Plate tectonics and thermo-chemical evolution of the mantle

Paul J. Tackley
+ many coauthors
ETH Zürich, Switzerland

Geophysics of slab dynamics: next summer

Geophysics of
Slab Dynamics

Objectives Program Committee Schedule Travel and Venue Registration Jeju Island Community

Conference Objectives and General Description

Understanding dynamics of subducting slabs is directly relevant to understanding of catastrophic earthquakes and arc-volcanisms which have significantly affected human lives through time.

Conference Schedule

Check in : Aug. 19th 2012
Check out : Aug. 23rd 2012

Jeju Island

http://english.jeju.go.kr

NOTICE more

- website is open

NEWS more

- news board

http://slab.snu.ac.kr/

Plan

a) Plate tectonics

b) Thermo-chemical mantle evolution

   a) Observations & hypotheses
   b) Primordial layering
   c) Dynamical layering (recycled crust)
   d) Implications

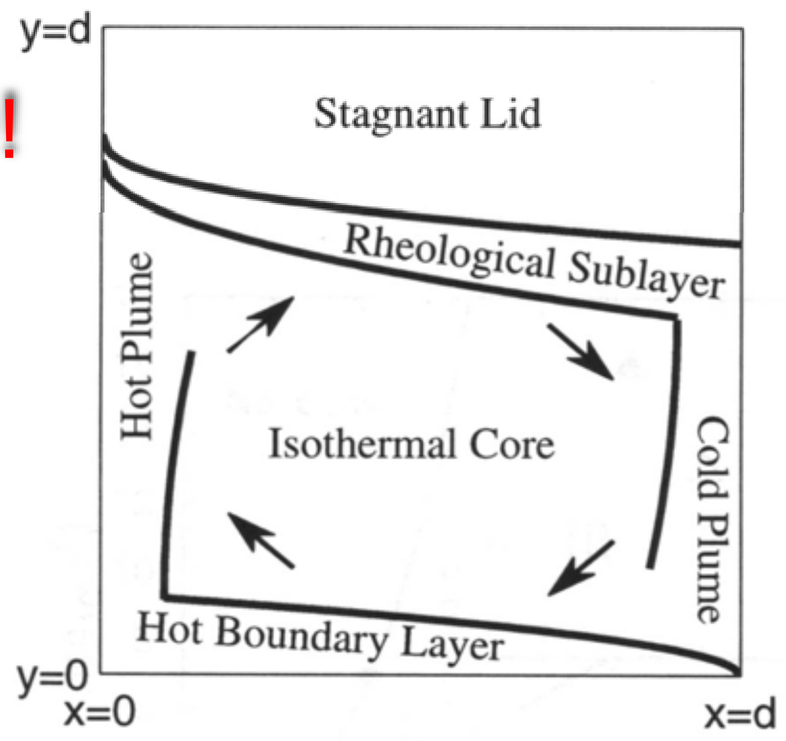
Plate tectonics: Earth unusual ?

- Mars: rigid lid
  - Had plate tectonics early?
- Venus: rigid lid
  - Plate tectonics->rigid lid?
  - Episodic overturn?
- Earth: Different early on?

The plate problem

- Viscous, T-dependent rheology appropriate for the mantle leads to a stagnant lid
- exp(E/kT) where E~340 kJ/mol
- T from 1600 -> 300 K
- =>**1.3x10^{48}** variation
- => RIGID/STAGNANT LID!

Only small ΔT participates in convection: enough to give Δη factor ~10



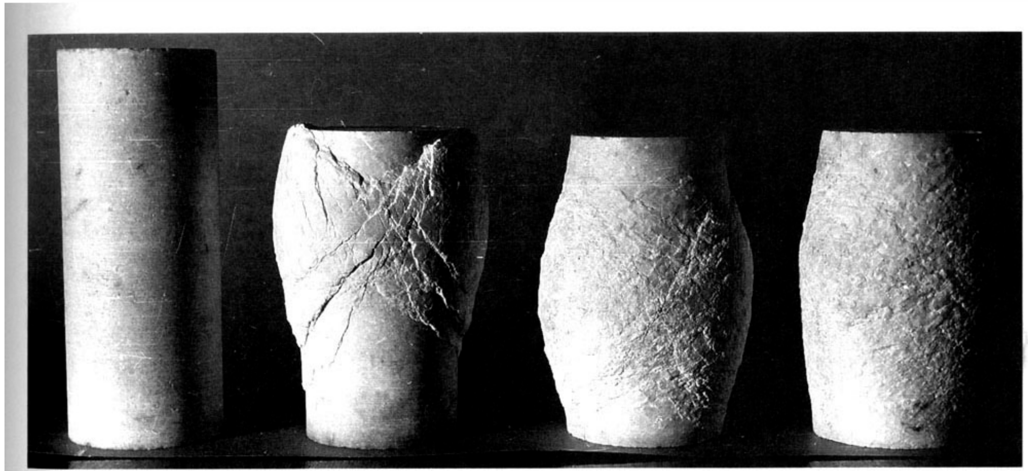
We don’t understand plate tectonics at a fundamental level

- Rock deformation is complex
  - Viscous, brittle, plastic, elastic, nonlinear
  - Dependent on grain size, composition (major and trace element, eg water)
- Multi-scale
  - Lengthscales from mm to 1000s km
  - Timescales from seconds - Gyr

Strength of rocks

- Increases with confining pressure (depth) then saturates

Low-T deformation: Effect of P



Undeformed | Low confining pressure | Intermediate confining pressure | High confining pressure

Low T: Effect of P

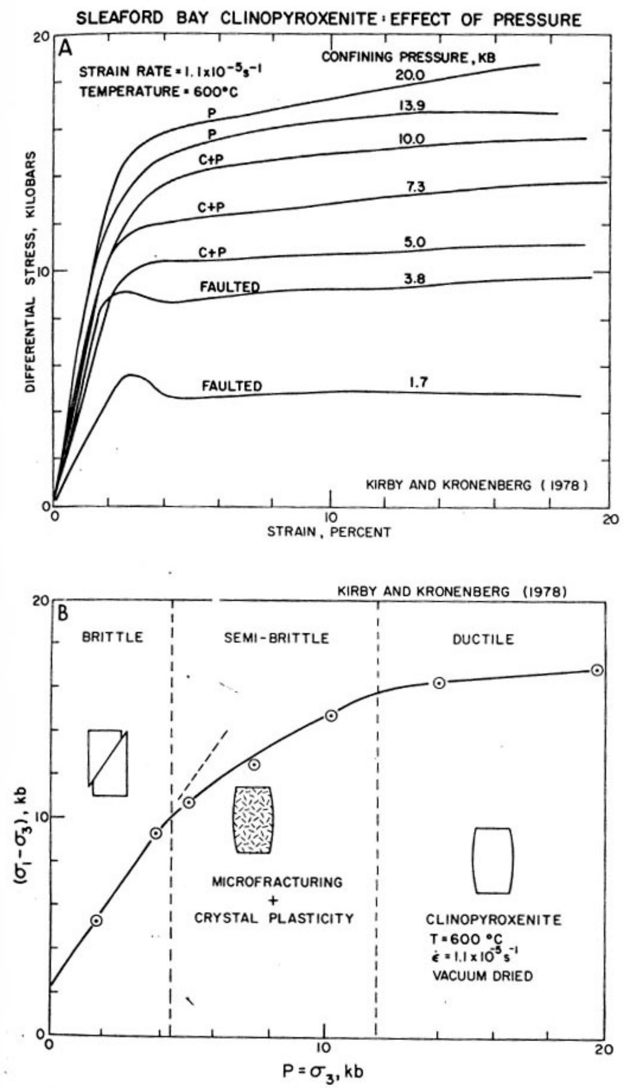
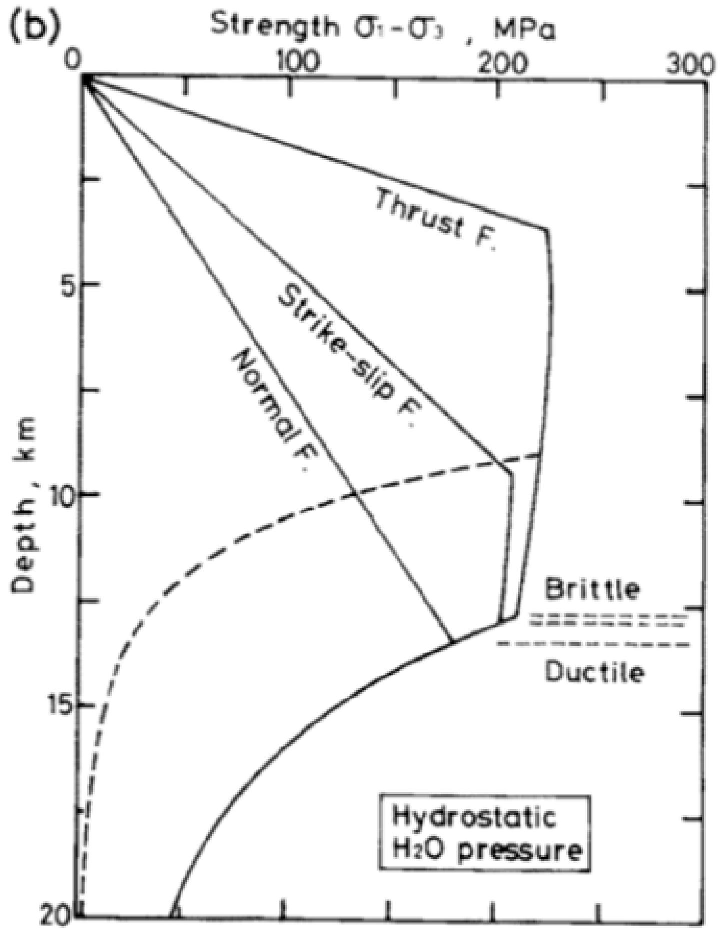


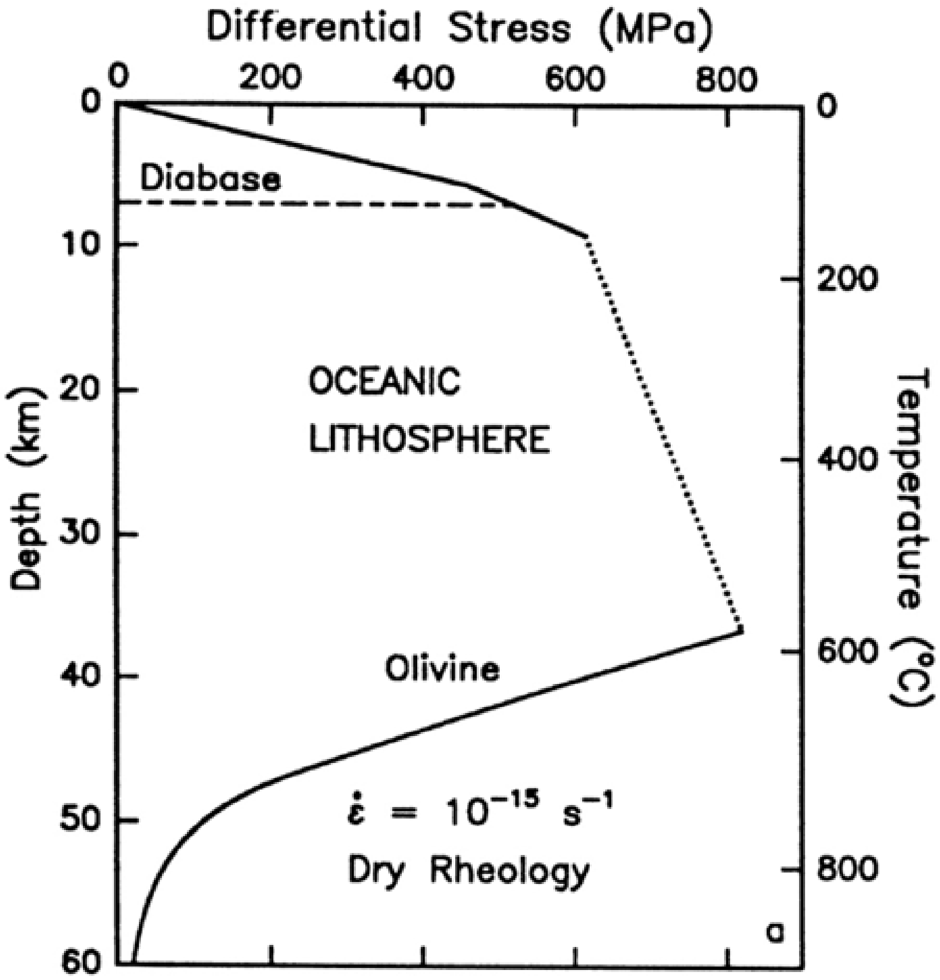
Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): *(a)* stress-strain curves, *(b)* ultimate strength or stress at 10% strain as a function of confining pressure.

Strength profile of lithosphere

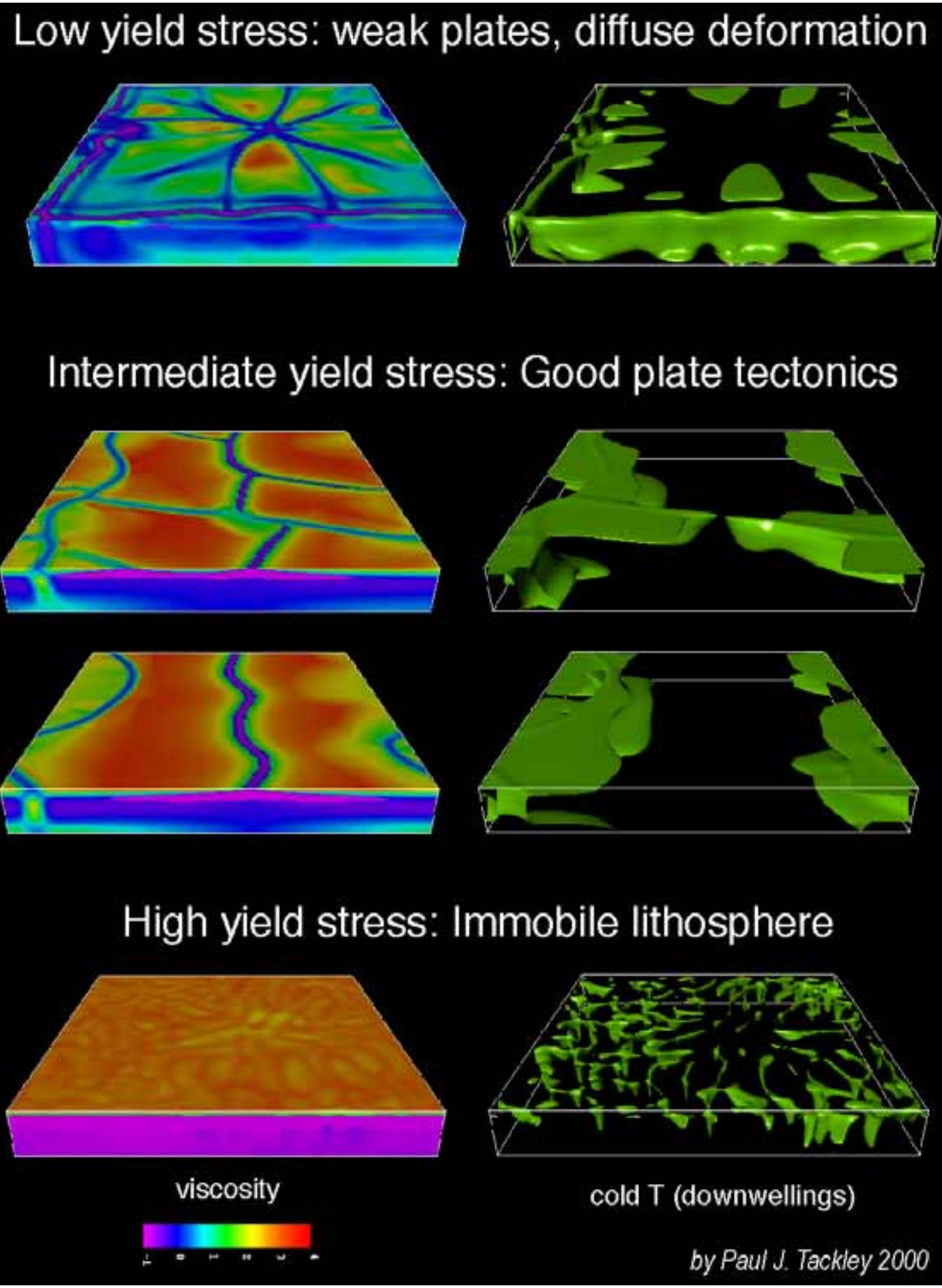
Continental (granite): Shimada 1993



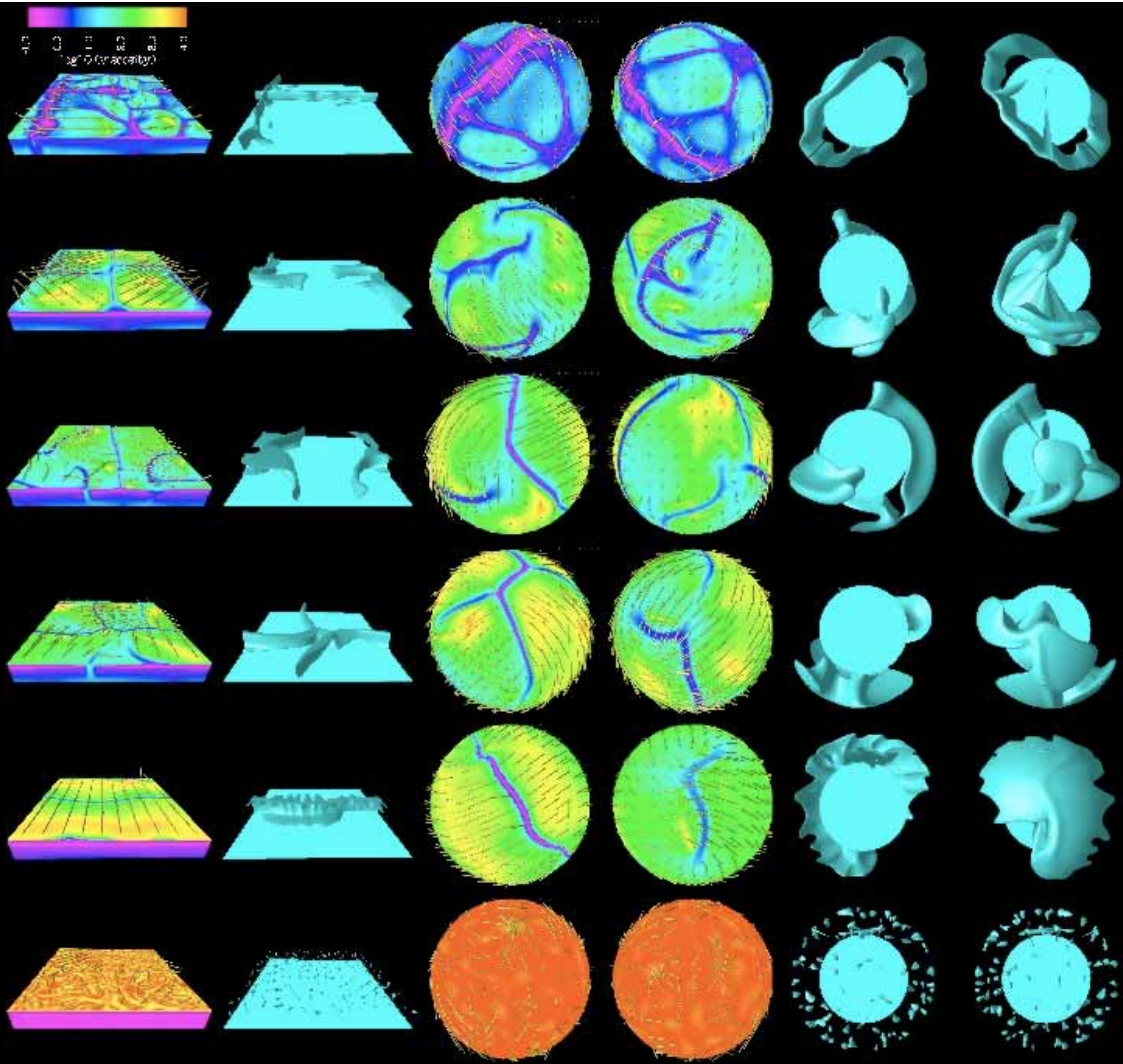
Oceanic: Kohlstedt 1995



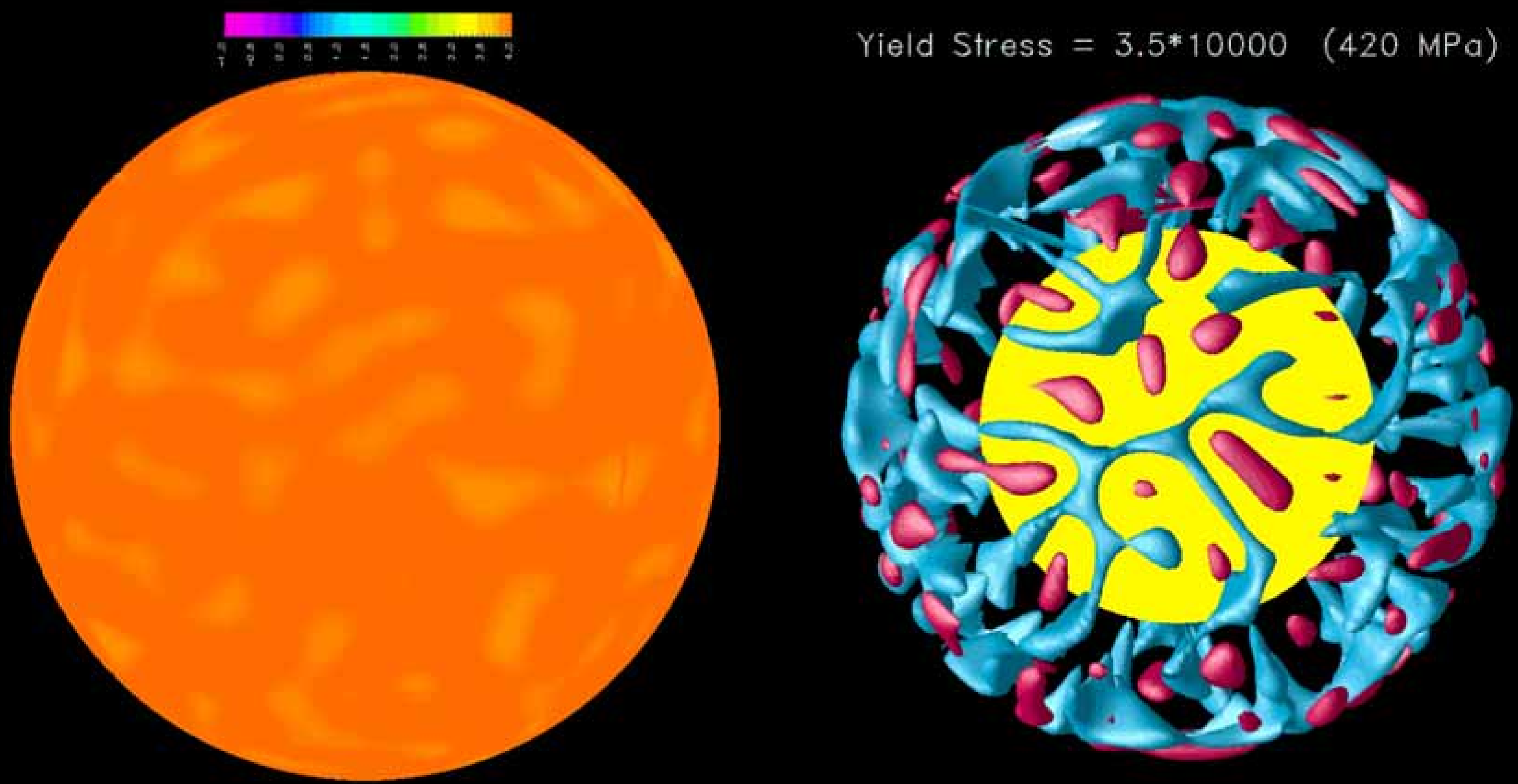
- Varying yield strength, including asthenosph.



