Geodynamics of Core-Mantle Interaction

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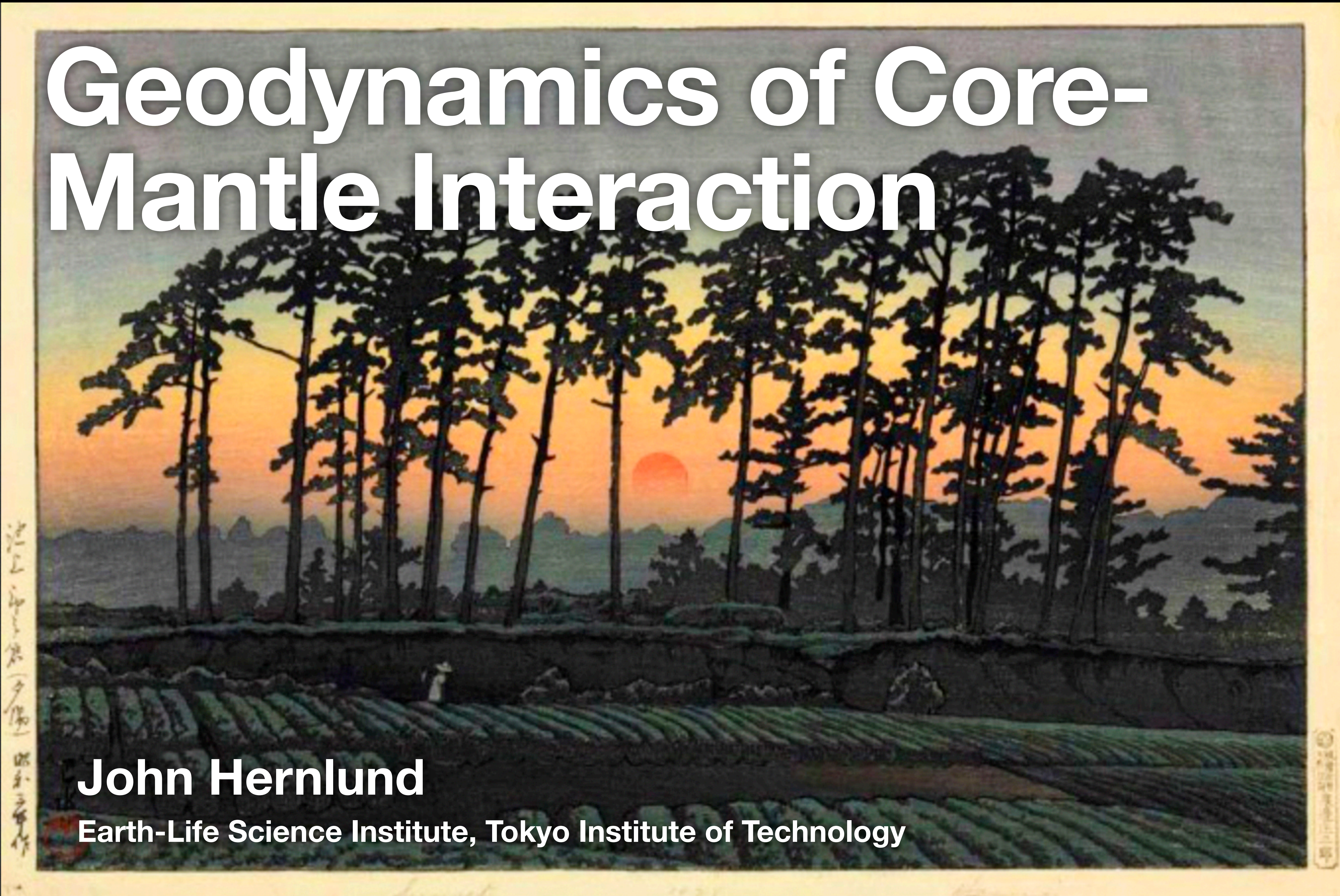


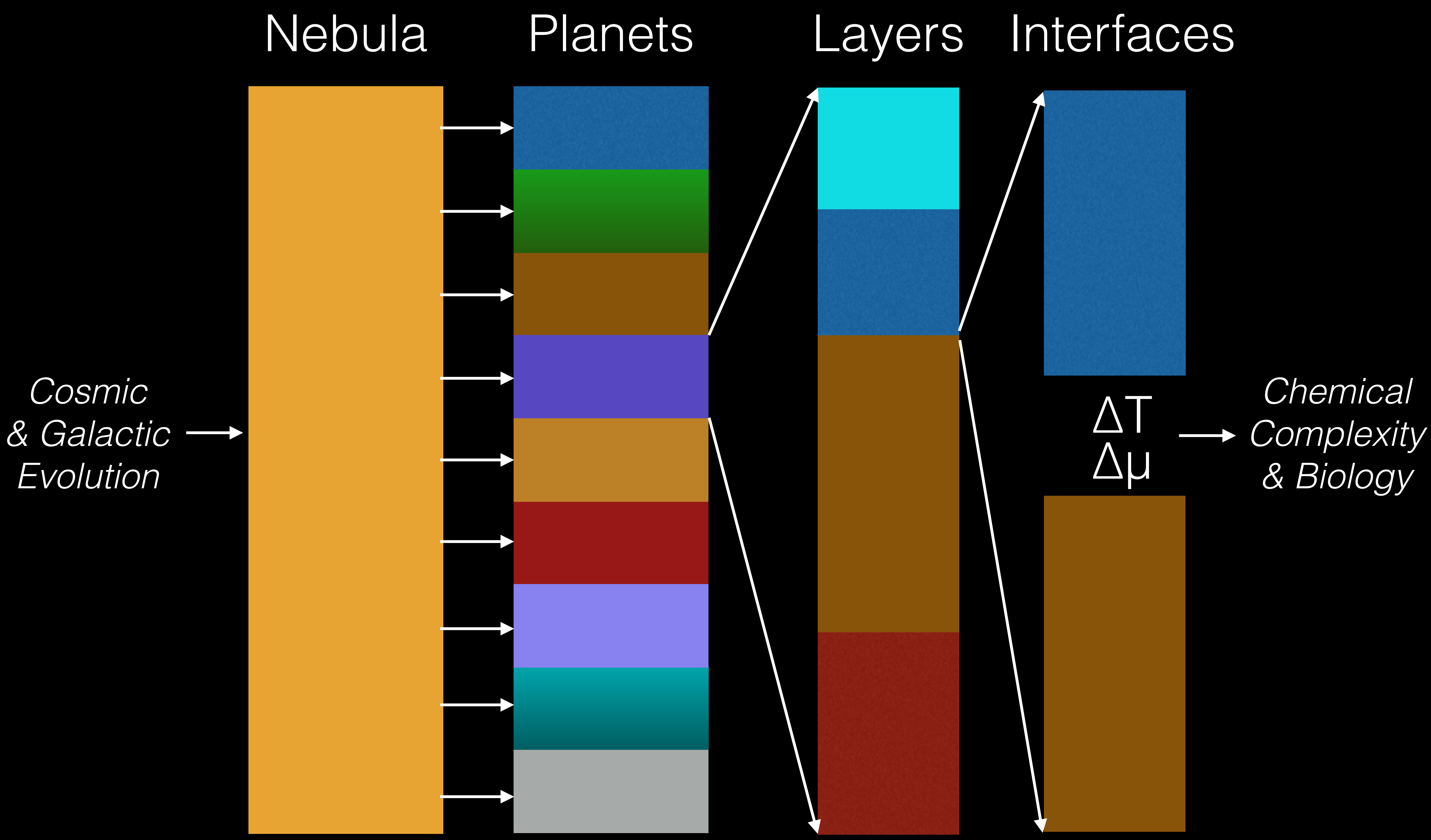
Background Image: Wood block print by Kawase Hasui, Ichinokura (my neighborhood in Tokyo, a century ago)

“Hernlund Lab” Students

Also new students (not pictured yet): Nathan van Alstine, Austin Taylor, and Takumi Matsunaga

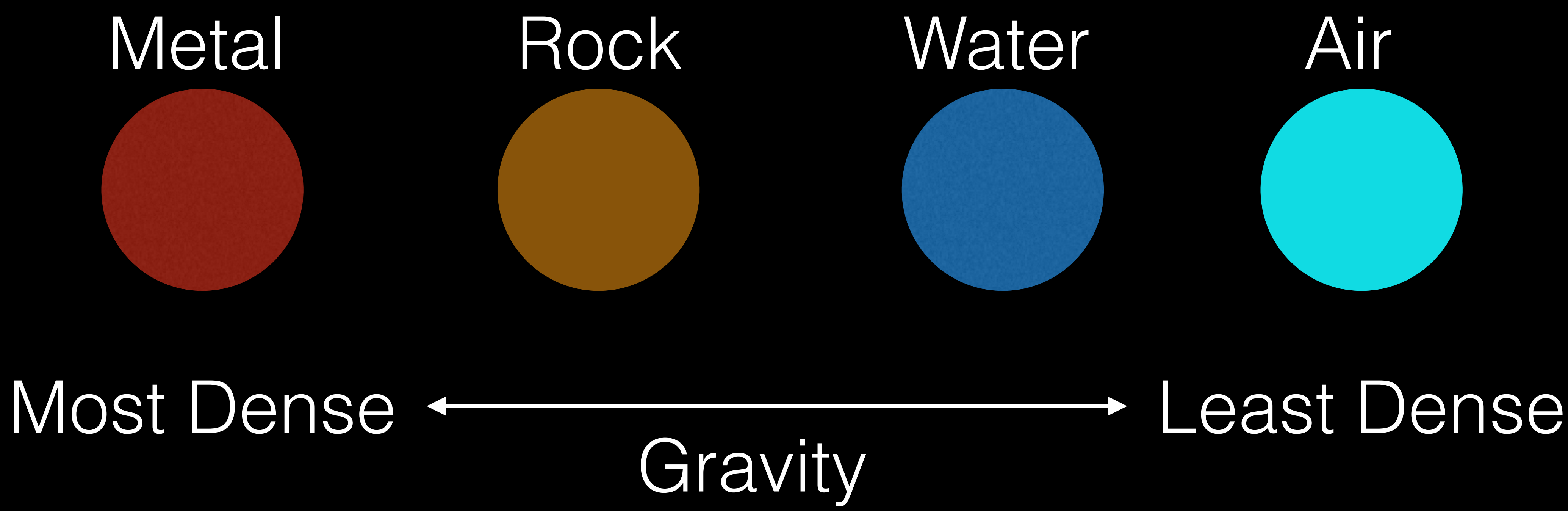
The CMB is Ancient

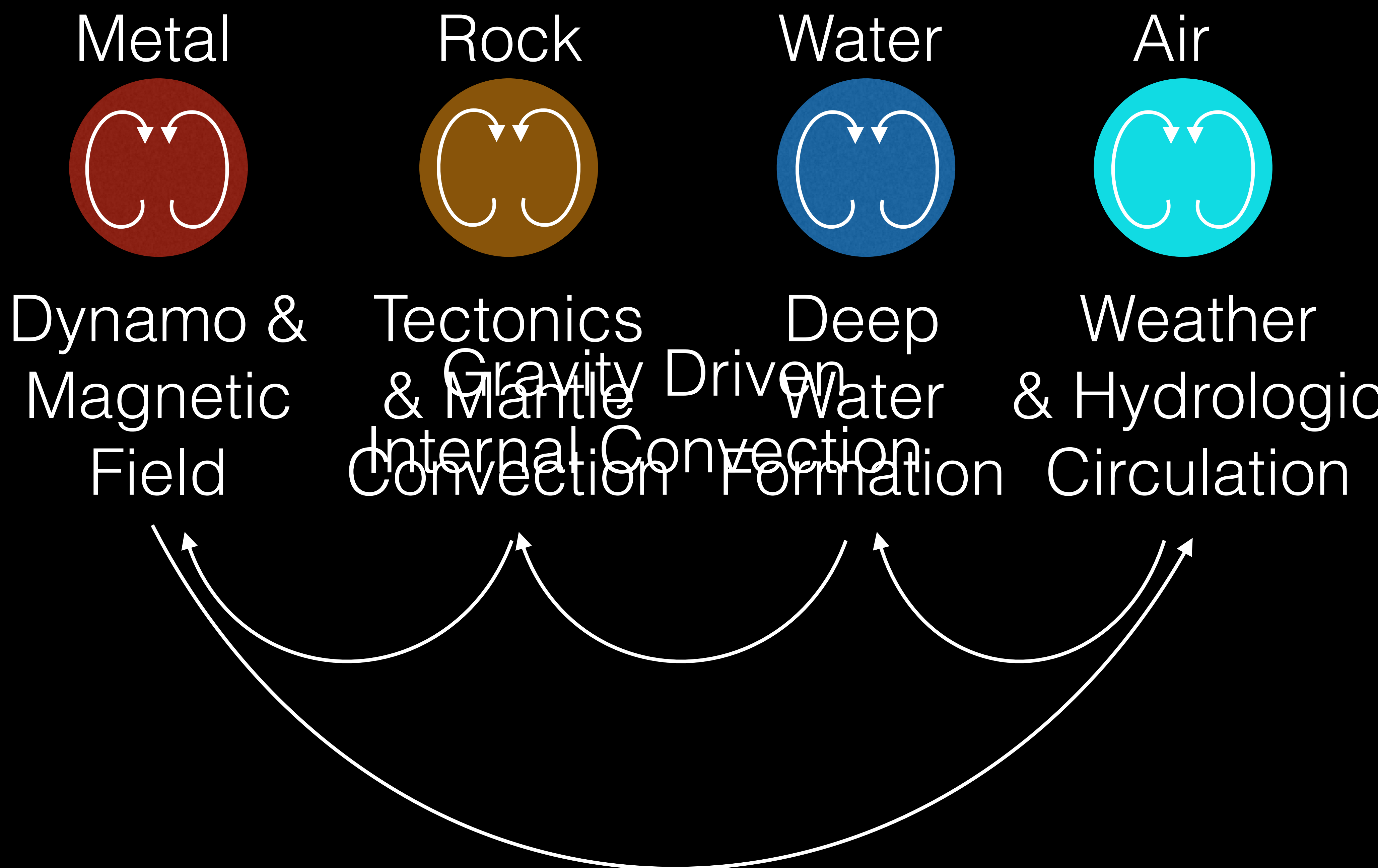
History: Series of Mixing and Unmixing Events

