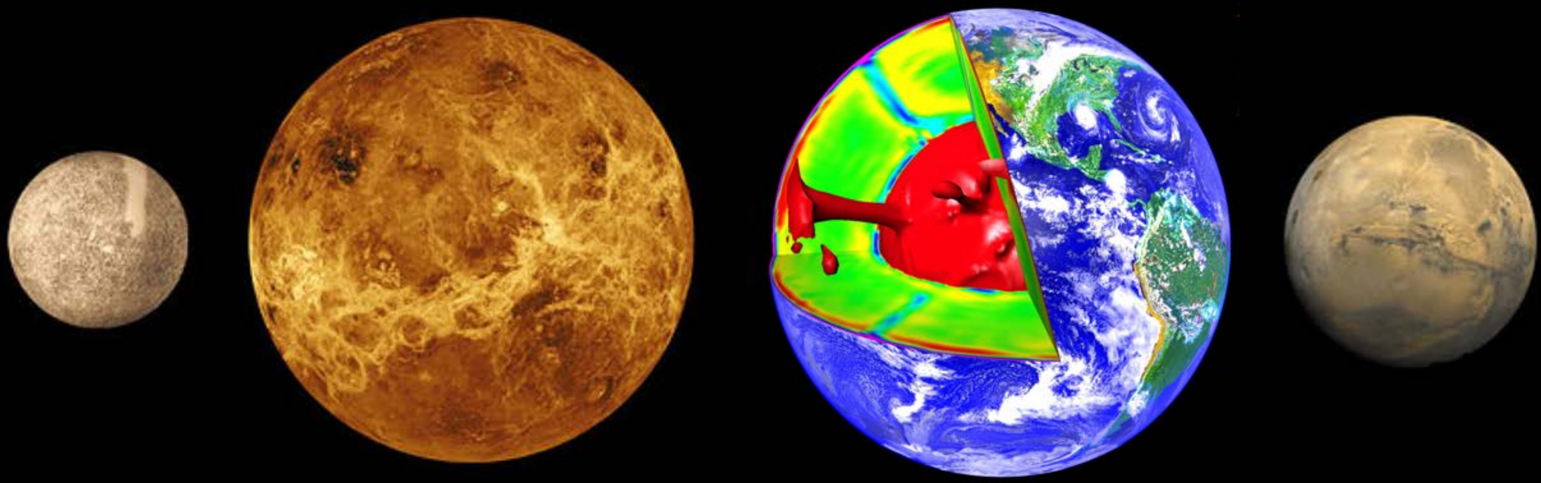
Mantle convection, plate tectonics and the thermo-chemical evolution of the Earth

Paul J. Tackley, ETH Zürich



Mantelkonvektion mit Plattentektonik und Kontinentaldrift auf der Erde

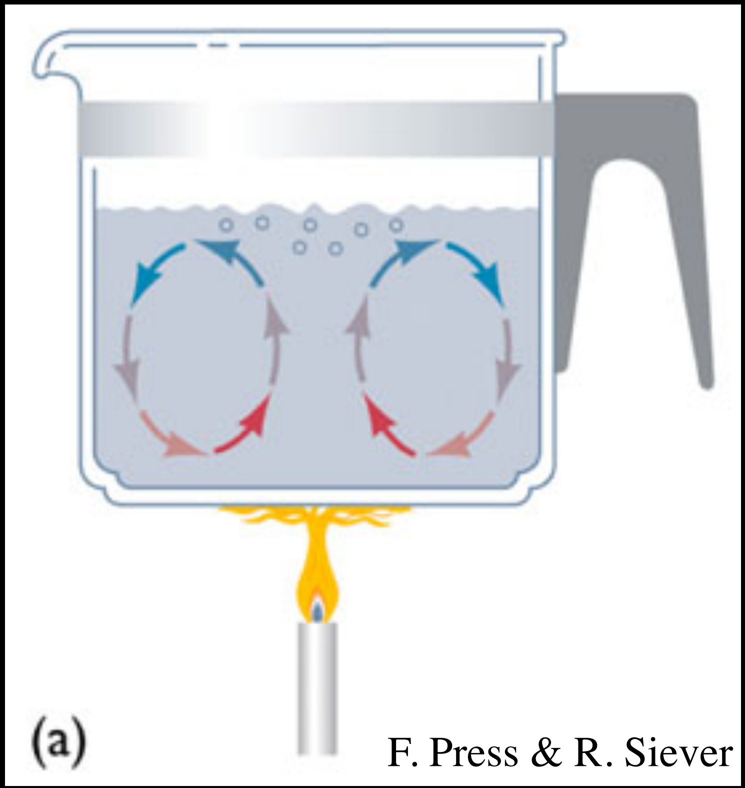
Mantle Convection with Plate Tectonics and Continental Drift on Earth

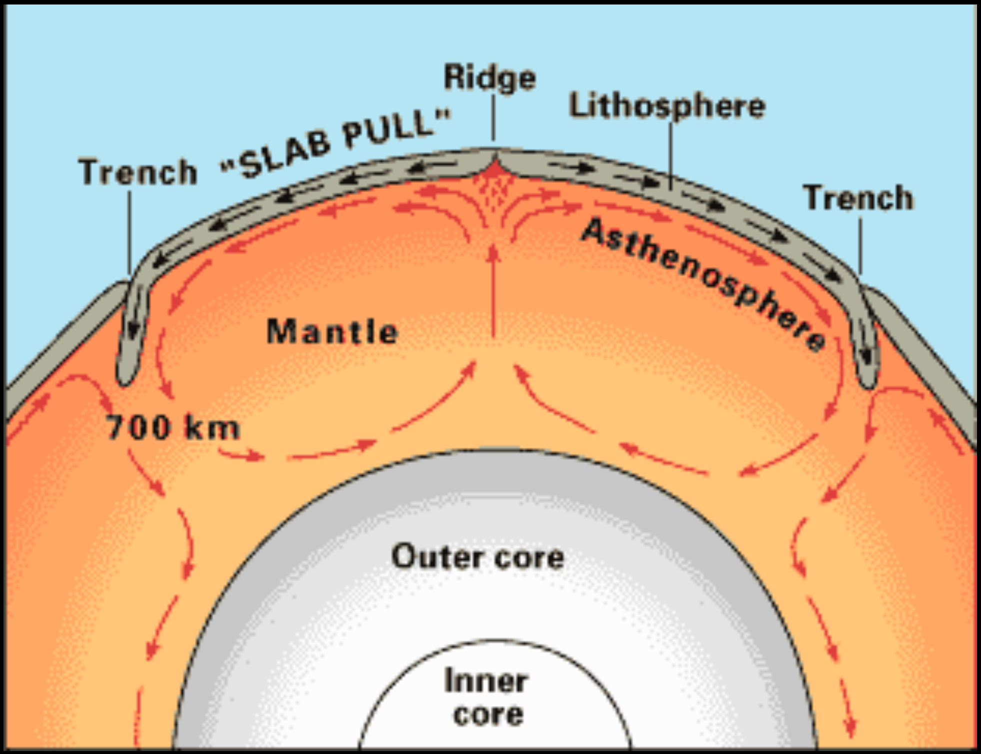
Movie by:

Tobias Rolf, Antoine Rozel, Paul Tackley

https://gfd.ethz.ch

Convection is the key process
Here focus on the solid mantle





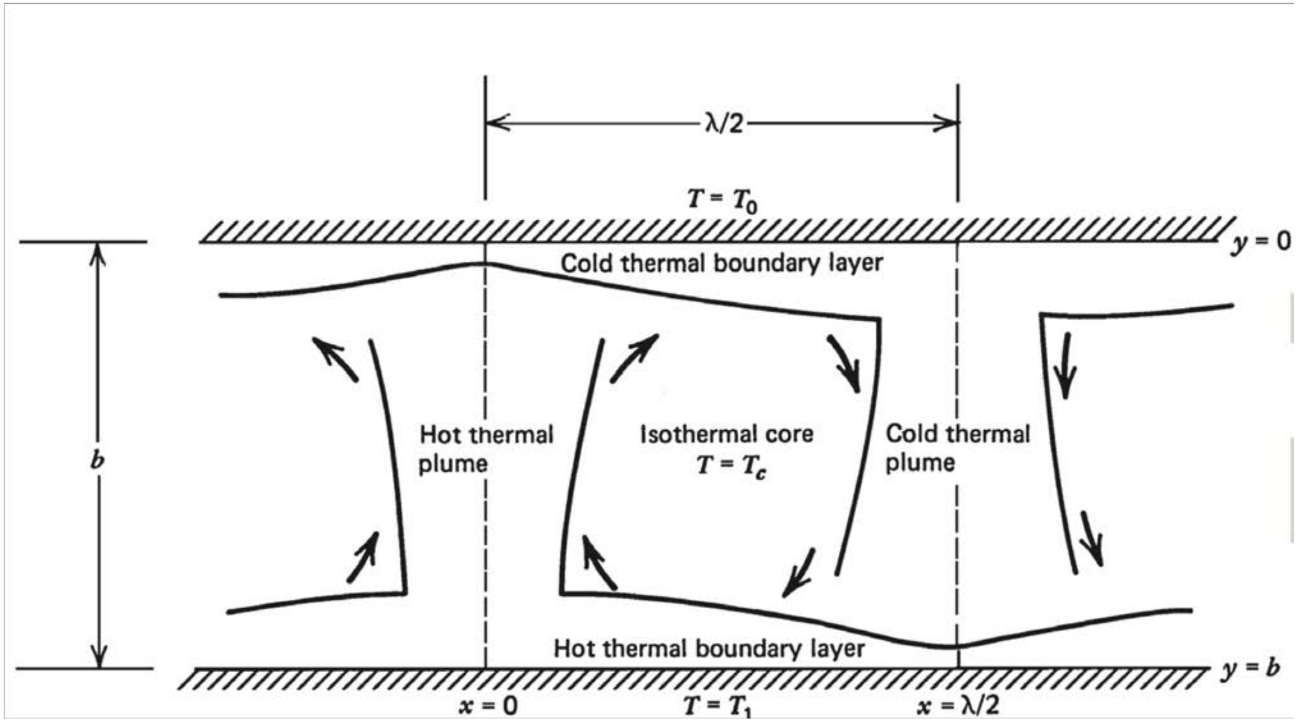
- Heat sources: radioactive heating (U, Th, K) & cooling from a hot/molten initial state
- Oceanic plates are part of this convection

Early on: Magma Ocean

Geoneutrino relevance: Radiogenic heating rate is key

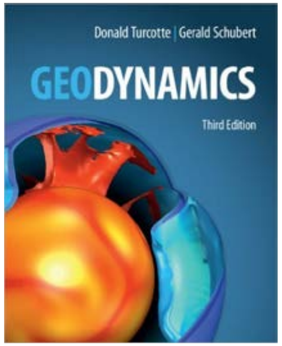
- Must be high according to conventional geophysical understanding of how mantle convection + Earth cooling work
- Geo/cosmo-chemistry estimates much lower
- How to reconcile?
- Where are the radioactive elements?

Geophysical estimates



Key result: Heat Flux (Nu) ∝ $Ra^{1/3}$

Turcotte and Schubert



$$Ra = \frac{\rho g \alpha \Delta T D^3}{\eta \kappa}$$

Allowable evolutions for different exponents β

Christensen, 1985

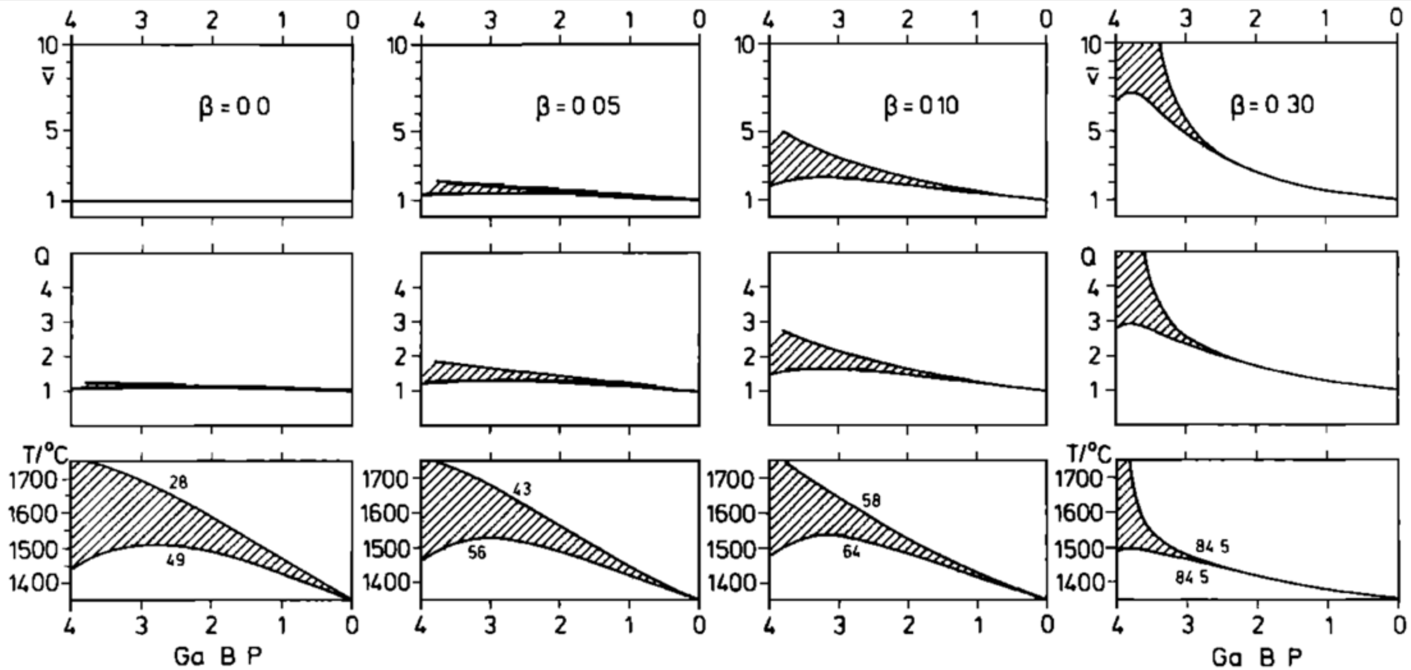
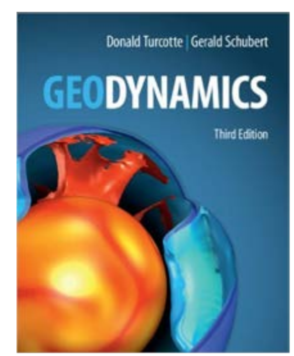


Fig. 3. Range of permissible solutions for four selected values of β. In each column, from bottom to top, the average mantle temperature $\bar{T}$ extrapolated to zero pressure, the relative variation of the heat loss Q, and the relative variation of plate velocities $\bar{v}$ during geological time are displayed. The present temperature is taken to be 1350°C and the present Q and $\bar{v}$ are set to unity. Proper dimensional values would be 80 mW m^{-2} and 3–4 cm/yr respectively. In the diagrams for the temperature also the limiting Urey ratios in percent are indicated.

For β=0.3, radioactive heating must be ~85% of the total heat loss!
(i.e. the Urey ratio = radioactive heating / total heat loss = 0.85)

Turcotte & Schubert: "..the cooling of the Earth is responsible for about 25% of the Earth's heat loss, while 75% is attributable to radiogenic heating. There is little room for uncertainty in this conclusion"



More likely

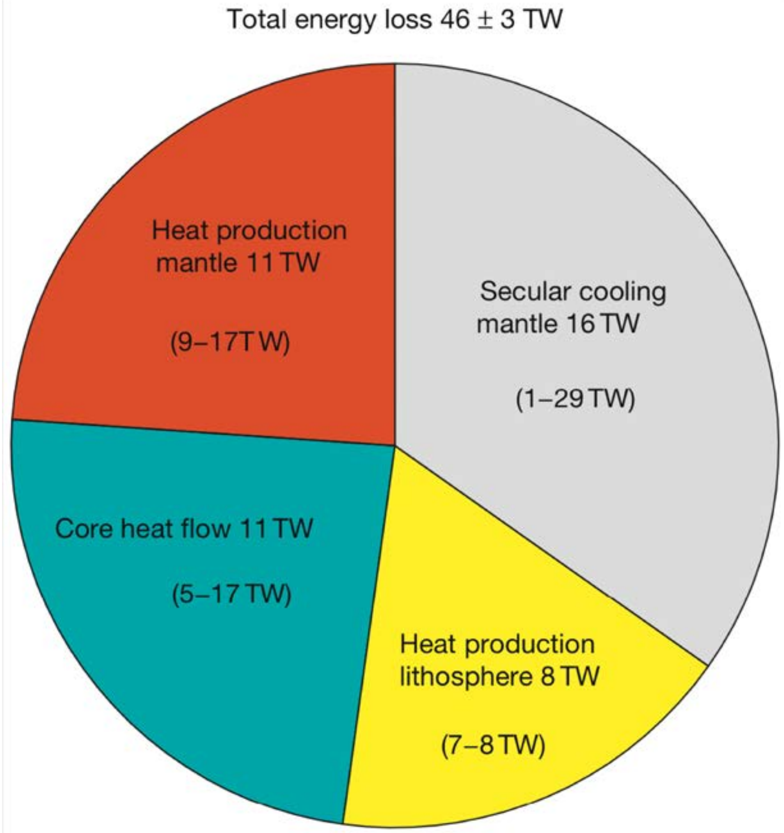


Figure 12 Proposed breakdown of the present energy budget of the Earth. With continental lithosphere, mantle heat production, and core heat loss constrained, the mantle cooling rate is adjusted to fit the total energy loss.

from *Jaupart et al. 2015 (Treatise on Geophysics)*

Reasons why $Nu \sim Ra^{1/3}$ does not apply to Earth?

