Thermo-chemical structure, dynamics and evolution of the deep mantle: spherical convection calculations

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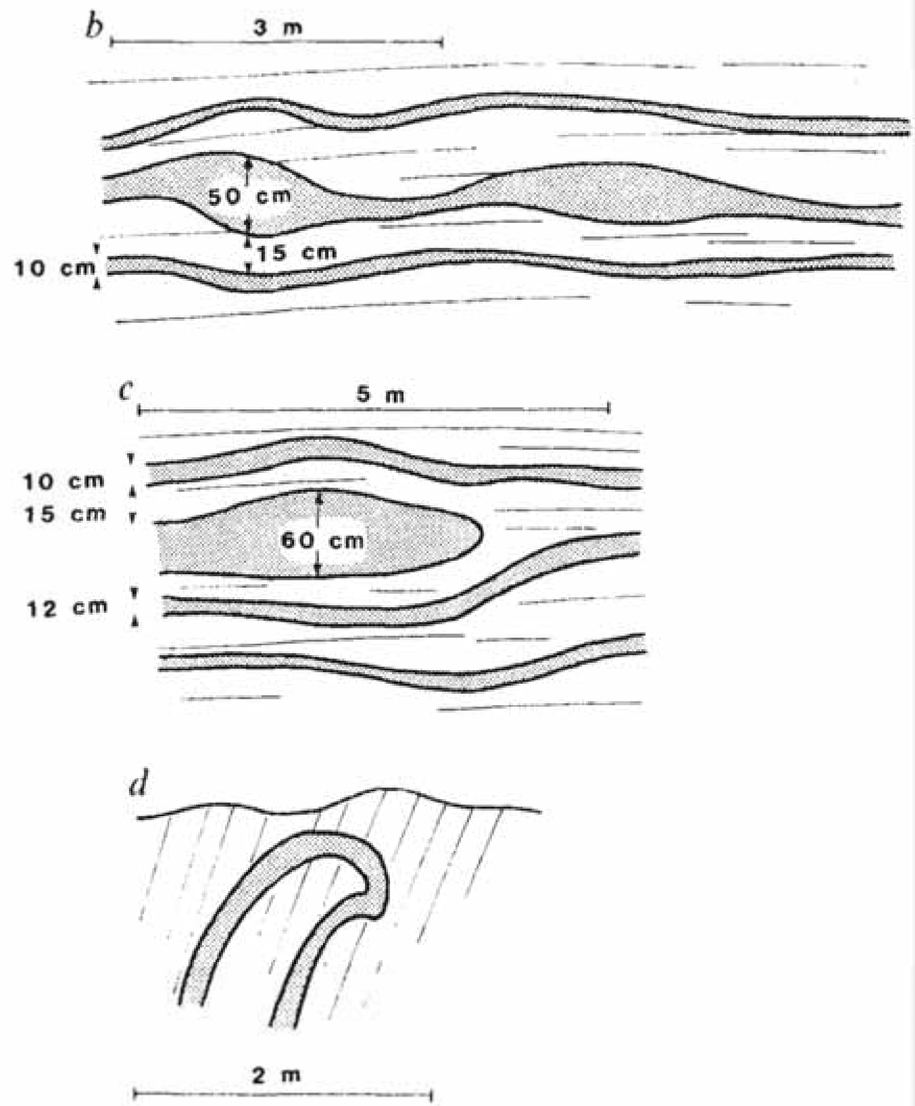
With help from Takashi Nakagawa, Frédéric Deschamps, James Connolly, Ludwig Auer, Lapo Boschi

Outline

- Motivation
- Self-consistent treatment of mineralogy
- Mantle thermo-chemical evolution
  - Effect of composition
  - Effect of initial CMB temperature
  - Effect of weak post-perovskite
- Seismic signature
  - Radial profiles in CMB region
  - Synthetic seismic tomography

Small-scale variations in composition

Outcrops of mantle rocks: 'Marble cake' structure



Isotope ratio variations in erupted basalts

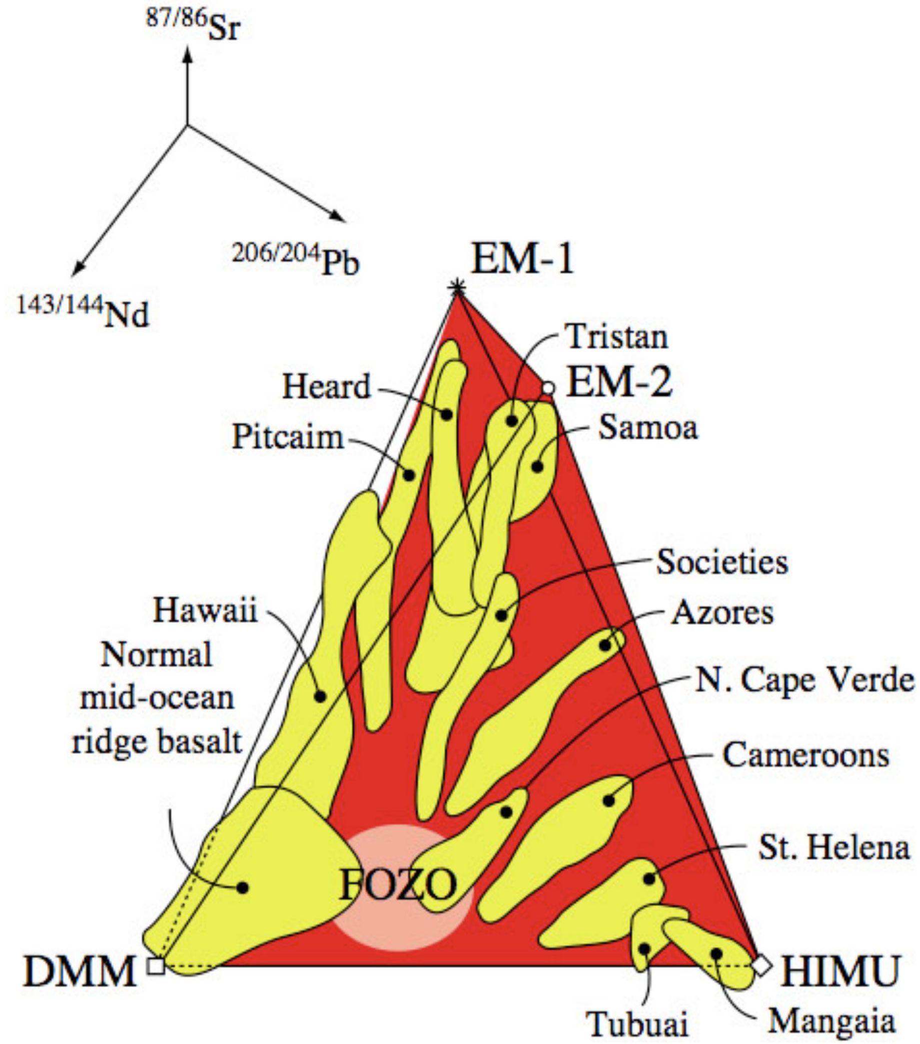
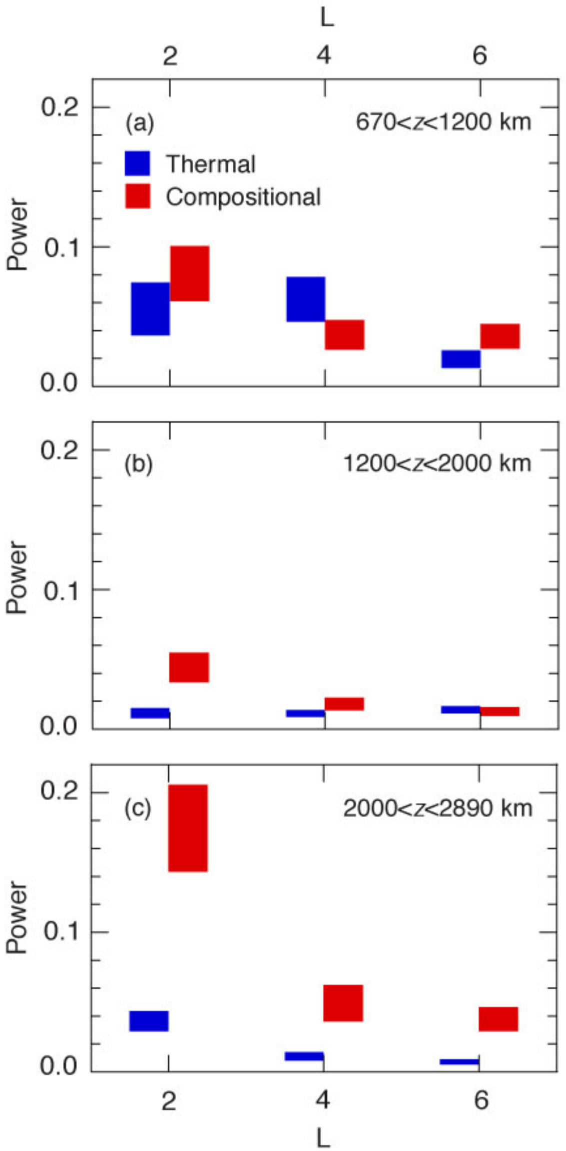
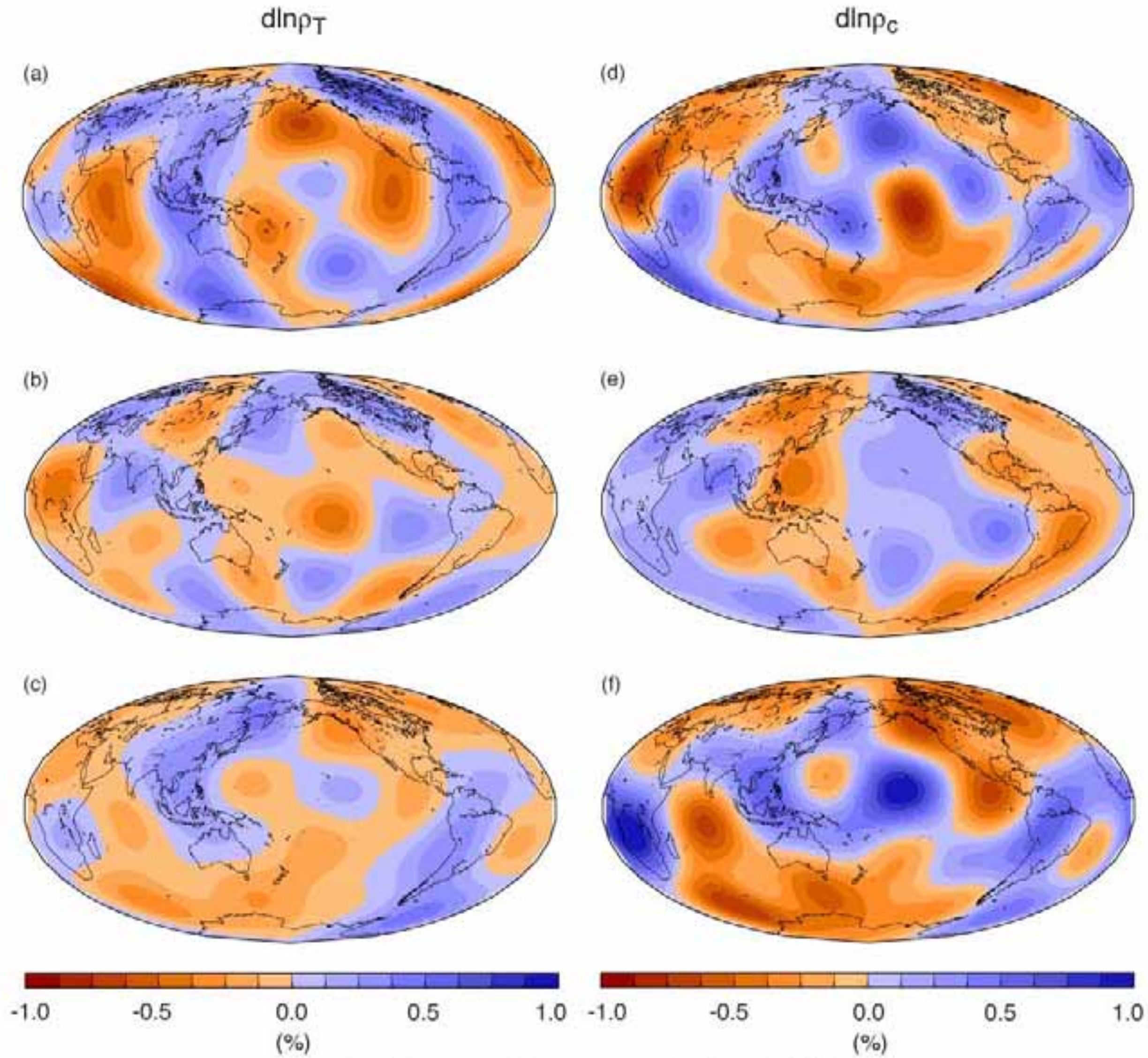


Figure 16 Three-dimensional projection of $^{87}Sr/^{86}Sr$

Probabilistic seismic inversion finds that composition dominates long-wavelength density variations in lower mantle

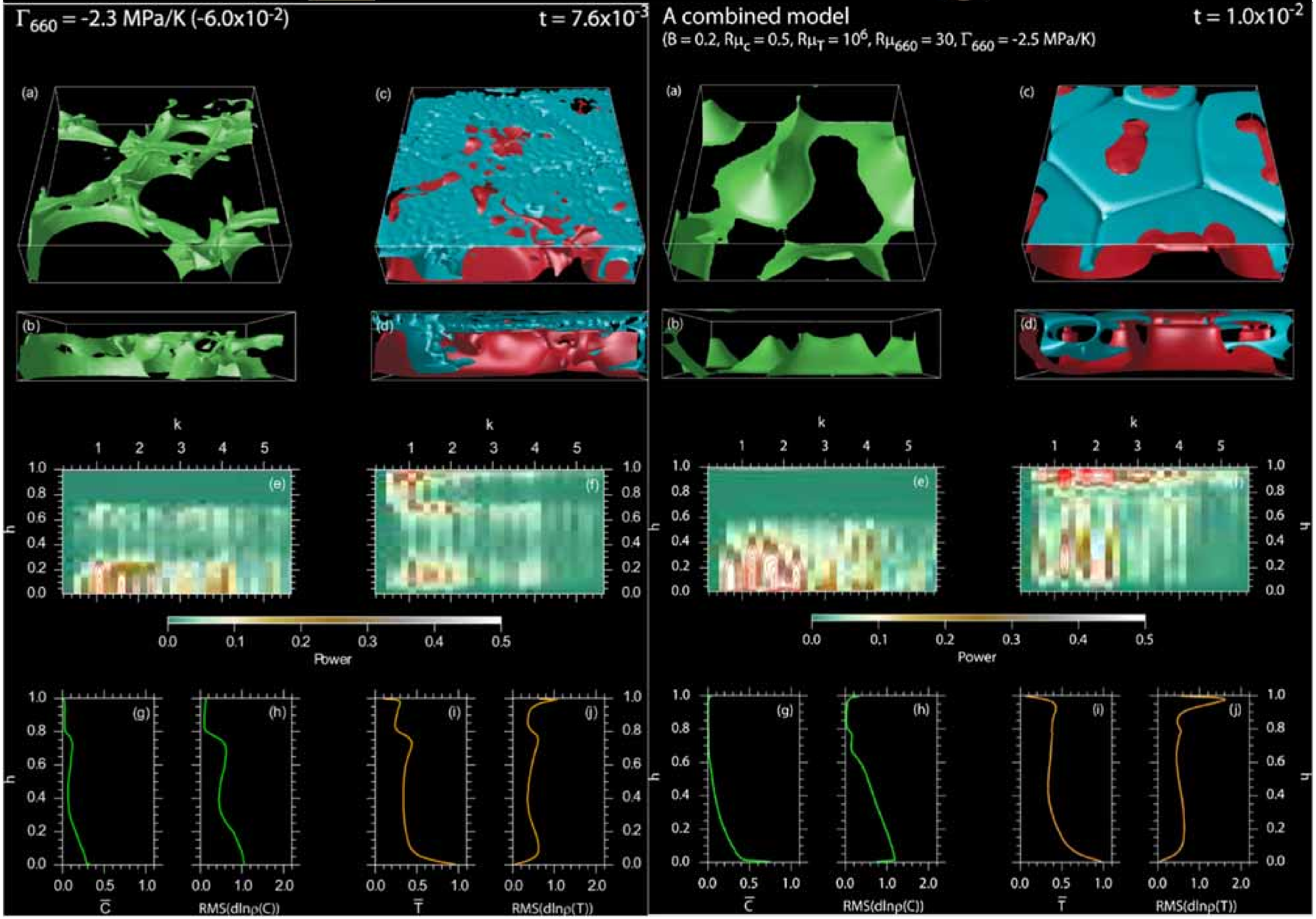


Deschamps, Trampert, Tackley (2005)



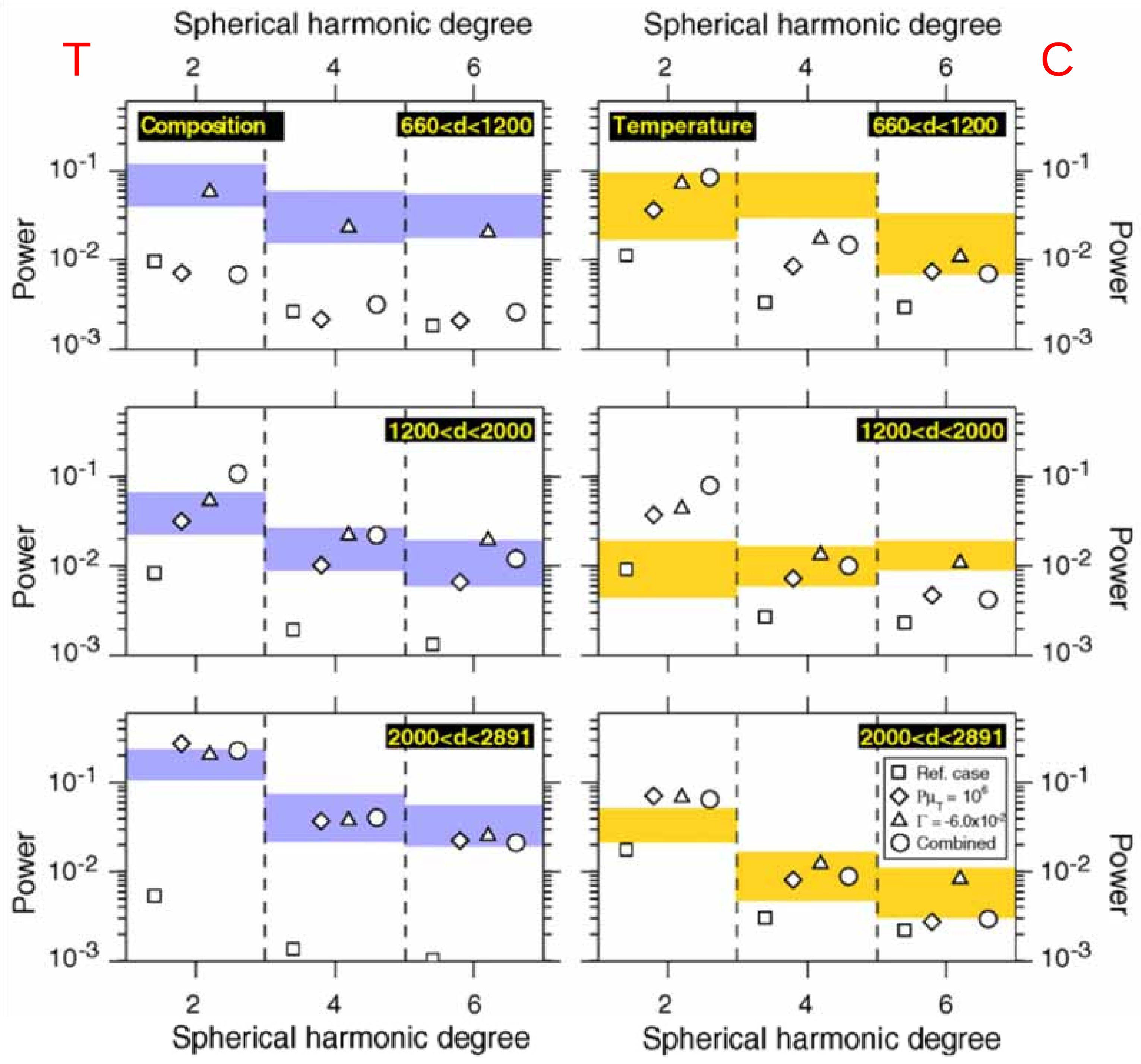
Deschamps, Trampert, Tackley (2005)

Deschamps & me PEPI 2008, 2009



Frédéric Deschamps & me PEPI 2008, 2009:

3-D convection models to match probabilistic tomography density variations

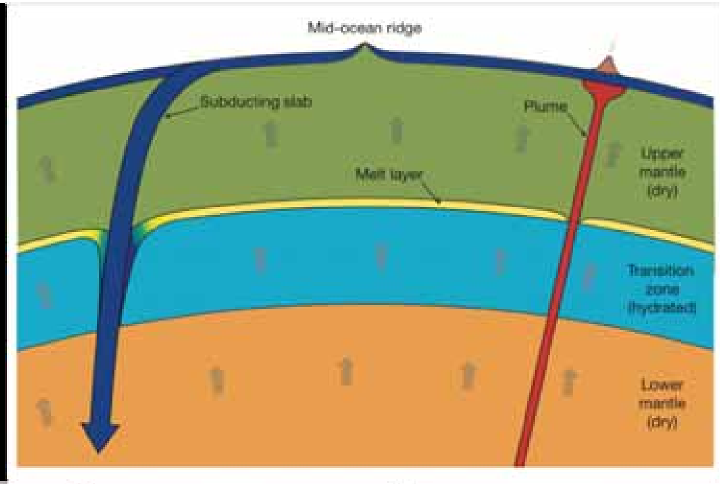


Deep dense stuff: Where does it come from?

