Enigmatic Martian mantle reservoirs: Can dynamic models help?

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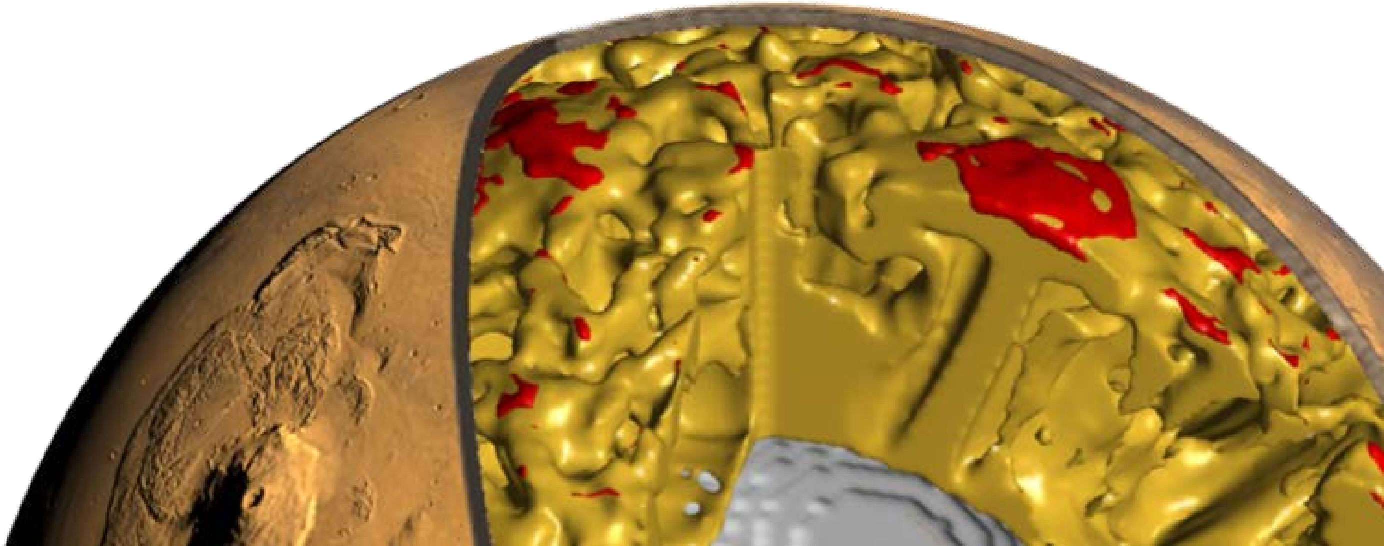
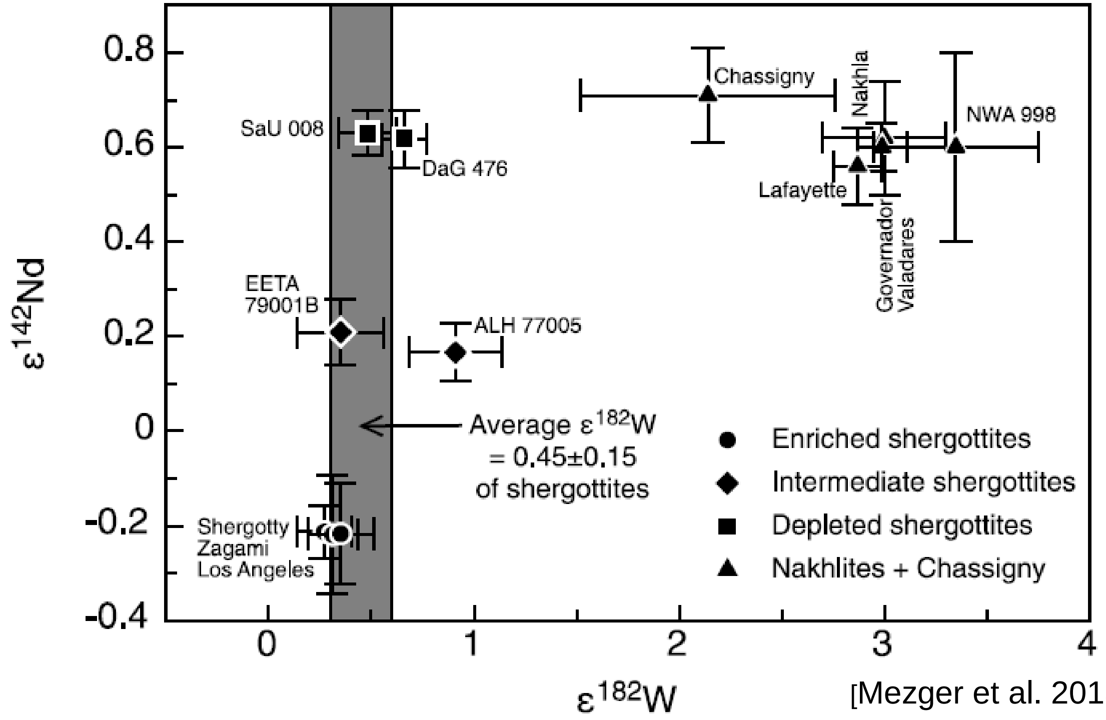


Geochemical models

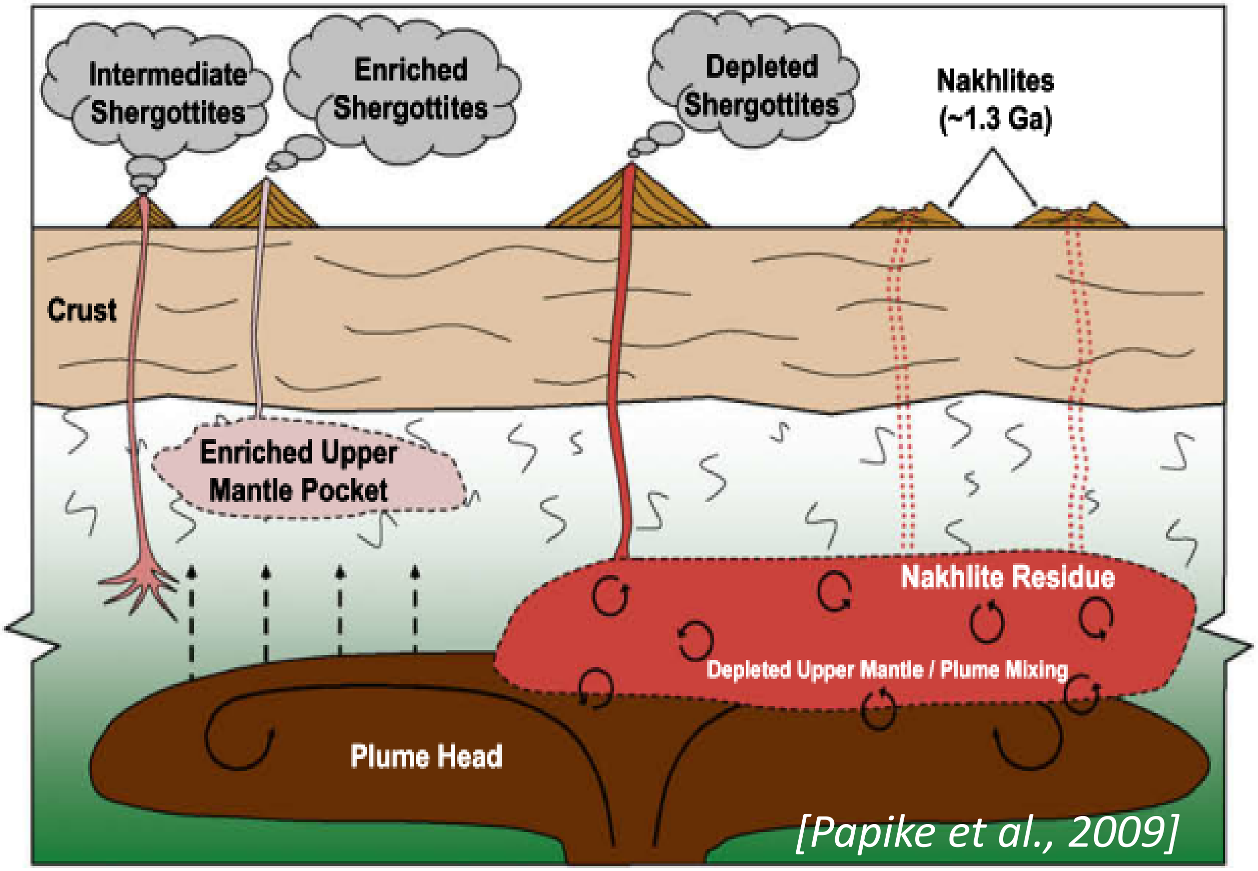


[Mezger et al. 2013]

- Nd anomalies in the SNCs indicate the existence of at least 3 reservoirs, which formed early and did not remix.
- As a comparison, Earth has ε^{142}Nd of 0 to 0.1.

- Large spatial separation and ineffiecent mantle mixing could account for reservoir preservation.
- This appears to be incompatible with vigorous whole mantle convection.

