@ 2650 km depth

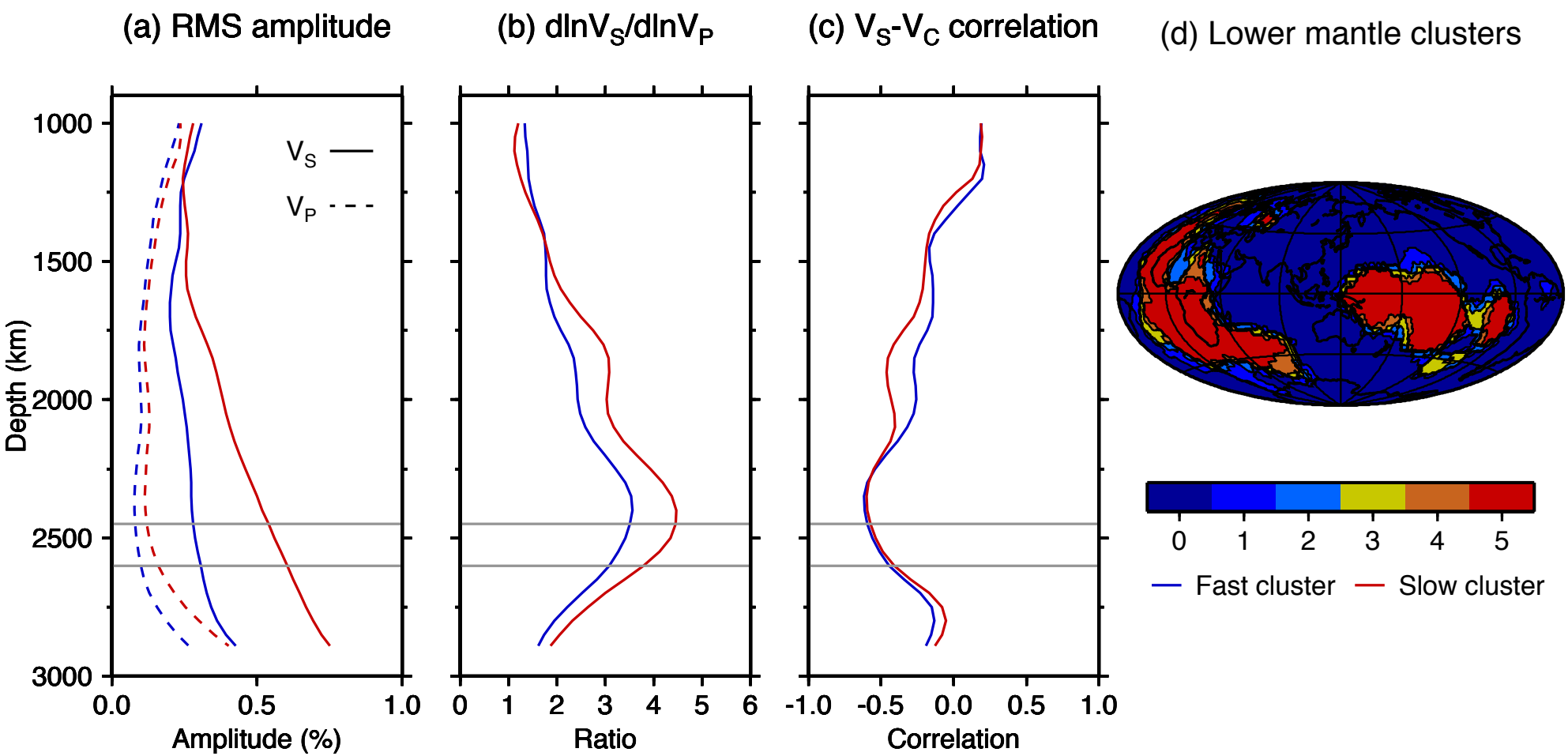
Dependent on plate-tectonic reconstructions ➔ better to compare statistical model properties!

