Comparison of Global Convection Models with Seismic Tomographic Models

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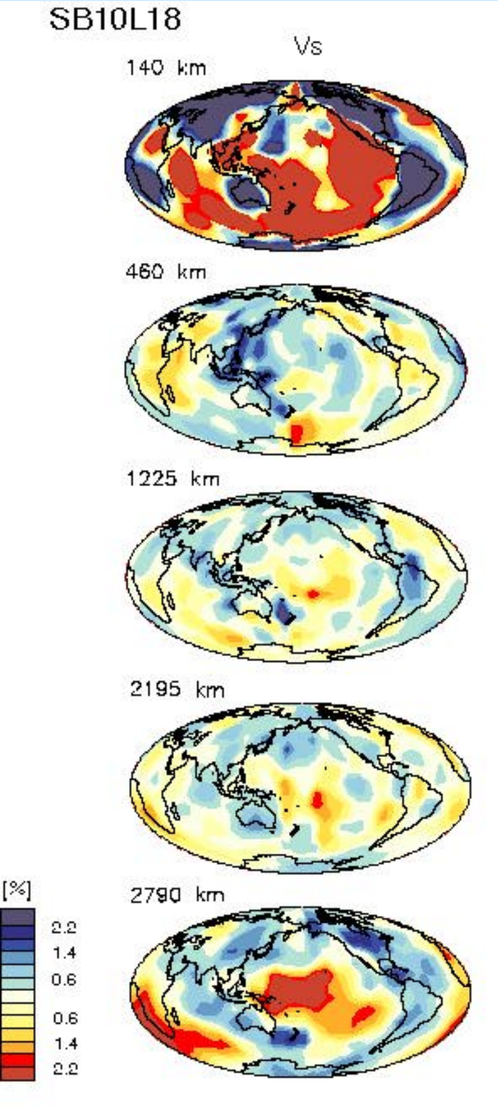
Mao & Zhong [2018, Nature-Geo; 2019, JGR]

Outline

- **Overview of mantle seismic structure – long-wavelength (degree-2 and LLSVP) and slab structures.**
- **Brief discussion of controls on long-wavelength structures – the roles of plate motion and beyond.**
- **Horizontally deflected slabs (or stagnant slabs) in the mantle transition zone and at 1000 km depth (?).**
- **Correlation with seismic model and effects of different model parameters.**
- **Conclusion remarks.**

A global model of mantle seismic structure



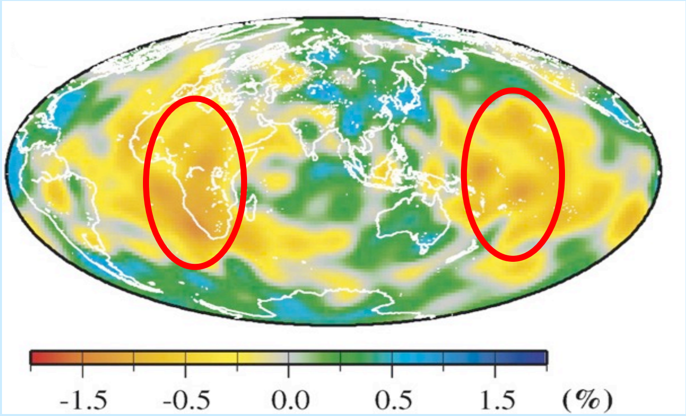
Masters et al., [2000]

Structure at shallow depths reflects lithospheric structure (e.g., craton and mid-ocean ridges) [Zhang & Tonimoto, 1992].

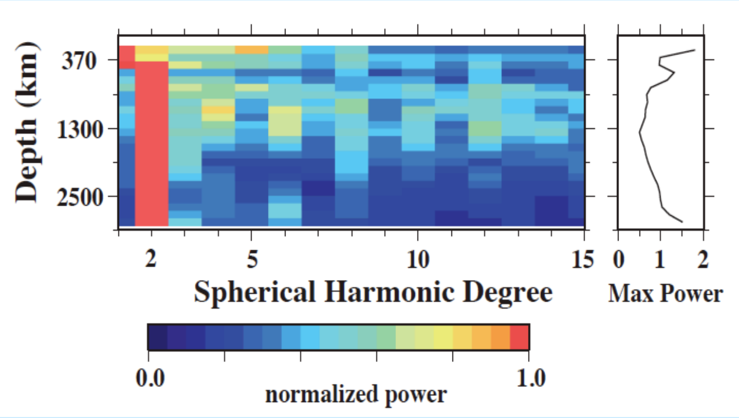
Circum-Pacific seismically fast anomalies from the upper to lower mantles that are related to past subduction [Dziewonski et al., 1977].

African and Pacific seismically slow anomalies (LLSVP) that are related to hot-spot volcanism [Anderson, 1982; Hager et al., 1985; Thorne et al., 2004; Torsvik et al., 2010]

Shear-wave anomalies at 2300 km depth [Ritsema et al., 1999, 2011]

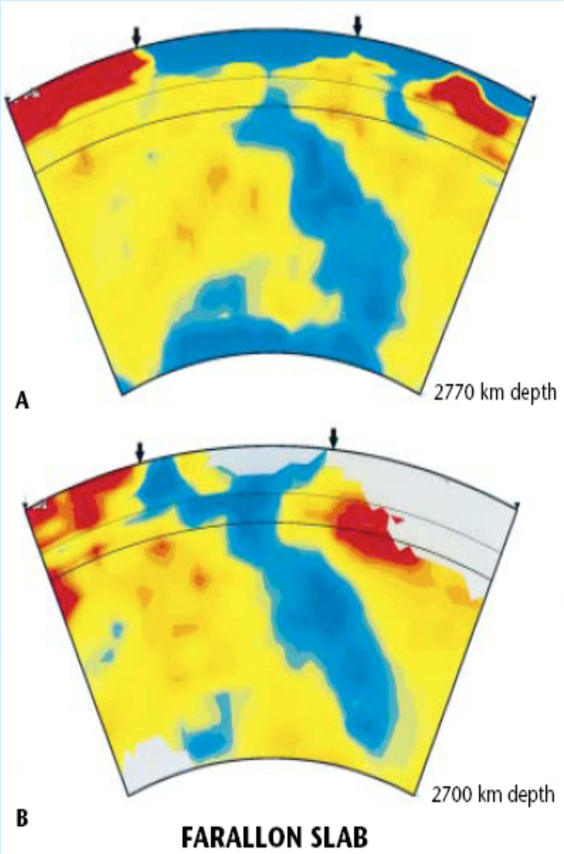


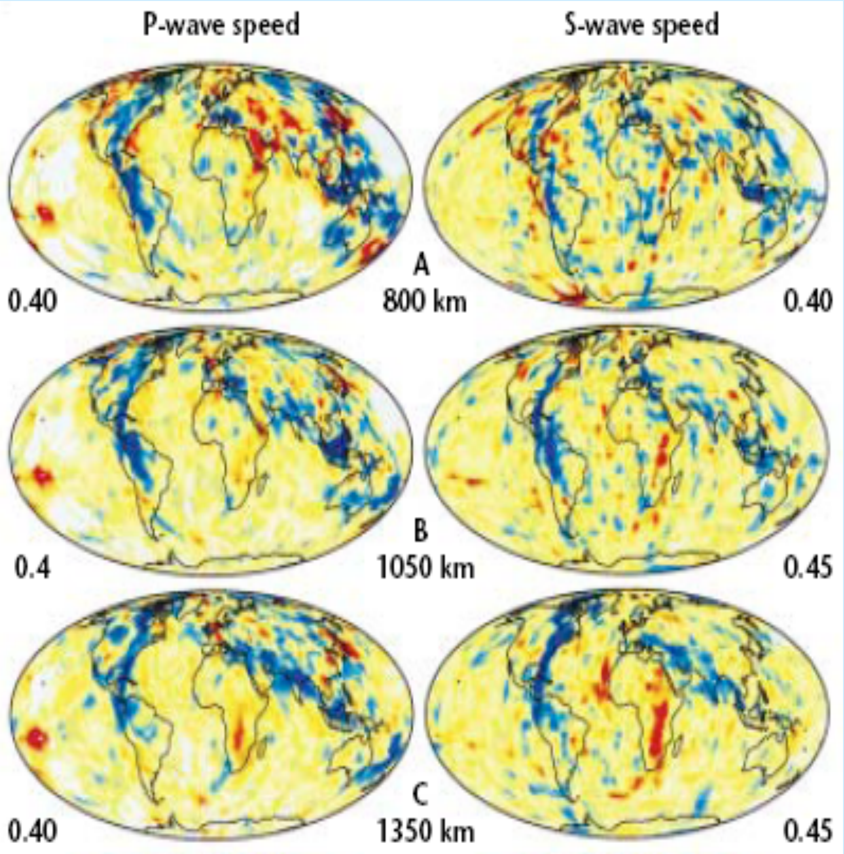
Seismic spectra at different depths



Dziewonski et al. [1984], Tanimoto [1990], Romanowicz & Gung [2002], Grand [2002], Becker & Boschi [2002]; Houser et al., [2008].

Slab penetration into the lower mantle





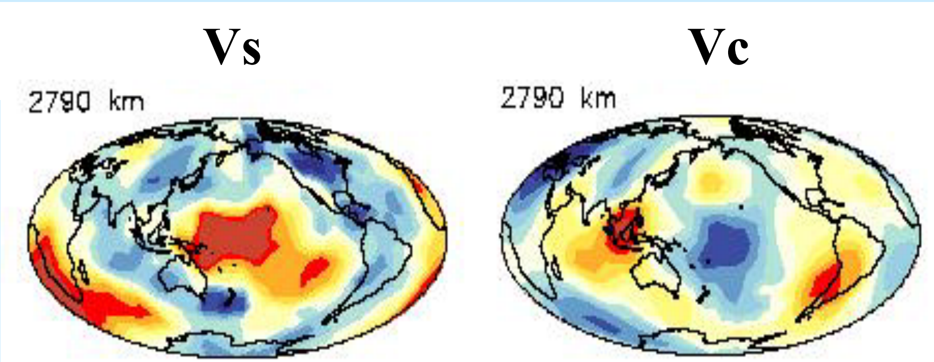
Grand, van der Hilst, & Widiyantoro [1997]

van der Hilst et al., [1991, 1992]; Grand [1994]; Zhao et al., [2004]; French and Romanowicz [2015]; Fukao and Obayashi [2013].

Two prominent new features discussed in the last 20 years

1) Thermochemical LLSVPs?

Anti-correlation between Vs and Vc



Masters et al. [2000]

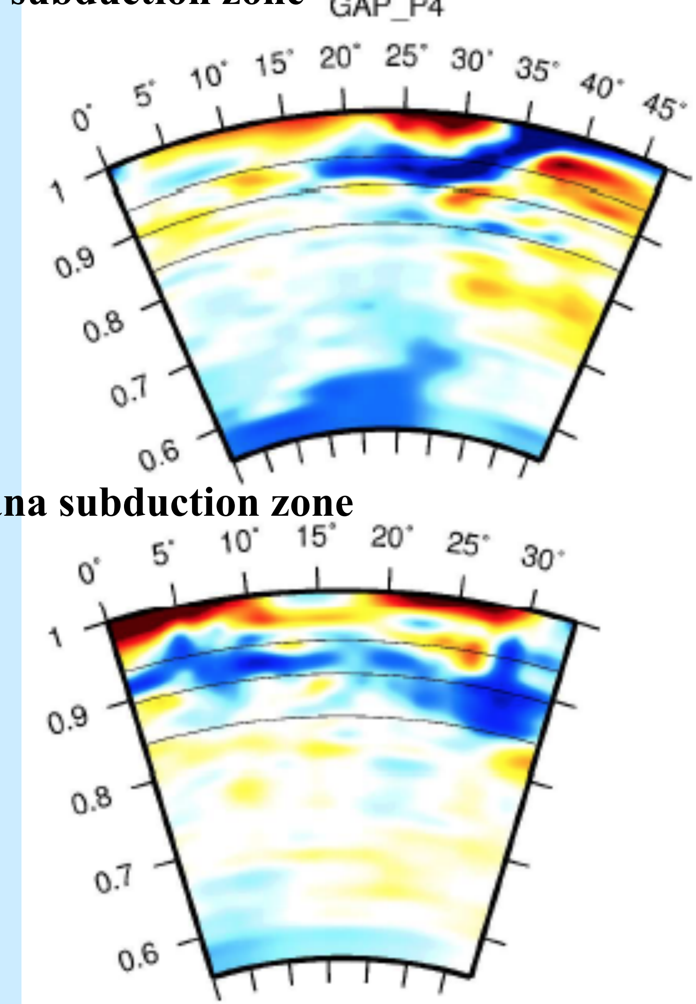
- **Waveform modeling of the two LLSVP structures [e.g., Wen et al., 2001; Ni et al., 2002; He & Wen, 2010]**
- **Seismic anisotropy [e.g., Lynner & Long, 2014; Cottaar & Romanowicz, 2013].**
- **Negatively buoyant [e.g., Ishii & Trump, 1999; Hau et al., 2017].**

However, some suggest no need for compositional anomalies [Davies et al., 2012; Koelemeijer et al., 2017].

2) Stagnant slabs in the transition zone

Honshu subduction zone

Mariana subduction zone



Fukao & Obayashi [2013]

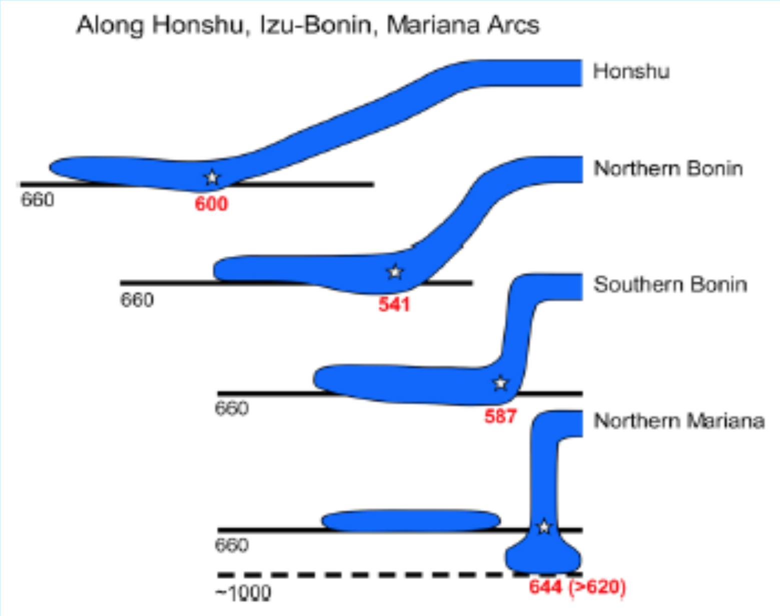
Also Fukao et al., [2009], and van der Hilst et al., [1991]

Seismic structure changes at ~1000 km depth?

Two-stage slab stagnation at 670 and 1000 km depths [Fukao & Obayashi, 2013].

Also for Kurile and Java subduction zones.

This has motivated geodynamic studies looking for explanations [e.g., Rudolph et al., 2015; Ballmer et al., 2015; 2017]. However, Goes et al. [2017] questioned the robustness of slab stagnation at 1000 km.



Plume structure change at 1000 km depth [French & Romanowicz, 2015].