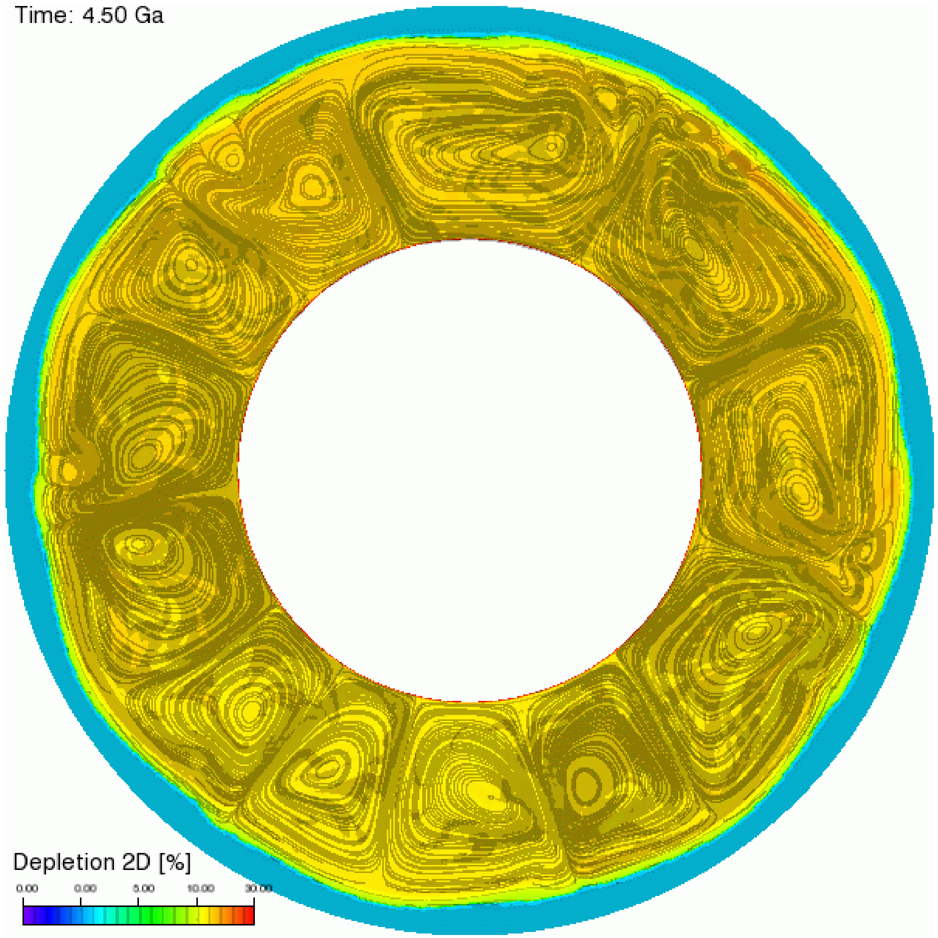
Reservoir formation

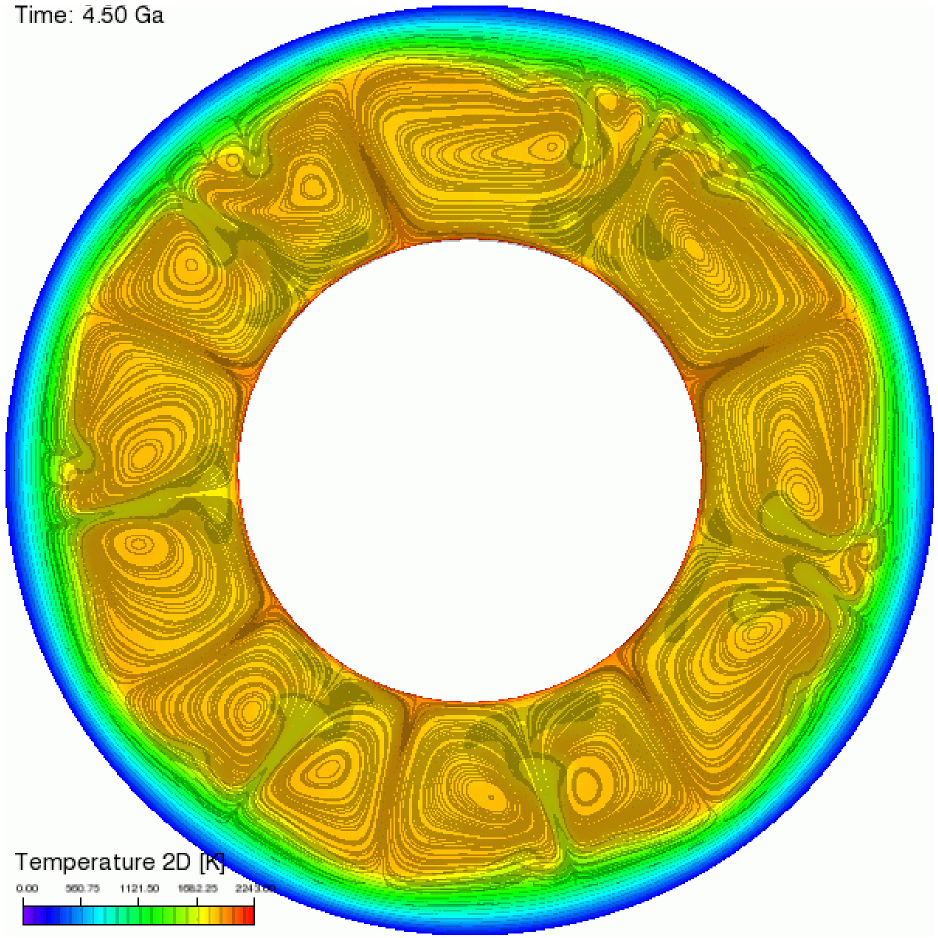


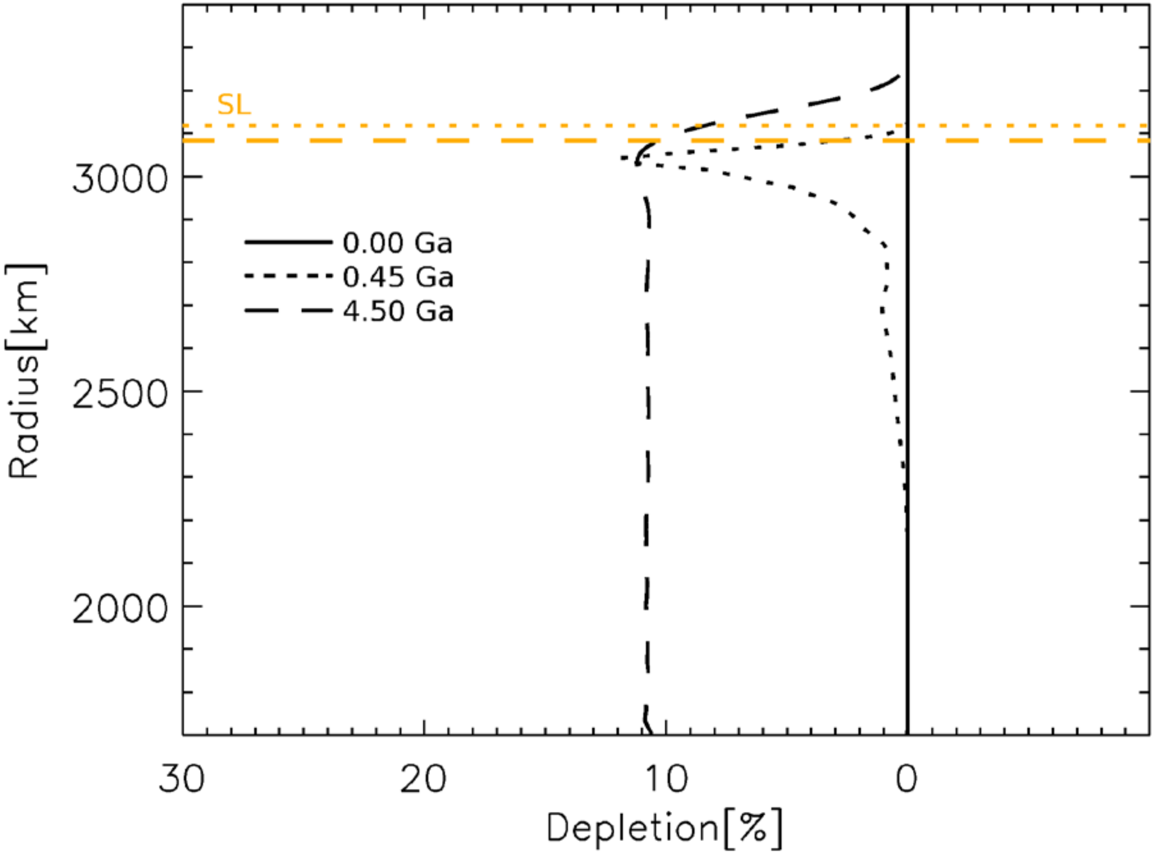
[Papike et al., 2009]

How did they form and remain stable over the entire Martian history?

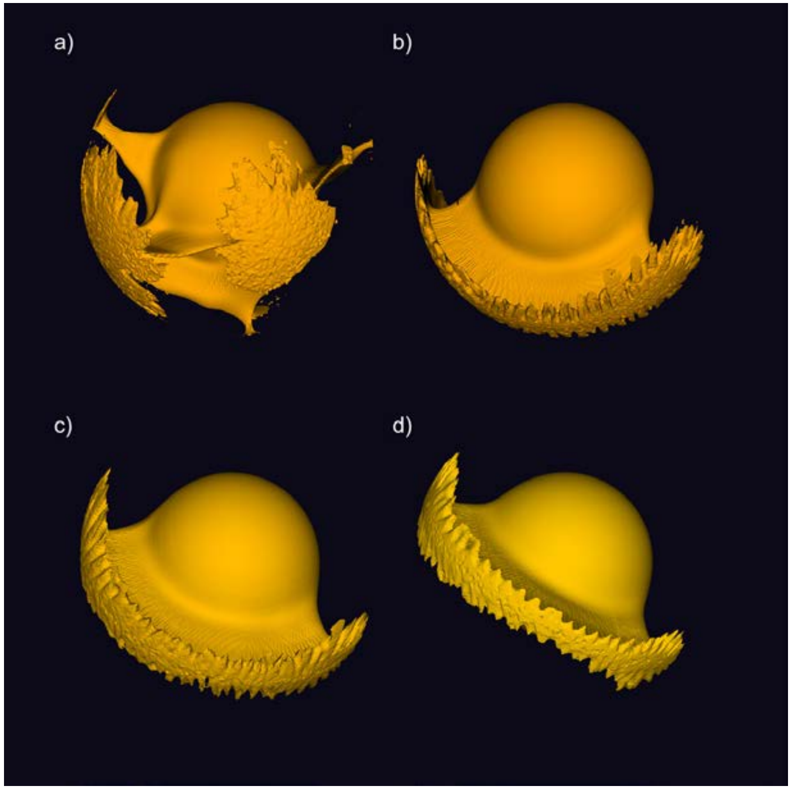
Geodynamical models

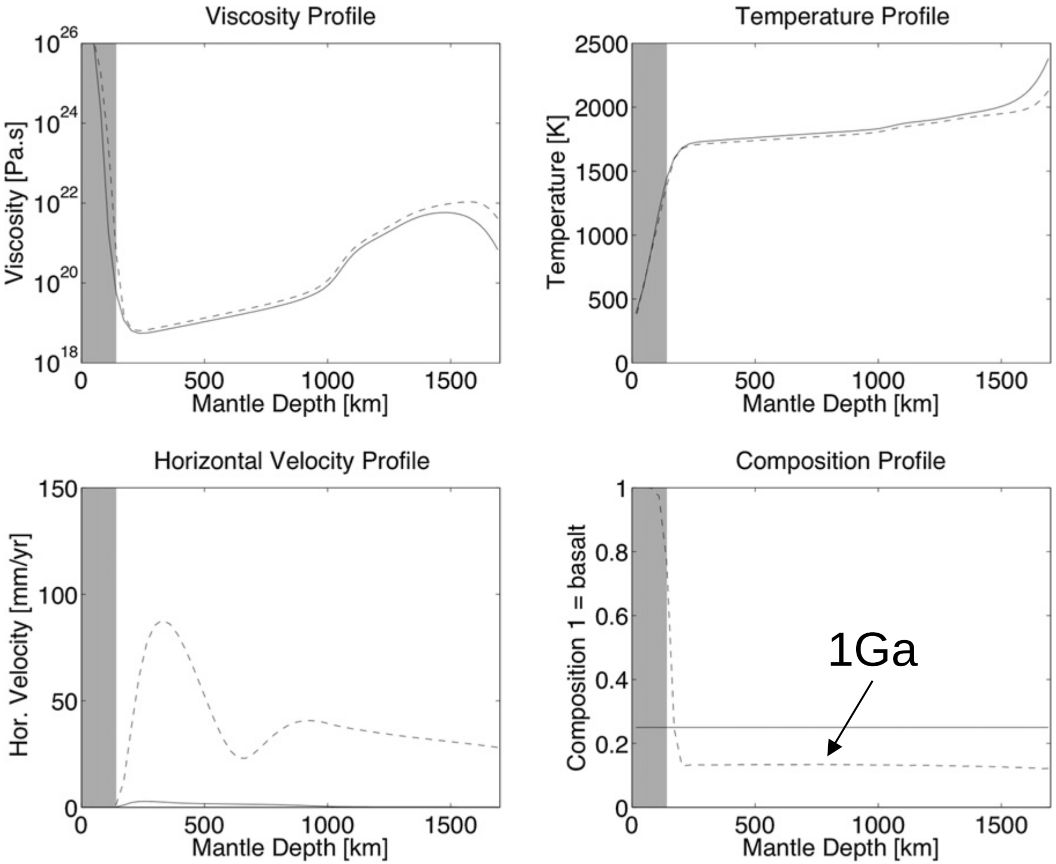





SL
3000
2500
2000
Radius[km]
0.00 Ga
0.45 Ga
4.50 Ga
30
20
10
0
Depletion[%]

Efficient mixing with low degree convection?

