# Deep Mantle Seismic Structure and Dynamics

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UBC

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25 years cifar
Canadian Institute for Advanced Research

NSF

# COHORTS…

- Paul Tackley
- Tine Thomas
- Thorne Lay
- Eddie Garnero
- David Gubbins
- Shigehiko Tateno
- Mark Jellinek
- Stéphane Labrosse
- Michael Manga
- Kei Hirose
- Michael Thorne
- Christine Houser
- Nicolas Coltice
- And many others…

# What's Happening in Deep Mantle Science?

| Mineral Physics: | Dynamical Relevance: |
| --- | --- |
| • Post-Perovskite | ➡ D" Thermal Structure |
| • Electronic Transitions | ➡ Signature of Deep Mantle? |
| • Deep Melting | ➡ Initial Conditions, Evolution |
| • Metal-Silicate Equilibrium | ➡ Core-Mantle Mass Flux |

| Seismology: | Dynamical Relevance: |
| --- | --- |
| • Waveform Inversion | ➡ Attenuation |
| • Migration | ➡ Interfaces/Phase Changes |
| • Tomography | ➡ Amplitudes/Resolution |

| Geochemistry: | Dynamical Relevance: |
| --- | --- |
| • Neodymium! | ➡ Chondritic? Hadean? |
| • Melting w/o Degassing | ➡ Noble Gases |
| • Box Models Re-revisited | ➡ Need to couple w/heat |

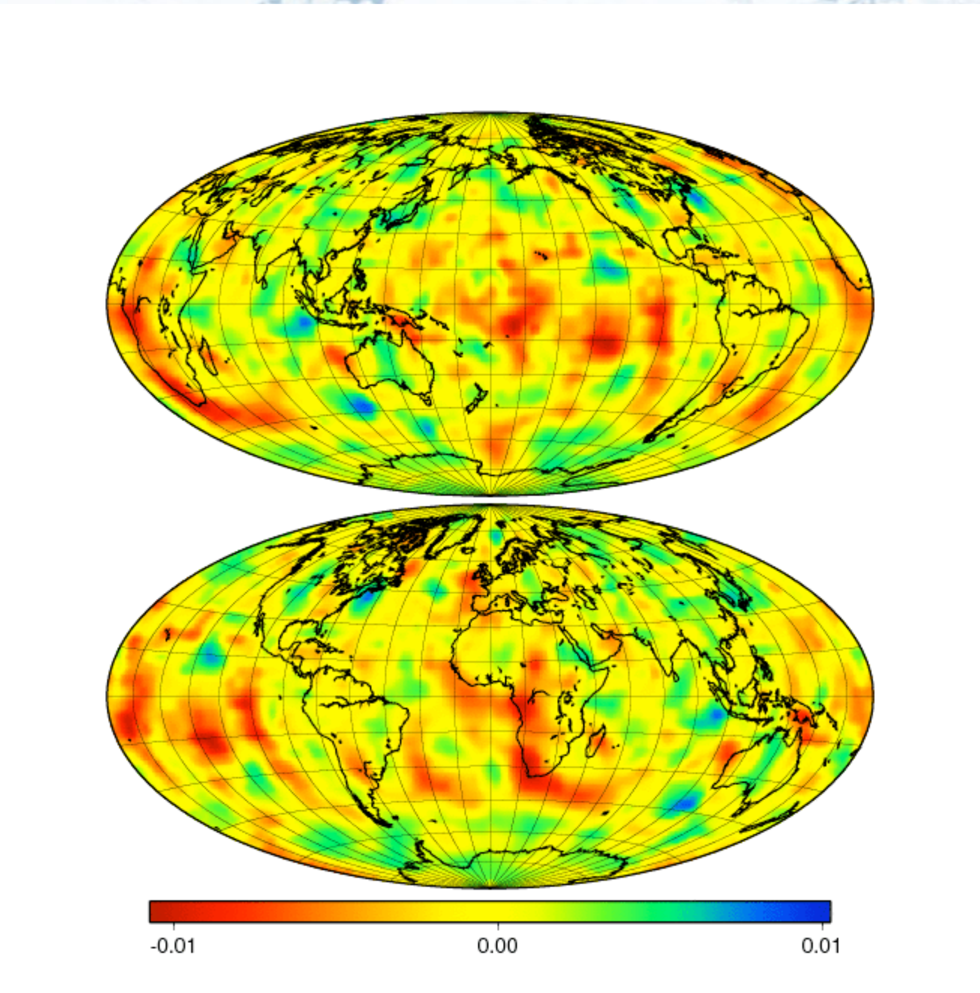
# Vp Tomography @2200 km Depth

**"Scripps"**

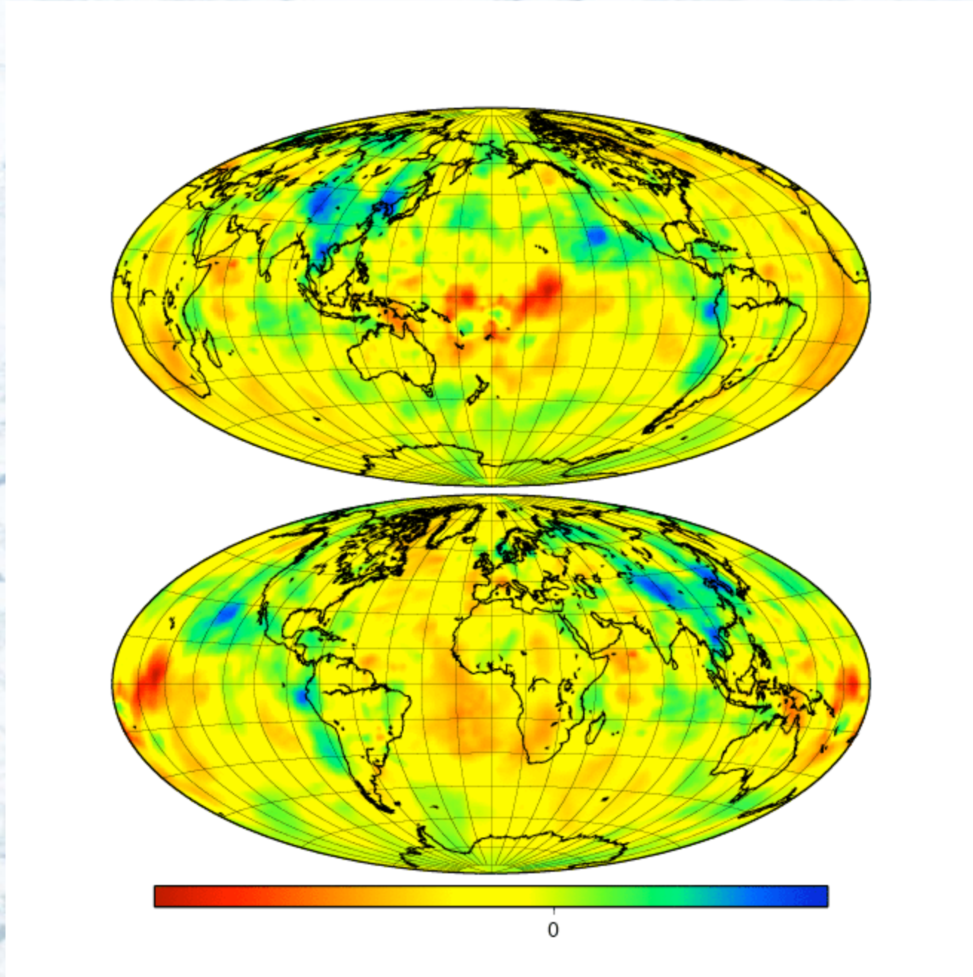
- Long Period, High QC
- Newest model includes Pdiff

**"MIT"**

- Short period ISC data
- Low QC, massive data set




Houser et al., (2008)




Li et al., (2008)

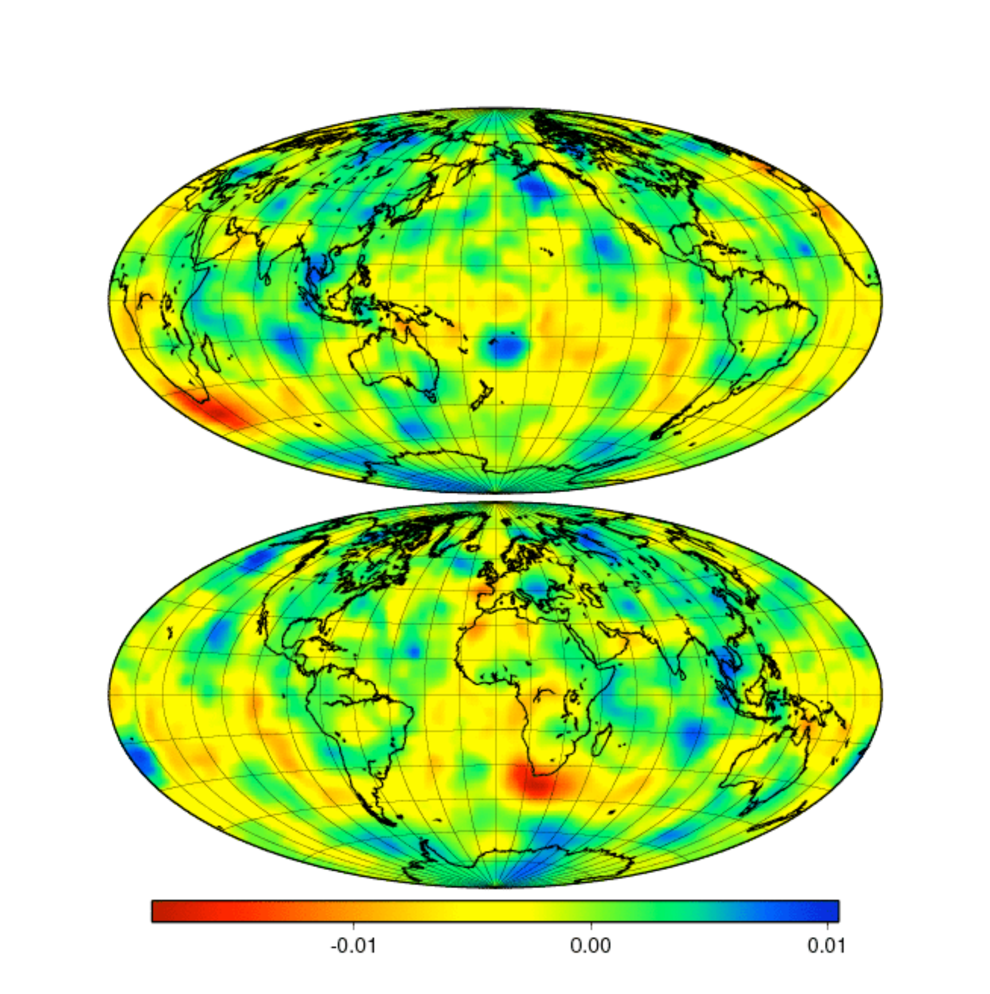
# Vp Tomography @2700 km Depth

## "Scripps"

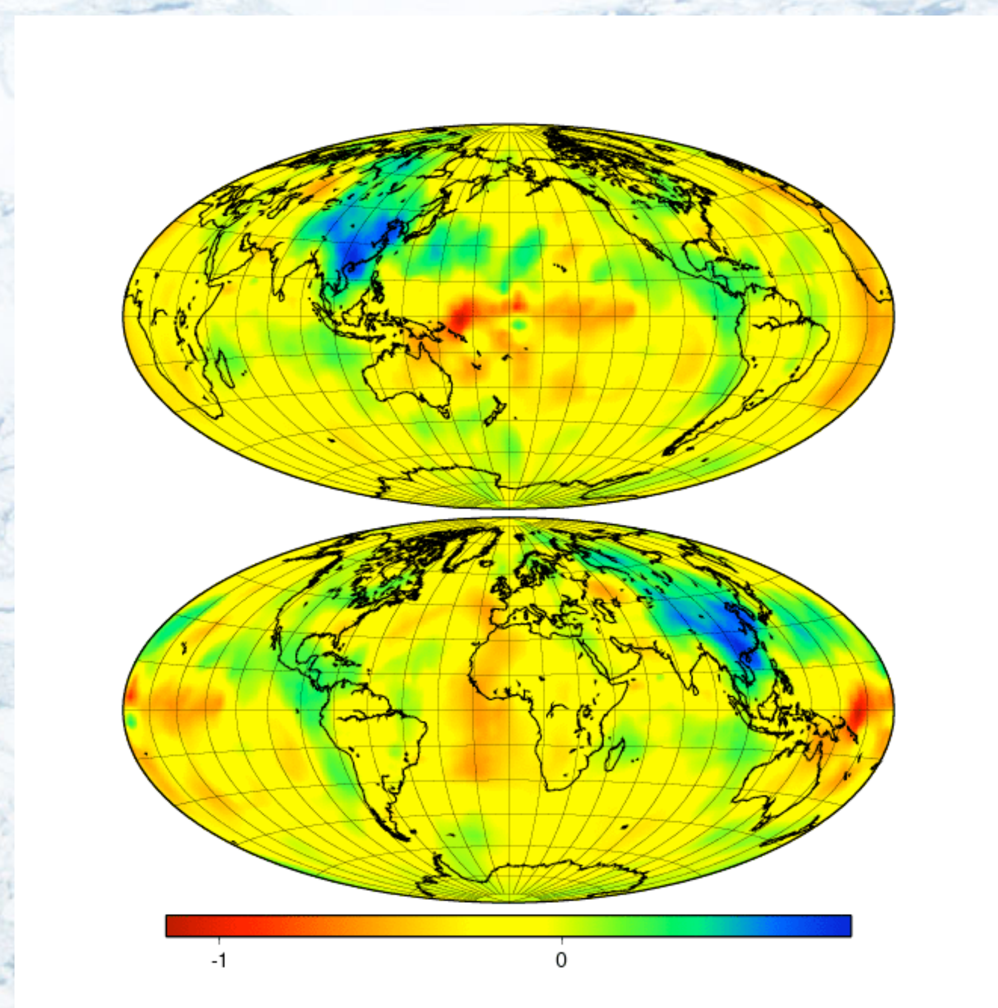
- Long Period, High QC
- Newest model includes Pdiff

## "MIT"

- ISC picks, short period
- Low QC, but massive data set



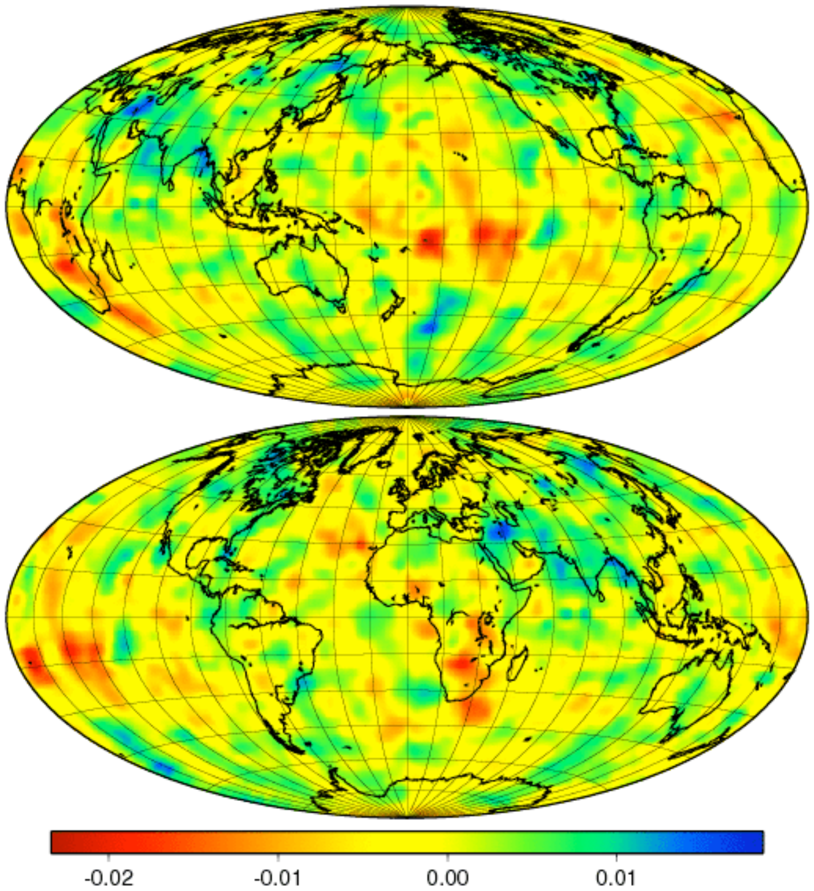

Houser et al., (2008)



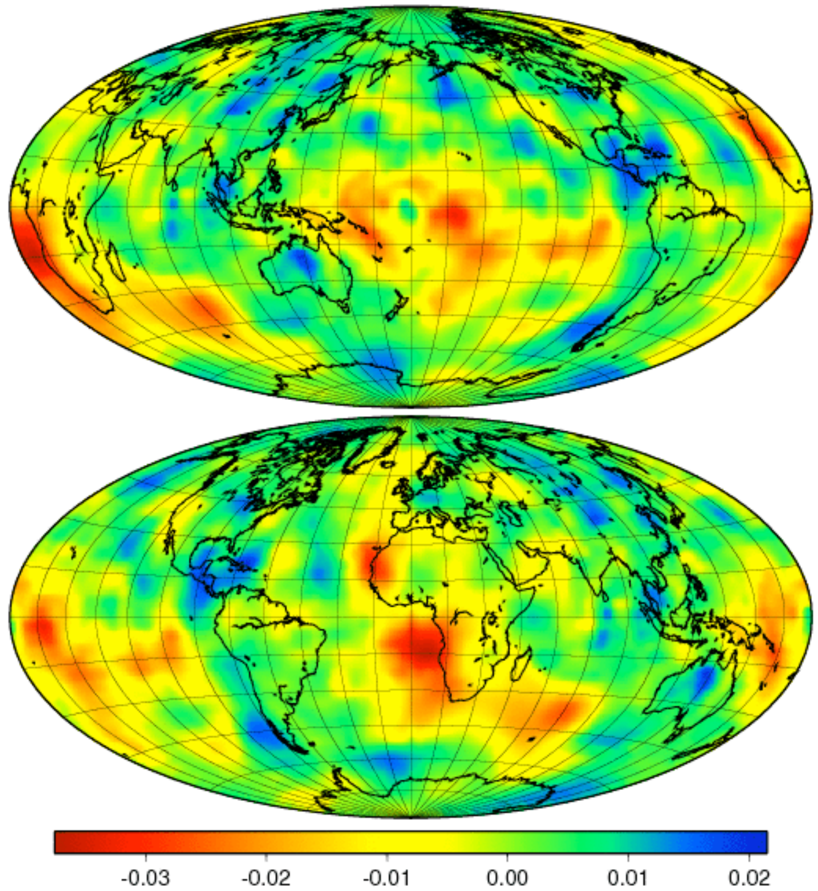

Li et al., (2008)

# Vs Tomography

## 1600 km depth




## 2700 km depth




Houser et al., (2008)

# Vp Tomography Progress

- ***Important***: Vp is less affected by bulk composition, post-perovskite, etc., than Vs => Good proxy for temperature variations.
- Dramatically increased data sets (>10X).
- Models agree at low order for relative variations in selected regions...amplitudes still disagree (also true of Vs models).
- Dispersion? Possibly more frequency dependence in lower mantle (Oki and Shearer, JGR, 2008).