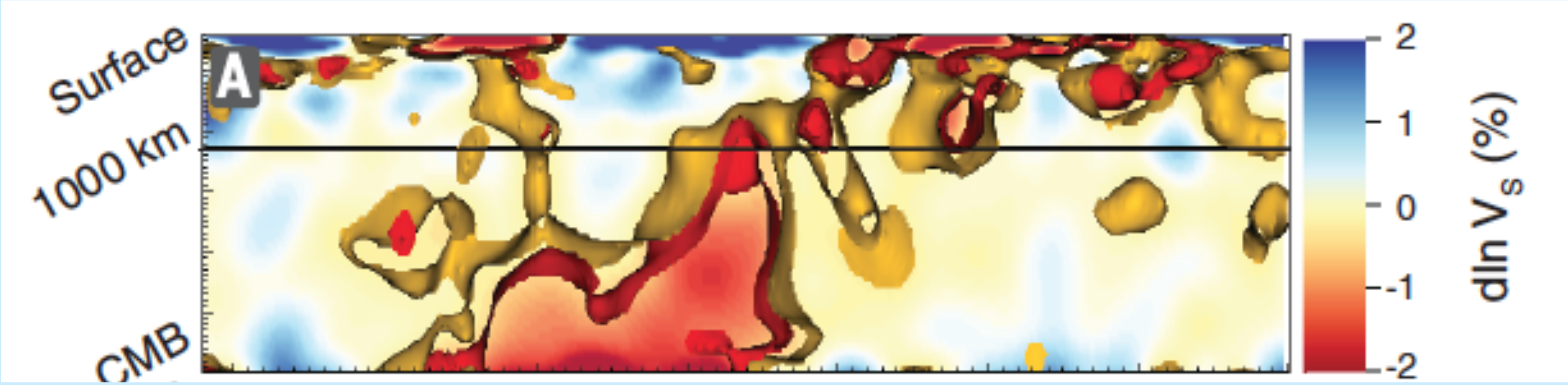


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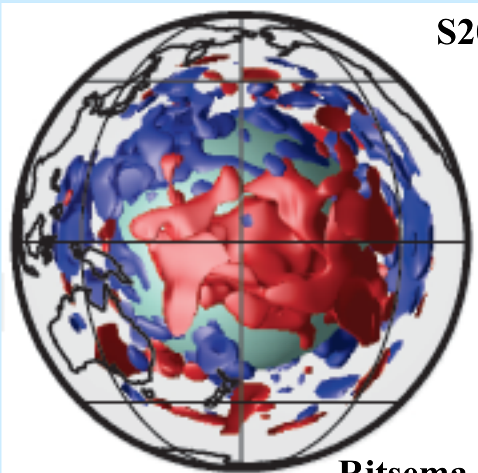
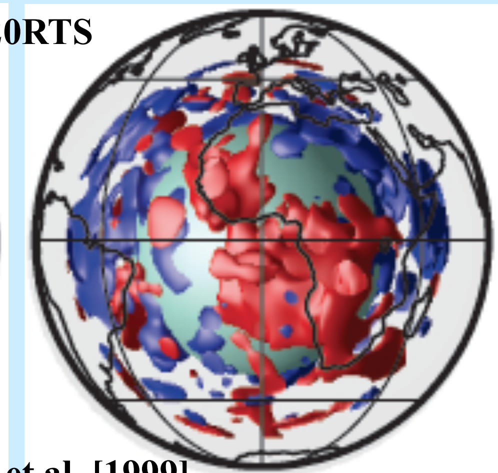
Plate motions responsible for the degree-2 structure or LLSVPs in the lower mantle

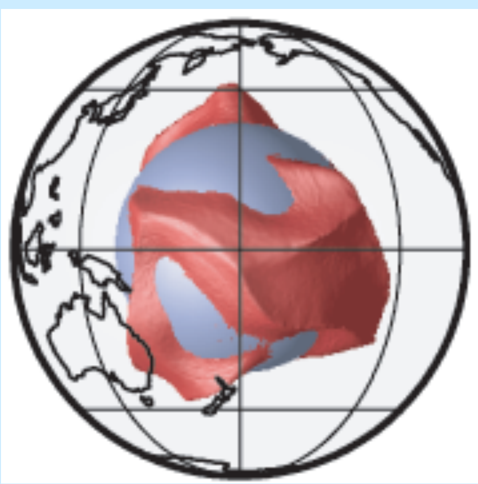
above Africa **above the Pacific**

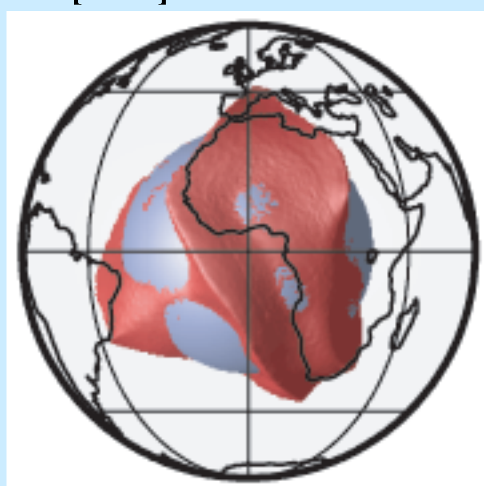
S20RTS



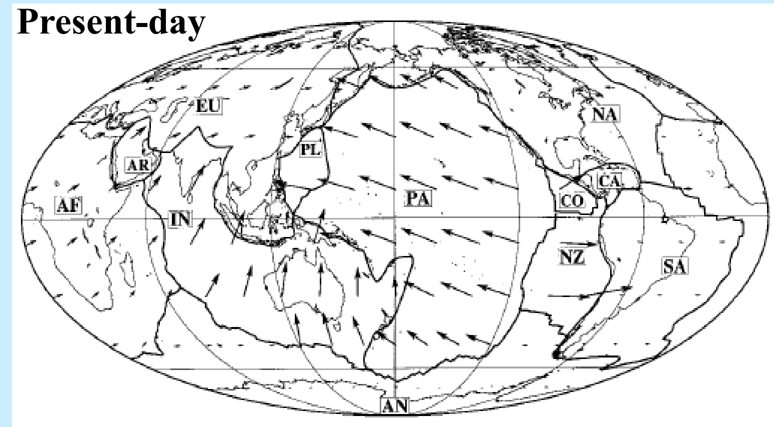


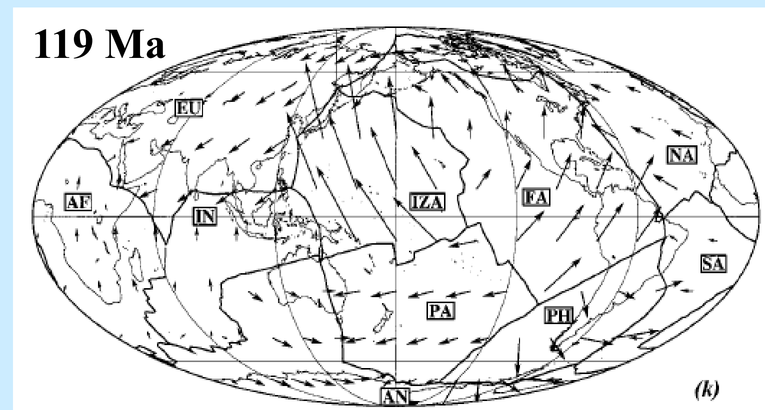
Ritsema et al. [1999]





McNamara and Zhong [2005]





Engebretson et al. [1992]; Lithgow-Bertelloni & Richards [1998].

Mantle structure is controlled by plate motions [e.g., Dziewonski et al., 1977; Hager & O'Connell, 1981; Ricard et al. 1993; Lithgow-Bertelloni & Richards, 1998; Bunge et al., 1998].

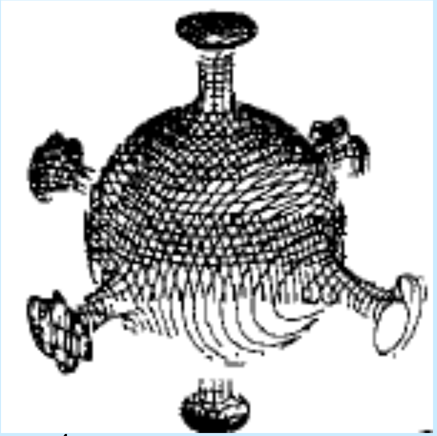
A chicken or egg question?
Convective structure from dynamically self-consistent models

Temperature-dependent viscosity

Constant viscosity

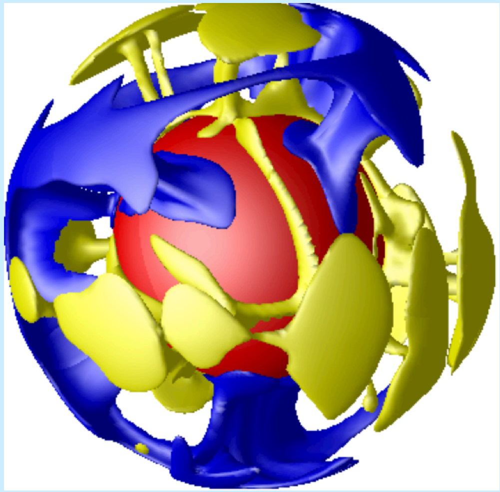
Tetrahedral

Cubic

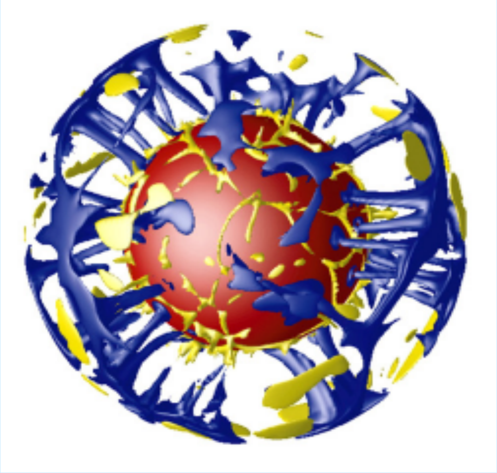


Ra=7x10^4

Bercovici et al. [1988]



Ra=7.3x10^5

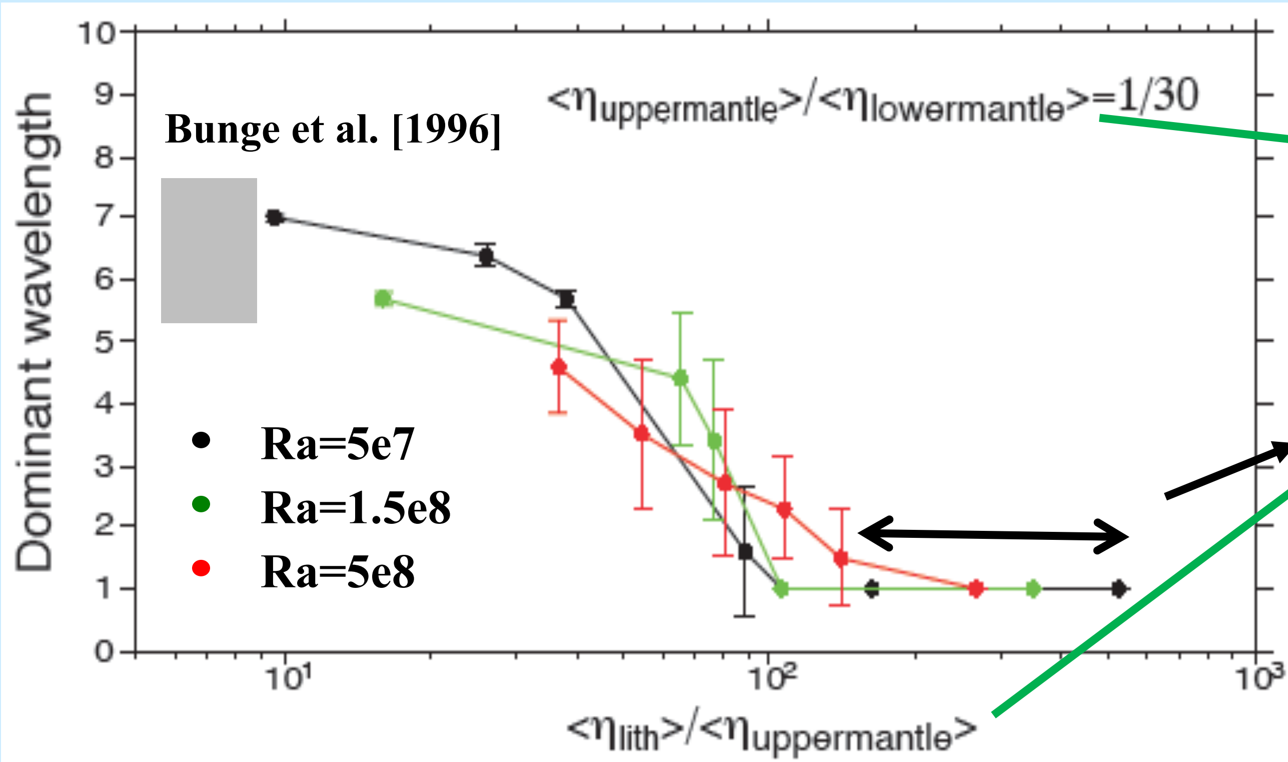


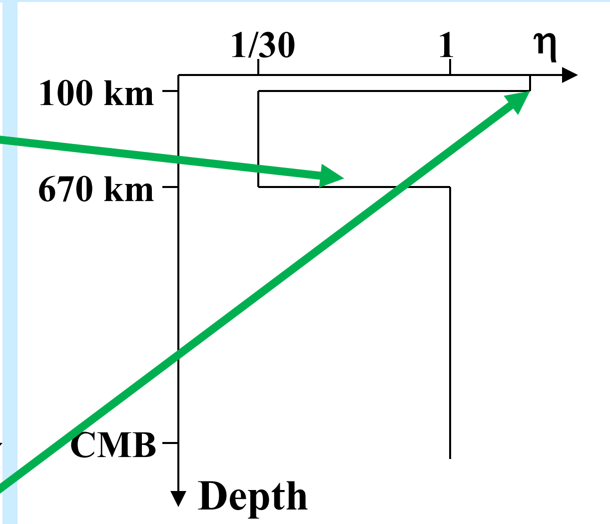
Ra=4.6x10^6

Zhong et al. [2000, 2007]

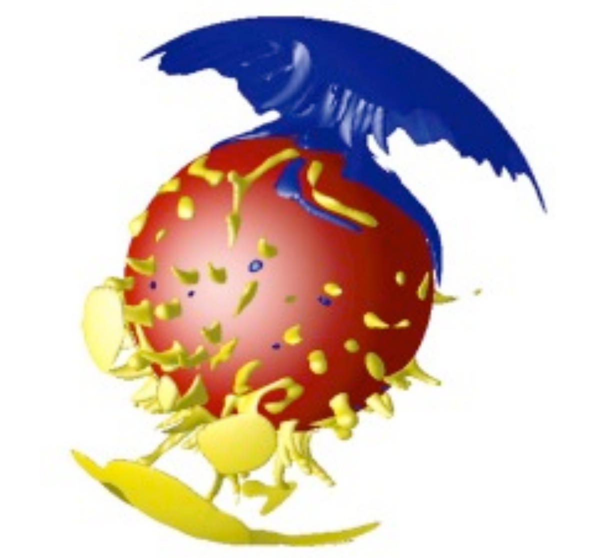
How to generate long-wavelength (degree-2) structure for the Earth's mantle? [e.g., Tackley, 1996; Bunge et al., 1996; McNamara & Zhong, 2005; Lenardic et al., 2006; Yoshida & Kageyama, 2006; van Heck & Tackley, 2008]

Role of lithospheric viscosity in producing long-wavelength mantle convection





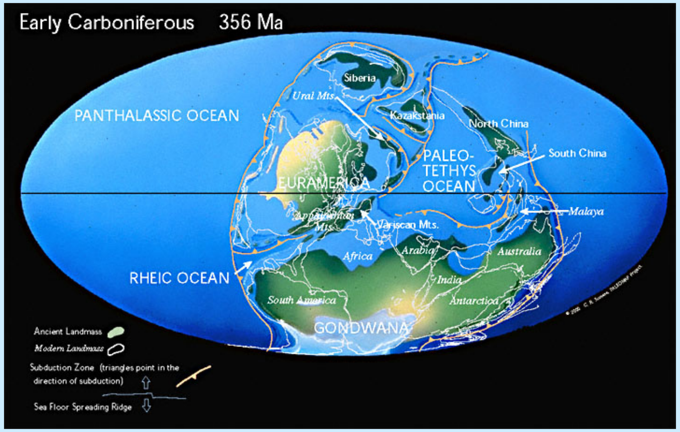
Zhong et al., [2007]; Zhong & Liu [2016]



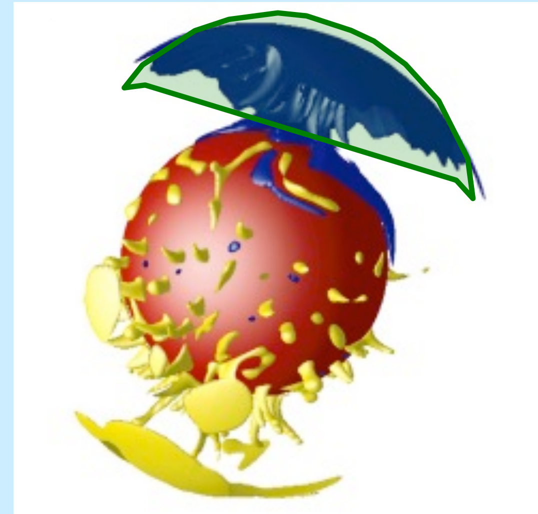
Why does the Earth have degree-2 structure presently, not degree-1?

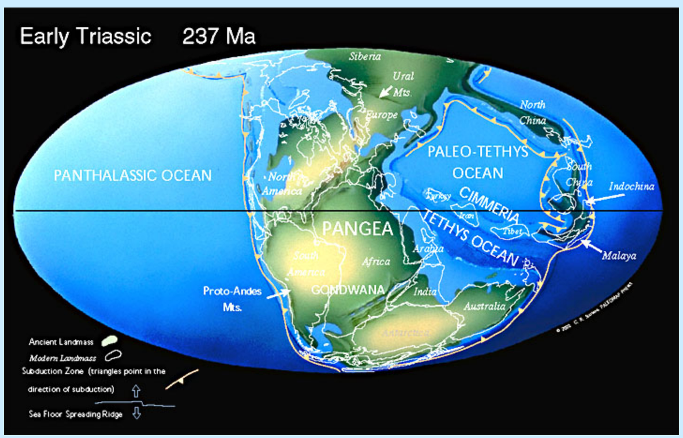
For how long have the degree-2 structures or LLSVPs existed?

Pangea formed at ~330 Ma.

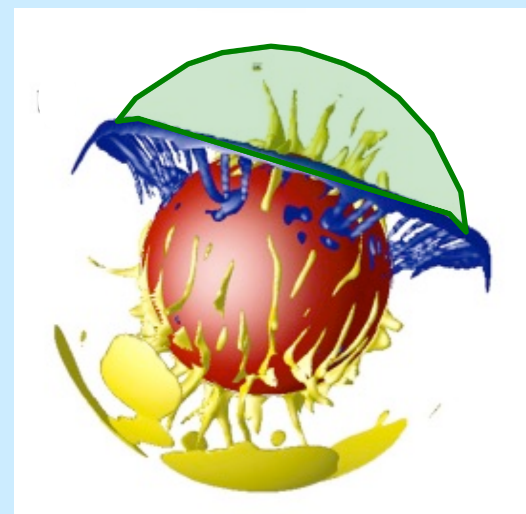


Degree-1 and forming a supercontinent.





