GyPSuM: A Joint Seismic-geodynamic Tomographic Image of the Mantle with Minimal Compositional Heterogeneity

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Lapo Boschi *ETH Zurich*
Stephen P. Grand *University of Texas at Austin*

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Outline

- ❑Motivation and our previous work
- ❑GyPSuM Earth model development
- ❑Observations from GyPSuM
- ❑Summary

Motivation for joint seismic-geodynamic tomography

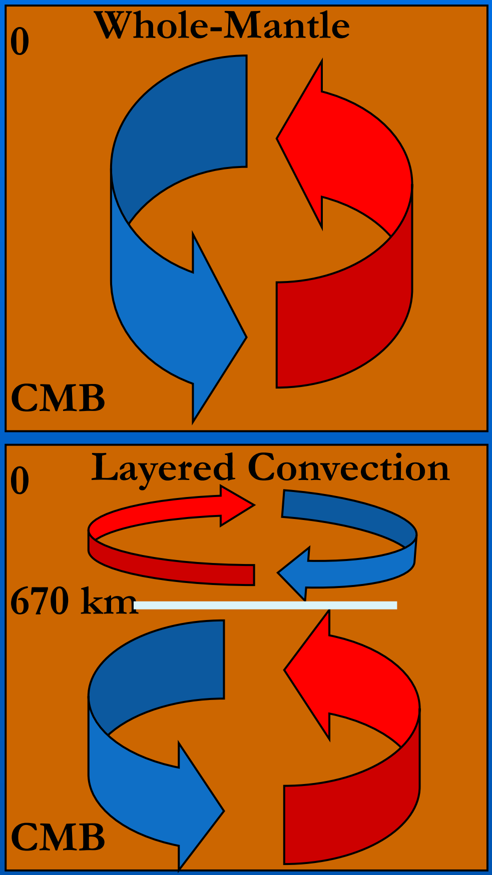
- ❑Combining multiple data types yields more robust seismic images
  - ➢ Reduce non-uniqueness
  - ➢ Predict heterogeneity where certain seismic constraints are weak or non-existent

- ❑Need detailed density structure for flow modeling
  - ➢ Scaling a model derived with only seismic data is inadequate
  - ➢ Density heterogeneity should be consistent with geodynamic observations
  - ➢ Solve for density directly and simultaneously

- ❑Evaluate the relative behavior of mantle properties

Joint seismic-geodynamic mantle imaging

***Simmons, Forte & Grand* [2006]**

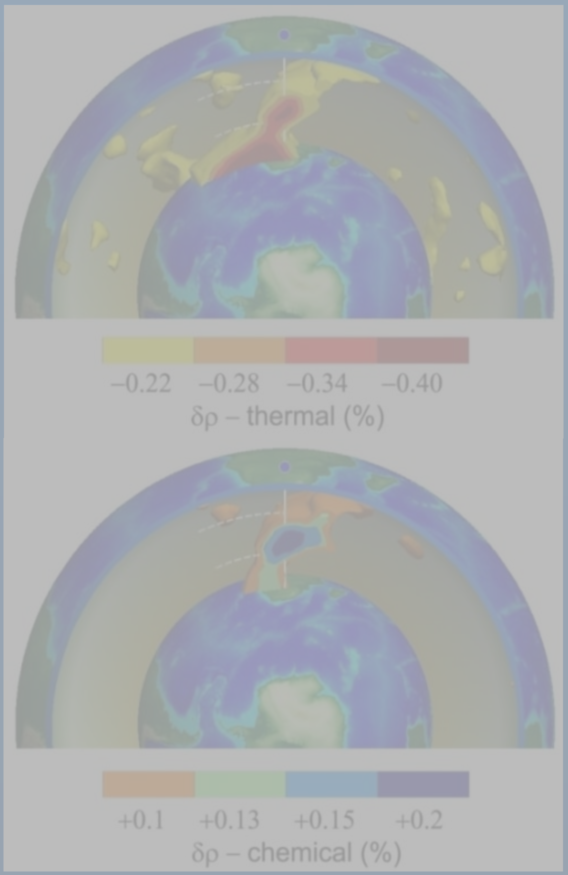


Tested mantle flow hypotheses

→ *Effects the forward system*

→ *Whole-mantle style prevailed*

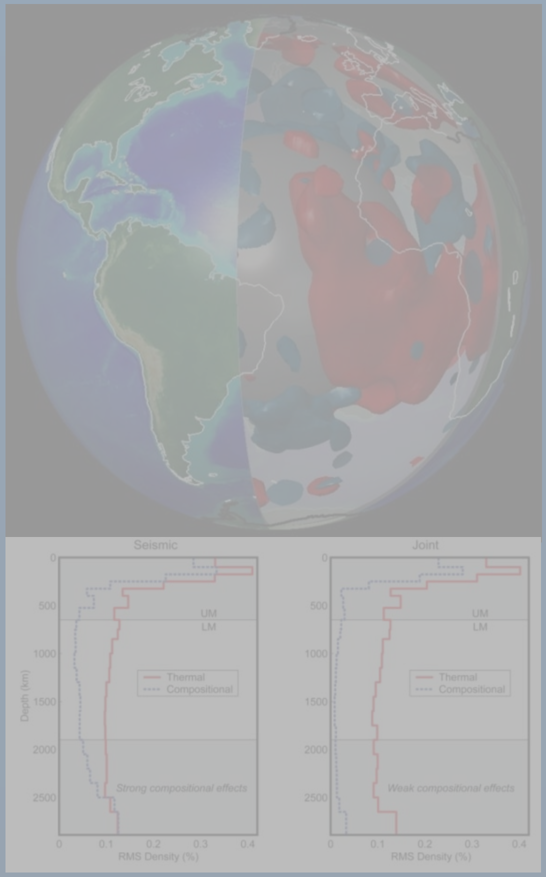
***Simmons, Forte & Grand* [2007]**



Imaged mantle density

→ *Detailed image of the intrinsically dense material in the African superplume*

***Simmons, Forte & Grand* [2009]**



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→ *Evaluated the relative effects of temperature and composition*

→ *Minimize the apparent role of composition*

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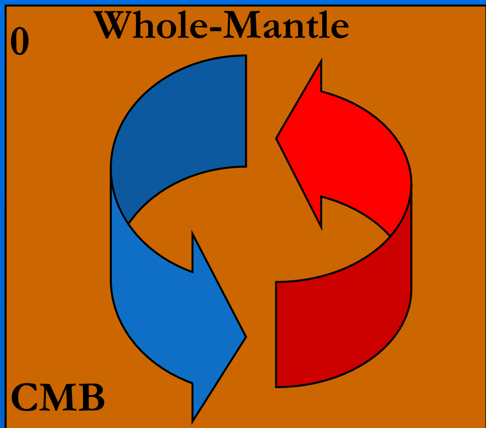

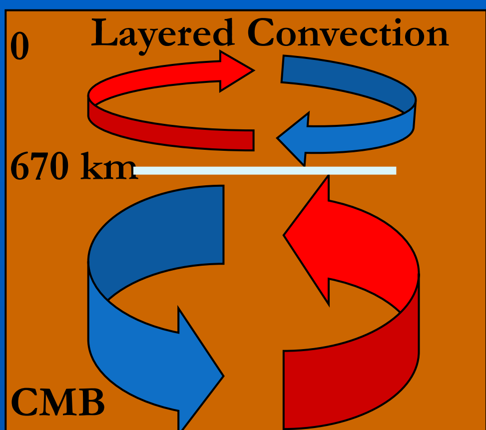

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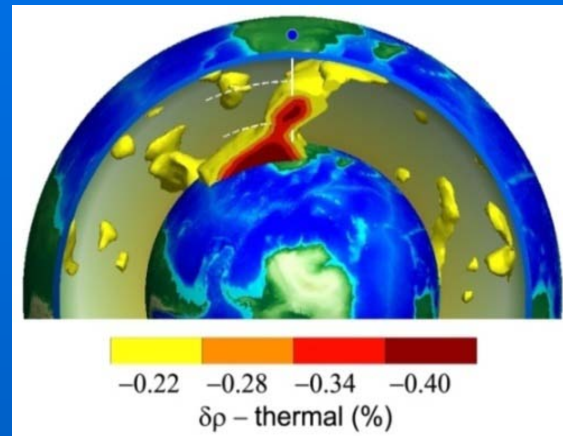

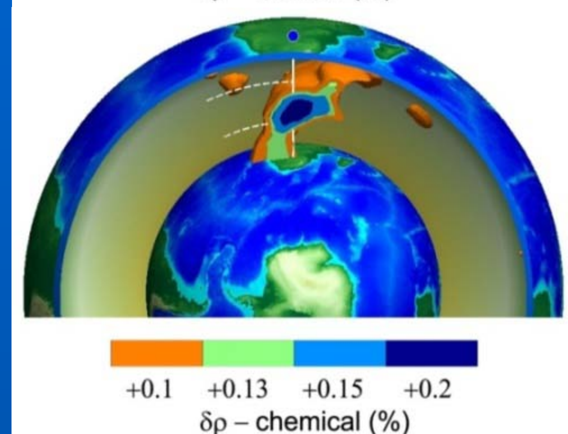

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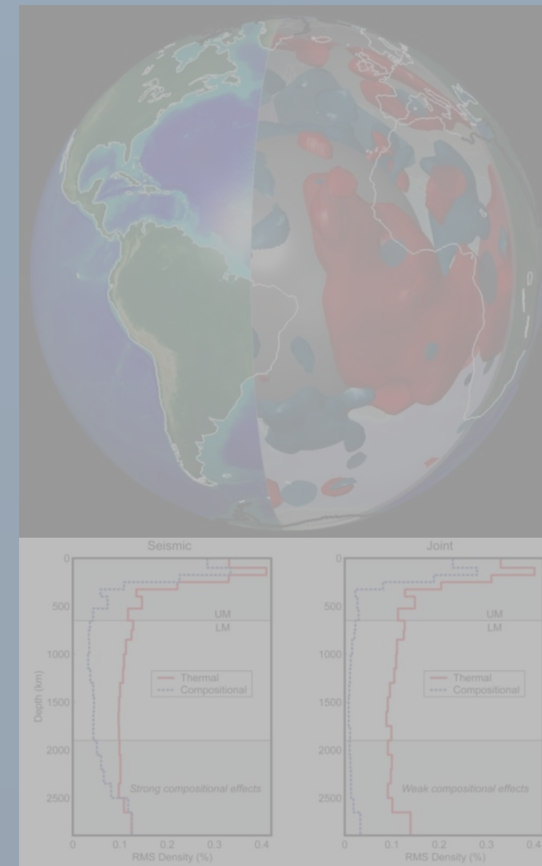

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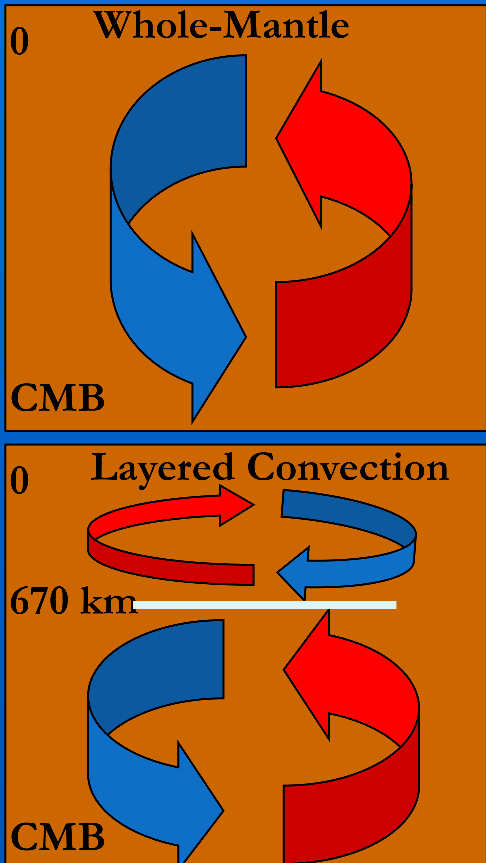

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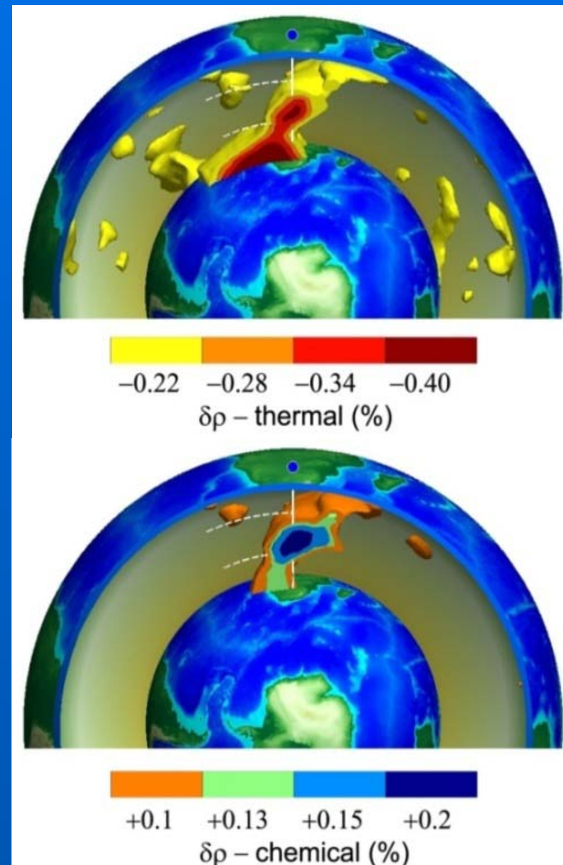