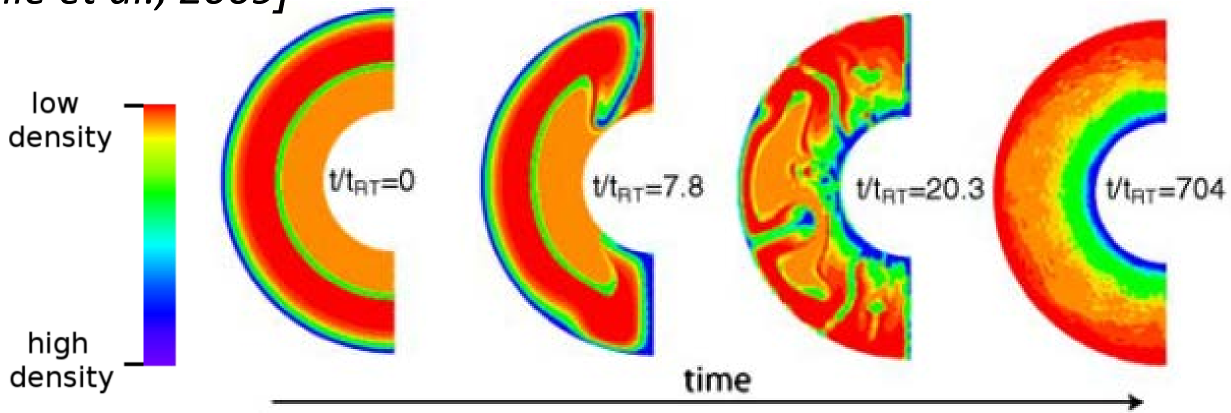




Keller and Tackley (2009)

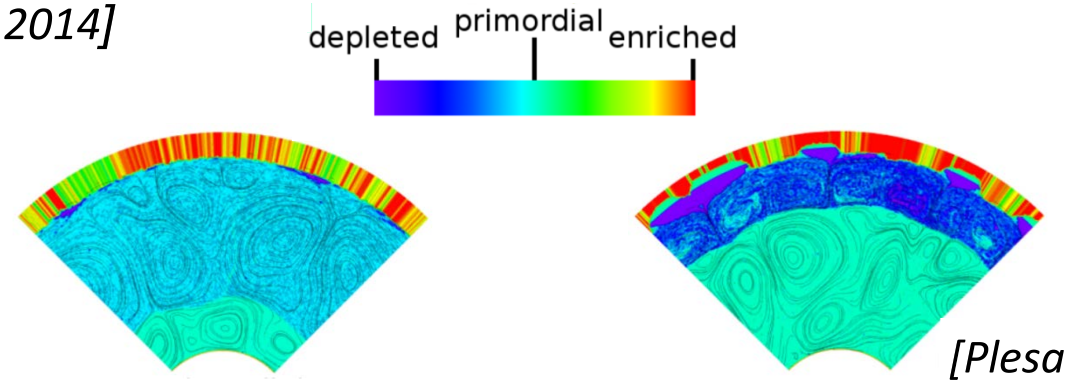
Geodynamical scenarios

- Magma ocean cumulate overturn *[Elkins-Tanton et al., 2003, 2005; Debaille et al., 2009]*



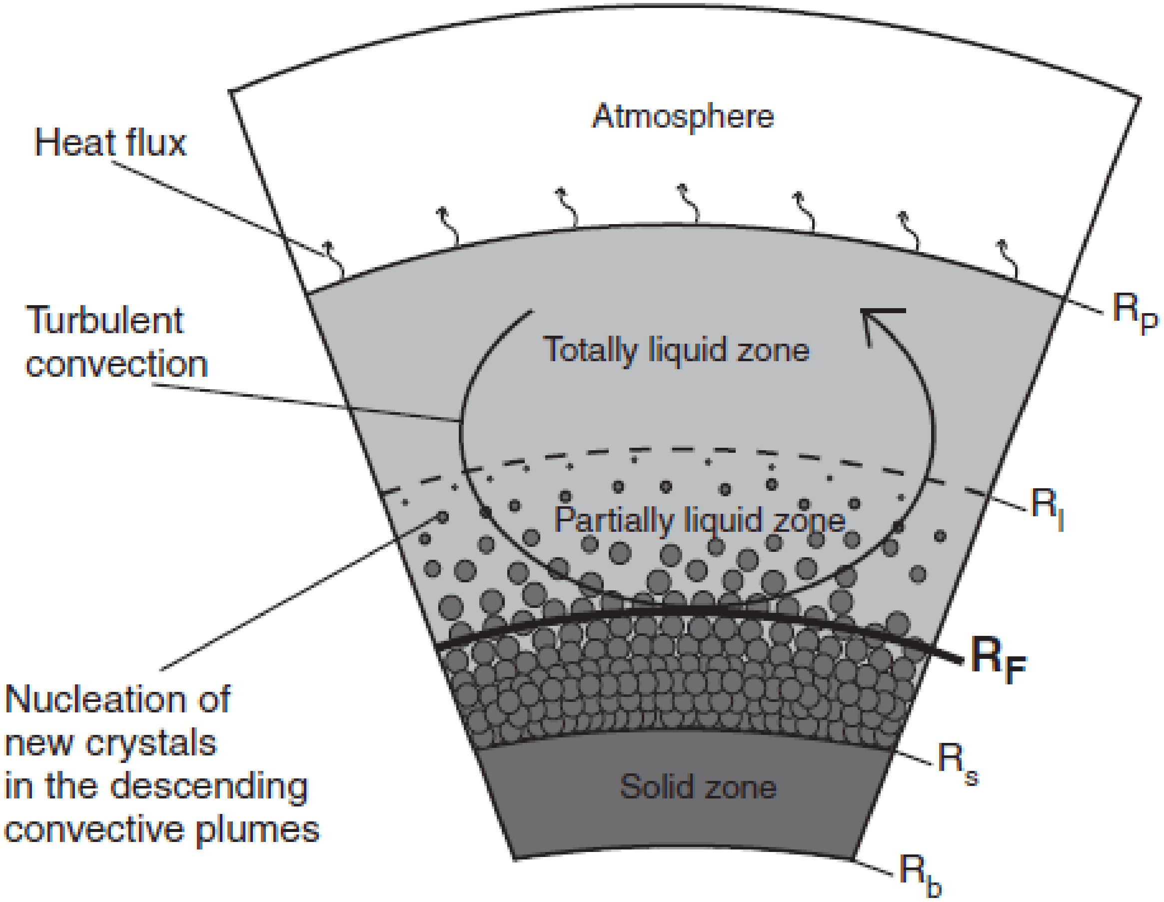
[Elkins-Tanton et al., 2005]

- Partial melting and mantle differentiation *[Ogawa & Yanagisawa, 2011, Plesa & Breuer, 2014]*



[Plesa & Breuer, 2014]

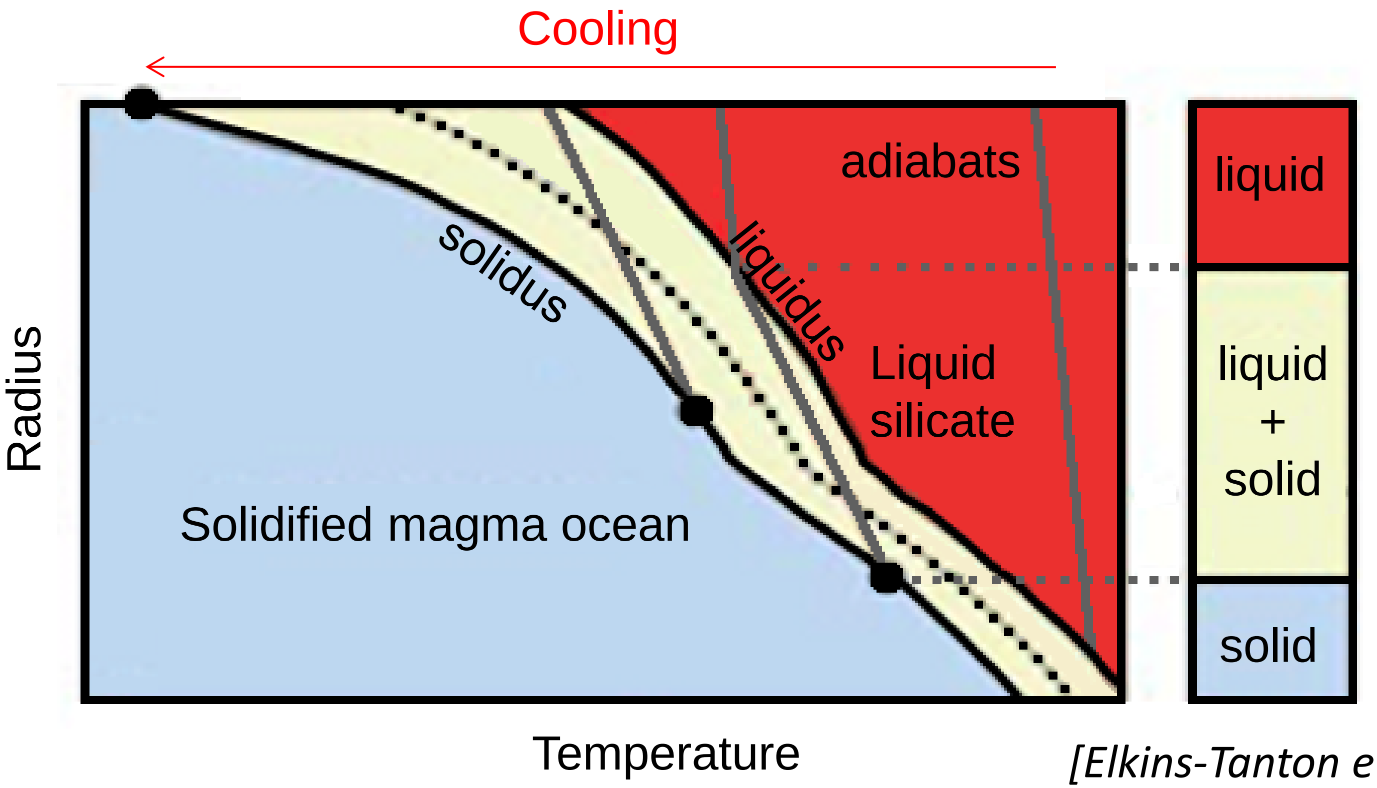
Magma ocean crystalization



[Lebrun et al., 2013]