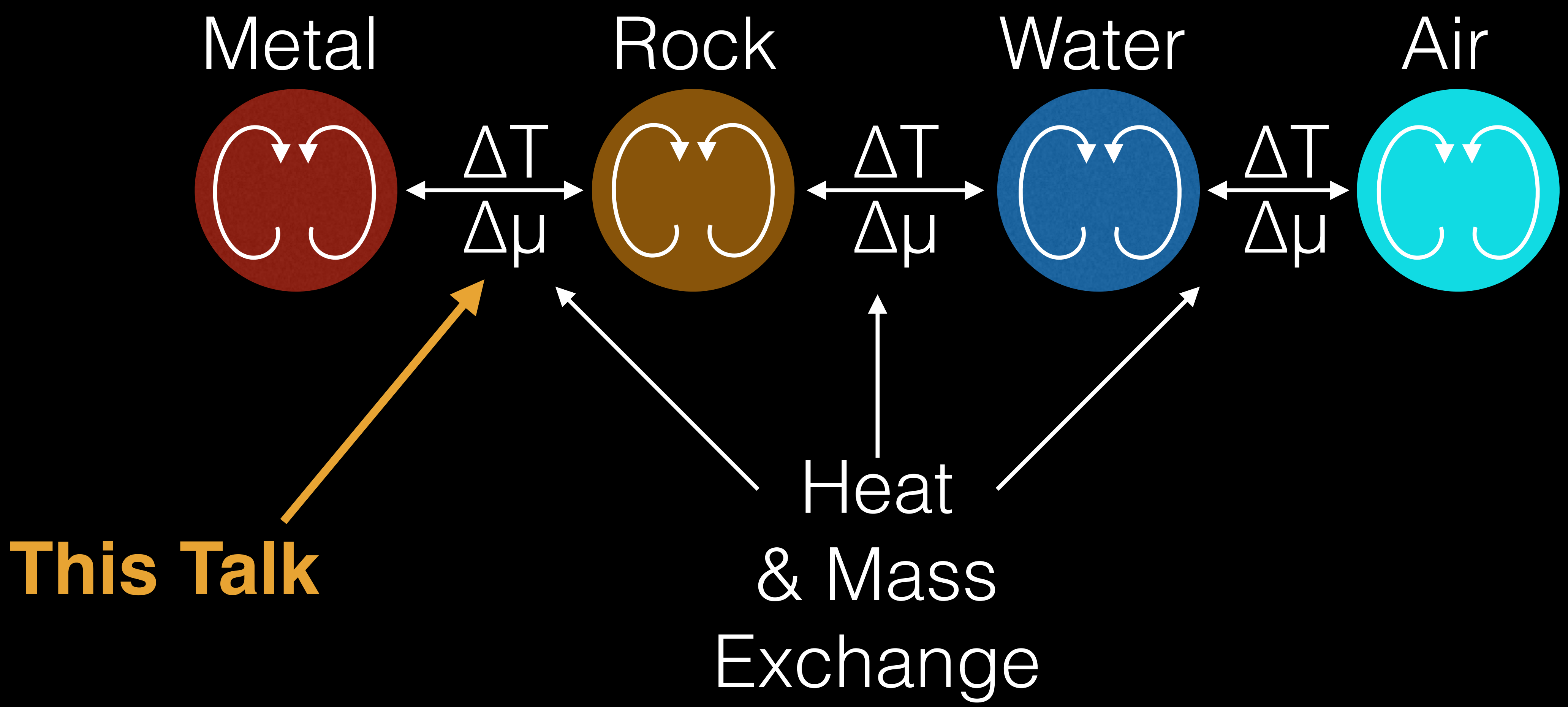


Metal Rock Water Air

Magma Ocean
Gravitational Energy Release
of Accretion
Melting and Mixing


Metal
Rock
Water
Air
Most Dense
Least Dense
Gravity

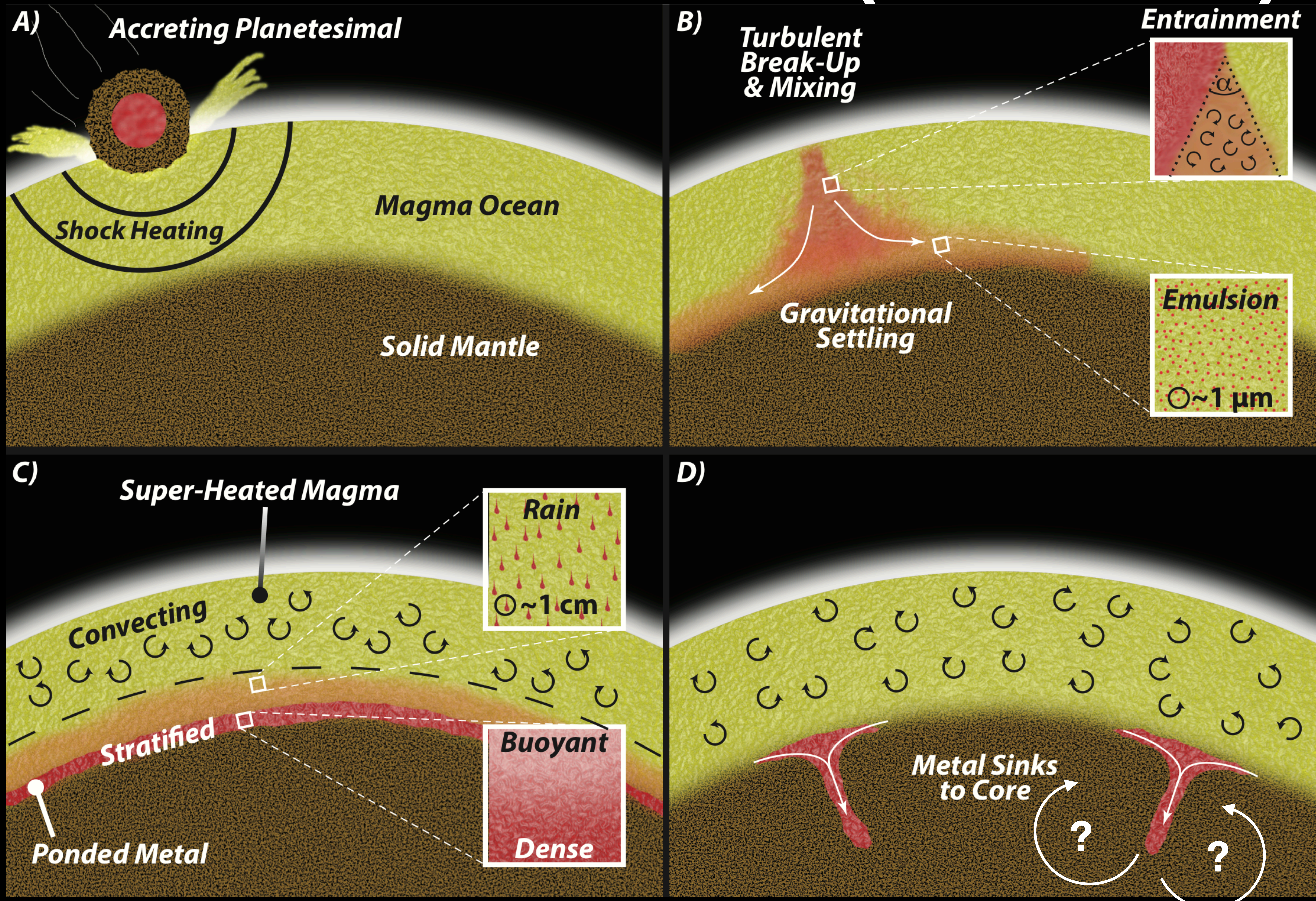

Metal
Rock
Water
Air
Dynamo & Magnetic Field
Tectonics & Mantle Convection
Deep Water Formation
Weather & Hydrologic Circulation
Gravity Driven Internal Convection



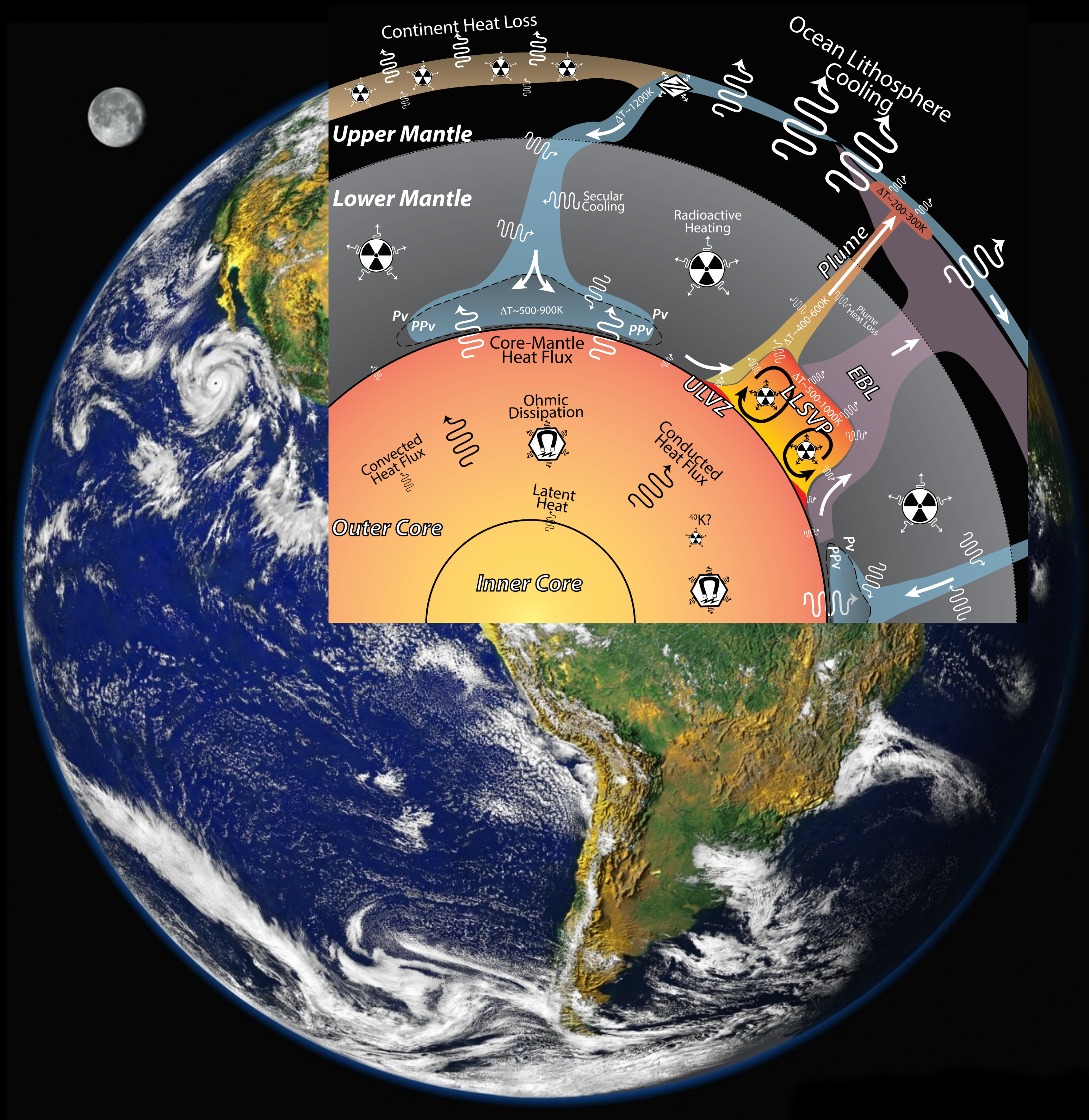
- Driver of ΔT: Unequal release of gravitational and radioactive heat.
- Driver of Δμ: Originally equilibrated* at conditions *very* different from later environments.

*In some cases only partially equilibrated

Core Formation (~4.5 Ga)



The Present System

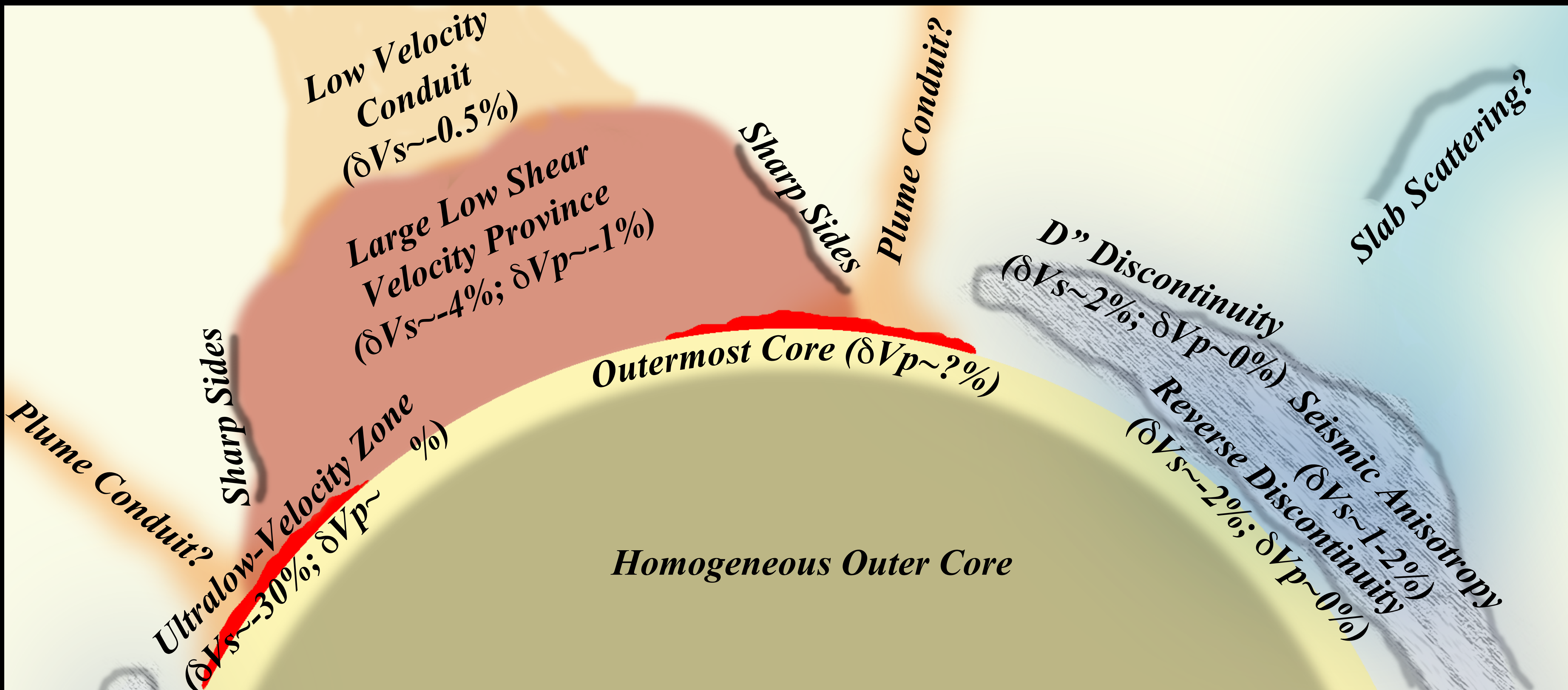


Key Uncertainties in Original Context

- Conditions (possibly transient) in magma ocean(s) during metal-silicate equilibration (P, T, O & H fugacity, etc.). This establishes the initial difference in bulk composition between the mantle and core.

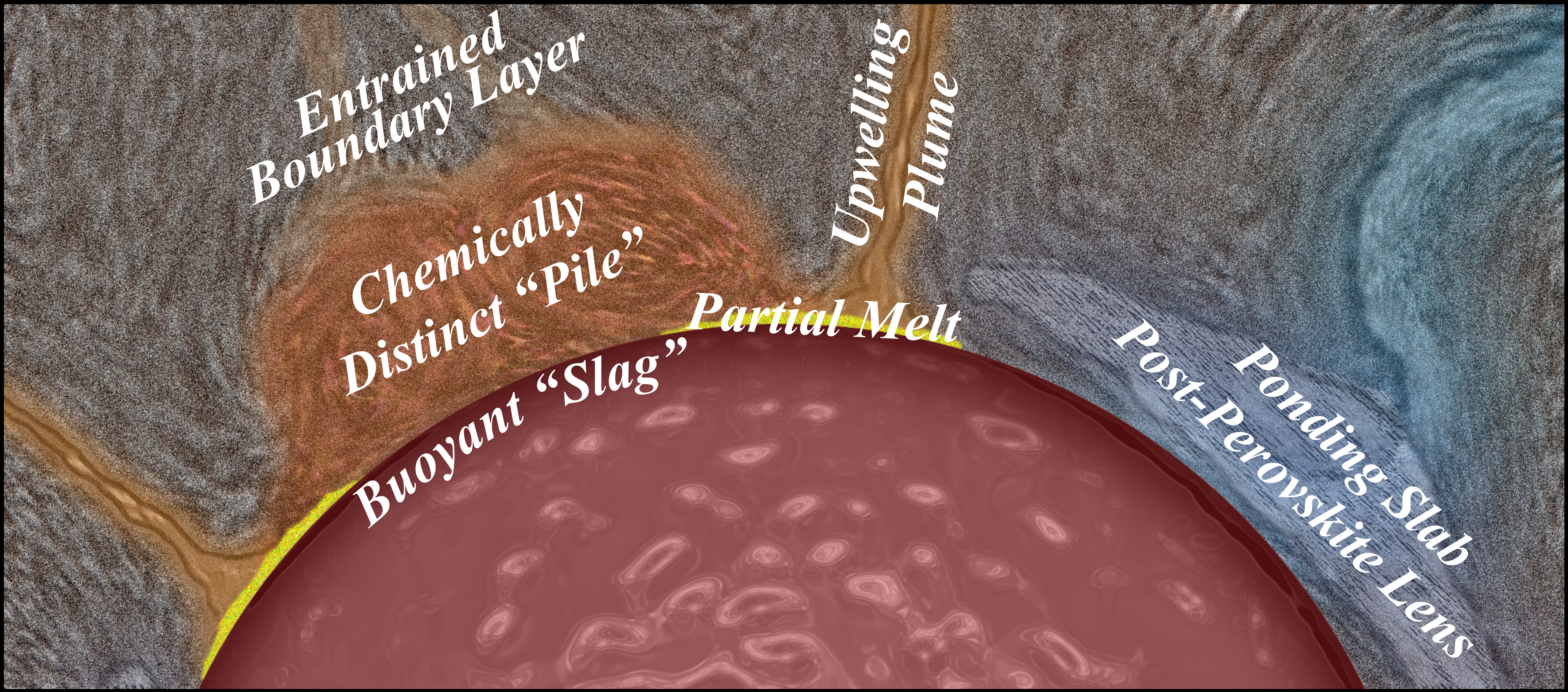
- Mechanism(s) of metal delivery to the core (ballistic/injection, conduits/jets, diapirs, percolation). This establishes the initial temperatures and states of the mantle and core, and extent of re-equilibration during core segregation.

Some Seismologically Inferred Features of the CMB Region



Hernlund & McNamara (2014)

Some Interpretations of Features in the CMB Region



Hernlund & McNamara (2014)

Stability of the CMB

- **Today's core-mantle boundary is sharp (~1 km or less gradient thickness).**
- **This sharpness reflects the density contrast (~4.4x water-air) and rheological contrast (>20 orders of magnitude viscosity difference).**
- **Viewed in this context, re-entrainment of the core *back* into the mantle should be extremely difficult.**

Three Mechanisms for Significant Exchange Between Core and Mantle

1. Basal Magma Ocean: Large volume liquid-liquid exchange for several hundred Myrs

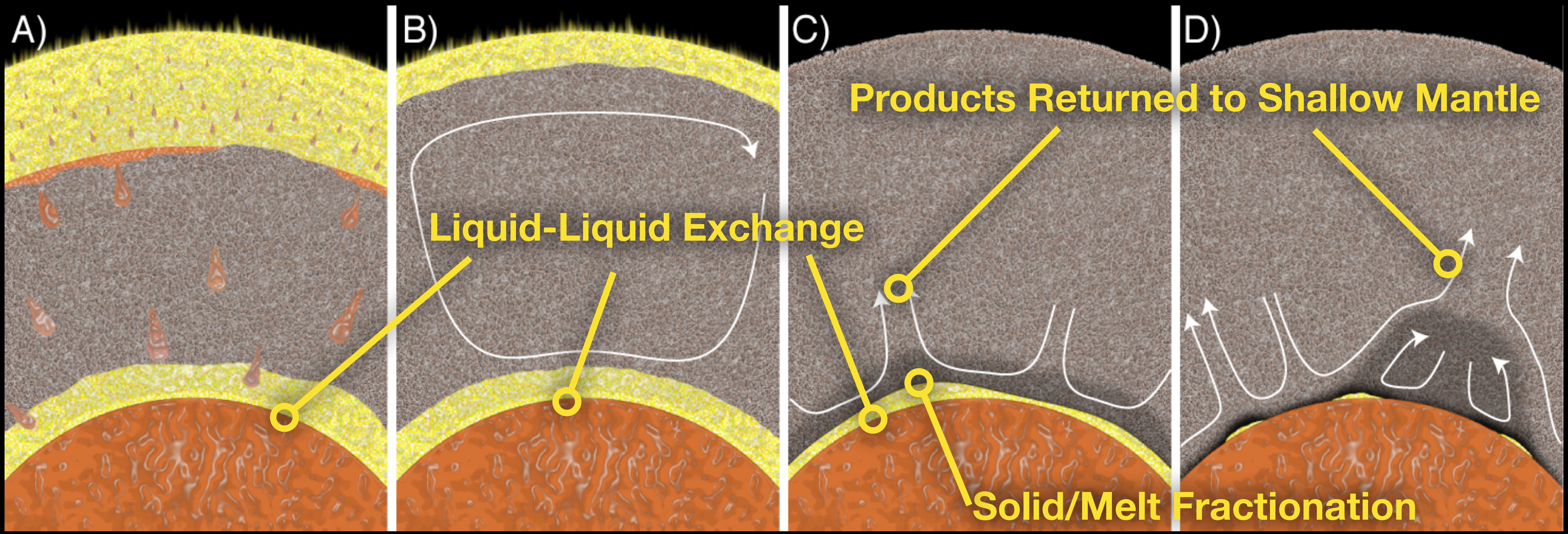
2. "Suction" Mechanism: Dipping the core into the mantle, soaking in metal, then subsequent drainage

3. Core "Exsolution": Precipitation of solids/liquids from the core, upward compaction onto the mantle from below

Note: The 3 mechanisms I am discussing today are not exhaustive!

