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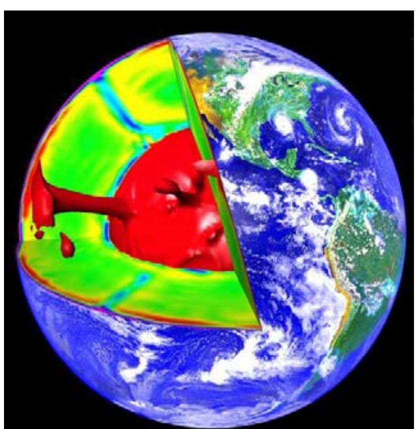
Dynamics and Structure of the Mantle

Paul J. Tackley

(ETH Zürich)



Mantelkonvektion mit Plattentektonik und Kontinentaldrift auf der Erde

Mantle Convection with Plate Tectonics and Continental Drift on Earth

Movie by:

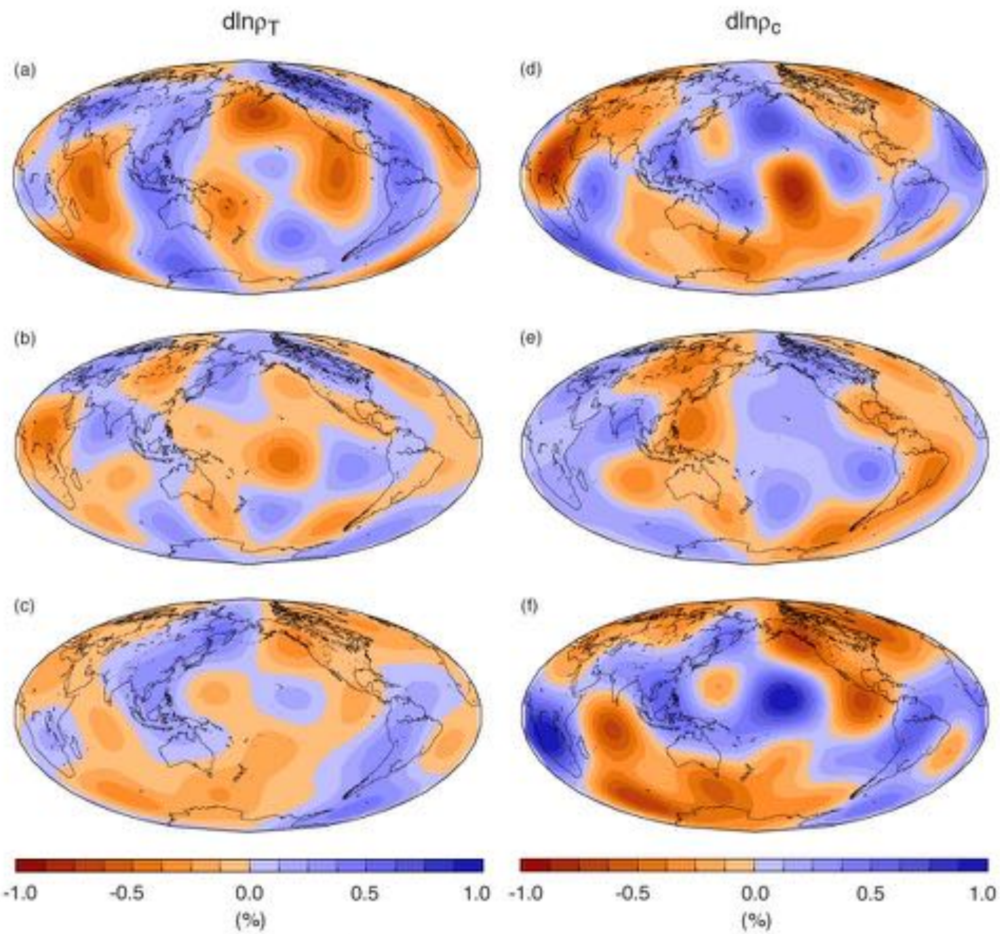
Tobias Rolf, Antoine Rozel, Paul Tackley

https://gfd.ethz.ch

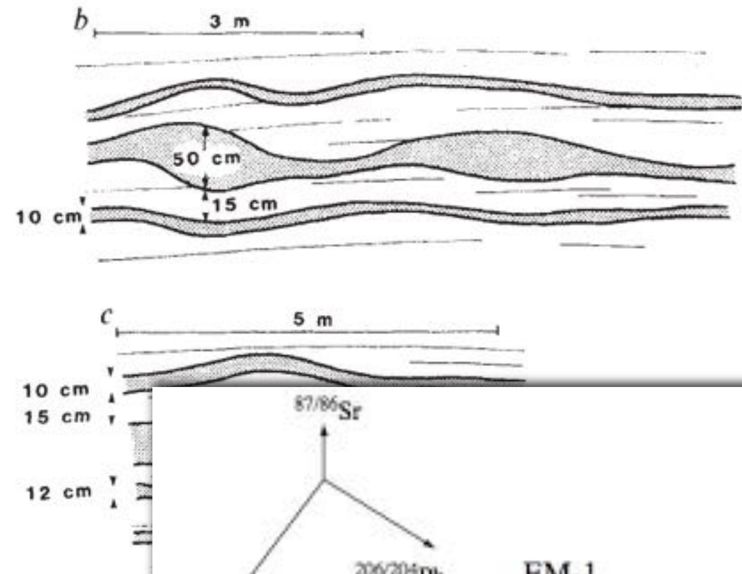
Overview

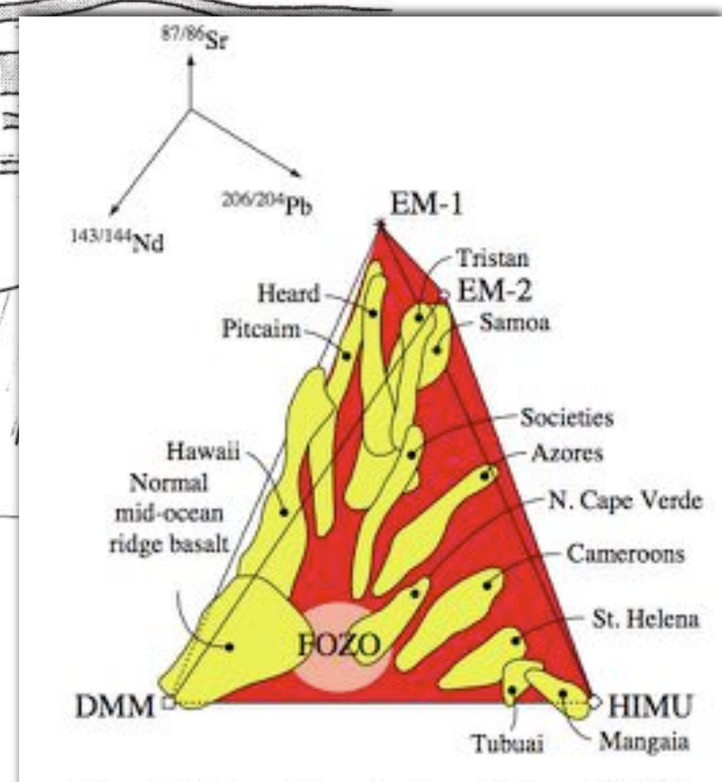
- Concepts & cartoon models
- Tectonics: recent and early Earth
- Recyled crust & Earth evolution
- Importance of compositional viscosity contrast on deep mantle structure & dynamics

Compositional variations exist at all scales! …and are a result of (partial) melting

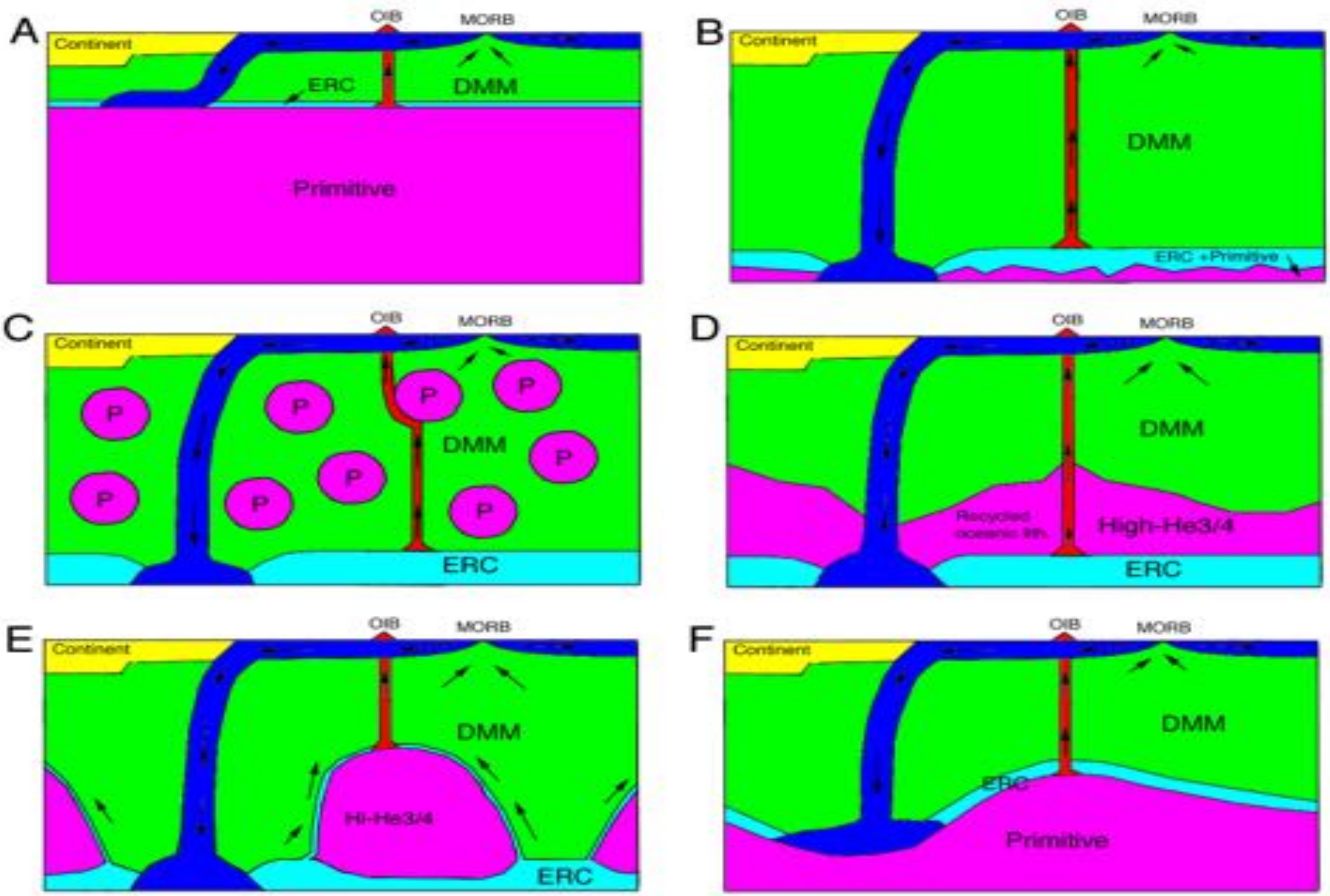


Deschamps, Trampert, Tackley (2005)





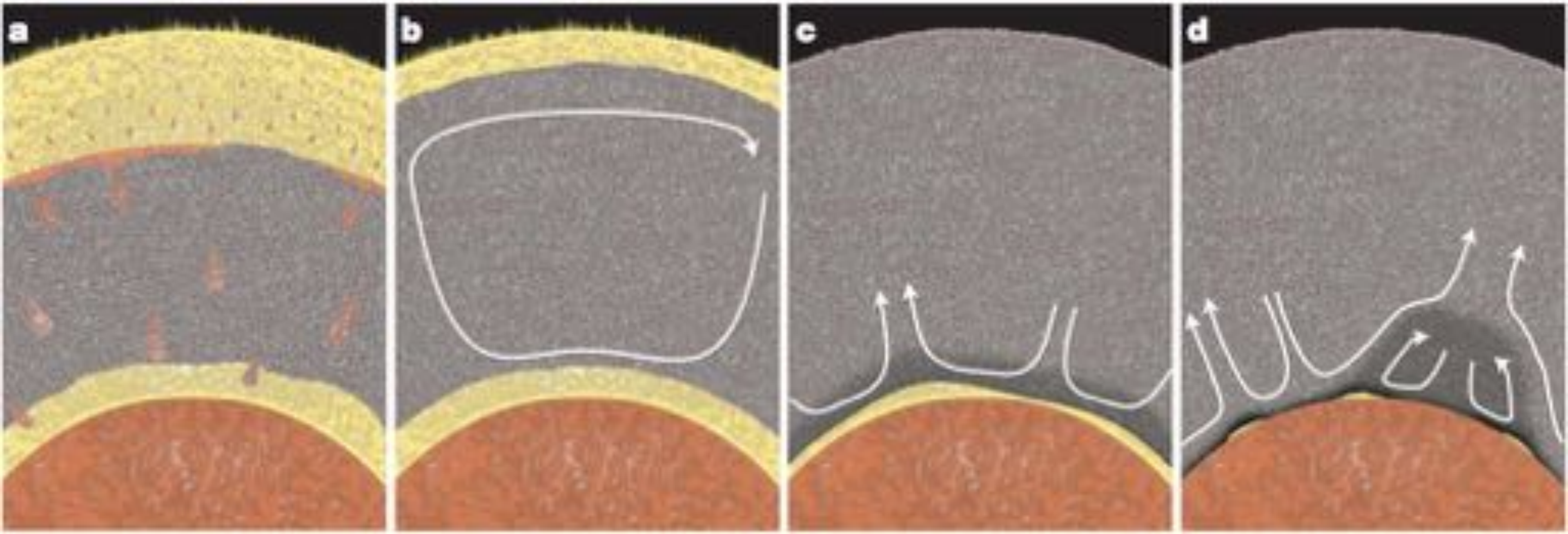
Geochemical mantle: Old cartoons (2000)



from Tackley, Science, 2000: Figure 2

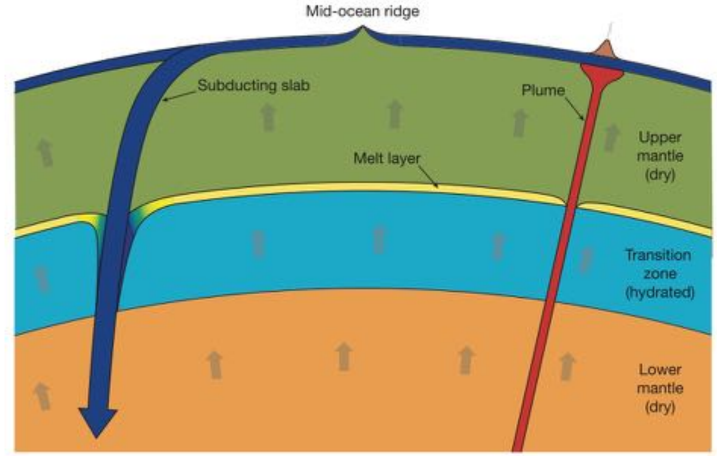
Long-term persistence of melting: Basal Magma Ocean