Magma Ocean Cumulate Overturn

- Fractional crystallization ⇒ unstable density gradient ⇒ overturn ⇒ stably stratified mantle
- Late mantle cumulates enriched in incompatible heat producing elements ⇒ upon overturn, heat sources accumulate at the CMB



[Elkins-Tanton et al., 2005]

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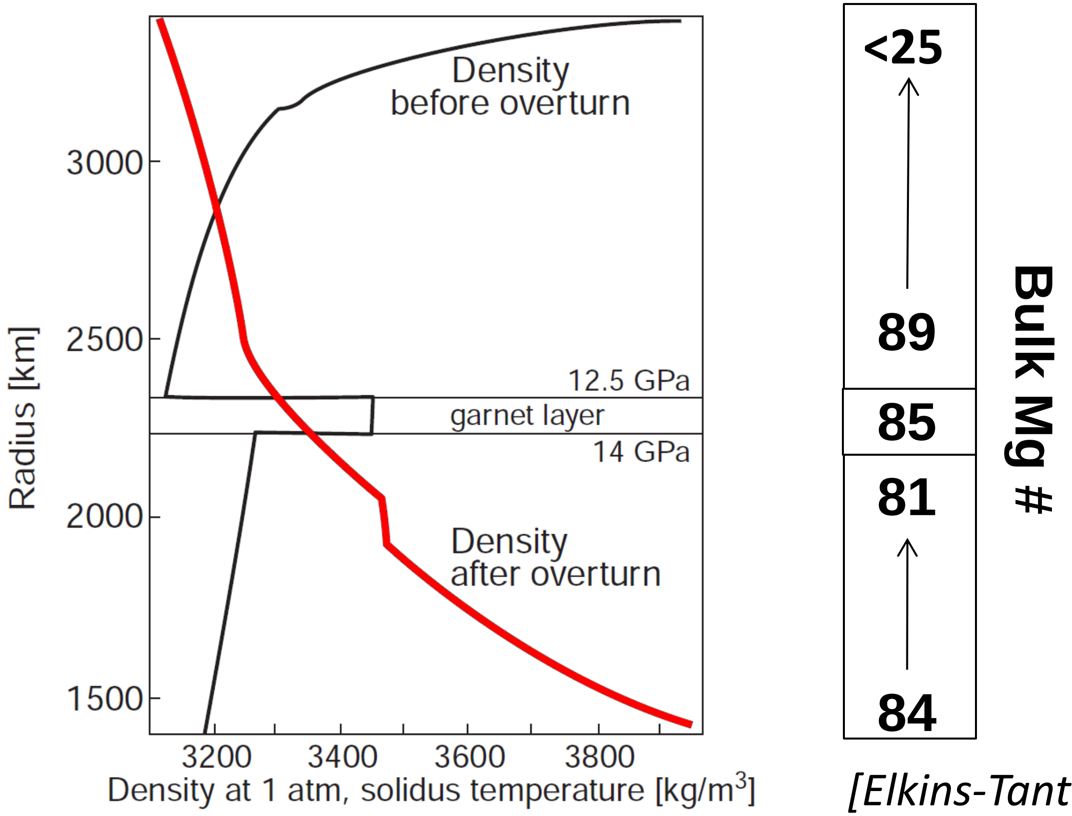
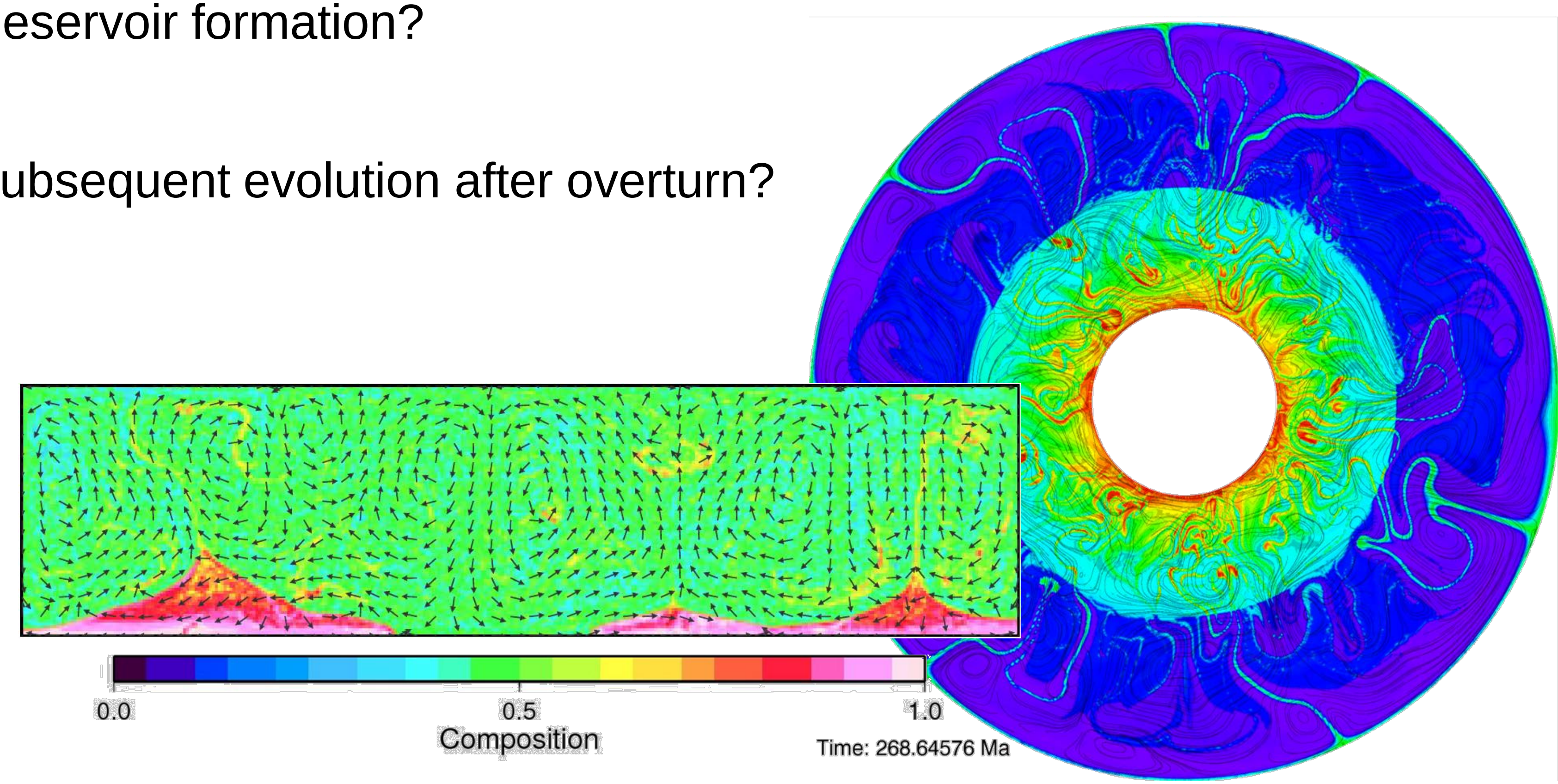


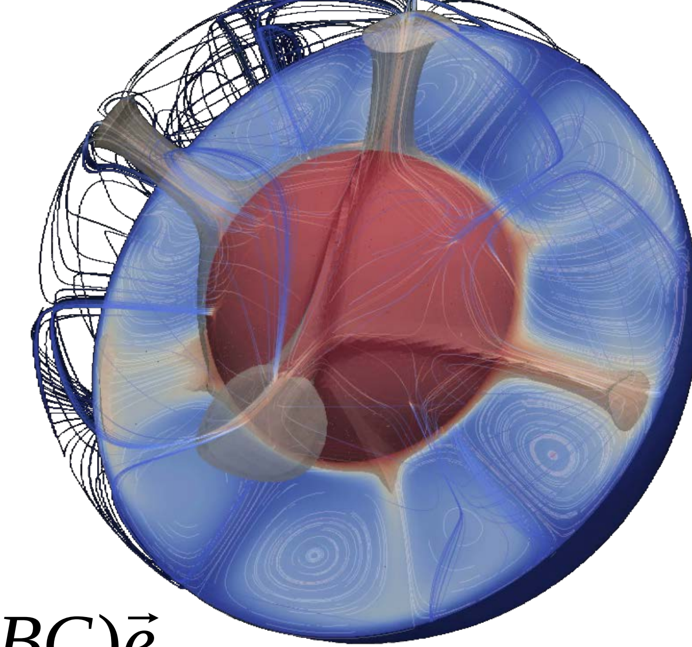
[Elkins-Tanton et al., 2005]

Magma Ocean Cumulate Overturn

- Overturn style?
- Reservoir formation?
- Subsequent evolution after overturn?



Thermo-chemical Convection



Conservation equations of

- mass

$$\nabla \cdot \vec{u} = 0$$

- linear momentum

$$\nabla \cdot [\eta(\nabla\vec{u} + (\nabla\vec{u})^T)] - \nabla p = Ra(T - BC)\vec{e}_r,$$

- thermal energy

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T - \nabla^2 T = \frac{Ra_Q}{Ra}$$

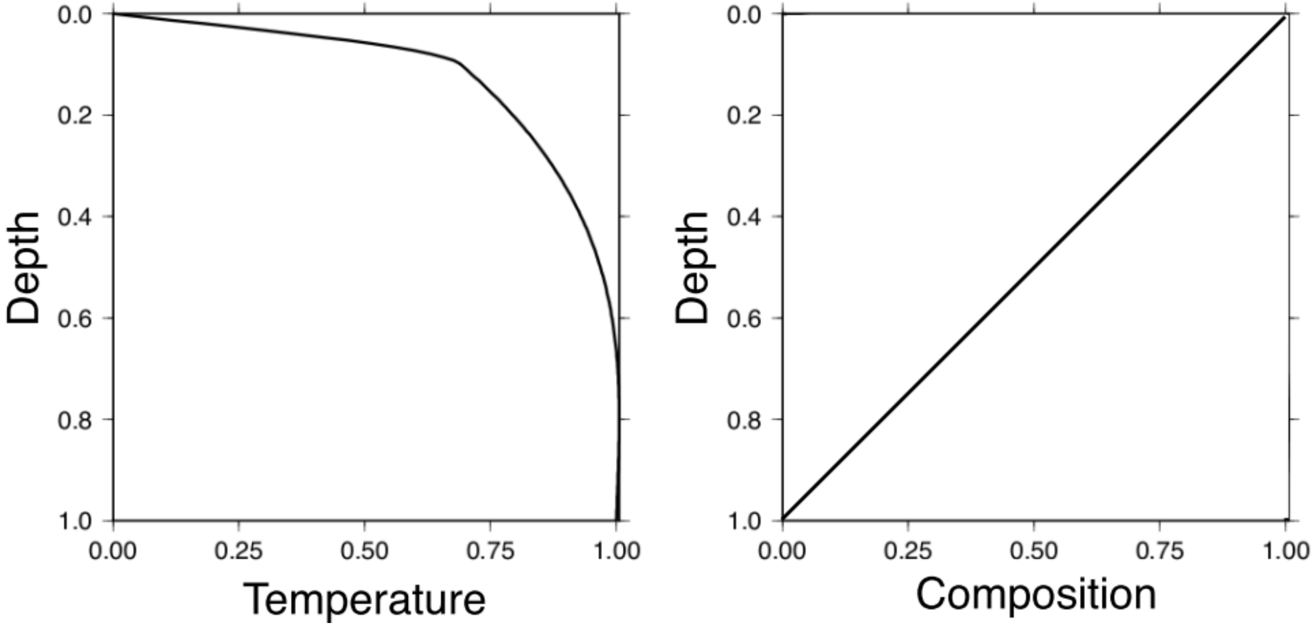
- material transport

$$\frac{\partial C}{\partial t} + \vec{u} \cdot \nabla C = 0$$

Buoyancy number:

$$\boxed{B = \frac{Ra_C}{Ra} = \frac{\Delta\rho}{\rho\alpha\Delta T}}$$

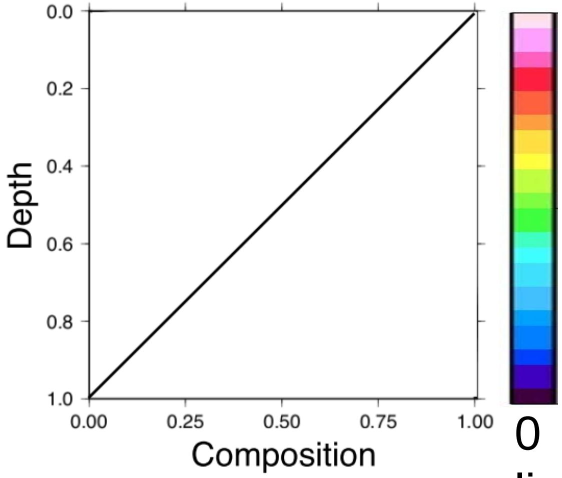
Cartesian models: a parameter study



- Systems heated from below or from within
- Initial temperature at the solidus of peridotite + upper TBL
- Present-day surface temperature (250 K)
- Unstable linear composition with $B \in [0,2] \Rightarrow \Delta\rho \in [30, 300]$ kg/m^3
- Reference Rayleigh number $10^6 – 10^7$ (T=1600 K, P=3 GPa)
- Constant, T-dependent or T- and stress-dependent viscosity

Overturn style

Initial stage



dense material

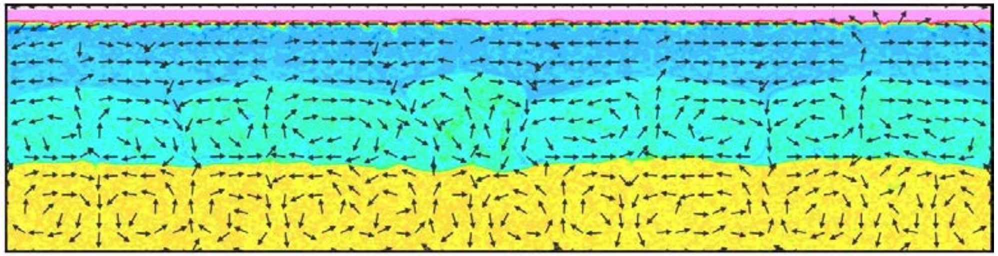
1

0

light material

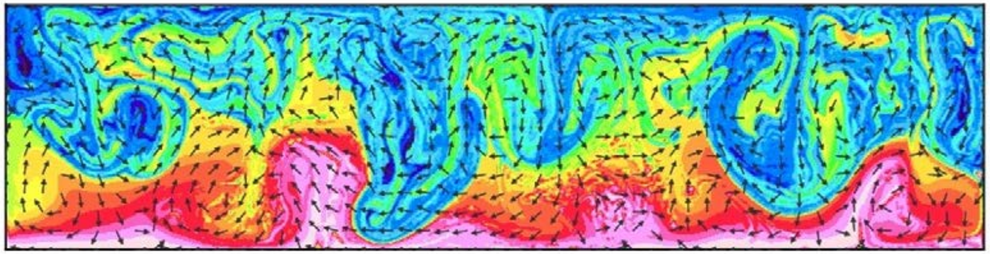
Temperature dependent viscosity → Stagnant lid

Overturn below the lid



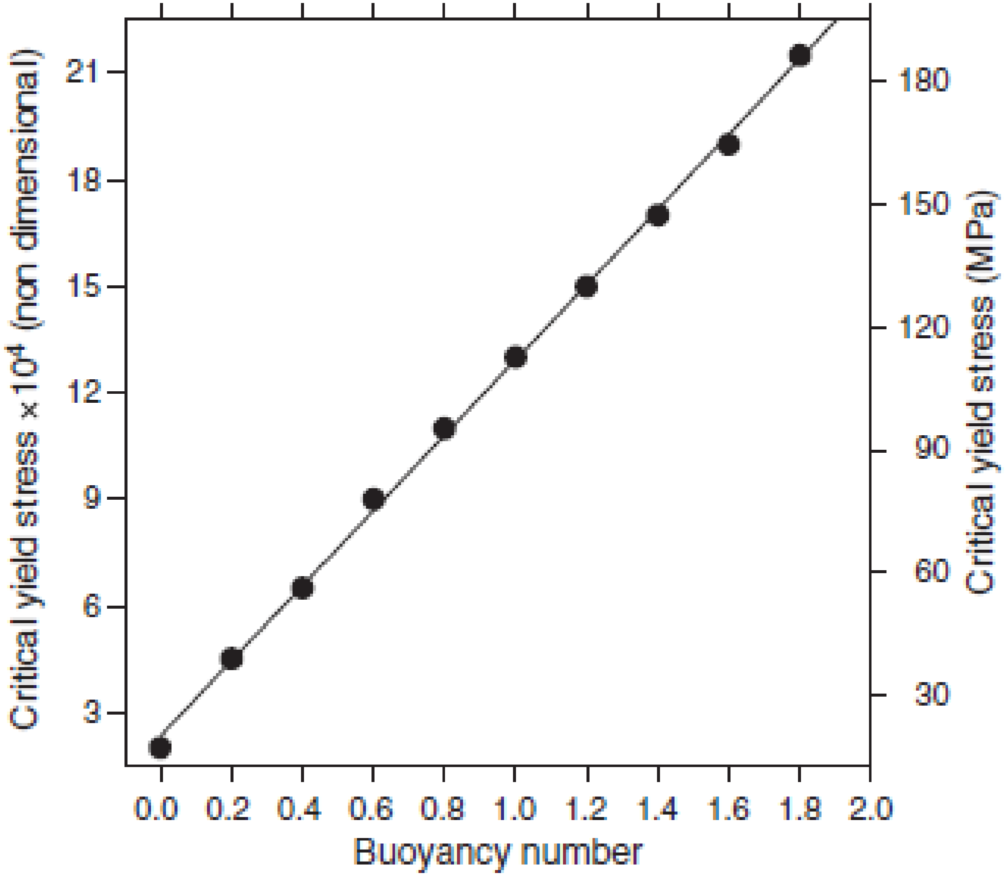
Constant viscosity → Mobile lid

Whole mantle overturn



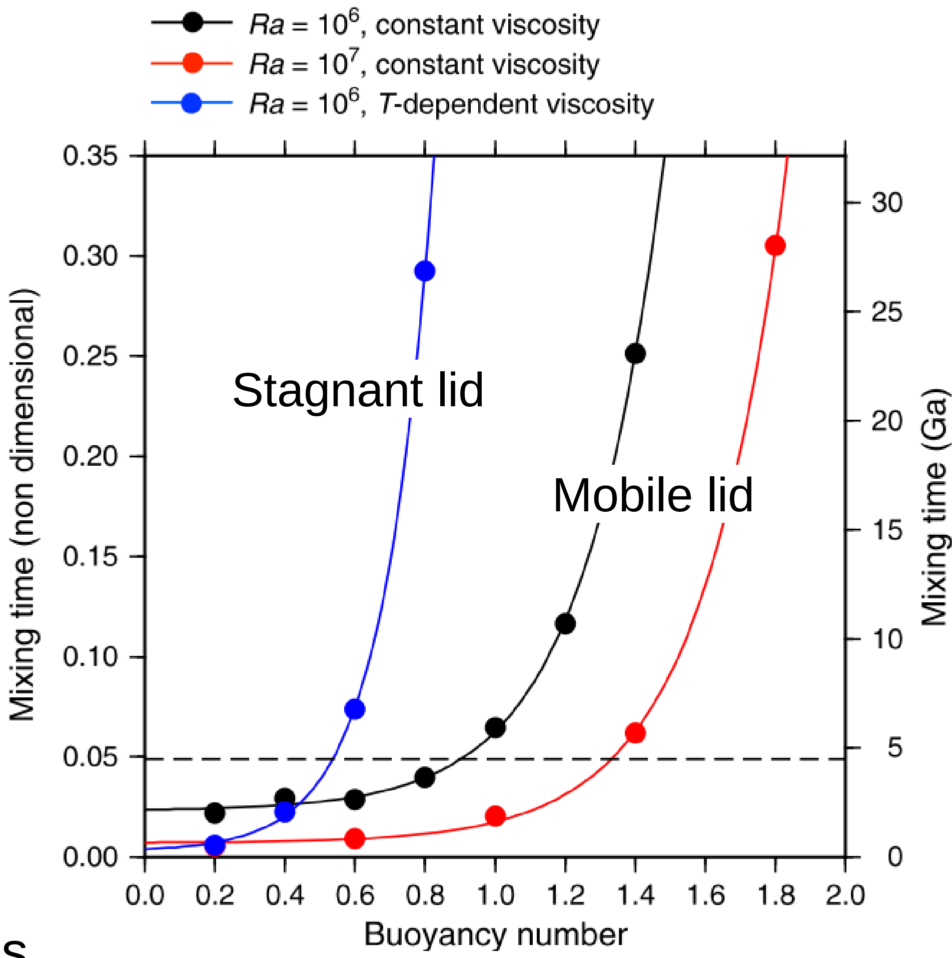
[Tosi et al., 2013]