Degree-2 formed after supercontinent formation, and the new plume system eventually caused supercontinent breakup.



Pangea broke up at ~180 Ma.

The African superplume was formed after the Pangea assembly (i.e., 330 Ma), possibly at ~250 Ma, so did the degree-2 structure [Zhong et al., 2007; Zhang et al., 2010].

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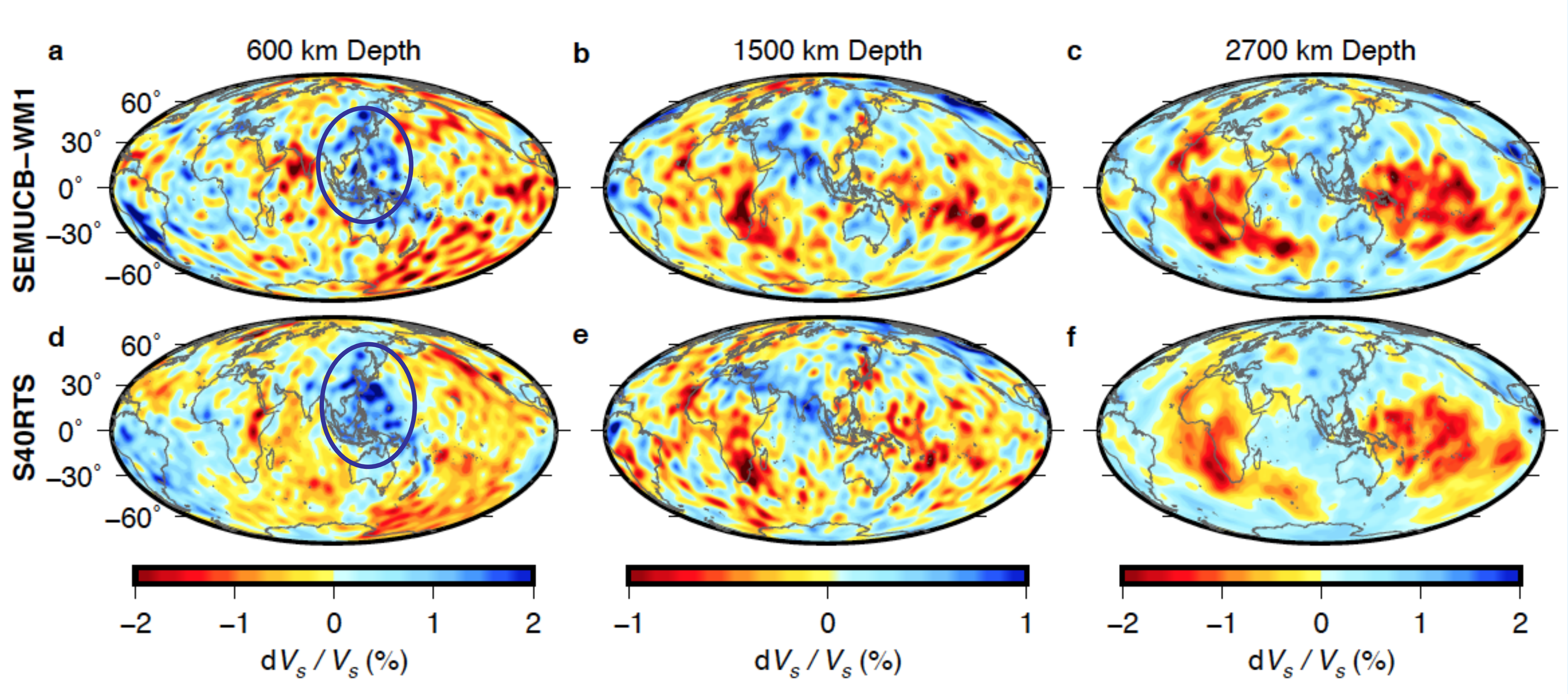
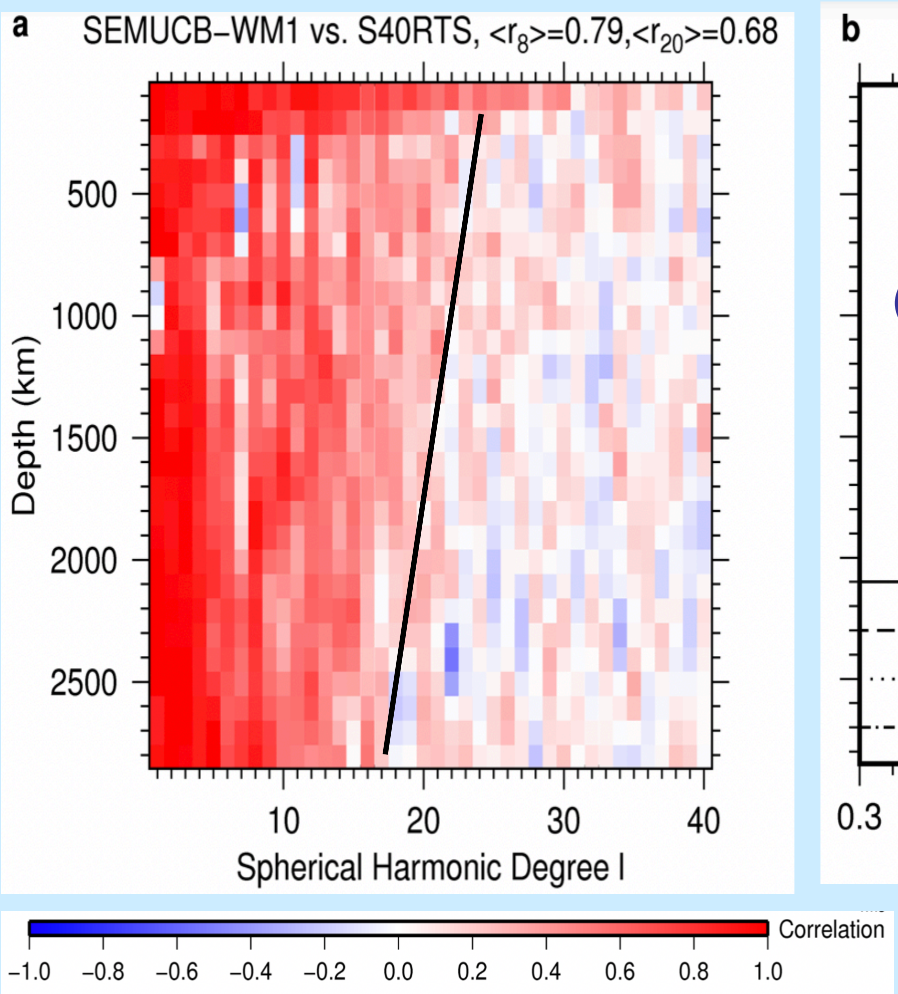
Compare seismic models: SEMUCB-WM1 and S40RTS



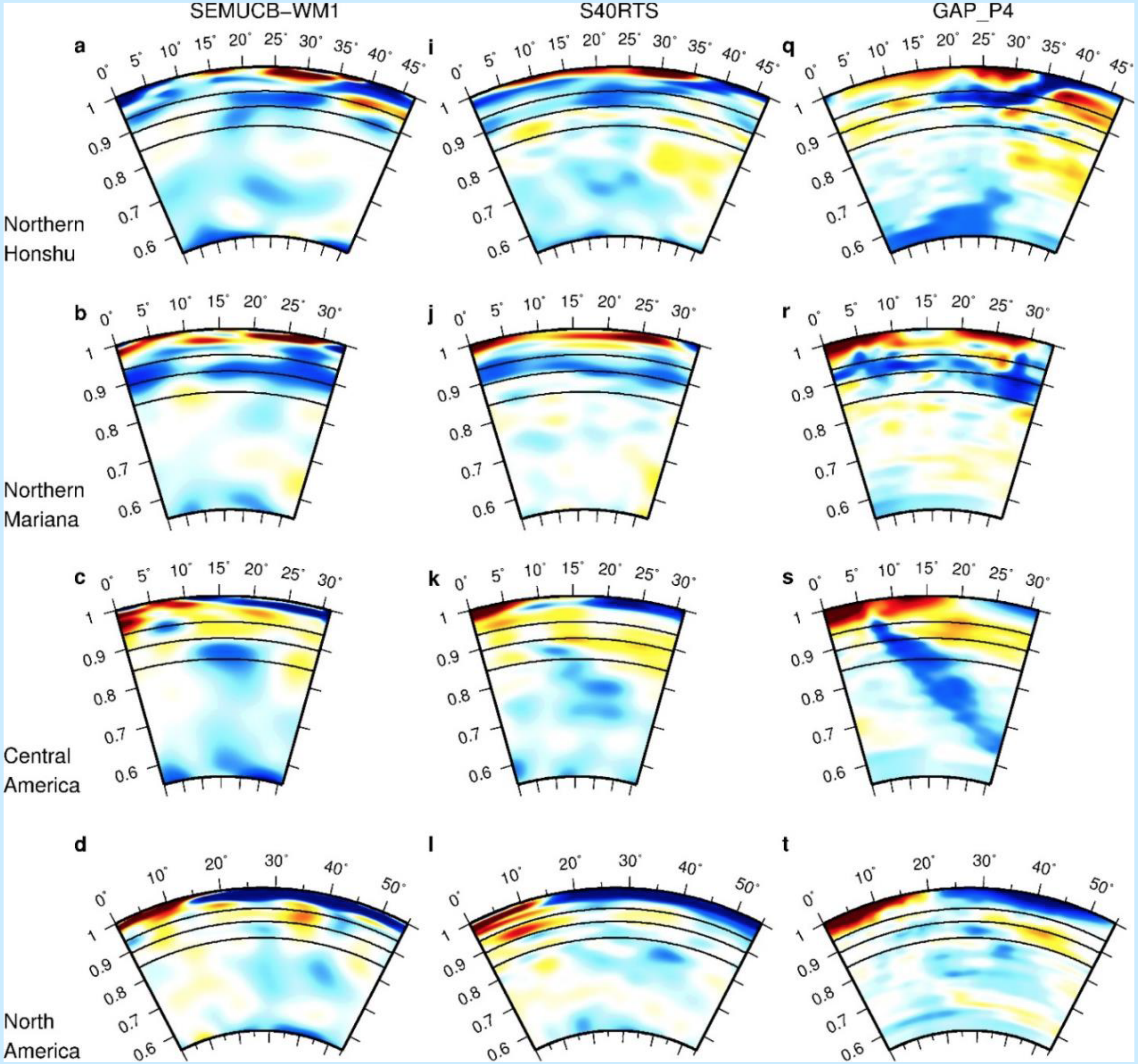
Similar comparisons were done for Smean [Becker and Boschi, 2002] and Steve Grand's models with similar conclusions.

High correlations between SEMUCB-WM1 and S40RTS for degrees up to 20 throughout the mantle (with a couple of exceptions)

Following Becker and Boschi [2002], correlations are computed to quantify how well models are compared.



Let's look at slab structures – Do slabs experience 2 stages of stagnation at 670 and 1000 km depths?



stagnation at 670 km; slabs in the lower mantle.

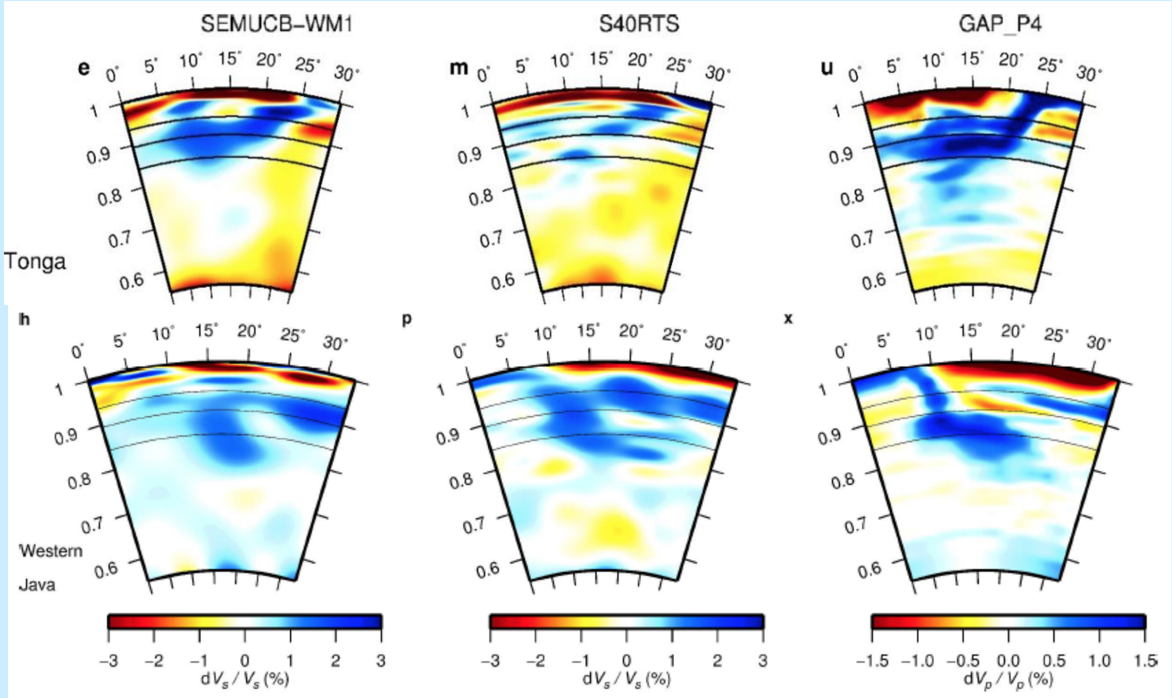
stagnation at 670 km; but not necessarily at 1000 km.

Neither at 670 nor at 1000 km depth.

Neither at 670 nor at 1000 km depth.

French & Romanowicz [2015]; Ritsema et al., [2011]; Fukao & Obayashi [2013]

Do slabs experience 2 stages of stagnation at 670 km and 1000 km depths?



Not necessarily a flat bottom at 1000 km.

Stagnation at 670 km; but not necessarily at 1000 km.

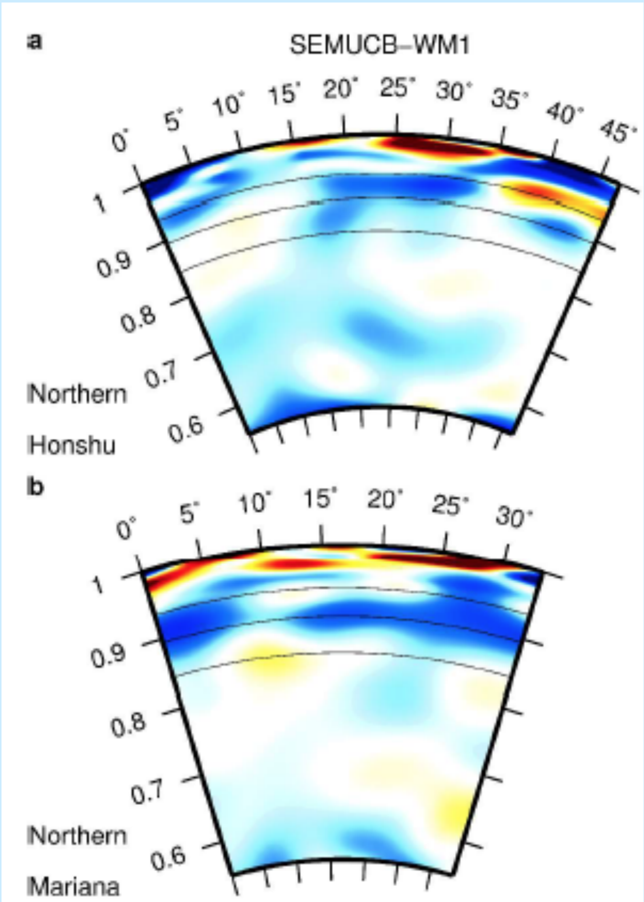
French & Romanowicz [2015]; Ritsema et al., [2011]; Fukao & Obayashi [2013]

1) Robust features: Slab stagnation above 670 km depth in the western Pacific, and slab penetration into the lower mantle of many parts of the world.

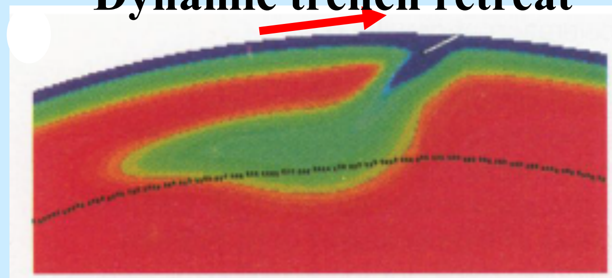
2) Not as a robust feature: Slab stagnation above 1000 km depth.

Mao & Zhong [2018]; also see Goes et al., [2017].

