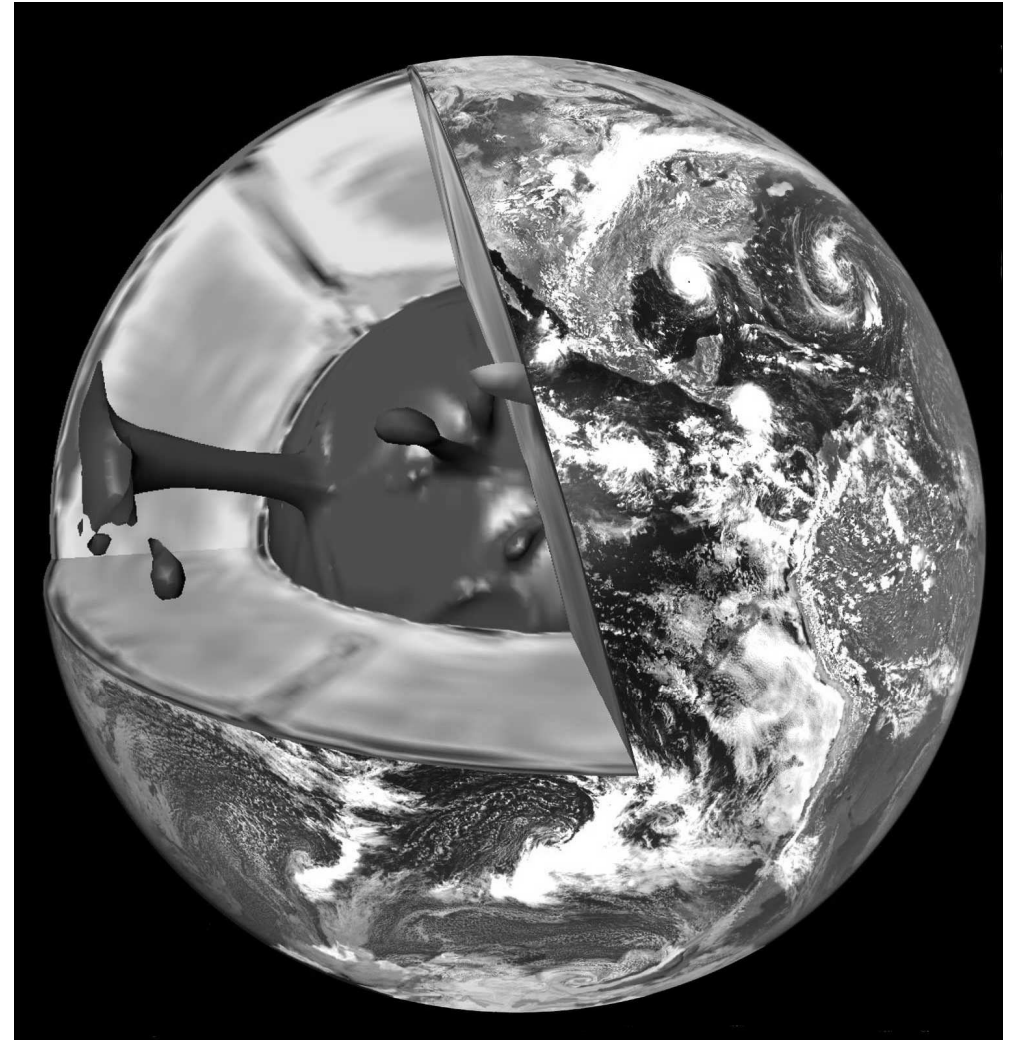


Modelling the thermo-chemical structure and evolution of the mantle (and core)

Paul J. Tackley
with help from
Takashi Nakagawa
Shunxing Xie



Compositional variations are important in the mantle

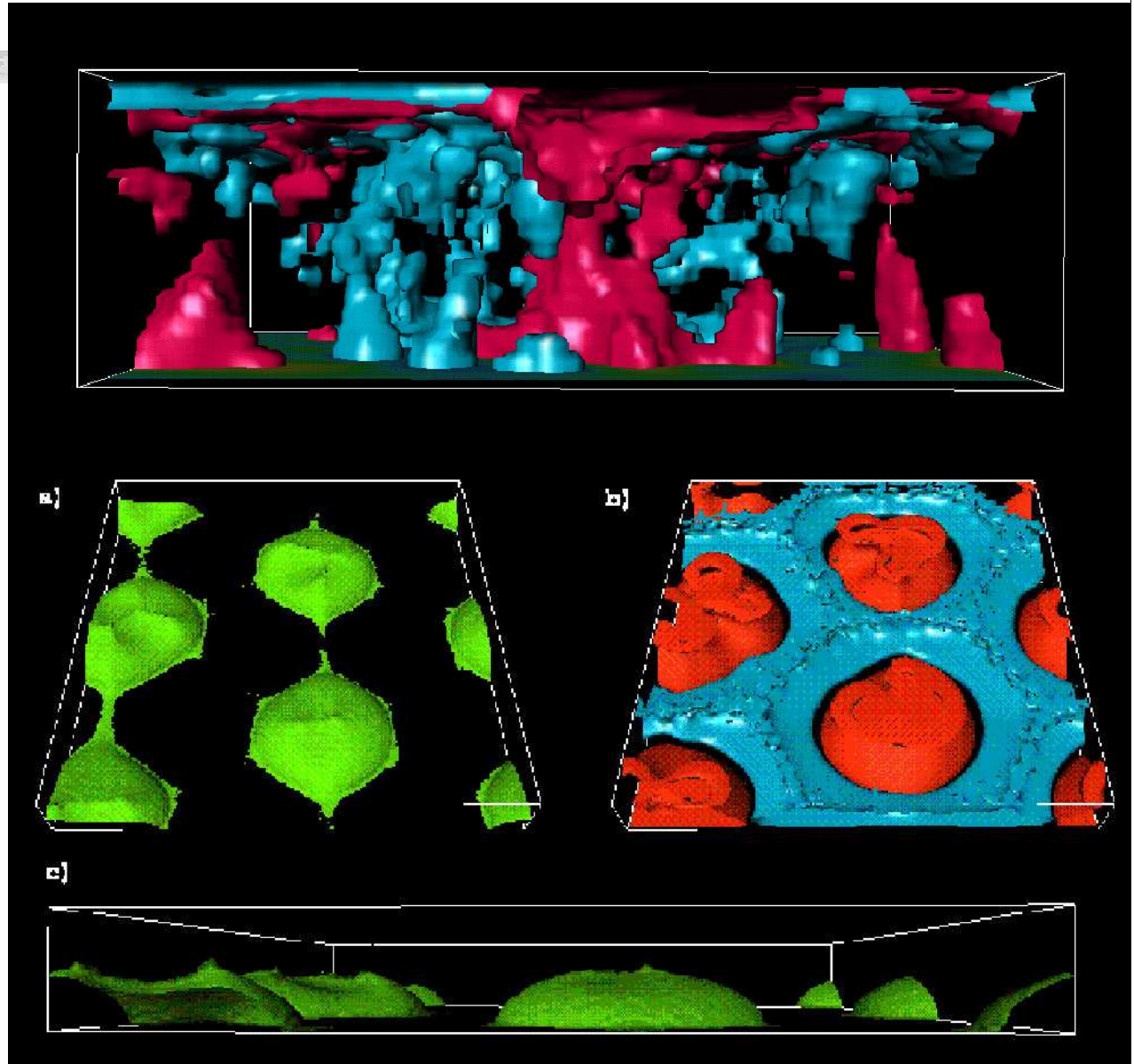
⌘ We know they're there because

- ⊞ Subducted slabs are compositionally stratified
- ⊞ Seismologists “observe” compositional variations
- ⊞ Geochemists measuring isotope ratios in erupted magmas find that several chemically-distinct components are required

⌘ They affect mantle convection (through density and other physical properties) and are affected by mantle convection => study using thermo-chemical convection models

Seismology: “piles” of dense material look like features in tomography models

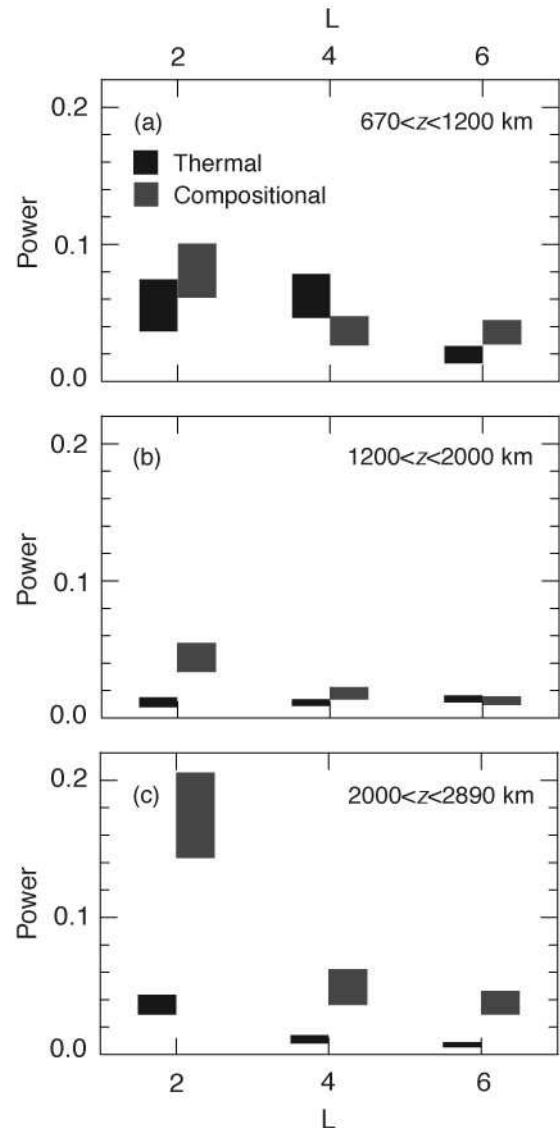
⌘ Masters et al
tomography



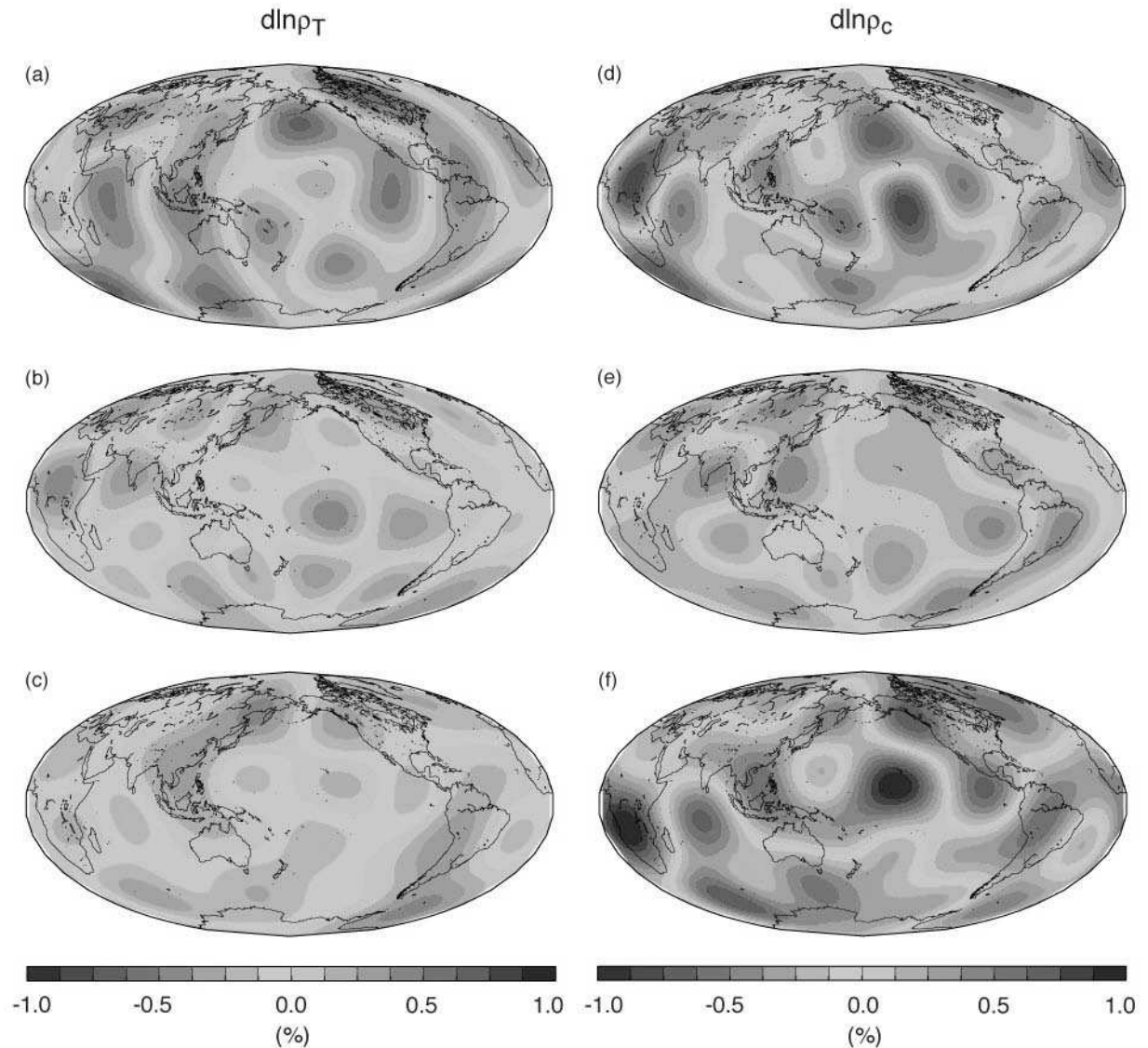
⌘ Tackley, 1998

⌘ (green=C)