- The mantle is not constant viscosity => plates are stiff
  - Plate tectonics doesn’t scale like constant viscosity convection?
  - Change in tectonic mode as Earth cooled?
- Melting and crustal production
  - Change tectonic mode
  - Transport heat when plate tectonics not operating
- Grain-size evolution: viscosity does not decrease with increasing temperature

Grain-size evolution could change heat flux-Ra scaling

Can hotter mantle have a larger viscosity?

V. S. Solomatov

GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 9, PAGES 937-940, MAY 1, 1996

$$\eta \propto d^m \exp(Q/RT)$$

d = grain size
Large=> high viscosity
Small=> low viscosity

A. Rozel @ETH is now observing this in fully dynamic models

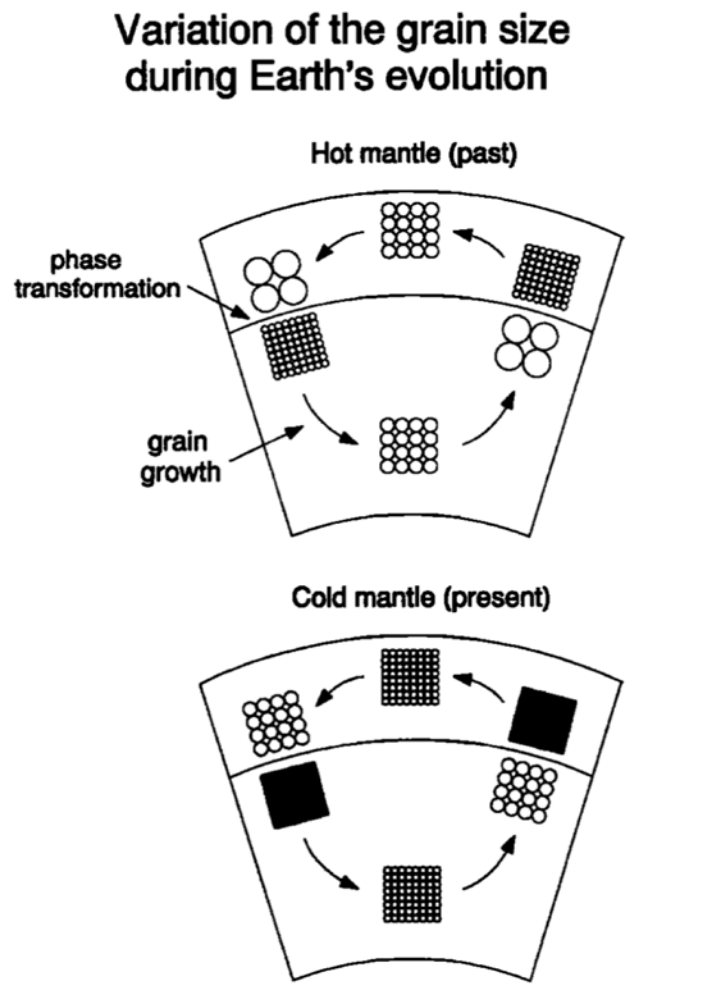


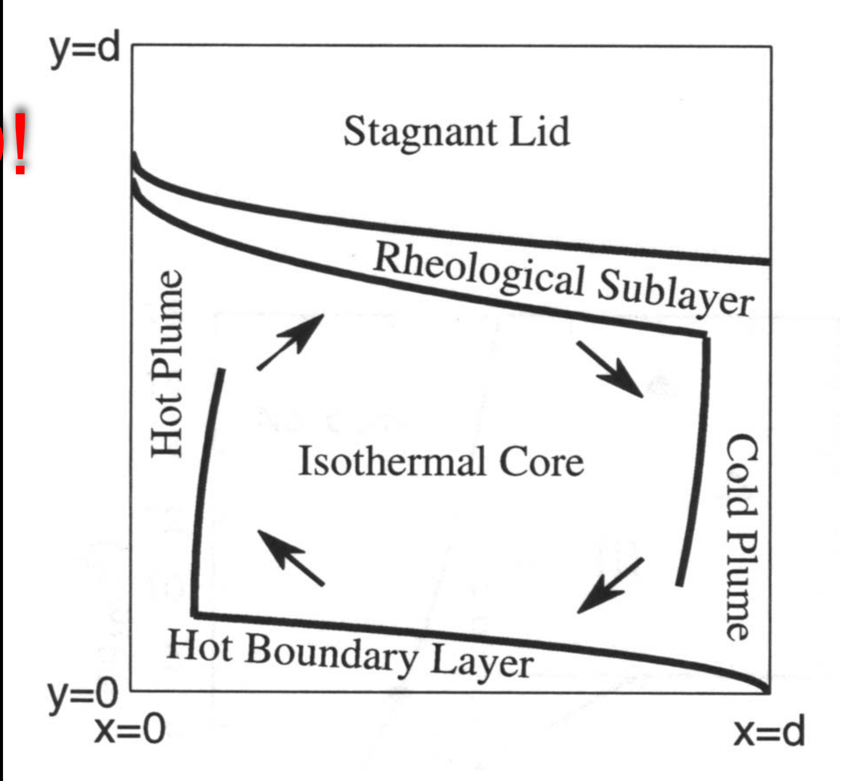
Figure 2. Variation of the grain size during Earth's evolution. The grain size can either decrease or increase during Earth's cooling depending on the specific ranges of kinetic parameters. The cartoon shows the first case.

Why does Earth have plate tectonics?

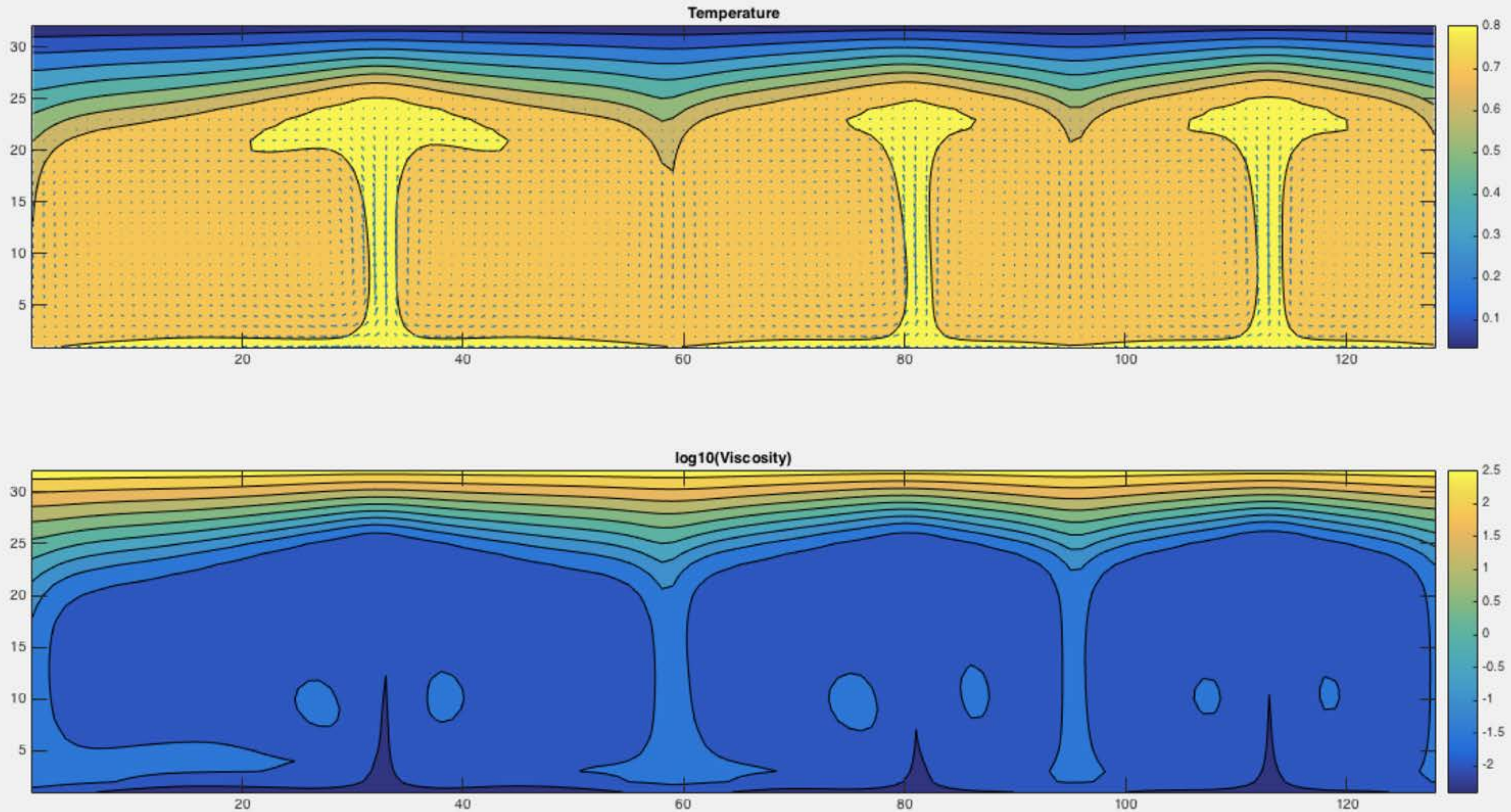
The plate problem

- 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
- => STAGNANT (rigid) LID!

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



Stagnant lid convection

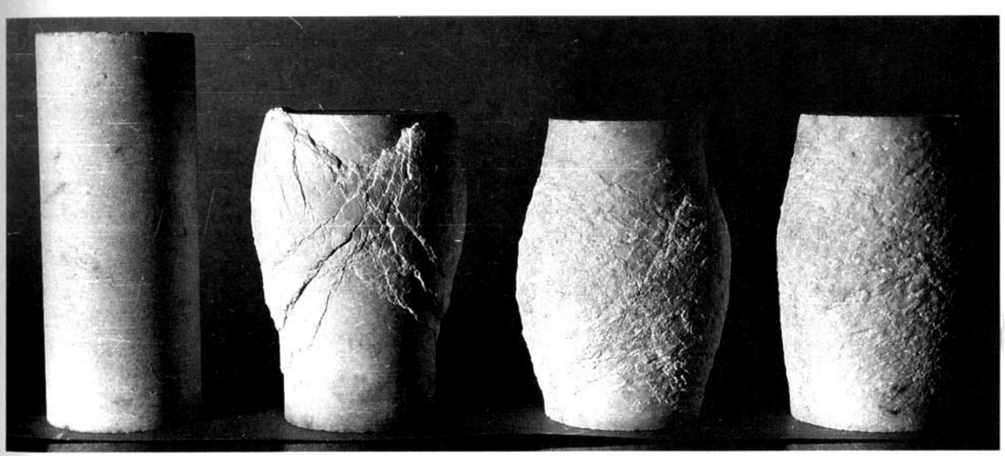


Strength of rocks

Low T: Effect of P

- Increases with confining pressure (depth) then saturates

Low-T deformation: Effect of P



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

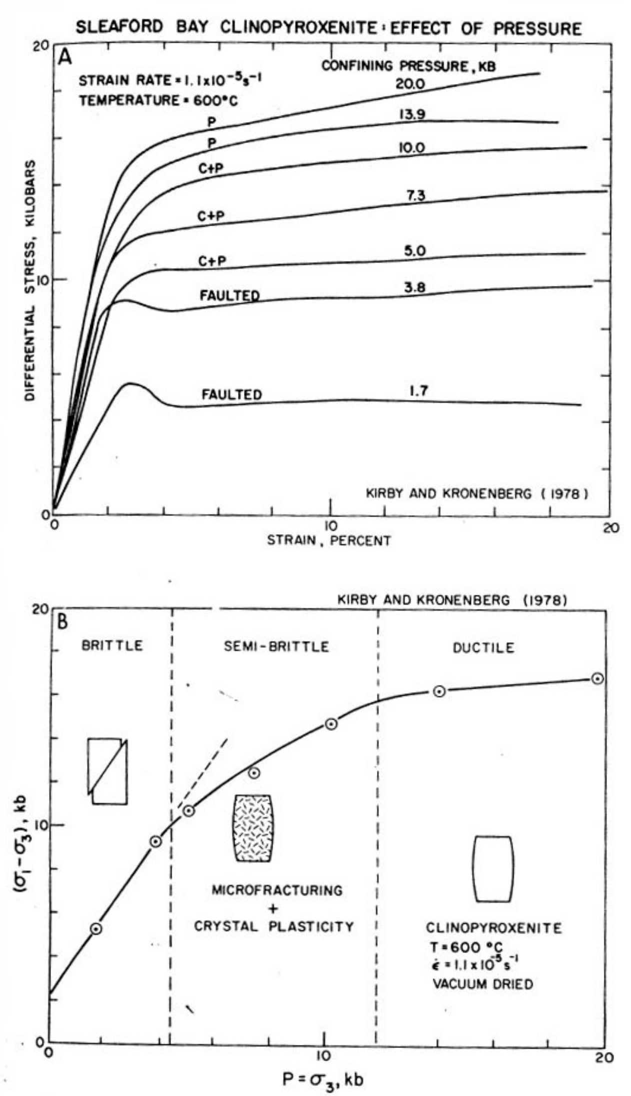
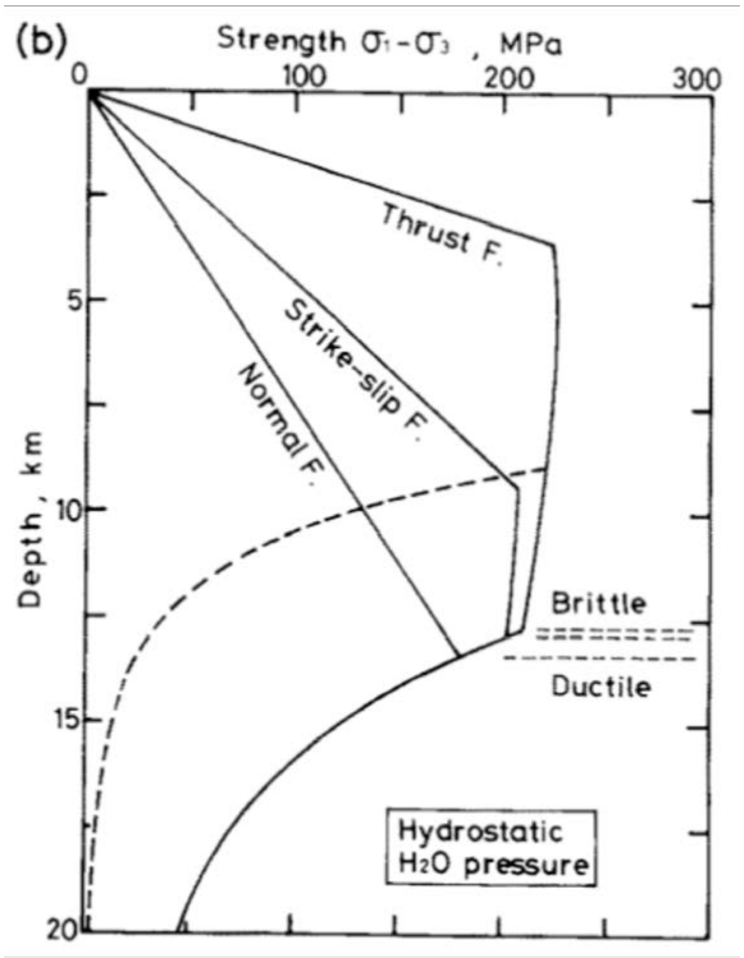