Surface mobilization increases with increasing B



Reservoir stability: Mixing time scaling

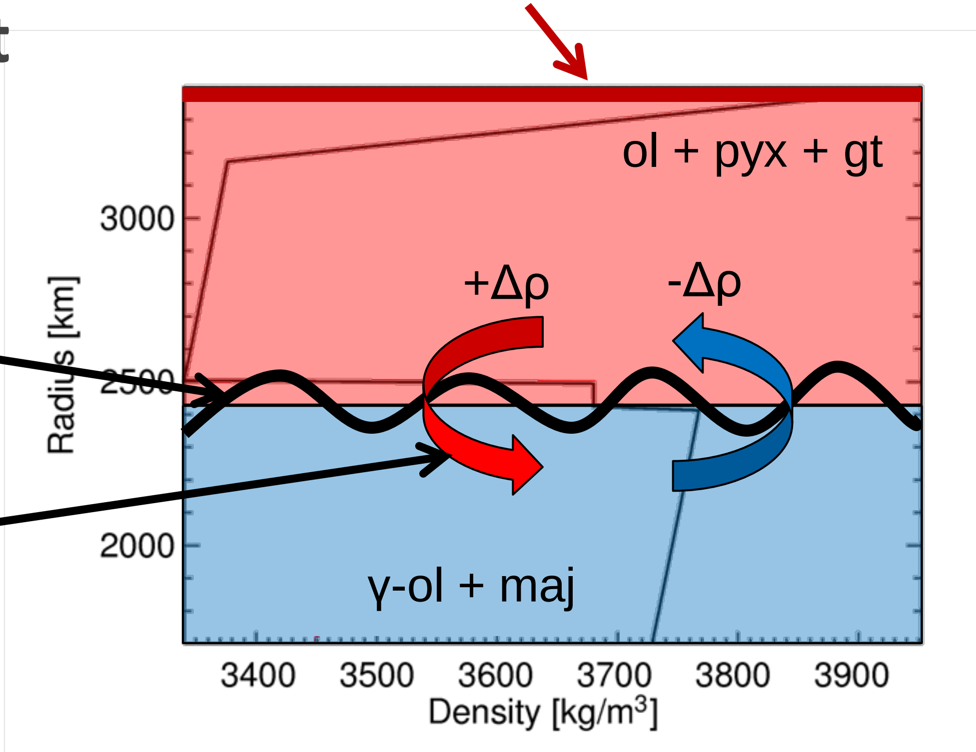
- Mixing time scales exponentially with *B*
- Internally heated systems have much longer mixing times and complete mixing only occurs for the smallest values of *B* ($B < 0.4$ i.e, $\Delta\rho < 60 kg/m^3$)
- For a one-plate planet heated from within, it is very difficult to erase chemical heterogeneities via mantle mixing apart from the smallest *B*



[Tosi et al., 2013]

Overturn and subsequent evolution

radiogenic heat producing elements



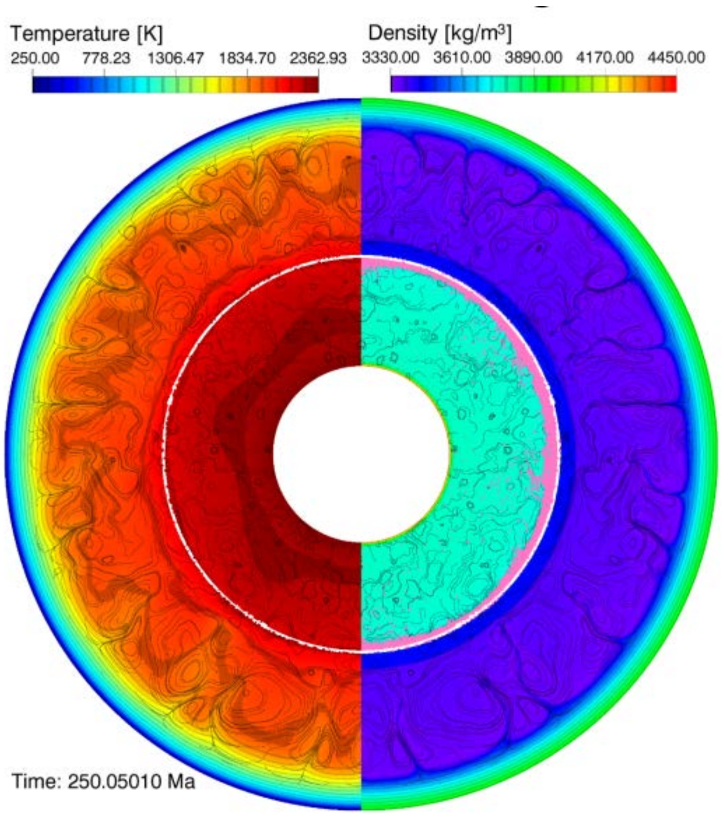
exothermic phase transition

compositional phase transition

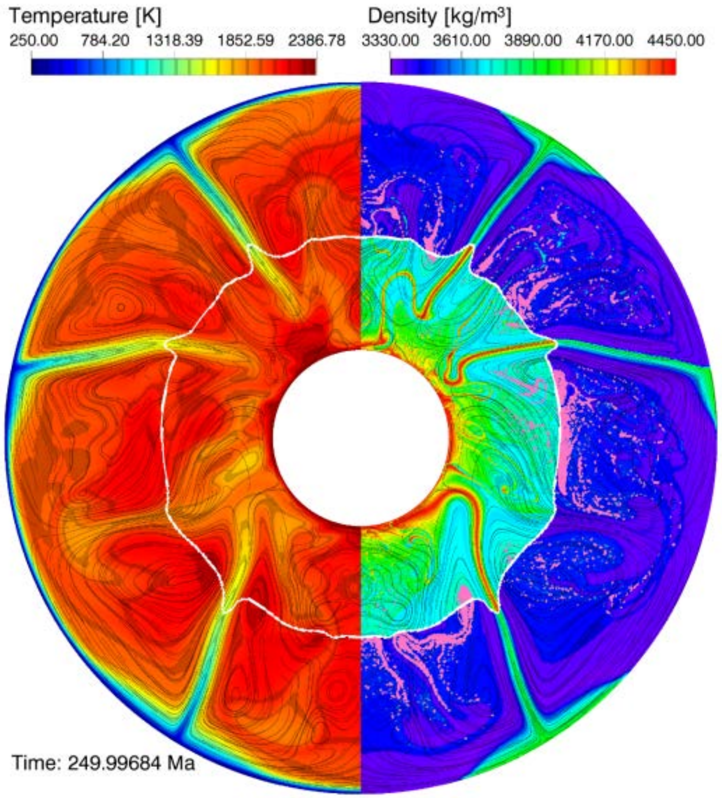
- Initial density profile: Δρ > 600 kg/m^3 *[Elkins-Tanton et al., 2005]*
- Initial temperature at the solidus + upper TBL
- Present-day surface temperature (250 K)
- Heat sources enriched in the upper 50 km
- Viscoplastic rheology

Subsequent evolution after overturn

overturn below the stagnant lid

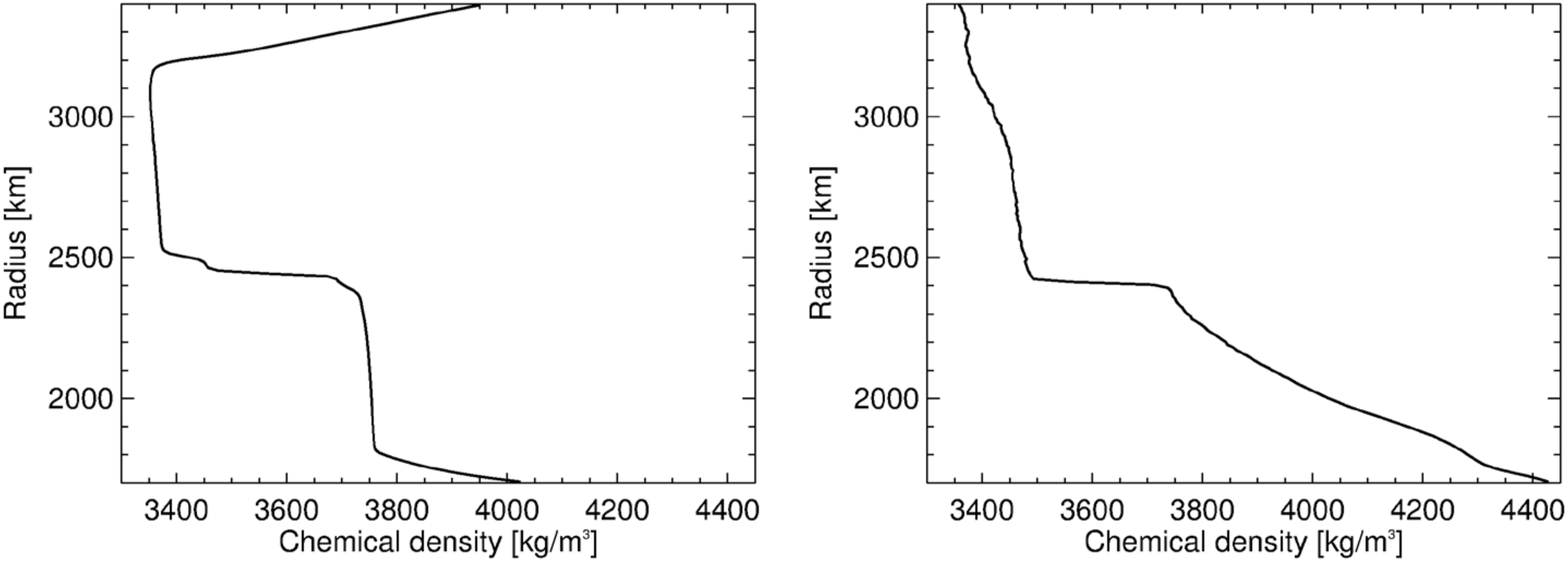


whole-mantle overturn



[Plesa et al., 2014]

Subsequent evolution after overturn

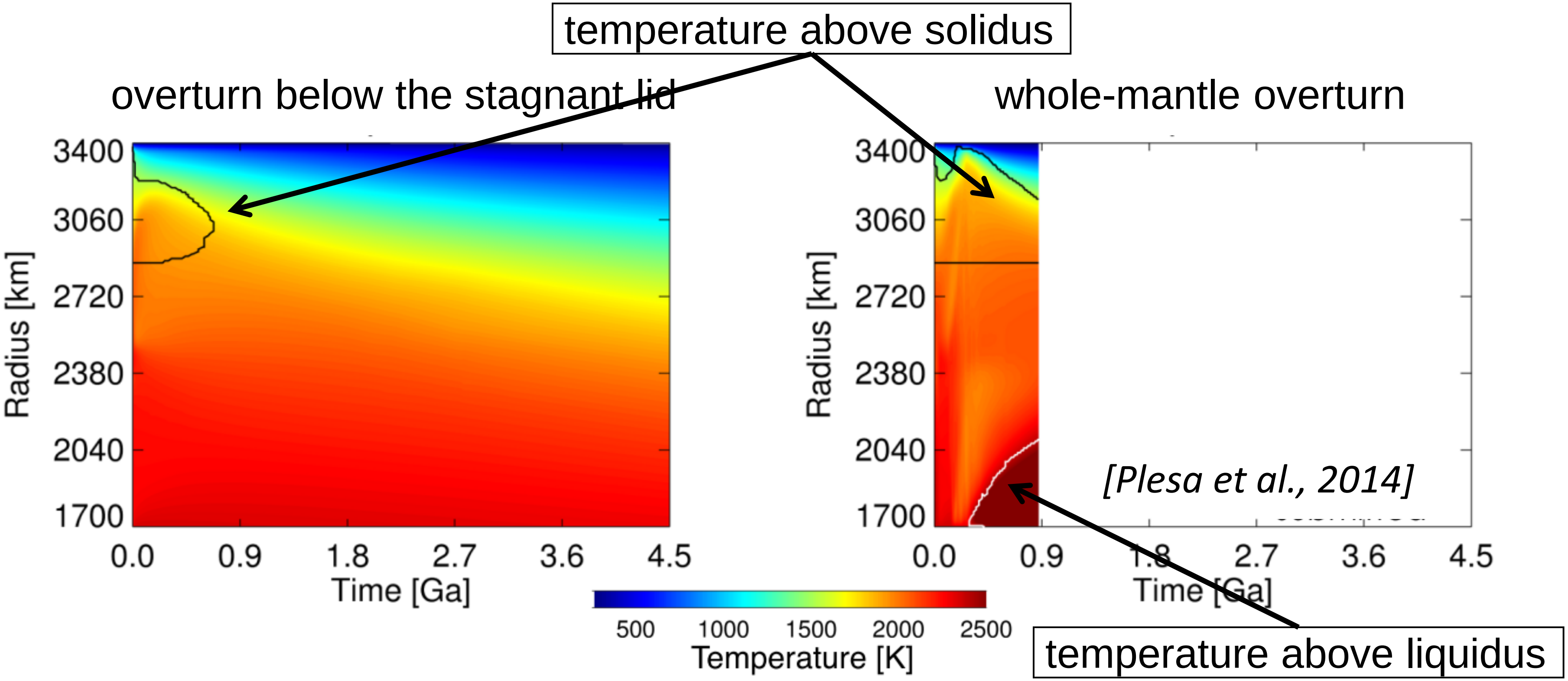


overturn below the stagnant lid

whole-mantle overturn

[Plesa et al., 2014]