Effect of reparameterisation and filtering



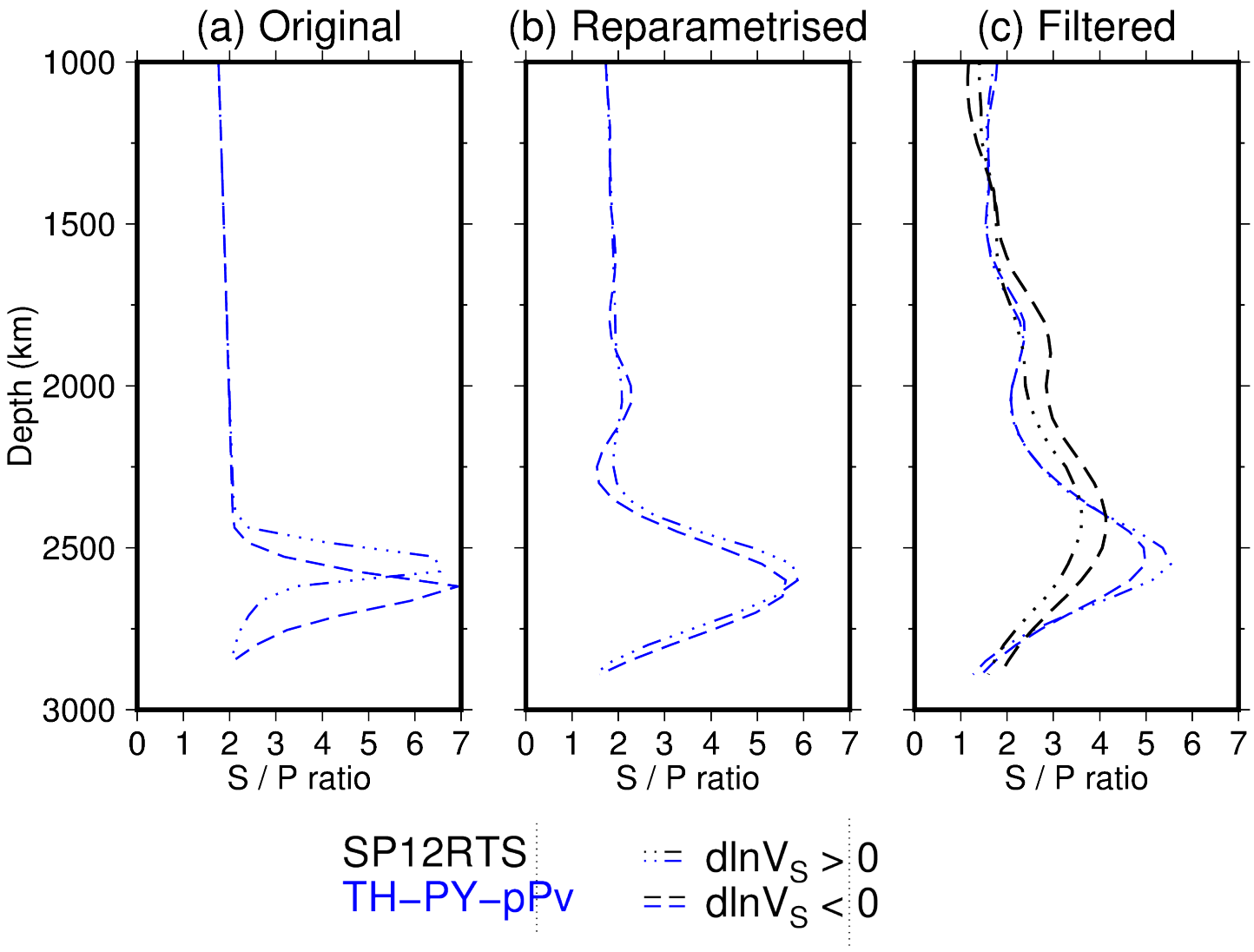


SP12RTS: Fast and slow clusters

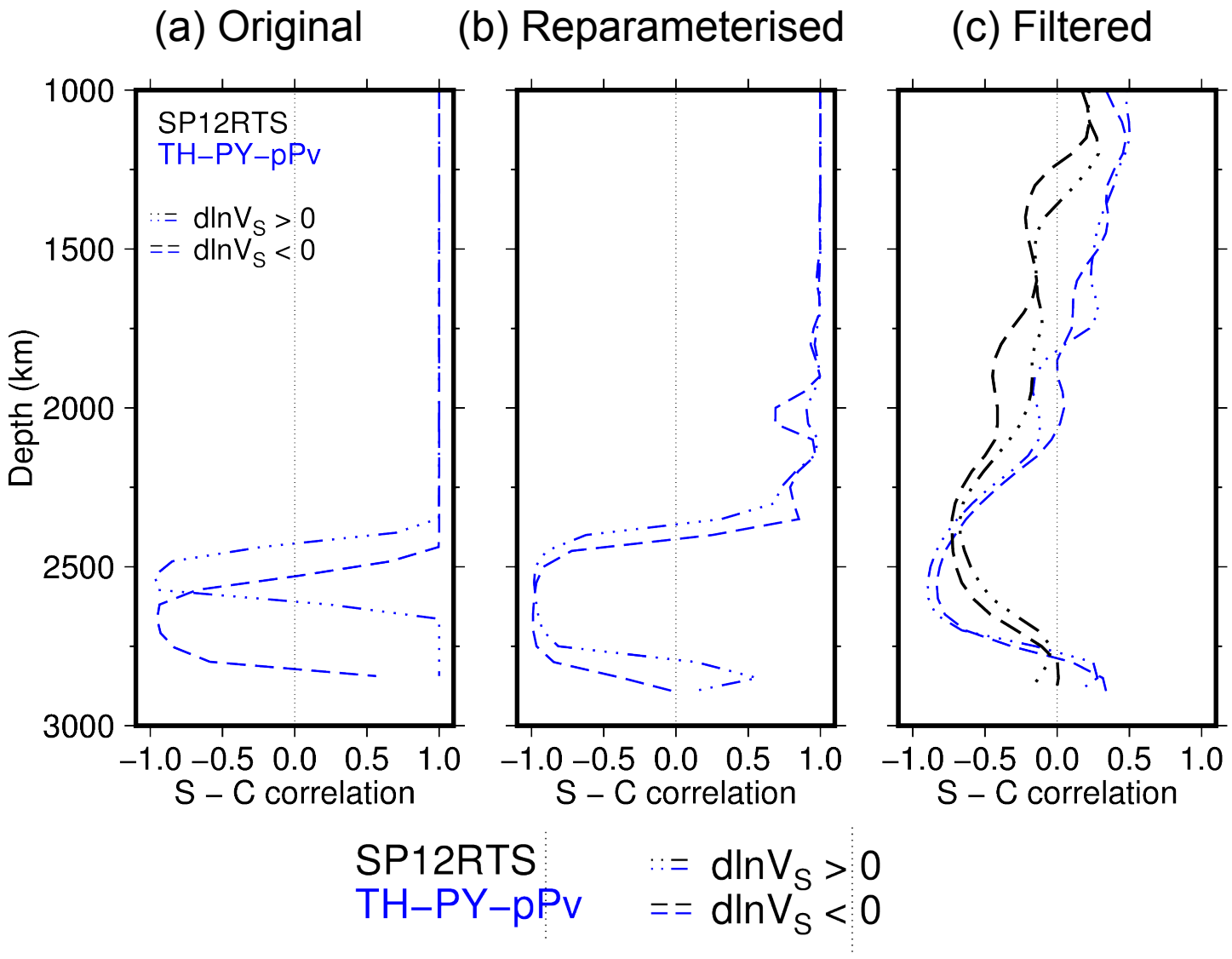


Koelemeijer et al., GJI, 2016

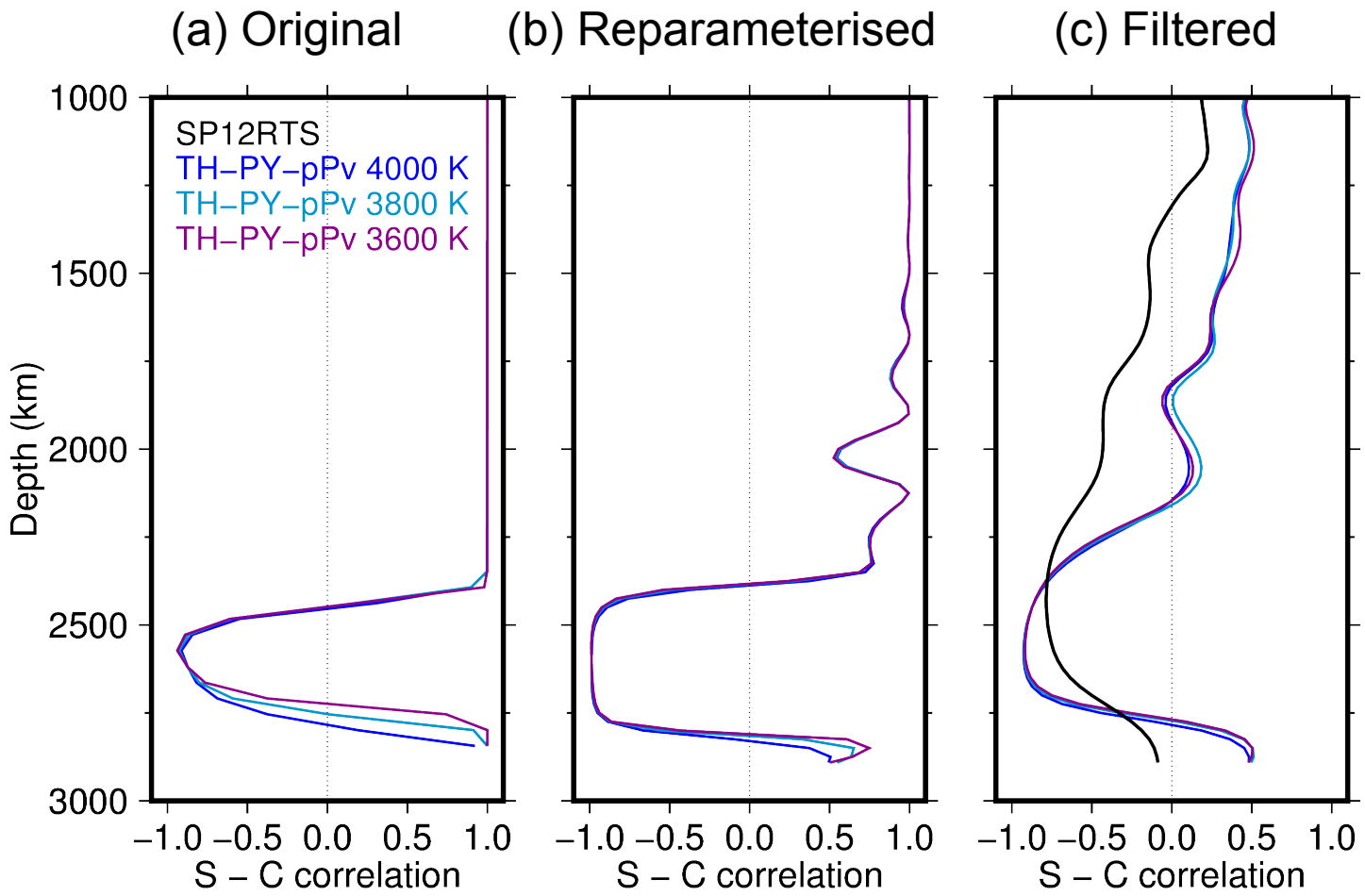
Clusters and tomographic filtering: ratio



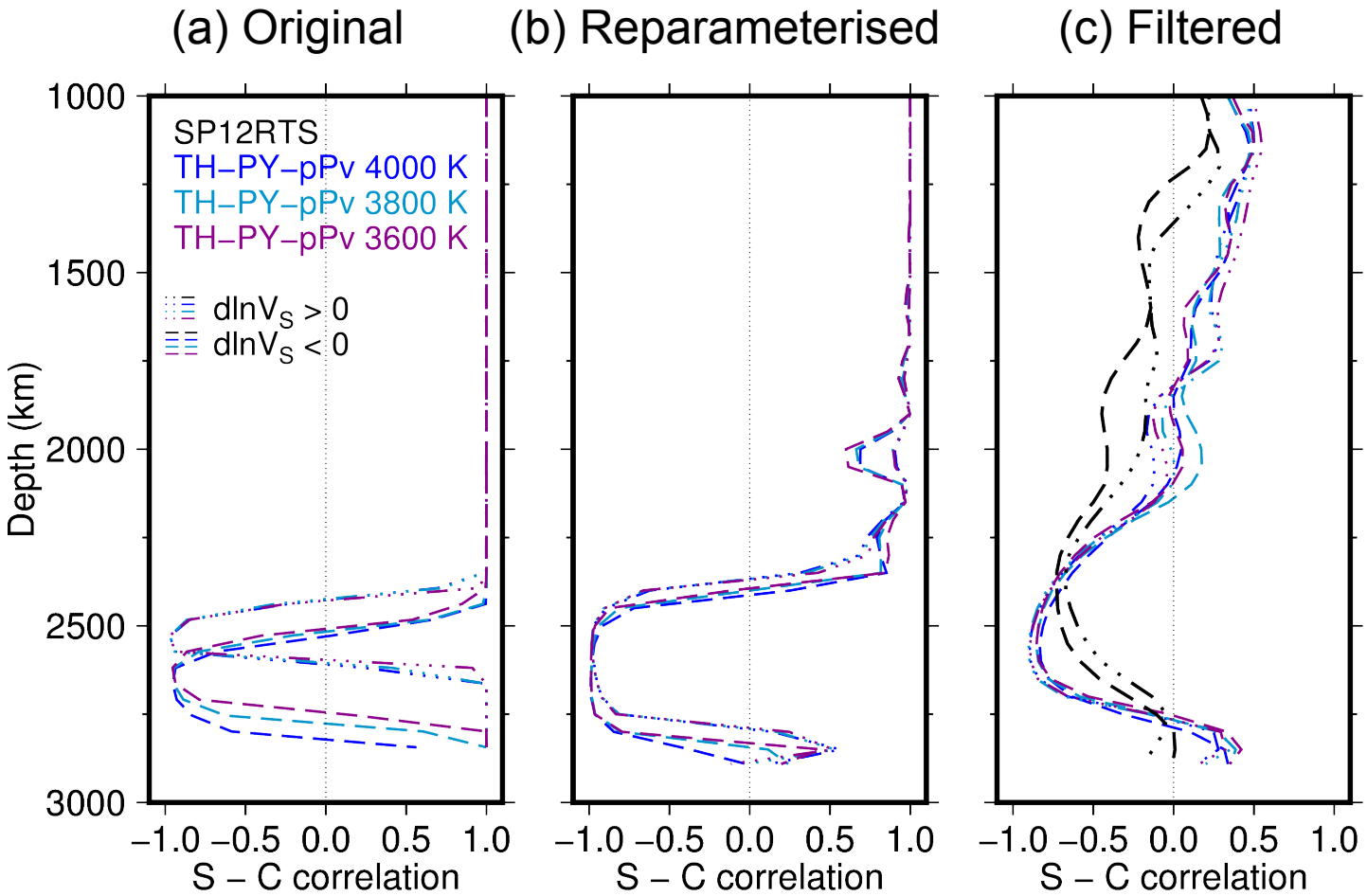
Clusters and tomographic filtering: correlation



