A re-analysis of tomographic models reveals a new flavor of lower-mantle structure

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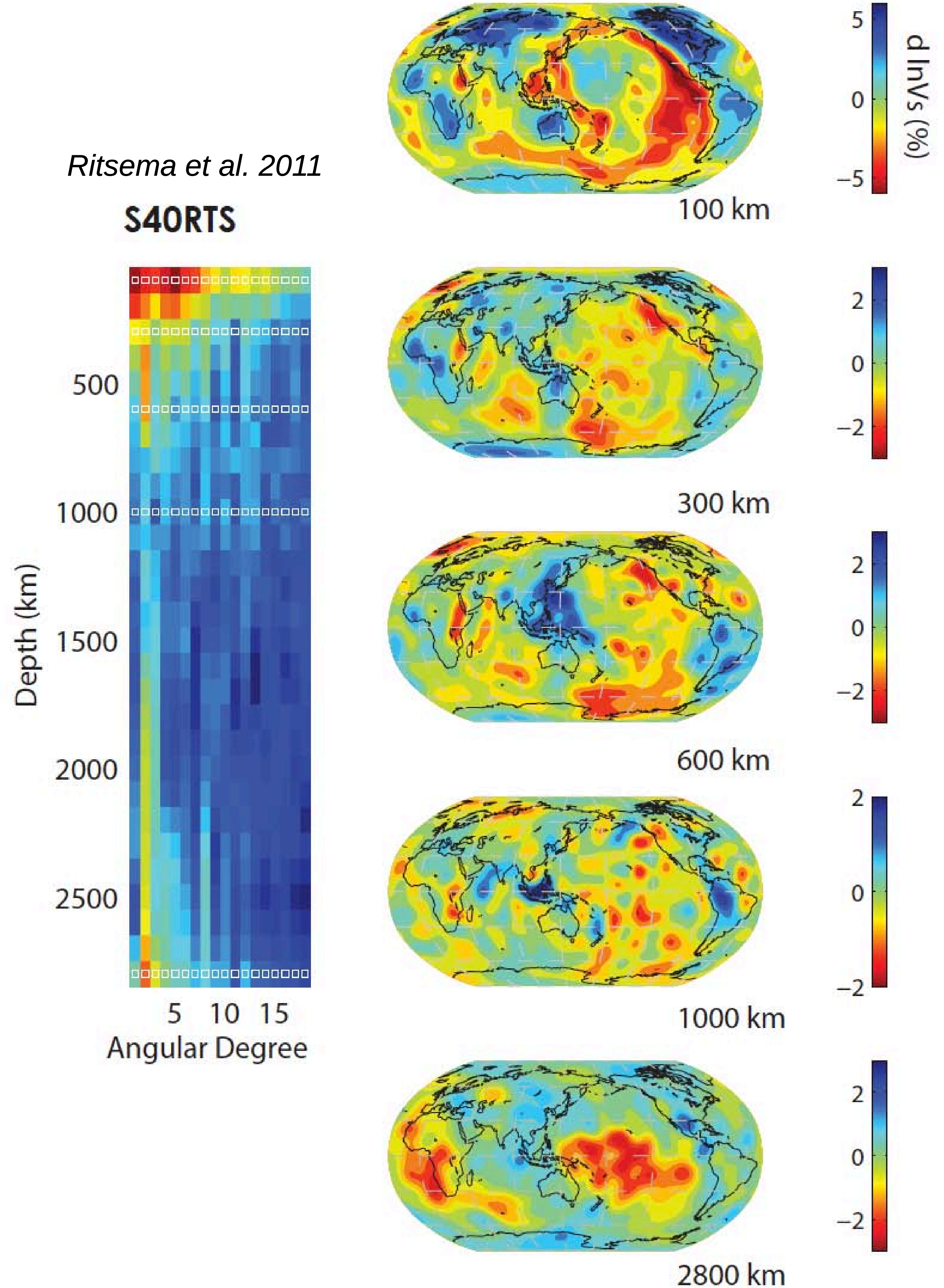
Large-scale view of mantle seismic structure

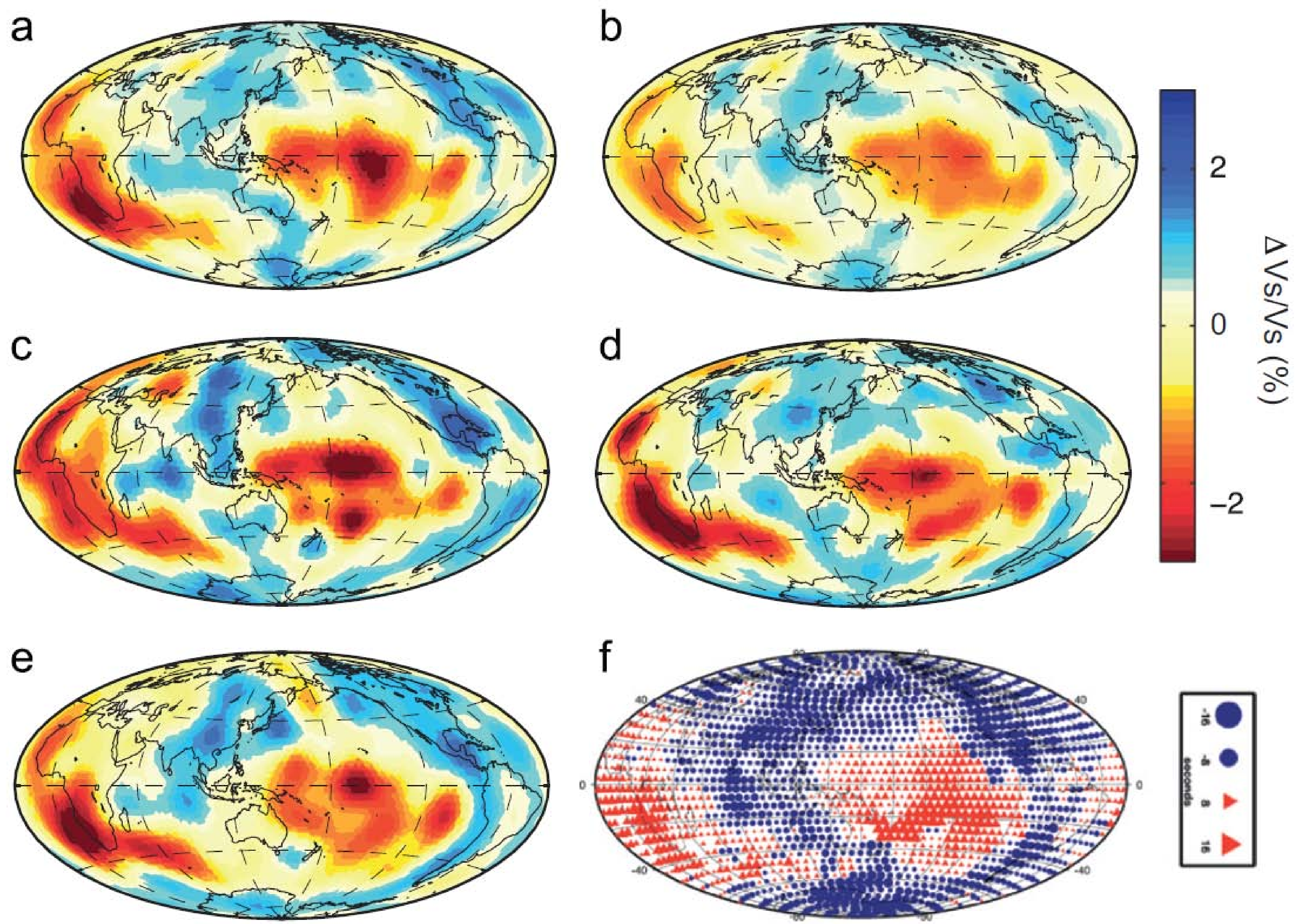
- Different depths in the mantle have distinct spatial and spectral characteristics in long period Vs global tomographic models:
- Heterosphere – upper 250 km where tectonic signals dominate
- Transition Zone – signal of slabs in Western Pacific and slow anomalies related to hot spots
- Upper lower mantle – smaller amplitudes and lengthscales of heterogeneity
- Lower lower mantle – dominance of degree 2 structure consisting of pair of antipodal LLSVPs surrounded by a ring of faster-than-average Vs.

Ritsema et al. 2011



after Dziewonski et al. EPSL 2010

How similar is lower mantle structure across models?



S362ANI – Kustowski et al., 2008
S40RTS – Ritsema et al., 2011
SAW24B16 – Megnin & Romanowicz, 2000
HMSL-S – Houser et al., 2008
GyPSuM – Simmons et al., 2010
Data from Manners, 2008

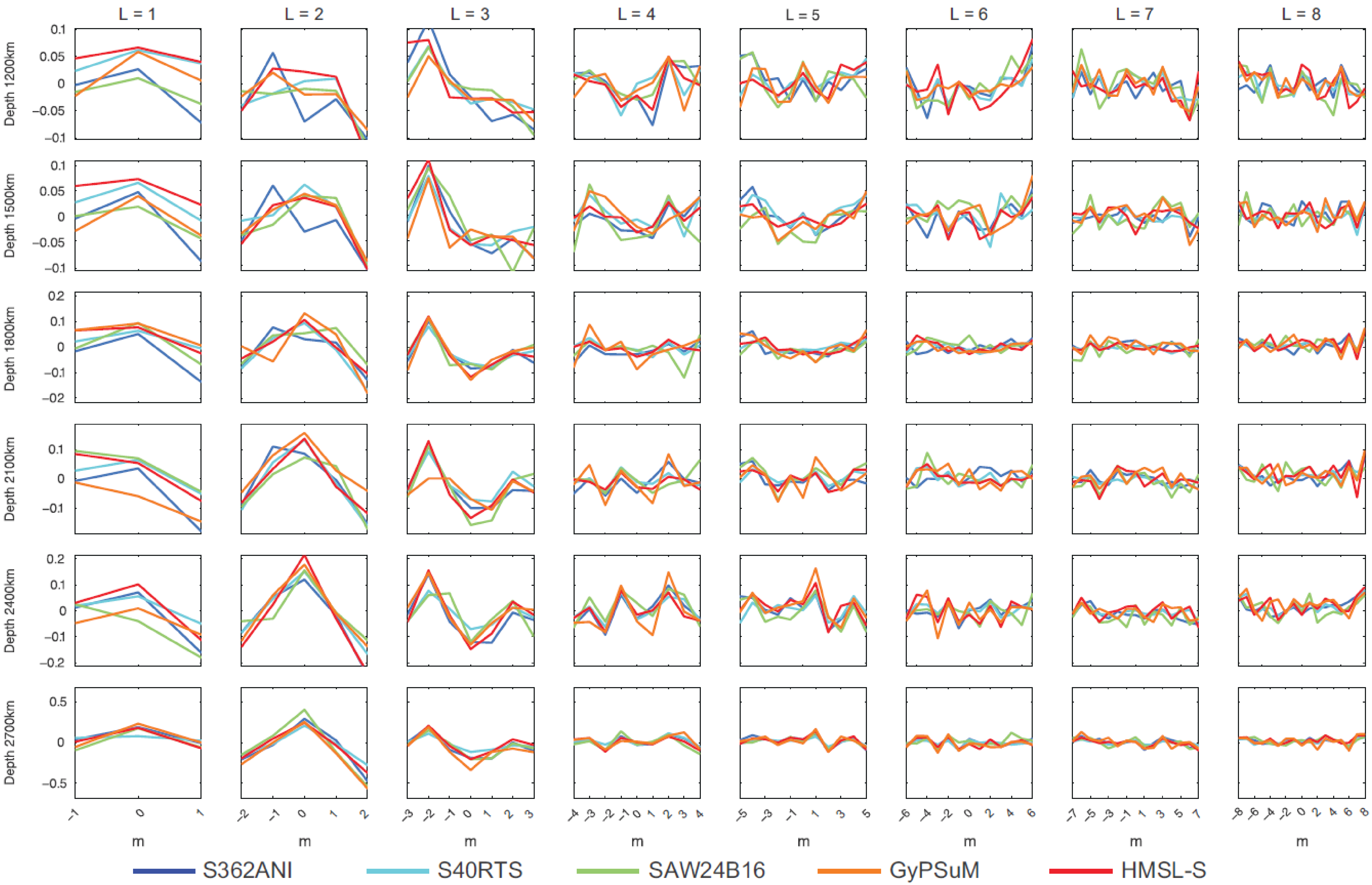
- Differences in model paramterization, regularization, data selection, and theoretical formalism can result in differences between models

- Features that are common across tomographic models are unlikely to be artifacts of theoretical approximations or to reside in the null space

How are global Vs models constructed?

Tomographic model	Parameterization		Lower mantle data	Theoretical Framework	Regularization
	Horizontal	Vertical			
SAW24B16	Spherical harmonics up to degree 24	16 cubic b-splines	Transverse component waveforms ($T > 30$ s) subdivided into wave packets to isolate body waves from fundamental mode surface waves	Full waveform inversion via non-linear asymptotic coupling theory NACT (Li and Romanowicz, 1995)	A priori model covariance matrix incorporating norm damping, horizontal and vertical first-derivative and vertical second derivative smoothing
HMSL-S	4° blocks	18 layers of equal thickness	S, SS travel-times from transverse component cross-correlation ($T > 15$ s), hand-picked SS-S and ScS-S differential measurements	Ray theory with 1D ray tracing	Horizontal and vertical smoothing
GYPSUM	275 km × 275 km blocks	22 layers (75–240 km thick)	S, sS, ScS, sScS, SKS, SKKS travel times ($T > 14$ s), P summary travel times, horizontal plate divergence model, free-air gravity model, dynamic topography model, excess ellipticity of core–mantle boundary	Ray theory with 1D ray tracing, viscous flow in a radially symmetric viscosity profile	Second derivative horizontal and vertical smoothing
S40RTS	Spherical harmonics up to degree 40	21 vertical splines, spacing increasing with depth	Normal mode splitting ($T > 333$ s) functions, cross-correlation travel-times of S, Sdiff, SS, SSS and major-arc SS_M, SSS_M, $SSSS_M$, and SKS, SKKS on radial component	Ray theory with 1D ray tracing, normal mode splitting related to Vs through depth-dependent kernel functions computed in PREM (Dziewonski and Anderson, 1981)	Norm damping
S362ANI	362 spherical splines	16 cubic splines, discontinuous across 650 km	Long period waveforms of body ($T > 50$ s) and mantle ($T > 125$ s) waves. Travel times of S, SS, ScS, ScSScS, SS-S, ScS-S, S-SKS, SKKS-SKS, SS-S, ScS-S obtained using cross-correlation, with dominant period of 20 s	Full waveform inversion of body ($T > 50$ s) and mantle waves ($T > 125$ s) via path-average approximation PAVA (Woodhouse and Dziewonski, 1984); ray theory with 1D ray tracing for travel time data	Horizontal and vertical smoothing

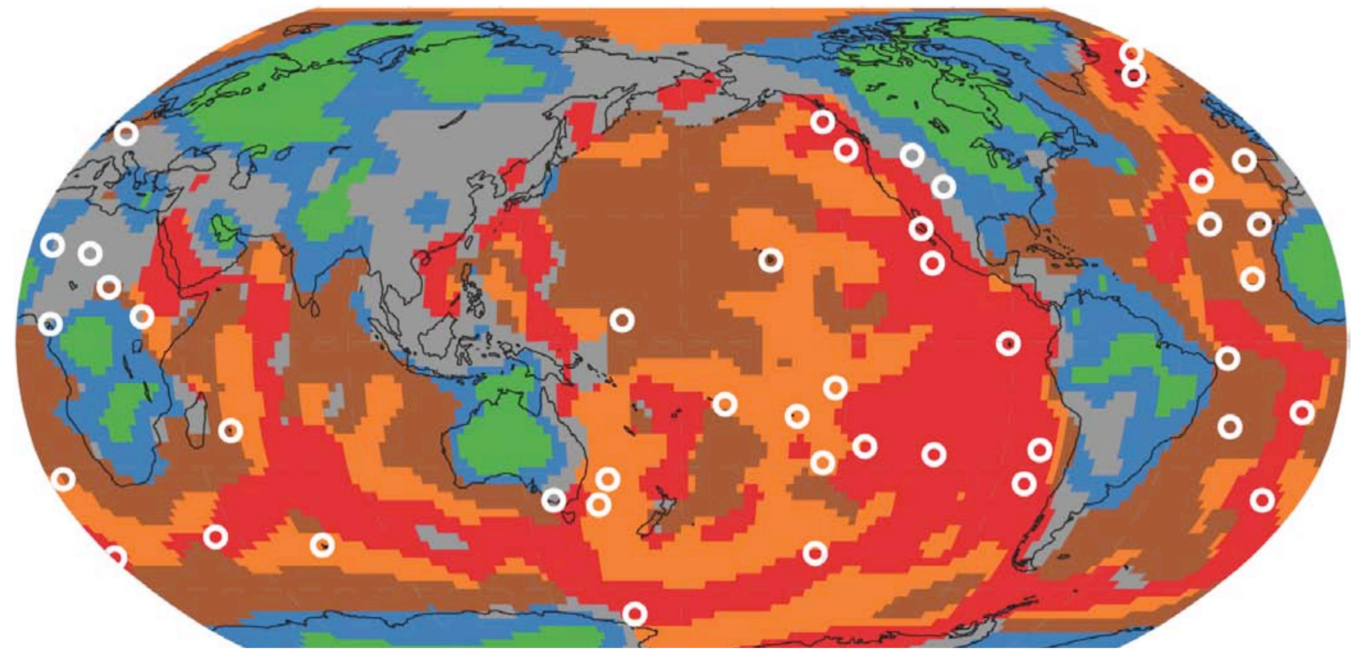
Comparing models in the wavenumber domain