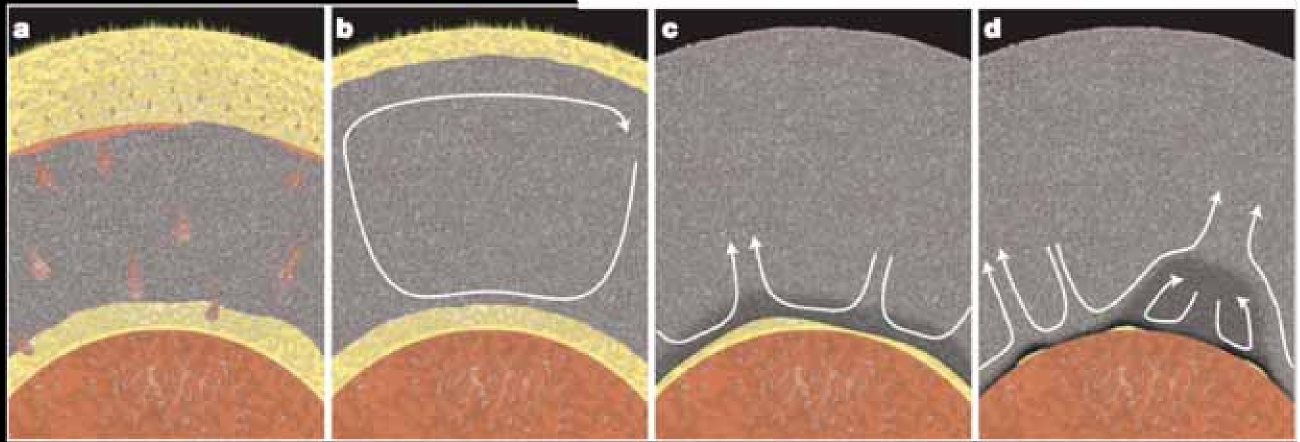
- Generated over time
  - Recycled oceanic crust
  - Crystallization of basal magma ocean (Labrosse et al)
- 'Primordial'
  - Crystallization of magma ocean (Solomatov…)
  - Subducted early crust (Tolstikhin et al 2006)
  - Early KREEP-like liquid (Boyet&Carlson 2005)
  - Upside-down differentiation (Lee et al 2010)

Cartoon Models

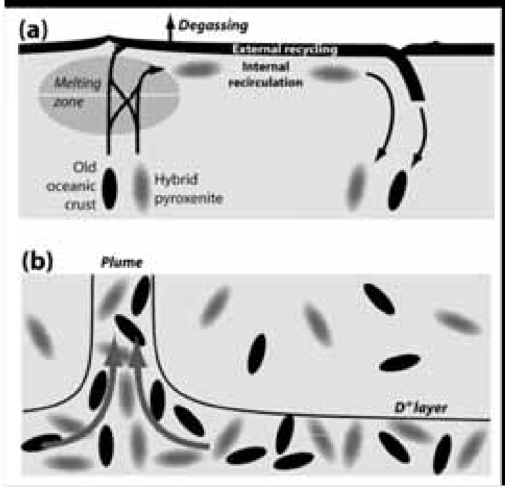
Transition Zone Water Filter
Bercovici & Karato 2003



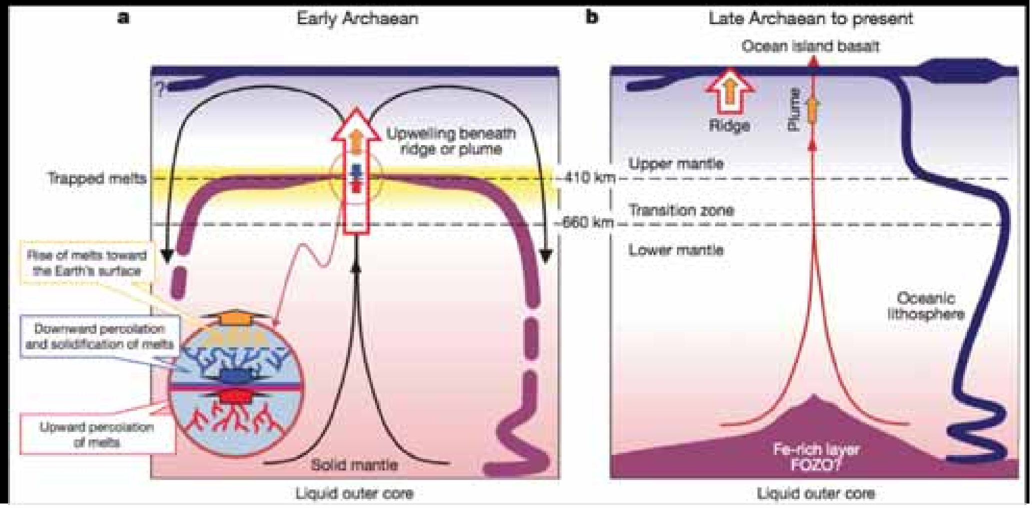
Basal Magma Ocean
Labrosse et al., 2007



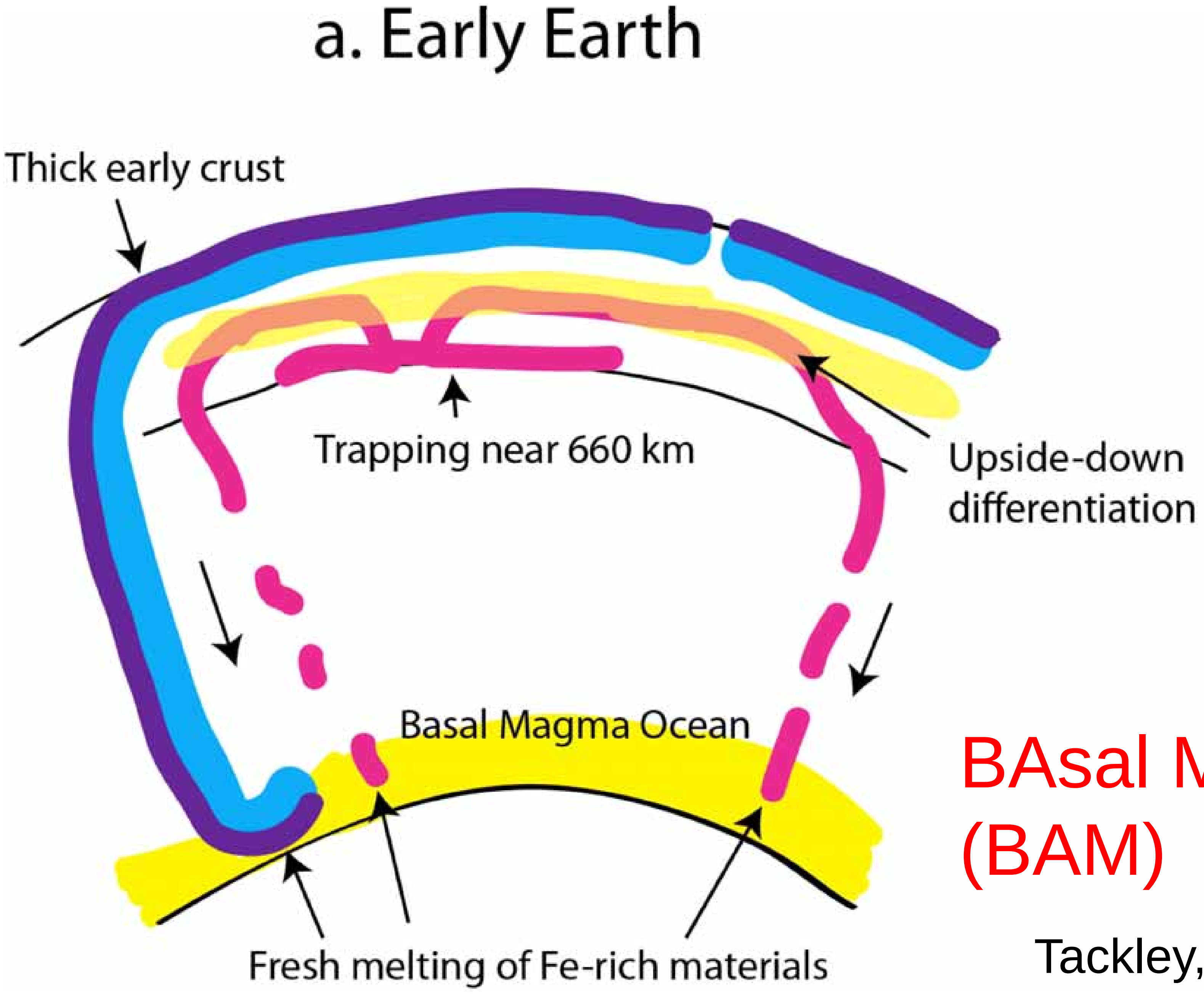
Davies 2009



Upside-down differentiation
Lee et al
2010



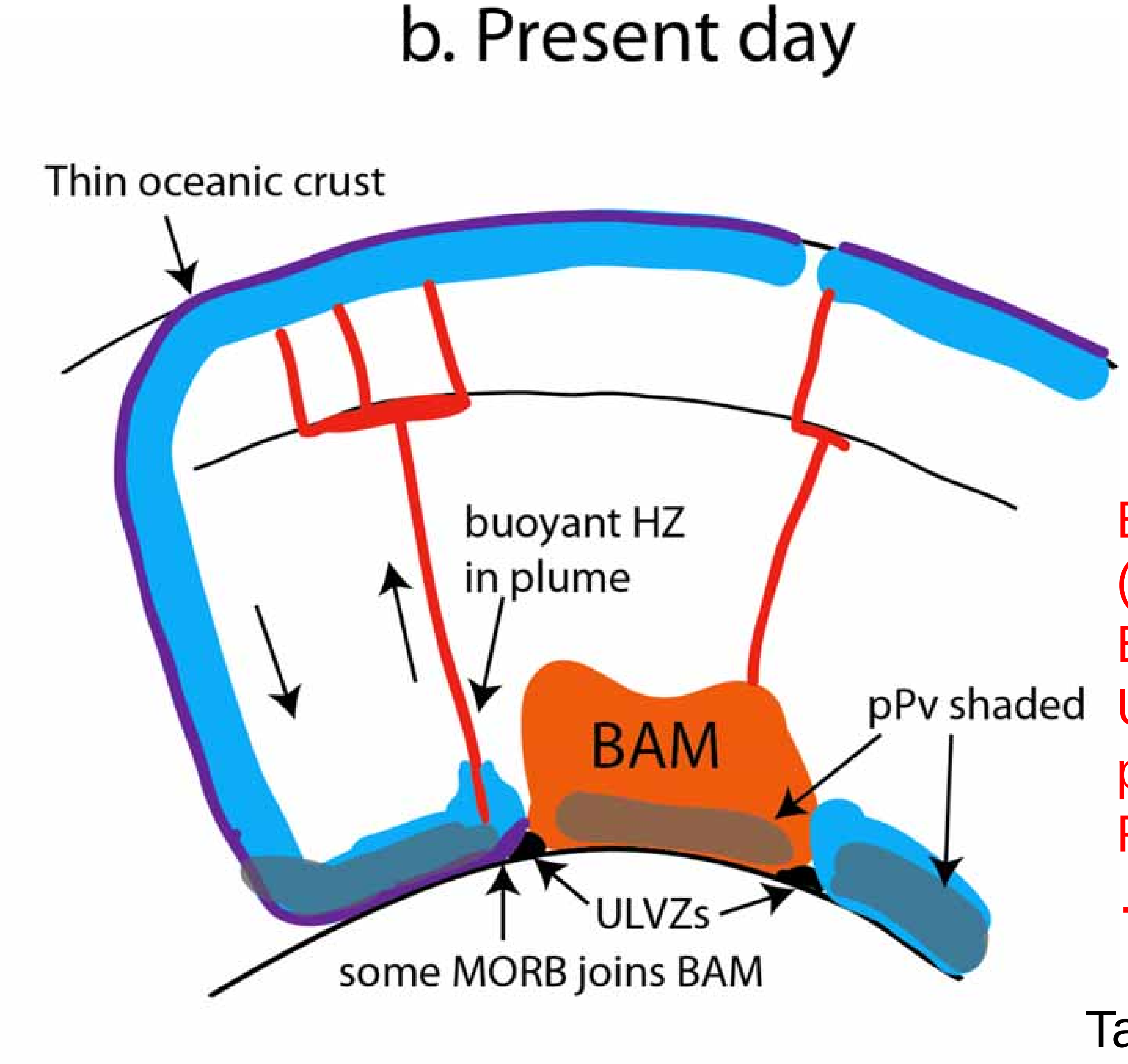
More than one process operating!



BAsal Mélange
(BAM)

Tackley, ESR 2012

More than one process operating!



BAsal Mélange (BAM) mix:
BMO remnants
UM differentiated products
Recycled crust
…

Tackley, ESR 2'12

Volume of oceanic crust subducted in 4.5 Gyr

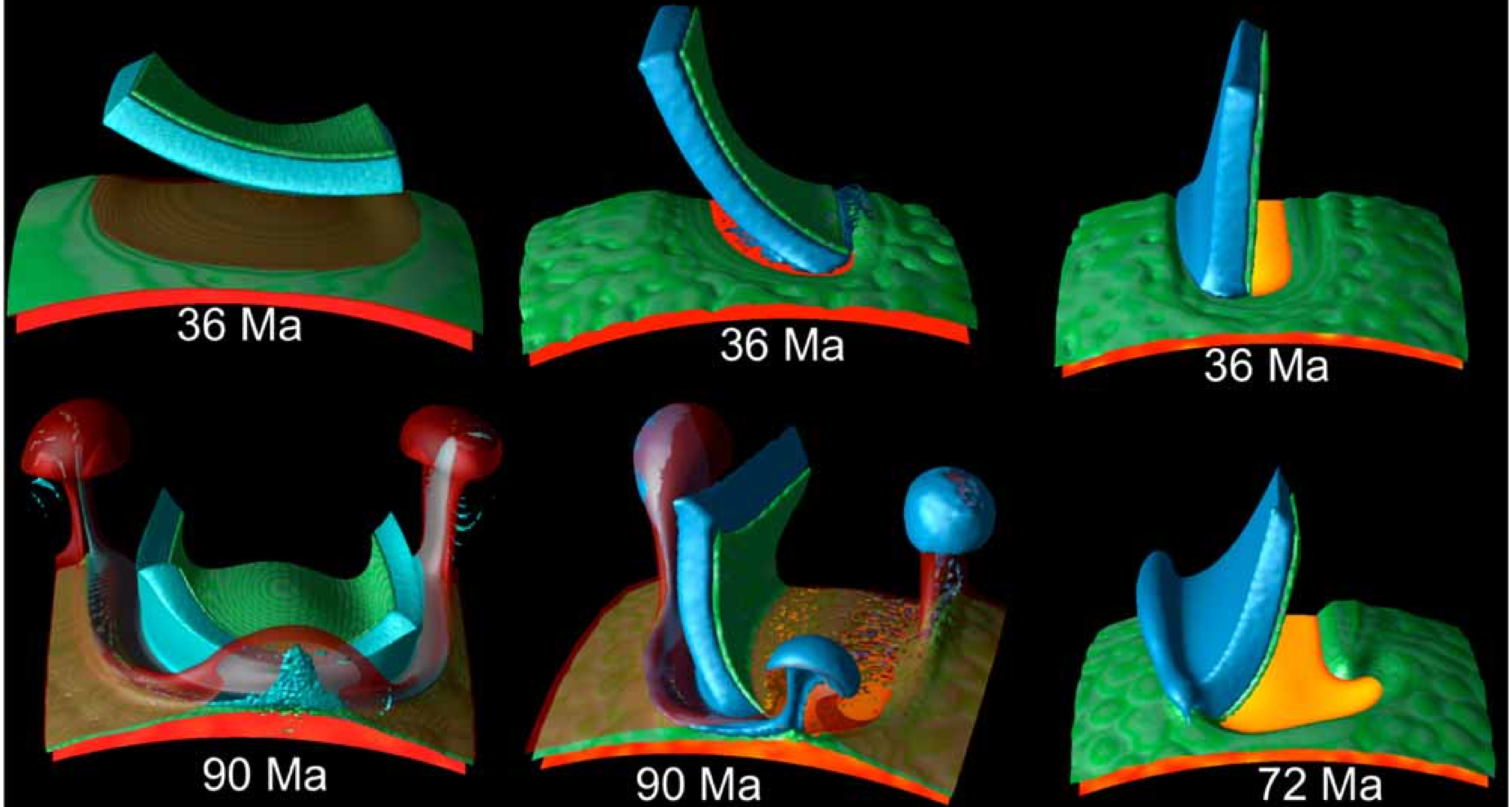
- Present-day production rate: 10% of mantle
- Production rate ∝ H^2: 53%