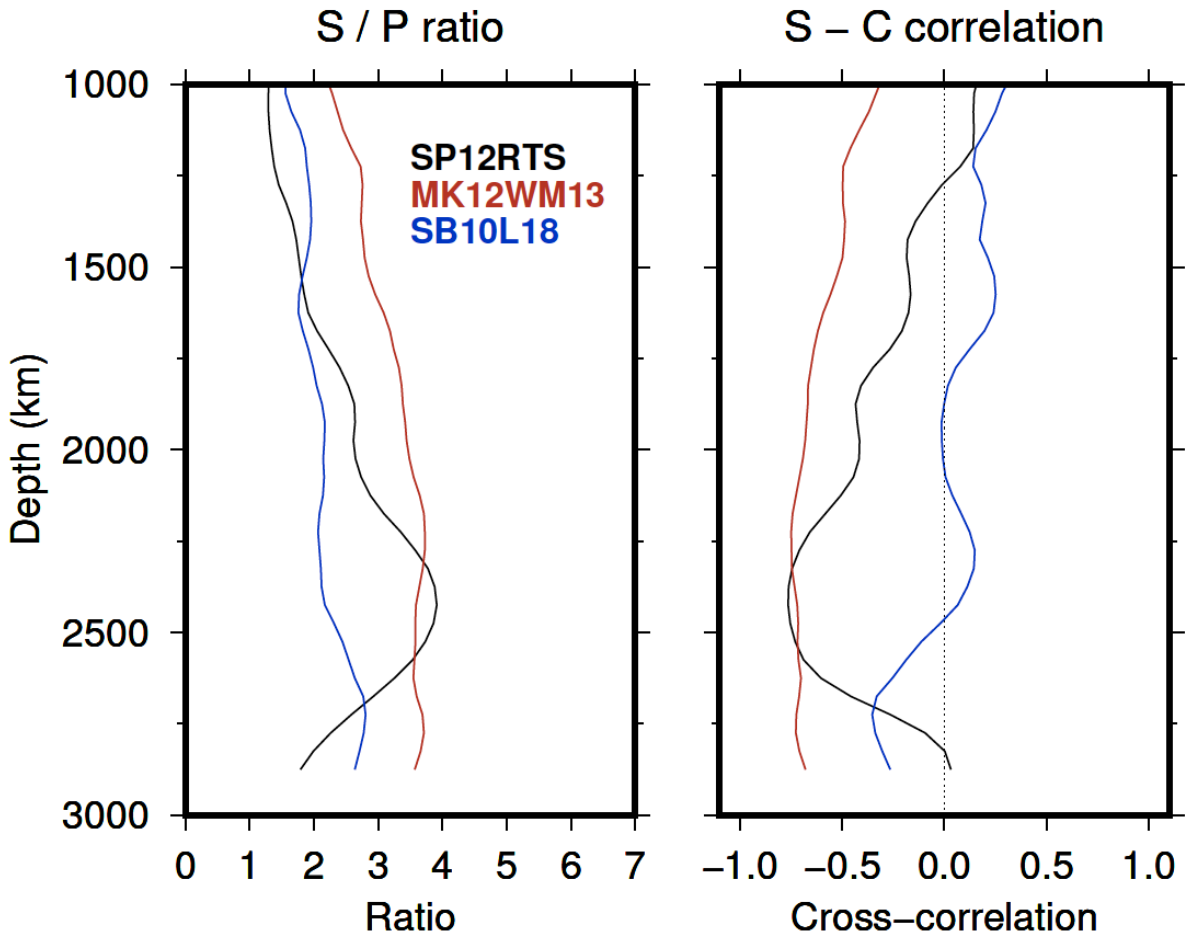
Influence of CMB temperature



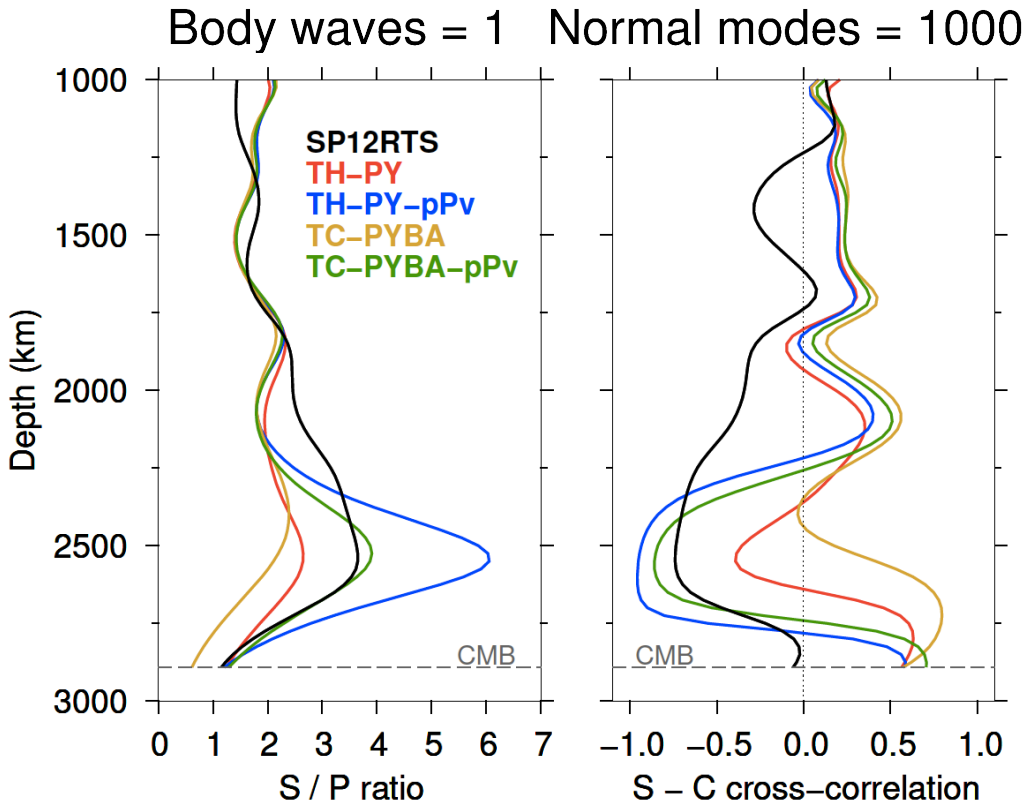
Influence of CMB temperature: clusters



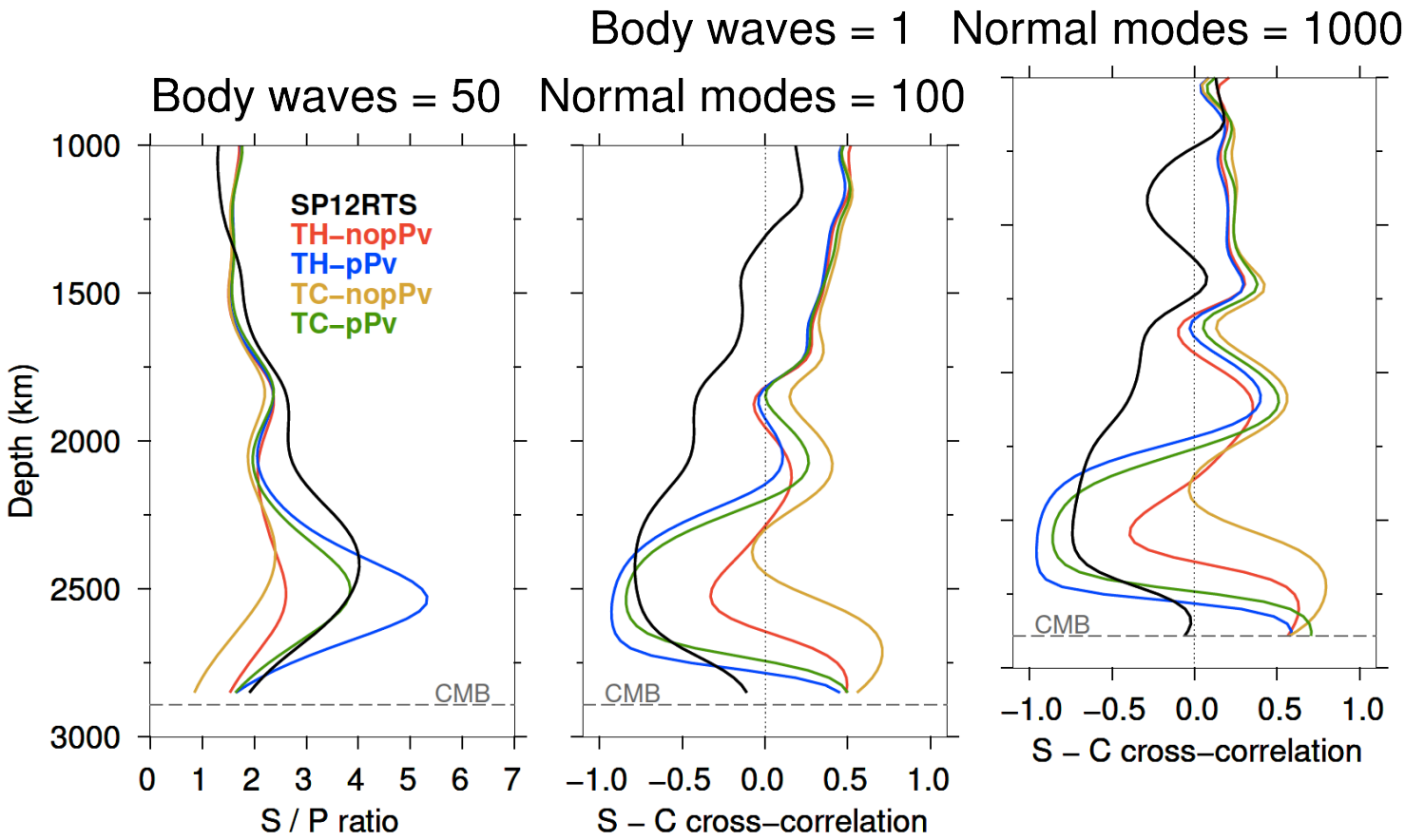
Depth of the $dlnV_S$- $dlnV_C$ anti-correlation