Spherical: van Heck & me, GRL 2008

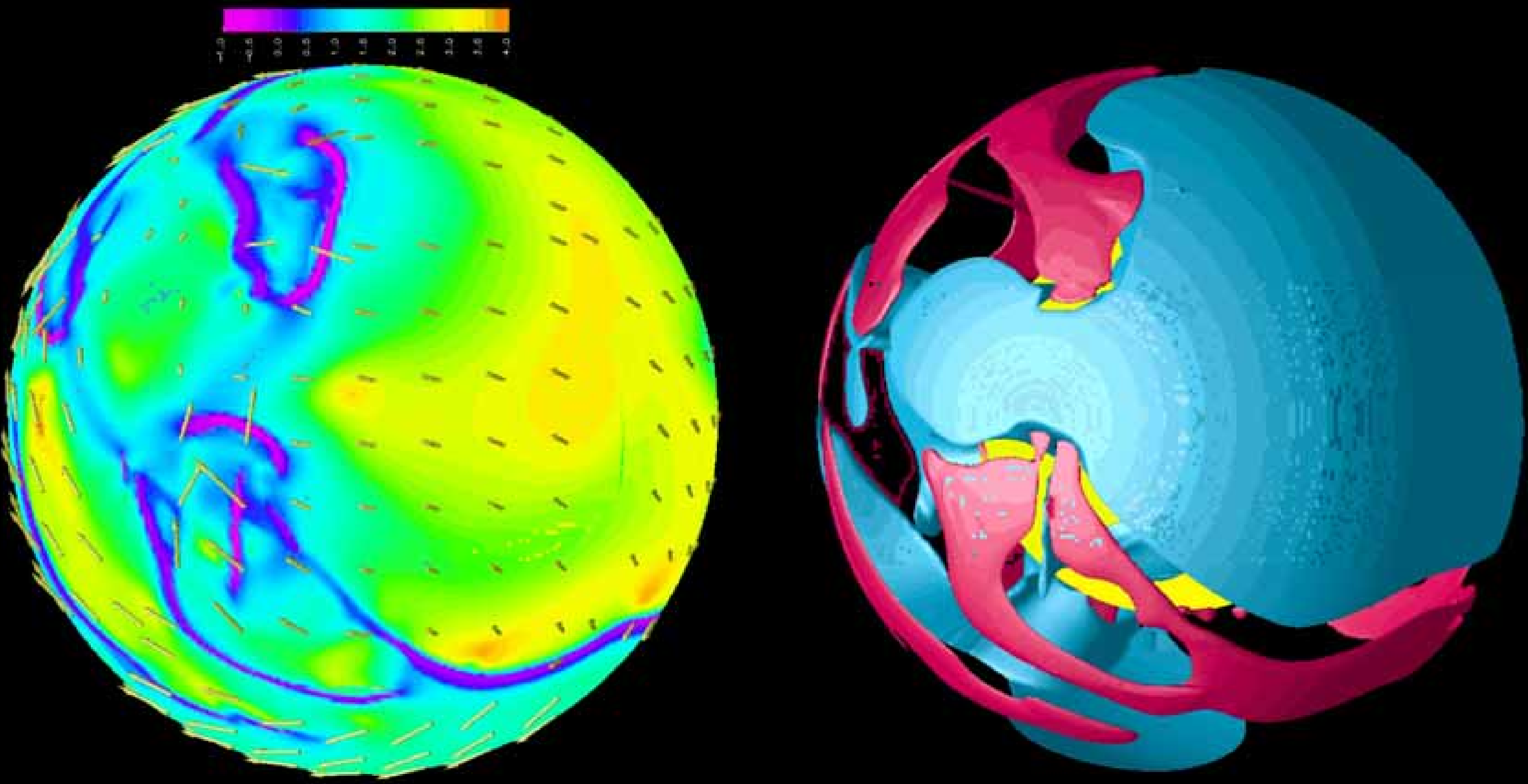


Stagnant lid mode



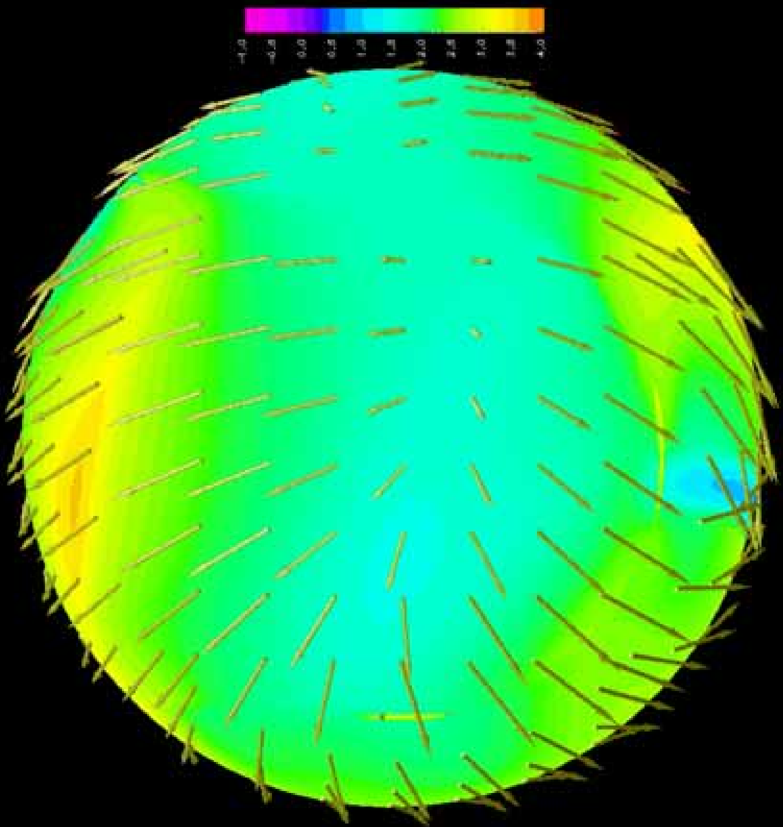
H. Van Heck

Mobile lid mode



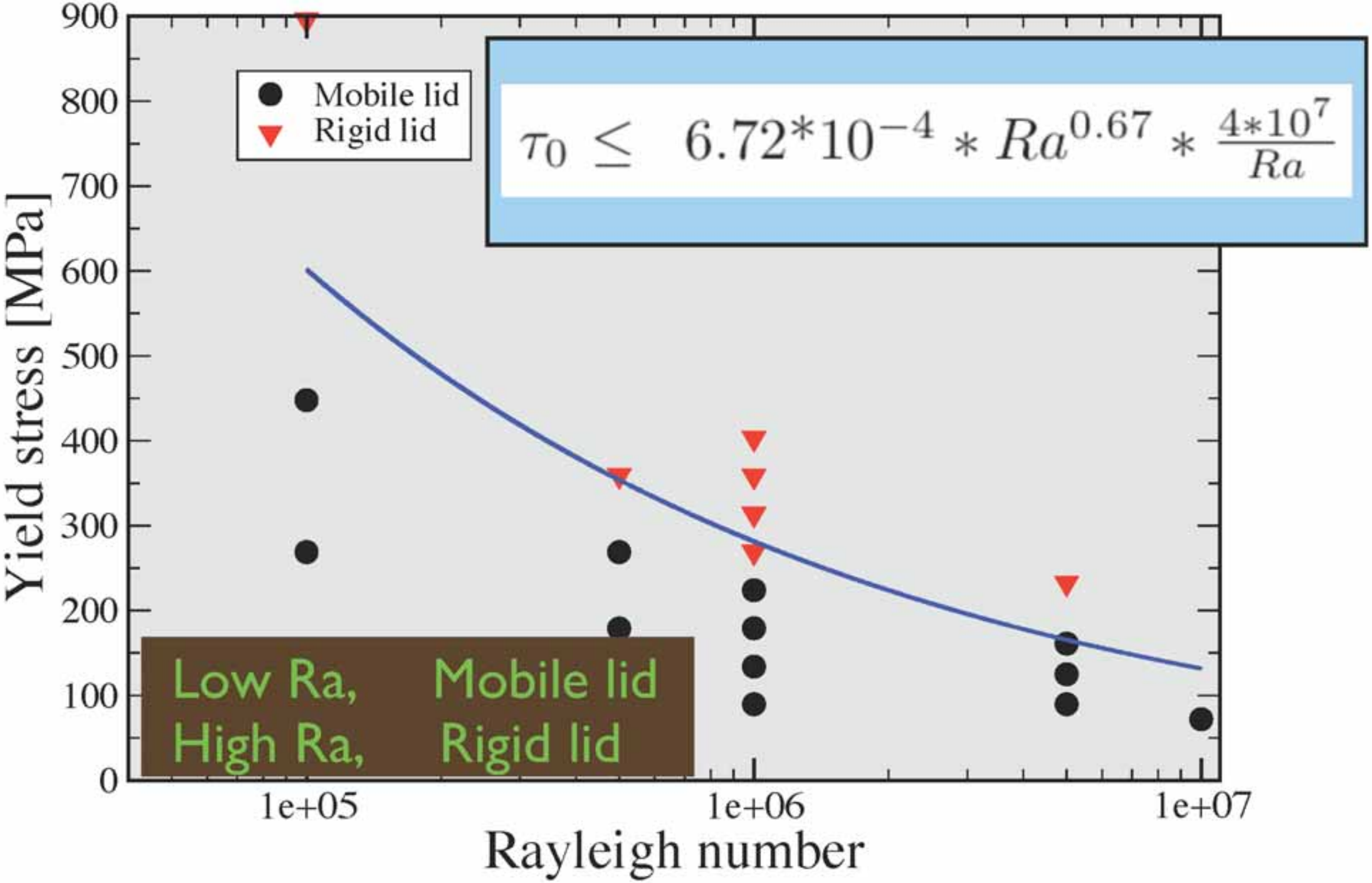
H. Van Heck

Mobile lid mode



H. Van Heck

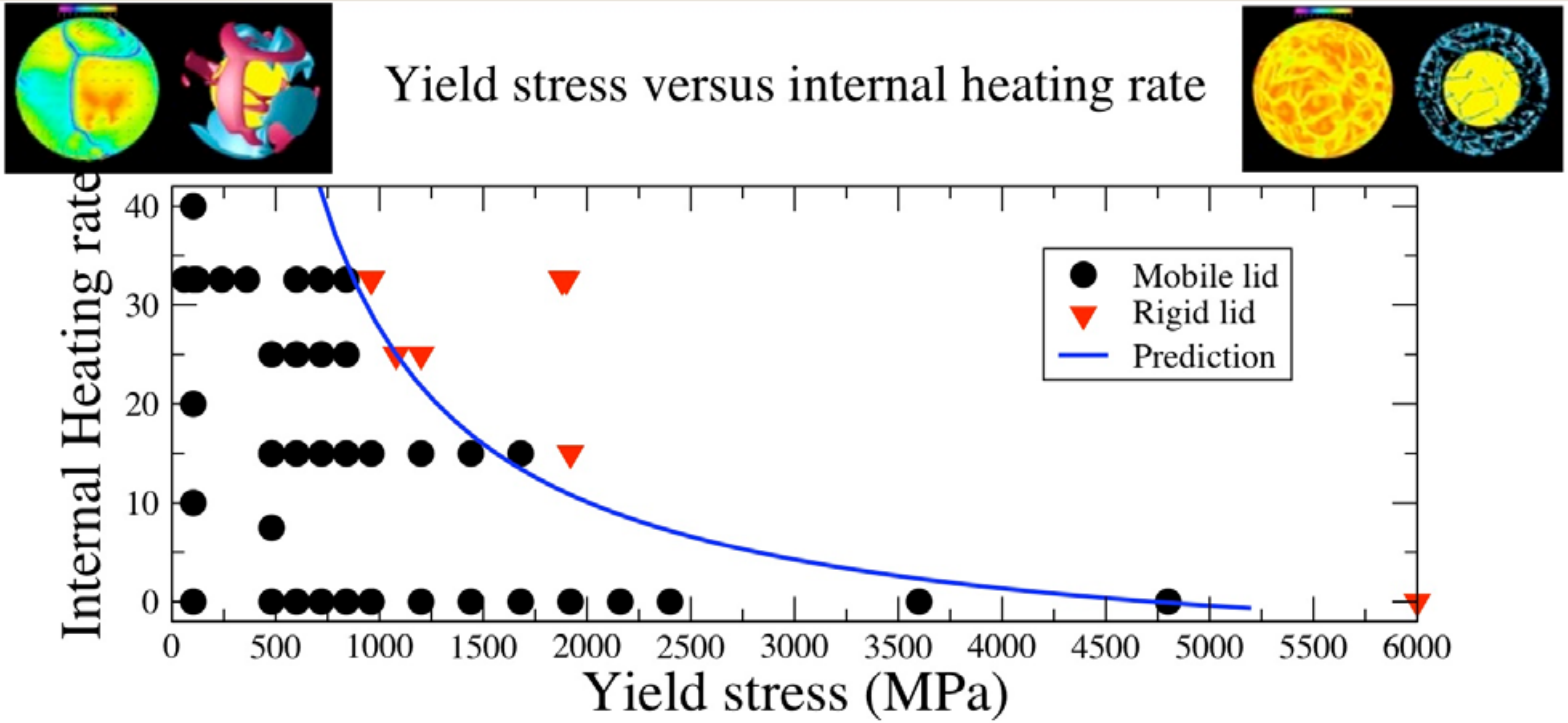
Rayleigh number versus yield stress



H. van Heck & Tackley

Internal heating rate

Strength of the lithosphere vs convective stresses



H. van Heck & Tackley

Implications for terrestrial planet evolution

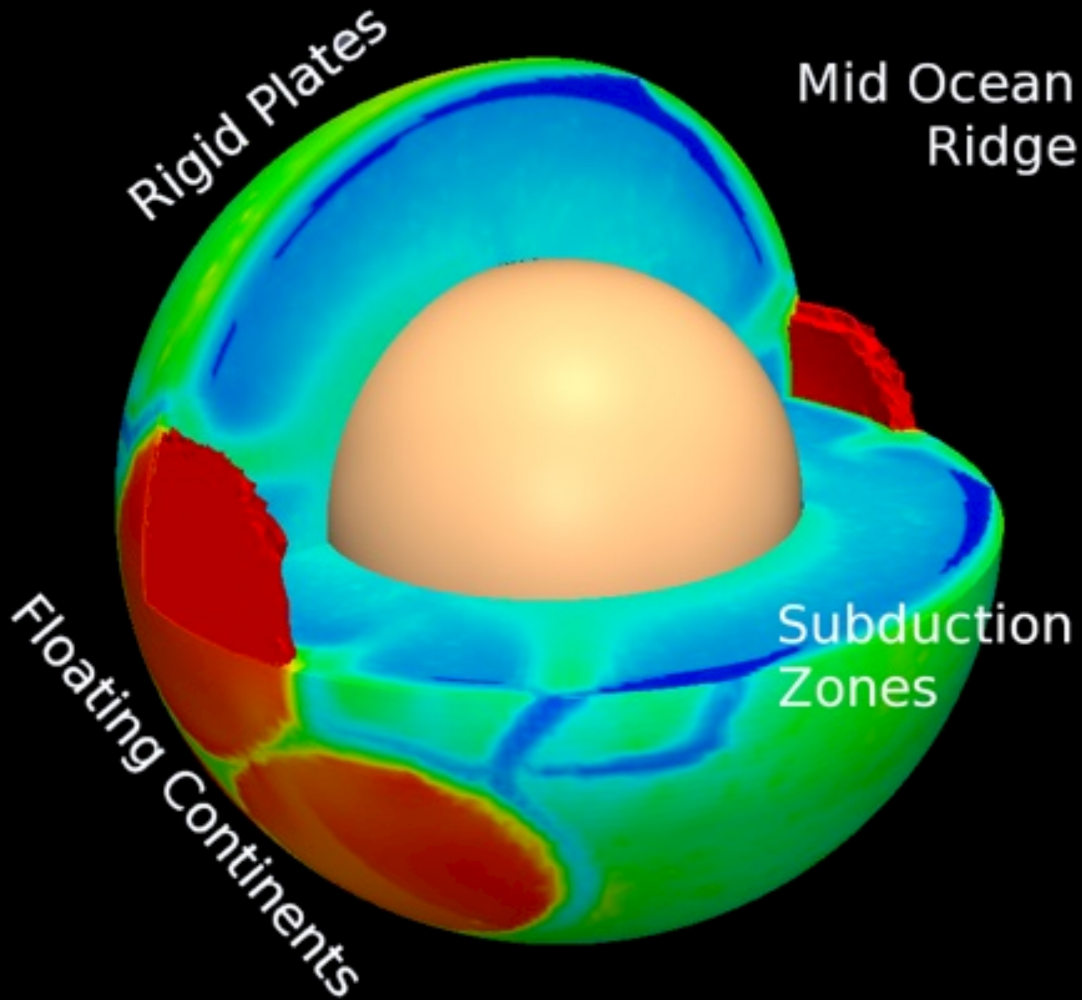
- Plate tectonics favoured at
  - higher mantle viscosity (lower Ra)
  - Lower internal heating
- Transitions stagnant->episodic->plates as Earth cooled?

Dynamics of extrasolar Super-Earths?

- A few Super-Earths (1-10 * mass of Earth) have been found; many more expected.
  Do we expect them to have plate tectonics?
- Extending our previous study of self-consistent plate tectonics to study this question, using a joint analytic – numerical approach: (van Heck & Tackley 2011)
- **Super-Earths are equally-likely or more likely to have plate tectonics than Earth, other things being equal**

Influence of continents on self-consistent plate tectonics?

Tobias Rolf

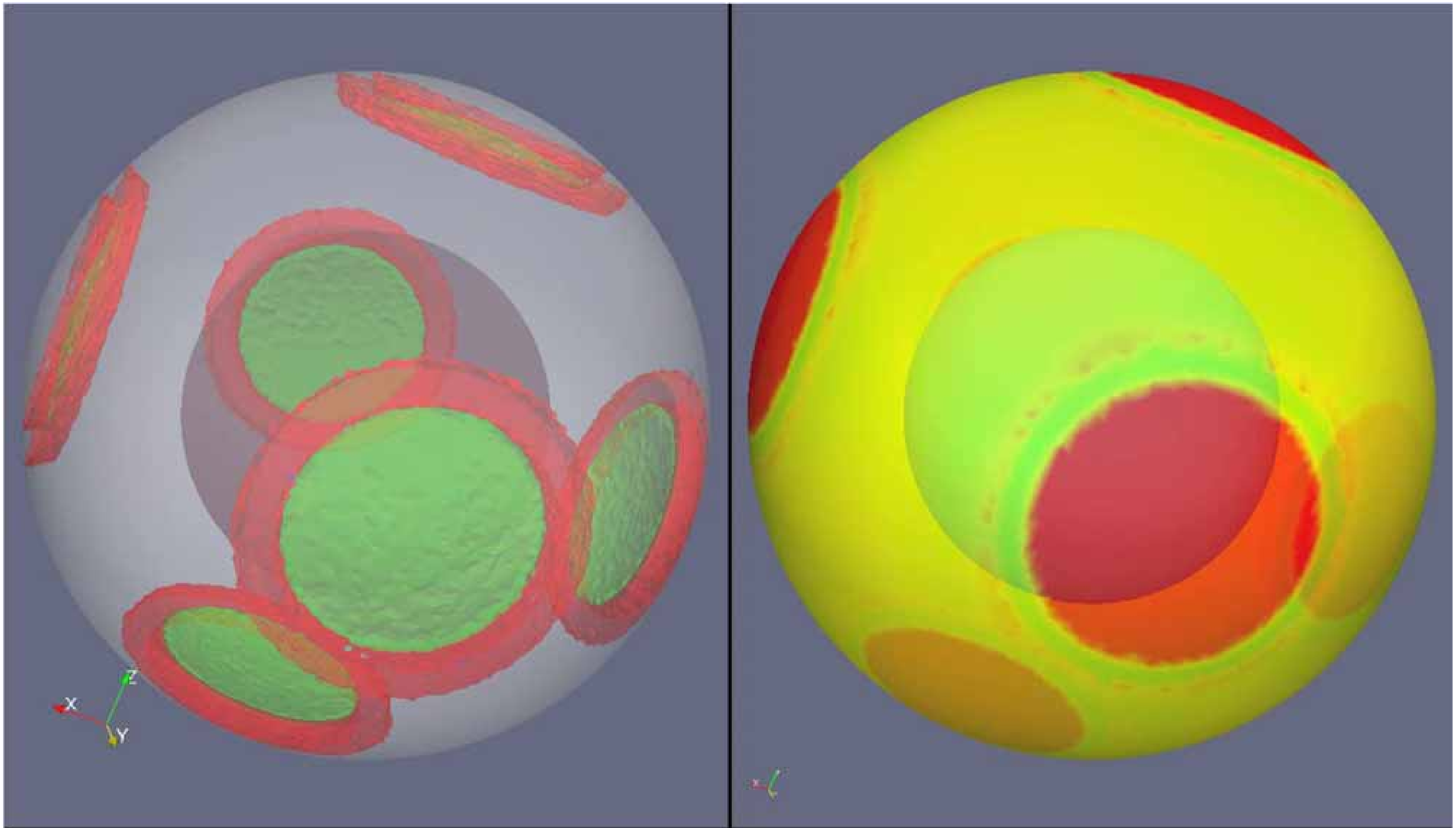


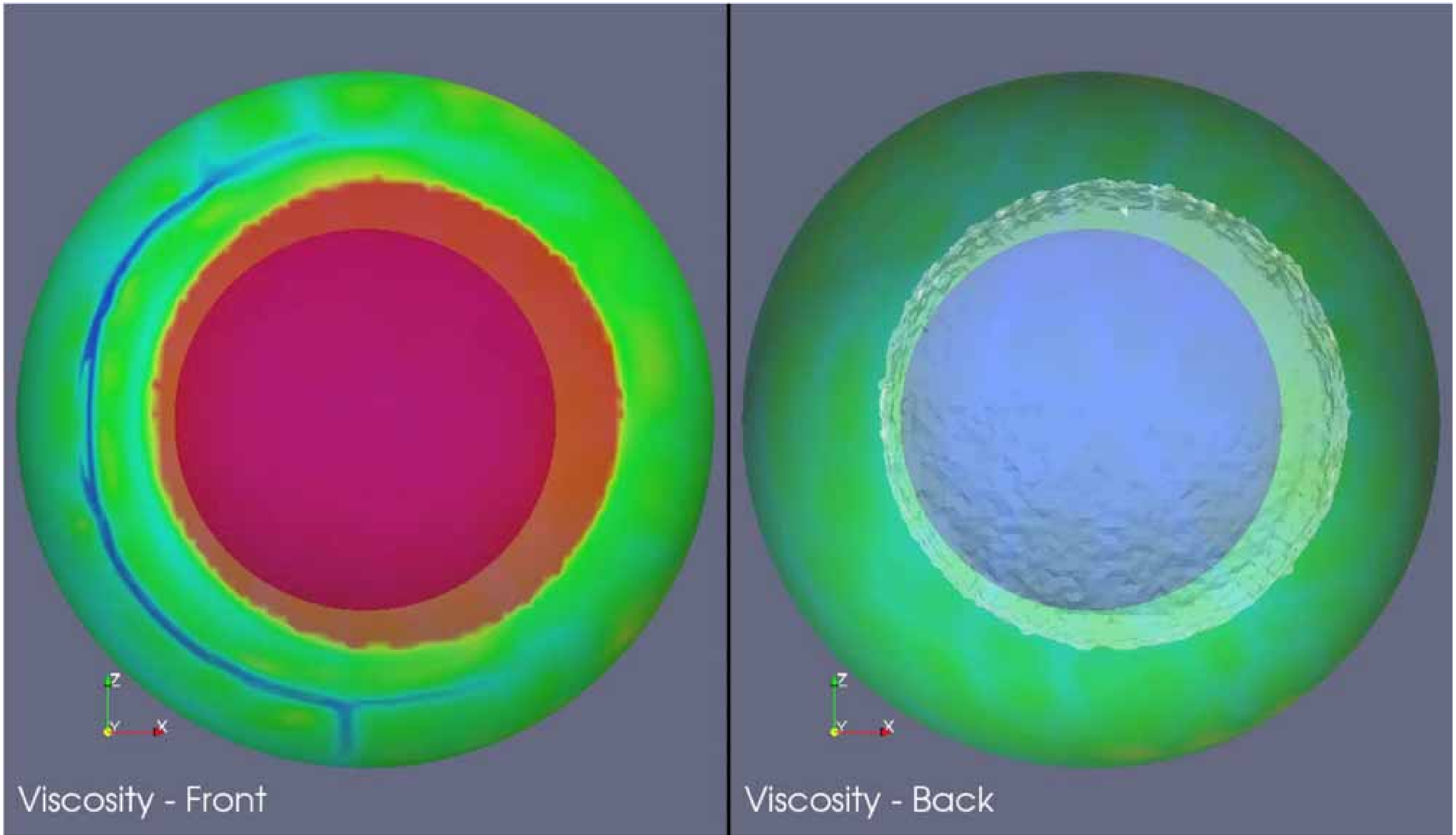
CRYSTAL2PLATE

CRYSTAL2PLATE
How does plate tectonics work:
From crystal-scale processes to mantle convection with self-consistent plates

MARIE CURIE ACTIONS

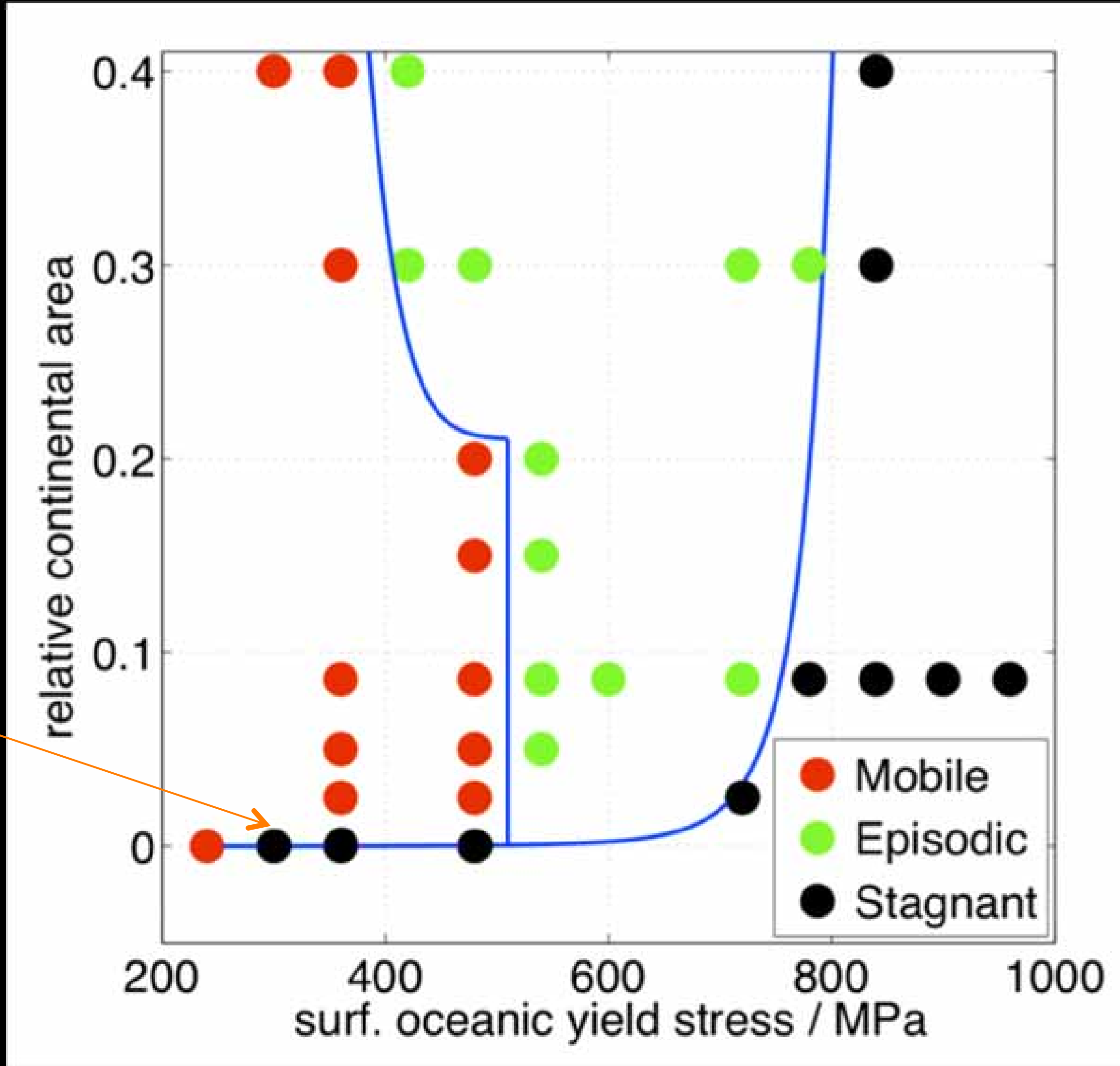
SEVENTH FRAMEWORK PROGRAMME


X
Z
Y

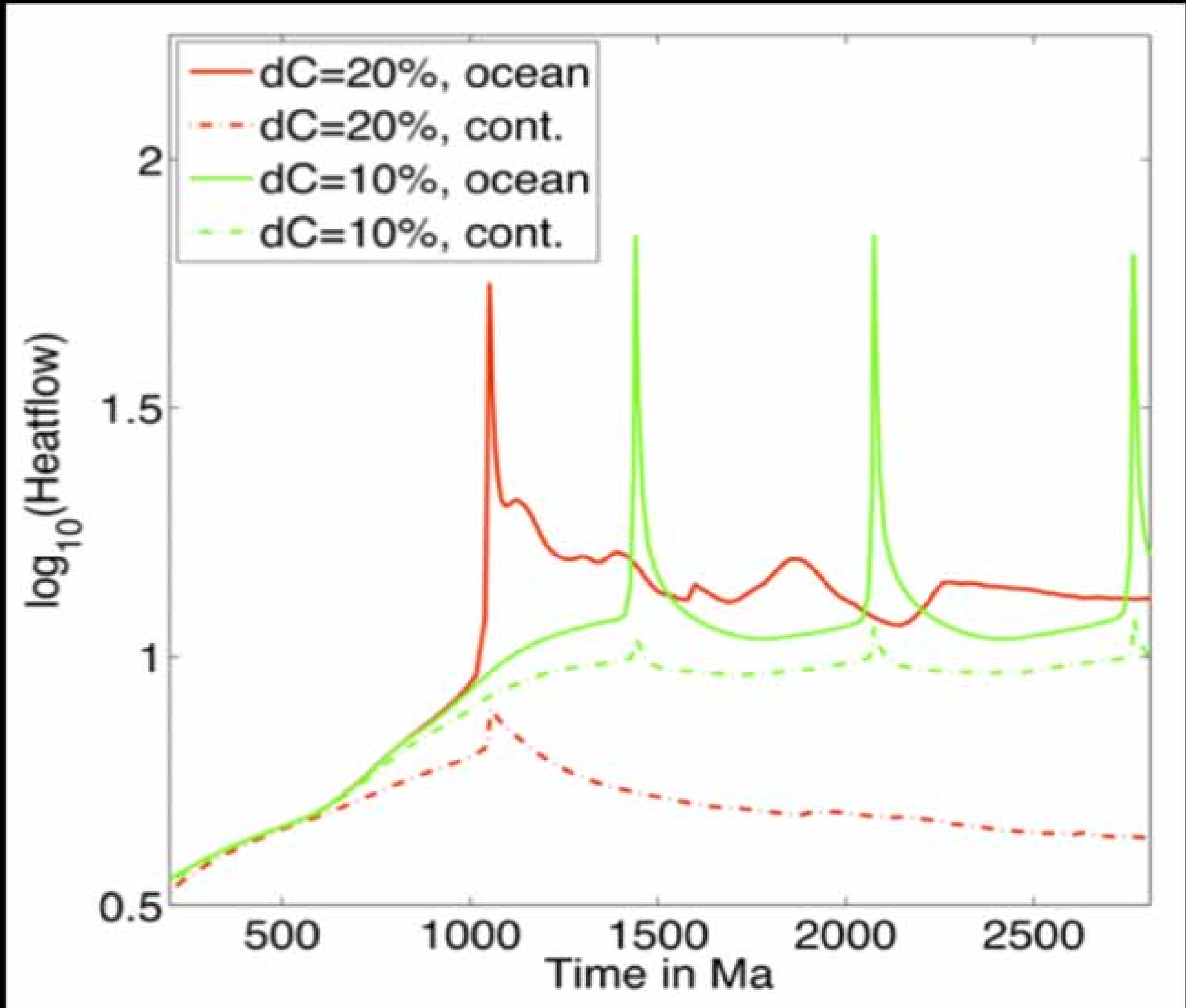

Z
Y
X
Viscosity - Front
Z
Y
X
Viscosity - Back

Continents help plate tectonics!