# OK, what about relative Vs and Vp variations?

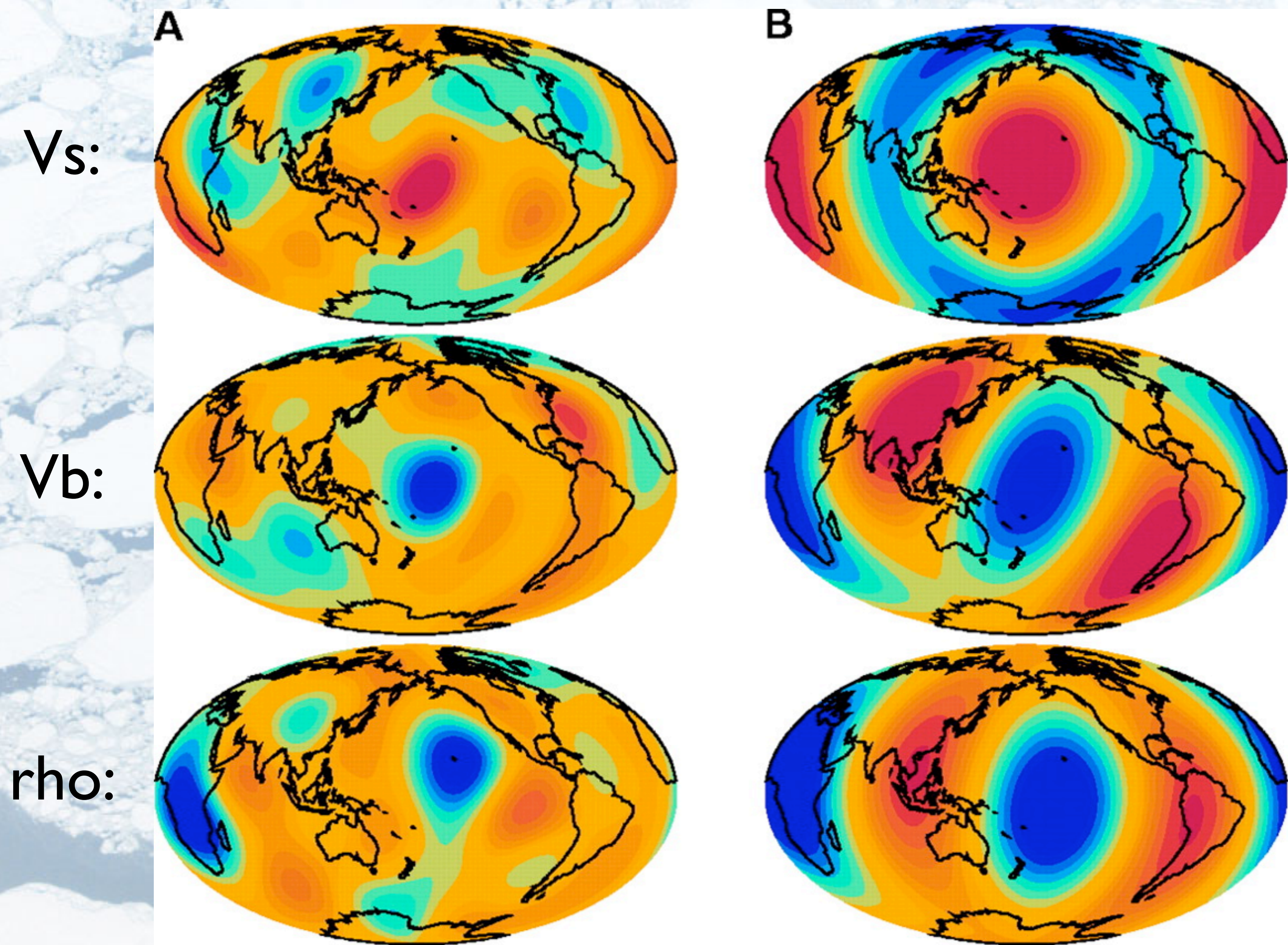
# OK, what about relative Vs and Vb variations?

$$Vb^2 = K/rho$$

$$Vp^2 = (K + 4/3mu)/rho$$

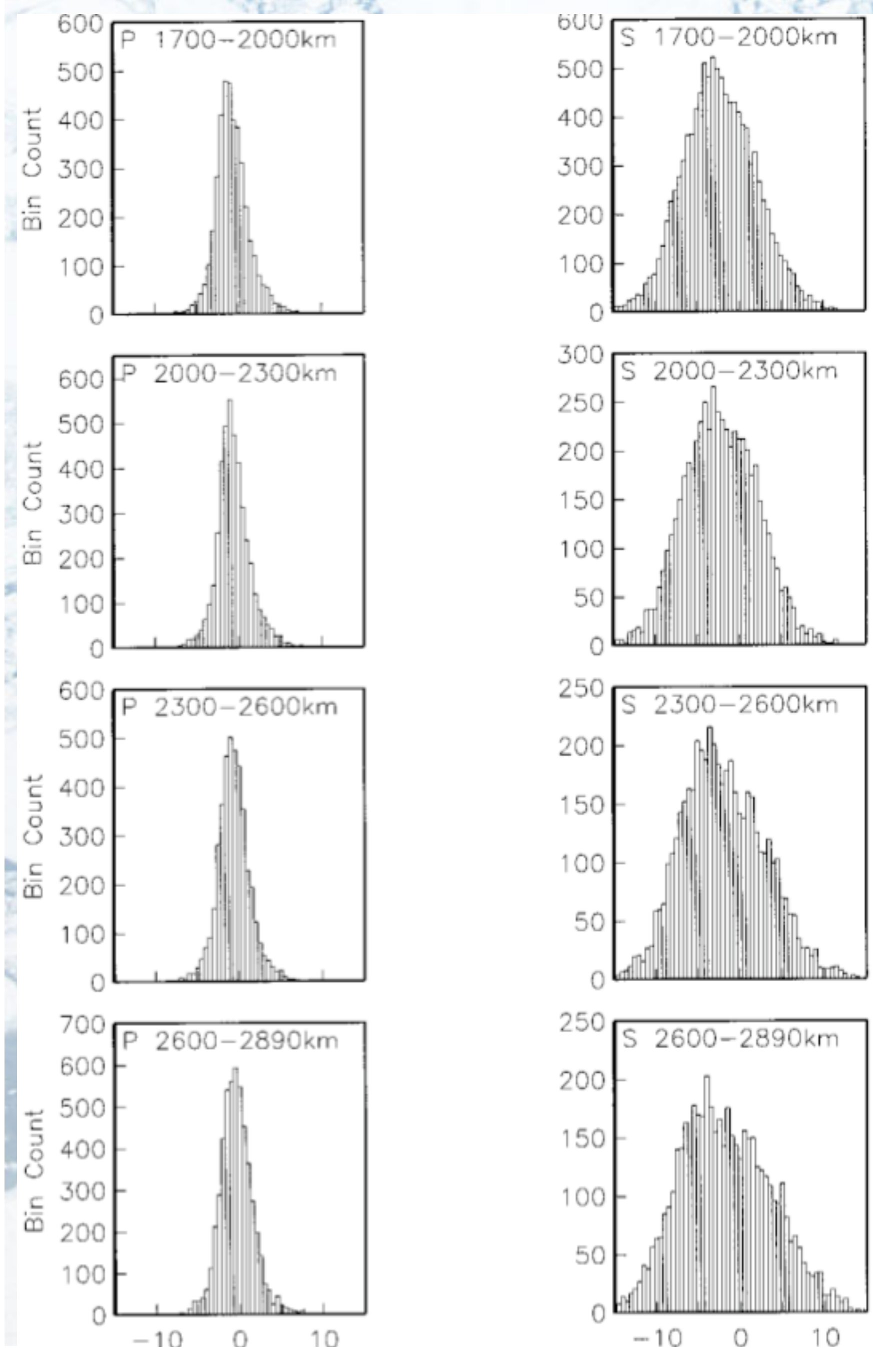
$$Vs^2 = mu/rho$$

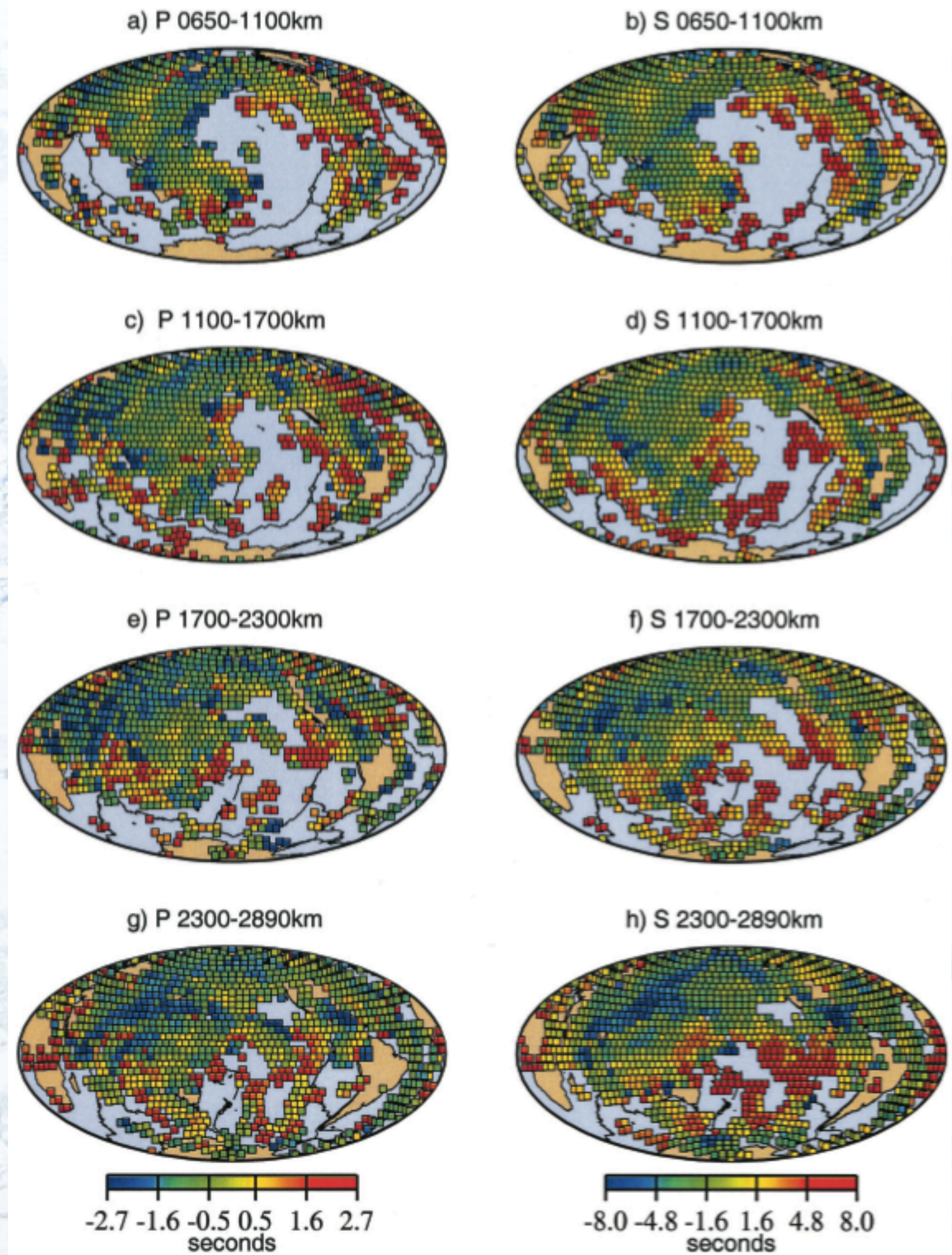
# Relative Vs & Vb




Ishii and Tromp (Science, 1999)