Labrosse et al., 2007



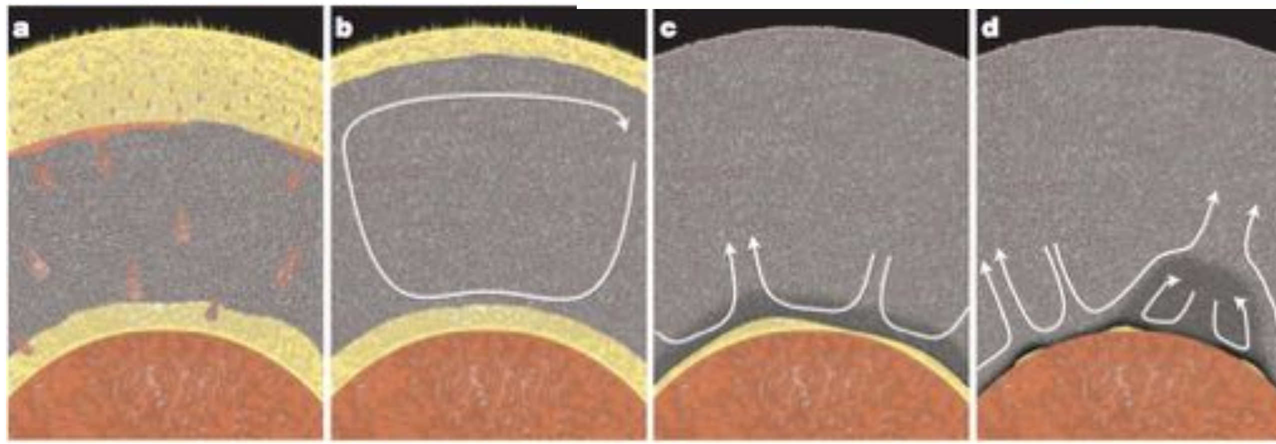
Early Earth Present day

Deep melting: cartoon models

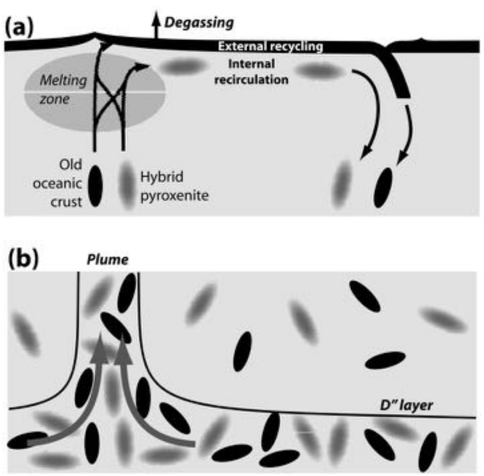


Transition Zone Water Filter
Bercovici & Karato 2003

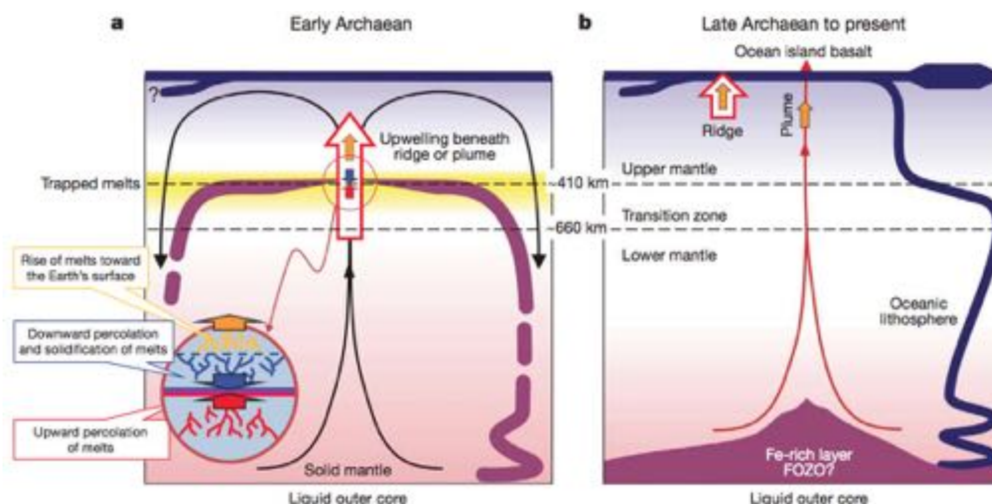
Basal Magma Ocean
Labrosse et al., 2007



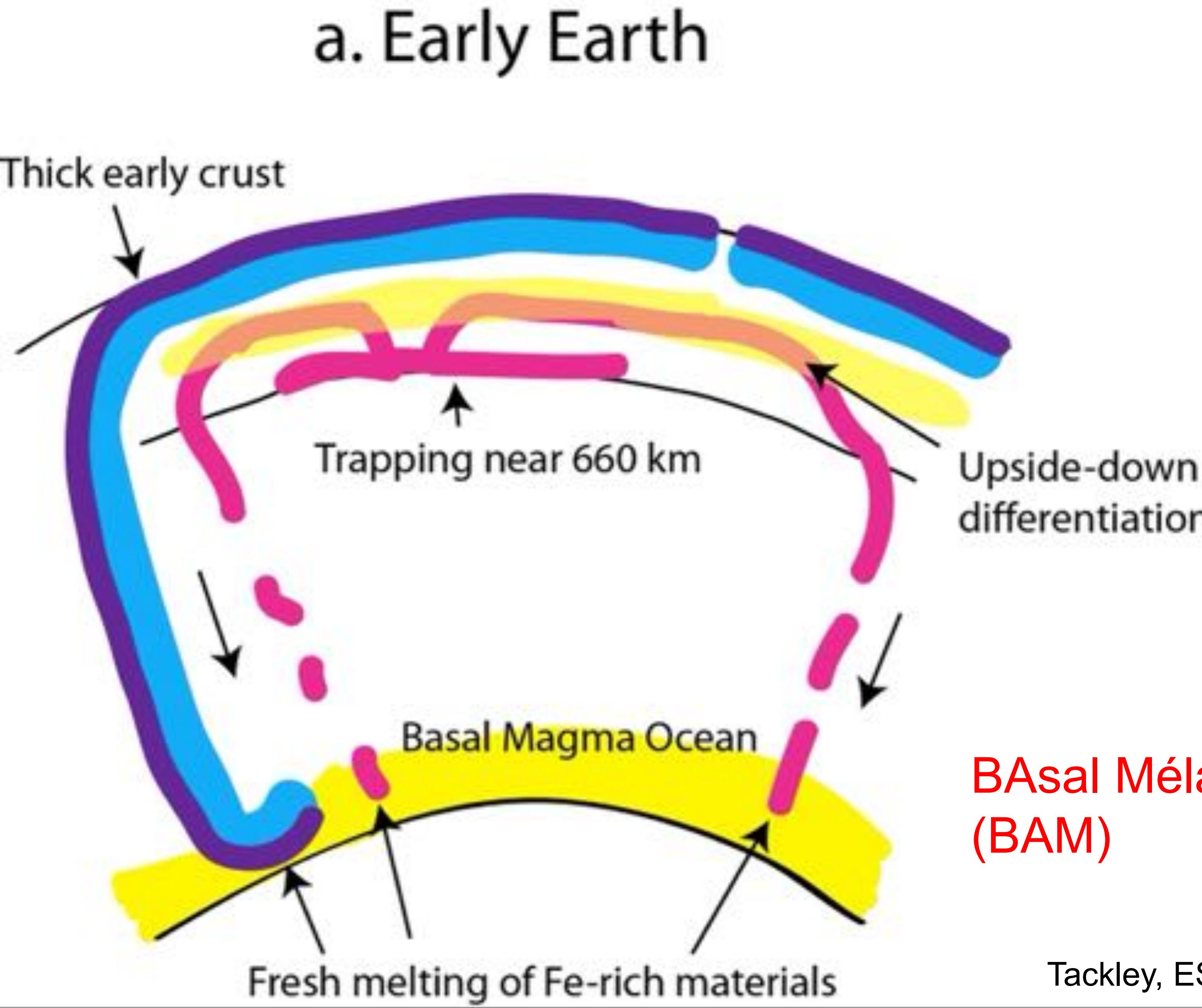
Davies 2009



Upside-down differentiation
Lee et al
2010



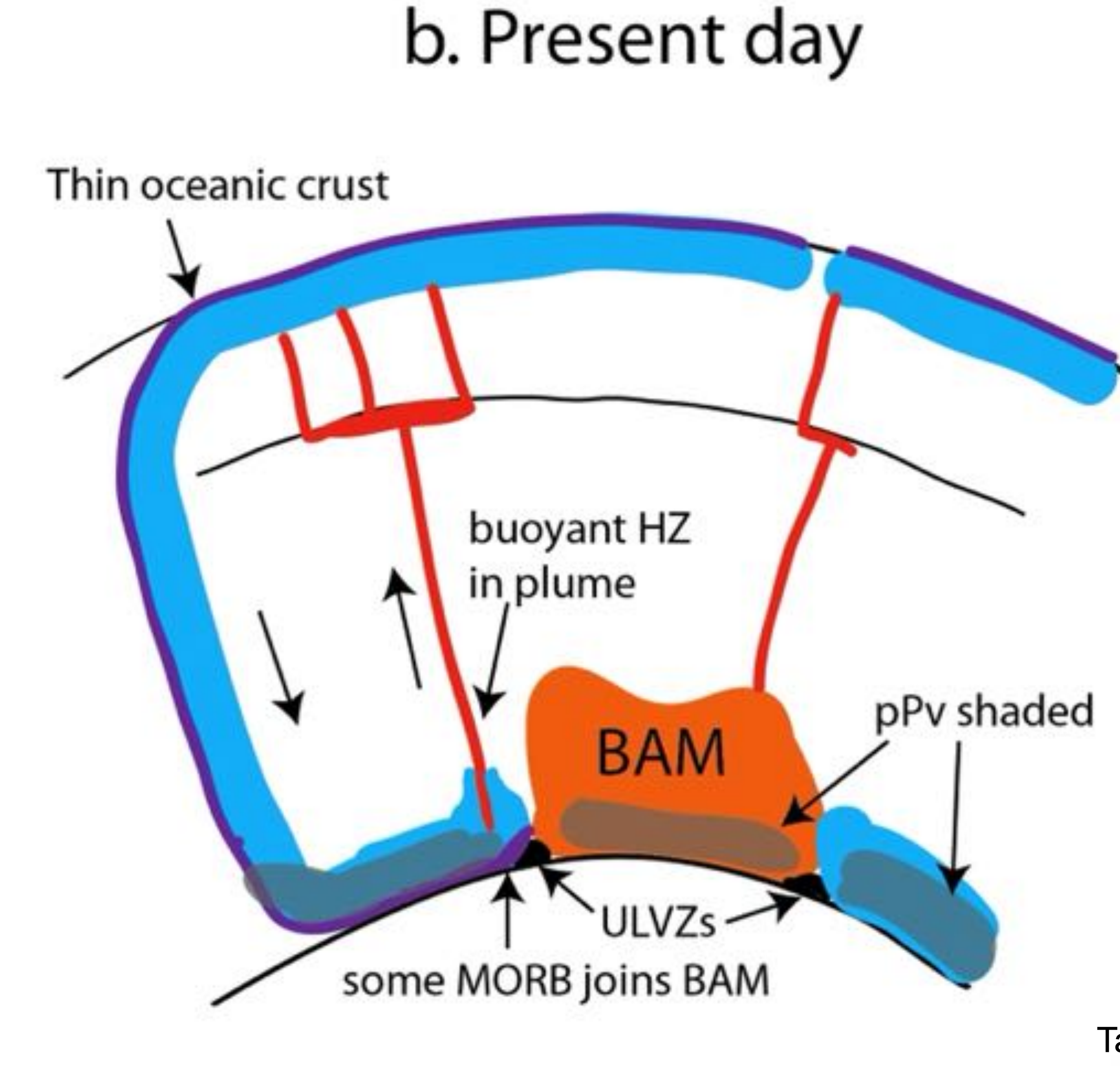
More than one process operating!



BAsal Mélange (BAM)

Tackley, ESR 2012

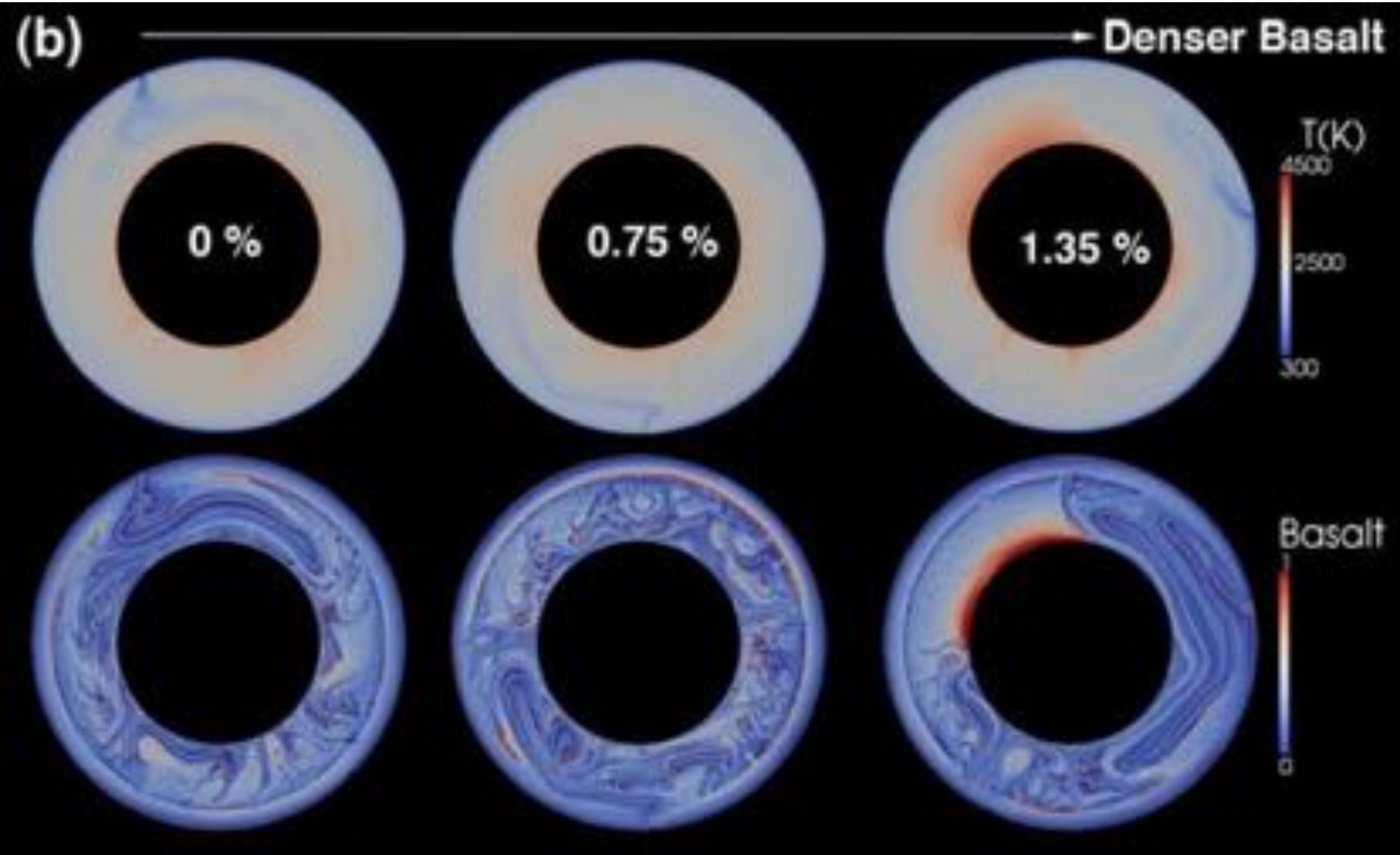
More than one process operating!



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

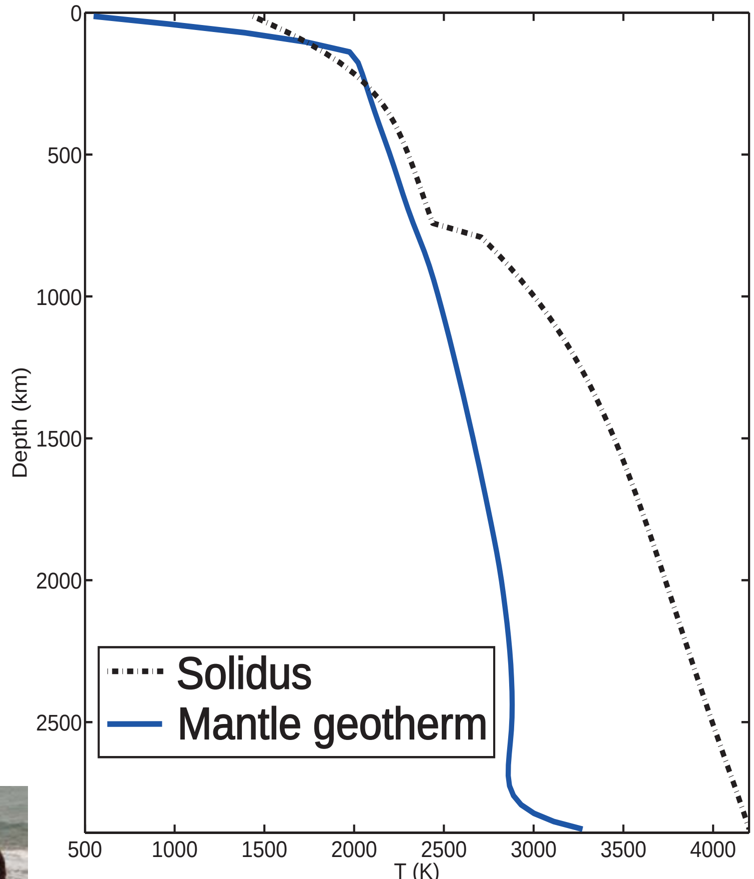
Tackley, ESR 2012

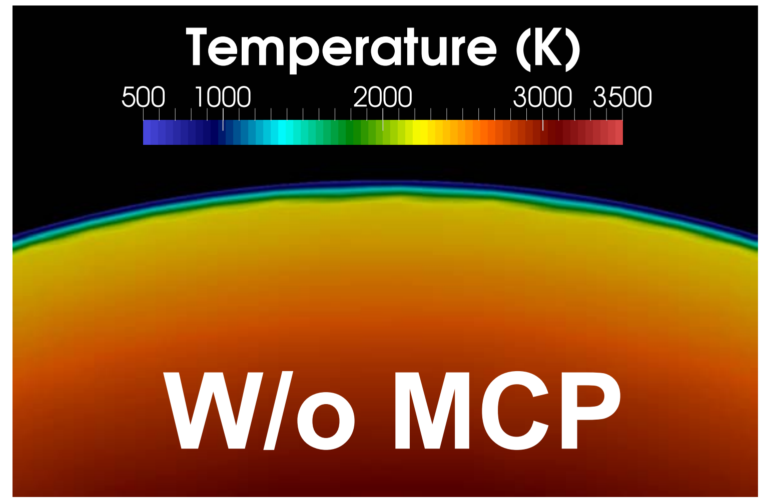
Production of oceanic crust by partial melting