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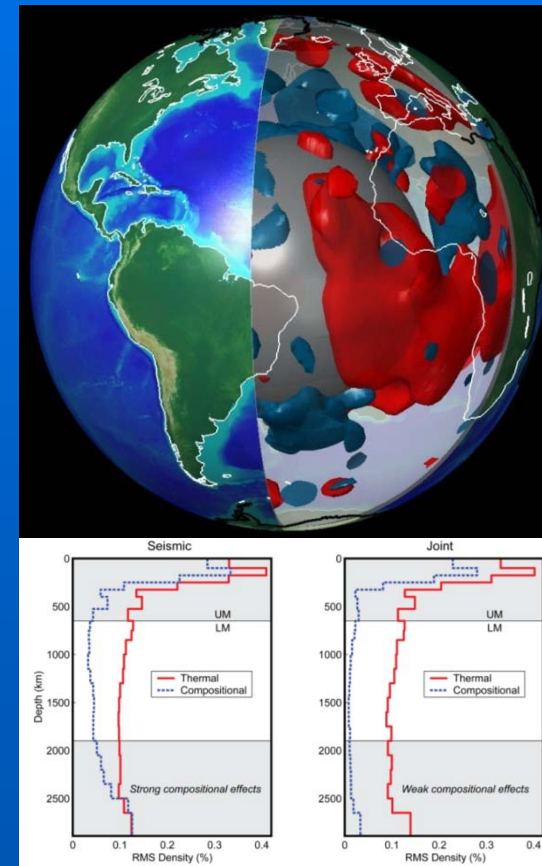

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Joint seismic-geodynamic mantle imaging

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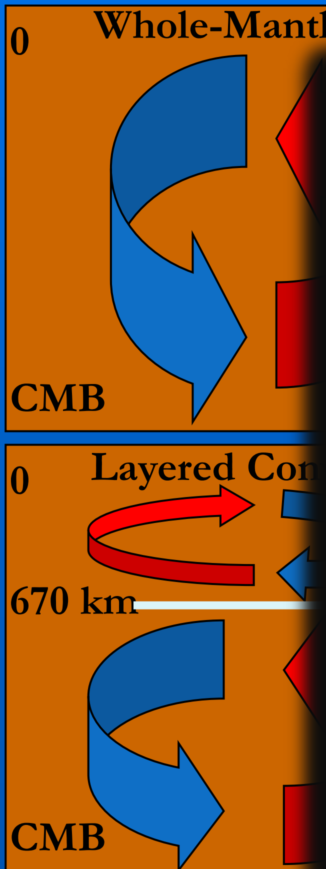

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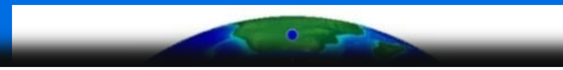

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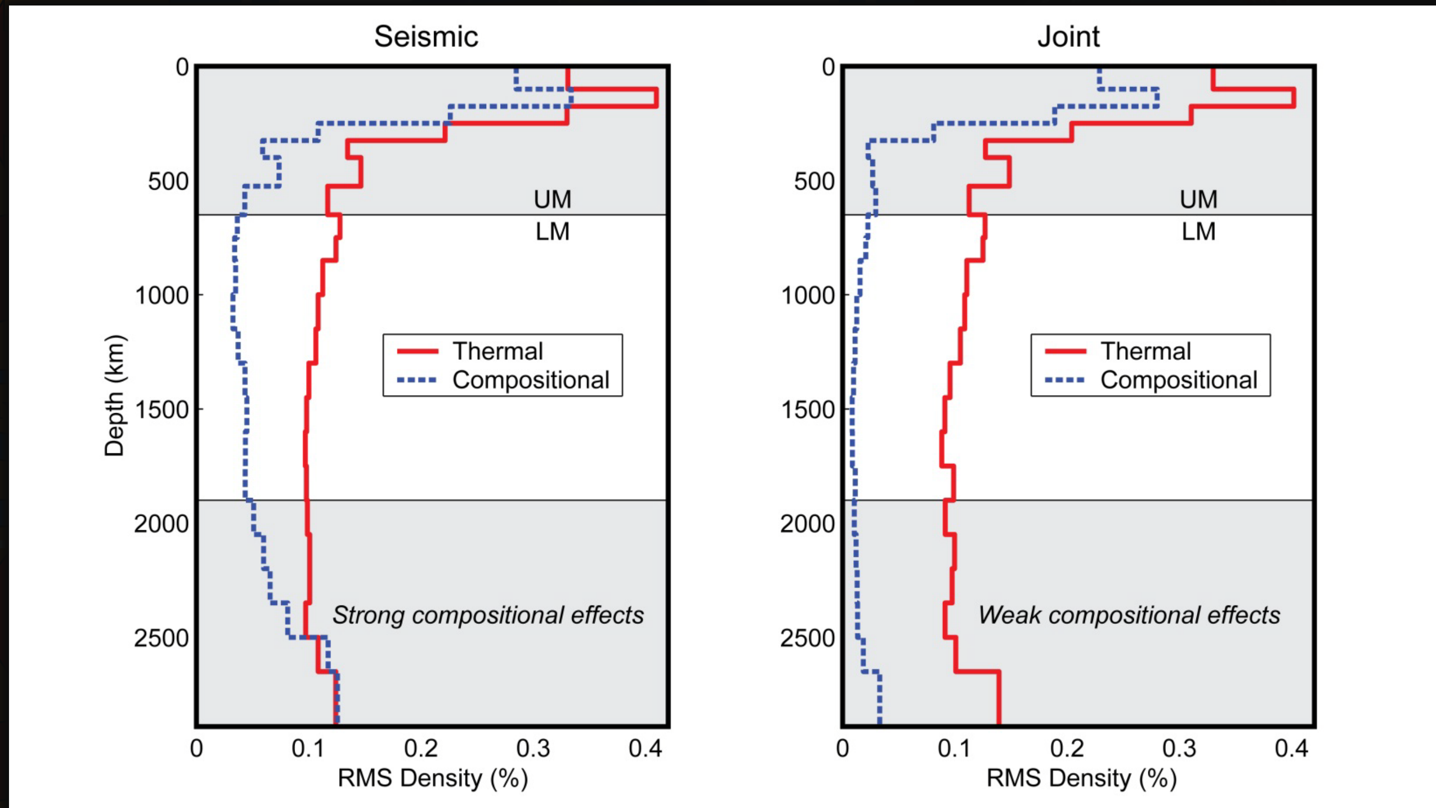
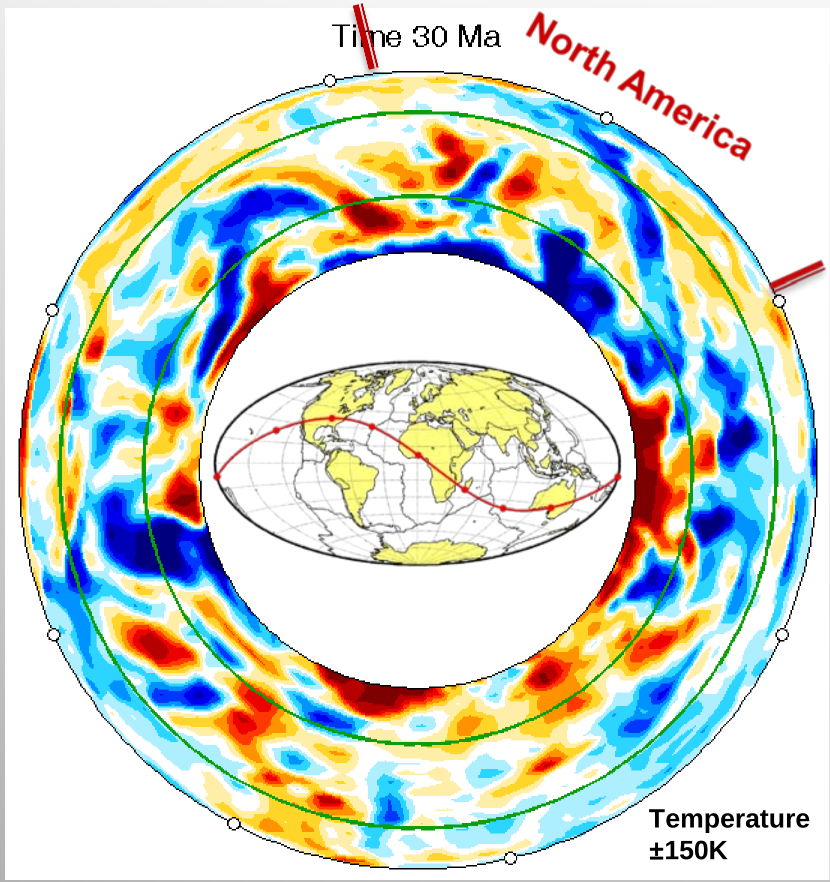
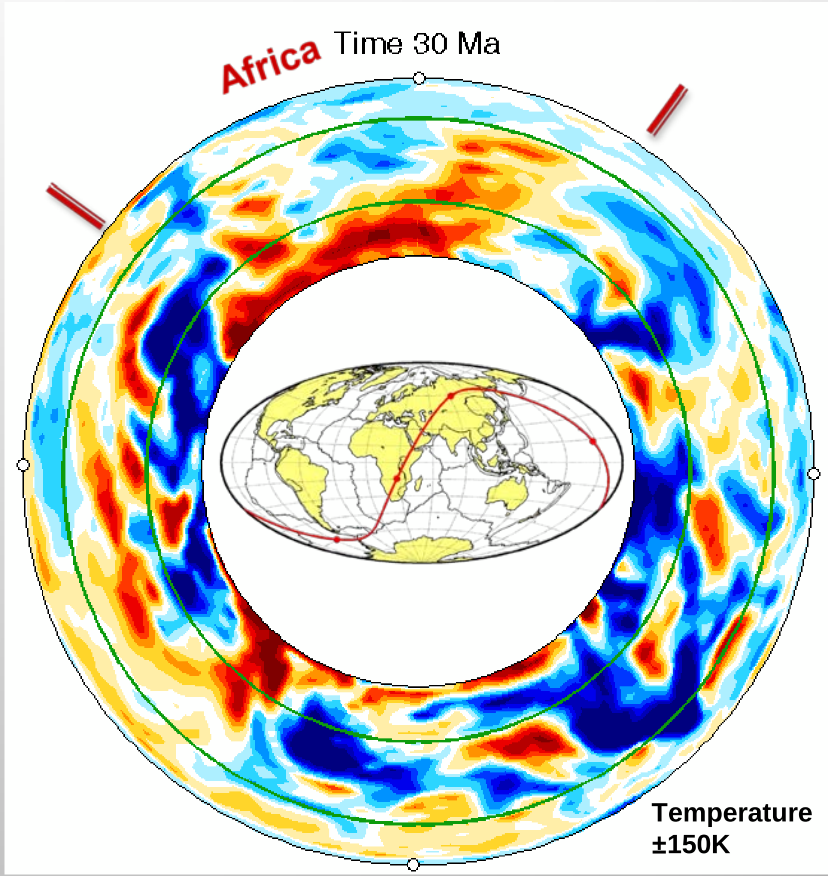


Joint models are used for flow simulations



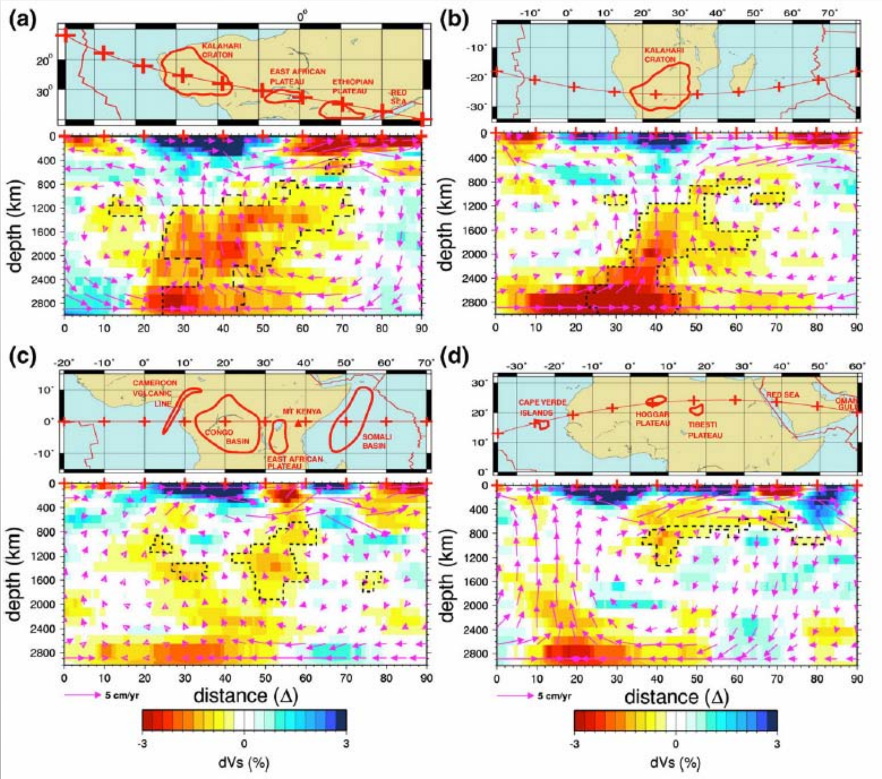


<u>**Geodynamics/Tectonophysics Collaborators**</u>:

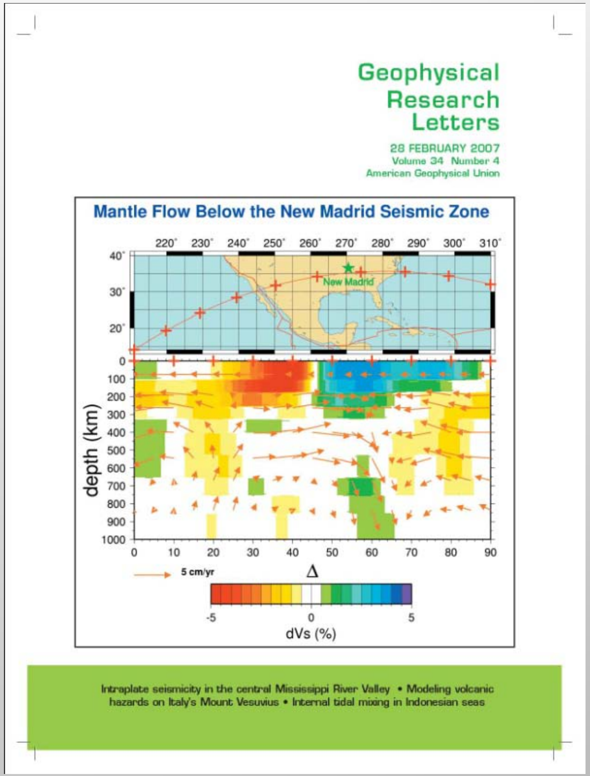
Alessandro Forte ***Université du Québec***, **Robert Moucha** ***Syracuse University***, **Jerry Mitrovica** ***Harvard***, **David Rowley** ***University of Chicago***, **Sandrine Quéré** ***Utrecht University***

Linking the deep mantle to the surface

Mantle flow beneath Africa and surface manifestations
***Forte et al.* [2010b] in EPSL**

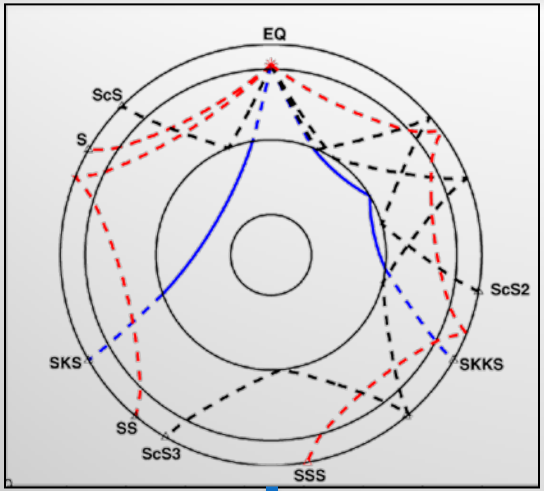


Possible contribution to New Madrid EQs *Forte et al.* [2007] in GRL



- **Uplift of the Colorado Plateau *Moucha et al.* [2008a] in Geology, *Moucha et al.* [2009] in GRL**
- **Instability of the "stable" Eastern US *Moucha et al.* [2008b] in EPSL, *Rowley et al.* [2012, submitted]**
- **Global plate decelerations *Forte et al.* [2009] in GRL**
- **Deep-mantle contributions to North American surface dynamics *Forte et al.* [2010a] in Tectonophysics**
- **African topography driven by mantle convection *Moucha and Forte* [2012] in Nature Geoscience**

GyPSuM: What is it?



G = Geodynamic
y
P = P waves
S = S waves
u
M = Mineral physics

Geodynamic Observations
Global free-air gravity (EGM96)
Tectonic plate motions (NUVEL-1)
Dynamic Topography (*Forte & Perry* 2000)
CMB ellipticity (*Mathews et al.* 2002)

Density

S-wave Data
S, ScS, SKS, SKKS, sS, sScS, and multiples
Grand (2002); *Simmons et al.* (2006)

S-wave Velocity

Mineral Physics Constraints

$$R_{\rho/S} = \frac{d\ln\rho}{d\ln V_S} \qquad R_{P/S} = \frac{d\ln V_P}{d\ln V_S}$$

Karato & Karki (2001)
Cammarano et al. (2003)

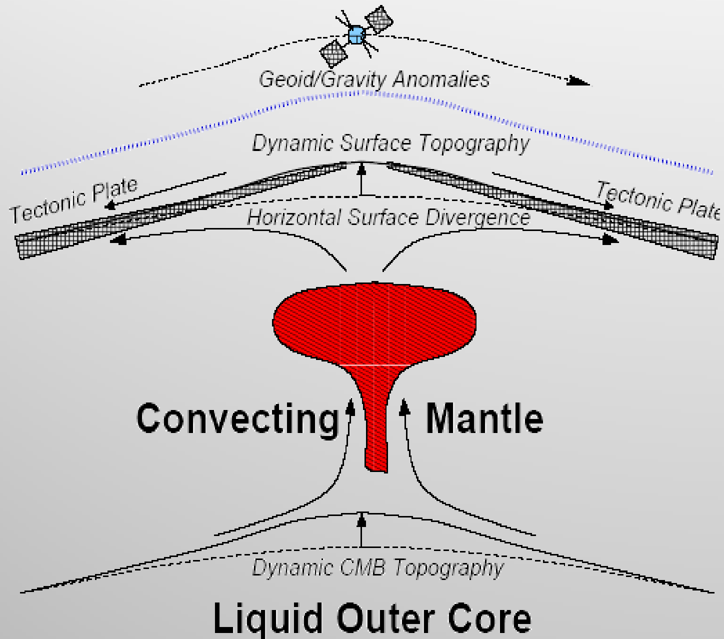
P-wave Velocity

P-wave Data
~626,000 teleseismic summary rays
Antolik et al. (2003)

3-D Global Model
S-wave velocity
P-wave velocity
Density

$$\begin{bmatrix} \mathbf{L}_S \\ \mathbf{L}_P(R_{P/S}) \\ \mathbf{G}(R_{\rho/S}) \end{bmatrix} \Delta\mathbf{m}_S = \begin{bmatrix} \mathbf{r}_S \\ \mathbf{r}_P \\ \mathbf{g} \end{bmatrix}$$

GyPSuM: Relating geodynamic observations



Geodynamic Observations

- Density anomalies drive flow
- Fields are dynamically coupled
- Numerical description in:
  - *Richards & Hager* [1984]
  - *Ricard et al.* [1984]
  - *Forte & Peltier* [1987]

Observation

Spherical harmonic component

Up to degree = 16

Density-velocity conversion

$$R_{\rho/S} = \frac{d\ln\rho}{d\ln V_S}$$

Based on mineral physics

$$s_l^m = \int_b^a \mathbf{K}_l\left(\boldsymbol{\eta}(\mathbf{r})/\boldsymbol{\eta}_0;\mathbf{r}\right) R_{\rho/s}\left(\frac{\delta \mathbf{V_S}}{\mathbf{V_S}}\right)_l^m d\,\mathbf{r}$$

Viscous Flow Response

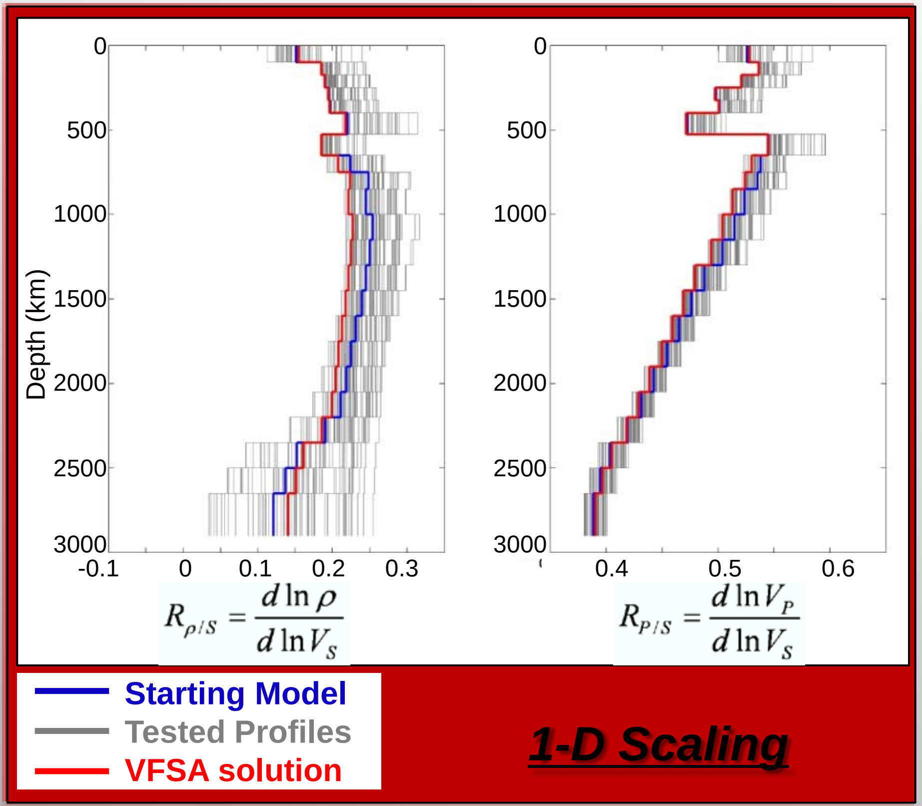
Response of internal density loads on the observation

Seismic velocity

S-wave speed in this case

$$\Rightarrow R_{P/S} = \frac{(\delta_s - 1)}{2} R_{\rho/S}(1-\gamma) + \gamma \qquad \gamma \equiv \frac{4}{3}\frac{V_S^2}{V_P^2} \qquad \delta_s \equiv \frac{\delta \log K}{\delta \log \rho}$$

GyPSuM: Scaling model optimization



- Range defined by mineral physics
  - *Expected thermal values*
- Simulated annealing (VFSA)
- Full joint inversion performed with each update

Starting 1-D scaling profile

$$R_{\rho/S} = aR^{\text{1-D}}_{\rho/S} + b$$

a = Profile Amplification

i) Upper mantle

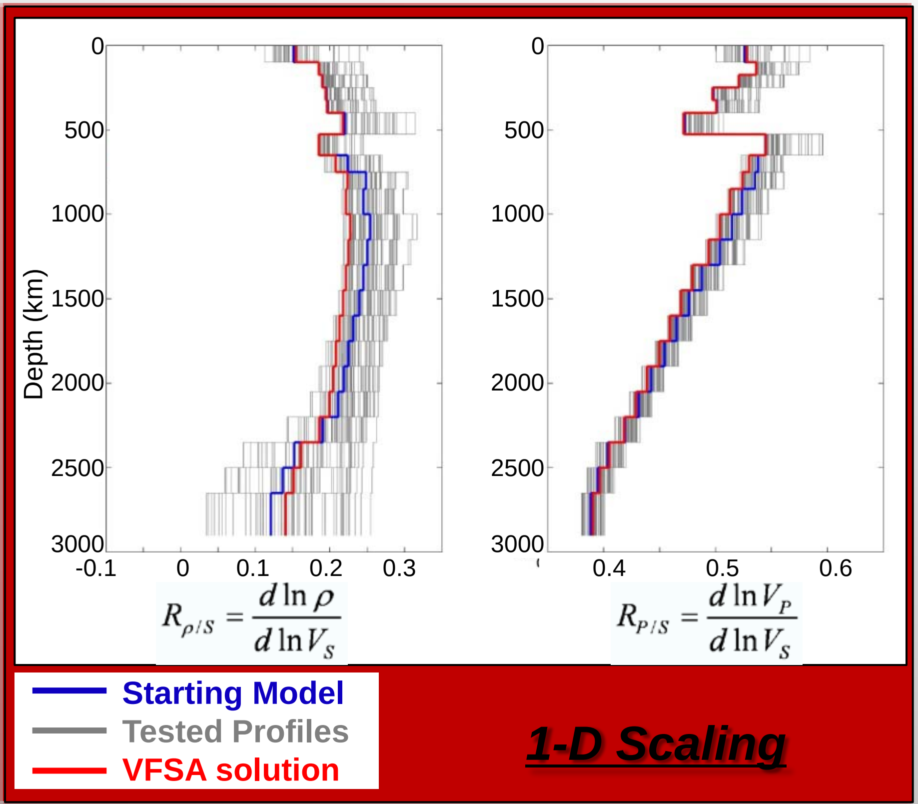
ii) Lower mantle

b = Profile Shifting

i) Upper mantle

ii) Lower mantle

GyPSuM: Scaling model optimization



- ❑ Range defined by mineral physics
  - ➢ *Expected thermal values*
- ❑ Simulated annealing (VFSA)
- ❑ Full joint inversion performed with each update