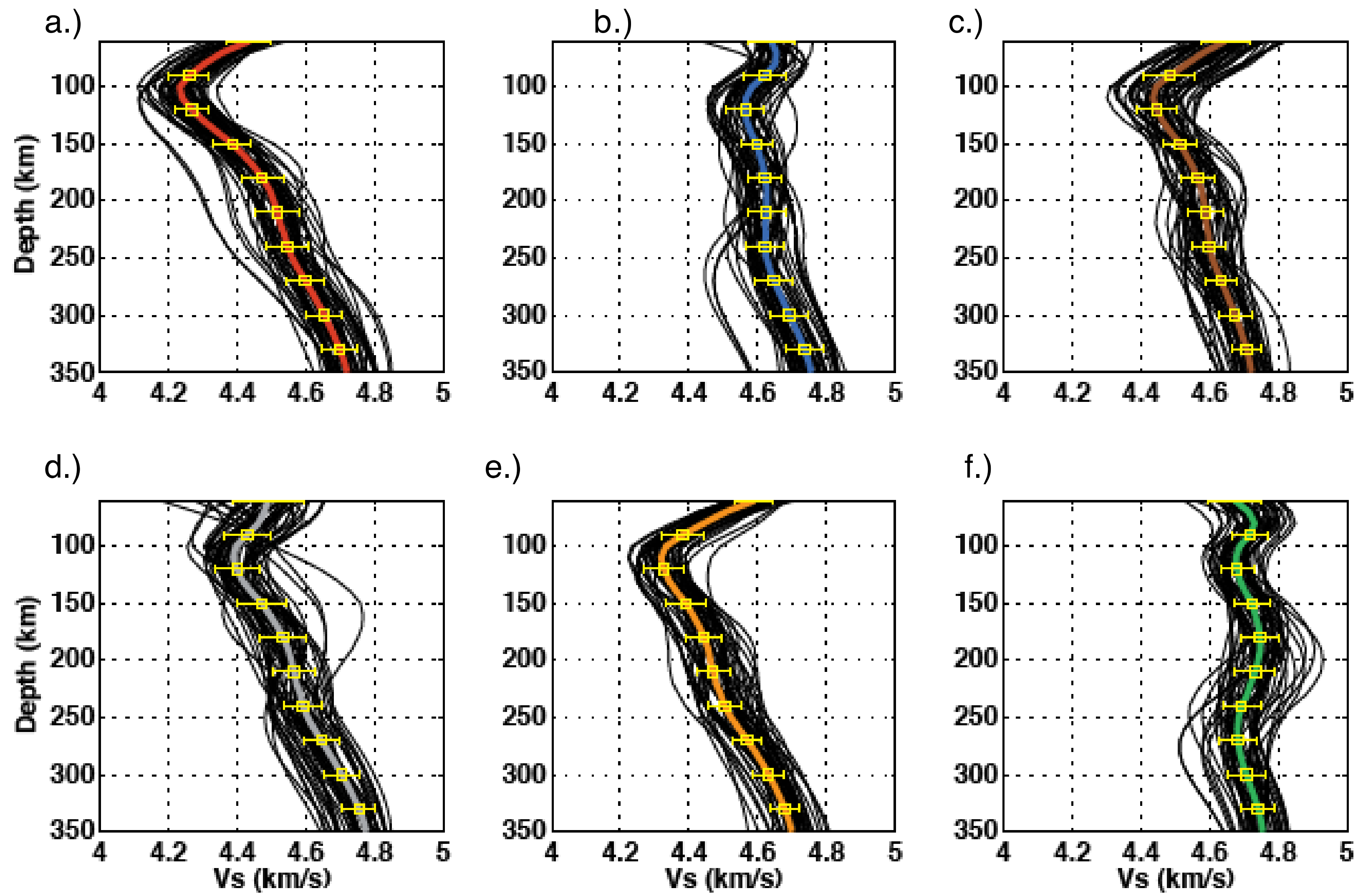


Cluster Analysis

- Cluster analysis allows tomographic models to be represented by N groups/families/clusters of similar Vs profiles.
- Each group/family/cluster traces out a geographic region.
- The set of average Vs profiles for each region summarizes the tomographic model.
- In the upper mantle, cluster analysis brings out tectonic provinces one by one starting with the ocean-continent dichotomy.

SEMum model: Lekic & Romanowicz, GJI 2011





Lekic & Romanowicz, EPSL 2011

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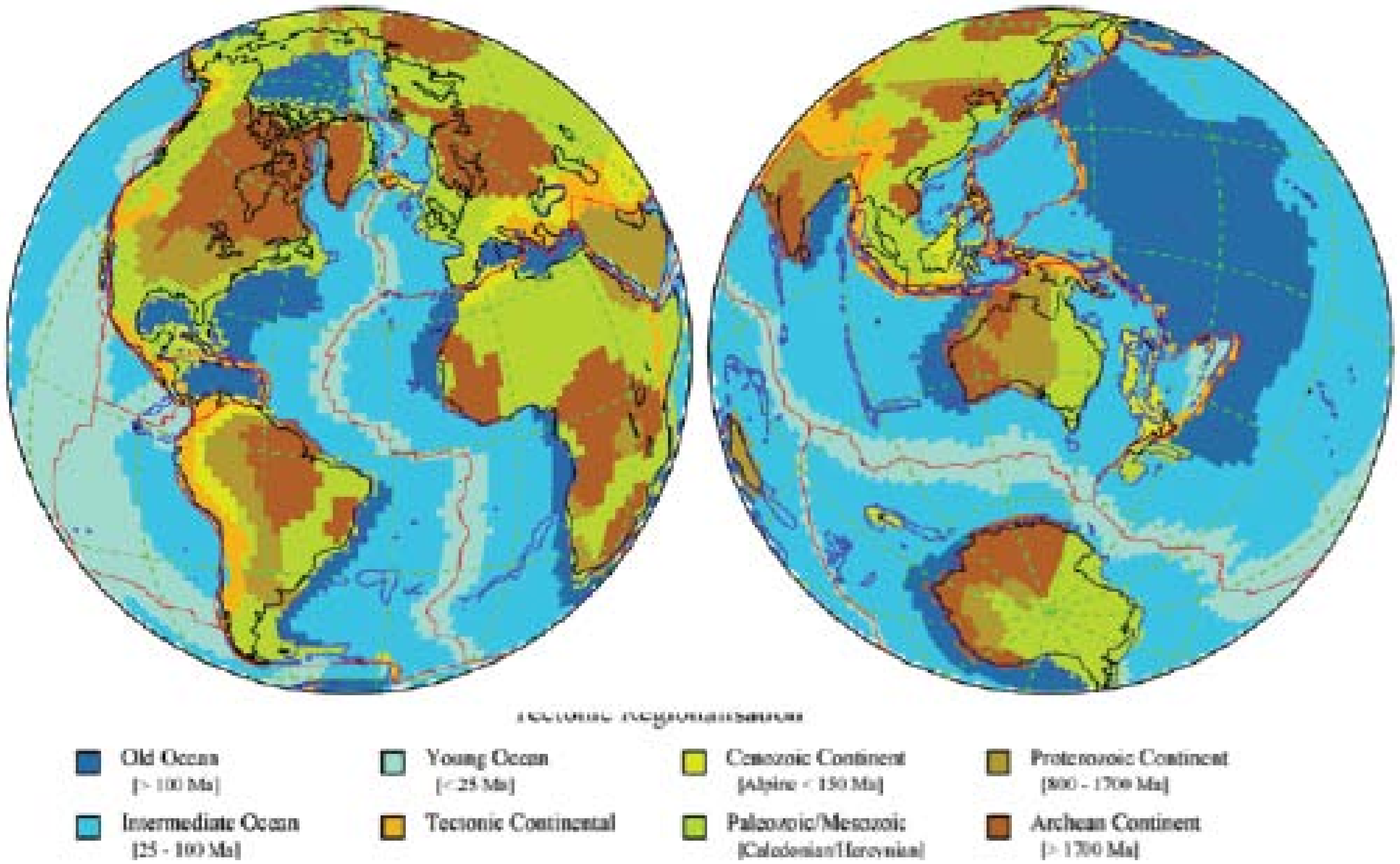

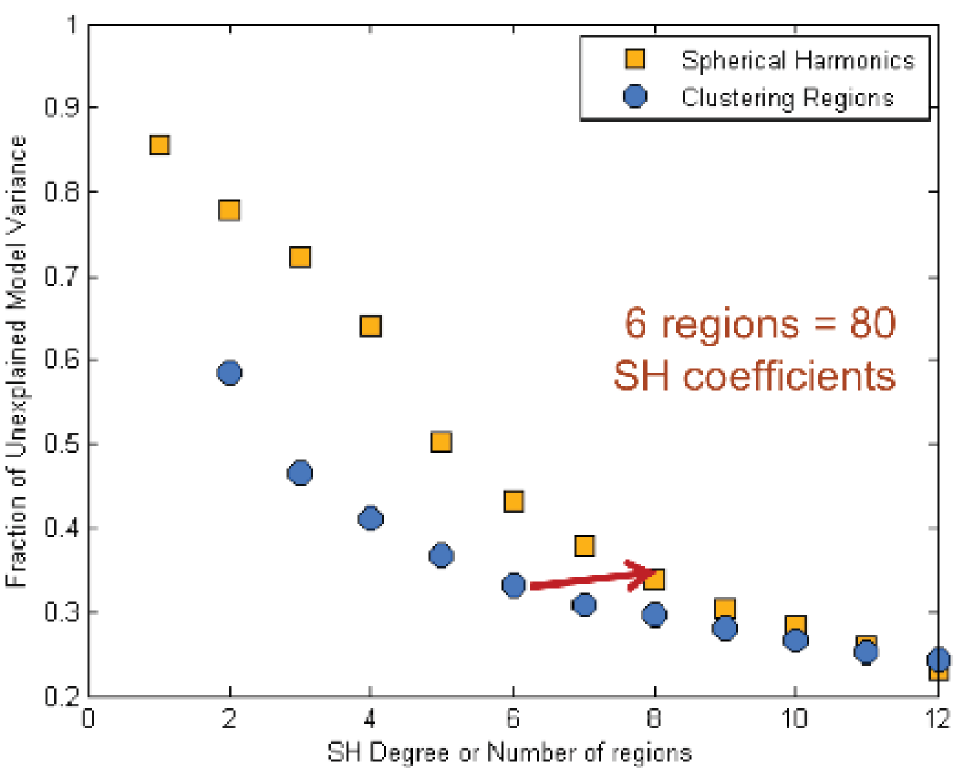

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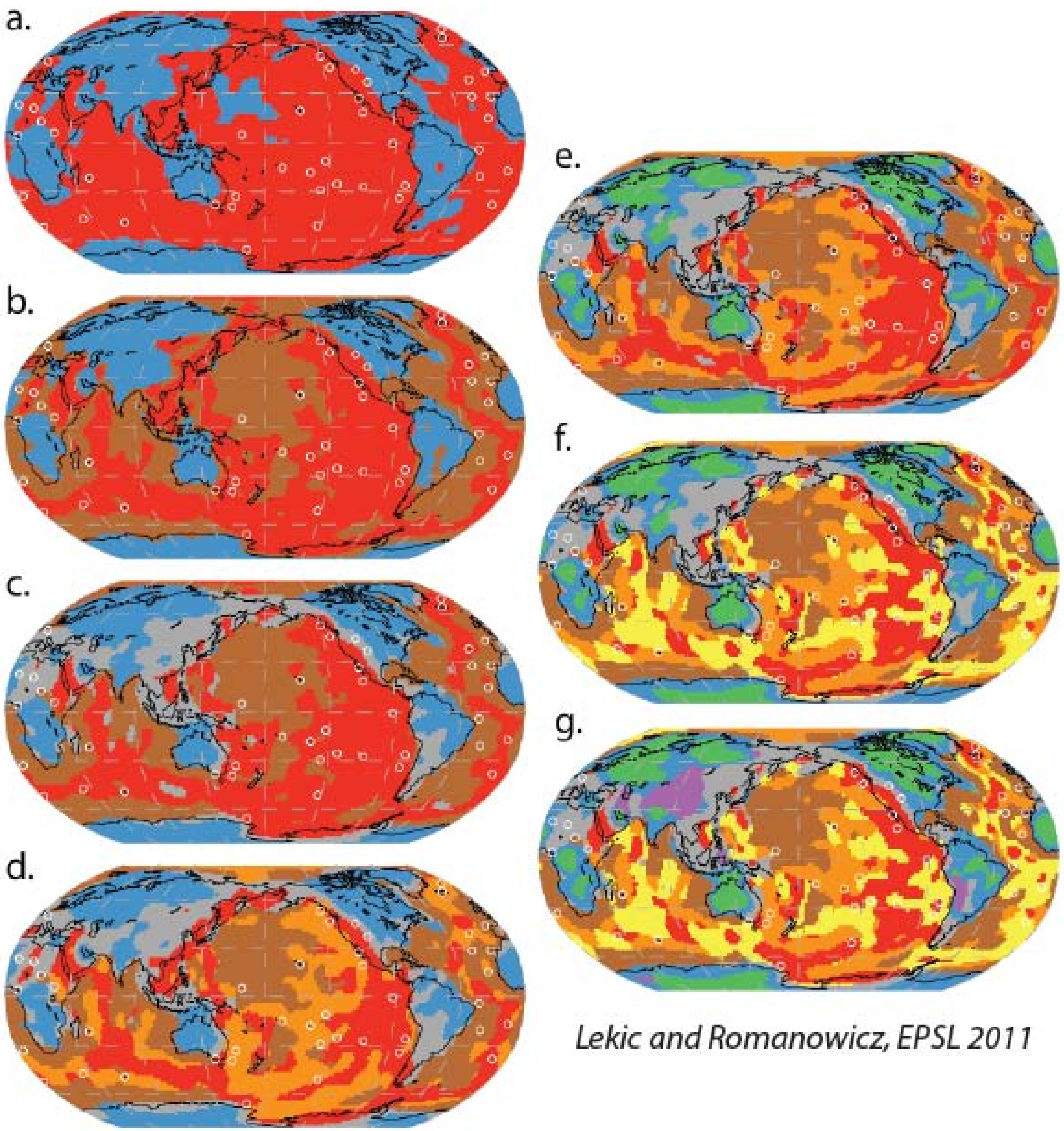
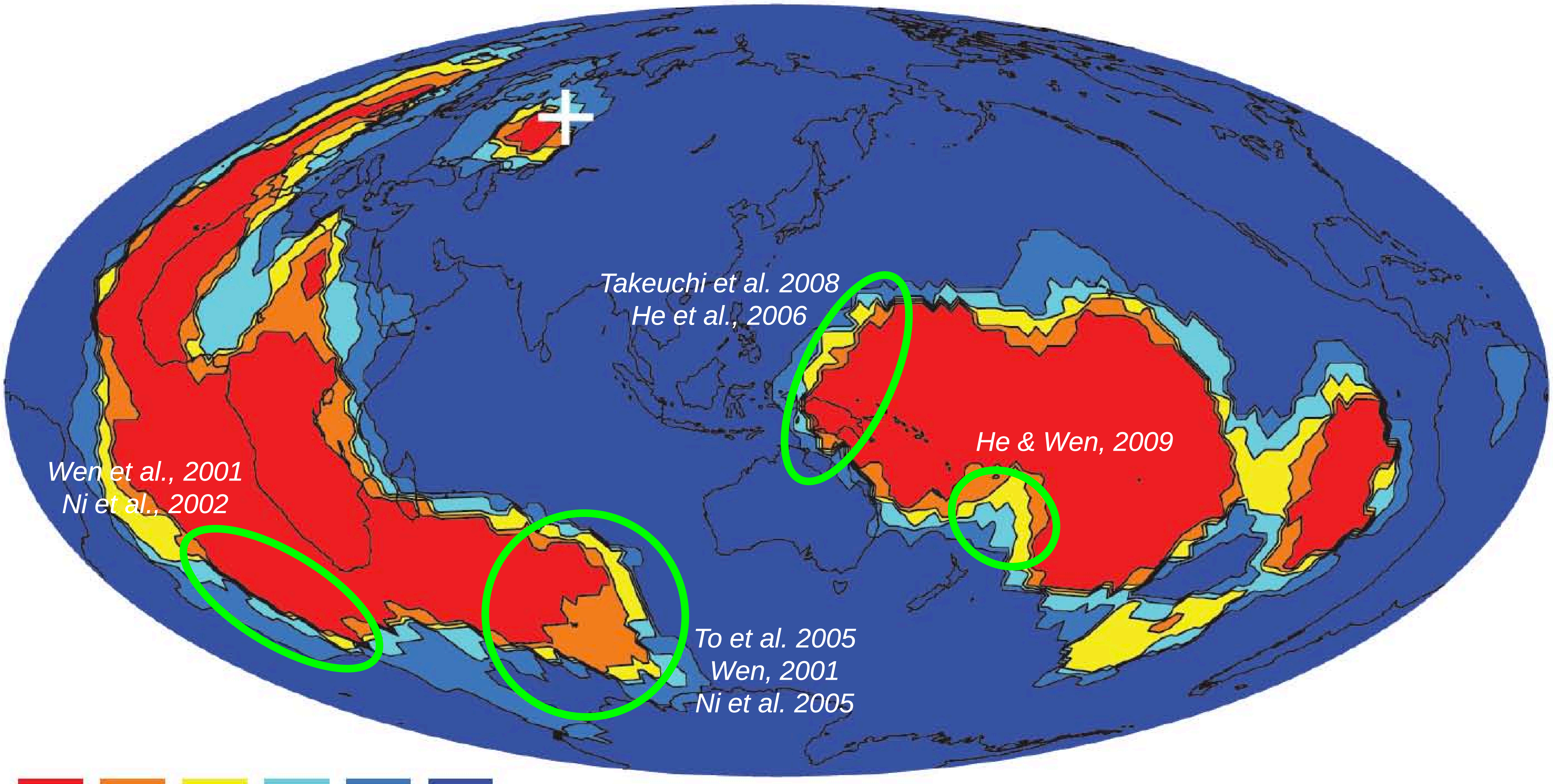


Lekic and Romanowicz, EPSL 2011

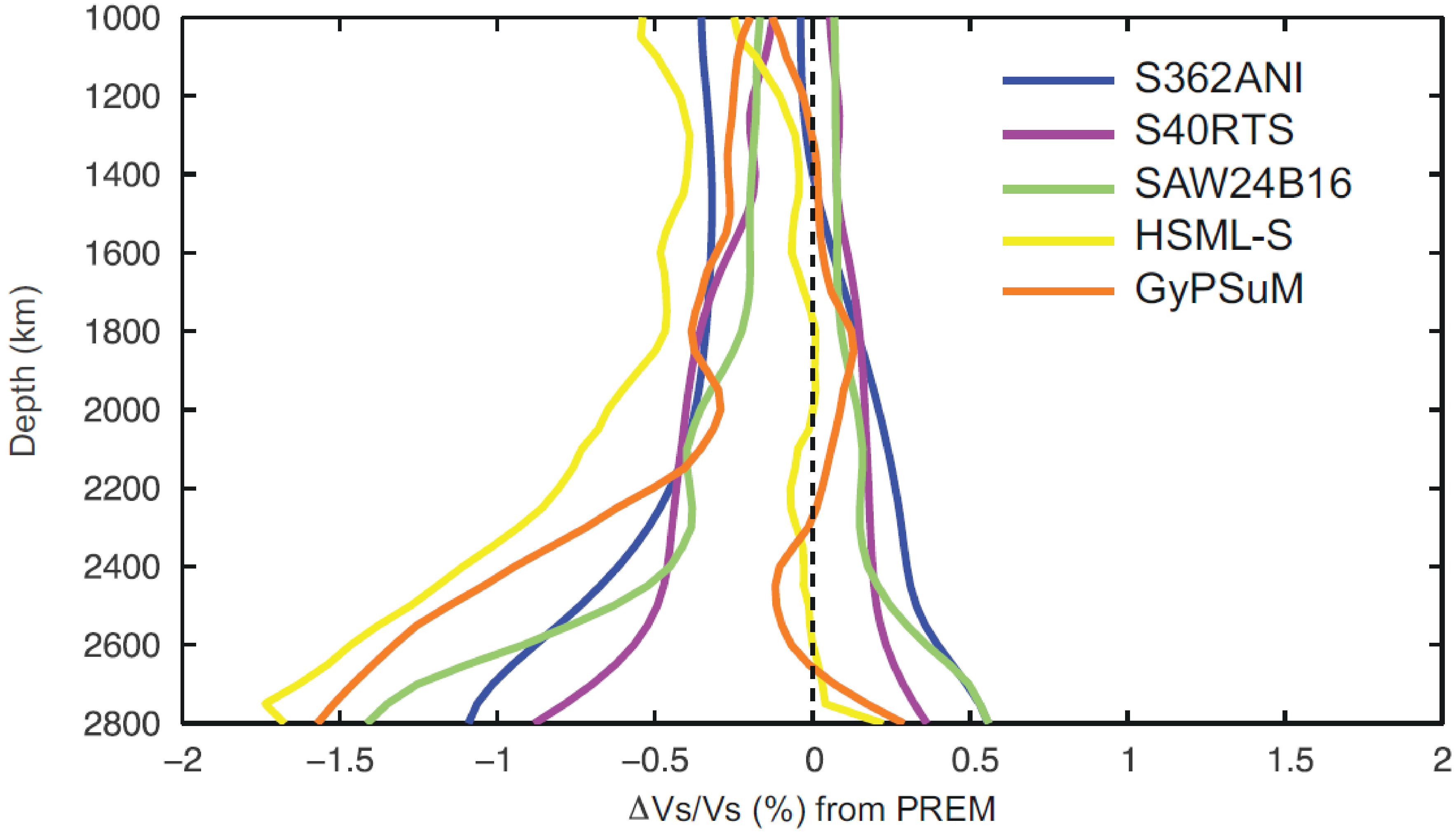
Cluster analysis of lower mantle

- Cluster analysis of lower mantle tomography divides mantle into two antipodal regions (LLSVPs) and a contiguous circumpolar torus of faster-than-average Vs.
- Remarkable inter-model consistency, especially along LLSVP boundaries → consistent with high-resolution waveform modeling studies.