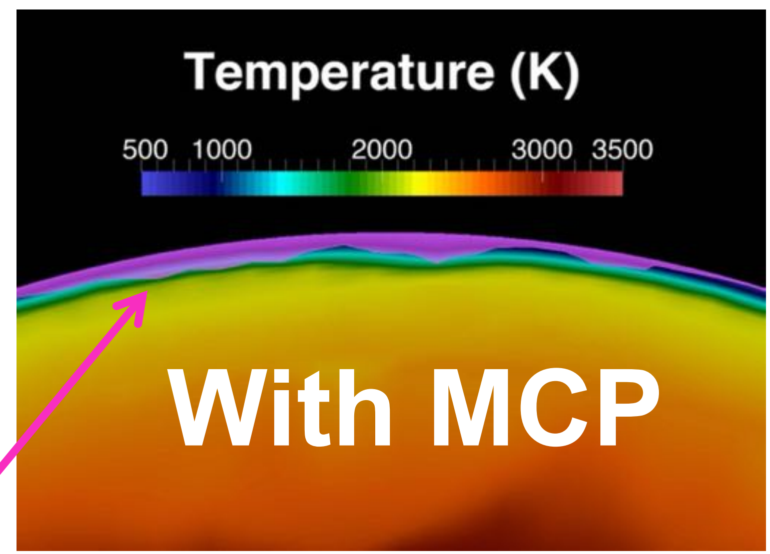


Numerical and physical model

Melting-induced crustal production (MCP)







Basaltic crust

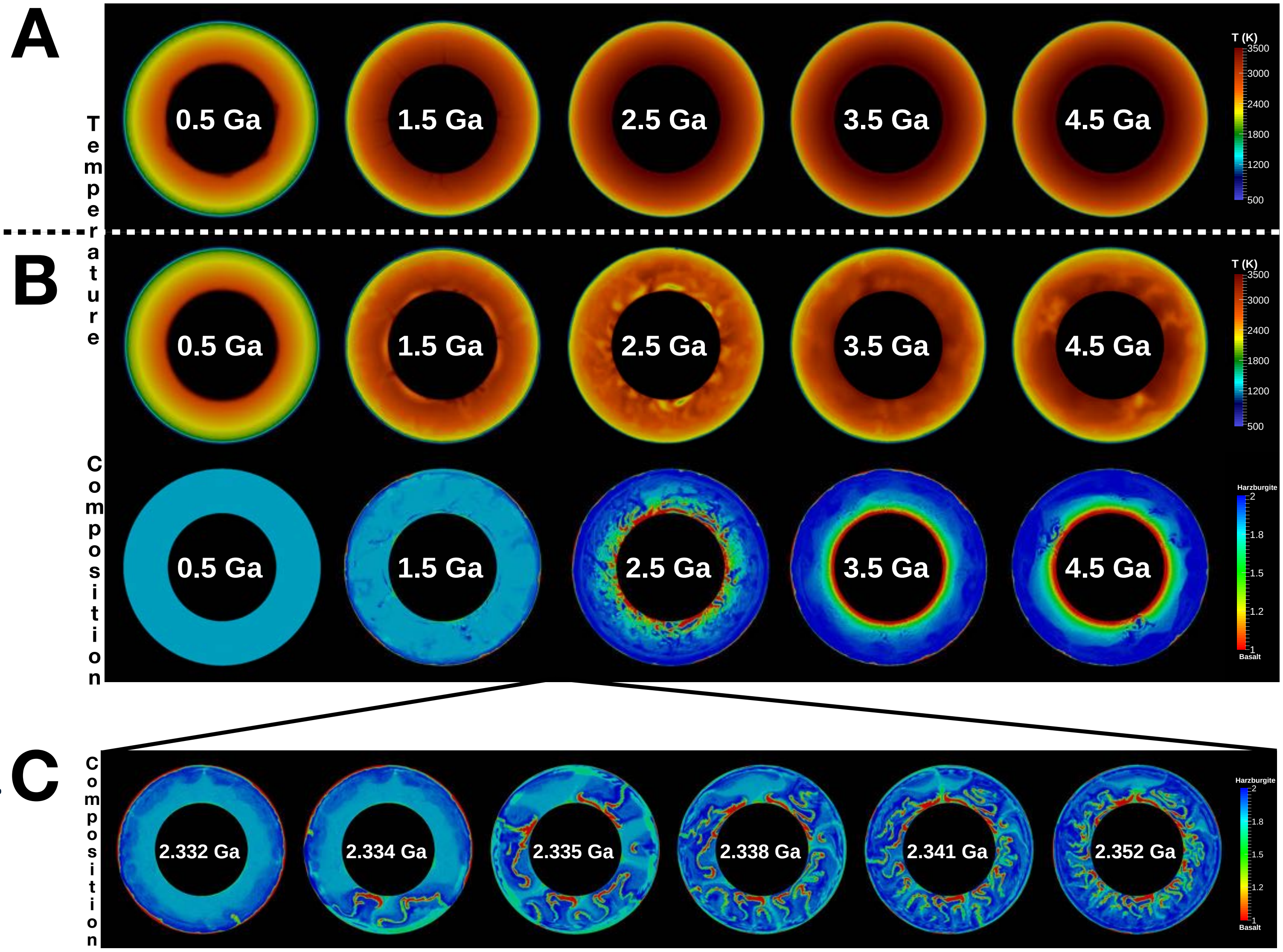
Diogo Lourenco

Magmatism->crust helps plate tectonics

Purely thermal
-> Stagnant

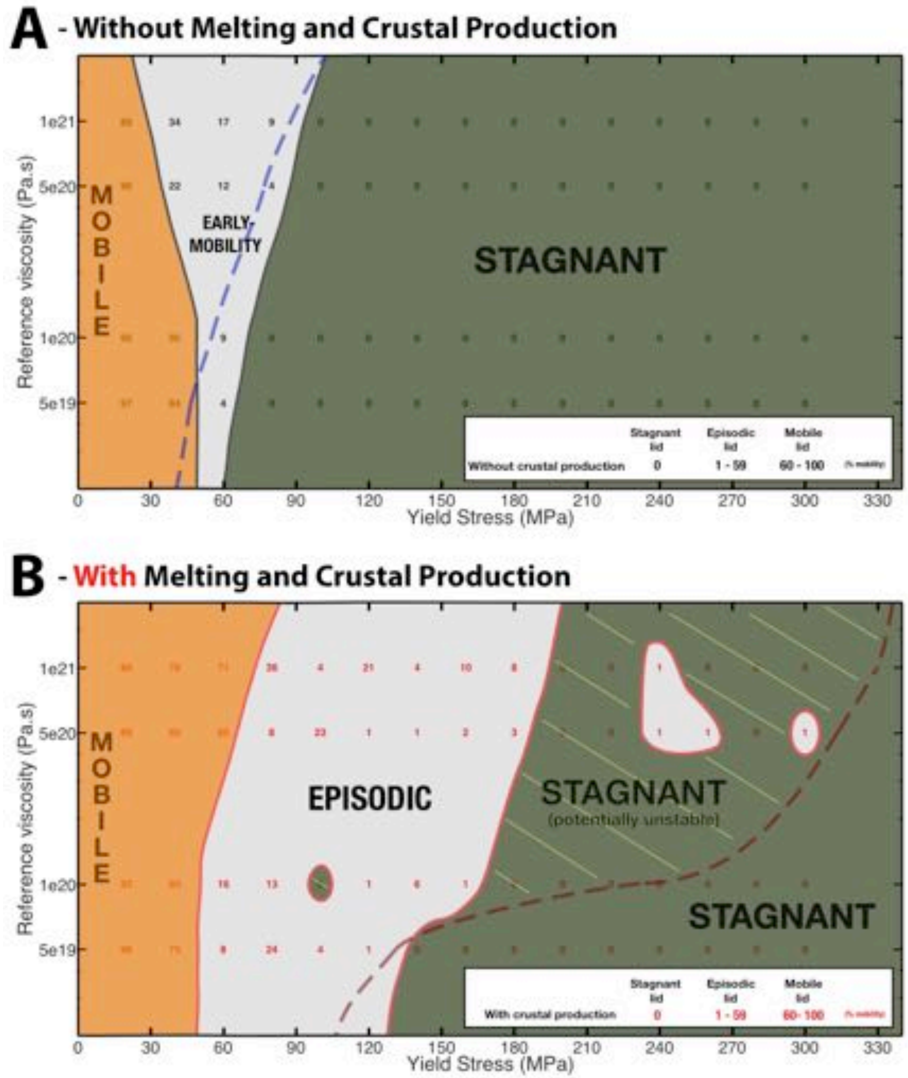
With magma & crust
Episodic plate tectonics

Diogo Lourenco A. Rozel & Tackley, EPSL 2016



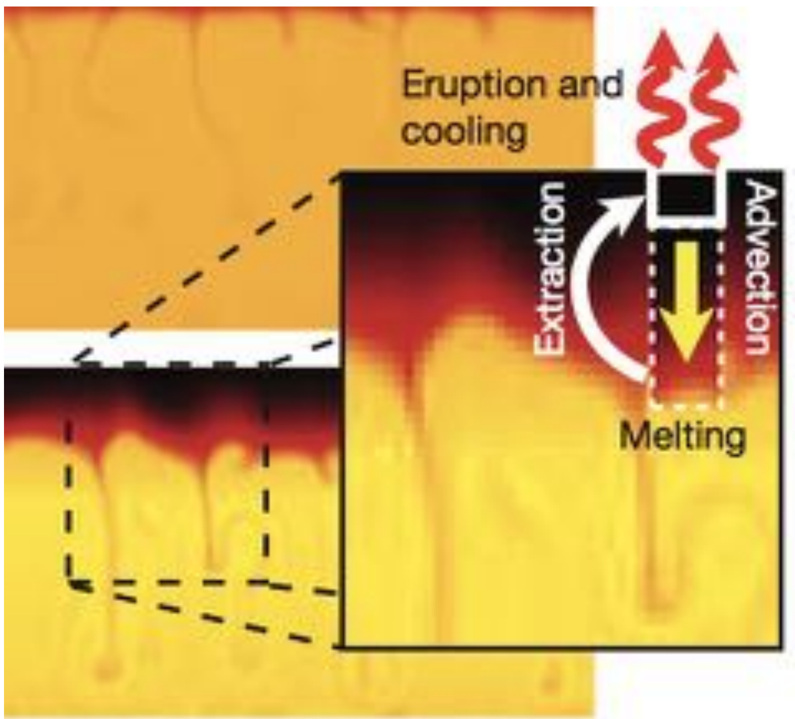
Melting + crustal production makes stagnant lid less likely

Lourenco et al., EPSL 2016



08/04/2014

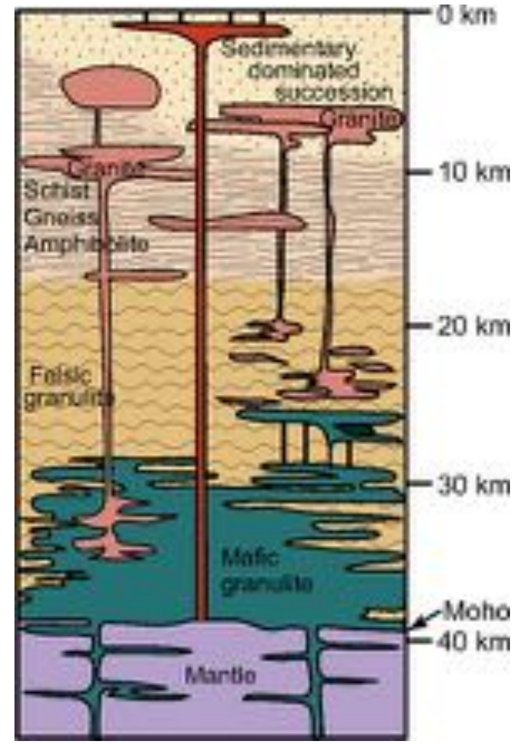
Extrusive heat pipe magmatism



(picture from Moore&Webb 2013)

-> COLD, STRONG crust/lithosphere

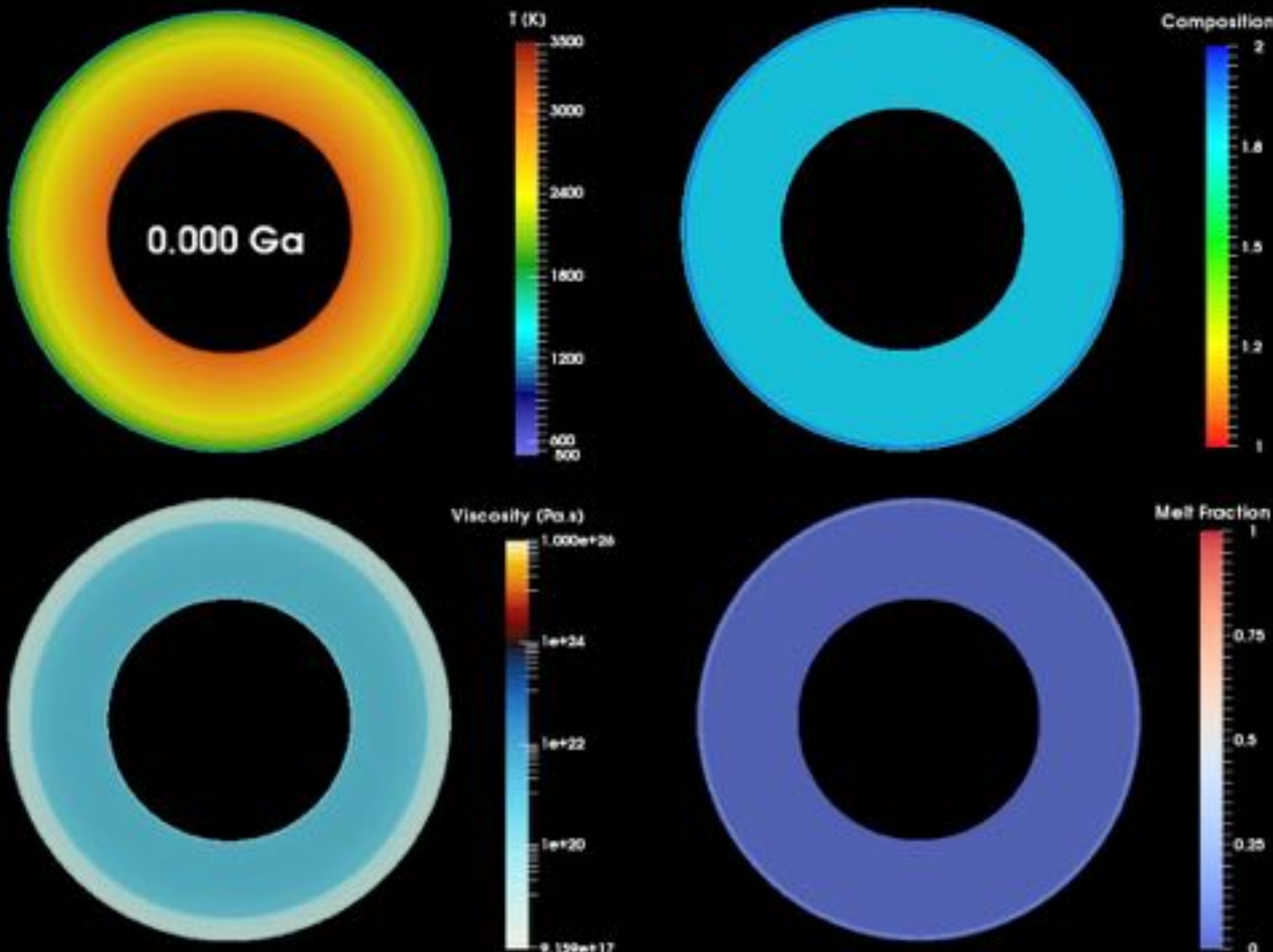
But probably most magmatism is intrusive