Let's focus on the robust features:
Stagnant slabs in the transition zone in the western Pacific



Dynamic trench retreat

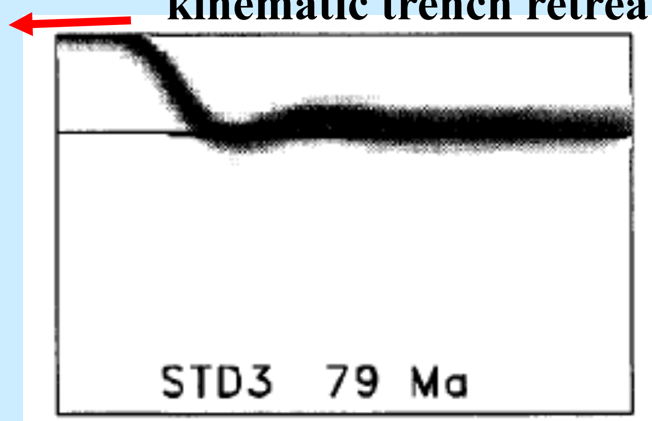


Zhong & Gurnis [1995], also van der Hilst & Seno [1993] and Yang et al., [2018]

The key for stagnant slabs in the transition zone:

1) **Clapeyron slope for the spinel-post-spinel phase change ~ -3.0 MPa/K.**
2) **Trench retreat.**

kinematic trench retreat



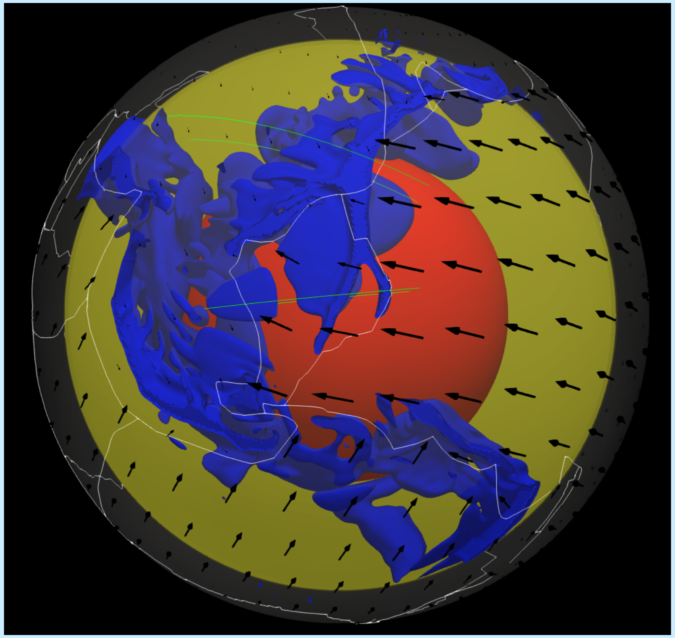
[Christensen, 1996]

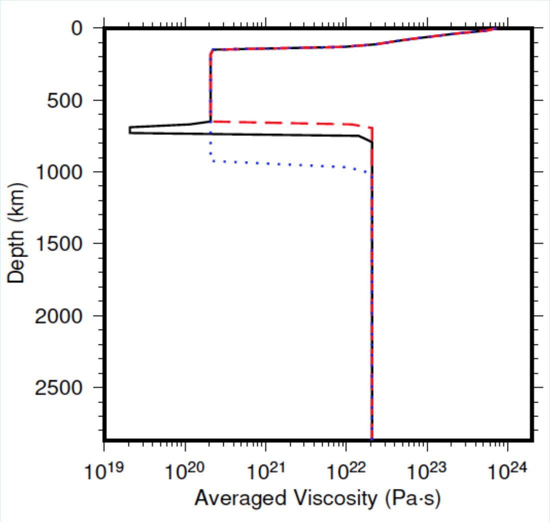
Roles of mobile trench: Ribe [2010]; Stegman et al., [2010]; Lee & King [2011].

However, recent experimental studies suggest a much smaller Clapeyron slope (~ -1.4 to -2 MPa/K) [Fei et al., 2004].

Convection models for subducted slabs with plate motion history of variable time durations

Present-day

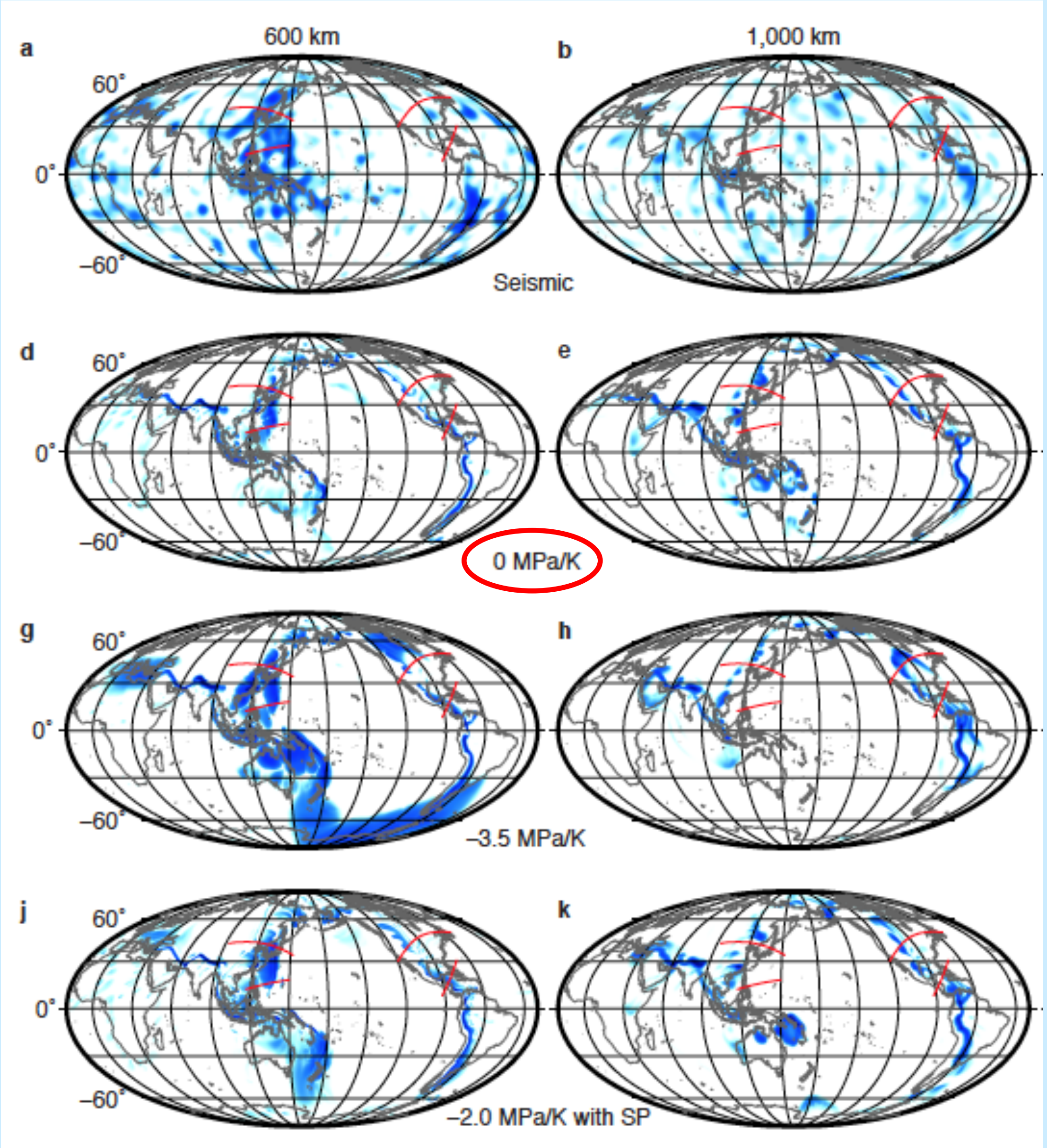




- **3-D spherical convection model, using Seton et al., [2012] plate motion model → realistic trench migration.**
- **Using either thermally insulating or isothermal boundary condition at CMB.**
- **A phase change at 670 km depth.**
- **Depth- and temperature-dependent viscosity (X100 increase at 670 km or 1000 km depth).**
- **Otherwise, similar to previous convection models for different purposes [e.g., McNamara and Zhong, 2005; Zhang et al., 2010; Bower et al., 2013; Hassan et al., 2015].**

The goal is to examine convective structure, especially the slab structure.

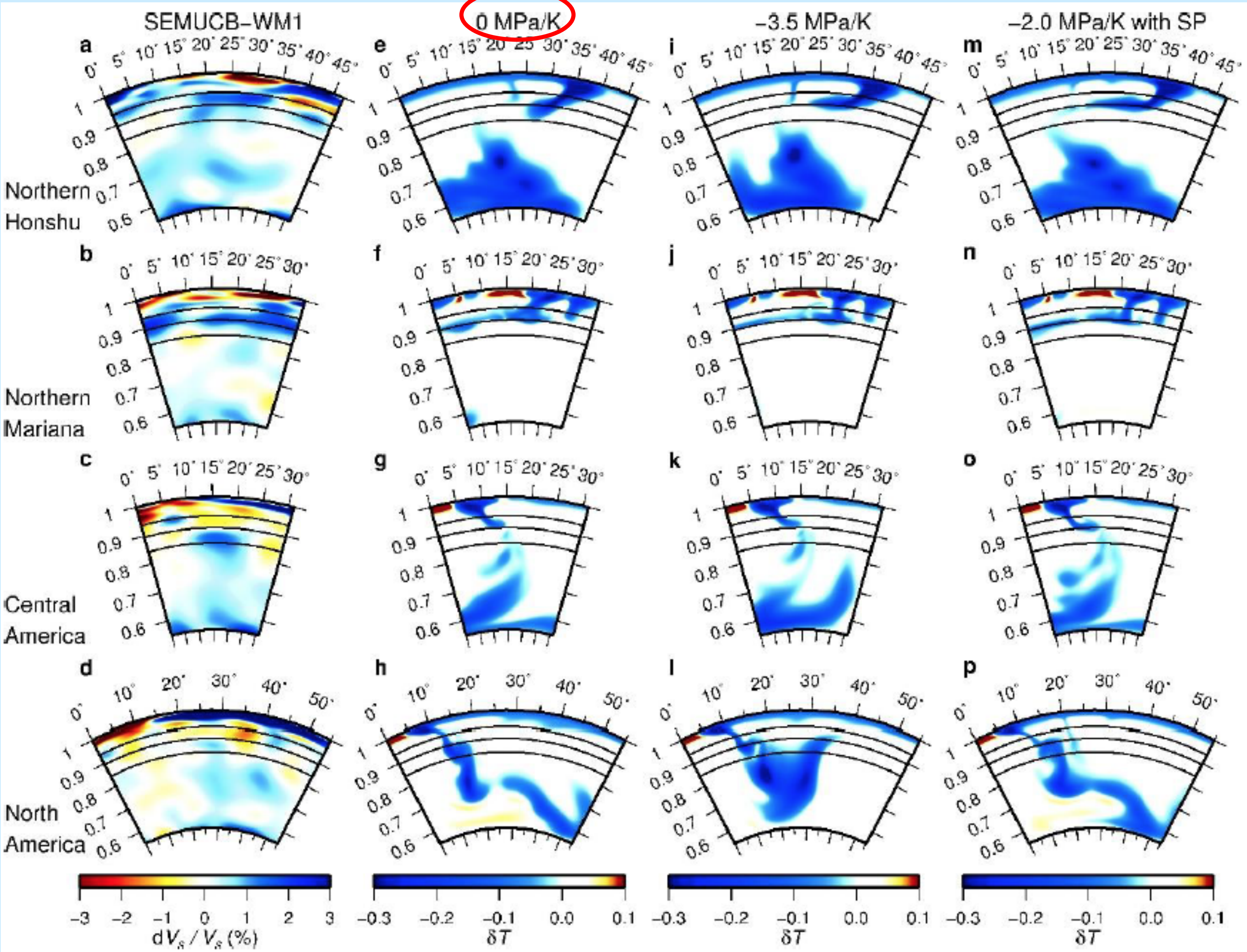
Present-day slab structure from seismic and convection models



130 Ma plate motion history; Ra=5e7 (or lower mantle viscosity ~2e22 Pas), unless specified otherwise.

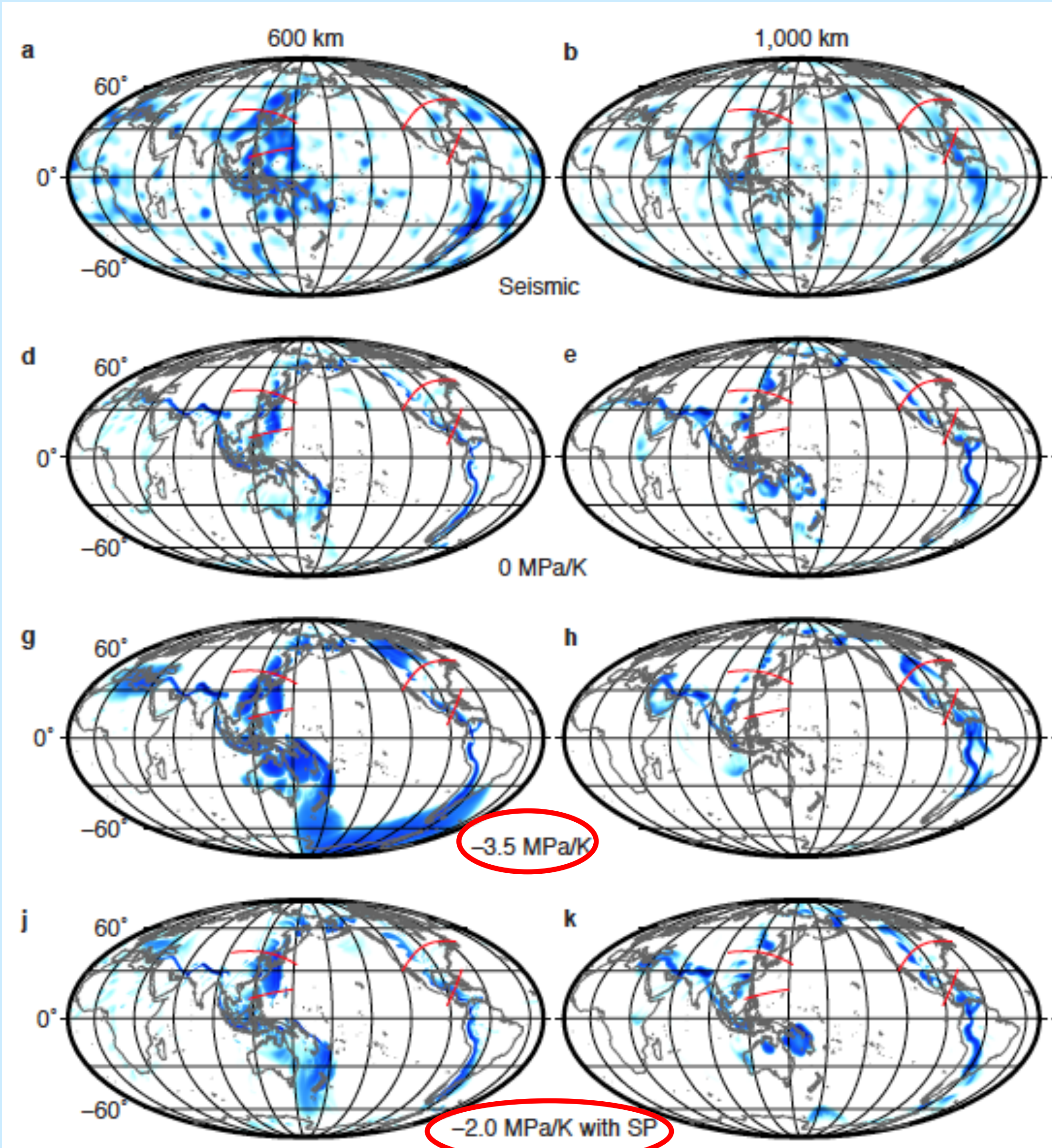
Mao & Zhong [2018]

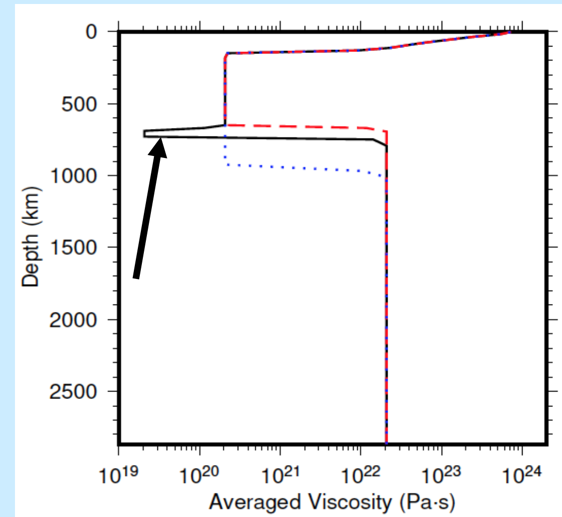
Slab structure from mantle convection models with plate motion history



Mao & Zhong [2018]