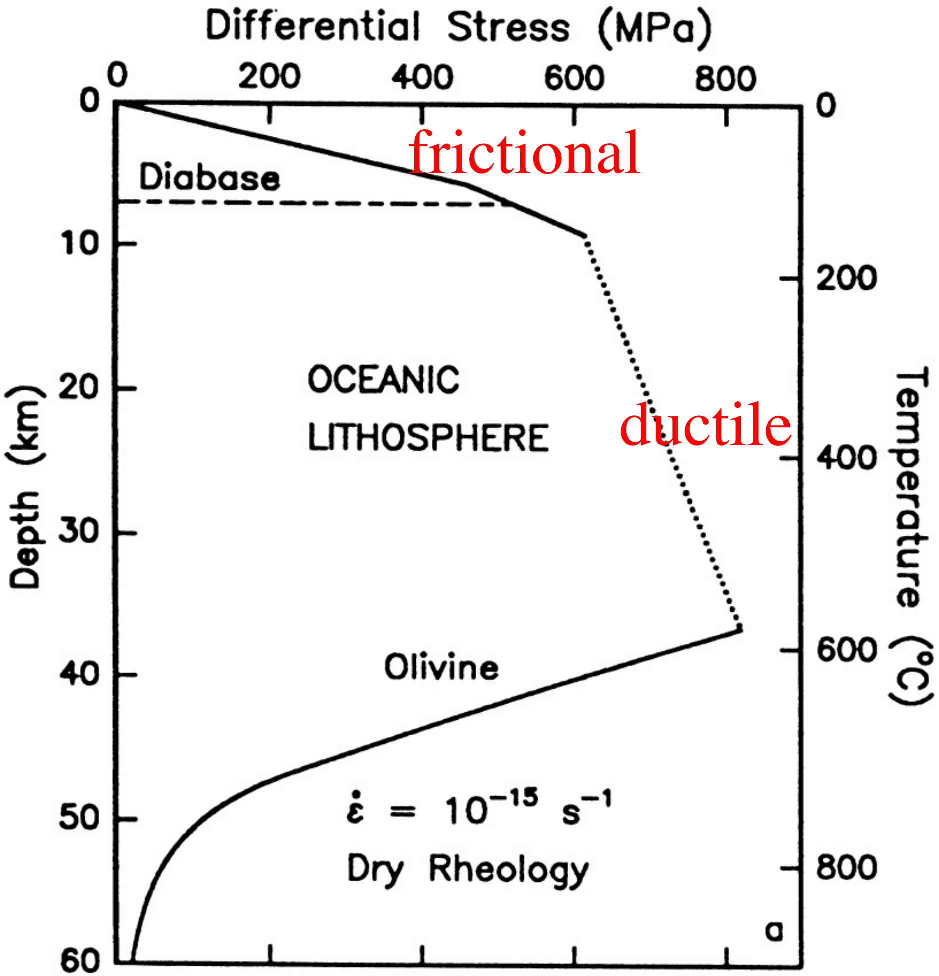
Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxenite tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): (*a*) stress-strain curves, (*b*) ultimate strength or stress at 10% strain as a function of confining pressure.

Strength profile of lithosphere

Continental (granite): Shimada 1993



Oceanic: Kohlstedt 1995

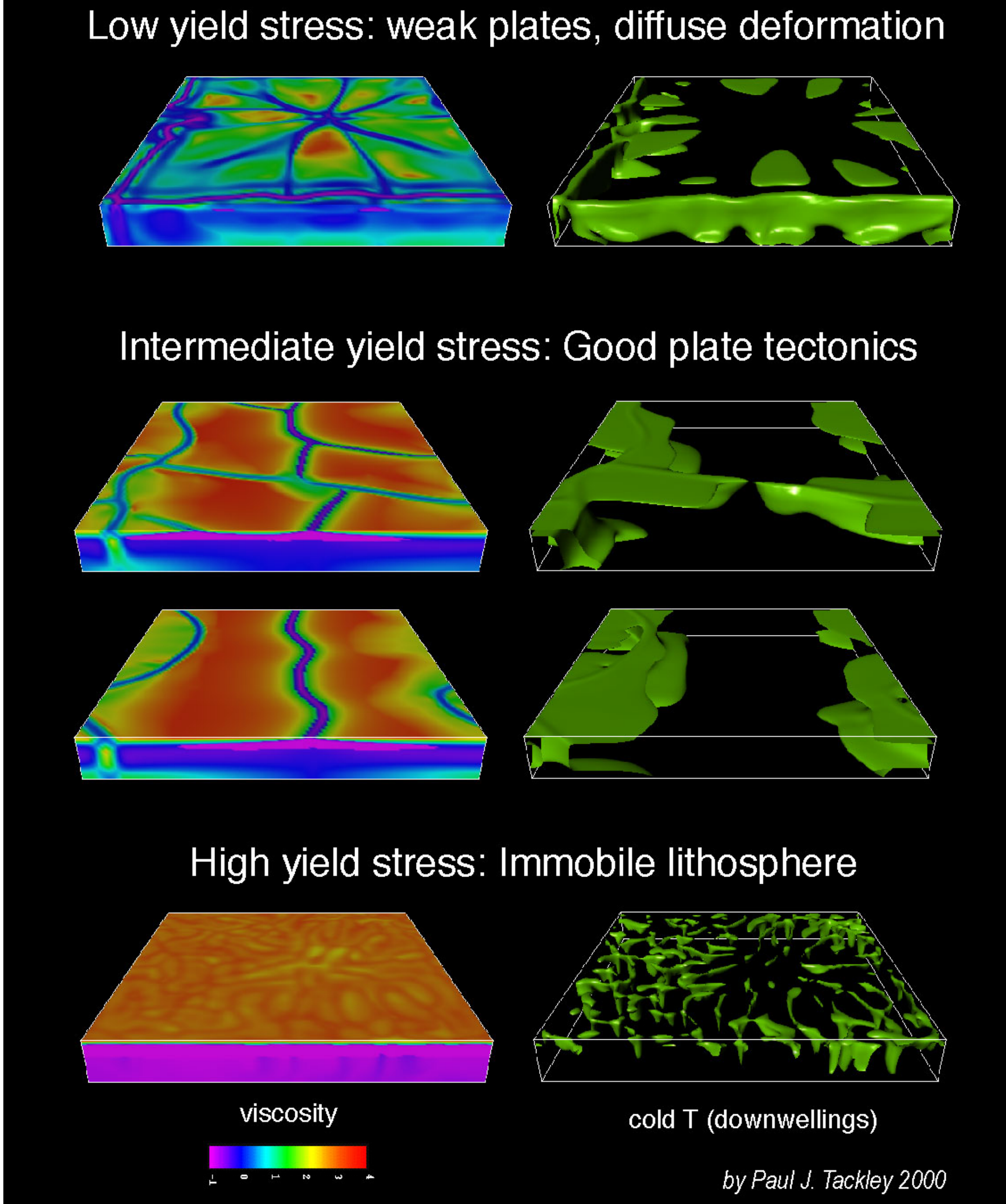


Reminder:

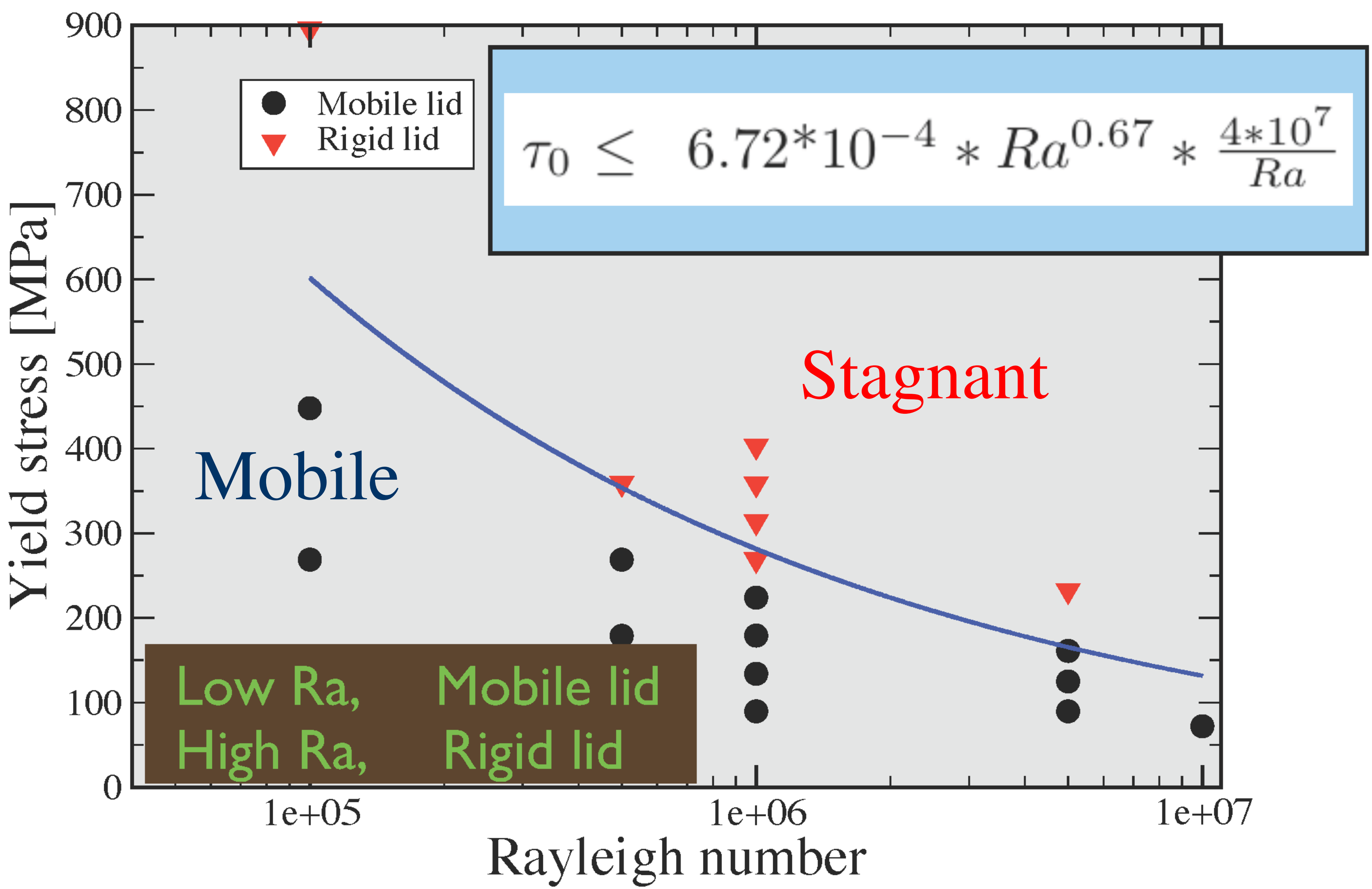
Plastic yielding + T-dependent viscosity can produce

- mobile lid,
- episodic lid
- stagnant lid

depending on the yield stress.



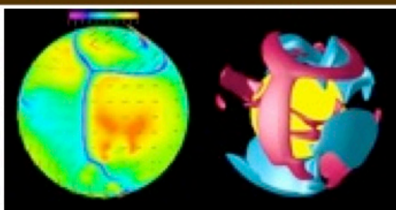
Rayleigh number versus yield stress



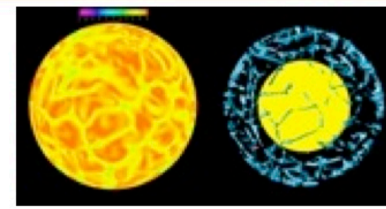
H. van Heck & Tackley

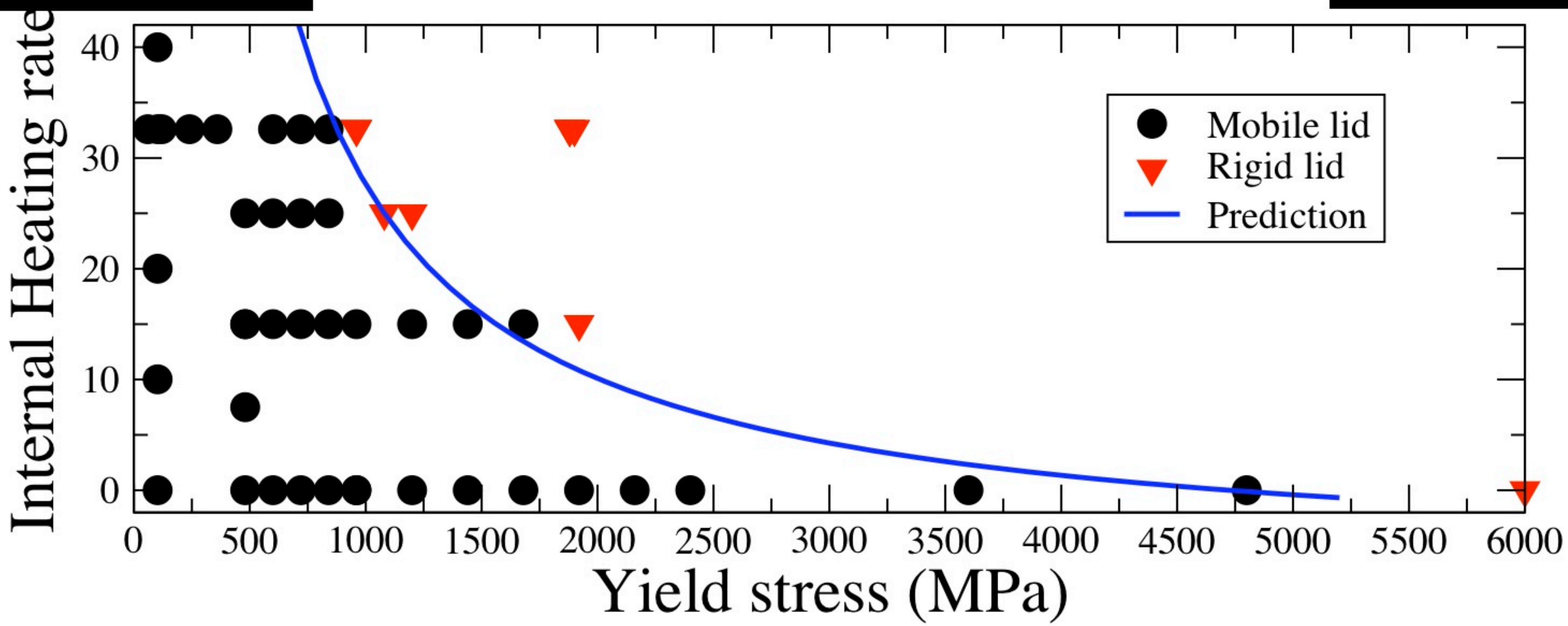
Internal heating rate

Strength of the lithosphere vs convective stresses



Yield stress versus internal heating rate





H. van Heck & Tackley

Implications for terrestrial planet evolution

- Plate tectonics favoured at
  - higher mantle viscosity (lower Ra)
  - Lower internal (radioactive) heating
- Both predict transition stagnant lid->plates as planet cools.