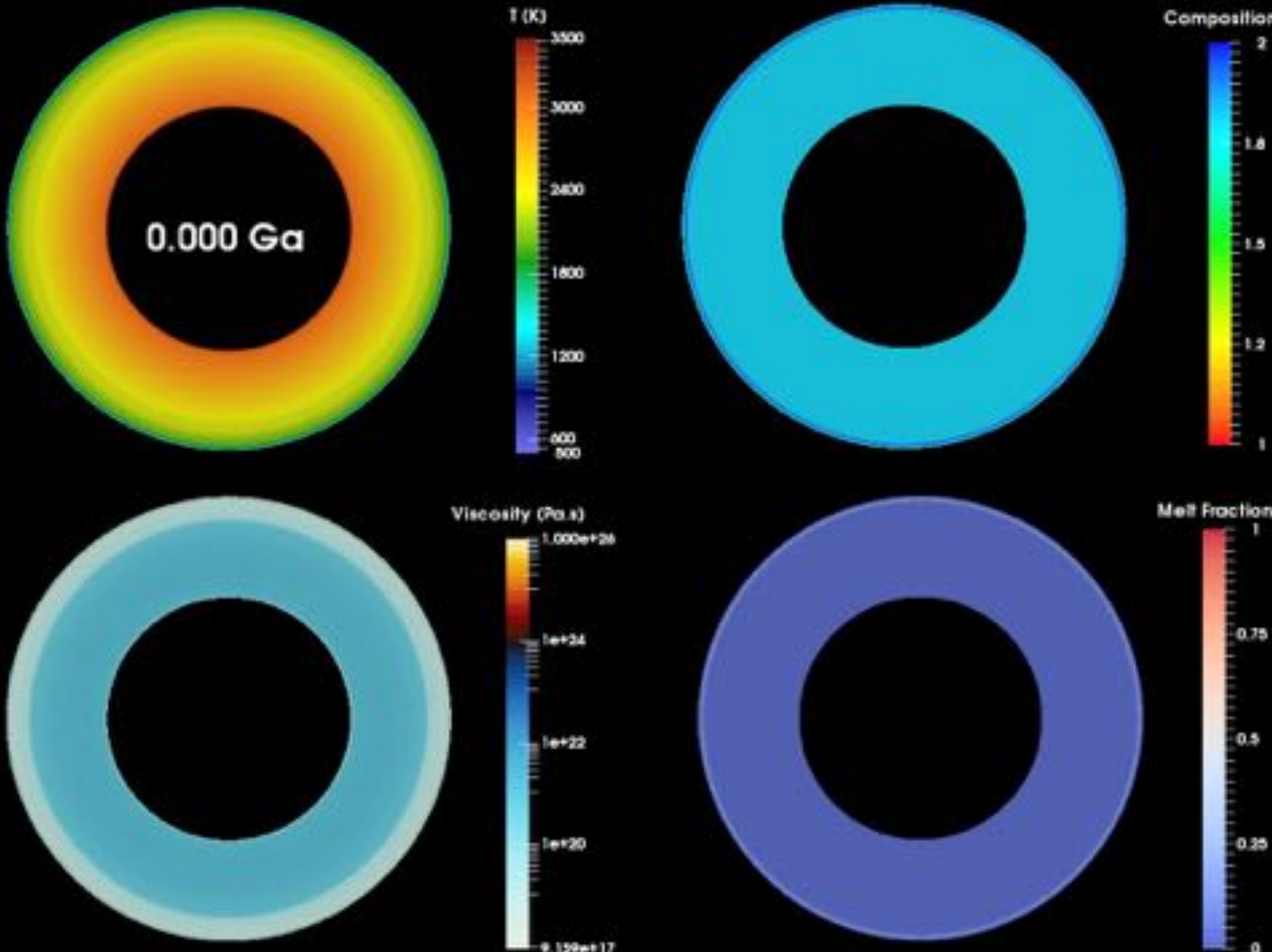
(picture from Cawood et al 2013)

-> WARM, WEAK crust/lithosphere

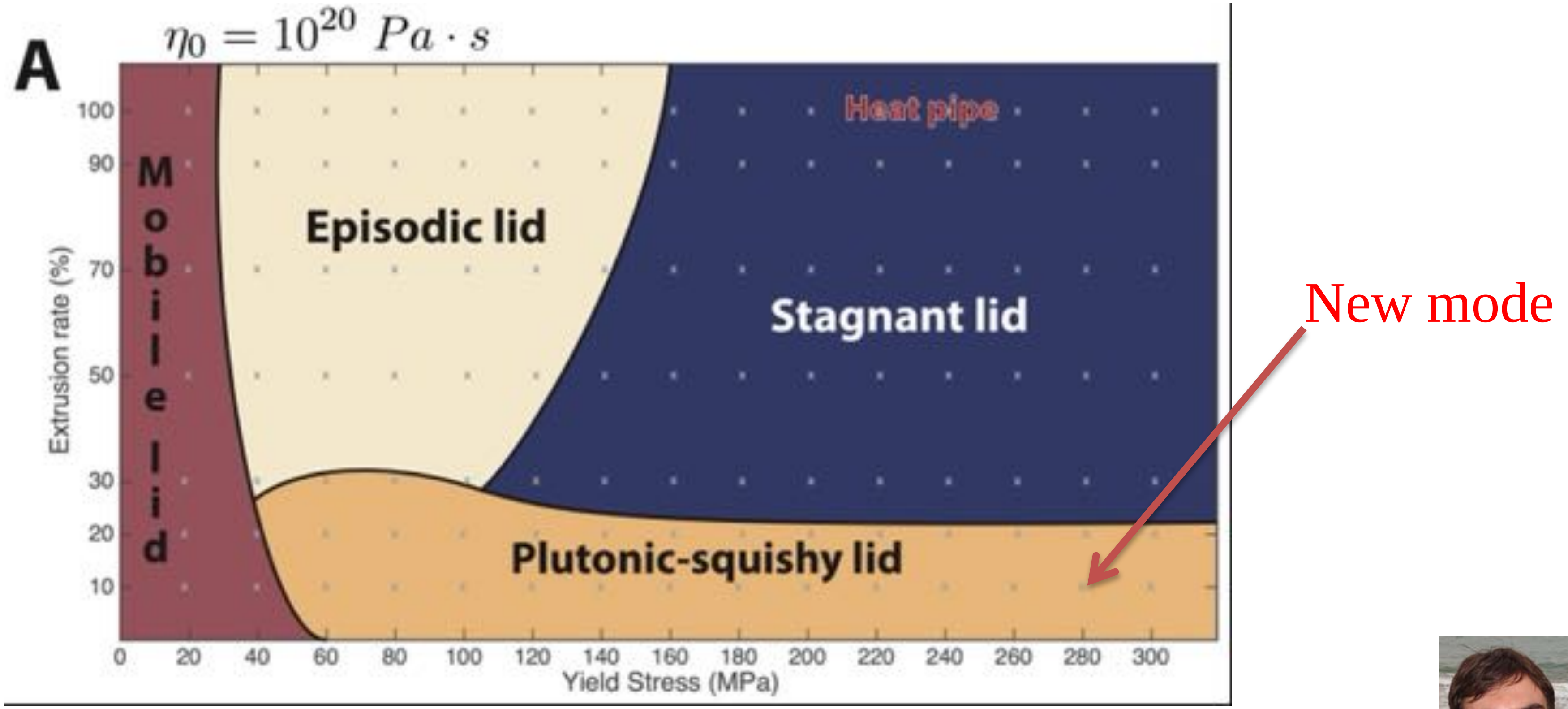
Typical episodic evolution - extrusive



In comparison – 90% intrusive

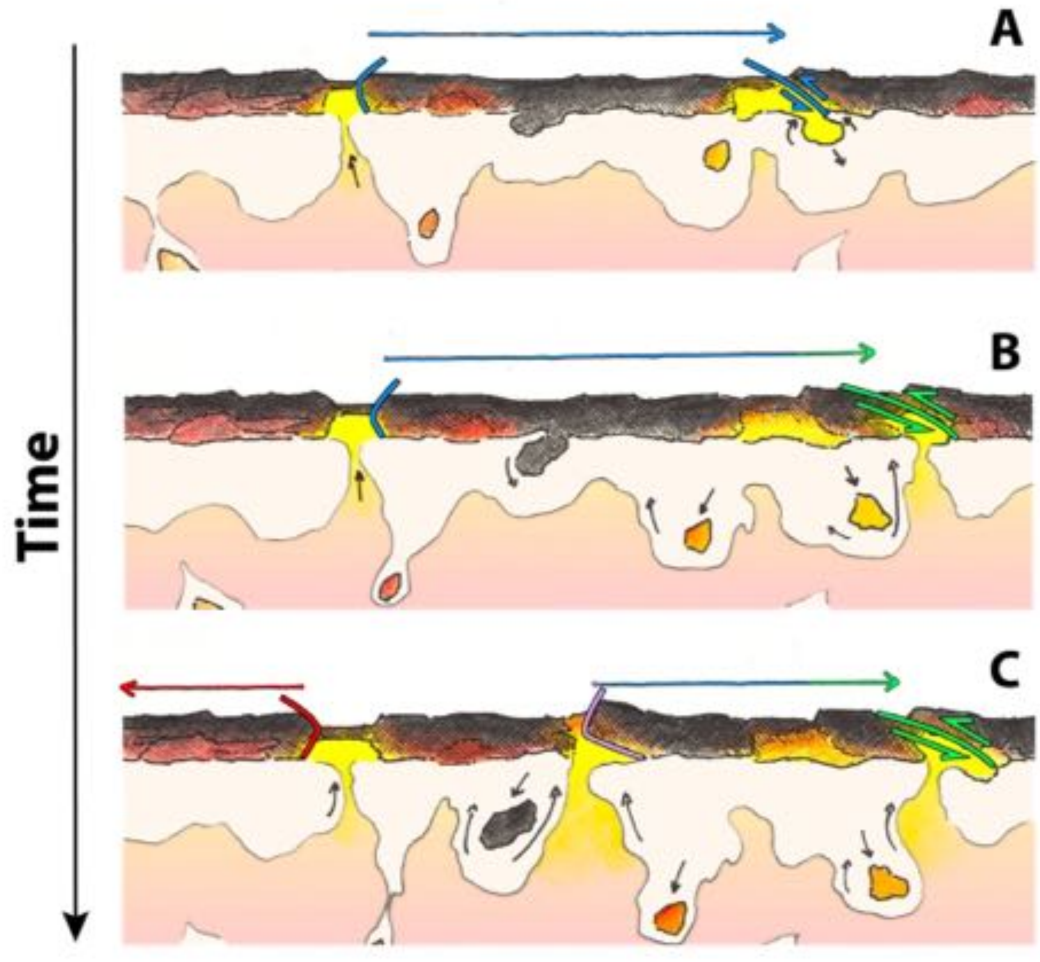


New regime found!



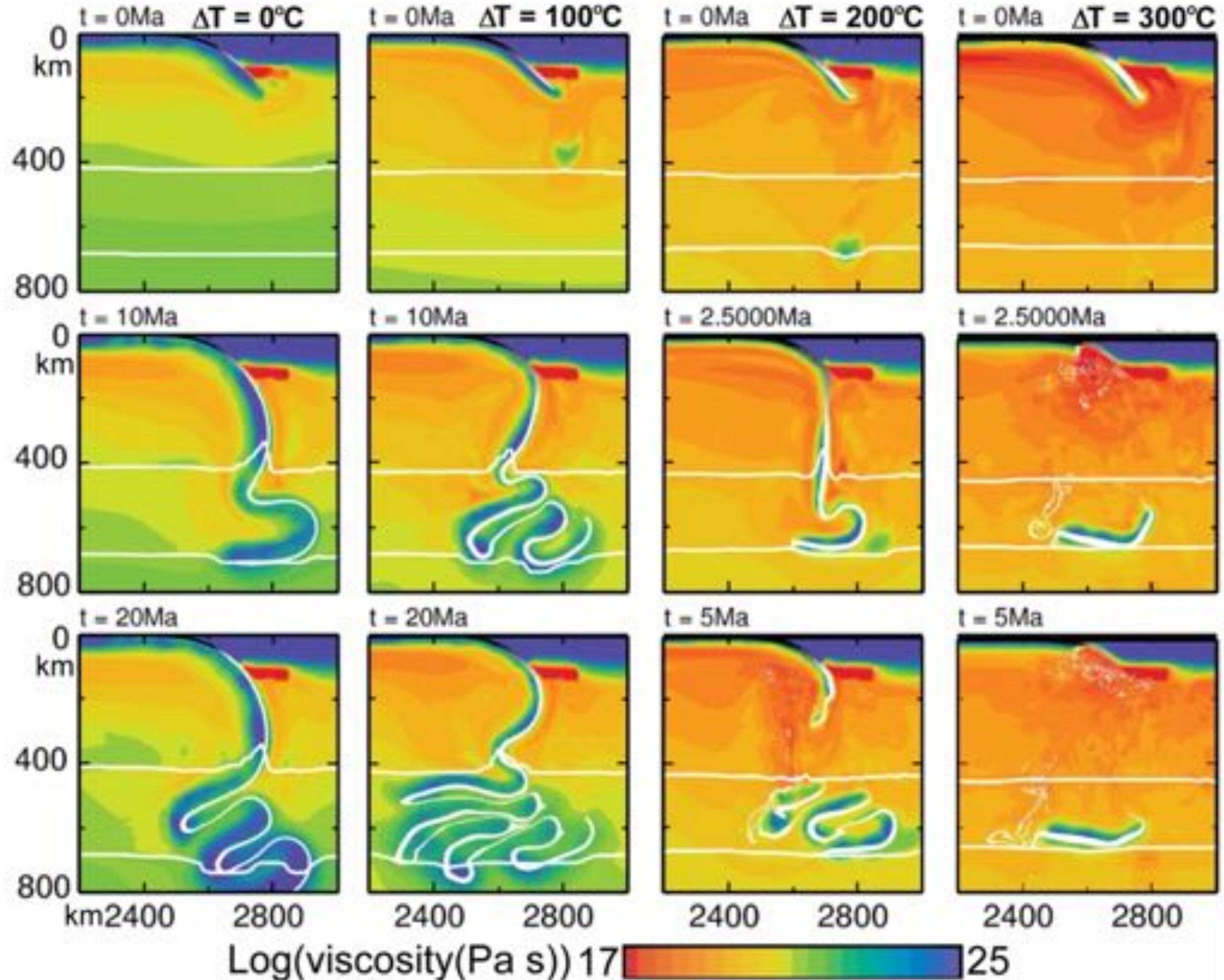
Diogo Lourenco et al., 2020 G-Cubed

“Plutonic Squishy Lid” mode



Lourenco et al., 2020

Subduction doesn't work on a hotter Earth

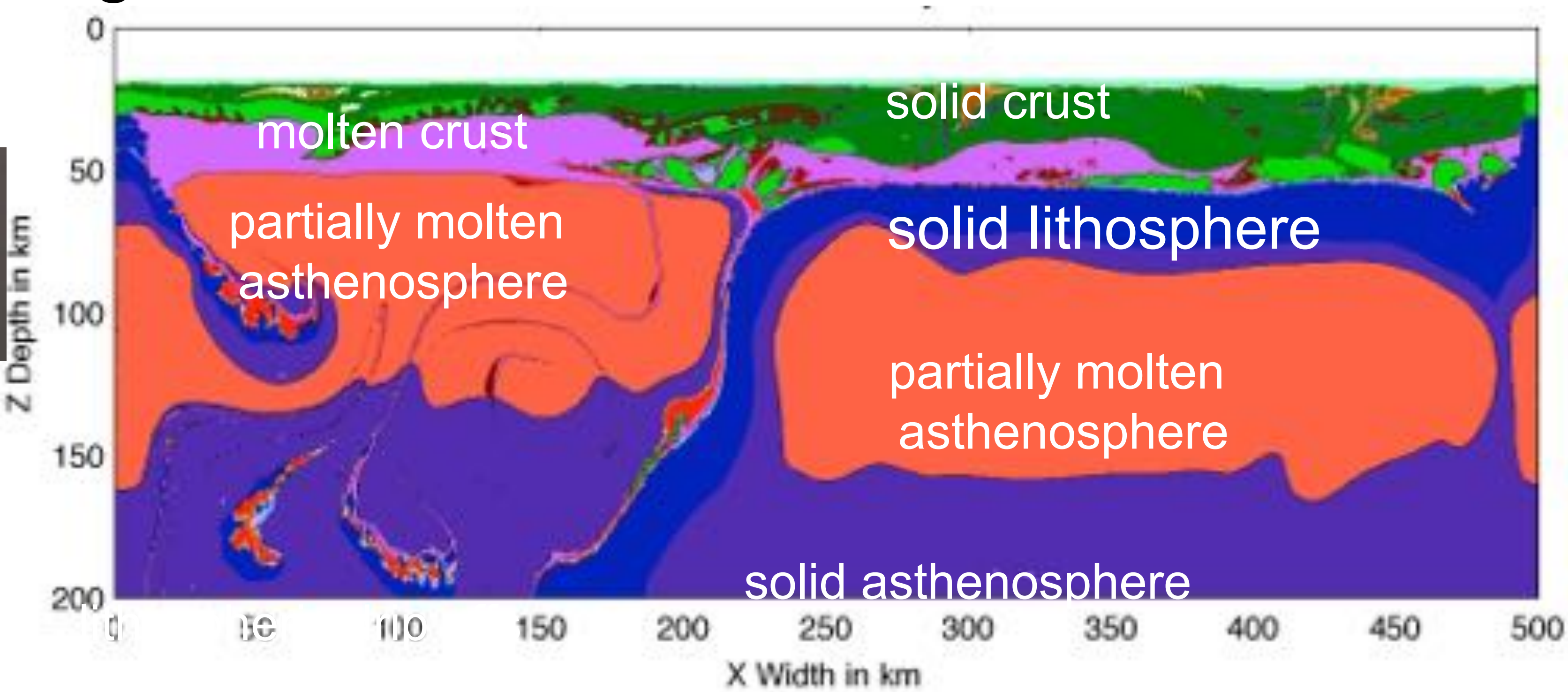


(van Hunen & van den Berg, 2008)