Starting 1-D scaling profile

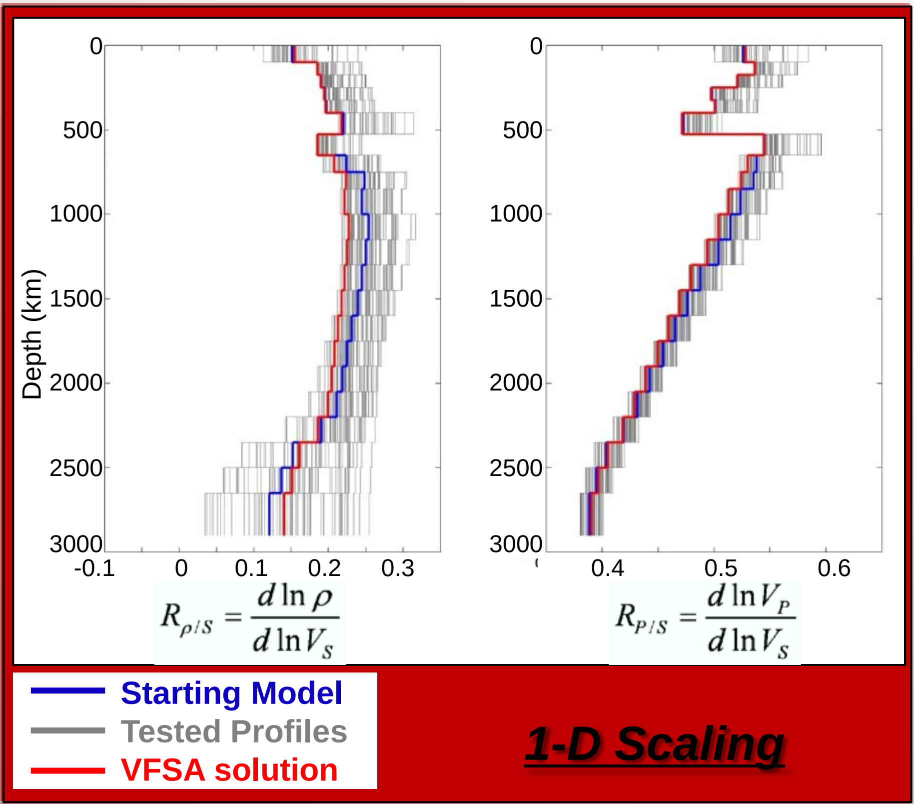
$$R_{\rho/S} = aR^{\text{1-D}}_{\rho/S} + b + \kappa\delta\ln V_S$$

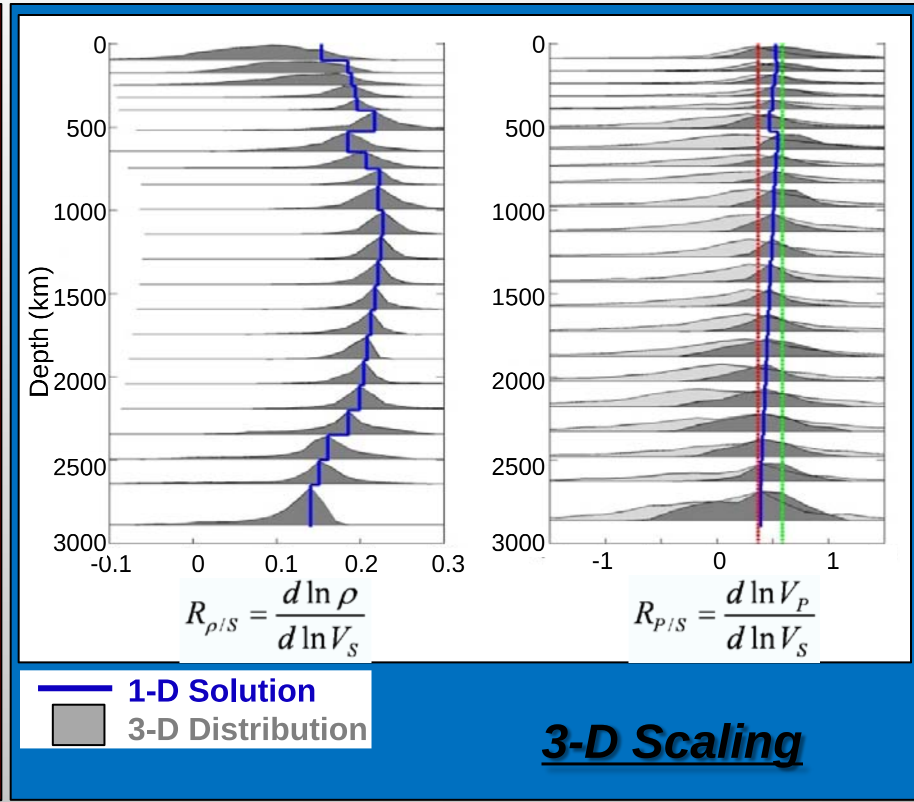
κ = Correction factors for:

Cratonic mass depletion
&
Temperature dependence of Q

****Shear velocity used as a proxy for local temperature variations***

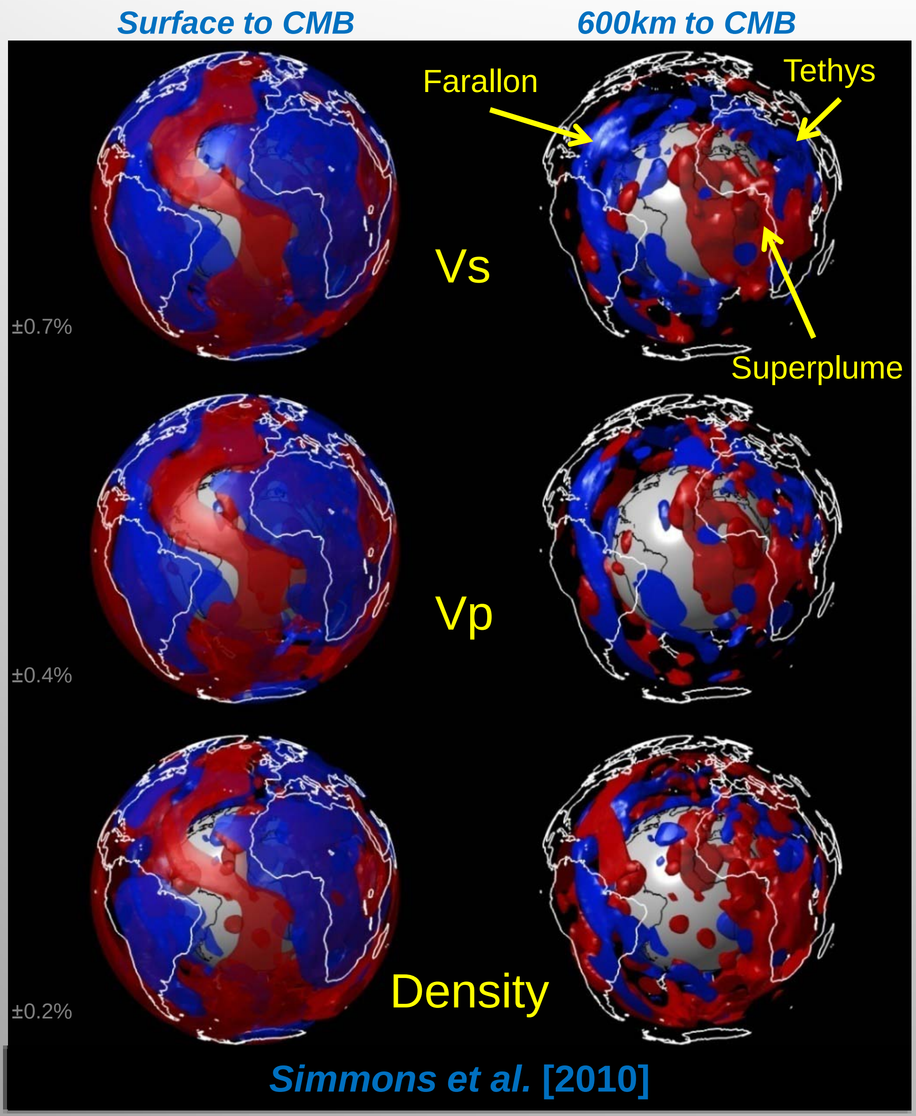
GyPSuM: Scaling model optimization





- ❑ Range defined by mineral physics
  - ➢ *Expected thermal values*
- ❑ Simulated annealing (VFSA)
- ❑ Full joint inversion performed with each update

- ❑ Scaling factors allowed to diverge from thermal
- ❑ Non-linear inversion process
- ❑ Allows reconciliation of all seismic/geodynamic data
- ❑ Produces model most closely resembling thermal

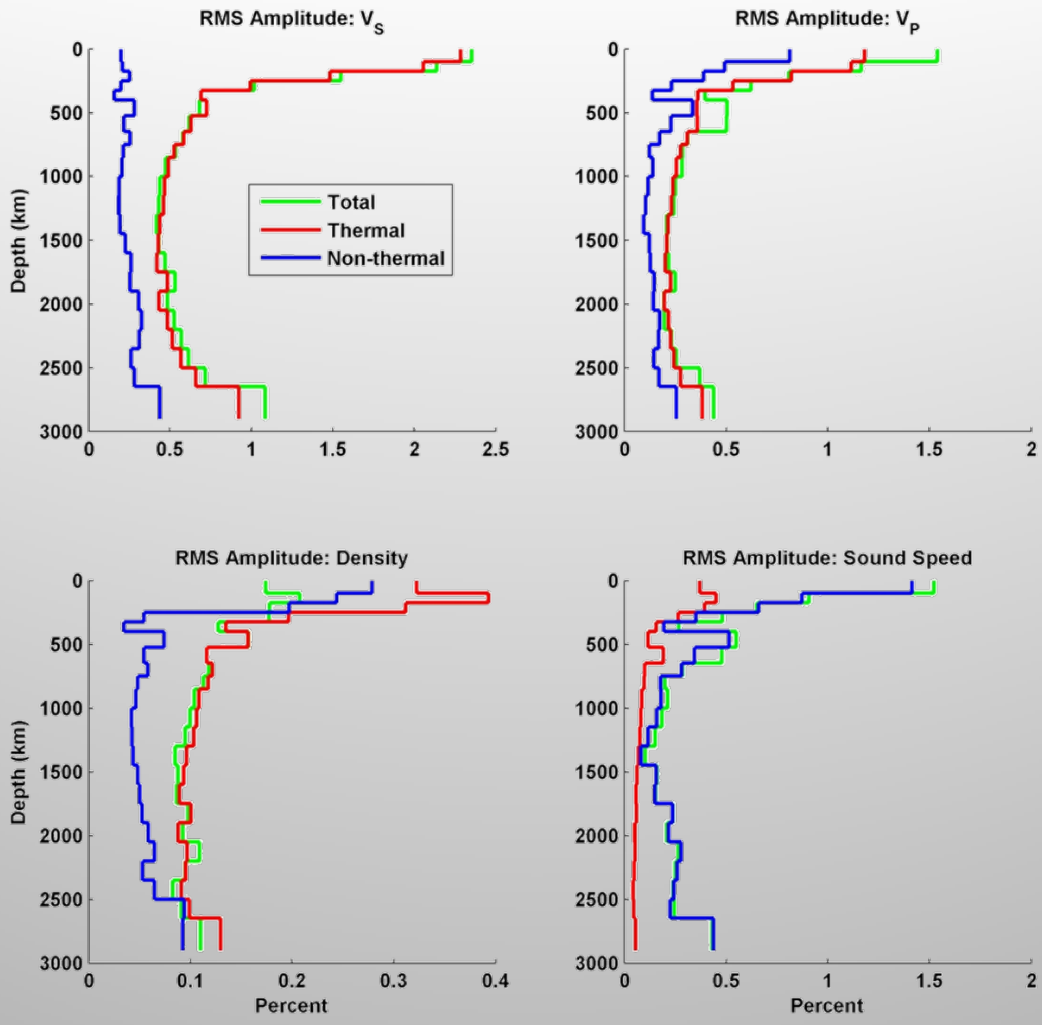


Joint model of mantle S-wave velocity, P-wave velocity and density

- Built with the hypothesis that temperature variations dominate
- The role of composition is minimized
- Detailed, (more) dynamically consistent density model of the mantle

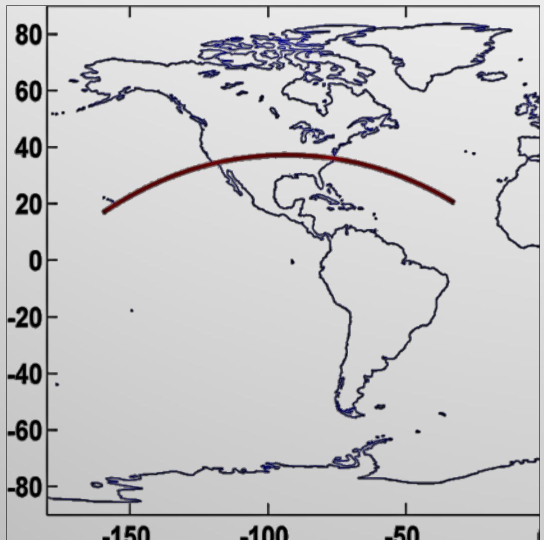
S-wave Data	P-wave Data	Free-air Gravity	Plate Div.	Dynamic Topo.	CMB Excess Ellip.
93%	31% *Variance*: 2.6s → 1.8s	88%	99%	72%	100% (0.4 km)