Subsequent evolution after overturn



temperature above solidus

overturn below the stagnant lid

whole-mantle overturn

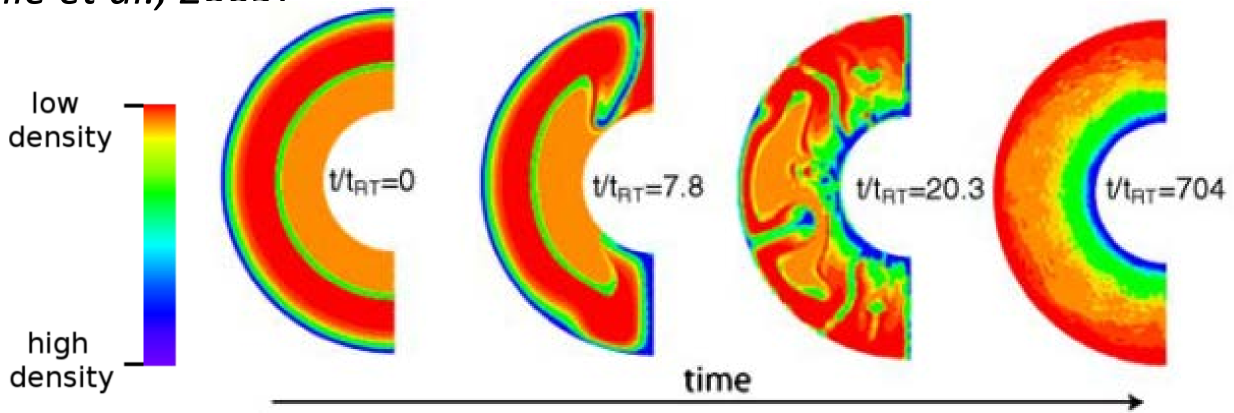
[Plesa et al., 2014]

temperature above liquidus

- ➢ Overturn below the stagnant lid: mantle cools conductively, short phase of mantle melting (< 1Ga)
- ➢ Whole-mantle overturn: mantle overheating above the CMB, temperatures above the liquidus, melt likely negatively buoyant

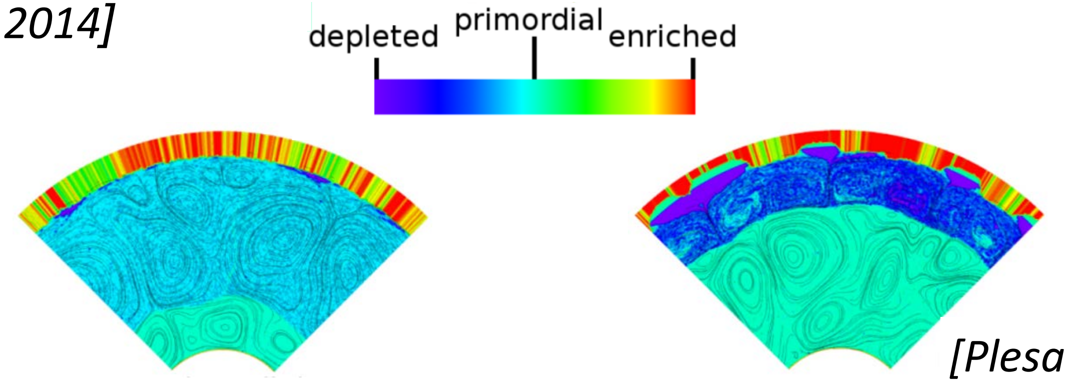
Geodynamical scenarios

- Magma ocean cumulate overturn *[Elkins-Tanton et al., 2003, 2005; Debaille et al., 2009]*



[Elkins-Tanton et al., 2005]

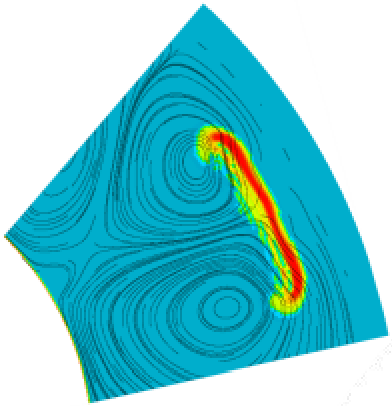
- Partial melting and mantle differentiation *[Ogawa & Yanagisawa, 2011, Plesa & Breuer, 2014]*



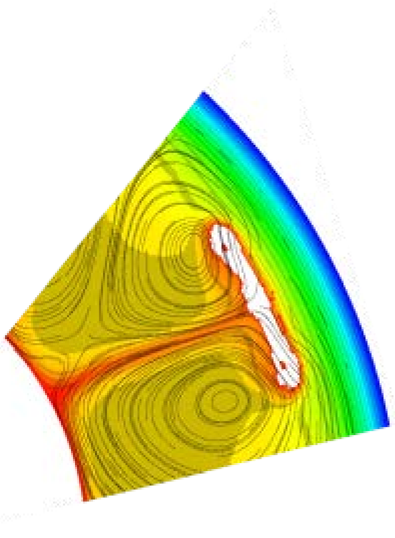
[Plesa & Breuer, 2014]

Mantle Depletion

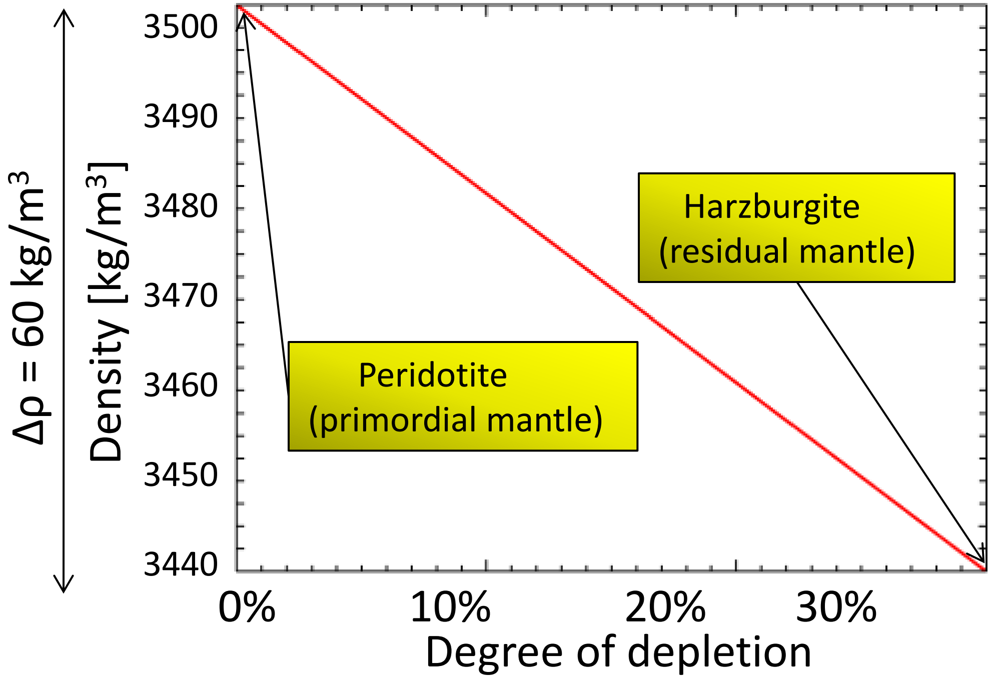
- Density decrease due to the depletion of the mantle in crustal components



Depletion

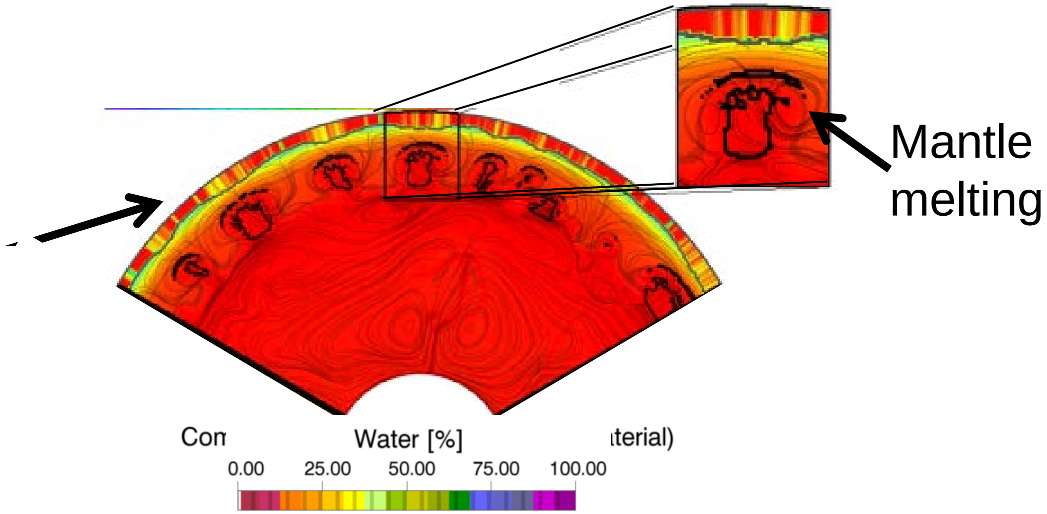


Temperature



[deSmet et al., 1999]