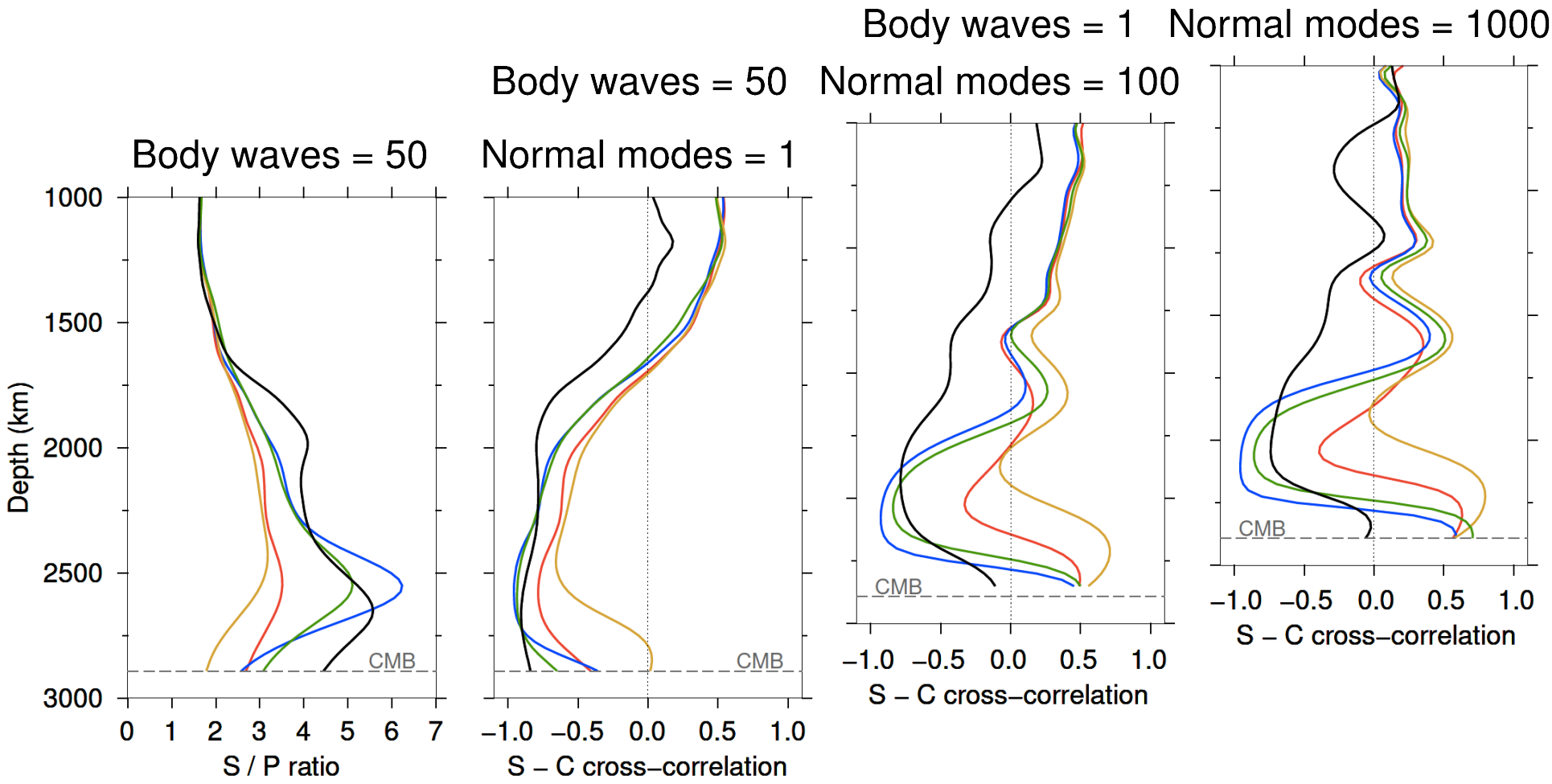
Effects of data set weighting factors



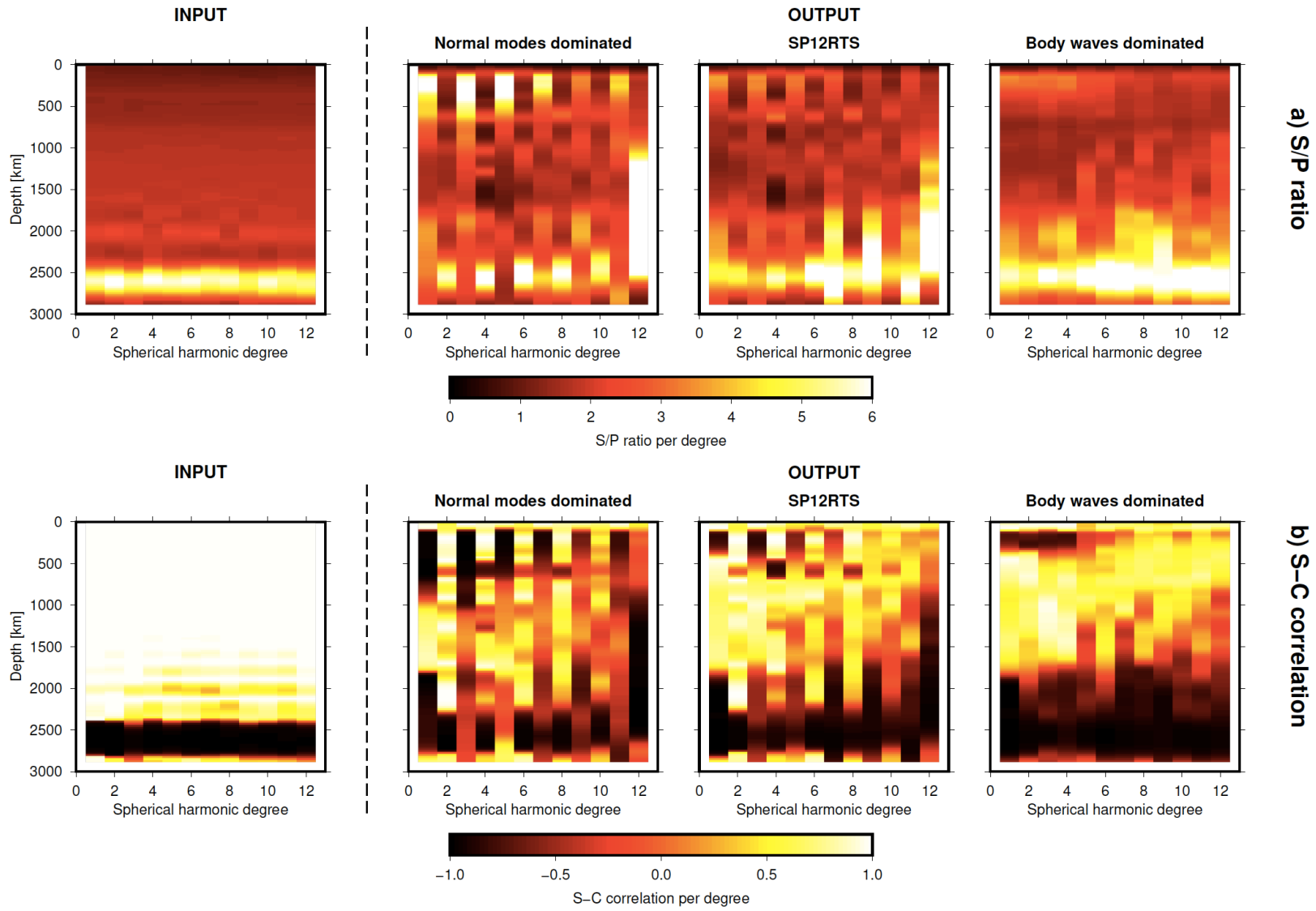
Effects of data set weighting factors



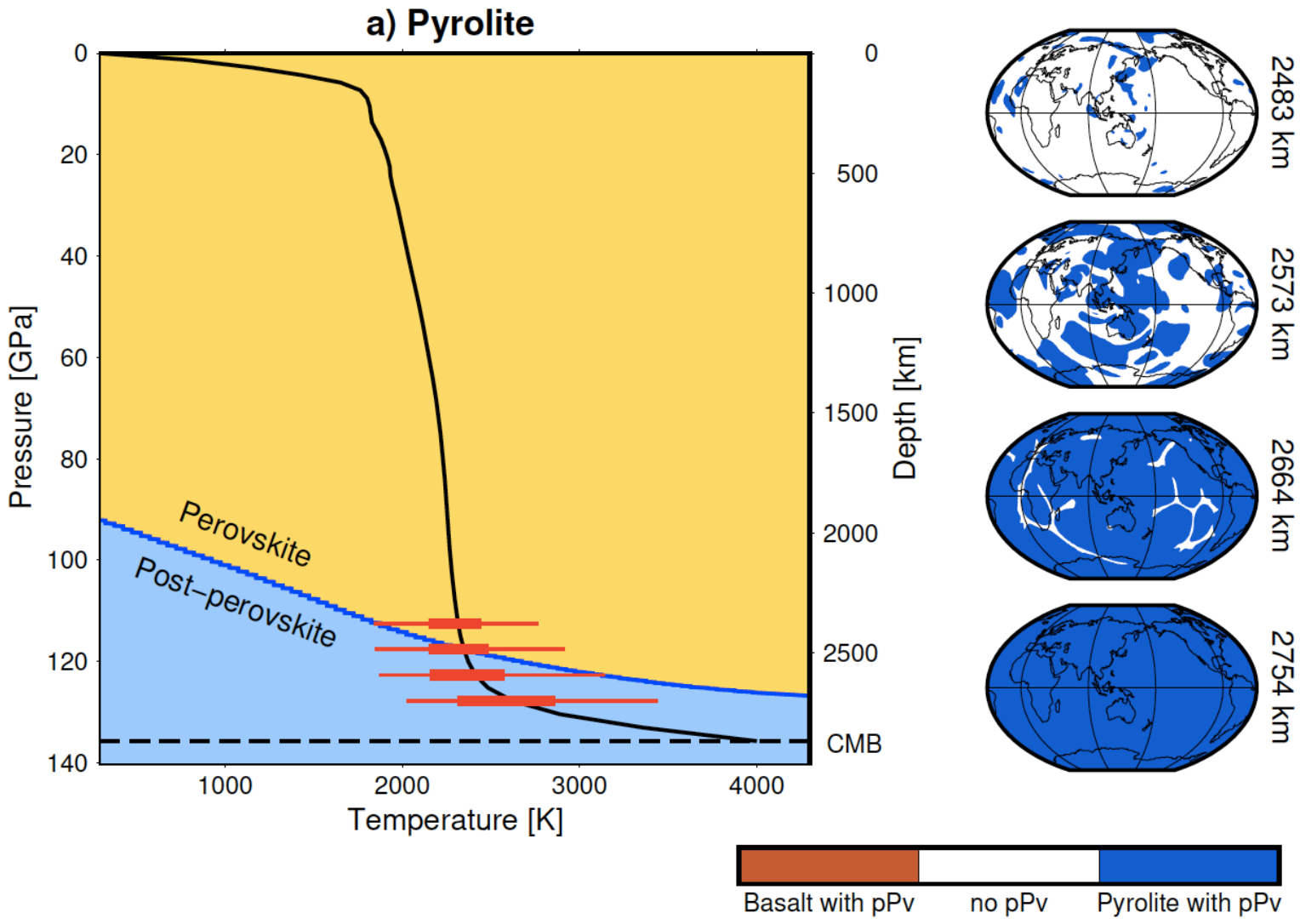
Effects of data set weighting factors



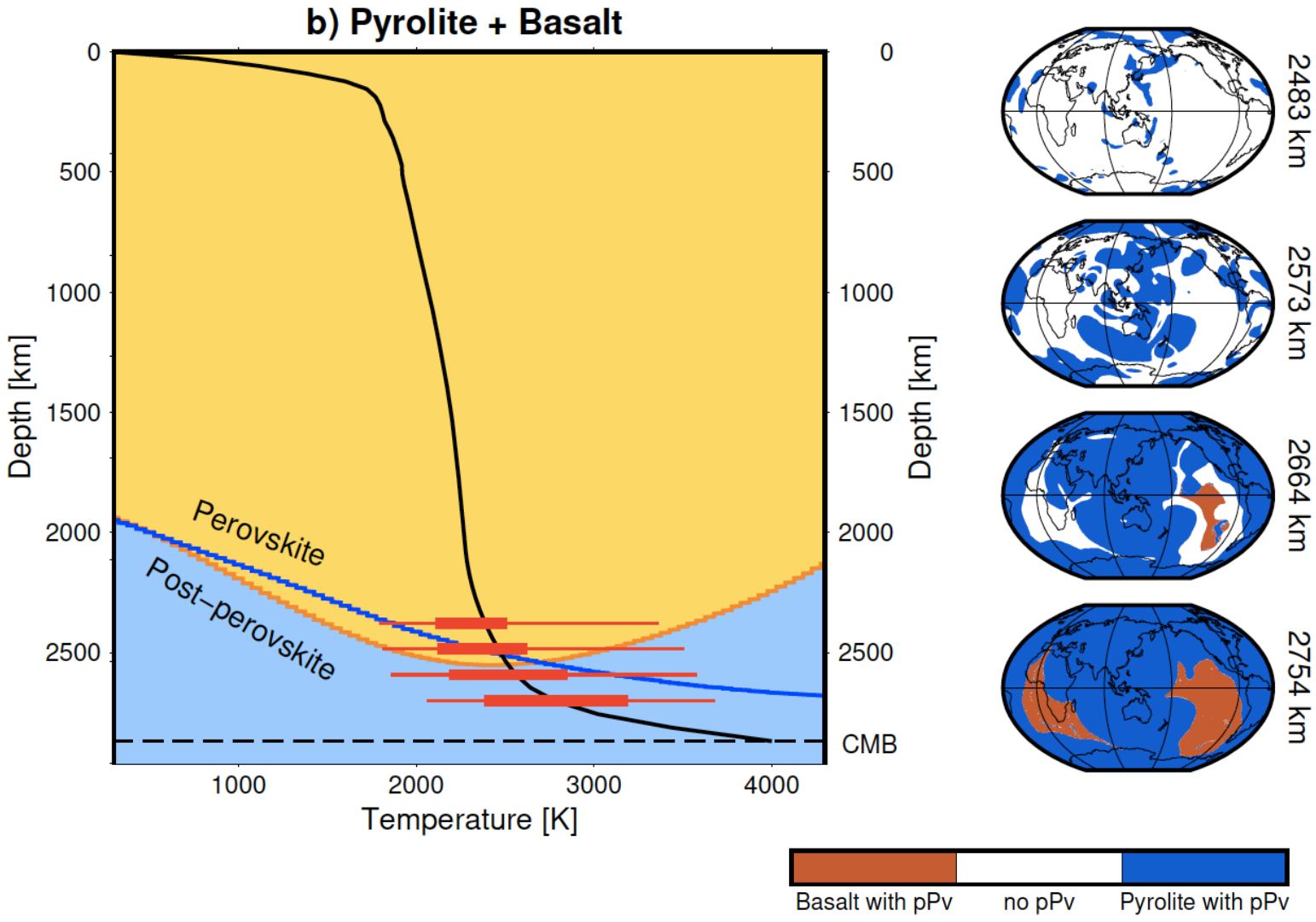
Influence of data weighting



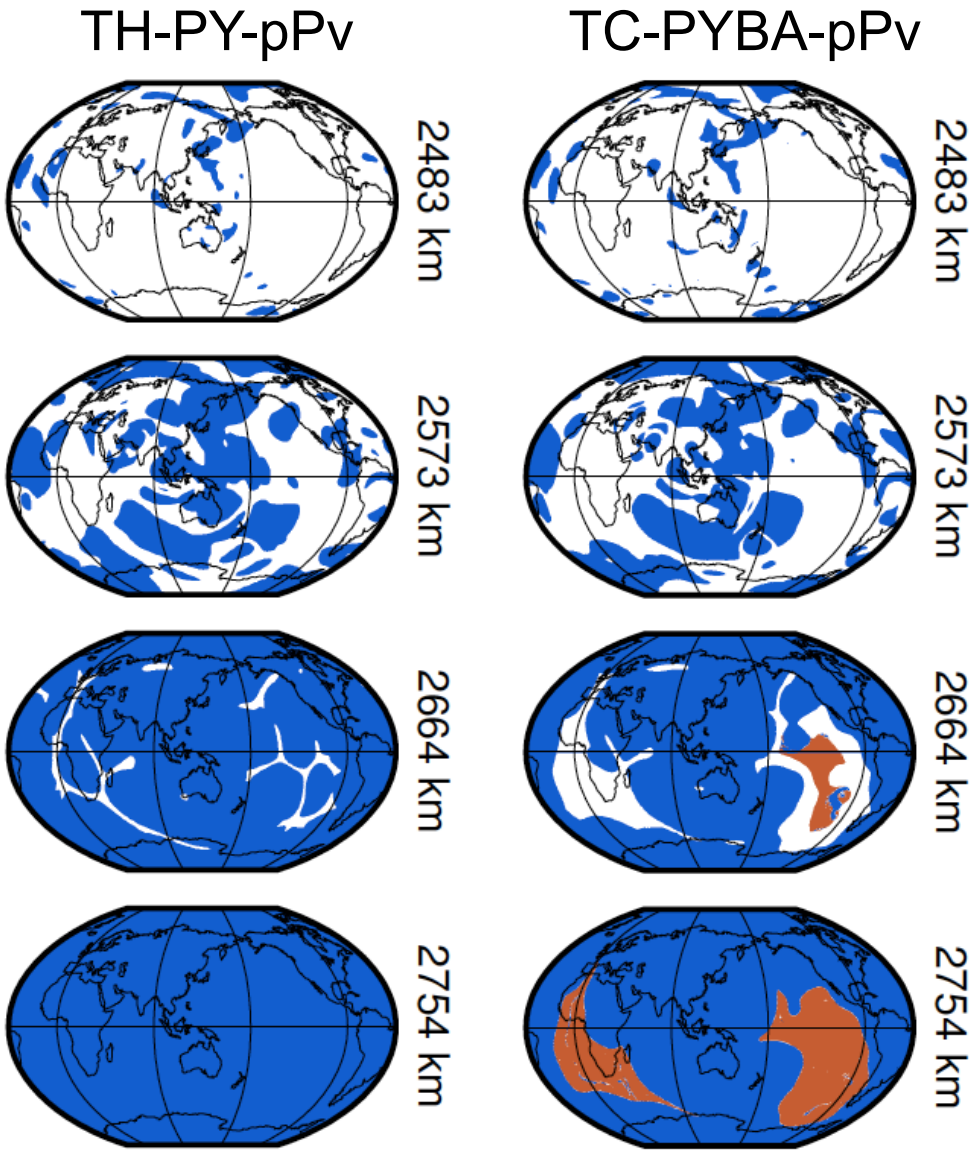
Occurrence of pPv in geodynamic models