Recent probabilistic seismic inversion finds that composition dominates long-wavelength seismic signal in lower mantle



Deschamps, Trampert, Tackley (2005)



Deschamps, Trampert, Tackley (2005)

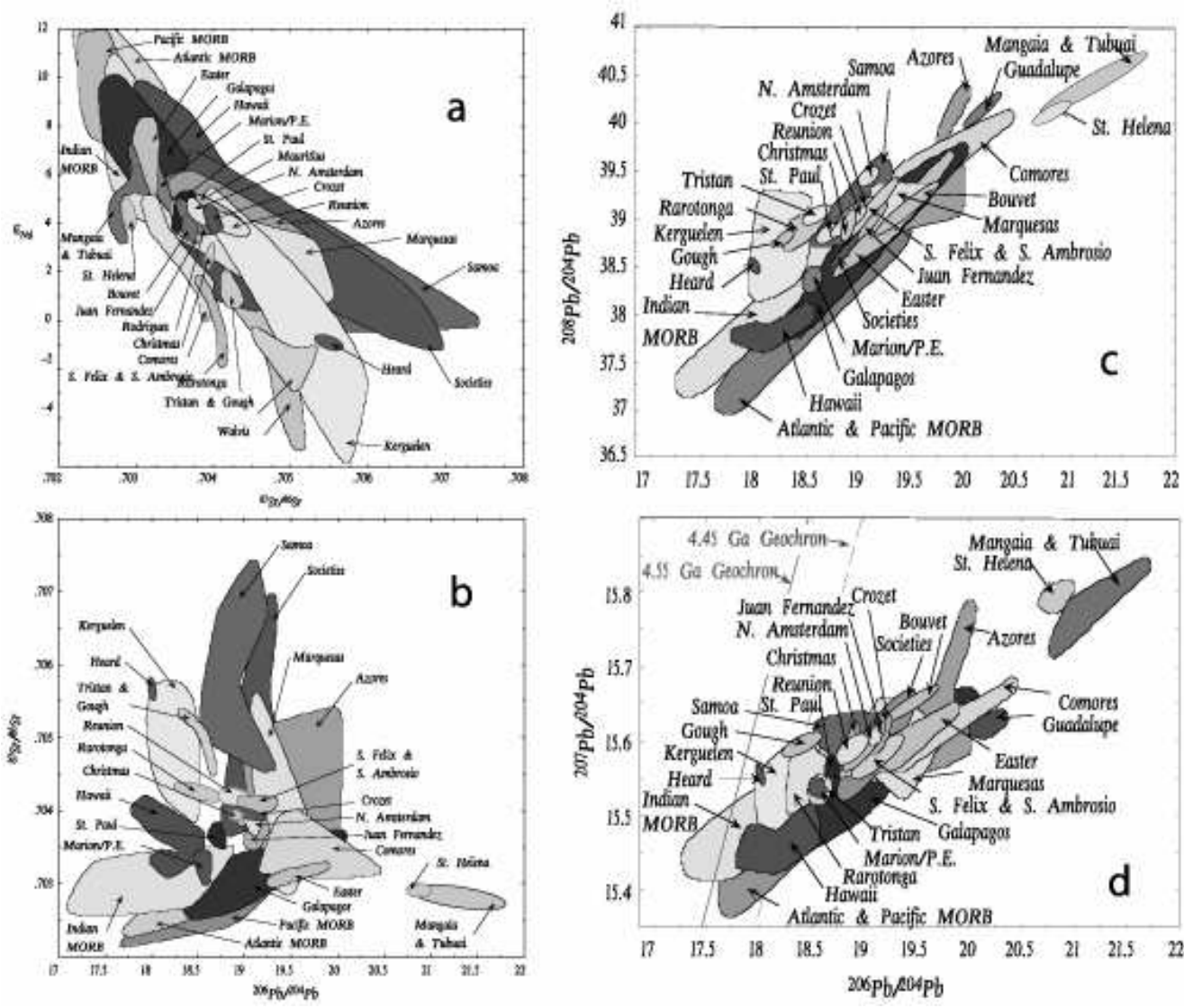
Compositional variations are important in the mantle

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Geochemistry: Example isotope diagrams



Slope →
"Age"

(White, 2003)

Compositional variations are important in the mantle

⌘ We know they're there because

- ⊞ Subducted slabs are compositionally stratified
- ⊞ Seismologists “observe” compositional variations
- ⊞ Geochemists measuring isotope ratios in erupted magmas find that several chemically-distinct components are required

⌘ They affect mantle convection (through density and other physical properties) and are affected by mantle convection => **study using thermo-chemical convection models**

Uncertainties in mineral physics have 1st order influence, e.g. on

⌘ The existence & nature of compositional stratification & heterogeneity

⊠ in D''

⊠ around 660 km

⌘ The location of **post-perovskite** material and how it interacts with chemical variations

⌘ The conversion of T & ρ to Vs and Vp

⌘ And indirectly on:

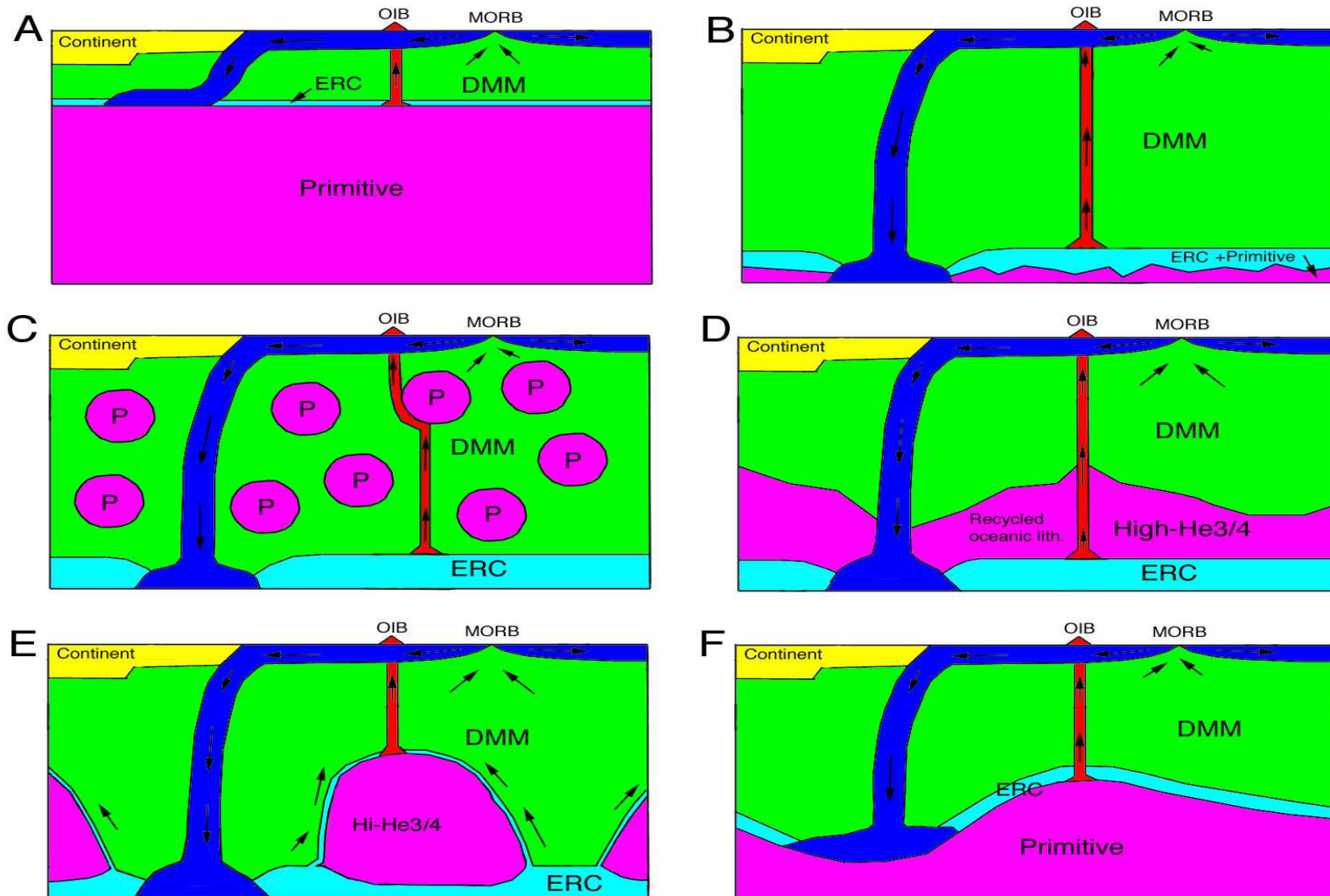
⊠ Mantle geochemical (trace element) evolution

⊠ **Core evolution**: CMB heat flux must be high enough for geodynamo without inner core growing too large - **chemical heterogeneity above CMB affects this**

Numerically modeling mantle thermo-chemical evolution: like baking a cake

- **Ingredients**
 - Physical & chemical properties & behaviors (mineral physics, rheology, partition coefficients, melting, etc.)
 - Initial condition (homogeneous? layered?)
- **Baking method (computer 'oven')**
 - Convection calculations with geochemical tracers
 - Need to run for billions of years for geochemistry
- **Outputs: what type of cake?**
 - Geophysical: compare structure to seismology, heat flow & T vs. time, core evolution...
 - Geochemical: Isotope ratios ($^3\text{He}/^4\text{He}$ distributions etc.), outgassing, layering, heterogeneity lengthscales, etc.
- **Hypothesis testing:** which mantle models are consistent with both geochemical and geophysical constraints?
- Today **focus on the deep mantle** (CMB heat flow, core evolution, interaction with PPV transition) and geochemistry if time permits. (He/Ar, and Pb-Pb isotopic ages)

Geochemical cartoon models: which ones “work” both geophysically and geochemically?



from Tackley, Science, 2000: Figure 2

Ingredients: Physics

- ⌘ Compressible anelastic (physical properties depend on depth/pressure)
- ⌘ Viscosity dependent on:
 - ⊠ Temperature (factor 10^6)
 - ⊠ Depth (factor 10, exponential + jump @660)
 - ⊠ Stress (yielding gives “plate-like” behavior)
- ⌘ Pyroxene-garnet phase transitions as well as olivine-system transitions, with post-perovskite included in both
- ⌘ Internal heating + isothermal, cooling CMB
- ⌘ Parameterized core energy balance similar to Buffett's (Nimmo's gives similar results)
- ⌘ Cylindrical geometry (2-D)

Ingredients: Chemistry

⌘ Major elements:

- ⊞ 2-components: 'crust' (basalt/eclogite) <-> 'residue' (harzburgite).
- ⊞ **Solidus** (*Herzberg et al 2000; Zerr et al 1998*); melt instantly removed to form surface crust.
- ⊞ **Chemical density variation** depends on depth (2-component system)

⌘ Trace elements:

- ⊞ ^{207}Pb , ^{206}Pb , ^{204}Pb , ^{143}Nd , ^{144}Nd , ^{147}Sm , ^{235}U , ^{238}U , ^3He , ^4He , ^{36}Ar , ^{40}Ar , ^{40}K , ^{232}Th
- ⊞ **Initial concentrations** represent mantle after extraction of CC.
- ⊞ Unmelted material would have $^3\text{He}/^4\text{He}=35$ today.
- ⊞ Radioactive decay
- ⊞ **Partitioning** between crust + residue on melting. **Coefficients** from (*Hofmann 88*) and variations on (*Hiyagon+Ozima 86*)
- ⊞ Noble gases outgas on eruption (**outgassing fraction** 90% in presented models)