Present-day slab structure from seismic and convection models

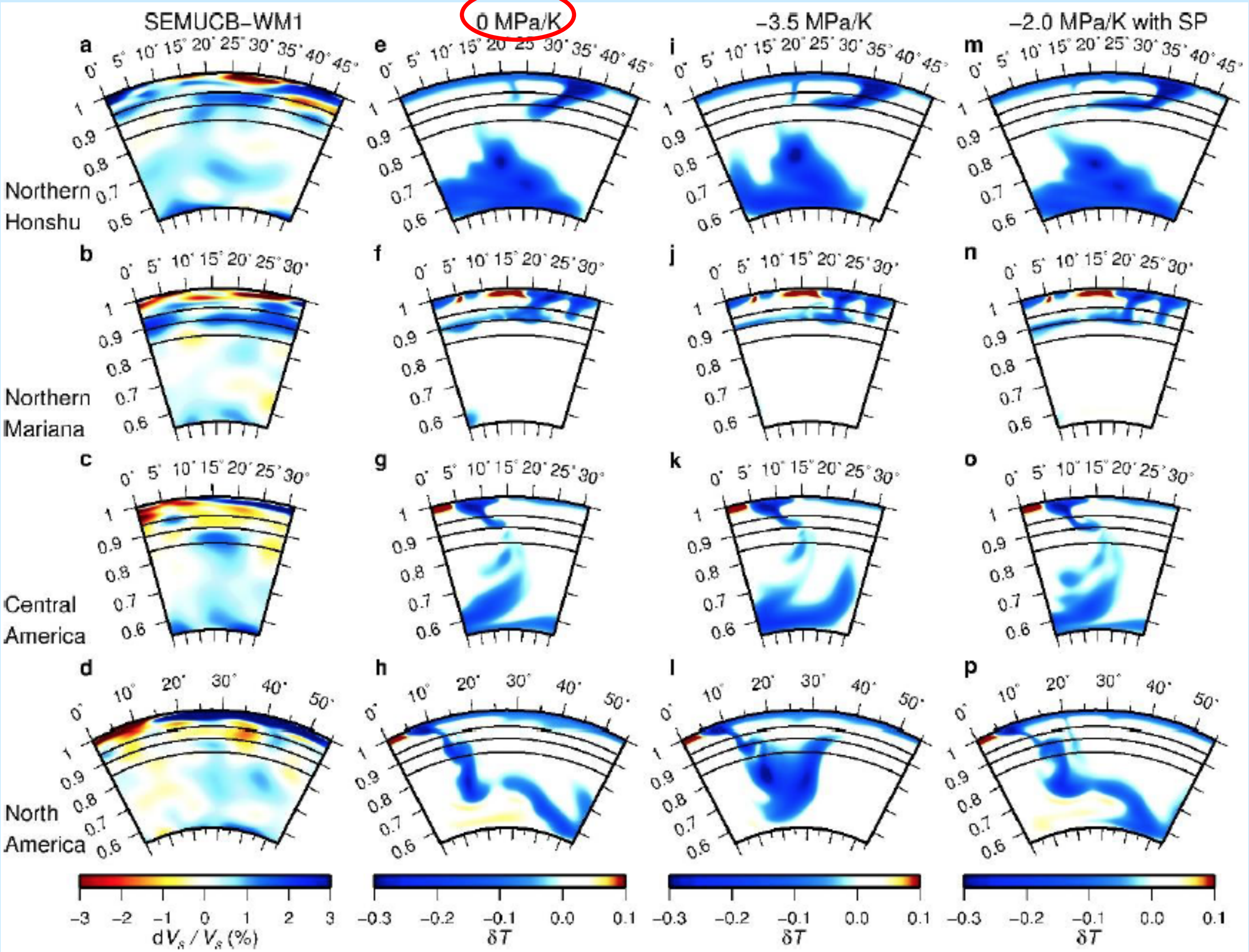




Weakening effect of phase change or superplasticity [e.g., Panasuyk and Hager, 1998; Karato, 2007; Mitrovica and Forte, 2004]

Mao & Zhong [2018]

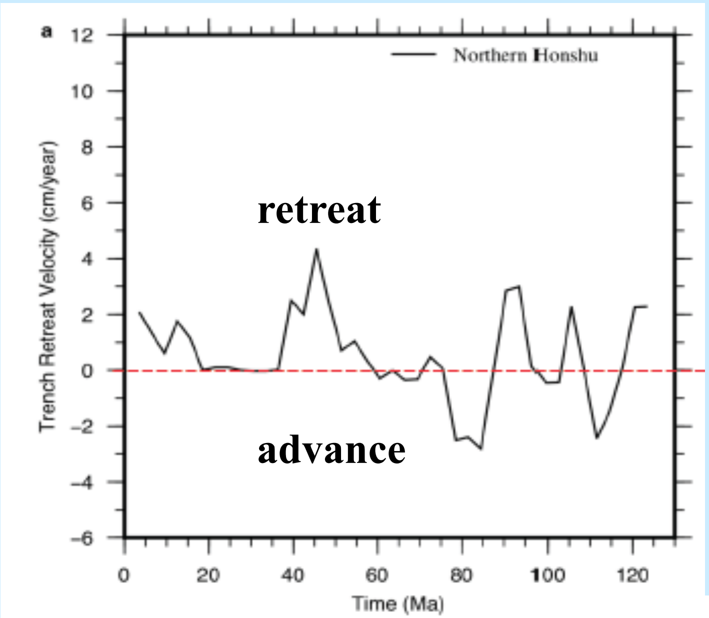
Slab structure from mantle convection models with plate motion history



Mao & Zhong [2018]

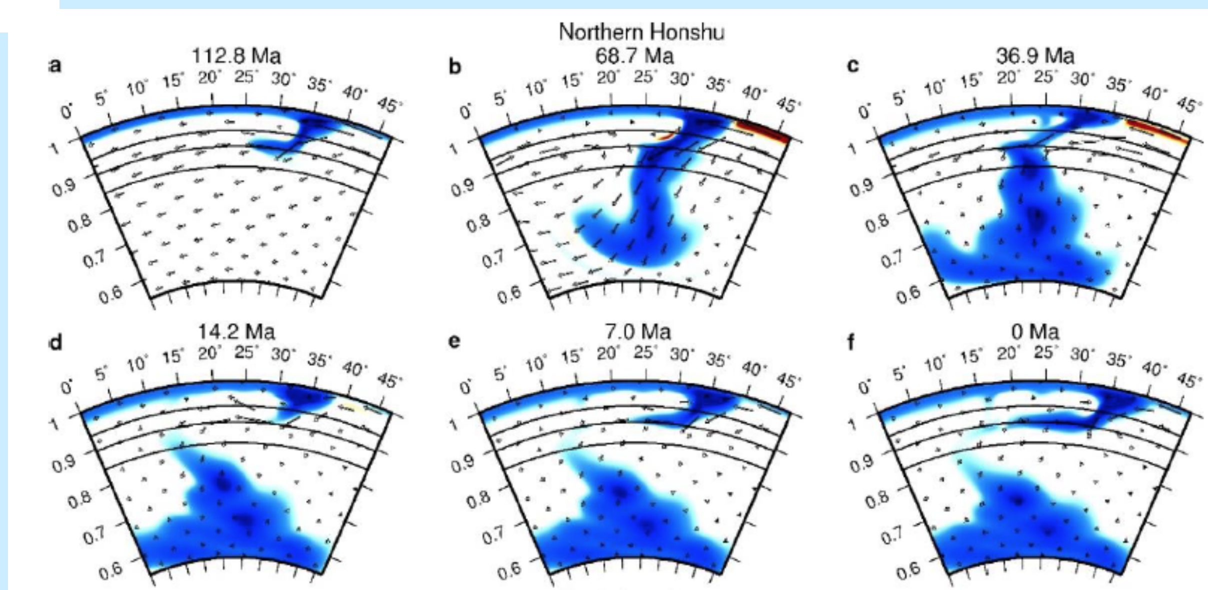
Realistic 3D geometry and plate motion history are important to interpret seismic structure!

Trench retreat effect and short time scales of slab stagnation



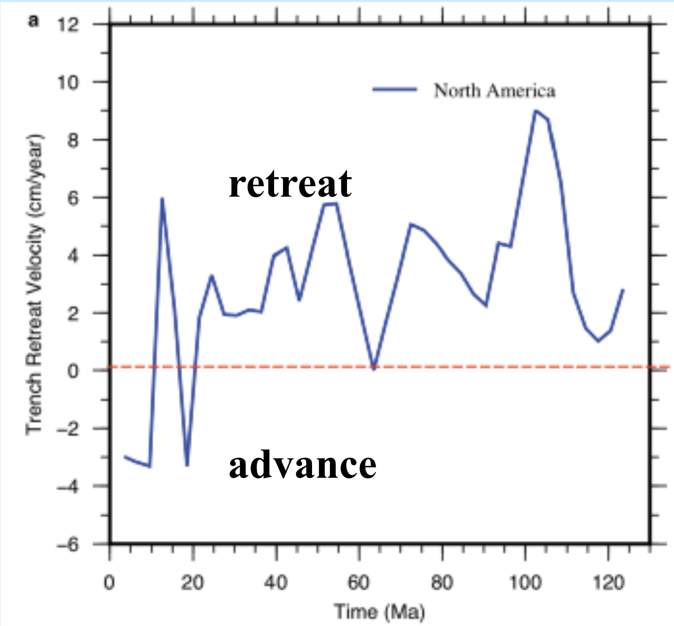
Trench retreat remains the important control for slab stagnation at 670 km depth.

1) The Japan sea opening in the last 20 Myrs may be responsible for the long deflected slab in the Honshu.
2) Slab stagnation is short-lived (~10's Myrs) and may happen frequently.



Mao & Zhong [2018]

Trench retreat effect and short time scales of slab stagnation



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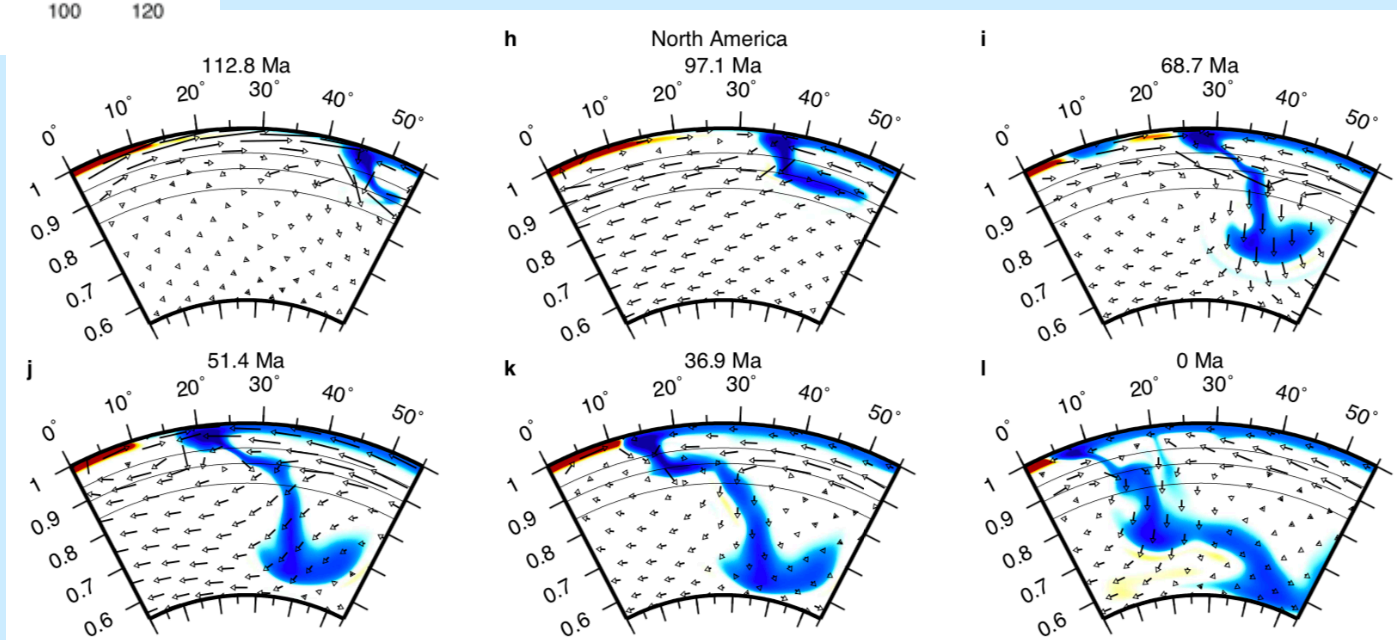
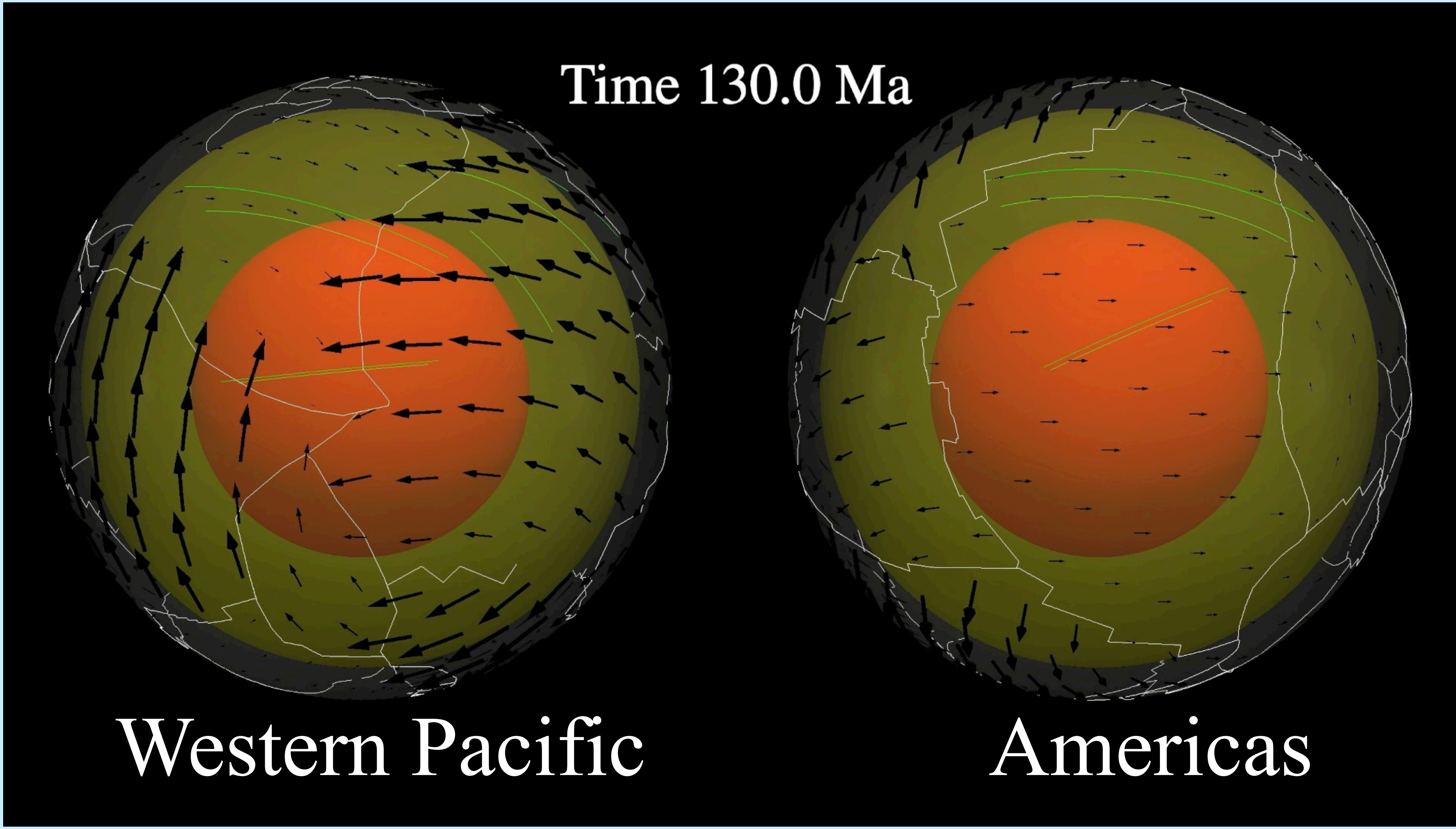


Mao & Zhong [2018]

Slab structure from convection model with plate motion history



Both Honshu and Mariana stagnant slabs formed largely in the last 10 Myr, as the Japan Sea opened and Mariana trench rotated.

Mao & Zhong [2018]

3-D slab structure data is available online.