Lekic et al. EPSL submitted

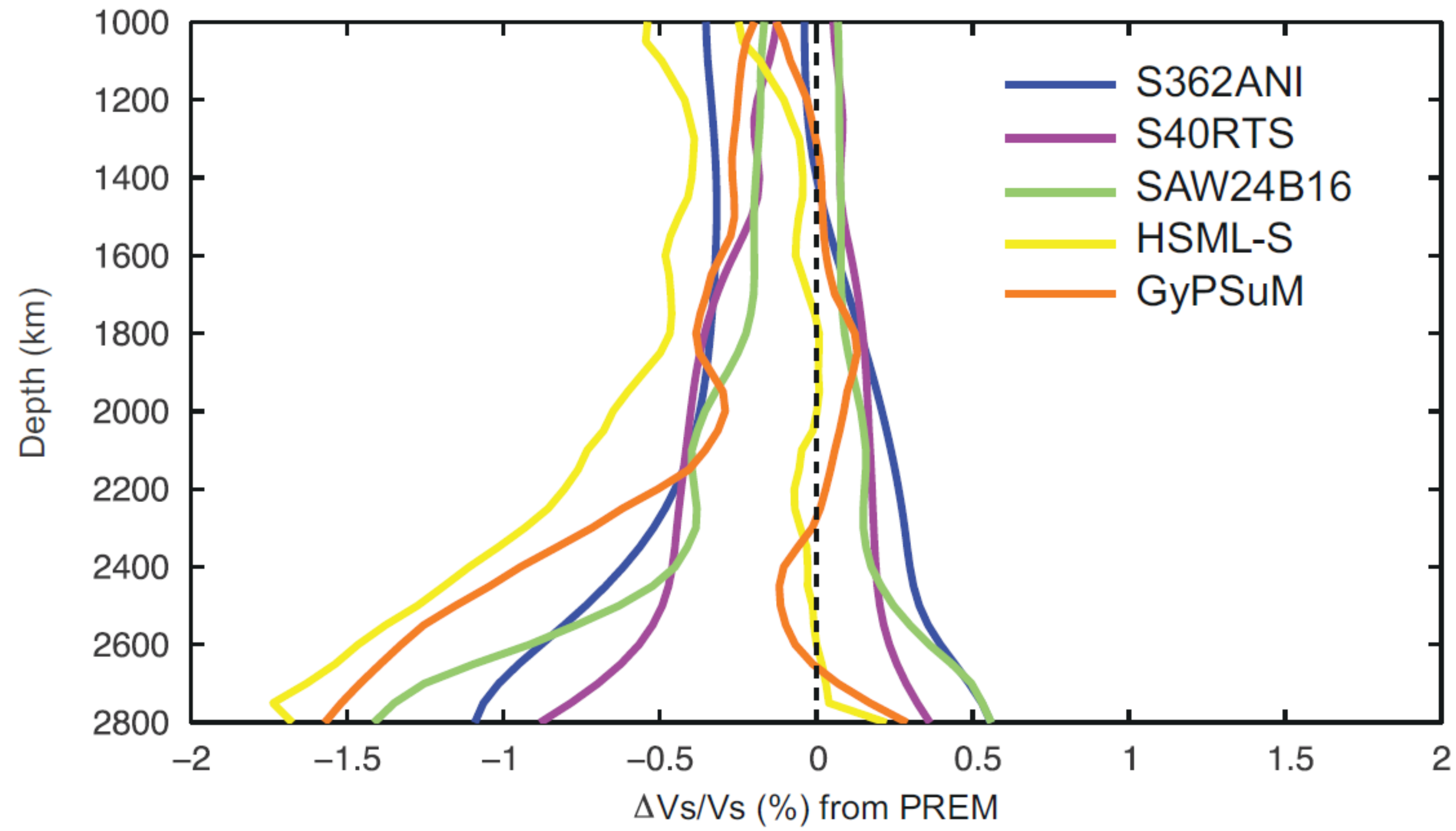
Vs characteristics of clusters



- Average Vs profiles of fast and slow clusters differ by >0.5% 1200 km up from the CMB.
- Differences increase abruptly starting at ~2200 km depth.
- Deviation of slow clusters from 1D average is more pronounced resulting in significantly reduced dVs/dz w.r.t PREM.
- Consistent with compositional component of heterogeneity.

Vs characteristics of clusters

- Average Vs profiles of fast and slow clusters differ by >0.5% 1200 km up from the CMB.
- Differences increase abruptly starting at ~2200 km depth.
- Deviation of slow clusters is more pronounced resulting in significantly reduced dVs/dz w.r.t PREM.
- Differences between average Vs profiles span the range of predictions for end-member mantle compositions (at same T conditions)



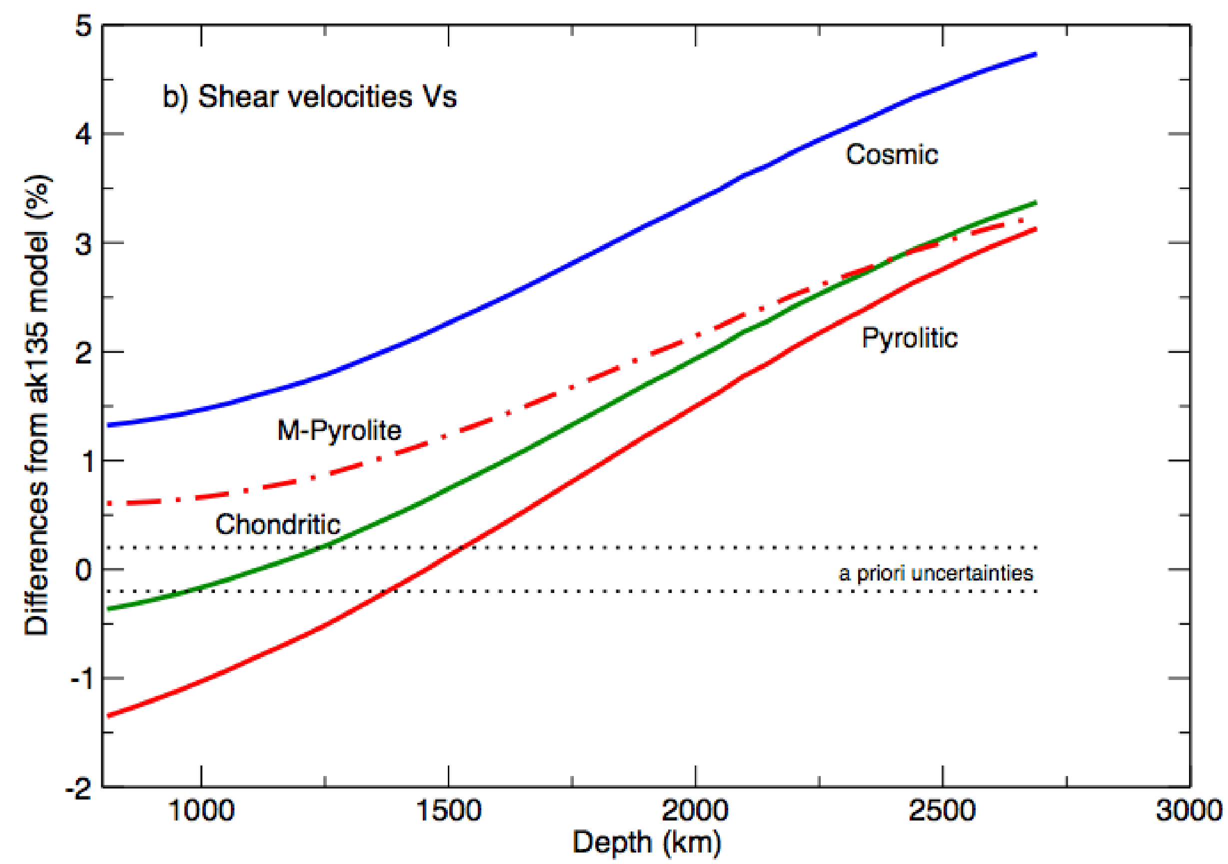


Figure 1 - Differences between predicted and observed seismic shear wavespeeds (Vs) for a lower mantle having uniform bulk composition together with the Brown and Shankland's (1981) geotherm: pyrolite (solid line), modified pyrolite (dot-dashed line), chondritic model (dashed line), cosmic model (dotted line). The range of predicted Vs for the different compositional models decreases to ~1.5% at the base of the mantle.

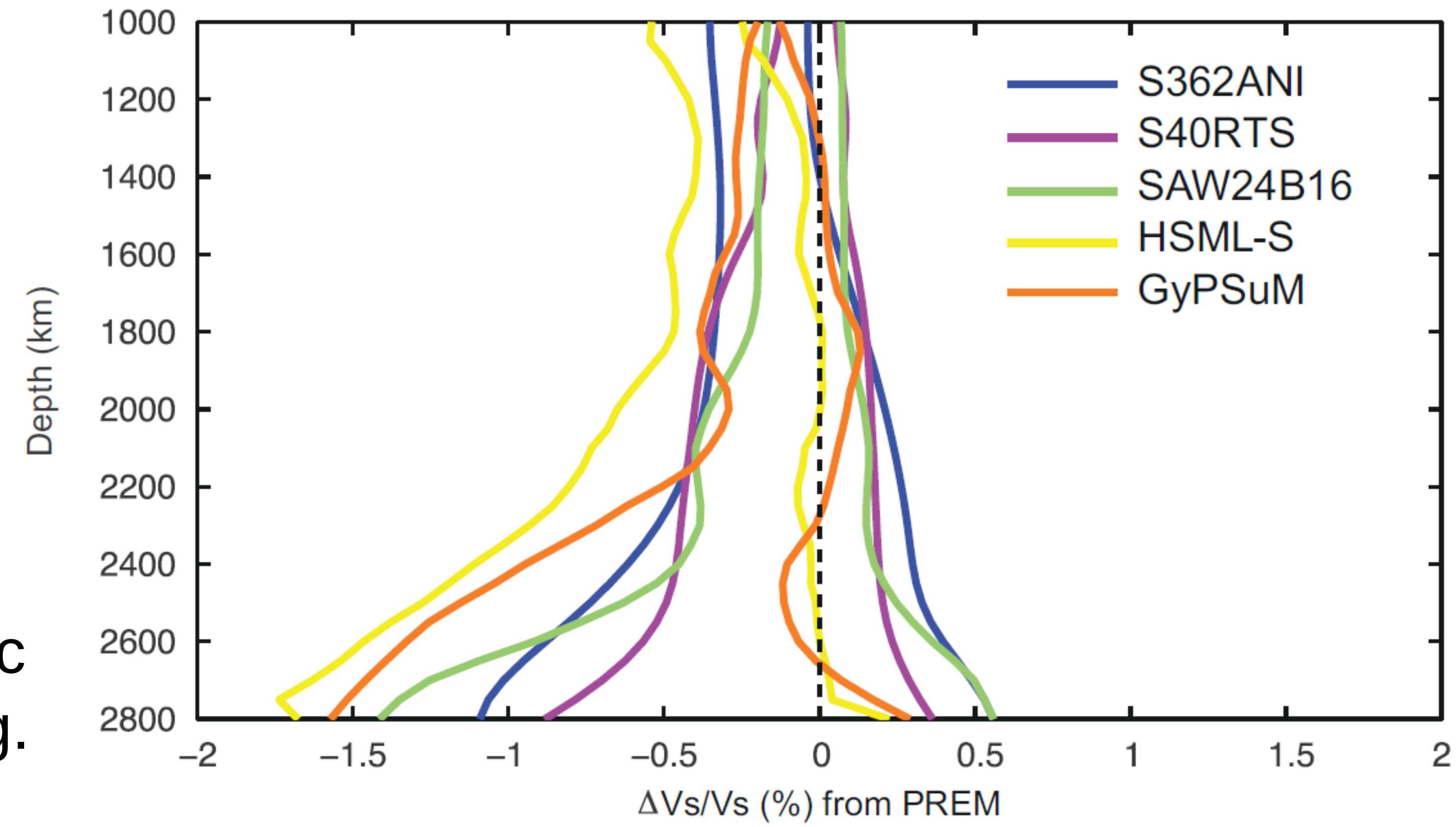
Matas et al. 2007

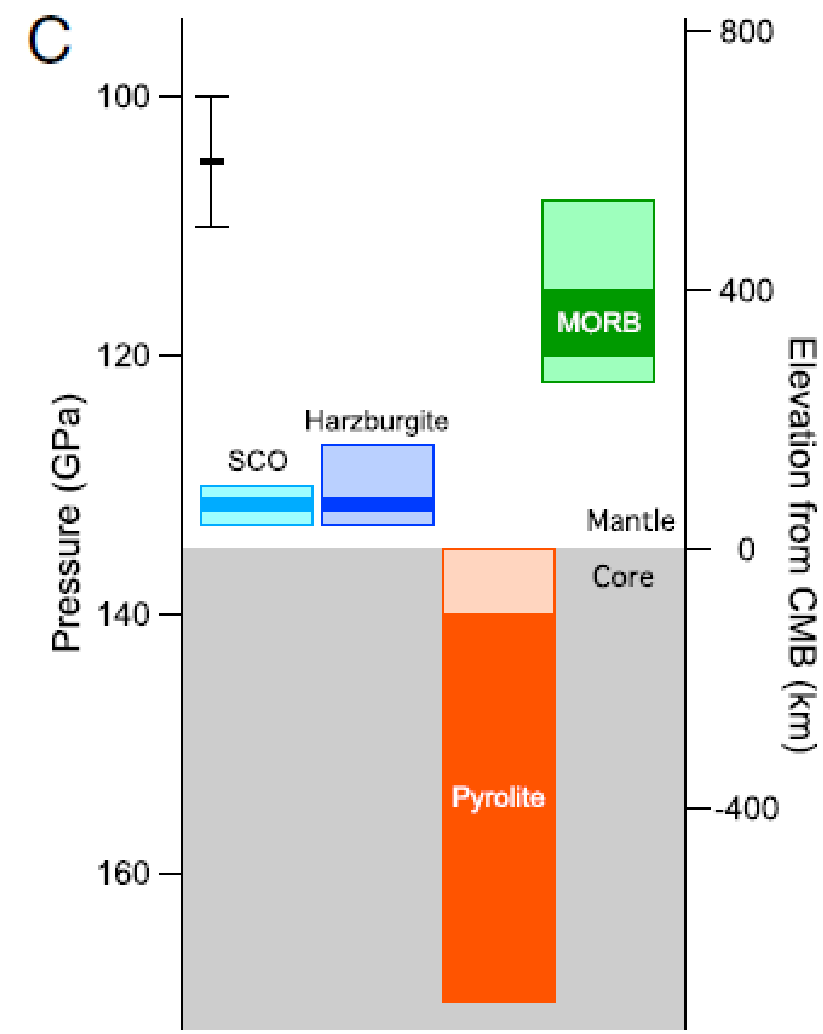
Vs characteristics of clusters

- Pv to pPv transition increases Vs and reduces bulk sound speed. → If present in fast regions may explain anticorrelation of Vs and Vc and sharp lateral Vs variations (e.g. Wookey et al., 2005).

- To explain the differences between slow and fast clusters pPv must be stable (in the fast regions) ~500 km above the CMB.

- But!
  - Recent experiments put depth of Pv-pPv transition at or near CMB except in MORB
  - Is the change in Vs gradient with depth in PREM consistent with Pv-pPv transition (if not, then it would be fast not slow cluster showing strong deviations)?





