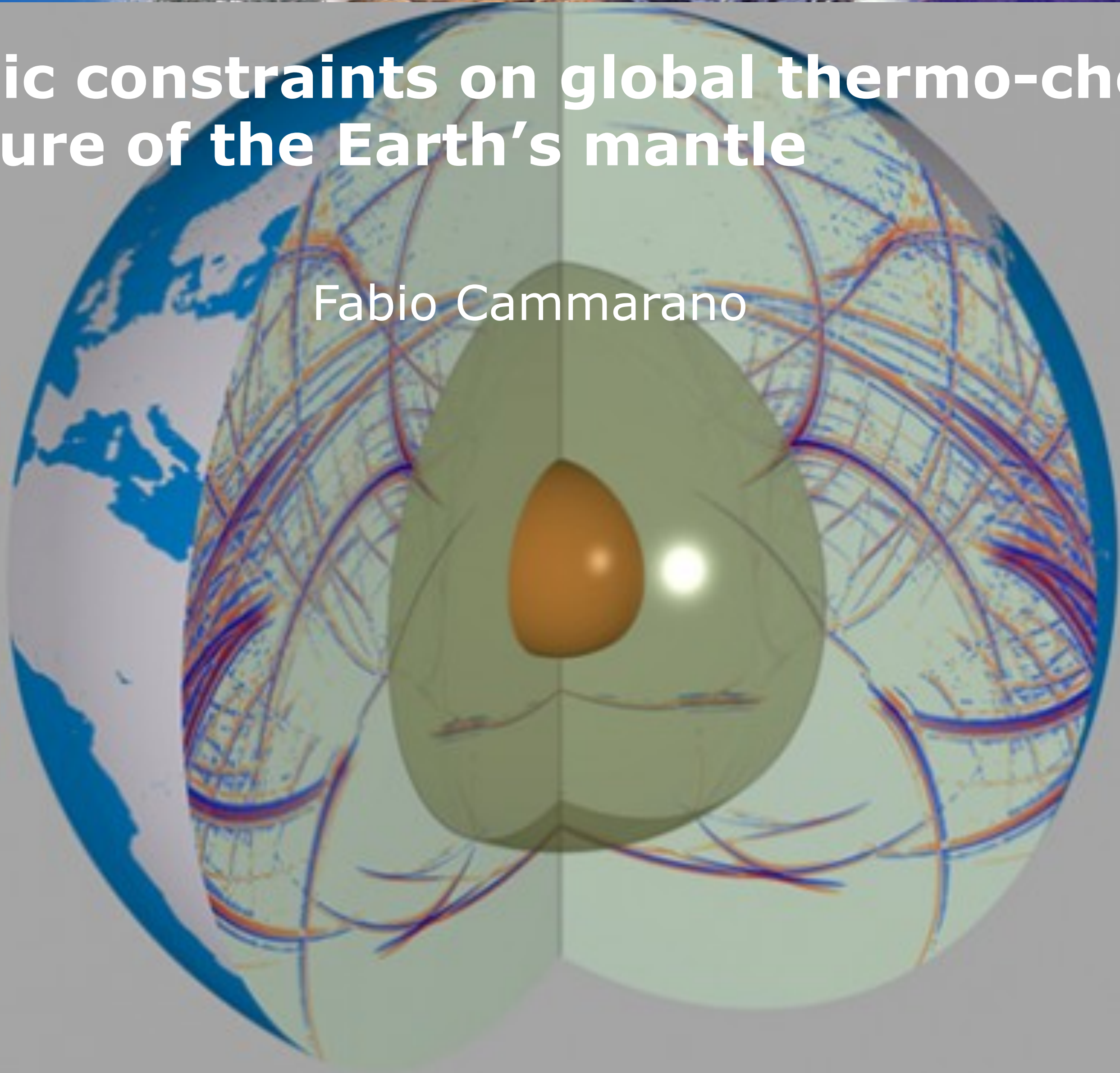
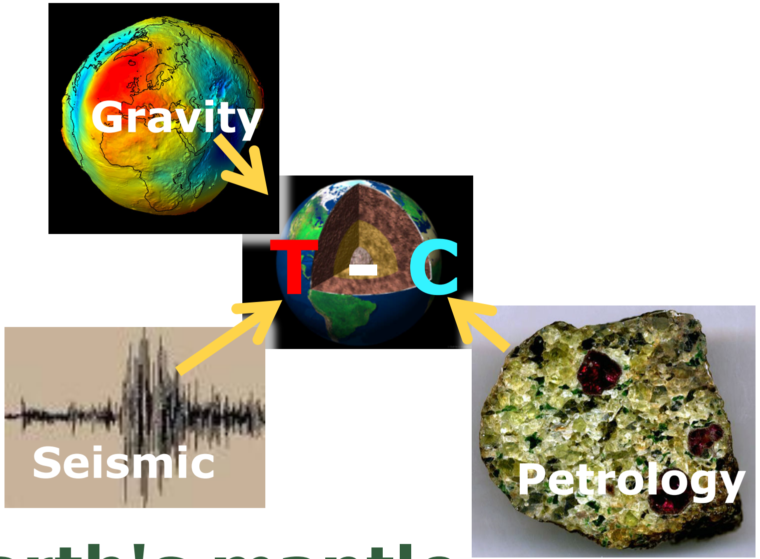
ROMA TRE
UNIVERSITÀ DEGLI STUDI
DIPARTIMENTO DI SCIENZE GEOLOGICHE
Seismology

Seismic constraints on global thermo-chemical structure of the Earth's mantle

Fabio Cammarano



I use an interdisciplinary approach - seismology, mineral physics, geodynamics - to study the interior of the Earth and planetary bodies.



- **Physical properties of the Earth's mantle**

- **Inversion of Seismic waveforms and gravity data for temperature and composition**

- **Compositional and thermal structure of the lithosphere**

- **Planetary studies**

Seismology provides the best resolved images of Earth's interior structure!

- ✓ Since the 80's, seismic tomography helped to resolve mantle 3-D structure. Yet, even large scale structures lack a clear physical meaning.

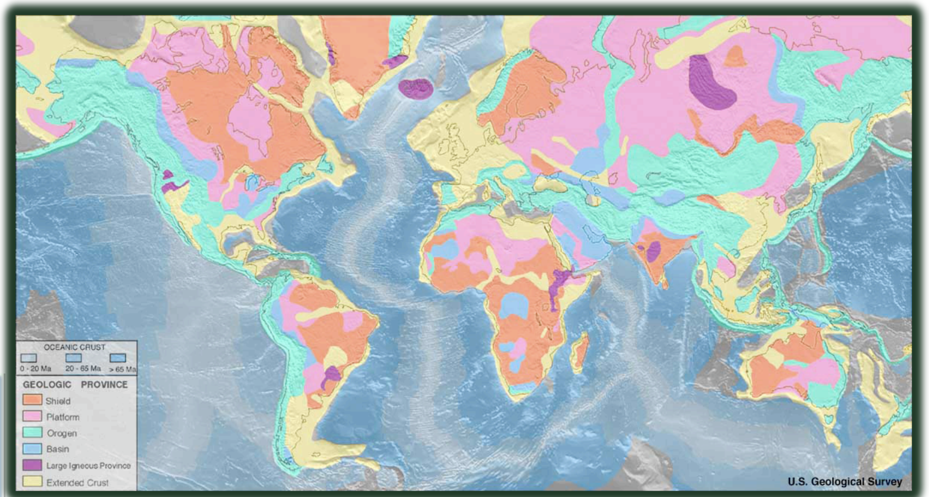
WHY?

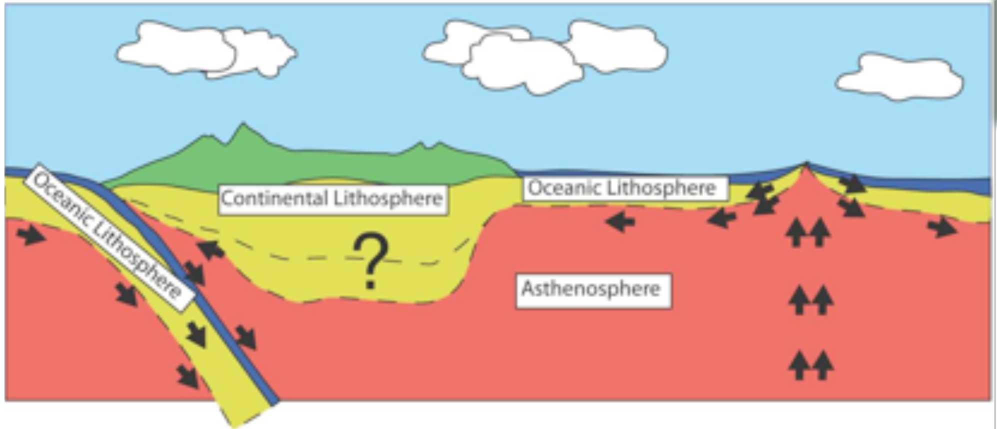
- ✓ Trade-off between temperature (T) and composition (C)
- ✓ Uncertainties in mineral physics, i.e. in the relationships between seismic velocities and T-C
- ✓ Interpretation requires absolute seismic velocities
- ✓ Seismic models are different => *it is known that differences arises from **data types** used and **coverage**, their relative **weighting**, **damping** factors, model **parametrization**, **crustal and anisotropic corrections, starting reference model**..., but tracing back the exact sources of differences between models is very hard.*

➢ T-C Upper mantle (top 300km)

- Relation with surface processes: Plate-tectonics => active subductions, volcanism
- Old, stable continents (> 3 billion y.) and young oceans

❖ Earth is a very dynamic system, yet the stable part of continents formed > 3 billion of years ago and, since then, survive destruction!





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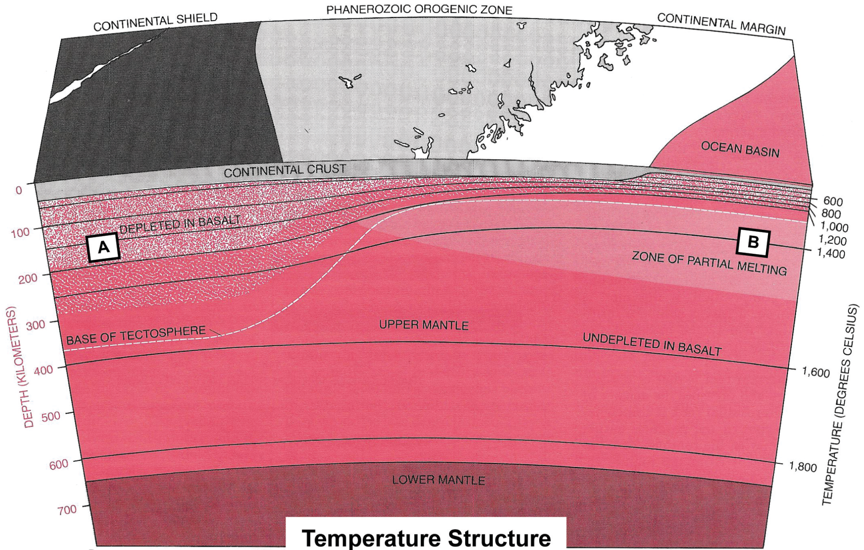
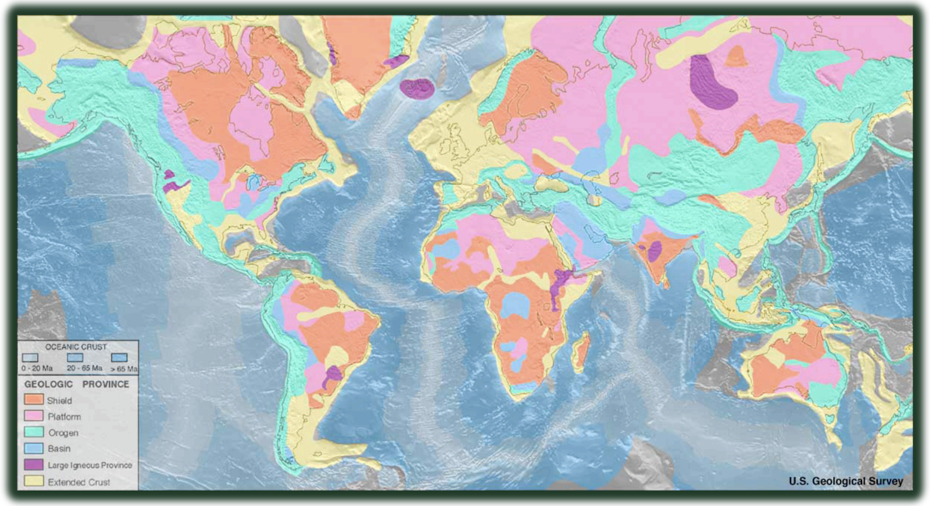


After Jordan 1978



❖ Continental lithospheric mantle is cold (seismically fast) and chemically depleted ➔ tectosphere

➢ T-C Upper mantle (top 300km)

- Relation with surface processes: Plate-tectonics => active subductions, volcanism
- Old, stable continents (> 3 billion y.) and young oceans

Some open questions:

✓ **How deep** is the continental lithosphere?

✓ Is there an incontrovertible **compositional signature** in global seismic models?

✓ Are the continents compositionally **different**?

✓ **How much water** (and how deep) is carried out by the slabs within the mantle?

✓ How this affect **dynamics**?

➢ Upper mantle (top 300km)

✓ Oceanic lithosphere and upper mantle → understand plate-tectonics dynamics

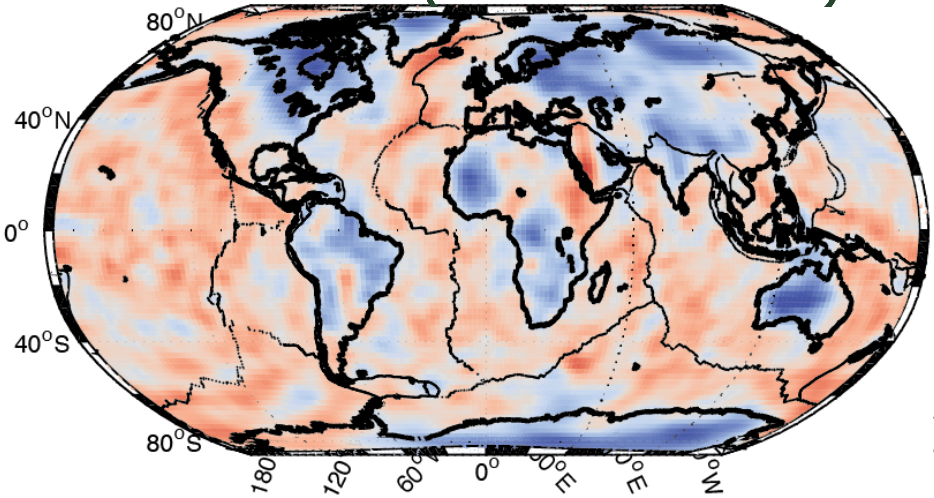
✓ Understand the origin and evolution of stable continental regions → understand evolution of our planet

❖ In order to do this, it is fundamental to determine the **thermal** and **compositional heterogeneity** of the lithosphere and .