PSL in early Earth

- **weak deformable plates with low topography**
- **mantle-flows-driven orogeny** **(Sizova et al., in progress)**
- **magma-assisted crustal convection**

Elena Sizova

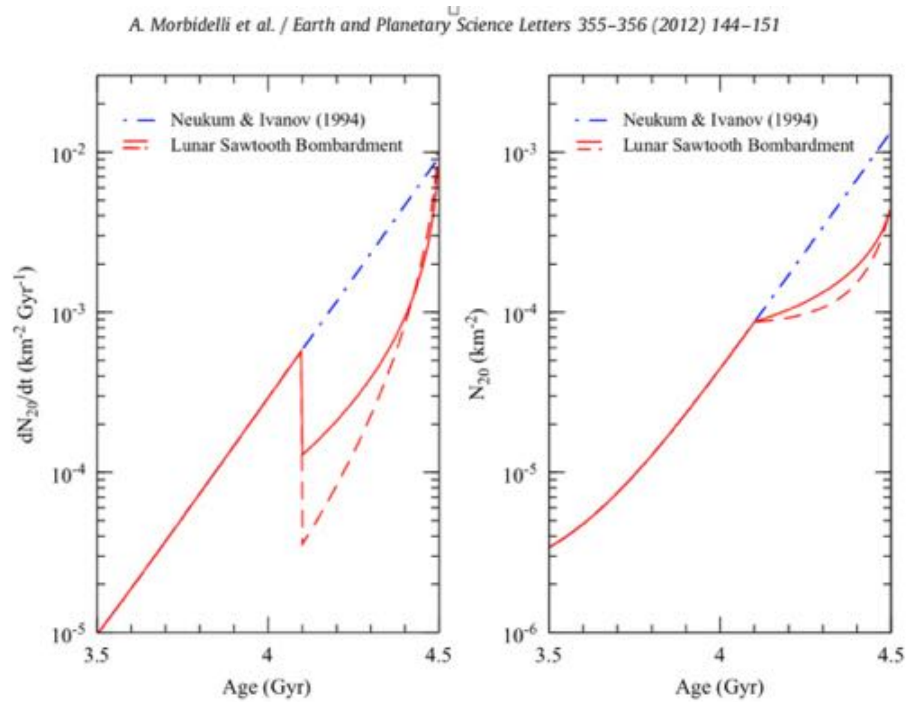


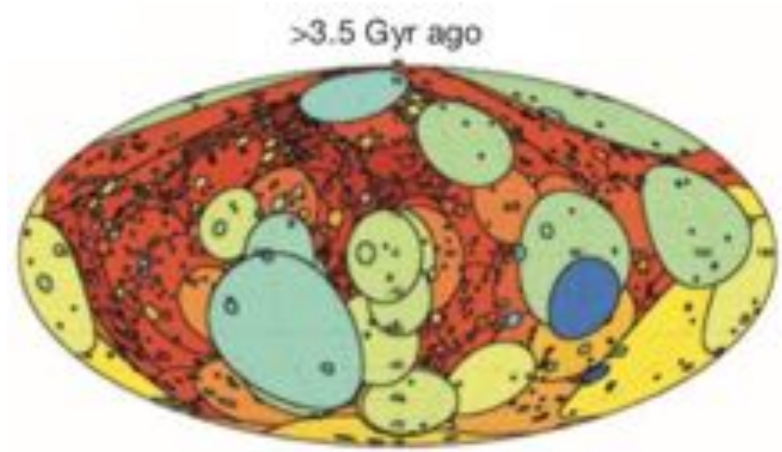
No plate tectonics but not a rigid lid either!

-> Plutonic Squishy-Lid tectonics

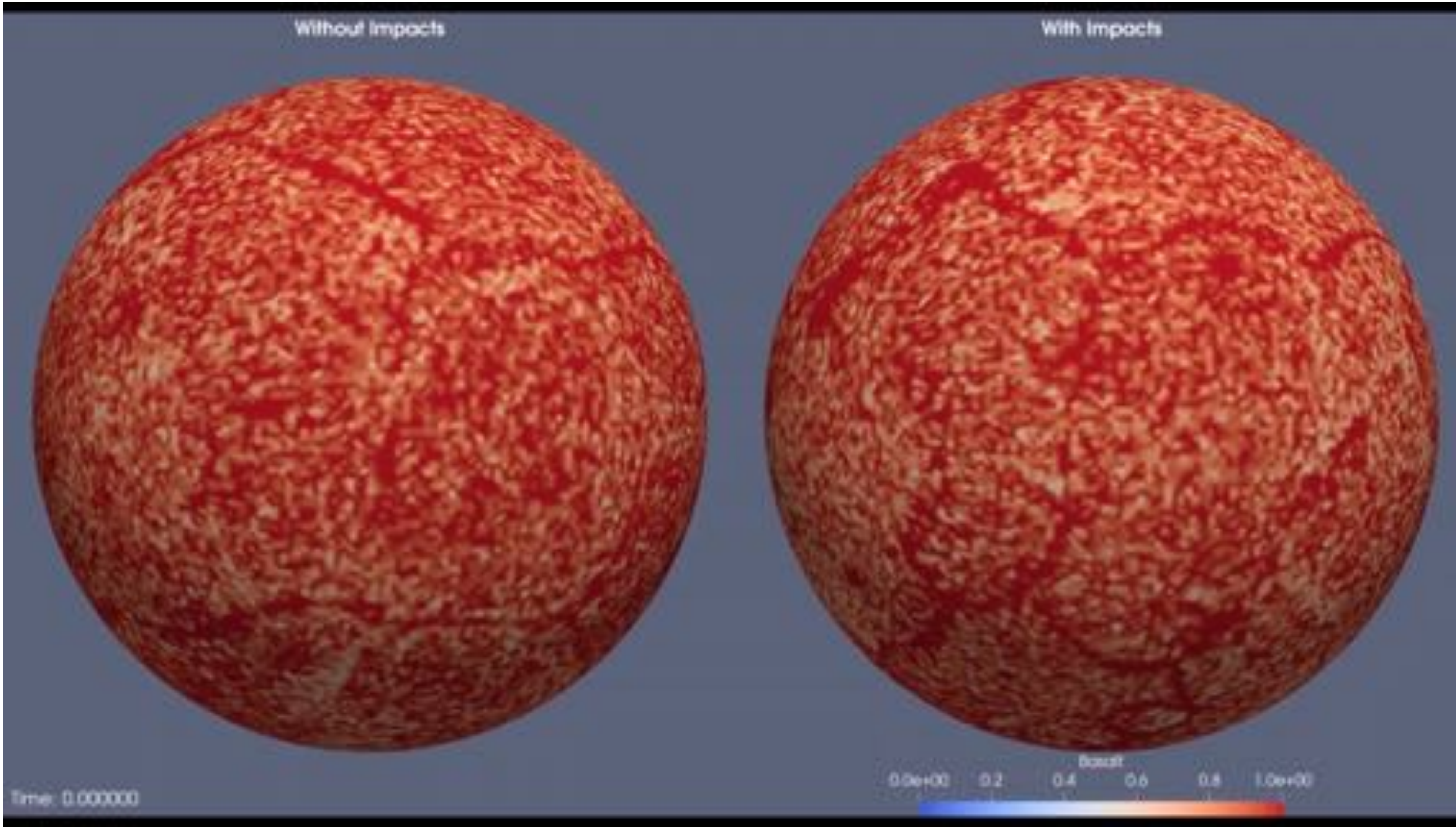
Impacts (*late heavy bombardment*, *late veneer*)

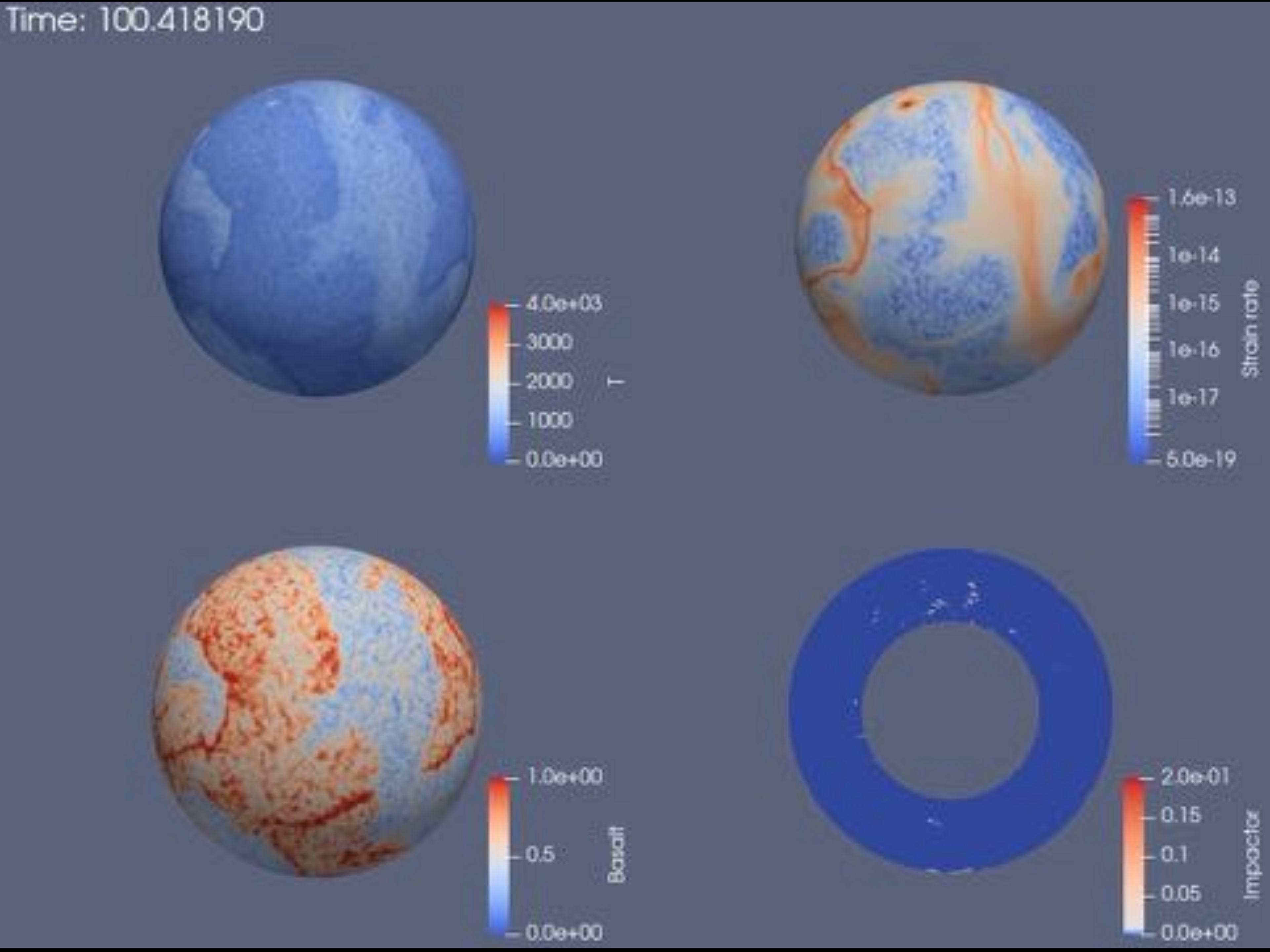
- Sawtooth bombardment (Morbidelli et al. 2012)
- Supplies late veneer as in Marchi et al. (2014 Nature)
- O'Neill et al. (2017 NGeo) presented 2D models, here we explore 3D models
- BSc project of Xavier Borgeat





Greatly influence tectonics & crust!





Time: 100.418190
4.0e+03
3000
2000
1000
0.0e+00
T
1.6e-13
1e-14
1e-15
1e-16
1e-17
5.0e-19
Strain rate
1.0e+00
0.5
0.0e+00
Basalt
2.0e-01
0.15
0.1
0.05
0.0e+00
Impactor

Surface mobility

Impacts can break a stagnant lid, giving temporary mobility, BUT when the impacts stop, stagnant lid returns.

If anyway a mobile-lid case, does not influence average mobility.

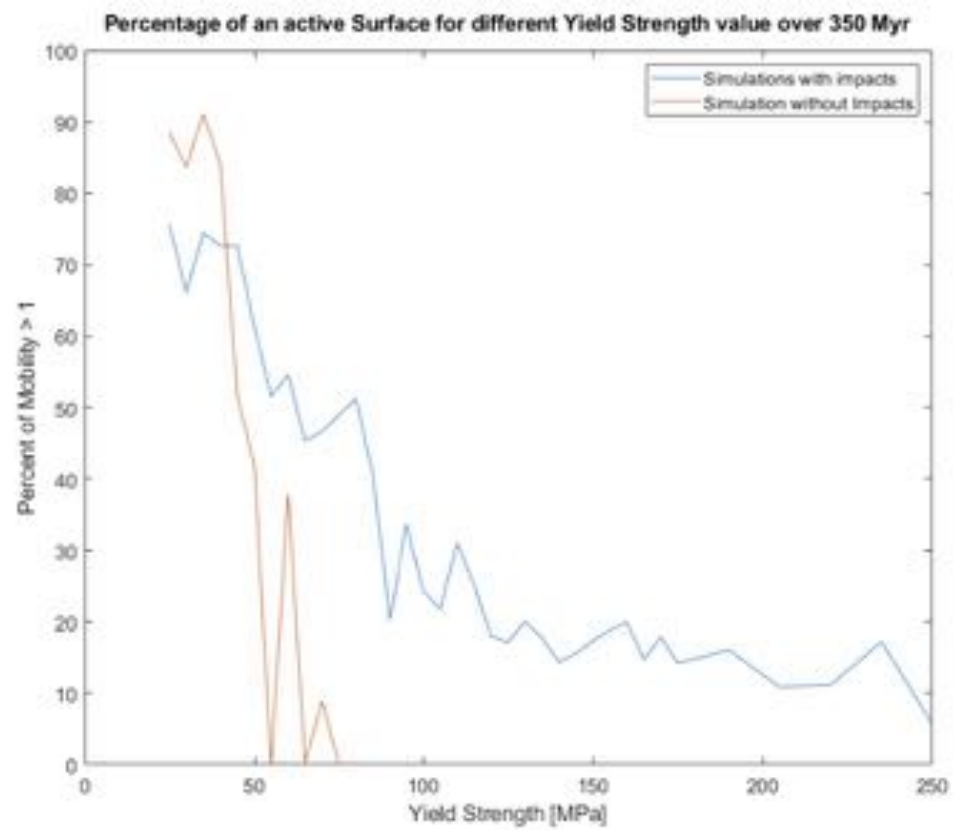


Figure 4.6: Comparison of the surface mobility for the cases with and without impacts (blue cases 3-38, orange 39-49)

Early Earth: Summary

- Archean tectonics likely characterized by hot, weak, deformable lithosphere undergoing delamination and horizontal motion.
- Intrusive magmatism dominant during Archean (as opposed to “heat pipe” extrusive magmatism)
- Subduction does not appear to be necessary for production of early TTG crust
- Impacts can play a major role in promoting mobility and melting in first ~600-700 Myrs