# Vs & Vp

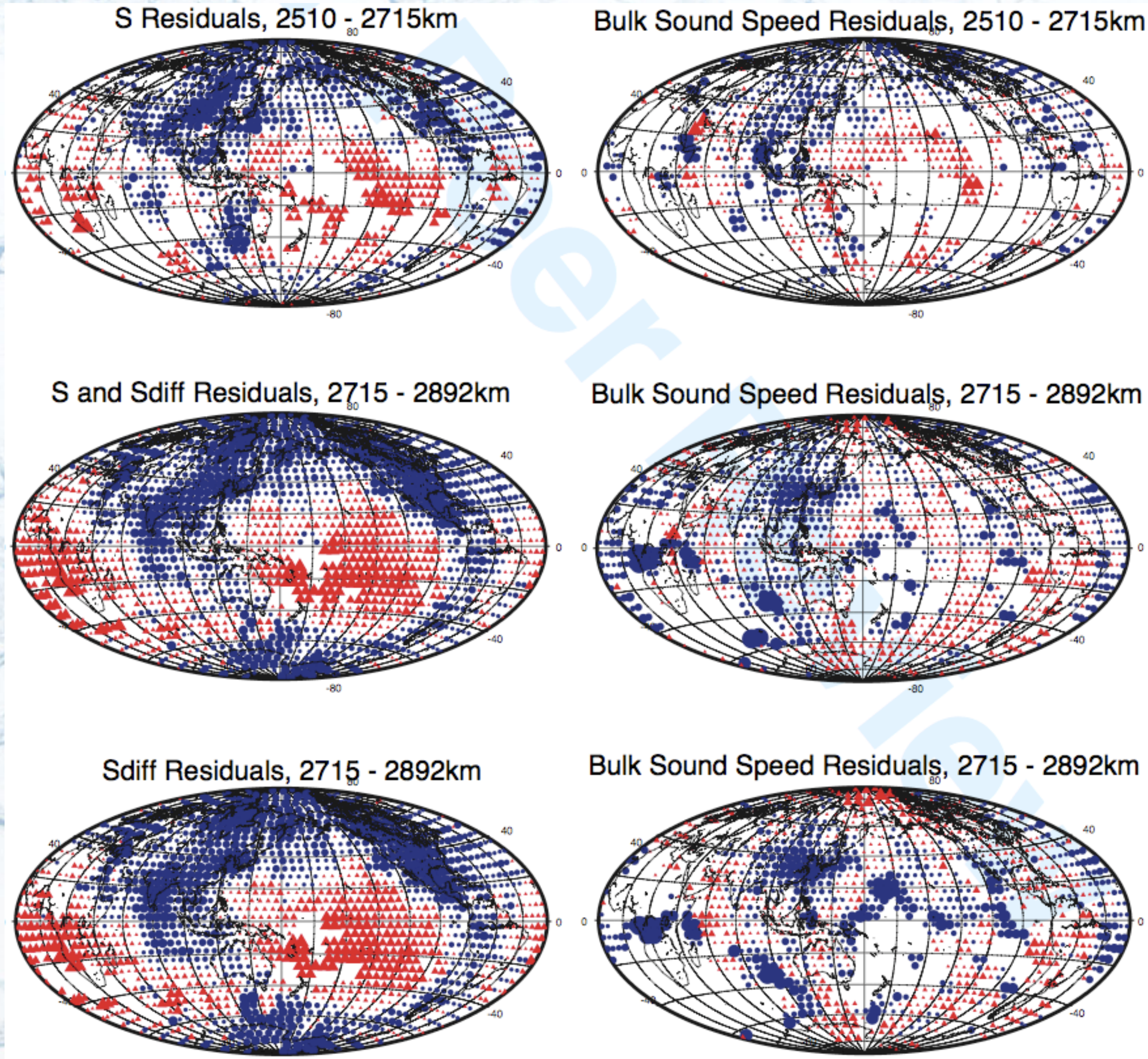


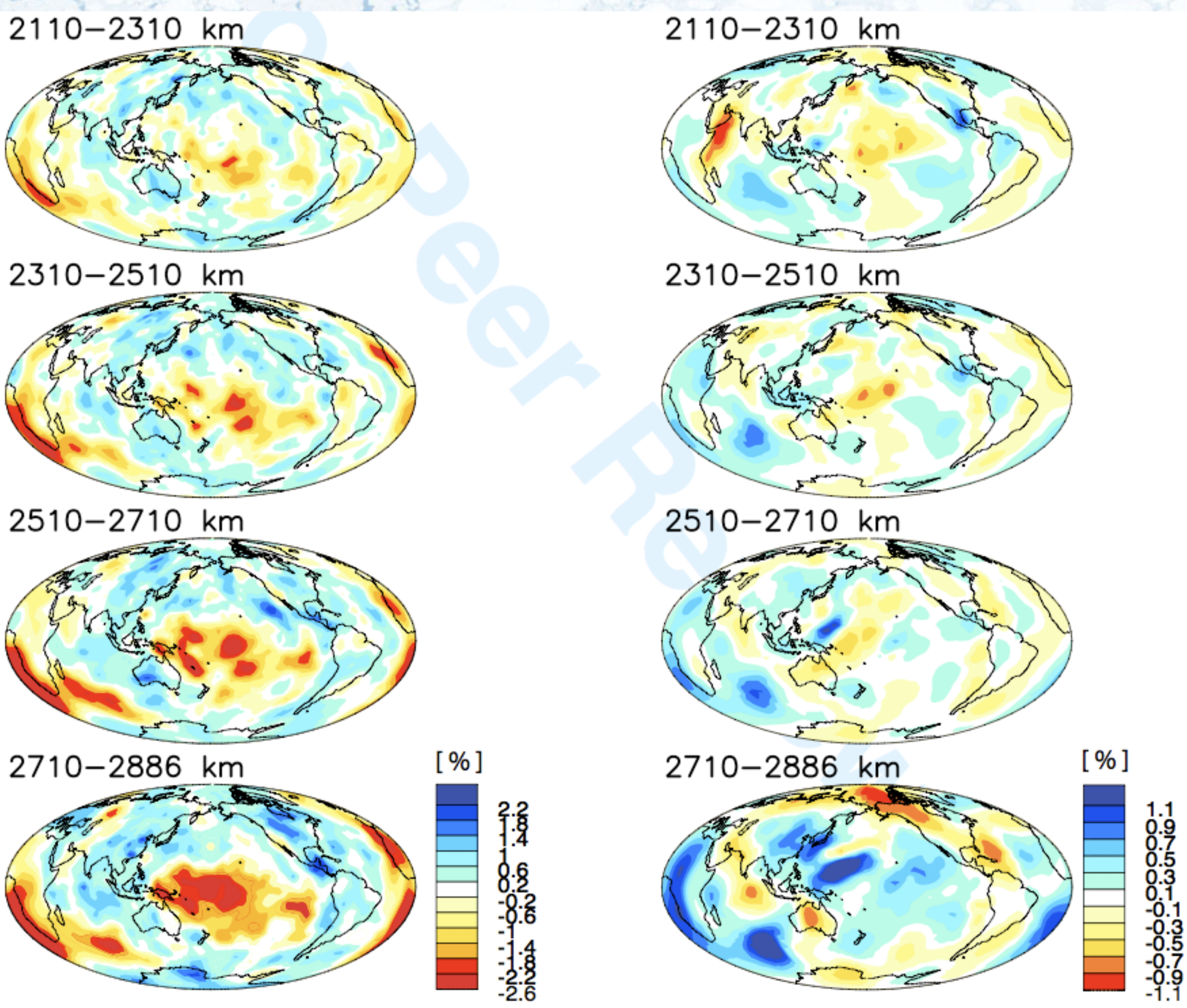

Bolton and Masters (JGR, 2001)

# Vs & Vb

- Direct Measurement of bulk sound speed residuals from S-P pairs
- EQ Relocation procedure to obtain better time resolution

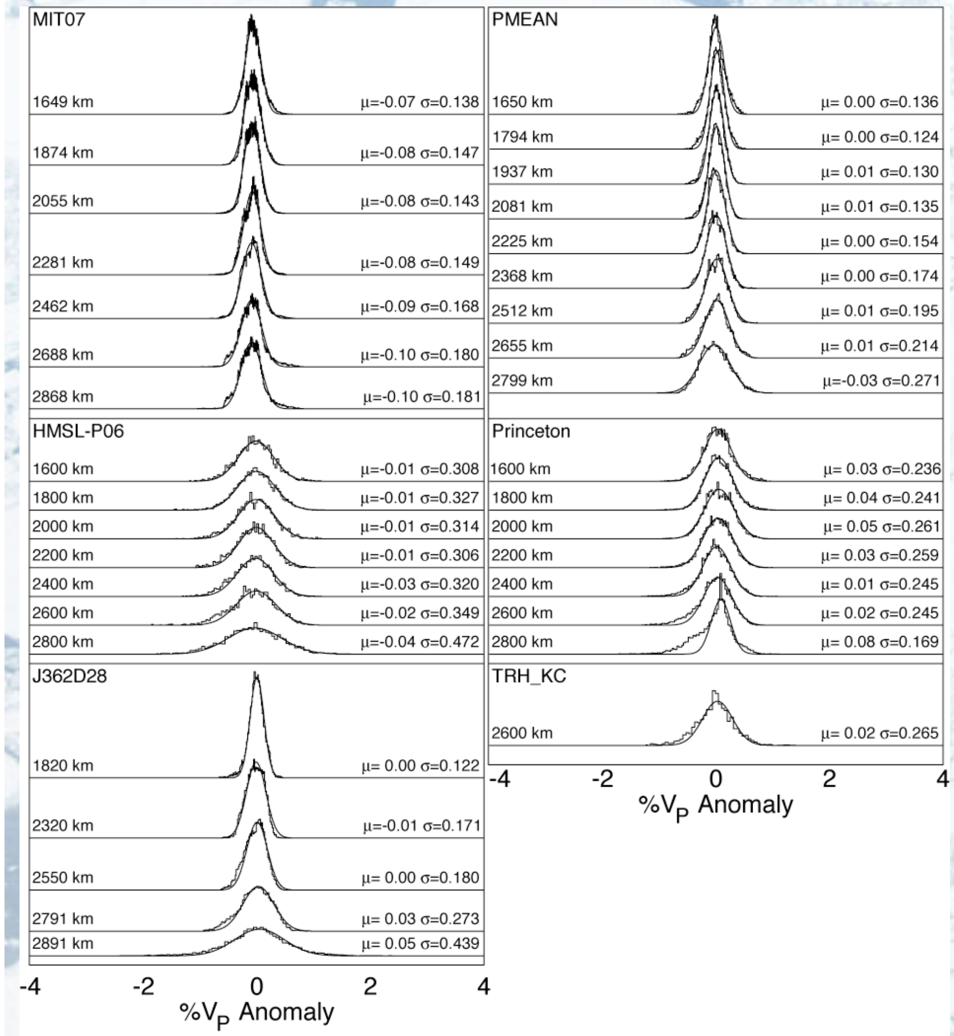


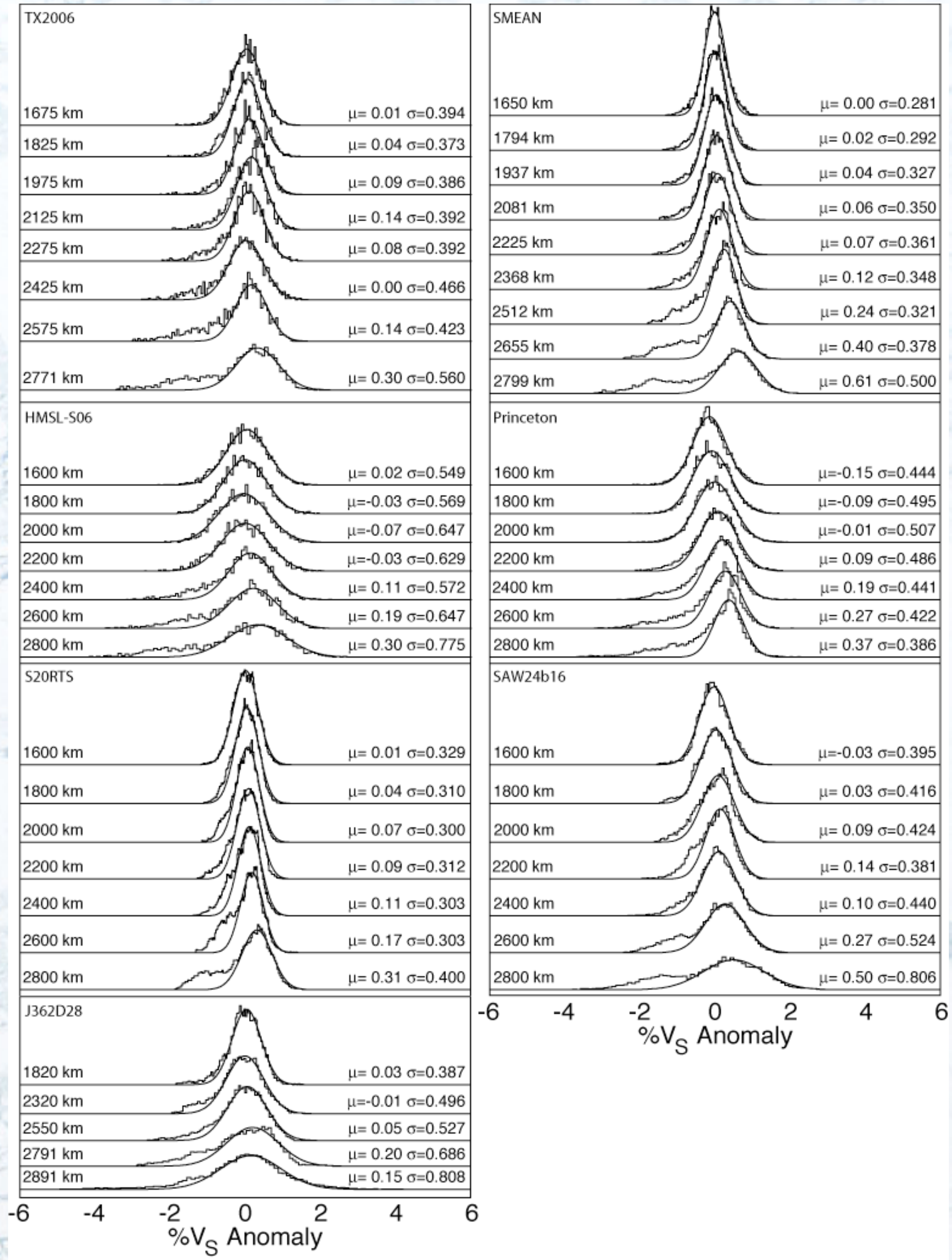

Manners and Masters (GJI, in revision)




Manners and Masters (GJI, in revision)

# Statistical Distributions



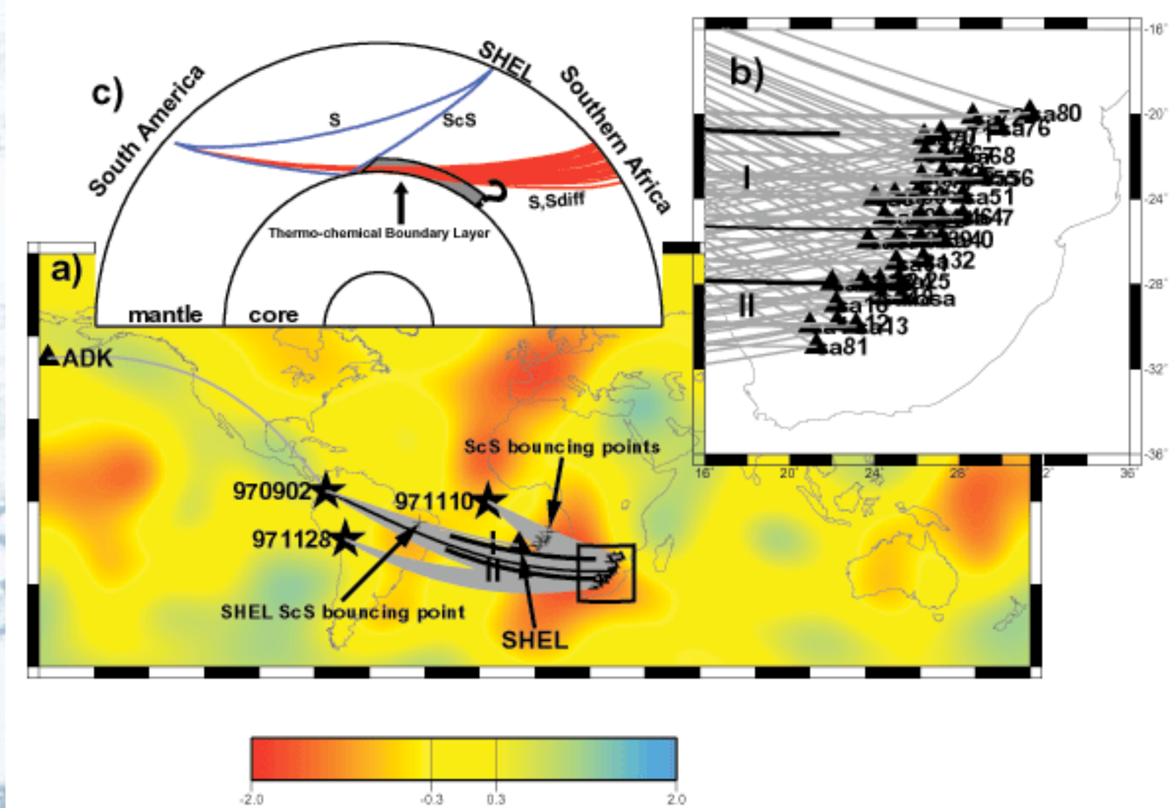




Hernlund & Houser (2008)

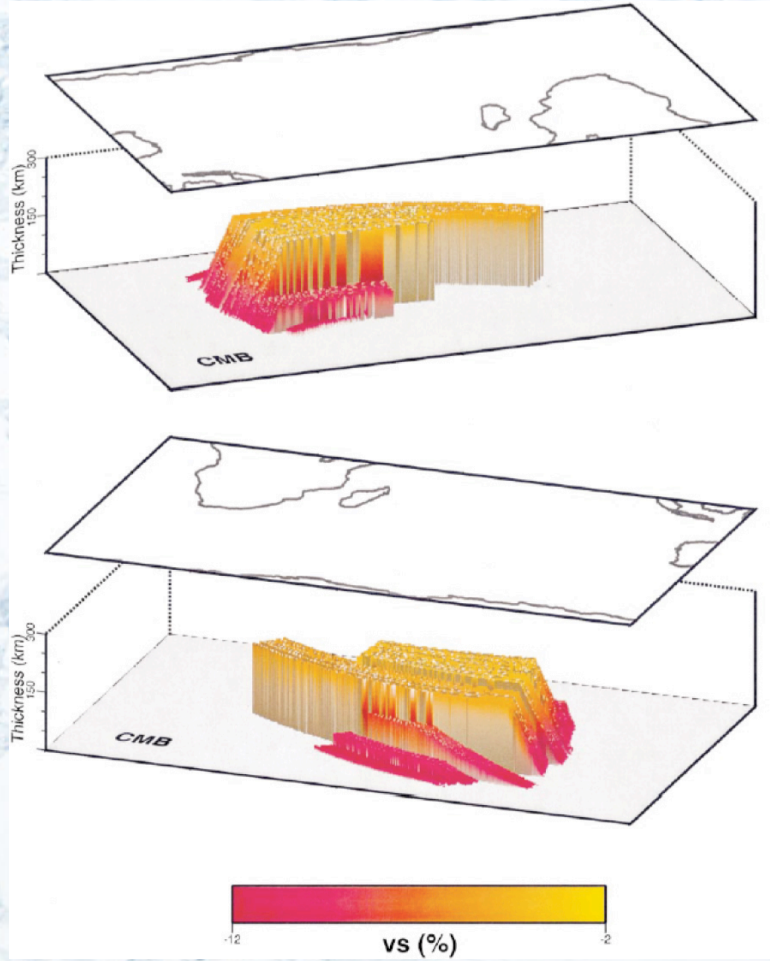
# Consensus View?
# As Close as it Gets!

Travel time, normal mode, and short period waveform studies all show that there is an anti-correlation between Vs and Vb in the lowermost ~700 km of the mantle, and a sharp boundary has been detected in some locations.