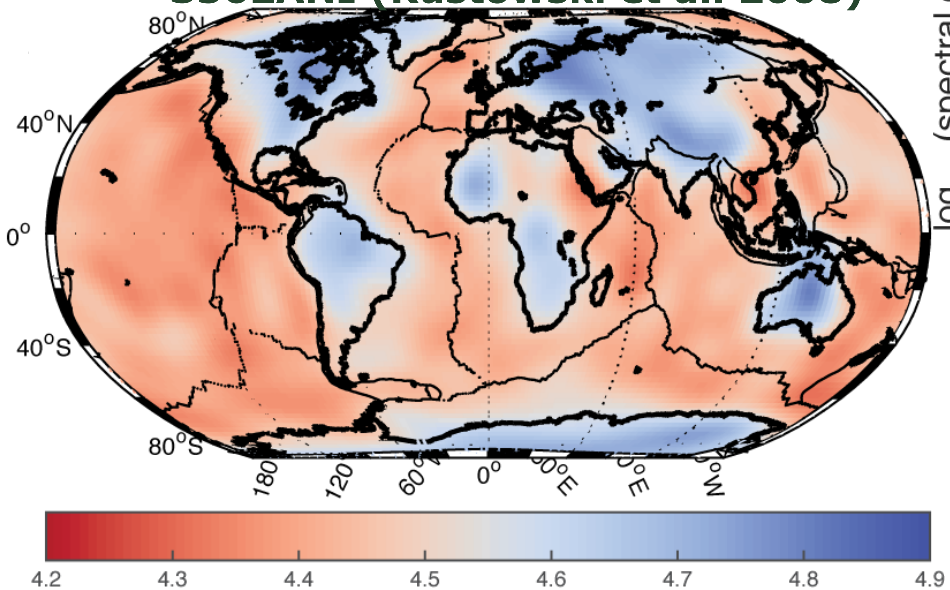
On a global scale, top of upper mantle well sampled by surface waves

➢ All global V_S models show very similar long-wavelength structure at 100-200 km depth

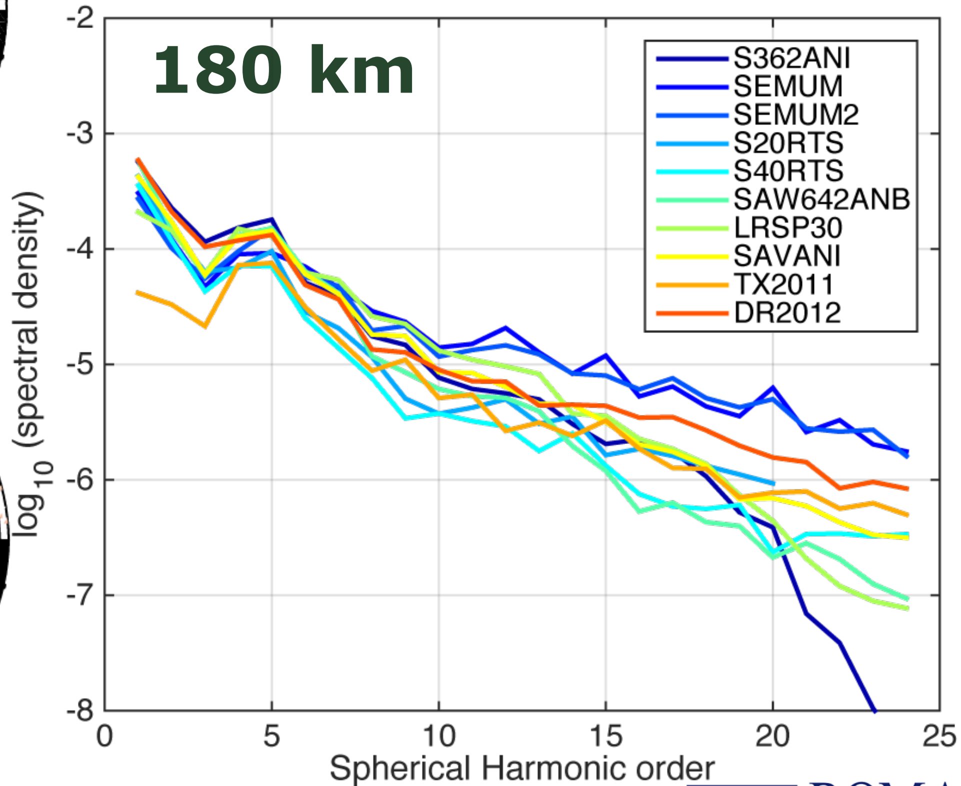
SEMUM 2 (French et al. 2013)



S362ANI (Kustowski et al. 2008)



V_S (km/s)



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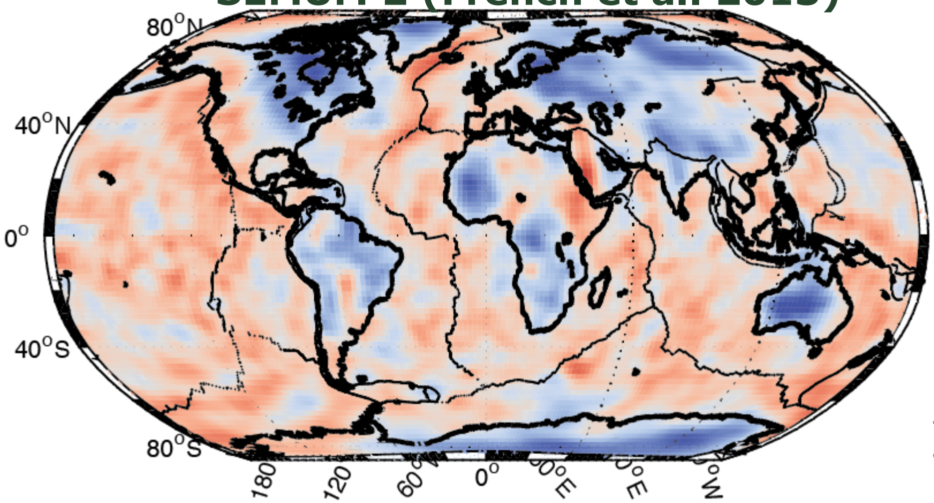

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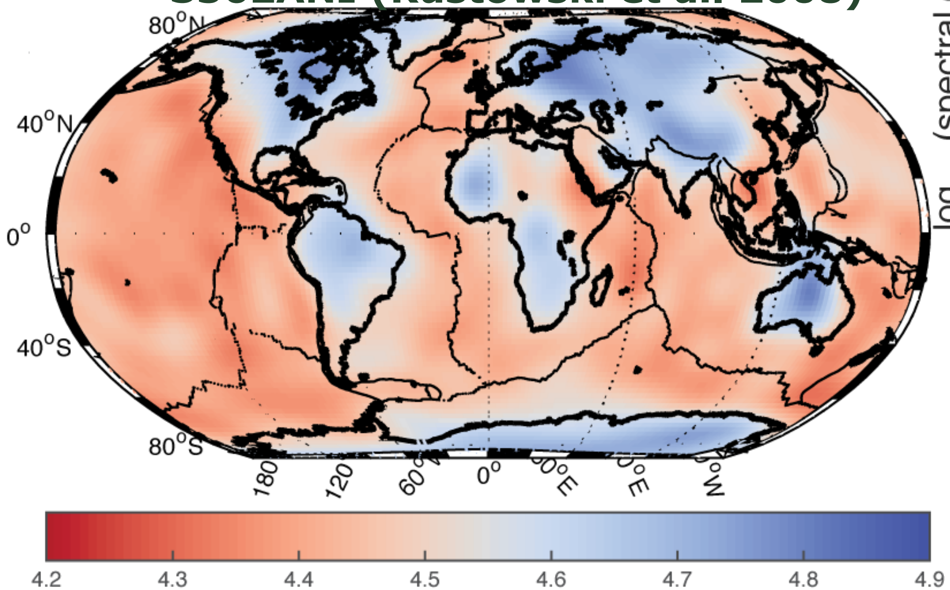
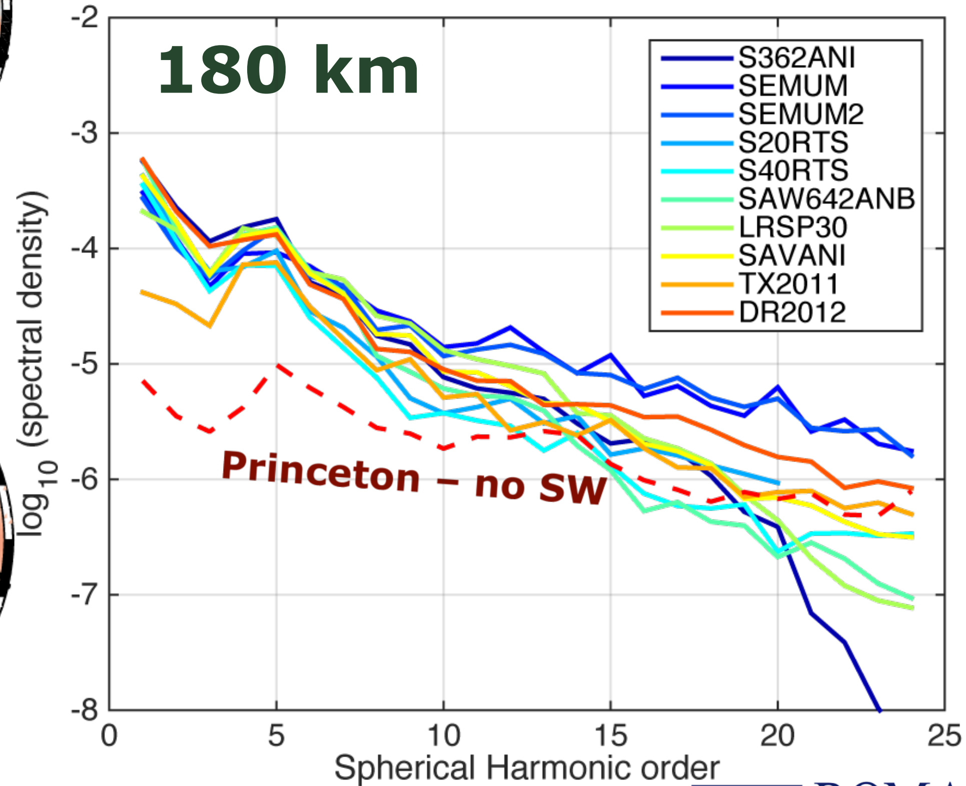
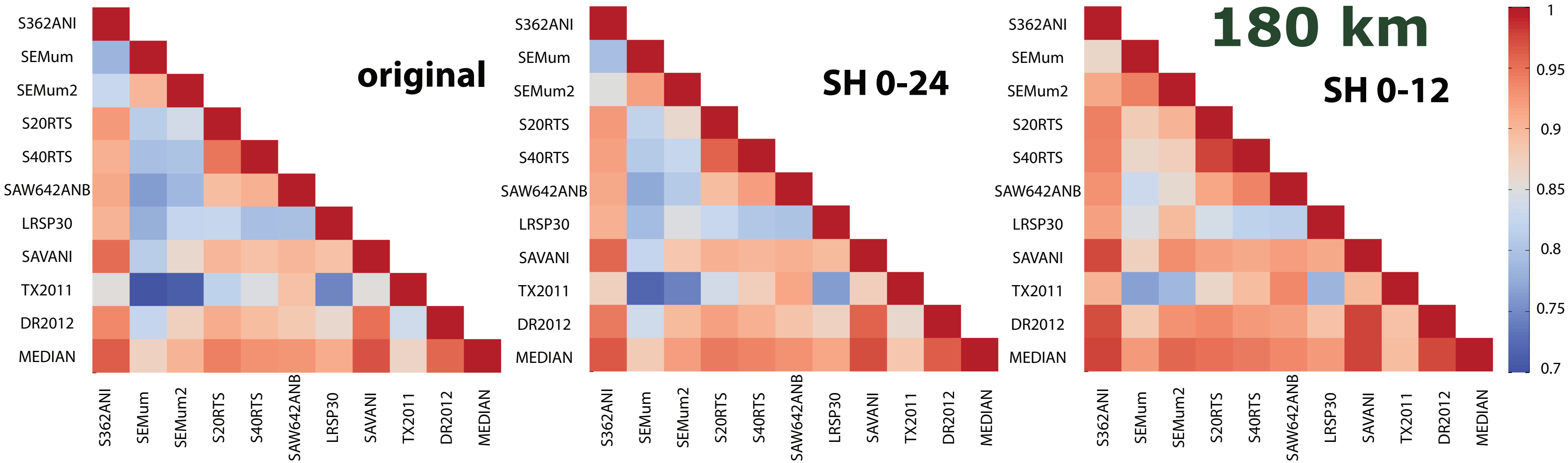
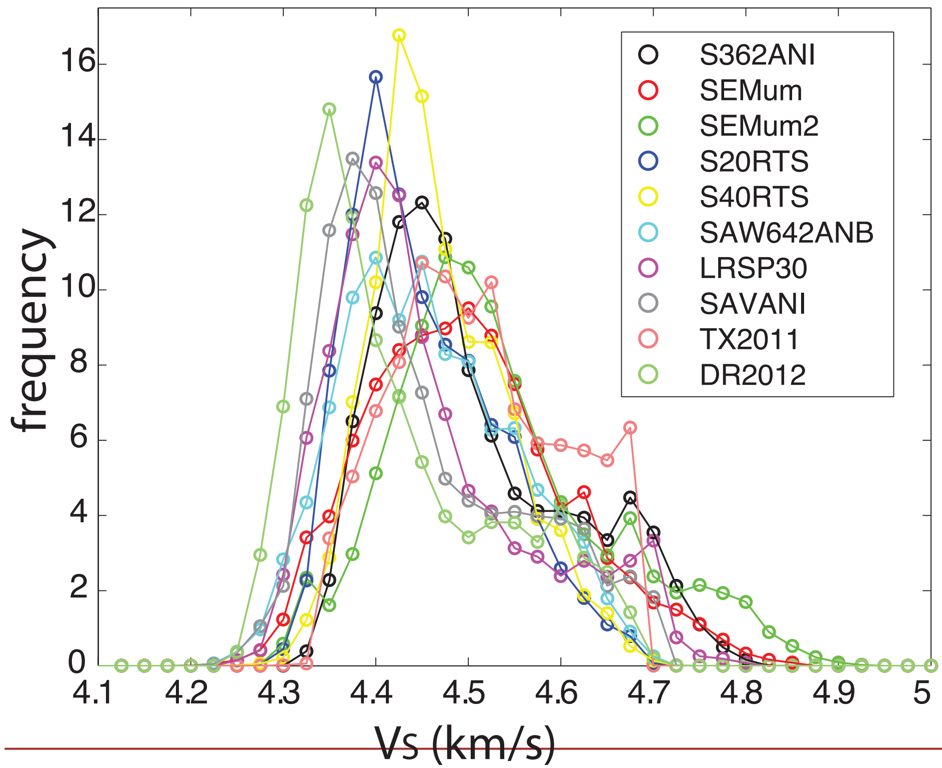


V_S (km/s)