Nature finds a way…

1: Basal Magma Ocean



Labrosse et al., 2007

Note 1: Crystallization with $MgSiO_3$ -Bridgmanite on the liquidus leads to residual liquid depleted in SiO_2 and enriched in FeO

Note 2: Compared to subduction, fractional crystallization of a large magma body is a FAR more effective way to increase H concentration at the CMB.

2: “Suction?”

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L02310, doi:10.1029/2005GL025009, 2006

Suction mechanism for iron entrainment into the lower mantle

Ravi V. S. Kanda[1] and David J. Stevenson[2]

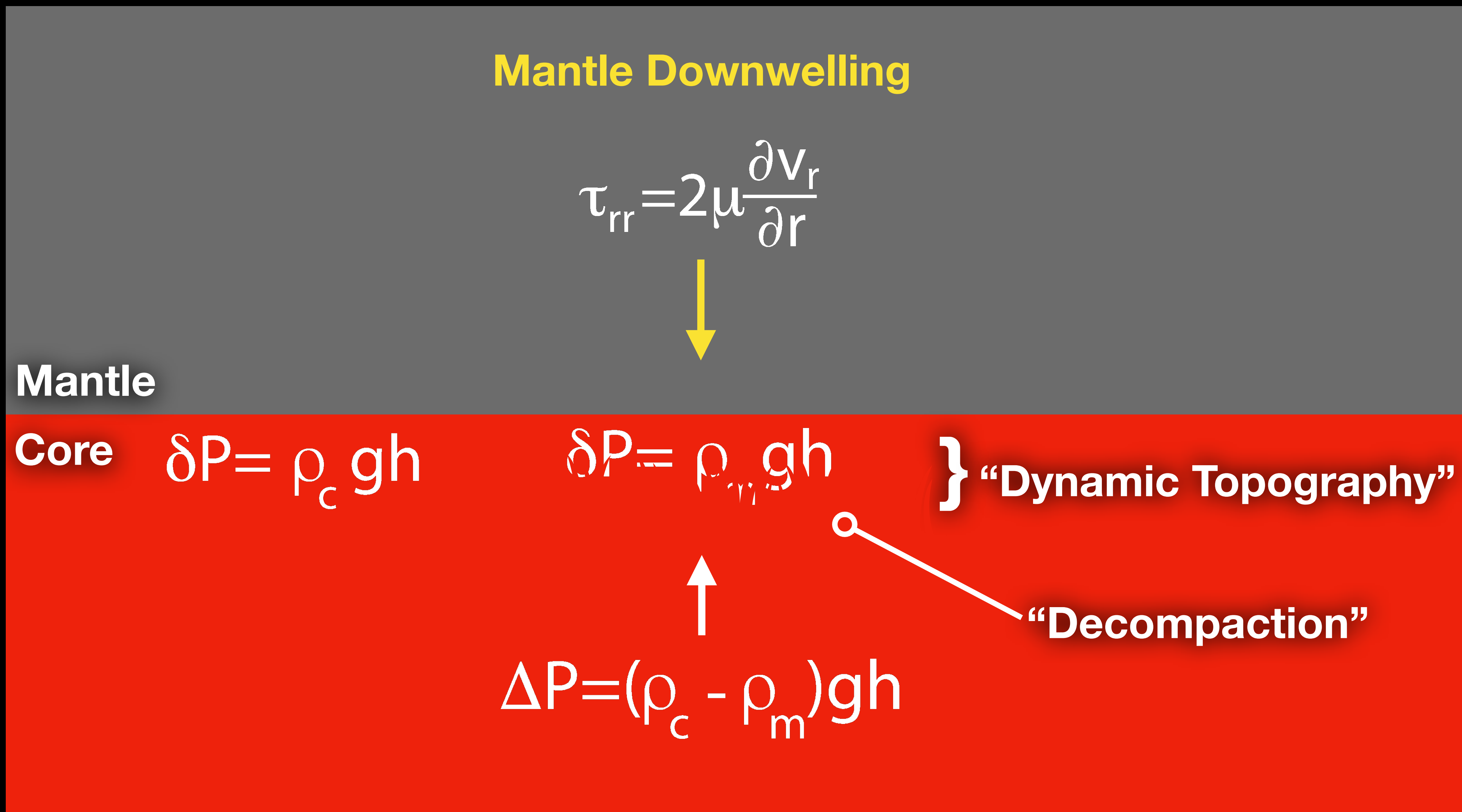
Received 19 October 2005; revised 7 December 2005; accepted 13 December 2005; published 25 January 2006.

[1] Perturbations in the Earth’s rotation rate at decadal time periods strongly favor the existence of dissipative coupling at the Core–Mantle Boundary (CMB). Here, we explored the plausibility of maintaining a conducting layer on the mantle-side of the CMB, which can couple the outer core and mantle through Lorentz torques. We propose a suction mechanism that maintains a porous medium on the mantle side of the CMB, with the interconnected pore-space partly or entirely filled with liquid iron up to a thickness of ~1 km. The suction arises from the deviatoric stresses supported by the mantle-solid in regions of mantle downwelling. Infiltration of liquid iron occurs by percolation, but is inhibited by the rate of viscous dilation of the solid mantle. Our model enables core-mantle material exchange, and maintains a thin conducting layer that has seismic detection potential. Our model is only marginally satisfactory in explaining the inferred CMB coupling.

Citation: Kanda, R. V. S., and D. J. Stevenson (2006), Suction mechanism for iron entrainment into the lower mantle, *Geophys. Res. Lett.*, *33*, L02310, doi:10.1029/2005GL025009.

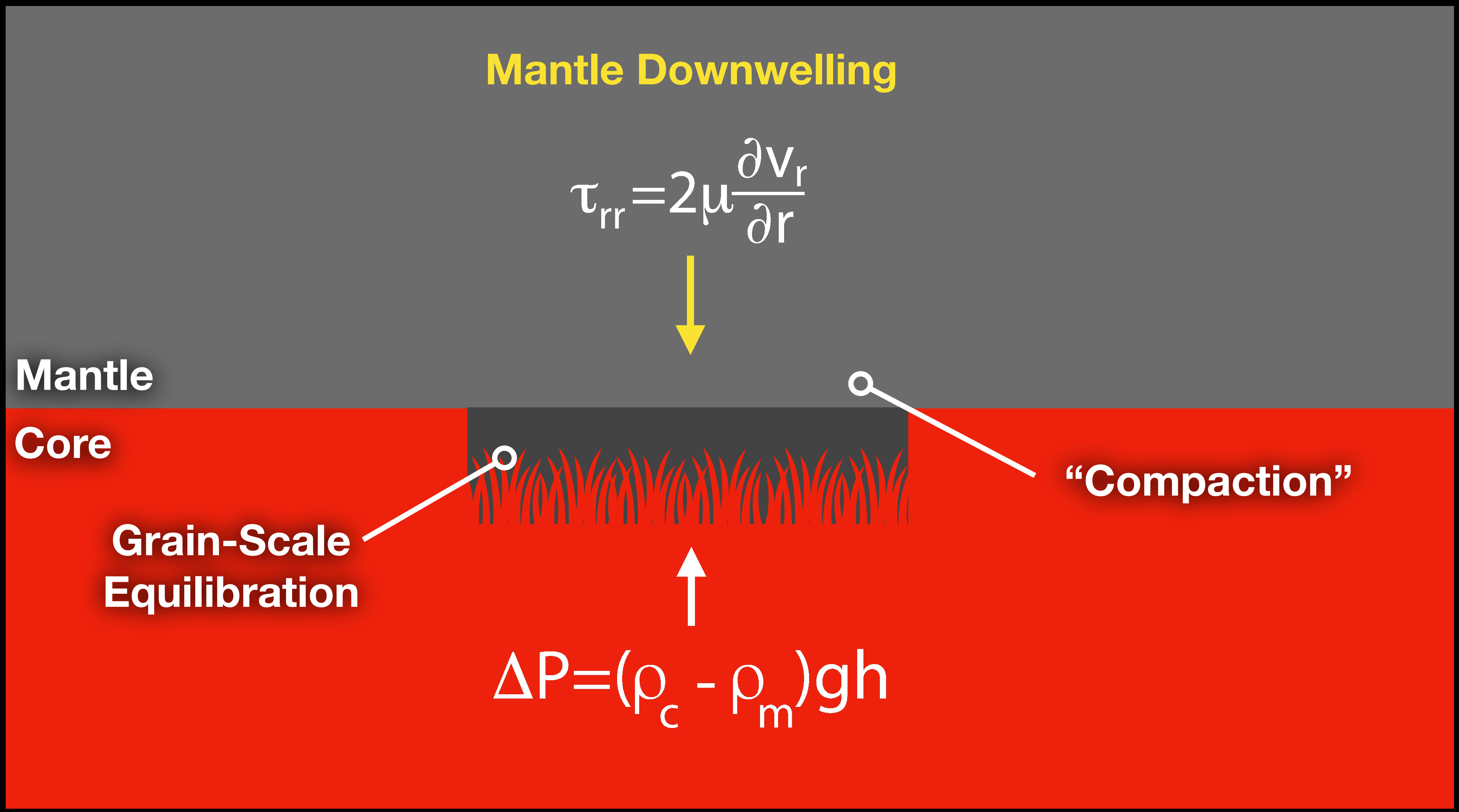
core and mantle through Lorentz torques associated with eddy currents. The conductance of this layer - defined as the product of conductivity and thickness of the conducting layer in some average sense - strongly influences the total Lorentz torque at the CMB [*Holme*, 1998a, 1998b]. A coupling-torque of $\sim 10^{17}$ Nm, inferred from matching nutation theory to VLBI data, requires that this layer have a conductance of 10^8 S or greater [*Buffett*, 1992]. Also, given that this layer is of the order of a kilometer or less, it must have metallic conductivities. If we define the mantle geodetically then it must include all materials that move almost rigidly with the mantle (irrespective of composition) and the conducting layer must lie on the mantle side of the CMB. It could nonetheless have formed by upward sedimentation of material from the core, as proposed by *Buffett et al.* [2000]. Their model requires either very small (sub-micron) grain size for the silicate sediments to trap iron (thereby making the permeability very low) or a very high compaction viscosity (thereby preventing the iron from escaping despite assuming high permeability). The model we describe below is an antithesis

“Suction” Explained

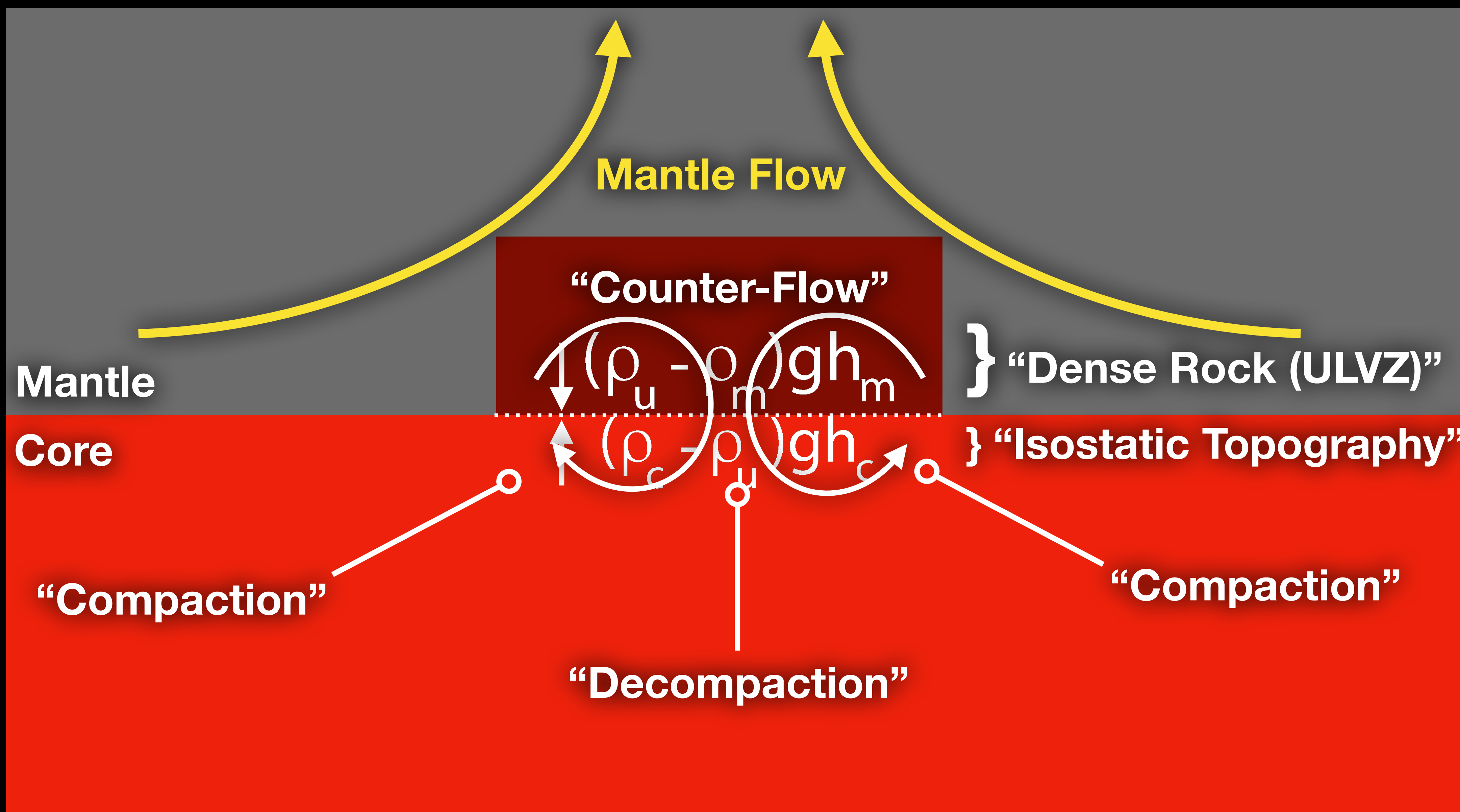


Kanda & Stevenson (2006)

“Suction” Explained



ULVZ Scenario



Hernlund & Tackley (2007), Hernlund & Jellinek (2010)

Size of Suctioned Region

- **Dynamic Topography:** ~100-1000 m variations produced by ~10-100 MPa viscous mantle stresses

- **Isostatic Topography:** h_c ~ 1 km for 10 km thick ULVZ with 10% higher density than “normal” PREM mantle. Similar for LLSVP scale structures.

- **Sum of Topography:** CMB has both contributions, and also smaller scale variations. It is straightforward to dip ~1 km of mantle into the core.