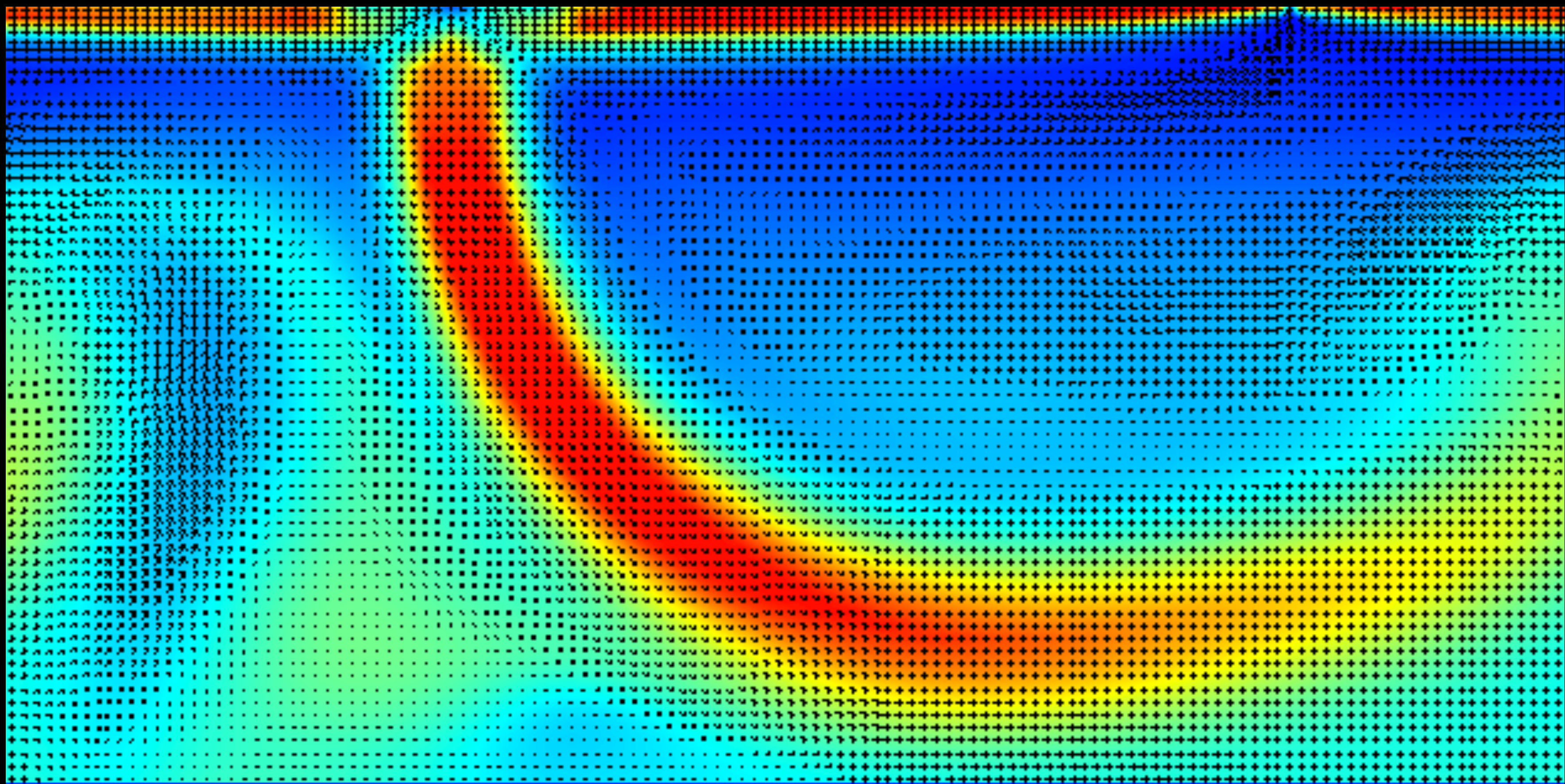
Presence of continent allows plate tectonics at higher yield stress



Partitioning of heat flux continents:oceans



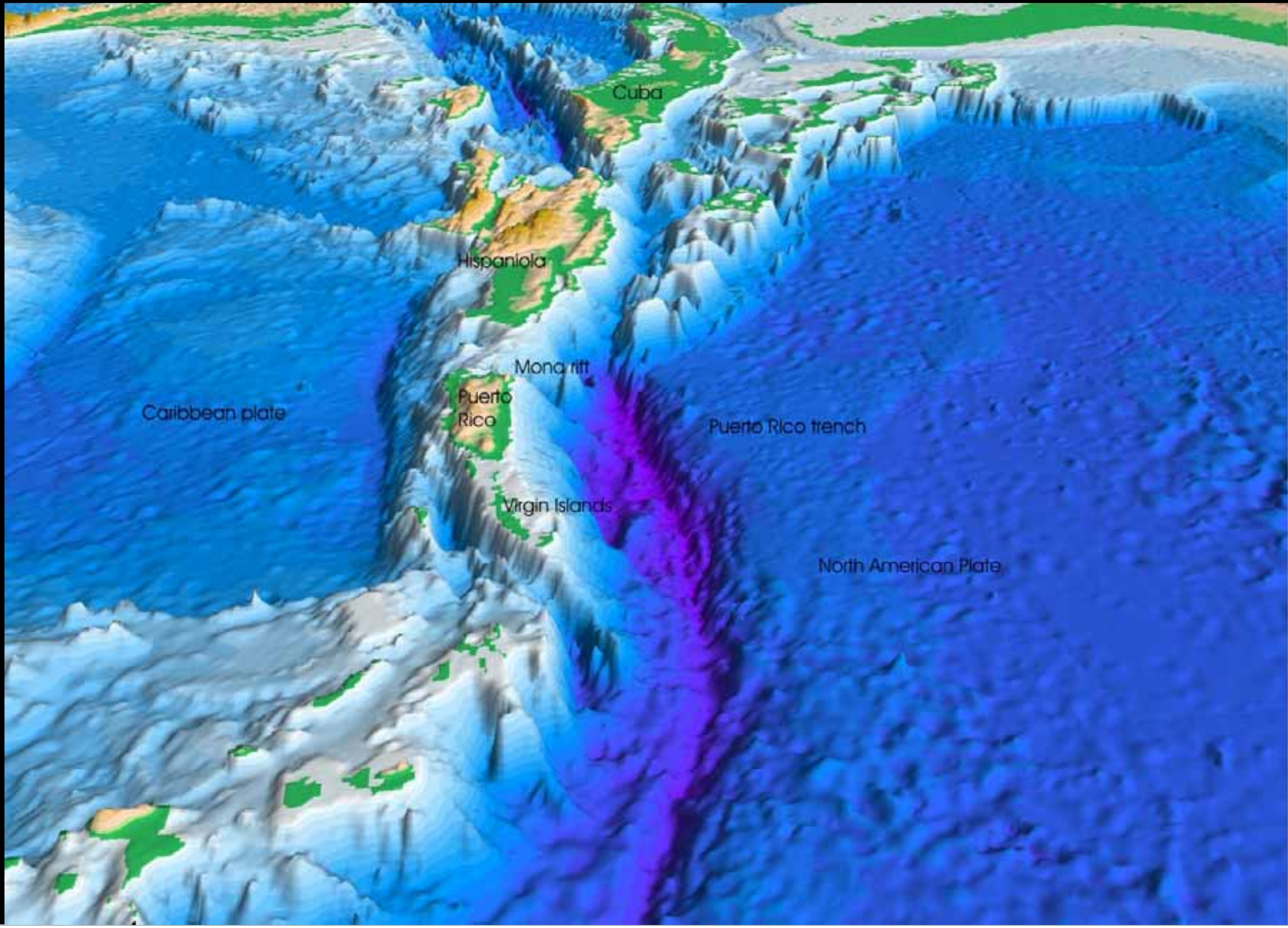
A problem: 2-sided subduction!



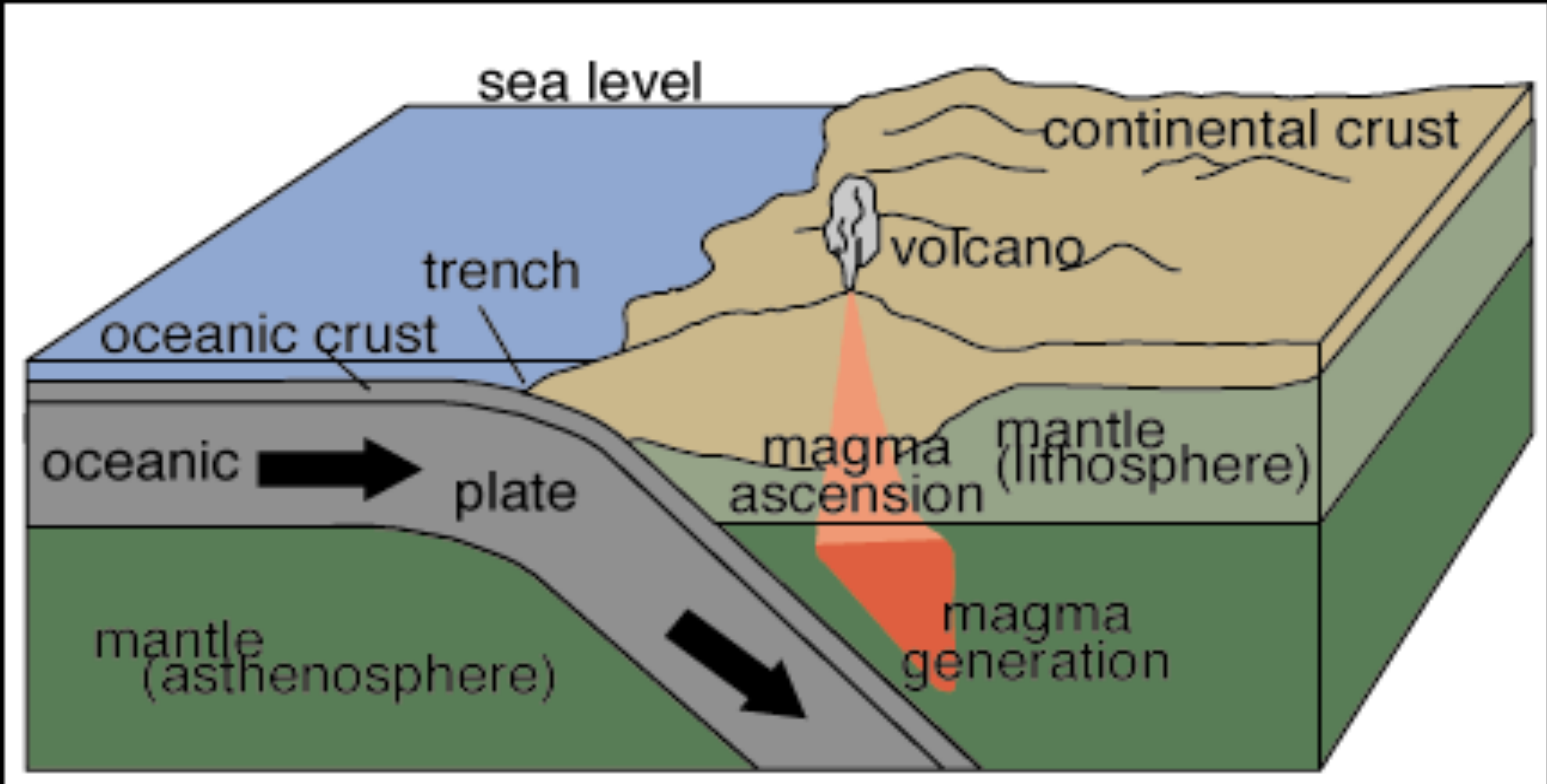
Mantle convection codes assume a free-slip upper boundary: surface is FLAT

- Zero shear stress but finite normal stress, proportional to what the topography would be if allowed.
- But this may create unnatural geometries at subduction zones….

Real subduction zone: NOT FLAT



Trench due to bending



Numerical models with a free surface: also get a trench

Physics of the Earth and Planetary Interiors 171 (2008) 198–223

A benchmark comparison of spontaneous subduction models—Towards a free surface

H. Schmeling[a,*], A.Y. Babeyko[a,b], A. Enns[a], C. Faccenna[c], F. Funiciello[c], T. Gerya[d], G.J. Golabek[a,d], S. Grigull[a,e], B.J.P. Kaus[d,g], G. Morra[c,d], S.M. Schmalholz[f], J. van Hunen[h]

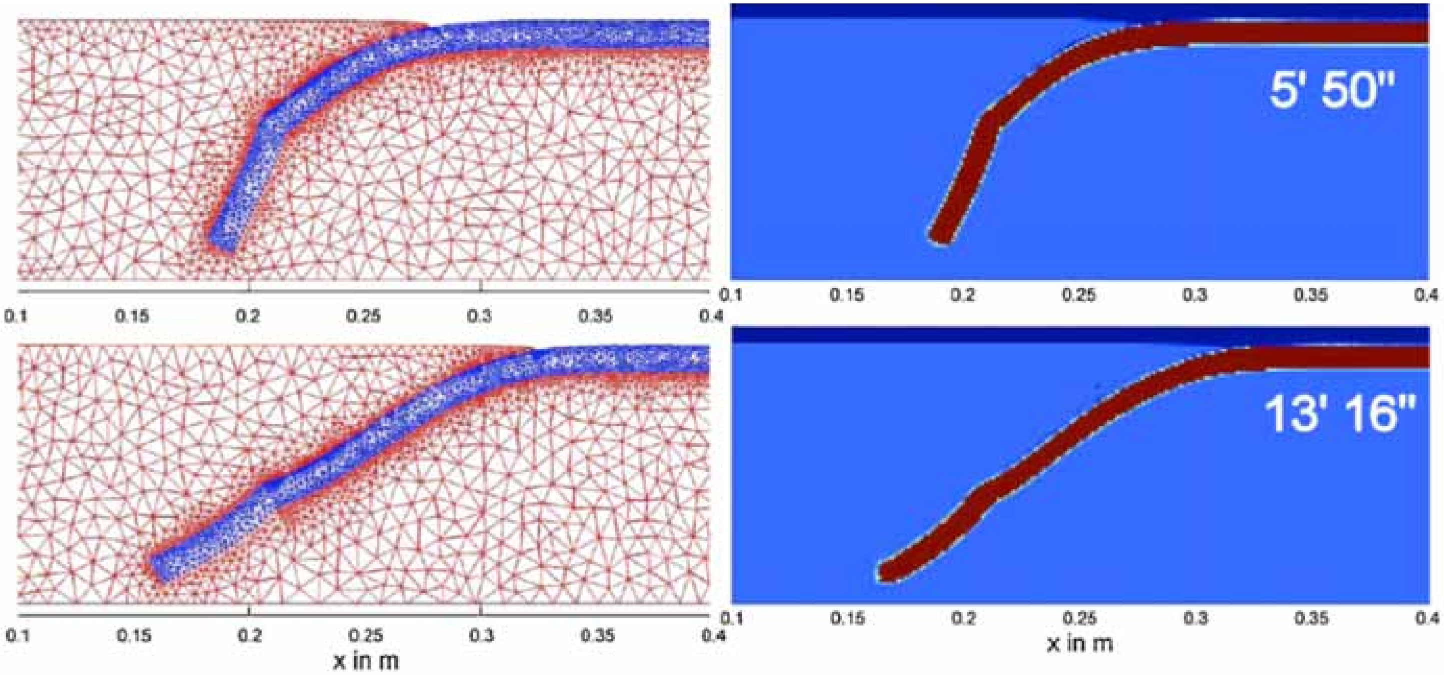


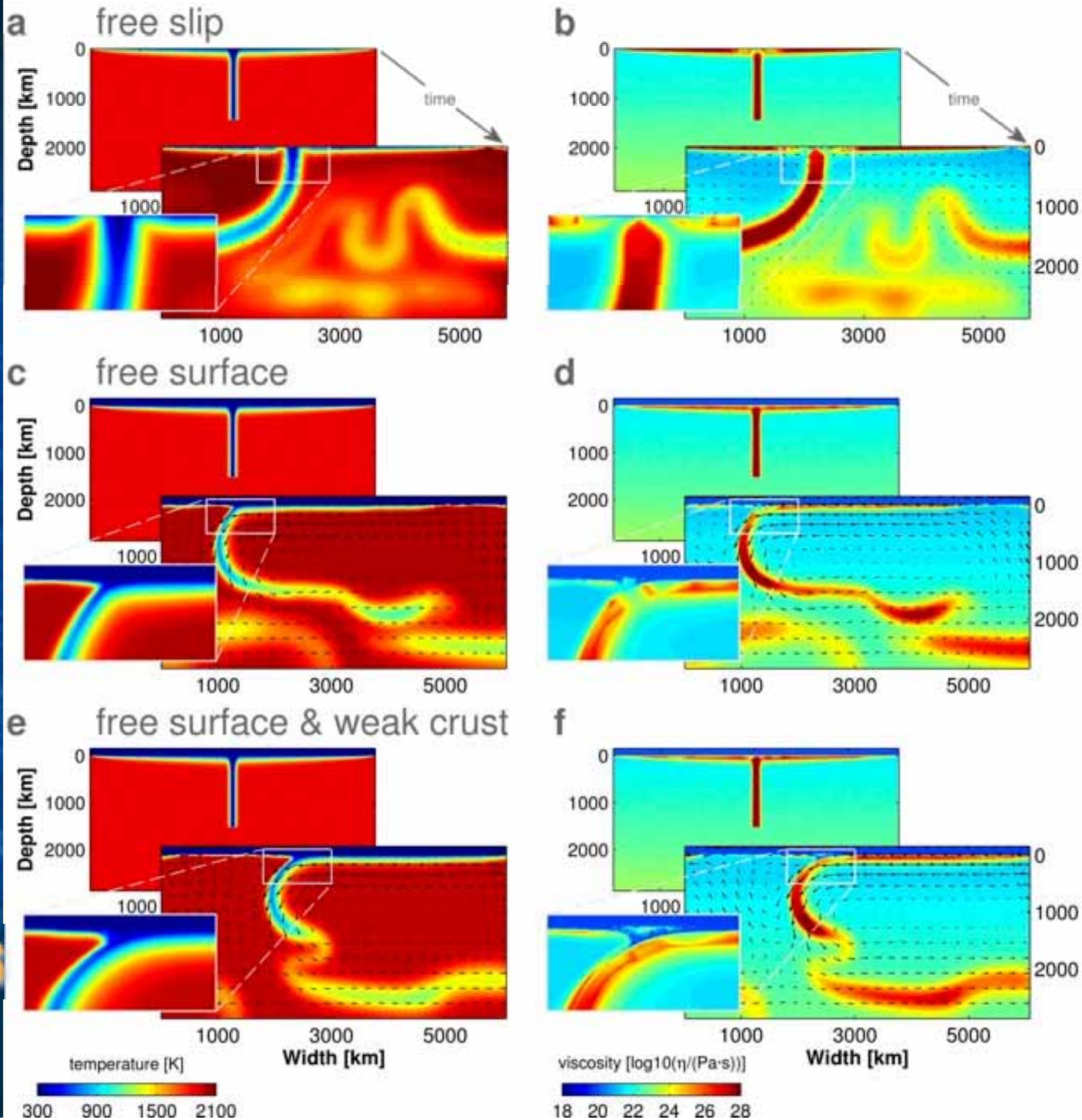
Fig. 16. Zoom in for viscosity snapshots of the FEMS-2D (left), FDCON (right) numerical models for times 57s, 5′ 50″, and 13′ 16″ which are comparable to the time steps presented for the laboratory experiment. For FDCON the harmonic mean for viscosity is used.

"Sticky-air" method gives same result as true free surface.
See also Crameri et al. (submitted)

Fabio Crameri

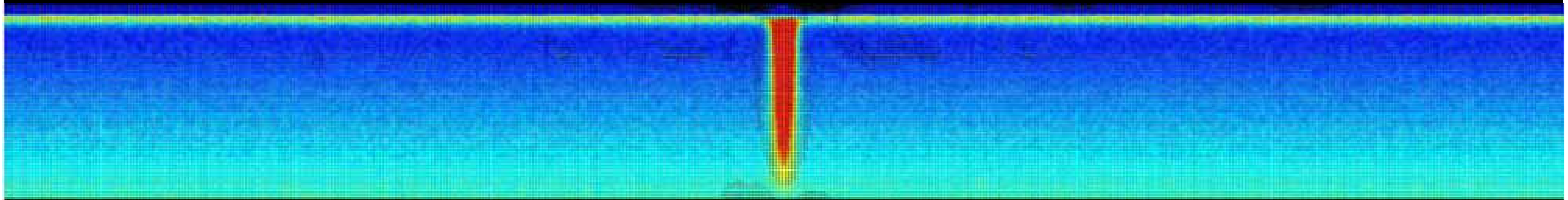
Taras Gerya

Boris Kaus

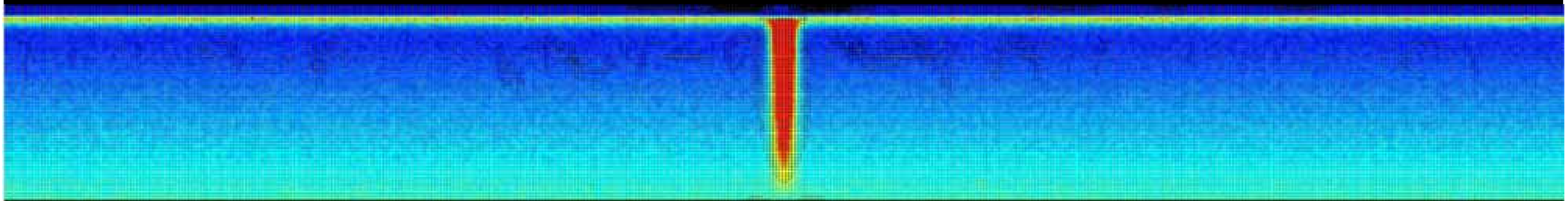


Effect of yield stress (friction coefficient)