# Origin of Vs/Vp Anomaly?

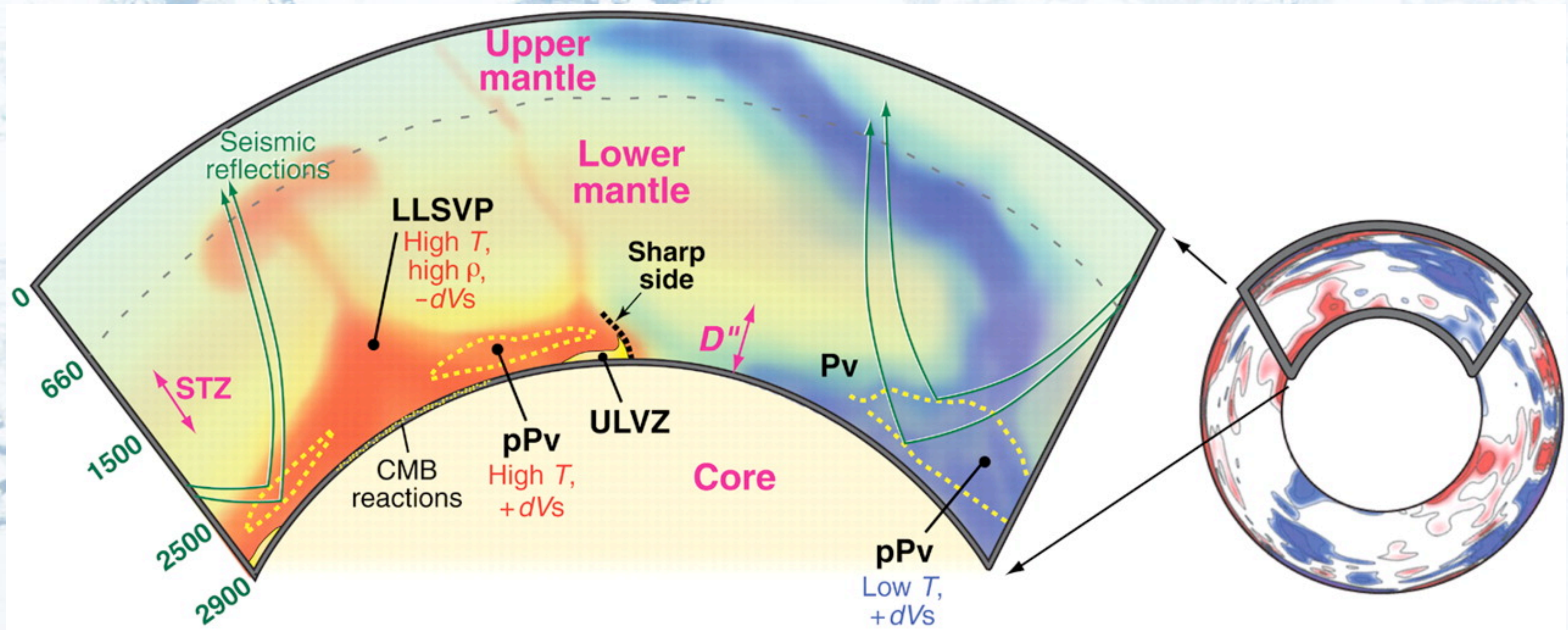



Lianxing Wen




- Travel times very rapidly around edge of low Vs features (Wen).
- Sides of features are steep, and reflect seismic energy (Ni & Helmberger)

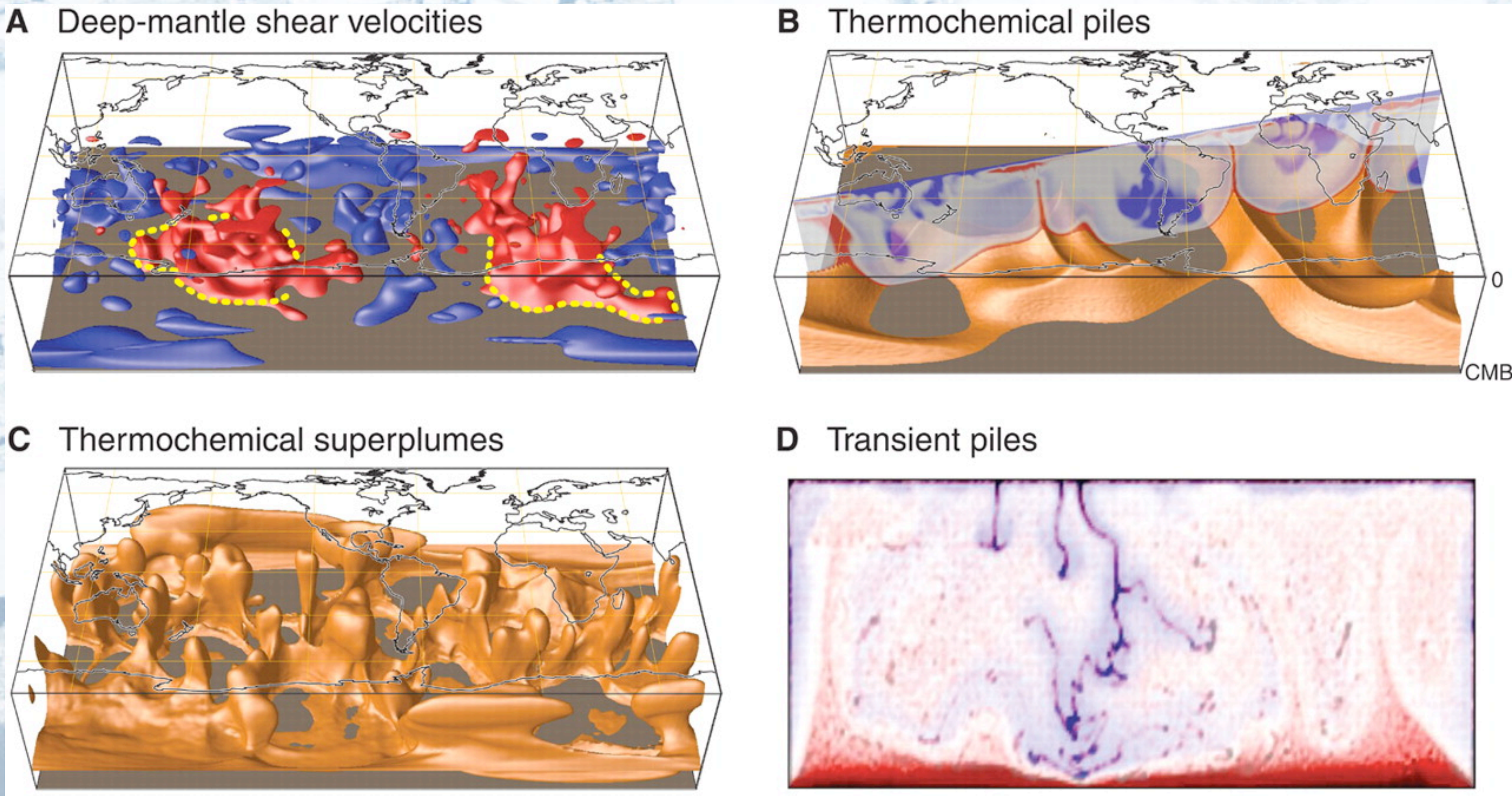
# Origin of Vs/Vp Anomaly?




Garnero & McNamara, Science, 2008

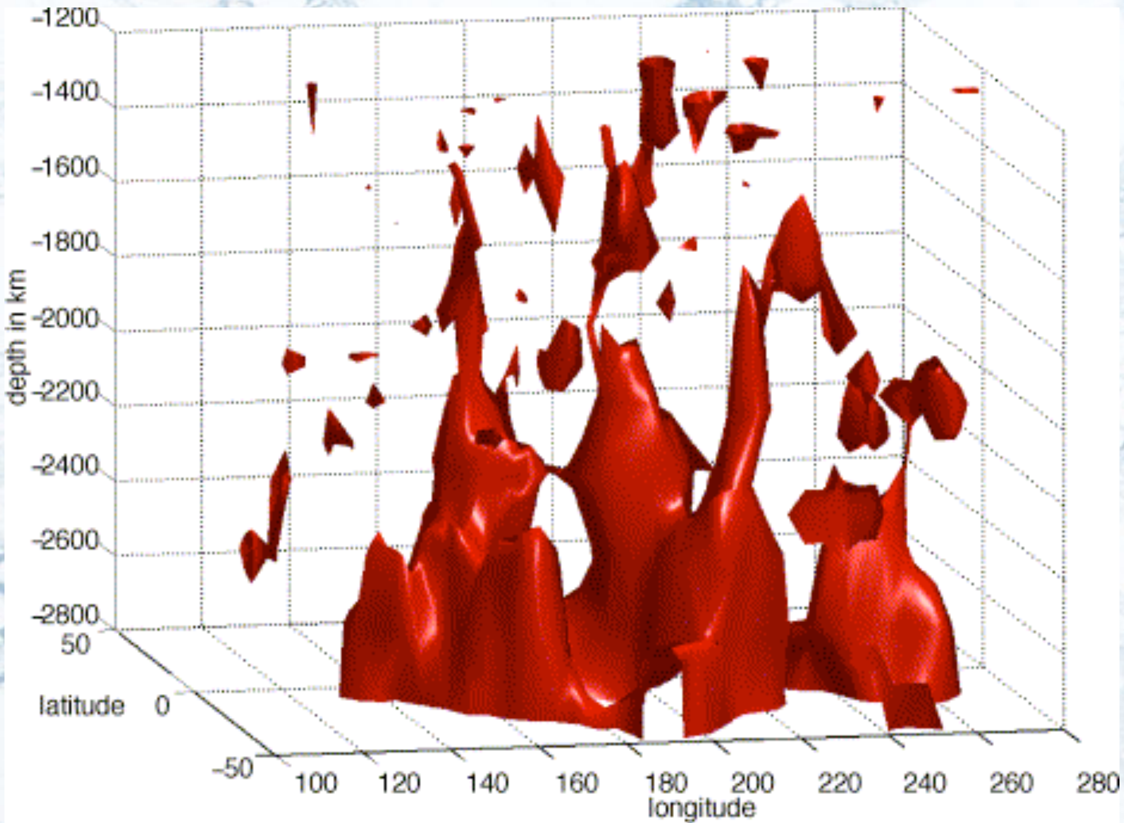
- Proposal that post-perovskite causes this cannot account for the magnitude of Vs variations, nor the distance above CMB that these features extend (Houser, 2007).

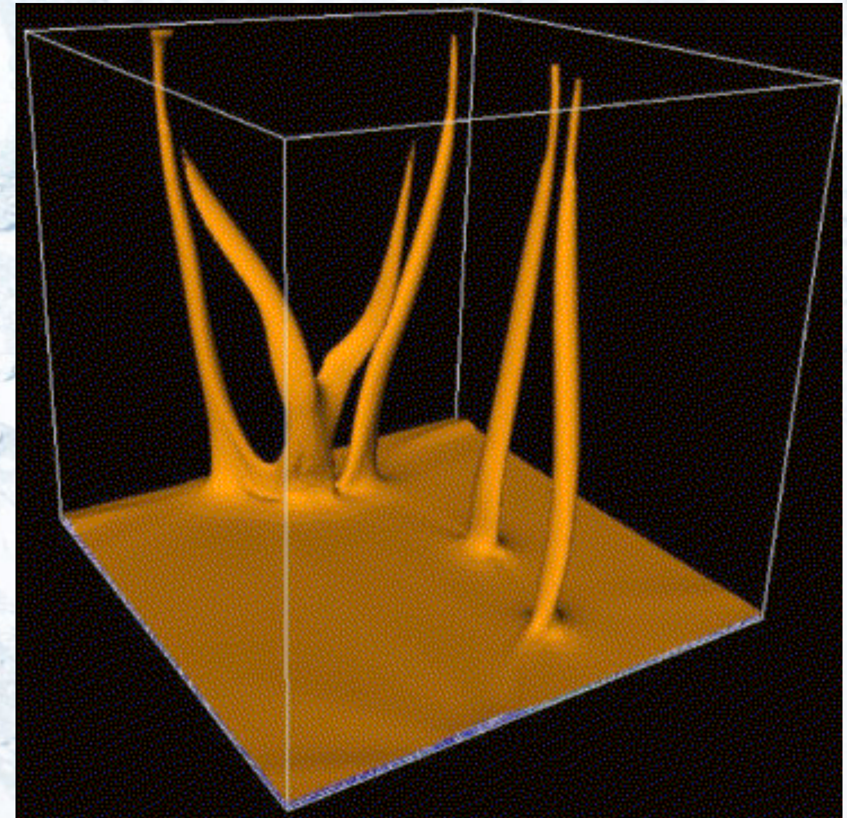
# Origin of Vs/Vp Anomaly?




Garnero & McNamara, Science, 2008

# Implausible Scenario!

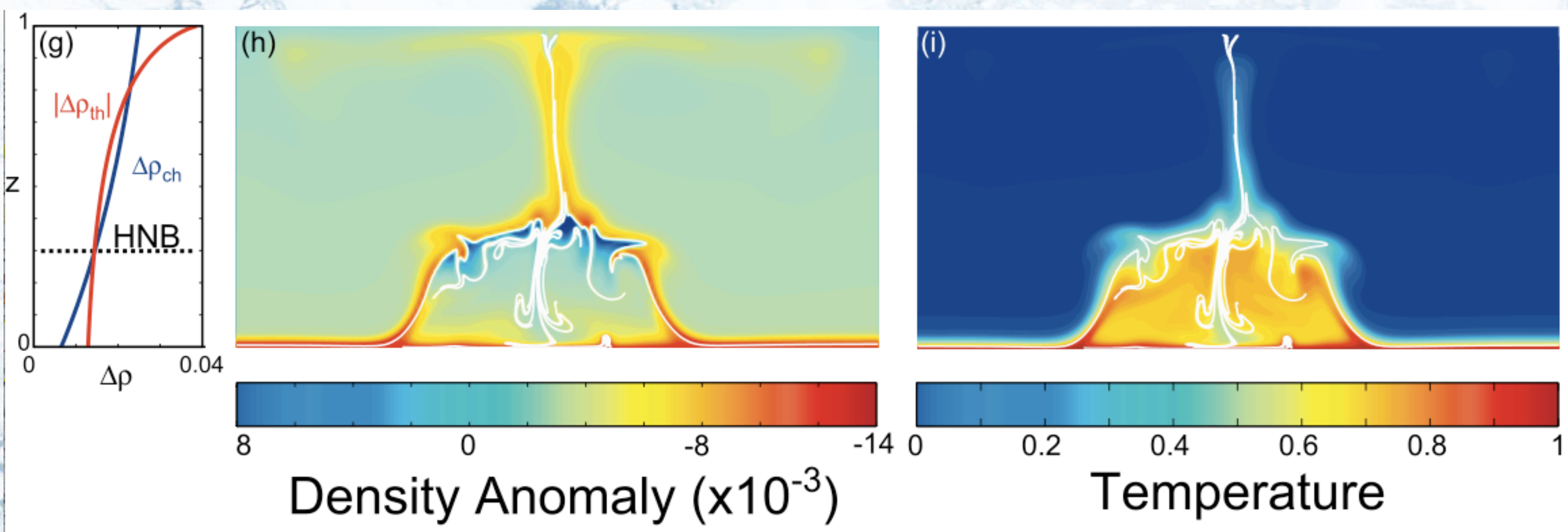


Schubert, Masters, Tackley, Olson (PEPI, 2004)

**Thermal plumes alone cannot explain Vs/Vb decoherence!**

# Plausible Scenario!



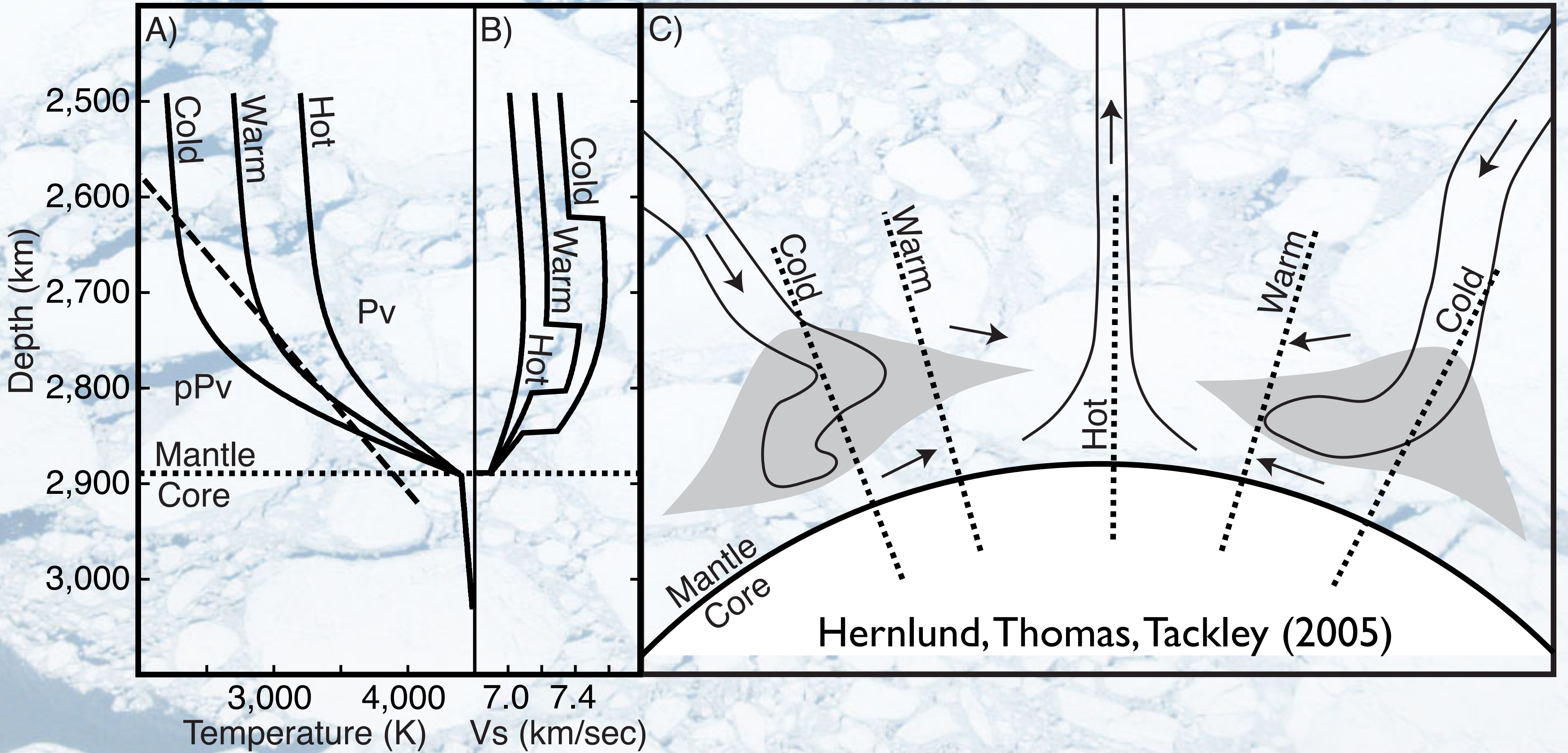

Eh Tan et al. (2005)

**Seismology implies high bulk modulus, relative incompressibility of anomalous material**

# Chemical Piles Remaining Issues

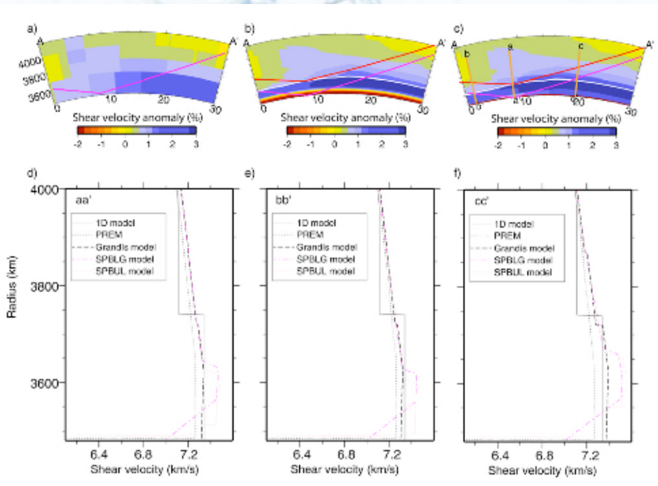
- Relationship to plumes, LIPs (e.g., Kevin Burke) implies upwellings at edges.
- Can transient piles (e.g., from segregated MORB) explain sharp edges? Or does this have to be formed another way?
- Dynamical inversions imply large buoyancy above/in these features. Where does it come from? Is this just a transient oscillation in the "upgoing" instant?