Grocholski et al. 2012

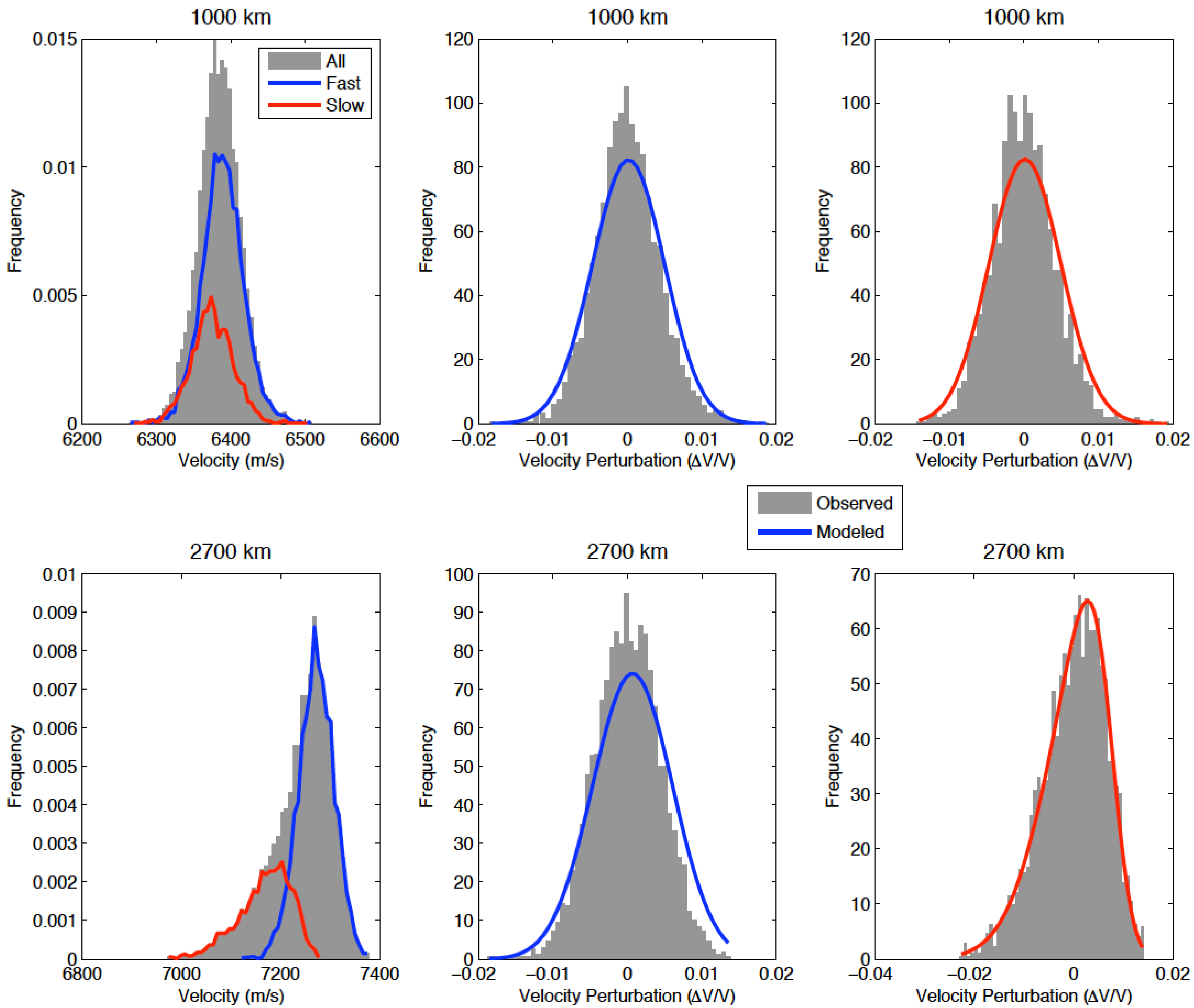
Vs characteristics of clusters

- The distribution of Vs in the lower mantle becomes increasingly skewed toward slow velocities with increasing depth

- The majority of this skew is due to emergence of LLSVPs

- Cluster analysis enables us to separate these two Vs distributions

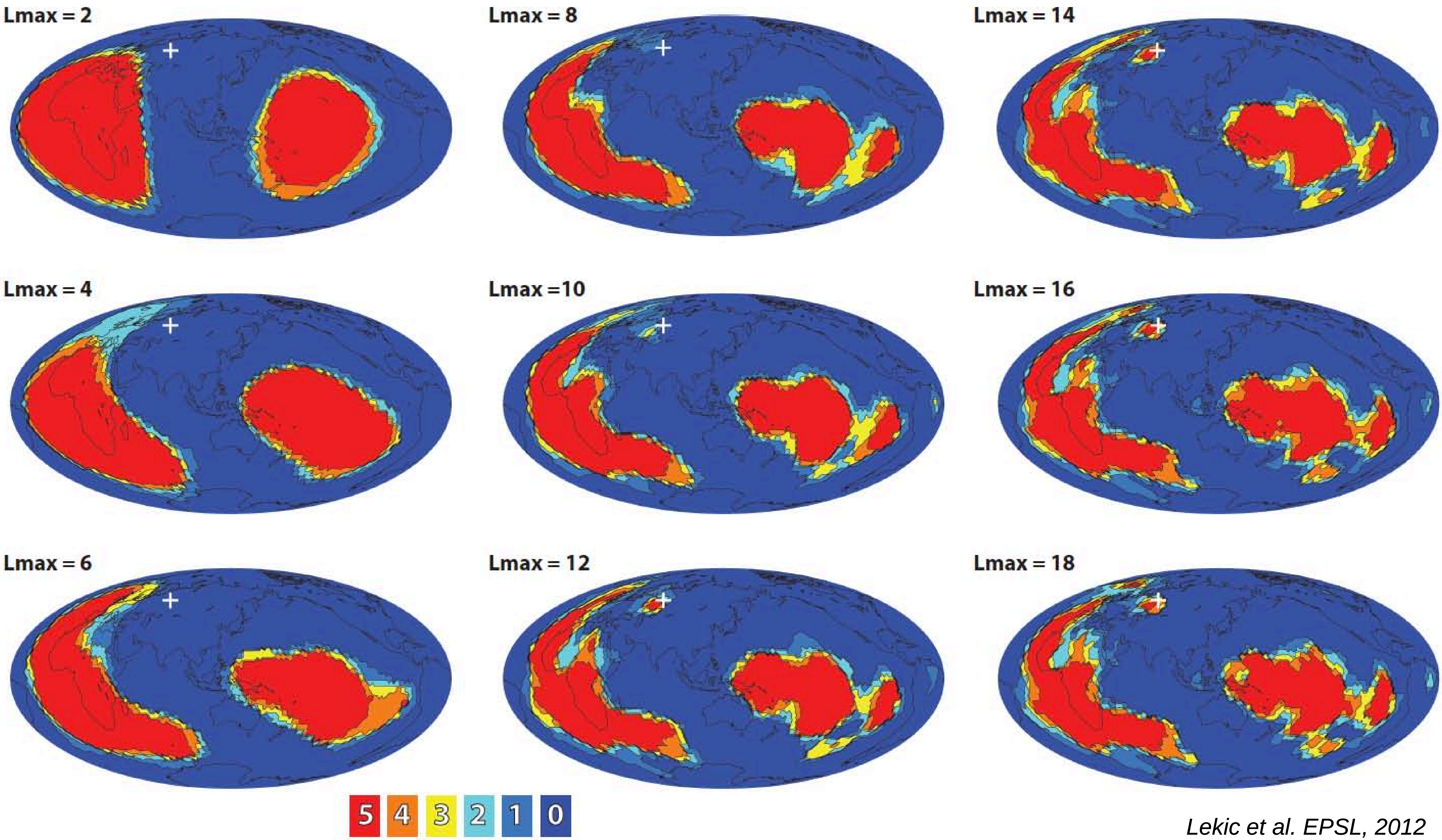
- BUT: Distribution of Vs in slow cluster remains skewed → opportunity to constrain lower mantle attenuation? Stay tuned for Jan Matas' talk.



Lekic and Matas, in prep.

Shorter wavelength structure

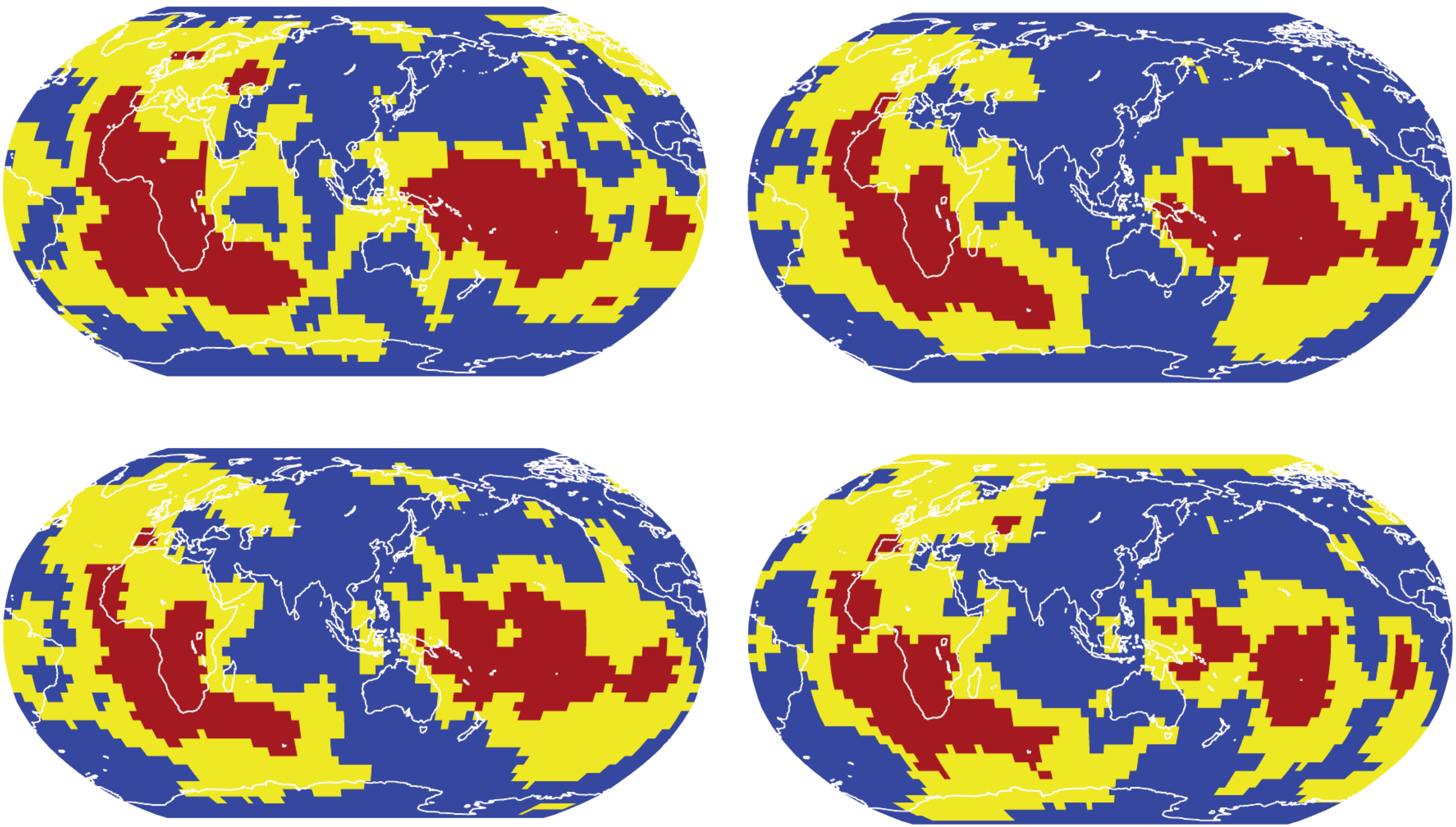
- Inter-model consistency persists to relatively high degrees
- Shorter-wavelength structure exhibits as undulation to LLSVP boundaries.



Lekic et al. EPSL, 2012

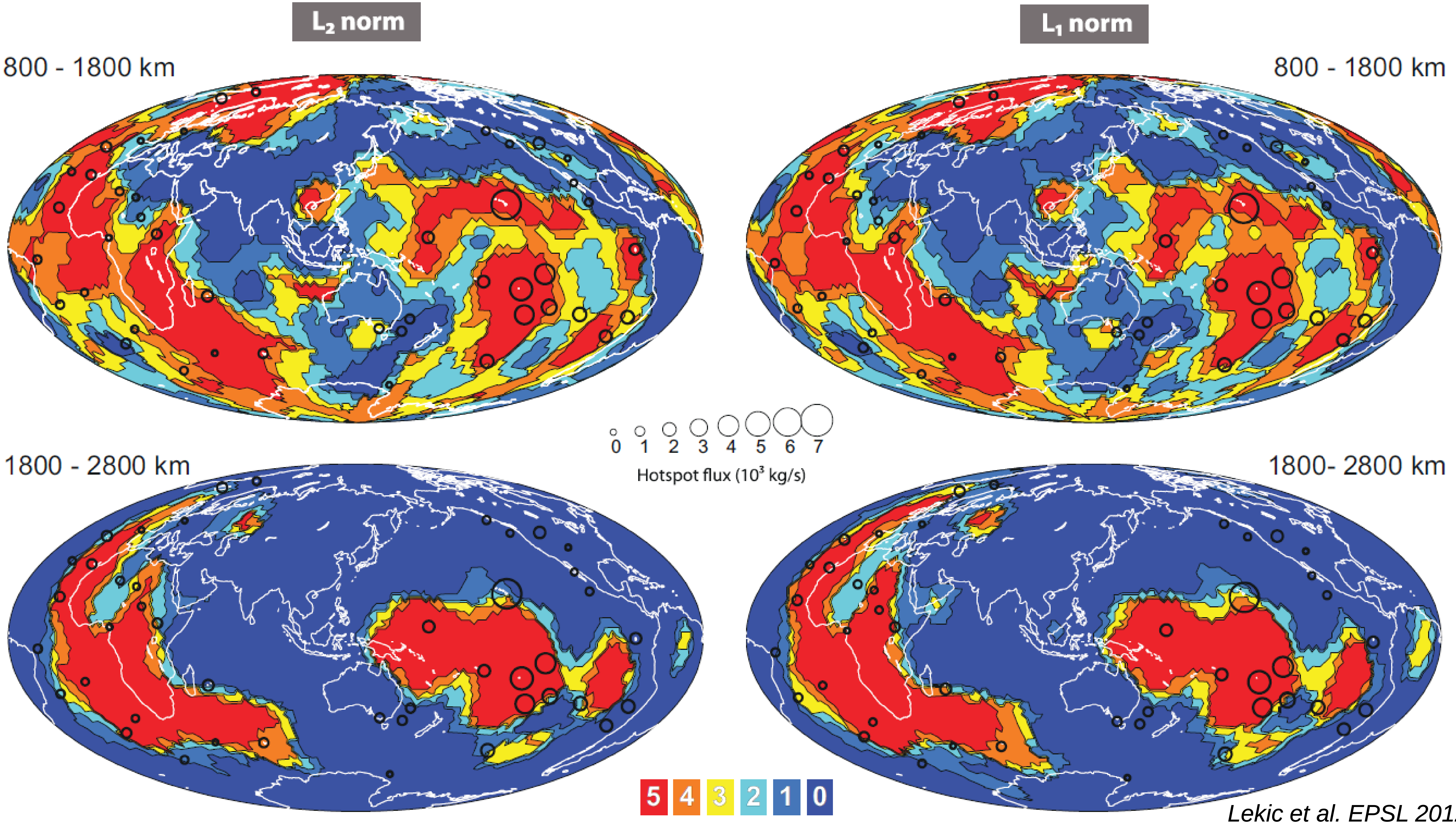
What if we grouped into 3 clusters?

- Even when 3 clusters are created, classification of structure remains relatively simple:
  - Cores of LLSVPs make up the slowest cluster, circumpolar ring remains the fastest cluster, and the intermediate cluster traces the margins of the LLSVPs.



What about the upper lower mantle?

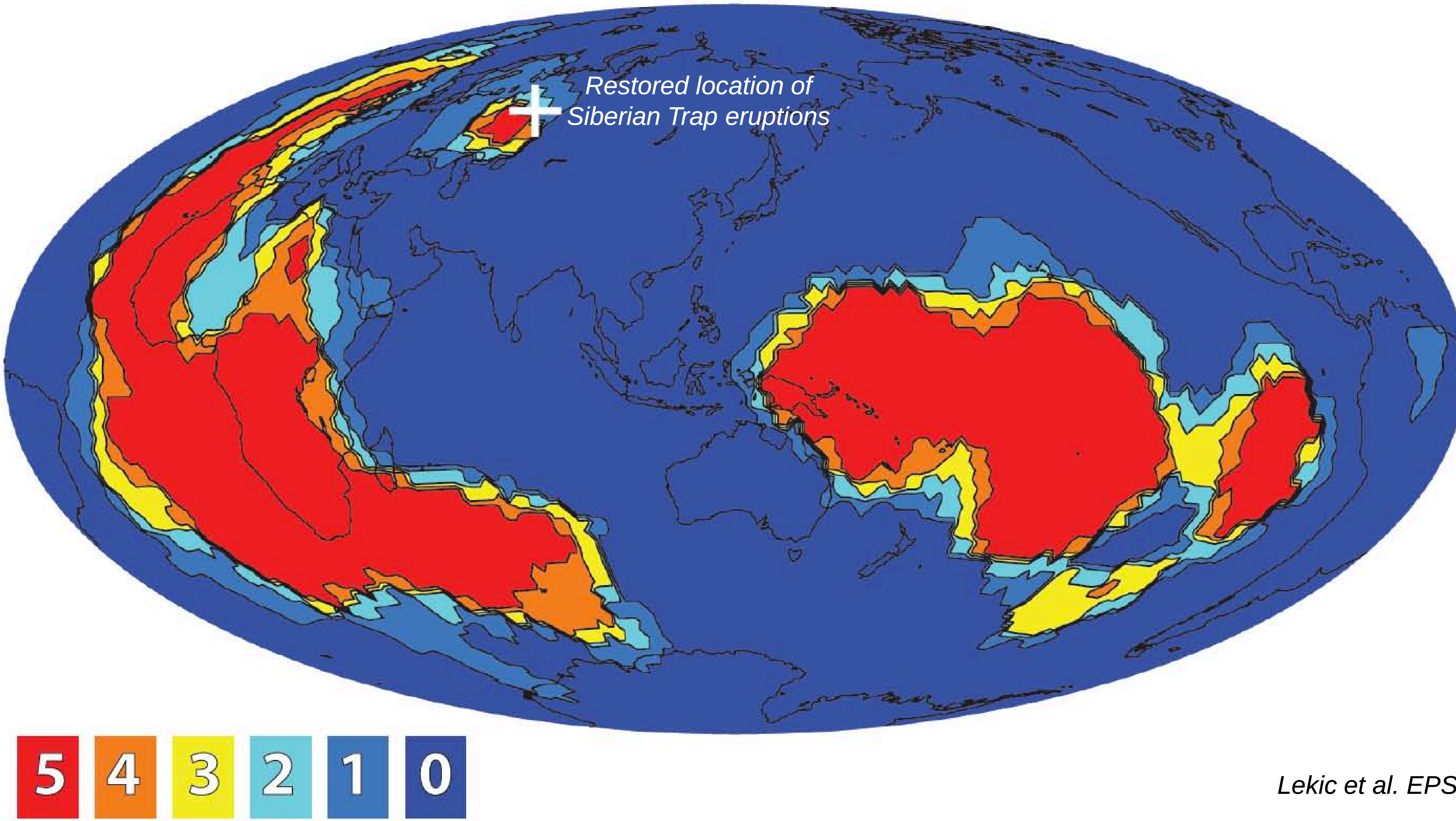
- General features of lower mantle clustering are retrieved even when only the 800-1800 km depth range is used.
- Slow cluster becomes more distributed, but remains associated (even more strongly?) with global hotspot distribution.