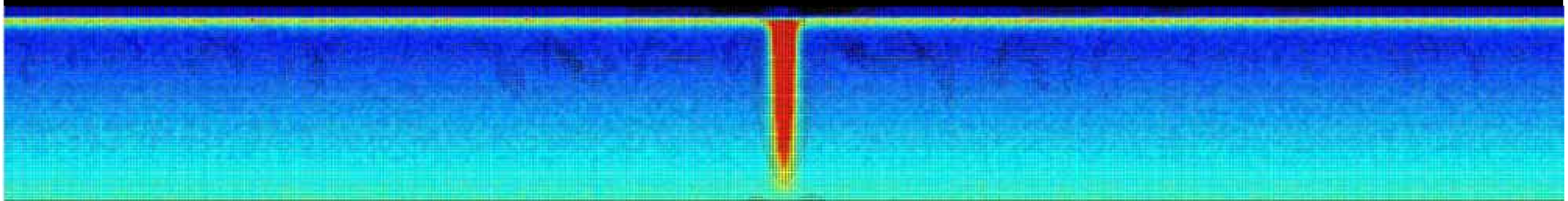
Friction coeff = 0.05

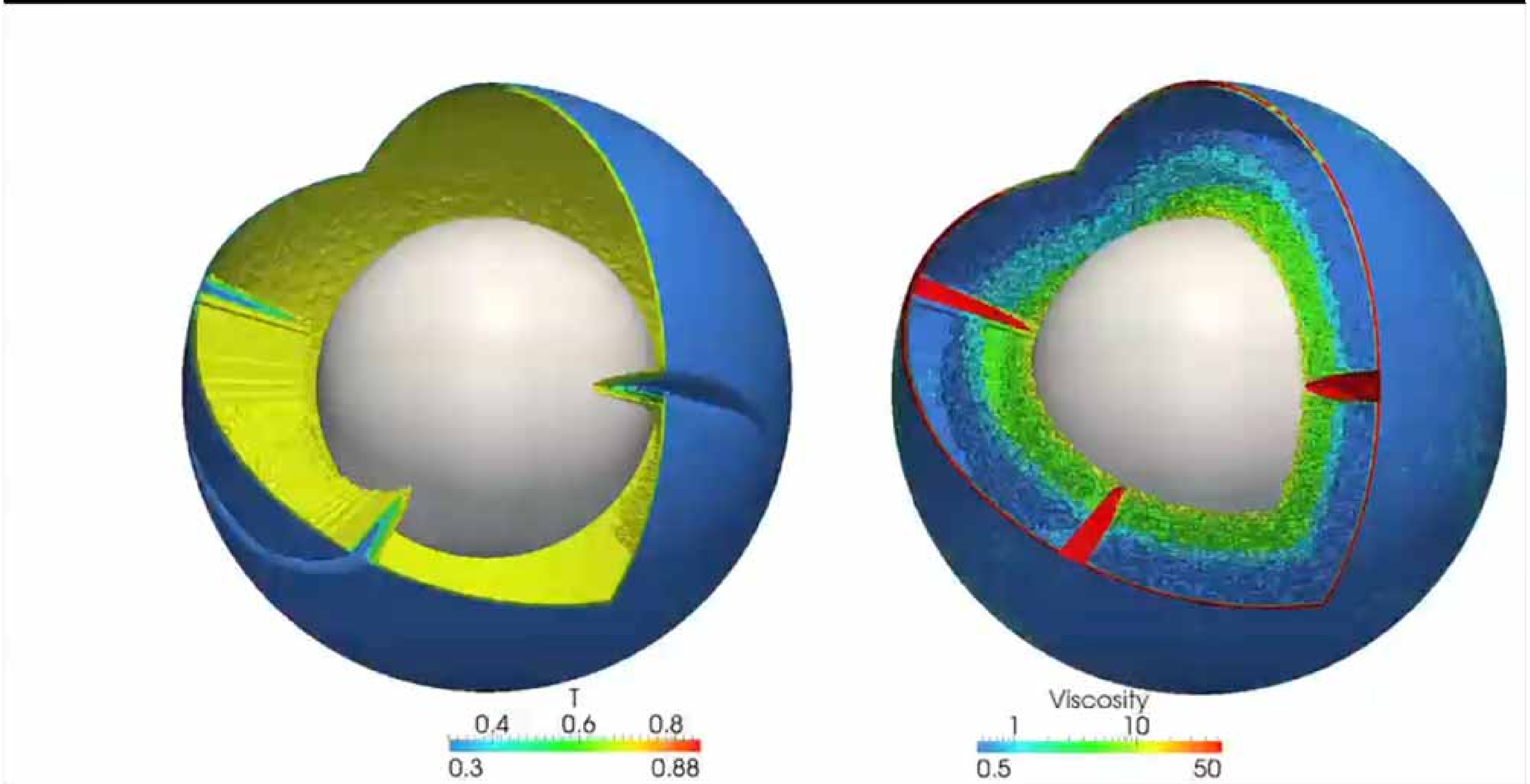


Friction coeff = 0.1

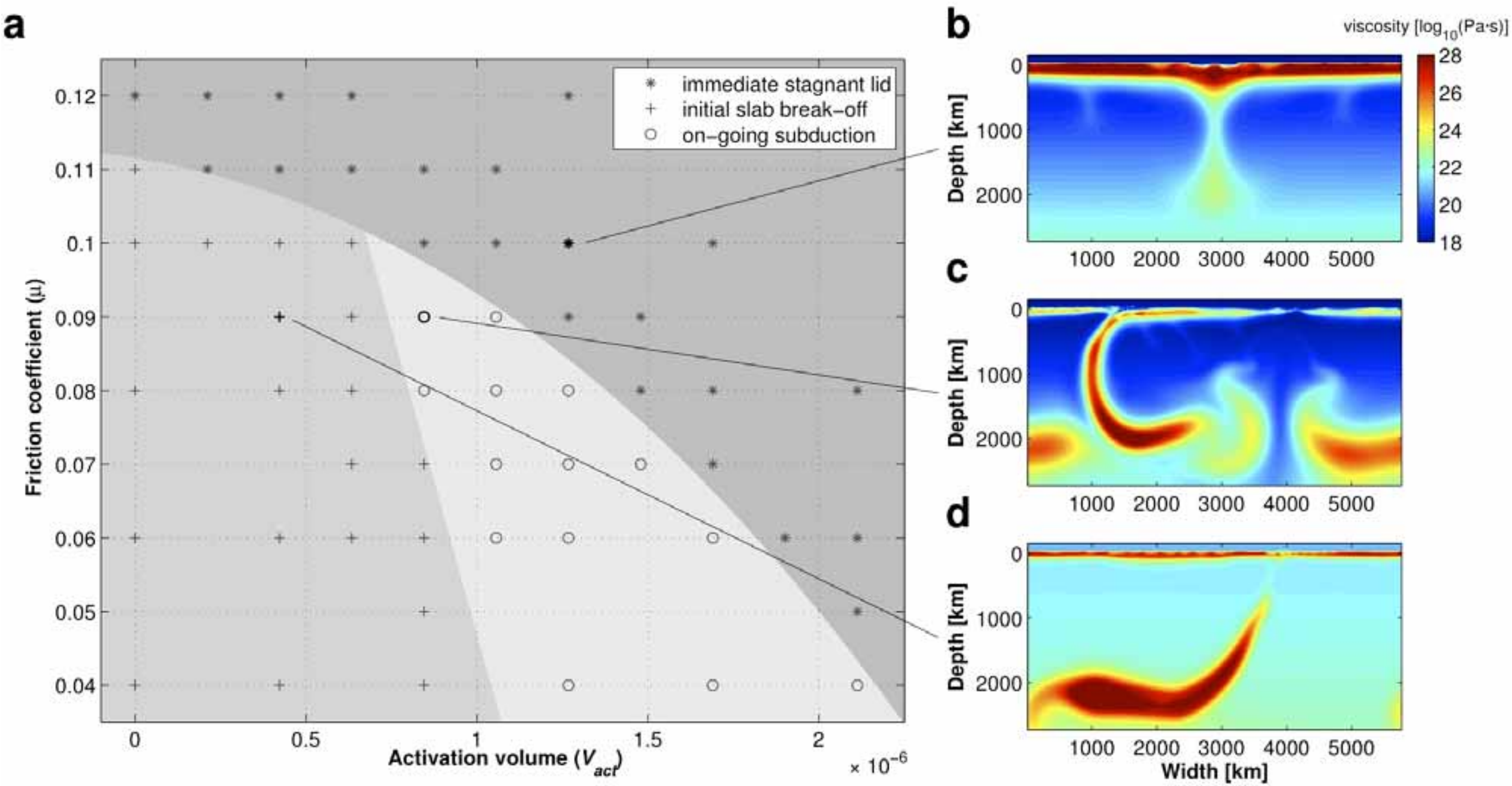


Friction coeff = 0.11




T
0.4 0.6 0.8
0.3
0.88
Viscosity
1 10
0.5
50

3 regimes



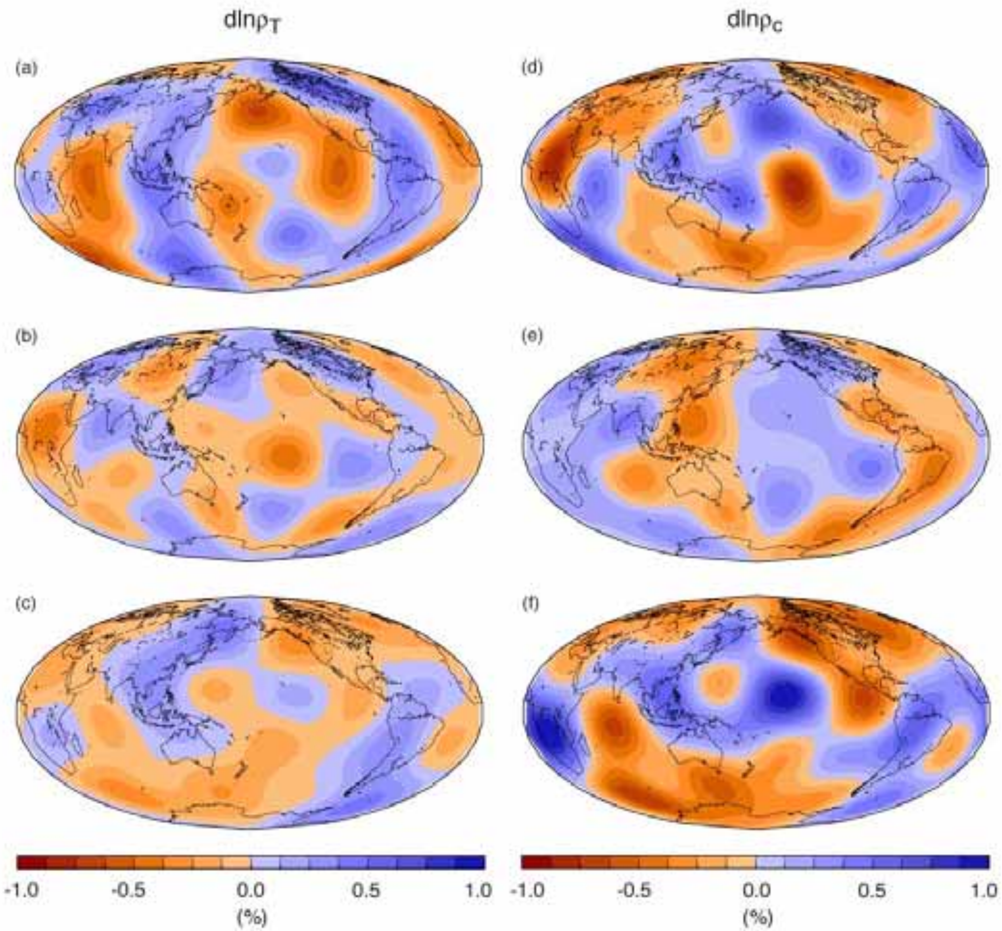
Depends on friction coefficient AND increase of viscosity with depth

Findings

- Free surface leads to (thermally) single-sided subduction over a wide parameter range
- But so far, eventually a rigid lid is obtained, even for parameters that lead to stable “plate tectonics” with a free-slip surface
- Research is ongoing…

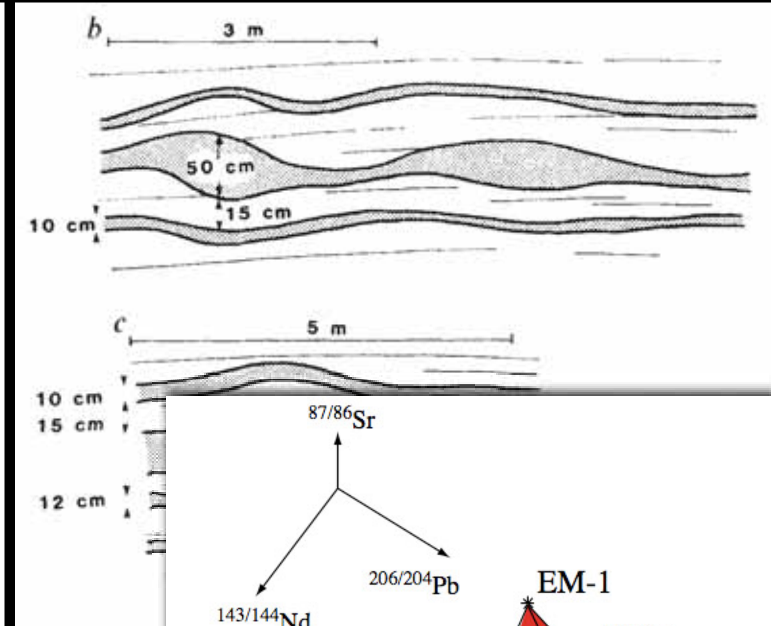
Compositional variations exist at all scales!

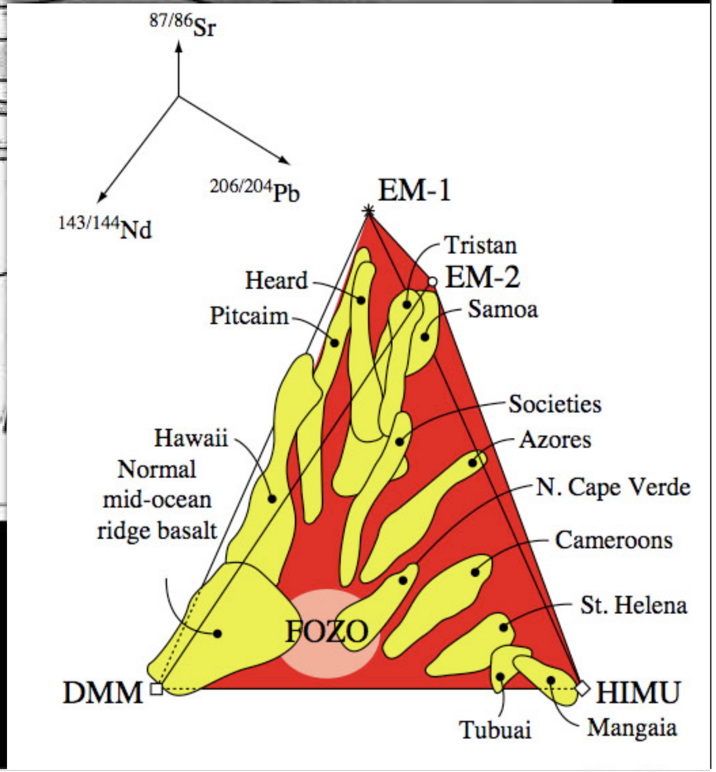
Large scale



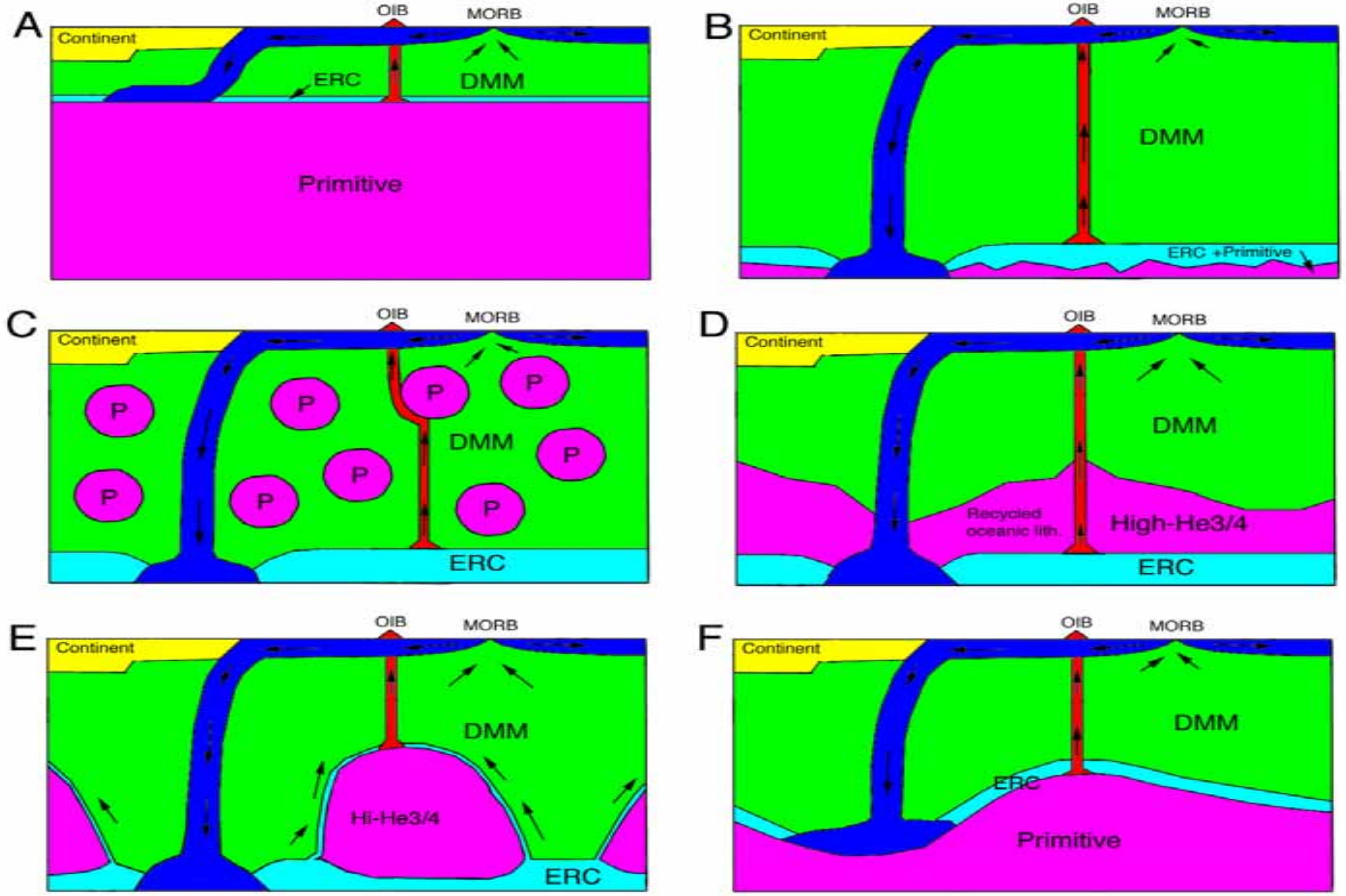
Deschamps, Trampert, Tackley (2005)

Small scale





Geochemical mantle: Old cartoons (2000)



from Tackley, Science, 2000: Figure 2

Deep dense stuff: Where does it come from?

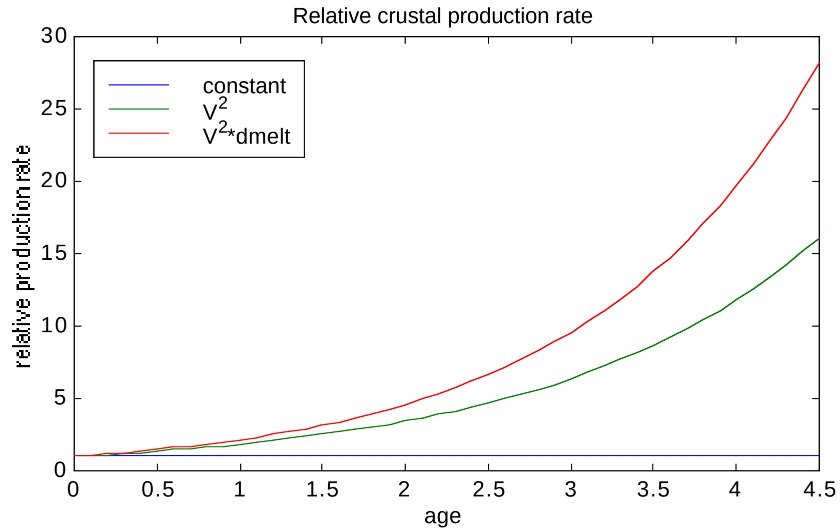
- Generated over time
  - Recycled oceanic crust
  - Crystallization of basal magma ocean (Labrosse et al)
- ‘Primordial’
  - Crystallization of magma ocean (Solomatov…)
  - Subducted early crust (Tolstikhin et al 2006)
  - Early KREEP-like liquid (Boyet&Carlson 2005)
  - Upside-down differentiation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

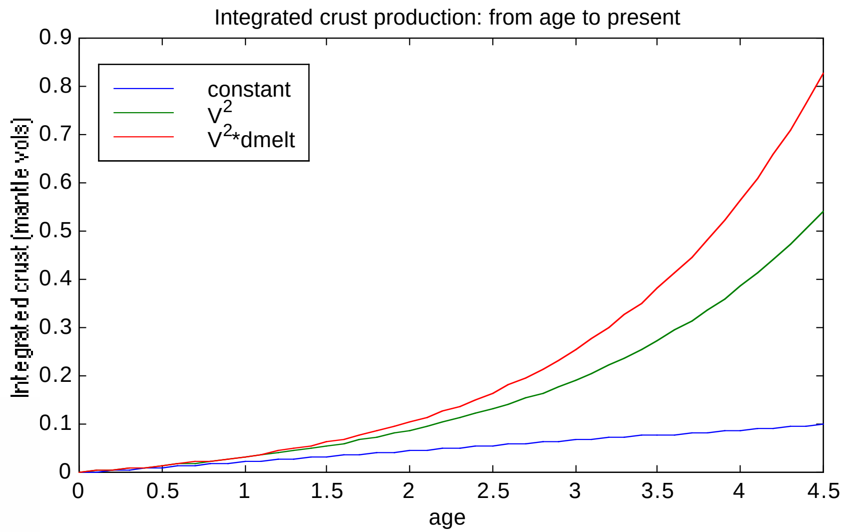
Oceanic Crust Production

- 3 melt vs. time models
  (V=internal heating rate)

Volume of oceanic crust subducted in 4.5 Gyr

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





Xie & Tackley 2004

Volume of oceanic crust subducted in 4.5 Gyr

- Present-day production rate: 10% of mantle
- Production rate $\propto$ H^2: 53%

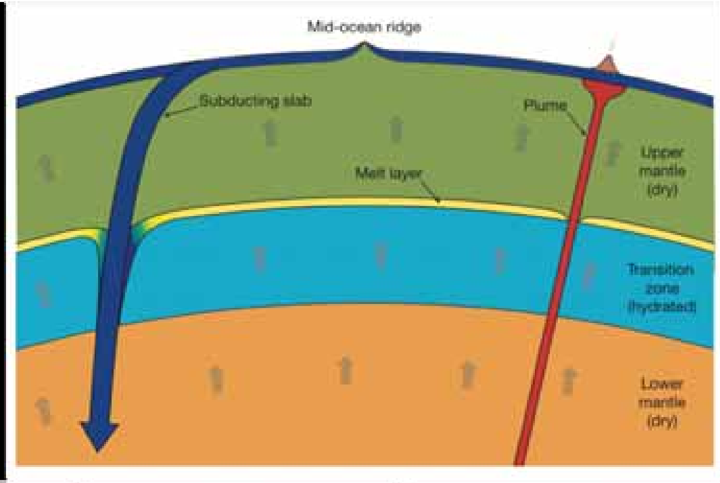
Volume of mantle "processed" by MOR melting in 4.5 Gyr

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

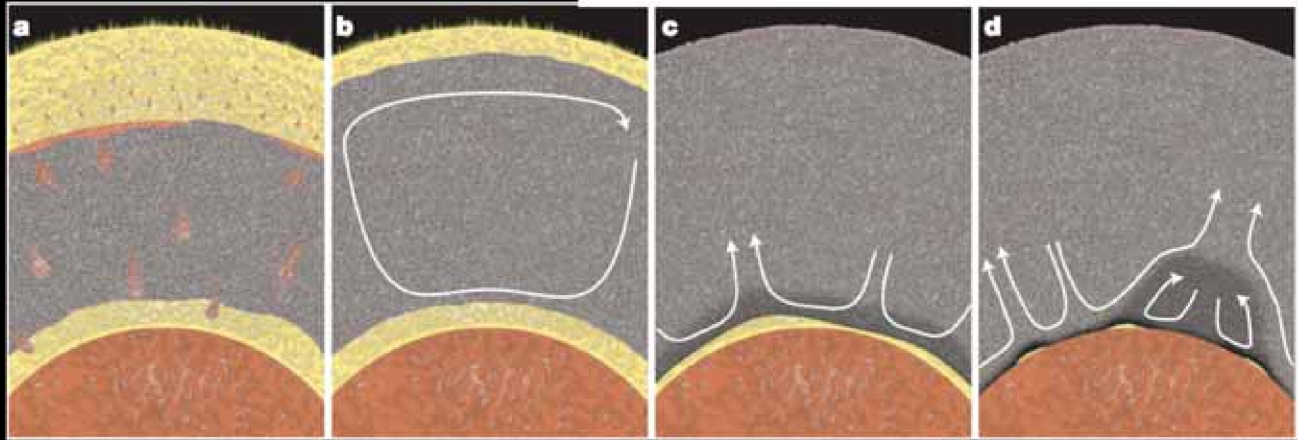
Almost no unprocessed material

Newer cartoons

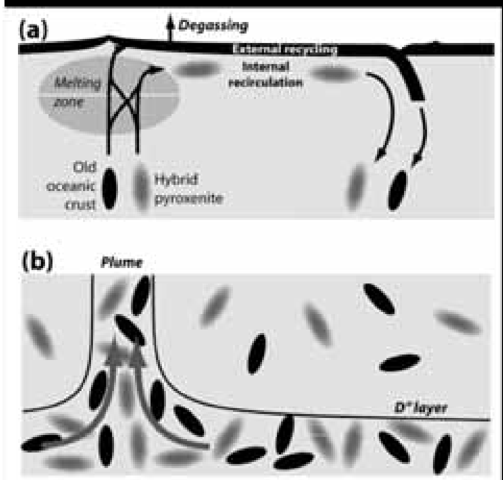
Transition Zone Water Filter
Bercovici & Karato 2003