# Post-Perovskite in Earth's D" Layer

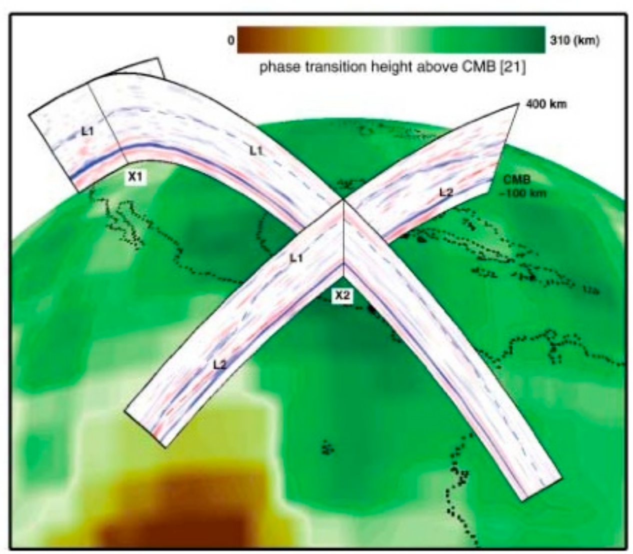



Hernlund, Thomas, Tackley (2005)

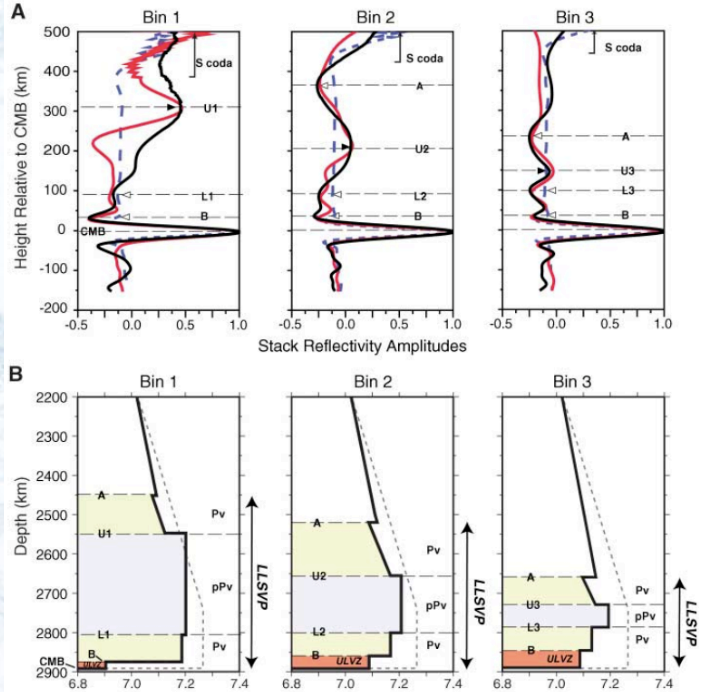
# Double-Crossings Everywhere?



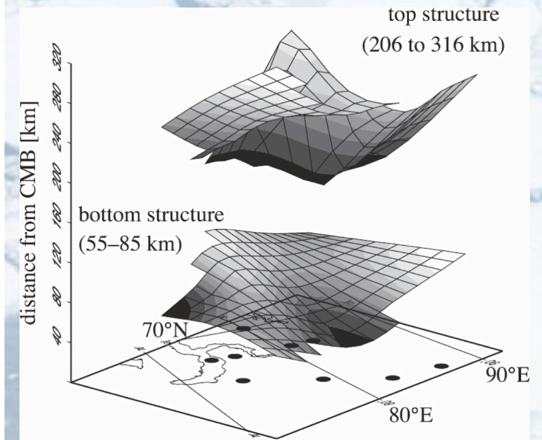

Sun et al., (2006)



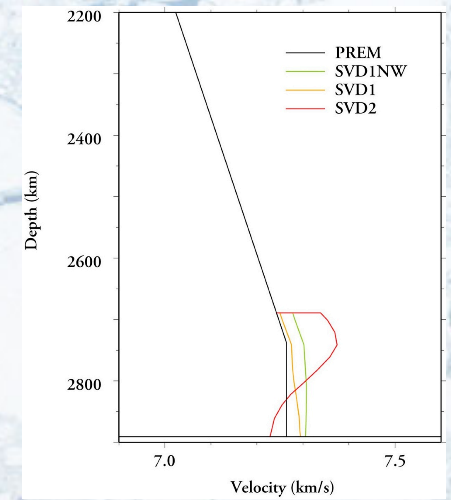

van der Hilst et al., (2007)



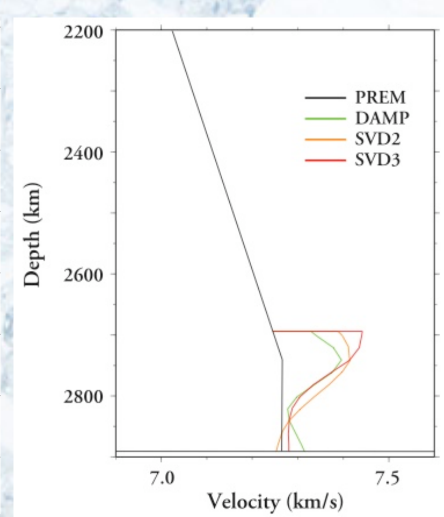

Lay et al., (2006)



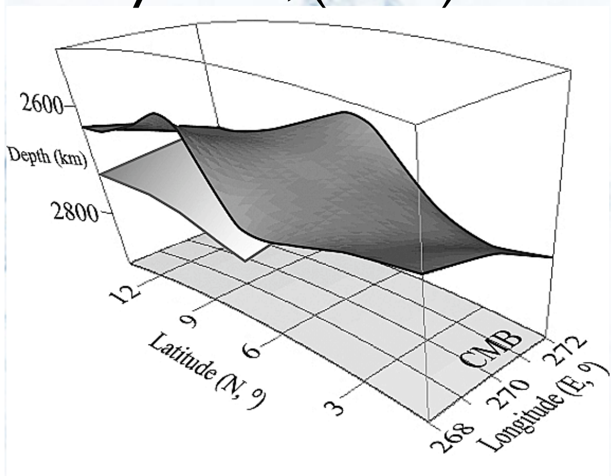

Thomas et al., (2004)




Kawai et al., (2007)




Kawai et al., (2007)




Thomas et al., (2004)

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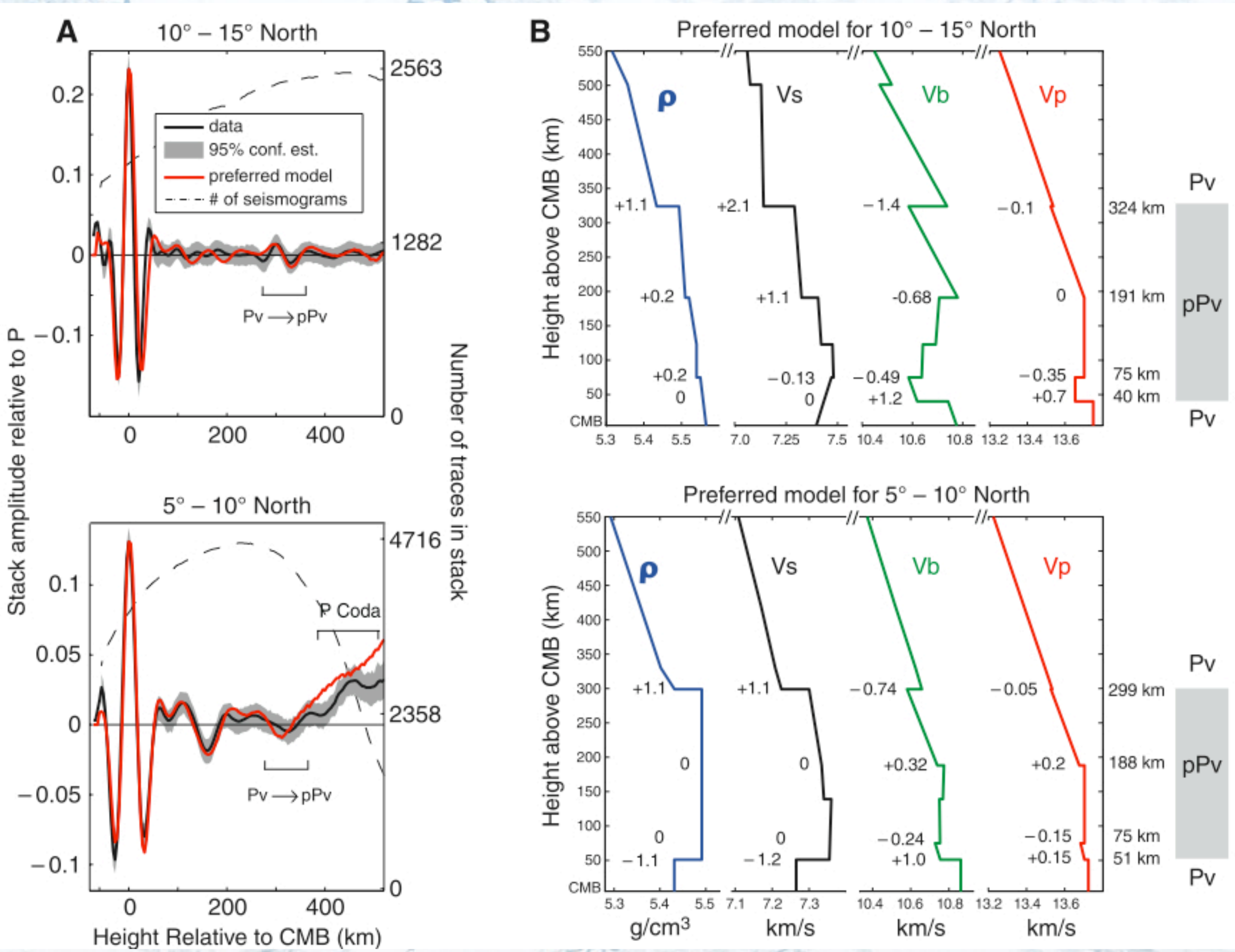



Hutko et al., Science, 2008

# Remaining Questions About Post-Perovskite and Seismic Discontinuities

- Lower discontinuity is hard to detect (Flores and Lay, 2005). Why do seismologists seem to be able to detect it easily?
- Solid solutions in Pv and pPv might substantially broaden the two phase co-existence region (e.g., alumina, Akber-Knutson et al., 2005). How do we obtain sharp discontinuities?
- How well characterized is the velocity jump? Is onset of anisotropy also required (e.g., Murakami et al., 2008)?
- Is there an important latent heat effect at the lower crossing as suggested by Bruce Buffett (GRL, 2007)?

# Interpreting Post-Perovskite Discontinuities in Light of Gibbs Phase Rule

$$f=2+c-p$$

Typical mantle away from phase changes (*c=1, p=1*):

$$f=2+c-p=2$$

Given depth => pressure:

$$f=1+c-p=1$$

At univariant transition, discontinuity depth (*c=1, p=2*):

$$f=1+c-p=0$$

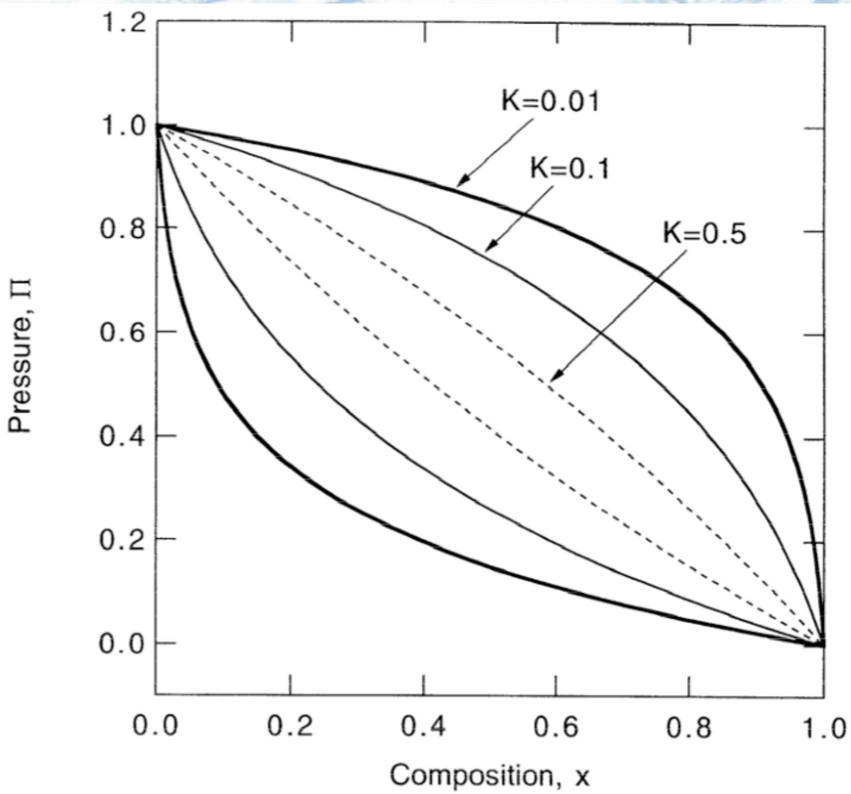
Add $MgSiO_3$ -$FeSiO_3$ solution (*c=2, p=2*):

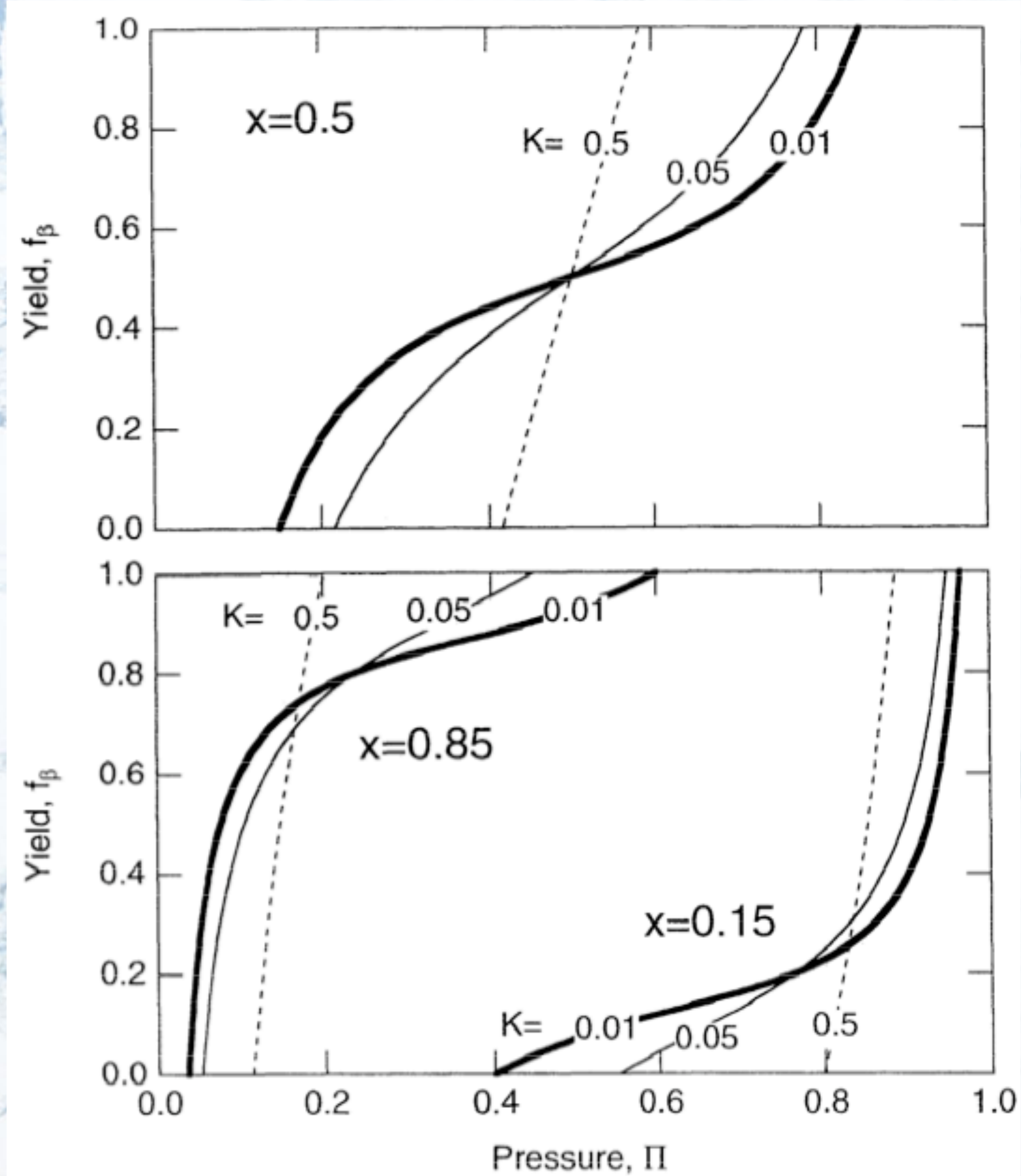
$$f=1+c-p=1$$

Add $Al_2O_3$ also in solution (*c=3, p=2*):