Coupled convection models of mantle-crust-core evolution

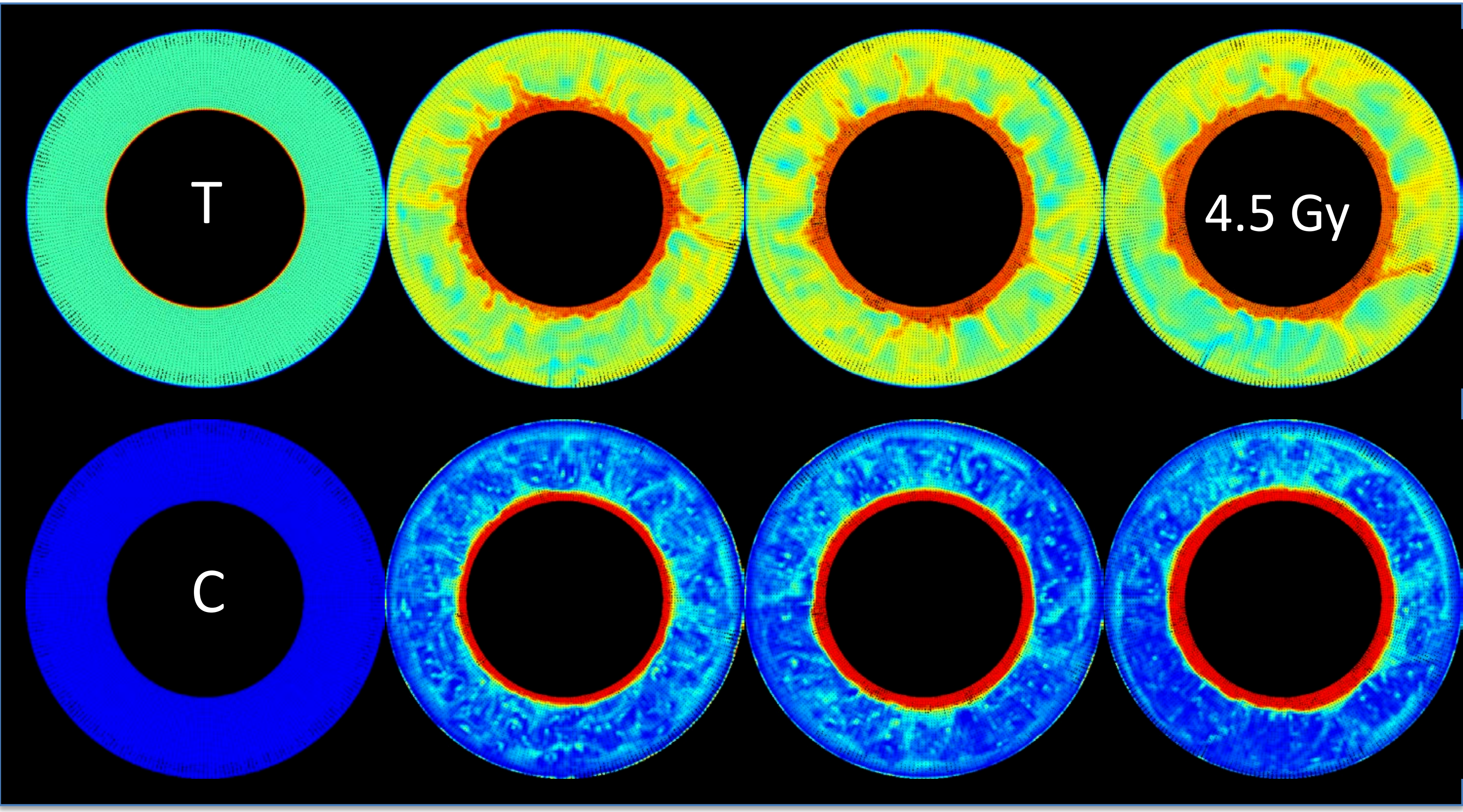
Calculations of mantle thermo-chemical evolution over 4.5 Gyr

- Include melting->crustal production,
  - viscosity dependent on T, d, and stress,
  - self-consistent plate tectonics,
  - decaying radiogenic elements and cooling core,

Many papers by Takashi Nakagawa & me

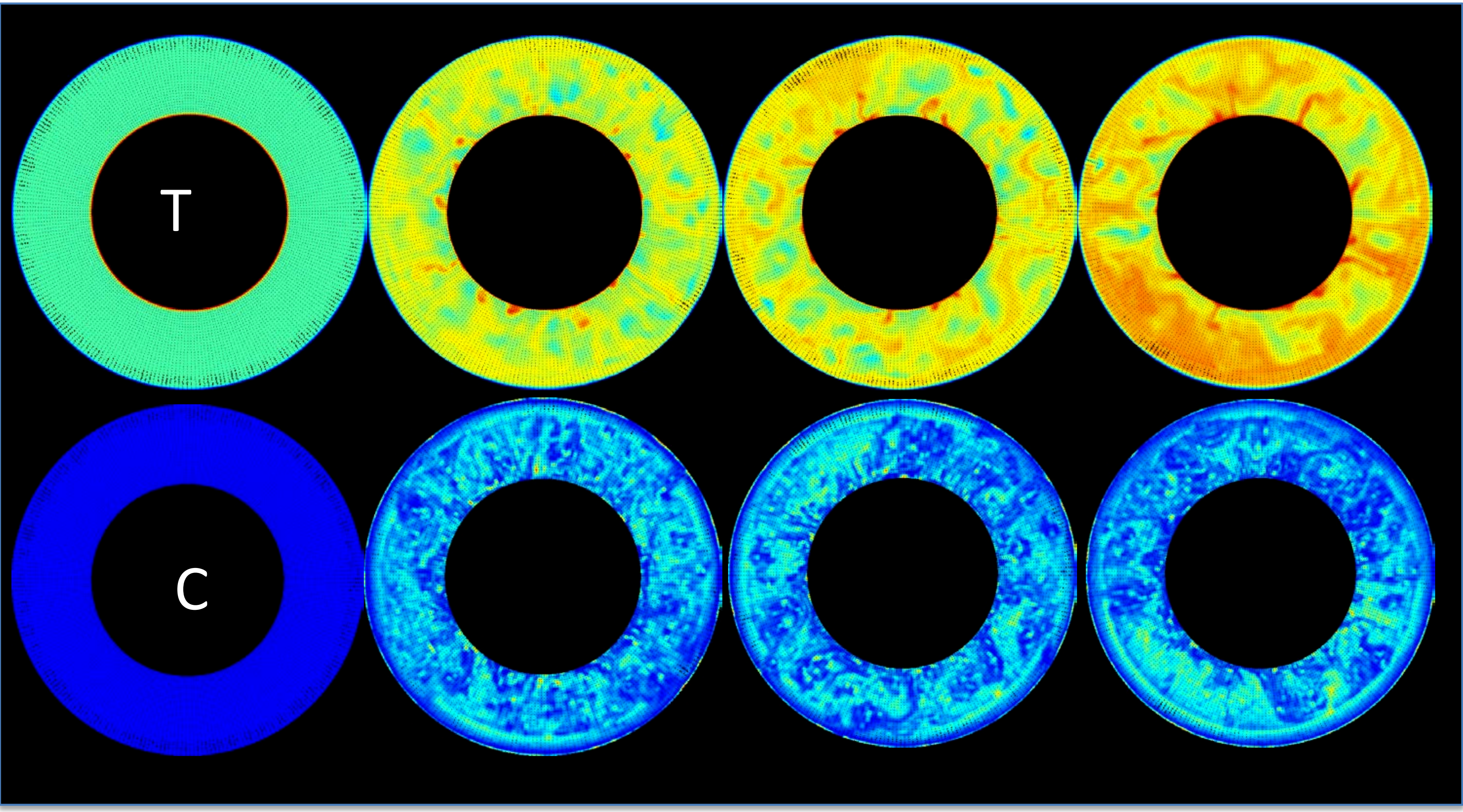
Typical evolution over 4.5 Gyr

($\eta_{ref}=10^{20}$ Pa.s, $\sigma_y=30$MPa)

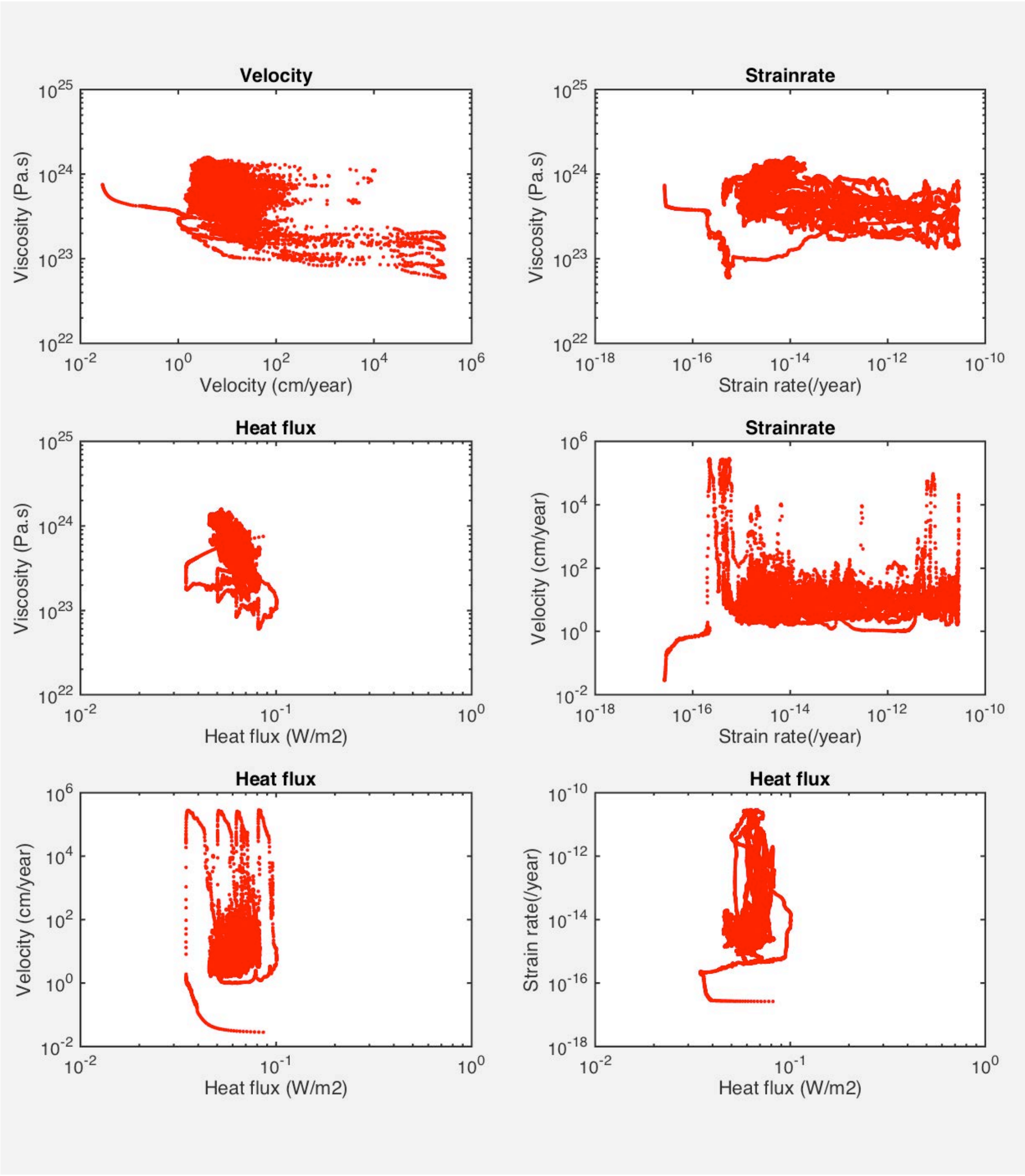


Mobile lid. Much chemical heterogeneity; basal MORB layer

With no basalt settling



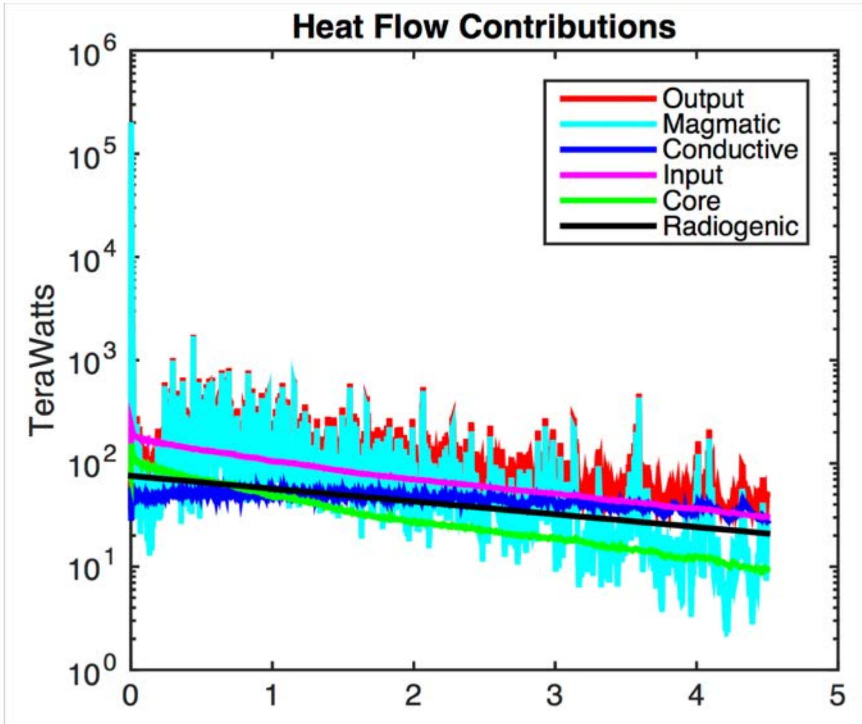
Scaling between velocity, strain-rate, heat flux and viscosity (Rayleigh #)?