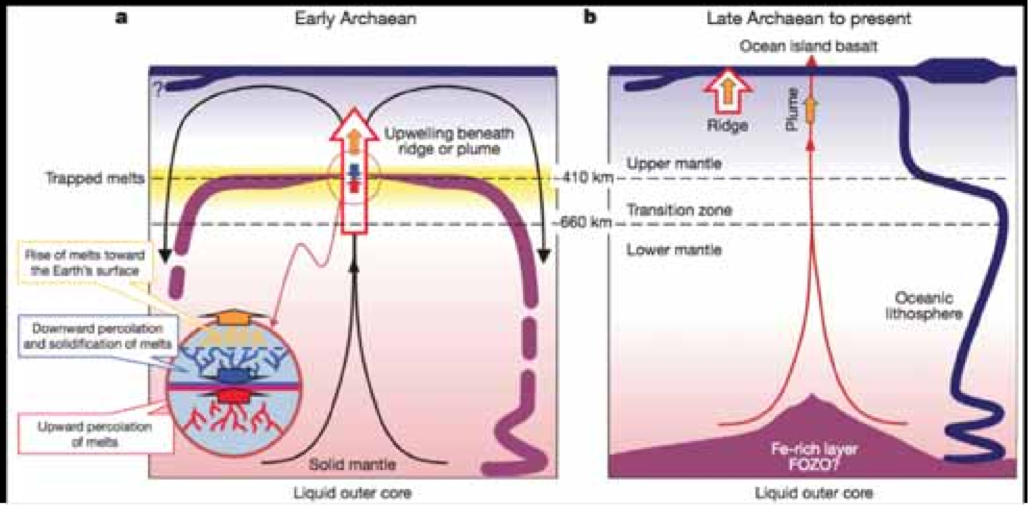
Basal Magma Ocean
Labrosse et al., 2007



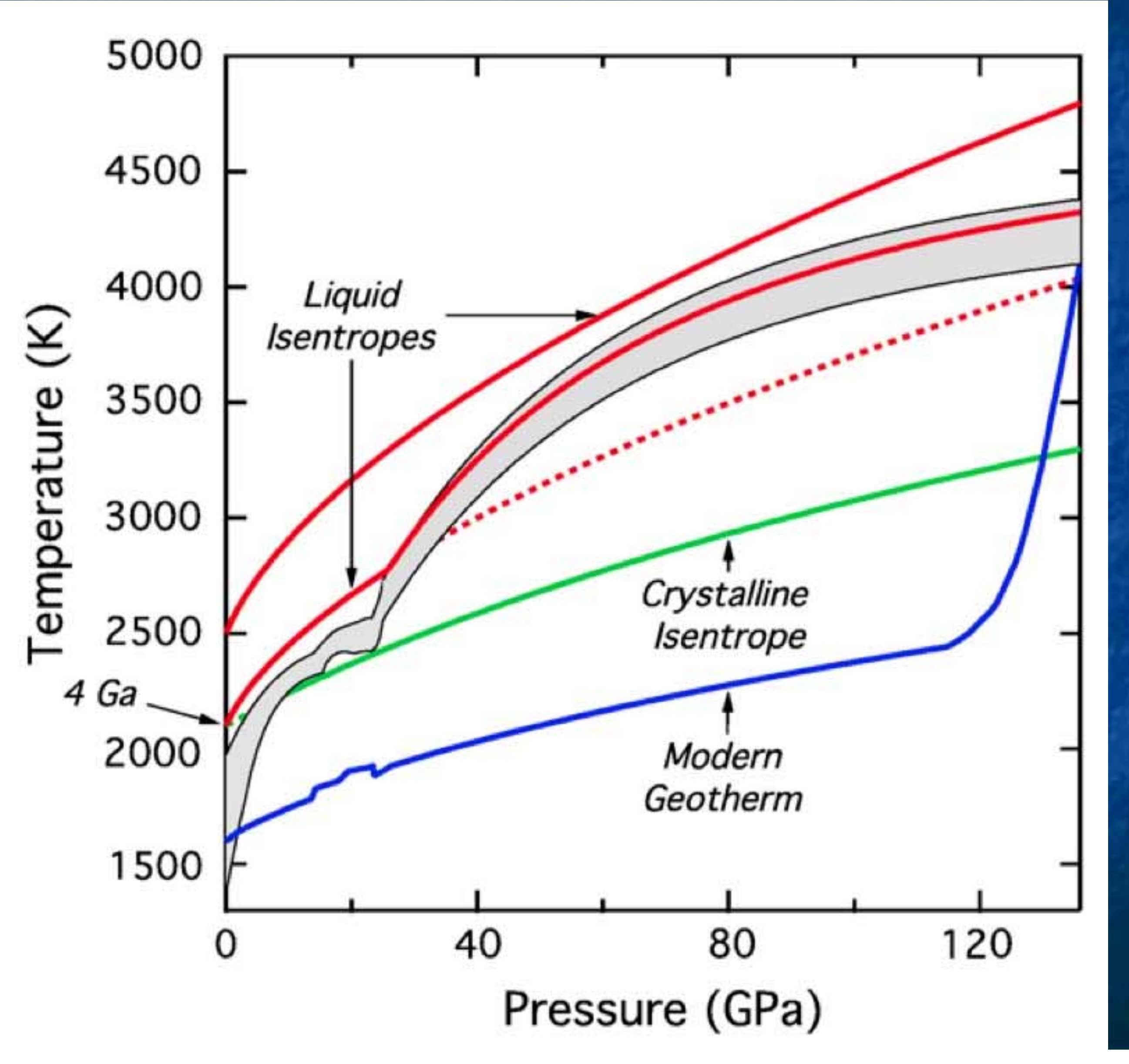
Davies 2009



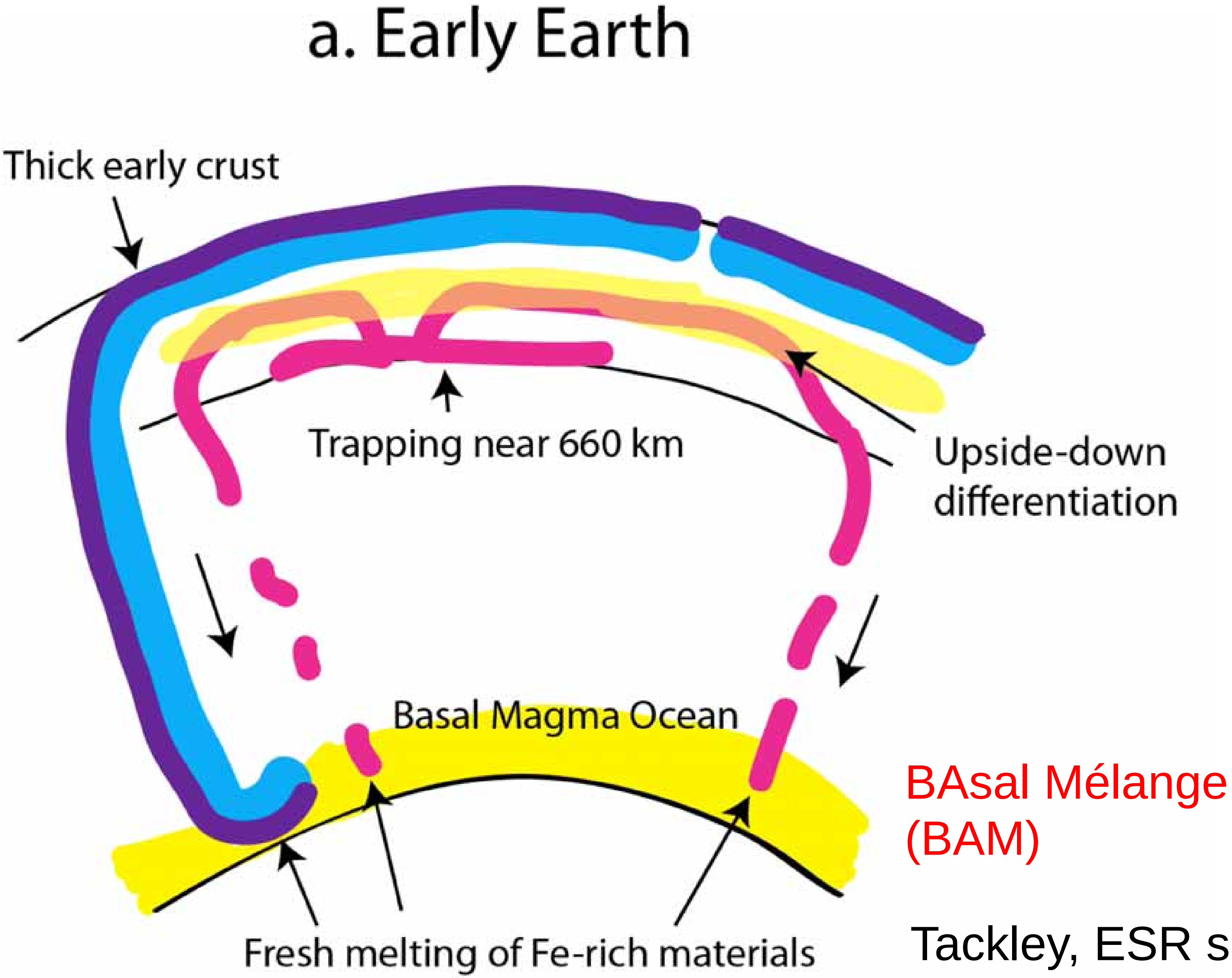
Upside-down differentiation
Lee et al
2010



Mineral physics support for Basal Magma Ocean (Stixrude et al 2009)



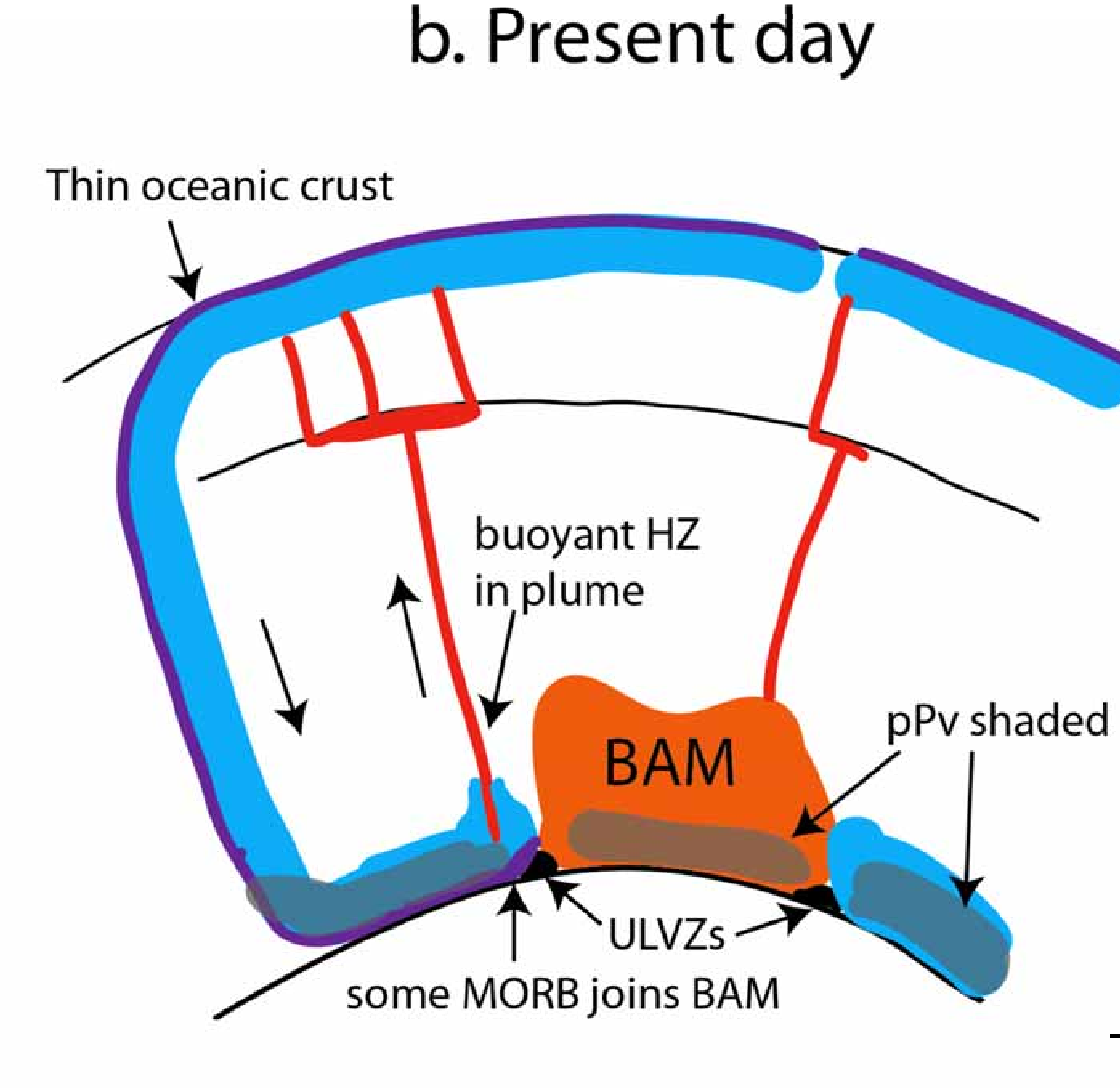
More than one process operating!



BAsal Mélange
(BAM)

Tackley, ESR subm

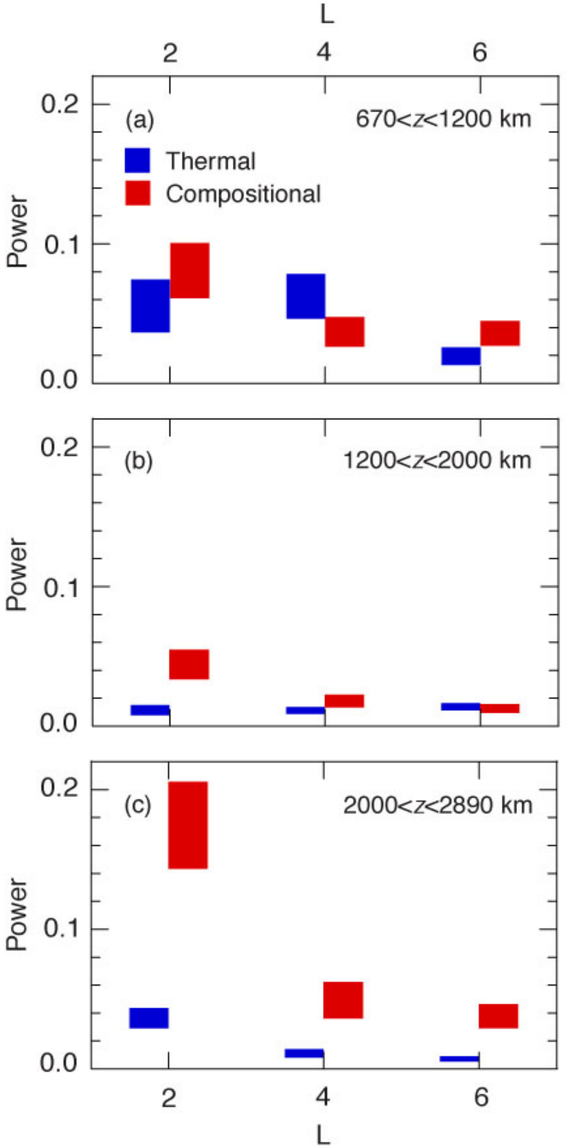
More than one process operating!



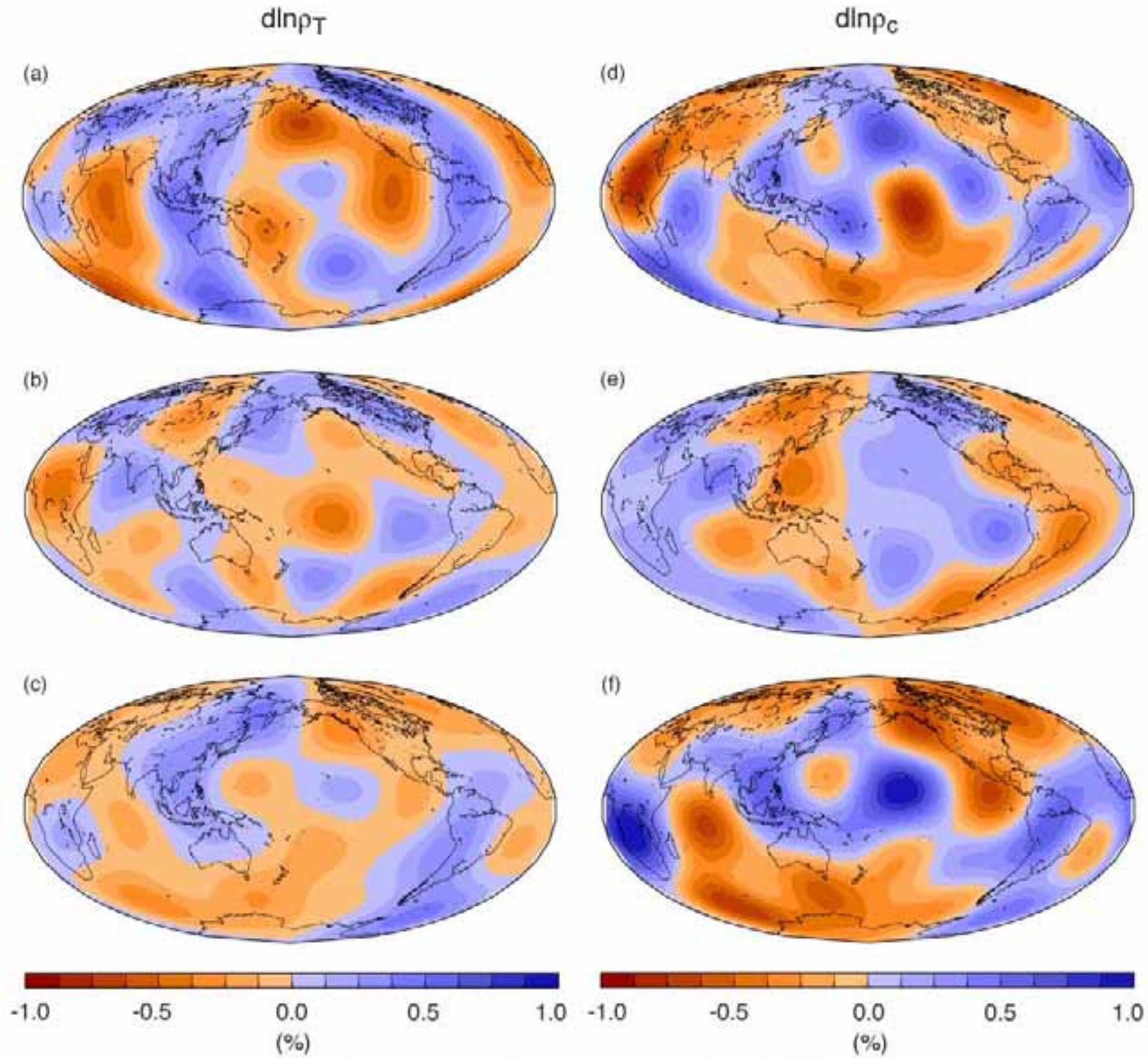
BAsal Mélange (BAM) mix:
BMO remnants
UM differentiated products
Recycled crust
…

Tackley, ESR subm

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



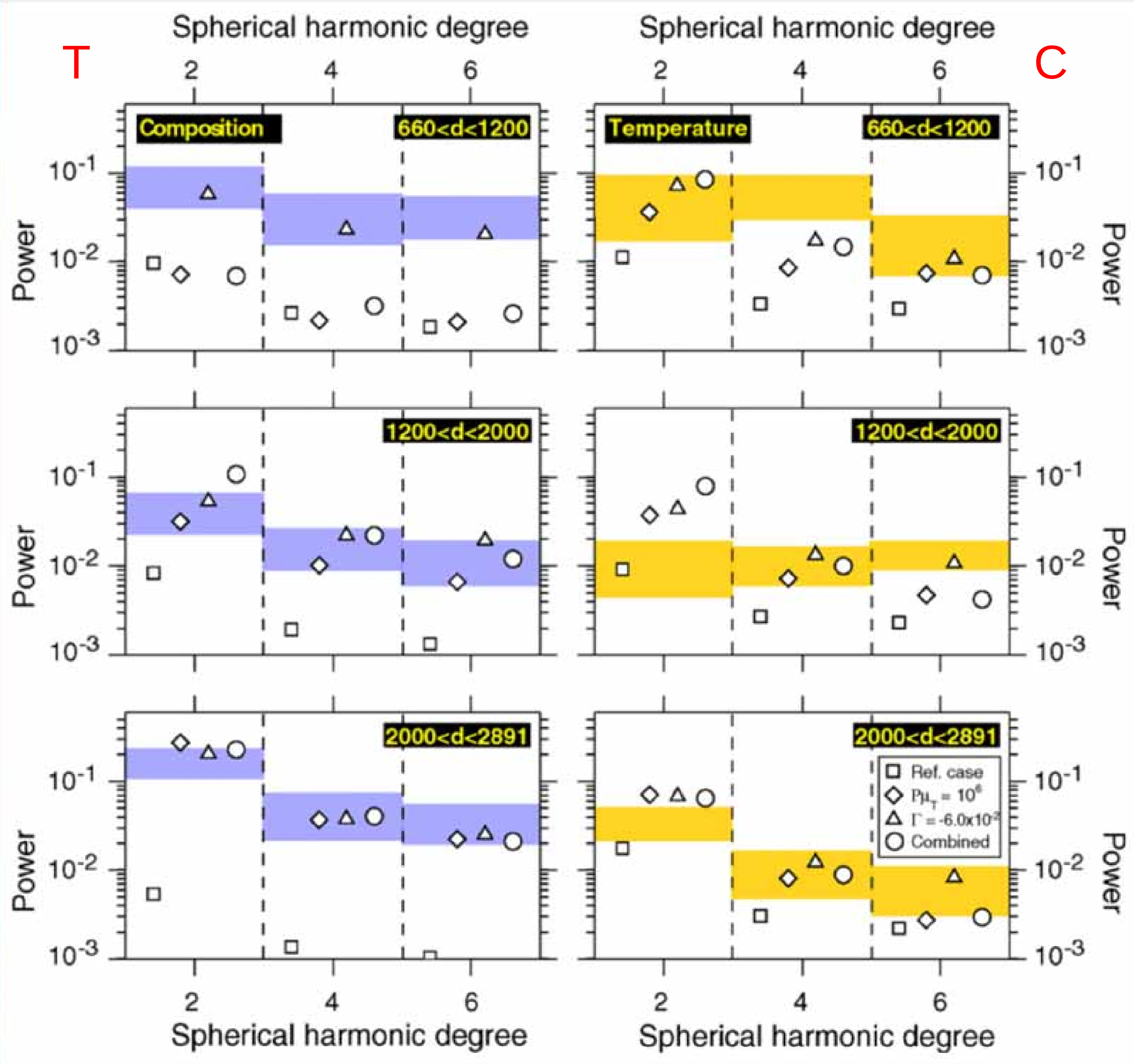
Deschamps, Trampert, Tackley (2005)



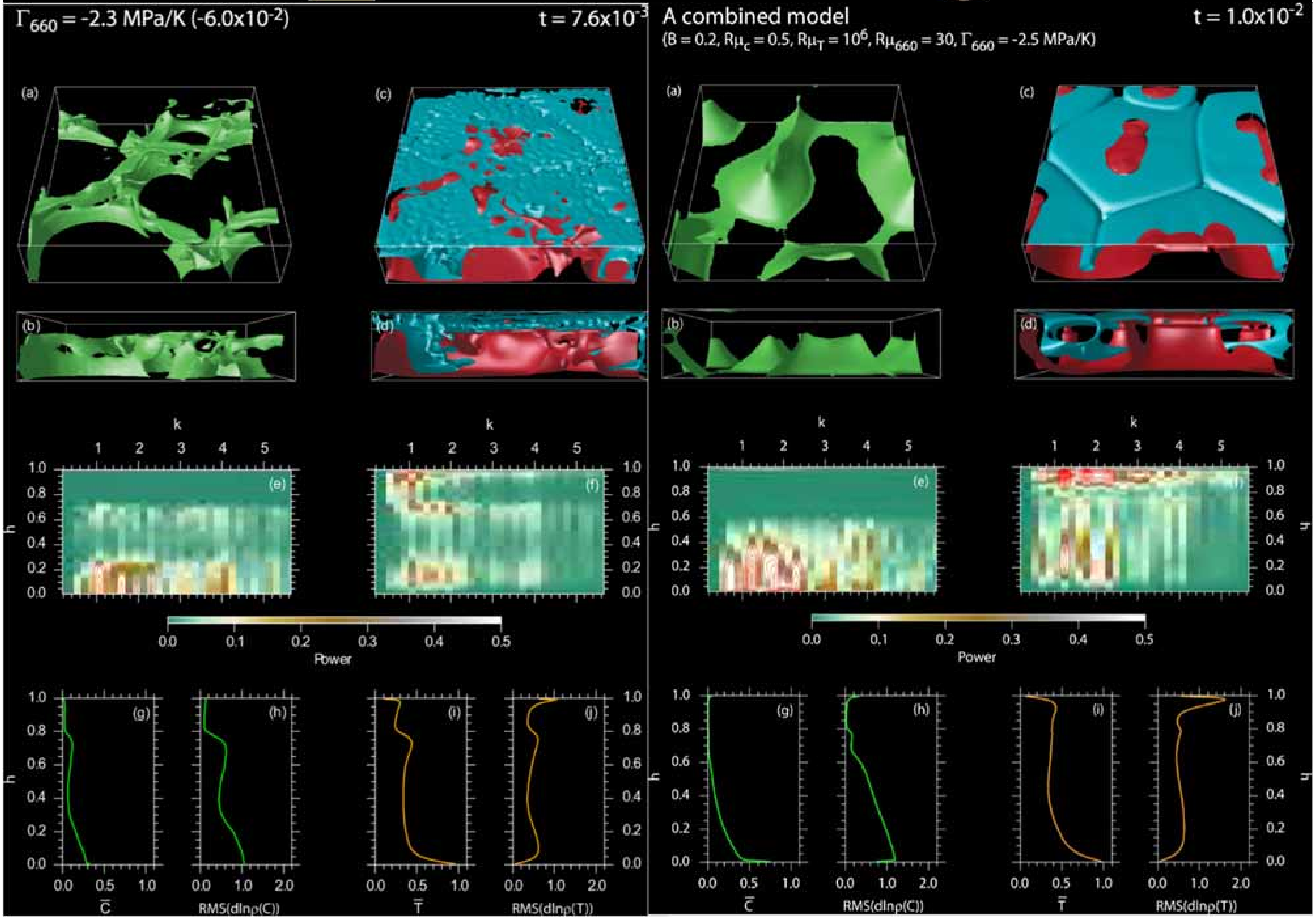
Deschamps, Trampert, Tackley (2005)

Frédéric Deschamps & me PEPI 2008, 2009:

3-D convection models to match probabilistic tomography density variations

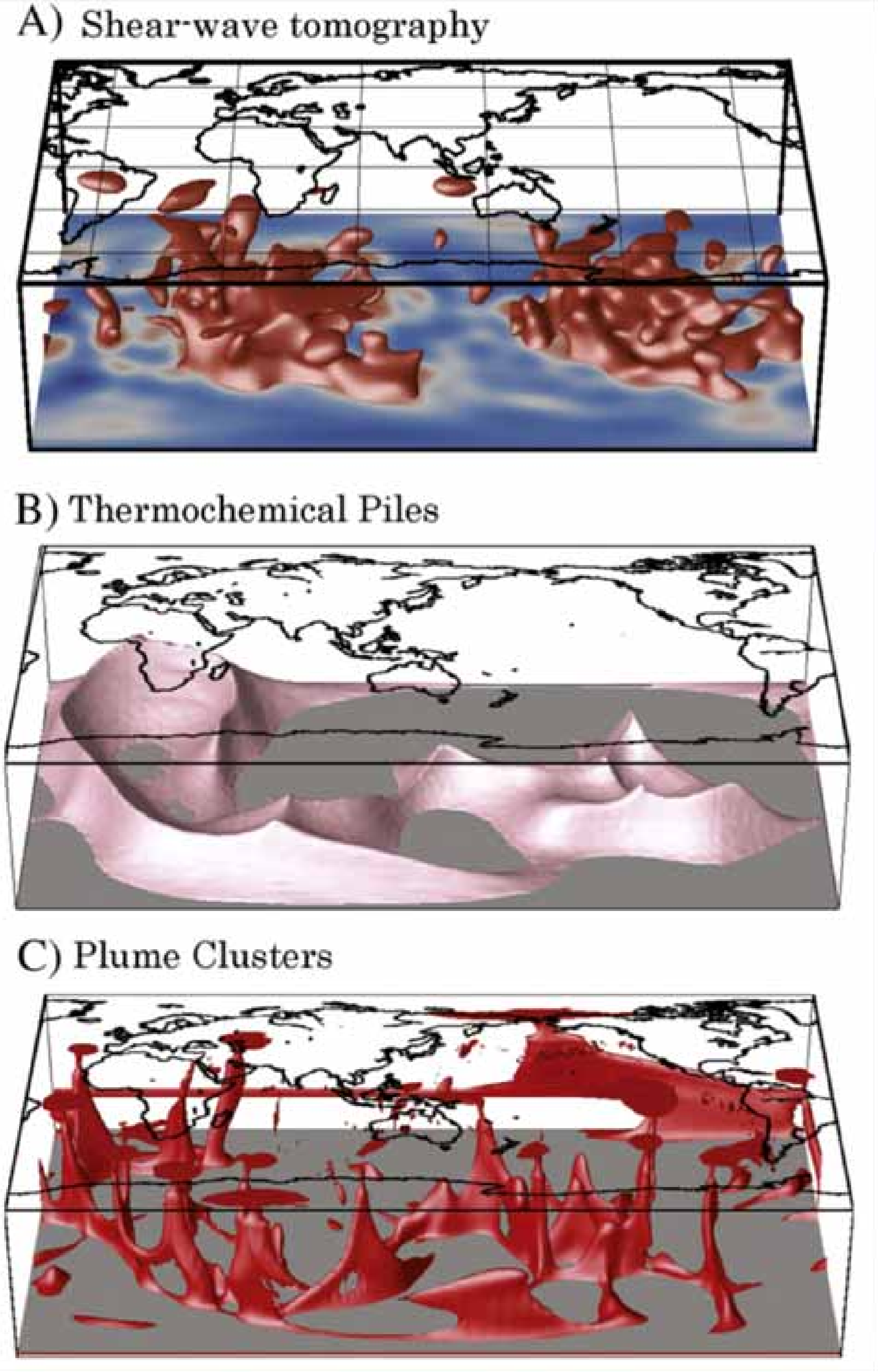


Deschamps & me PEPI 2008, 2009

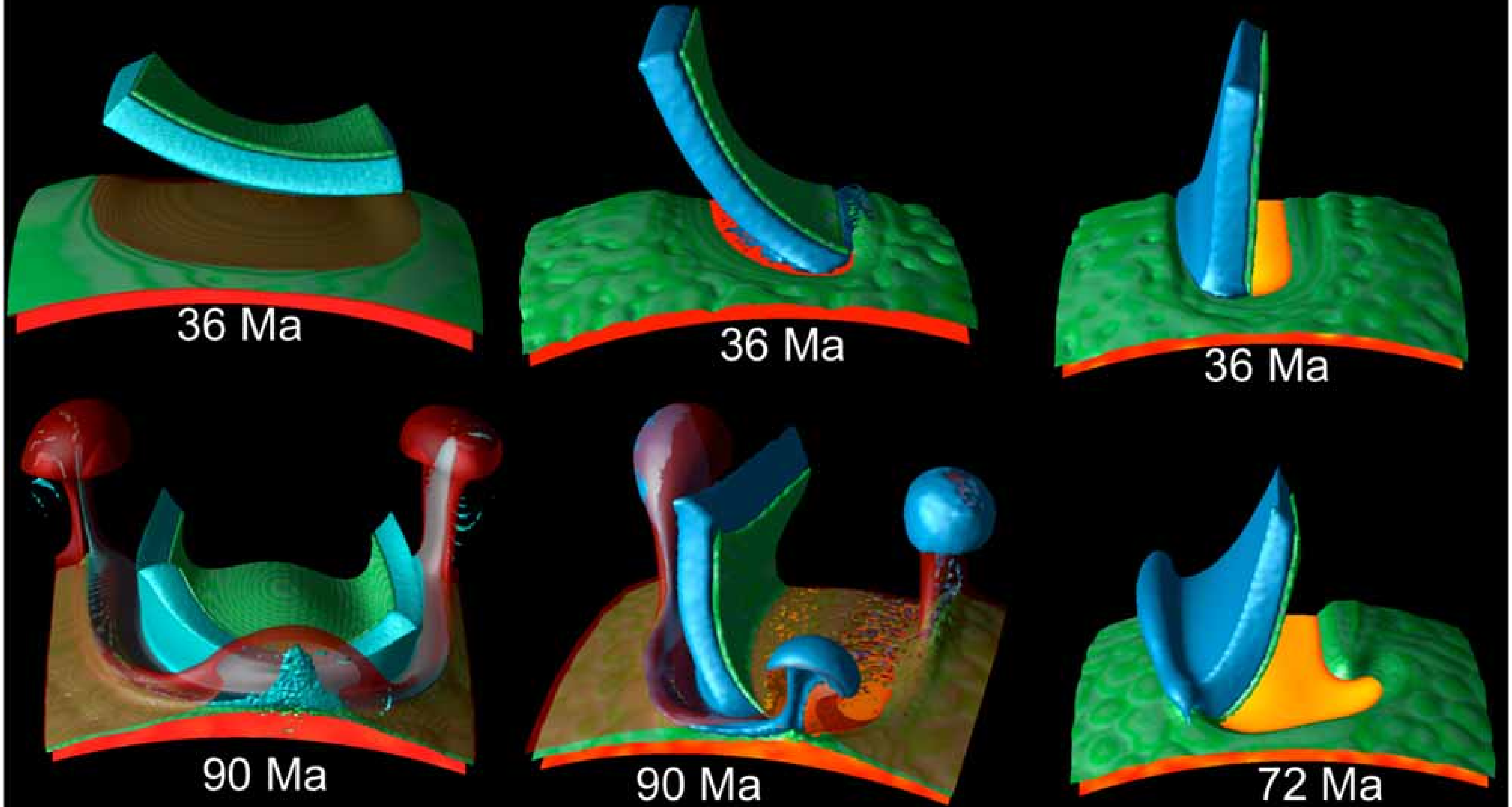


Consistent with others' results

Lassak, McNamara et al 2010

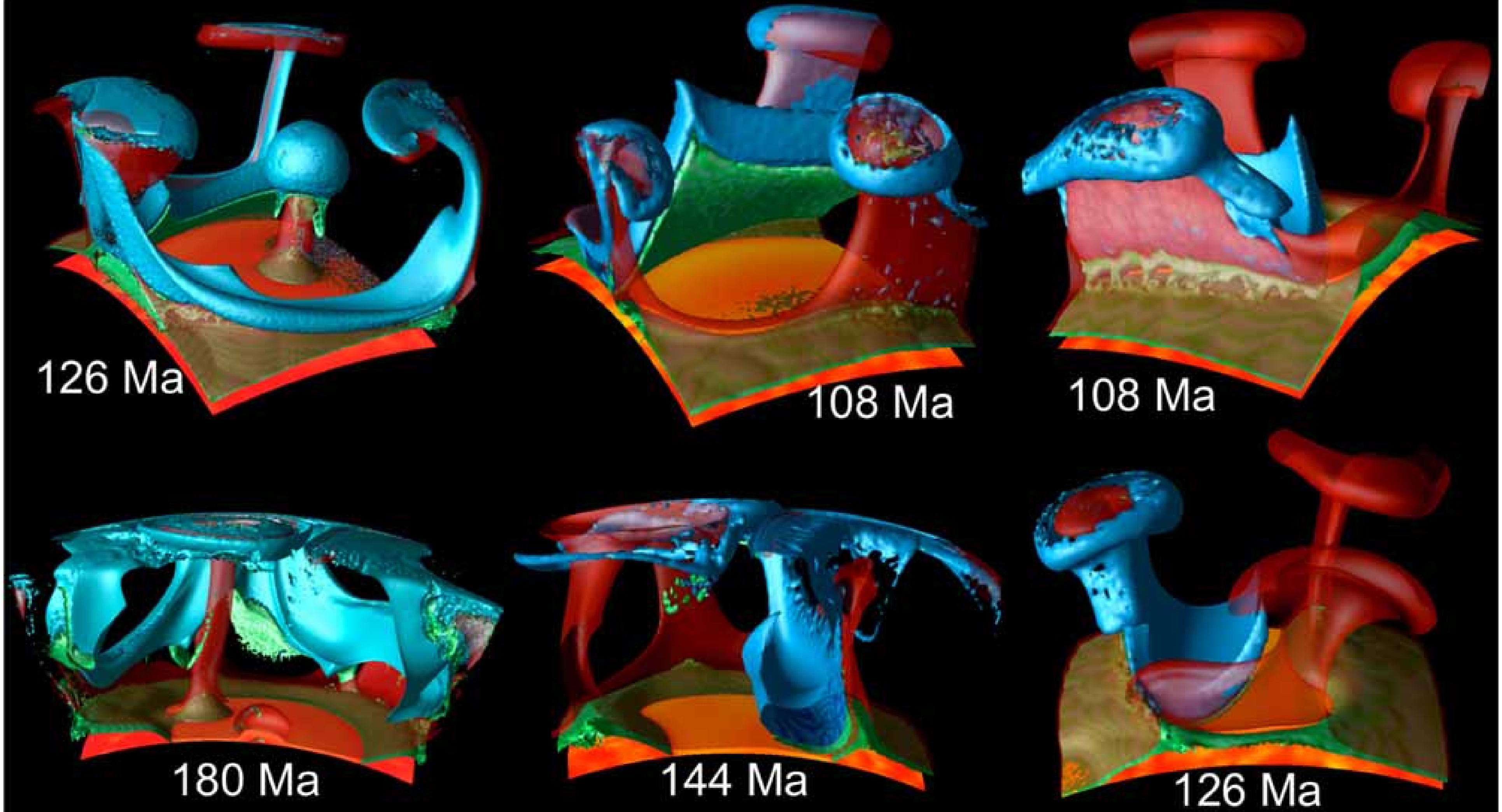


Slab-CMB interaction



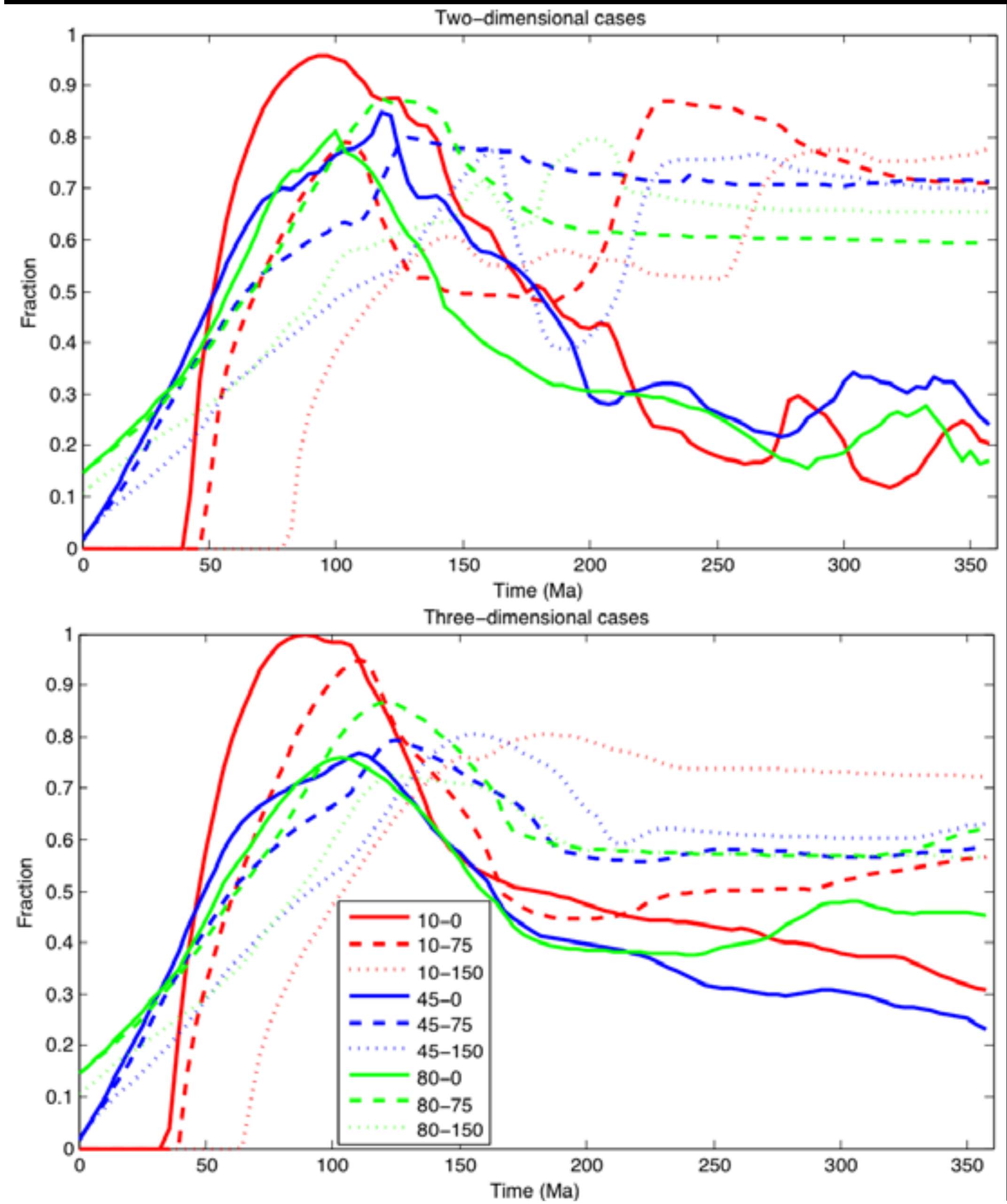
Tackley, PEPI 2011

Slab-CMB interaction



Tackley, PEPI 2011

% Slab basalt joining BAM layer



Much higher if existing layer

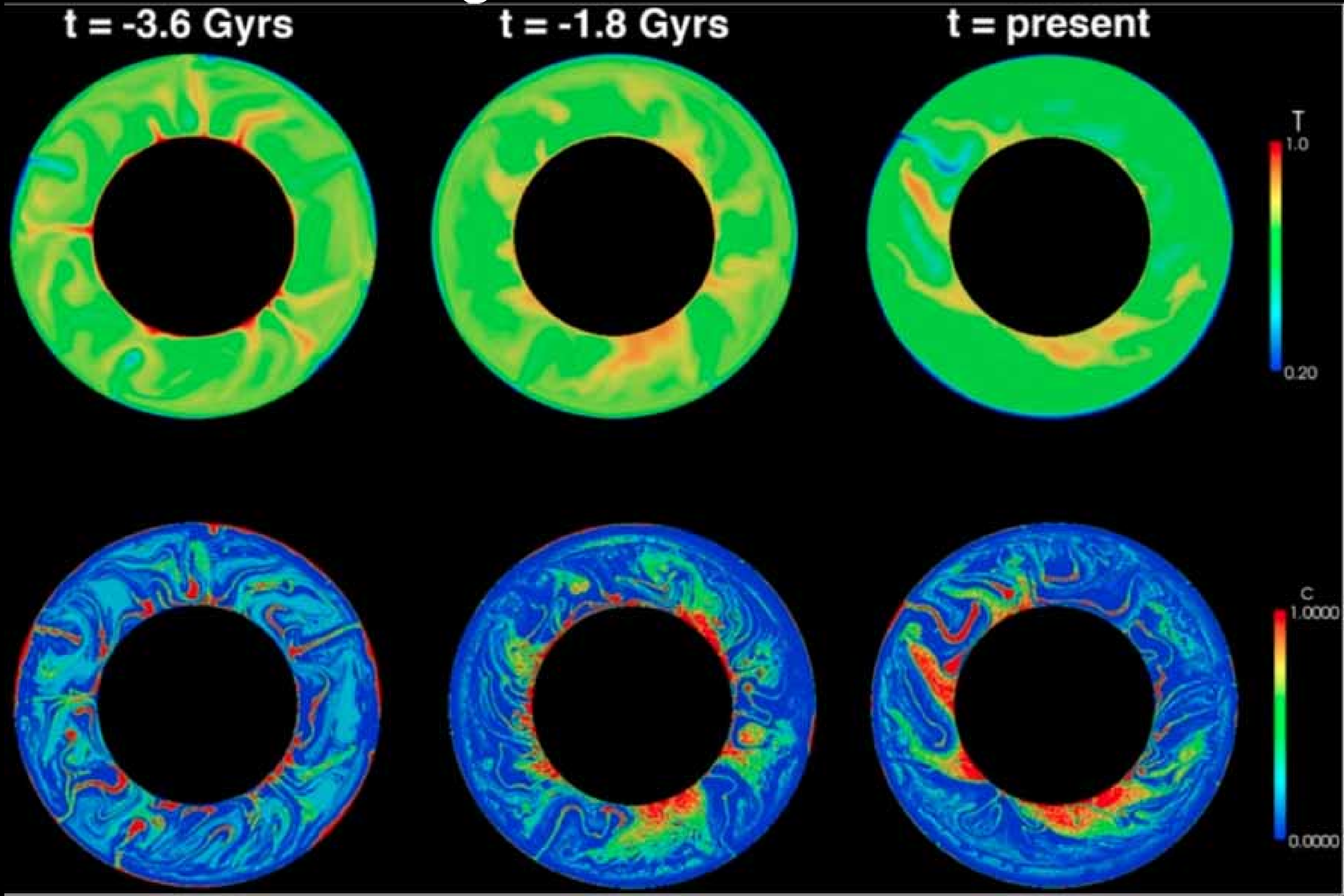
If no existing layer, then higher in 3D

Tackley, PEPI 2011

Now, calculations of mantle thermo-chemical evolution over 4.5 Gyr

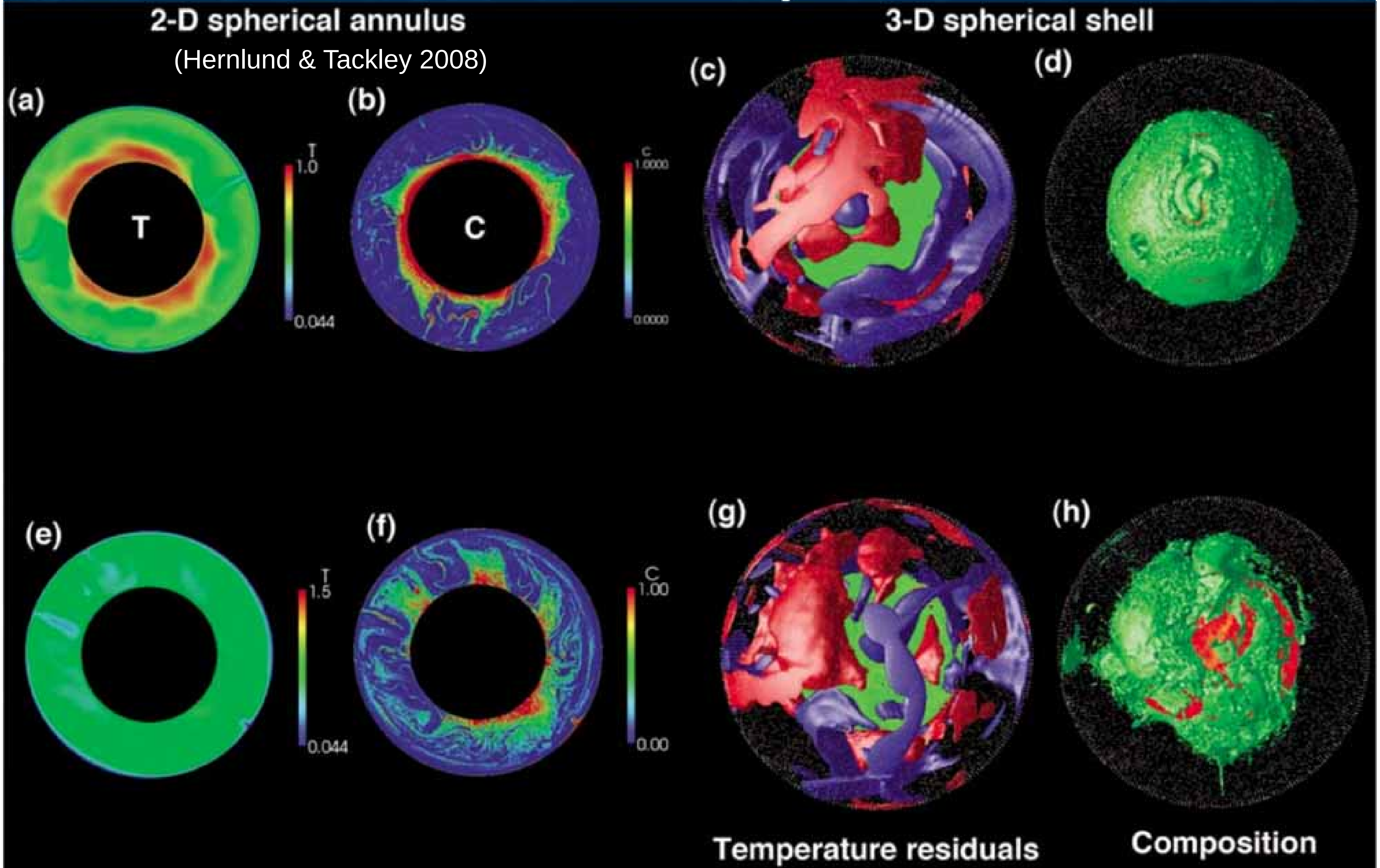
- Include melting->crustal production,
  - viscosity dependent on T, d, and stress,
  - self-consistent plate tectonics,
  - decaying radiogenic elements and cooling core,
  - compressible anelastic approximation
- Many papers by Takashi Nakagawa & me

Long-term evolution



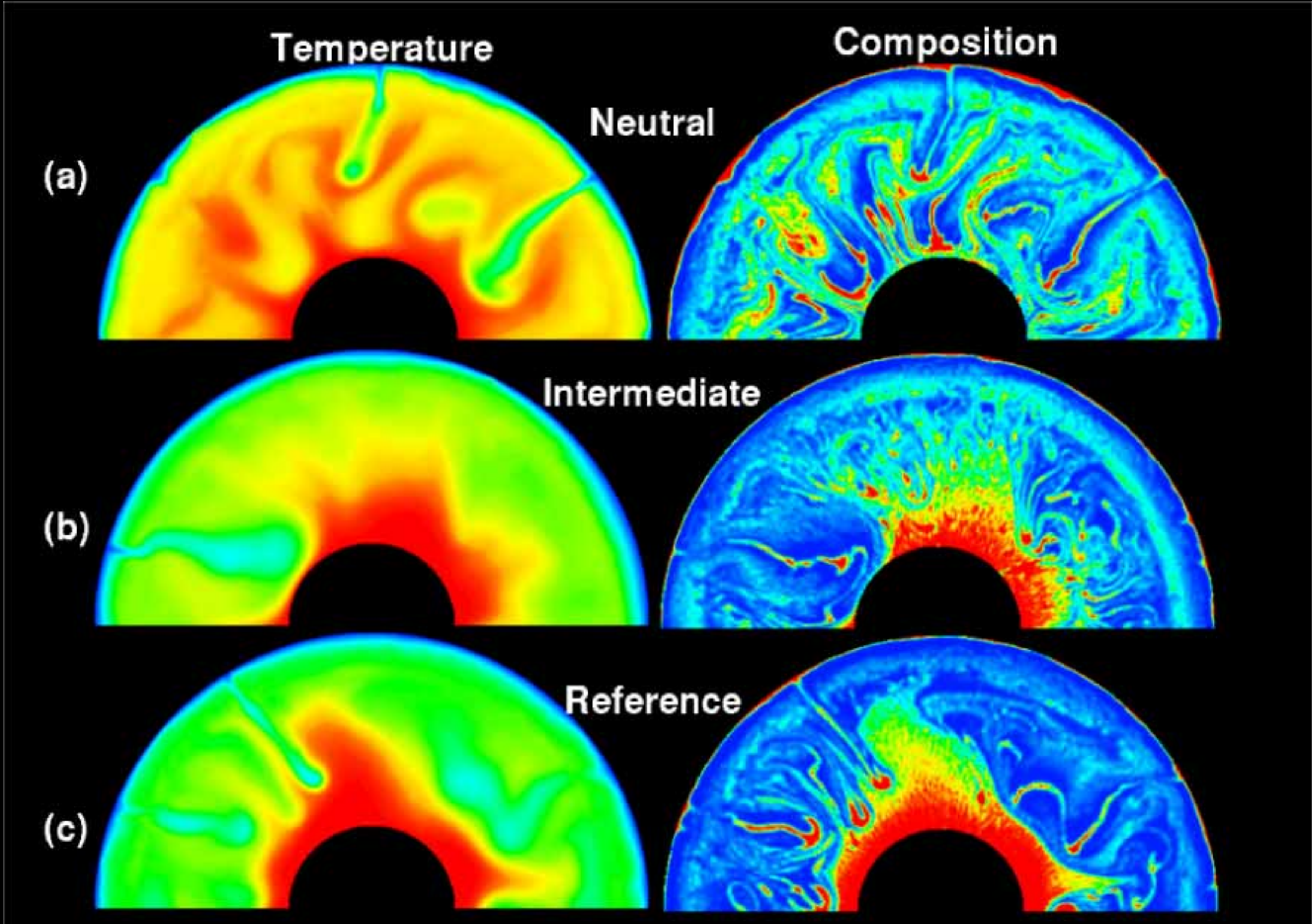
Nakagawa & Tackley 2010 Gcubed

2D - 3D comparison



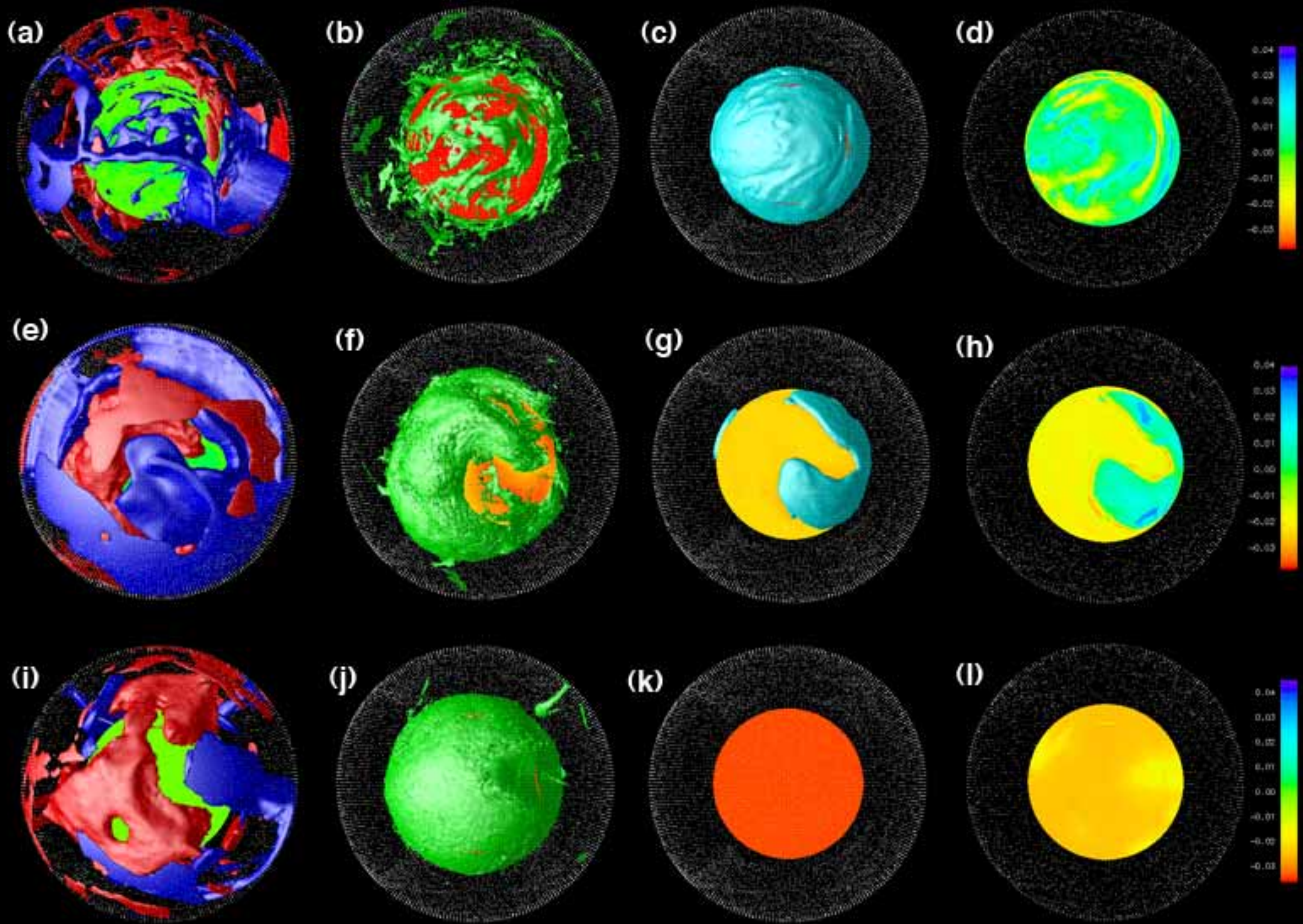
Nakagawa & Tackley 2010

Depends critically on MORB density contrast



Nakagawa & Tackley 2005 gcubed

Spherical: similar
(end results of 4.5 Gyr evolution)