Volume of mantle "processed" by MOR melting in 4.5 Gyr

- ~10 times the above: 100% or 530%

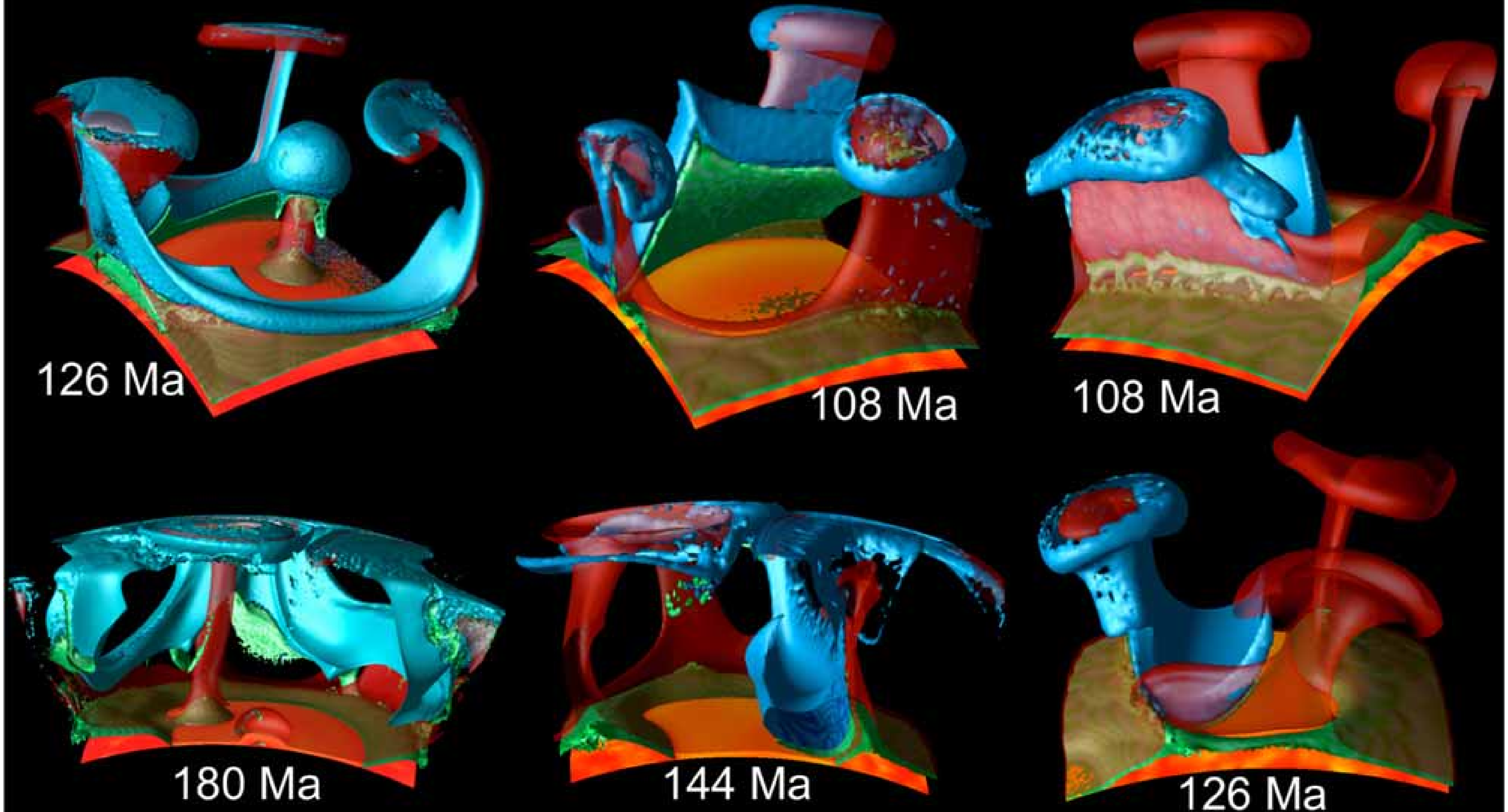
Almost no unprocessed material

Slab-CMB interaction



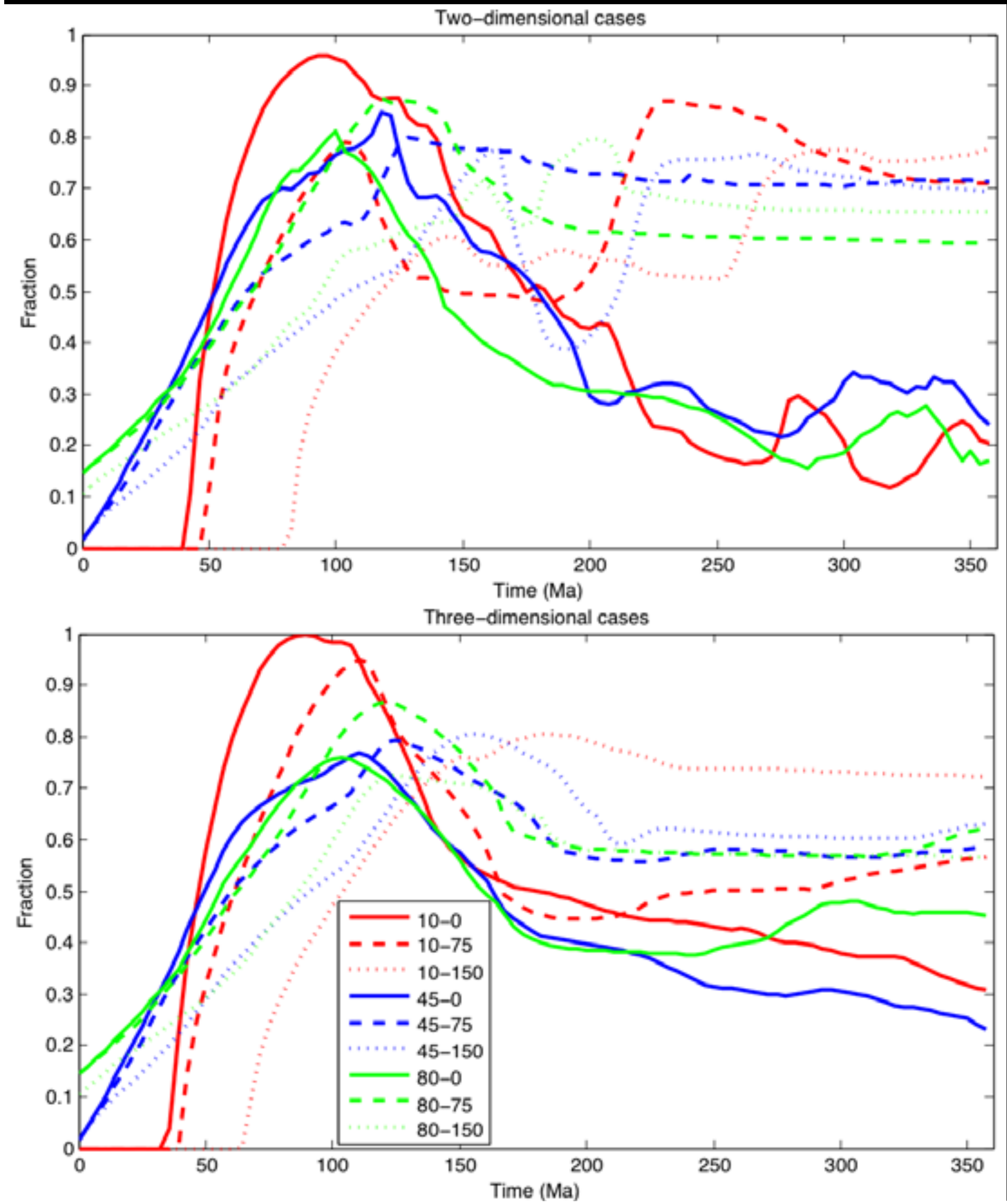
Tackley, PEPI 2011

Slab-CMB interaction



Tackley, PEPI 2011

% Slab basalt joining BAM layer

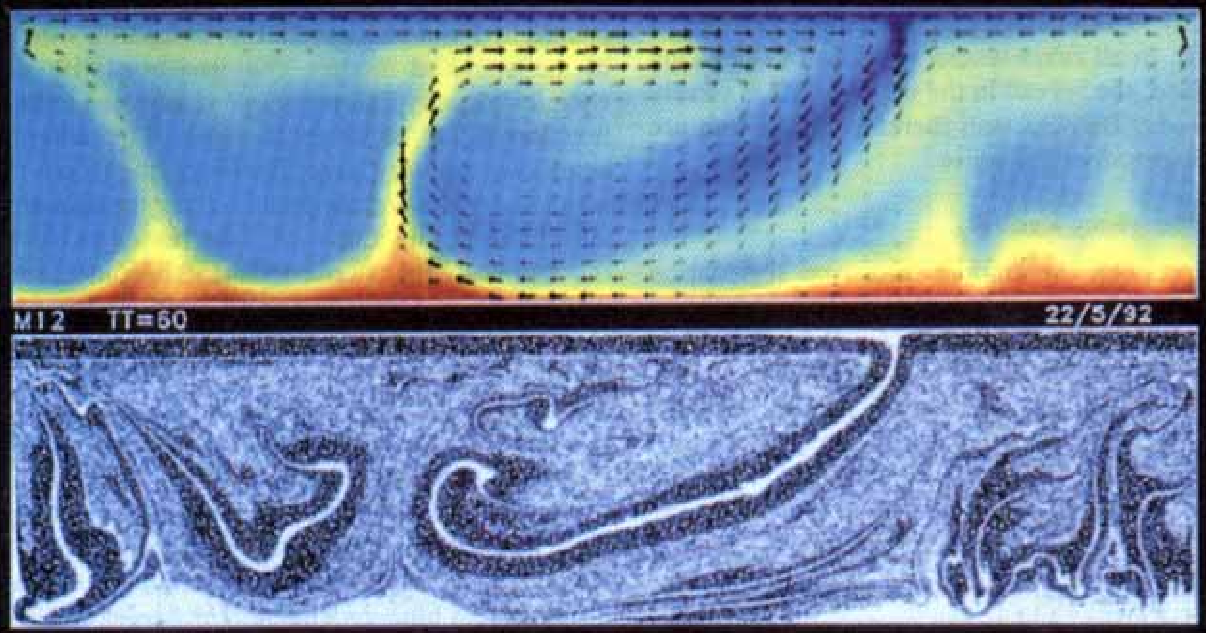


Much higher if existing layer

If no existing layer, then higher in 3D

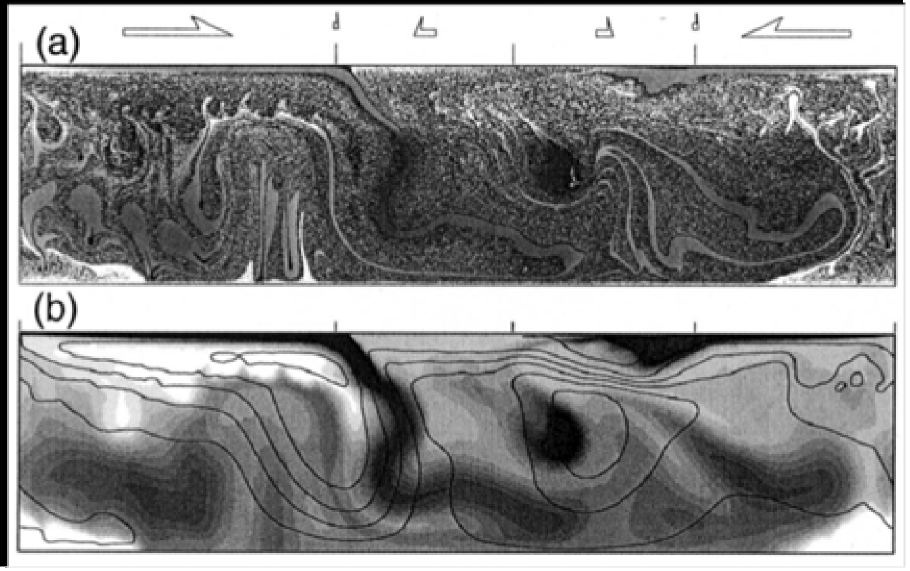
Tackley, PEPI 2011

Several dynamical studies

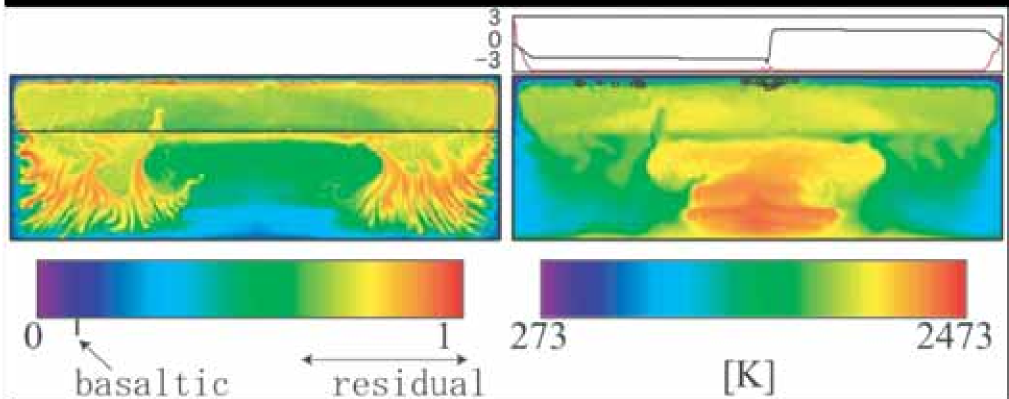


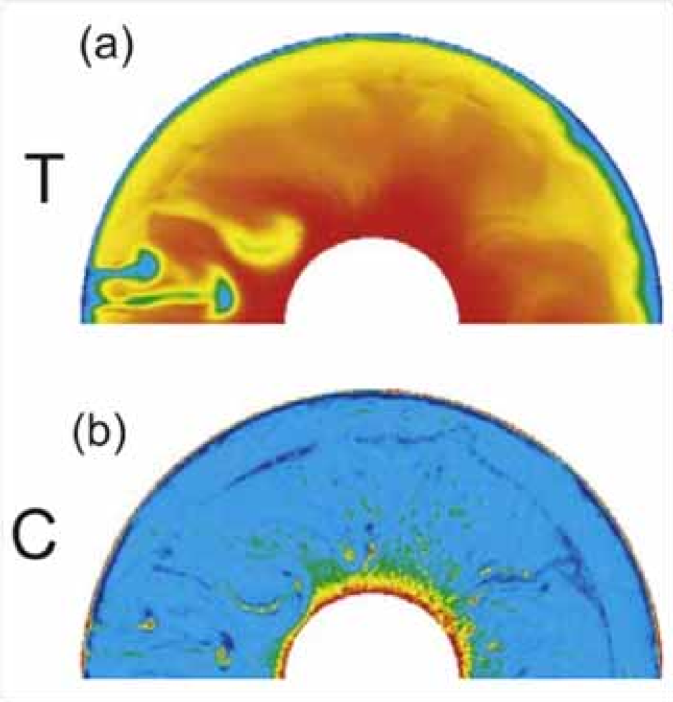
Christensen & Hofmann, 1994

Davies 2002



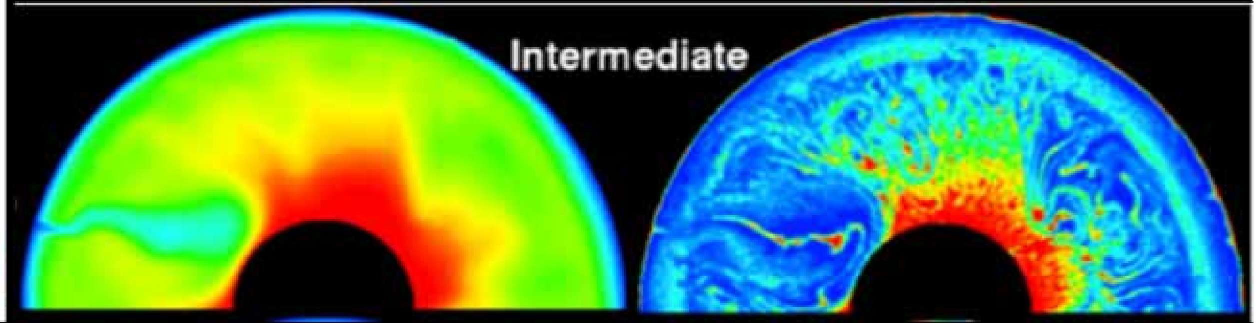
Ogawa 2003

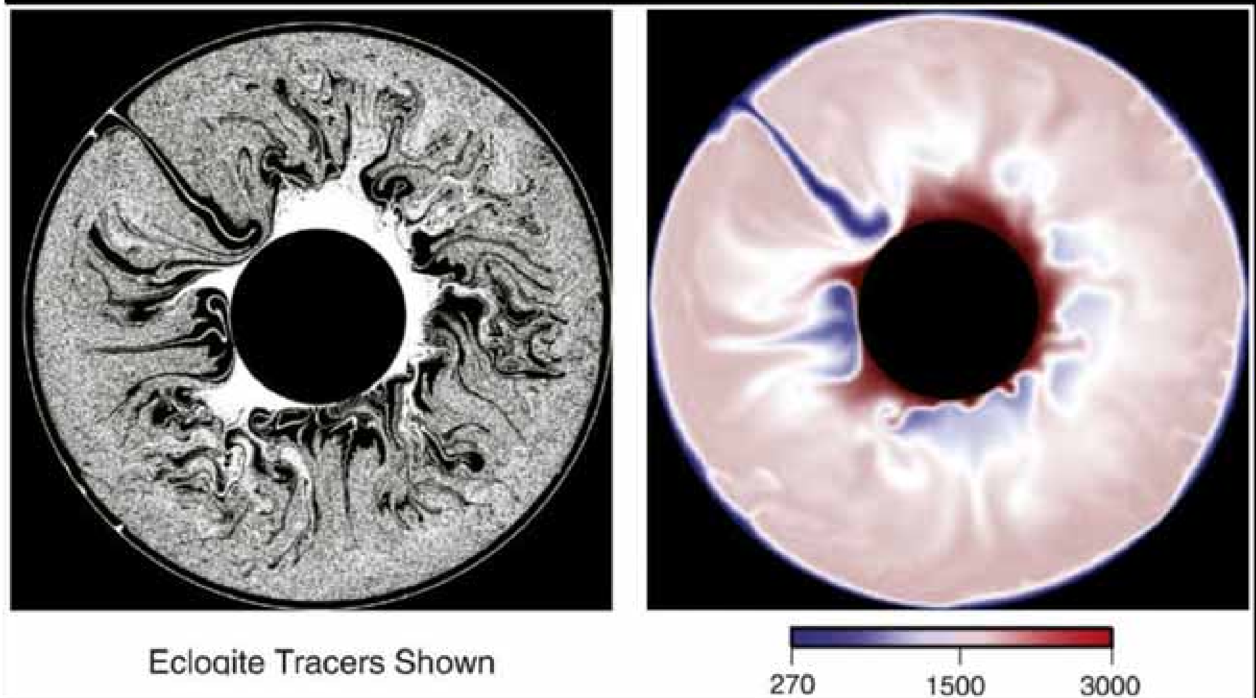




Xie & Tackley 2004

Nakagawa & Tackley 2005





Brandenburg et al, 2008

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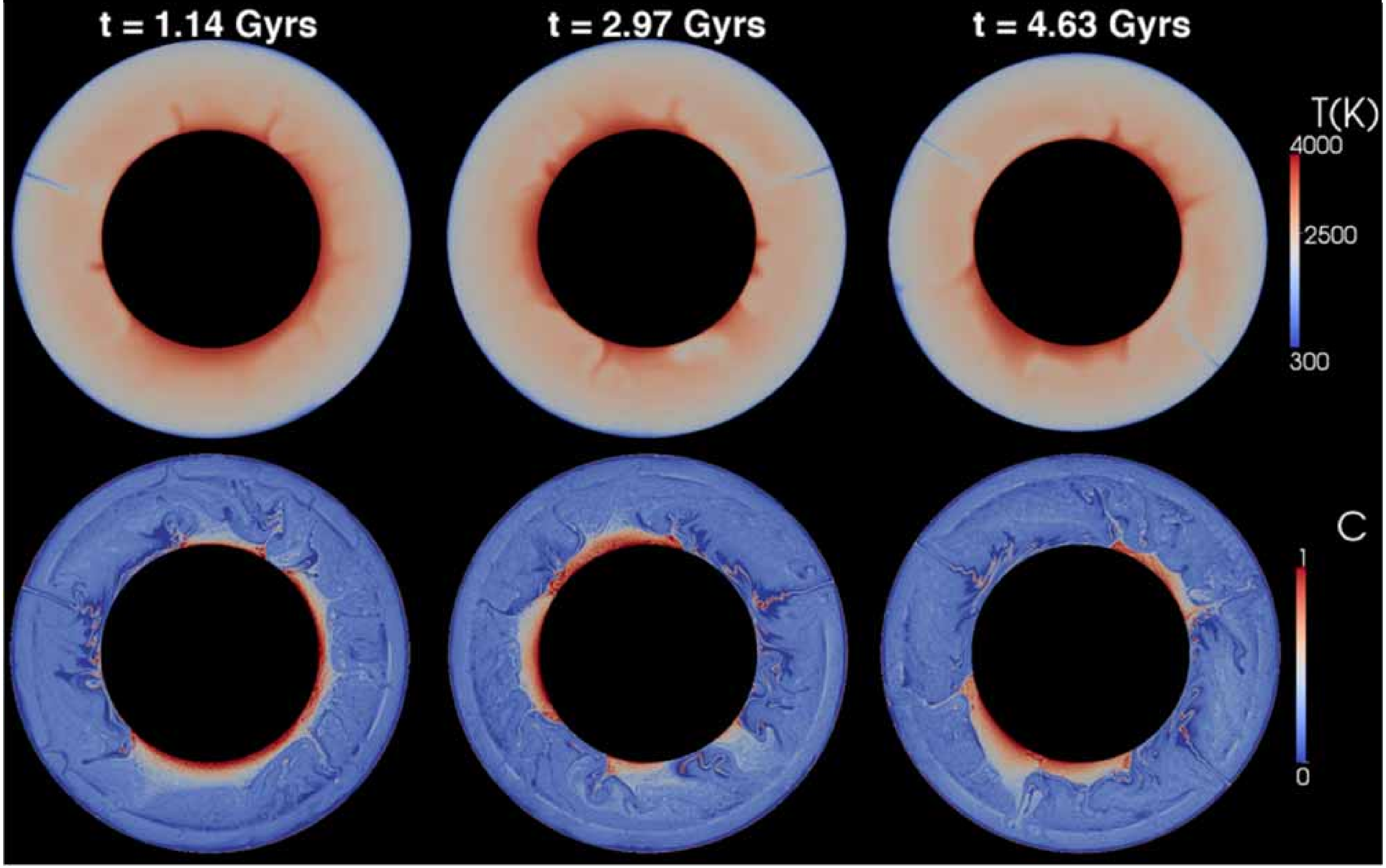
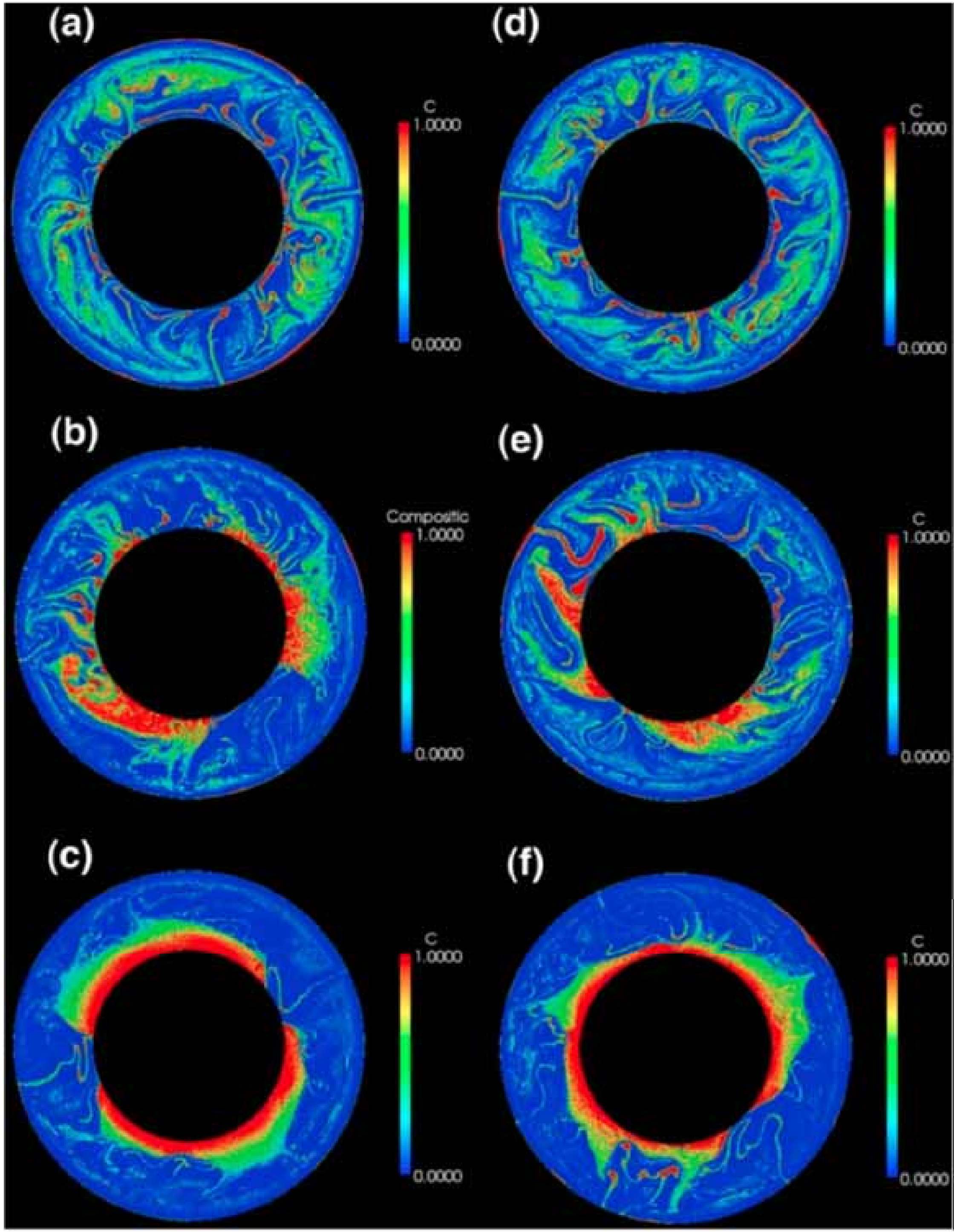
Calculations of mantle thermo-chemical evolution over 4.5 Gyr

- Include melting->crustal production,
  - viscosity dependent on T, d, and stress,
  - self-consistent plate tectonics,
  - decaying radiogenic elements and cooling core,
  - compressible anelastic approximation
- Several papers by Nakagawa & Tackley, often with Deschamps & Connolly

Time evolution (-I)





MORB density contrast in deep mantle (uncertain) controls layering above CMB

Nakagawa & Tackley 2010 GCubed

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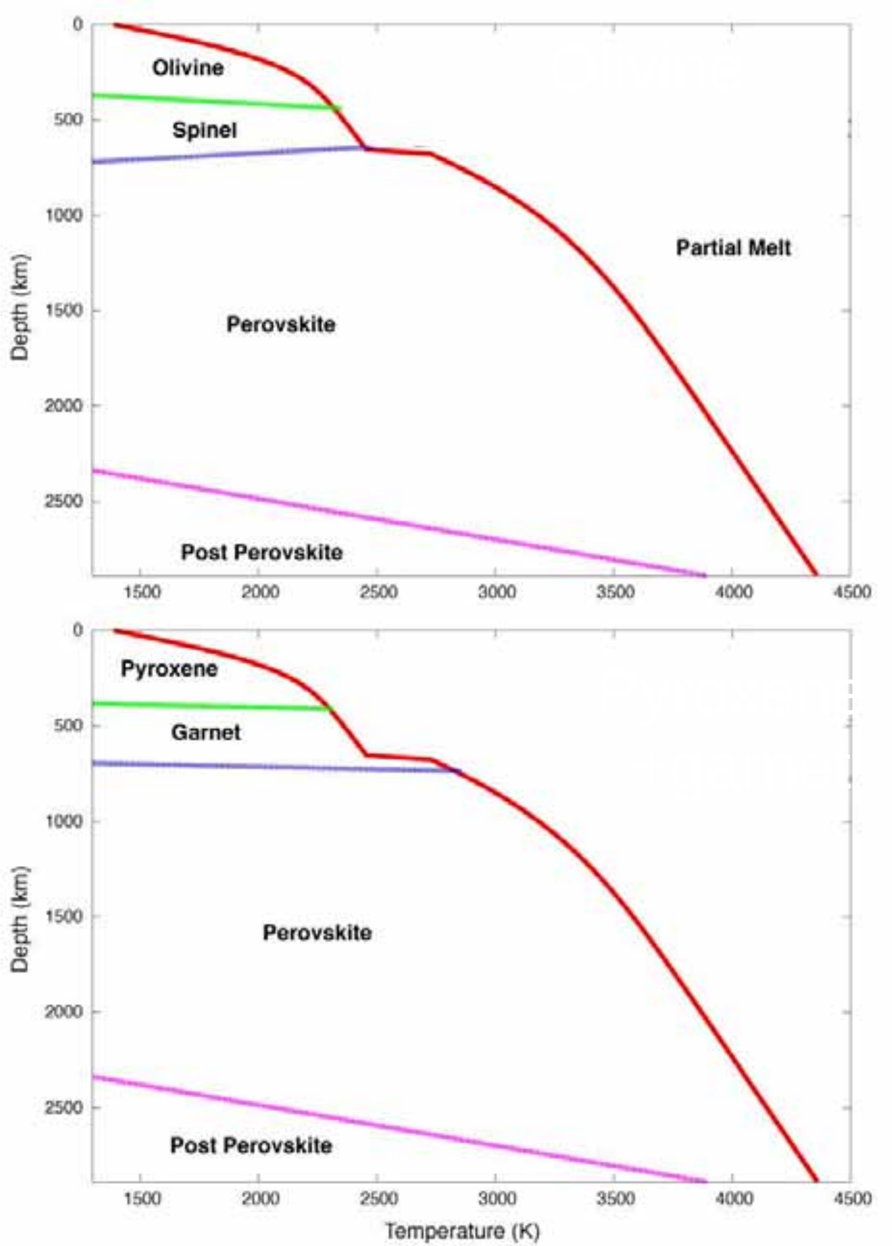
Usually studies parameterize phase transitions

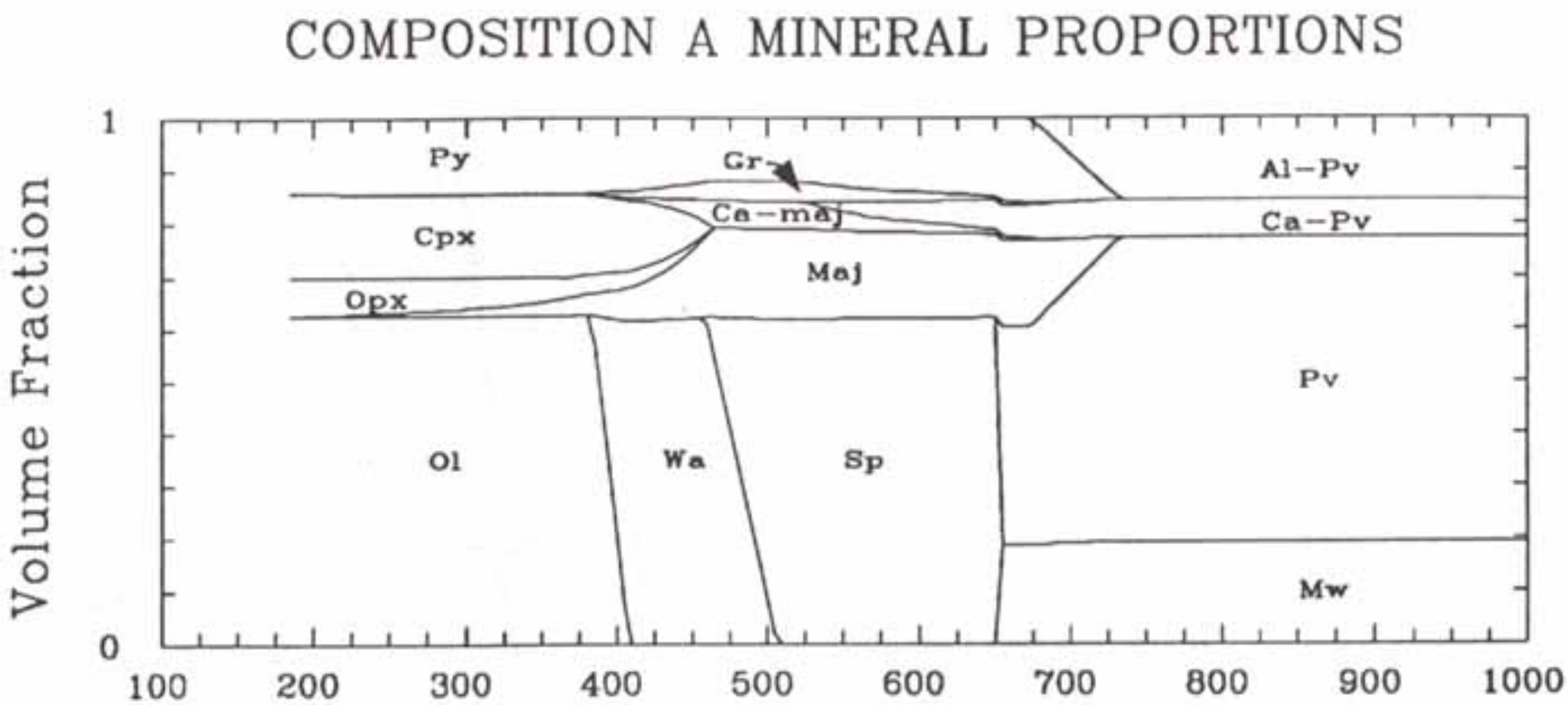


Input: Density jump and CS due to phase transitions into depth-dependence along with adiabat

Simplifying other complicated phase (e.g. Wadsleyite-Ringwoodite, Two phases of Garnet (Majorite and Akimotite)

Effects of more complicated phase relationship for mantle minerals in numerical mantle convection model ???