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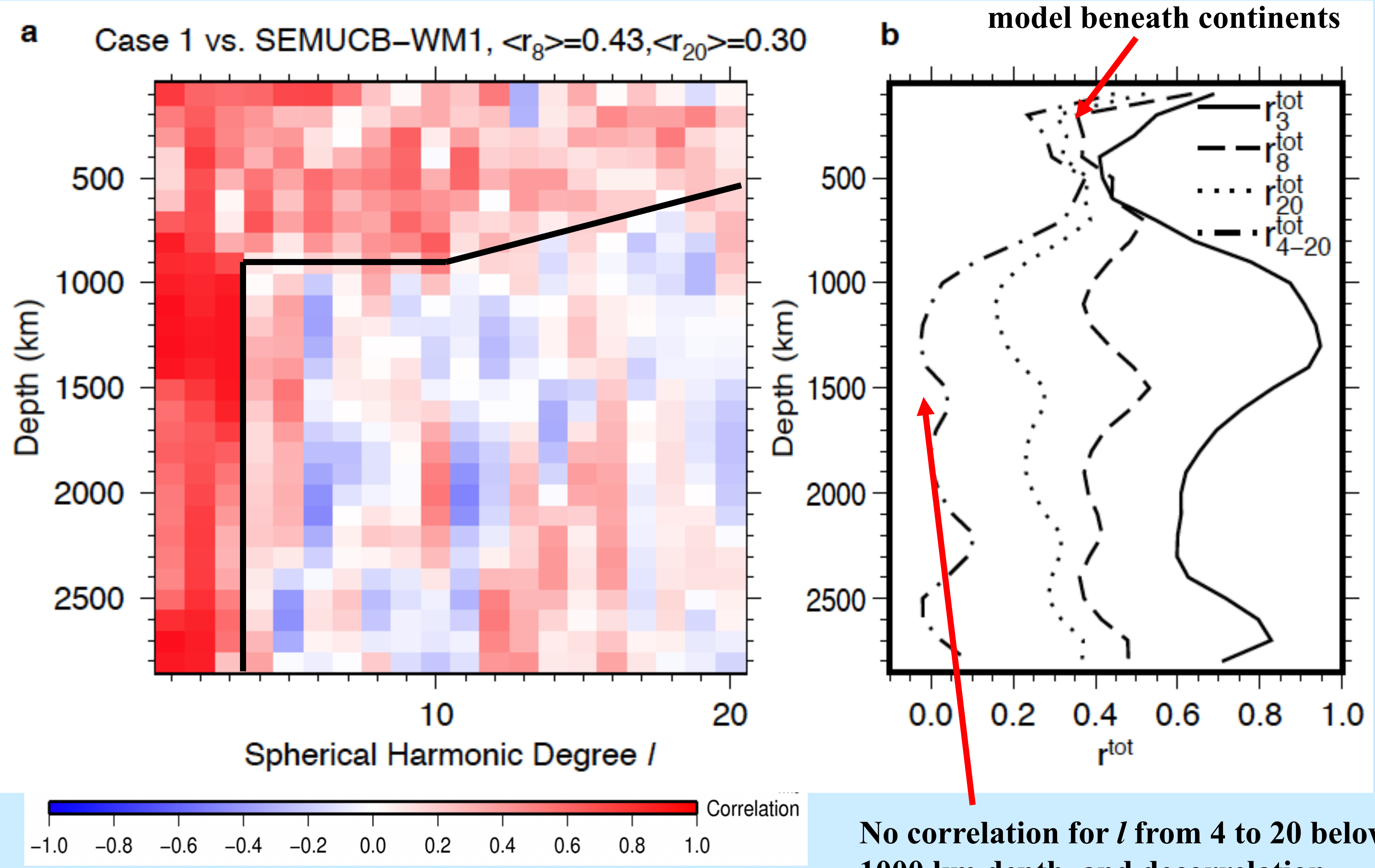
Model parameters: Upwelling plumes including LLSVPs from isothermal BC; time duration of plate motion history; non-thermal effects (e.g., craton); viscosity including Rayleigh number.

Correlation of "preferred" slab model with SEMUCB-WM1

Non-thermal effect in seismic model beneath continents

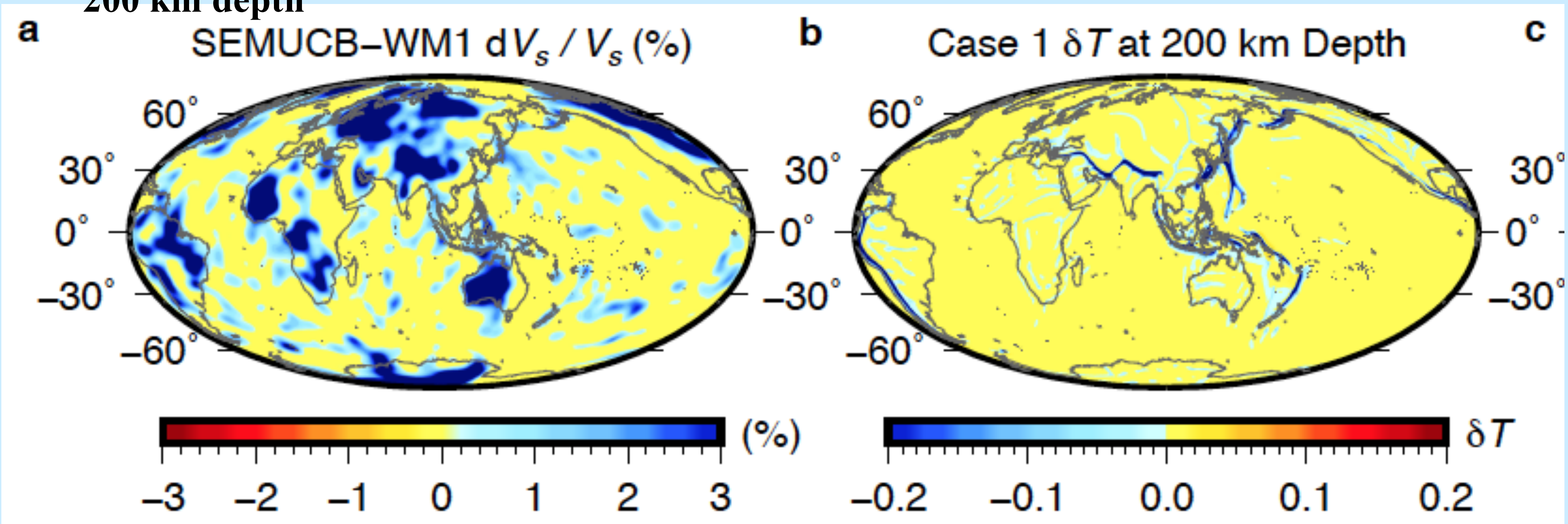


No correlation for *l* from 4 to 20 below 1000 km depth, and decorrelation starts at ~670 km depth.

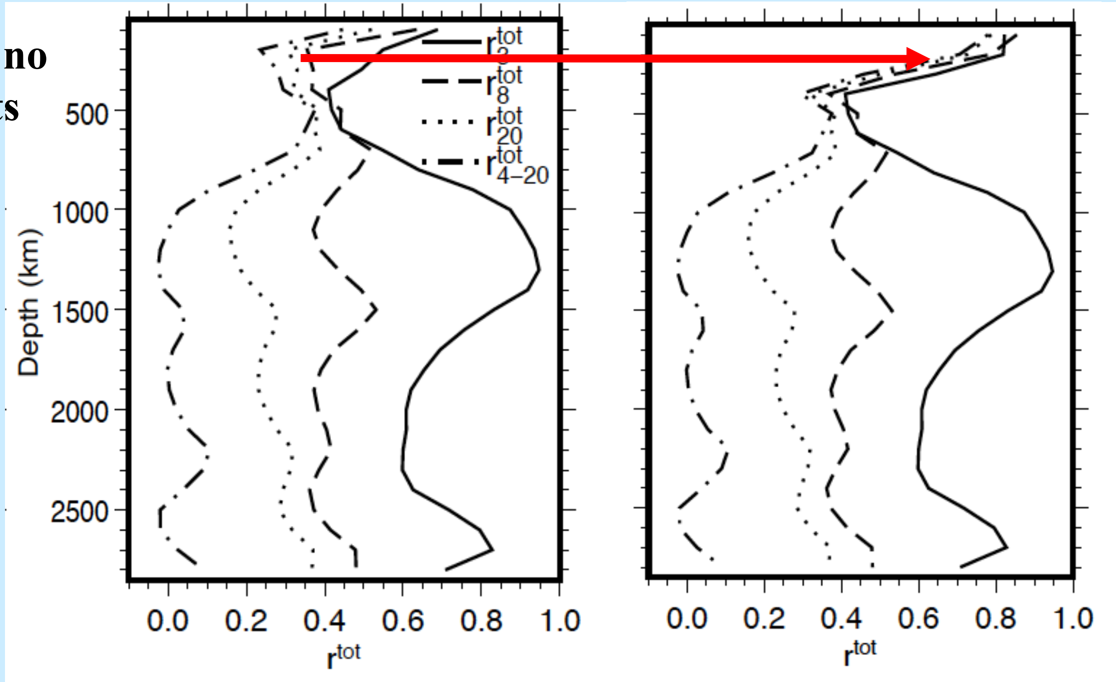
Mao & Zhong [2019]

1) Effect of cratonic lithosphere on the correlation

200 km depth



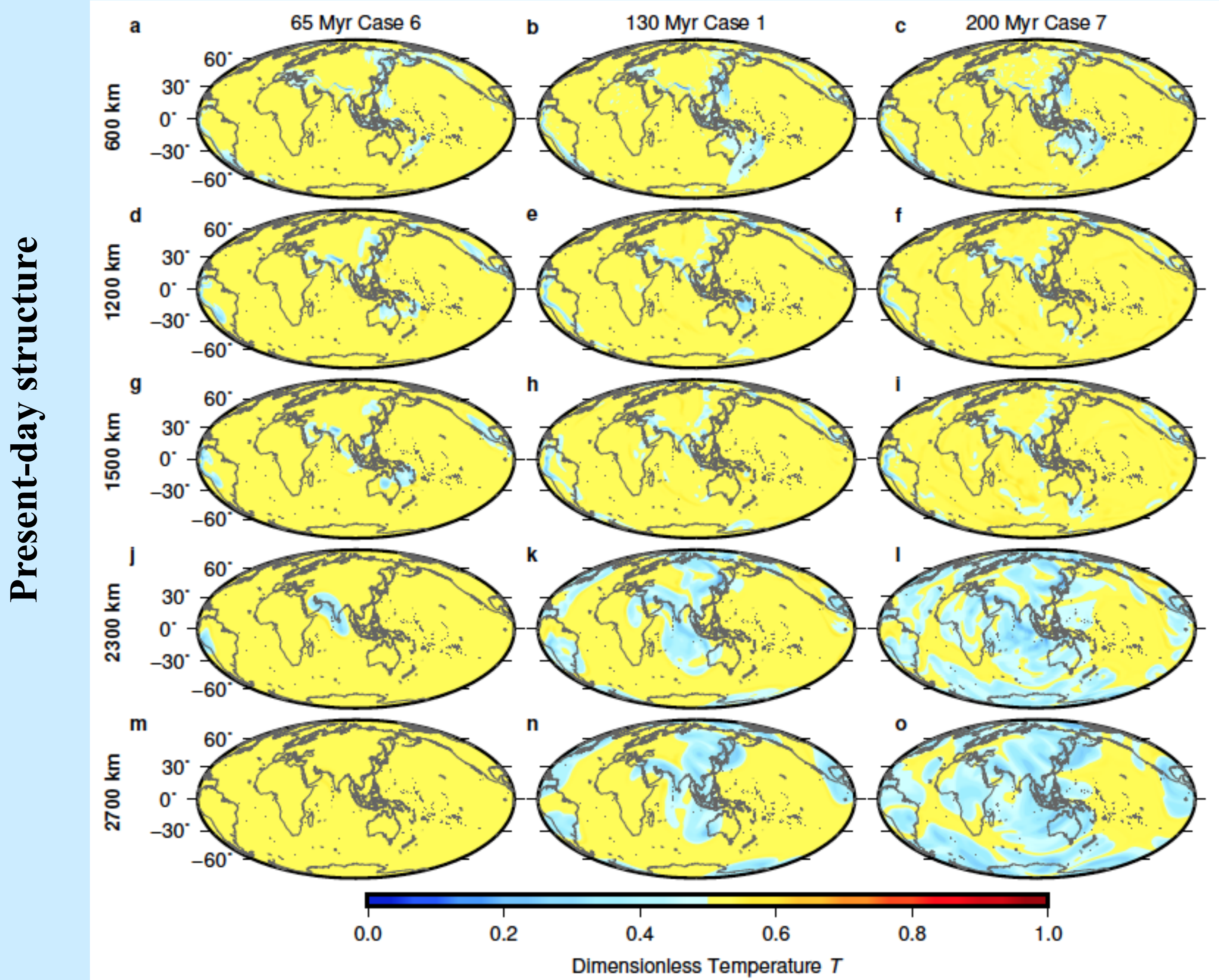
Original with no cratons' effects



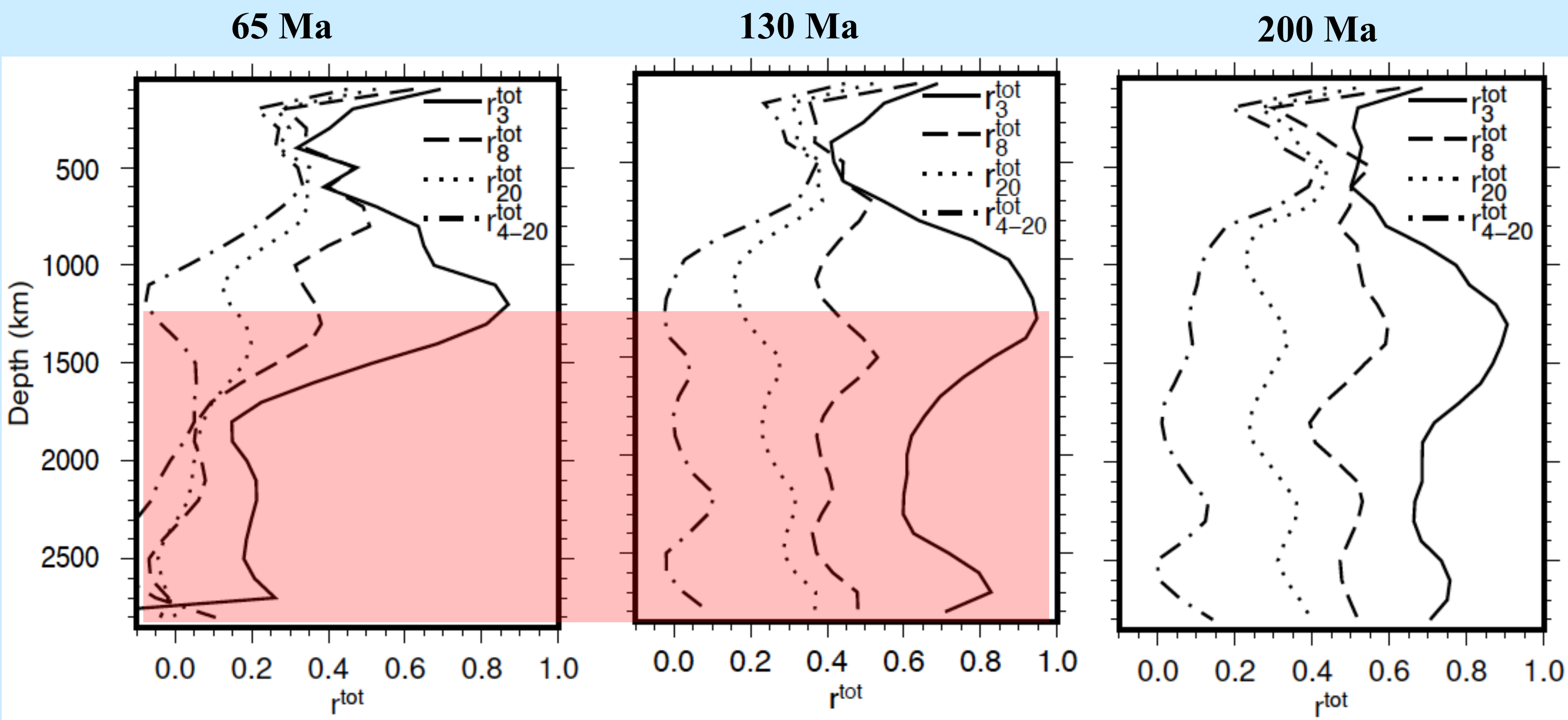
Improved correlation after including cratons' effects

Mao & Zhong [2019]

2) Effect of duration of plate motion history (65, 130 and 200 Ma)