0.0%

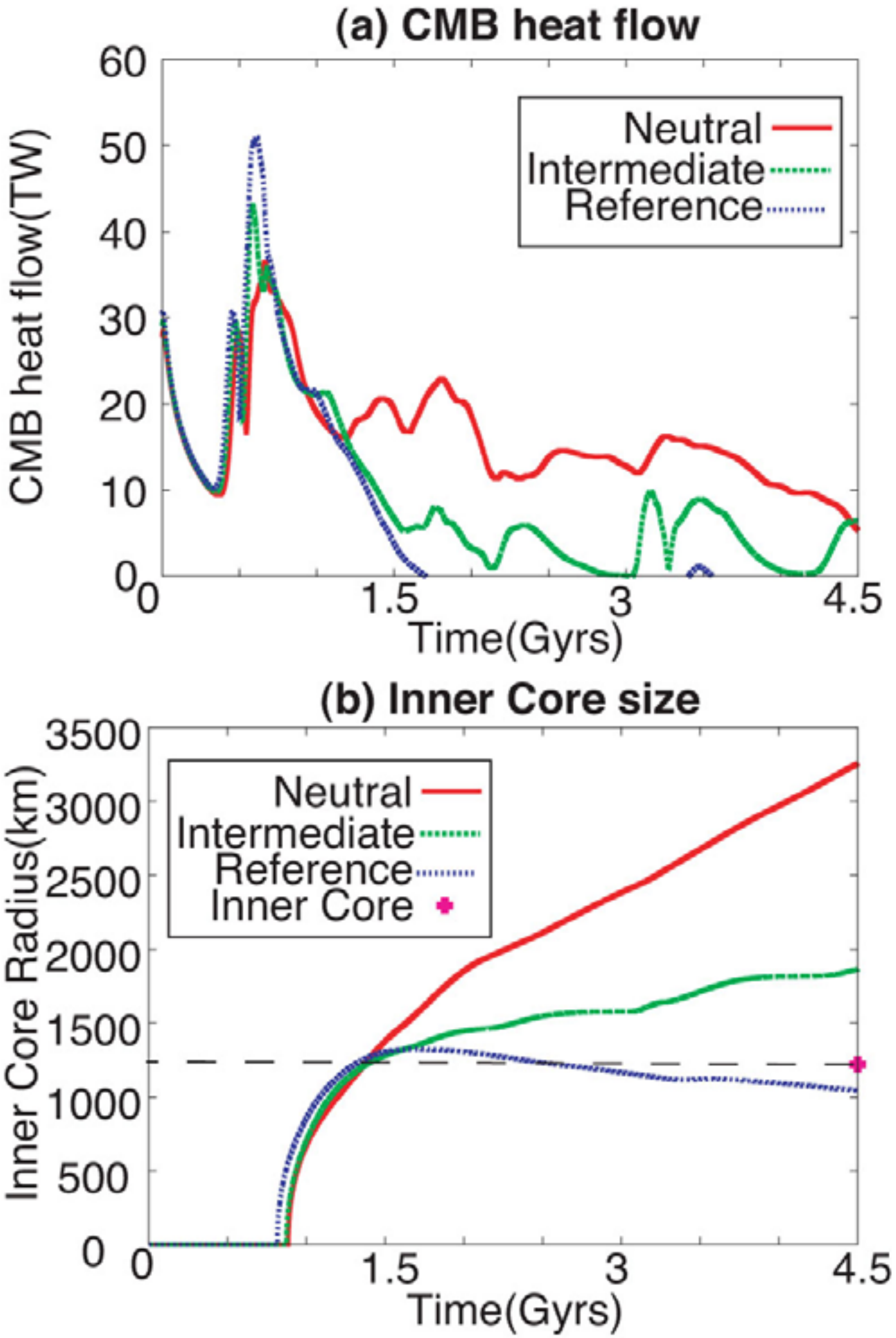
1.8%

3.6%

Temp. Comp. PPV S-anomalies

Strongly influences CMB heat flux hence core evolution

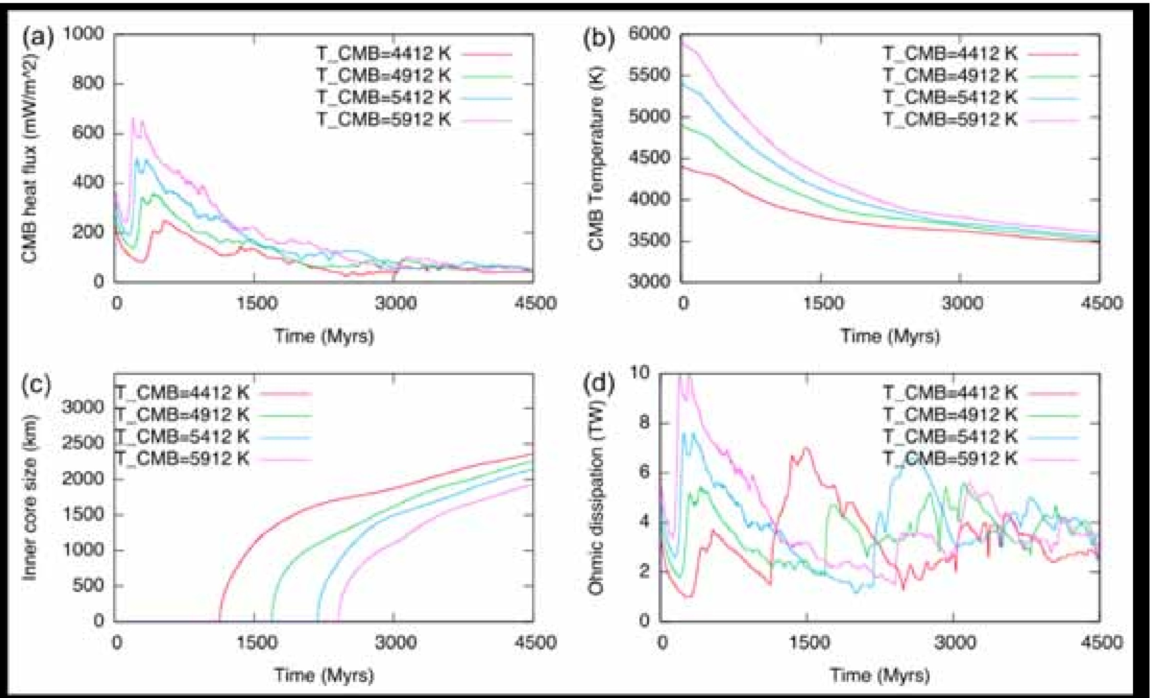
Nakagawa & Tackley, Gcubed 2005



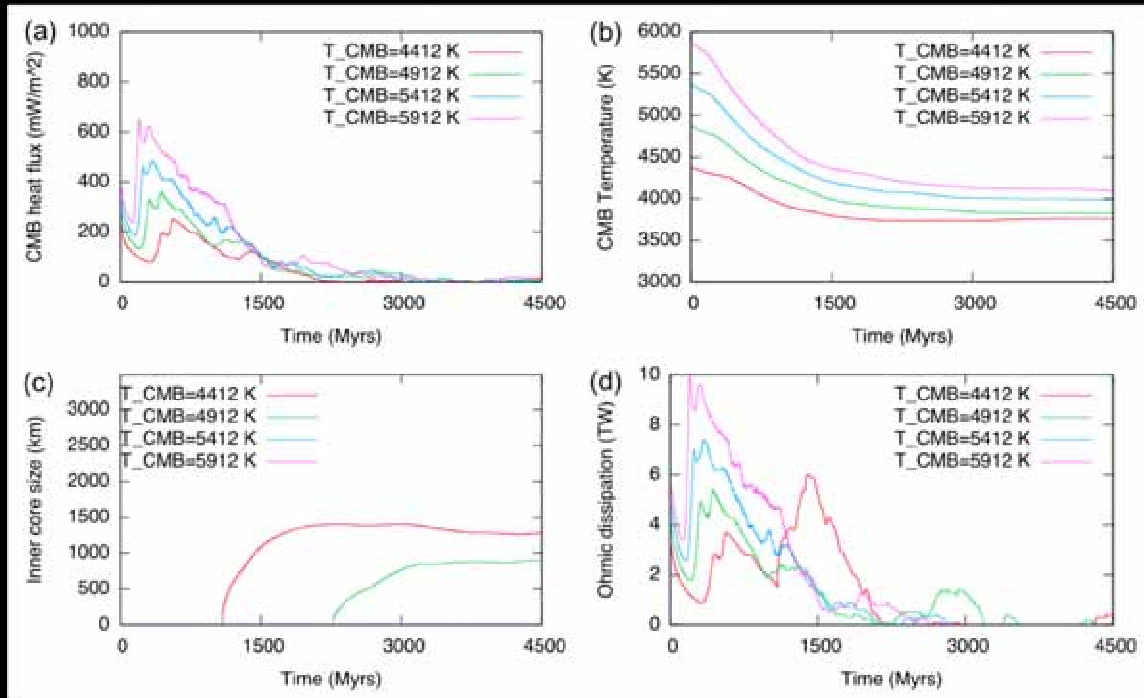
Initial condition important?

Nakagawa & me 2010 G3

Small influence if 'piles'

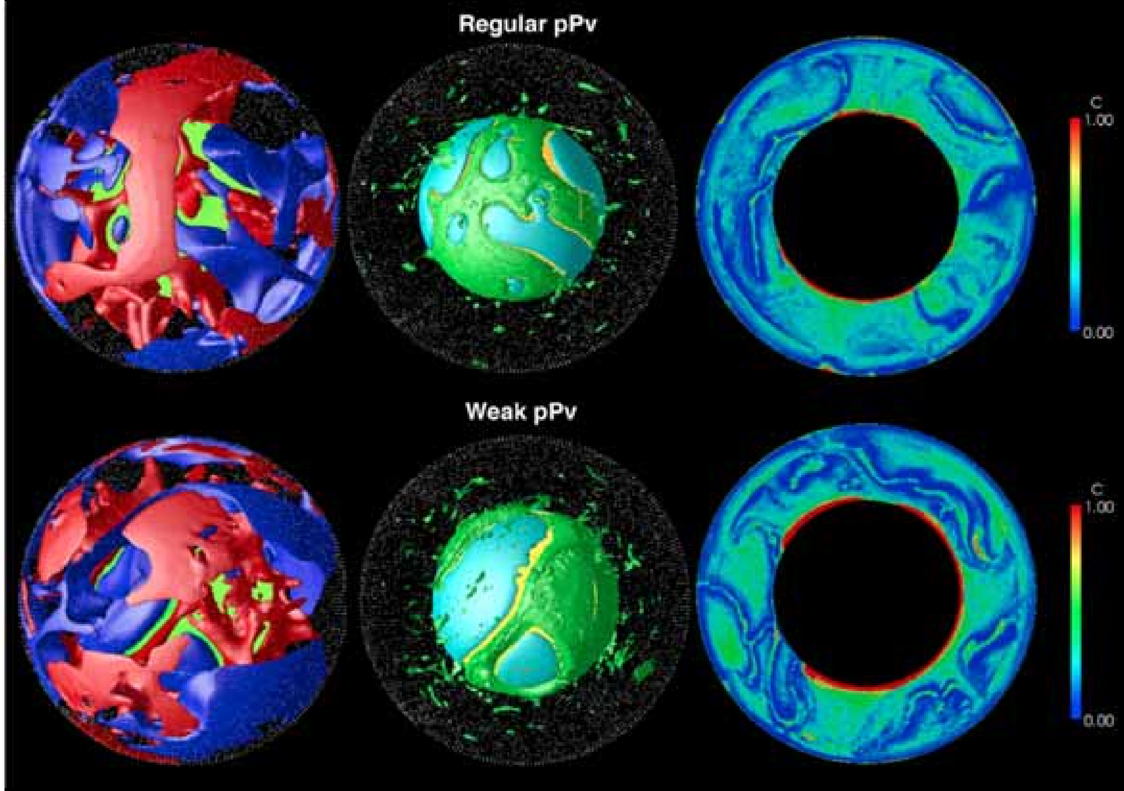


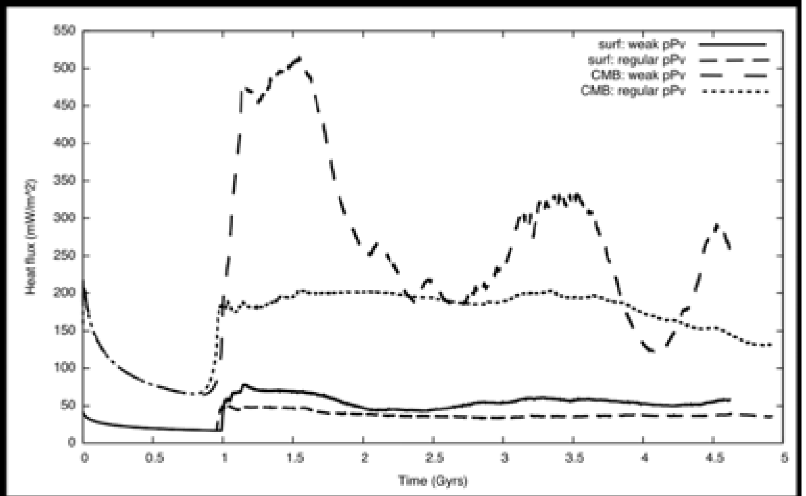
But significant influence if global layer



Low-viscosity post-perovskite can have big effect!

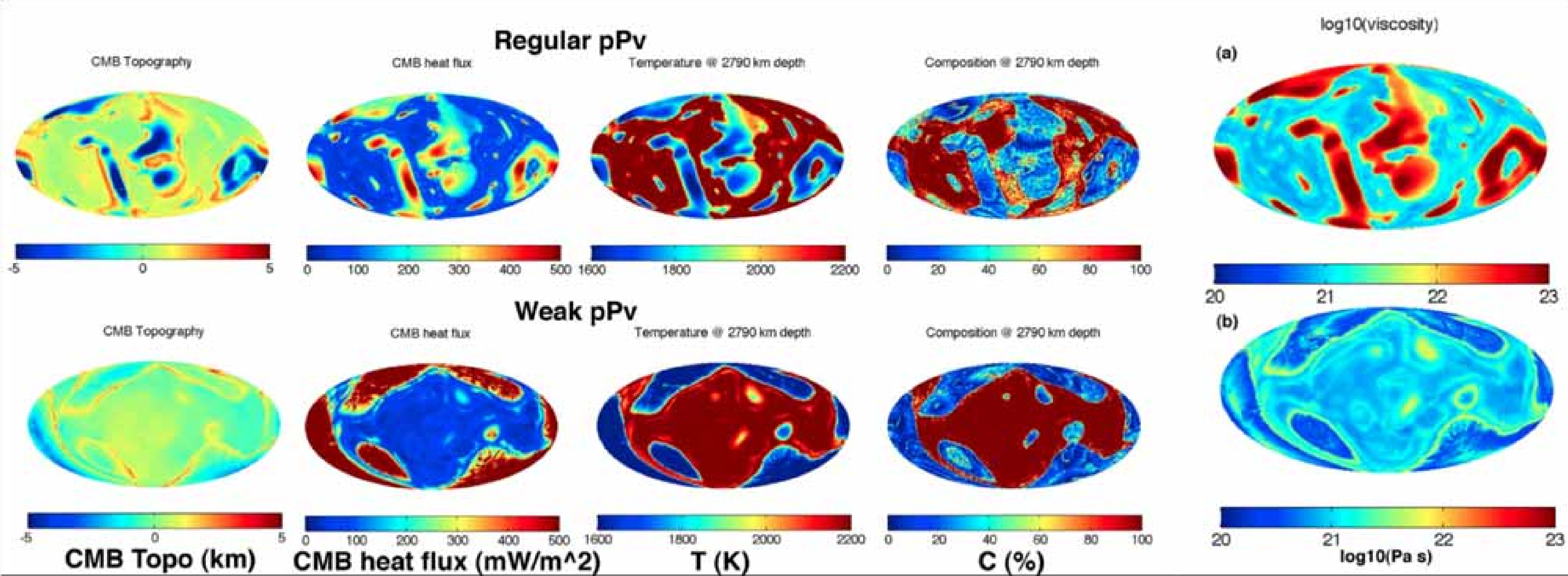
Increases overall convective vigour and amount of settled MORB





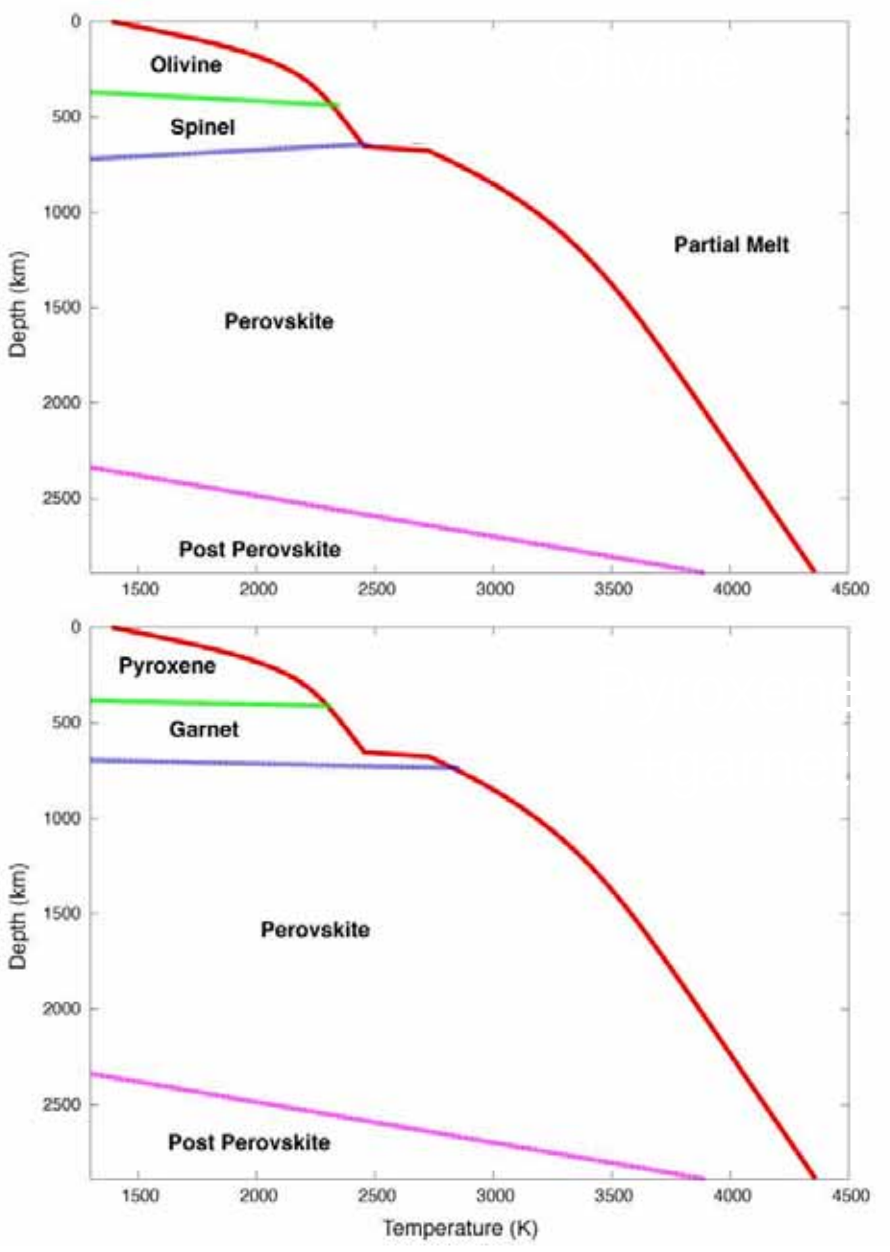
Nakagawa & Tackley 2011 GRL

…also reduces CMB topography & viscosity variations



Nakagawa & Tackley 2011 GRL

These studies parameterized phase transitions

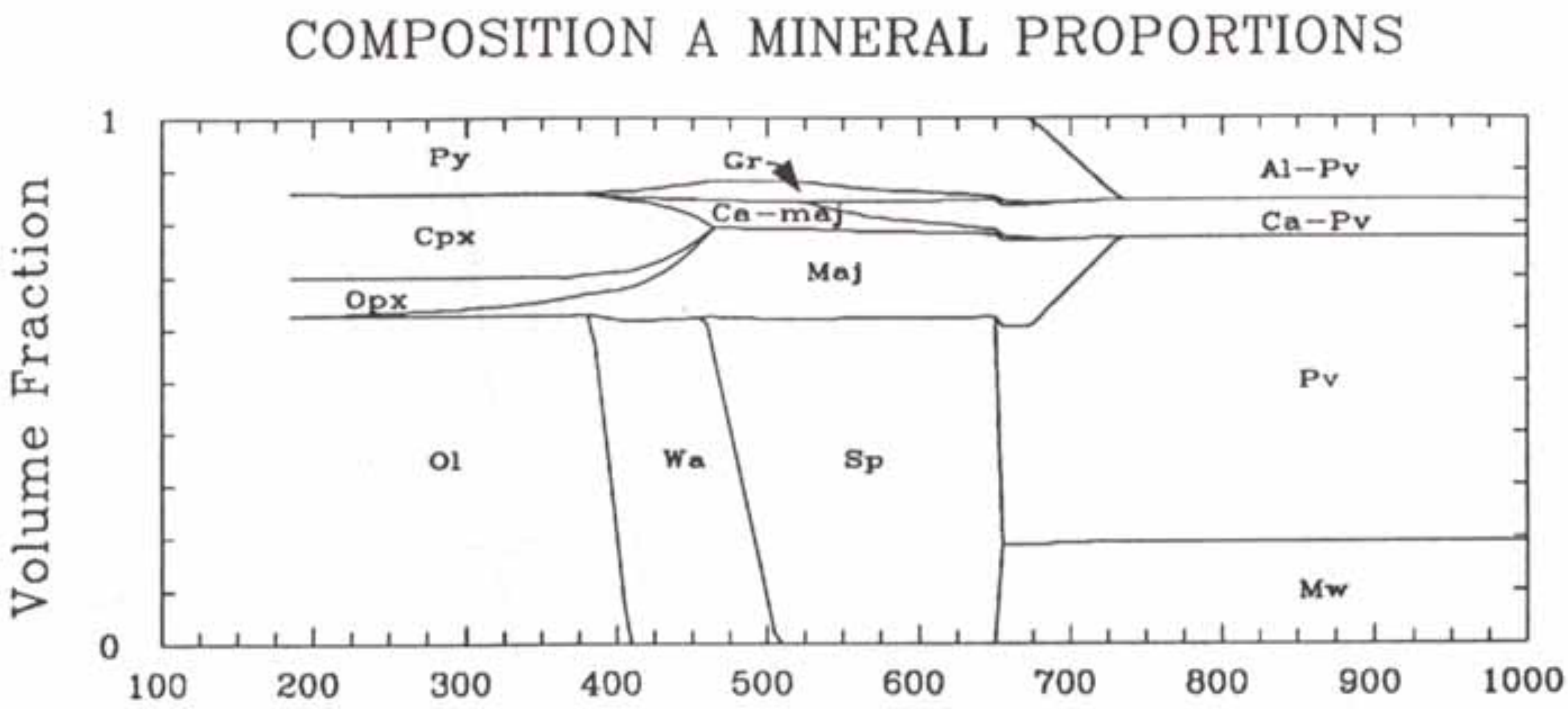


Input: Density jump and CS due to phase transitions into depth-dependence along with adiabat

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

Phase relationships of mantle materials

Hirose [2002]

$MgSiO_3$

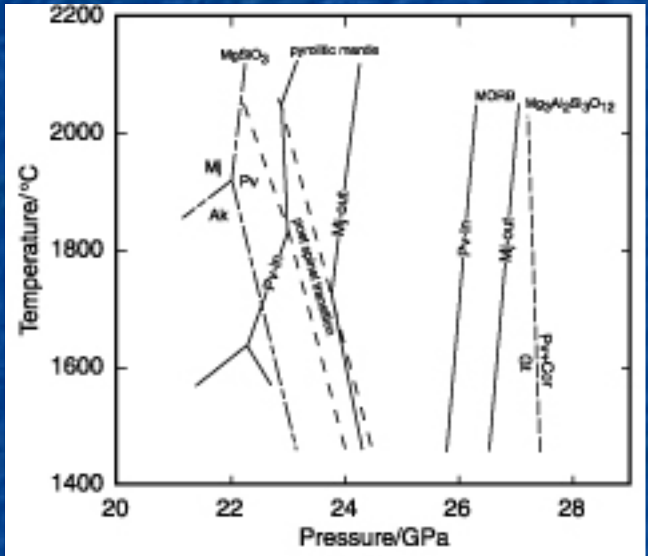


Figure 1. Majorite-perovskite transitions in different bulk compositions; majorite-perovskite transition in $MgSiO_3$ [*Hirose et al.*, 2001b]. Mg-perovskite-in and majorite-out curves in pyrolite (this study) and mid-ocean ridge basalt (MORB) [*Hirose et al.*, 1999], and garnet-perovskite plus corundum transition in $Mg_3Al_2Si_3O_{12}$ [*Hirose et al.*, 2001a]. The dashed lines indicate the postspinel phase boundary in pyrolite. Note that majorite-perovskite transition pressures are strongly dependent on the chemical composition, contrary to the postspinel phase boundary.

Mg_2SiO_4

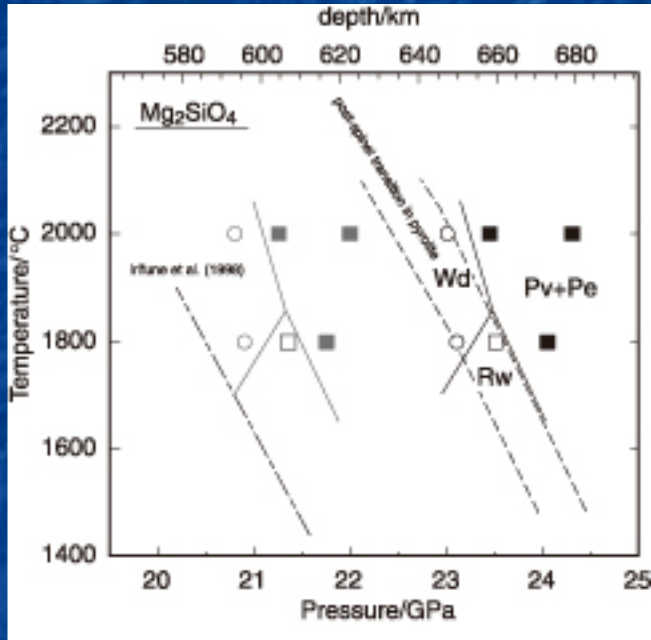


Figure 3. Phase boundaries in Mg_2SiO_4 determined in this study. The solid and shaded symbols are based on the *Jamieson et al.*'s [1982] and *Anderson et al.*'s [1989] gold pressure scales, respectively. The postspinel phase transition pressure based on the Jamieson et al.'s scale matches with the depth of the 670-km seismic discontinuity. The dashed lines indicate the postspinel phase boundary in pyrolite from Figure 4.