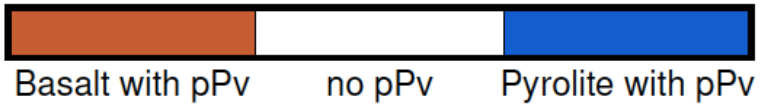
Occurrence of pPv in geodynamic models



Occurrence of pPv in geodynamic models



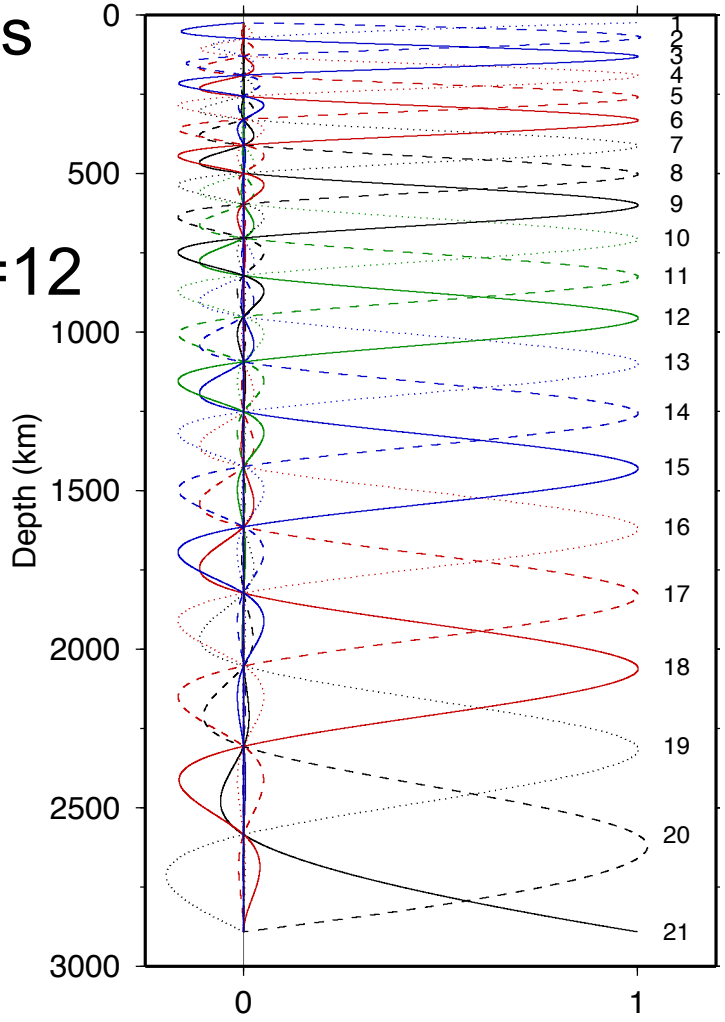
- Total amount of pPv is similar in TH and TC models
- Below 2730 km, pPv is everywhere
- pPv also occurs in the LLSVPs



Extra slides: SP12RTS

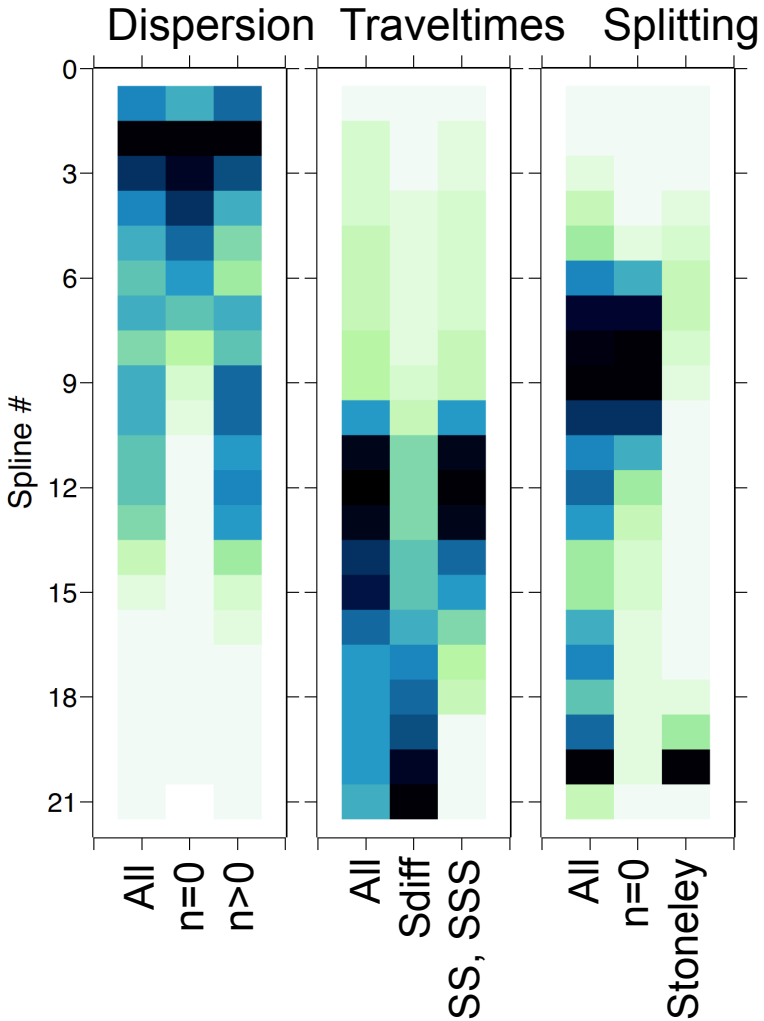
Multiple data type inversions

- Invert independently for $dlnV_S$ and $dlnV_P$
- Depth parameterized with 21 splines
  - ~ 60 km upper mantle
  - ~ 300 km lower mantle
- Lateral spherical harmonics up to l=12
  - ~ 1600 km @ the surface
  - ~ 900 km @ the CMB
- Correct for crustal structure
- Include density variations using:
  $dln\rho = 0.3 * dlnV_S$
- Vary data weighting and ρ scaling