Coupled mantle-core evolution

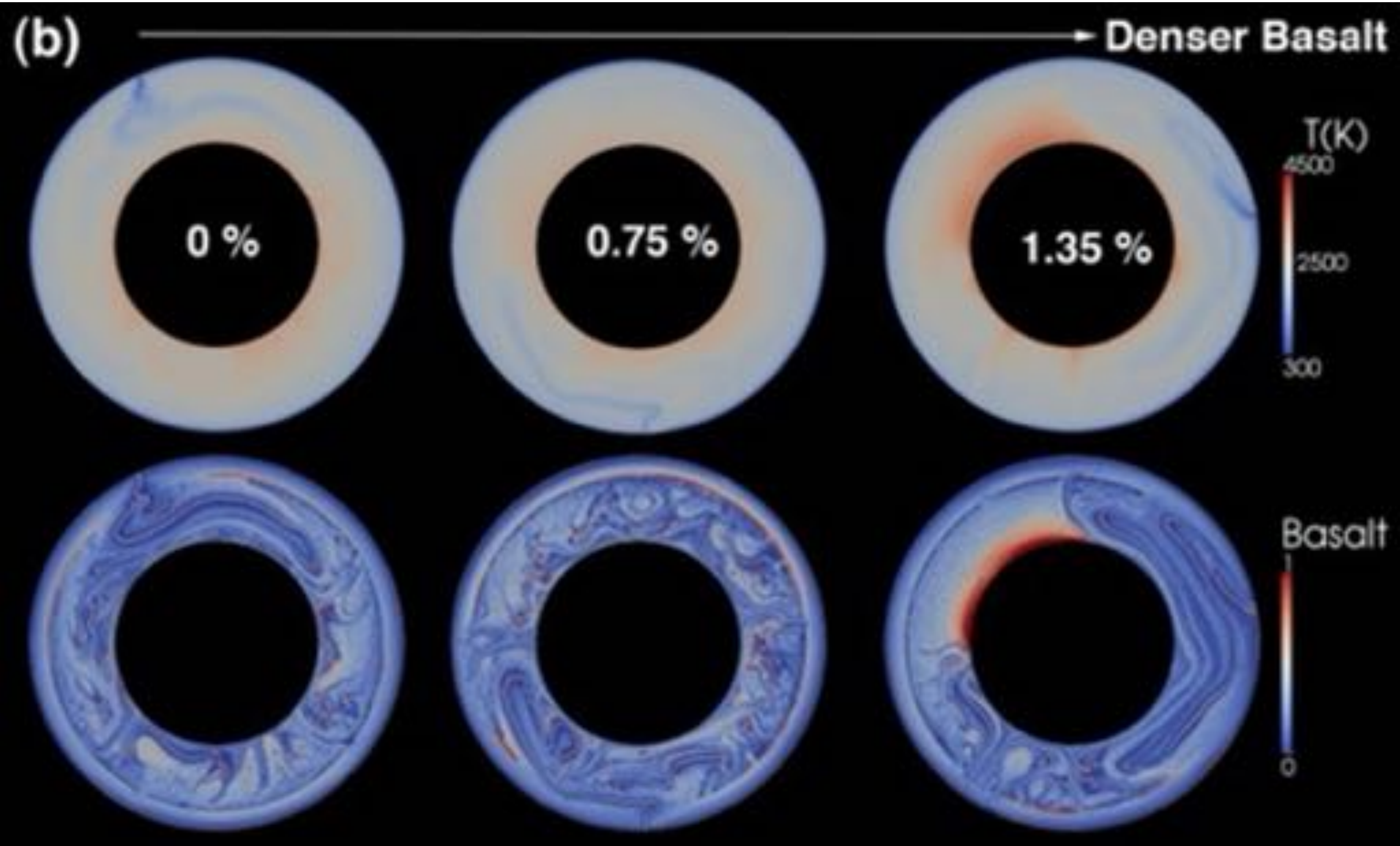
- The mantle controls the heat flow from the core
- Run mantle convection simulations for 4.5 Gyr of Earth history, coupling CMB heat flux to core evolution
- Which mantle evolution scenarios give a reasonable core evolution?
  - Geodynamo for at least 3.5 Gyr
  - Correct final inner core size / Tcmb
- Constrains mantle evolution & indicates what is possible

Calculations of mantle thermo-chemical evolution over 4.5 Gyr

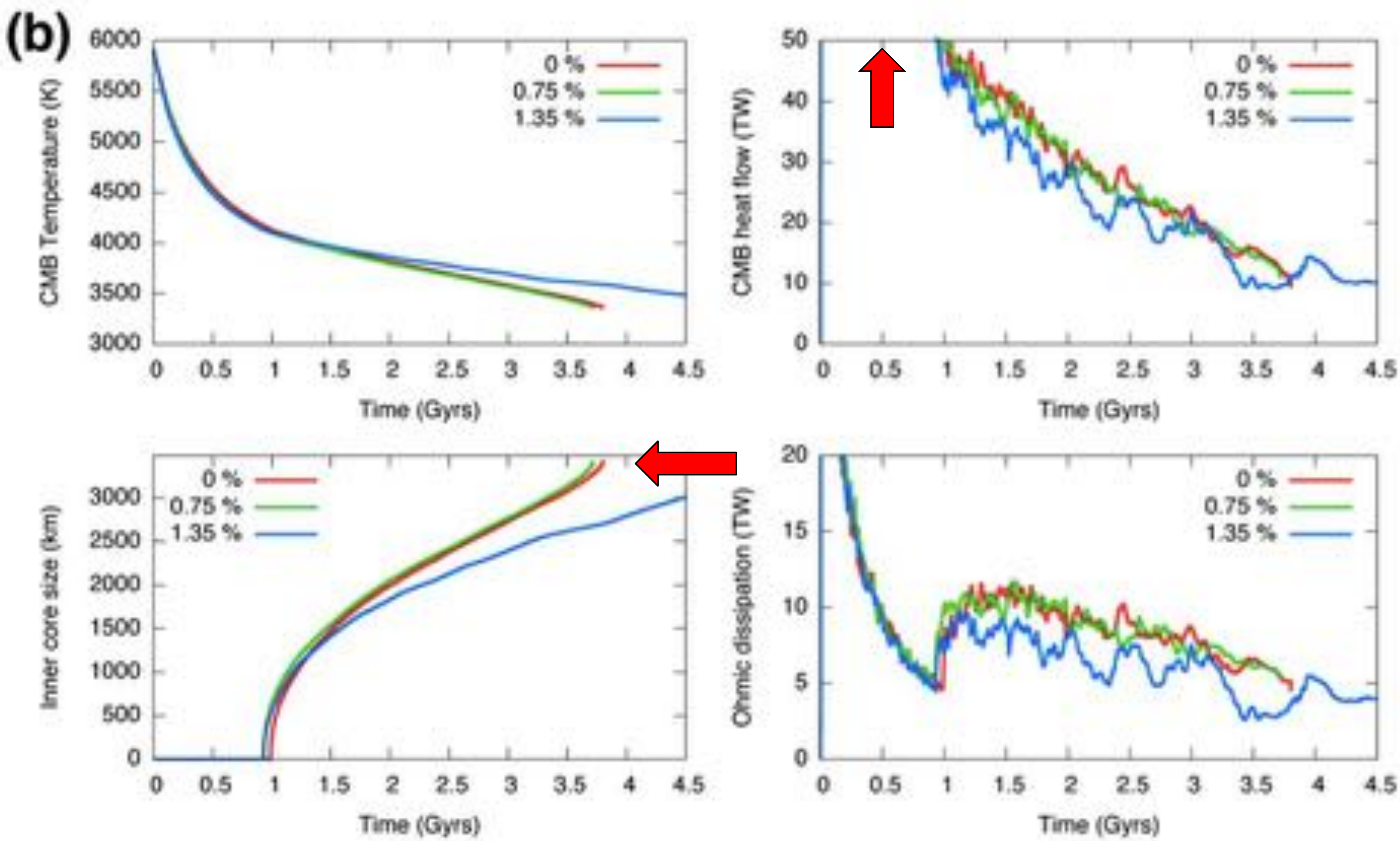
- Include melting->crustal production,
  - viscosity dependent on T, d, and stress,
  - self-consistent plate tectonics,
  - decaying radiogenic elements and cooling core,
  - compressible anelastic approximation
- Many papers by Takashi Nakagawa & me

Nakagawa & Tackley 2014 G3

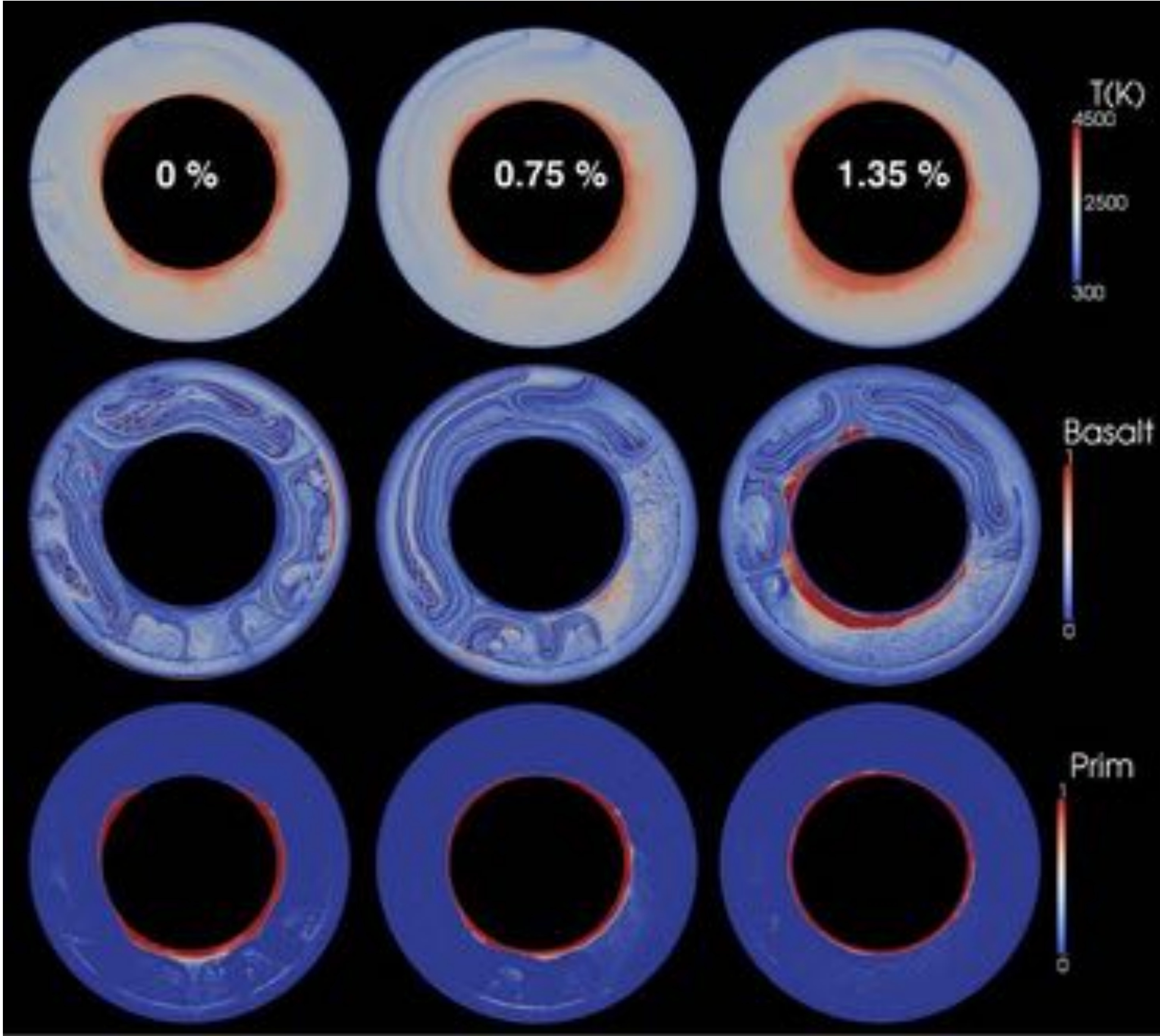
Only segregating MORB



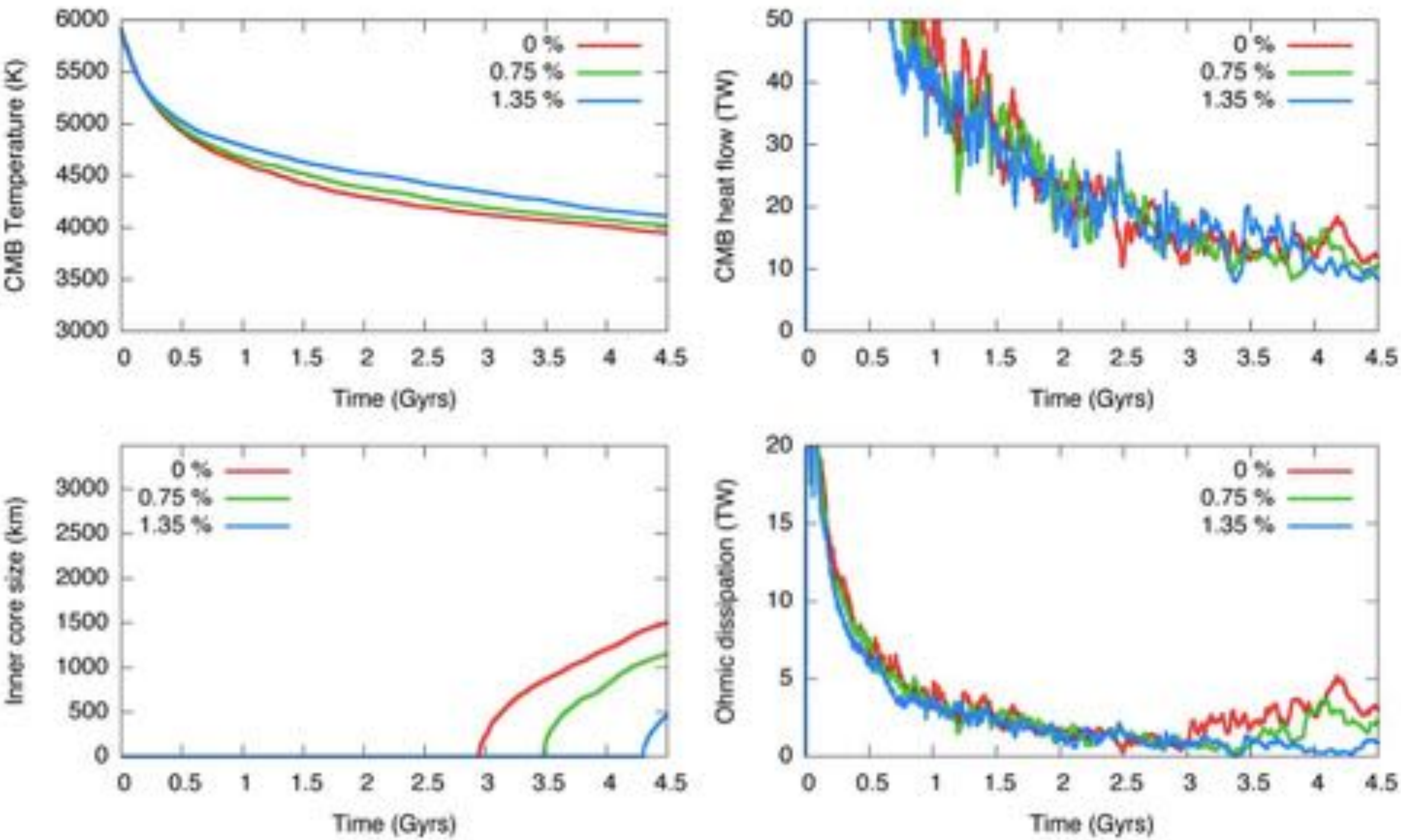
Too-large inner core!
(very high early CMB heat flow)



With prim. Layer + MORB



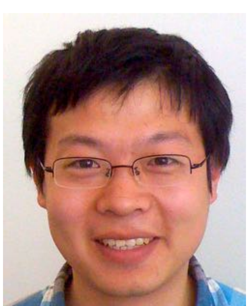
Successful core evolution
Deep dense layer reduces core cooling



Primordial dense material: Effect of viscosity contrast and plate tectonics

- Langemeyer, Lowman & Tackley (2020 GJI)

- Li, Deschamps, Yang, Chen, Zhao & Tackley (2019 GRL)