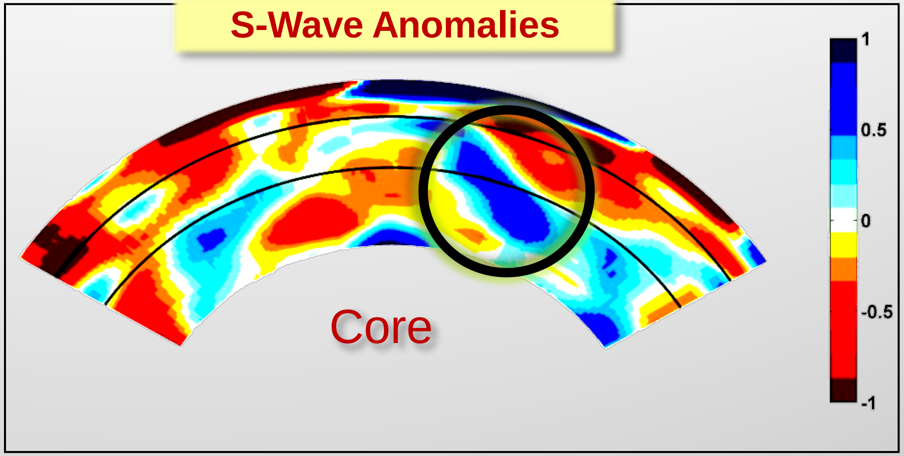
GyPSuM: Temperature is the primary contributor to P, S, and Density

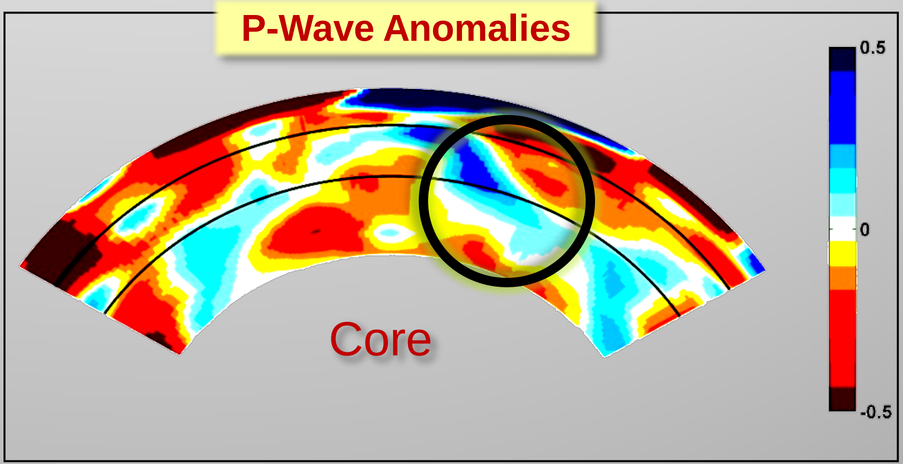


**Thermal and Non-thermal components may be constructive or destructive.*

GyPSuM: Systematic de-correlation of S- and P-velocity within ancient subducted slabs … compositional variations?







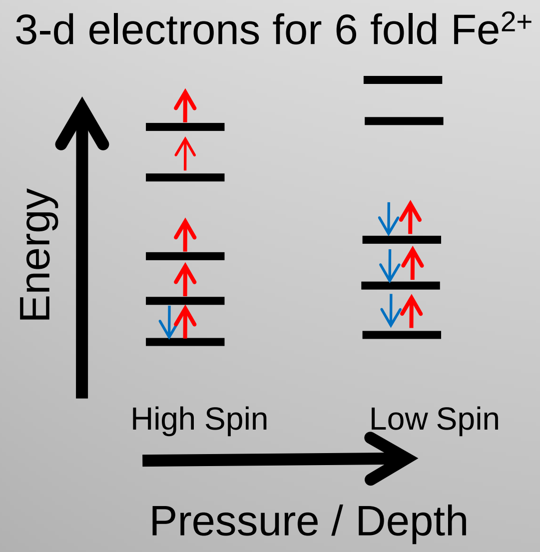
GyPSuM: Systematic de-correlation of S- and P-velocity within ancient subducted slabs ... compositional variations?

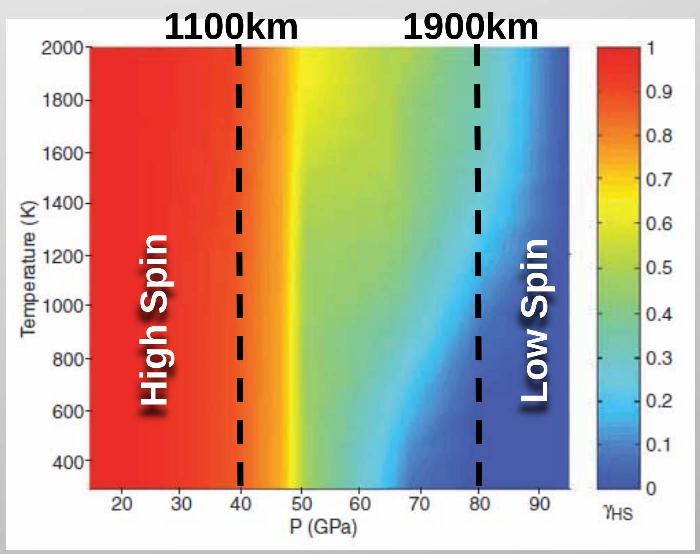
Electronic Spin Transitions:

➢Fe^{2+} undergoes a pressure induced transition from a high spin state to a low spin state…*under mid-mantle P/T conditions*

Affects major mantle minerals $(Mg,Fe)SiO_3$ and (Mg,Fe)O:

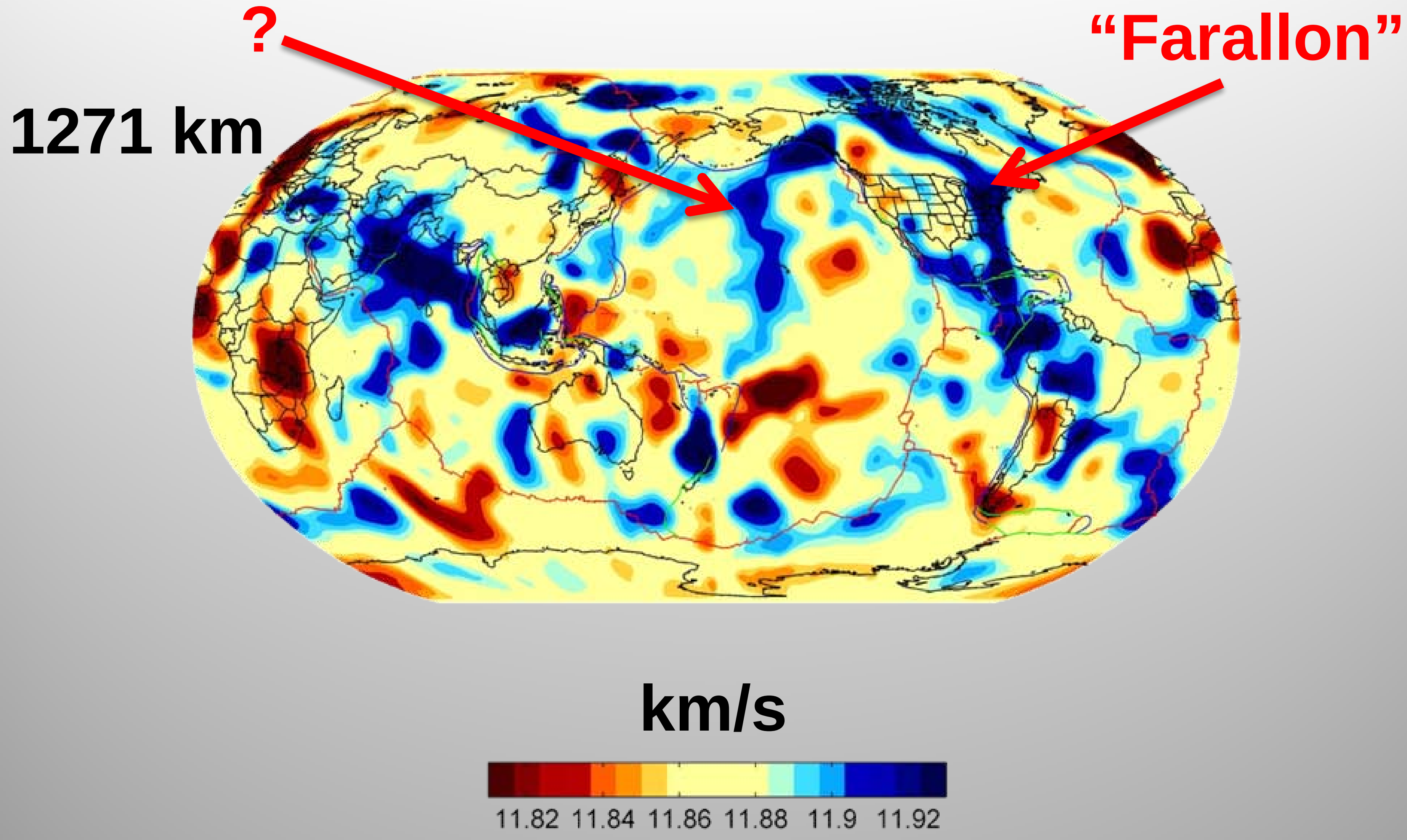
- ➢Elastic properties
- ➢Density
- ➢Iron partitioning
- ➢Thermal conductivity





From *Lin et al.* (2007)

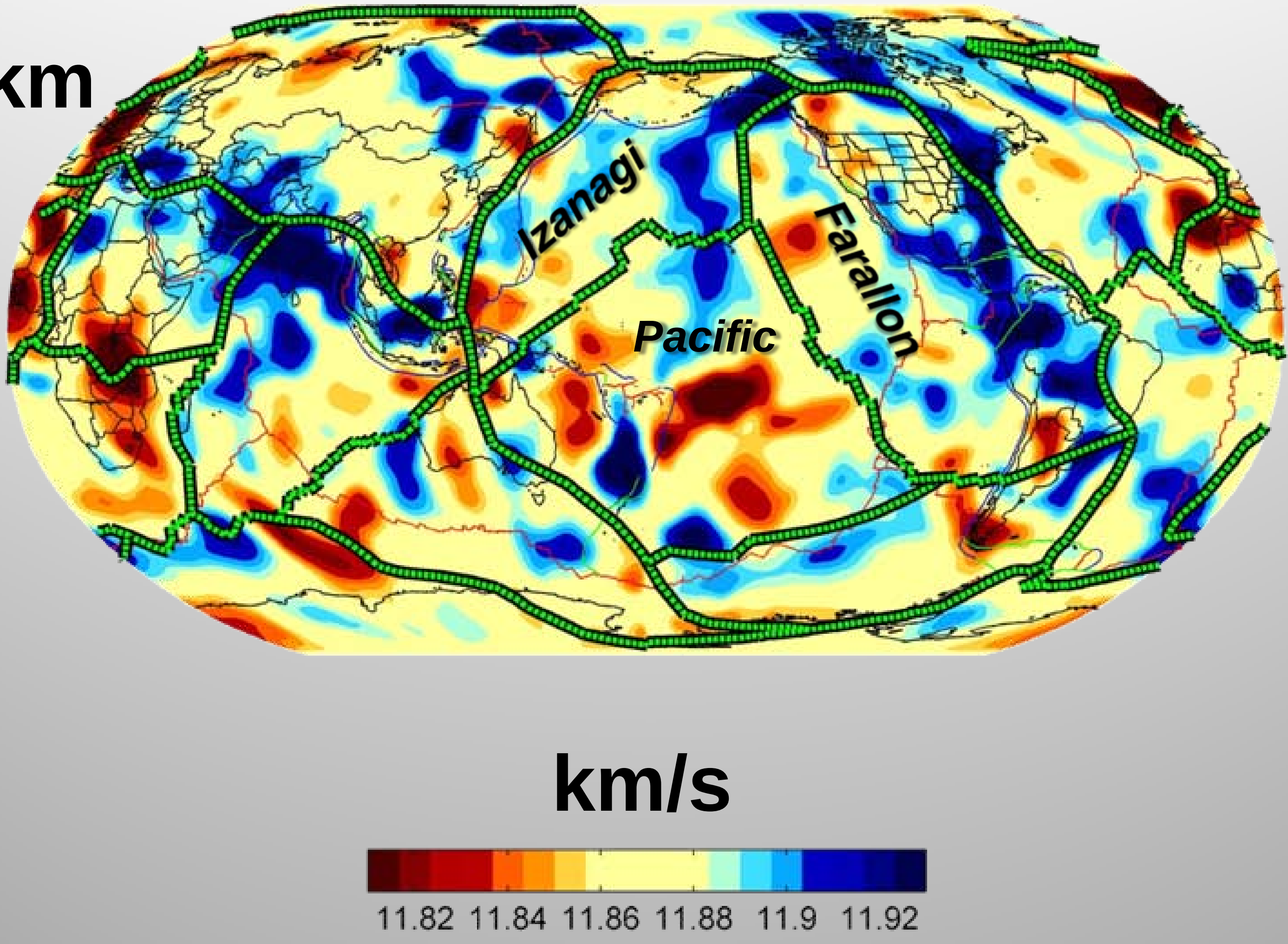
GyPSuM: An ancient slab remnant beneath the Pacific Ocean?