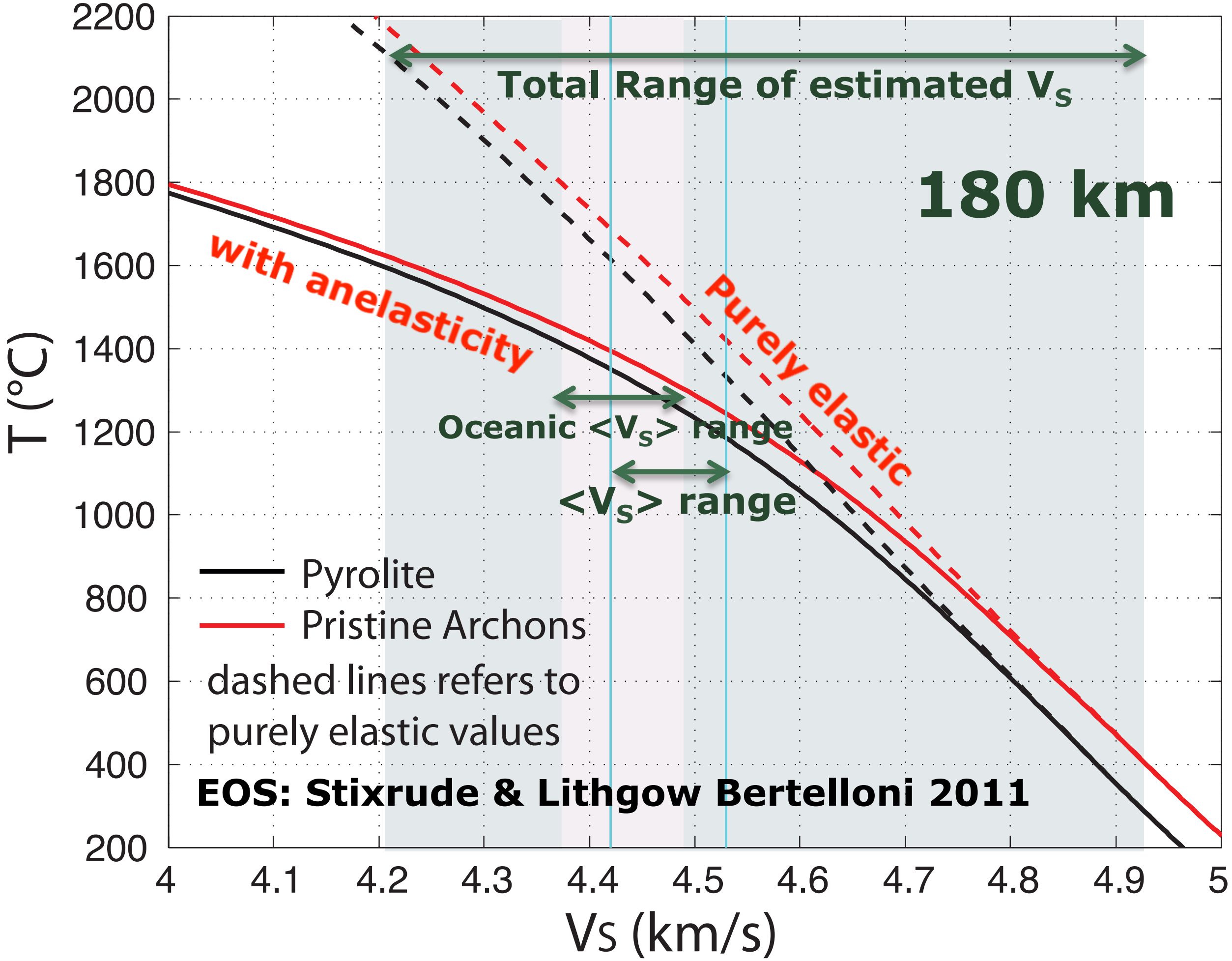




✓ Correlation coefficient >0.9

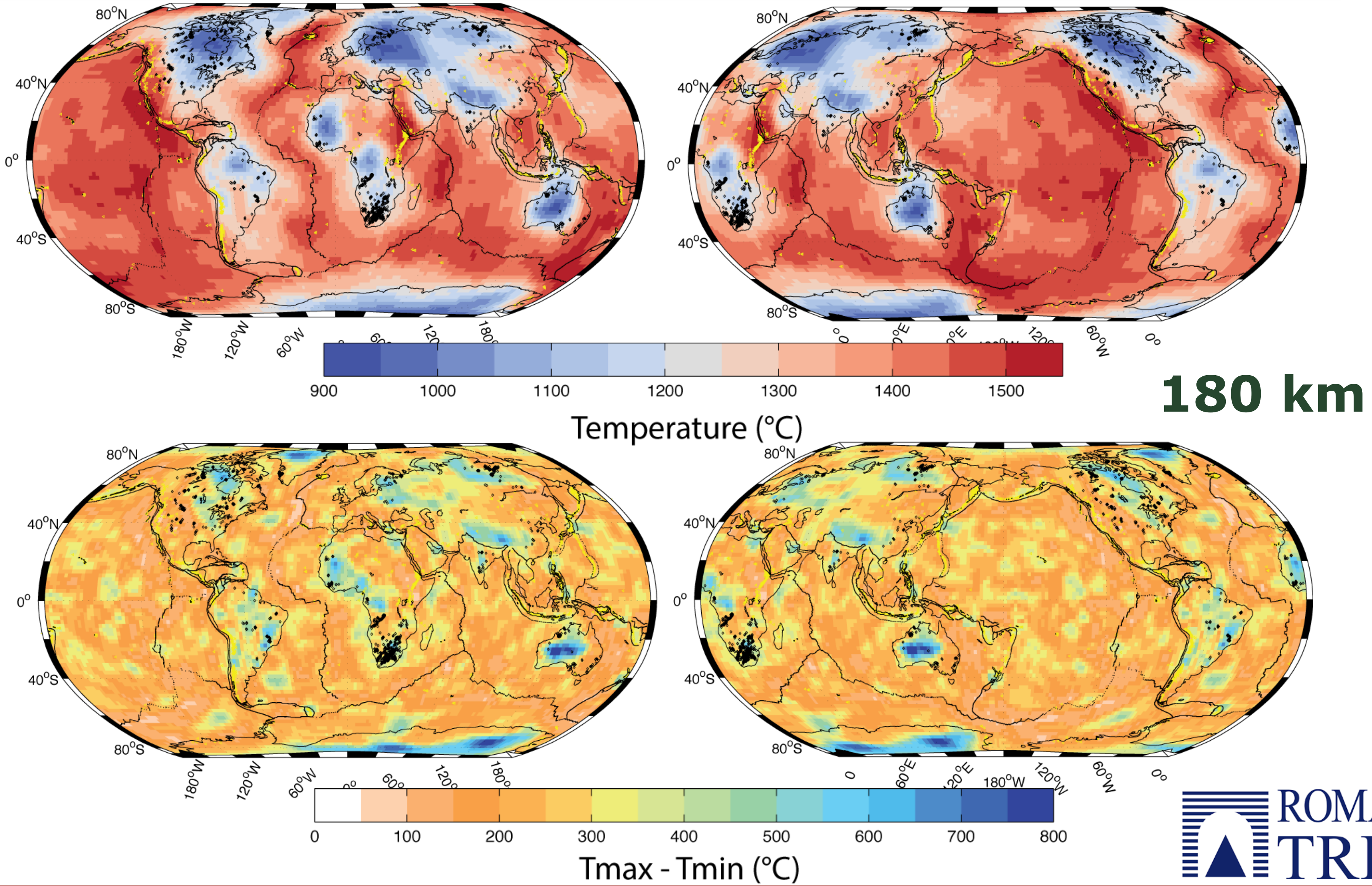
- All global VS models show very similar long-wavelength structure at 100-200 km depth

✓ Mineral physics (elastic and anelastic parameters) => V_S(P,T) for given compositions



- ➢ V_S variations mostly sensitive to T
- ➢ Anelasticity effects should be considered

- T structure is well determined, but absolute T is affected by variation in amplitudes of V_S anomalies.



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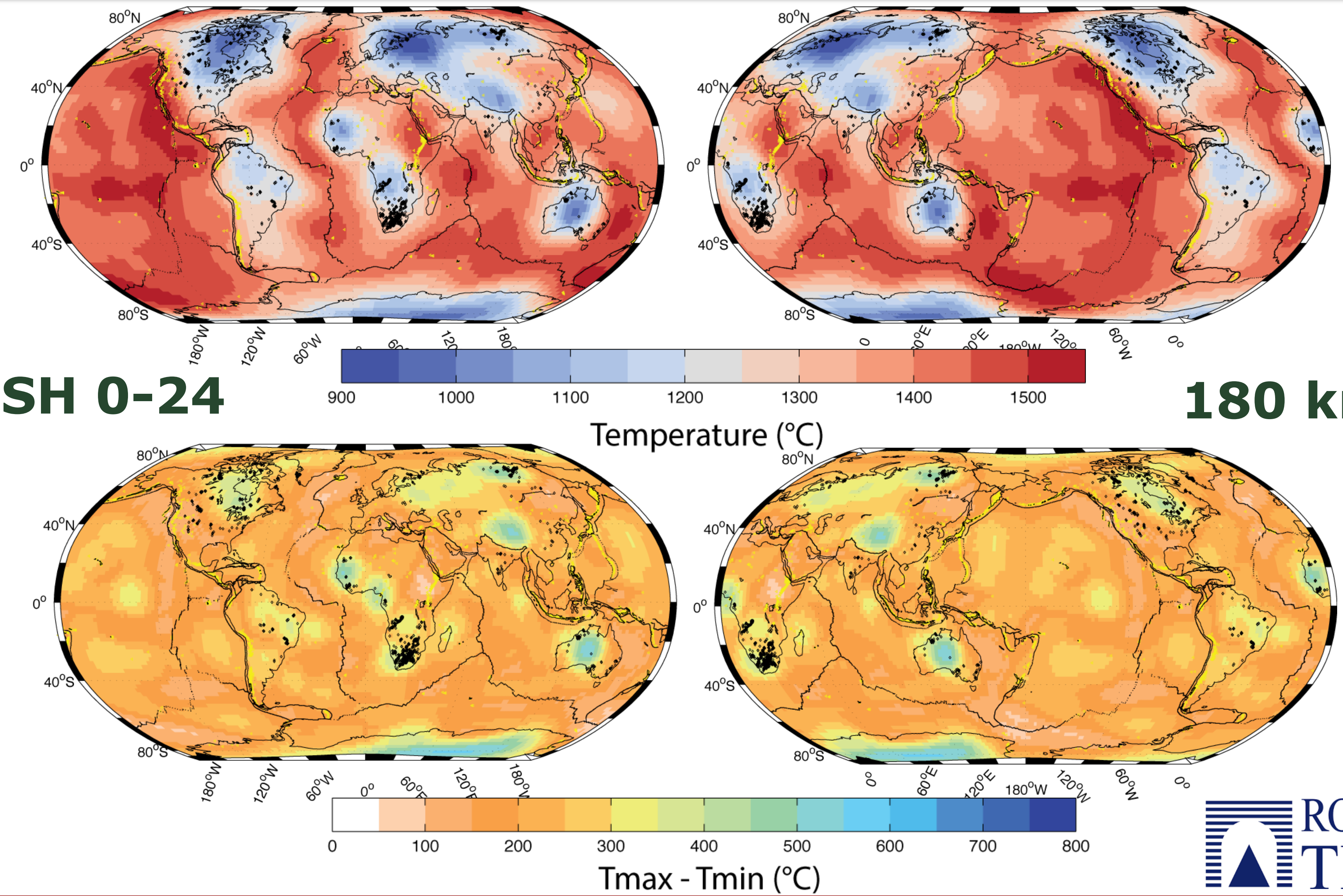
SH 0-24

180 km



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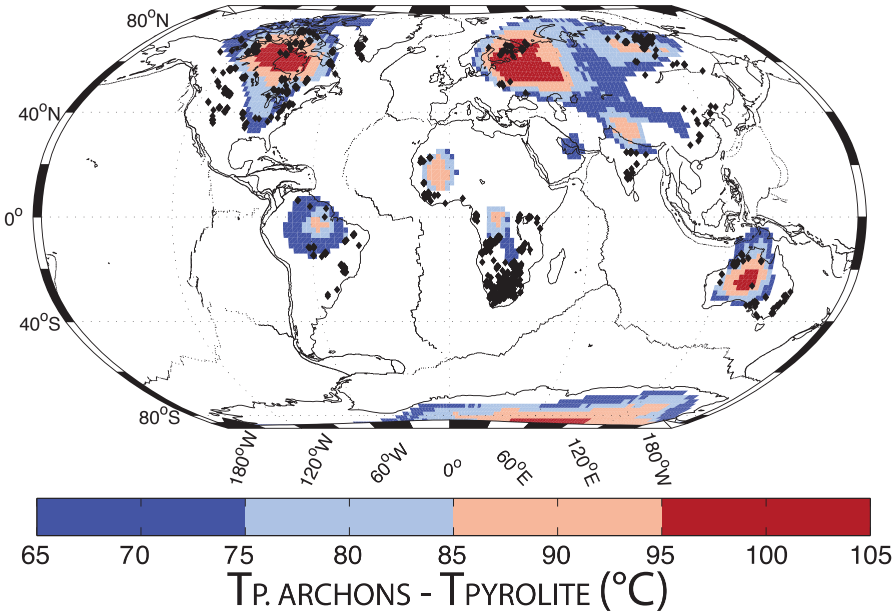
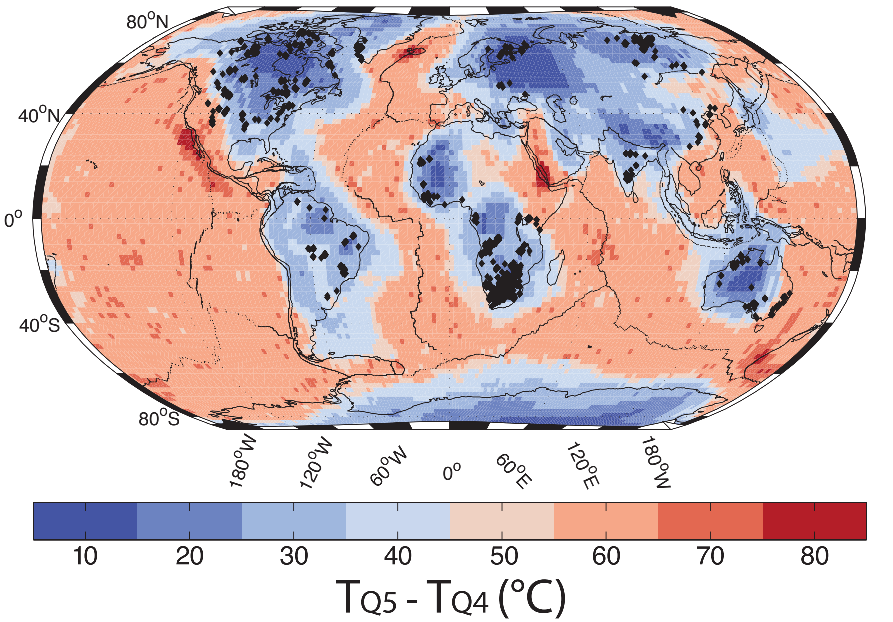
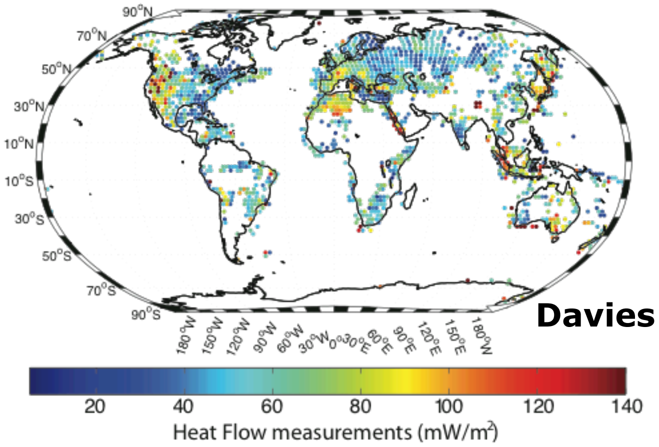
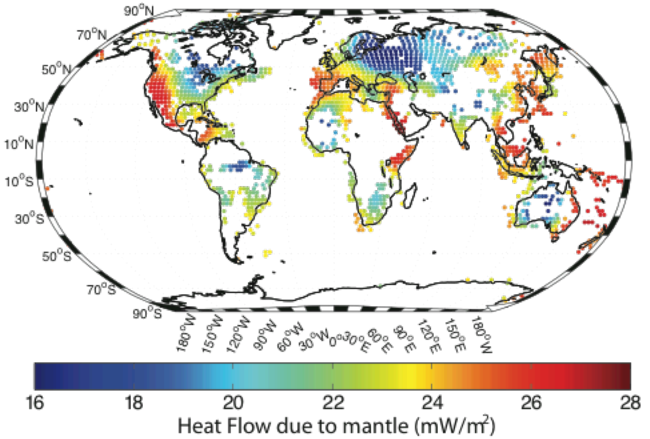


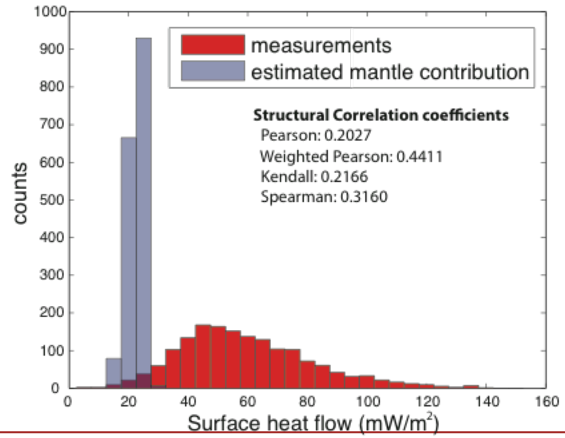


- Accounting for first-order C variations between continents/ ocean
- And for the large uncertainties in anelasticity do not vary much inferred T



Davies 2010 2X2 HF



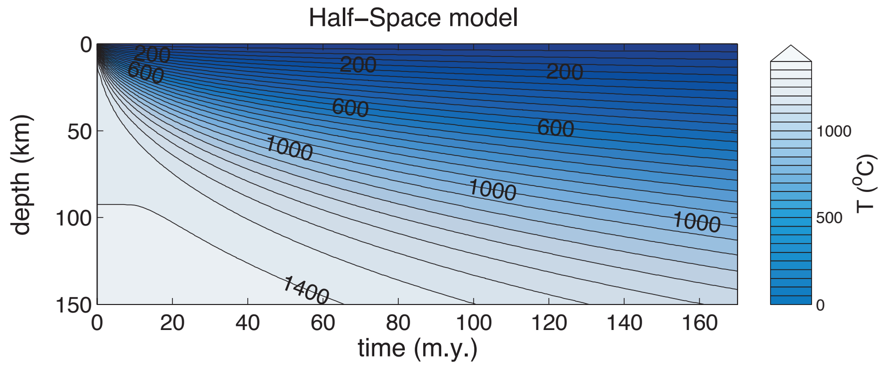


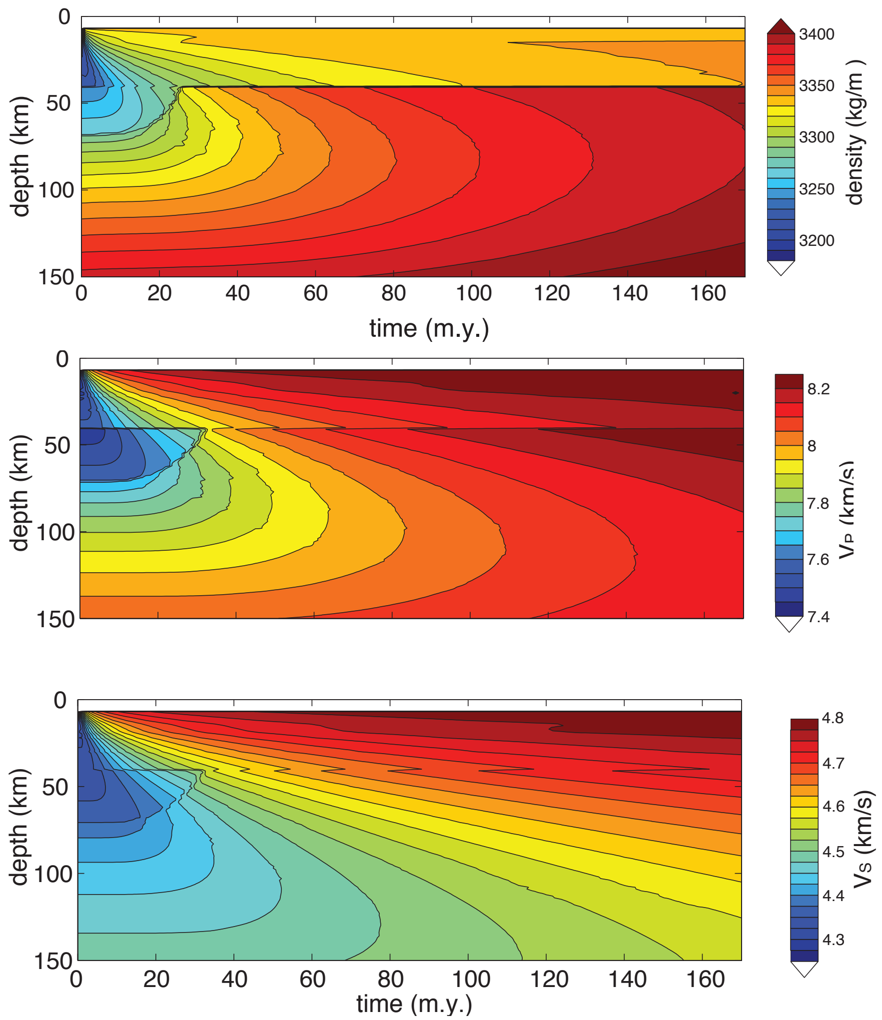
Constraints on absolute T:

- Heat-flow surface data provide additional constraints on continental lithospheric T structure
- Geochemical inferred oceanic T (1280-1400 °C, e.g. Gale 2014) and cooling models on oceanic regions.