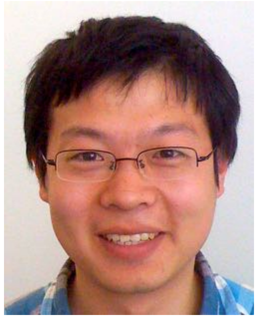


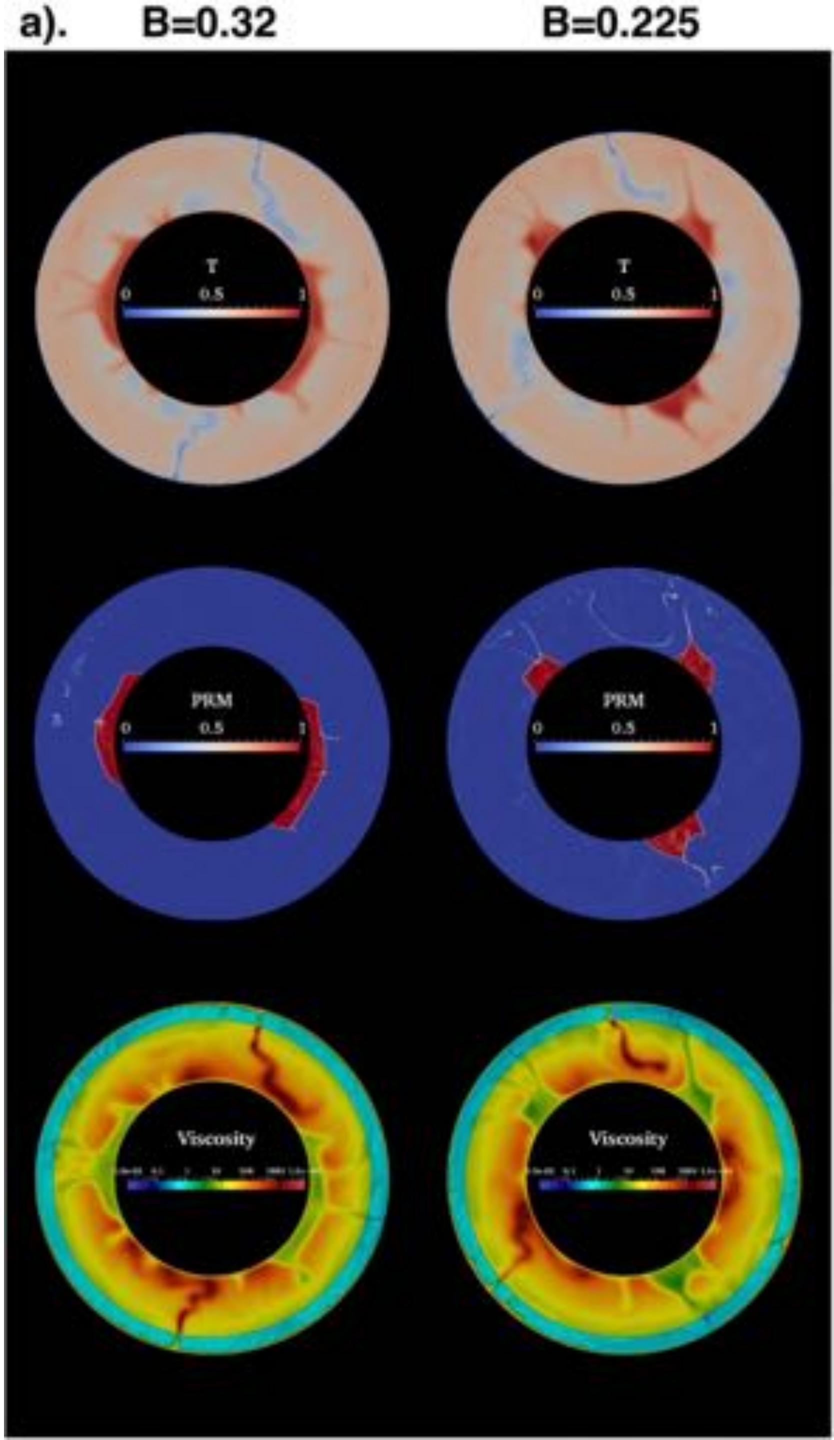
Why should there be an intrinsic (chemical) viscosity contrast?

- Different composition -> different mineralogy (brigmanite vs. magnesiowüstite)
- Different water content
- Different iron content
- Different grain size (grains grow with time, recrystallise in phase transitions)