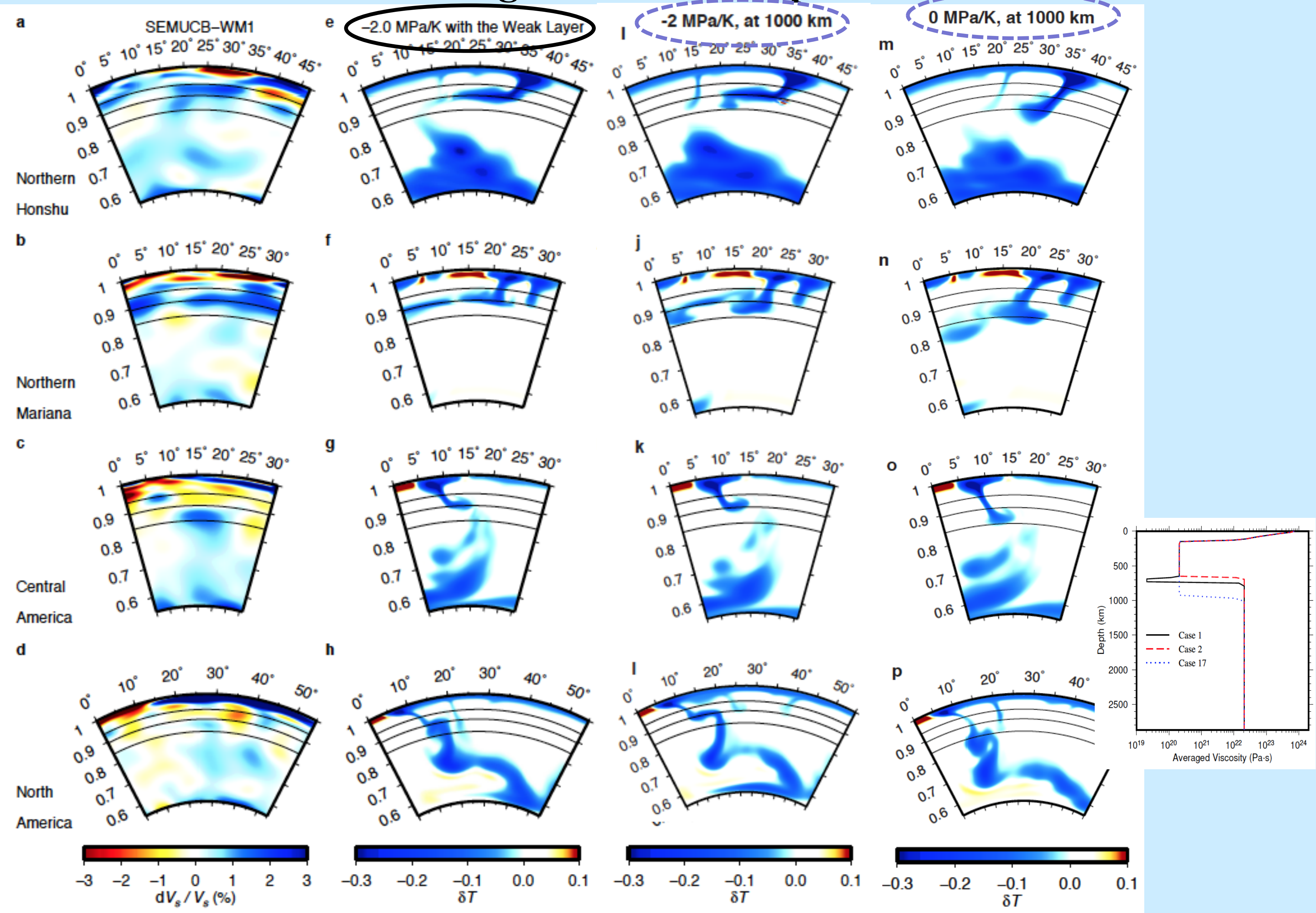
Effect of duration of plate motion history (65, 130 and 200 Ma)



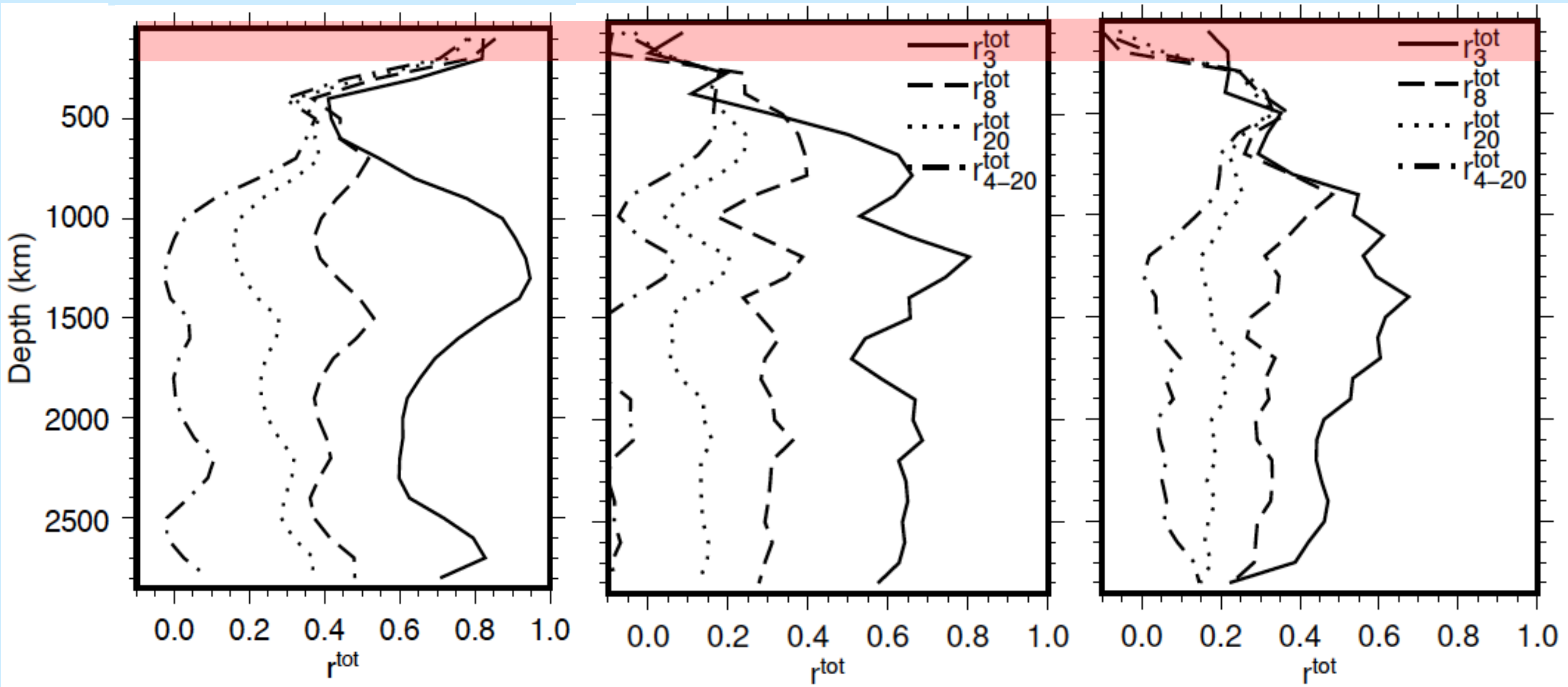
- **For models with 65 and 130 Ma, the structures above ~1200 km depths are largely the same (remember lower mantle viscosity ~2e22 Pas, and upper mantle is ~100 times weaker).**
- **Model with 200 Ma plate motion history shows slightly correlations with SEMUCB-WM1 than that with 130 Ma.**

Mao & Zhong [2019]

Effect of viscosity increase at 1000 km depth and a phase change at 670 km depth



4) Correlations of previously published slab models with SEMUCB-WM1



Our "preferred" model

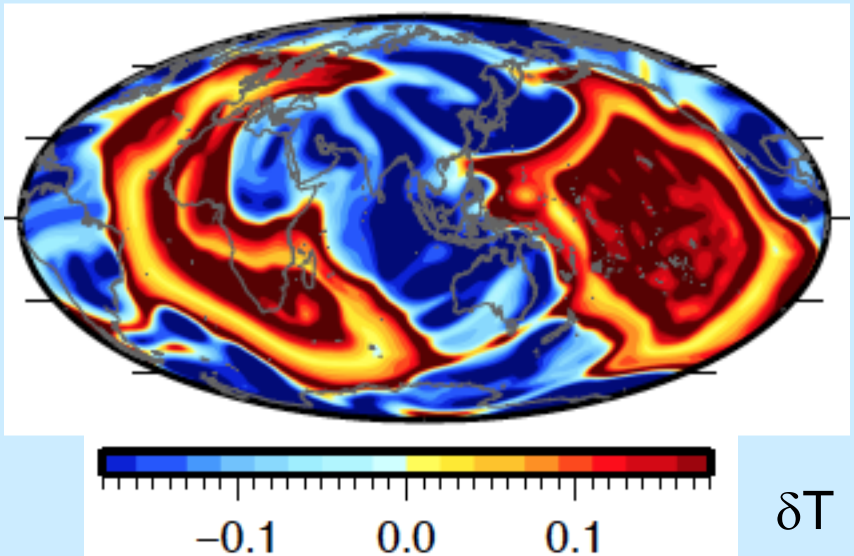
Slab model LRR98D [Ricard et al., 1993; Lithgow-Bertelloni & Richards, 1998]

Slab model STB00D [Steinberger, 2000]

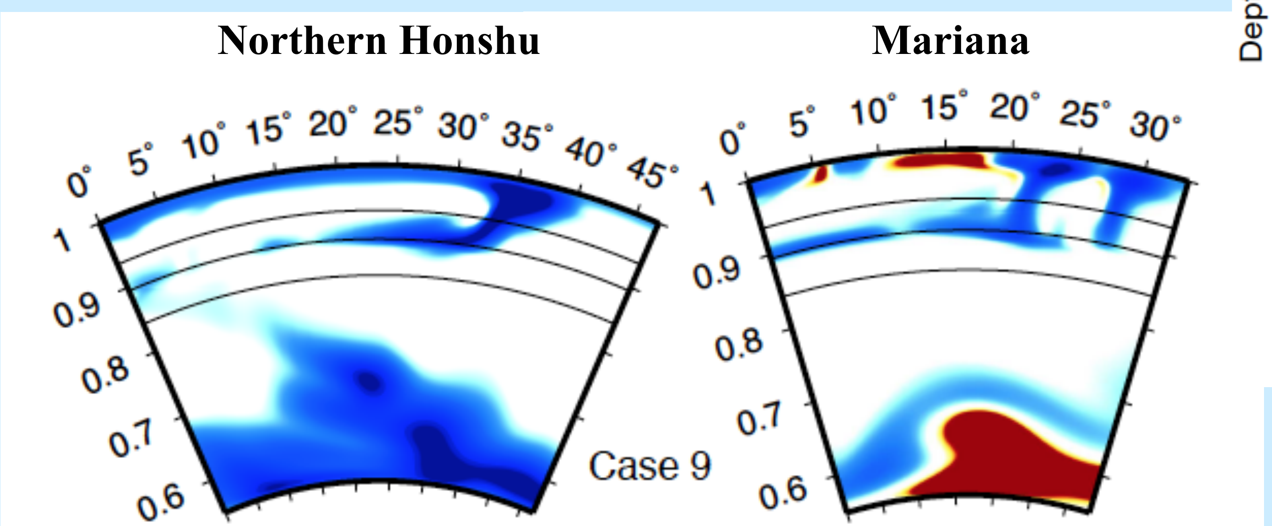
Mao & Zhong [2019]

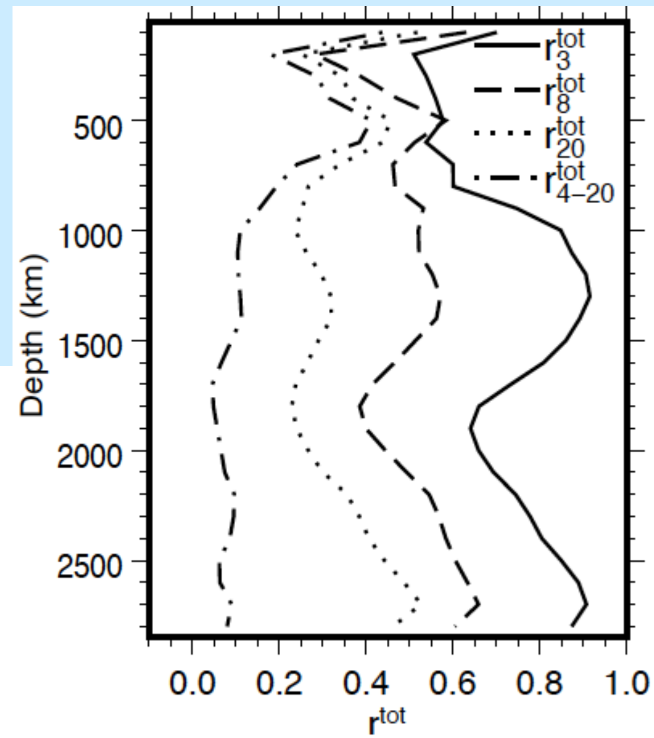
5) Effect of isothermal CMB or mantle upwellings: thermochemical

Present-day at 2700 km depth: LLSVPs



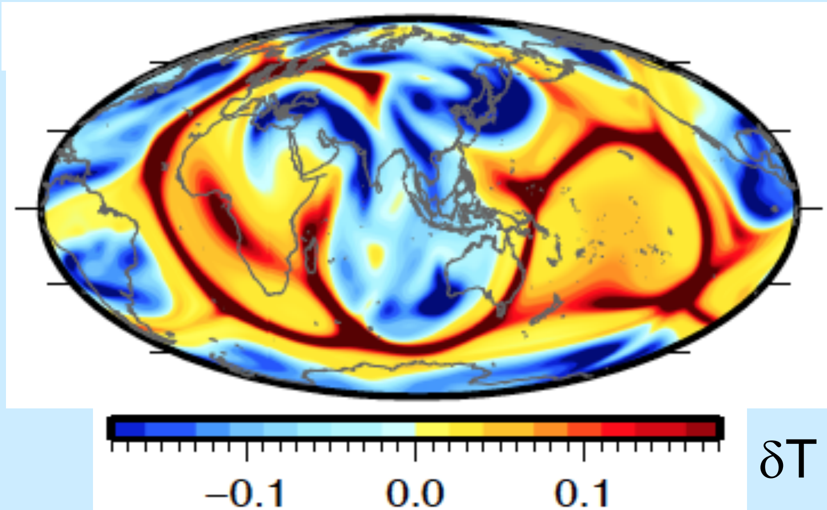
1) **200 Ma plate motion.**
2) **A layer of chemically denser material above the CMB – forming the LLSVPs.**
3) **Otherwise the same as the "preferred" slab model.**





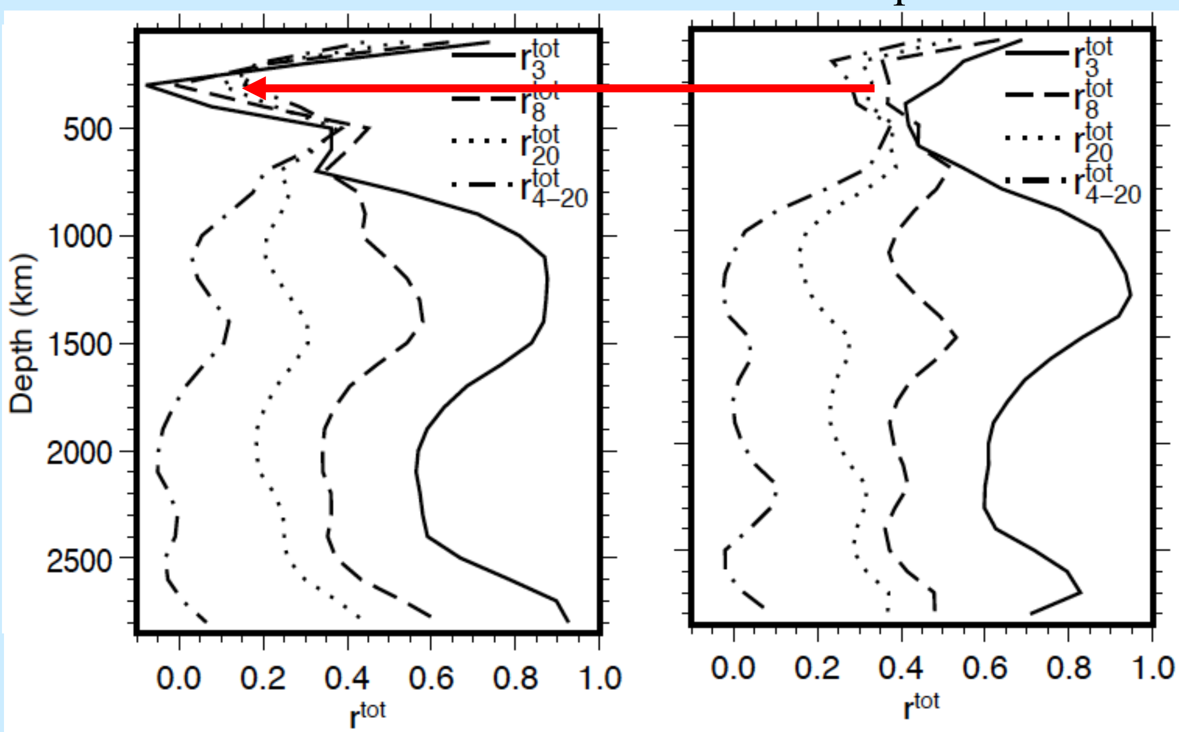
The best correlation of all the models

Effect of isothermal CMB or mantle upwellings: purely thermal



Present-day at 2700 km depth for a purely thermal convection model with isothermal CMB, and also 130 Ma plate motion history.