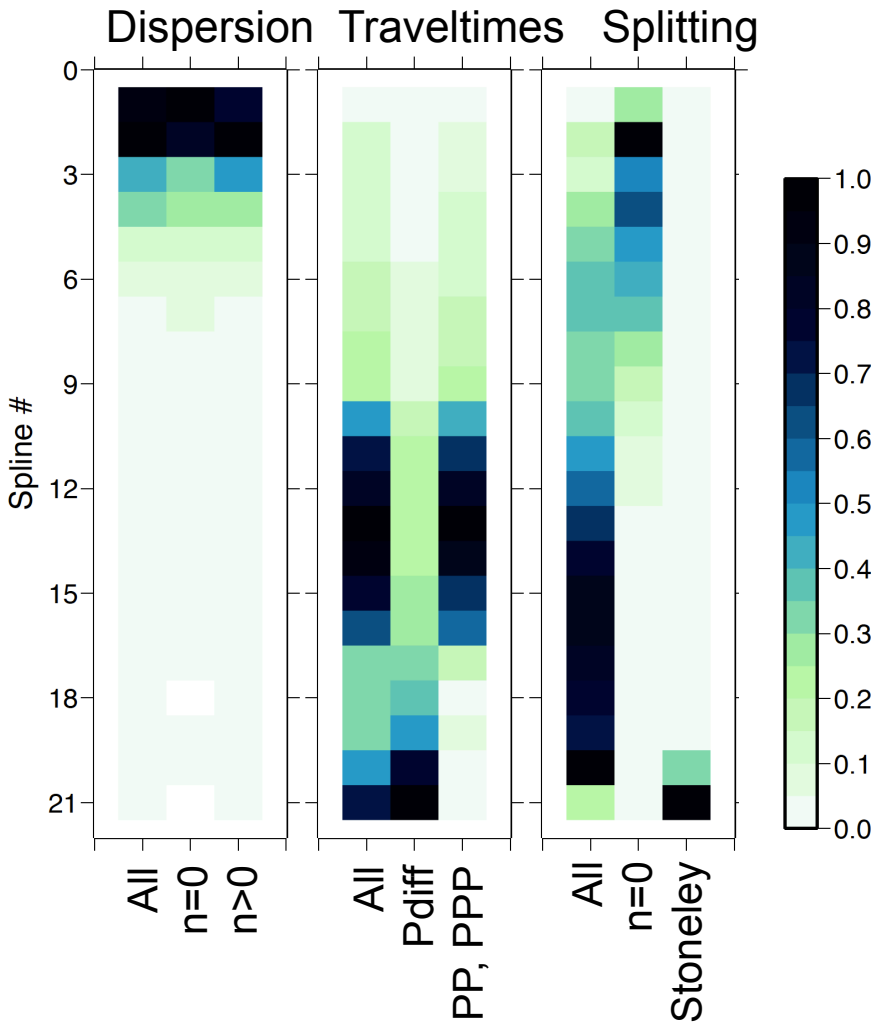


Data sensitivity in splines

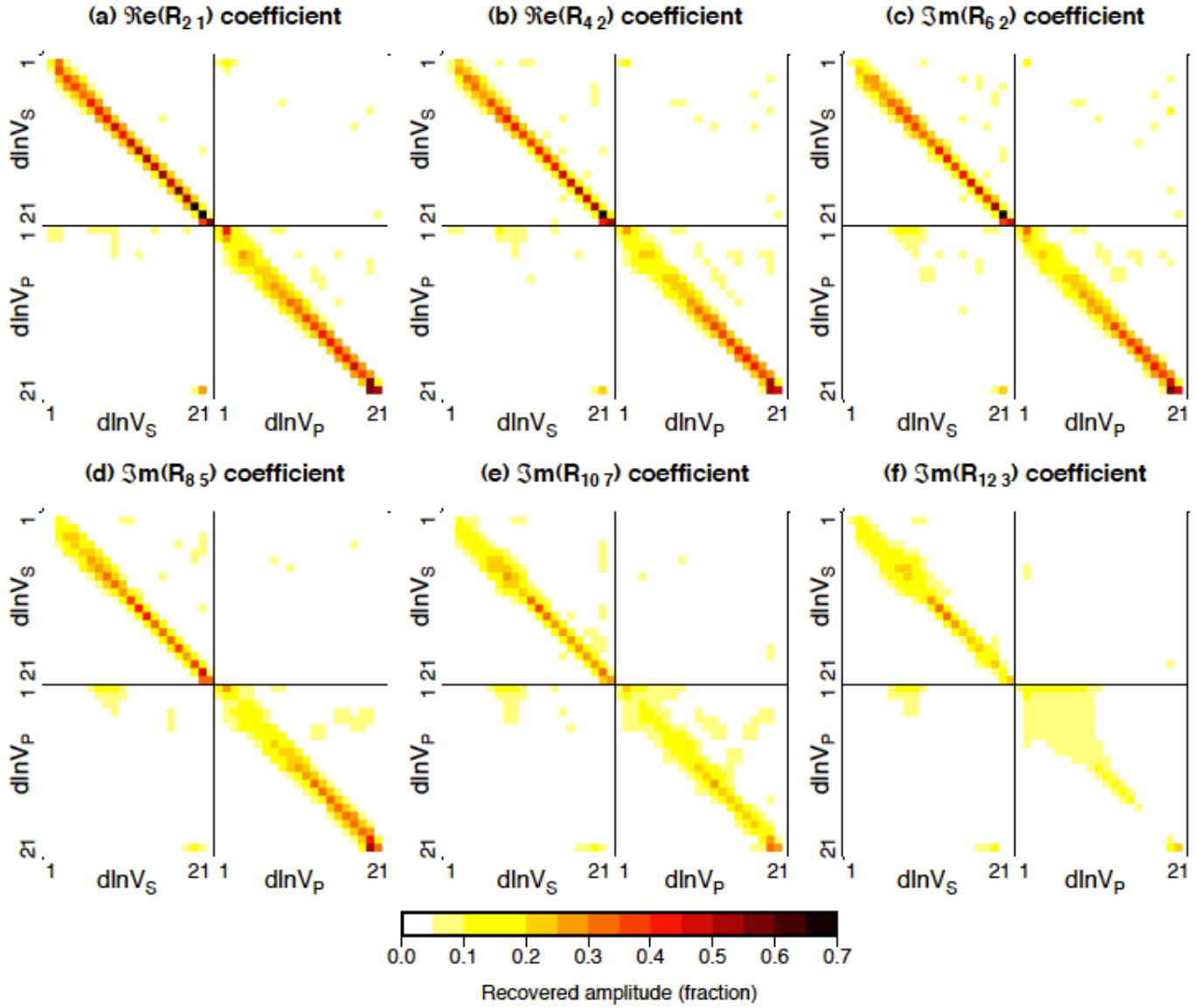
$dlnV_S$



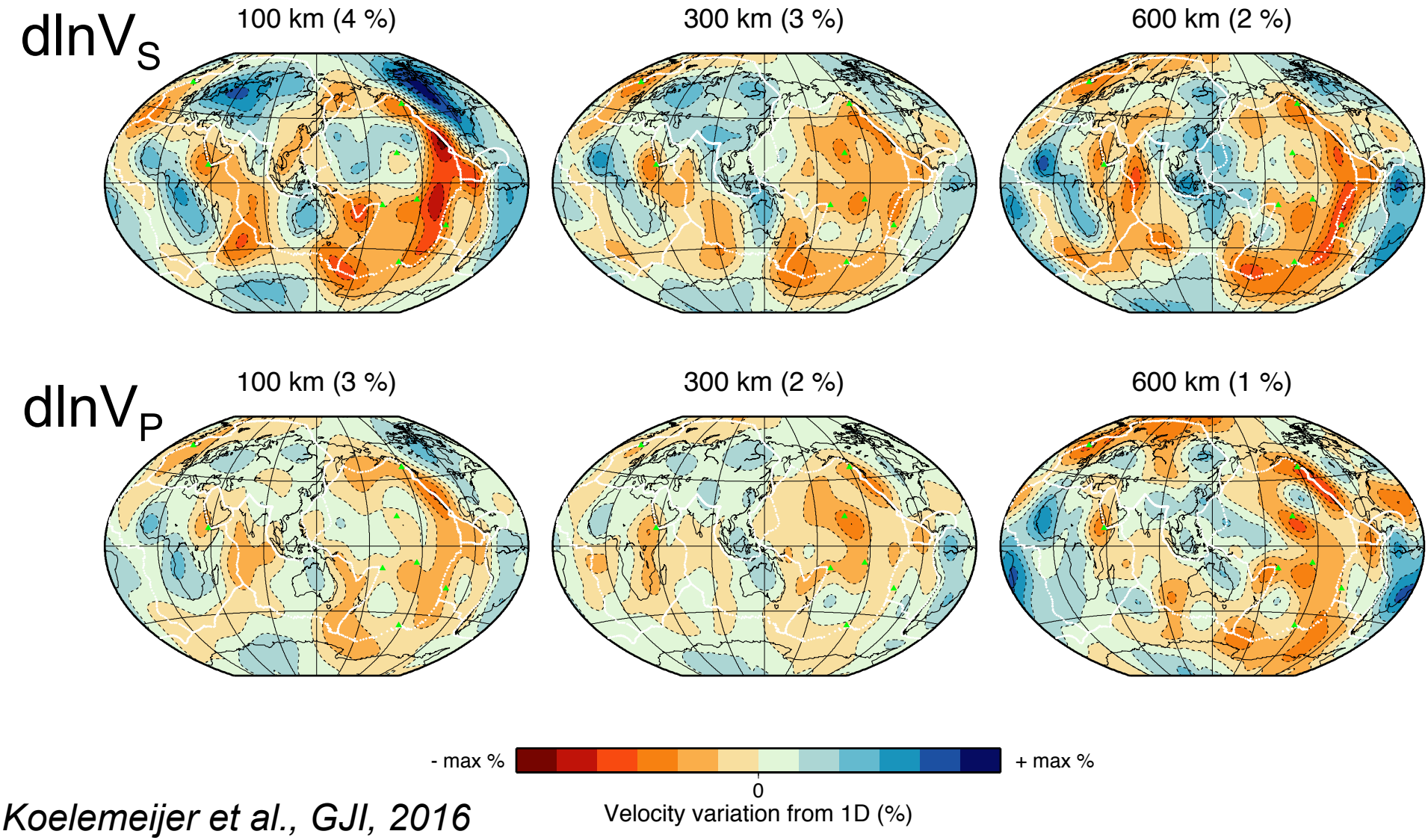
$dlnV_P$



SP12RTS: resolution matrix

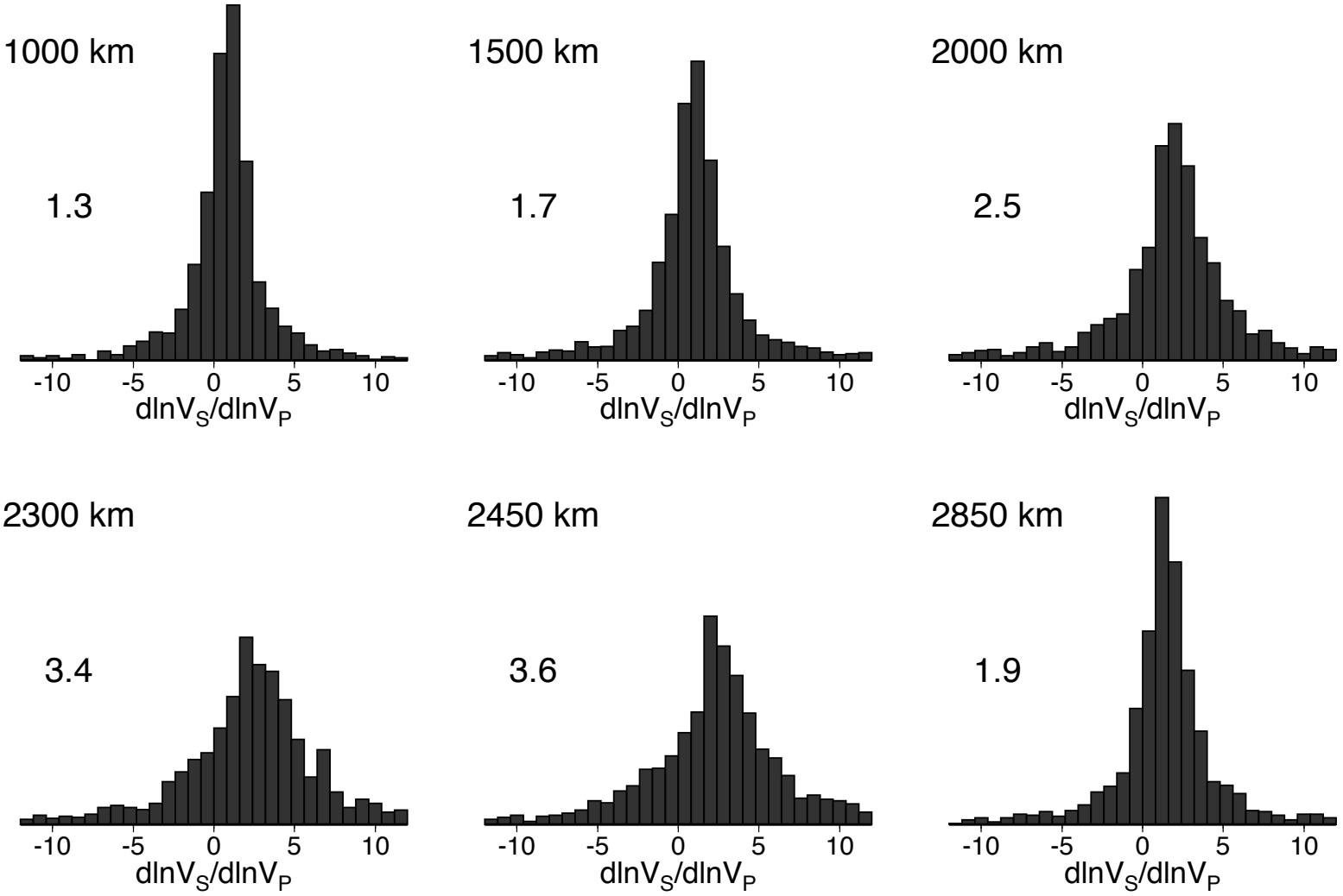