Long-wavelength T structure known in the UM => seismically inferred T models

What about composition?


Half–Space model
depth (km)
time (m.y.)
T (°C)
200
600
1000
1400


depth (km)
time (m.y.)
density (kg/m)
Vp (km/s)
Vs (km/s)

❖… additional constraints for global C field

- Adding **gravity data** => compute and remove T density field, look at the gravity anomaly residuals

Problems: uncertainties in the crustal density structure (Guerri et al. 2015), limited resolution of lithospheric mantle

- Run a **joint inversion for V_S and V_P structure** => **SPani** global model (Tesoniero et al 2015)

❖ SPani: a global V_P – V_S model

✓ **Invert a large database of surface waves and P and S body waves**

Table 1. Surface wave phases used in this study

Author	Phase and dominant period	Number of measurements
[Ekström, 2011]	R0 25-250s	1022706
	L0 25-250s	342261
[Visser et al., 2008]	R1 35-172s	396432
	R2 35-149s	364140
	R3 35-87s	253143
	R4 35-61s	159448
	R5 35-56s	114037
	R6 35-50s	71652
	L1 35-176s	331168
	L2 35-115s	250315
	L3 35-78s	154160
	L4 35-62s	81592
	L5 35-56s	42756

Table 2. Body wave phases used in this study

Author	Phase	Number of measurements
[Antolik et al., 2003]	P	621892
[Ritsema and van Heijst, 2002]	pPP	12054
	pP	20780
	PP	167144
	PPP	15060
	$pPPP$	2089
[Ritsema et al., 2011]	S	144696
	SKS	31971
	$SKKS$	8727
	ScS	8475
	$ScSScS$	13505
	$ScSScSScS$	7983

- Ray-theory
- Crustal corrections (as in *Boschi and Ekström 2002)*
- Parameterization: 5°x5° and 28 layers
- Solving for V_{SV} , V_{SH} , V_{PV} , V_{PH} with respect to **PREM**
- Applying roughness damping and a-priori mineral physics constraint

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❖ SPani: a global V_P – V_S model

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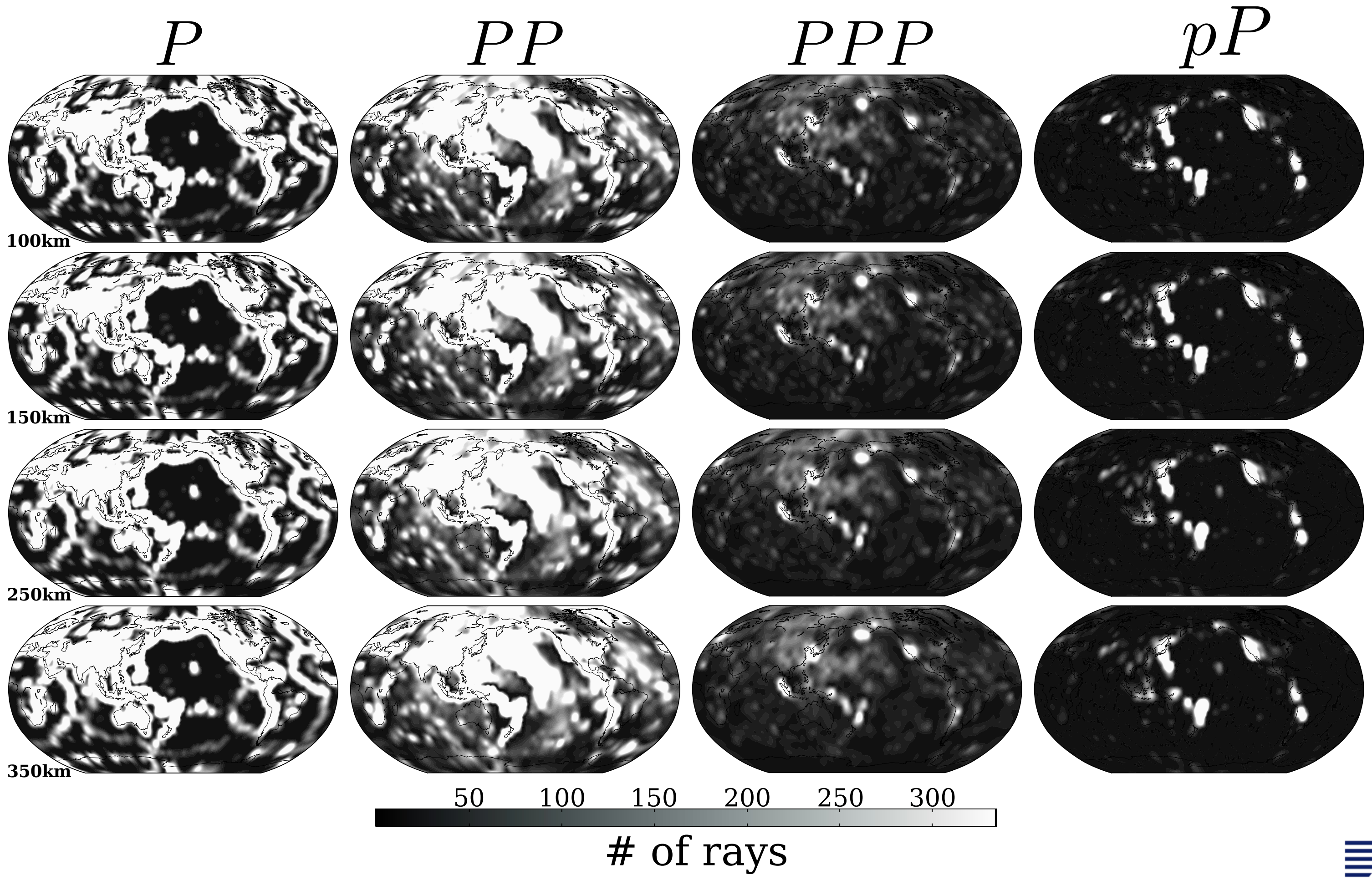
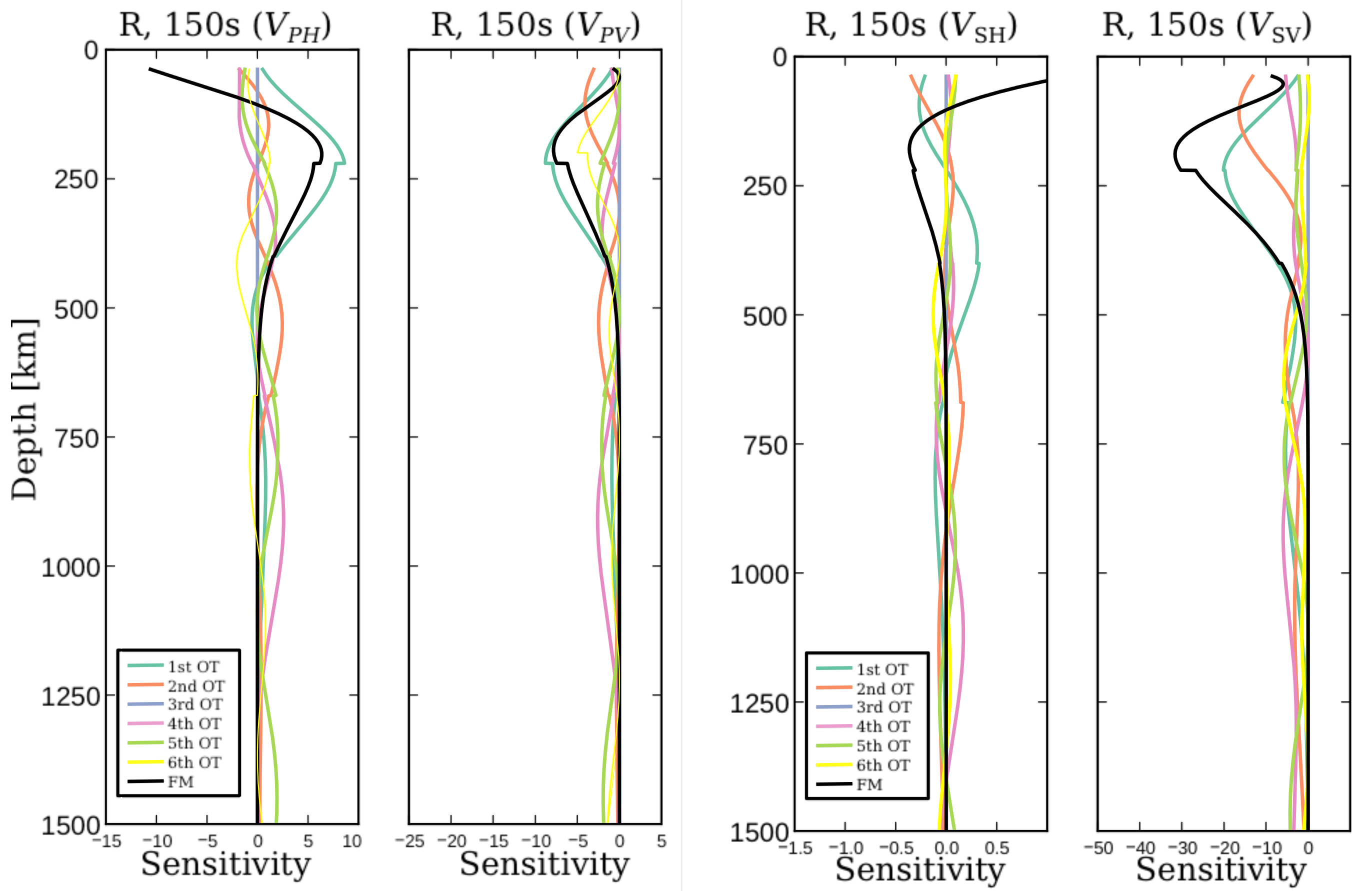


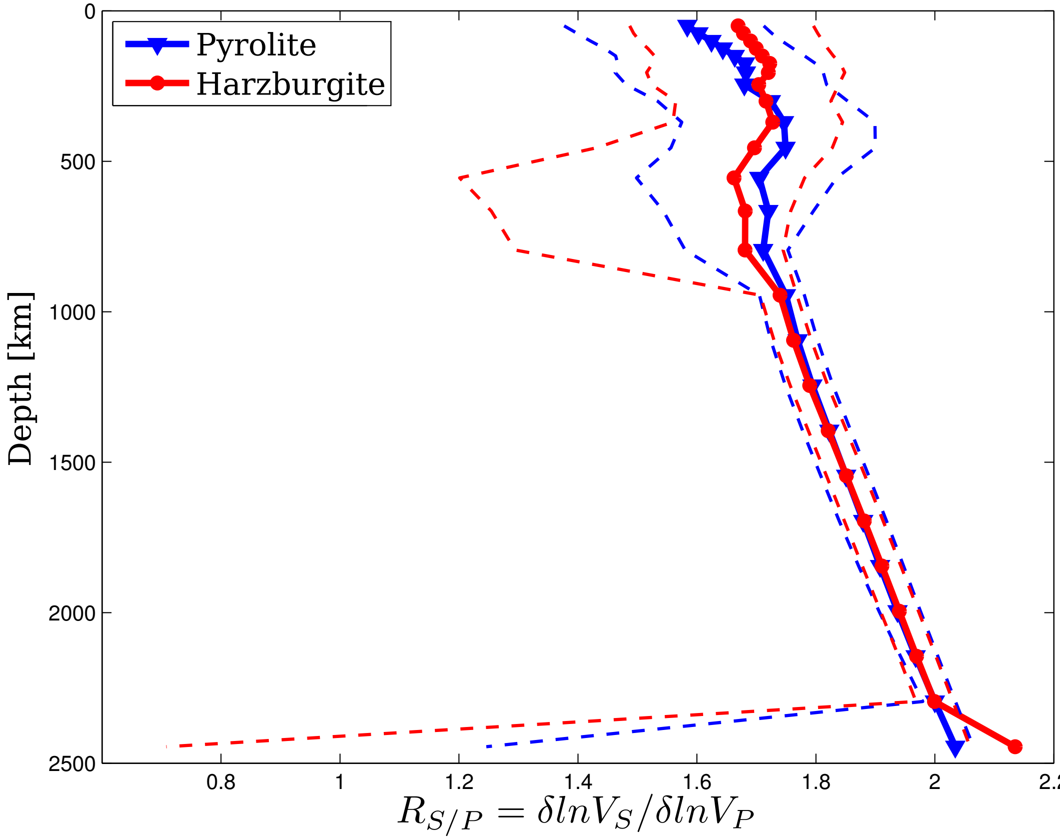
❖ SPani: a global V_P – V_S model

- ✓ **Invert a large database of surface waves and P and S body waves**
- ✓ **Exploit V_P sensitivity of Rayleigh waves**