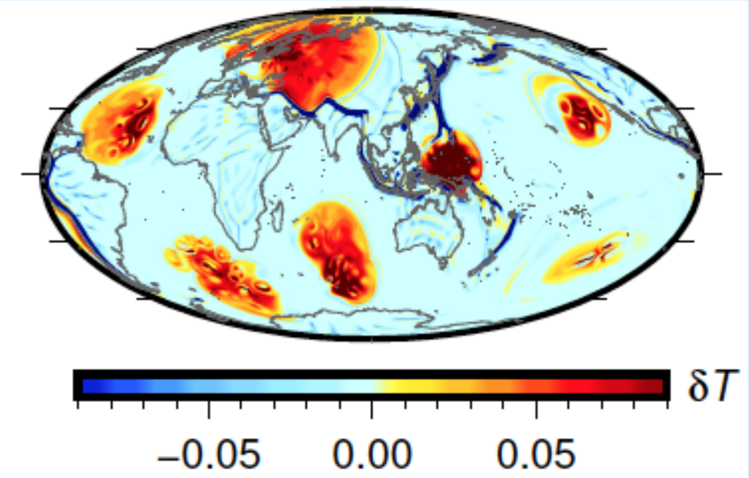
For the “preferred” slab model



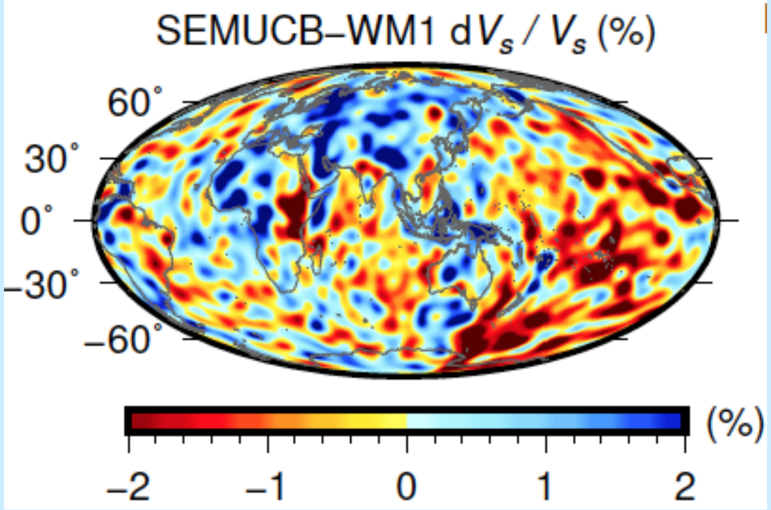
Reduced at 300 km depth!

Effect of isothermal CMB or mantle upwellings: purely thermal

plumes seen at 300 km depth



300 km depth

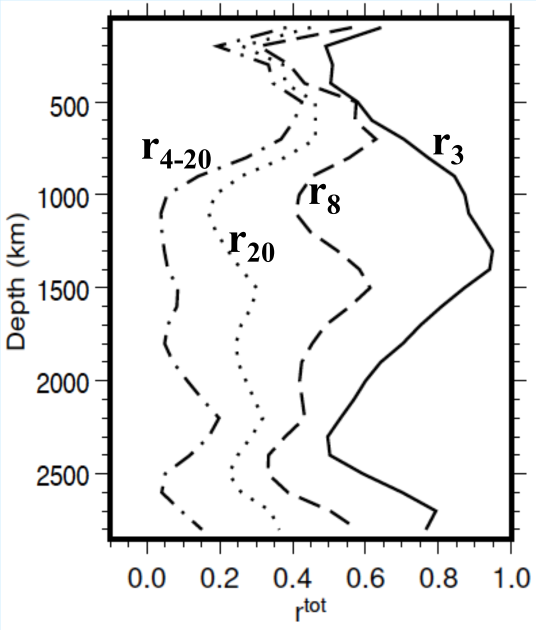


Perhaps, plumes in this purely thermal convection model are too strong? Transient?

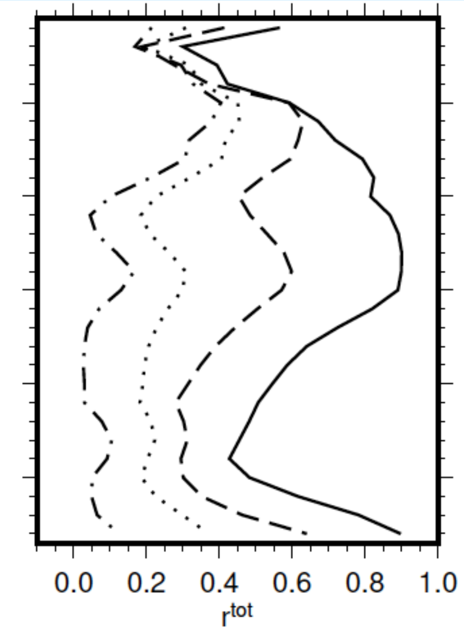
How about correlate cold anomalies in convection models with seismically fast anomalies?

"preferred" slab model

Purely thermal model



Insulating CMB with no plumes



Isothermal CMB with plumes

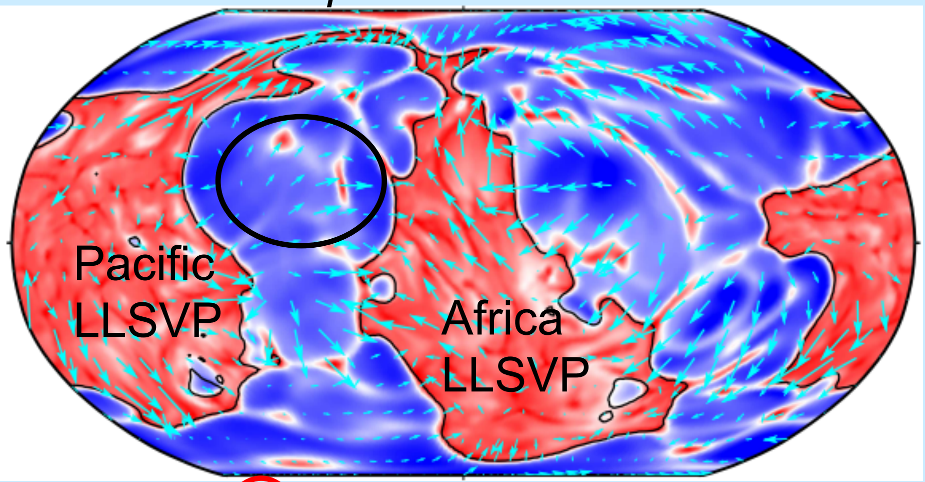
Plumes do not affect slabs much!

Finally, a bit on dynamics of mantle plumes in these models

Questions:
1) *Where are the plumes formed (relatively to the chemical piles)?*
2) *How rapidly do they move laterally and deform as they rise?*

[e.g., Davaille, 1999; Steinberger, 1998]

At 2800 km depth



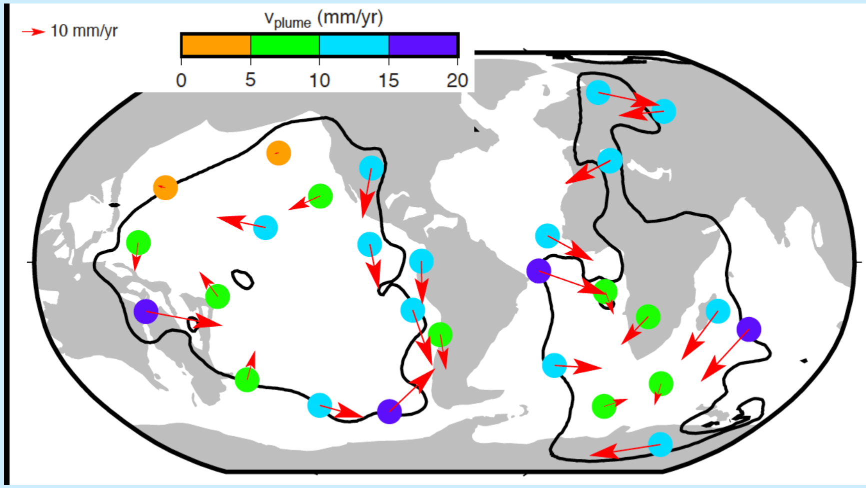
Case	α	κ	B	Ra	d (km)	η_l (Pa s)	Ra_l
1	1.0	1.0	0.48	2e8	47	3.3e21	41
2	0.2	2.18	0.18	2e8	79	2.4e21	23
3	1.0	1.0	0.52	4e7	66	1.7e22	23
4	0.2	1.0	0.18	2e8	63	2.7e21	24
5	1.0	2.18	0.48	2e8	59	2.6e21	45
6	1.0	1.0	0.50	1e8	56	6.5e21	38
7	0.33	2.18	0.23	2e8	73	2.4e21	31
8	0.33	2.18	0.24	1e8	84	5.1e21	23

Li & Zhong [2017, EPSL]

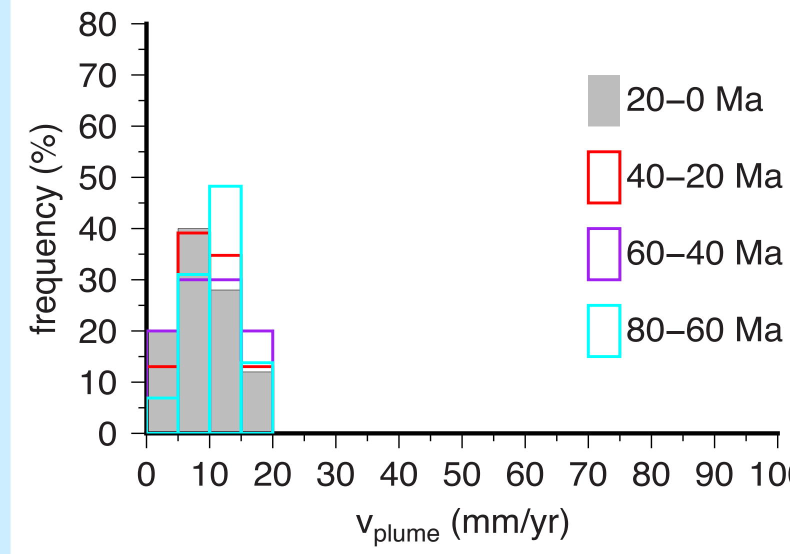
Formation of the plumes outside the piles is controlled by the simple boundary layer theory, i.e., instability that makes it difficult to predict precise plume locations. We determine the conditions under which the plumes form near the edges of the piles.

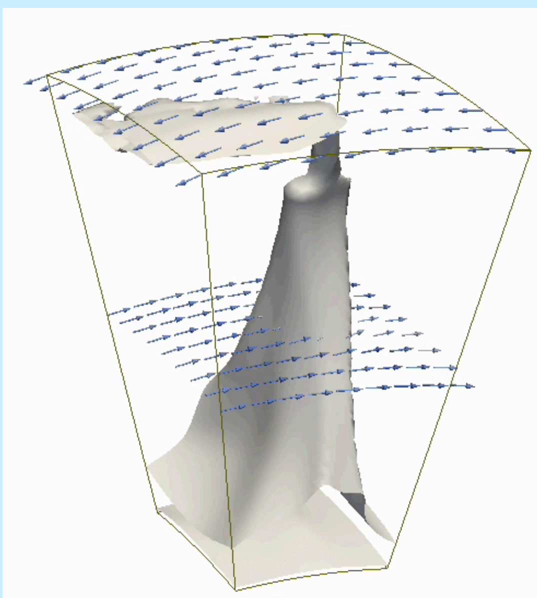
Lateral motion of mantle plumes

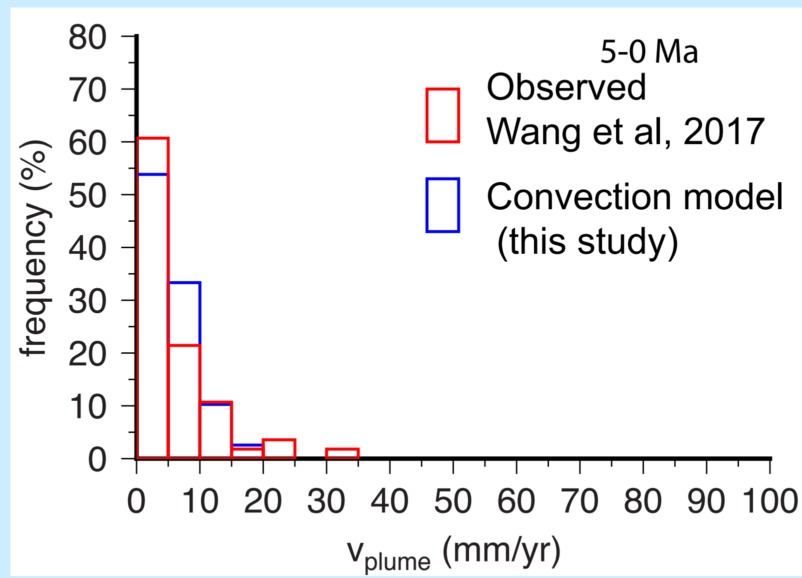
80-60 Ma, 300 km depth, in NNR frame



Black curves: Chemical pile edges

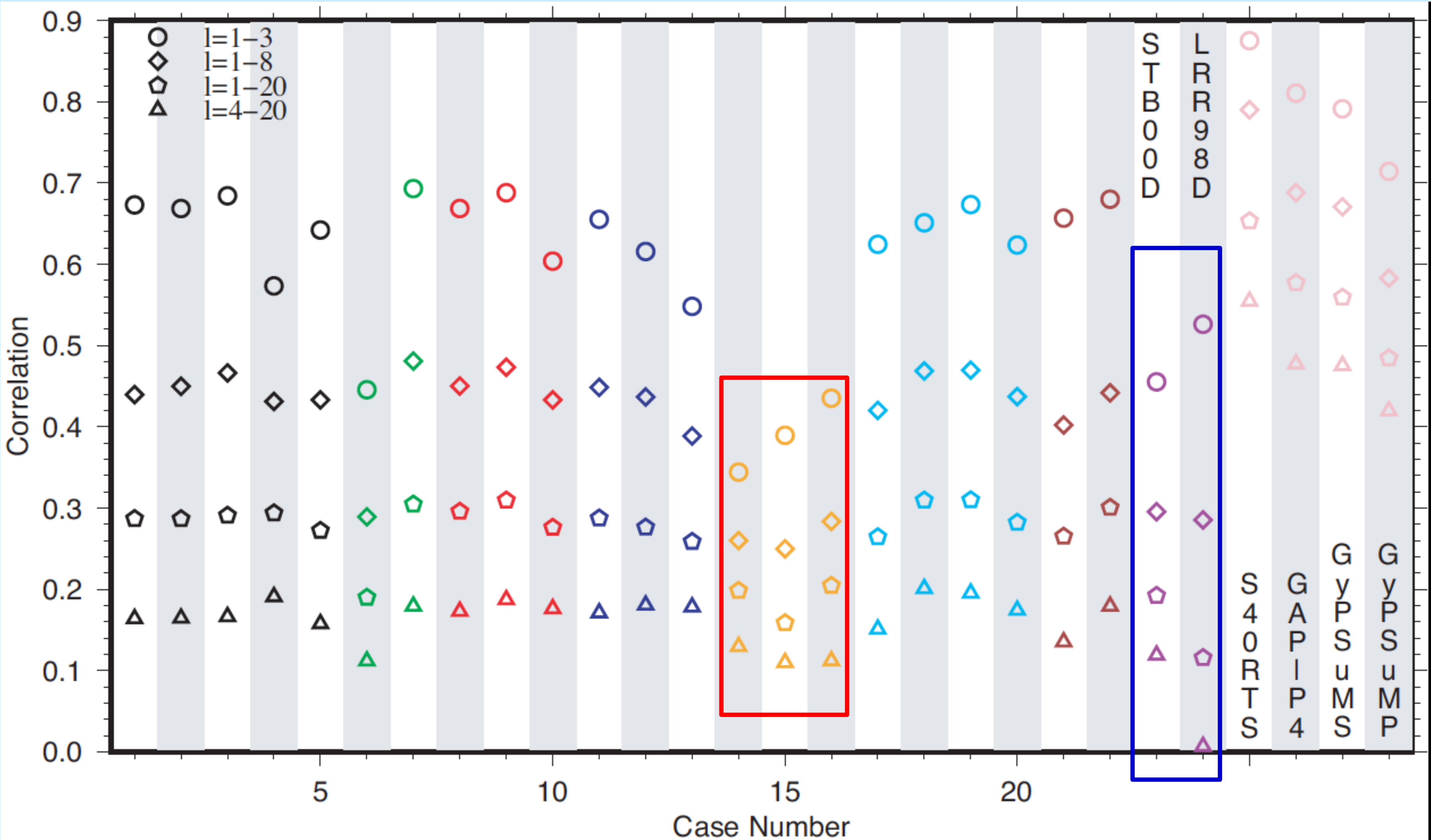






Li & Zhong [2019, GRL]

Summary plot of correlations with SEMUCB-WM1 for 22 models



preferred lower mantle: $2x10^{22}$ Pas

Mao and Zhong [2019]

Conclusions

1) A weak layer beneath the 670 km depth phase transition helps reproduce robust seismic structures in the mantle including **stagnant slabs in the mantle transition zone** in the western Pacific, **deep slabs** in the lower mantle of North America, Asia, and Tethys, and **the African and Pacific LLSVPs in the lowermost lower mantle**.
2) The overall correlations between our convection model and seismic models are high for spherical harmonic degree ***l*** **from 1 to 20 in the upper mantle and the uppermost lower mantle** (i.e., <1000 km depth), but our convection models can only consistently reproduce relatively long-wavelength seismic structures (***l*** **from 1 to 3 or 4**) **below 1000 km depth in the lower mantle**.
3) A viscosity increase at 1000 km depth **by itself** cannot cause slab stagnations at neither 670 km nor 1000 km depth. However, **together with the 670 km phase change**, it can reproduce **equally well** the stagnant slabs in the mantle transition zone in the western Pacific.
4) **Mantle plumes** have a minor effect on slab structures in our convection models. The cold slab structures and their correlations with the seismically fast anomalies are nearly identical for convection models with and without the plumes.
5) We have attempted to build a mantle convection model (as simple and realistic as it can) to interpret observations (of seismology, gravity and hotspot motion)