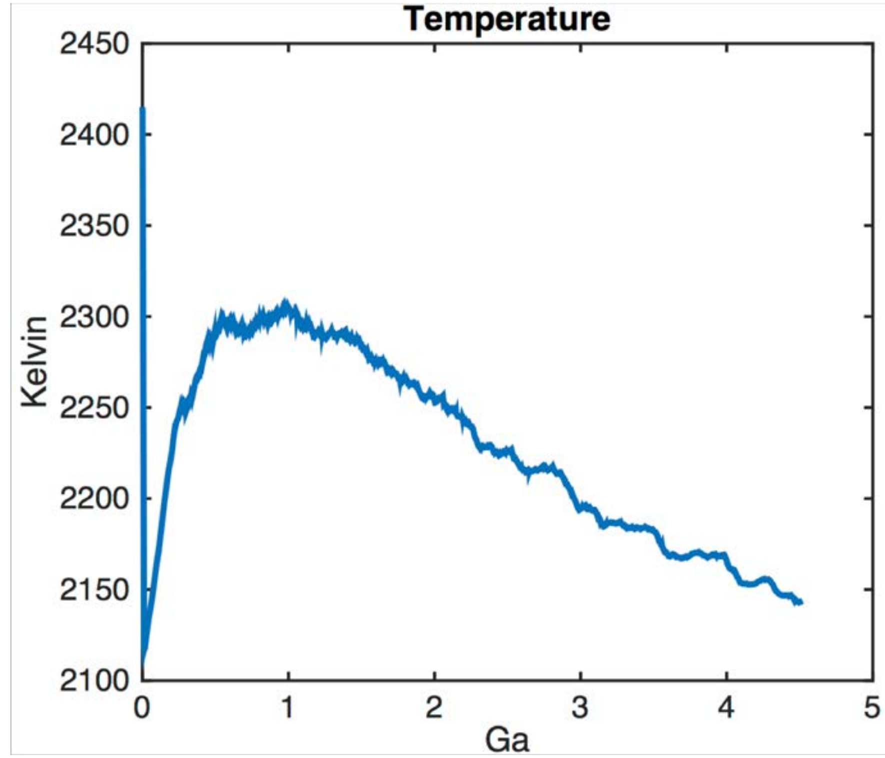


No clear scaling, unlike in simple convection

Each dot in these graphs is one time step; quantities are volume-averaged

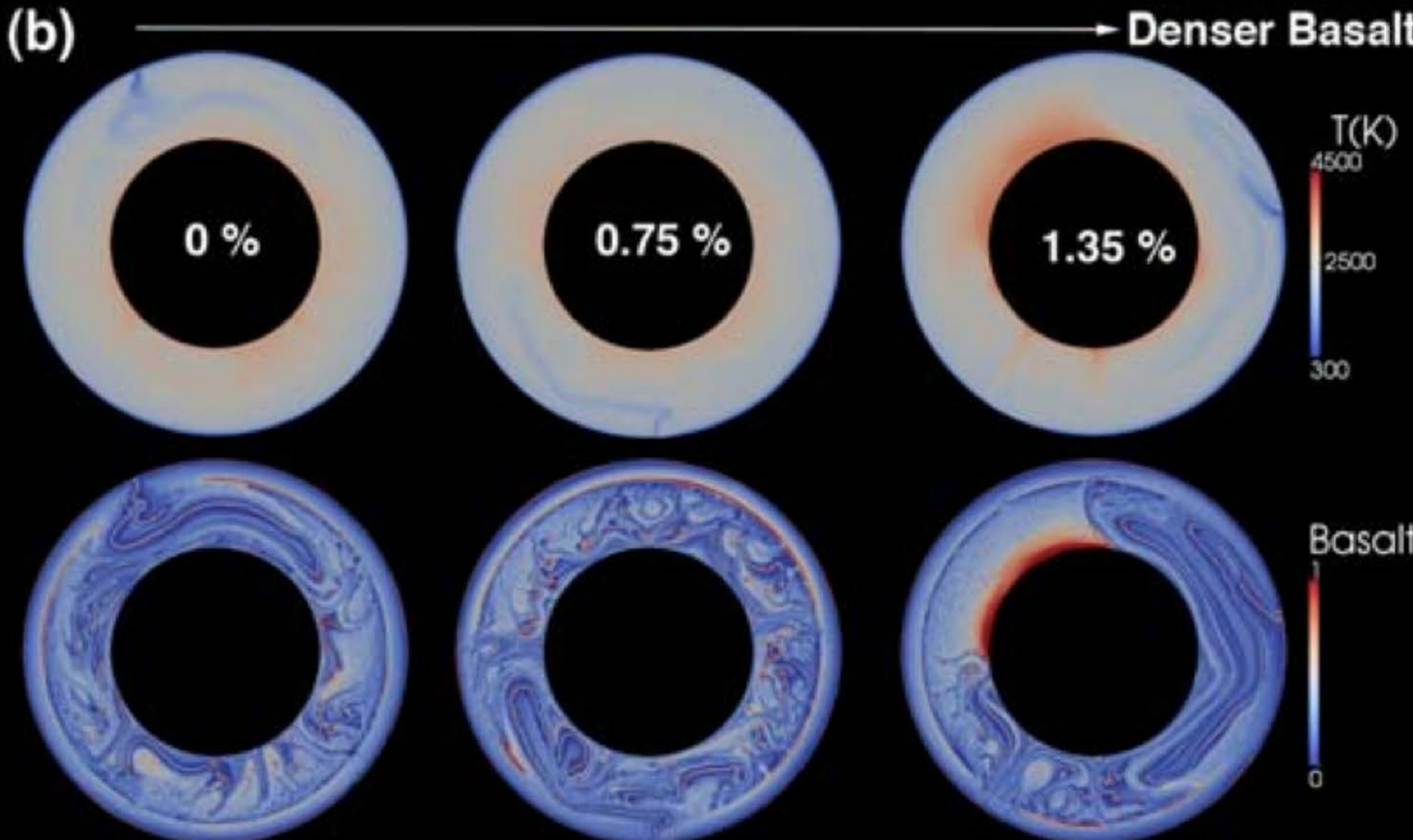
Typical thermal evolution





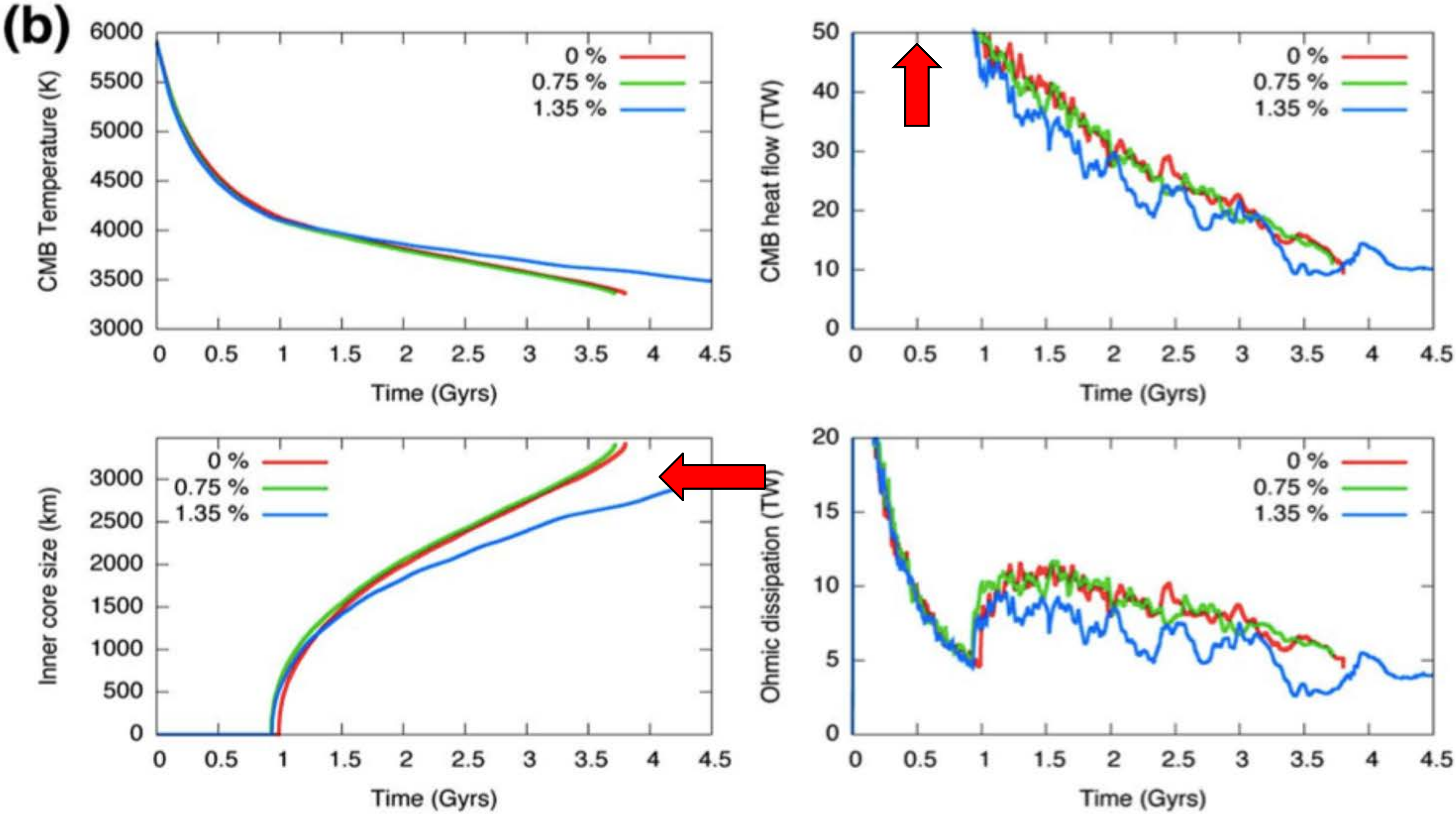
Magmatic resurfacing transports a lot of heat for much of the evolution

Core evolution?



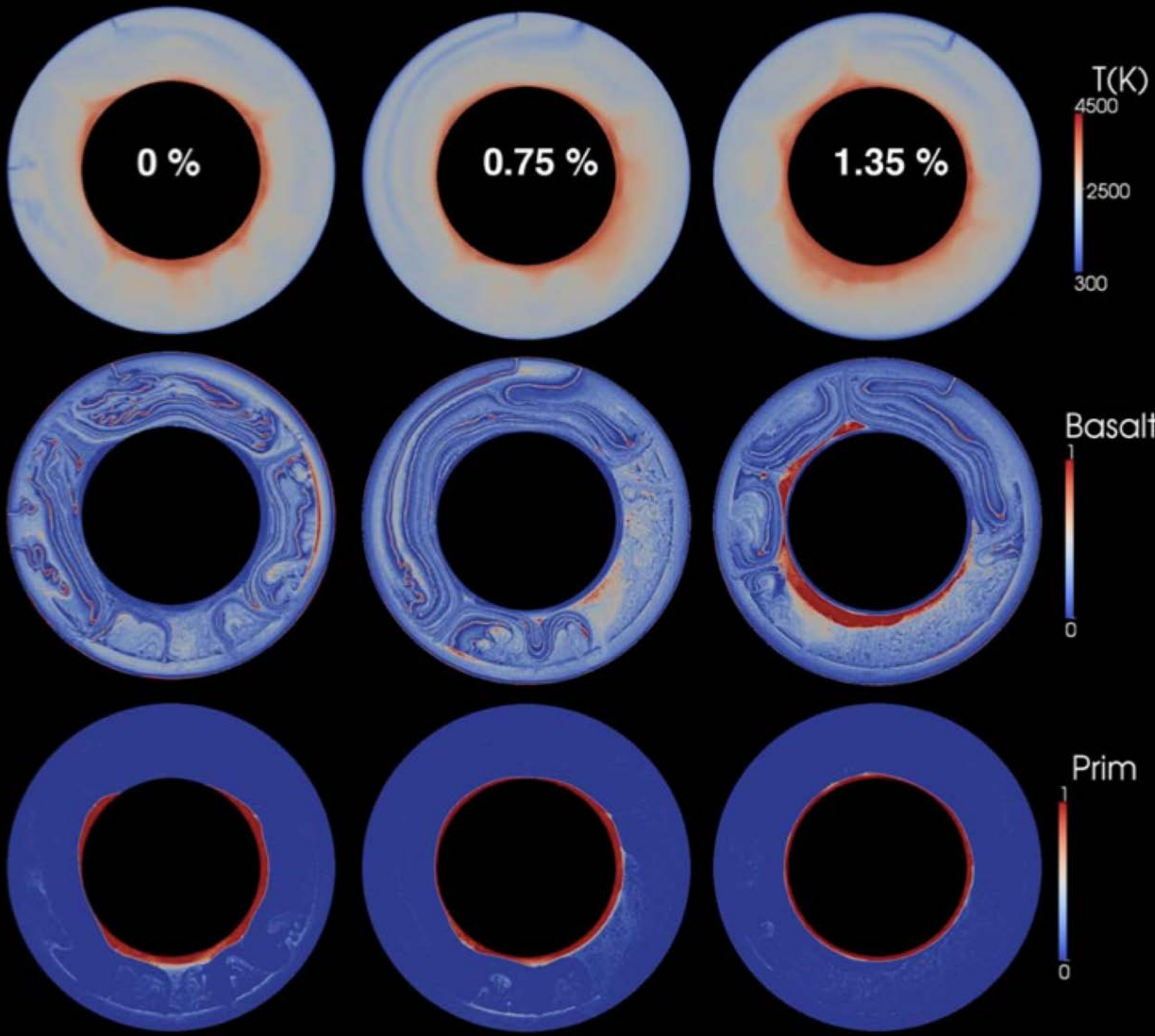
Nakagawa & Tackley, 2015 GCubed

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



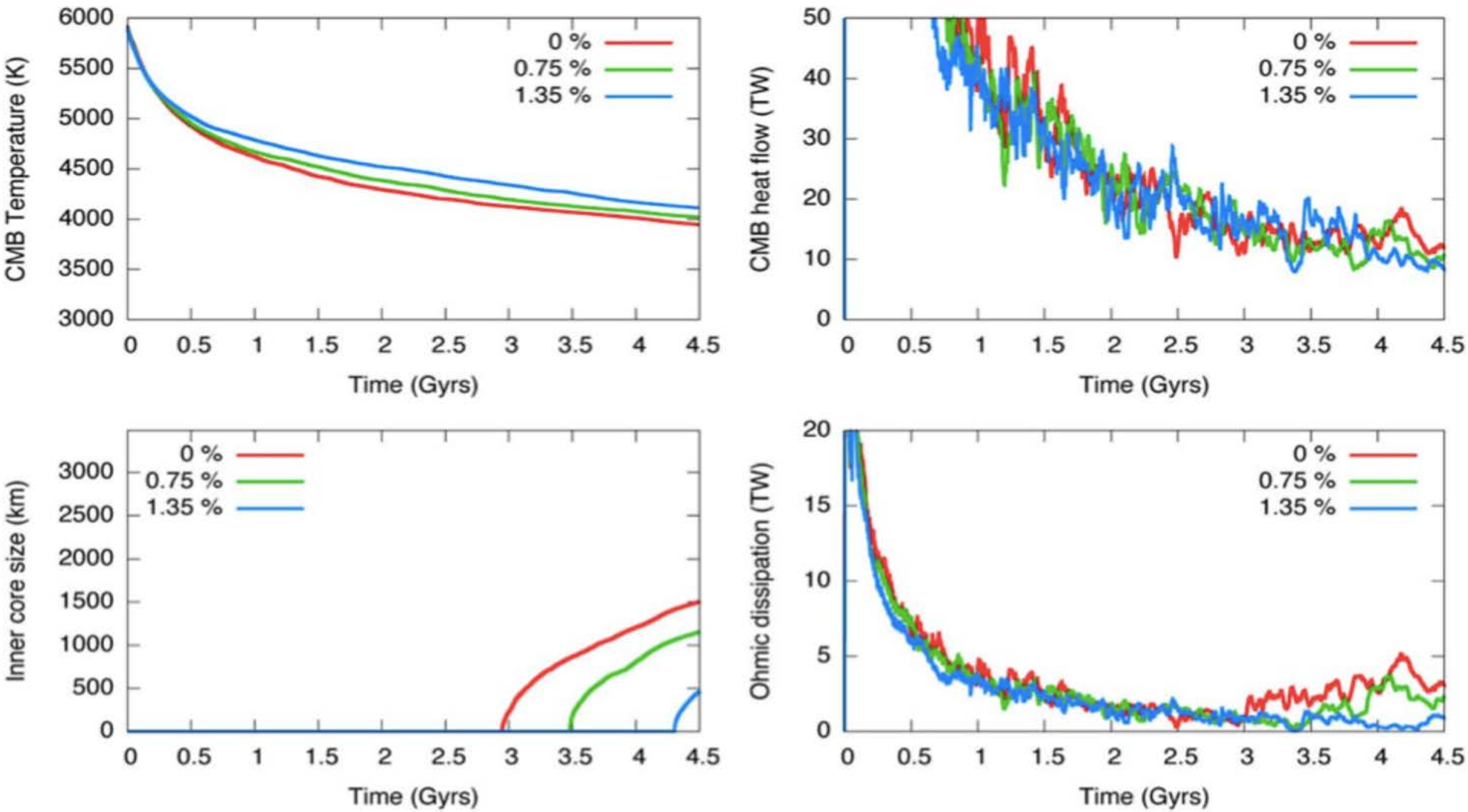
Nakagawa & Tackley, 2015 GCubed

With prim. Layer + MORB



Nakagawa & Tackley, 2015 GCubed

Successful core evolution
Deep dense layer reduces core cooling



Nakagawa & Tackley, 2015 GCubed

Core: Summary

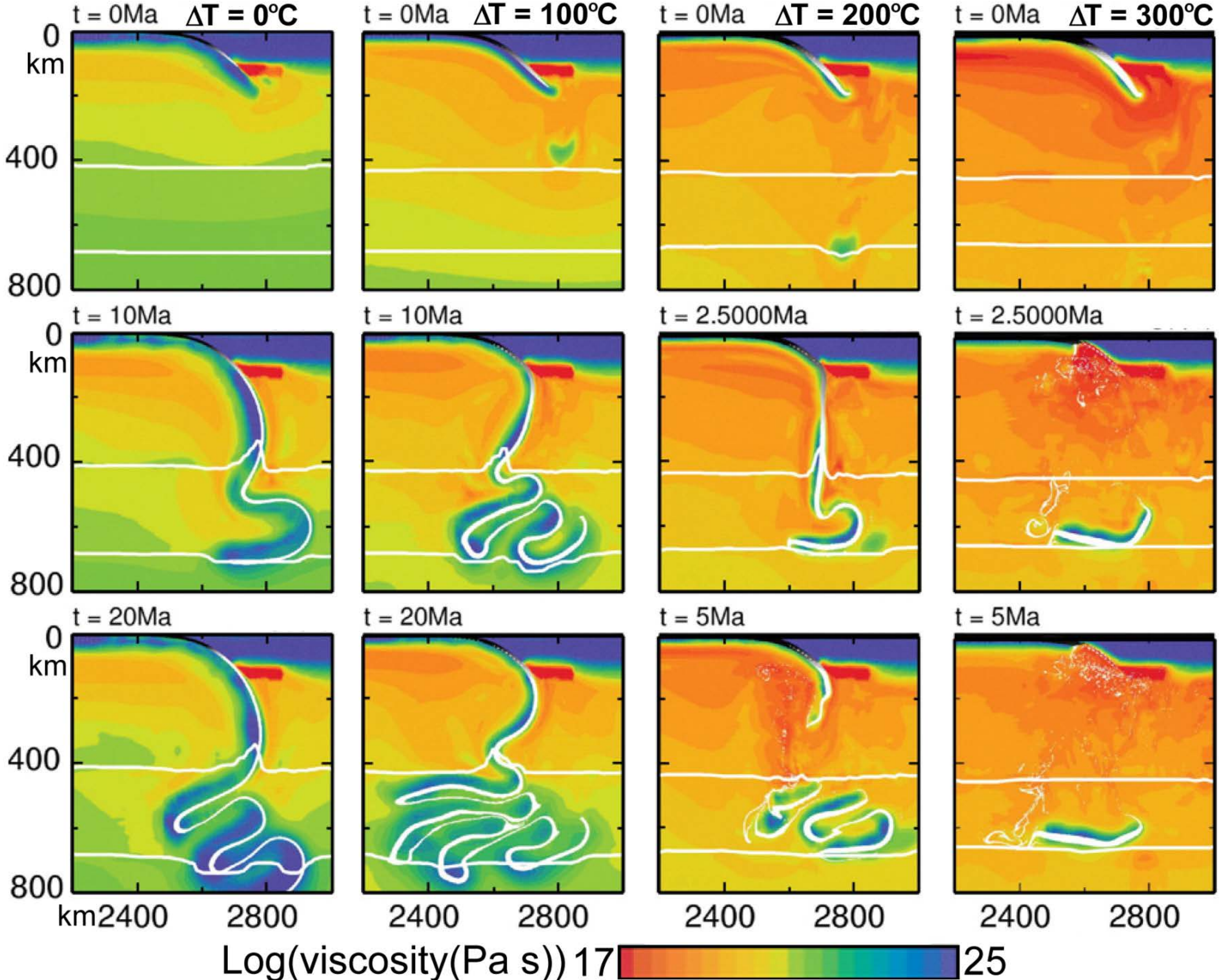
- If geodynamo driven by cooling + inner core crystallisation, favours primordial + recycled layer above the core-mantle boundary
- Other geodynamo driving mechanisms have been proposed recently (MgO or SiO2 precipitation, libration) which would allow lower CMB heat flux.