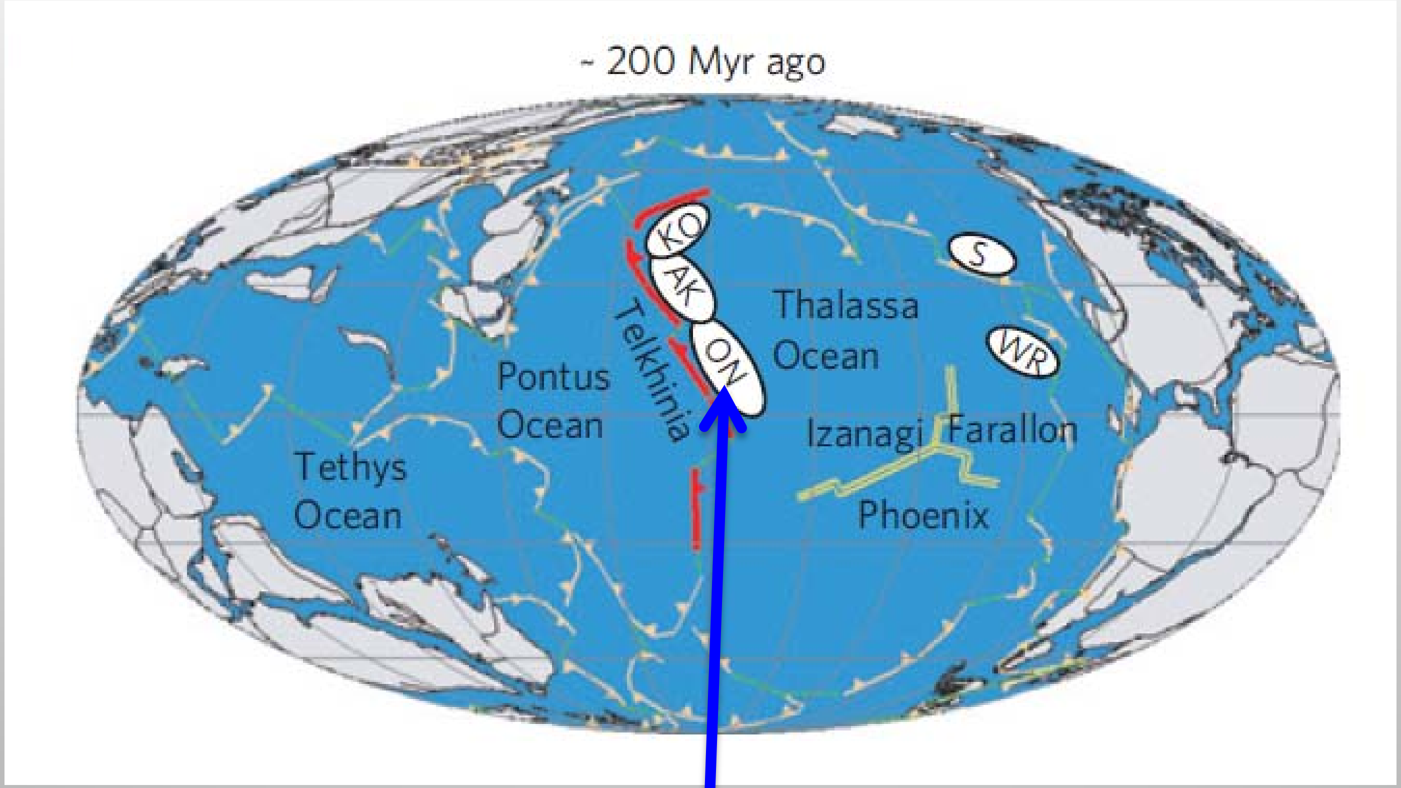
GyPSuM: An ancient slab remnant beneath the Pacific Ocean?

Paleo-plate boundaries @ 100 Ma: *Torsvik, Steinberger, Gurnis & Gaina* [2010]

1271 km



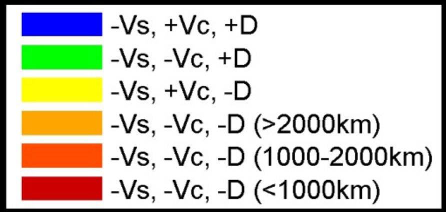
Paleo-plate boundaries @ 200 Ma: *van der Meer et al.* [2012]

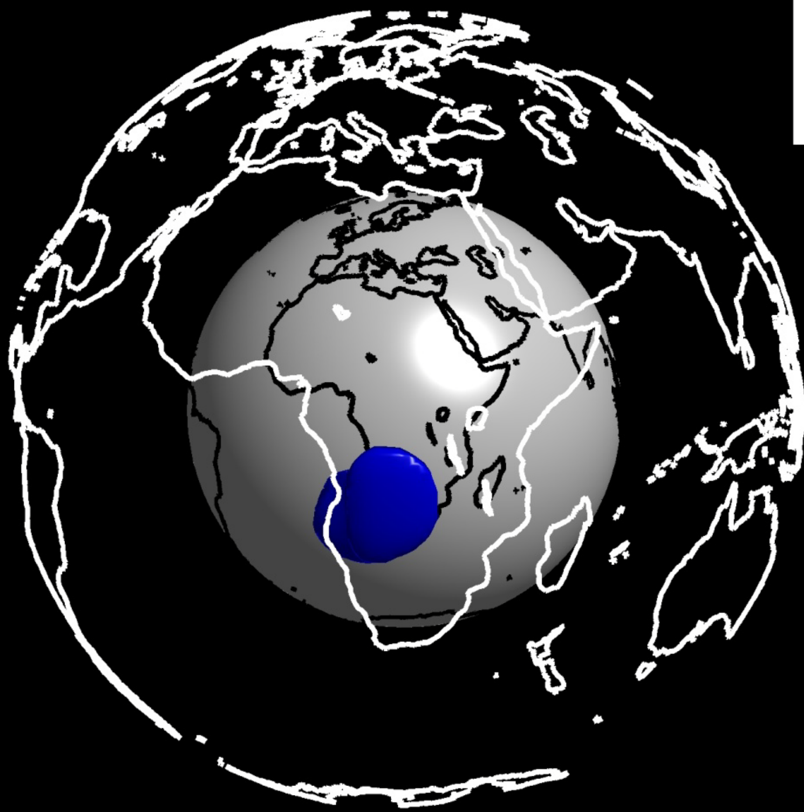


Extinct intra-oceanic volcanic arcs formed above ancient subduction zones

***Locations consistent with Paleomagnetism and Biostratigraphy**

GyPSuM: Deconstructing the African Superplume Structures





Dense Pile Part I

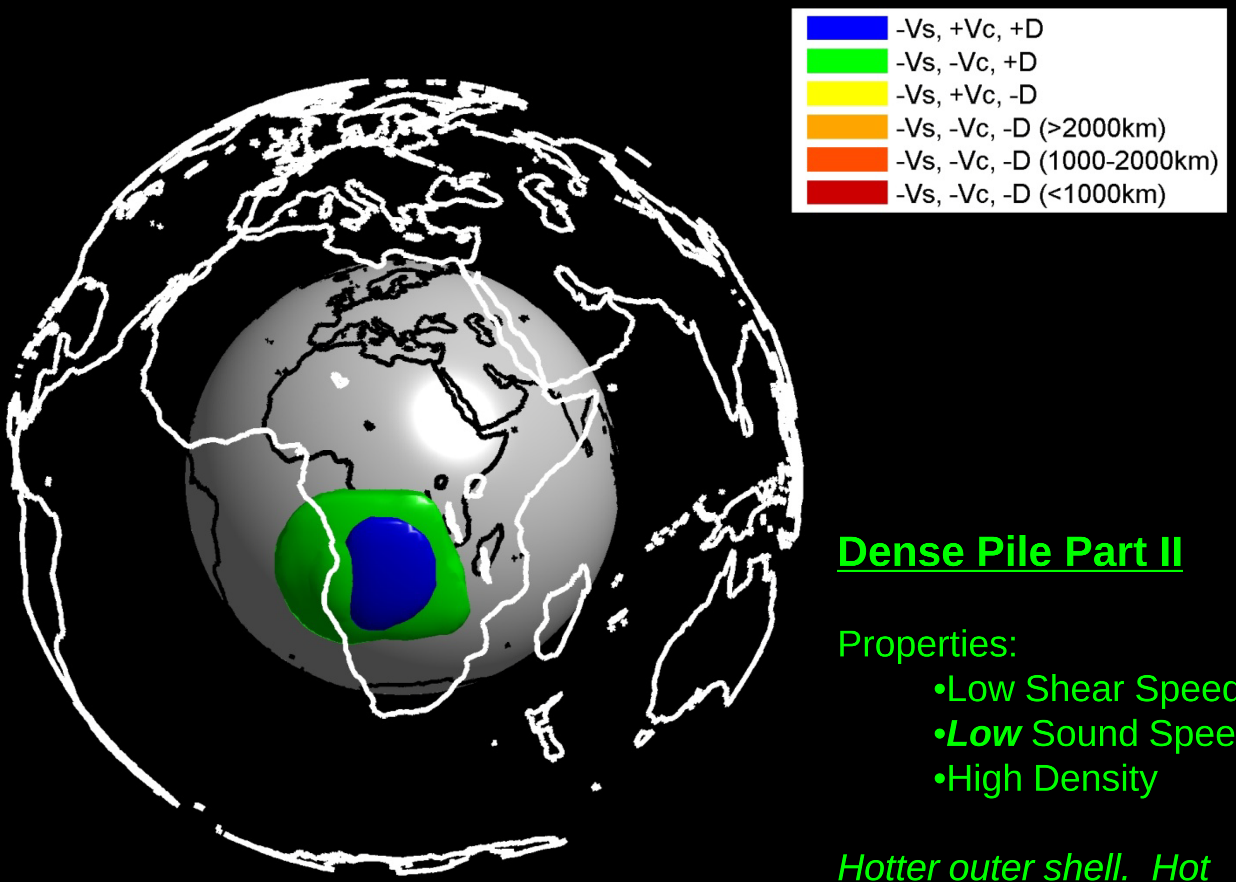
Properties:

- Low Shear Speed
- High Sound Speed
- High Density

Intrinsically dense, hot material.

Simmons, Forte, Boschi & Grand (2010)

GyPSuM: Deconstructing the African Superplume Structures



Dense Pile Part II

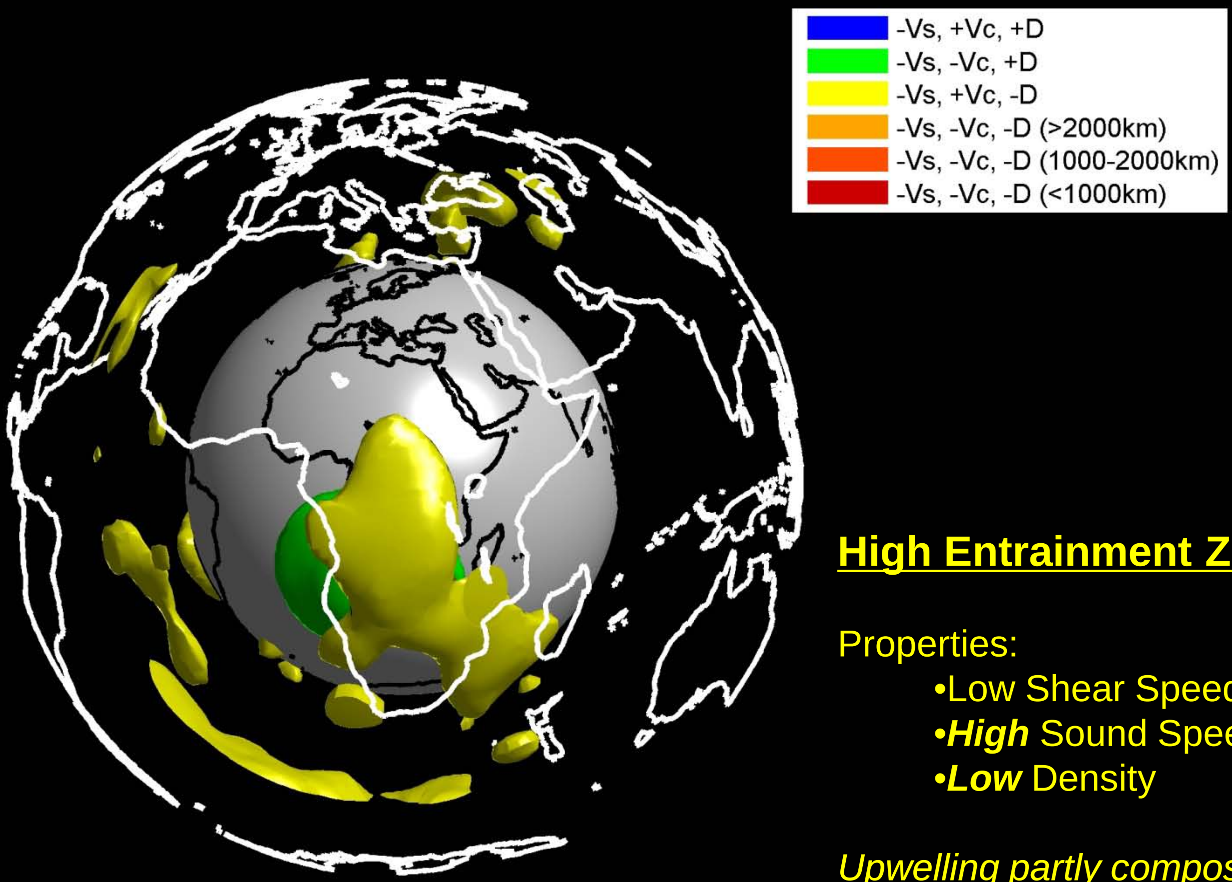
Properties:

- Low Shear Speed
- ***Low*** Sound Speed
- High Density

Hotter outer shell. Hot enough to reduce sound speed…dense, partial melt?