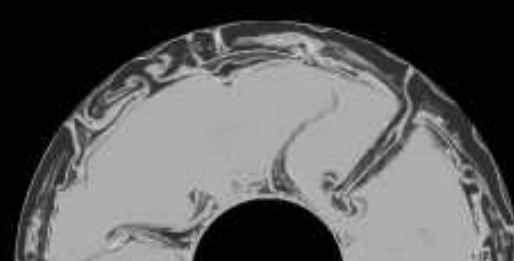
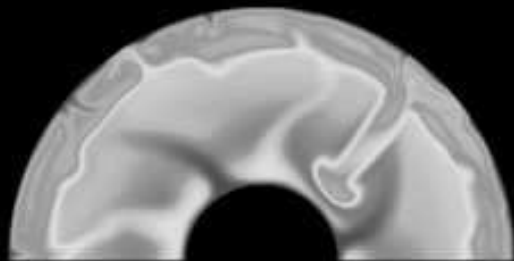
⌘ Homogeneous start

T

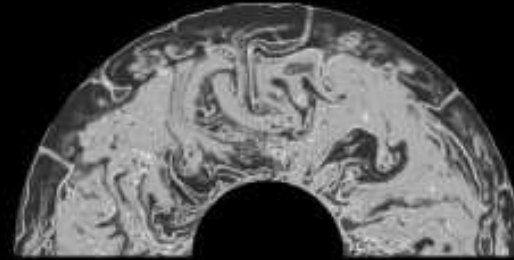
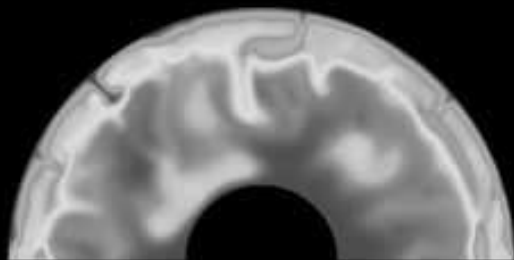
phase

C

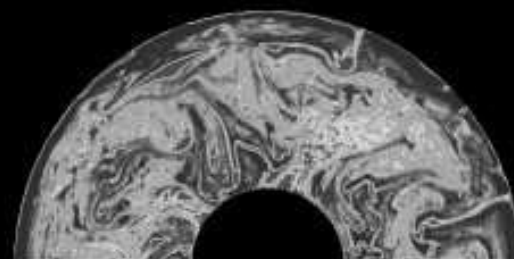
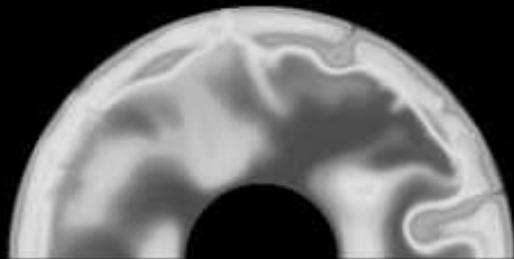
(a) -3.379 Gyrs



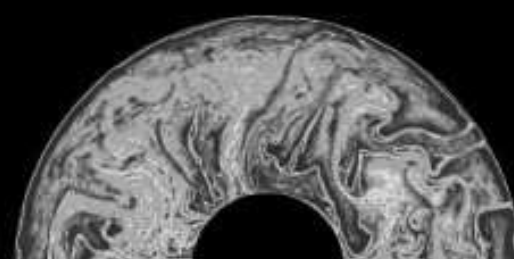
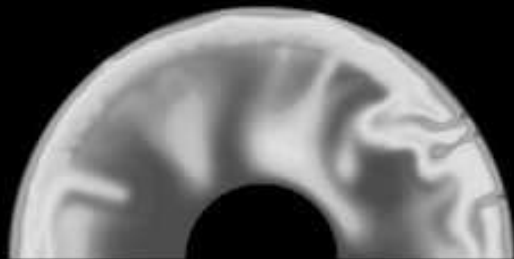
(b) -2.148 Gyrs



(c) -1.144 Gyrs



(d) present time

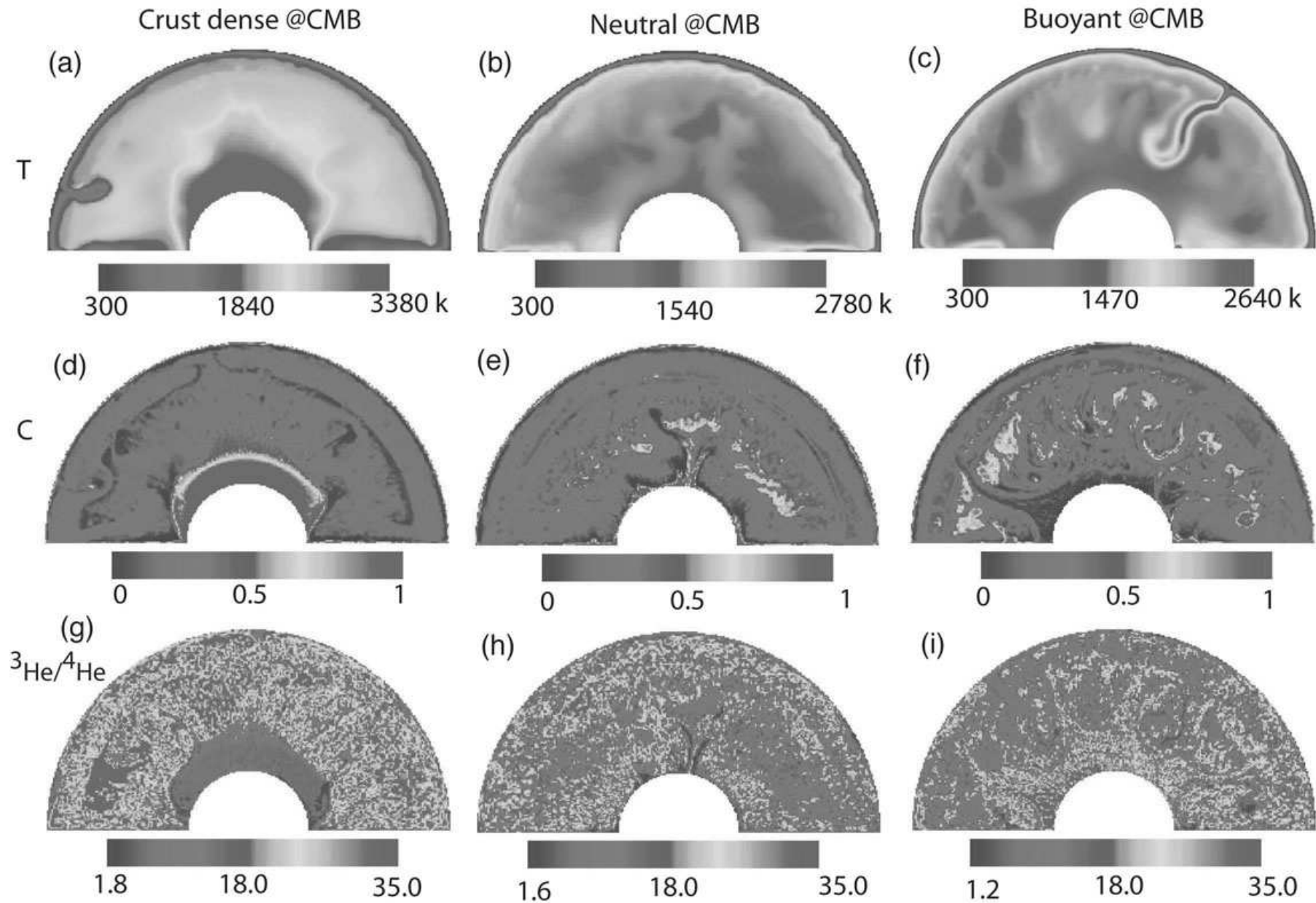


Temperature

Phase

Composition

Trace element ratios heterogeneous!



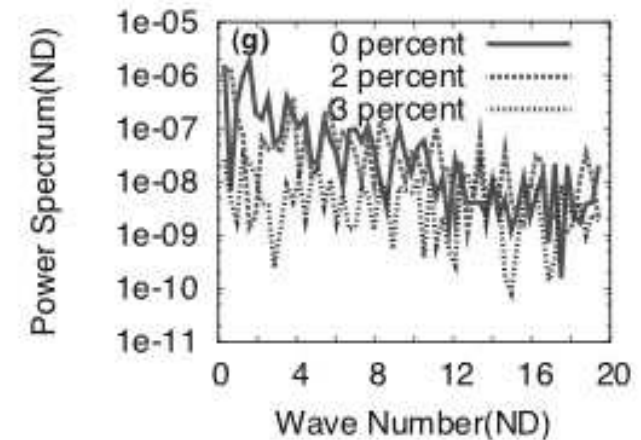
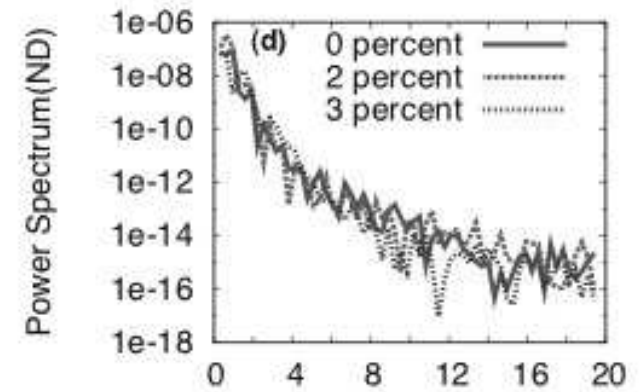
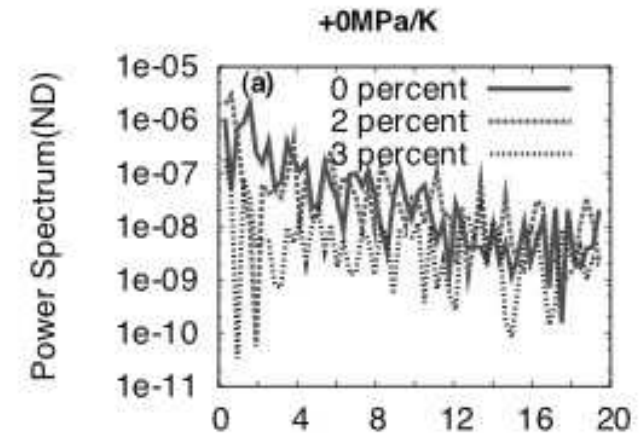
General structure and evolution

- ⌘ Highly heterogeneous in major- and trace-elements
- ⌘ Build-up of “messy” basal layer
- ⌘ >95% has differentiated- very little primitive ‘pyrolite’ - rather mixture of MORB and depleted compositions
- ⌘ Composition has a different spectrum (see next)