Key questions: Did Earth always have plate tectonics?

Box models assume it did

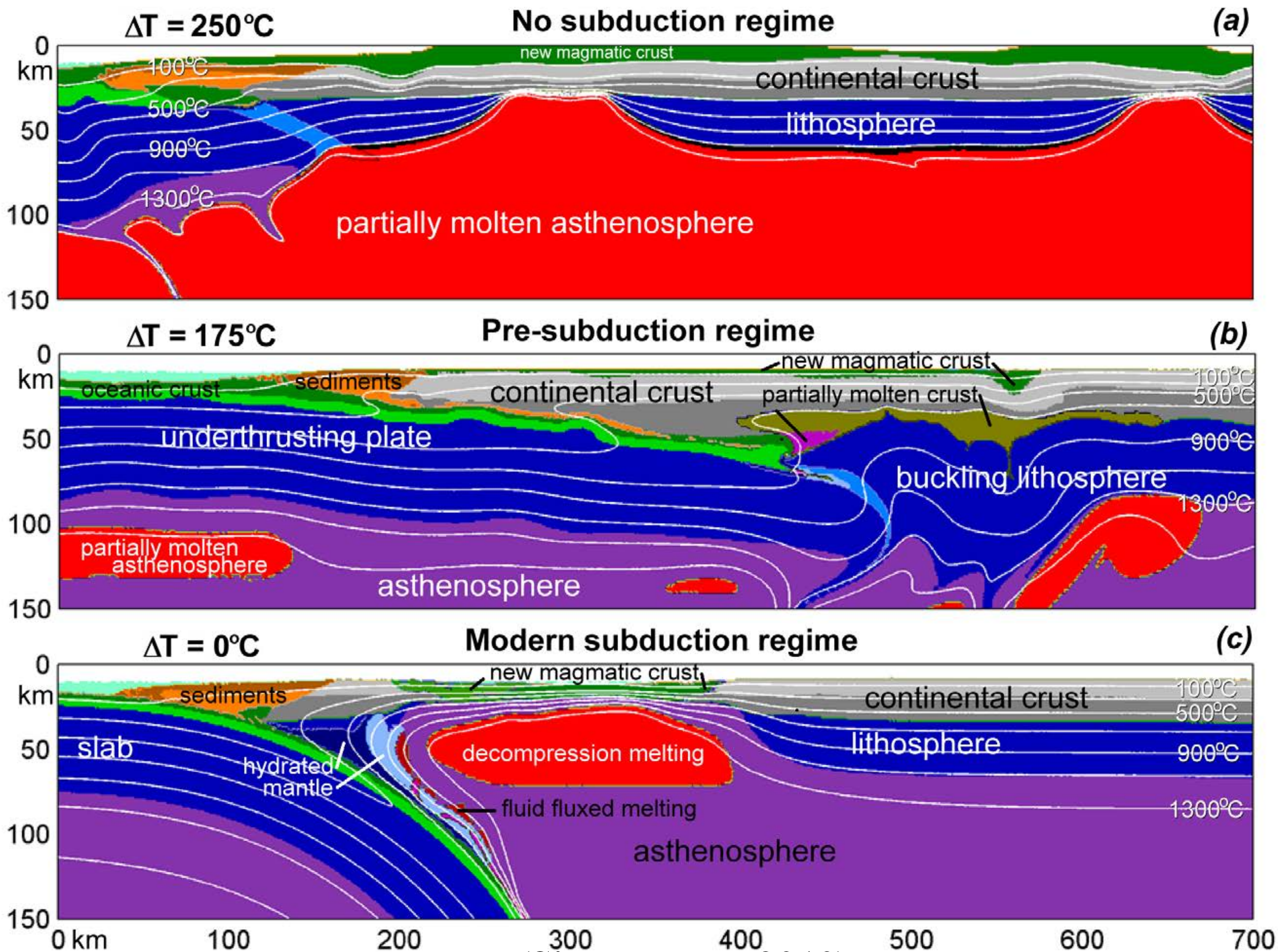
What was before plate tectonics?

Subduction doesn't work on a hotter Earth



(van Hunen & van den Berg, 2008)

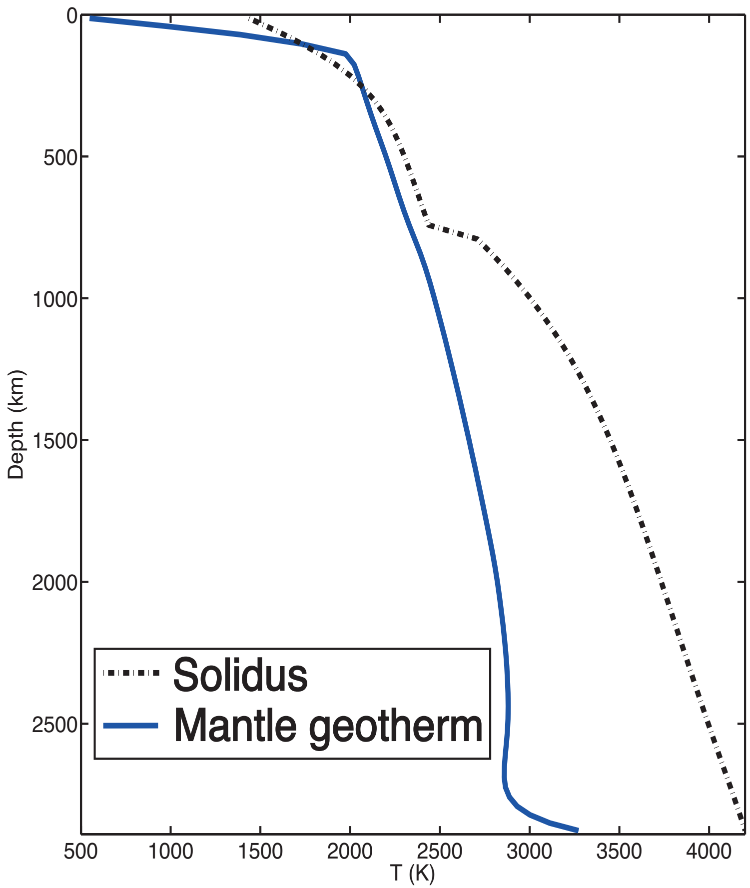
Subduction doesn't work on a hotter Earth

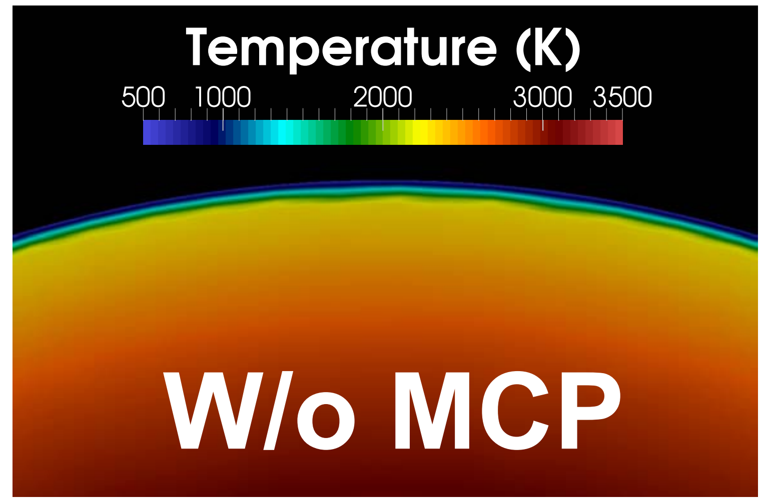


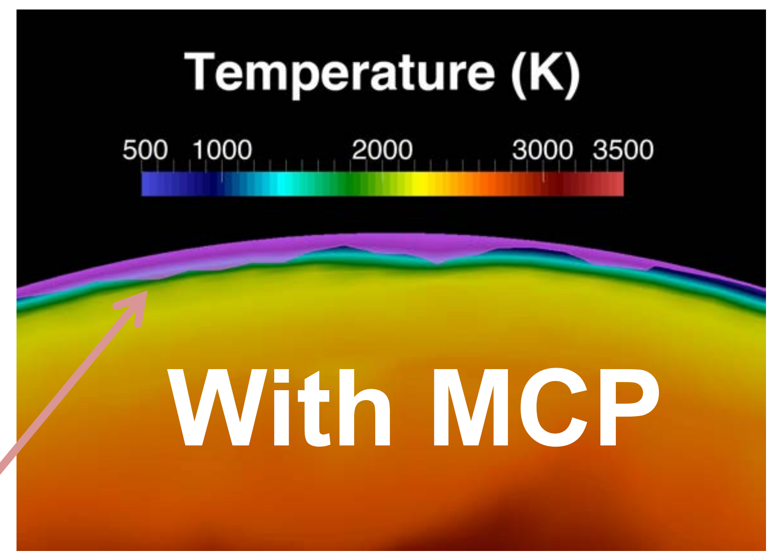
(Sizova et al., 2010)

Numerical and physical model

Melting-induced crustal production (MCP)





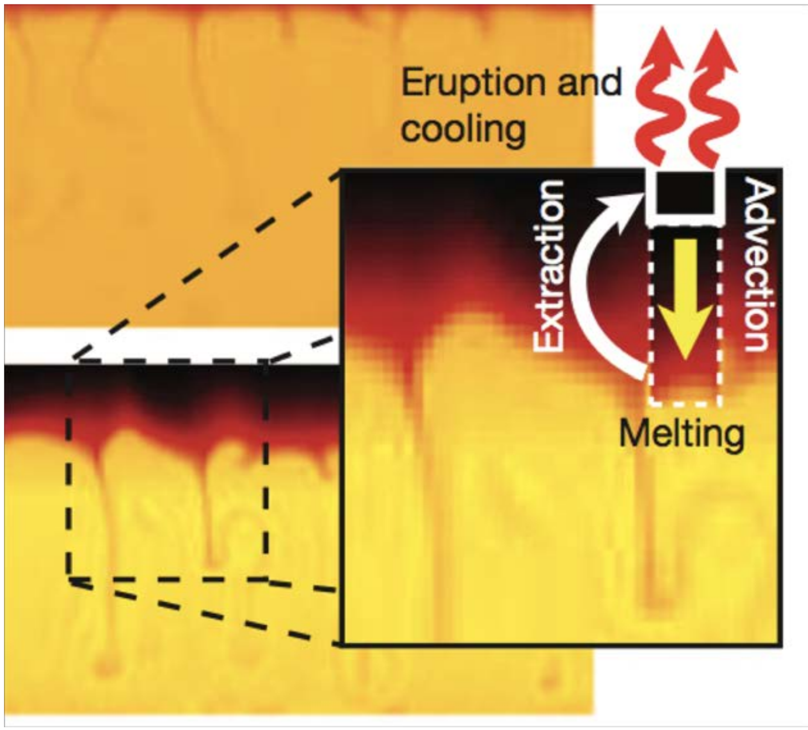


Basaltic crust

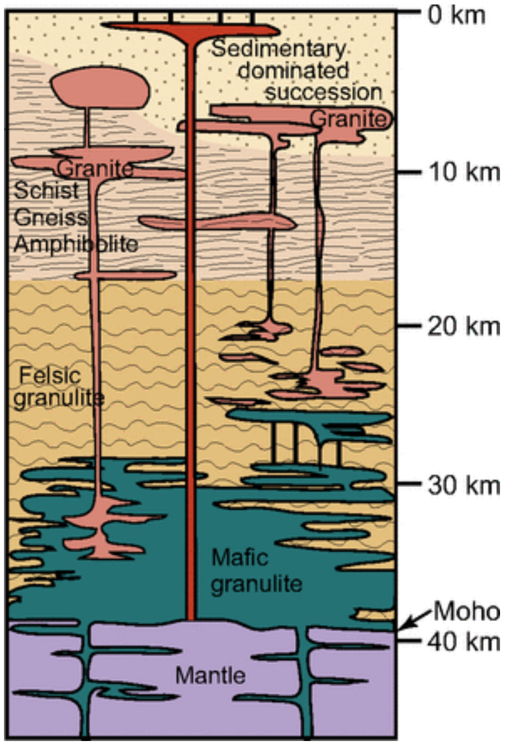
Diogo Lourenço

Extrusive heat pipe magmatism

But probably most magmatism is intrusive



(picture from Moore&Webb 2013)

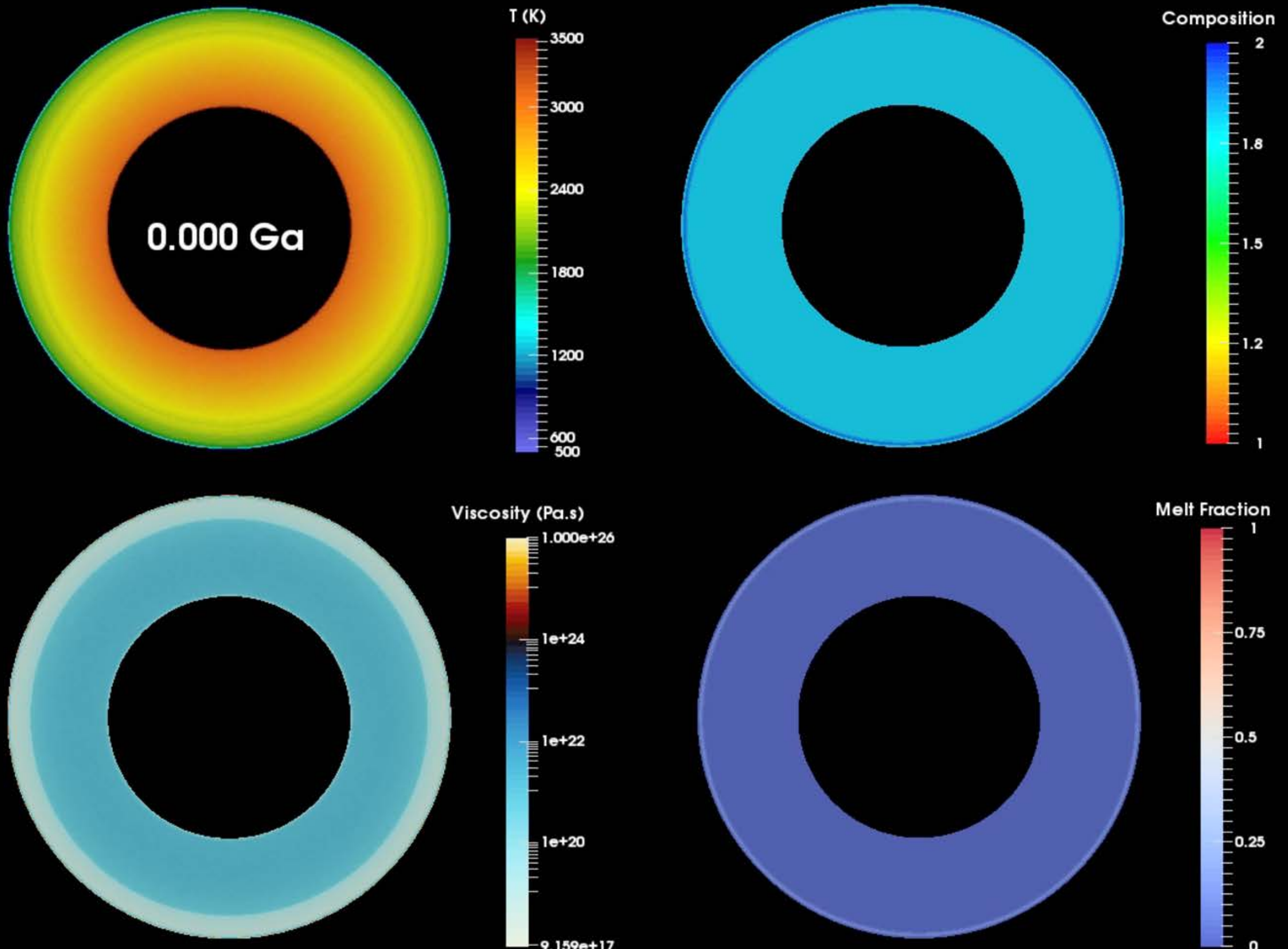


(picture from Cawood et al 2013)