Time Scale for Equilibration?

$$Time \sim \frac{L^2}{D}$$

L ← Grain Size

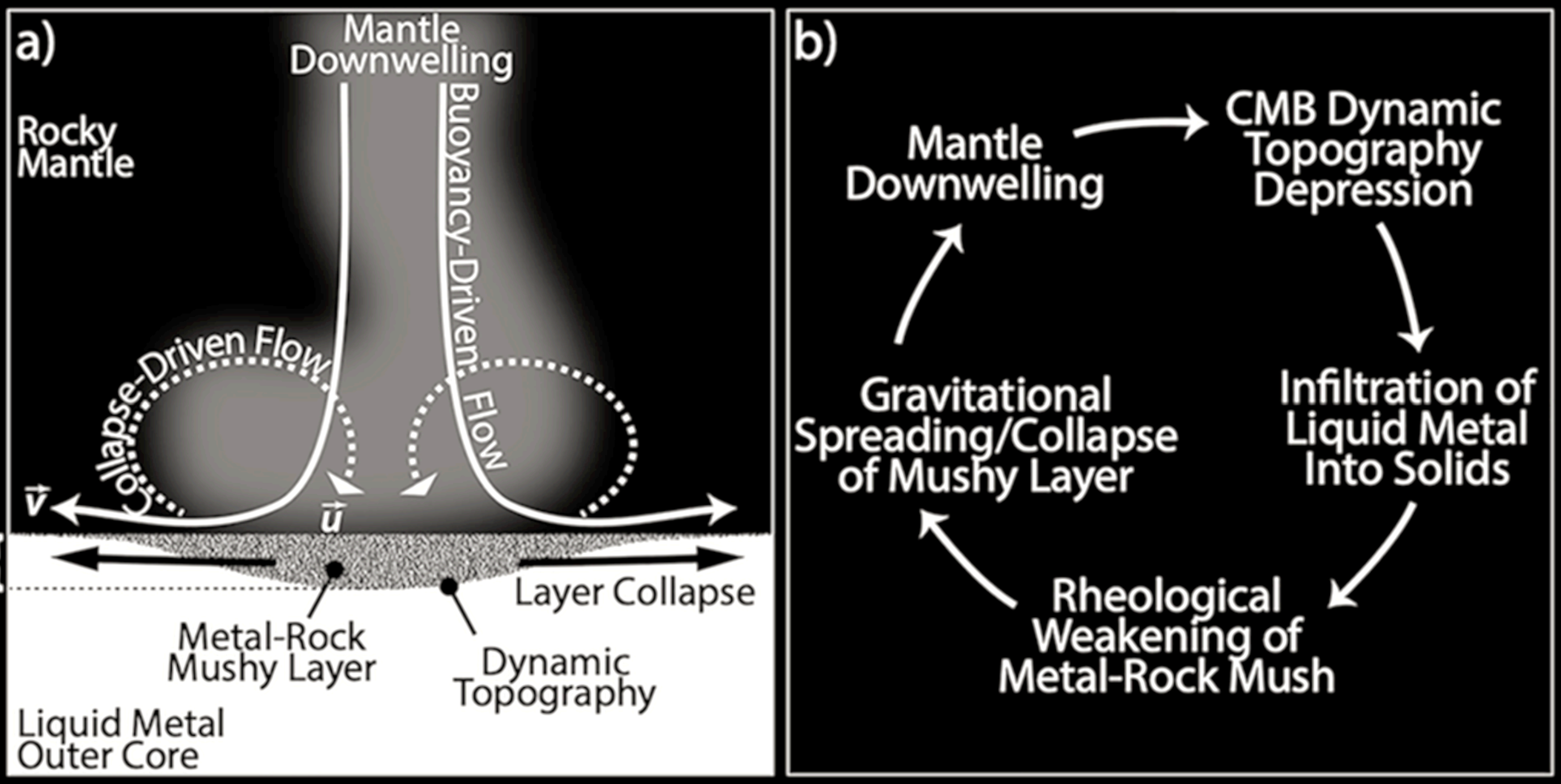
D ← Diffusivity

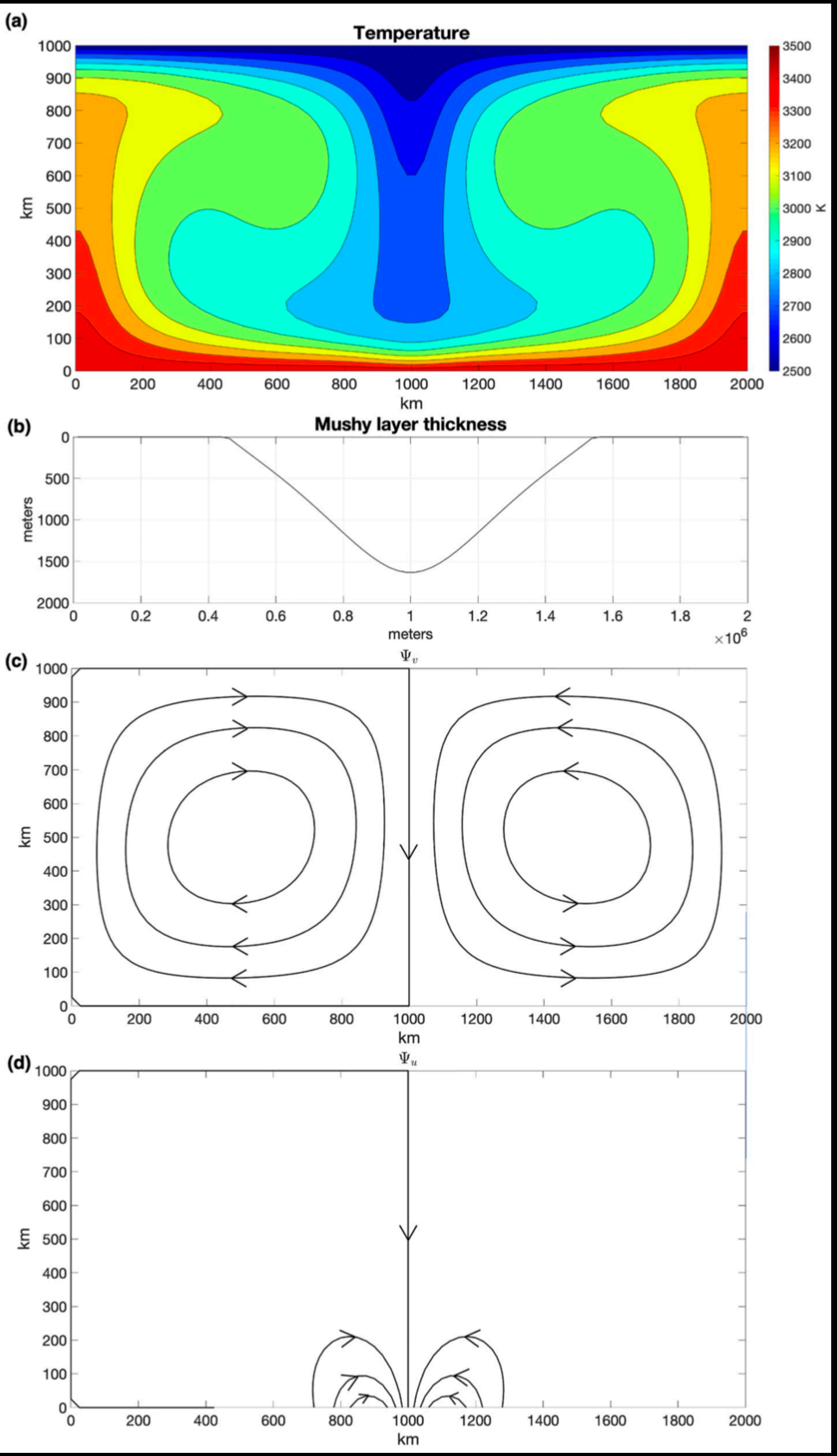
For $L \sim 1$ cm and $D \sim 1e\text{-}16$ m^2/sec

$Time \sim 10{,}000$ years

Note: These are NOT generous parameters

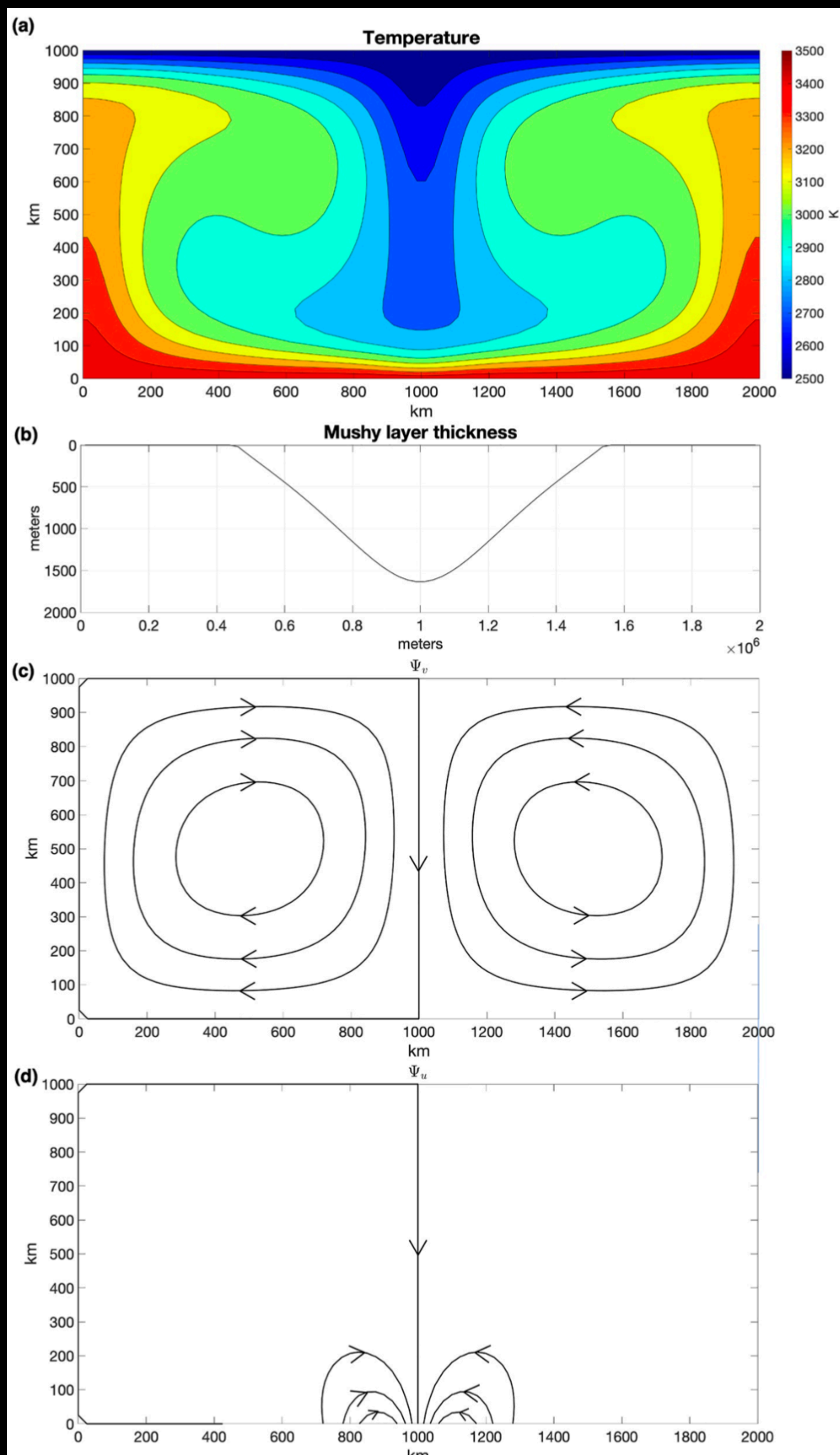
Gravitational Collapse of Mush Enhances CMCI

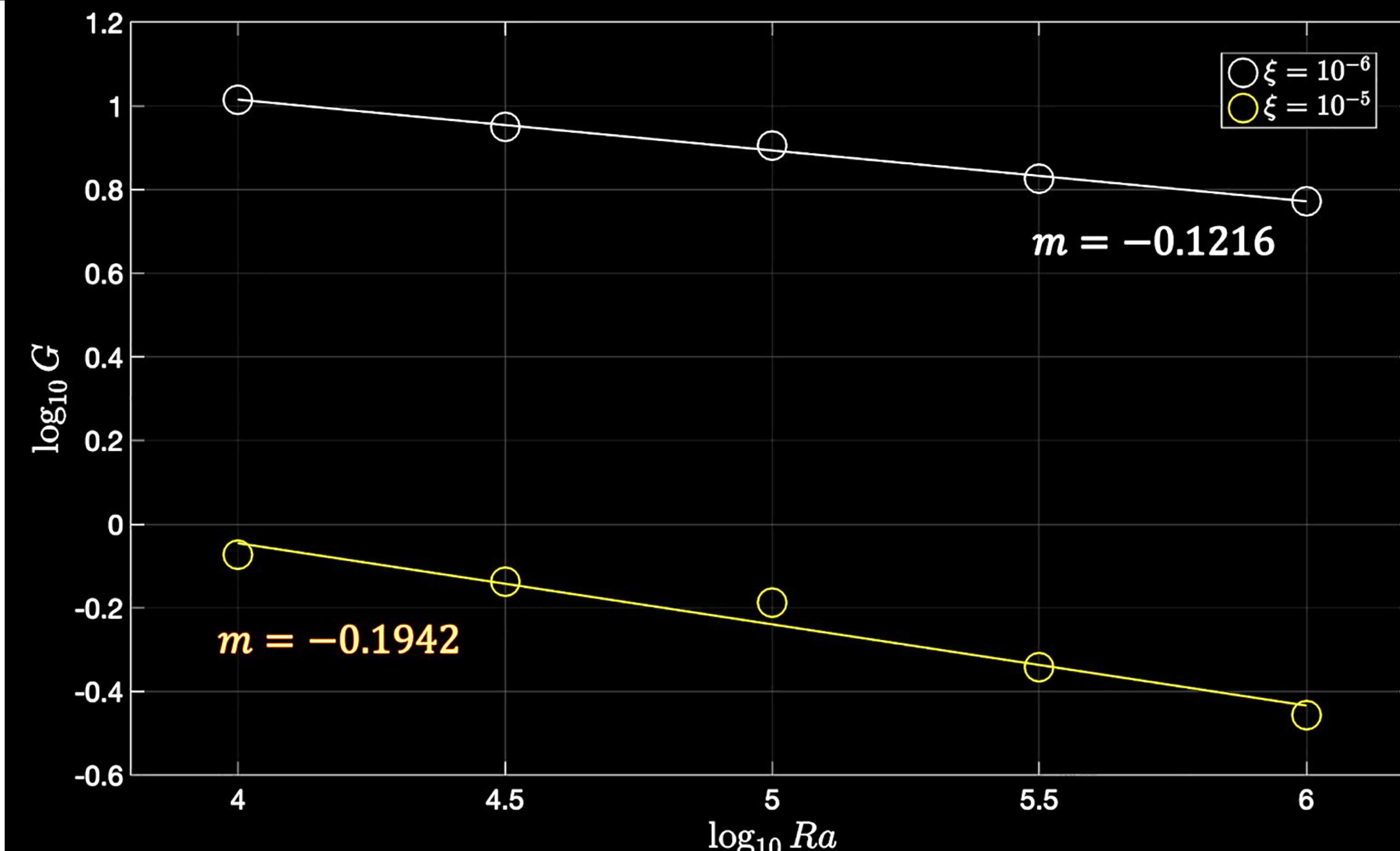




Lim et al., GRL (2021)

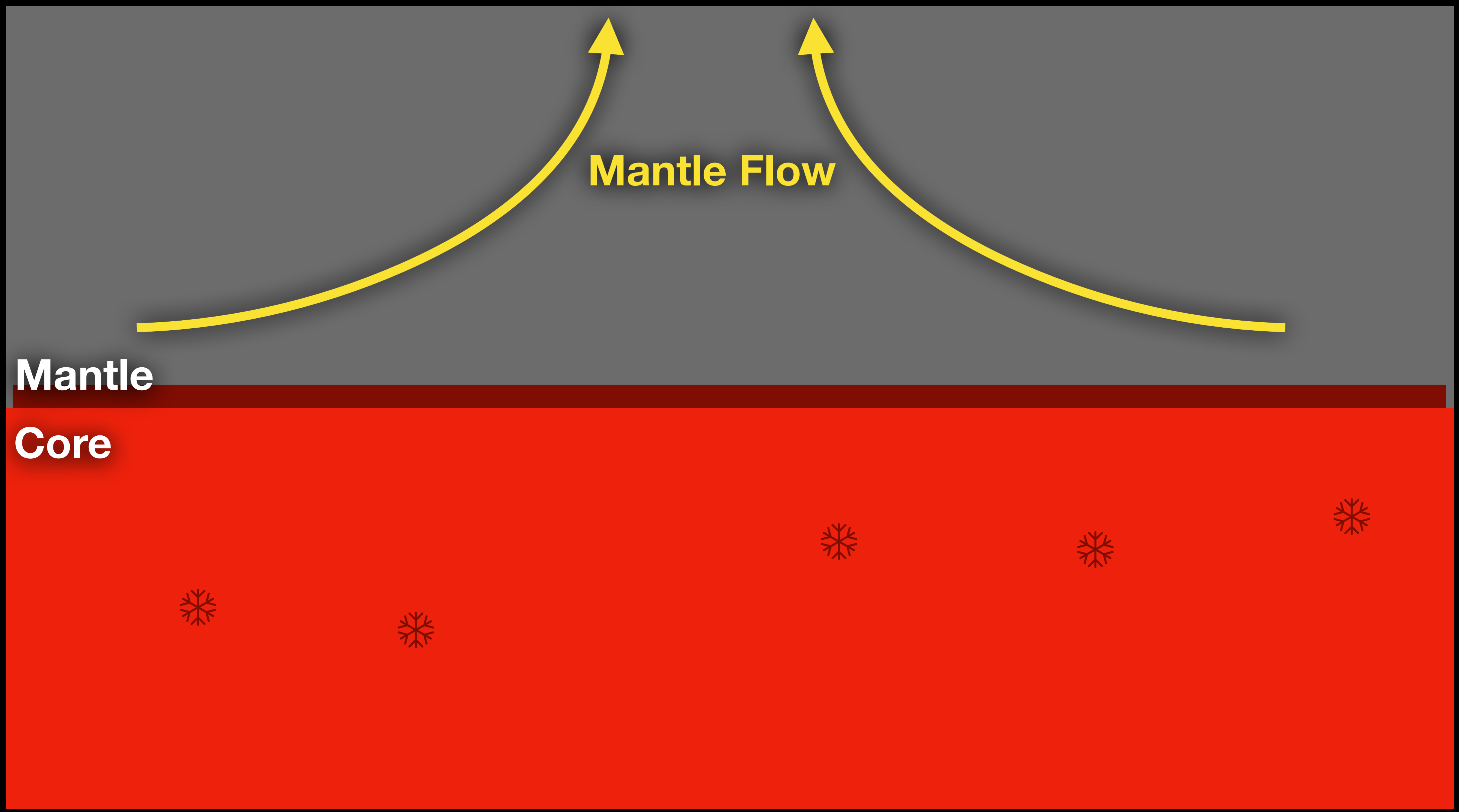
Mush Collapse Drives Small Scale Convection, Increases Core-Mantle Interaction