$$f=1+c-p=2!$$

# Stixrude, JGR, 1997




Broadening the phase loop yields non-linear phase variation

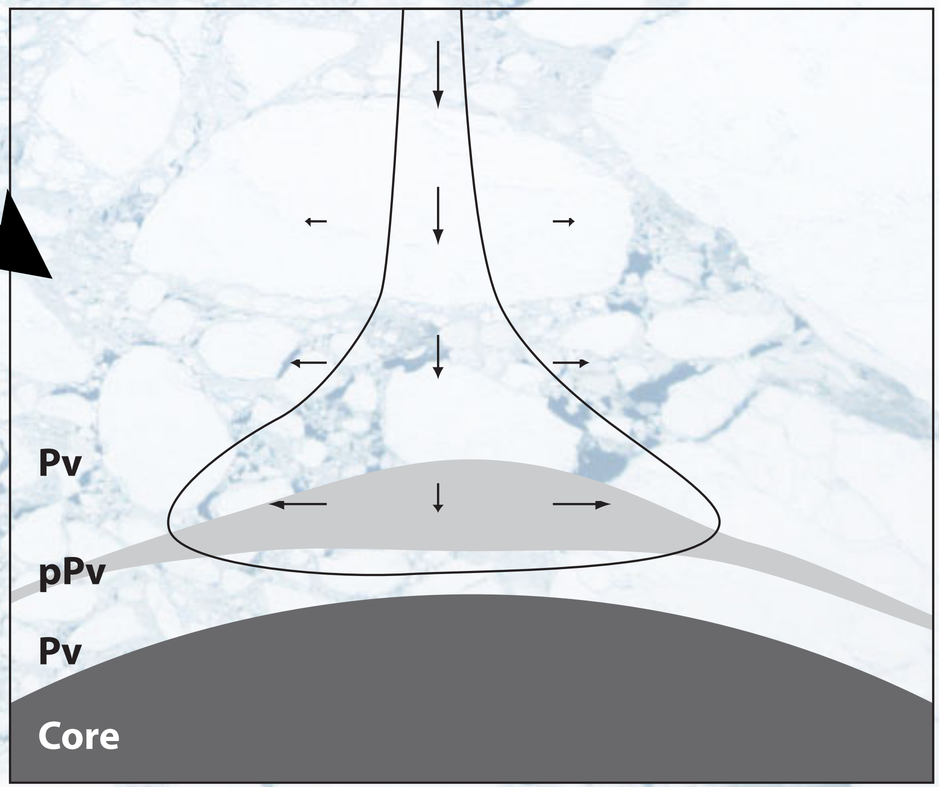
# Model of Geotherm and Post-Perovskite

$$\frac{\partial(\rho c_p T)}{\partial t} + \vec{\nabla} \cdot \left(\vec{v}\rho c_p T - k\vec{\nabla} T\right) = -T\Delta s\Gamma - \rho g \alpha T v_z + Q + \psi,$$ (Cons. Energy)

$$+ \frac{\partial(\rho_h \phi)}{\partial t} + \vec{\nabla} \cdot (\vec{v}\rho_h \phi) = \Gamma,$$ (Cons. Phase)

$$+ \vec{v} = v_x \hat{x} + v_z \hat{z} = \dot{\varepsilon}(x\hat{x} - z\hat{z}),$$ (Assumed Flow)

$$+ \frac{X - X_l}{X_h - X_l} = \phi \frac{\rho_h}{\rho},$$ (Lever Rule)



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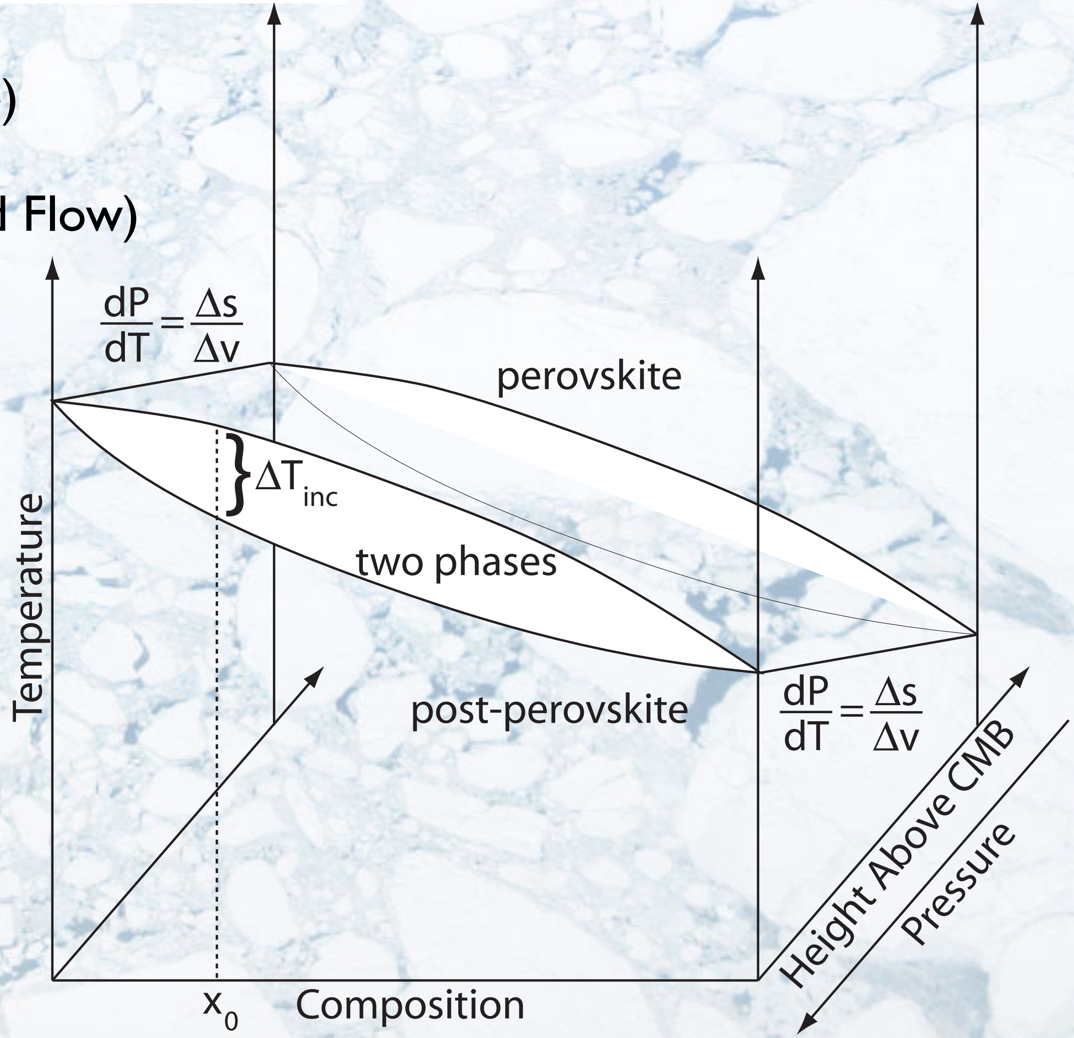
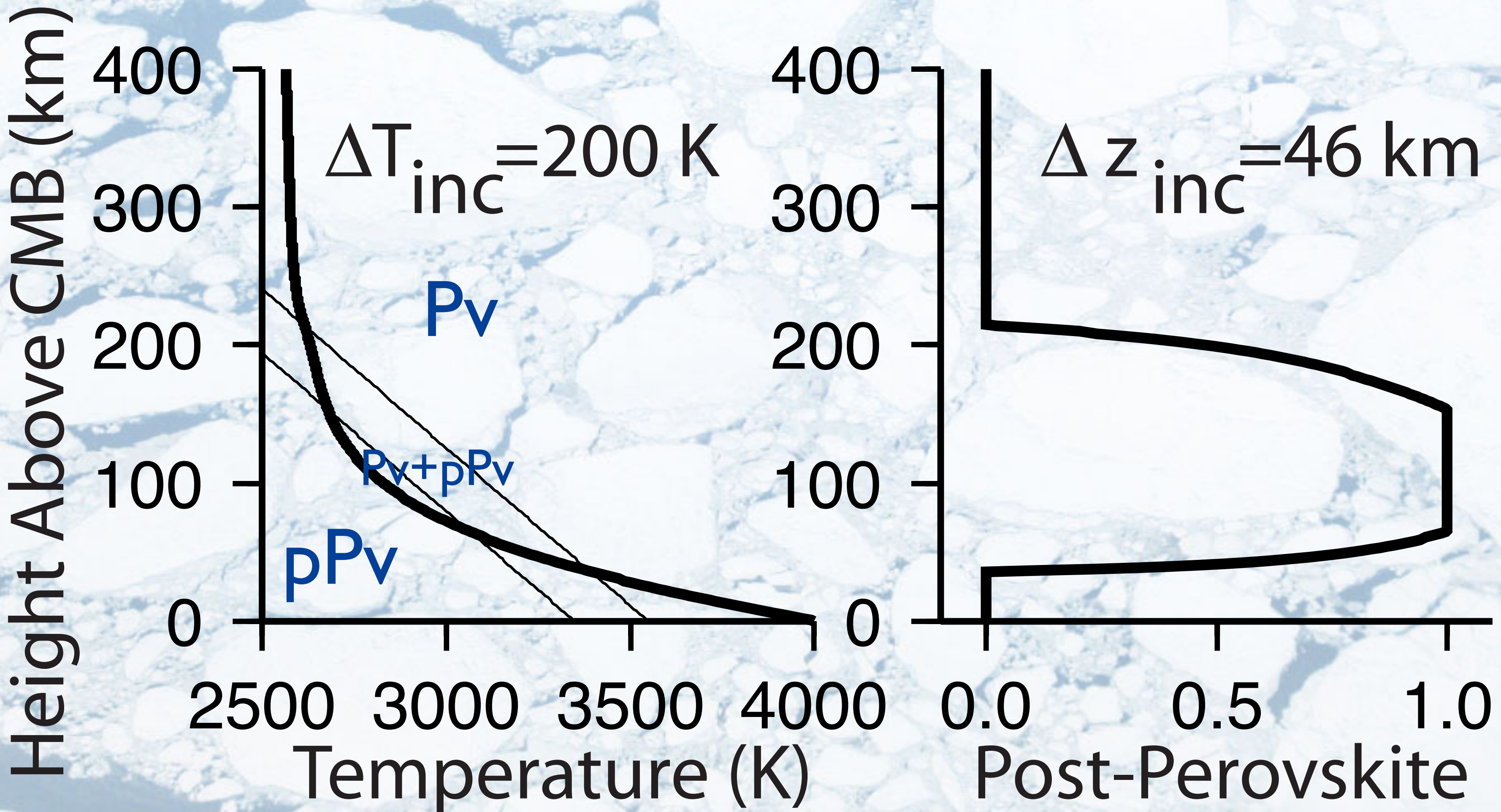
+Phase Diagram

= Solution for Temperature and Fraction of Phases



# Example Solution



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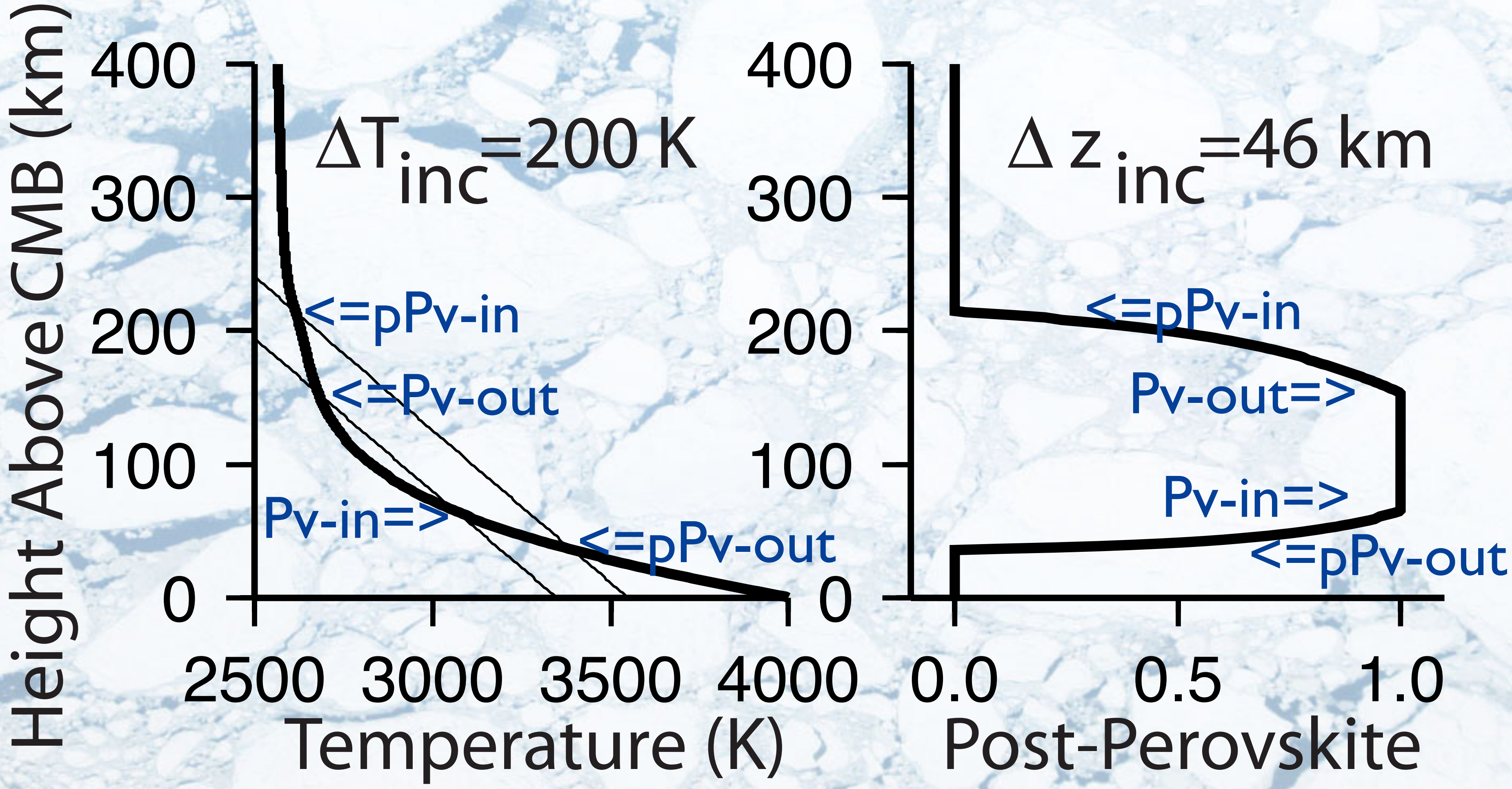
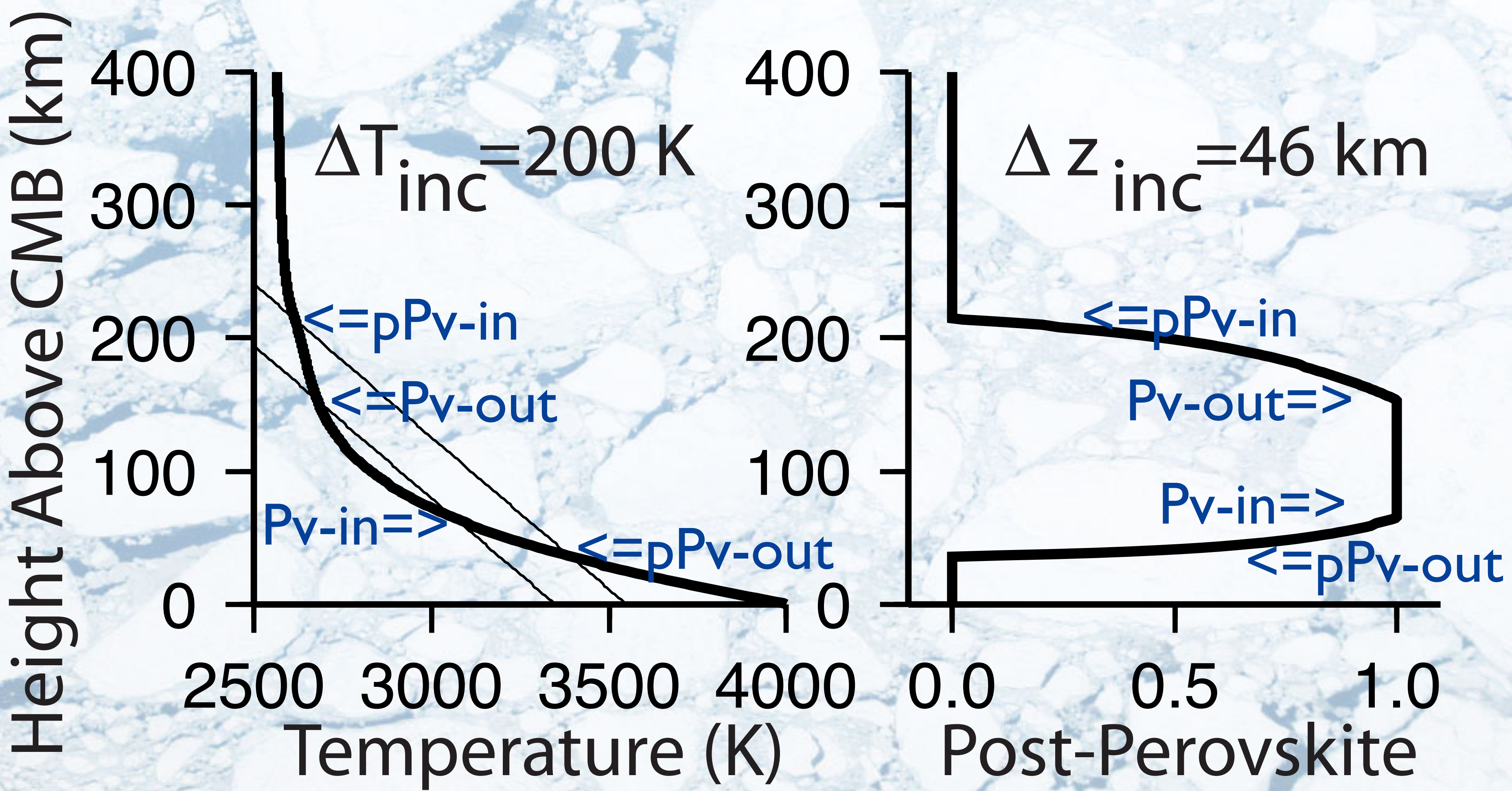



- The sharpest gradients in phase fraction occur at the top and bottom of the pPv-bearing region (pPv-in and pPv-out). This is where seismic energy will be affected most strongly.