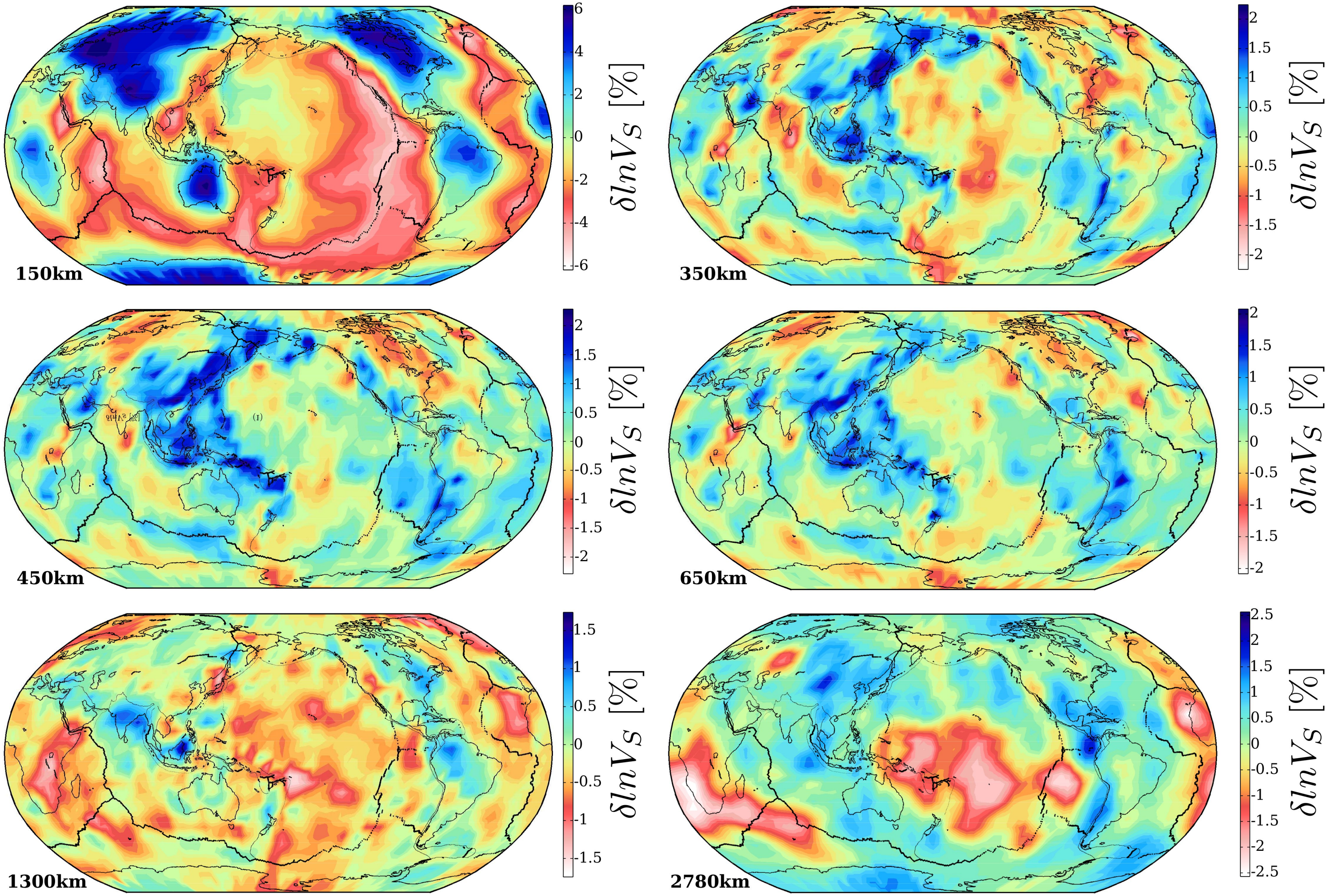


❖ SPani: a global V_P – V_S model

- ✓ Invert a large database of surface waves and P and S body waves
- ✓ Exploit V_P sensitivity of Rayleigh waves
- ✓ Include a regularization constraint on $\delta lnV_S/\delta lnV_P$



Shear velocity model



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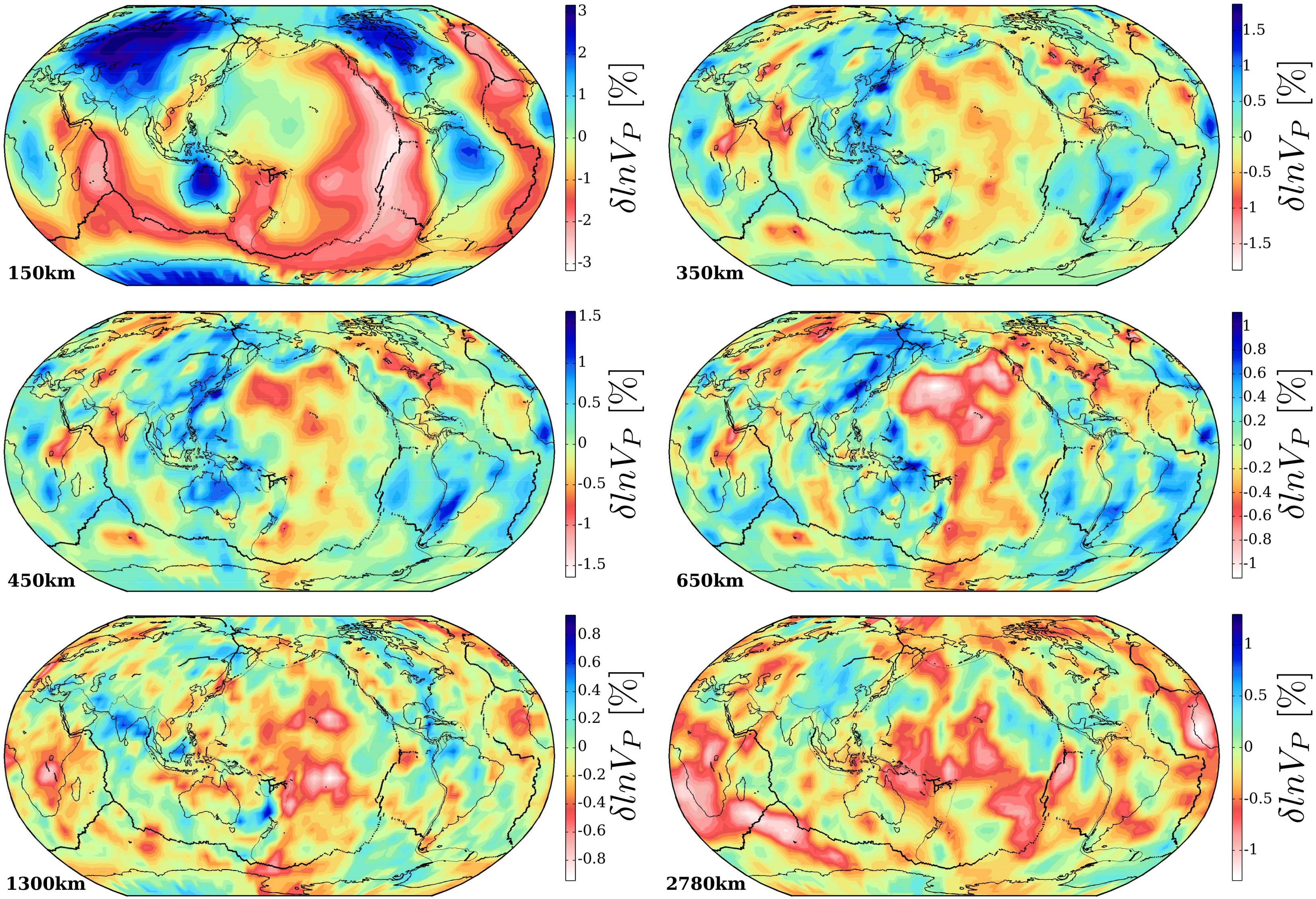
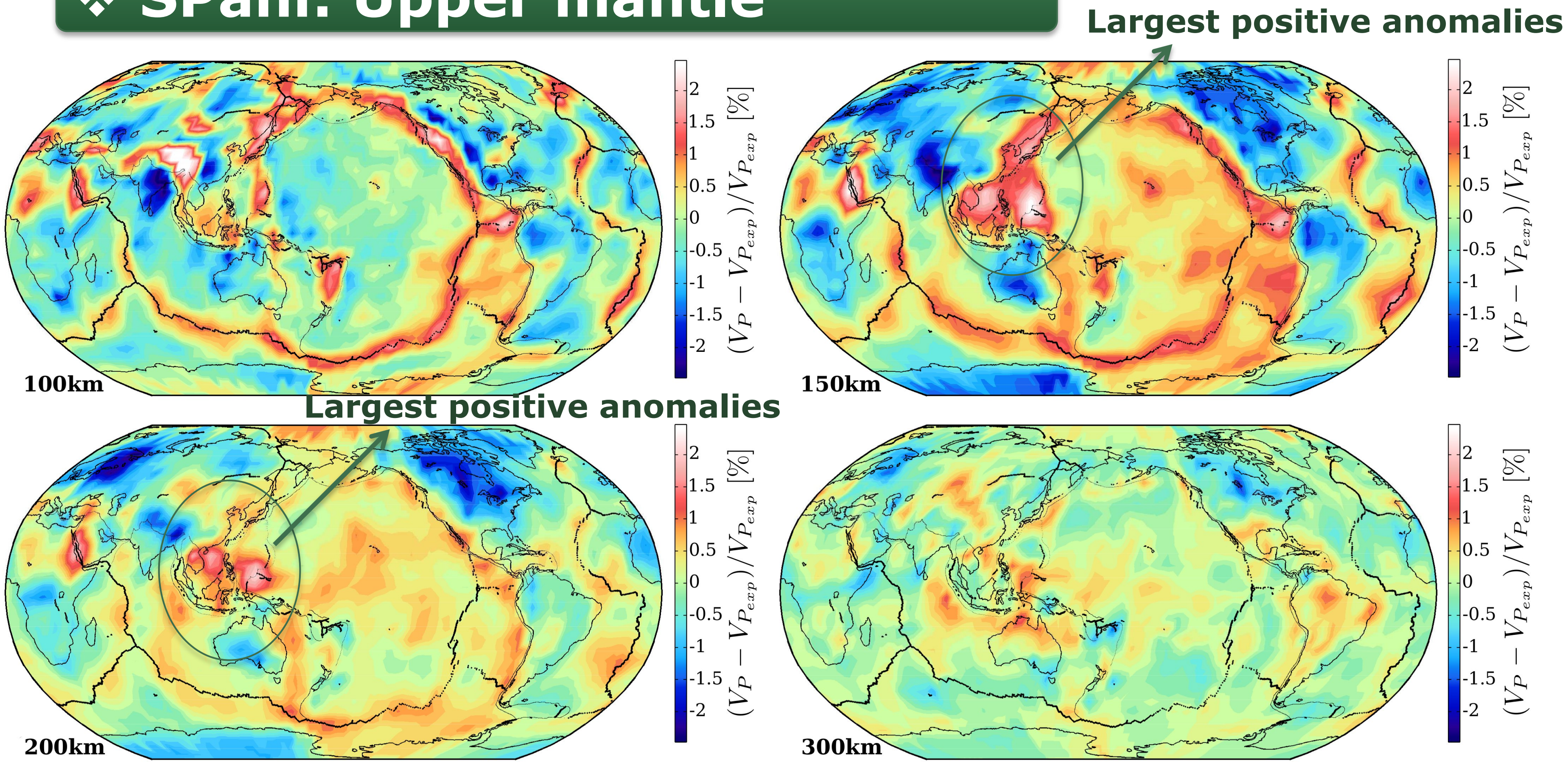
Compressional velocity model



❖ SPani: Upper mantle

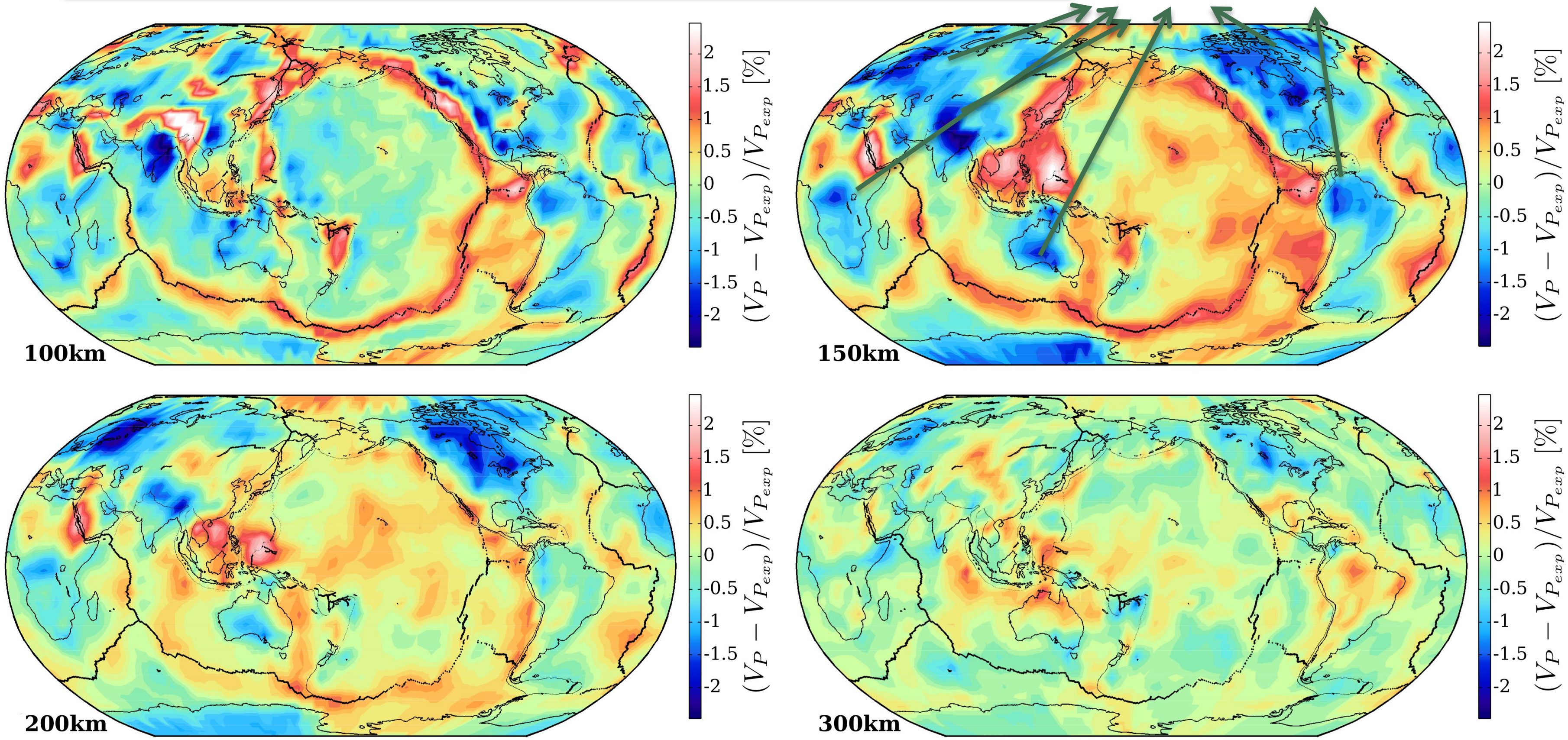


✓ Any decorrelation between V_P *and* V_S structure may be indicative of possible compositional effects

<u>Warning:</u> A quantitative analysis of the V_P/V_S ratio can only be done if absolute velocities are known

❖ SPani: Upper mantle

Largest negative anomalies in continental lithosphere



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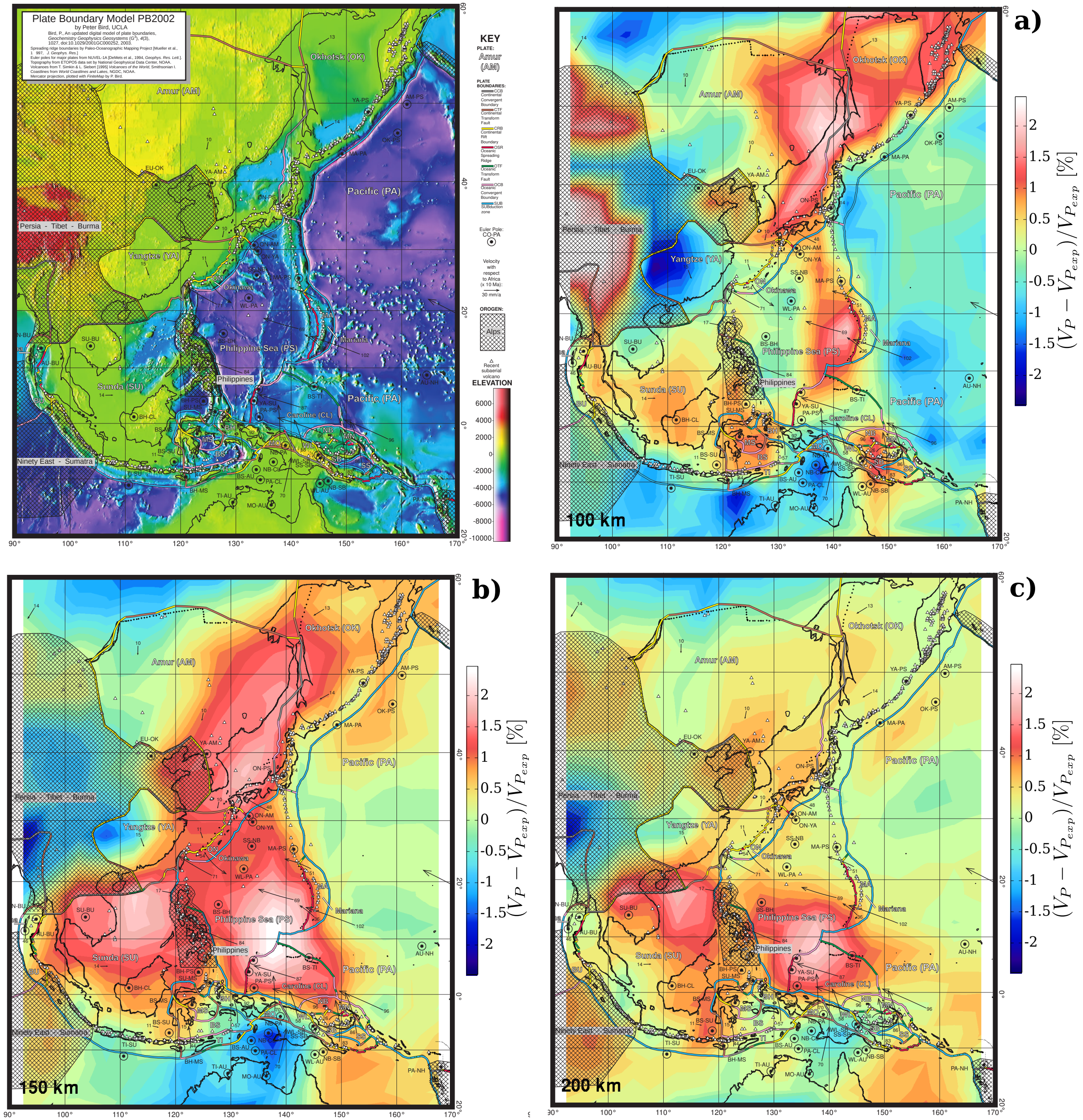