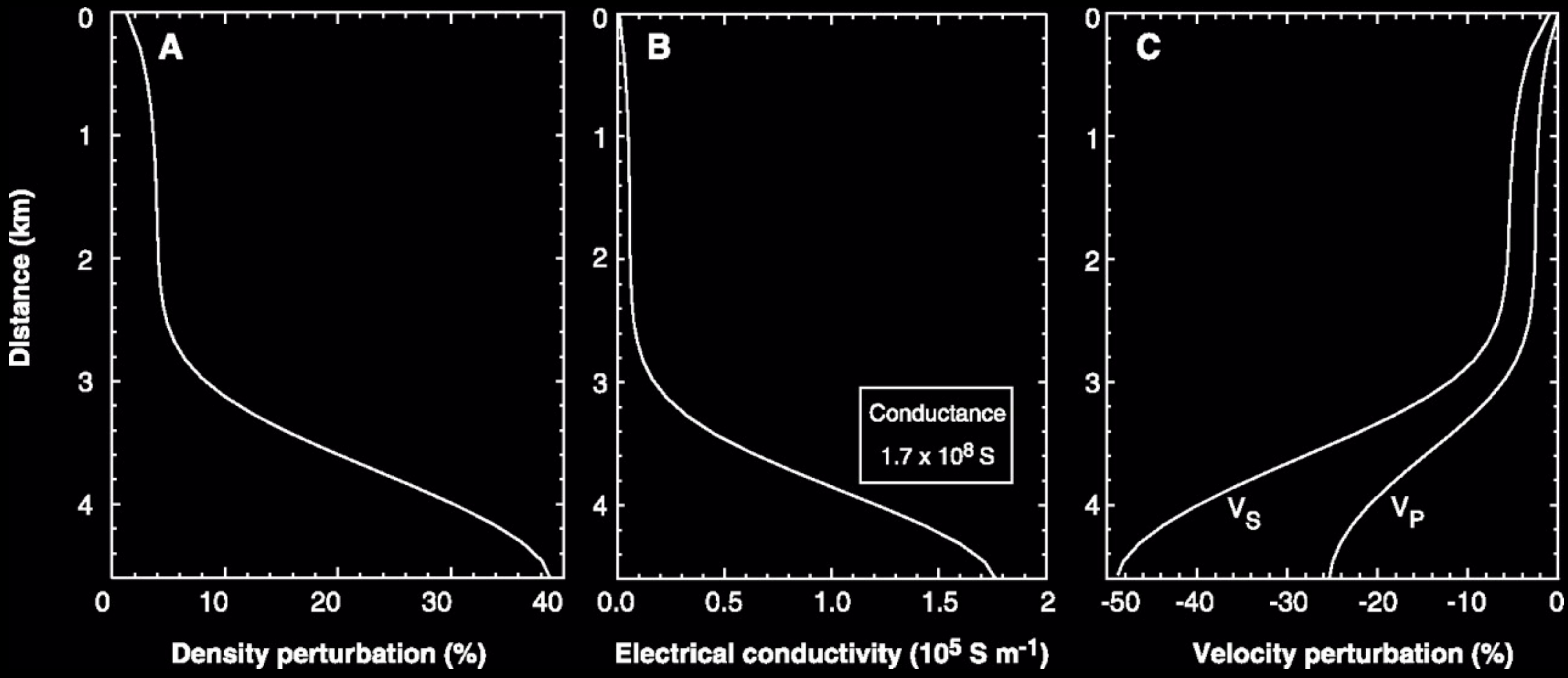
Lim et al., GRL (2021)

3: Core Sedimentation



e.g., Buffett et al., (2000); Helffrich et al., (2018)

Sediment Compaction



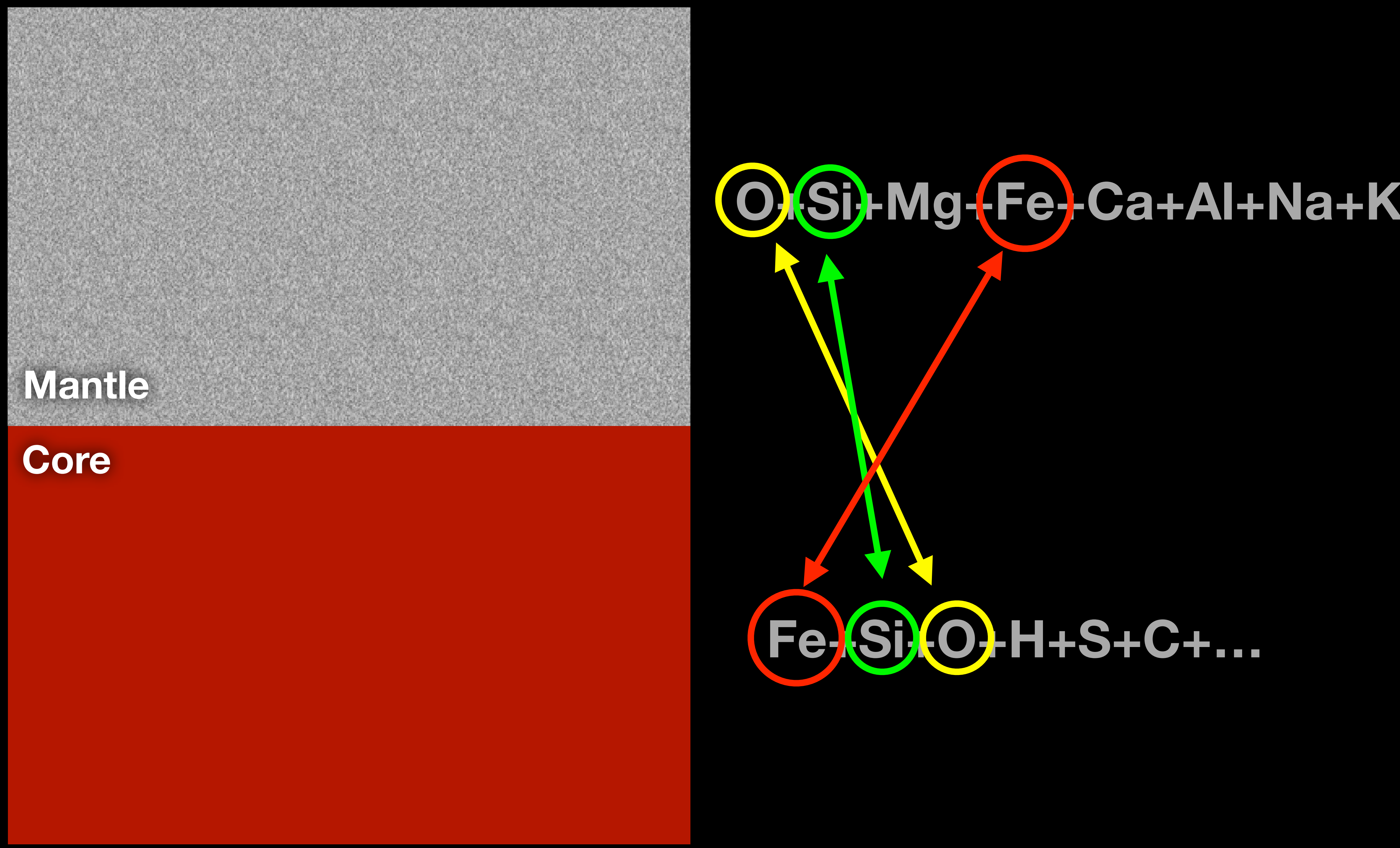
Buffett et al., (2000)

Note: This model only retains enough metal to explain core-mantle angular momentum exchange if the grain size is ~microns or smaller!

3 Mechanisms Summary

	1. BMO	2. Suction	3. Sediments
Timing of Interaction	Melt: First~1 Gyr Resid. Layers: Recent	Dynamic: Recent Isostatic: Ancient	Any time
Volume of Mantle Involved	Up to ~1/4 mantle	Up to ~1% of the mantle	Up to ~1% of the mantle
3-He/4-He Issues	U+Th Enrichment in BMO?	Small He concentration in core?	Small He concentration in core?
182-W Issues	Original Hf/W in BMO?	Small Volumes?	Small Volumes?
D/H Issues	Liquid-Liquid Fractionation?	Solid-Liquid Fractionation?	Solid-Liquid Fractionation?
Excess Siderophiles?	No Residual Metal Expected	Residual Metal After Compaction?	Residual Metal After Compaction?
Lithophile Fractionation?	Can explain low $^{142}Nd/^{144}Nd$	Additional Process Needed to Explain	Additional Process Needed to Explain

Core-Mantle Major Element Exchange



Core-Mantle Chemical Equilibria: The Big Players

Mantle (Rock & Magma): **Core (Metal Alloy):**

Core Segregation →

← *Secular Cooling*

$$FeO \leftrightarrow Fe + O$$

Magma Fractionation →

← *Exsolution*

← *Inner Core Crystallization*

Core Segregation →

← *Secular Cooling*

$$SiO_2 \leftrightarrow Si + 2O$$

← *Magma Fractionation*

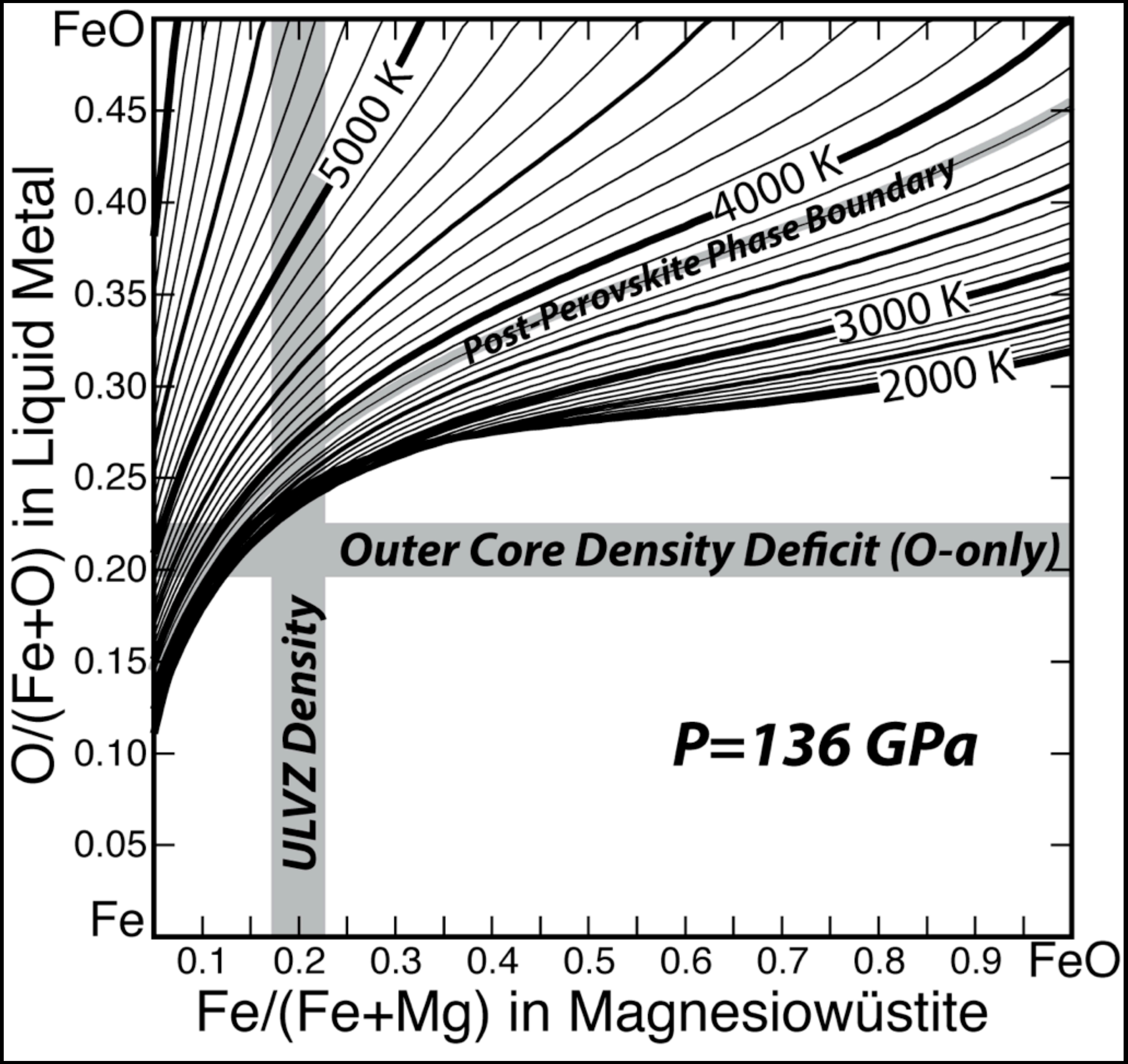
← *Exsolution*

← *Inner Core Crystallization*

Naha (Okinawa) Great “Tug of War” Festival

https://visitokinawajapan.com/discover/events/naha-tug-of-war-festival/

$FeO \longleftrightarrow Fe + O$



Model of Frost et al., (*JGR*, 2010)

ELSEVIER

Earth and Planetary Science Letters

Volume 257, Issues 3–4, 30 May 2007, Pages 435-449

Partitioning of FeO between magnesiowüstite and liquid iron at high pressures and temperatures: Implications for the composition of the Earth's outer core

Y. Asahara, D.J. Frost, D.C. Rubie

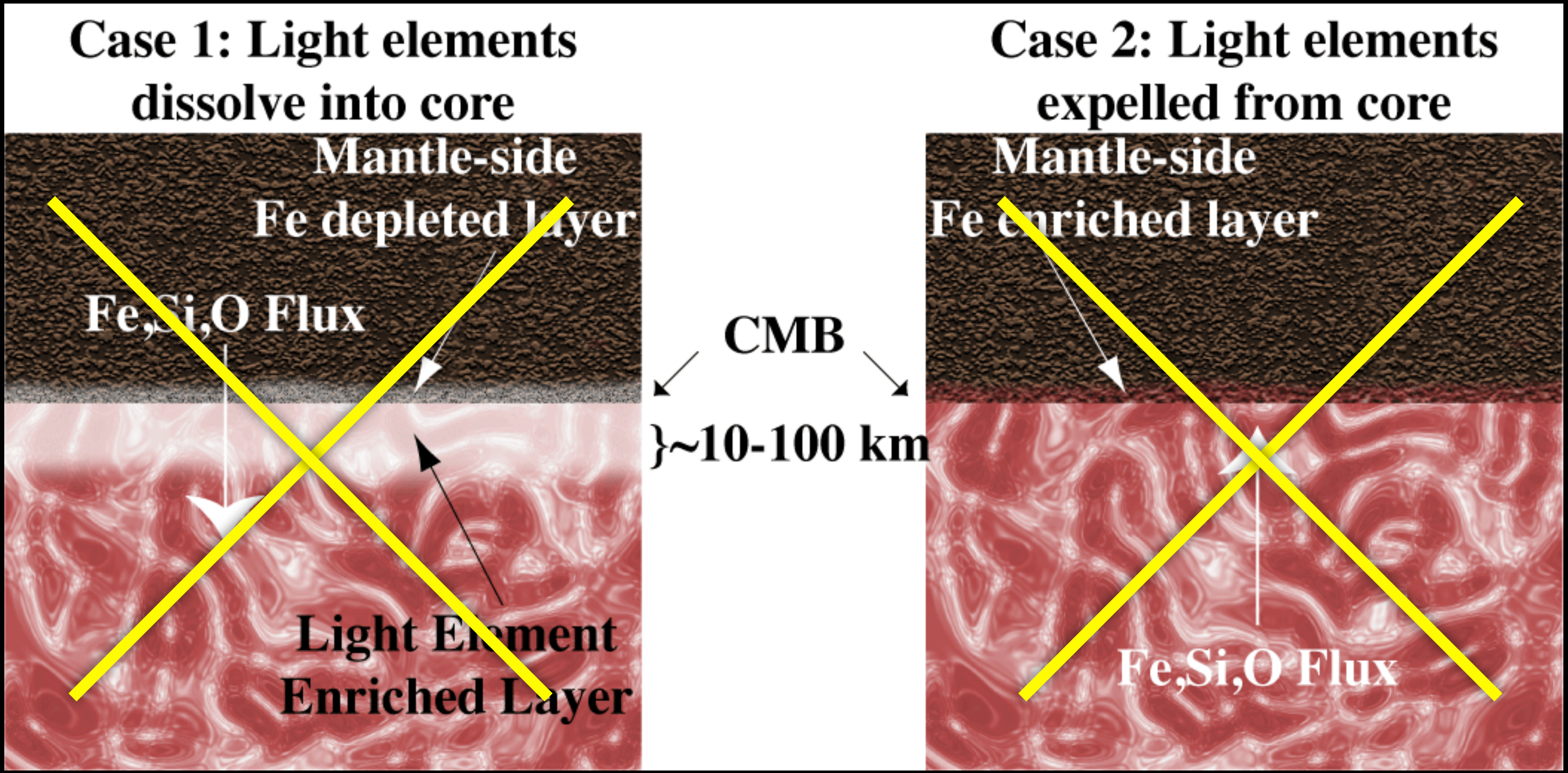
Show more

https://doi.org/10.1016/j.epsl.2007.03.006

Abstract

Although oxygen is a possible light element in the Earth's core, the effect of pressure on the concentration of this element in metallic iron has been a controversial issue for the last 20 yr. Completely opposite pressure effects have been advocated based on studies of phase relations and element partitioning, respectively. Here we report new data on the partitioning of FeO between magnesiowüstite and liquid iron over a wide pressure–temperature range (3–25 GPa and 2273–3200 K). The proportion of FeO partitioning into liquid iron decreases with increasing pressure below 10 GPa but increases with increasing pressure above 10–15 GPa. The change in the pressure effect is caused by the Fe + O component having different compressibilities in magnesiowüstite and liquid Fe respectively. The new experimental data, together with results from previous studies obtained over a wide *P*–*T* range (2–139 GPa, 2273–3150 K), have been fitted by a thermodynamic model that enables the results to be extrapolated to conditions of the outer core. Assuming core–mantle equilibrium, the results show that the outer core is undersaturated in oxygen, which causes a thin layer at the very base of the mantle to be strongly depleted in FeO. The results of core formation modeling indicate that oxygen is likely to be the main light element in the Earth's core (e.g. 7–8 wt.%) and that the FeO content of the proto-earth may have been similar to that of present day Mars (e.g. 18 wt.% FeO in the mantle).