Mantle material: Complicated phase relationship under various P and T conditions

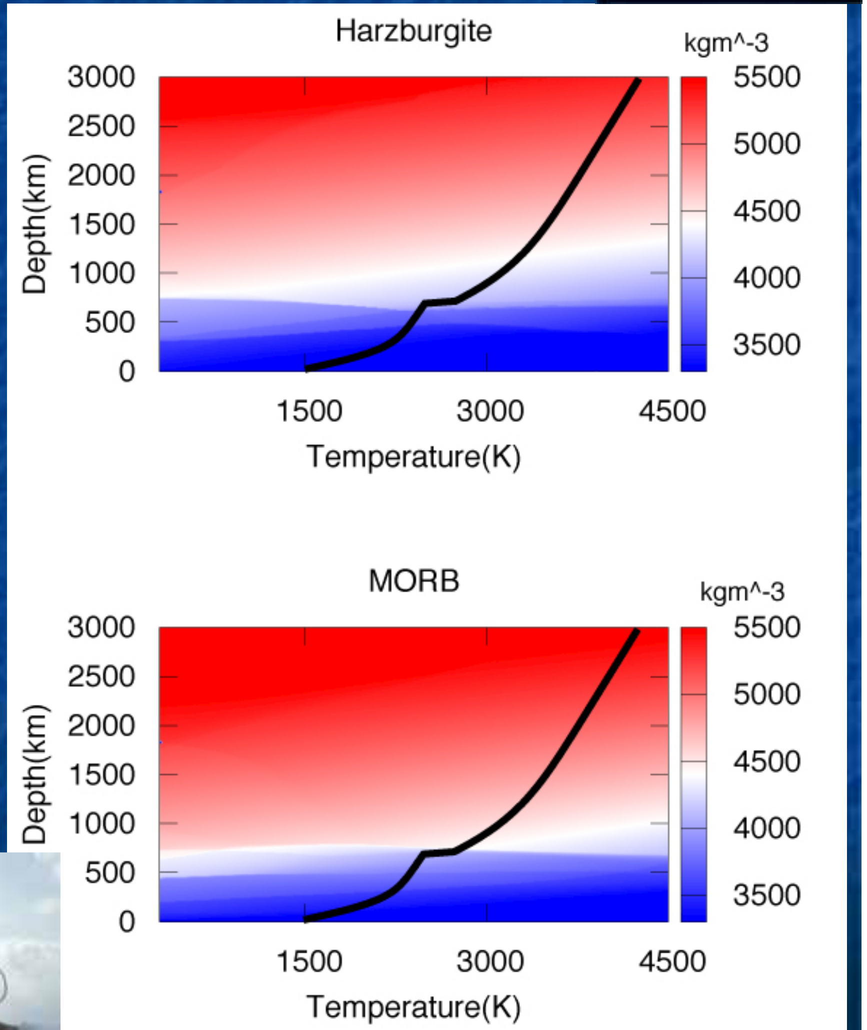
Generating realistic phase assemblages computationally

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

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

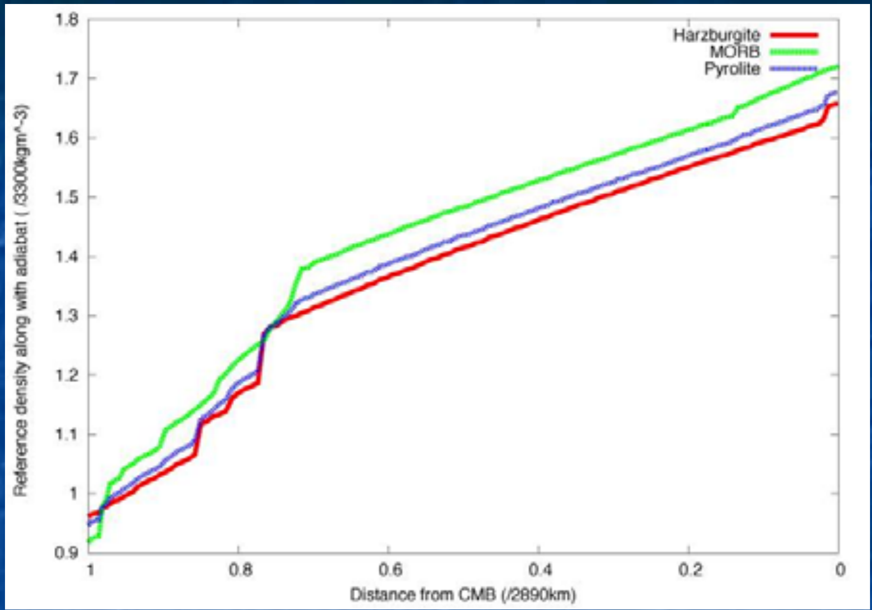
Data for components for two materials from [Stixrude and Lithgow-Bertelloni, 2005]

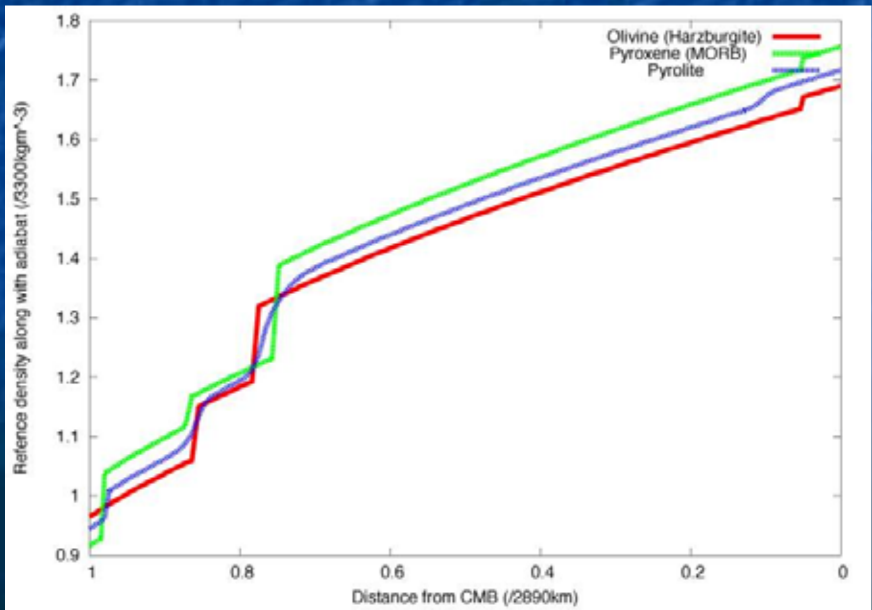
Component	Harzburgite (mol%)	MORB (mol%)
SiO_2	36.04	41.75
MgO	57.14	22.42
FeO	5.41	6.00
CaO	0.44	13.59
Al_2O_3	0.96	16.24



Solid line: Solidus

Reference density along an adiabat





Pyrolite: Combined two component via amount of MORB composition

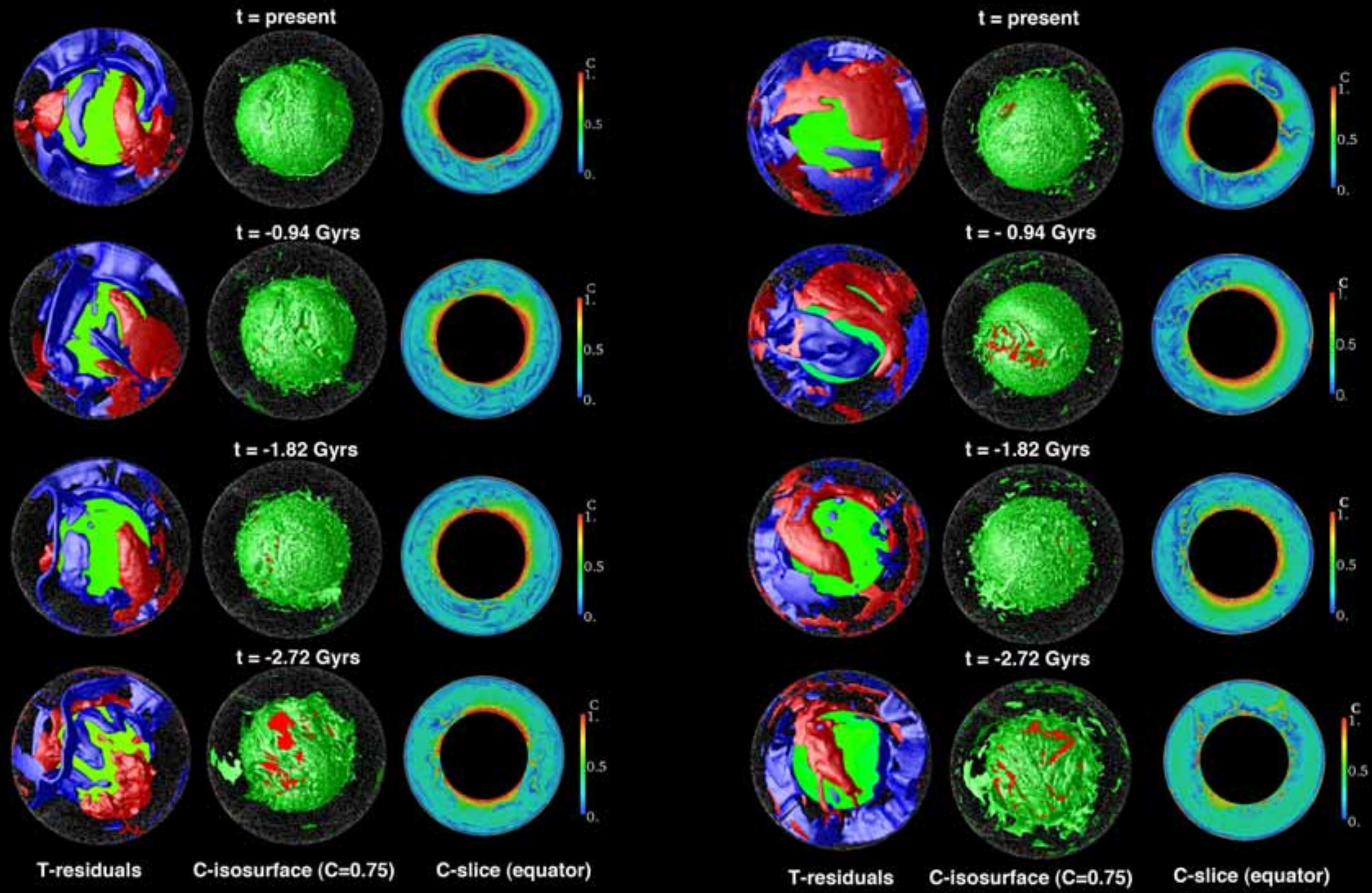
- Density difference @ CMB
= 2.7% between Harzburgite and MORB (PERPLEX)
=3.6% (Linearized)
= 2.16% between MORB and Pyrolite (PERPLEX)
=2.32% (Linearized)

- Olivine-Wadsleyite-Ringwoodite-Perovskite-pPv
- Px-gt(il or ak)-pv: gradual
-pPv: close to CMB (2800km depth ?)

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

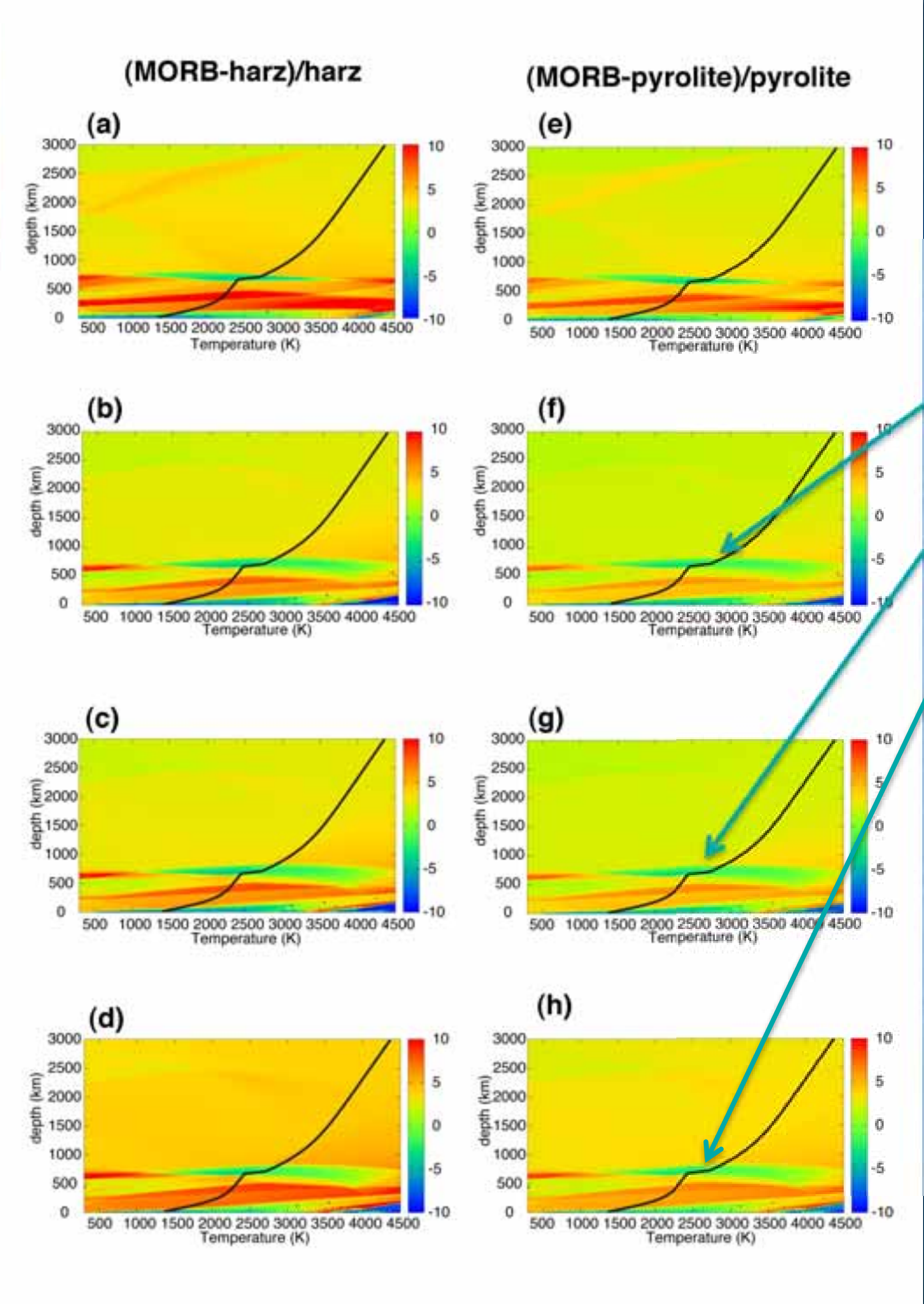
4 different compositions (Nakagawa & me 2010 EPSL)

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

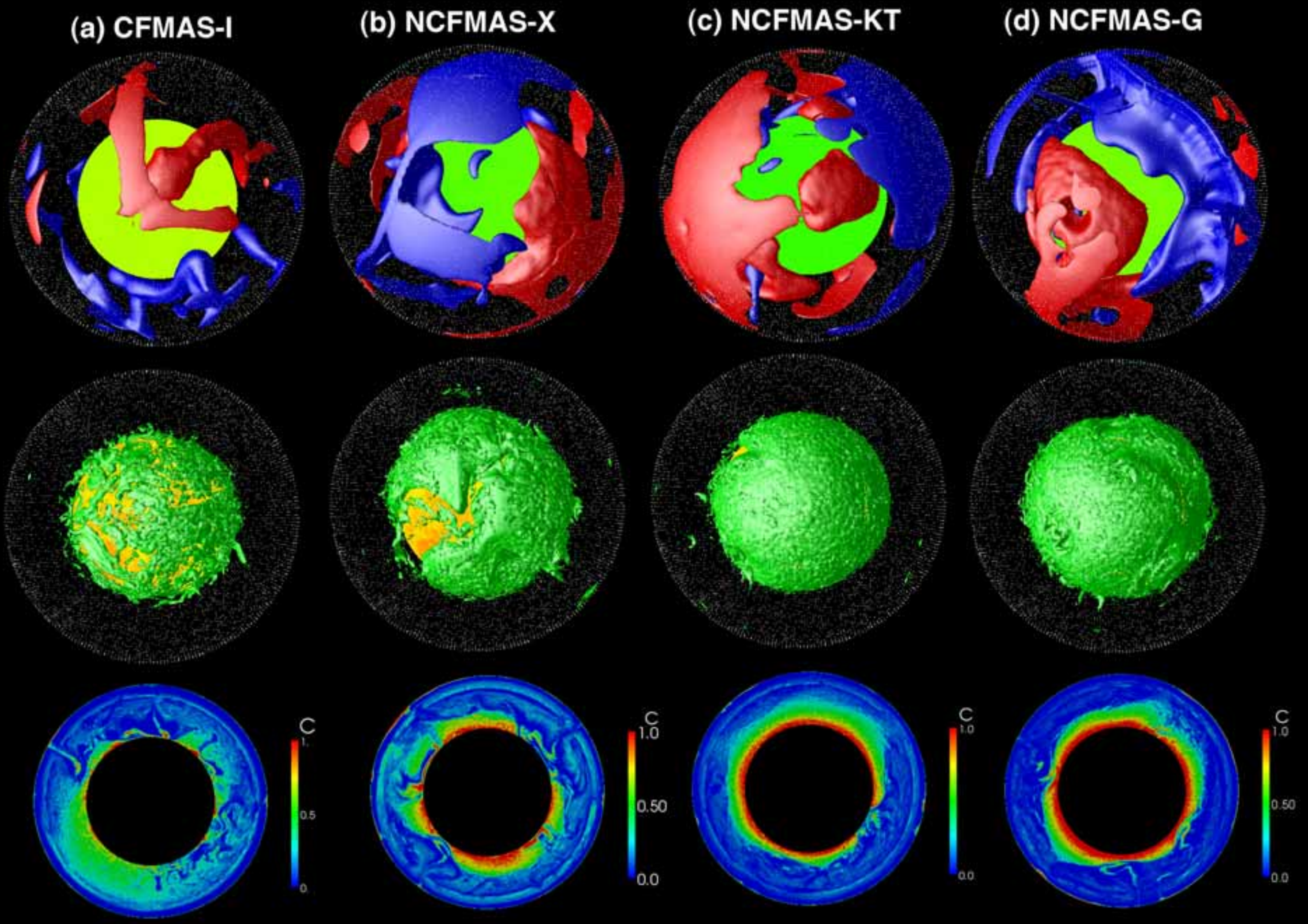
Xu et al.

Khan et al.

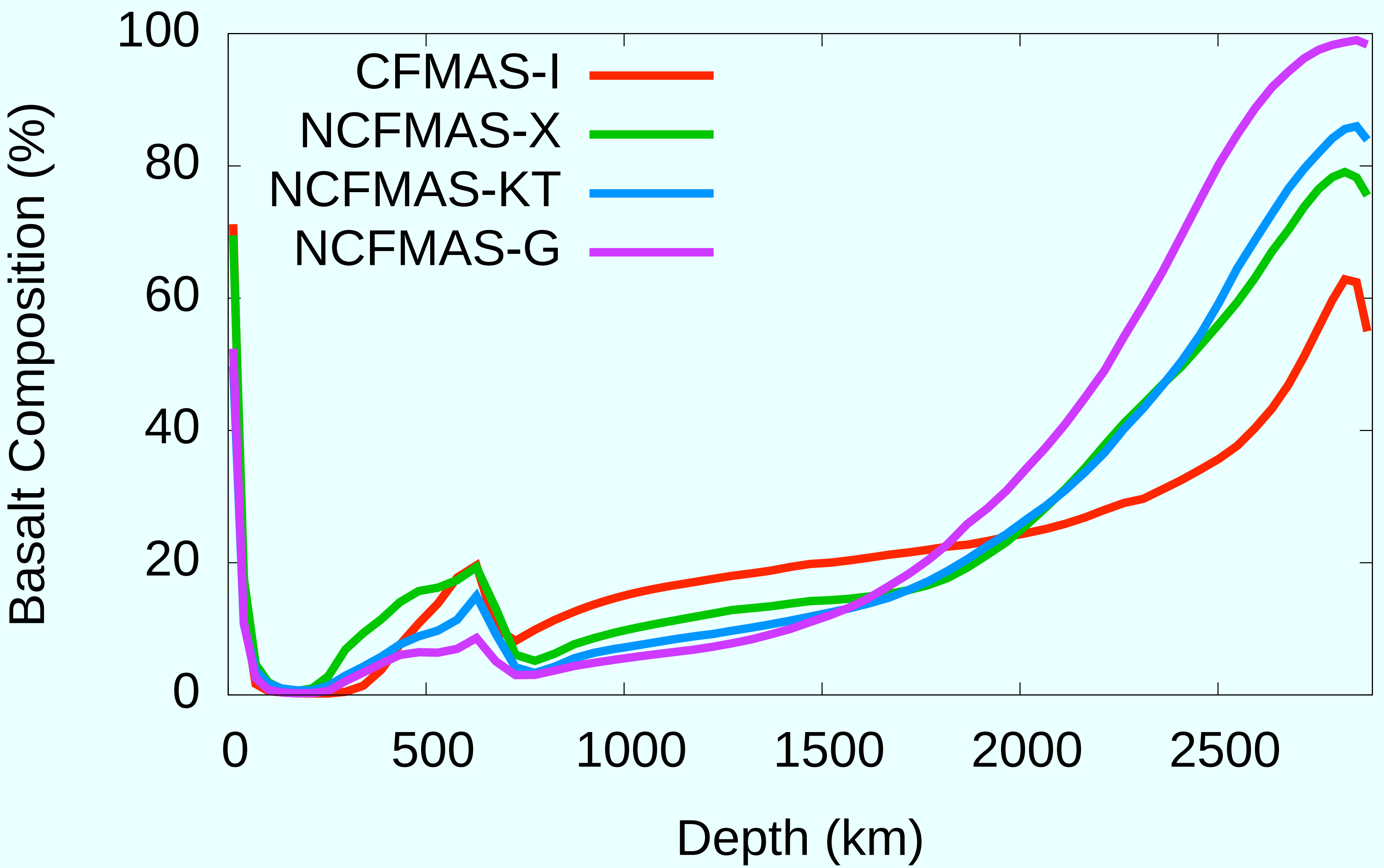
Ganguly et al.

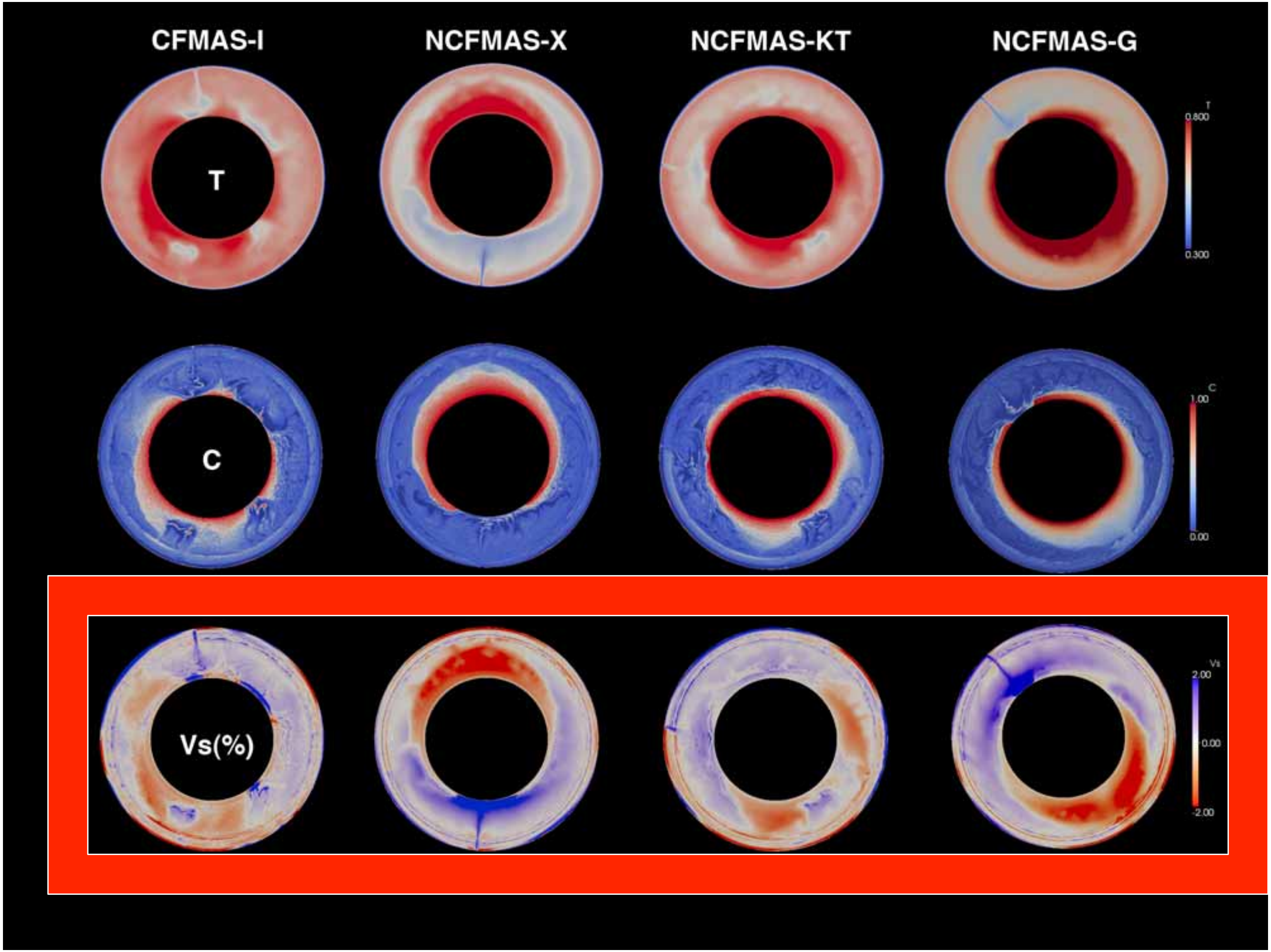
Unit %

MORB composition makes a difference!



Radial compositional structure

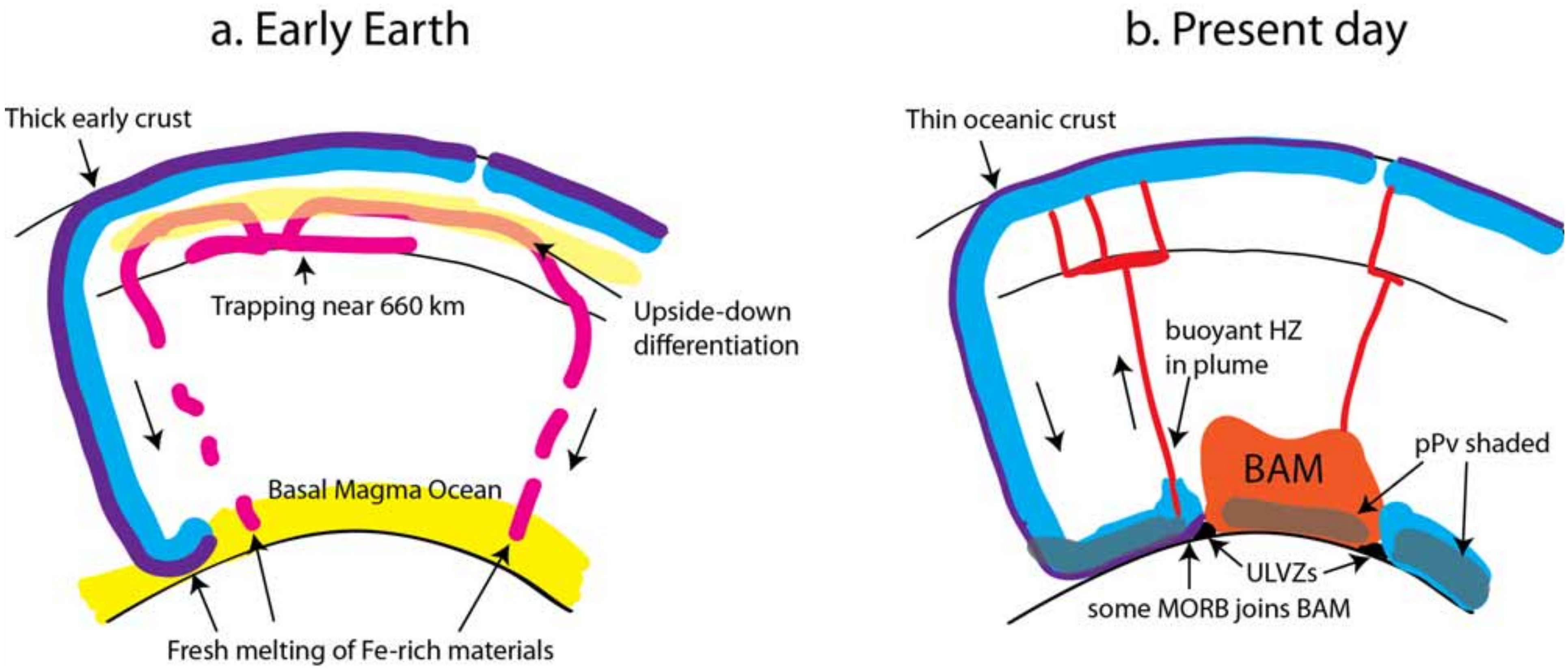



CFMAS-I
NCFMAS-X
NCFMAS-KT
NCFMAS-G
T
C
Vs(%)
T
0.800
0.300
C
1.00
0.00
Vs
2.00
0.00
-2.00

Summary

- Basal Mélange (BAM): mixture of materials above the CMB in 2 main ‘piles’
- Slab-CMB interaction
  - Basalt-side down preferred
  - Depleted residue starting plumes, MORB entrained by plume tails
  - Large basalt separation if existing BAM layer
- Long-term evolution
  - MORB density contrast critical
  - Layering influences core evolution
  - Initial condition unimportant unless a global layer
  - Weak pPv can dramatically change things
  - Exact compositions do matter!
- Future: include melt phase

Thank you for listening!



Tackley, ESR subm