However, mantle mineralogy is complex, dependent on T, P and C



- From Ita and Stixrude

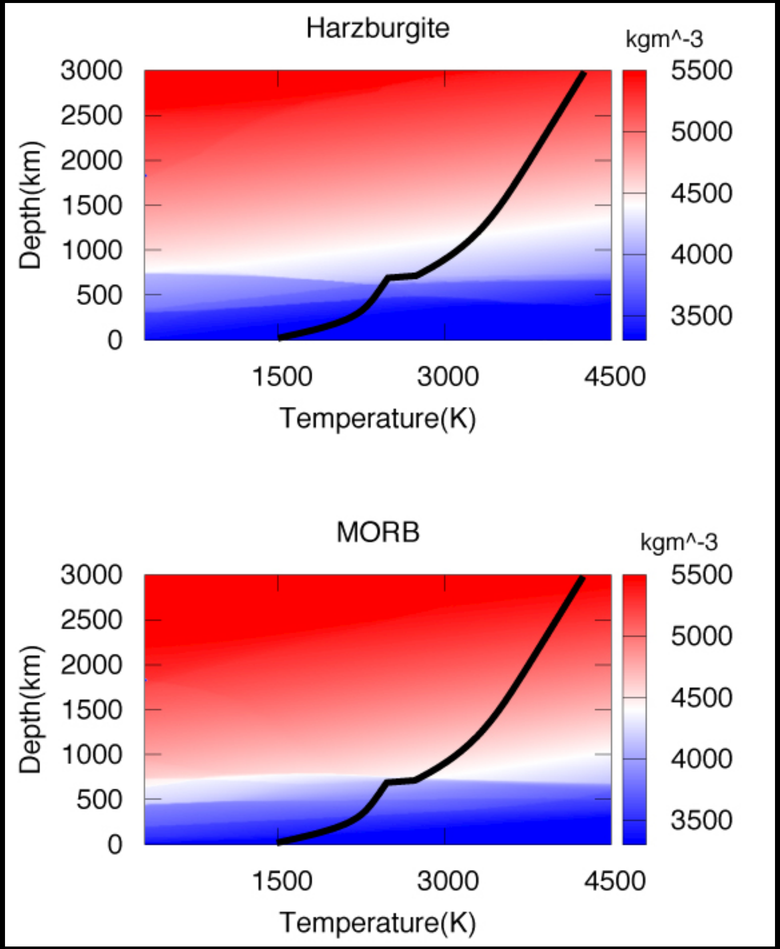
Generating realistic phase assemblages computationally

Determined by Free Energy Minimization technique: Perple_X [Connolly, 2005]

$$G(T,P) = \sum_i n_i(T,P)\mu_i(T,P)$$

Data for components for two materials from [Stixrude and Lithgow-Bertelloni, 2011 GJI]

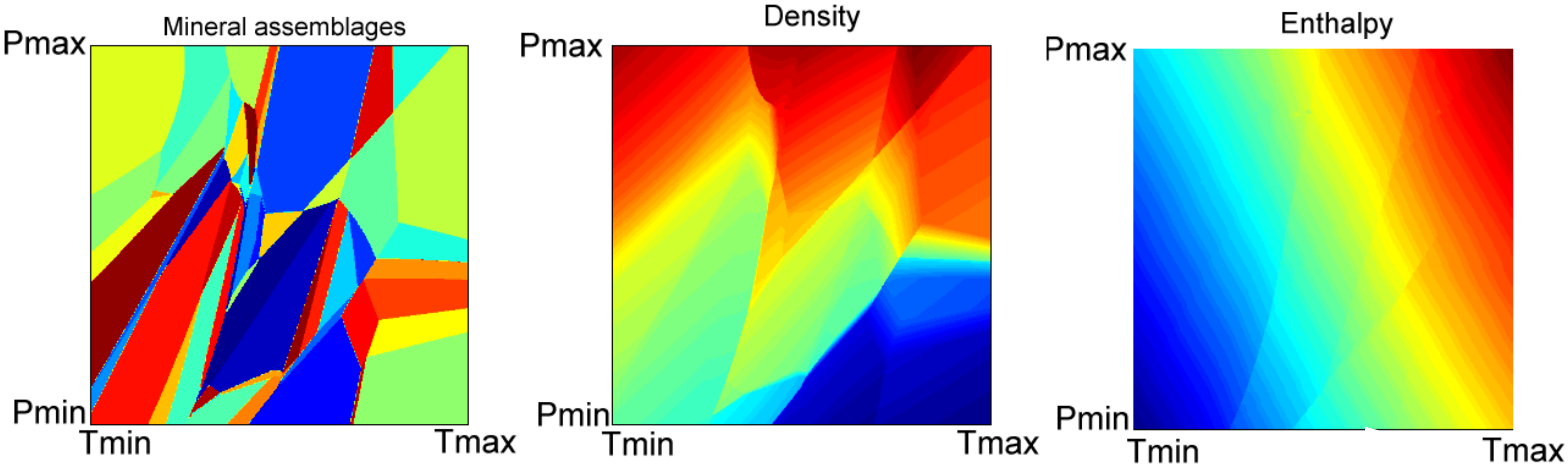
Component	Harzburgite (mol%)	MORB (mol%)
SiO_2	36.04	41.75
MgO	57.14	22.42
FeO	5.41	6.00
CaO	0.44	13.59
Al_2O_3	0.96	16.24



Solid line: Solidus

Look-up tables of density and enthalpy in P-T space

Gibbs free energy minimization



$H = H$ (***P**ressure*, ***T**emperature*, ***C**omposition*, ***M**ineralogy*)

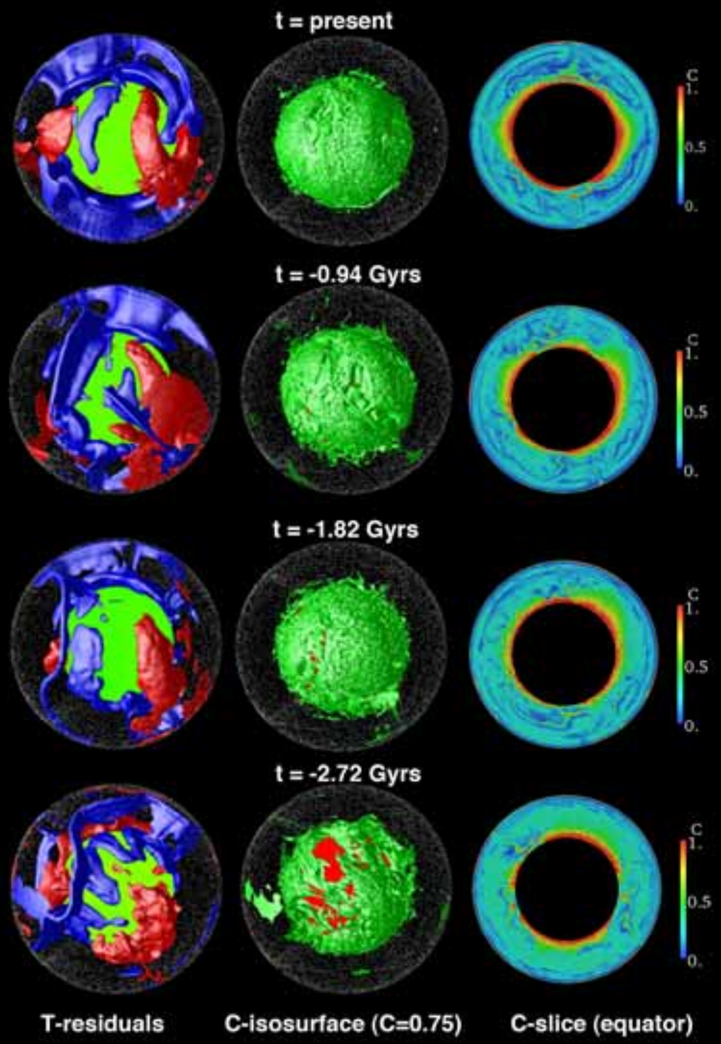
$\rho = \rho$ (***P**ressure*, ***T**emperature*, ***C**omposition*, ***M**ineralogy*)

(Gerya et al., 2001, 2004, Connolly & Petrini, 2002, Vasiliev et al., 2004)

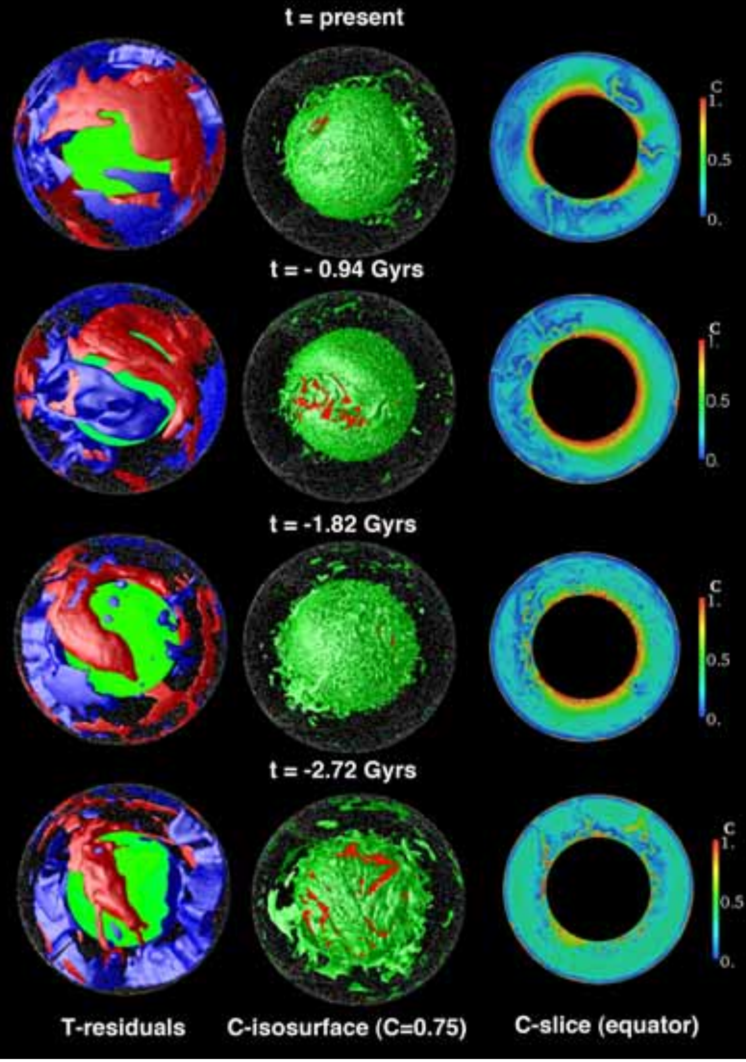
Our 2009 study: Nakagawa et al. (Gcubed)

- Pyrolite composition = harzburgite + MORB each expressed as 5 Oxides (C-F-M-A-S system)

Parameterized properties



Perple_X calculated



But… compositions are uncertain (particularly MORB)

- Mineral physics database
  - Not very accurate for post-spinel and post-garnet transitions.
  - No Sodium, which influences the density of MORB.
  - We improved the mineral physics database to be more accurate for perovskite transitions and include Sodium-oxide using recent studies on mantle mineral proportions [Xu et al., 2008; Khan et al., 2009], i.e., expanding to 6 oxide system (N-C-F-M-A-S system).
  - Amount of MORB composition in pyrolite changed.
- Mantle convection simulations: same parameters.

Check sensitivities to 5 or 6 oxide compositions

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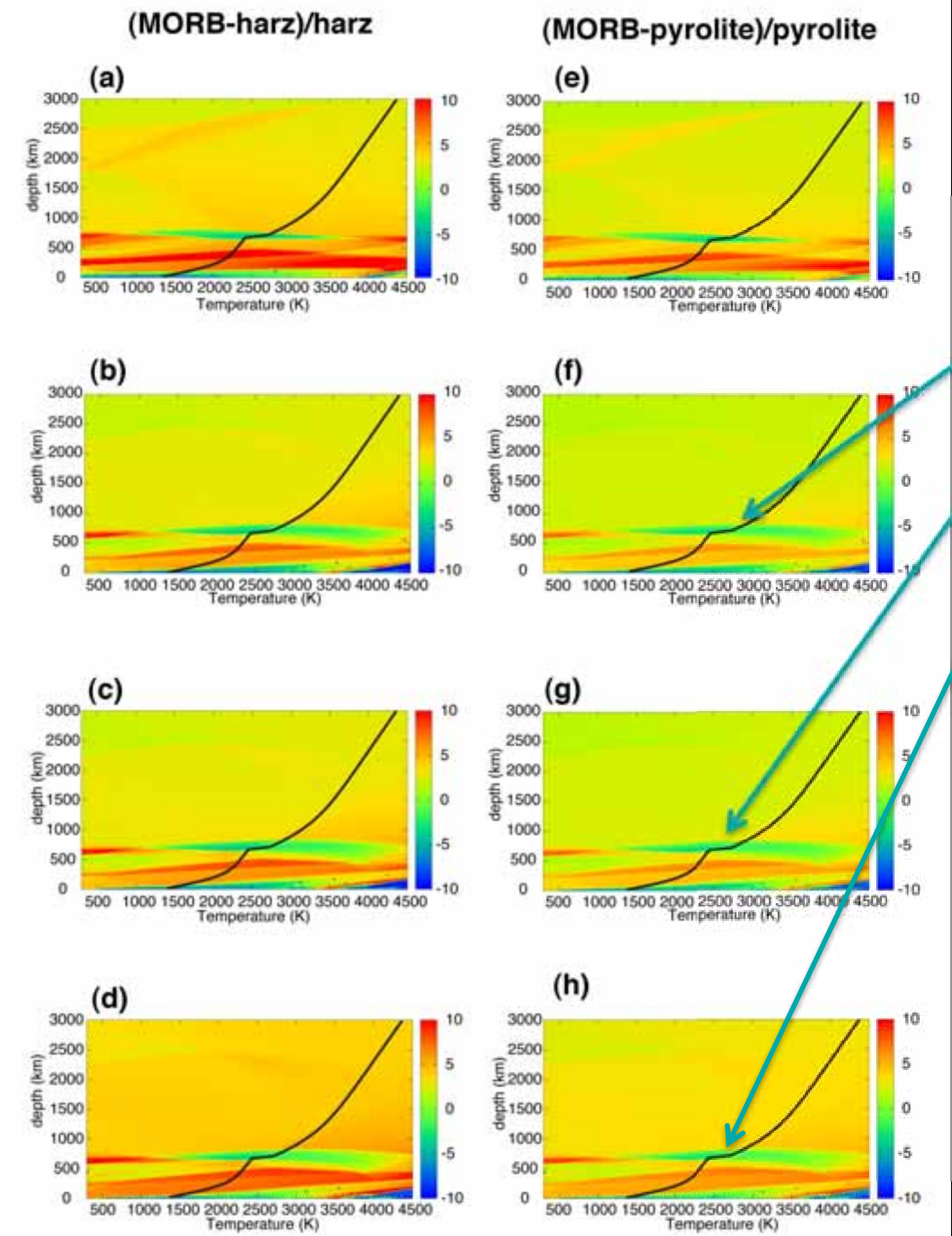
4 different compositions (2010 EPSL)

Table 1: Bulk compositions of MORB and harzburgite in molar %.

	CFMAS-I (improved)		NCFMAS-KT: Khan et al. [2009]		NCFMAS-X: Xu et al. [2008]		NCFMAS-G: Ganguly et al. [2009]	
	harz	MORB	harz	MORB	harz	MORB	harz	MORB
CaO	0.9	14.8	0.4	12.74	0.81	13.88	0.07	11.32
FeO	5.4	7.0	5.63	6.66	6.07	7.06	4.81	8.31
MgO	56.6	15.8	56.07	16.39	56.51	14.94	60.49	17.96
Al_2O_3	0.7	10.2	0.28	9.85	0.53	10.19	0.24	9.45
SiO_2	36.4	52.2	37.62	52.47	36.07	51.75	34.39	50.83
Na_2O	N/A	N/A	0.0	1.88	0.0	2.18	0.0	1.88

- CFMAS plus 3 NCFMAS compositions

Density difference



CFMAS Density Cross-over

Xu et al.

Khan et al.

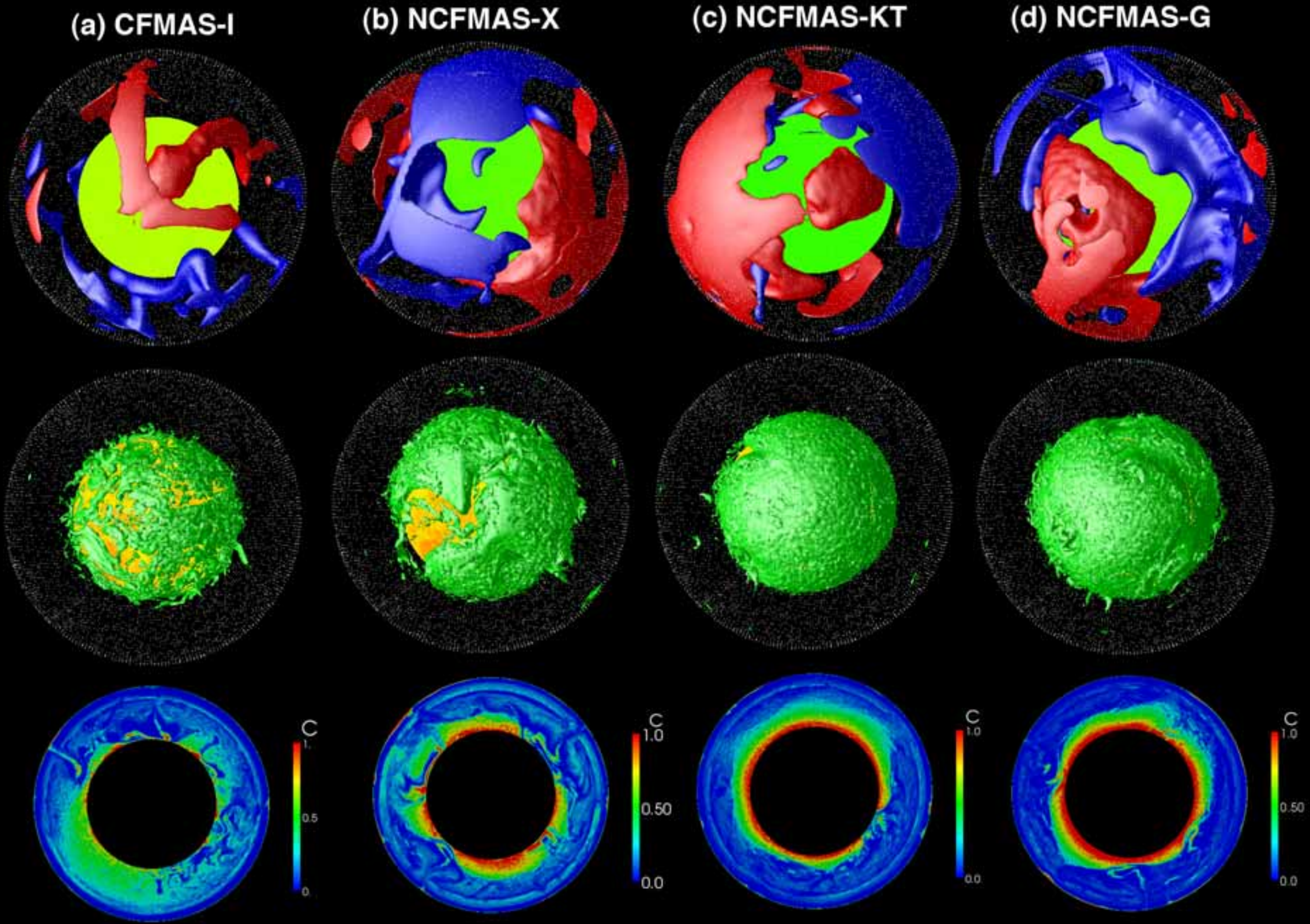
Ganguly et al.

Unit %

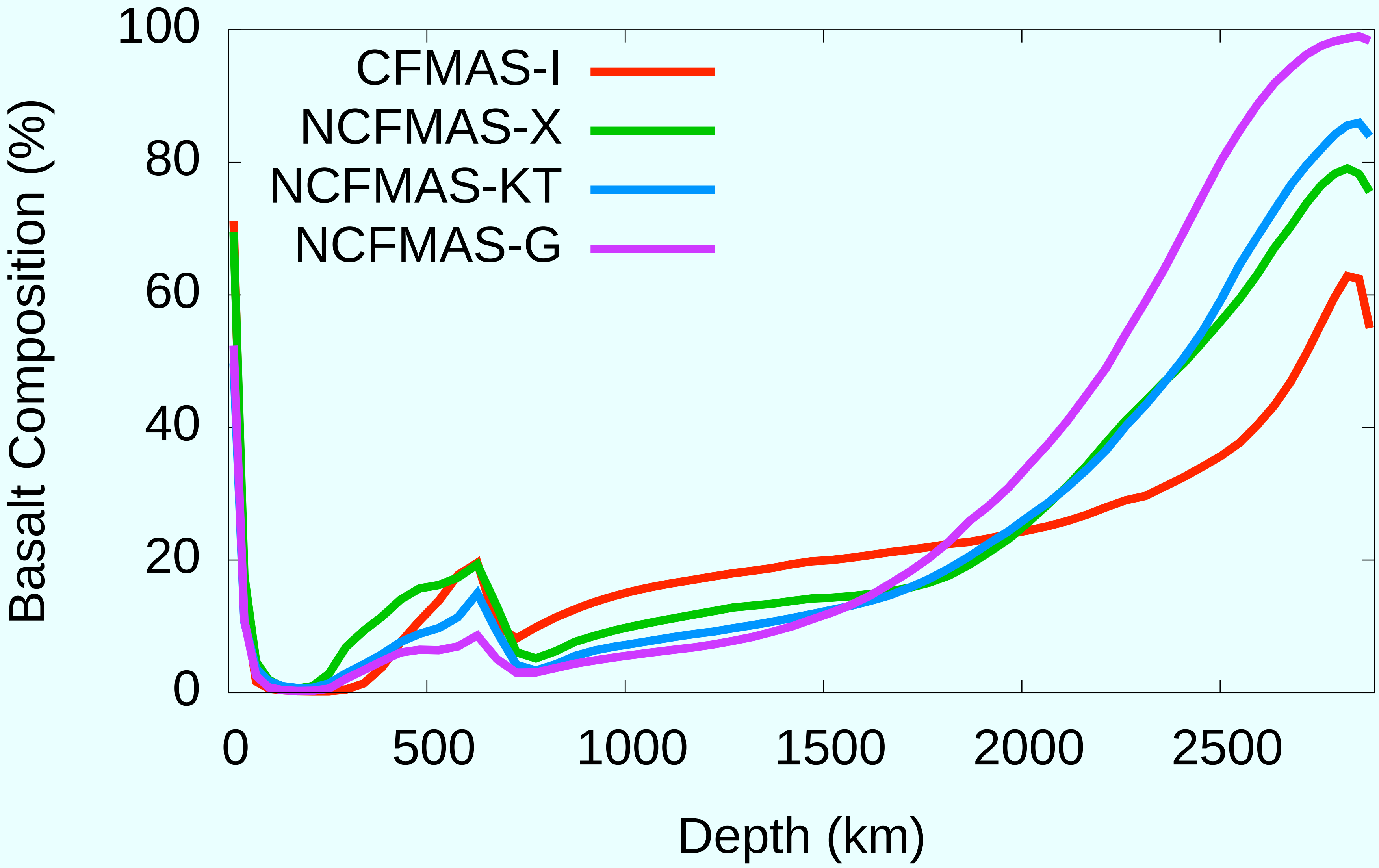
Mantle convection simulations

- Compressible and anelastic fluid with temperature-, depth- and yield stress-dependent viscosity
- Pyrolite = 80 % harzburgite + 20 % MORB (Xu et al., 2008]; Initially uniform composition.
- Melting generates oceanic crust.

Composition makes a difference!



Radial compositional structure



Conclusions: Self-consistent mineralogy

- Self-consistent mineralogy doesn't give much different convection results from a sensible parameterisation of phase changes & material properties, but is a useful framework for experimenting with the effects of composition
- Exact compositions do matter! (change in space & time)
- Treatment is only as good as the uncertainty in mineralogical parameters!
- MORB predicted density too large?