Lekic et al. EPSL 2012

Cluster analysis of lower mantle

- All models agree that there is only a single exception to the neat separation of structure into one fast and two slow regions.
- Because it is approximately centered beneath the city of Perm, Russia, we call it the “Perm Anomaly”

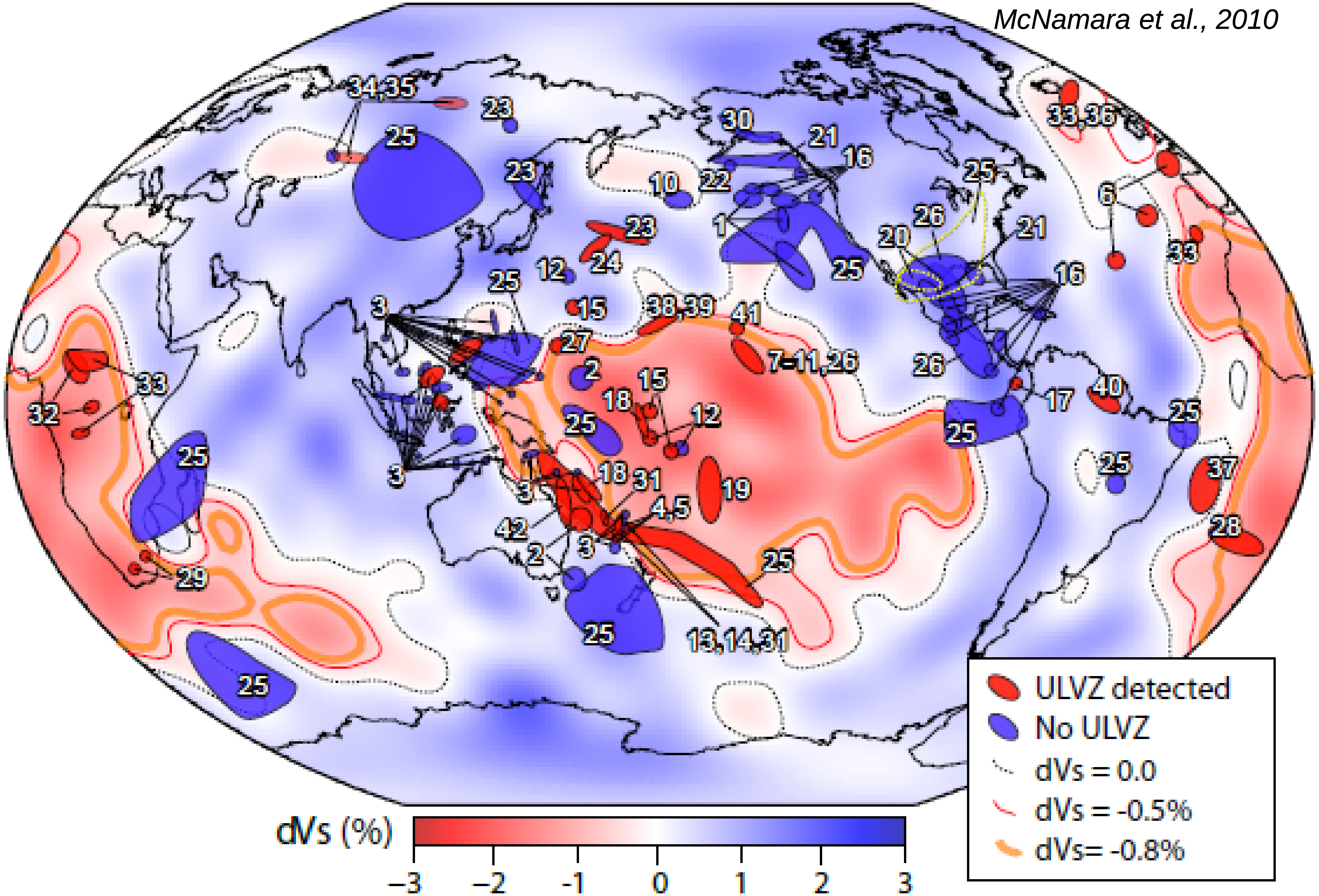


Lekic et al. EPSL 2012

Ultra-low velocity zones

- ULVZs are small (~10 km tall, ~100 km across) dense (~10%), slow (>10% reduction) anomalies
- Might be preferrentially associated with the edges of the LLSVPs
- Different size / character than “Perm-type” anomaly.

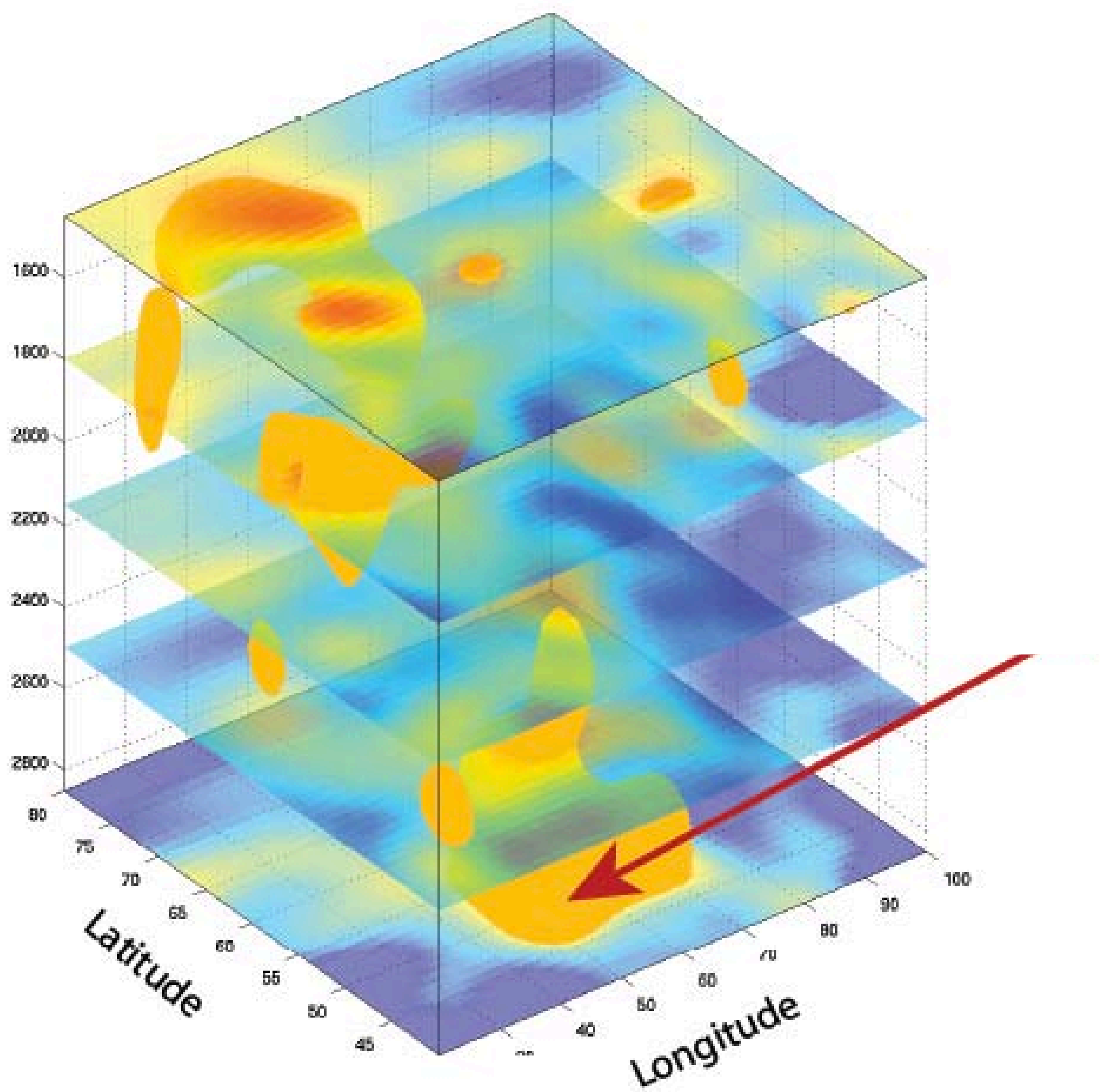
McNamara et al., 2010

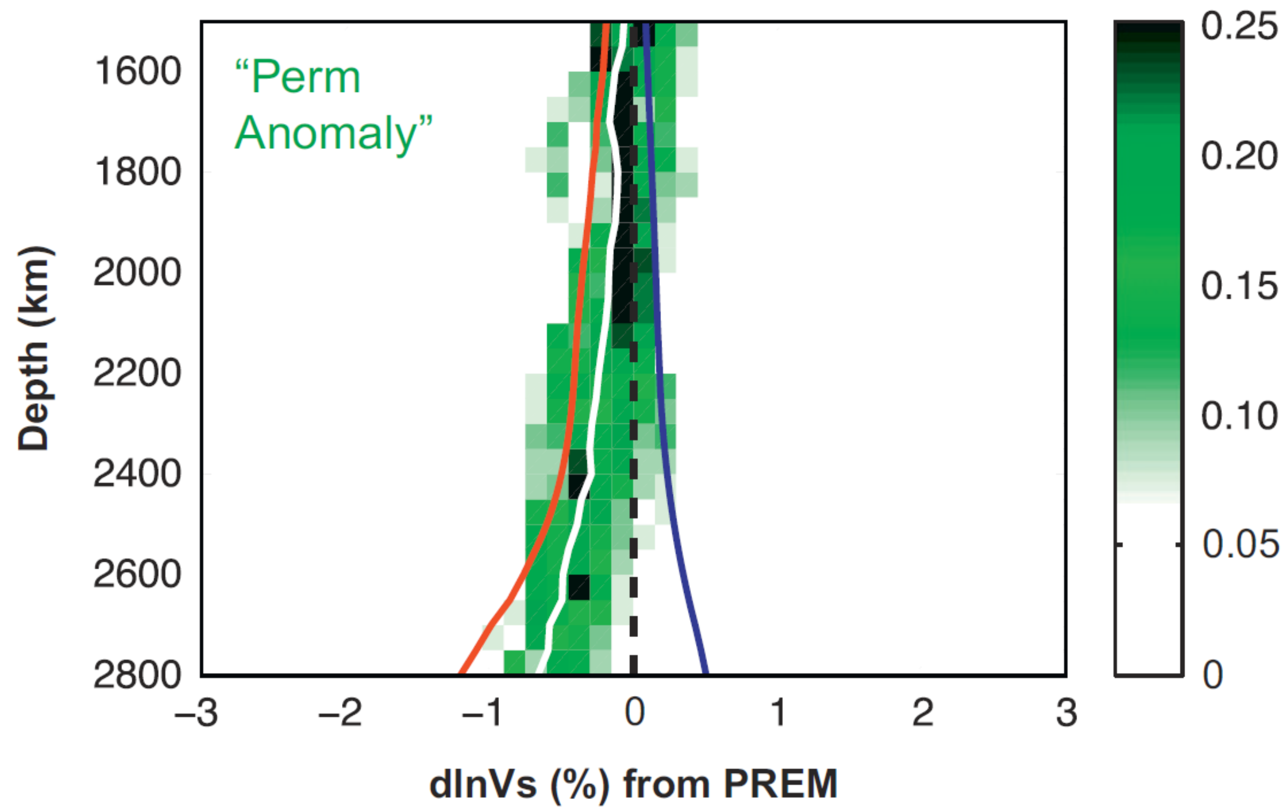


1. Rost et al. [2010, JGR]
2. Thomas et al. [2009, GJI]
3. Idehara et al. [2006, PEPI]
4 Rost et al. [2005, Nature]
5. Rost et al. [2006, JGR]
6. Rost and Garnero [2006, JGR]
7. Lay et al. [2006, Science]
8. Avants et al. [2006, GRL]
9. Mori and Helmberger [1995, JGR]
10. Kohler et al. [1997, GRL]
11. Revenaugh and Meyer [1997, Science]
12. Garnero and Vidale [1999, GRL]
13. Rost and Revenaugh [2001, Science]
14. Rost and Revenaugh [2003, JGR]
15. Reasoner and Revenaugh [2000, JGR]
16. Persh et al. [2001, GRL]
17. Niu and Wen [2001, GRL]
18. Wen and Helmberger [1998, Science]
19. Wen and Helmberger [1998, JGR]
20. Havens and Revenaugh [2001, JGR]
21. Castle and van der Hilst [2001, EPSL]
22. Vidale and Benz [1992, Nature]
23. Xu and Koper [2009, GRL]
24. Rondenay and Fischer [2003, JGR]
25. Thorne and Garnero [2004, JGR]
26. Hutko et al. [2009, PEPI]
27. He and Wen [2009, JGR]
28. Wen [2002, JGR]
29. Sun et al. [2009, JGR]
30. Rost and Thomas [2009, PEPI]
31. Rost et al. [2010, JGR, in press]
32. Ni and Helmberger [2001, GRL]
33. Helmberger et al. [2000, JGR]
34. Ross et al. [2004, JGR]
35. Thybo et al. [2003, EPSL]
36. Helmberger et al. [1998, Nature]
37. Ni and Helmberger [2001b, EPSL]
38. Luo et al. [2001, EPSL]
39. Sun et al. [2007, PNAS]
40. Zou et al. [2006, GJI]
41. Courtier et al. [2007, GRL]
42. Koper and Pyle [2004, JGR]

What does the Perm Anomaly look like?

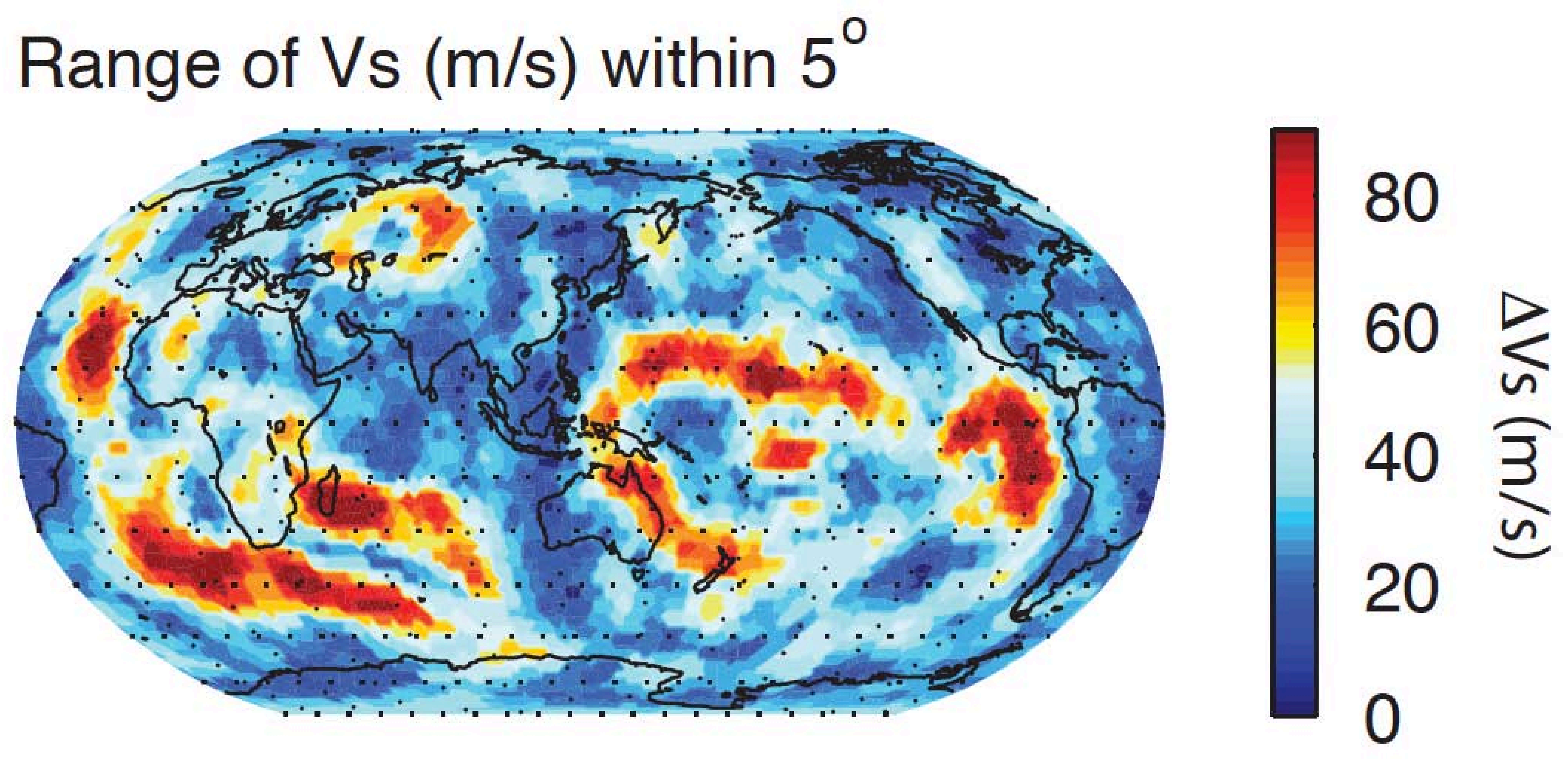
- Roughly circular in shape, ~800-1000 km across
- It appears to extend 300-500 km up from the CMB
- Does not appear to be connected to the African LLSVP