Simmons, Forte, Boschi & Grand (2010)

GyPSuM: Deconstructing the African Superplume Structures



High Entrainment Zone

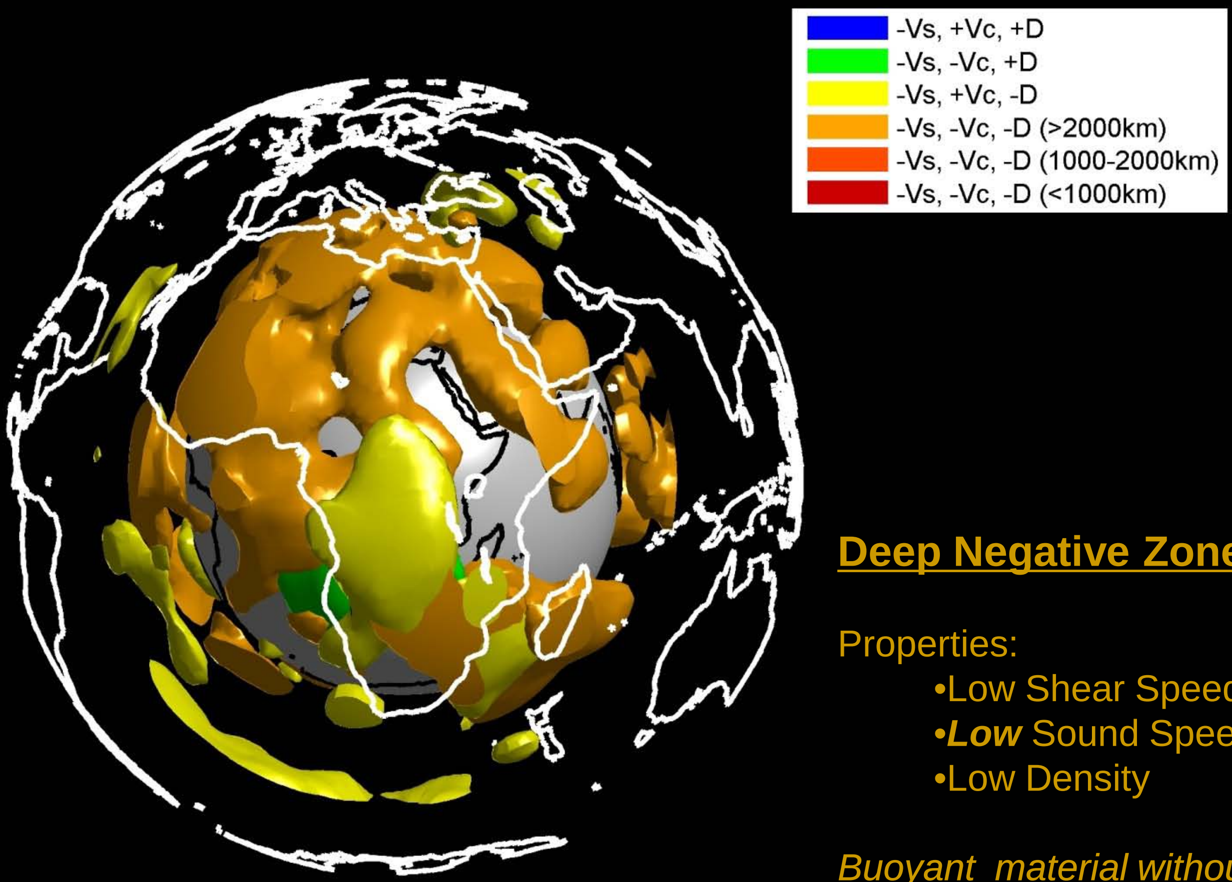
Properties:

- Low Shear Speed
- ***High*** Sound Speed
- ***Low*** Density

Upwelling partly composed of intrinsically dense material entrained from the dense pile. Seen in the SASP, but not the WASP.

Simmons, Forte, Boschi & Grand (2010)

GyPSuM: Deconstructing the African Superplume Structures



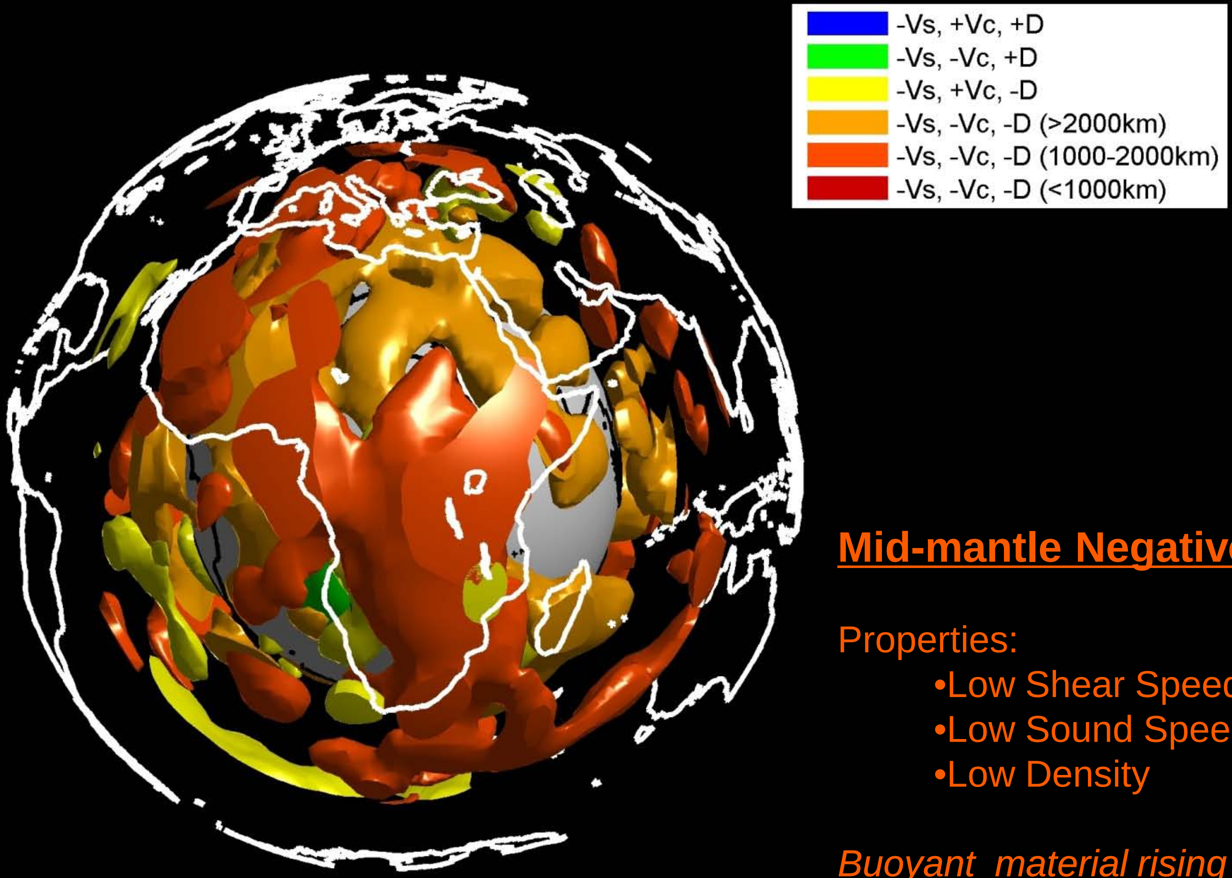
Deep Negative Zones

Properties:
- Low Shear Speed
- ***Low*** Sound Speed
- Low Density

Buoyant material without significant chemical signatures. Comprises the remaining low shear zones deep beneath Africa.

Simmons, Forte, Boschi & Grand (2010)

GyPSuM: Deconstructing the African Superplume Structures



Mid-mantle Negative Zone

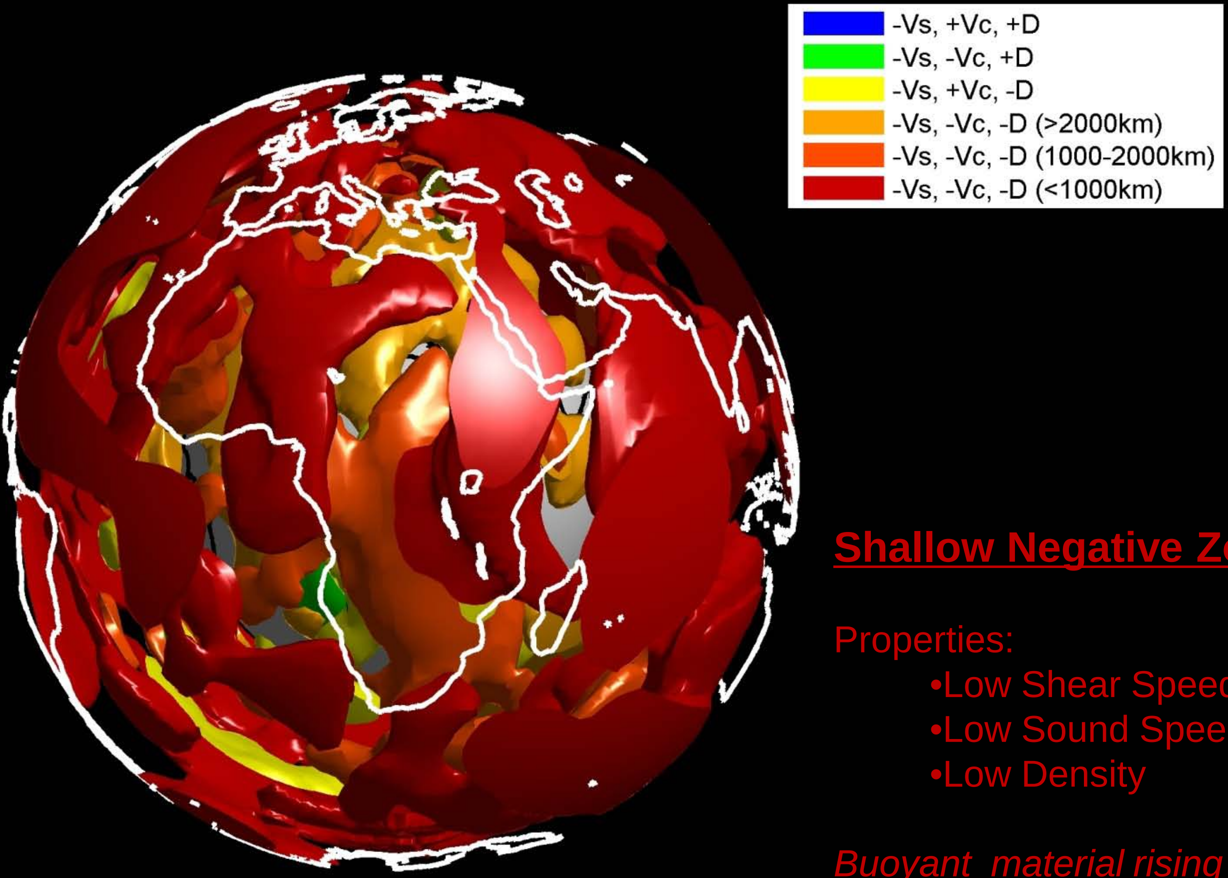
Properties:

- Low Shear Speed
- Low Sound Speed
- Low Density

Buoyant material rising towards the EARZ , Cameroon, and Cape Verde. High-density chemical signatures seen in extensions from the SASP.