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Geodynamo & influence of initial CMB temperature

- Mantle convection controls the heat flux out of the core
- If CMB heat flux is too low, a dynamo is not possible
- Layering above the CMB reduces heat flow
- Two key unknown parameters are concentration of radiogenic K in core, and initial core temperature

Nakagawa & Tackley 2010 GCubed

Low initial Tcmb (4400 K)

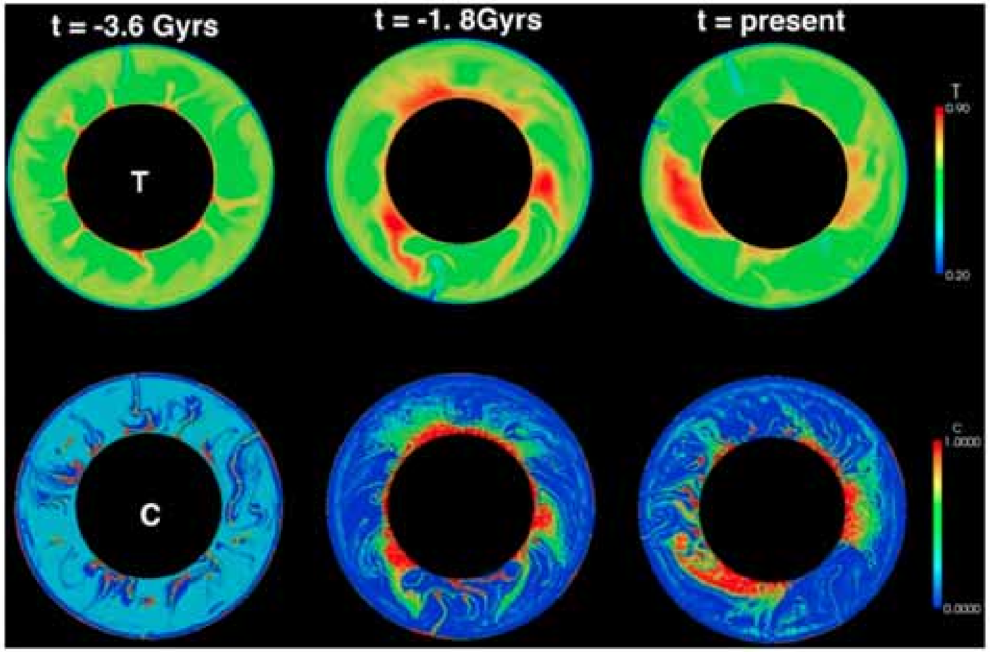


Figure 2. Time evolution of (top) temperature and (bottom) composition for the intermediate buoyancy case of an initial CMB te

High initial Tcmb (5900 K)

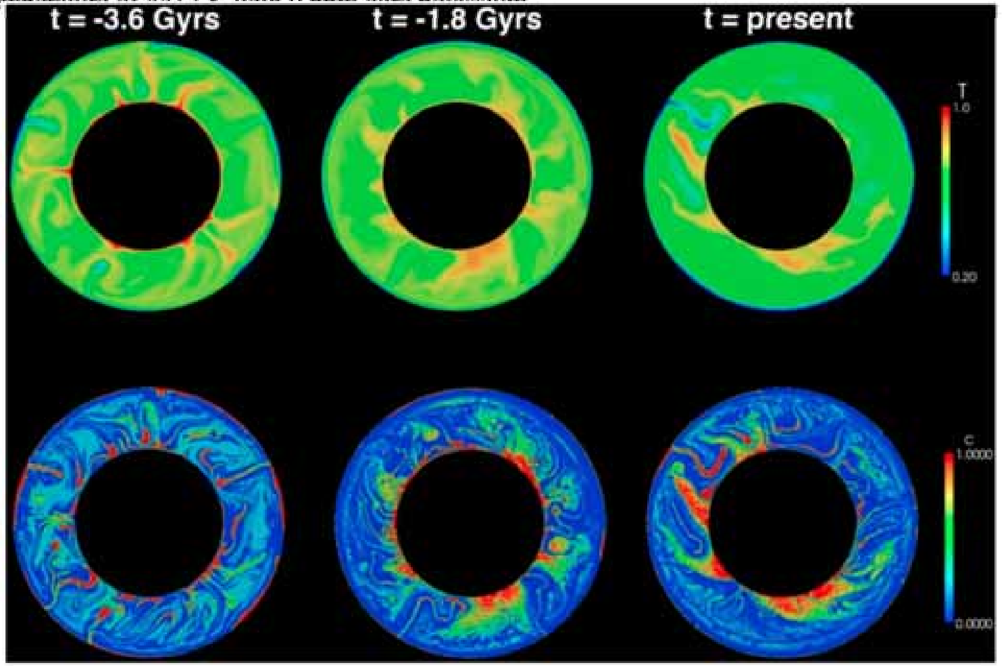


Figure 3. Same as Figure 2 but with higher initial CMB temperature that is 5912 K.

Time series: converge

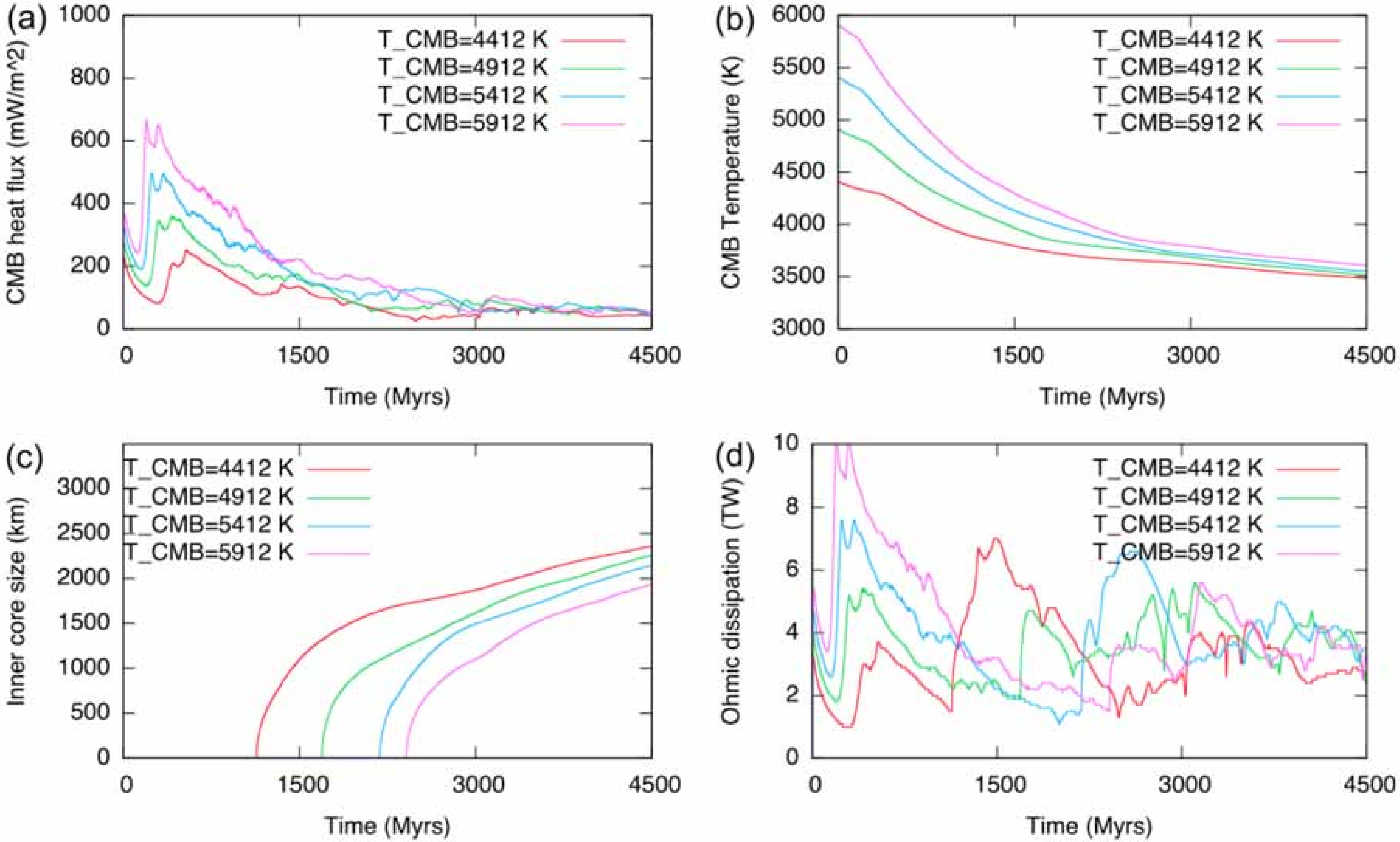


Figure 5. Time diagnostics of (a) CMB heat flux, (b) CMB temperature, (c) inner core size, and (d) ohmic dissipation for 0 ppm core potassium and an intermediate MORB density contrast.

Too much core cooling! (inner core too large)

K40 in core: less core cooling

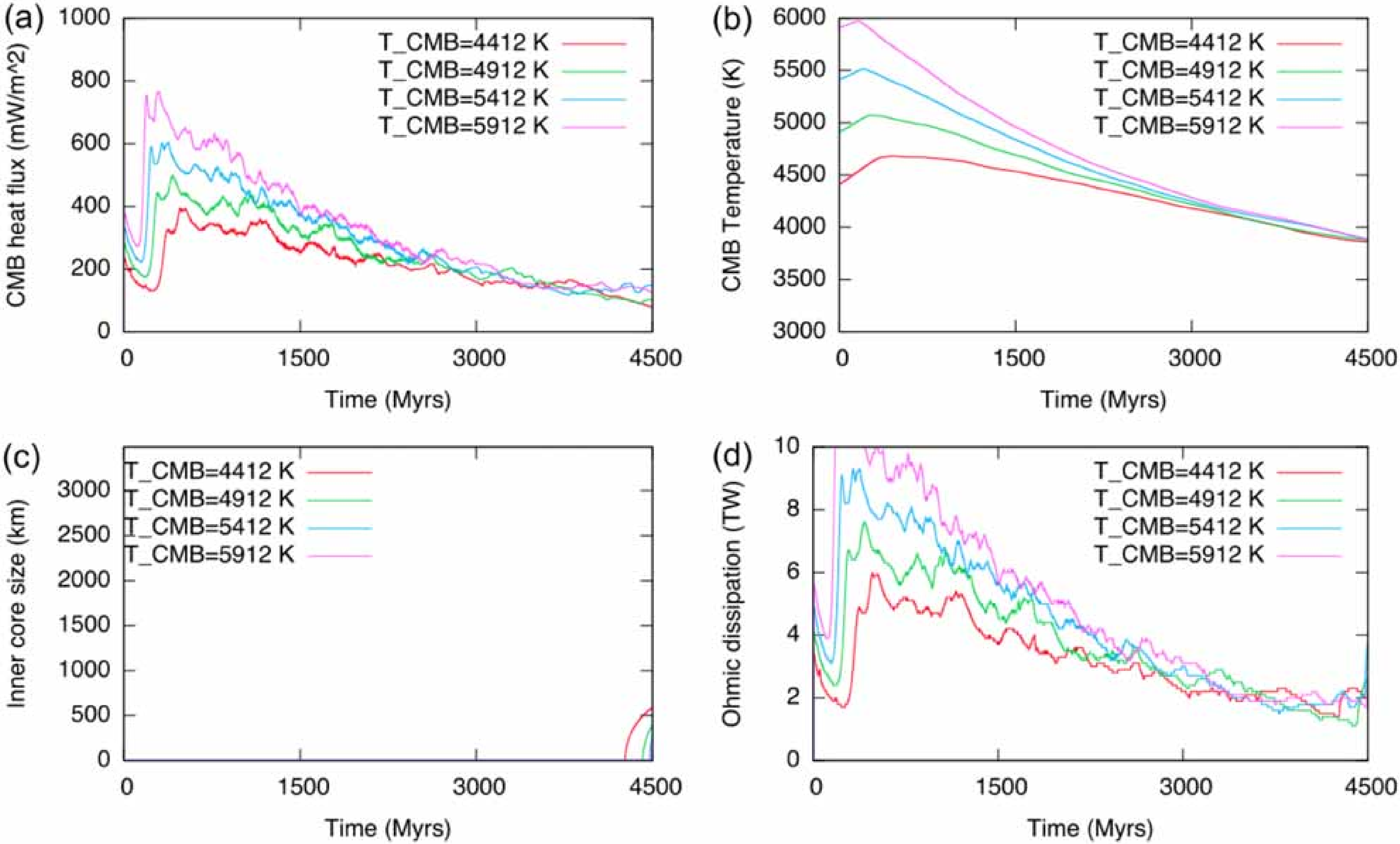
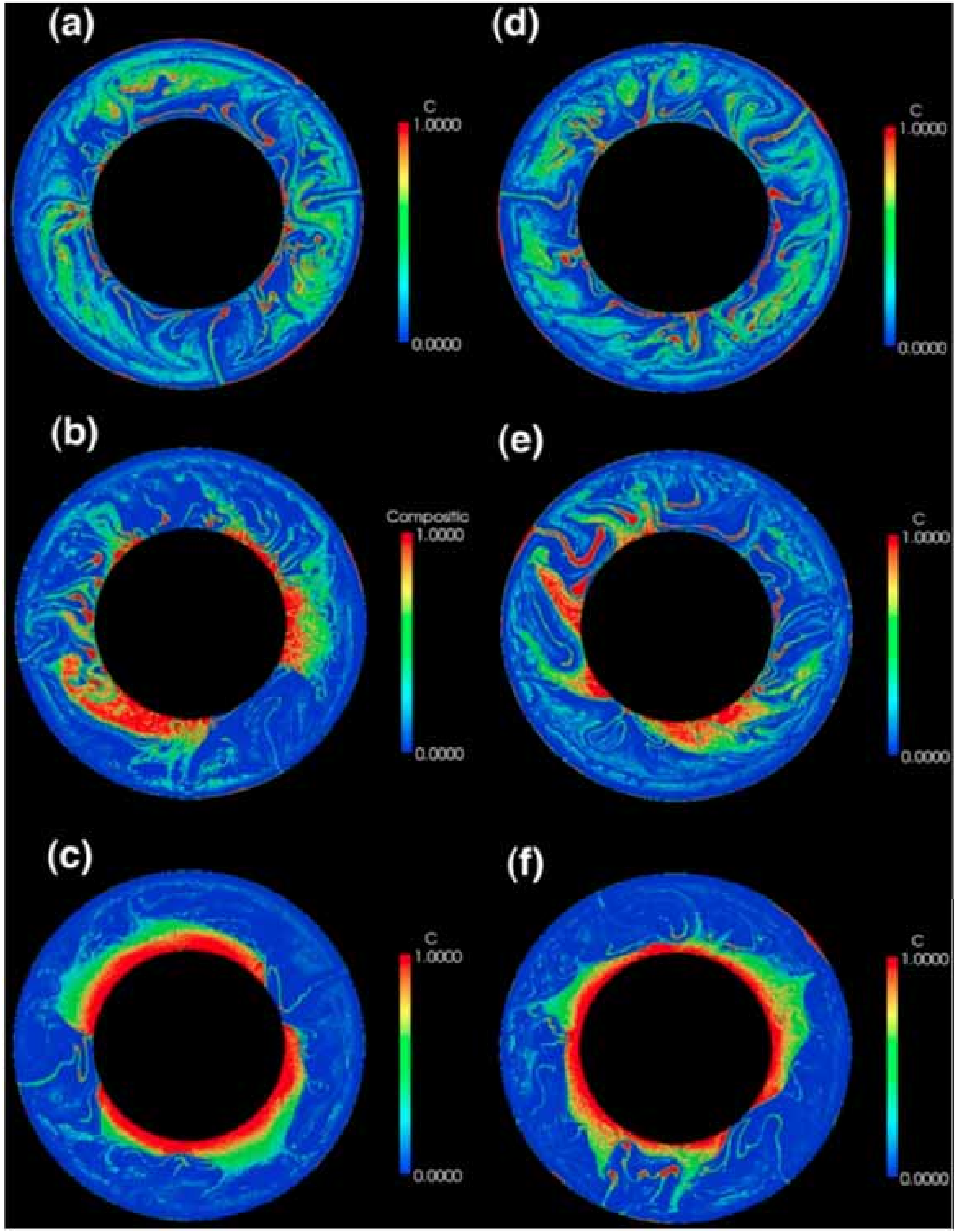


Figure 6. Same as Figure 5 but with 800 ppm core potassium.



MORB density contrast in deep mantle controls layering

Nakagawa & Tackley
2010 GCubed

Dense MORB -> dynamo shuts off!

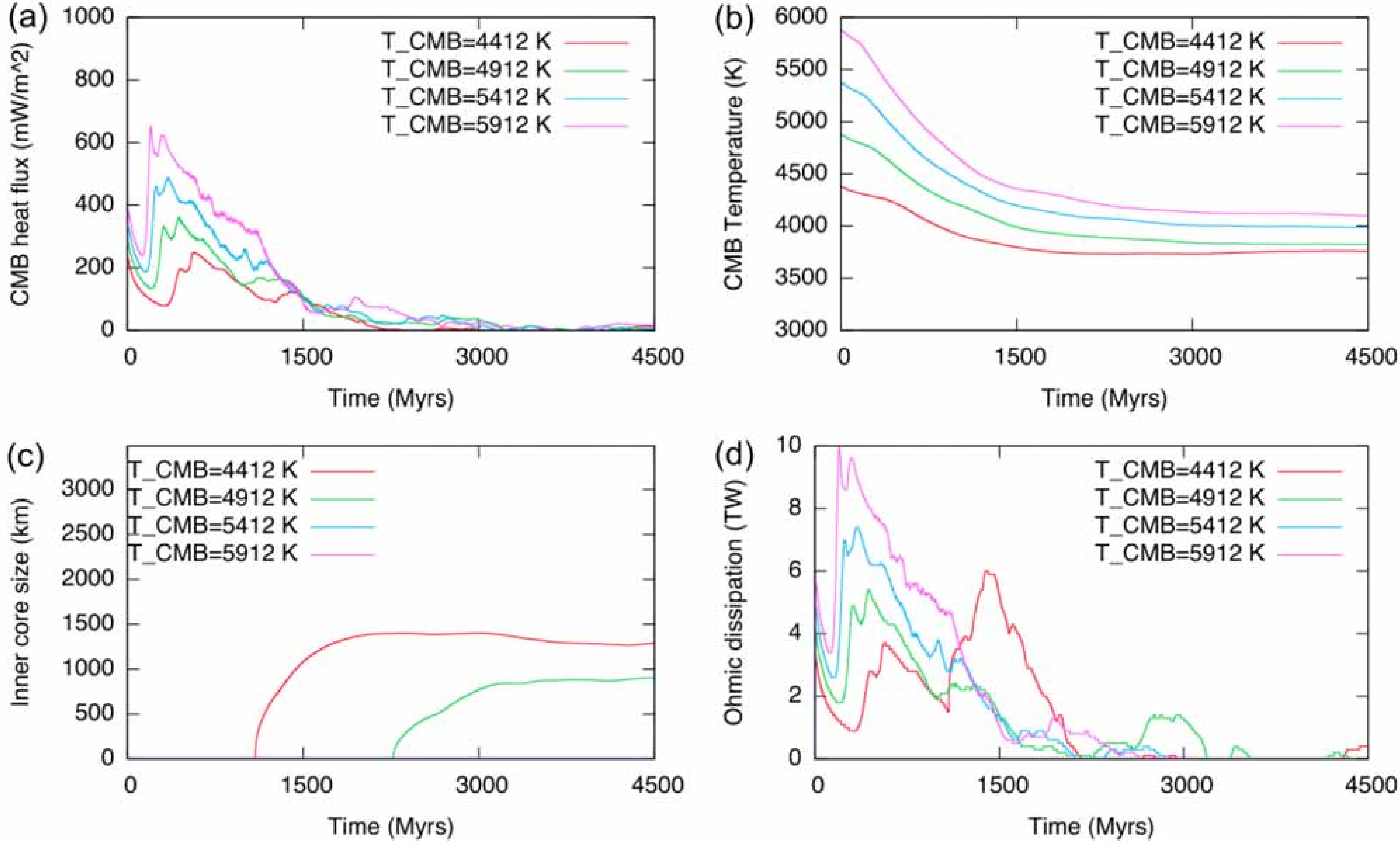


Figure 7. Same as Figure 5 but with dense MORB.

Neutral MORB -> even large I.C.!

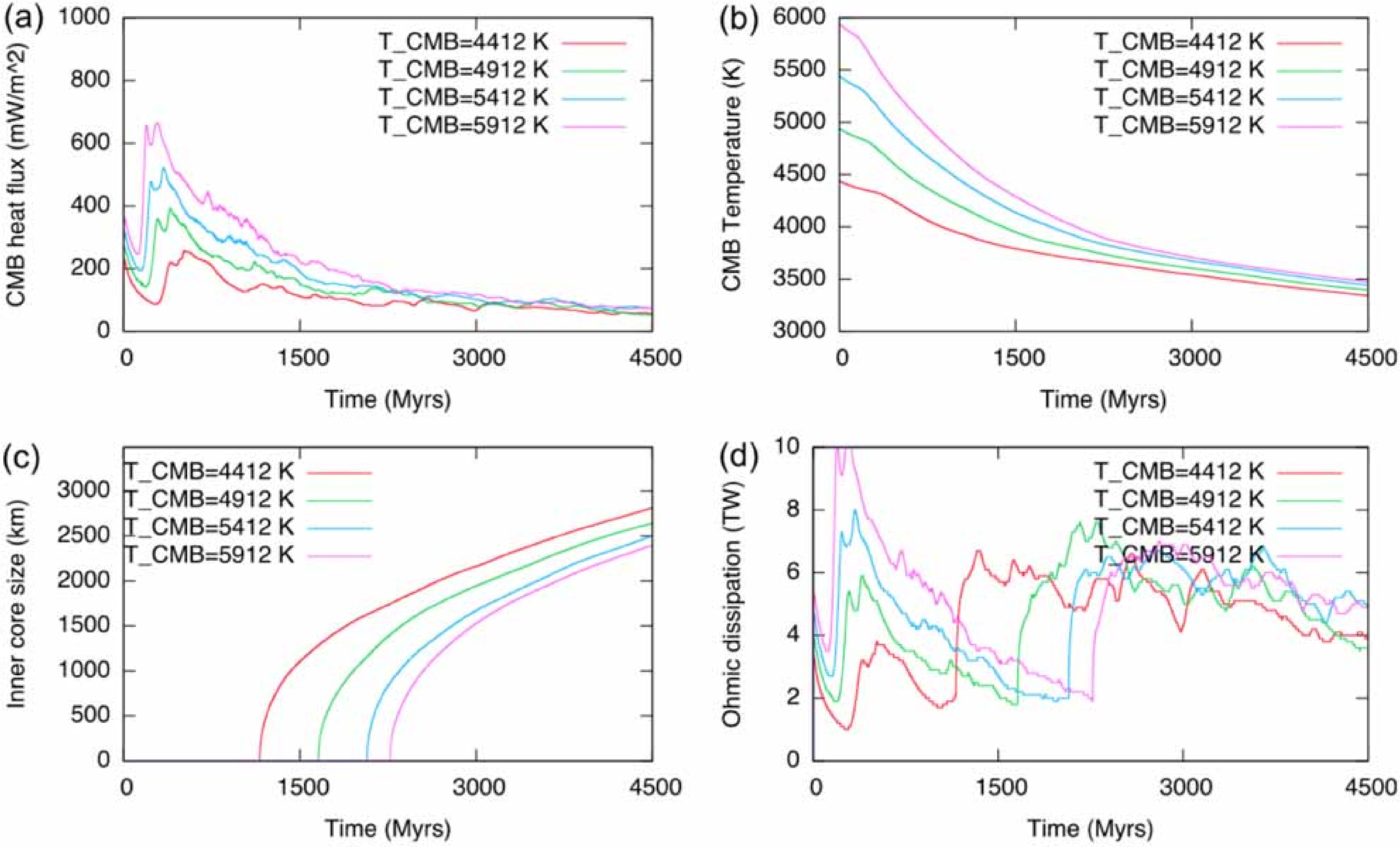
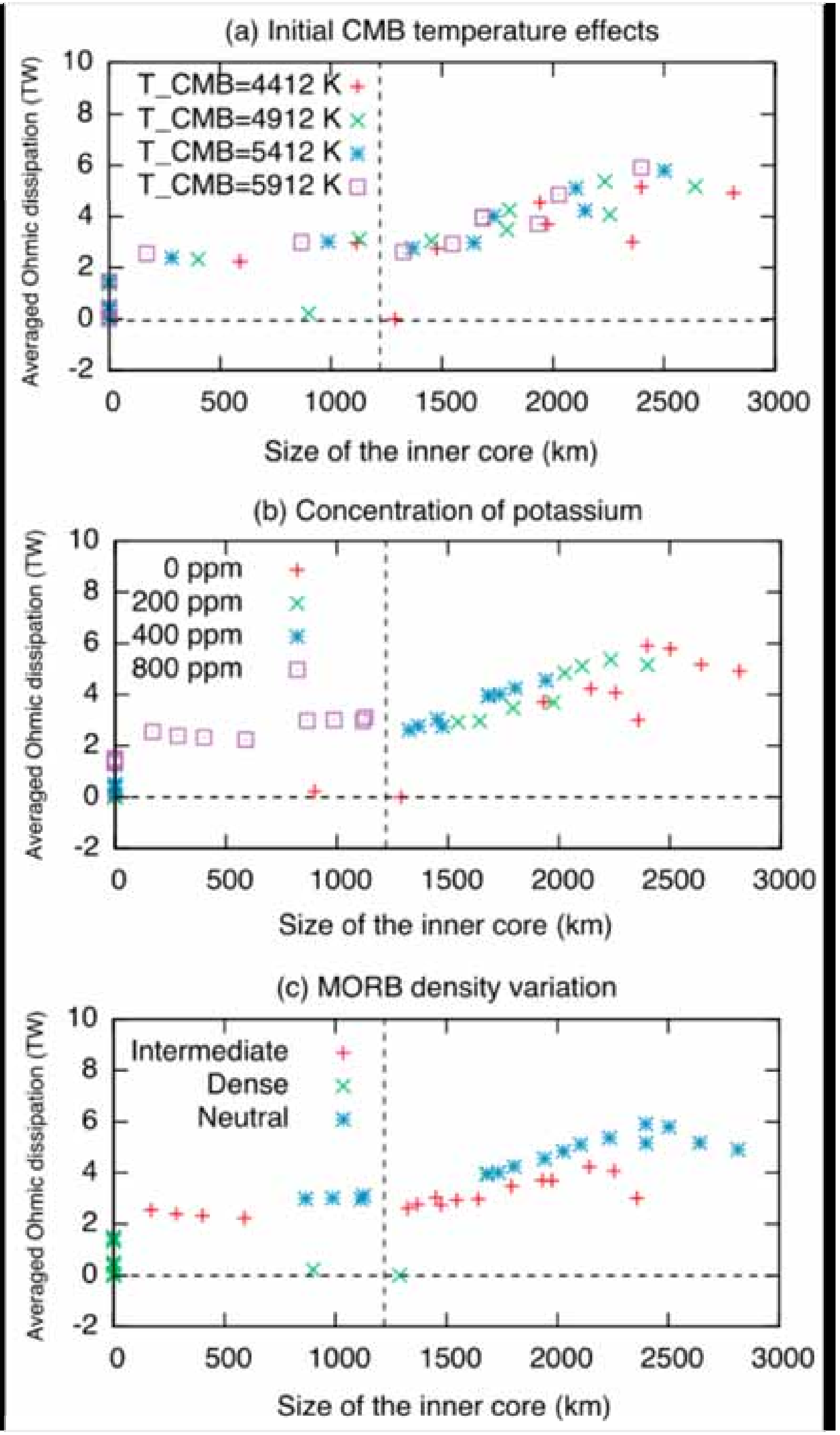