# Example Solution

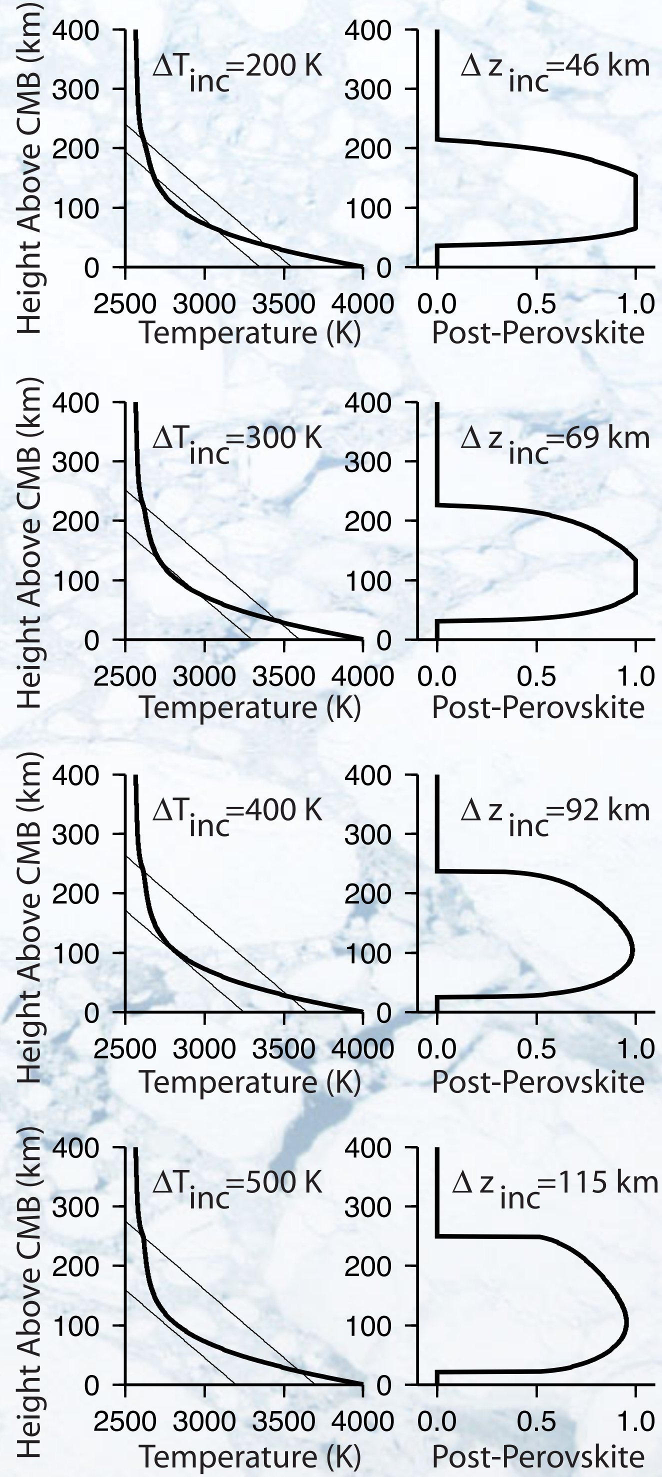



• This implies that the core-mantle boundary temperature must be higher than the temperature for pPv-out at CMB pressure in order to obtain a double-crossing.

# Phase Loop Broadening

- The sharp variation in phase fraction remains at the top and bottom of the pPv-bearing region even when the two phase loop is made so broad that the geotherm never dips into the pPv-only region (i.e., no Pv-out,Pv-in).

- Lower gradient is always sharper than upper gradient, hence more seismically reflective and detectable than otherwise.

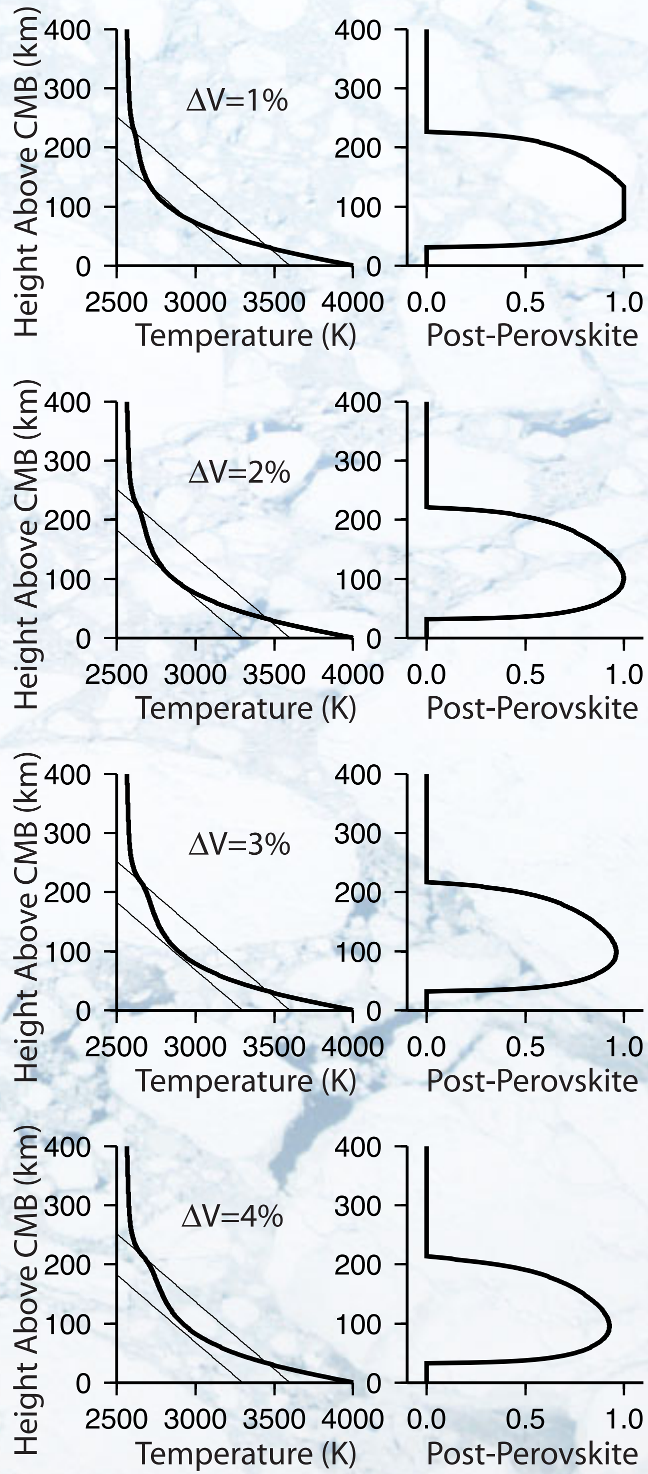


# Latent Heat Effects

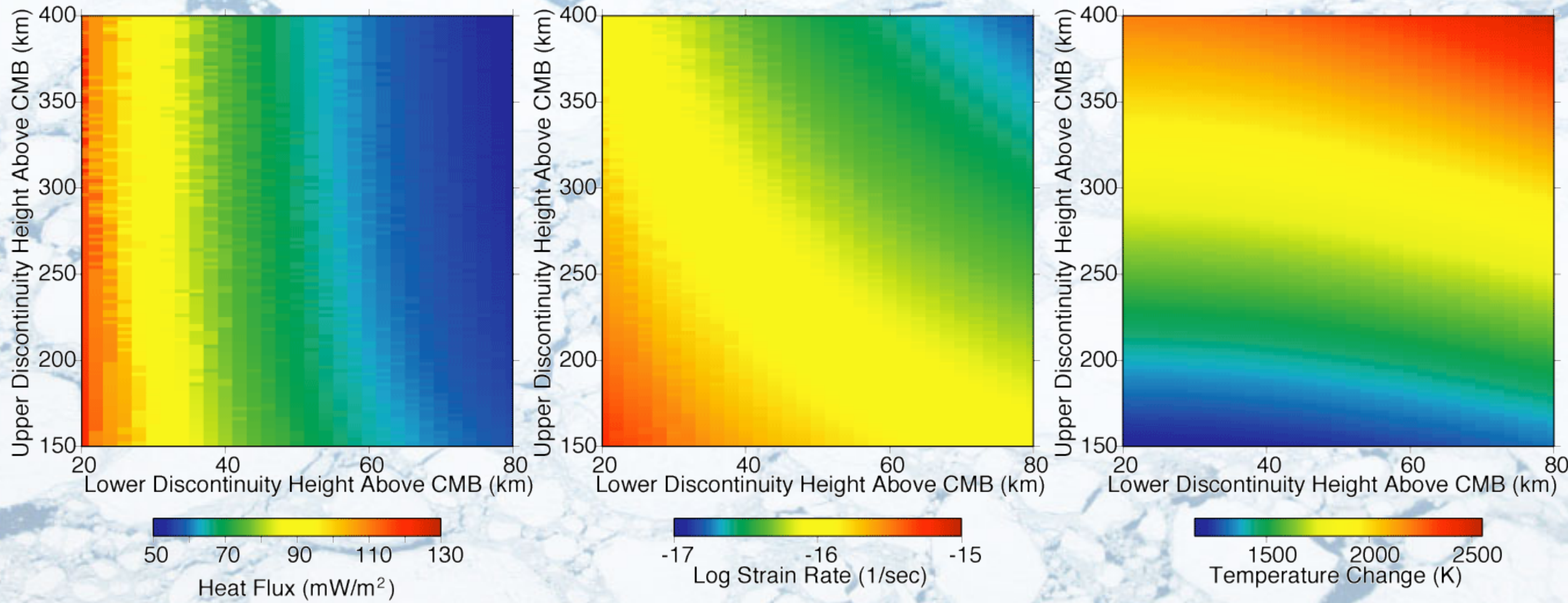
- As volume change is varied at constant Clapeyron slope, entropy change and latent heat varies in proportion.

- Latent heat release deflects the geotherm to higher temperatures at the upper crossing.

- The net effect of latent heat absorption on steepening of the geotherm at the lower crossing does not seem to be strong.

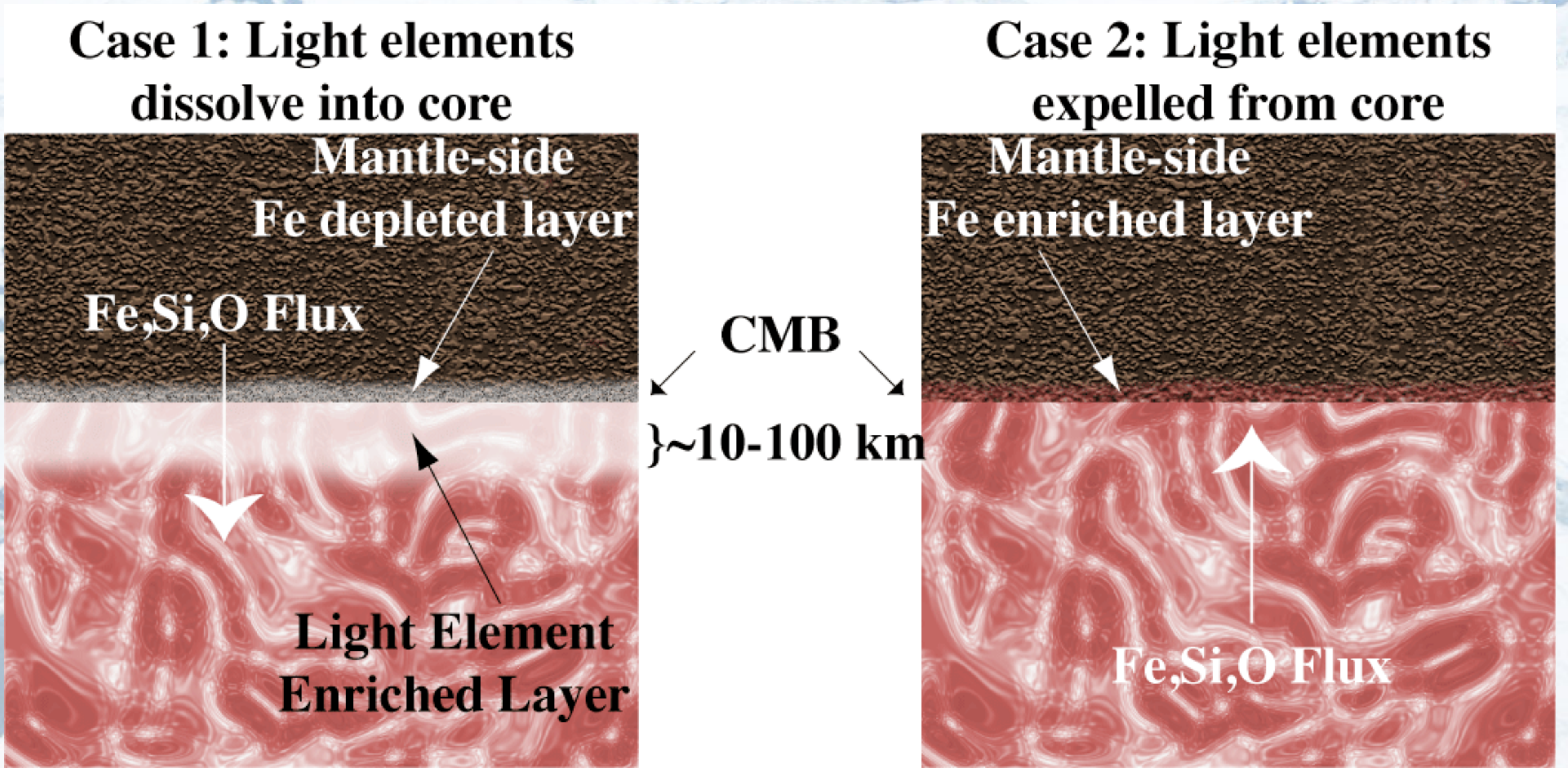


# Potential Uses of Geotherm Models that Incorporate Post-Perovskite




- Need thermal conductivity and appropriate phase diagram
- Constrains some groups of parameters, reducing uncertainties