Influence of Major Element Reactions on CMB Structure



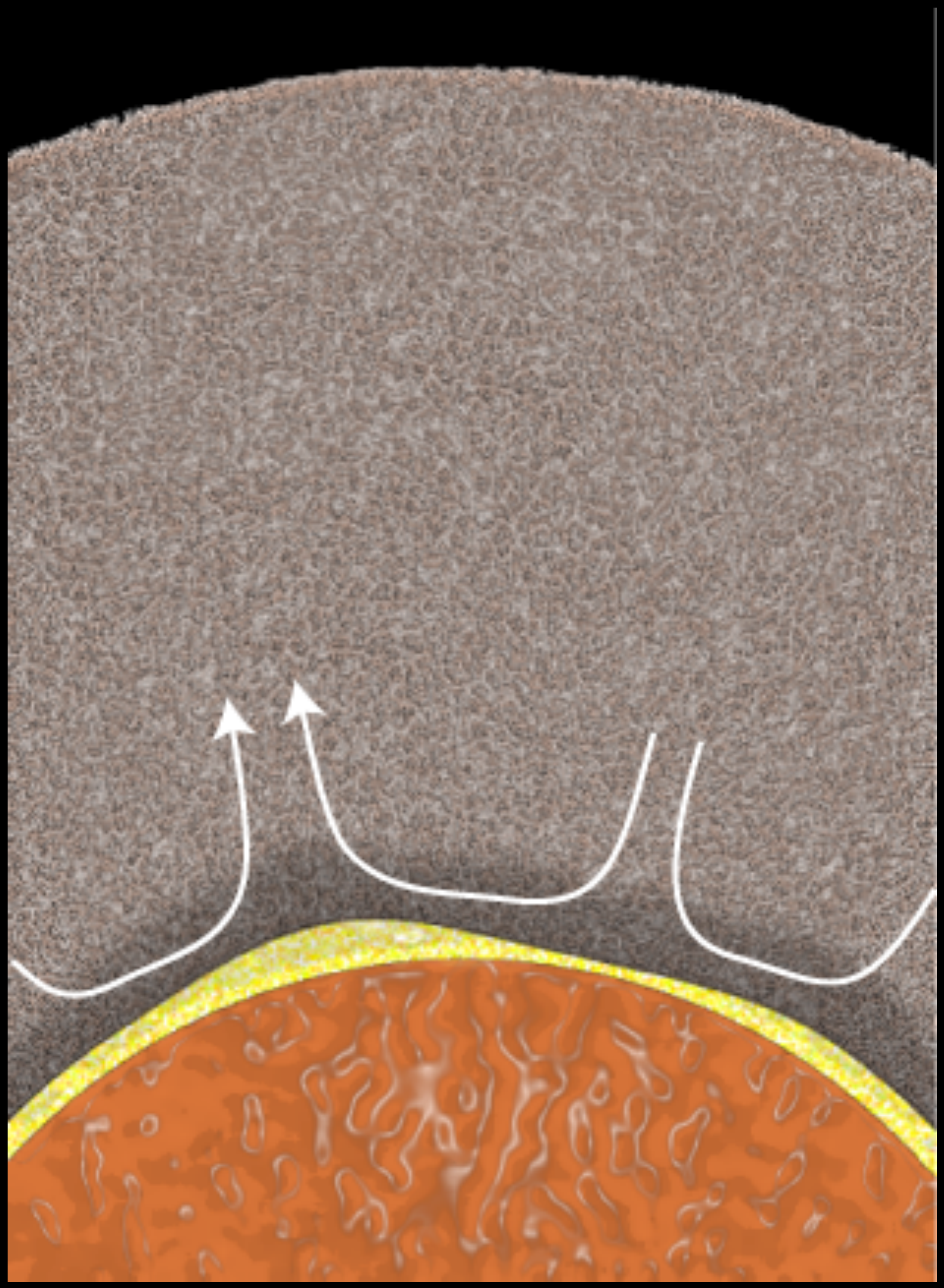
Knittle & Jeanloz (1991)
Asahara et alia (2007)

Problem: No FeO-rich ULVZ

Buffett, Garnero, & Jeanloz (2000)
Many Core Exsolution Papers

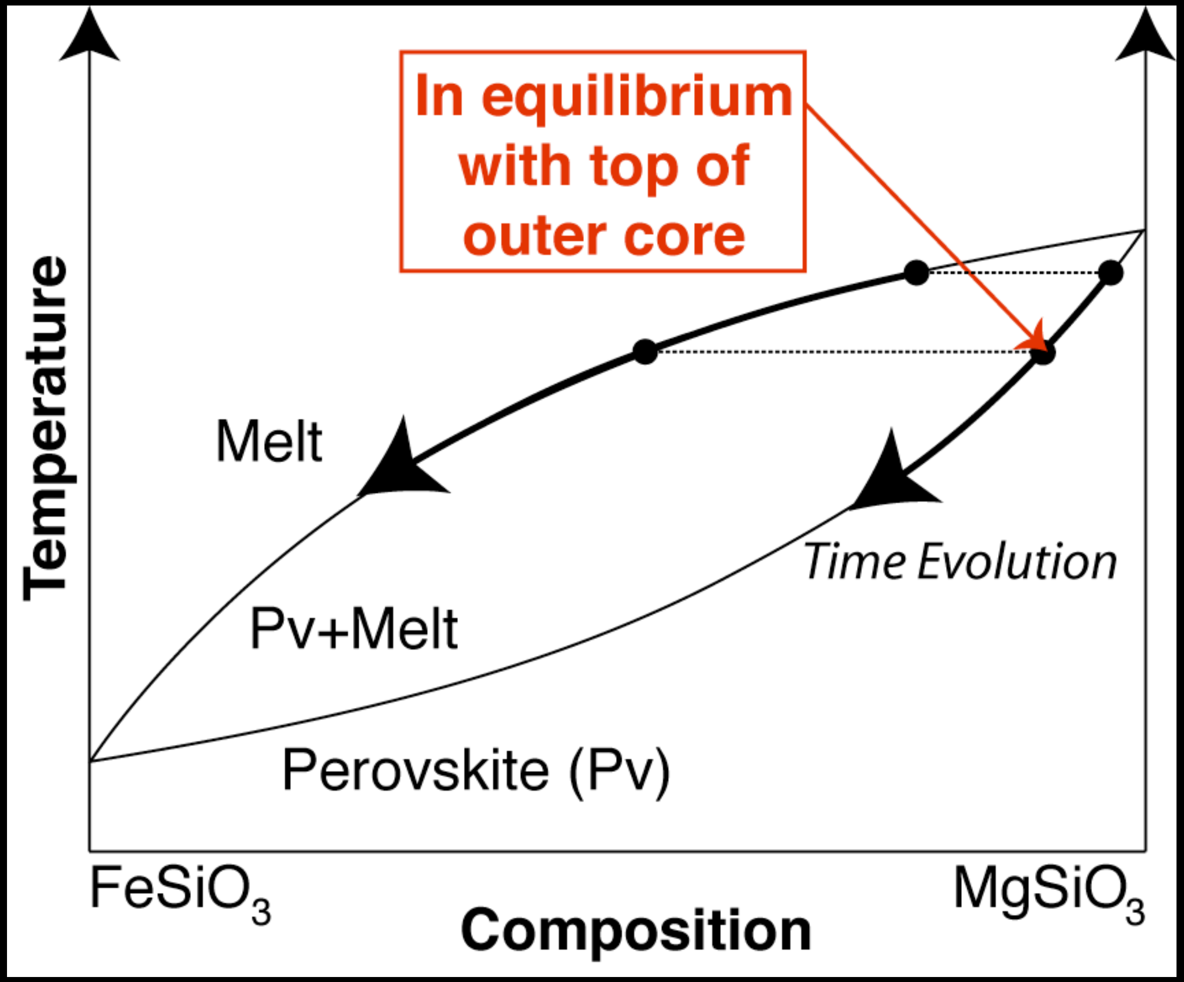
Problem: No Core Stratified Layer

Core-BMO Reaction Model



$$FeO^{Pe} \rightleftharpoons Fe^{M} + O^{M}$$
$$FeSiO_3^{Pv} \rightleftharpoons Fe^{M} + Si^{M} + 3O^{M}$$
$$MgSiO_3^{Pv} + FeO^{Pe} \rightleftharpoons FeSiO_3^{Pv} + MgO^{Pe}$$

Ozawa et al., *Phys. Chem. Minerals* (2009)



Core-Side Transport

Assume Stratification: Fick's Law Diffusion...

$$\frac{\partial X}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D\frac{\partial X}{\partial r}\right)$$

Flux Modified for Baro-Diffusion Effects...

$$-\frac{\partial X}{\partial r} \rightarrow -\frac{\partial X}{\partial r} + \frac{\left[(m_{Fe} - m_x) - \rho(V_{Fe} - V_x)\right] gX(1-X)}{k_B T}$$

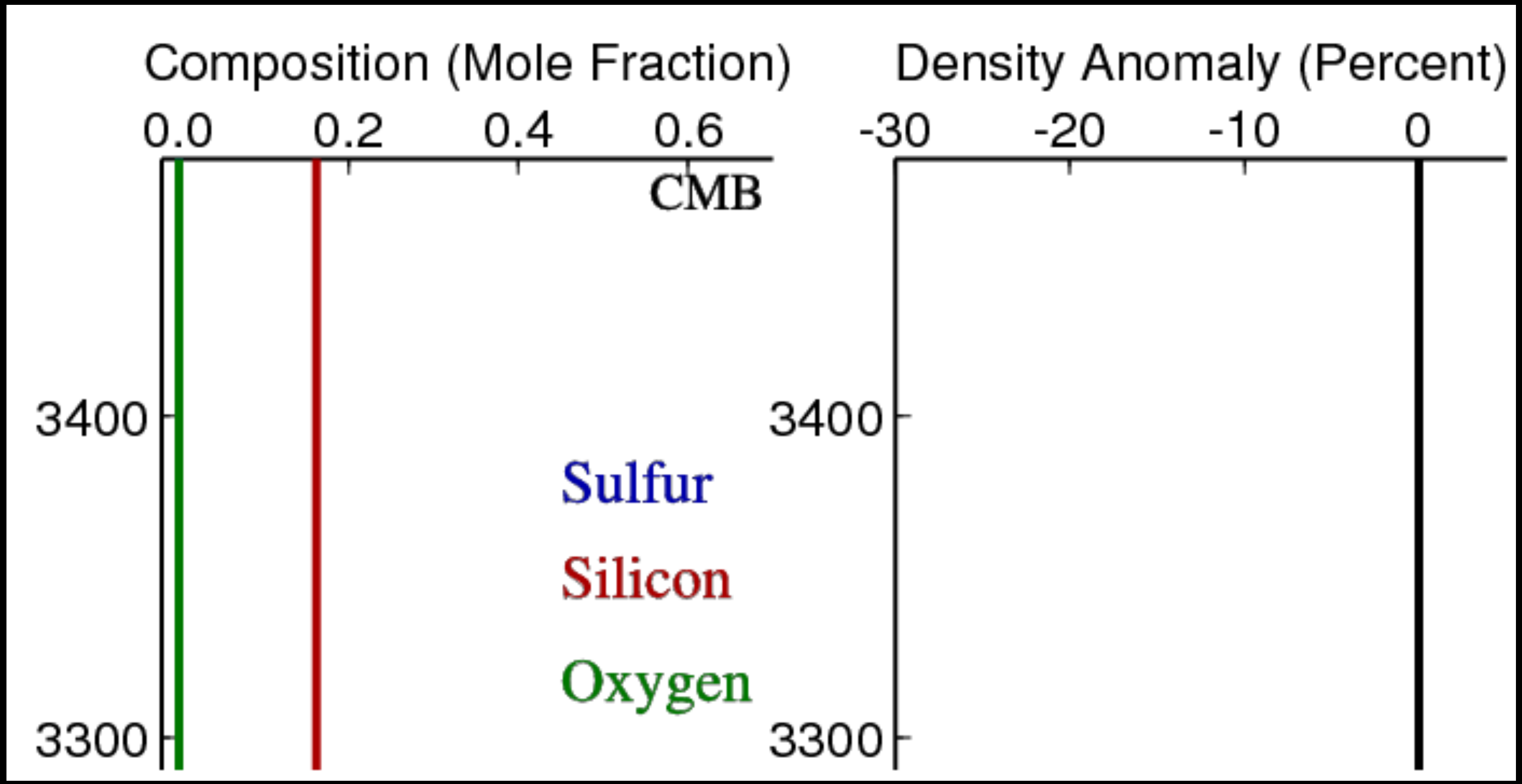
$$D_{Si} = 5 \times 10^{-9}\mathrm{m}^2/\mathrm{sec}$$
$$D_S = 5 \times 10^{-9}\mathrm{m}^2/\mathrm{sec}$$
$$D_O = 10 \times 10^{-9}\mathrm{m}^2/\mathrm{sec}$$

Alfé et al., *J. Chem. Phys.* (2002)
Gubbins et al., *Geophys. J. Int.* (2004)
Braginsky, *EPSL* (2006)

$$\mathrm{FeO}^{Pe} \rightleftharpoons \mathrm{Fe}^{M} + \mathrm{O}^{M}$$
$$\mathrm{FeSiO}_3^{Pv} \rightleftharpoons \mathrm{Fe}^{M} + \mathrm{Si}^{M} + 3\mathrm{O}^{M}$$
$$\mathrm{MgSiO}_3^{Pv} + \mathrm{FeO}^{Pe} \rightleftharpoons \mathrm{FeSiO}_3^{Pv} + \mathrm{MgO}^{Pe}$$

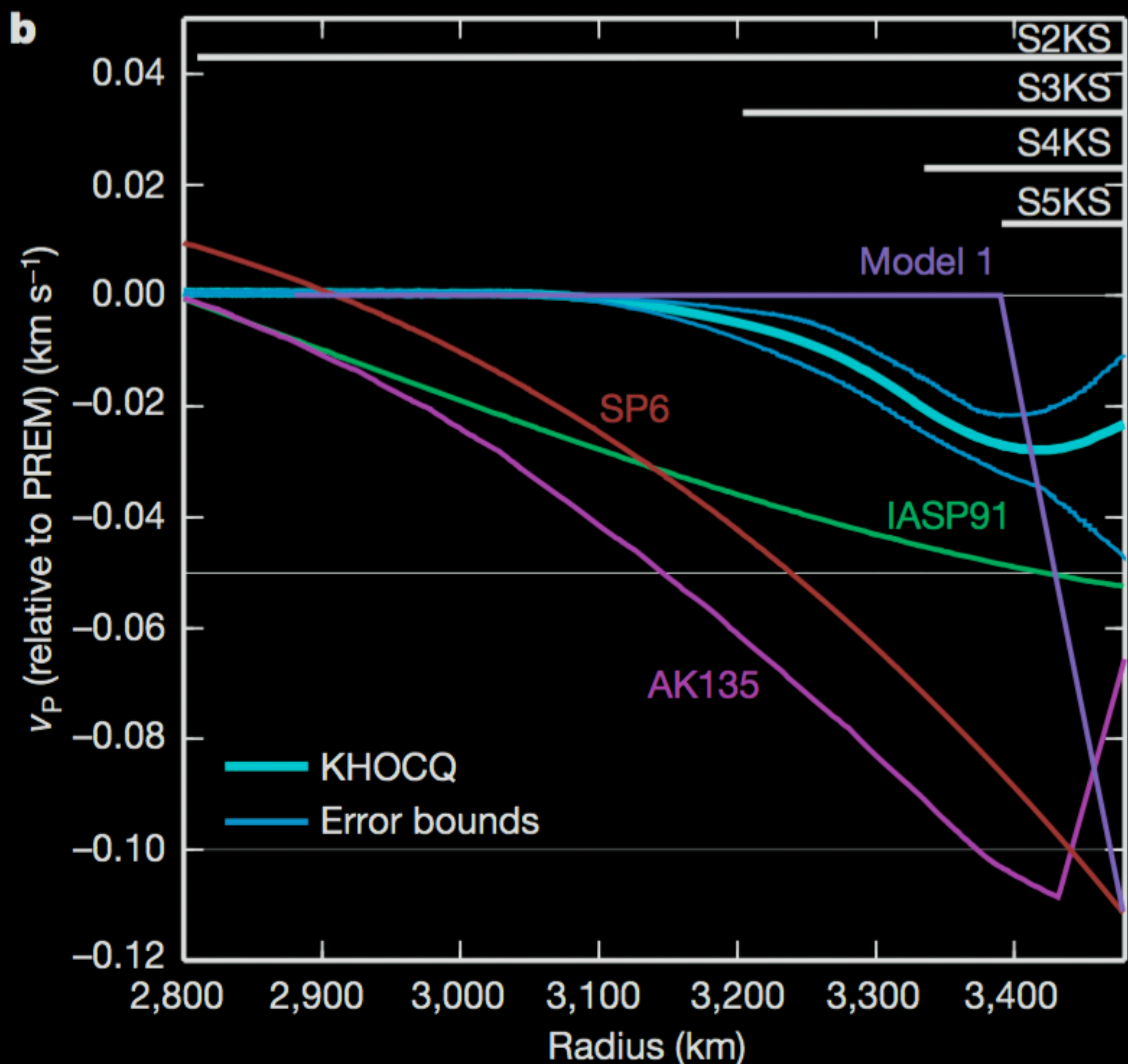
Ozawa et al., *Phys. Chem. Minerals* (2009)

Example: Initially Si-Rich Core



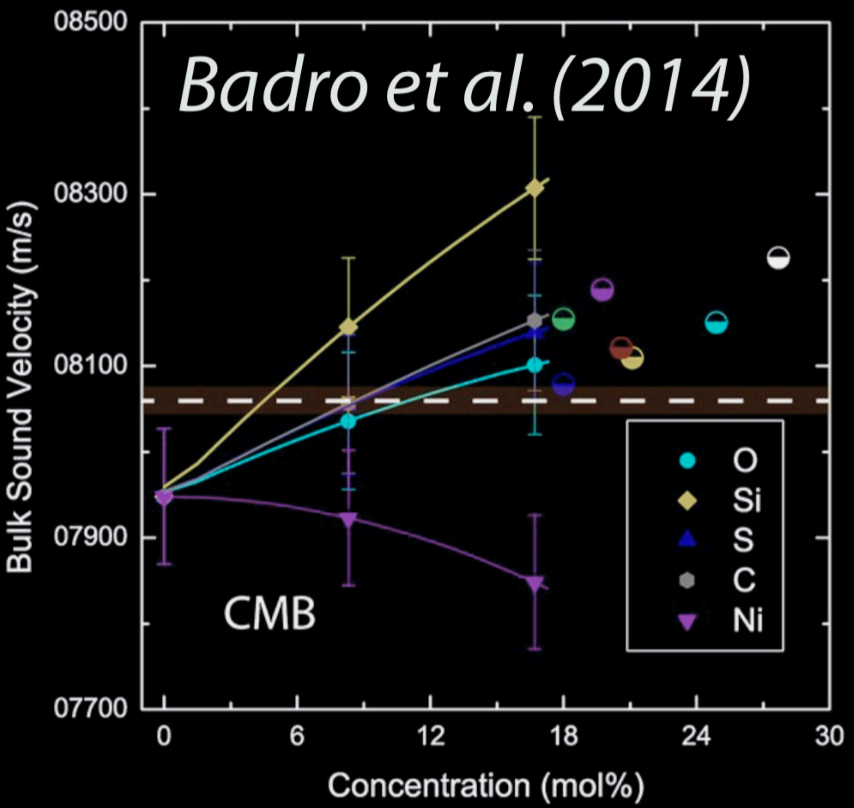
Time Evolution: 4.5 Billion Years

Negative Velocity Anomaly in Core Stratified Layer



Helffrich and Kaneshima (2010)

Effect on Core Seismic Velocity?