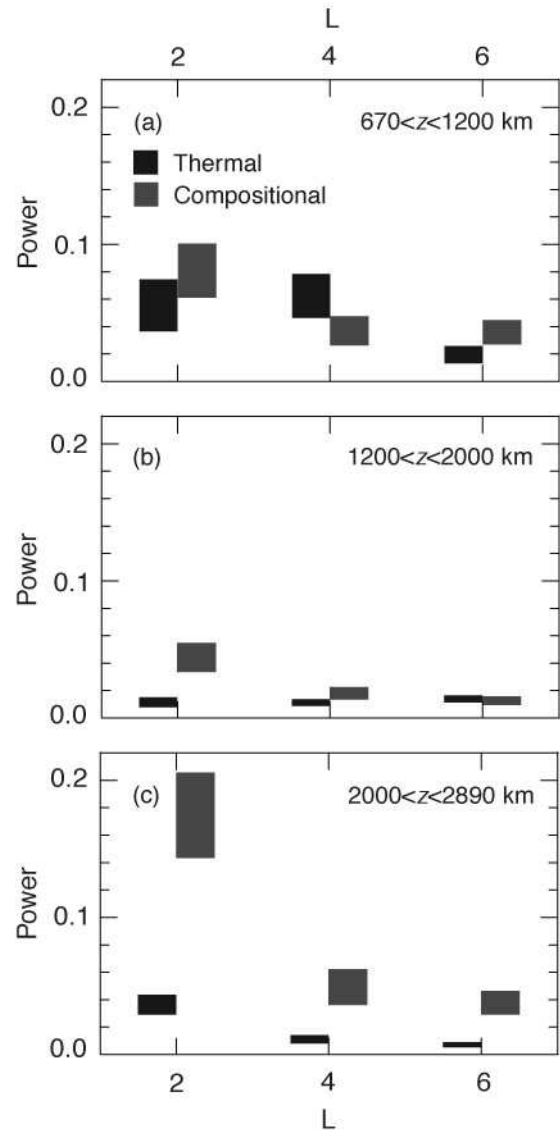
Total v_s spectrum

T spectrum

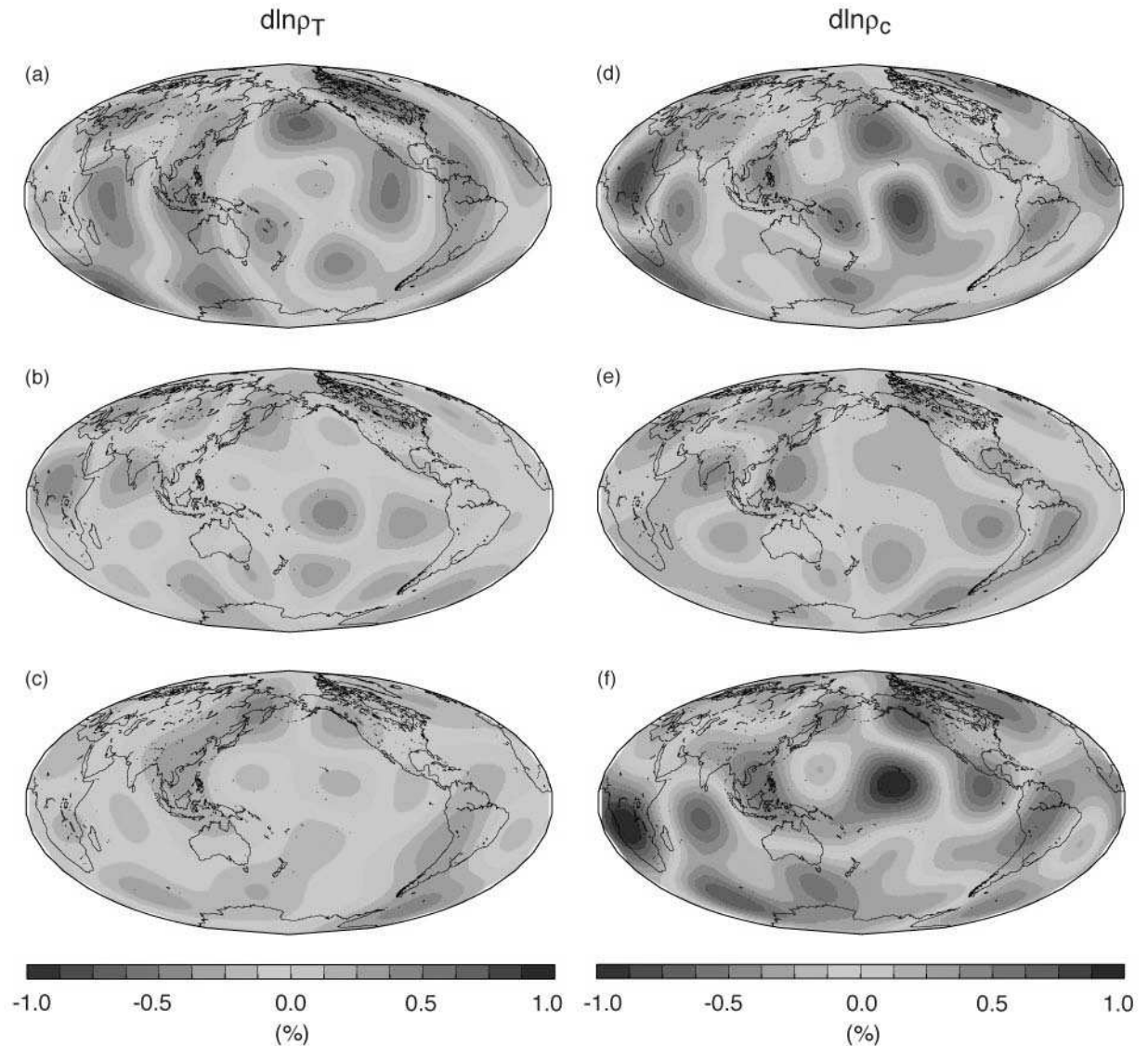
C spectrum



Recent probabilistic seismic inversion finds that composition dominates long-wavelength seismic signal in lower mantle



Deschamps, Trampert, Tackley (2005)



Deschamps, Trampert, Tackley (2005)

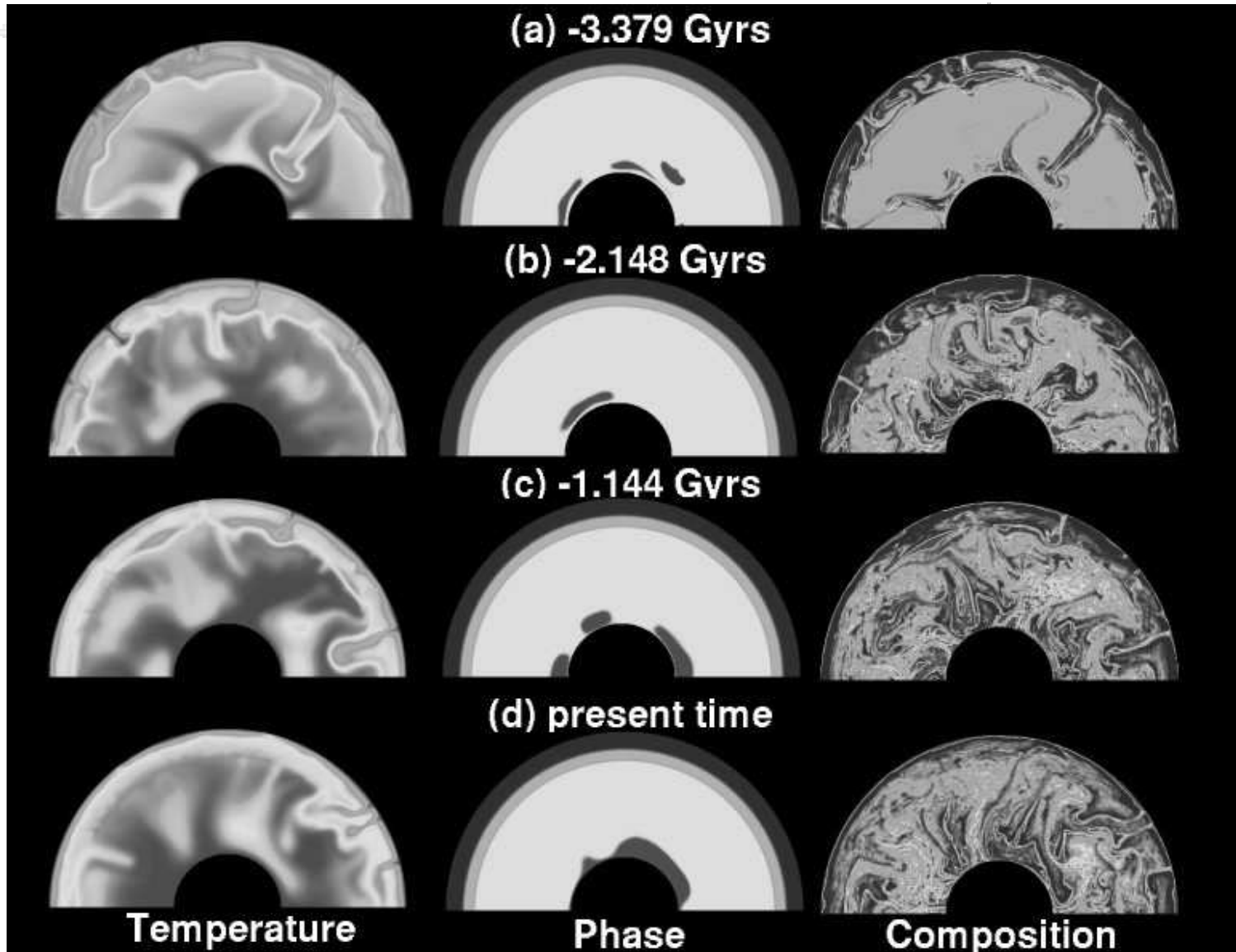
Spectrum conclusions

⌘ C dominates at short wavelengths due to a flatter spectrum



Focus on transition zone: is there any 'layering'?

If '660' assumes 100% olivine, there is an early layered phase



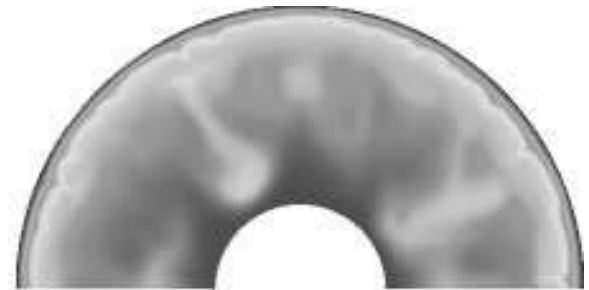
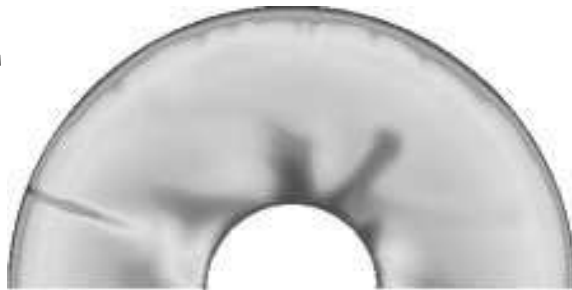
With both olivine and pyroxene systems, no early layered phase but...

1 Ga

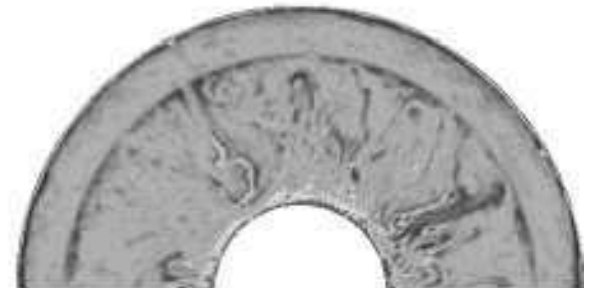
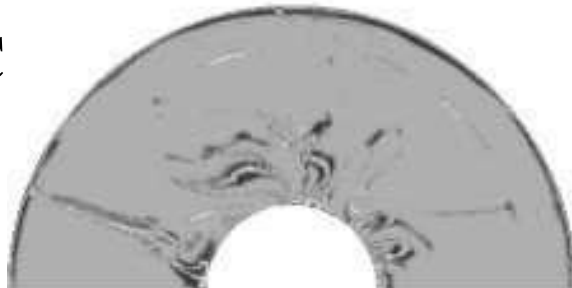
2 Ga

3 Ga

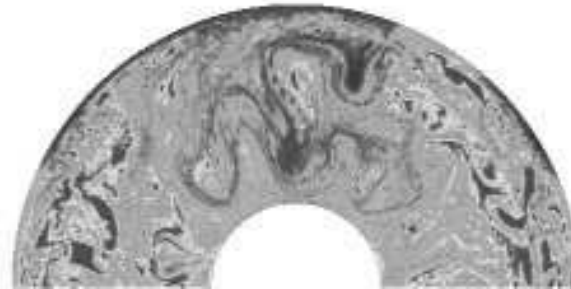
T



C



age

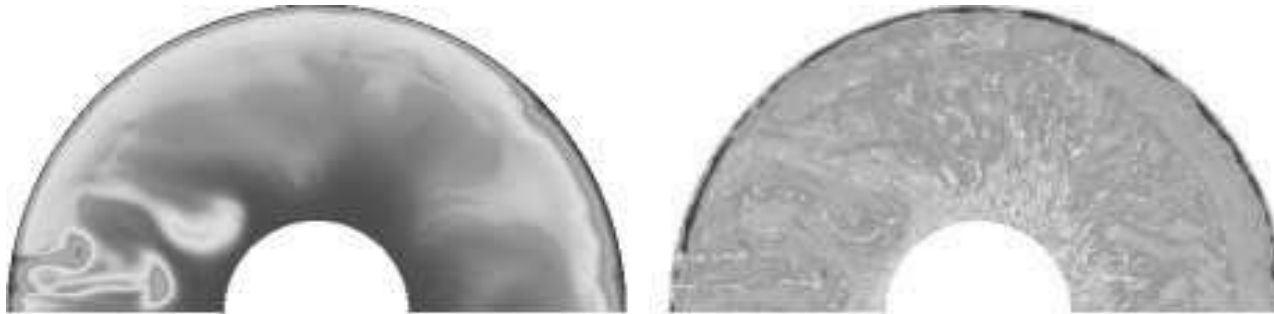


Time →

Local stratification builds up around 660 because of...