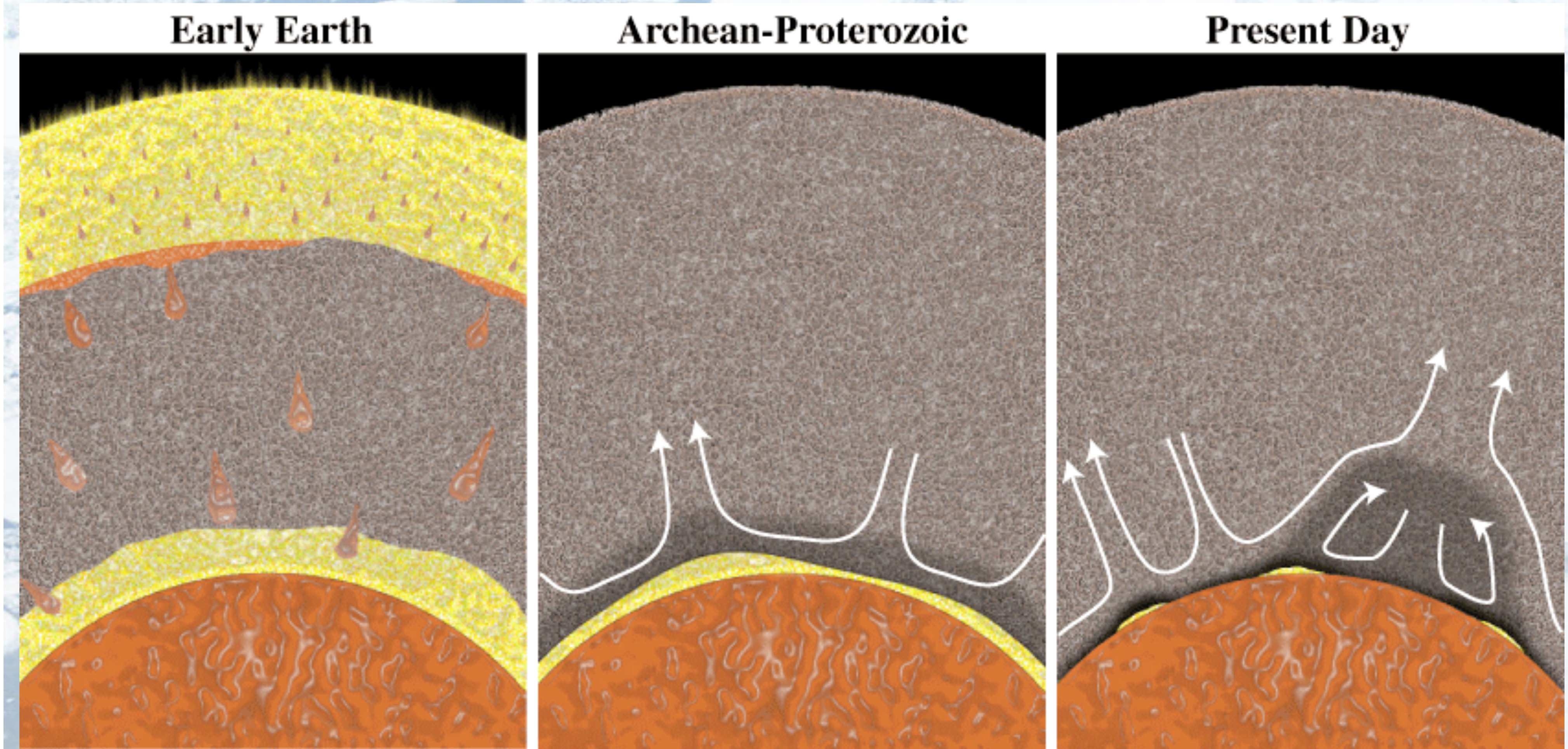
# CMB Mass Flux: Two Possibilities for Si/O



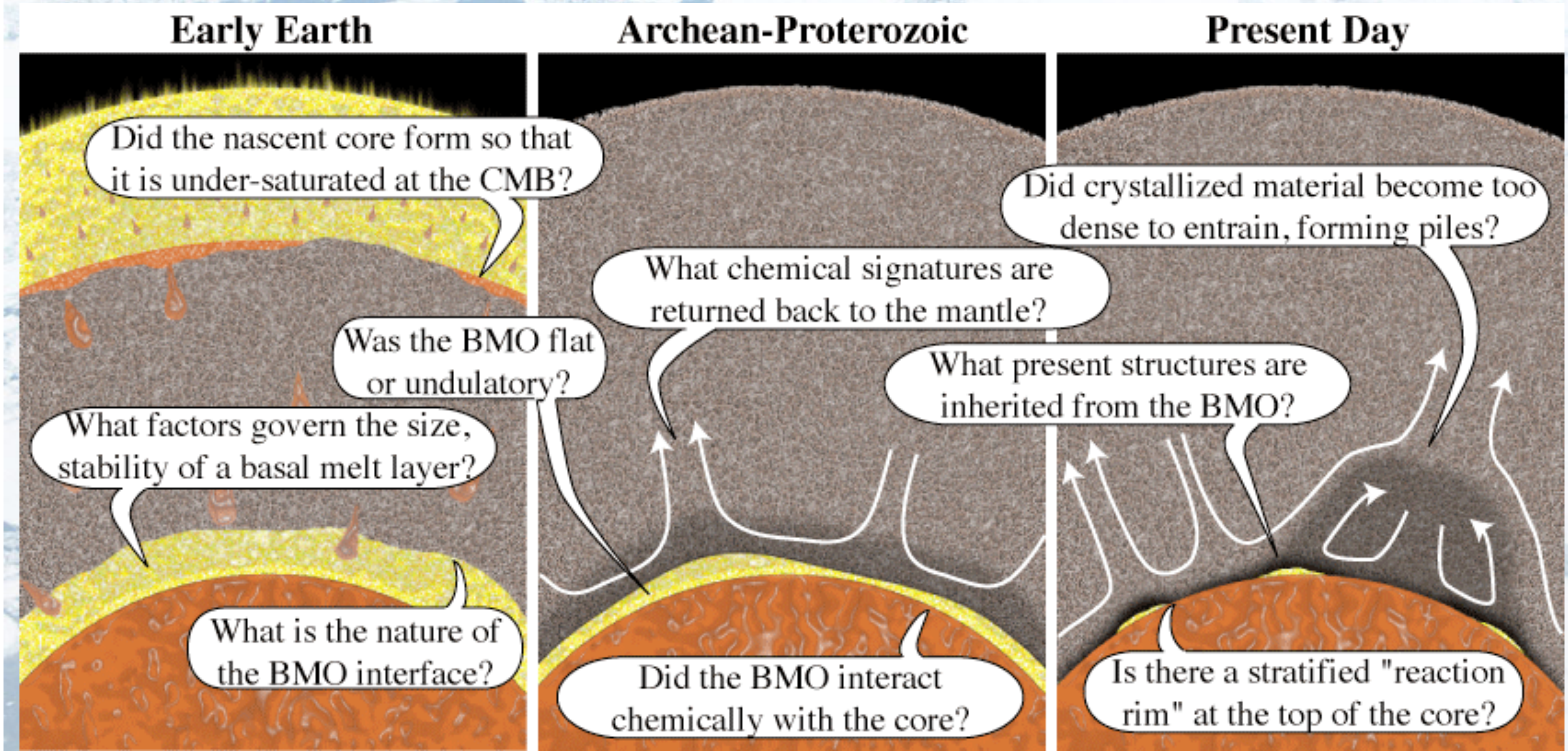

Knittle and Jeanloz (1991)

Buffett, Garnero, Jeanloz (2000)

# Exacerbated if Molten



# Initial Conditions?

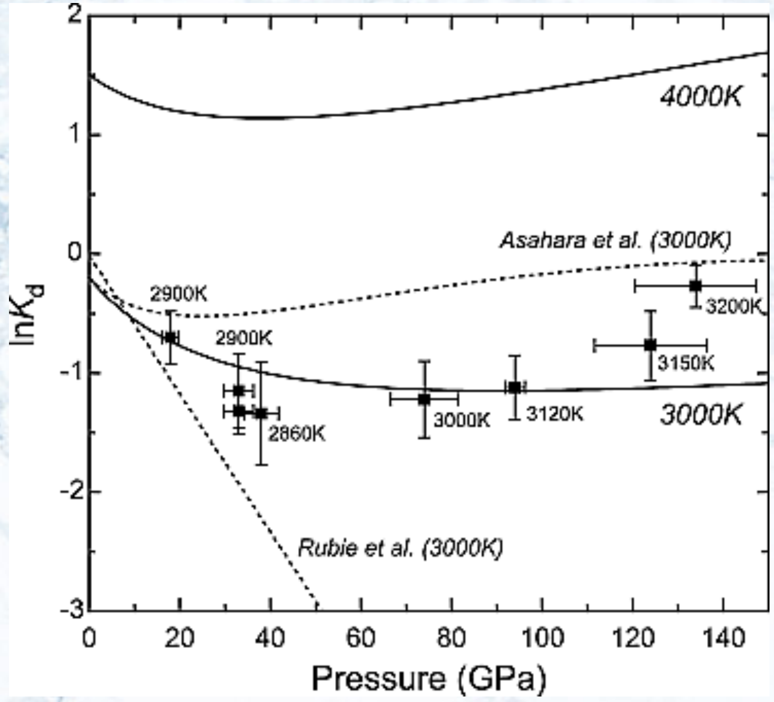


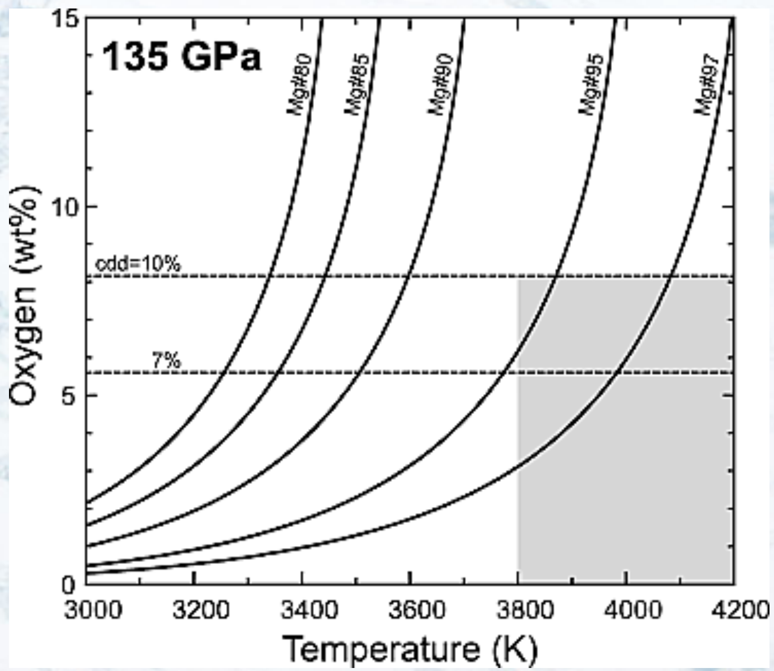

OC w/~10% light elements must have been in equilibrium with metal that formed the core at some time in the past.

# A Paradox?

Ozawa et al., 2008

- Si, O, seem readily soluble in Earth's core (Knittle and Jeanloz, Asahara et al., Ozawa et al., etc.)
- Equilibrium mostly sensitive to temperature, not pressure
- For plausible mantle Fe content, metal would have L.E. concentration much greater than the ~10% in the bulk of the core!



# No Paradox...Light Element Enriched Layer at Top of Core

- Density difference between Si, O enriched metal in equilibrium with mantle and underlying bulk core is large (~ocean-air).
- This ***cannot be mixed downward into the core***...the buoyancy exceeds every other available force by many orders of magnitude.

# No Paradox...Light Element Enriched Layer at Top of Core

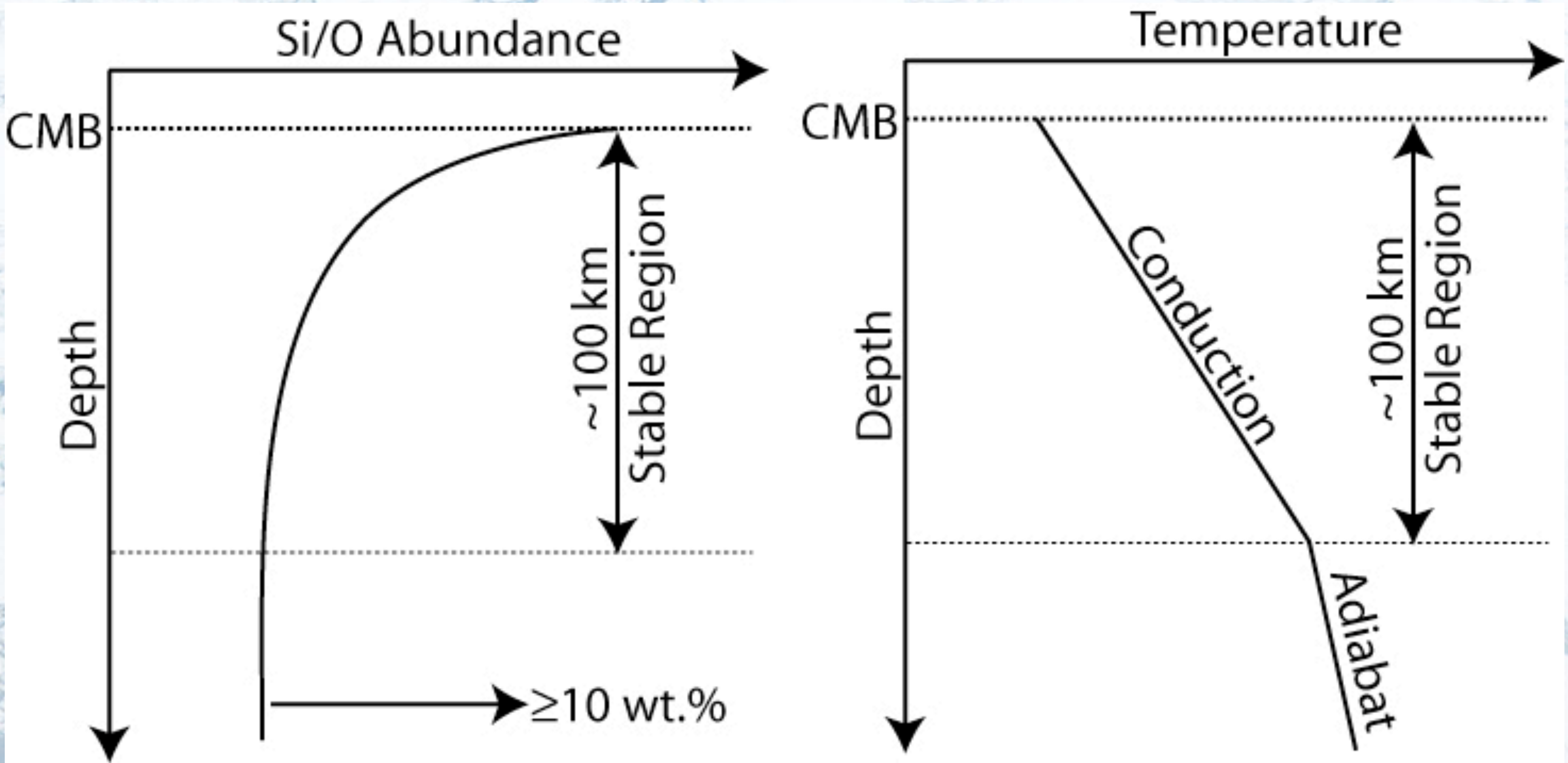
- This ***cannot be mixed downward into the core***...the buoyancy exceeds every other available force by about 7 orders of magnitude.

$$F_{adv} = \int_{Vc} \vec{\nabla} \bullet (\vec{v}\rho c T) dV \approx \pi r^2 \rho c \Delta T \langle v_r \rangle \approx O(\mathrm{TW})$$

$\Delta T \approx 10^{-4}\,\mathrm{K}$ (see also Braginsky and Roberts)

$$\Delta\rho_c \sim 10^3\,\mathrm{kg/m^3} >> \rho_0 \alpha \Delta T \sim 10^{-4}\,\mathrm{kg/m^3}$$

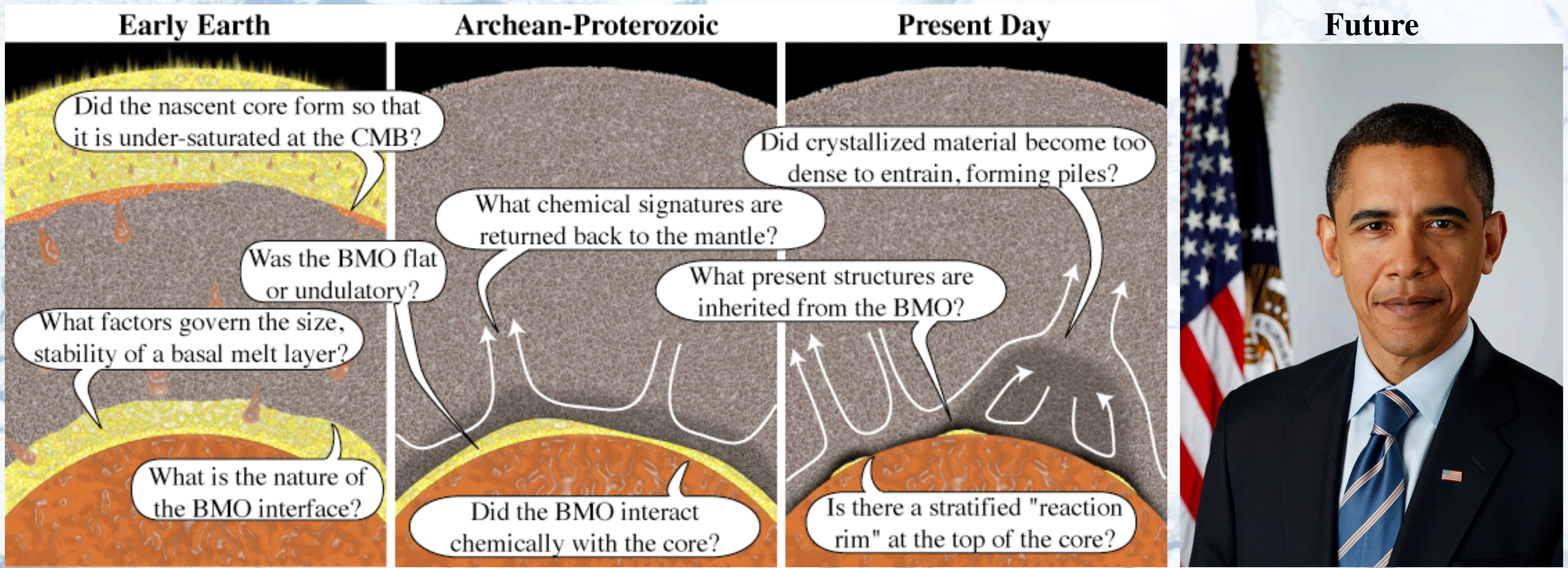
# Chemical Potential Gradient Maintained as Diffusion Boundary Layer




Hernlund, Gubbins, Labrosse, Caracas, Hirose, Lay, Manga, Jellinek, et al. (in Prep.)

- **Thickness ~ square root of 4 X diffusivity X age of Earth**

# Future Directions




**Ongoing work. BMO proposal funded by Obama “stimulus” (American Re-investment and Recovery Act, ARRA) via NSF**

# End of Talk