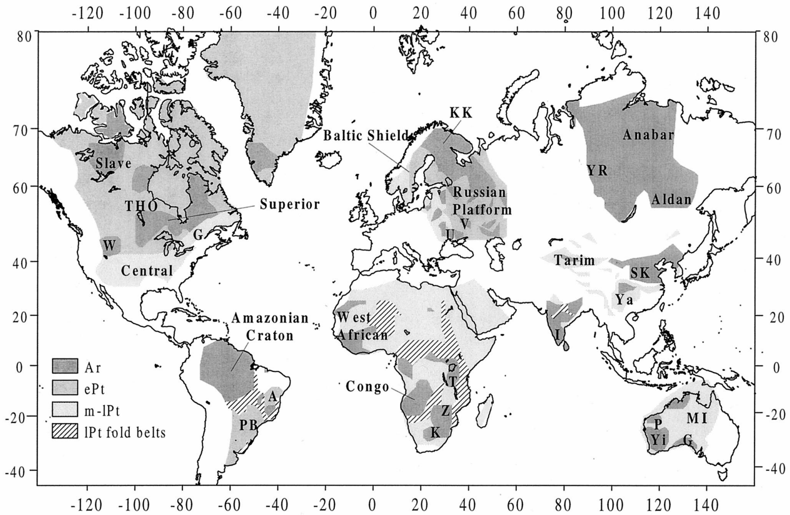
Hydration of marginal basins

- V_P is ~2% higher than expected and V_S is not extremely (lower than at mid-oceanic ridges)
- Relatively high V_P/V_S could be associated with presence of water

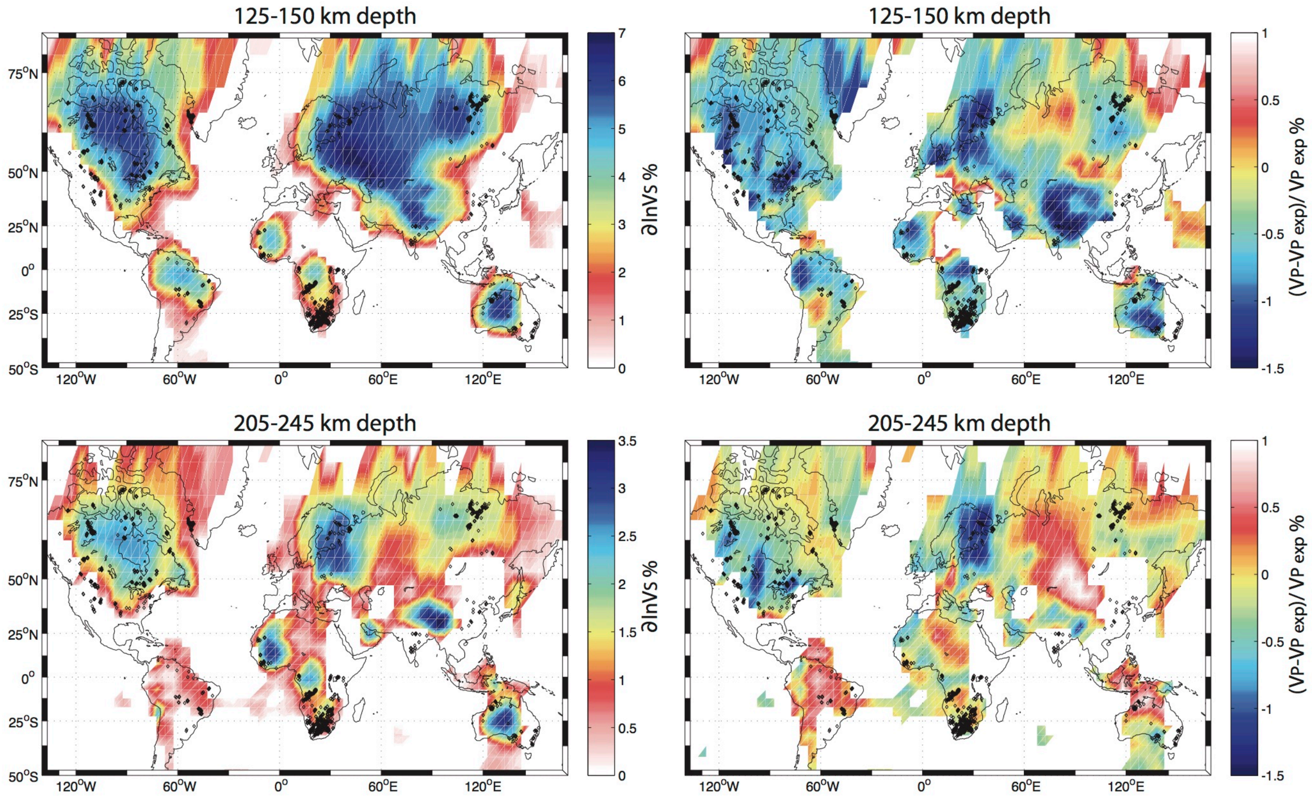
=> weakening of the overriding plate

Compositional anomalies within the continental lithosphere

- High V_S and low V_P/V_S down to 250 km
- Distinct structural variations within the continents emerge



Artemieva & Mooney 2001



- ✓A more fertile Russian platform vs the oldest part of the Baltic shield
- ✓ Deeper Baltic shield and North American cratons vs Australia, African

Conclusions (about T-C Upper mantle)

- Our new joint model resolves anomalies in the V_P/V_S ratio that have thermo-chemical implications.

- Marginal basins in the Western Pacific show an anomalously high V_P/V_S ratio which is compatible with high concentration of H_20

- Our model suggests large-scale compositional variations within continental regions: regions interested by rifting and collisions are more *enriched* than undeformed Precambrian areas

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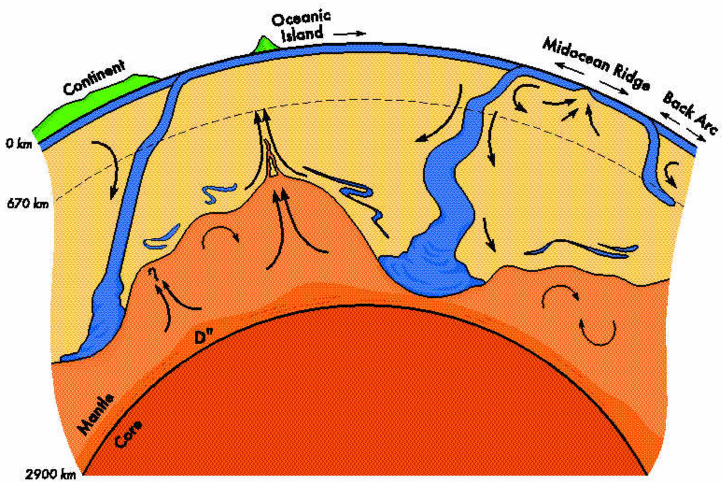
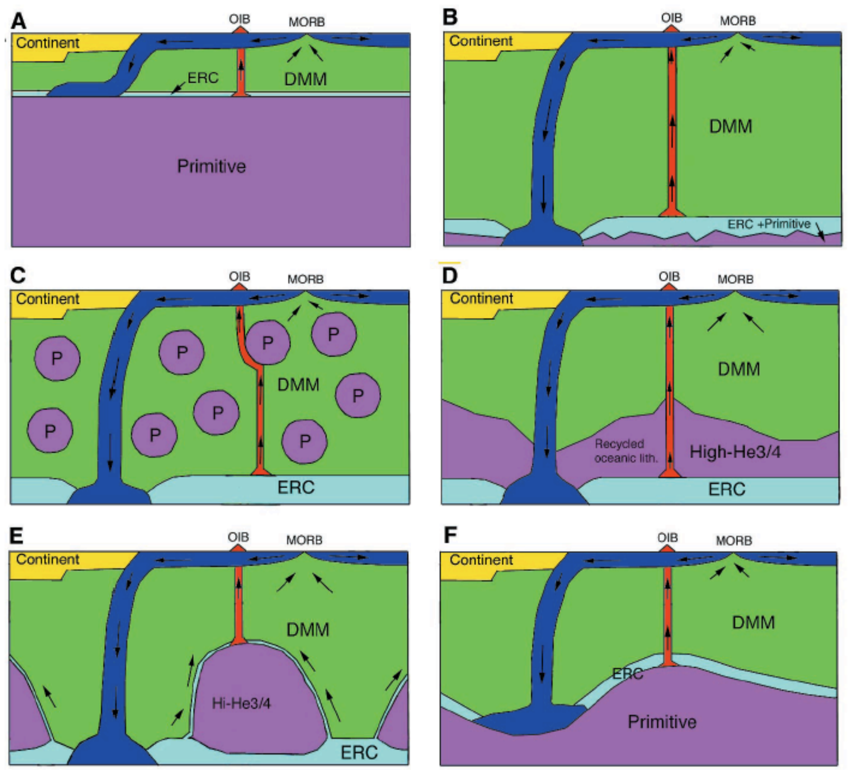
➢ T-C Lower mantle (from ~800km downward)

- Mantle convection: Fate of subducted slabs, upwelling
- Two large low shear-velocity provinces (LLSVPs) compatible with degree 2 geoid: thermal or thermo-chemical?



Kellogg et al., 1999



Tackley 2000

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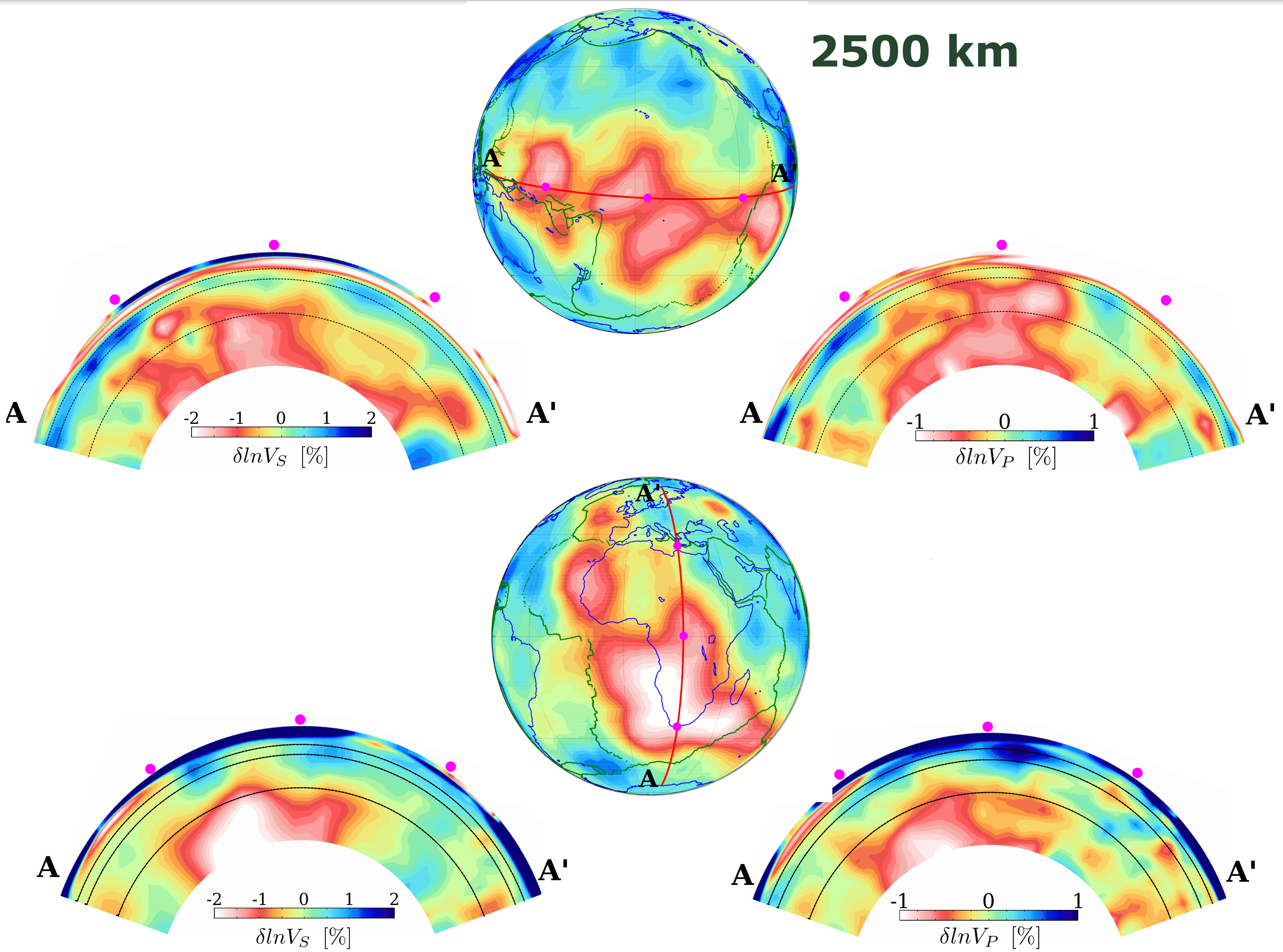
Some open questions:

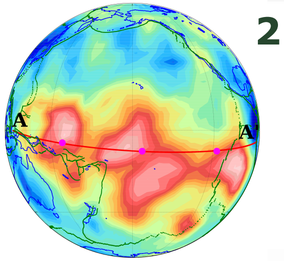
✓ Are the LLSVPs required to be **compositionally heterogeneous** and to what extent?

✓ Are the **slabs deflecting or stagnating** in the mid-mantle? => is there any **viscosity** (large) **variation** within the mantle?