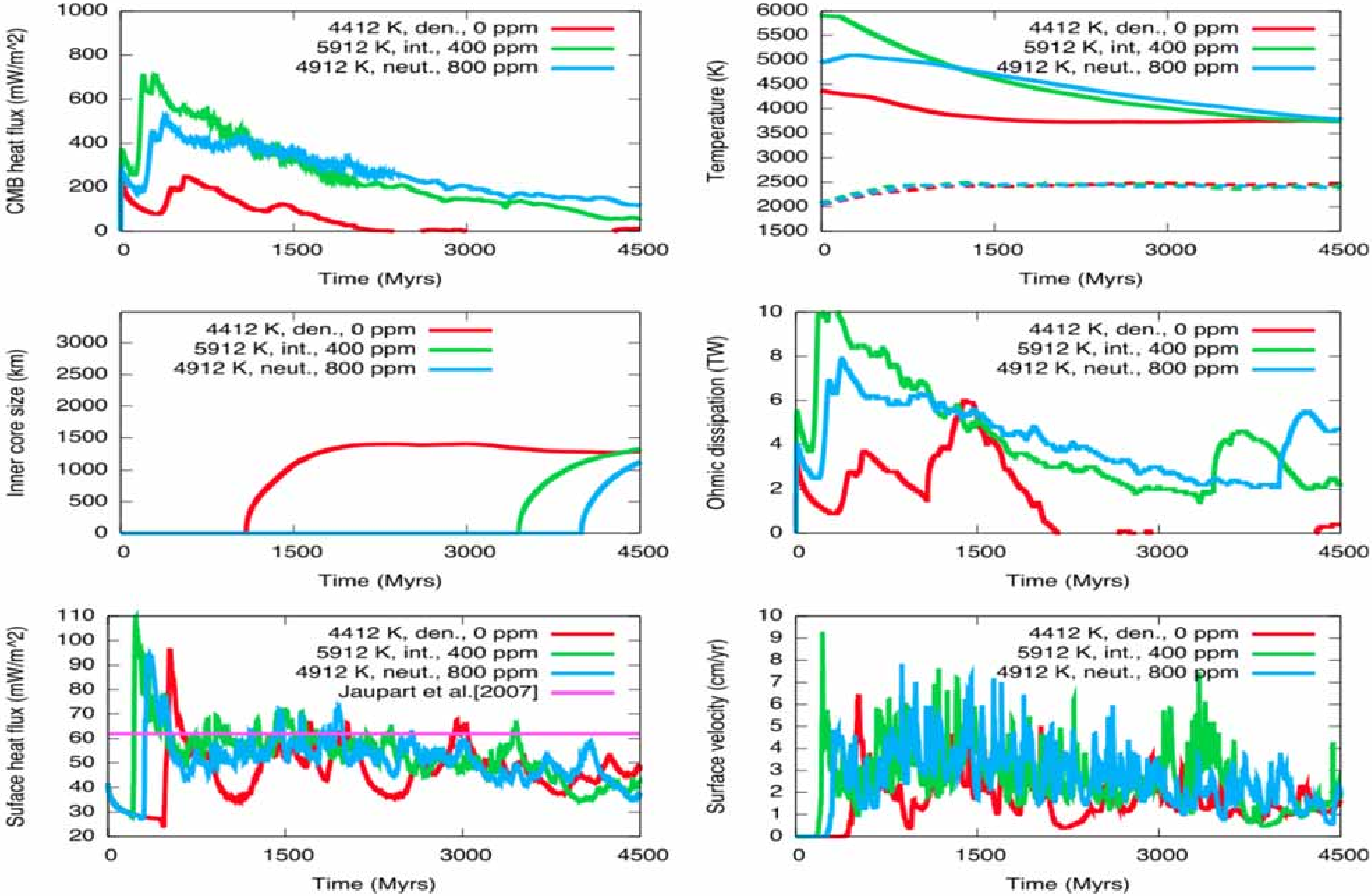
Figure 8. Same as Figure 5 but with neutral MORB density.

Summary

- Initial Tcmb not important
- Kcore important (400-800 ppm good)
- MORB density important (intermediate good)



Successful cases



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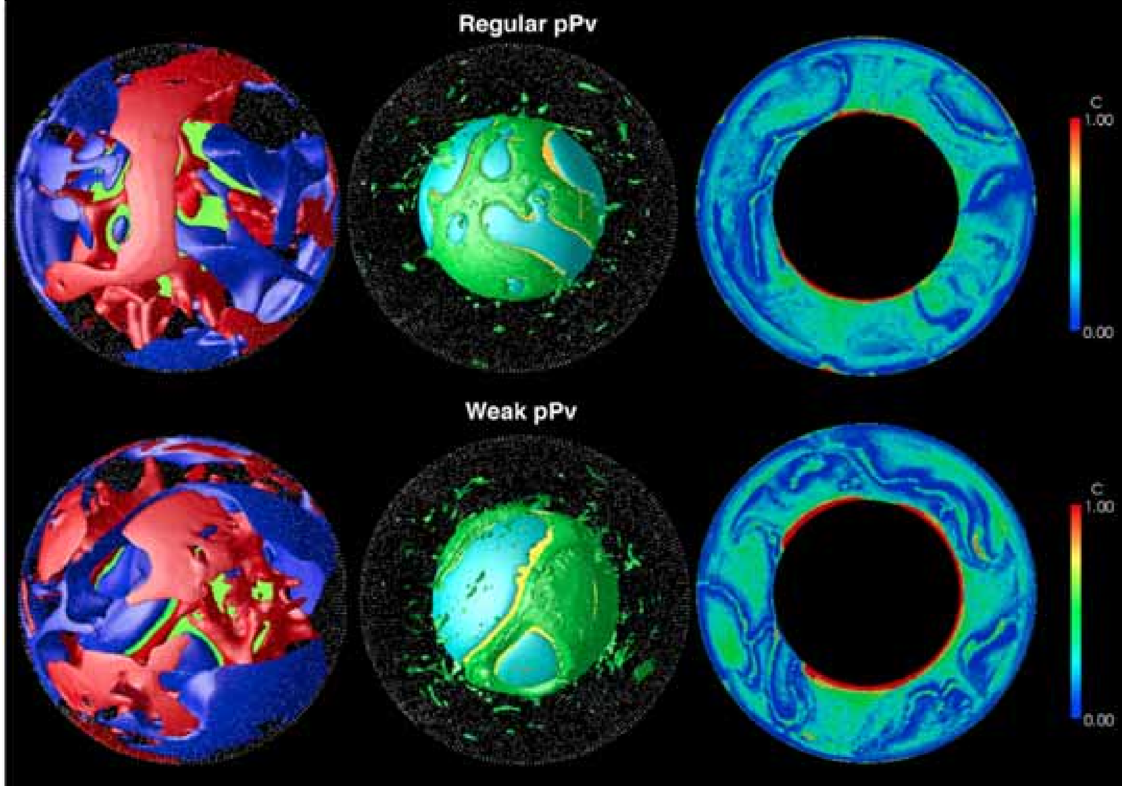
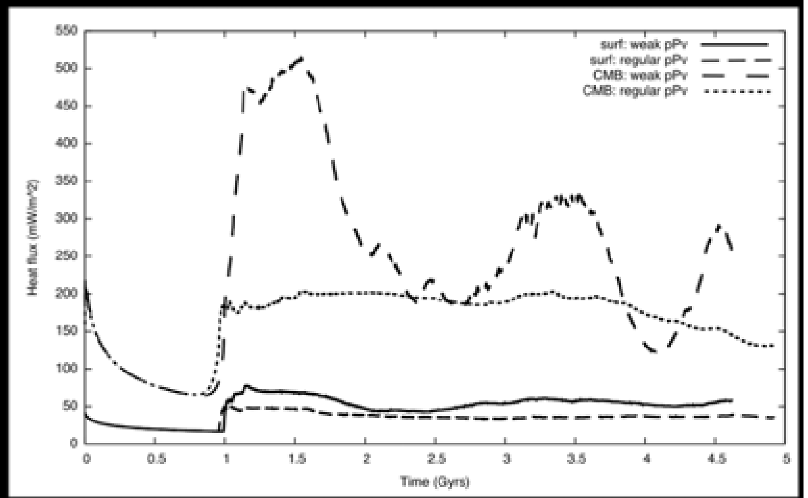
Low-viscosity post-perovskite can have big effect!

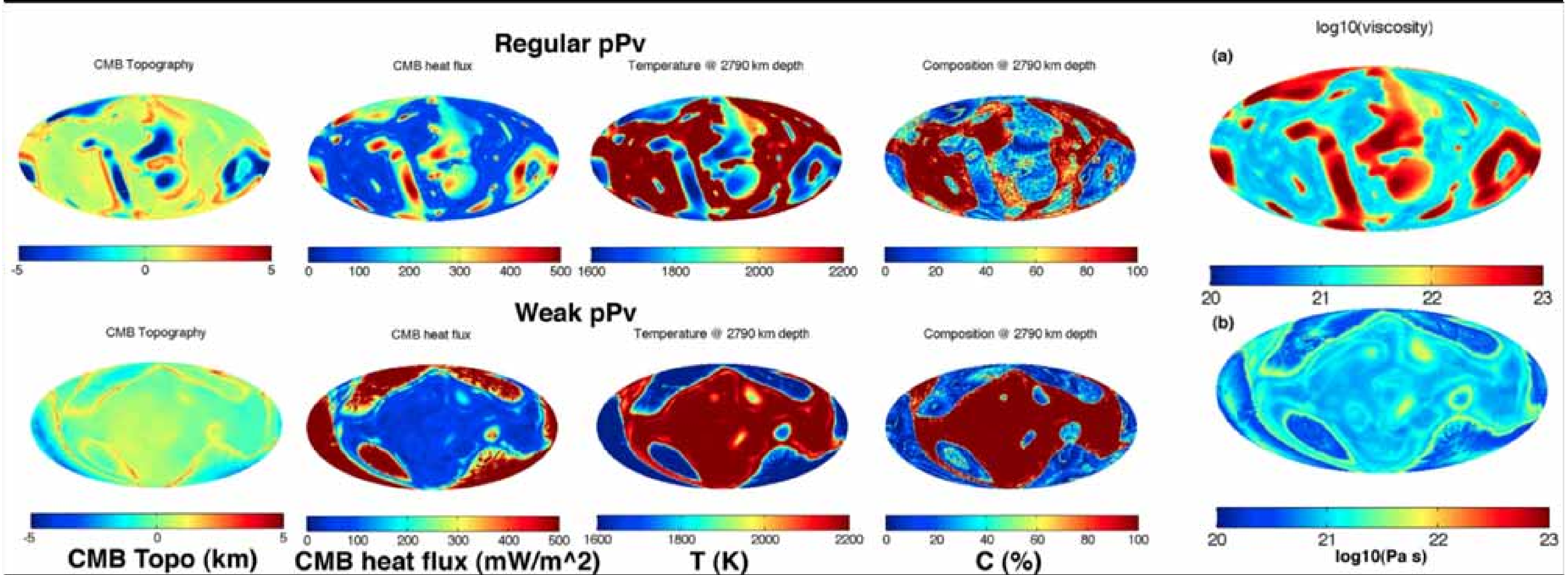
Increases overall convective vigour and amount of settled MORB





Nakagawa & Tackley 2011 GRL

…also reduces CMB topography & viscosity variations



Nakagawa & Tackley 2011 GRL

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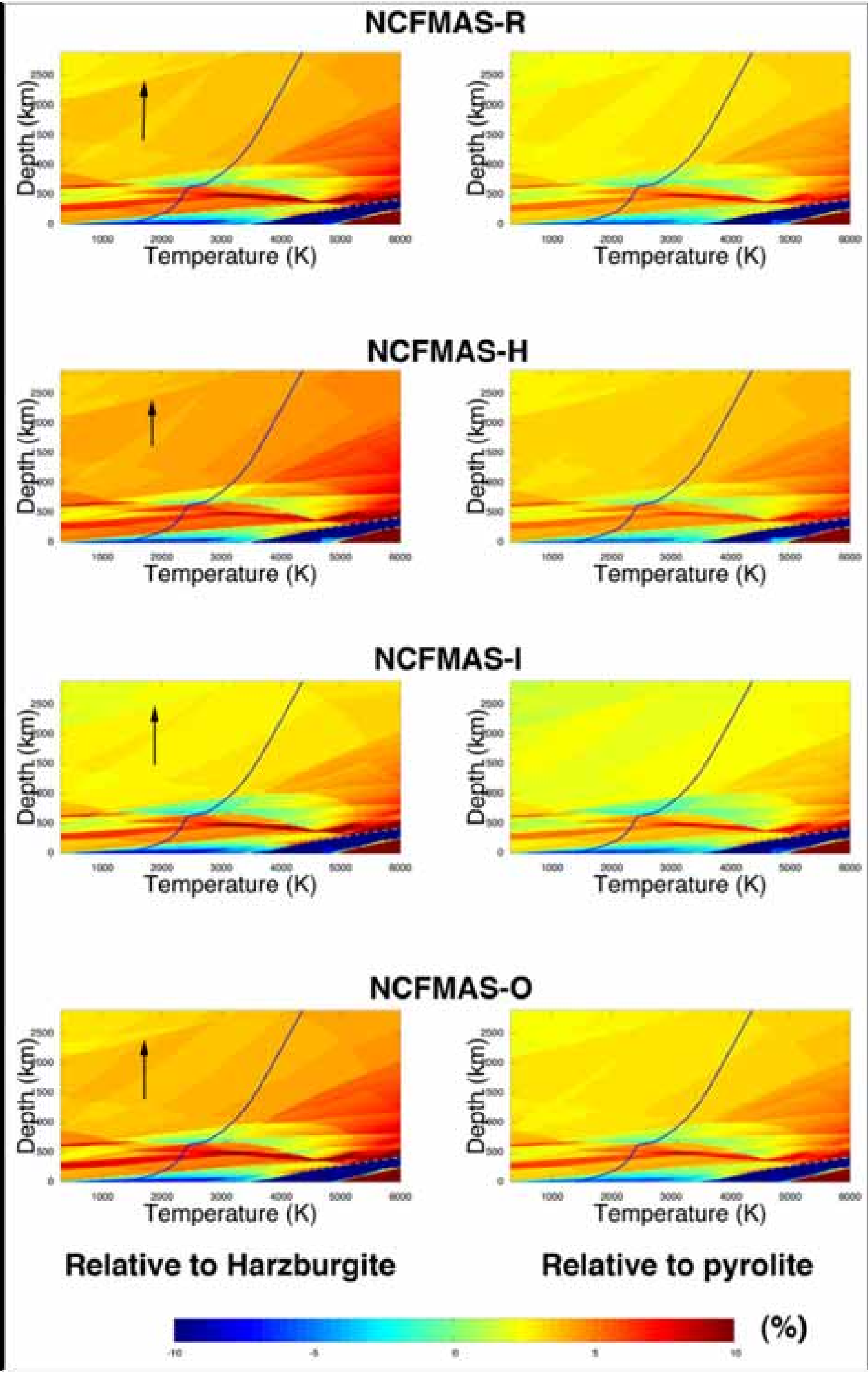
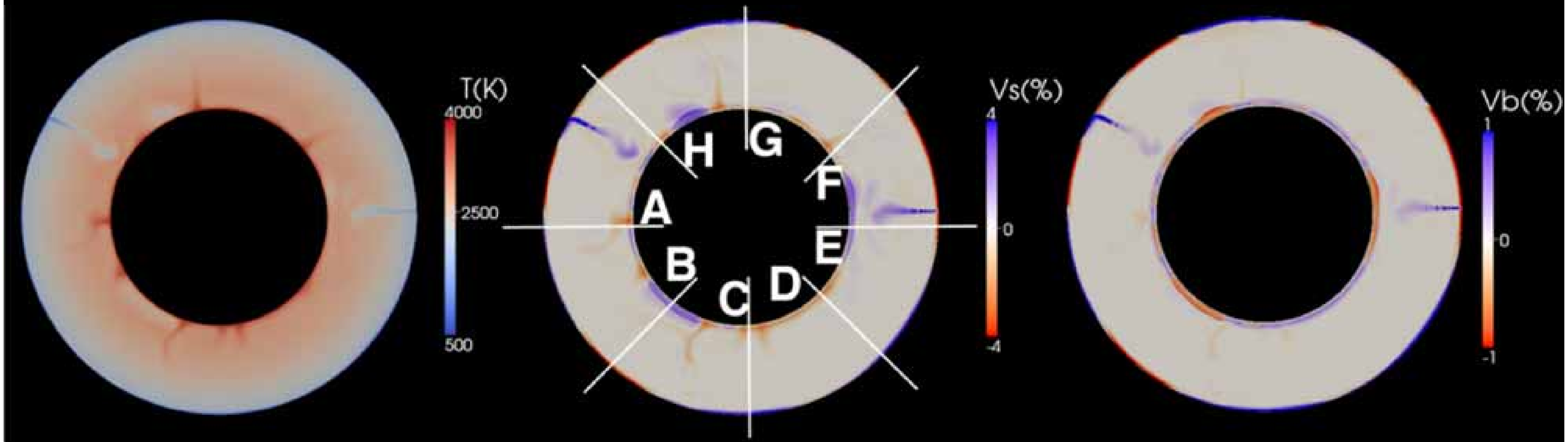
Density difference MORB (post-pV indicated)

Nakagawa et al. 2012 GCubed



Isochemical convection

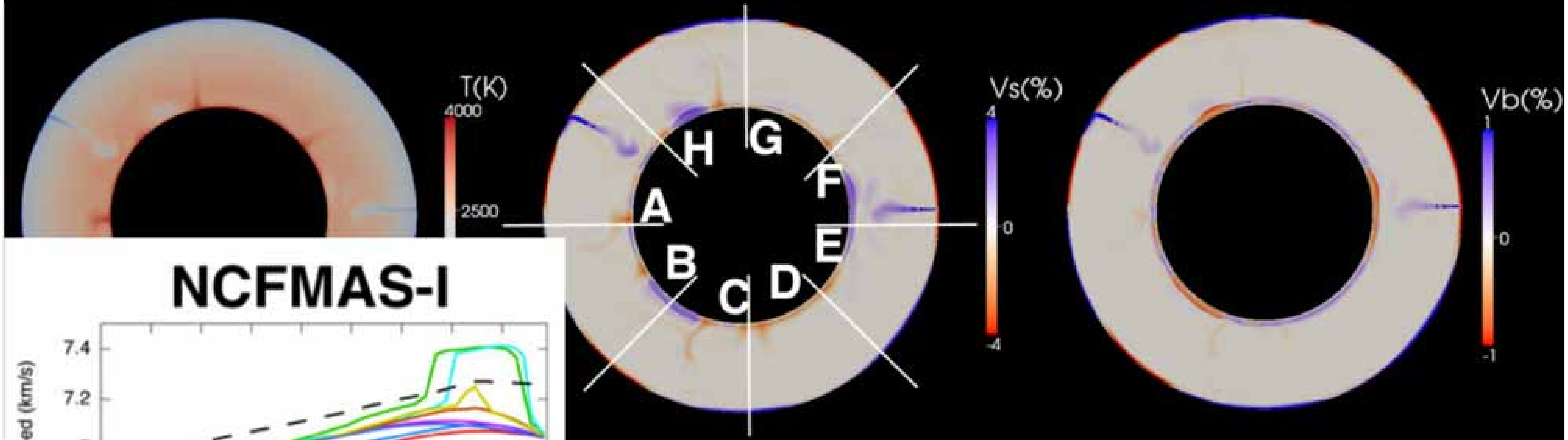


NCFMAS-I

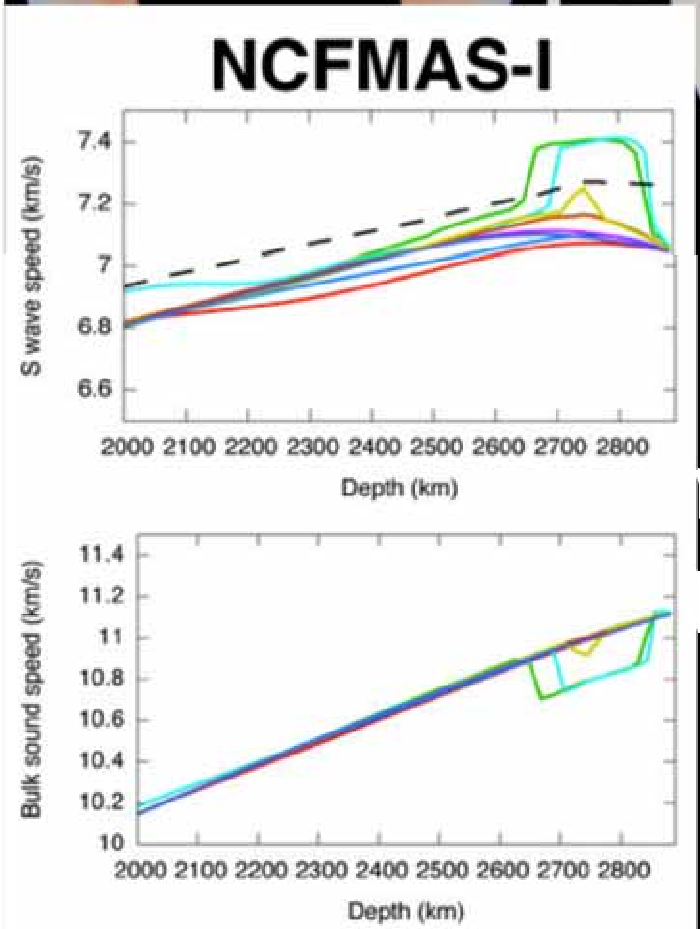
Strong signature of post-perovskite
Anticorrelation Vs-Vbulk