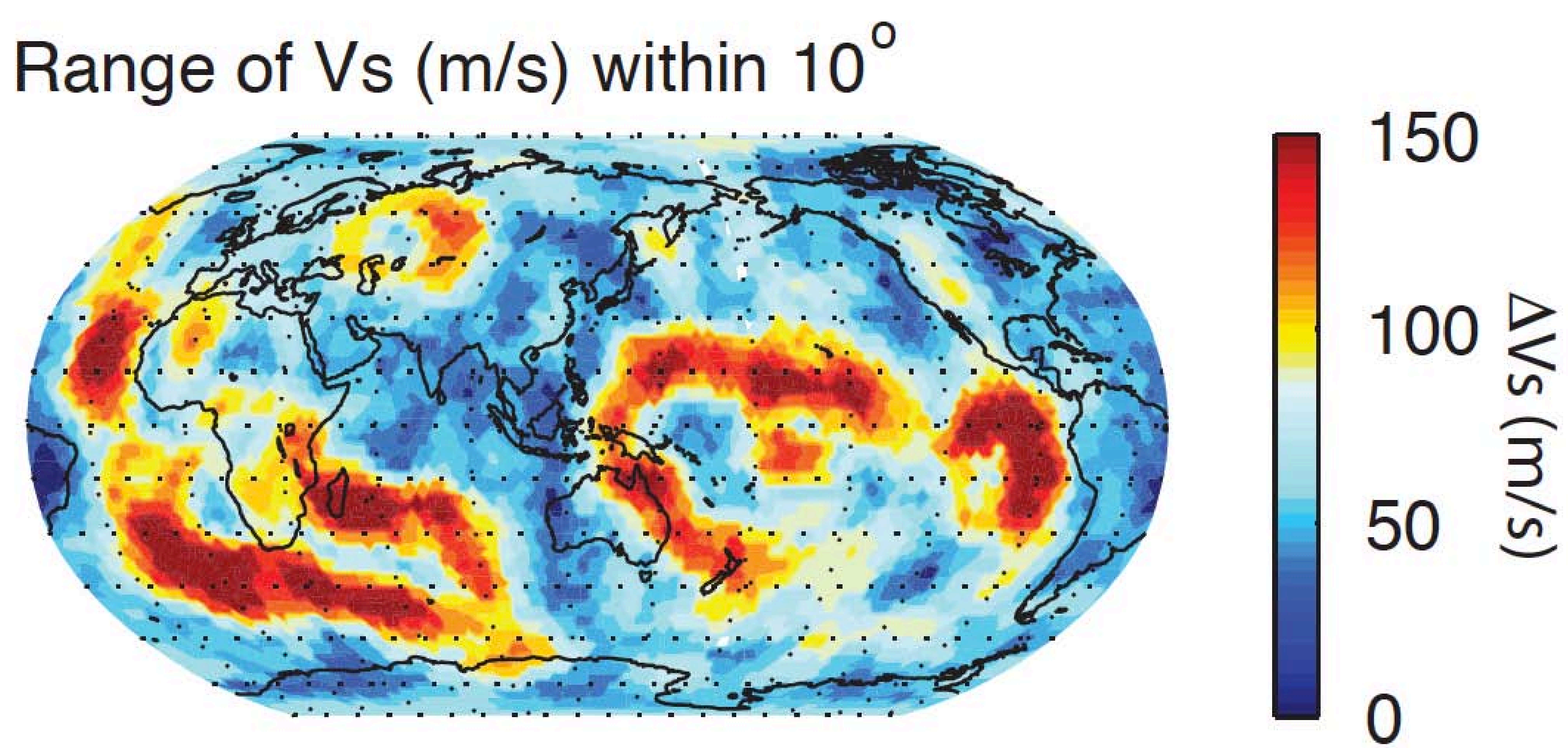




Horizontal Vs gradients

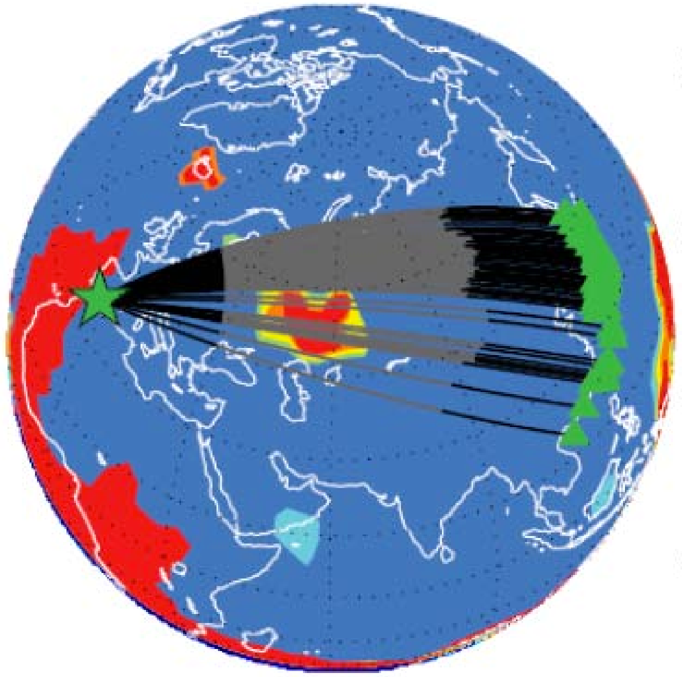
- Like the LLSVPs, the Perm Anomaly is bounded by sharp horizontal Vs gradients → chemical heterogeneity?
- Are there other, smaller "Permian-type" anomalies hidden by the dominant degree 2 structure?
- Horizontal gradients of Vs show a remarkable level of uniformity within each region especially in the fast regions.
- Other than intra-LLSVP complexity, no obvious candidates for "PA"-type structures

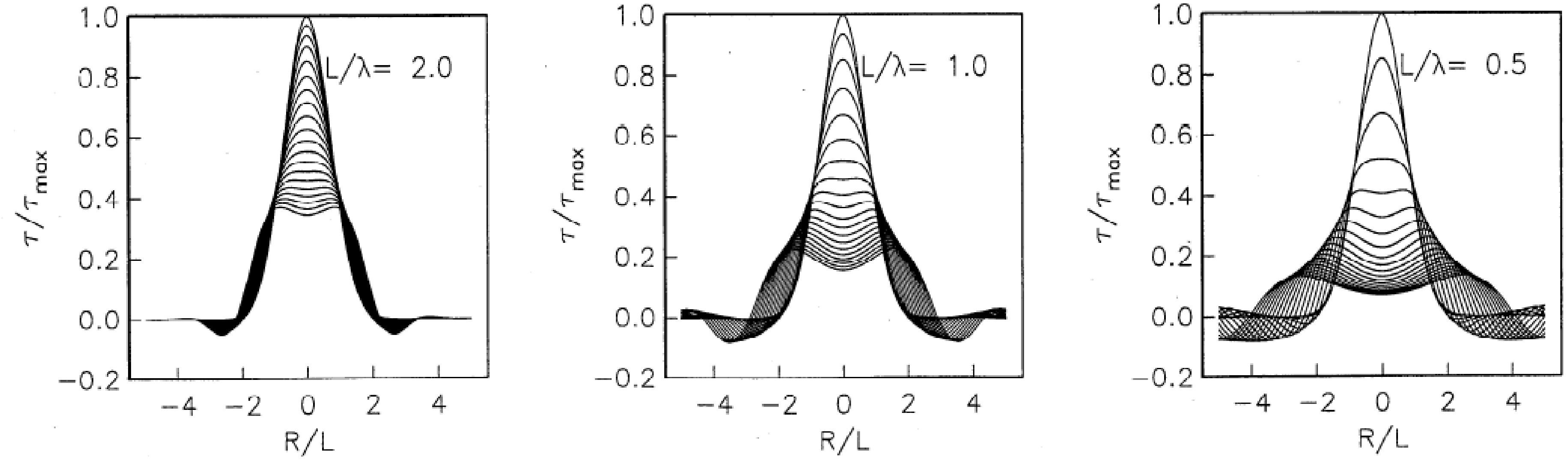


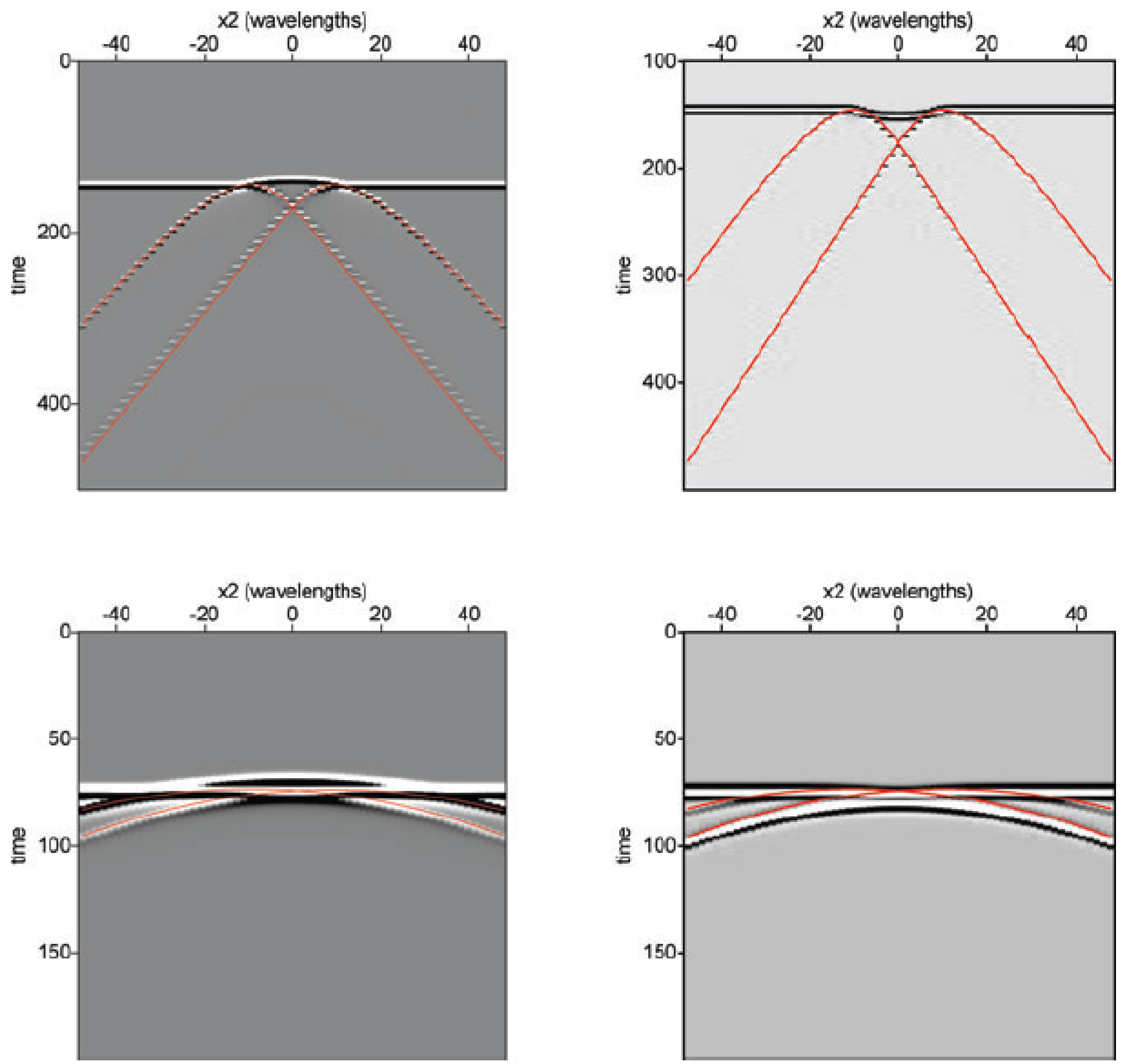


Lekic et al. EPSL 2012

Nolet and Dahlen, 2000





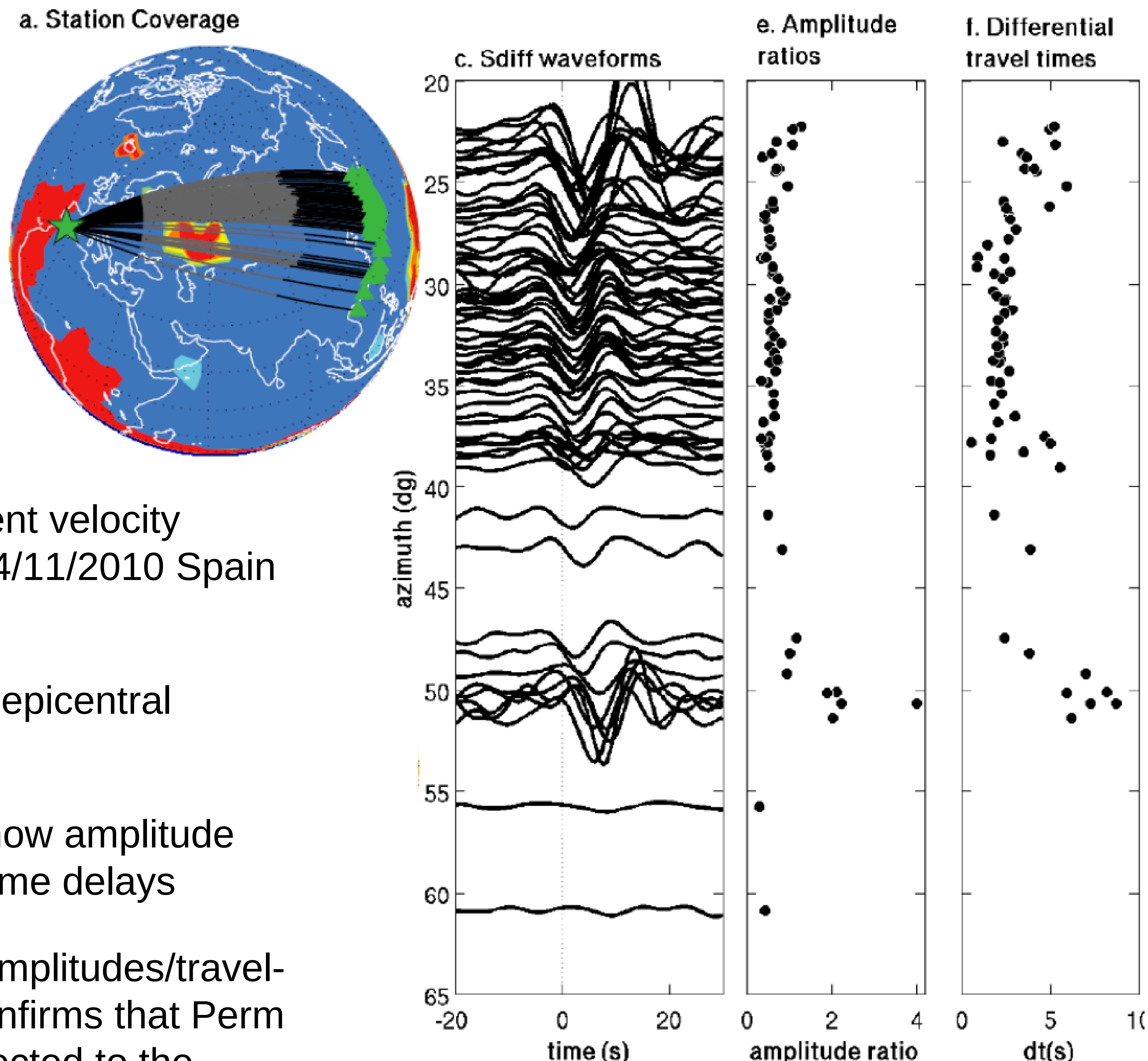


Malcolm and Trampert, 2011

Wave-front healing effect

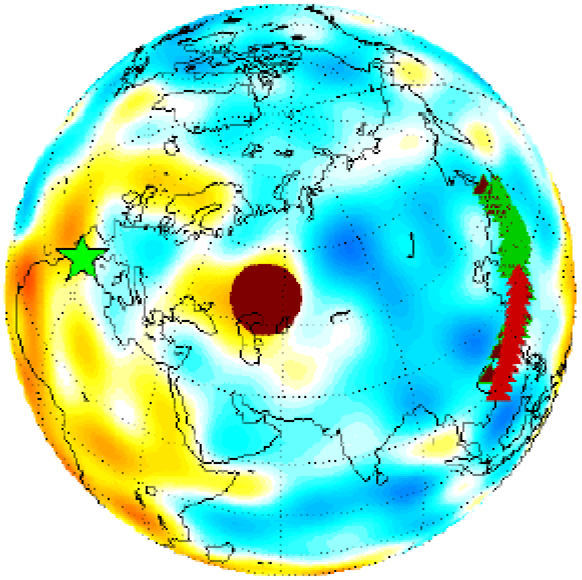
- Wavelength of 20s S waves near the CMB is ~150 km → radius of Perm Anomaly is only ~3λ!
- Wavefront healing effects make it more difficult to observe Perm-type anomalies
- This makes the non-discovery of a fast analogue to the Perm Anomaly more remarkable!

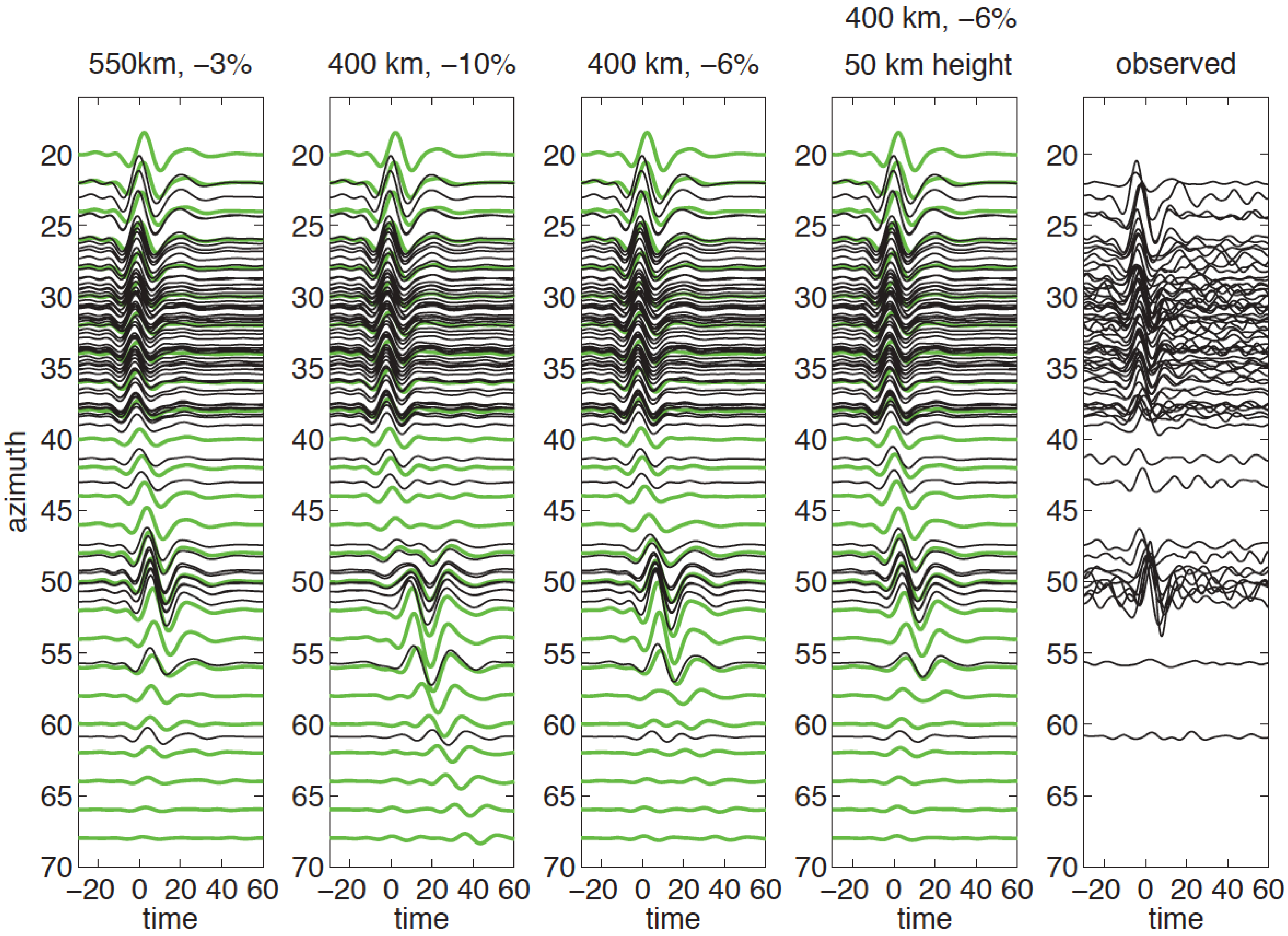
Direct waveform confirmation



- Transverse-component velocity waveforms from the 4/11/2010 Spain event
- Stations in 91º -102º epicentral distance range
- S/Sdiff waveforms show amplitude focusing and travel-time delays
- Lack of anomalous amplitudes/travel-times to the North confirms that Perm Anomaly is not connected to the African LLSVP