✓ What is the **length-scale** of compositional anomalies in the lower mantle

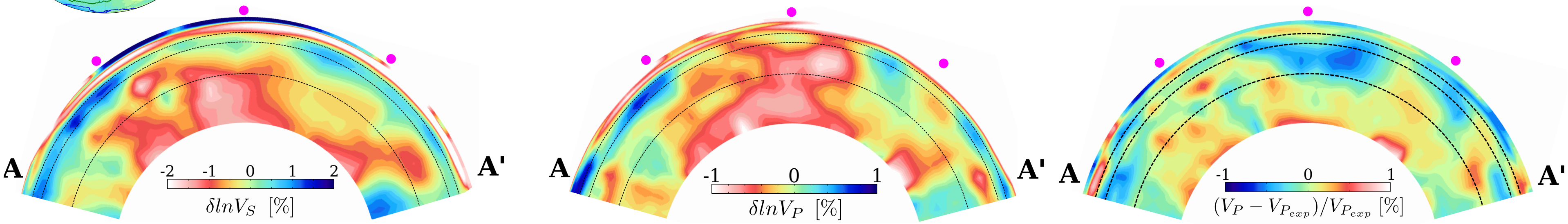


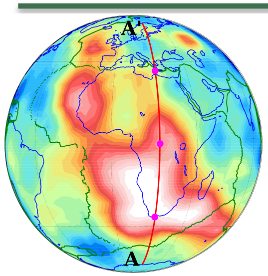
- ✓ In agreement with other models, **two LLSVPs** beneath Africa and Pacific
- ✓ Pacific V_S anomaly more scattered than African one
- ✓ In general , **high correlation** between V_P /V_S, **but also robust structural variations** throughout the mantle



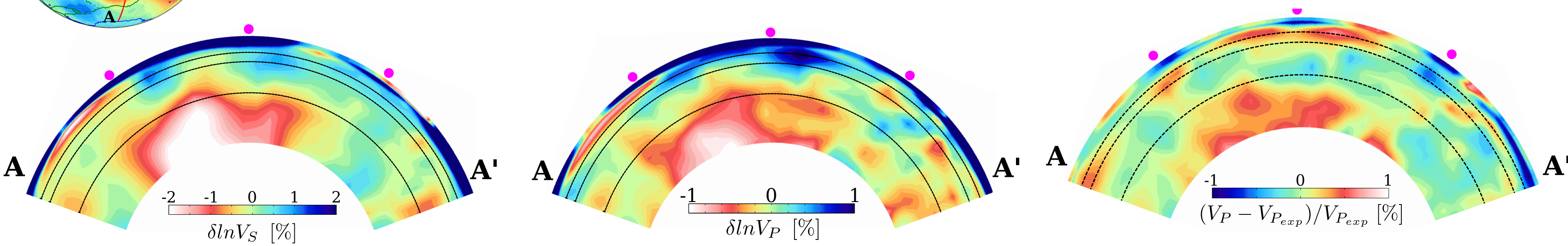
2500 km

Pacific





Africa



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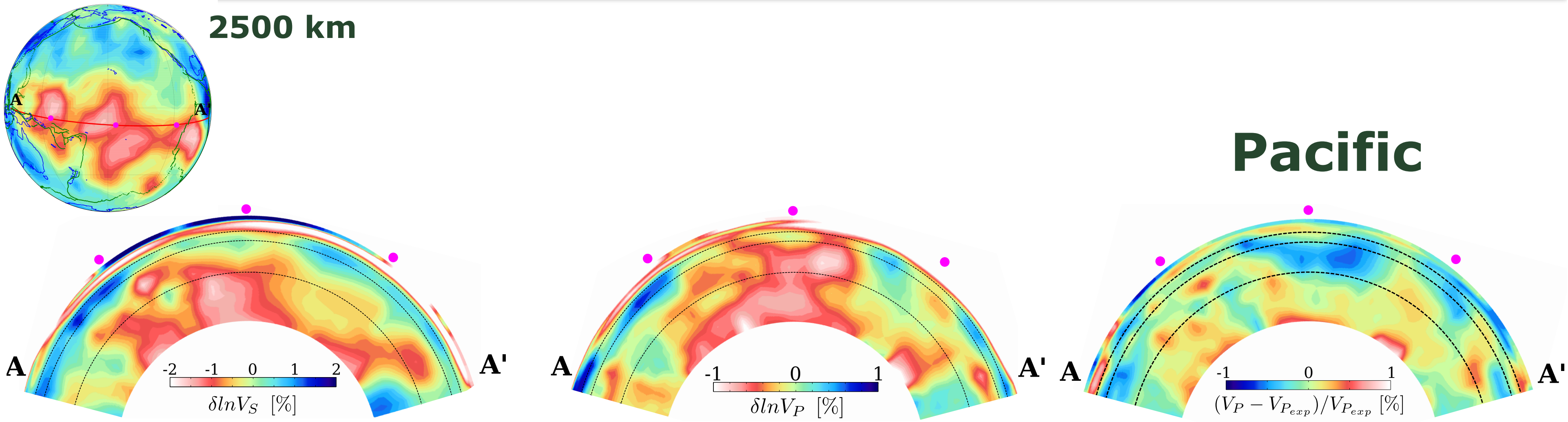
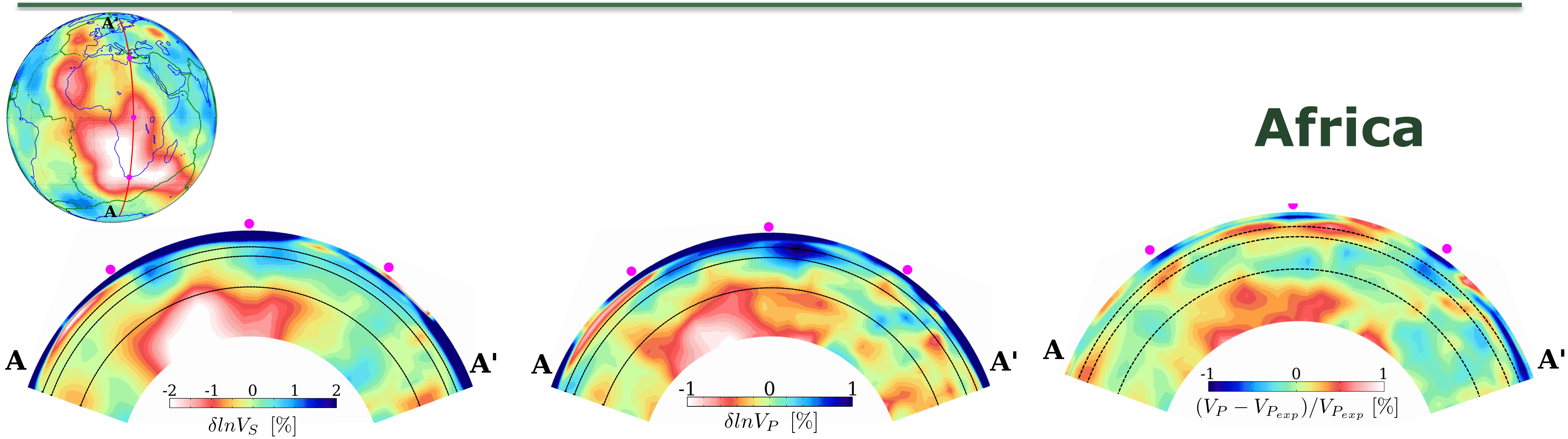
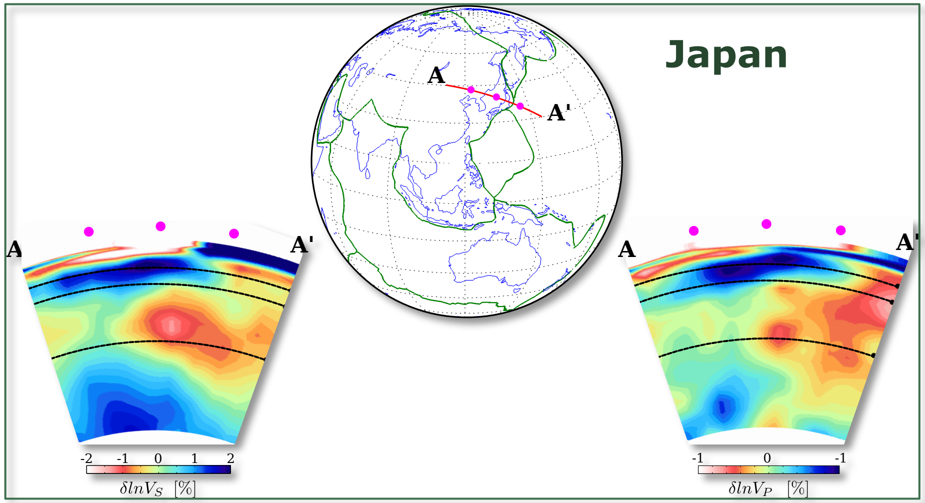
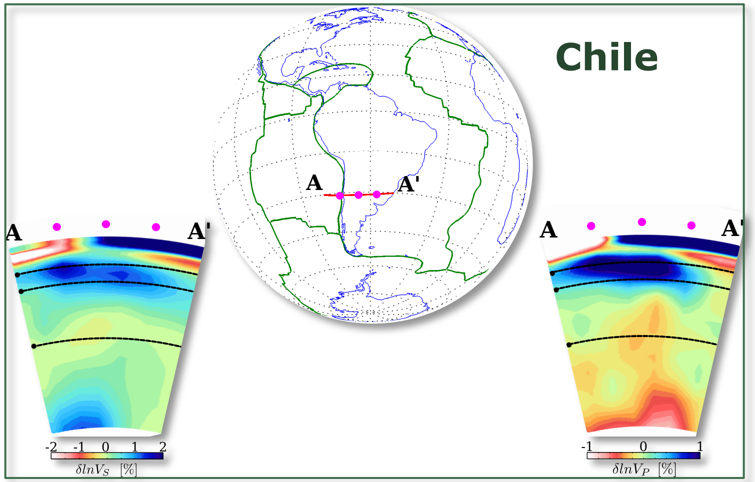


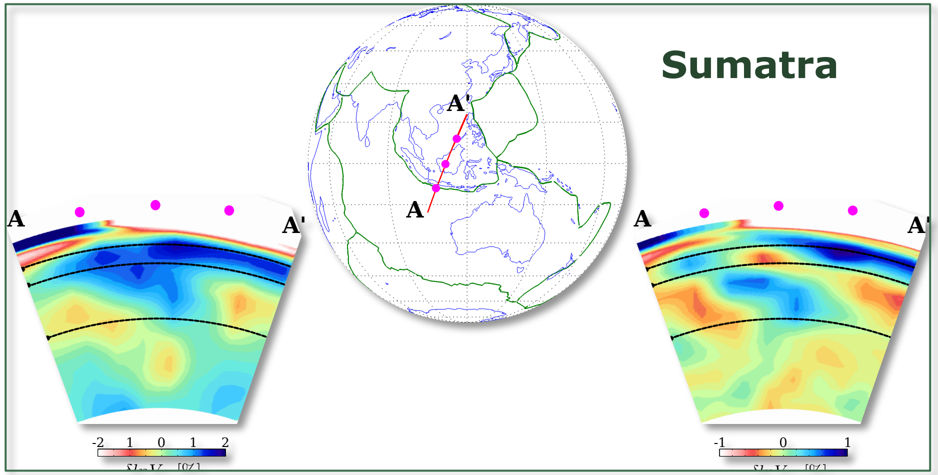
Africa

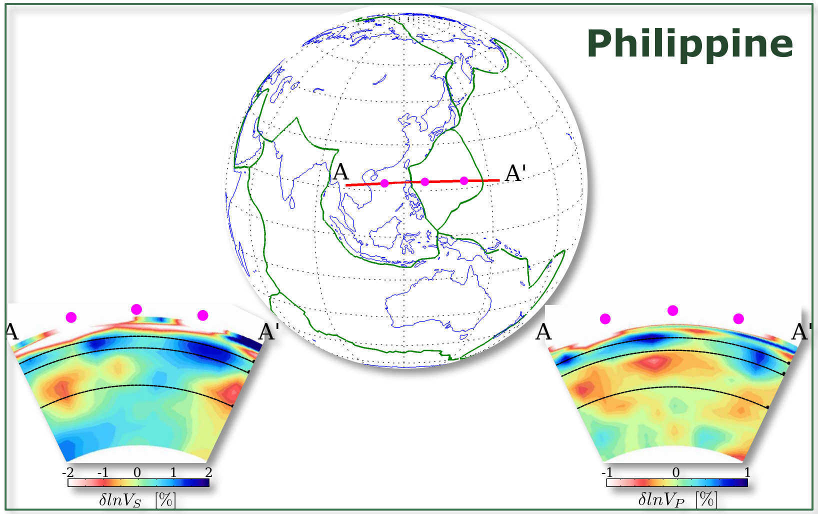


- Compositional heterogeneity: smaller length scale, mostly close to CMB



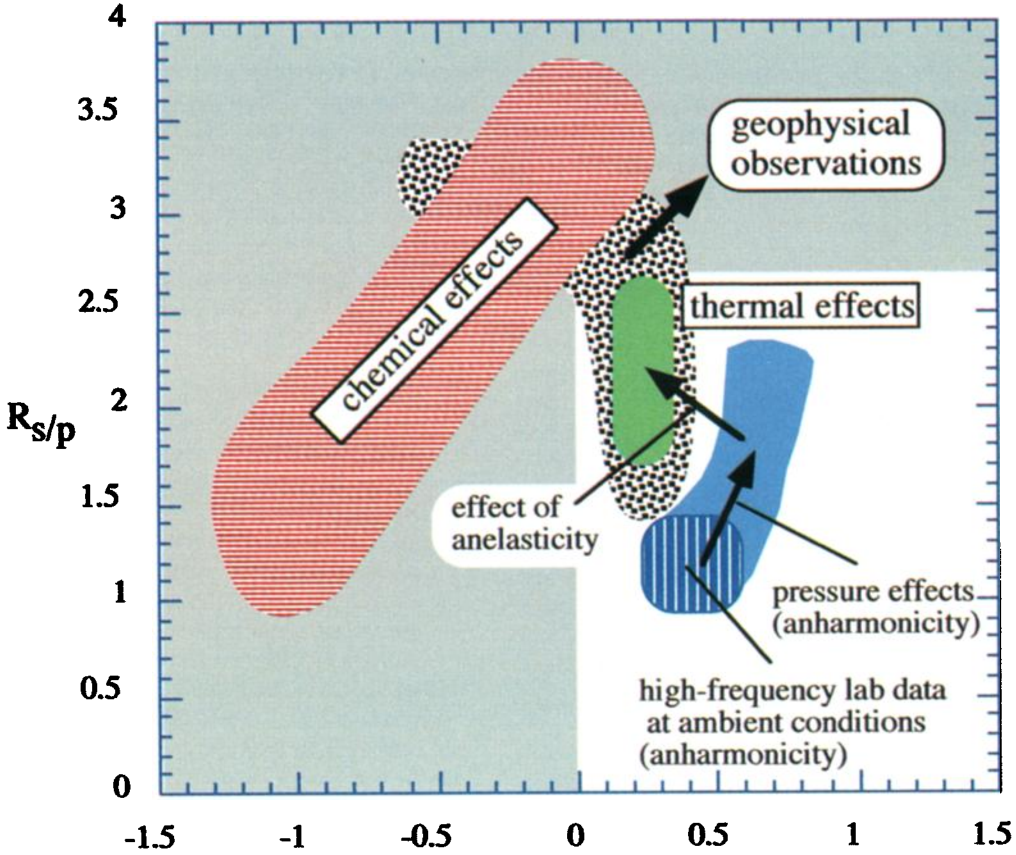






- ✓ Slab morphology is consistent with V_P recent images (Fukao & Obayashi 2013) => stagnant slabs above 660km or in the mid-mantle

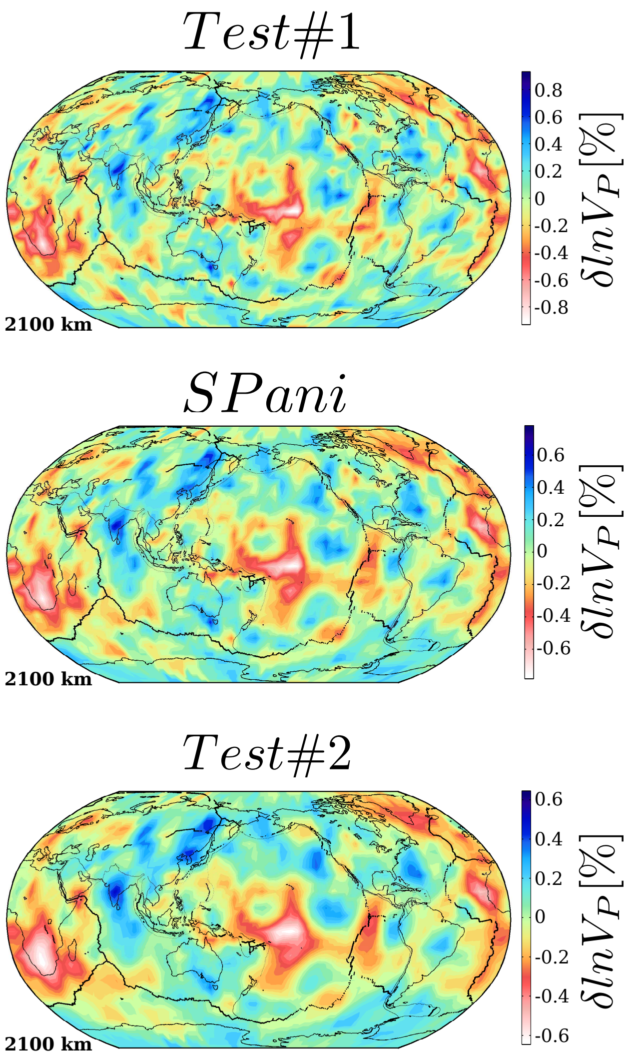
- Heterogeneity ratio $R=\delta \ln V_S/\delta \ln V_P$ is an important diagnostic parameter