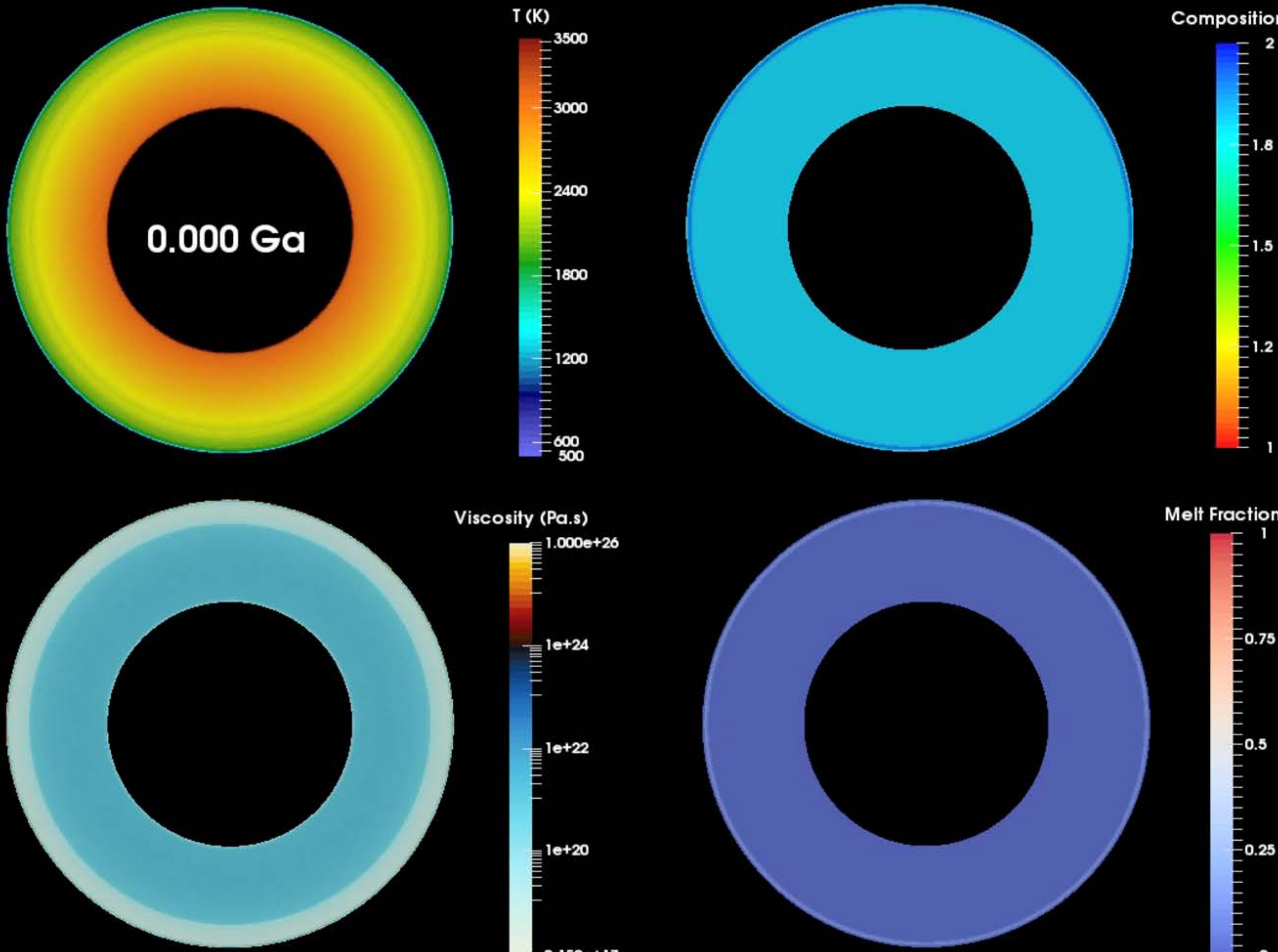
-> COLD, STRONG crust/lithosphere

-> WARM, WEAK crust/lithosphere

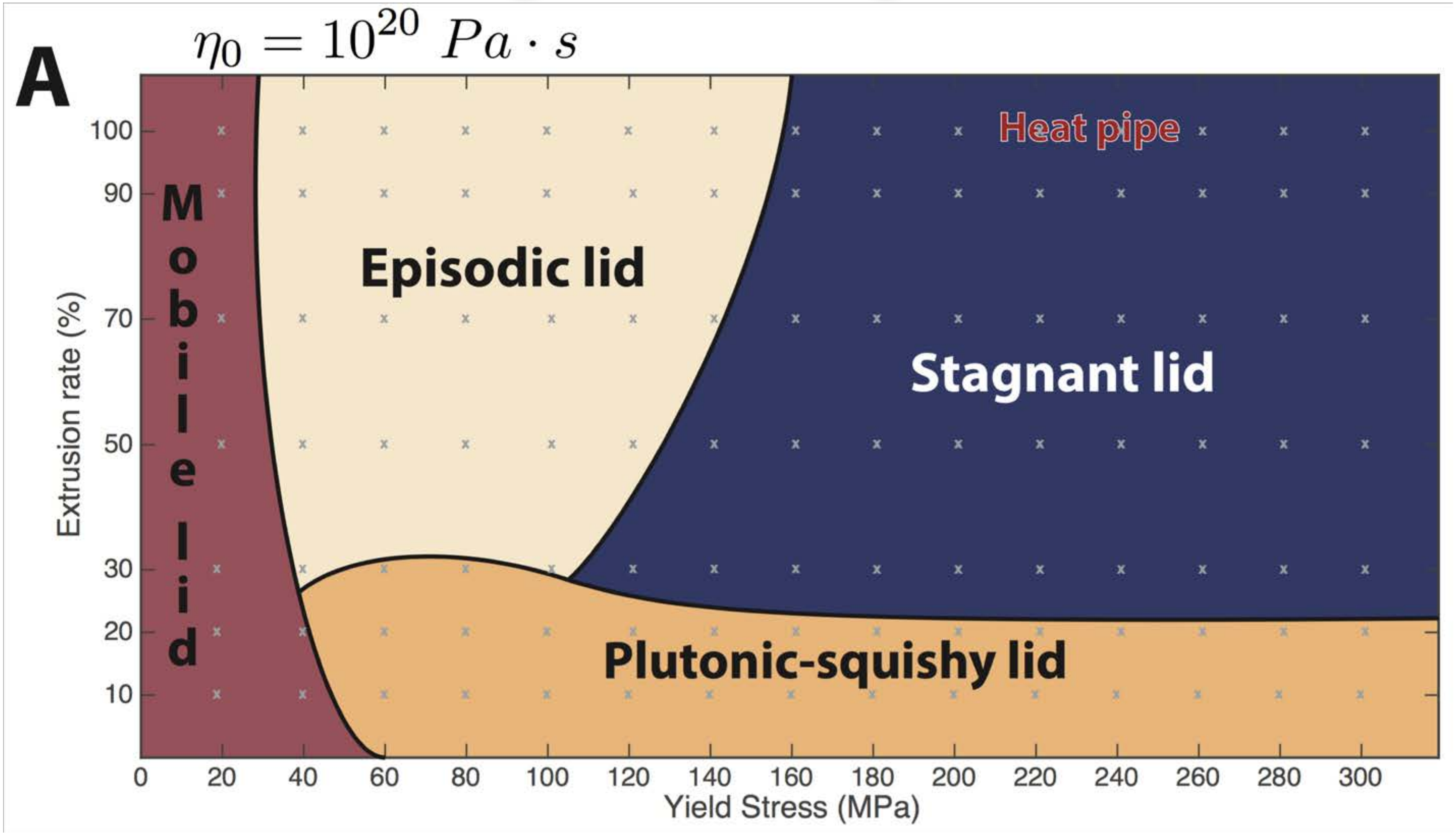
Typical episodic evolution - extrusive



In comparison – 90% intrusive

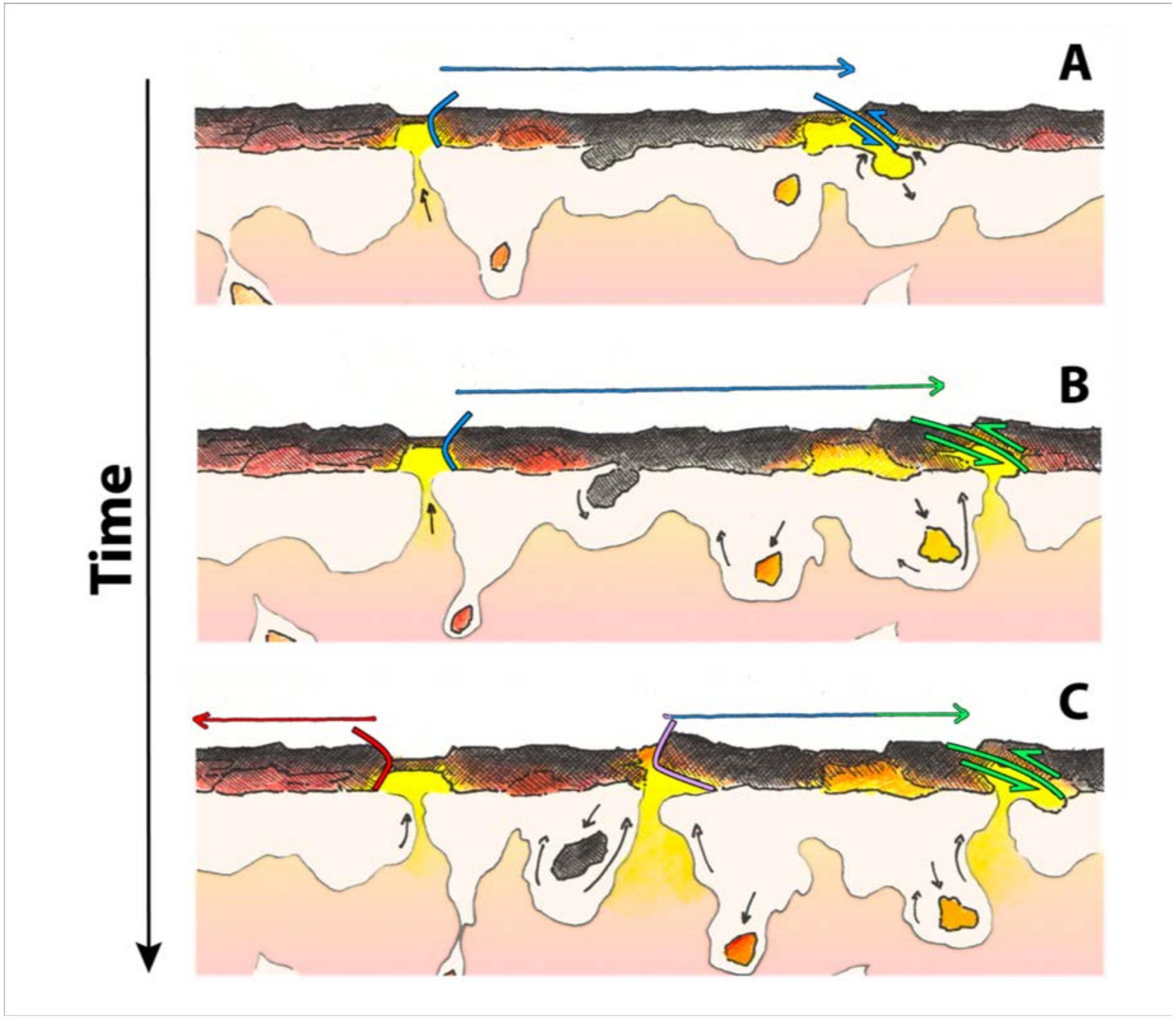


Regime diagram



Diogo Lourenco et al., submitted to G-Cubed

“Plutonic Squishy Lid” mode

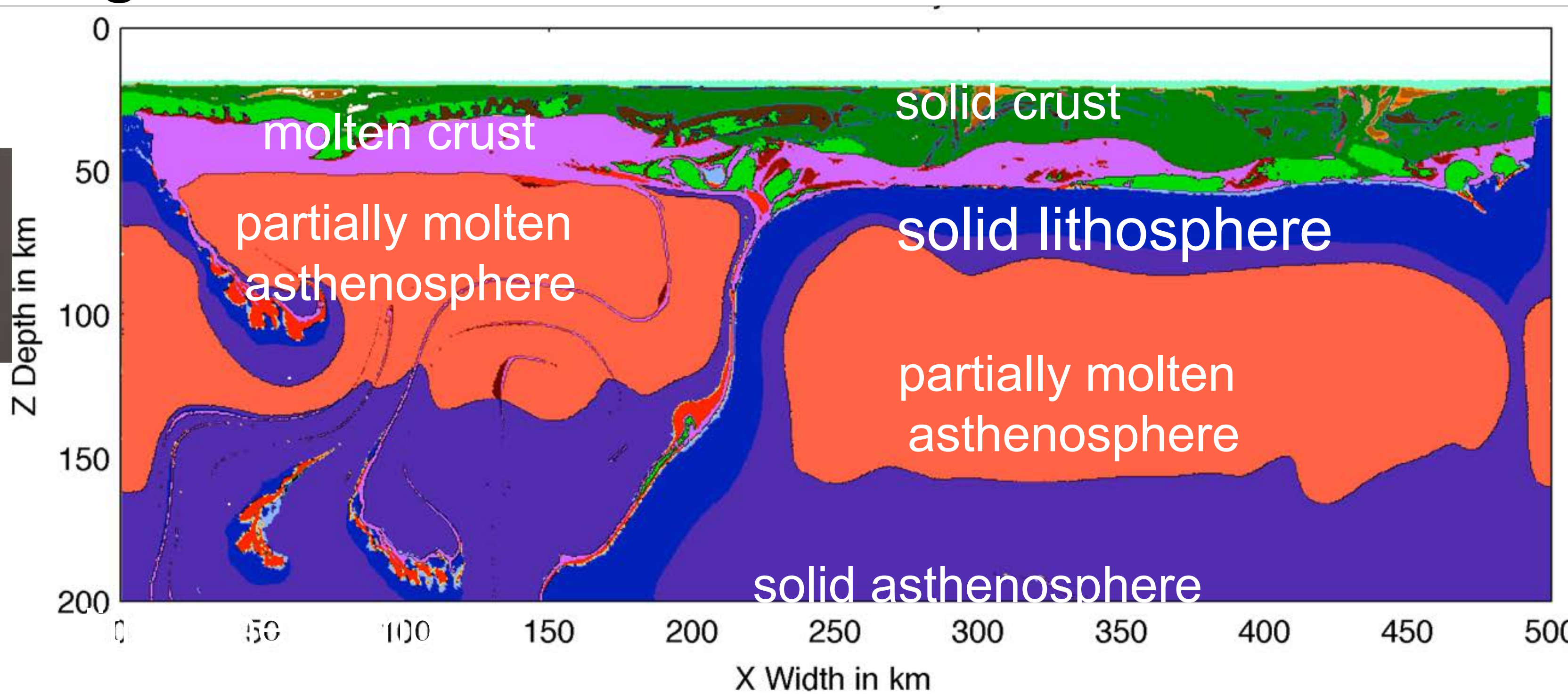


Lourenco et al., submitted

PSL in early Earth

- **weak** **deformable** **plates with low topography**
- **mantle-flows-driven orogeny** (Sizova et al., in 2015)
- **magma-assisted** **crustal convection**

Elena Sizova

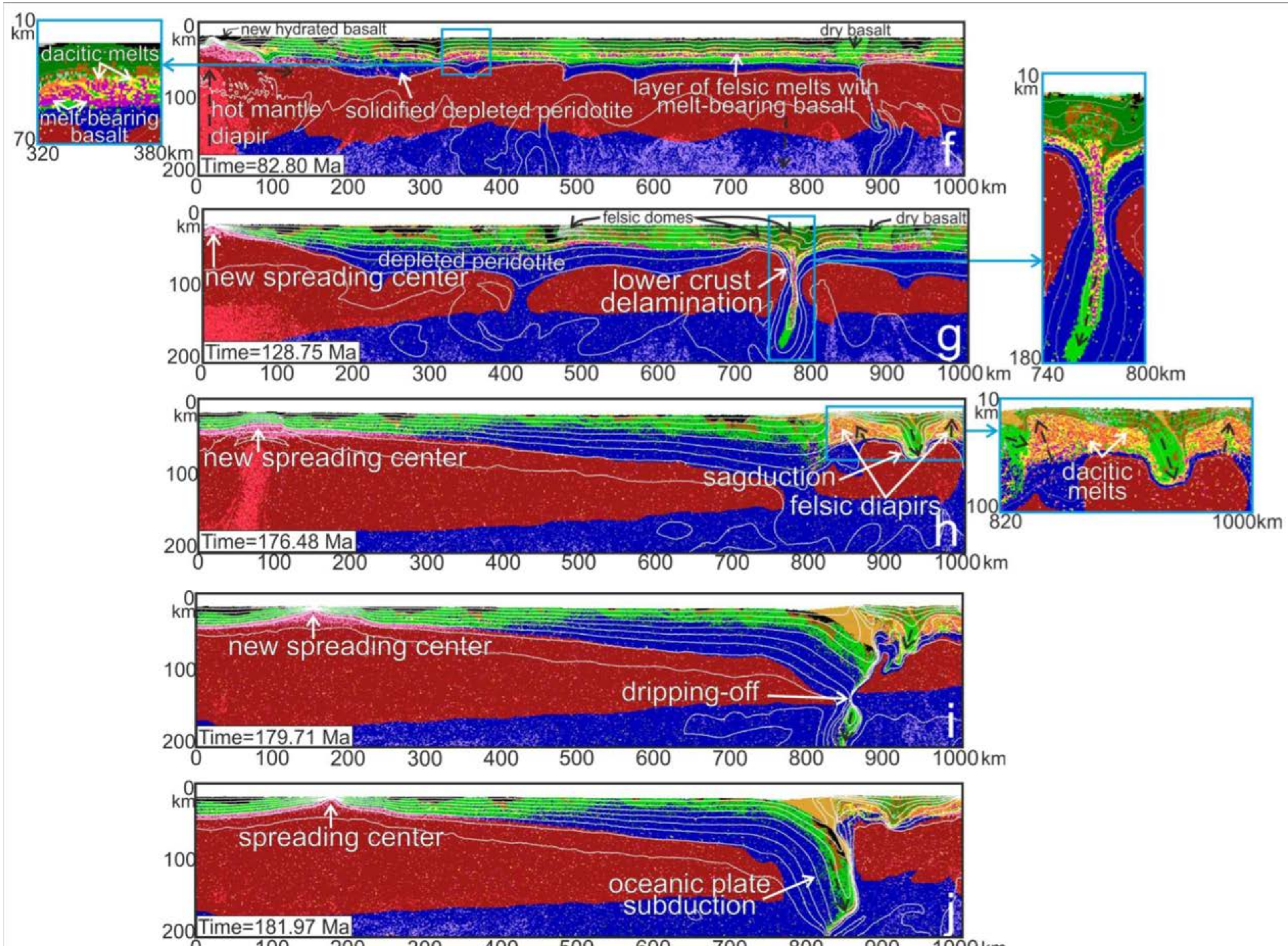


No plate tectonics but not a rigid lid either!