Lekic et al. EPSL 2012





Forward Modeling

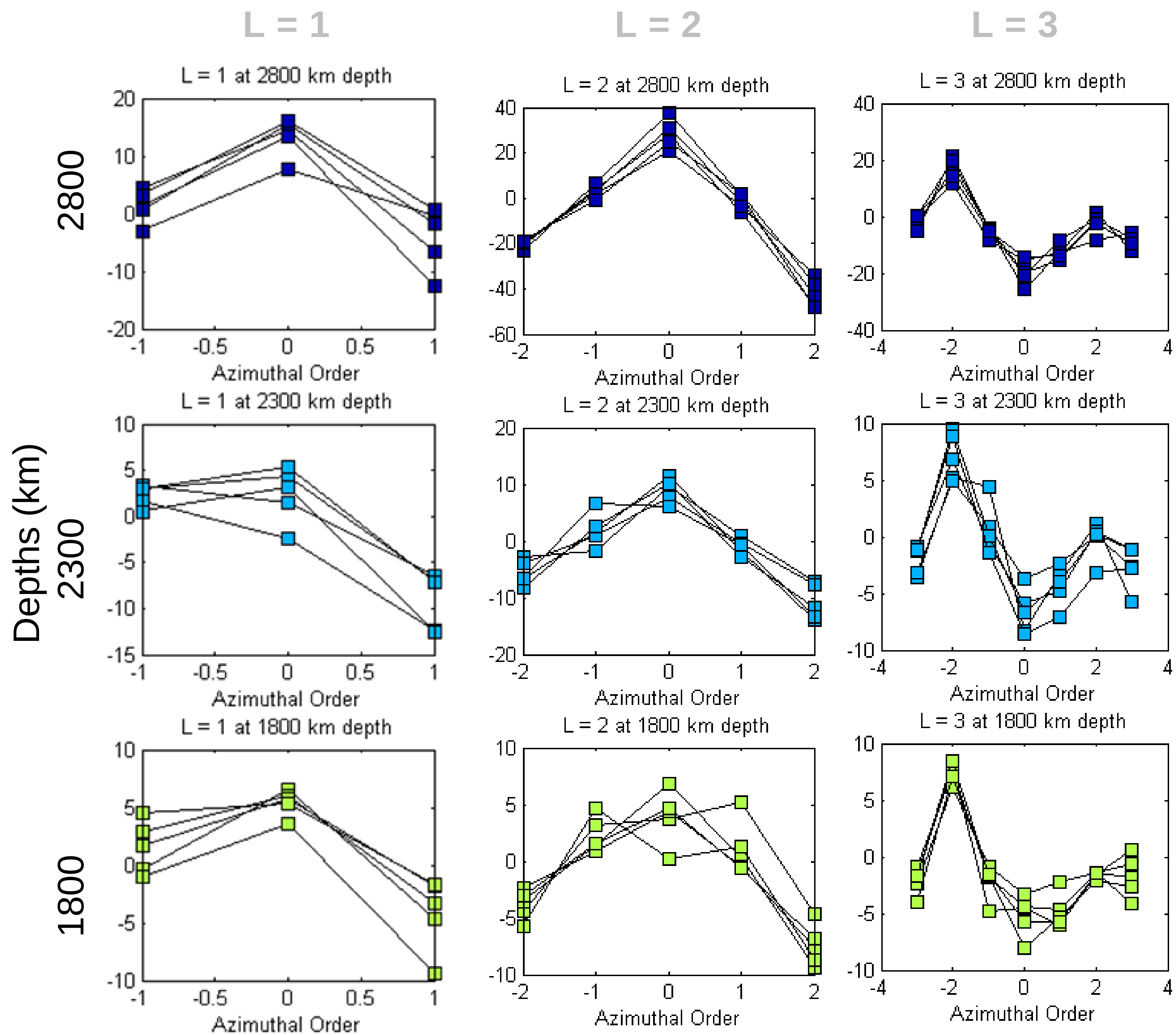
- Synthetics calculated using “sandwich” Spectral Element Method (Capdeville et al. 2003).
- Perm Anomaly has to be ~300-500 km tall, ~700-1000 km across, and ~6% Vs reduction.

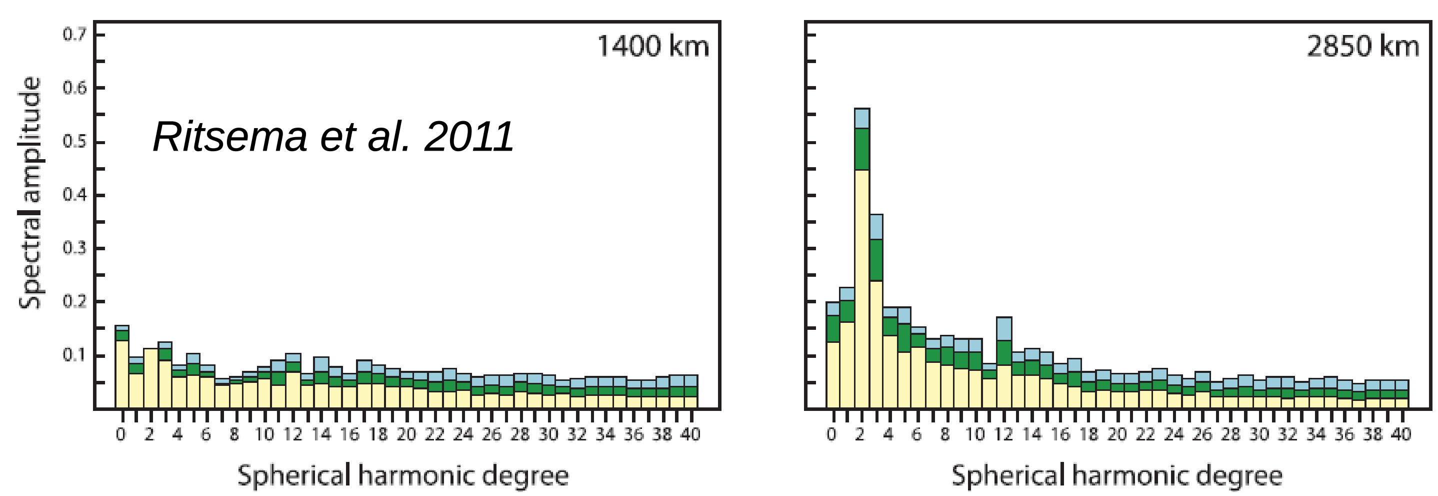
Conclusions

- Cluster analysis of lower mantle Vs profiles divides the Earth into one contiguous faster-than-average region and two antipodal slow regions.
- Remarkable inter-model consistency and agreement with detailed waveform-modeling studies confirms Vs global tomography has resolution of <1000 km at CMB → dominance of long-wavelength structure is real.
- Horizontal gradients of Vs show large-scale uniformity within slow and fast regions, and sharp boundaries between them.
- Vs distributions of two clusters have very different character → important for interpretations of Vs in terms of mineralogy and opportunity for modeling effects of attenuation.
- Single exception is Permian Anomaly (thus far, it is one-of-a-kind):
  - A new class of lower-mantle anomaly, bigger but weaker than a ULVZ, smaller than an LLSVP;
  - Bounded by sharp horizontal gradients like the LLSVPs suggesting chemical heterogeneity;
  - May be long-lived and has no "fast" analog, even though that would be more easily detected.

Degree 1 vs 2

- At the base of the lower mantle, degree 2 is dominant, accounting for ~50% of the power
- “Distorted” shape of African LLSVPS results in degree 3 structure
- Relative imbalance between African and Pacific LLSVPs manifests as a degree 1 signal
- Degree 1 is contains about 7x less power or ~2.5x smaller amplitude.





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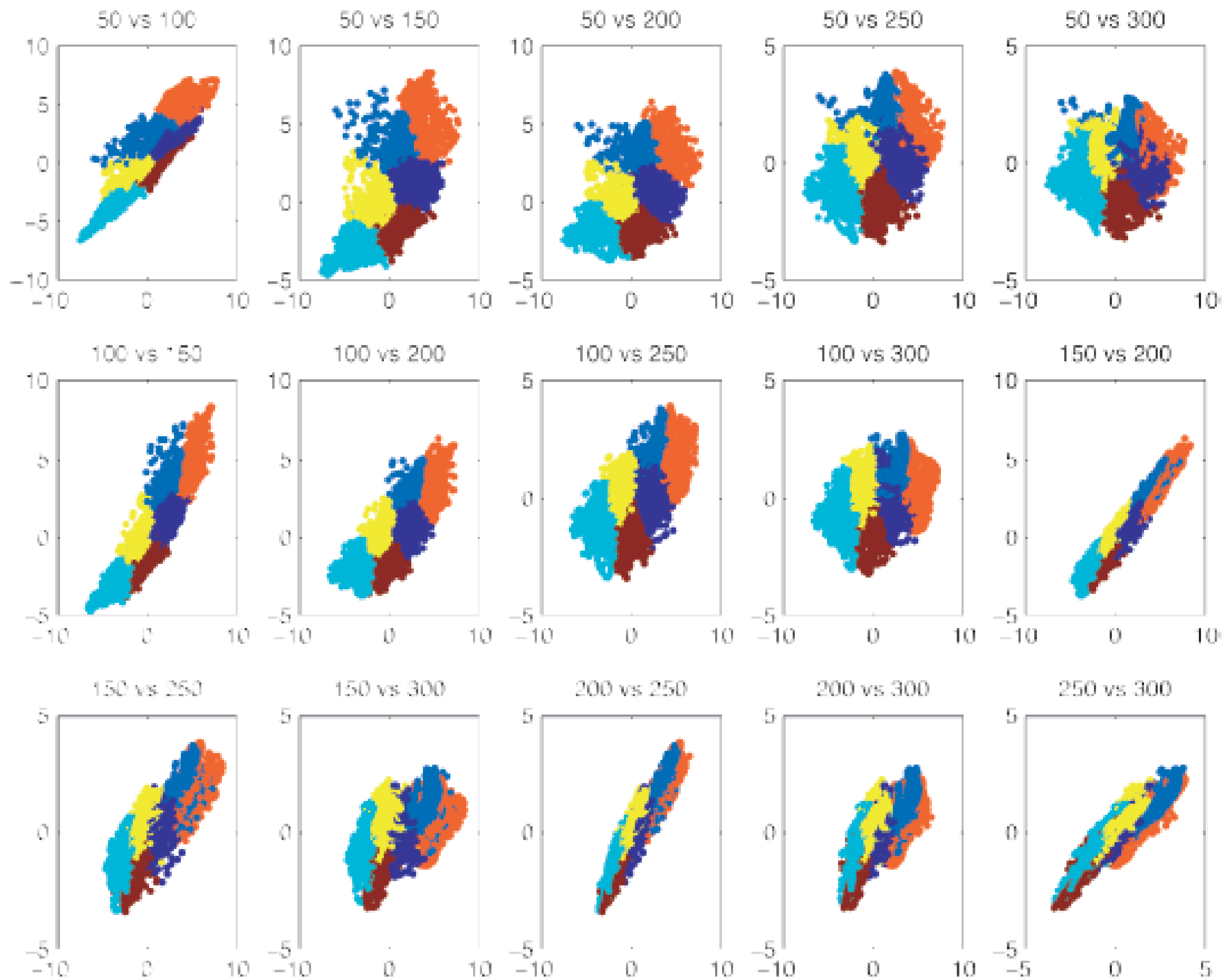
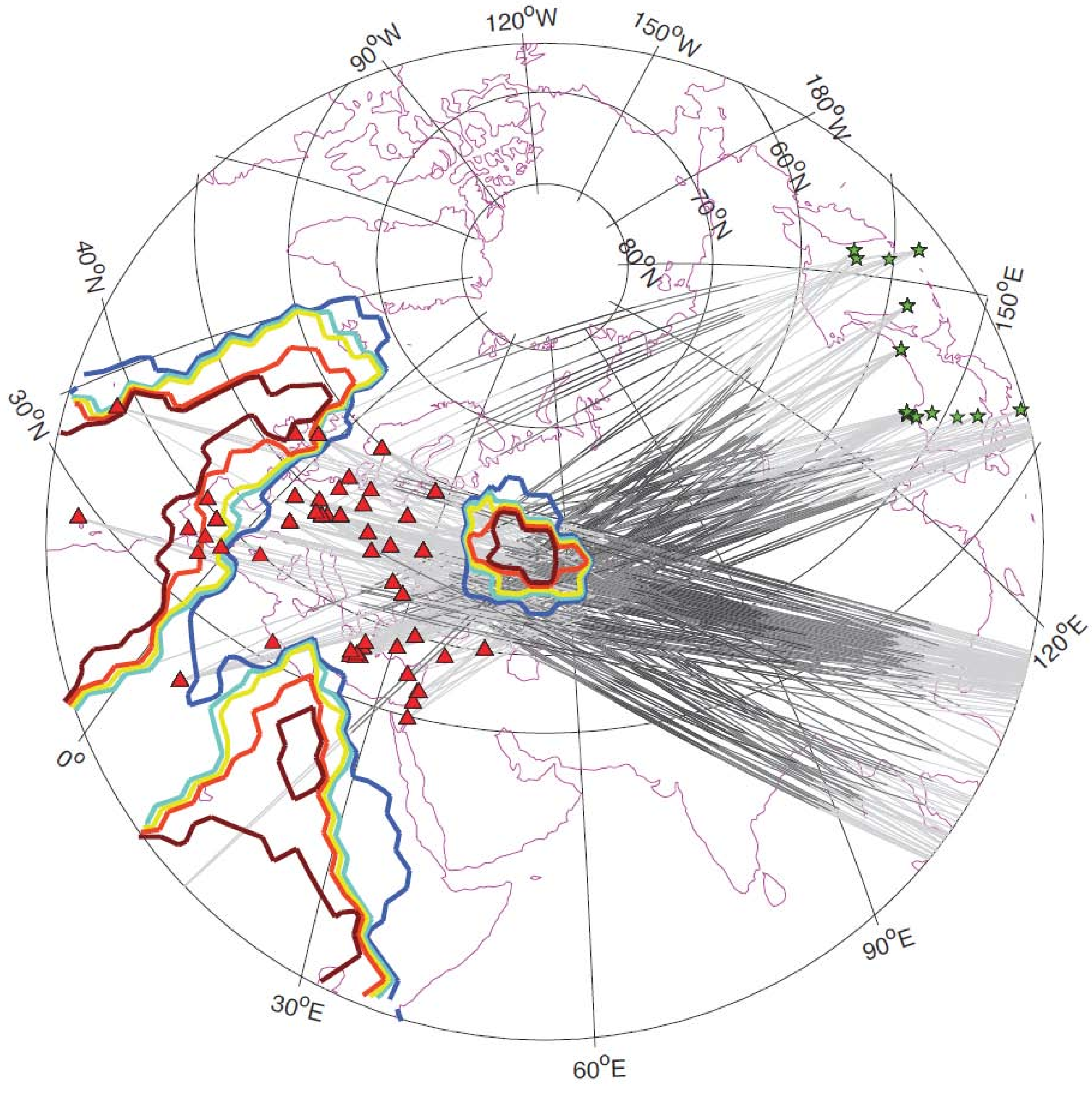
- The set of average Vs profiles for each region summarizes the tomographic model.
- In the upper mantle, geographic regions corresponding to different clusters are associated with tectonic setting.



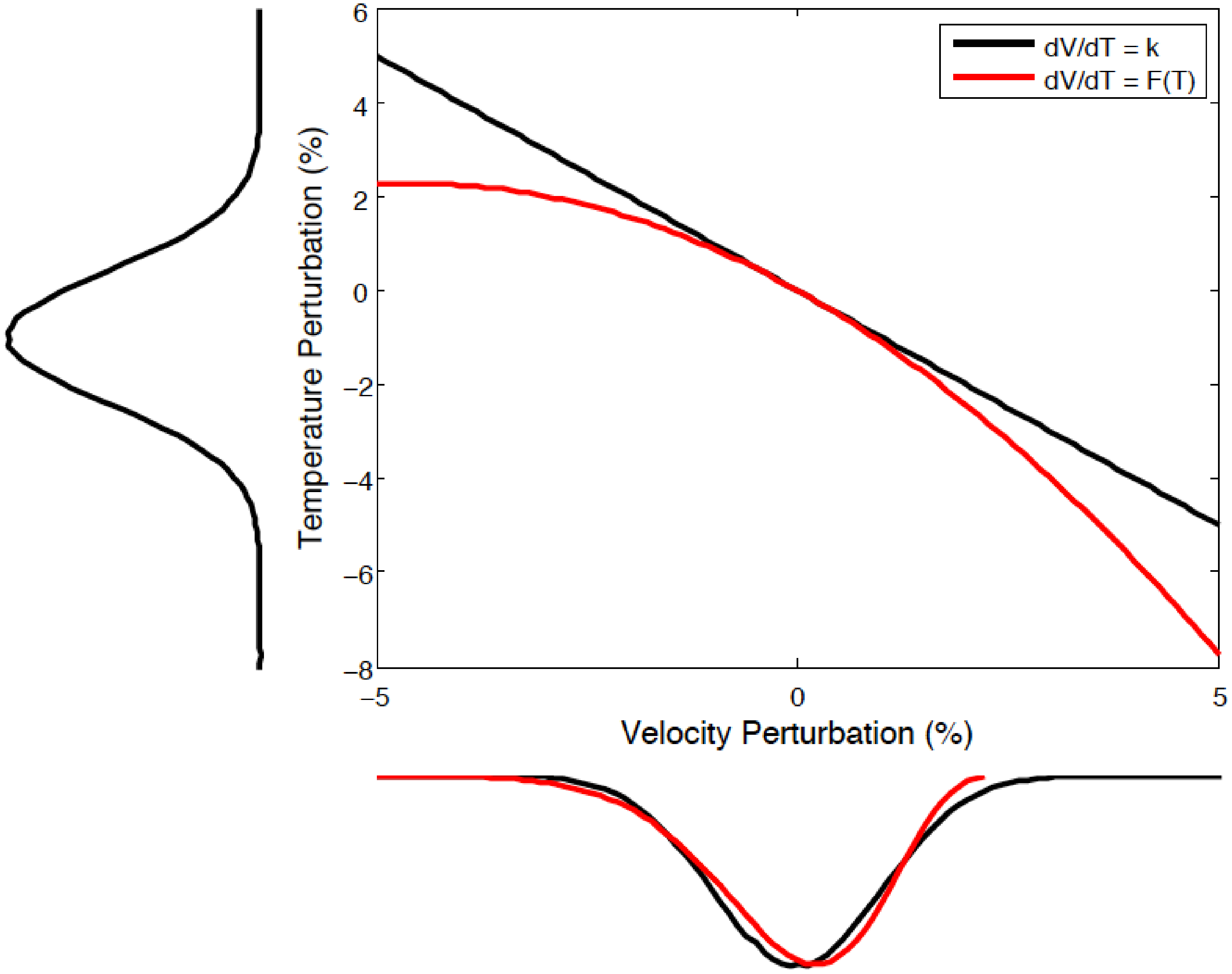
(top) Velocity profiles in the upper mantle cannot be represented in 2 dimensions, but rather occupy an N-dimensional space, where N is the number of depths at which the velocities are specified. Here, we consider velocities at 50, 100, 150, 200, 250 and 300 km, and plot 2D slices through the 6-D space in which the velocity profiles reside. Points are then assigned to 6 different families (clusters) and colored accordingly. We can see that each cluster corresponds to a region in 6-D space, and that the clusters remain reasonably well separated down to ~250km.