Nakagawa et al. 2012 GCubed

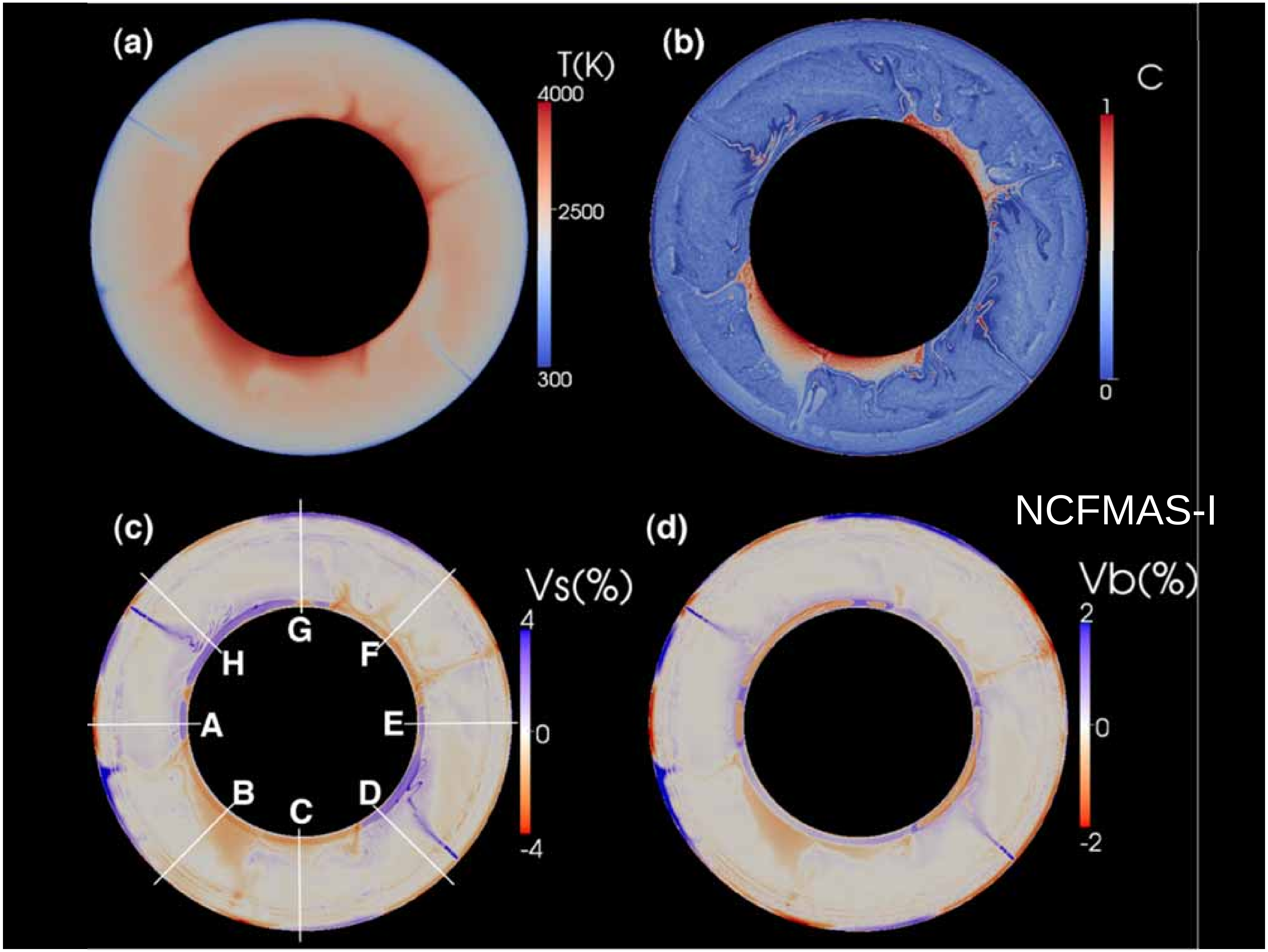
Isochemical convection



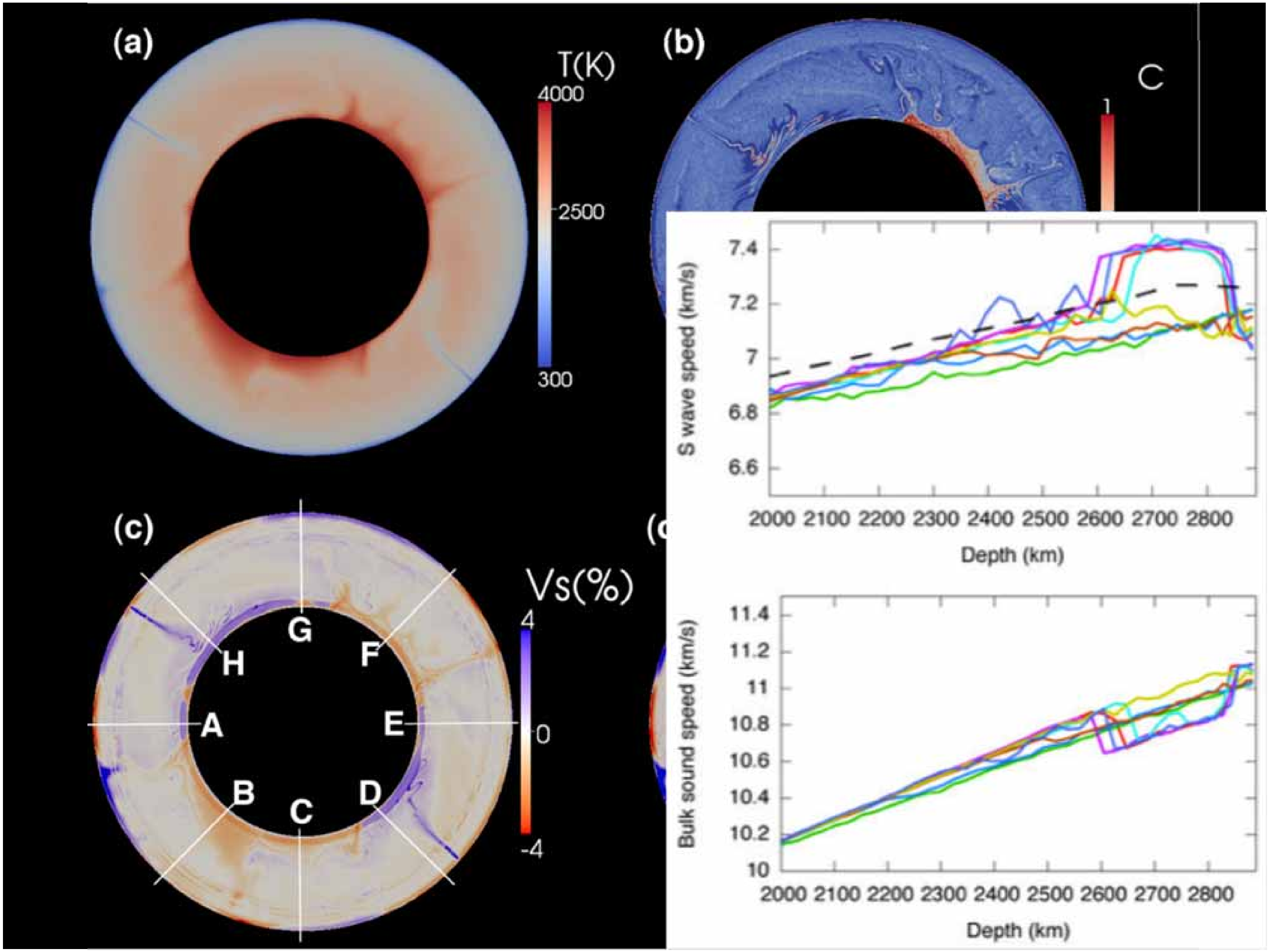
NCFMAS-I



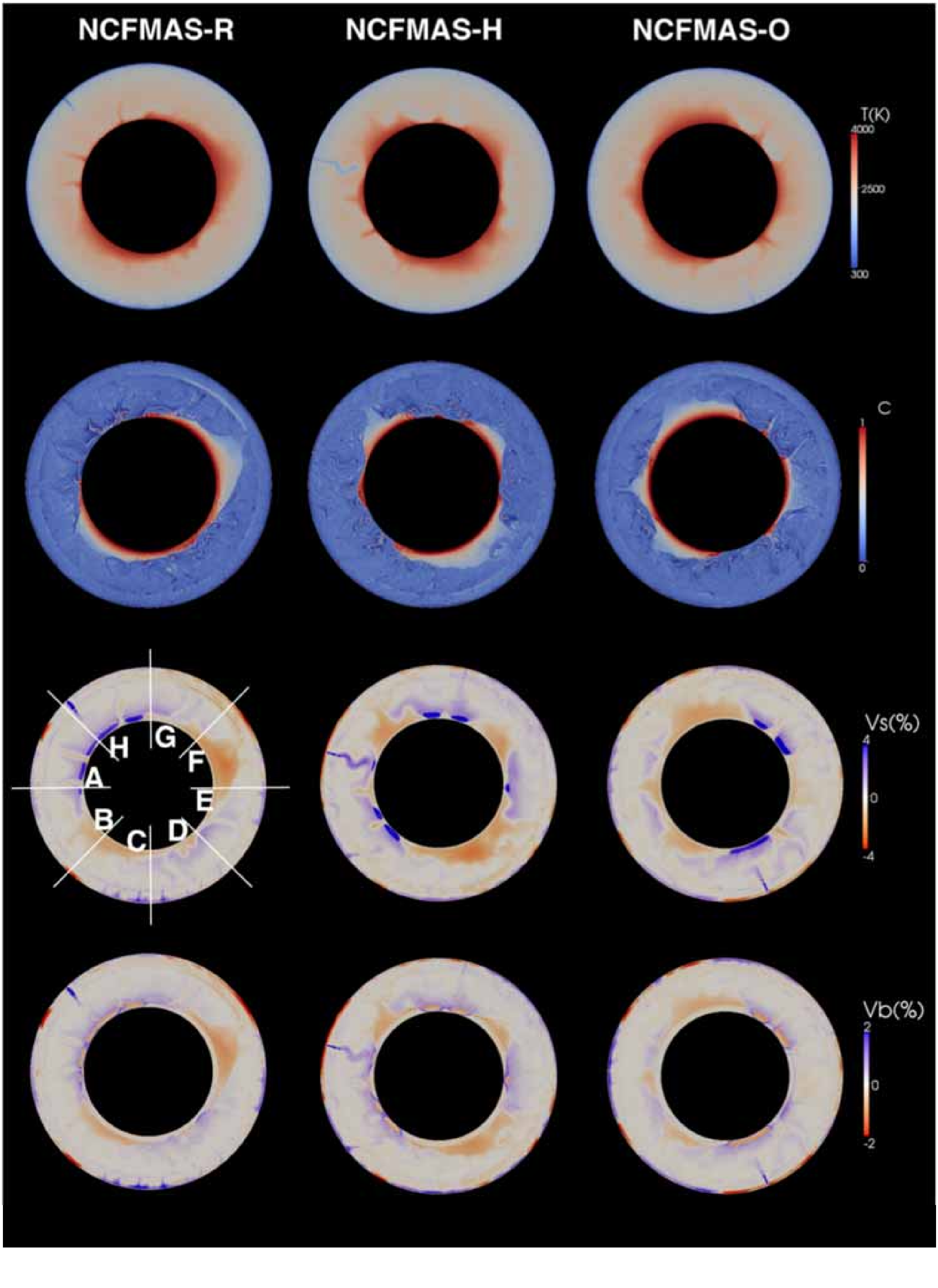
ature of post-perovskite
tion Vs-Vbulk

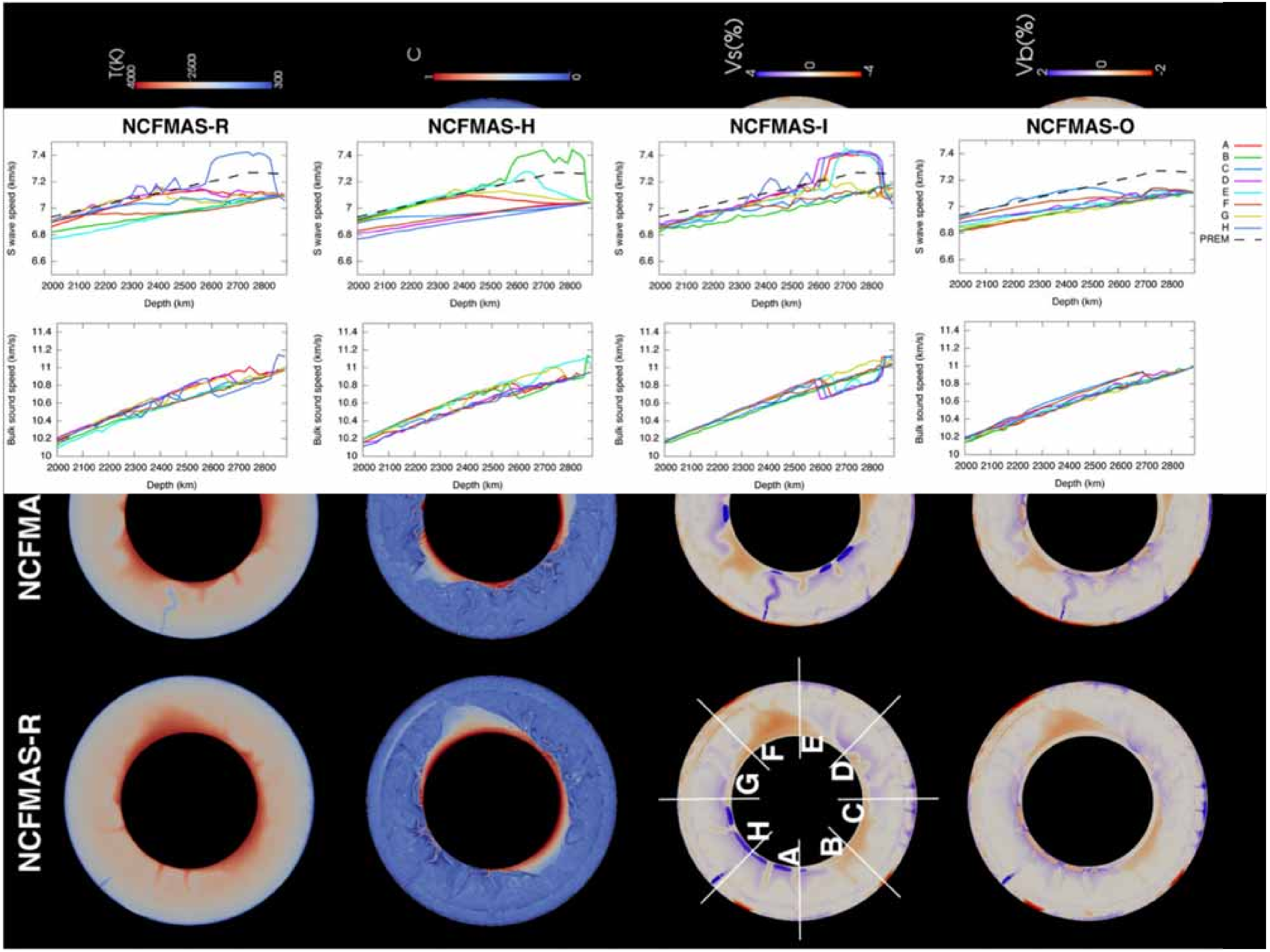


(a)
T(K)
4000
2500
300
(b)
C
1
0
(c)
Vs(%)
4
0
-4
G
H
F
A
E
B
C
D
(d)
Vb(%)
2
0
-2
NCFMAS-I



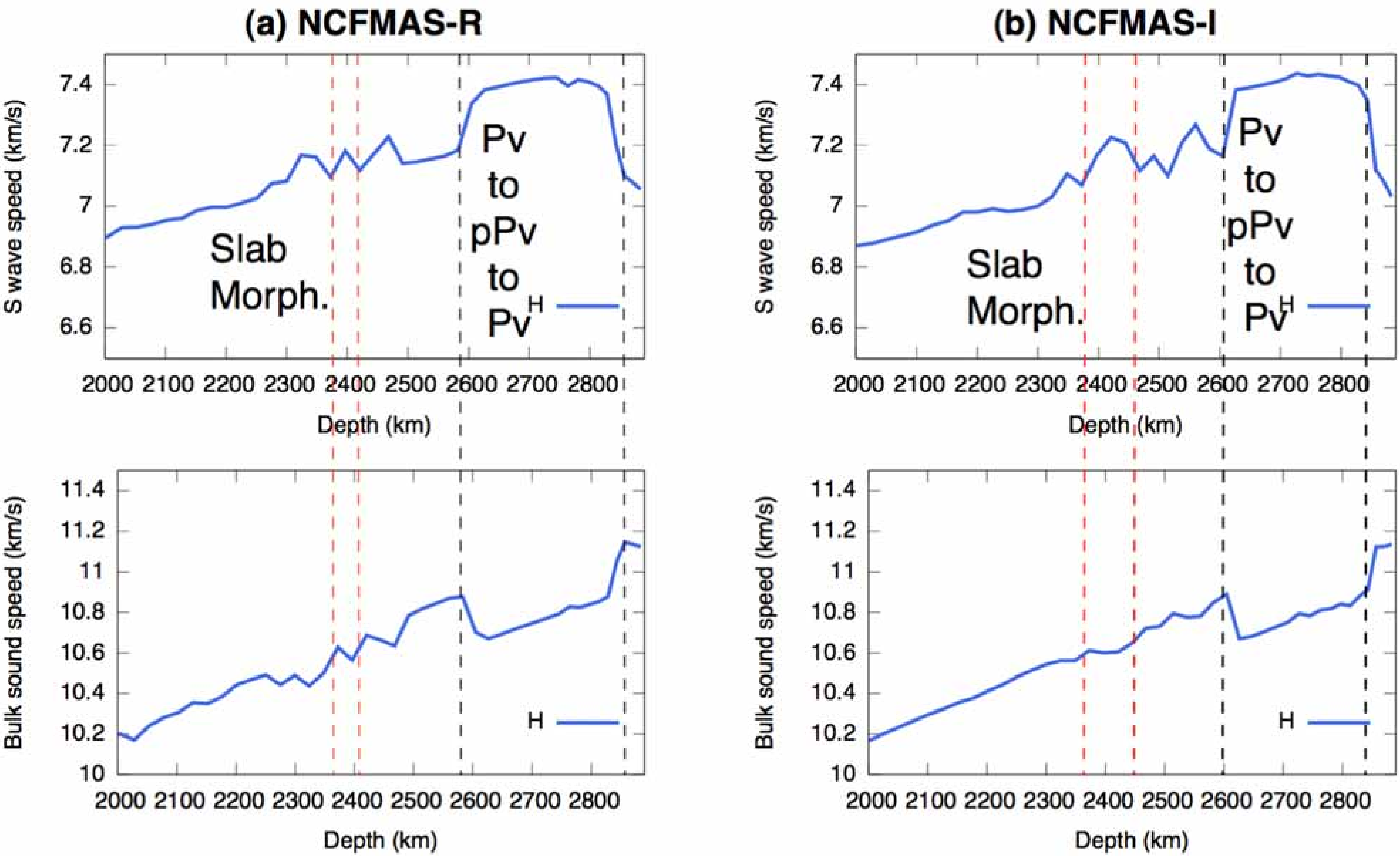
(a)
T(K)
4000
2500
300
(b)
C
1
(c)
Vs(%)
4
0
-4
G
H
F
A
E
B
C
D
S wave speed (km/s)
7.4
7.2
7
6.8
6.6
2000 2100 2200 2300 2400 2500 2600 2700 2800
Depth (km)
Bulk sound speed (km/s)
11.4
11.2
11
10.8
10.6
10.4
10.2
10
2000 2100 2200 2300 2400 2500 2600 2700 2800
Depth (km)


NCFMAS-R
NCFMAS-H
NCFMAS-O
T(K)
4000
2500
300
C
1
0
Vs(%)
4
0
-4
Vb(%)
2
0
-2
A
B
C
D
E
F
G
H

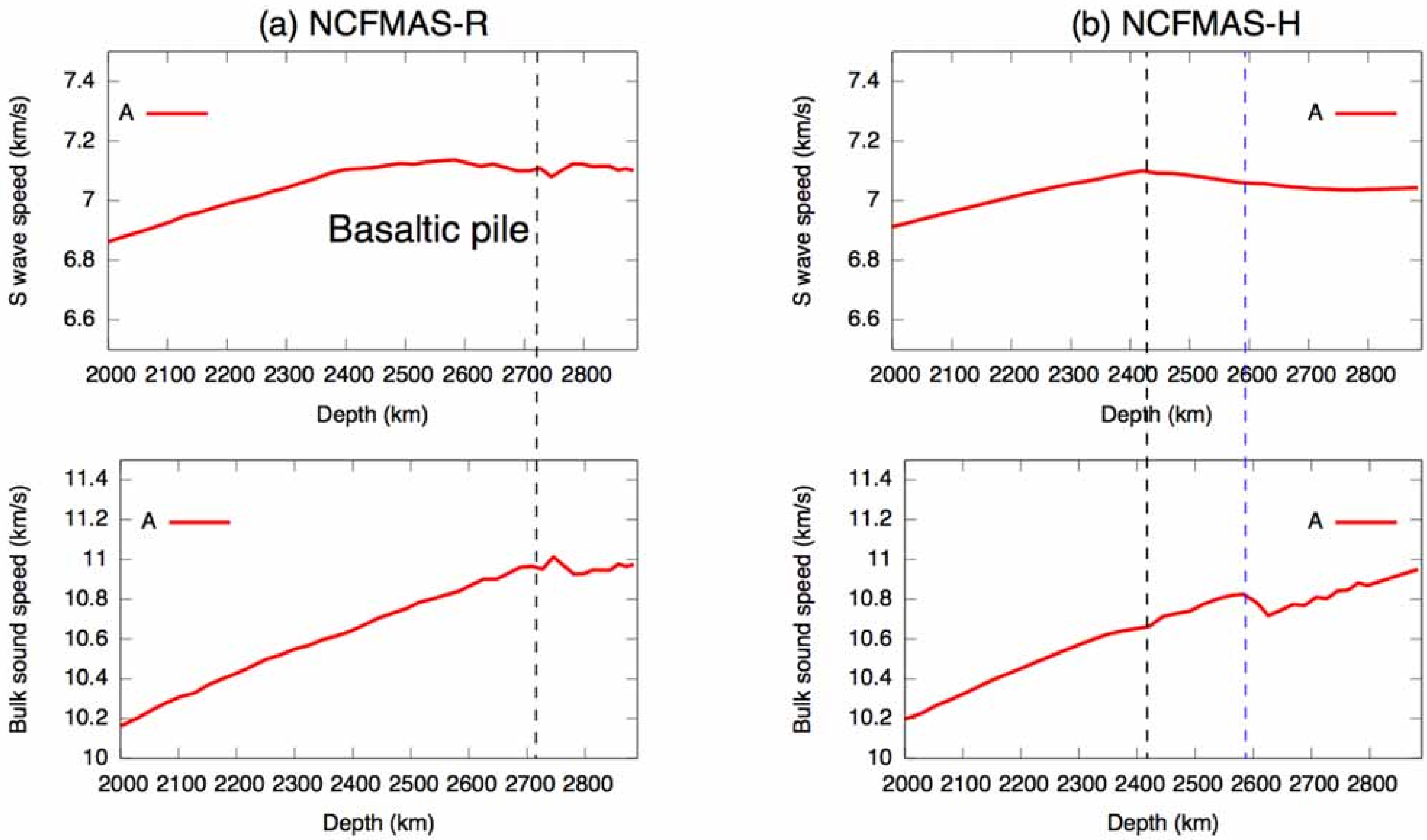


T(K)
4000
2500
300
C
1
0
Vs(%)
4
0
-4
Vb(%)
2
0
-2
NCFMAS-R
NCFMAS-H
NCFMAS-I
NCFMAS-O
S wave speed (km/s)
Depth (km)
Bulk sound speed (km/s)
A
B
C
D
E
F
G
H
PREM
NCFMA
NCFMAS-R