-> Plutonic Squishy-Lid tectonics

PSL is relevant to Early Earth?

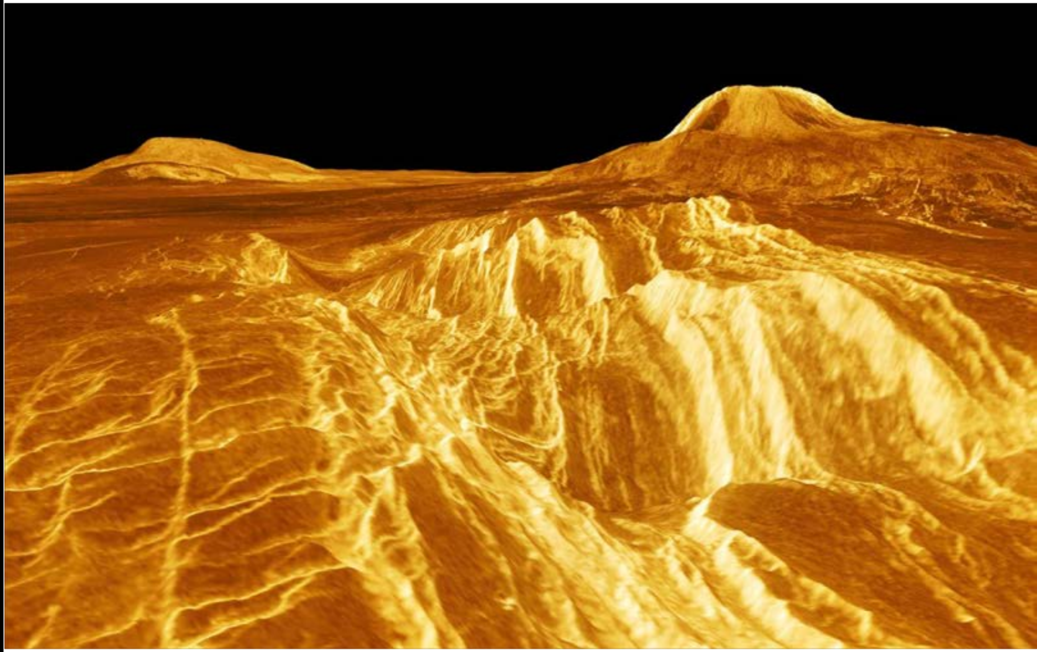
Elena Sizova



Lack of *plate* tectonics ≠ lack of *tectonics*

Venus is tectonically and volcanically active

"Stagnant lid" ≠ "Rigid lid"



ARTICLES
https://doi.org/10.1038/s41561-018-0094-8
nature geoscience

Efficient cooling of rocky planets by intrusive magmatism

Diogo L. Lourenço[1,2*], Antoine B. Rozel[1], Taras Gerya[1] and Paul J. Tackley[1]

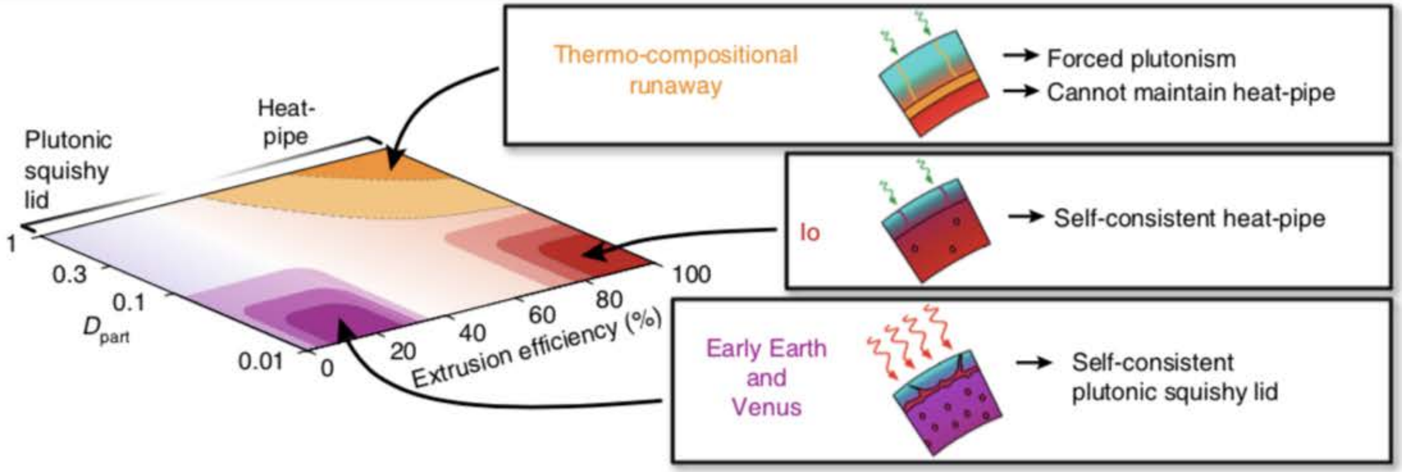


Fig. 3 | Regime diagram of the tectonic regimes discussed in this work. Parameter space in terms of extrusion efficiency and partitioning of HPEs where the different tectonic regimes discussed in this work are expected, together with a brief discussion of them.

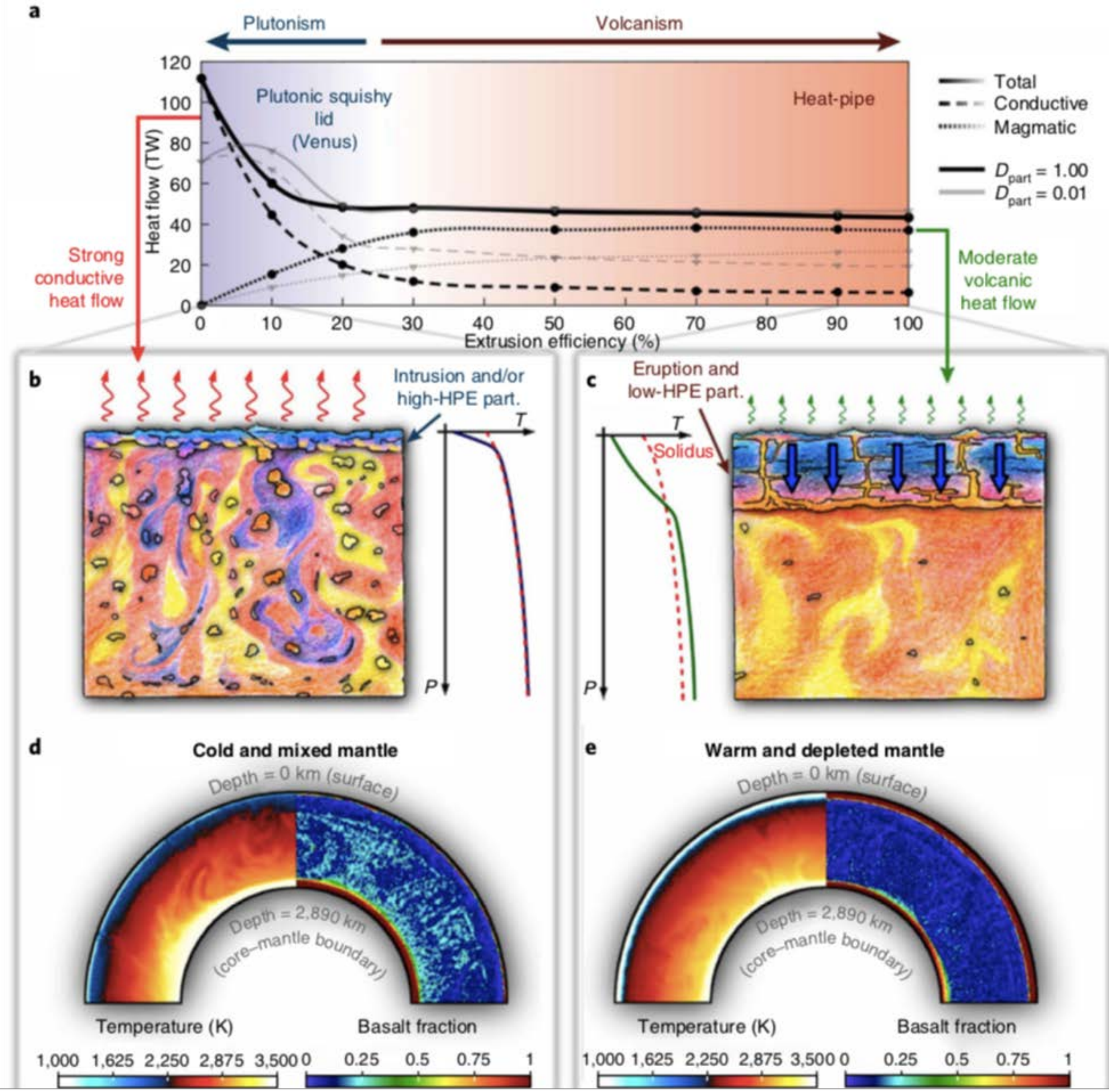
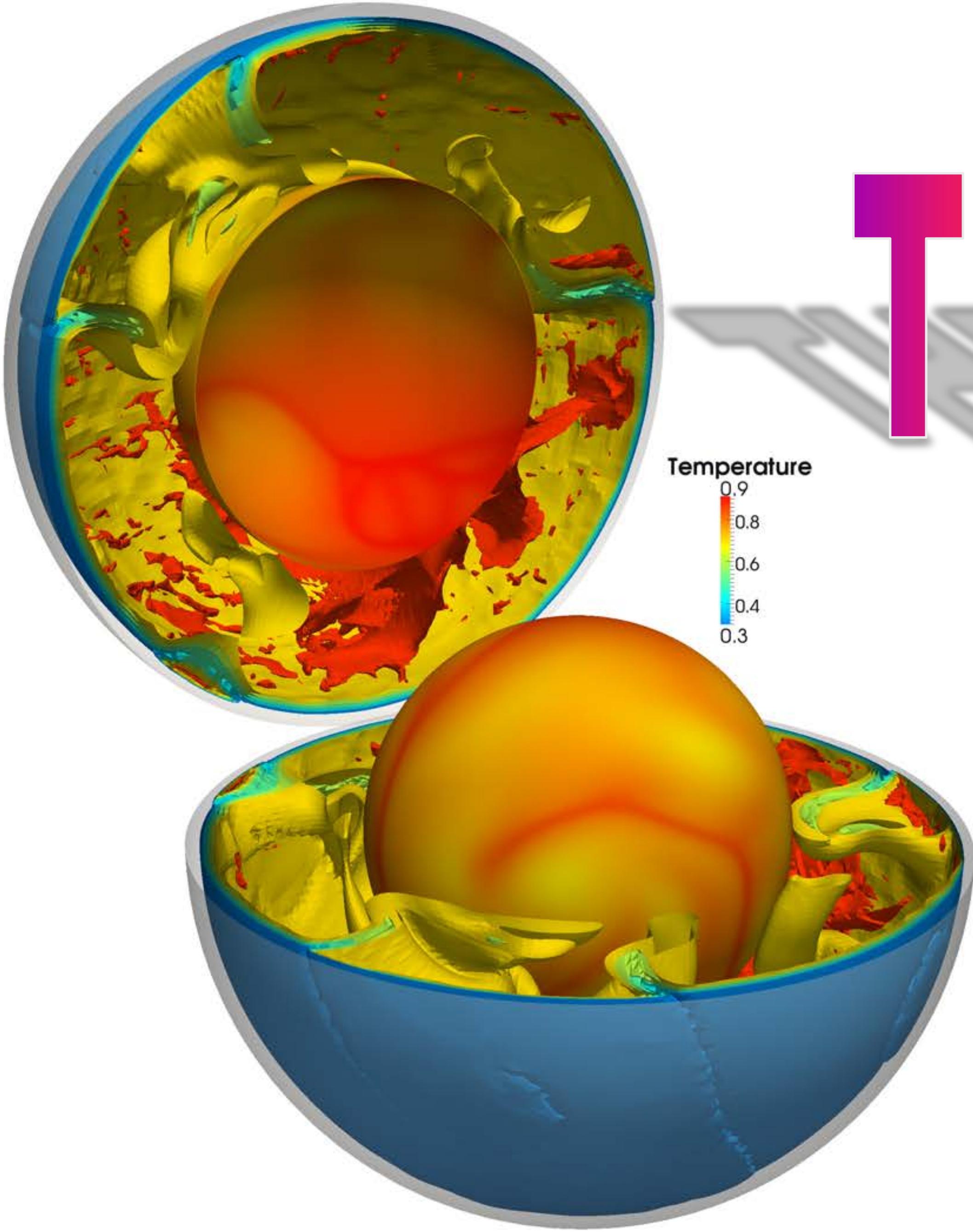


Fig. 2 | Surface heat loss, behaviour and internal state of a planet/moon in a plutonic squishy lid regime versus in a heat-pipe regime. The reference viscosity for these simulations is 10^{21} Pa s. **a**, Conductive, magmatic and total surface heat flow as a function of the eruption efficiency. **b**, Left, an illustration of the dynamics of a plutonic squishy lid. Right, a schematic representation of a typical upper mantle geotherm (solid blue line) and the solidus temperature curve for mixed mantle composition (red dashed line) . Part., partitioning. **c**, Left, an illustration of a typical upper-mantle geotherm (solid green line) and, again, the solidus curve (red dashed line). Right, an illustration of the dynamics of a heat-pipe regime. **d**,**e**, Final temperature and basalt-eclogite distribution at 4.5 Gyr of the evolution of a plutonic squishy lid case with a D_{part} of 1.0 and an extrusion efficiency of 0% (**d**), and of a heat-pipe case with a D_{part} of 1.0 and an extrusion efficiency of 100% (**e**).

Summary: Reconciling geophysical models with low internal heating

- The Problem: Simple convection scalings require a Urey ratio (=internal heating/total heat loss) of ~0.8 due to $Nu \sim Ra^{1/3}$, but this is not possible with geo/cosmo-chemical estimates of internal heating.
- Solutions:
  - Complex mantle convection with yielding-induced plate tectonics & magmatism does not follow the standard $Nu \sim Ra^{1/3}$ law.
  - There was likely a different tectonic mode in early Earth (plutonic squishy-lid) with lower heat transport efficiency than scaled-backwards plate tectonics.
  - Grain-size evolution could have caused the early Earth viscosity to have been higher than expected.



THE END