Waveform Analysis…

- We are currently analyzing waveforms from deep events in the Western Pacific and Indonesia, to better constrain the eastern and southern edges of the Perm anomaly.



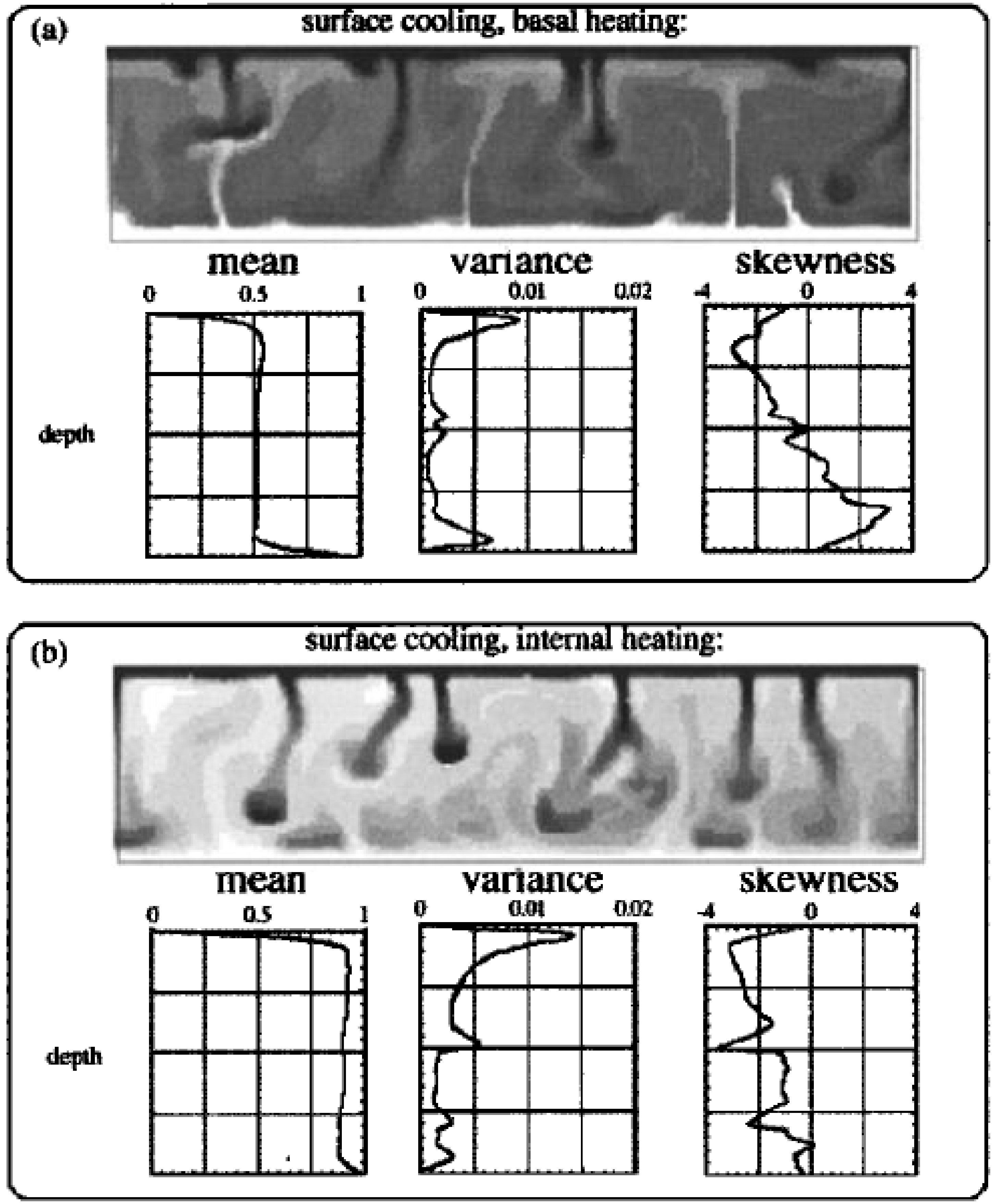
Anelasticity causes skewness of Vs distributions



Lekic and Matas, in prep.

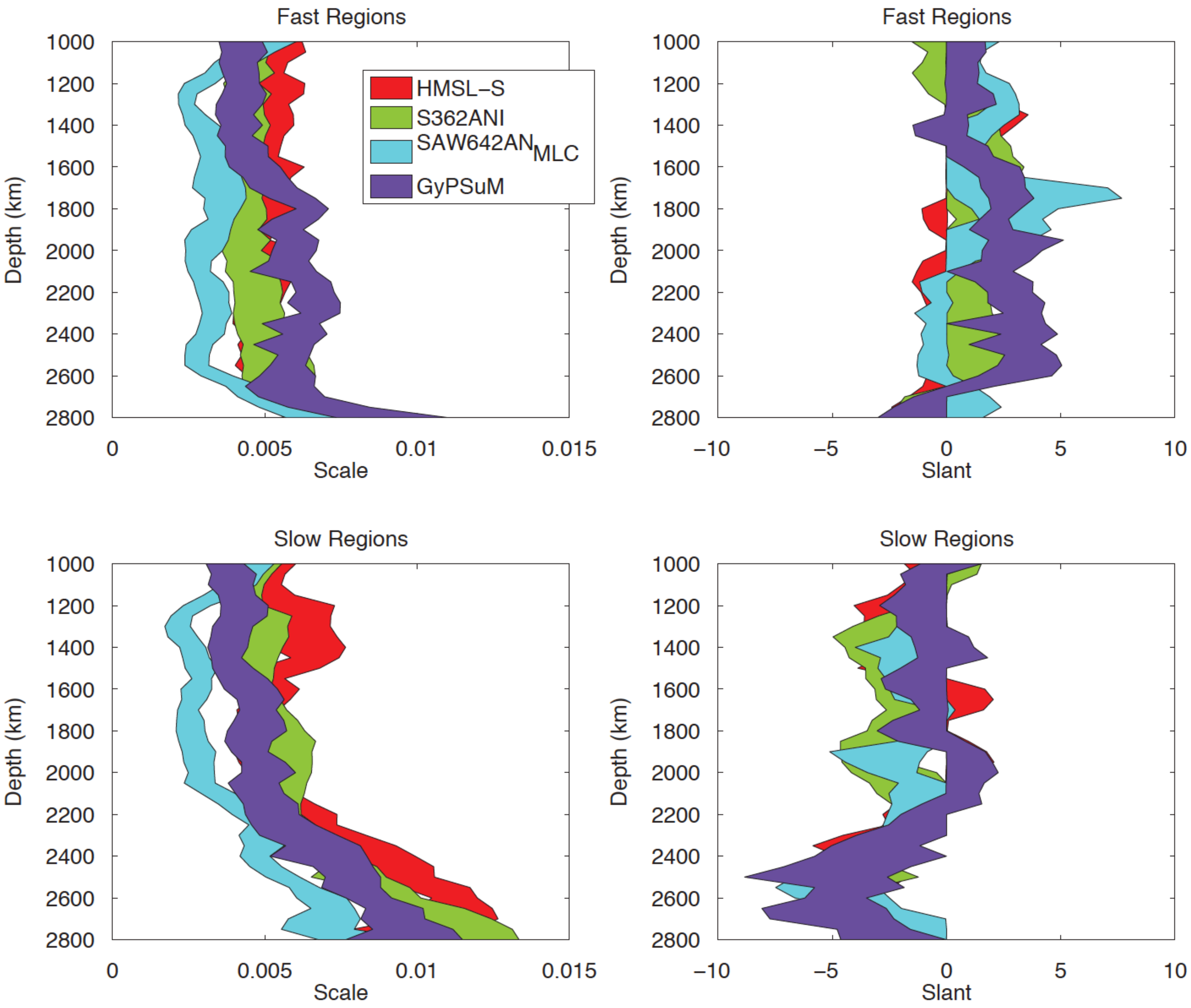
Should the distribution of T be skewed?

- Relative contributions of surface cooling, basal heating, and internal heating dictate the distribution of temperature (T)
- If internal heating > basal heating, then skewness of T should be negative (toward colder T) at all depths.
- If basal heating > internal heating, then T can have positive skewness in the lower mantle.



Yanagisawa & Hamano 1999

Cluster analysis of lower mantle



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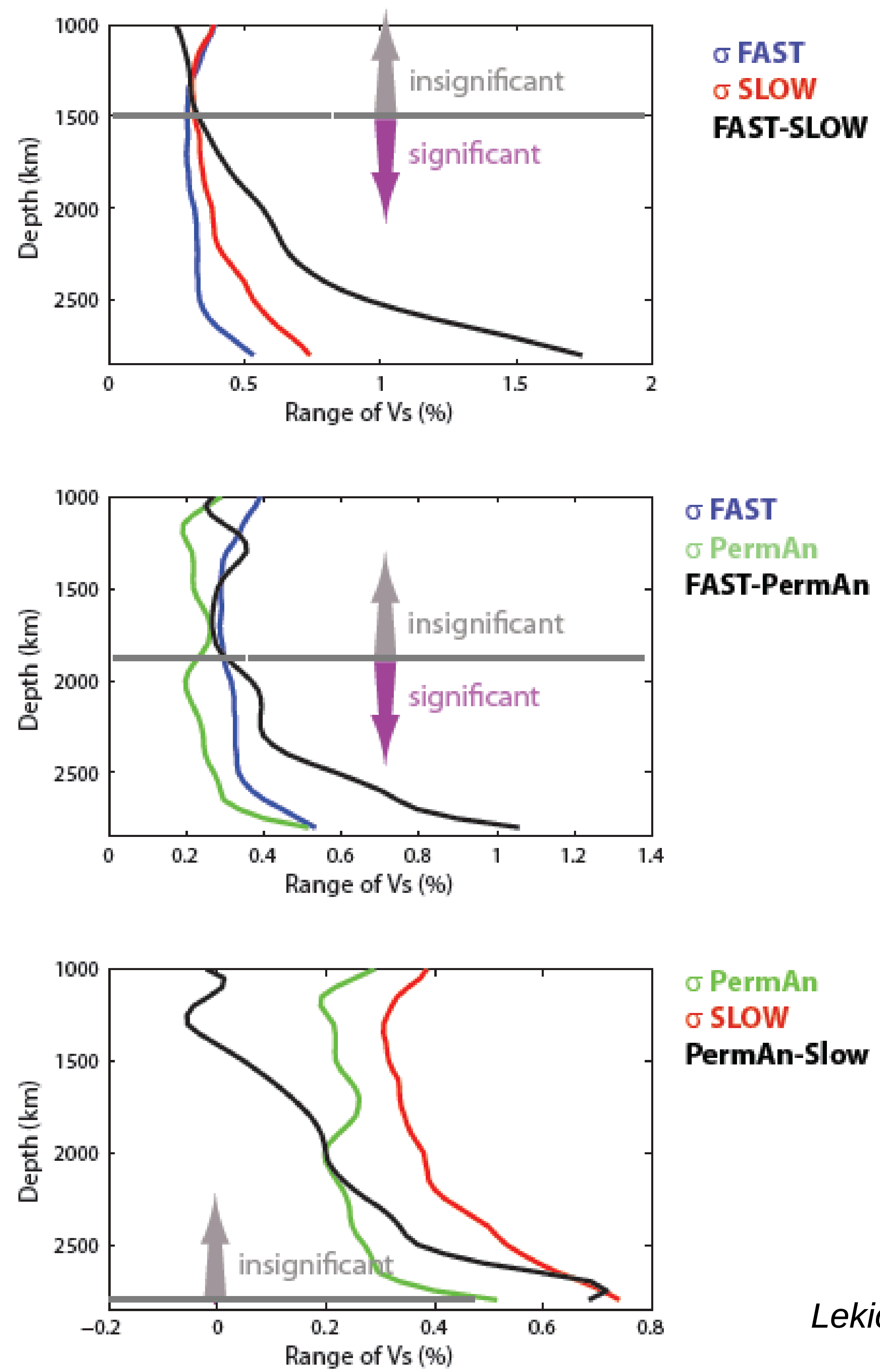

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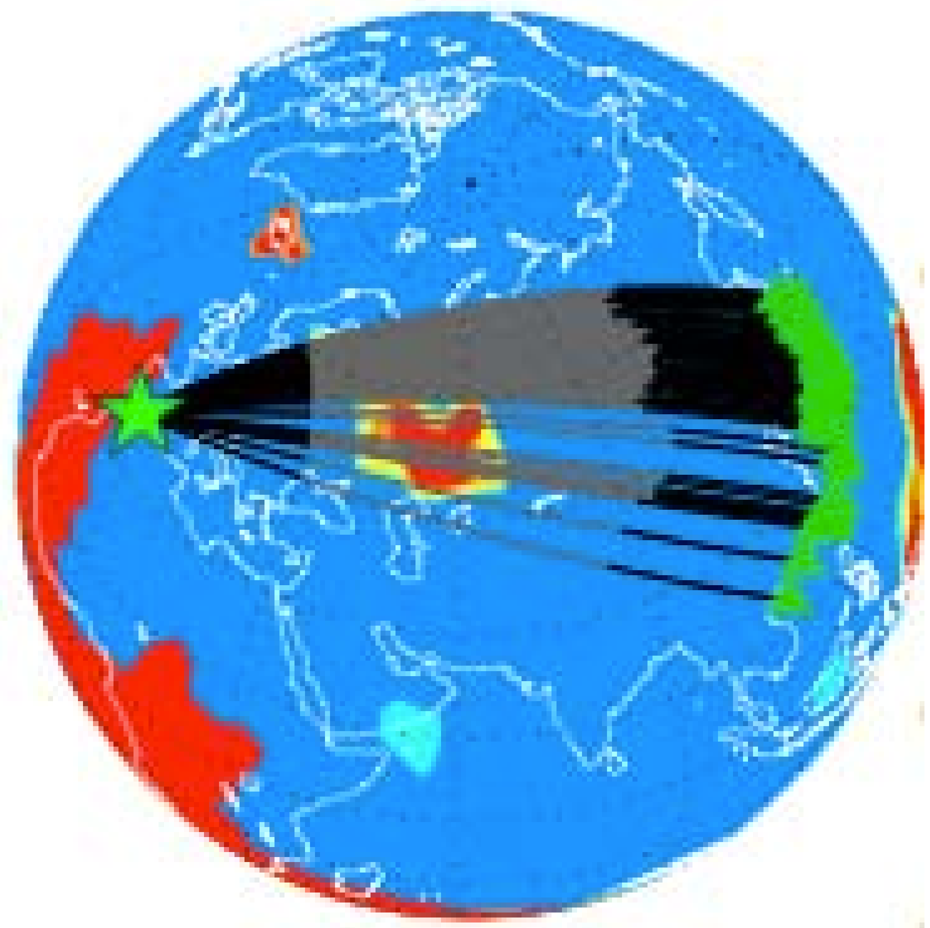

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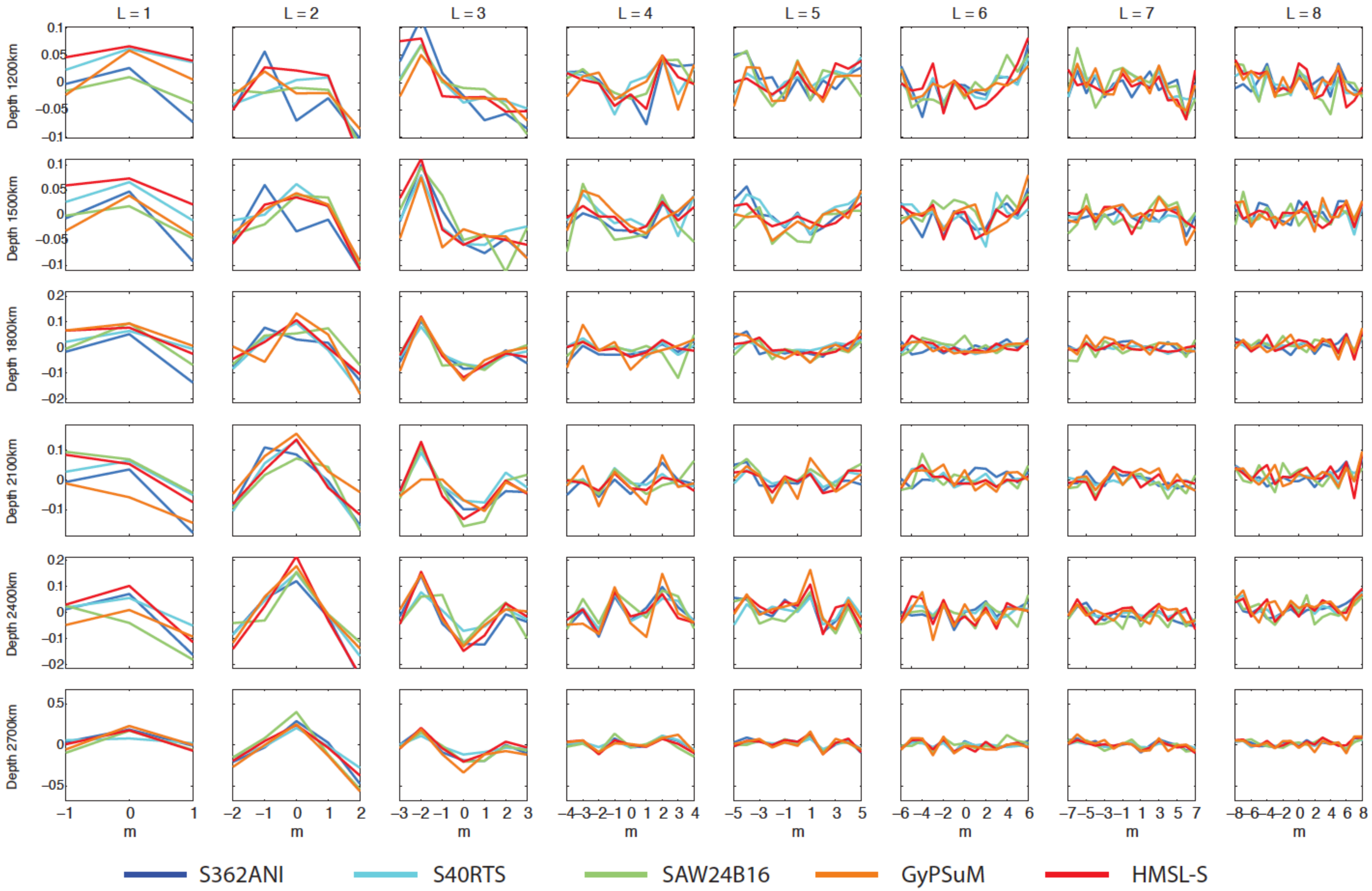
Lekic and Matas, in prep.

Cluster lower m

- Difference paramteriz regulariza selection, formalism difference models
- Features a across ton models ar artifacts of approximations or to reside in the null space



Lekic et al. EPSL submitted