3.6 Ga

T



$\mu=^{238}\text{U}/^{204}\text{Pb}$

C



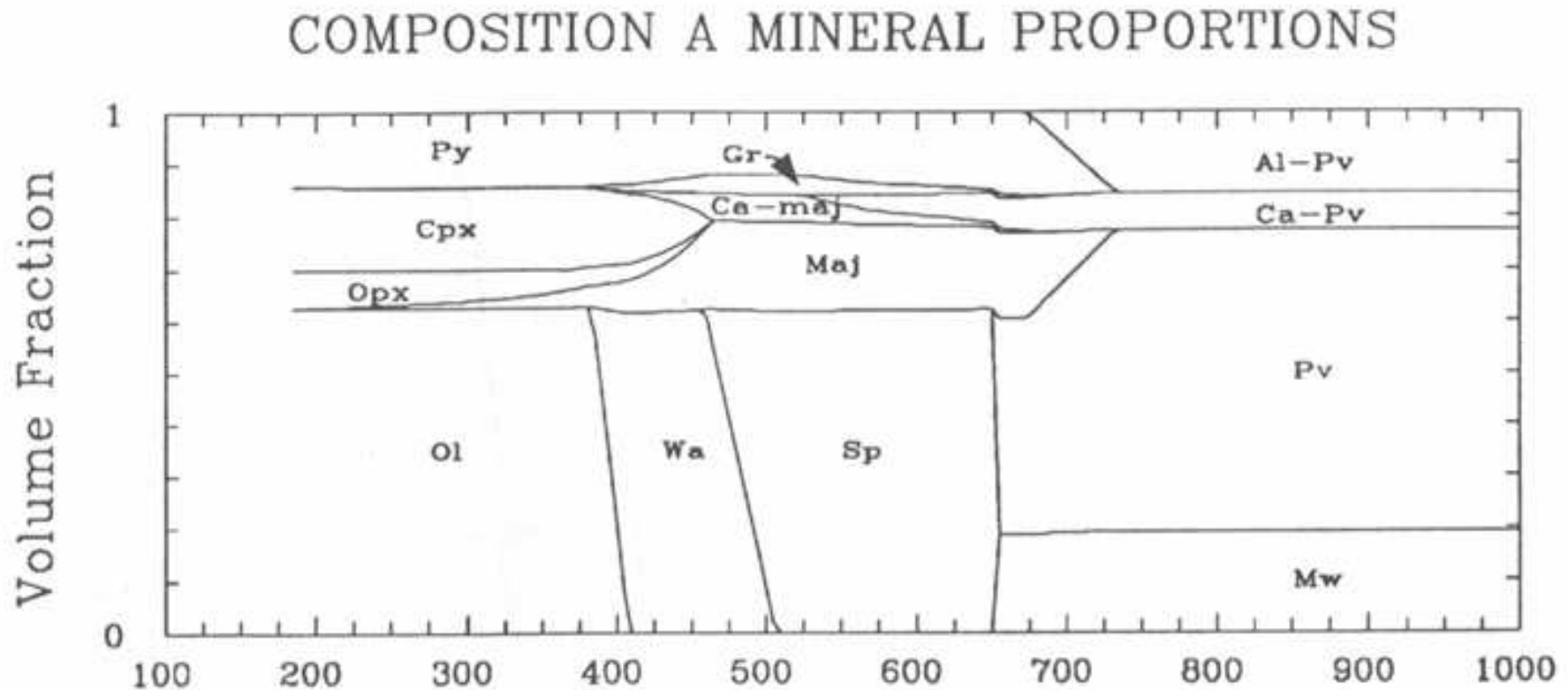
$^{206}\text{Pb}/^{204}\text{Pb}$

age



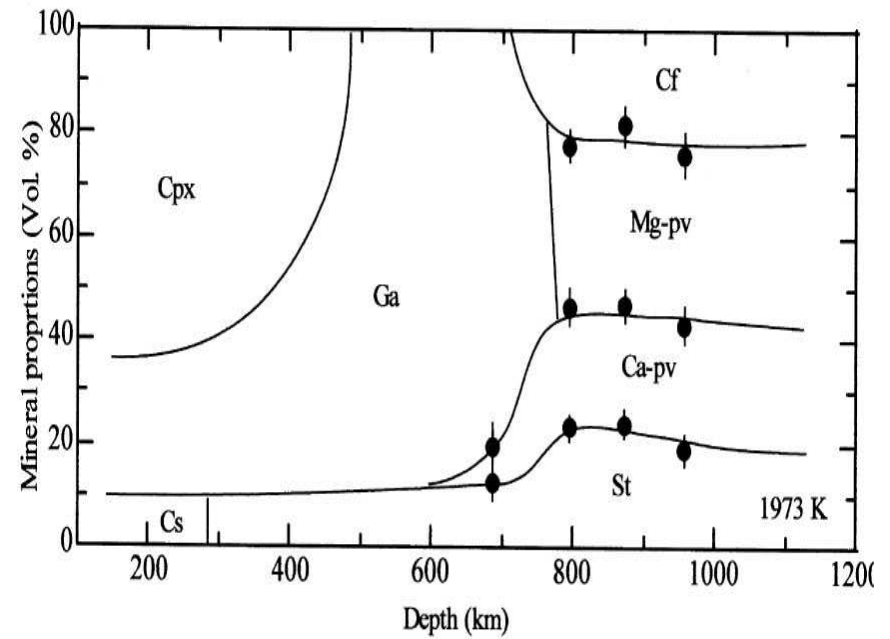
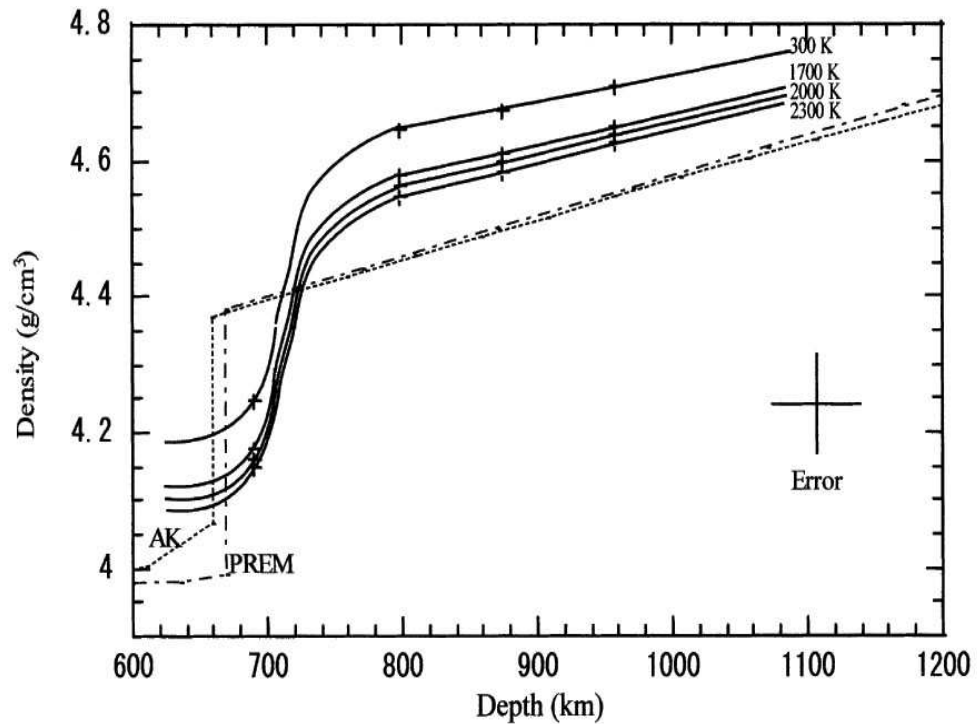
$^{147}\text{Sm}/^{144}\text{Nd}$

Different depths of perovskite transition in olivine and pyroxene systems

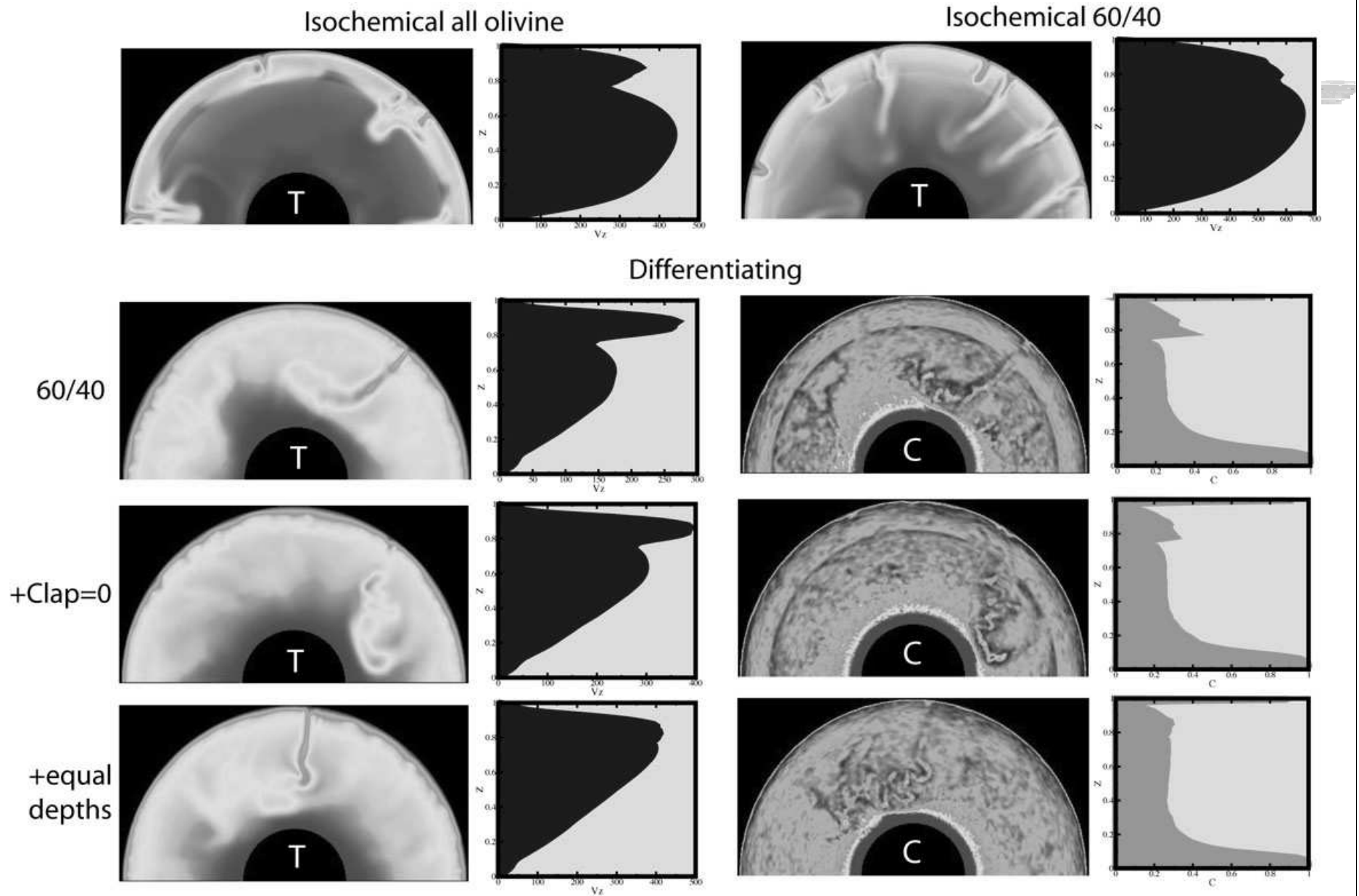


⌘ From Ita and Stixrude

Consistent with recent measurements: Ono et al 2001



Demonstration of this



TZ Conclusions

- ⌘ Purely thermal convection: ~no layering with both phase systems included
- ⌘ +chemical variations: Different depths of perovskite transition in olivine and pyroxene systems leads to partial layering of flow and composition

Focus on deep mantle



**Can the chemically-anomalous material
near the base of the mantle be
subducted MORB?**

Can subducted MORB form a layer above the CMB?