Different causes of discontinuities



Profiles in hot regions

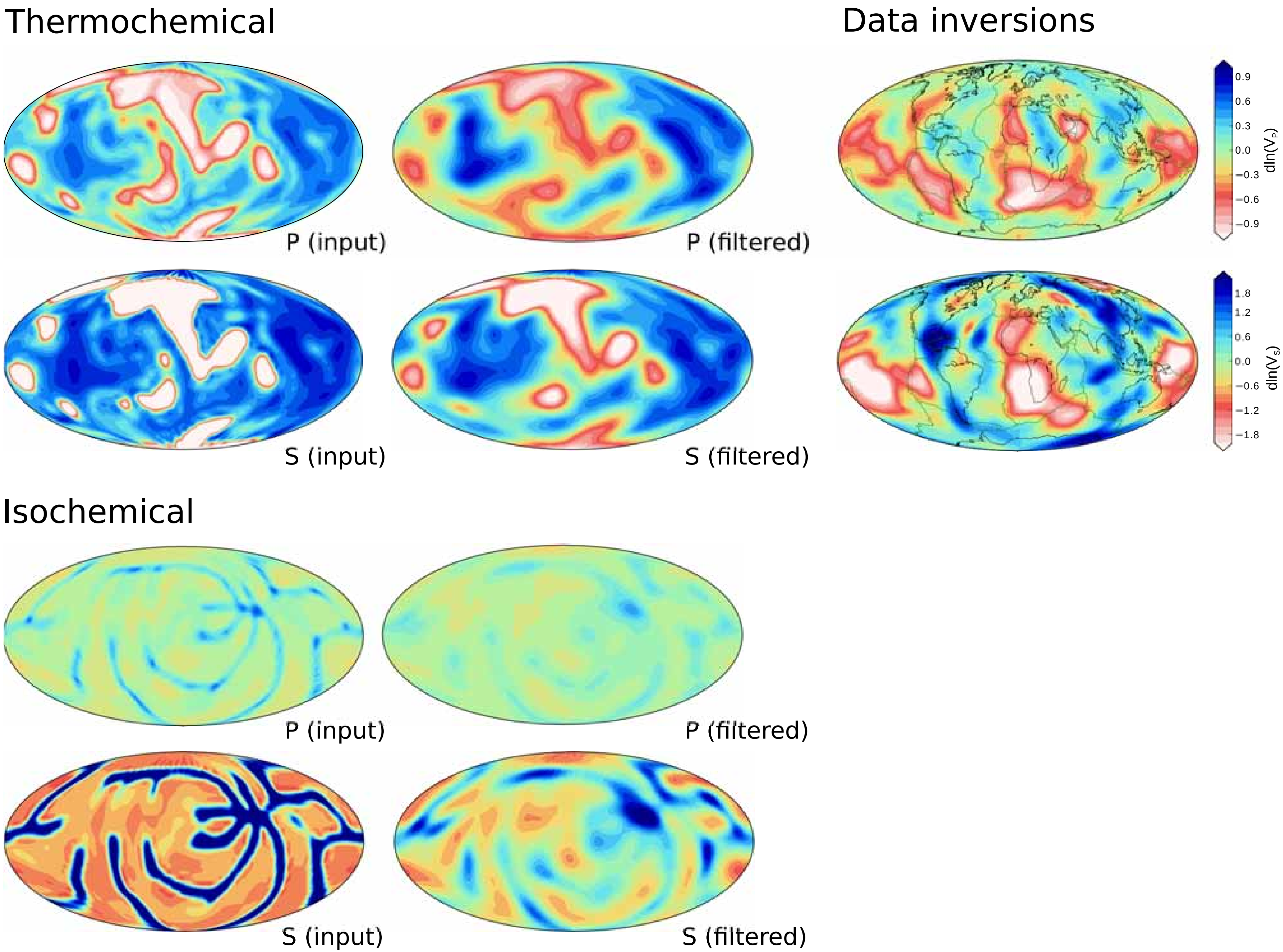


Profiles conclusions

- Piles of basalt still slow in Vs
- pPv introduces anticorrelation Vs:Vb
- Discontinuities may be compositional or phase

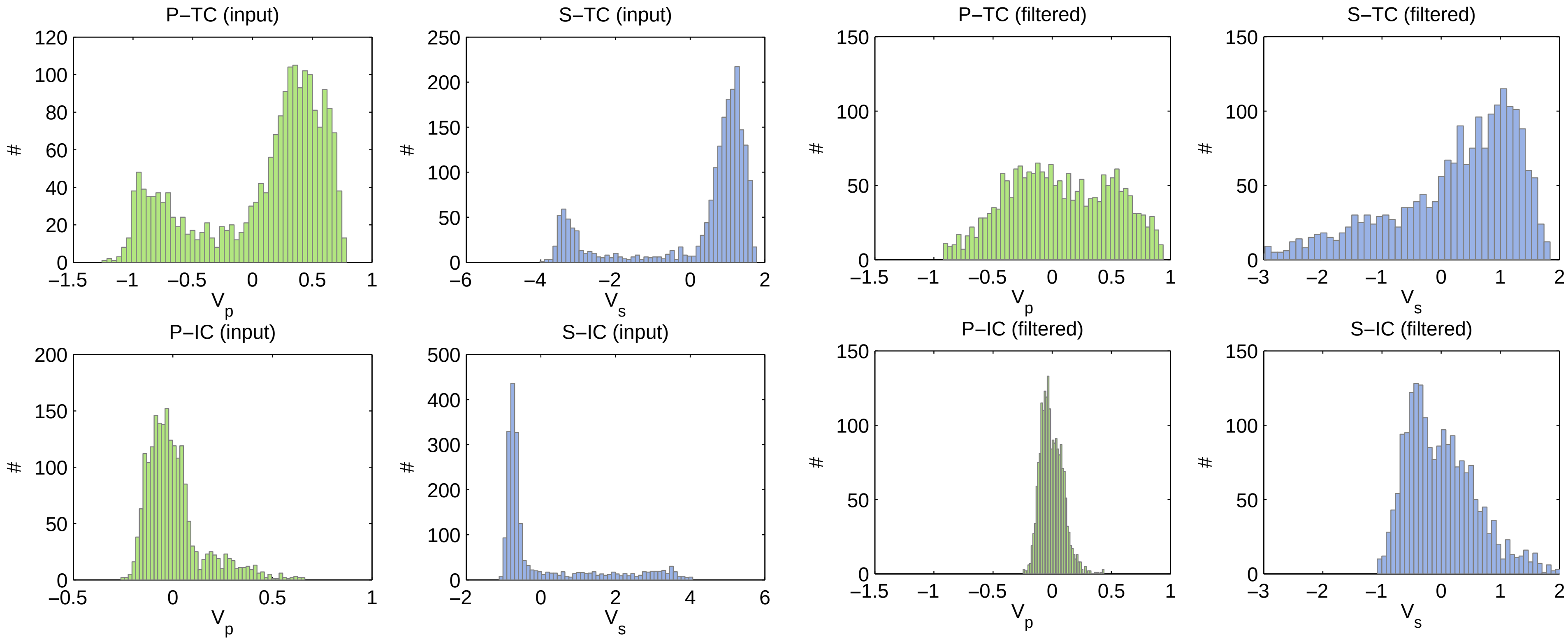
Outline

- Motivation
- Self-consistent treatment of mineralogy
- Mantle thermo-chemical evolution
  - Effect of composition
  - Effect of initial CMB temperature
  - Effect of weak post-perovskite
- Seismic signature
  - Radial profiles in CMB region
  - Synthetic seismic tomography (L. Auer & L. Boschi)


Thermochemical
Data inversions
P (input)
P (filtered)
S (input)
S (filtered)
0.9
0.6
0.3
0.0
−0.3
−0.6
−0.9
dln(V_P)
1.8
1.2
0.6
0.0
−0.6
−1.2
−1.8
dln(V_S)
Isochemical
P (input)
P (filtered)
S (input)
S (filtered)

Histograms at 2750 km

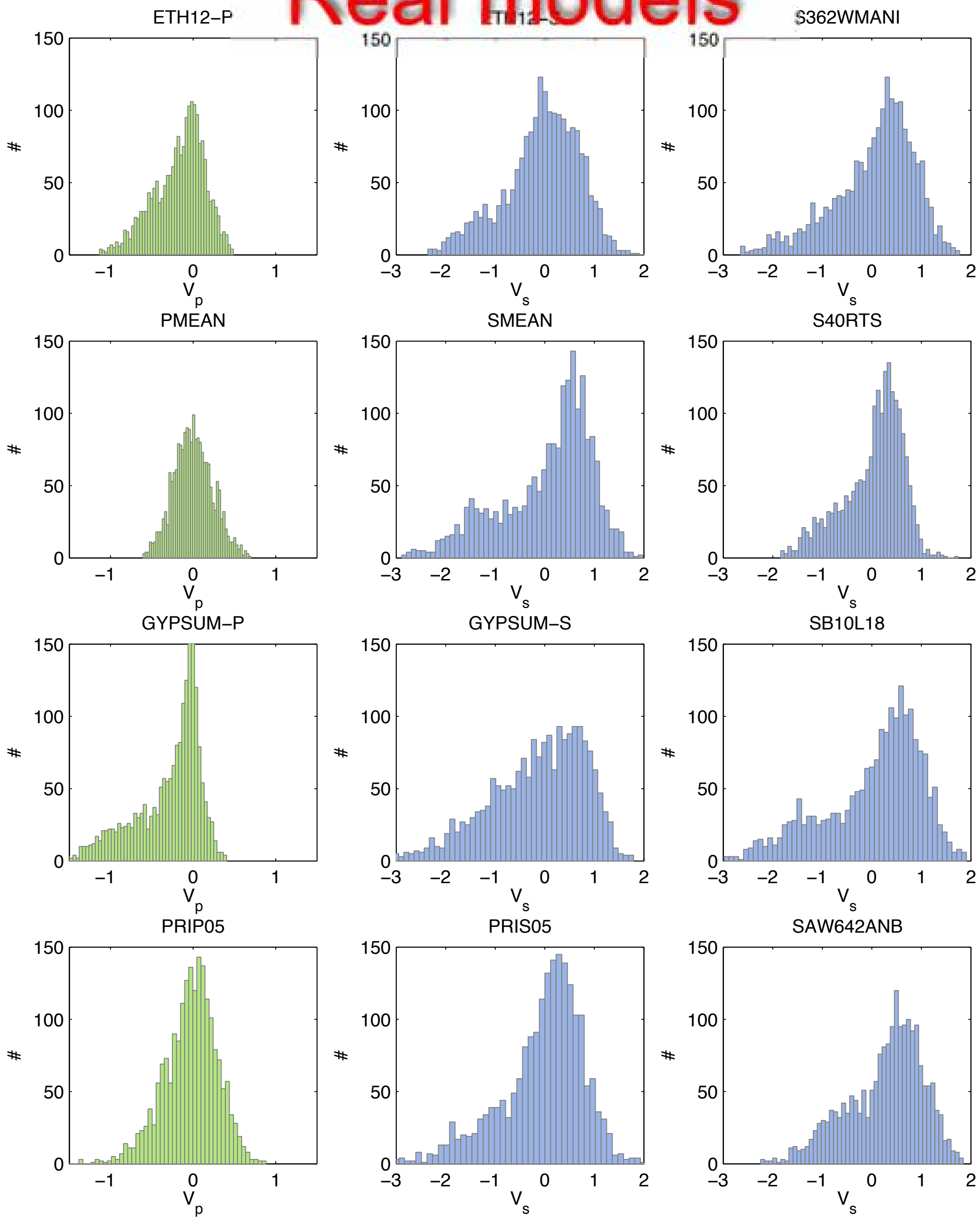
Input / Tomograpic Filtered



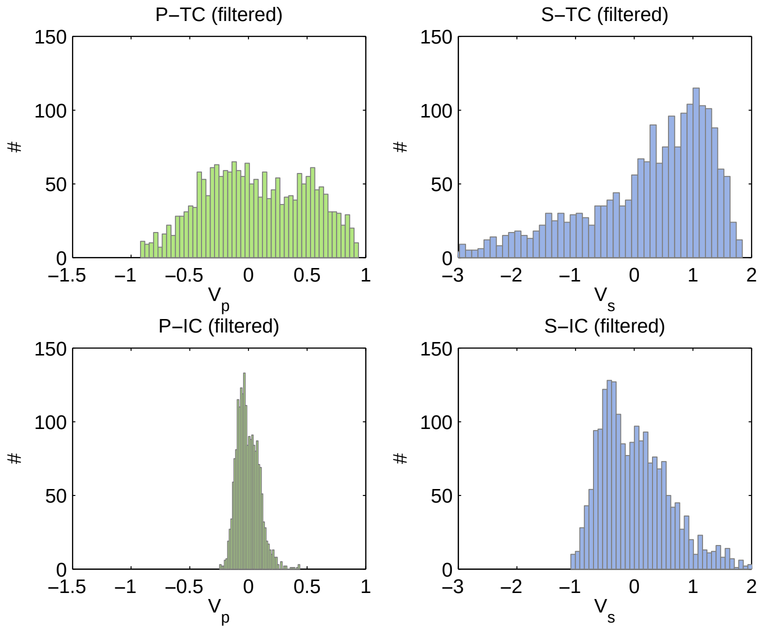
Lose bimodality!

Lose extrema!

Real models

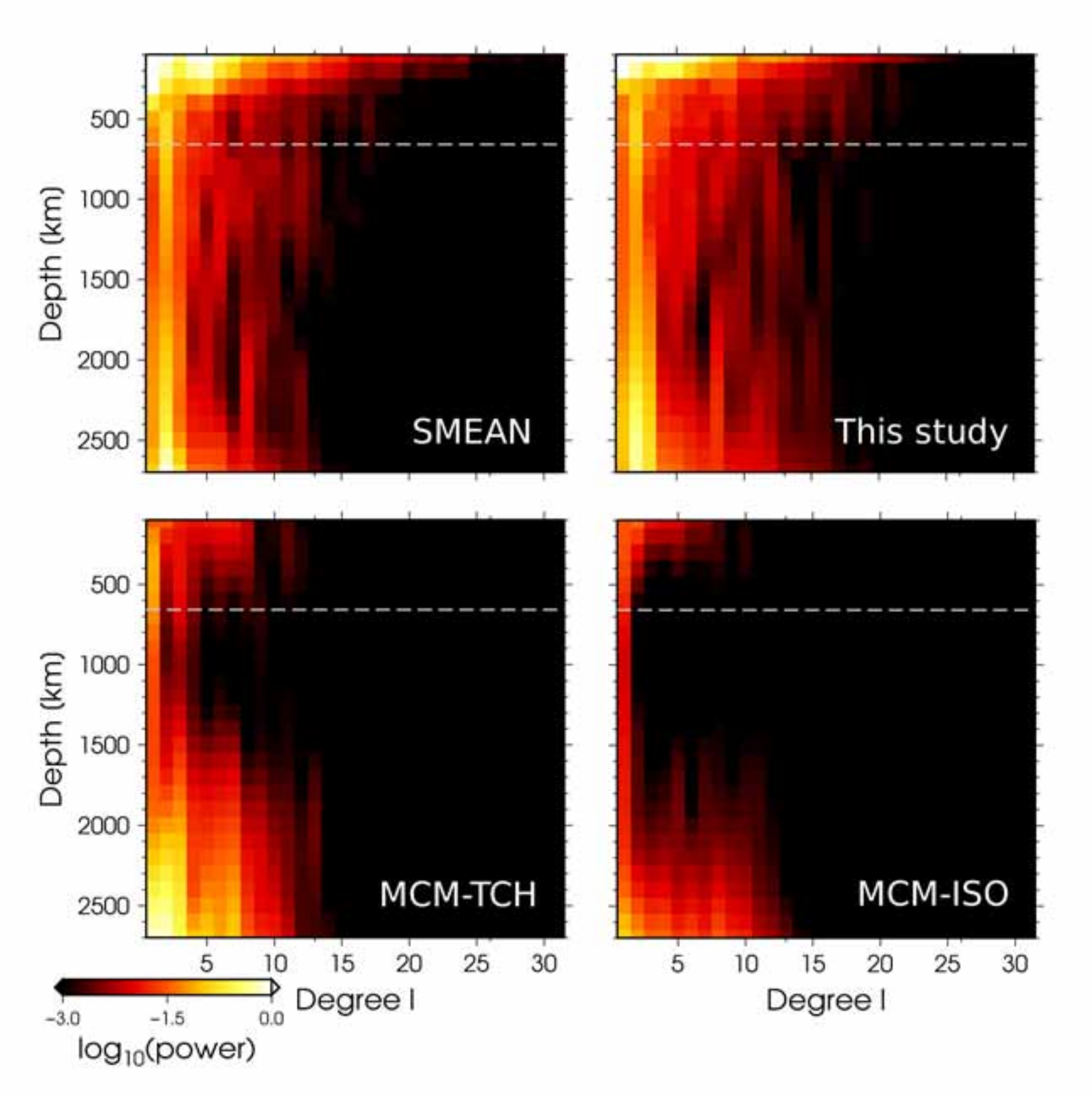


Synthetic model

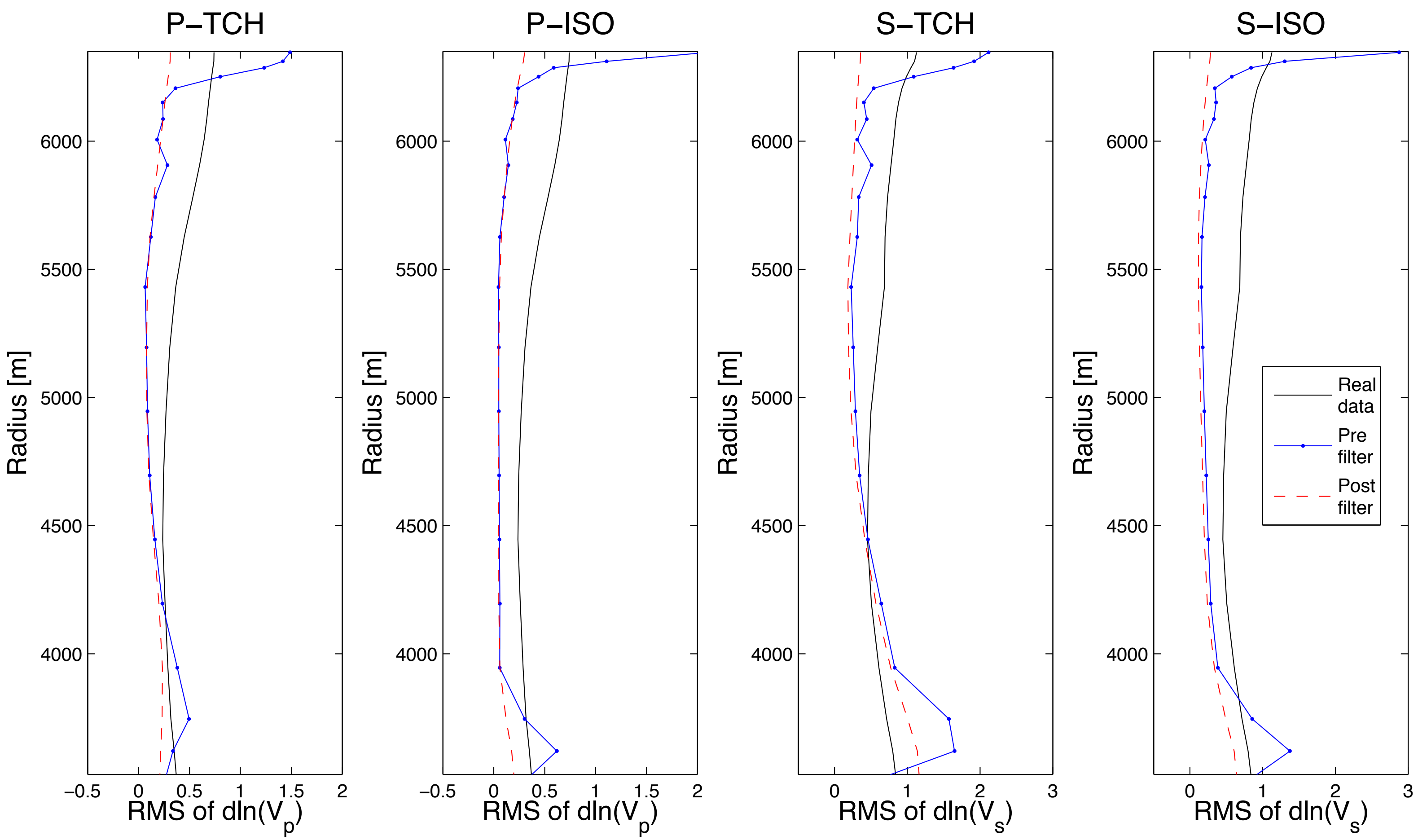


Thermo-Chem model looks more like actual tomography

Spectral heterogeneity maps



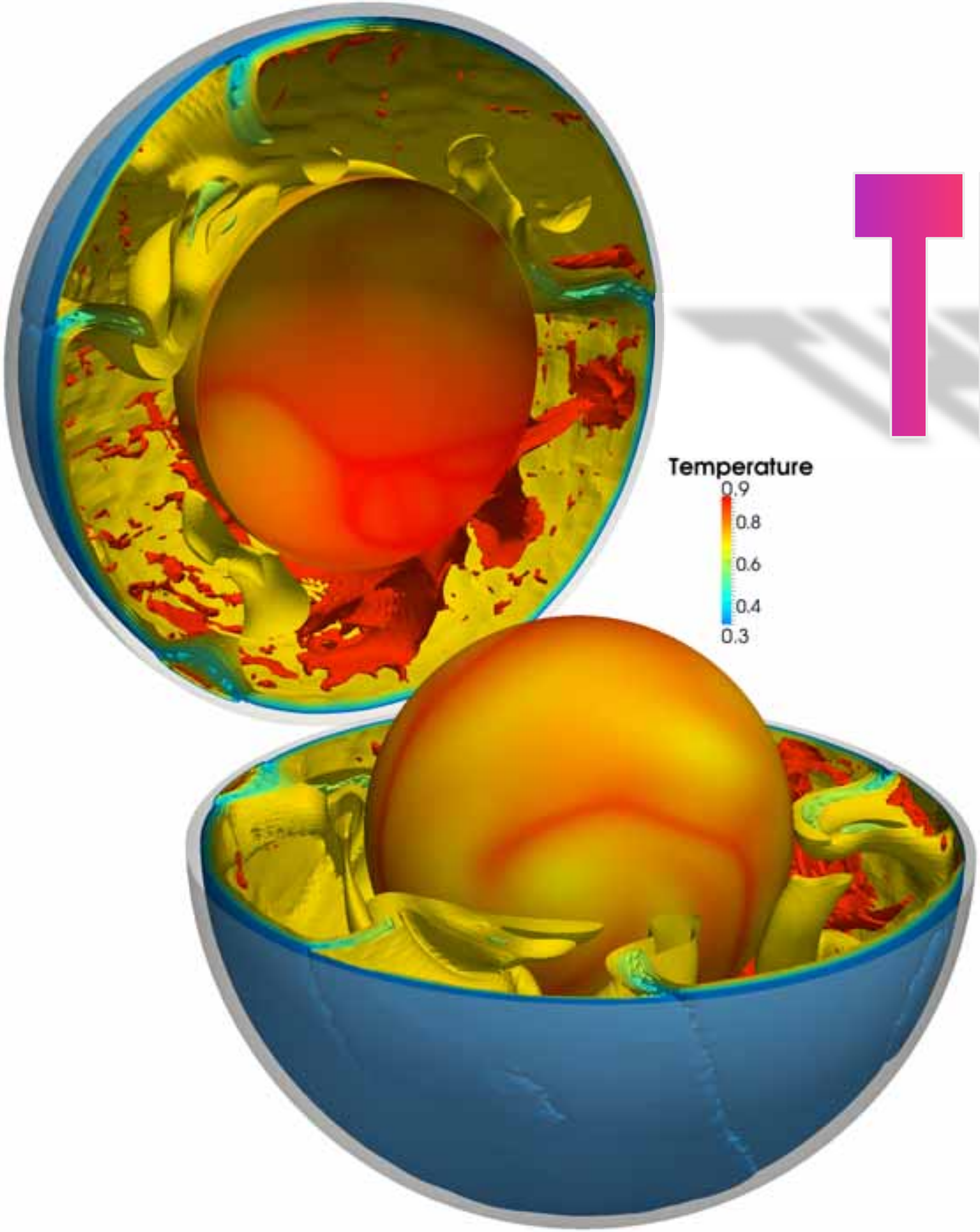
Rms. Heterogeneity (r)



Thermo-chem models closer to real data inversions

Conclusions

- Compositional variations. BAM
- Unimportant:
  - Initial CMB temperature
- Important:
  - Density of MORB
  - Viscosity of post-perovskite
  - Post-perovskite strong seismic heterogeneity
- Seismic
  - discontinuities can be compositional or phase
  - Tomography loses bimodality
  - Tomography can be fit by thermo-chem models



THE END