If *Si is abundant in the deep core, but depleted in the stratified layer, and oxygen is enriched in the stratified layer...*

Then *the influence of a BMO can explain the observed negative seismic velocity anomaly in the stratified layer.*

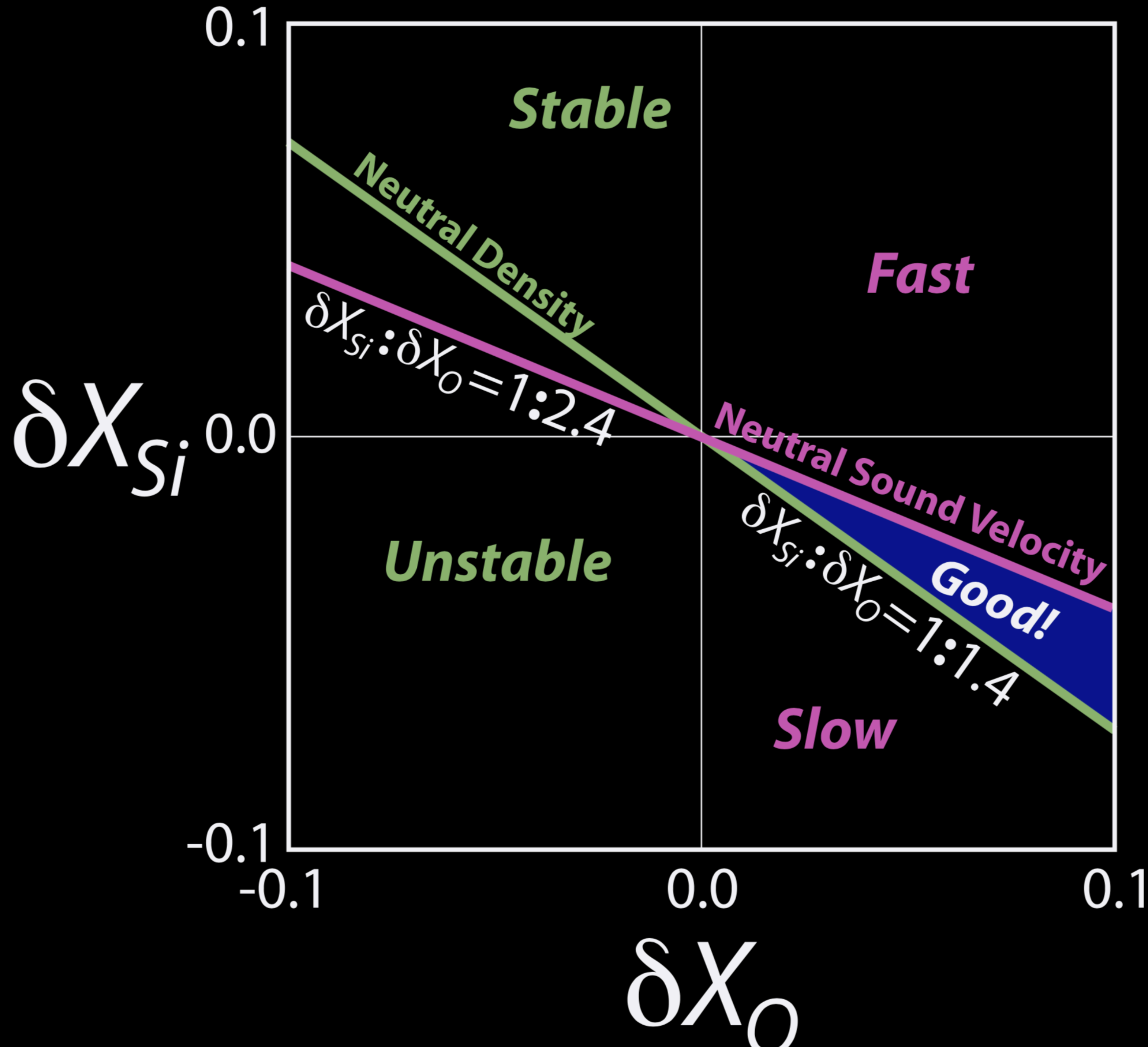
But *the range which also yields stable density atop the core is about 14-24 more atoms of O for every 10 atoms of Si removed*

Hernlund & Geissman (2016)

Badro & Brodholt (2017)

Note: Assumes linear mixing of components, but this is probably not safe in the Fe-Si-O system (e.g., Hirose et al., 2017)

Explains Low Velocity Atop Core?

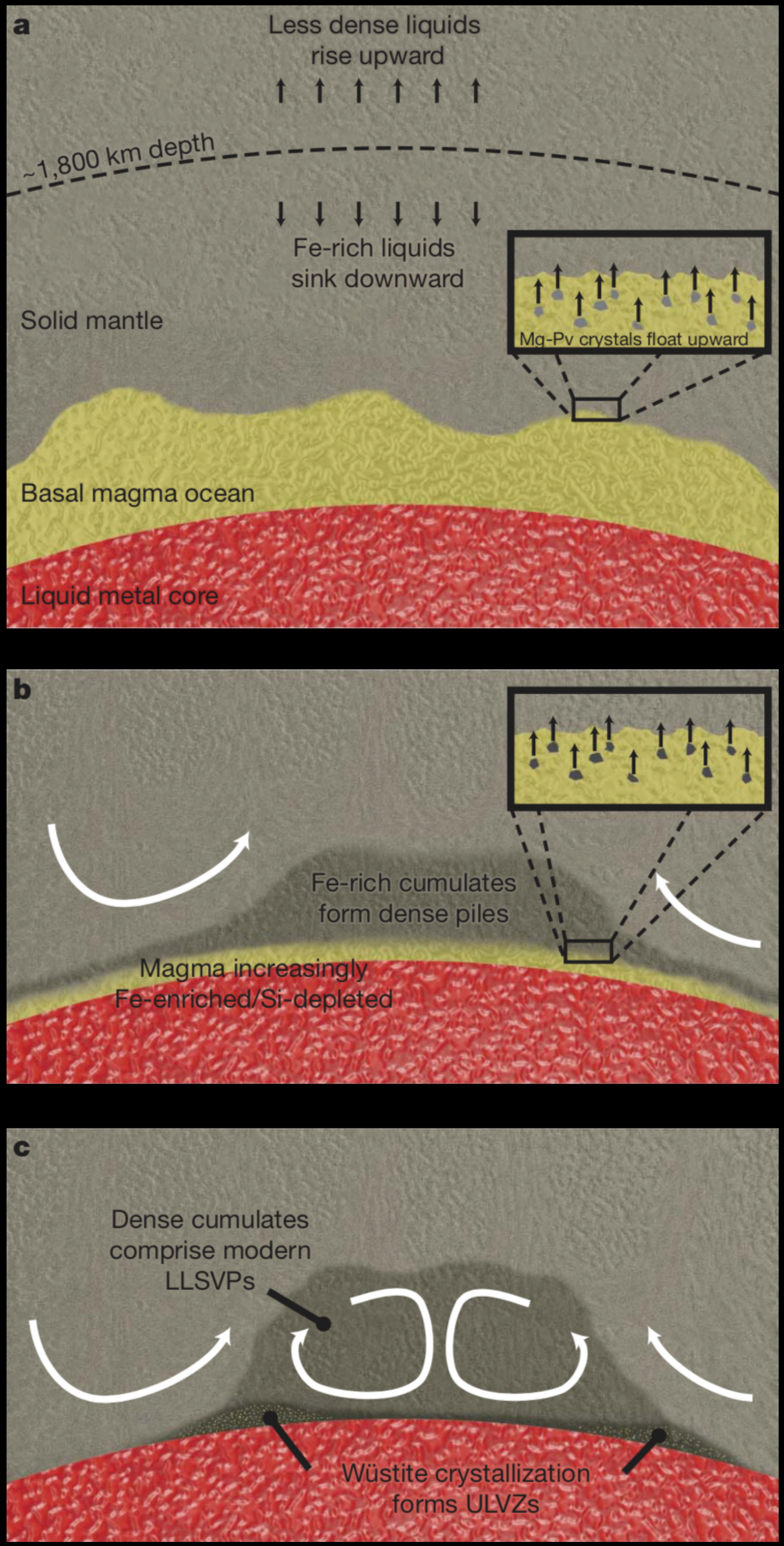


Hernlund & Geissman (2016)

Badro & Brodholt (2017)

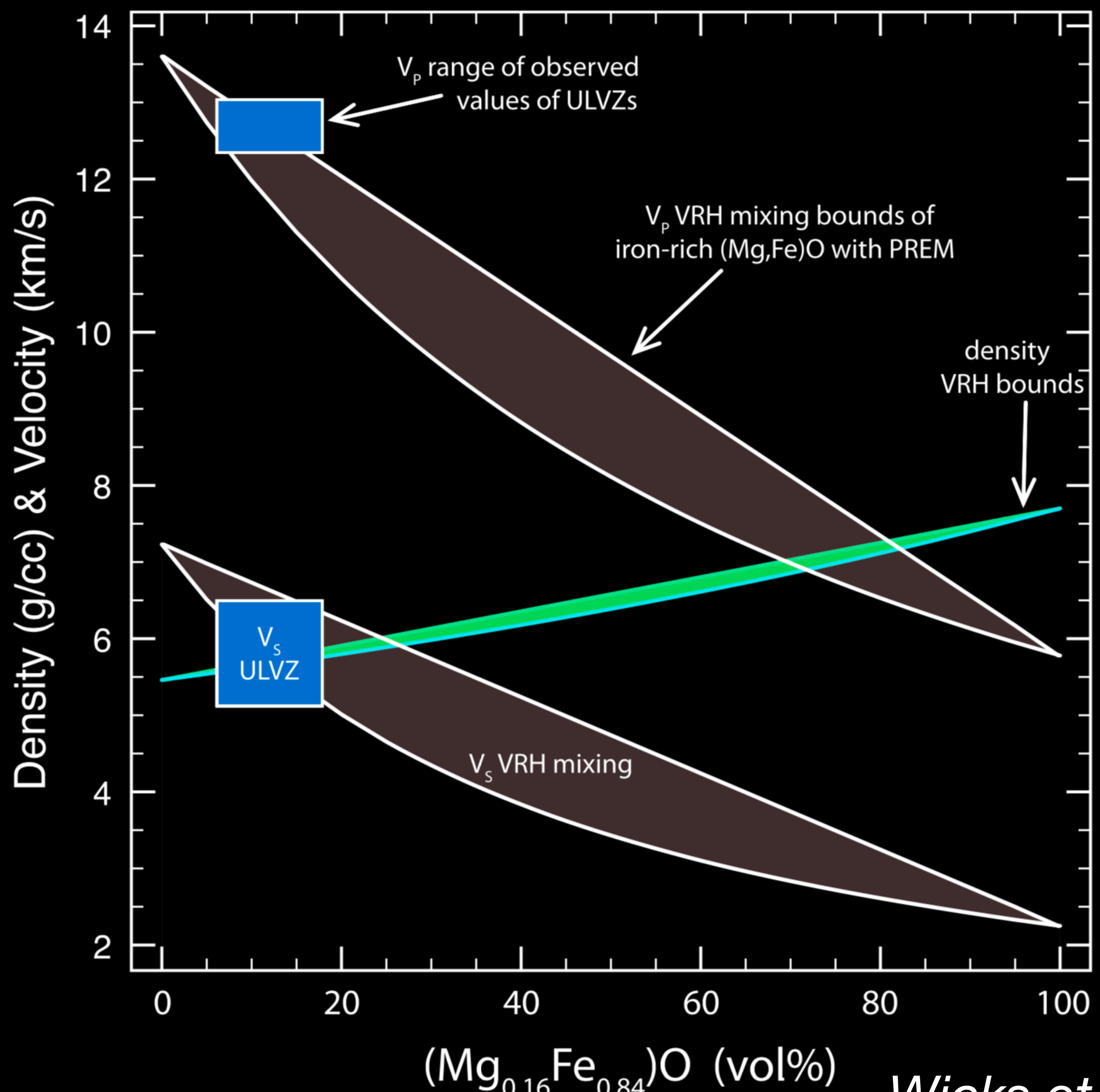
Maybe

What About Deep Mantle Structures?



Nomura et al., 2011

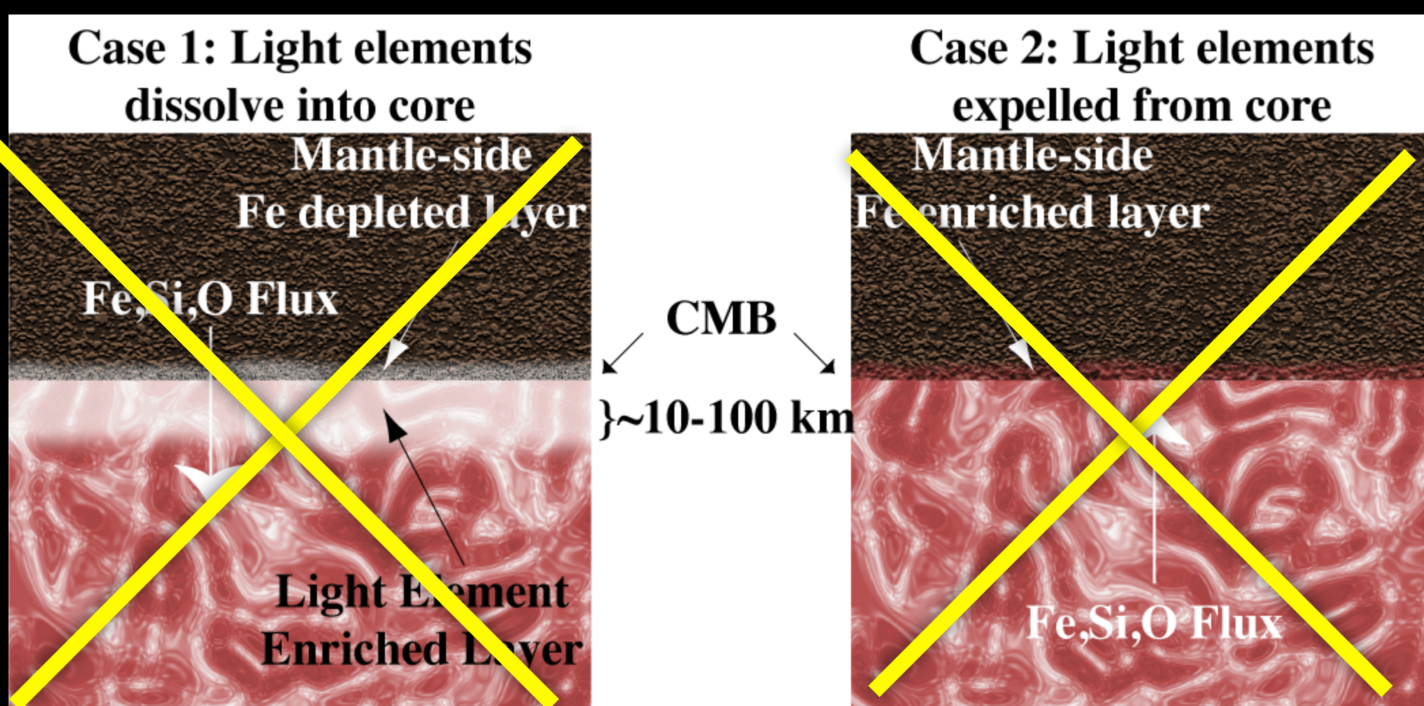
Fractional crystallization models predict that the residue becomes increasingly rich in FeO. Mineral physics models suggest a very good agreement between FeO-rich (wüstite) rocks and ULVZ properties.



Wicks et al., 2010

Influence of Major Element Reactions on CMB Structure

- Due to its ability to enrich the CMB in Fe+O *and* its uniquely opposite influence on Si and O movement between the core and mantle, BMO fractionation is able to explain both the presence of FeO-rich material (ULVZ) at the base of the mantle and an Si-depleted/O-enriched low velocity stratified layer atop the core.