- ⌘ Olson & Kincaid 1991: Laboratory, $B=0.6$, almost all crust settles
- ⌘ Christensen & Hofmann 1994: $B=1.5$, $\sim 1/6$ crust settles
- ⌘ Ogawa 2003: 120 kg/m^3 : almost all crust settles
- ⌘ Nakagawa & Tackley, Xie & Tackley: $60\text{-}120 \text{ kg/m}^3$ ($B=0.4\text{-}0.8$) enough to produce settling, with large-topography layer

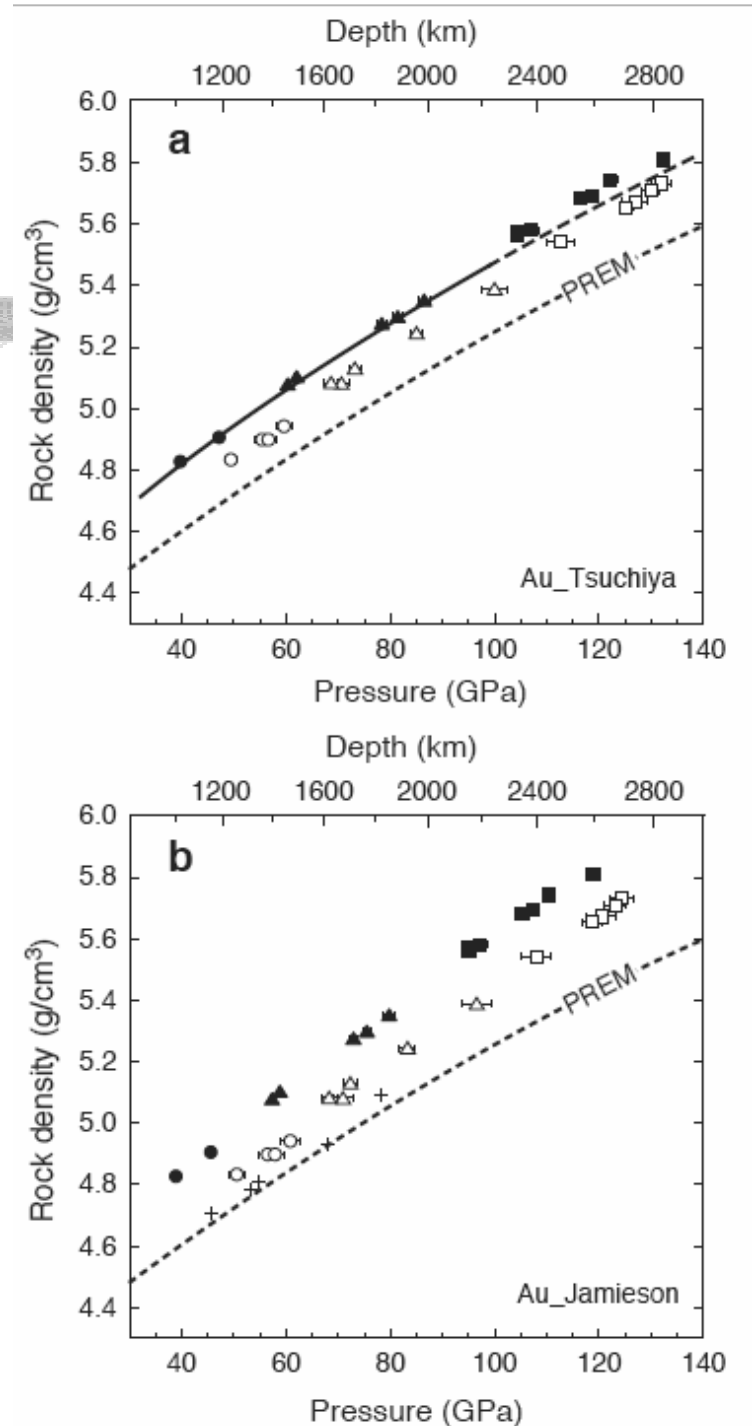
SUMMARY: MORB can settle if dense enough, assisted by low (T-dependent) viscosity

How dense is MORB near the CMB?

- ⌘ Ringwood 1990: 2-4% denser throughout lower mantle (110-220 kg/m³ @ cmb)
- ⌘ Kesson 1998: 30 kg/m³ less dense than pyrolite, 11 kg/m³ denser than depleted residue
- ⌘ Ono et al 2001: less dense than pyrolite in deep mantle
- ⌘ Guignot & Andraut 2004: 25-95 kg/m³ denser
- ⌘ Hirose et al 2005: 200-300 kg/m³ denser throughout lower mantle

Hirose et al. 2005

- ⌘ MORB 200-300 kg/m³ denser than PREM at all lower mantle depths
- ⌘ (3.5-5.3% @ CMB)



Density contrast required for a stable layer to not be entrained after 4.5 billion years

⌘ Scaled to thermal expansivity= $1.0 \times 10^{-5} \text{ K}^{-1}$

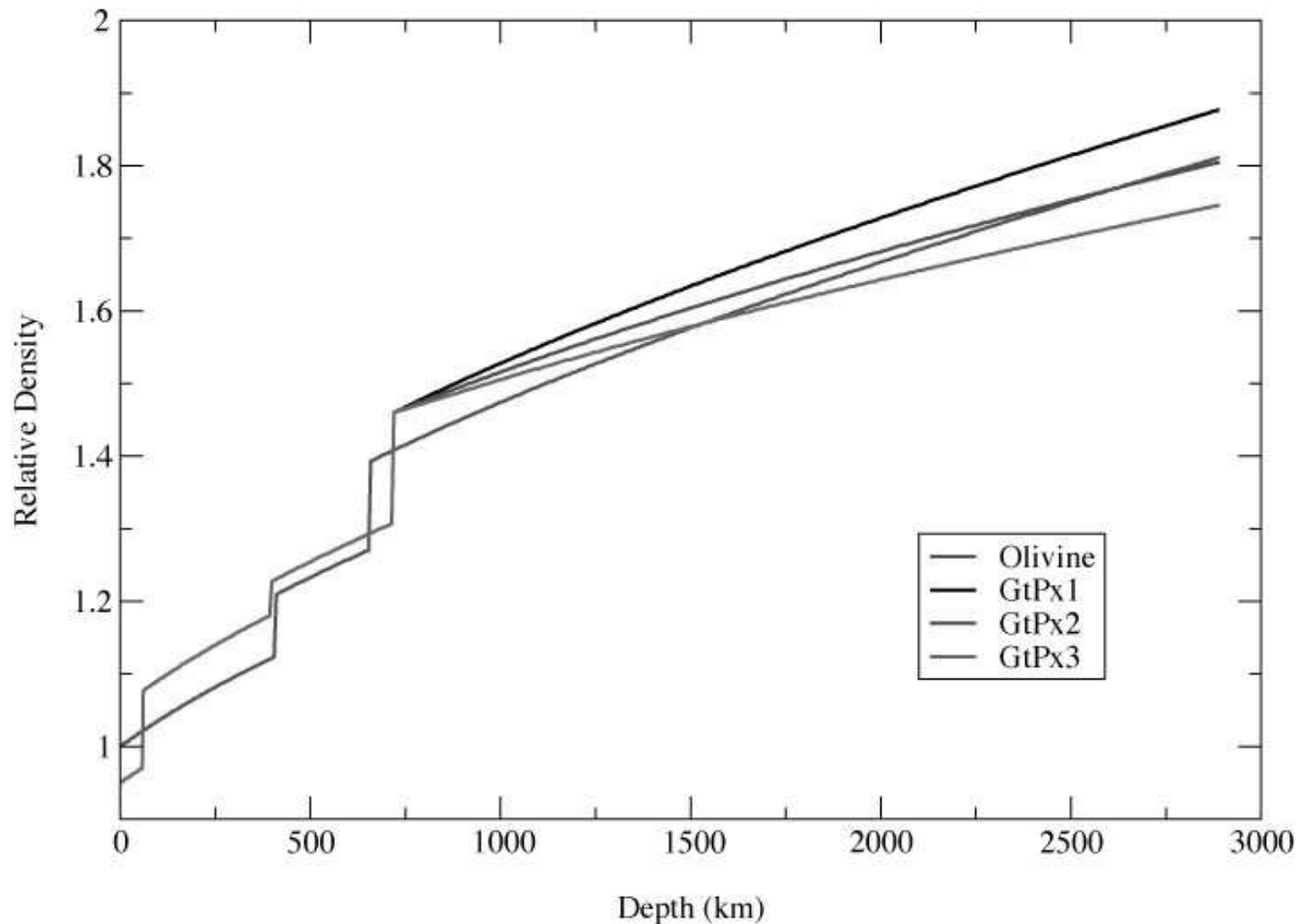
Study	Thickness (km)	$\Delta\rho$	η
[<i>Sleep</i> , 1988]	100	3.0%	1
[<i>Davaille, et al.</i> , 2002]	100	3.5%	1
[<i>Davaille, et al.</i> , 2002]	100	2.0%	10
[<i>Gonnermann, et al.</i> , 2002]	300	2.0%	1
[<i>Namiki</i> , 2003]	200	2.75%	0.01
[<i>Zhong and Hager</i> , 2003]	1000	1.5%	1
[<i>Lin and Van Keken</i> , 2005]	>75	>0.5%	0.001

Layer of MORB above the CMB: Conclusion

- ⌘ With the density contrast found by Hirose et al (2005) it is highly likely that subducted MORB settles into a layer at the base of the mantle that survives over geological time

Modeling approximation: vary compressibility in lower mantle

2-component reference state



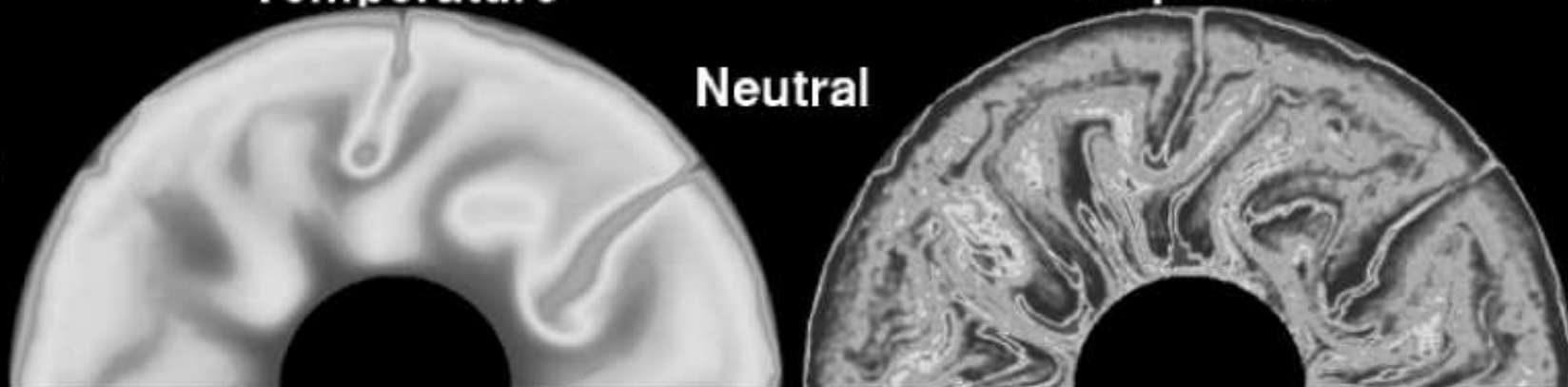
- ⌘ Dense
- ⌘ Neutral
- ⌘ Less dense (buoyant)

Temperature

Composition

Neutral

(a)



Intermediate

(b)



Reference

(c)



Focus on post-perovskite



**Single-crossing, double-crossing, effect
on stability of dense layer**

New (2004) phase change near the core-mantle boundary

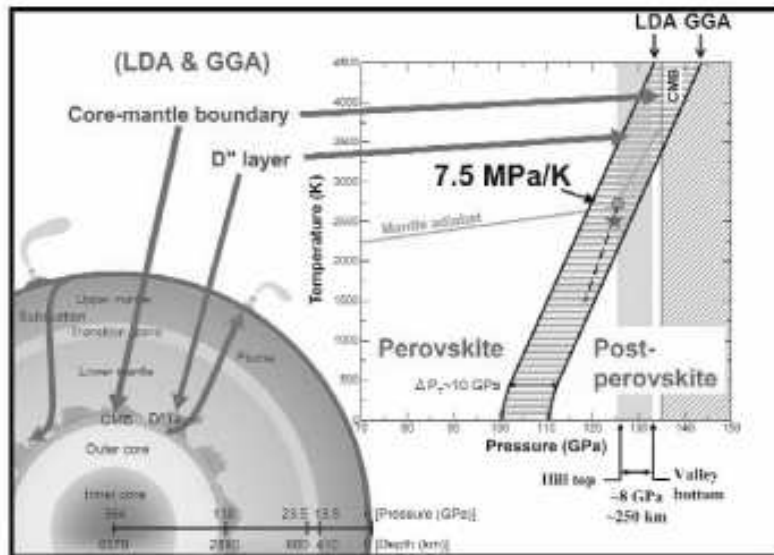


Fig. 3. High PT phase diagram of $MgSiO_3$ predicted by first principles calculation based on the local density approximation (LDA) and generalized gradient approximation (GGA) [Tsuchiya et al., 2004b]. The lower and upper bounds were determined from LDA and GGA calculations, respectively. The calculated Clapeyron slope is about 7.5 MPa/K. The dashed line is the phase boundary proposed by combining data of the experimental transition condition (red star) [Murakami et al., 2004] and the Clapeyron slope assumed to explain the D'' topography by solid-solid phase change [Sidorin et al., 1999]. The vertical shaded bound is the pressure range across the D'' topography. The schematic Earth cross section demonstrates the correspondence of the Earth's structure and the post-perovskite phase transition.