SP12RTS: upper mantle structure

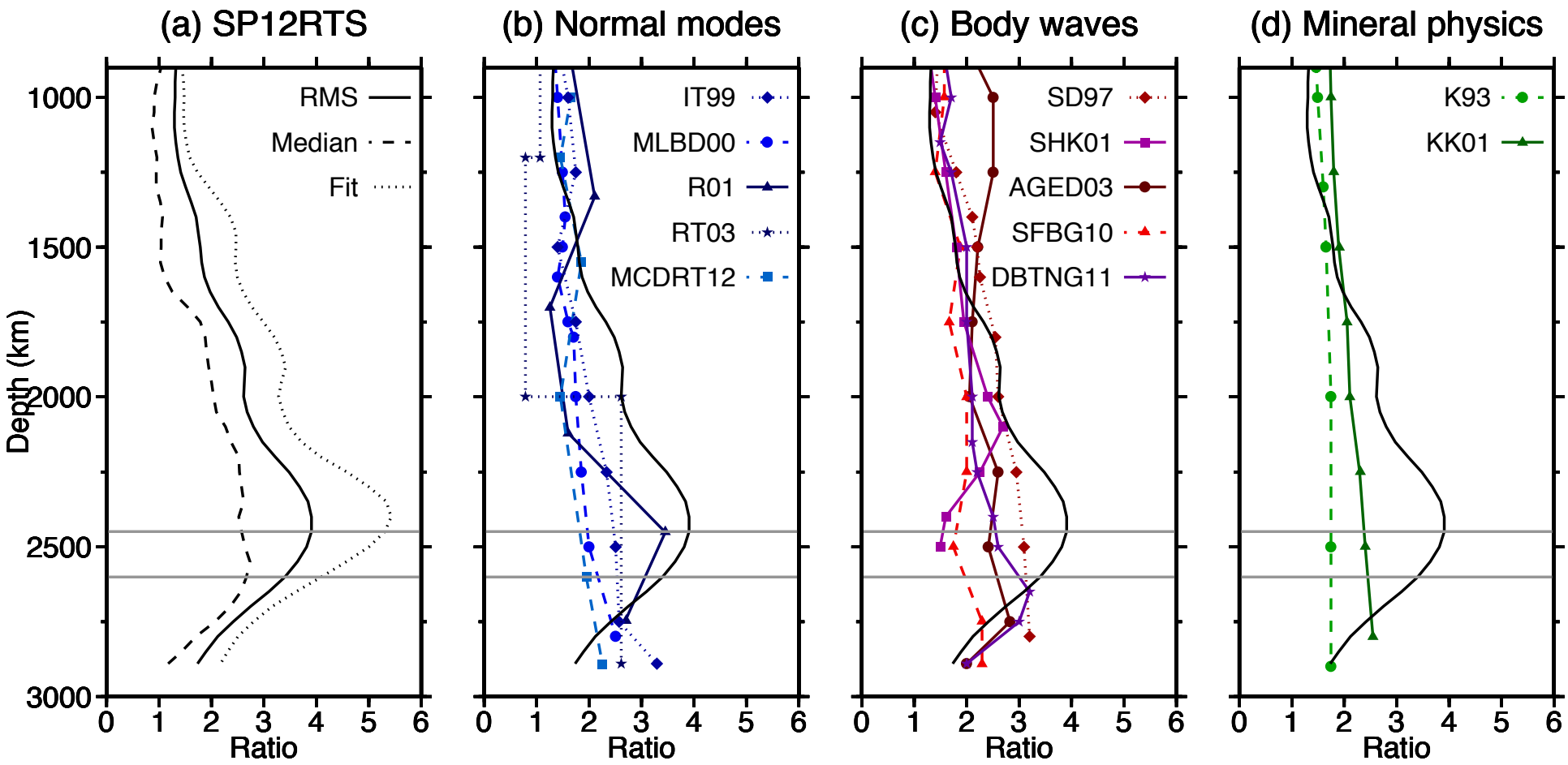


Koelemeijer et al., GJI, 2016

SP12RTS: lower mantle $dlnV_S/dlnV_P$



SP12RTS: lower mantle $dlnV_S/dlnV_P$



Koelemeijer et al., GJI, 2016