Simmons, Forte, Boschi & Grand (2010)

GyPSuM: Deconstructing the African Superplume Structures



Shallow Negative Zone

Properties:
- Low Shear Speed
- Low Sound Speed
- Low Density

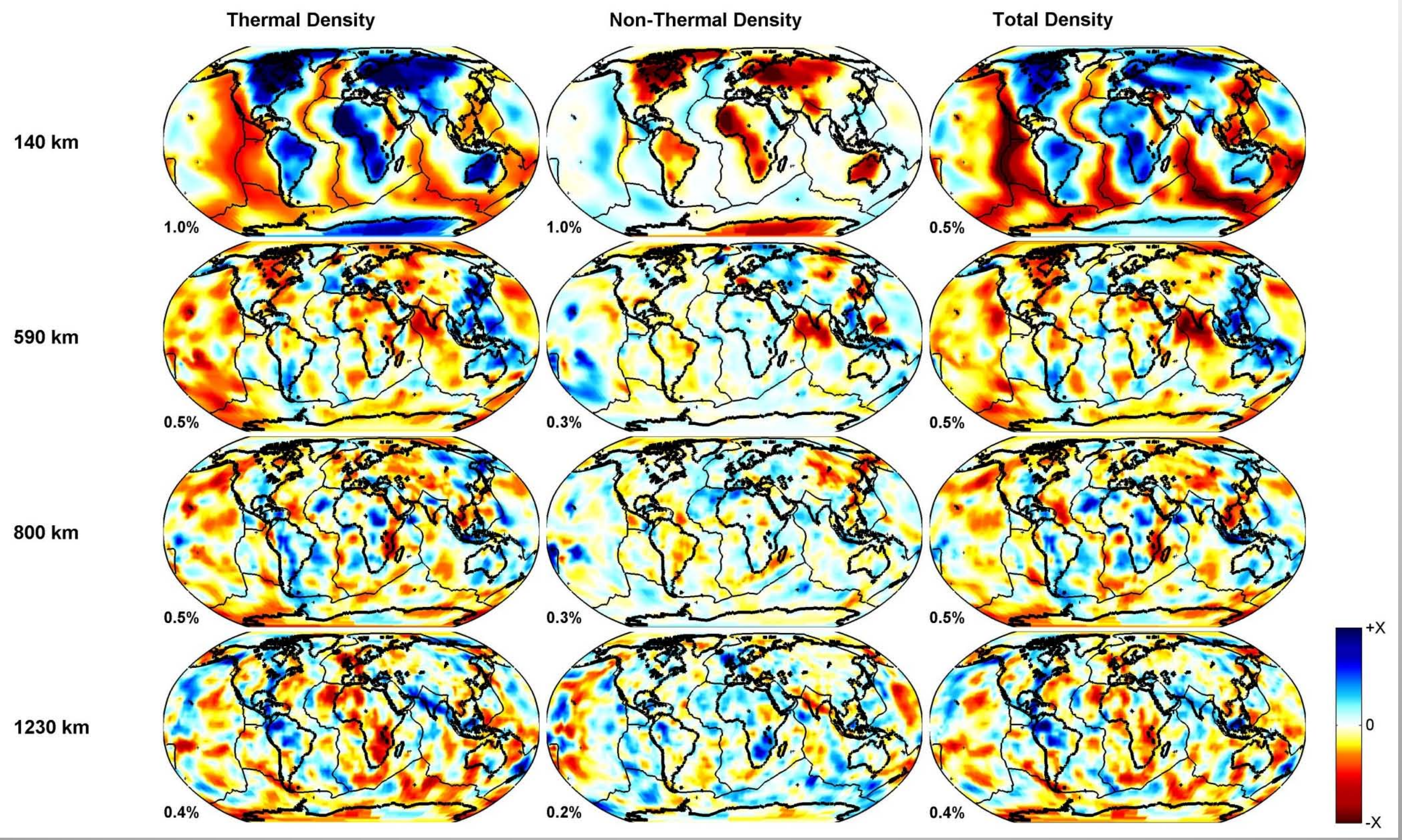
Buoyant material rising towards the EARZ , Cameroon, and Cape Verde. Extension toward Hoggar with compositional signature. Possible SASP fingerprint.

Simmons, Forte, Boschi & Grand (2010)

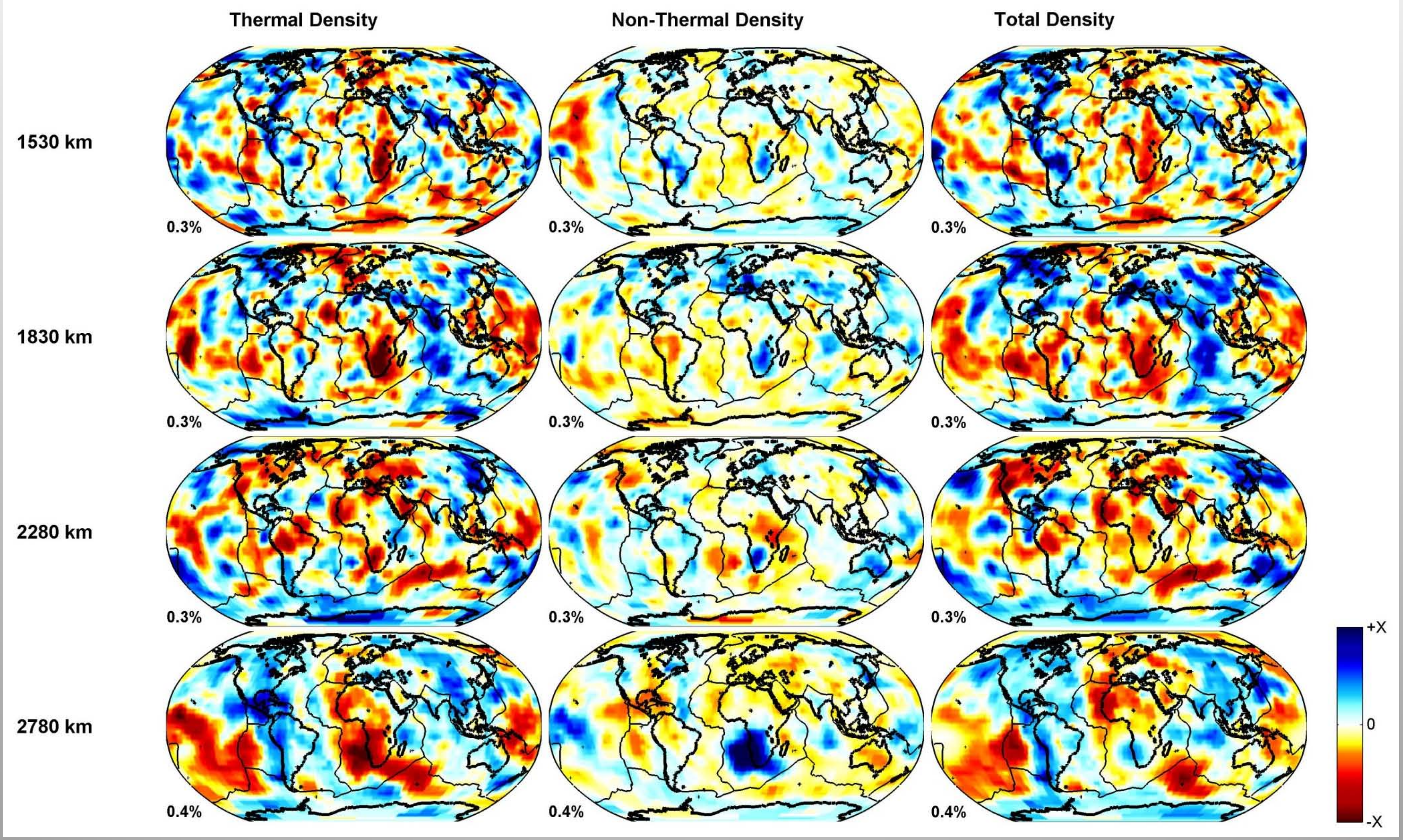
Summary

- We have constructed a global-scale joint seismic-geodynamic-mineral-physics model (GyPSuM)
  - With a "minimum composition" approach
  - Except for cratonic roots and parts of D", temperature seems to dominate
- We have started with broadly-defined mineral physics constraints
  - Future models should incorporate more recent and complete mineral physics relationships
  - Trade-offs are problematic
- Model available for download on the IRIS website:
  - http://www.iris.edu/dms/products/emc/

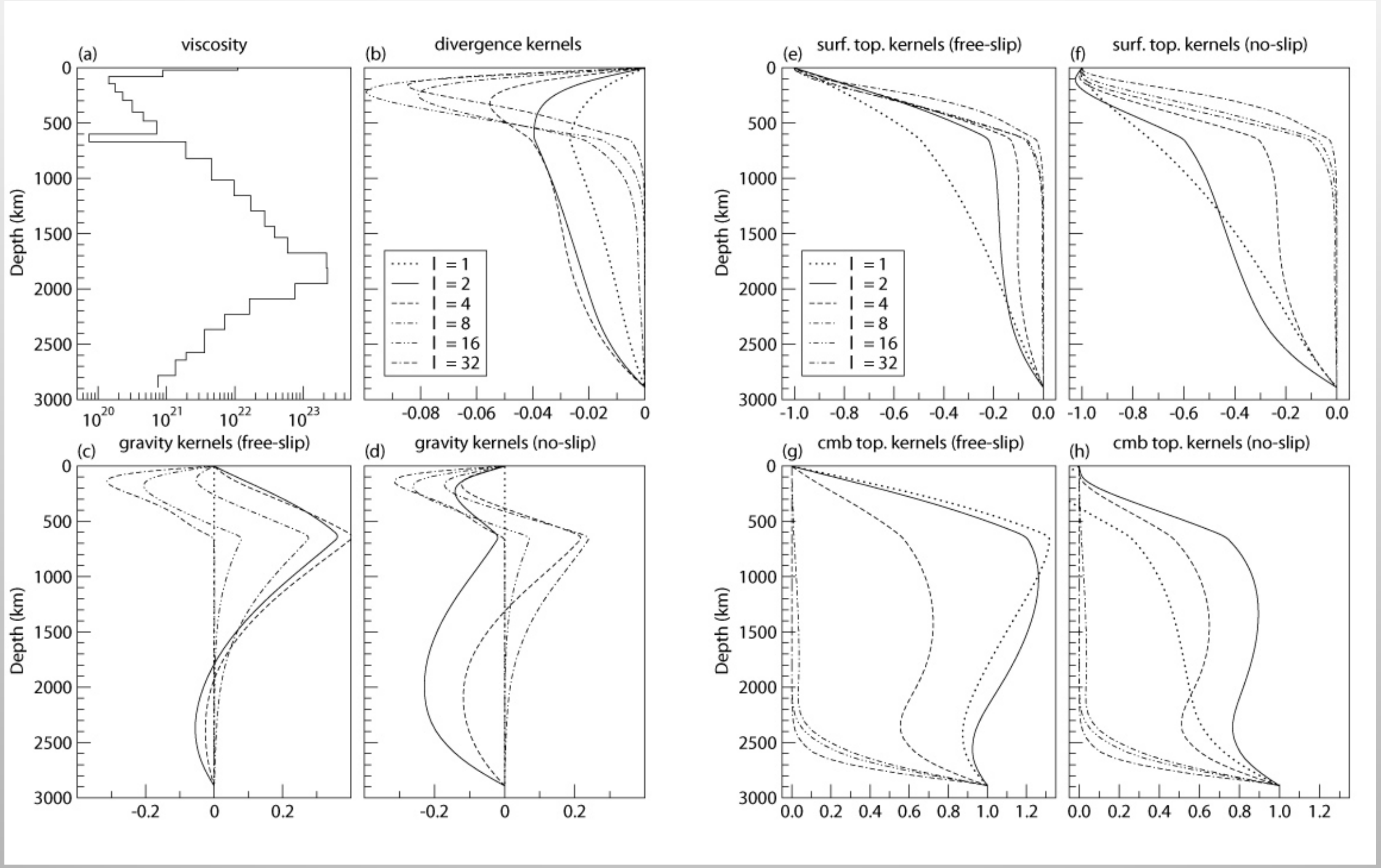
GyPSuM: Thermal VS non-thermal heterogeneity



GyPSuM: Thermal VS non-thermal heterogeneity



GyPSuM: Viscous Flow Response Kernels



GyPSuM: Density-P-S Coupling

$$R_{\rho/S} = \frac{2}{(\Gamma - 1) + 2Q_S^{-1}X(\xi)C}$$

anharmonic: $(\Gamma - 1)$; anelastic: $2Q_S^{-1}X(\xi)C$

$$\Gamma \equiv \frac{\delta \log \mu}{\delta \log \rho}$$

Anderson-Grüneisen parameter

$$R_{\phi/S} = \frac{(\delta_s - 1)}{(\Gamma - 1) + 2Q_S^{-1}X(\xi)C} = \frac{(\delta_s - 1)}{2} R_{\rho/S}$$

anharmonic: $(\Gamma - 1)$; anelastic: $2Q_S^{-1}X(\xi)C$

$$\delta_S \equiv \frac{\delta \log K}{\delta \log \rho}$$

Anderson-Grüneisen parameter

$$\frac{\delta V_P}{V_P} = \gamma \frac{\delta V_S}{V_S} + (1-\gamma)\frac{\delta V_\phi}{V_\phi}$$

$$\gamma \equiv \frac{4}{3}\frac{V_S^2}{V_P^2}$$

$$\Rightarrow R_{P/S} = \frac{(\delta_s - 1)}{2} R_{\rho/S}(1-\gamma) + \gamma$$

$$\begin{bmatrix} \mathbf{L}_S \\ \mathbf{L}_P(R_{P/S}) \\ \mathbf{G}(R_{\rho/S}) \end{bmatrix} \Delta \mathbf{m}_S = \begin{bmatrix} \mathbf{r}_S \\ \mathbf{r}_P \\ \mathbf{g} \end{bmatrix}$$