Perovskite to post-perovskite phase change

Pressure: approximately 120GPa (2700km)

Temperature: 2650K

Clapeyron slopes: +7 to +10MPa/K

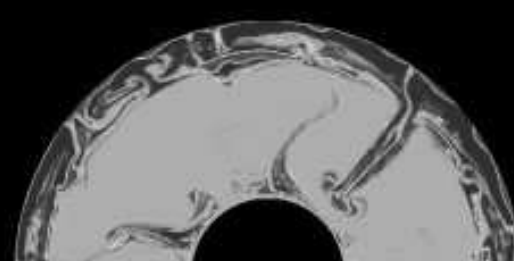
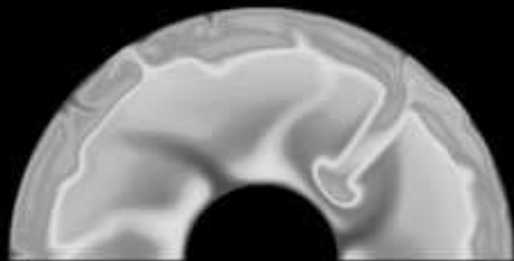
Lay et al.[2005 in EOS]

T

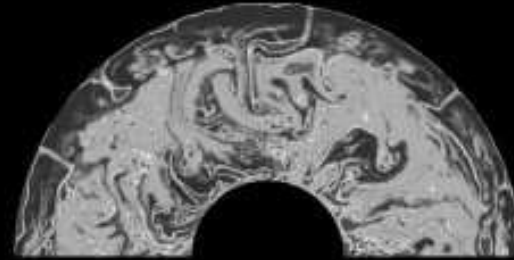
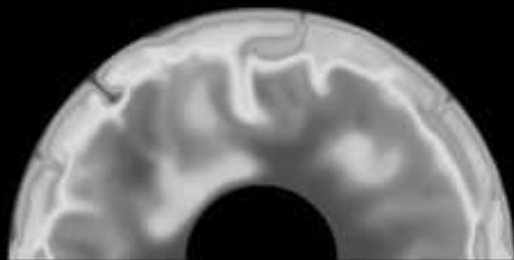
phase

C

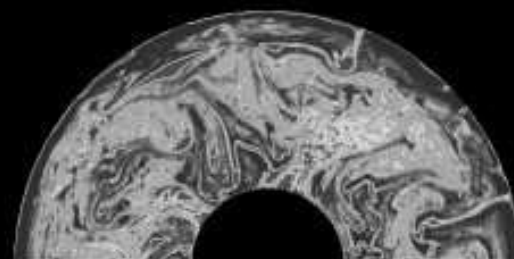
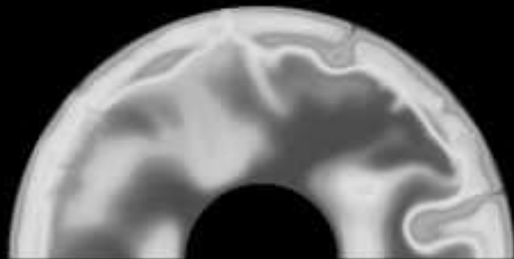
(a) -3.379 Gyrs



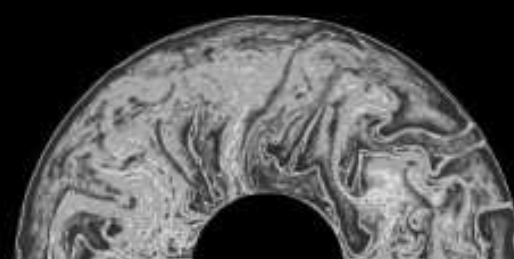
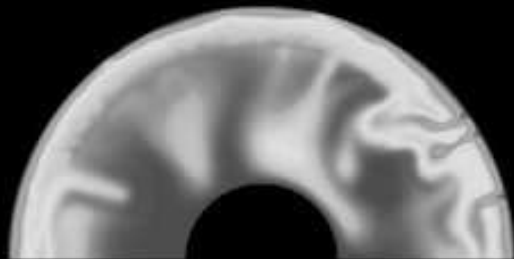
(b) -2.148 Gyrs



(c) -1.144 Gyrs



(d) present time

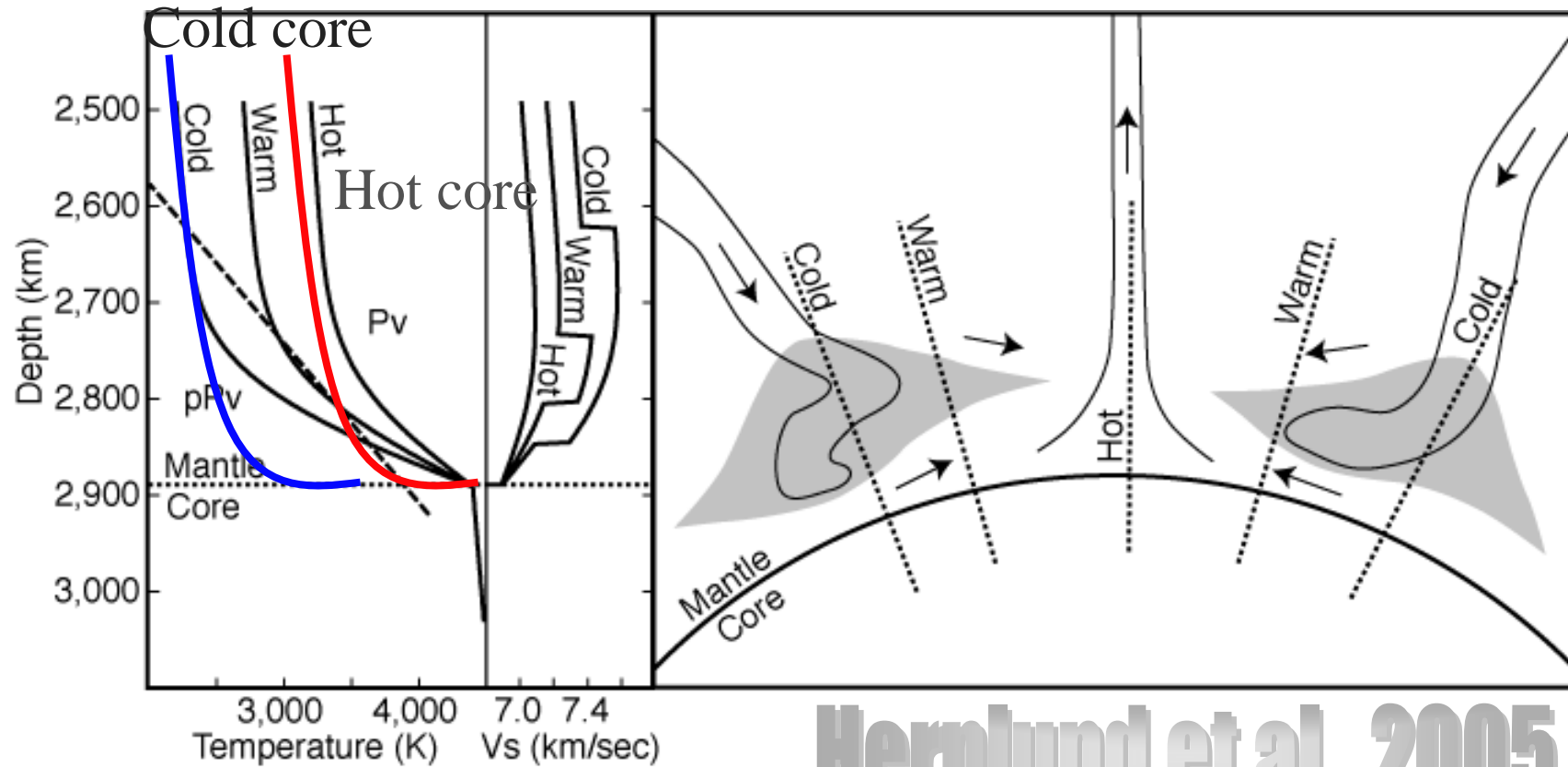


Temperature

Phase

Composition

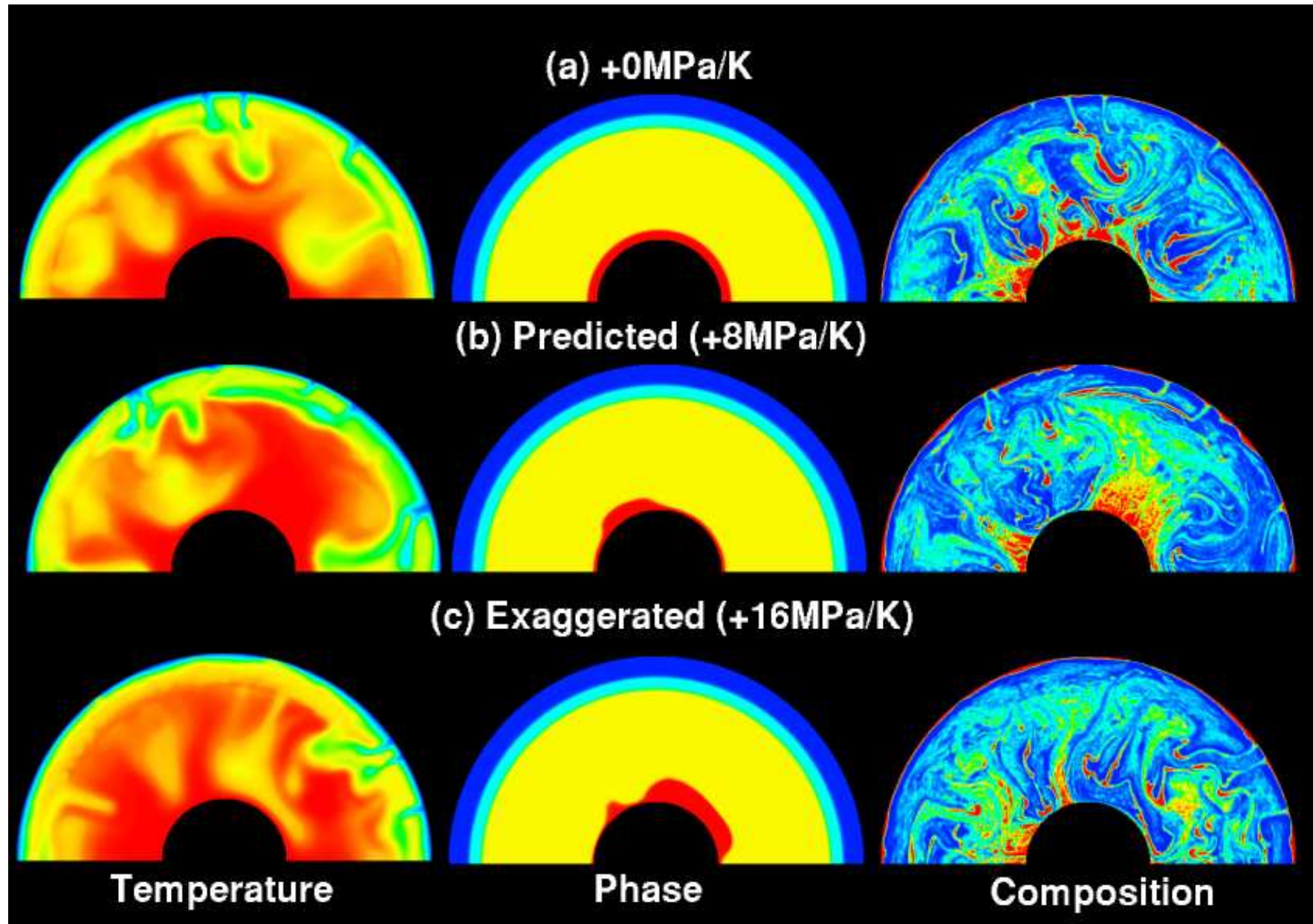
Transition from double to single phase boundary