Buoyancy ratio (chemical:thermal) has a first-order influence on pile topography

- Well-known from previous studies; this is just a reminder

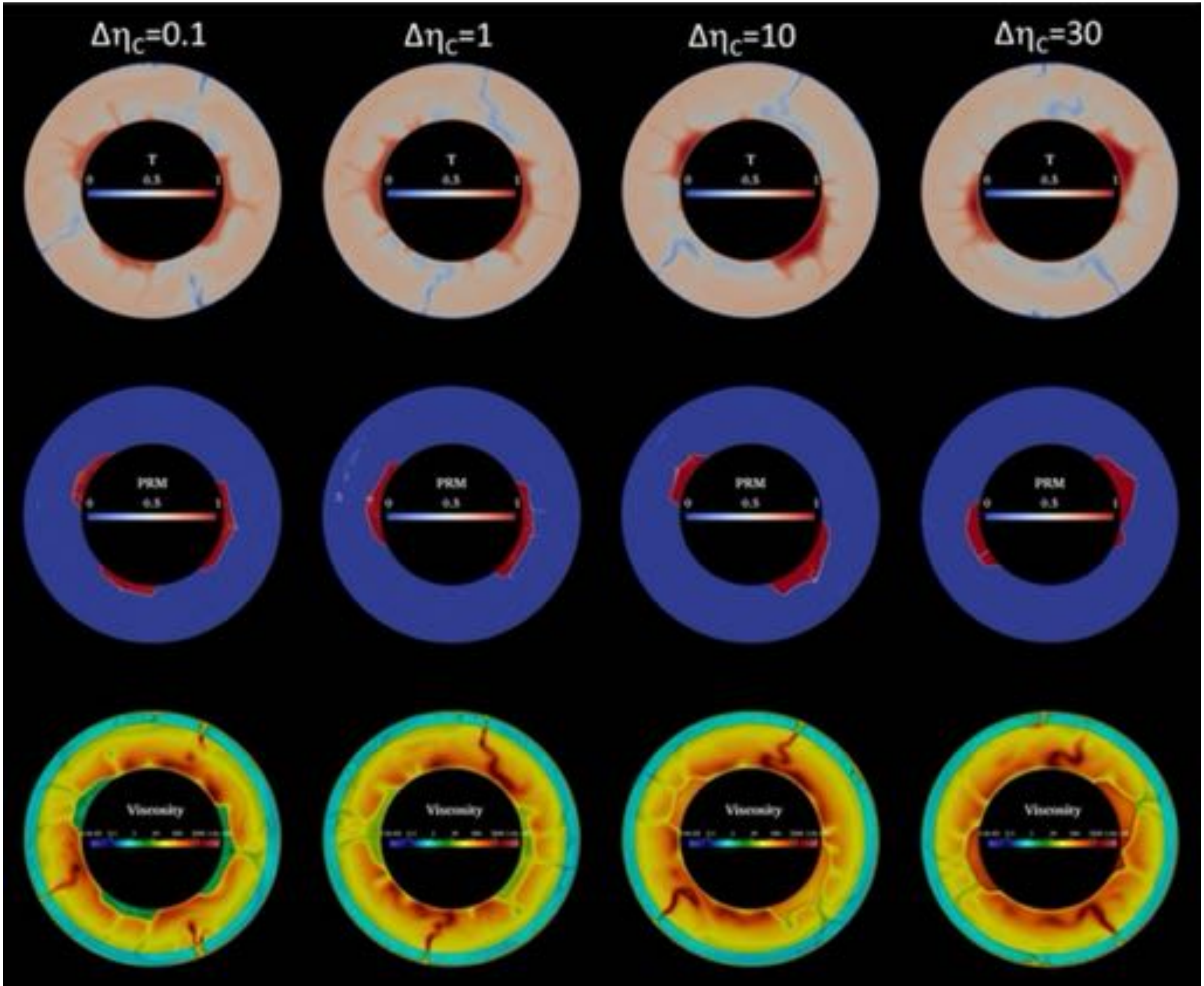


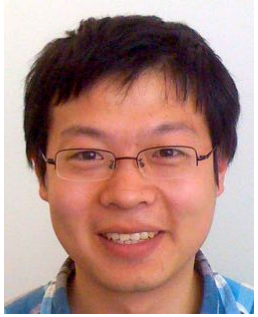


Viscosity contrast doesn't hugely affect the dynamics

Temperature contrast increases, so does pile topography

B=0.32

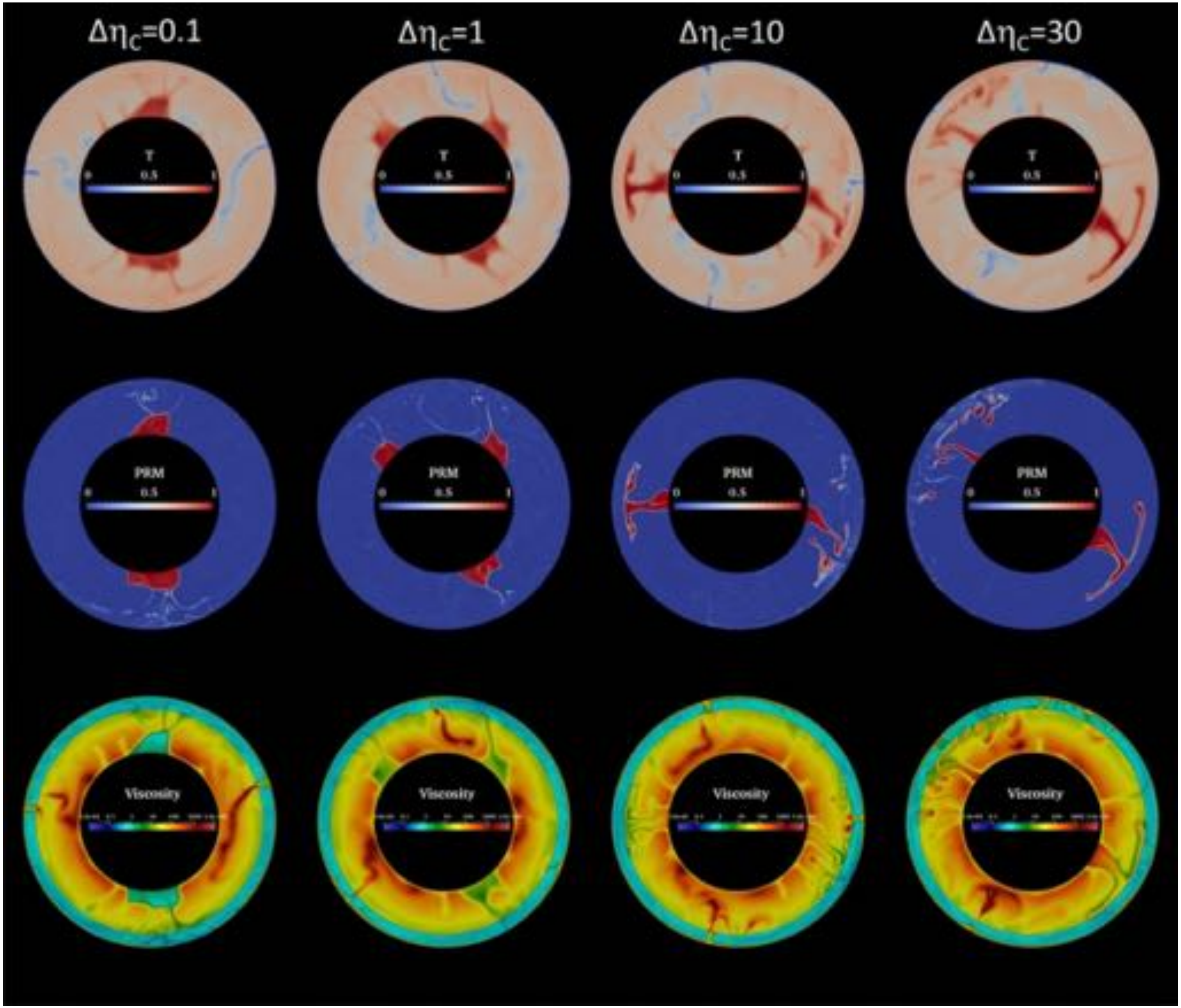


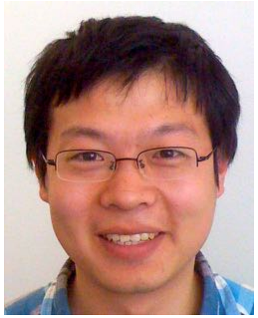


But near the threshold, it makes a key difference

High-viscosity piles are more unstable because they become hotter

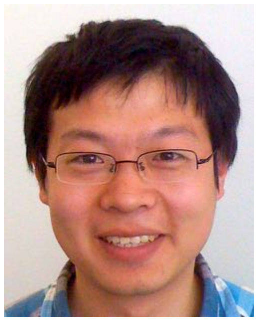
B=0.225



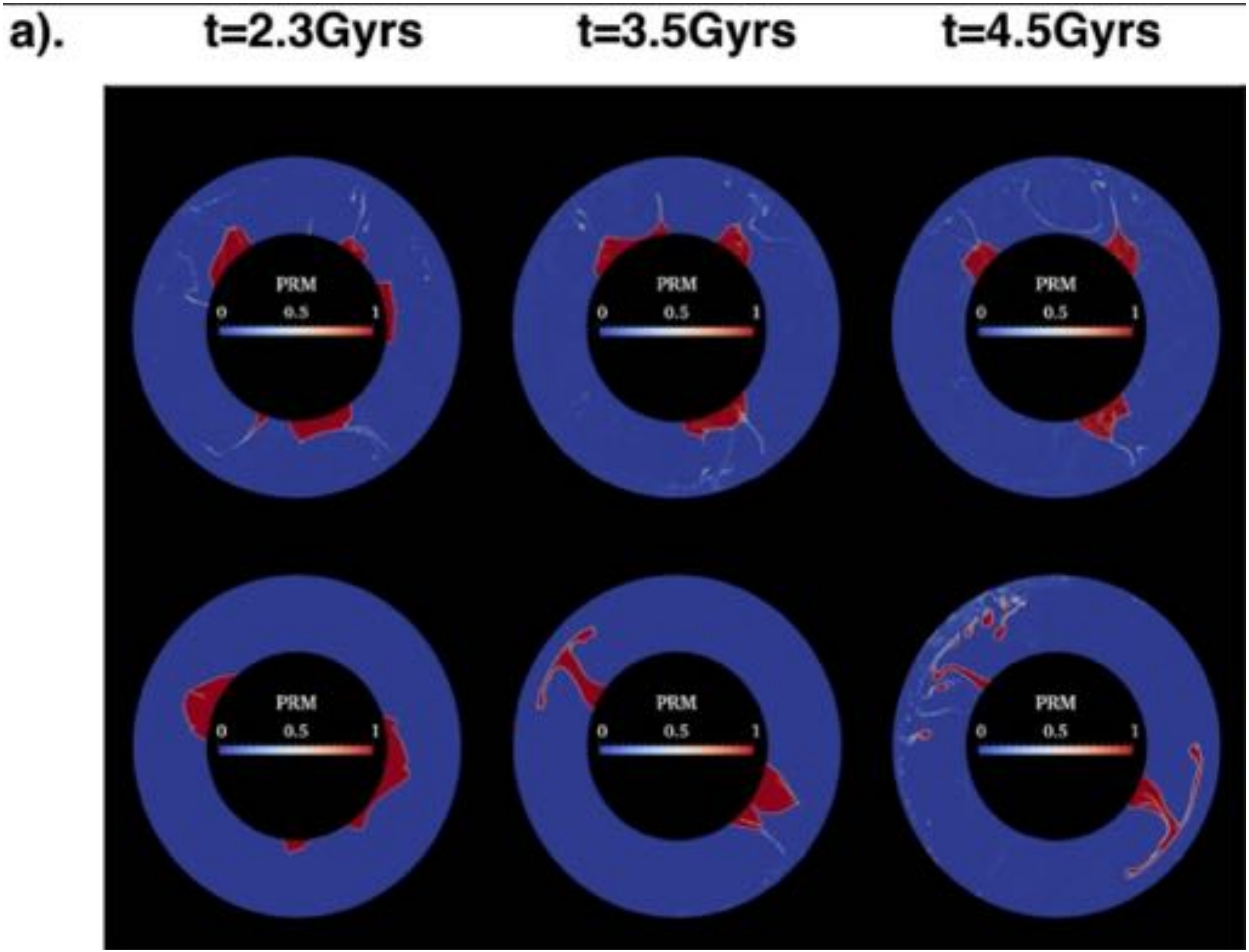


It takes a while for the layer to become unstable

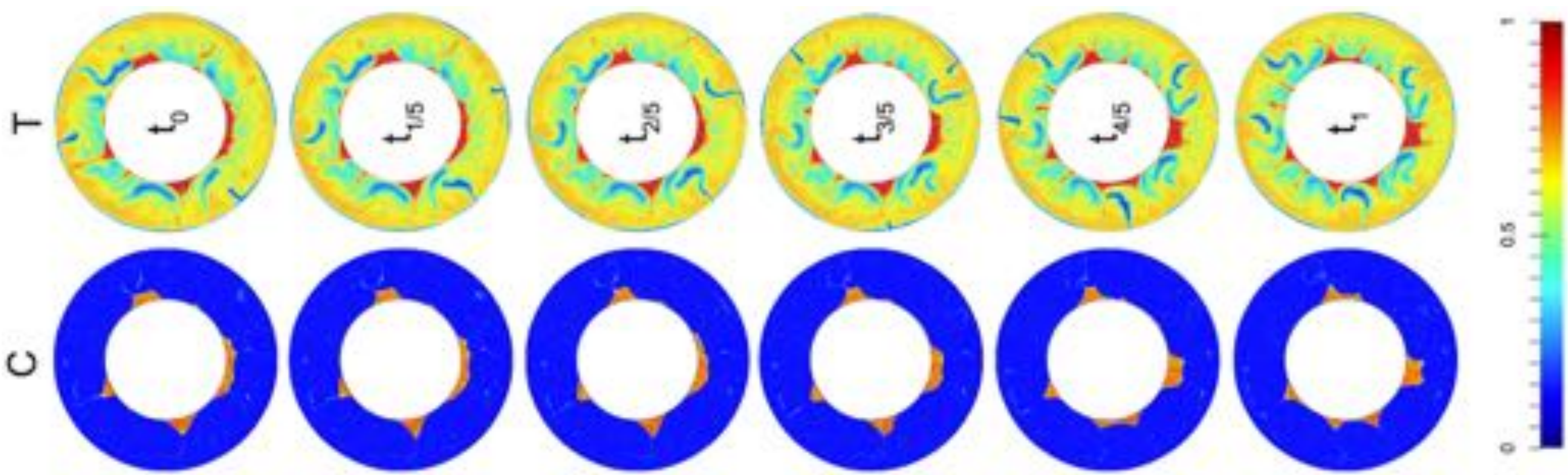
B=0.32



B=0.225



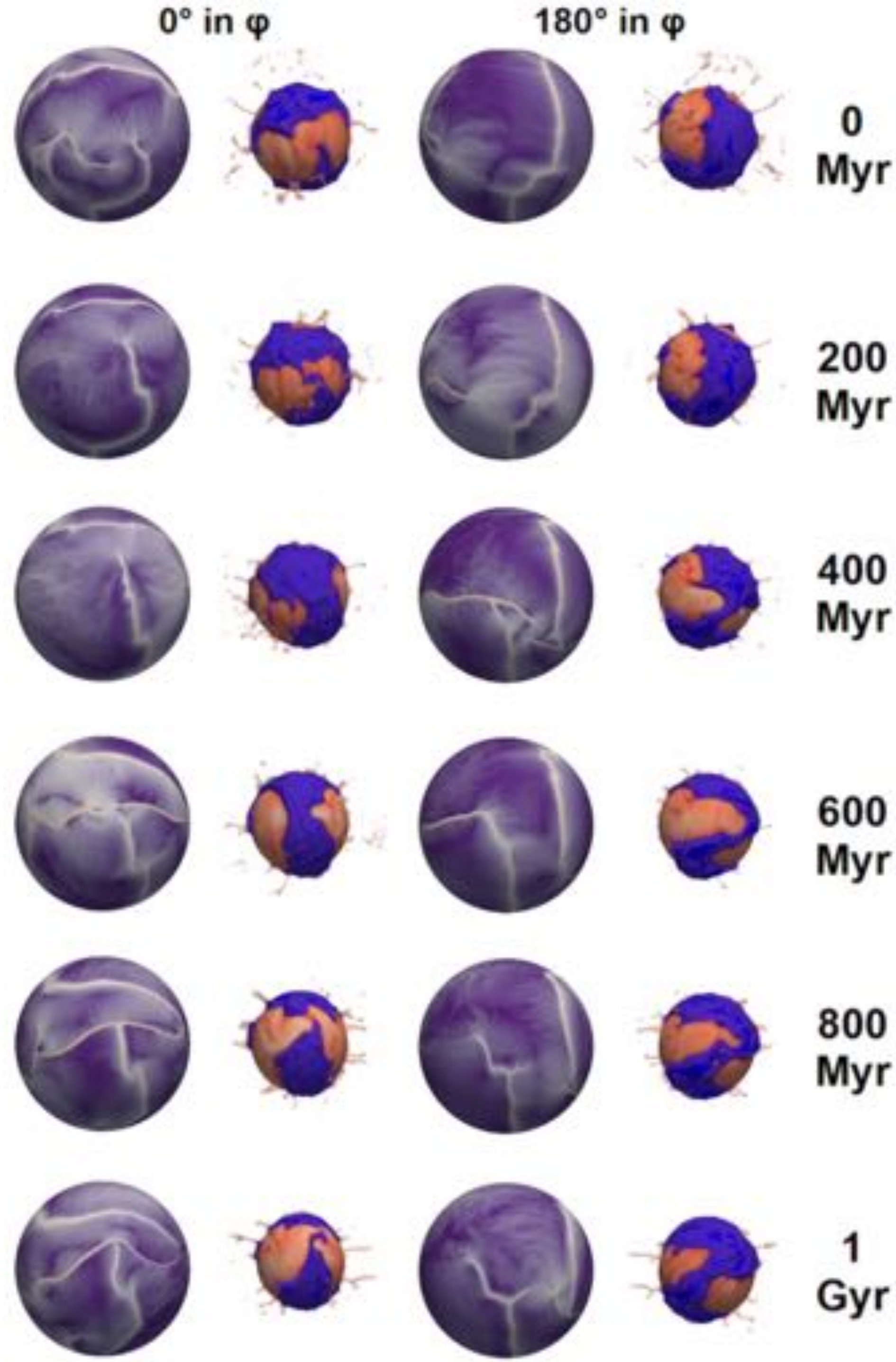
Piles don't stay fixed over billions of years



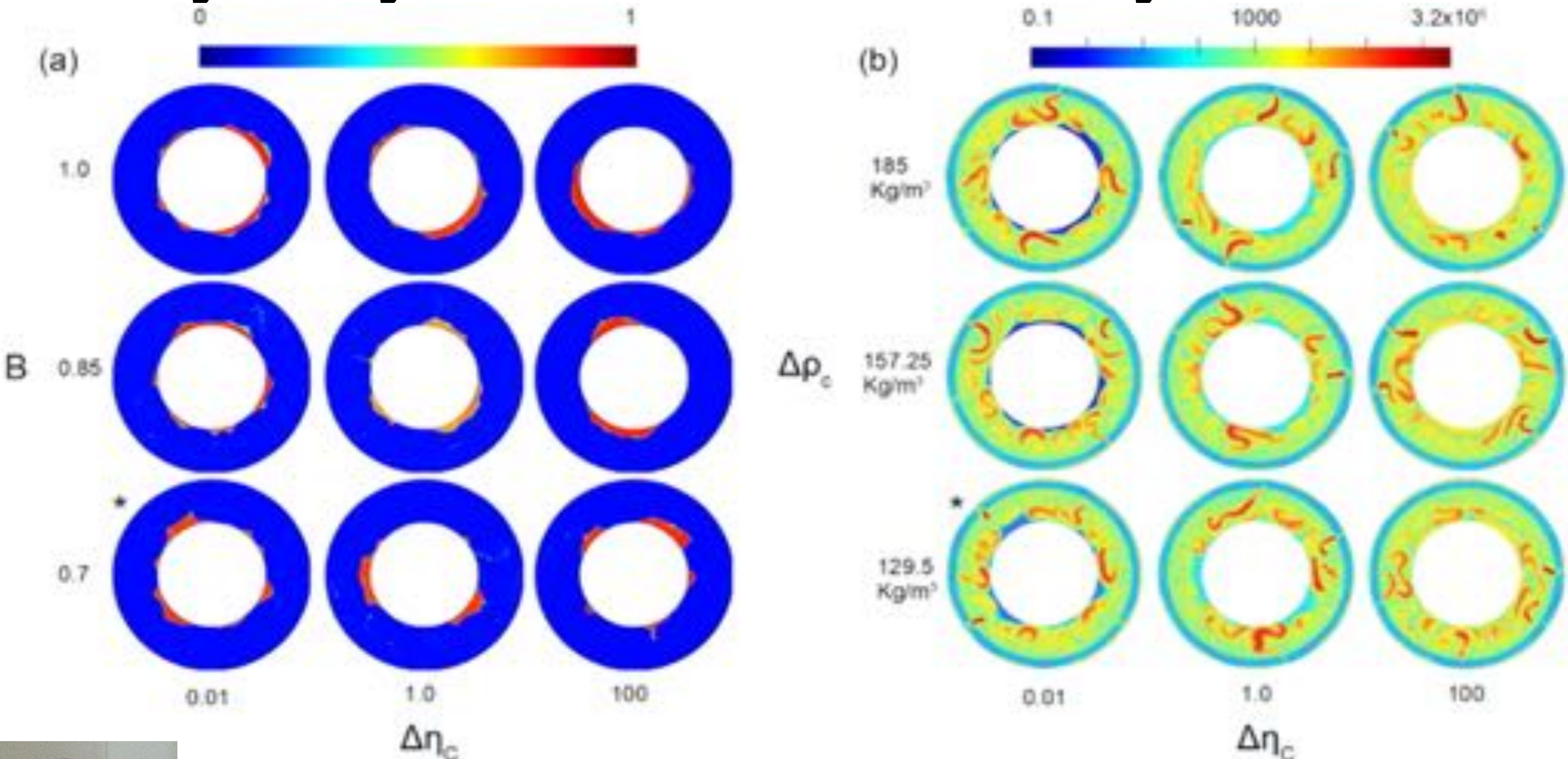
- Downwelling slabs move them around, split them, merge them, change their topography

3D piles are also time-dependent

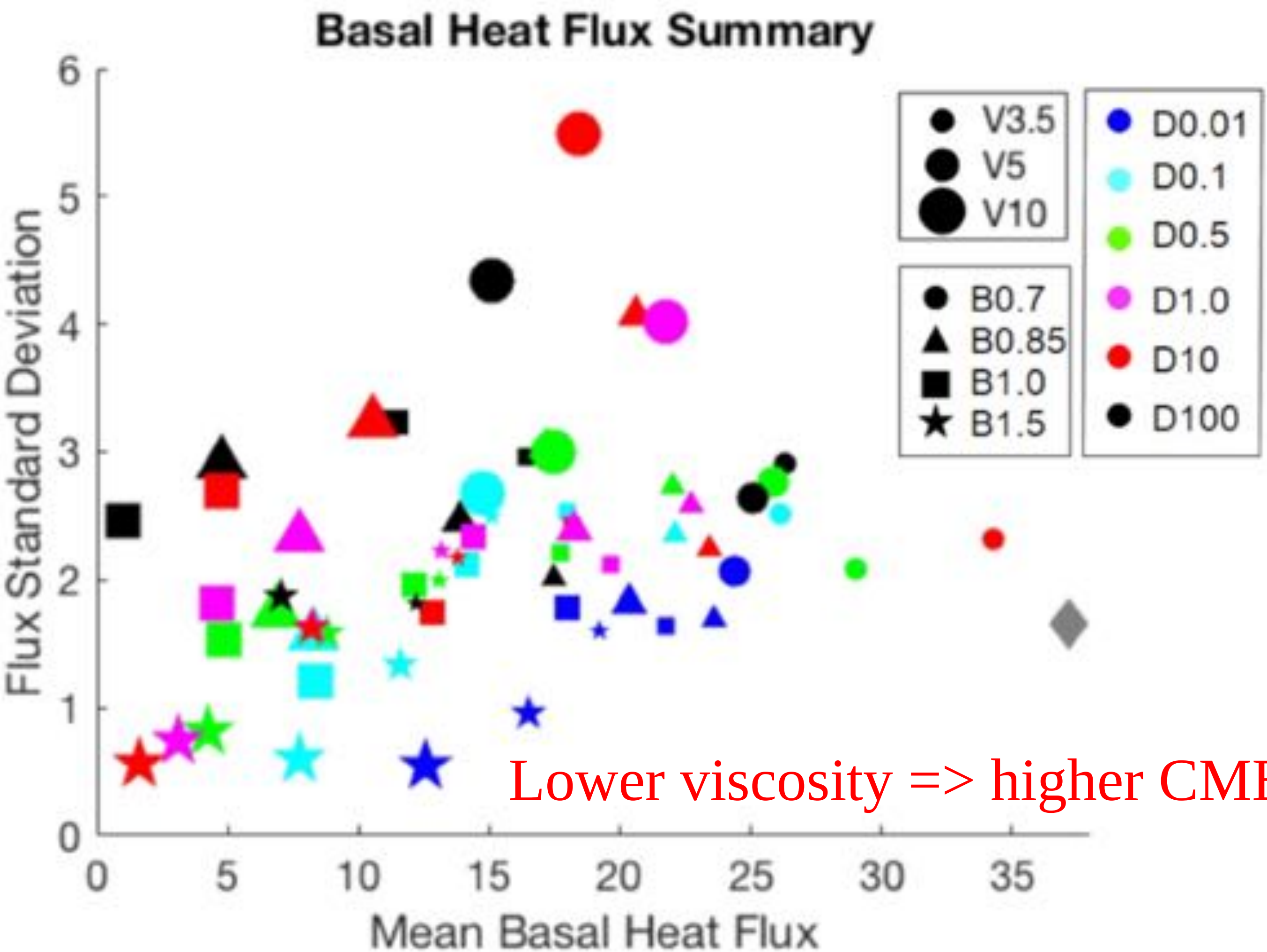
Langemeyer, Lowman & Tackley, GJI submitted



Pile morphology depends more on buoyancy ratio than viscosity contrast



Viscosity contrast greatly affects CMB heat flux



Lower viscosity => higher CMB heat flux

Summary

- Basal Melange (BAM): any “piles” are likely a mixture of materials, much of which subducted
- Early Earth tectonics: Plutonic Squishy-Lid, also impacted by impacts
- CMB piles have a strong influence on CMB heat flux; may even be needed for a successful geodynamo evolution
- Intrinsic viscosity contrast of piles influences heat flux and stability

THE END

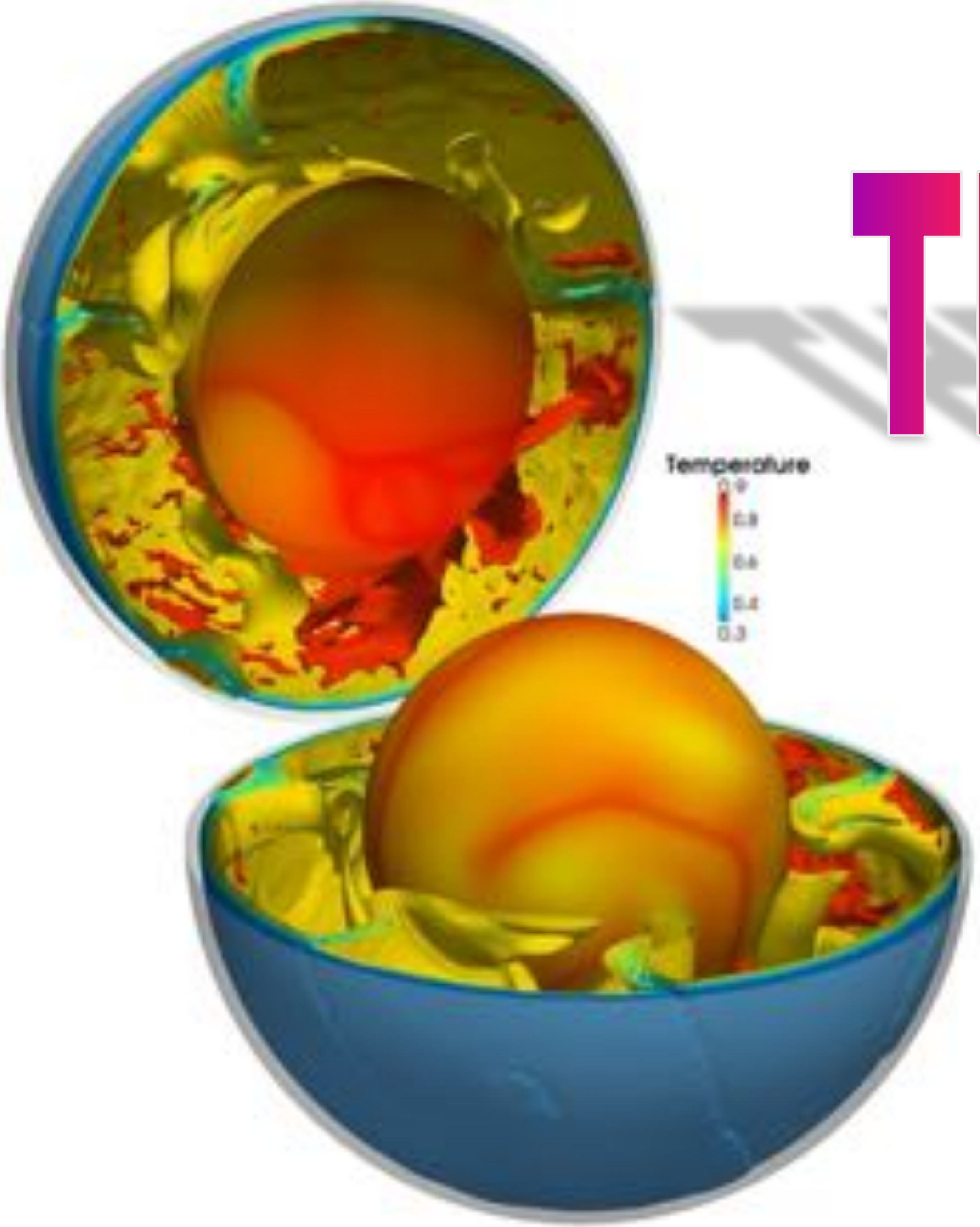


Image by Fabio Crameri