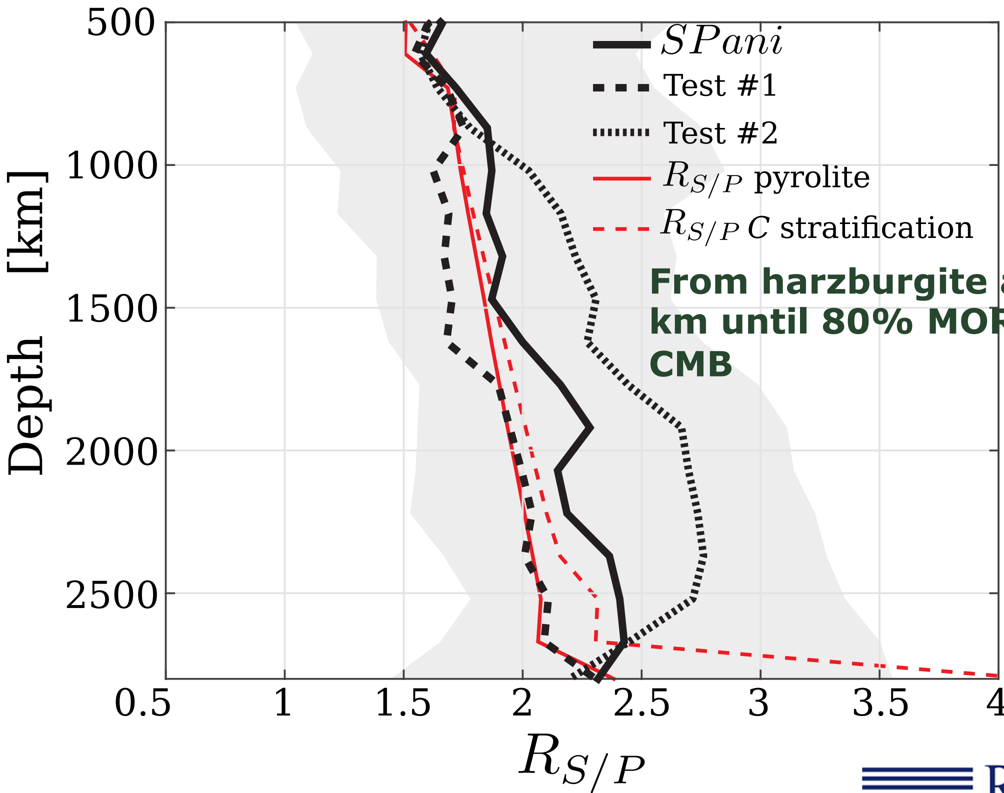
from Karato & Karki 2001

✓ High spherically-averaged R in the lower mantle and high R in LLSVPs has been used as an indicator of compositional heterogeneity

✓ <R> is affected by model resolution and regularization



- <R> predicted by purely T is not able to explain the large lateral variations, but seismic <R> is difficult to determine
- Smoother models give higher R

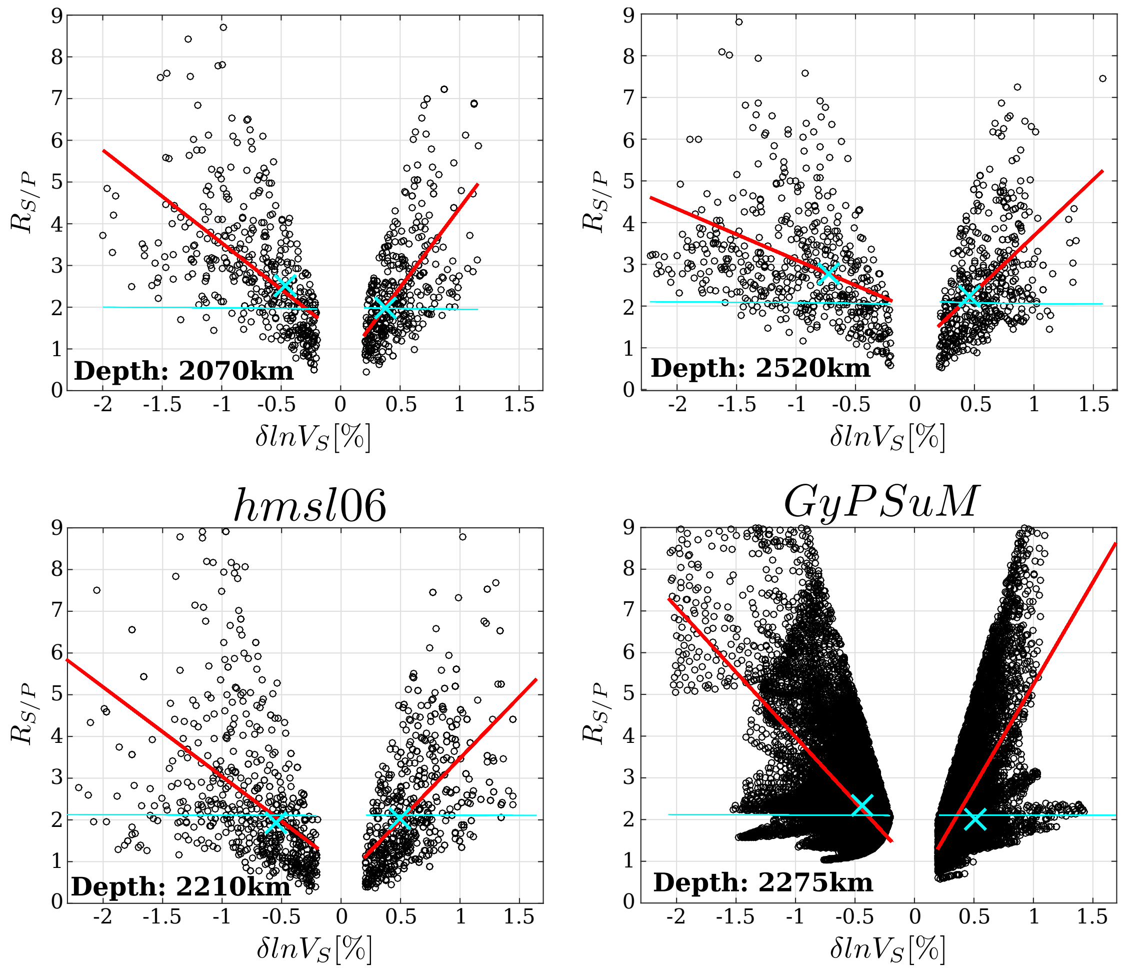


From harzburgite at 660 km until 80% MORB at CMB

Note small anomalies are discarded for the determination of R

ROMA TRE

✓ R in LLSVPs is affected by model resolution and regularization

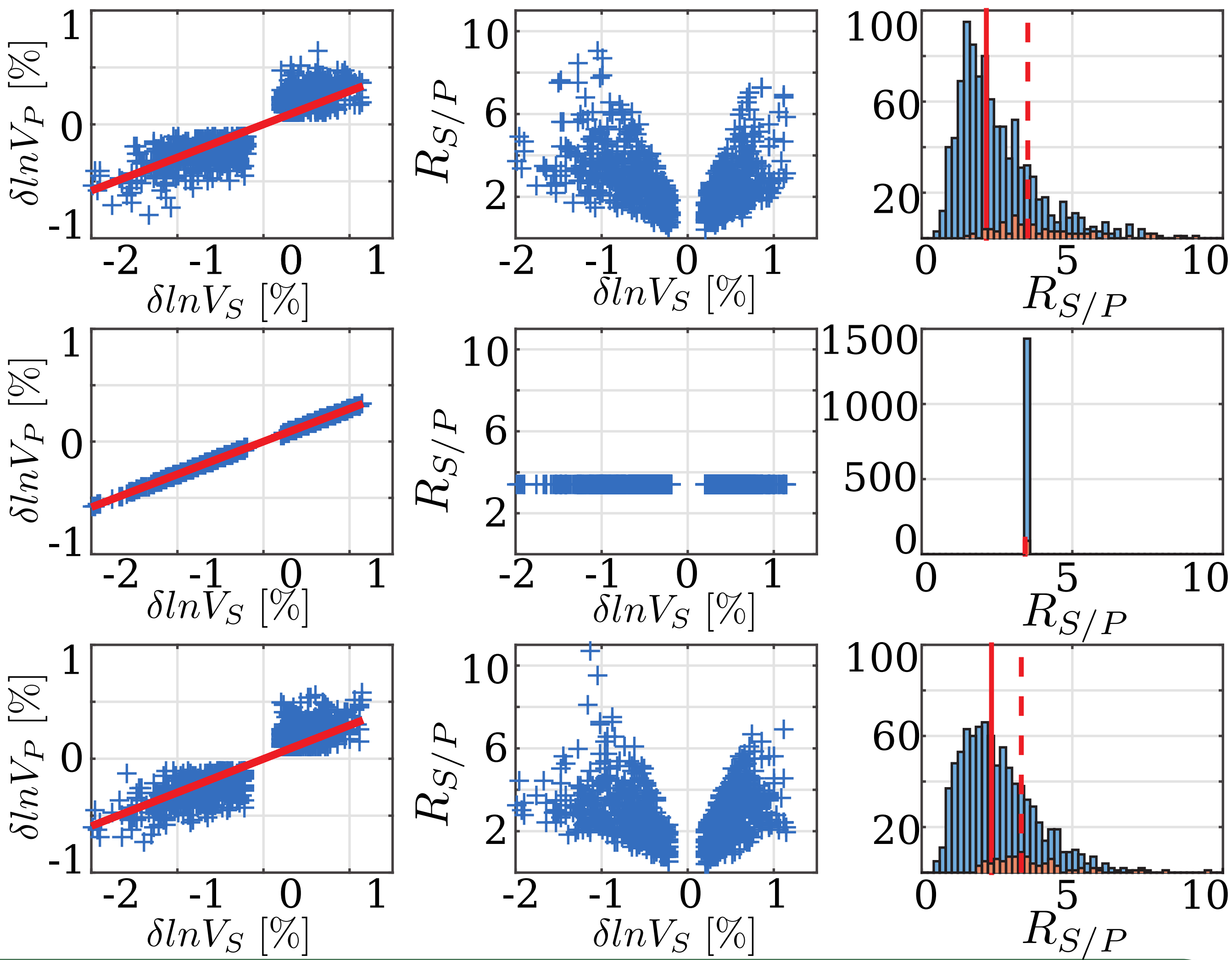


SPani

Note: small anomalies are discarded

- **All V_P-V_S models (non only SPani) show a trend towards high R as anomalies (negative and positive) get larger**

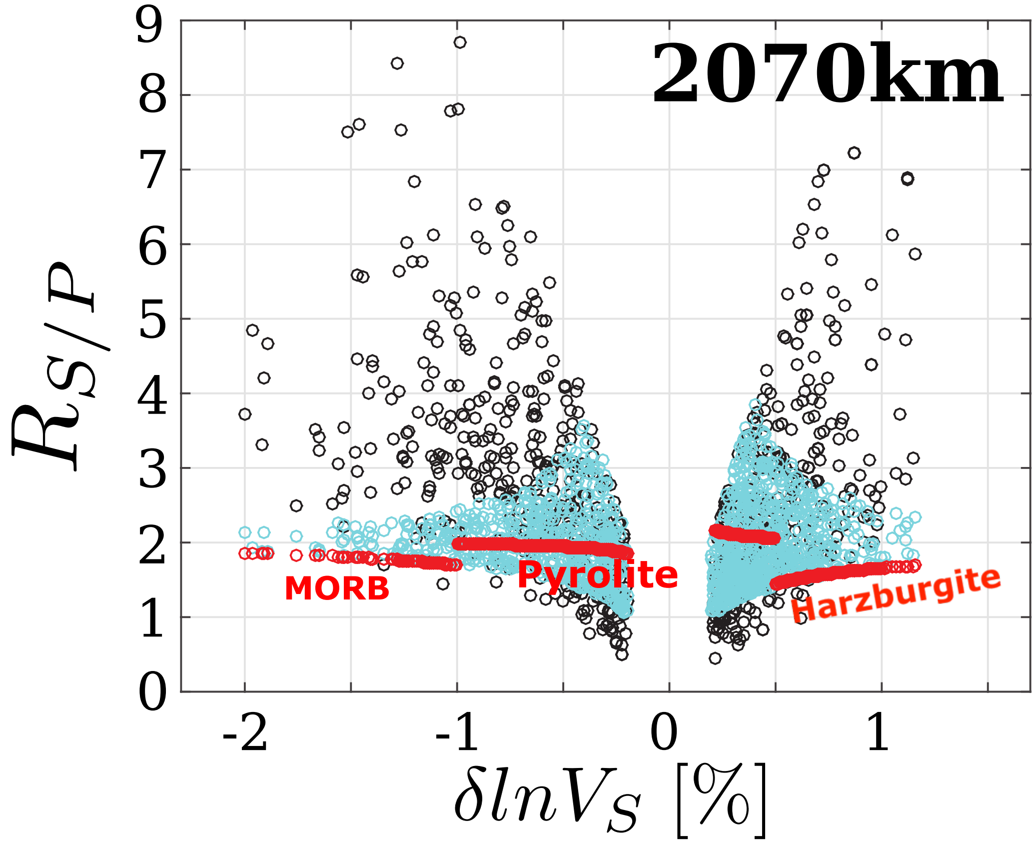
ROMA TRE



- **Synthetic test shows that small decorrelations between V_P and V_S modifies the statistical distribution and overestimates R in LLSVPs**

➢ Are large-scale chemical anomalies required in correspondence of LLSVPs?

- **Owing to uncertainties in mineral physics, lower R values than previously estimated in LLSVPs do not preclude the occurrence of first-order C anomalies**



- Adding random Compositional heterogeneity between Hz and 40% MORB

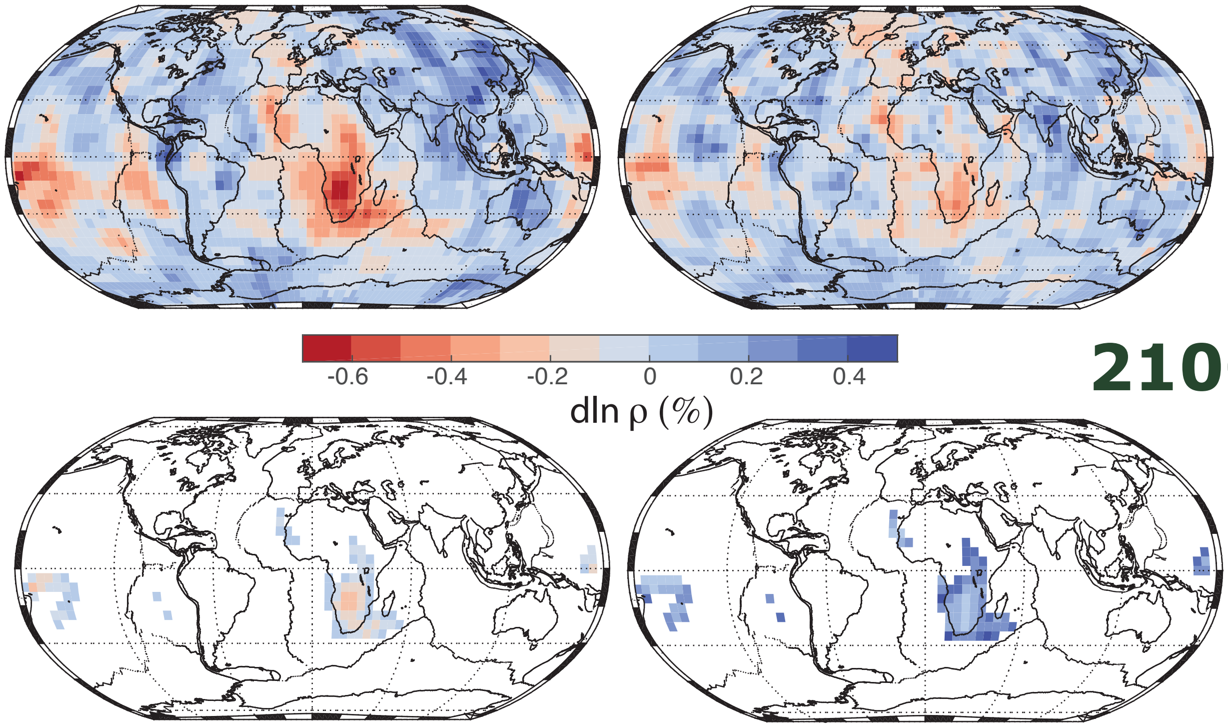
- **Important to use additional constraints**

Effects on density

Density from V_S | **Density from V_P**

Purely T assuming Pyrolite

Assuming enriched (MORB) LLSVPs (∂lnVS < 1%)



2100 km

EOS: Stixrude & Lithgow Bertelloni 2011

- Trade-off with (depth-dependent) viscosity and low-resolution from geoid do not provide conclusive evidence that LLSVPs are isolated reservoirs => more diffuse chemical variations throughout the mantle!

Conclusions (about T-C Lower mantle)

- Statistical distribution of $R = \delta \ln V_S / \delta \ln V_P$ hardly to be determined since strongly depends on model resolution and regularization
  - ➔ Spherically average value: possible range of models (more or less smooth) give significantly different values compared to predicted R from thermal interpretation.
  - ➔ R in LLSVPs could be overestimated

- We do not find any conclusive evidence for LLSVPs corresponding to thermo-chemical piles ➔ V_P vs V_S seismic structure suggests diffuse chemical heterogeneity and thus a more complex lower mantle