Hernlund et al., 2005

- ⌘ Cold core => Single crossing
- ⌘ Hot core => Double-crossing or no crossing (No PPV in hot plumes)

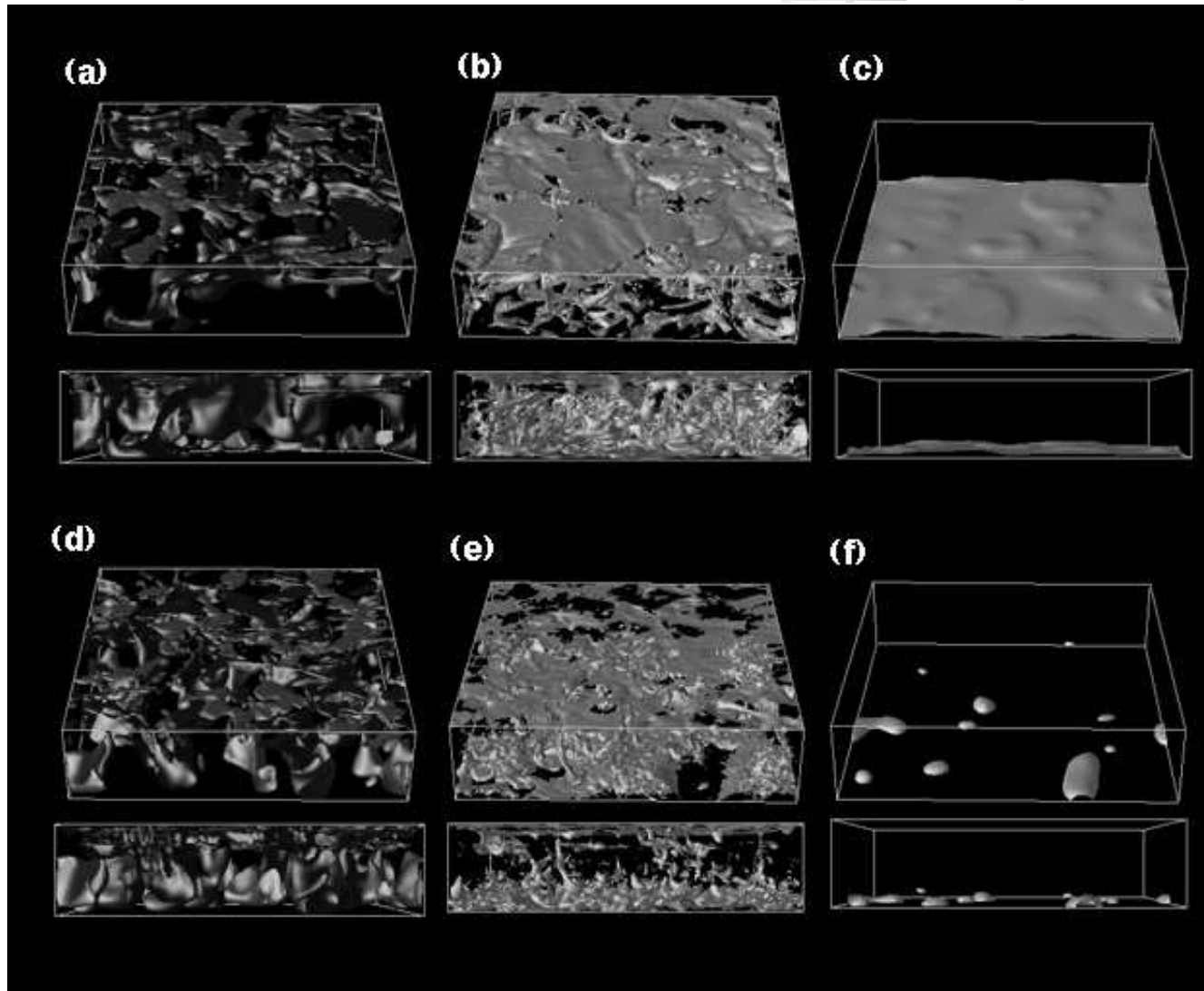
Parameter dependence: Clapeyron Slope of ppv (Comp. density var. = 2%)



3-D results: Thermo-chemical structures

CS_ppv = +8MPa/K

Top: 0% comp. density var.; Bottom: 2% comp. density var.



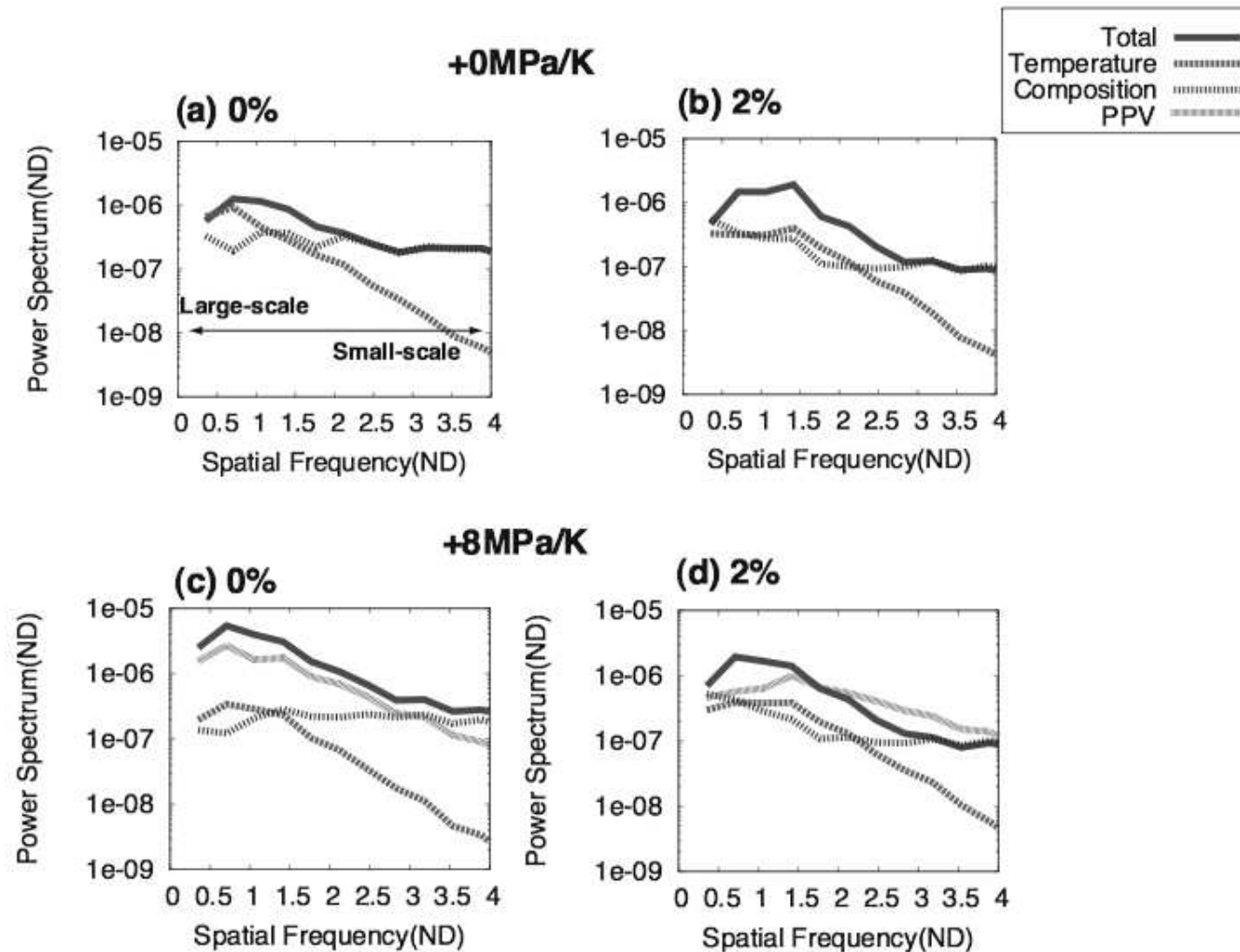
(a), (d) T-residuals
Red: +312.5K
Blue: -312.5K

(b), (e) Comp.
C=0.75

(c), (f) Phase func.
 $\Gamma=2.5$ (ppv)

Lateral spectrum of V_s @ 2700km, 3-D cases

Signature of PPV can be very large!



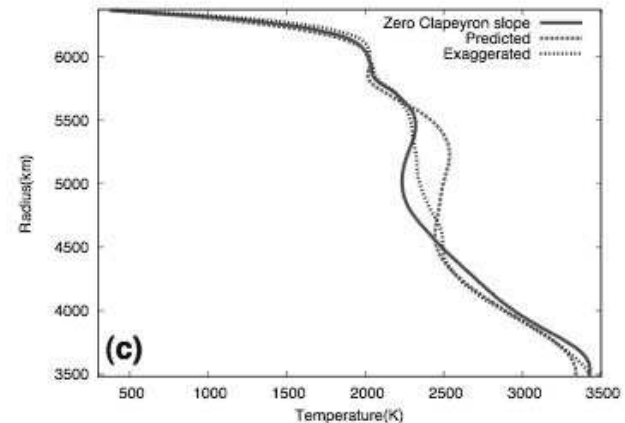
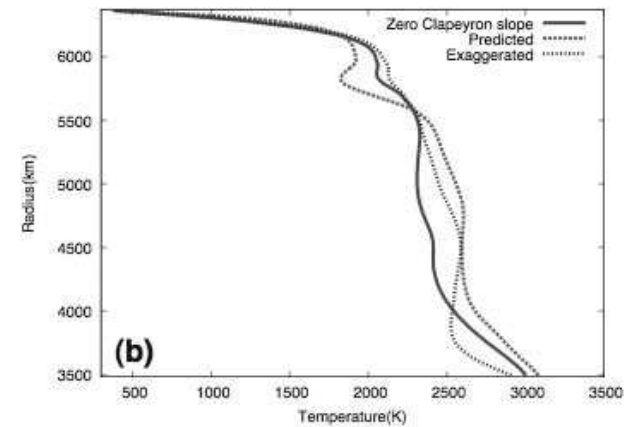
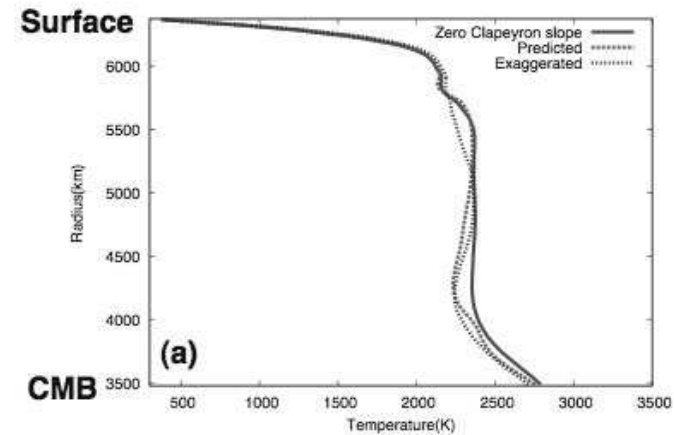
PPV Conclusions

- ⌘ Several features as predicted:
 - ☒ Transition from double-crossing to single crossing as core cools
 - ☒ Anticorrelation with hot chemical 'piles'
- ⌘ Strong effect on deep mantle seismic heterogeneity
- ⌘ Slightly destabilizes chemical layering

**Presence or absence of
dense layering above the
CMB has strong
implications for core
thermal evolution and
mantle geotherm**

Effect on mantle geotherm

(Sub)adiabatic except where compositional stratification



Main points

- ⌘ Presence or absence of dense layering above the CMB has strong implications for core thermal evolution and mantle geotherm
- ⌘ With the latest parameters MORB is likely to settle into a long-lived layer above the CMB
- ⌘ Local stratification around 660 caused by interaction of C with different-depth perovskite transitions
- ⌘ Chemical heterogeneity has a flatter spectrum than thermal and dominates at most wavelengths. Mantle highly heterogeneous at all scales
- ⌘ Post-perovskite transition anticorrelated with “piles”
- ⌘ Post-perovskite transition may be important contributor to Vs heterogeneity in the deepest mantle
- ⌘ Convection models can generate synthetic geochemical data to act as a further constraint

THE END