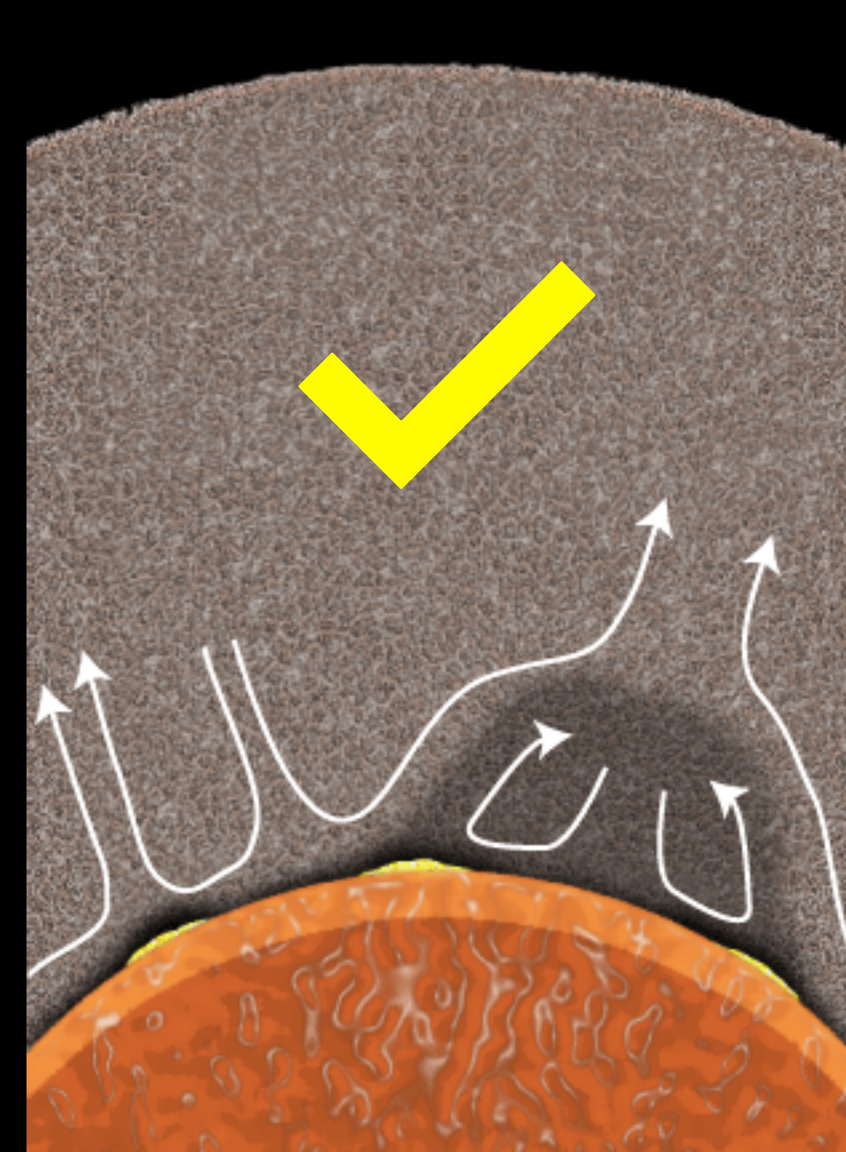


Knittle & Jeanloz (1991)
Asahara et alia (2007)

Buffett, Garnero, & Jeanloz (2000)
Many Core Exsolution Papers

Problem: No FeO-rich ULVZ

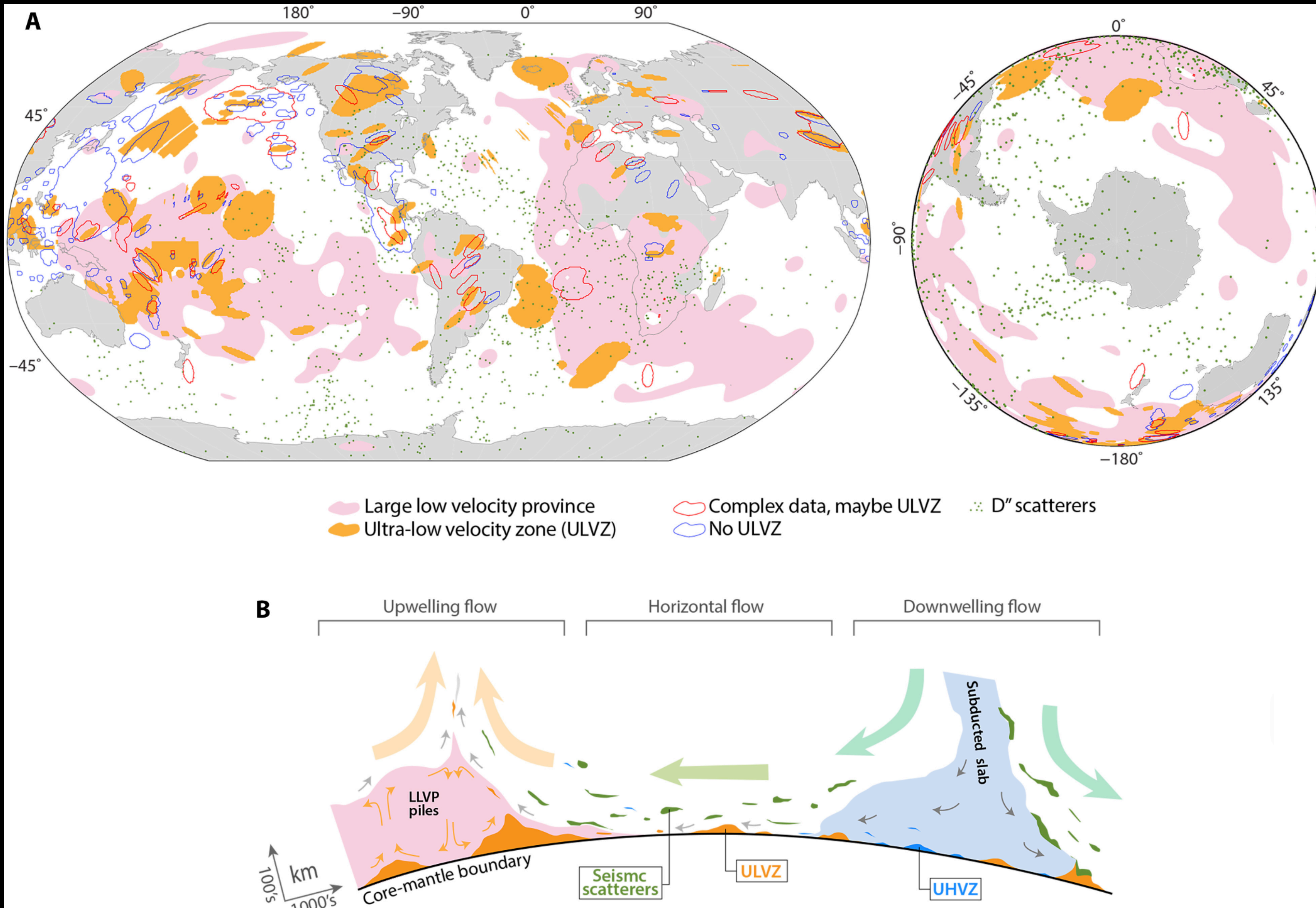
Problem: No Core Stratified Layer



No Problem!

Note: The BMO model itself doesn't address the issue of the over all direction of core-mantle disequilibrium in major shared elements. However, it suggests that the process of fractional crystallization over-prints the signature.

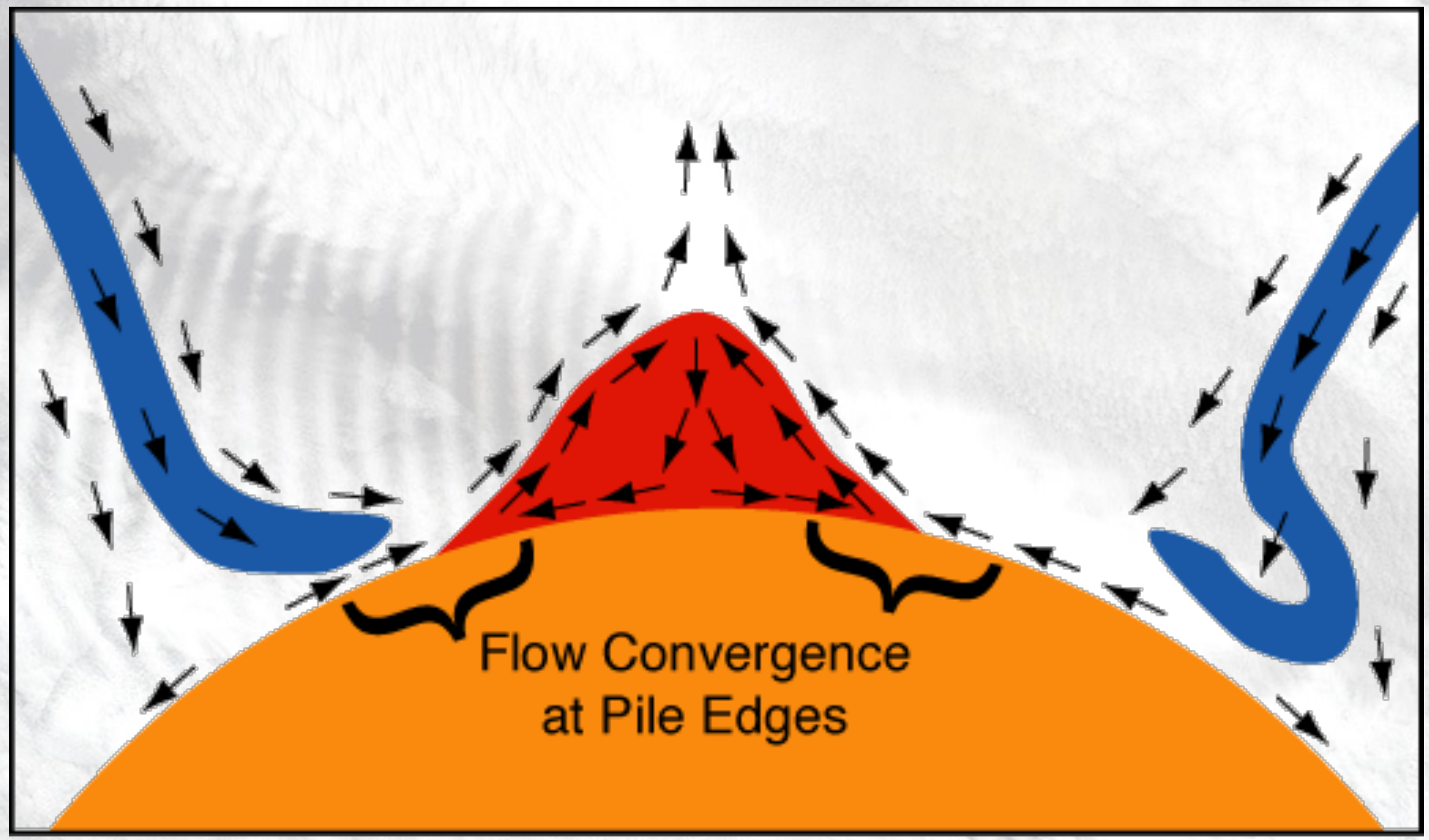
ULVZs Everywhere?



Hansen et alia (2023)

ULVZs Everywhere?

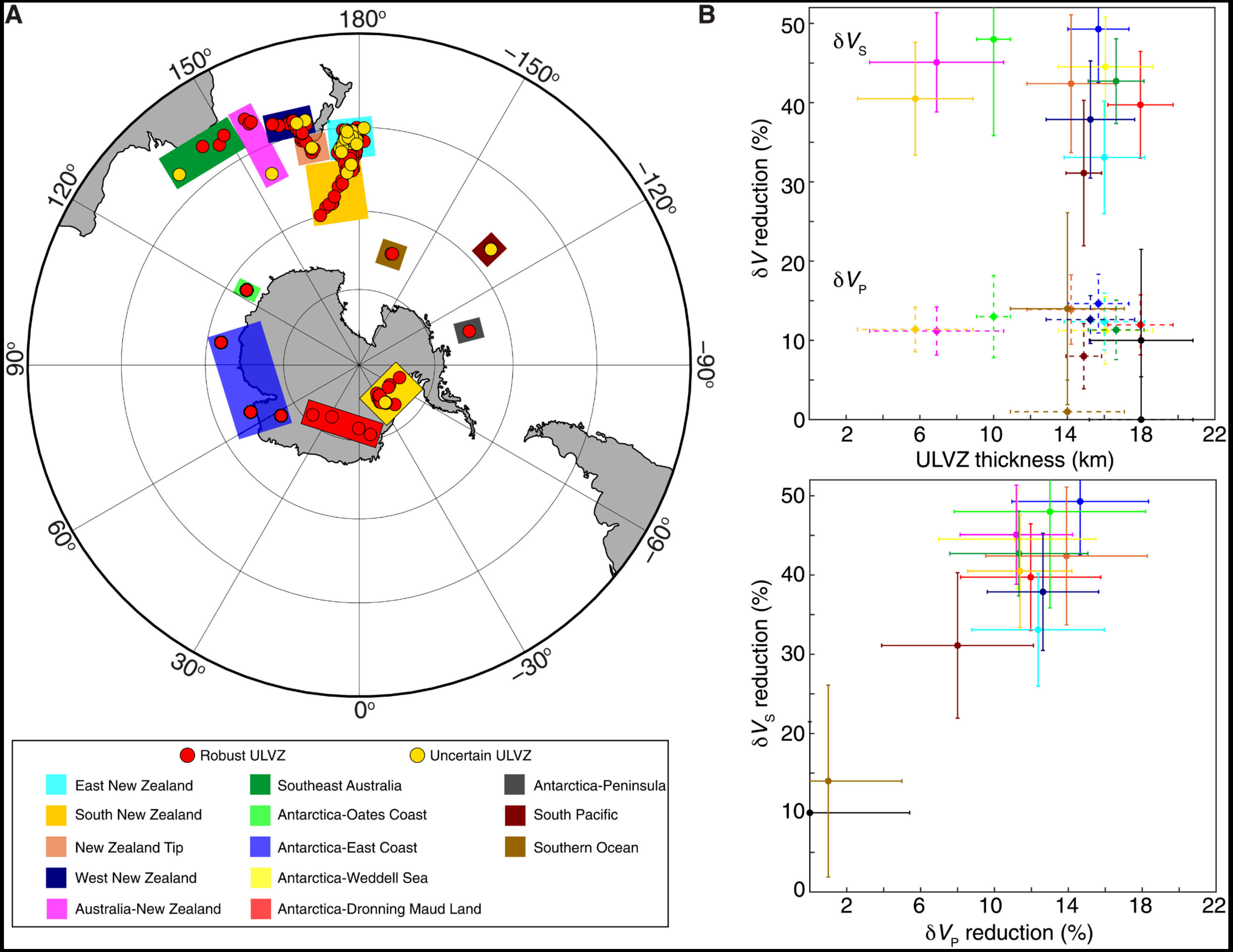
Where should ULVZ be?



Anything existing in the lowermost mantle should be swept around by mantle flow, and be concentrated where the flow along the CMB converges…

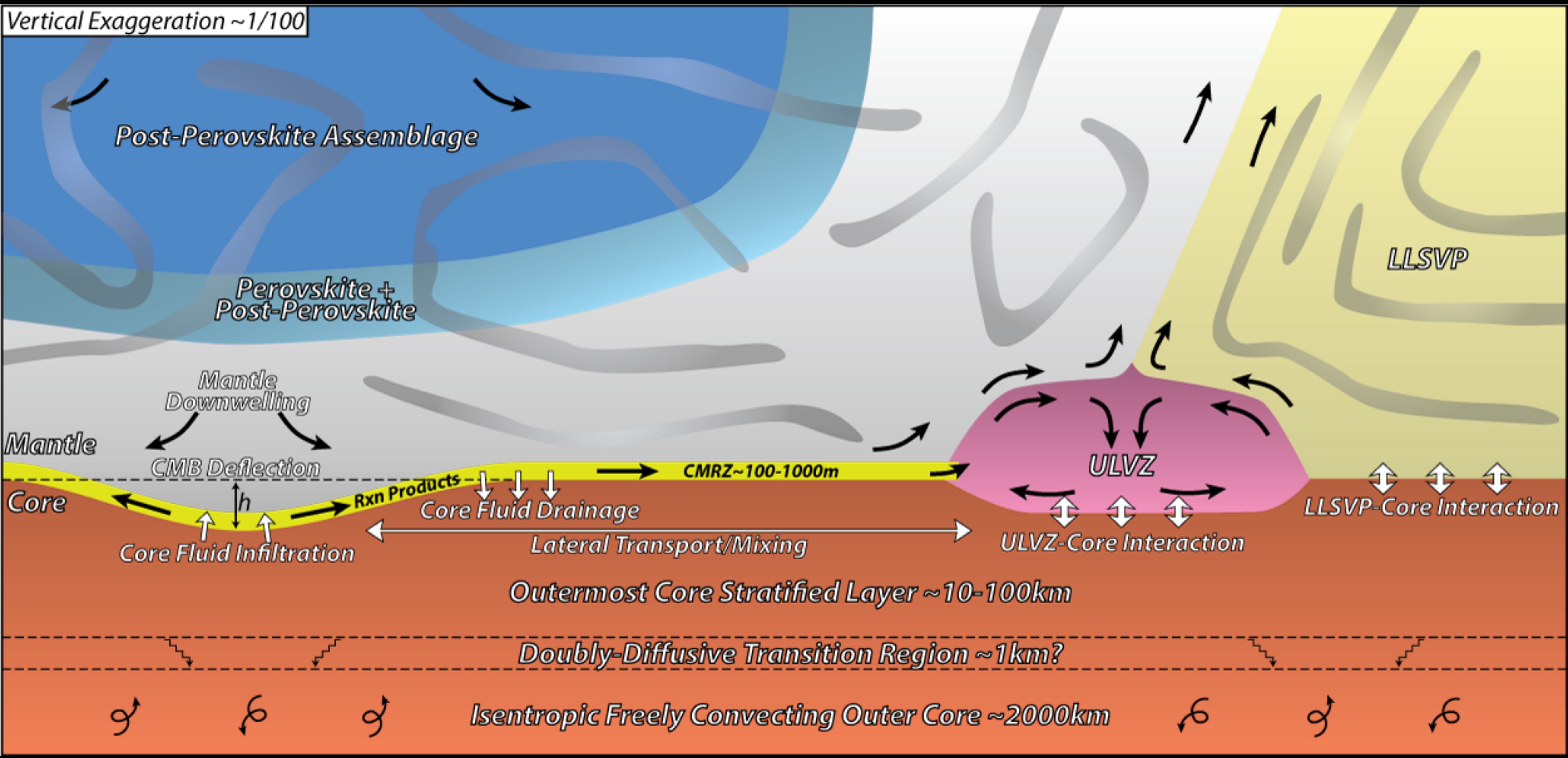
Hernlund and Tackley (2007)

ULVZ in Downwelling Regions?



Hansen et alia (2023)

Lateral Core-Mantle Reactions?



Lim, Taylor, Matsunaga, Matsui, Hernlund (in progress)

End of Talk Slides