Reservoir formation: partial melting



Mantle melting

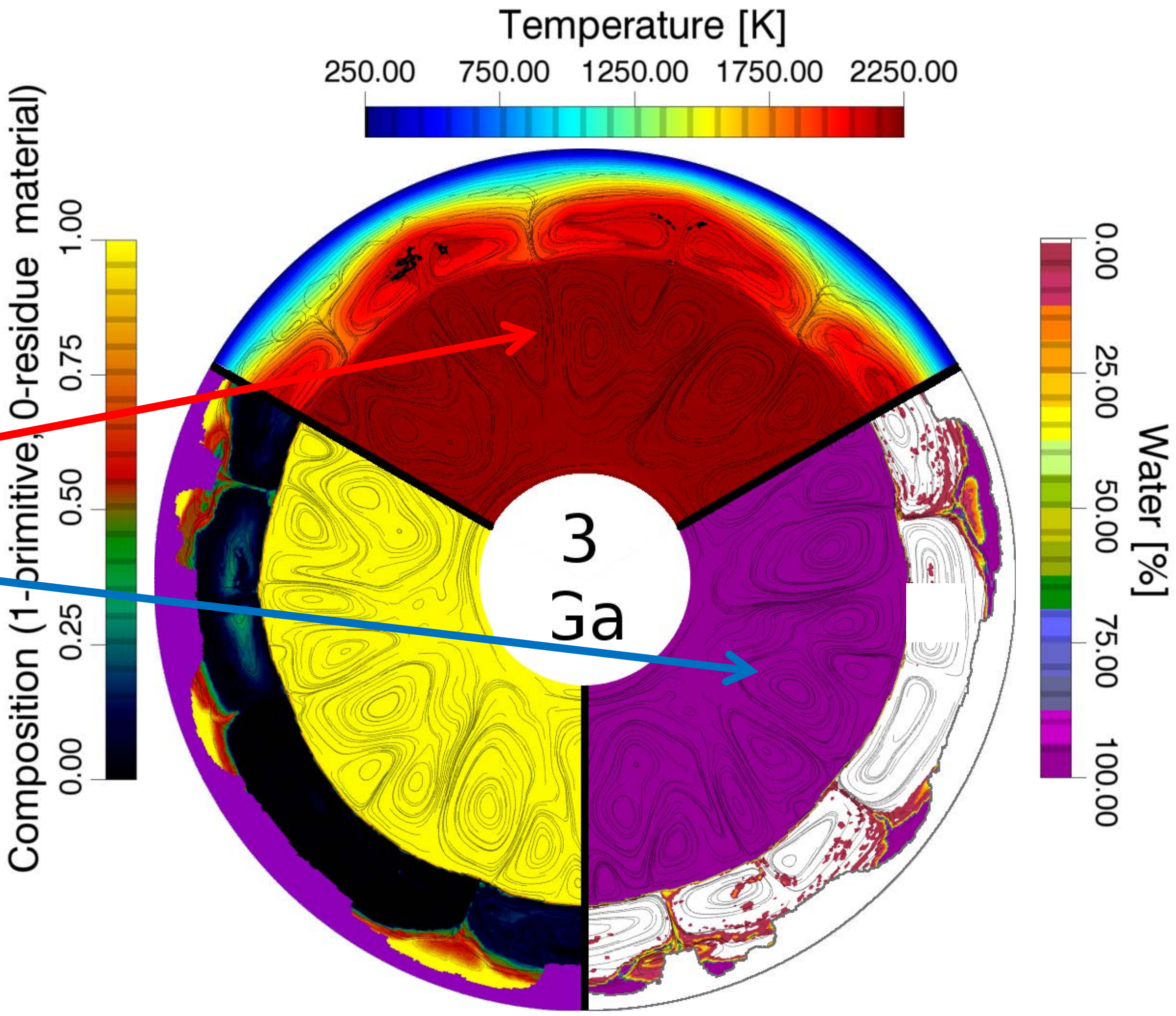
Model features:

- Mantle depletion ⇒ density variations
- Mantle dehydration ⇒ stiffening of residual ma
- Tracer particles carry density, water concentration, he ources, thermal conductivity

Alternative scenario: partial melting

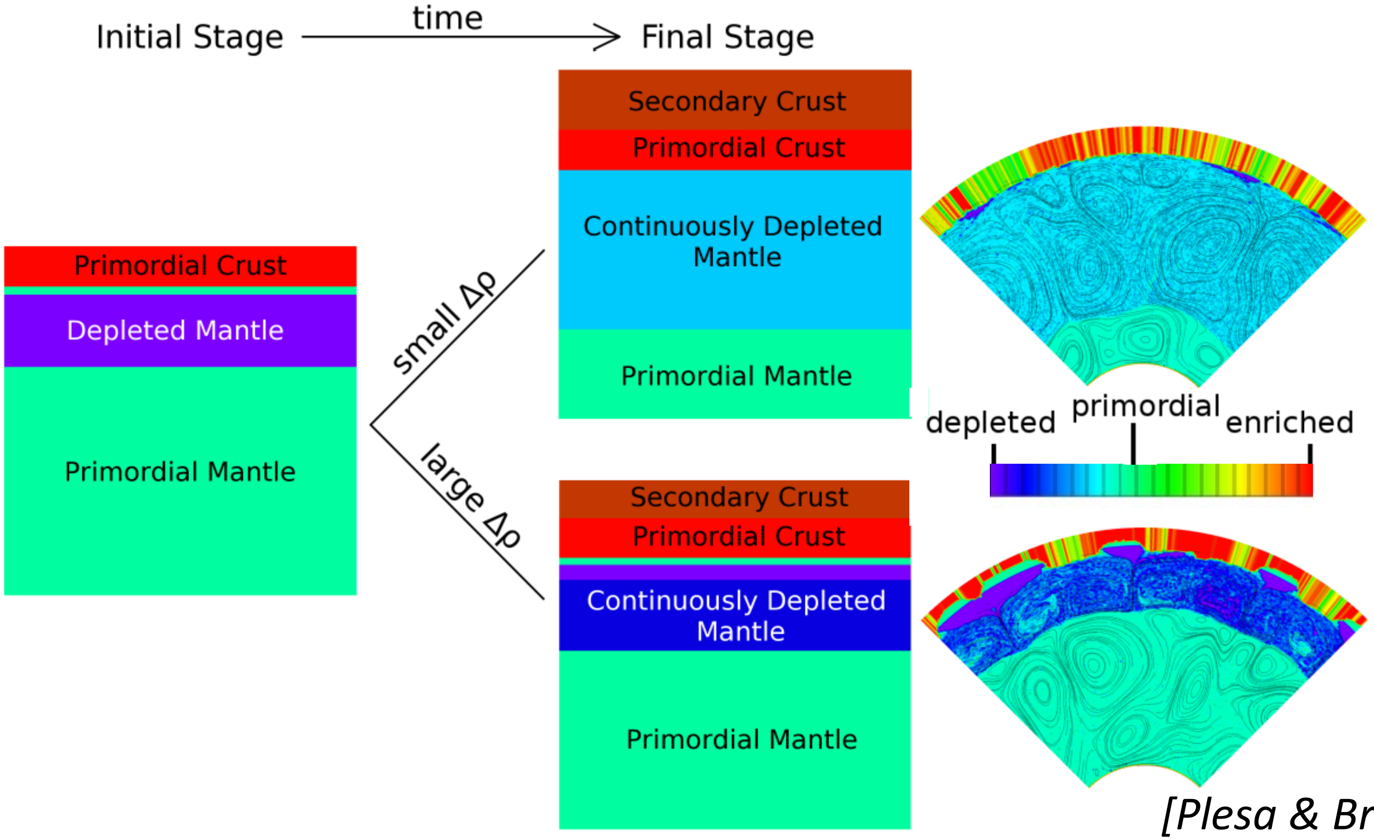
[Plesa & Breuer, 2014]

- Two layered convection
- Stable upwellings in the upper depleted mantle ⇒ variations of the crustal thickness
- Warm and wet lower mantle insulated by a dry depleted upper layer ⇒ prolonged mantle melting



Alternative scenario: partial melting

- Generation of reservoirs by partial melting and secondary differentiation



Initial Stage → time → Final Stage

Primordial Crust
Depleted Mantle
Primordial Mantle

small Δρ

Secondary Crust
Primordial Crust
Continuously Depleted Mantle
Primordial Mantle

large Δρ

Secondary Crust
Primordial Crust
Continuously Depleted Mantle
Primordial Mantle

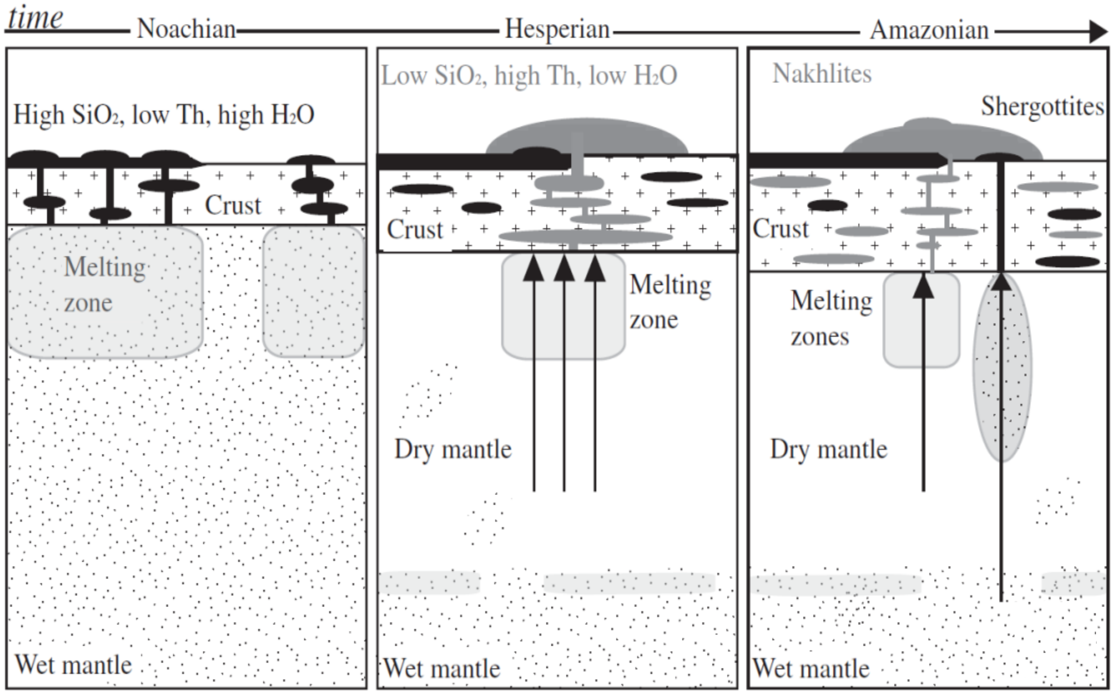
depleted
primordial
enriched

[Plesa & Breuer, 2014]

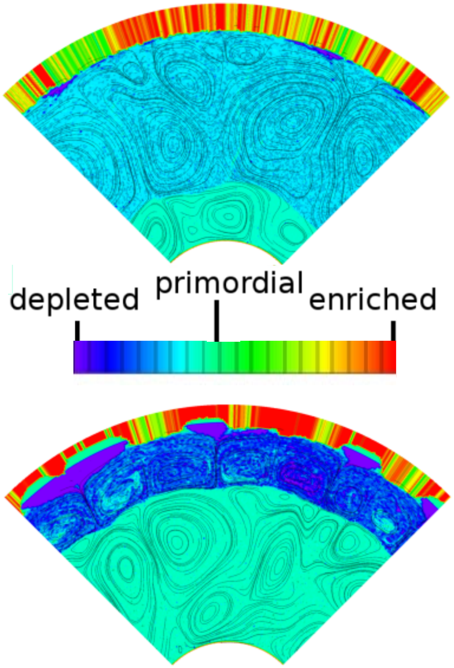
- Reservoirs may change/new reservoirs can form depending in particular on the density difference between primordial and depleted mantle

Alternative scenario: partial melting

- Generation of reservoirs by partial melting and secondary differentiation



[Balta & McSween, 2013]

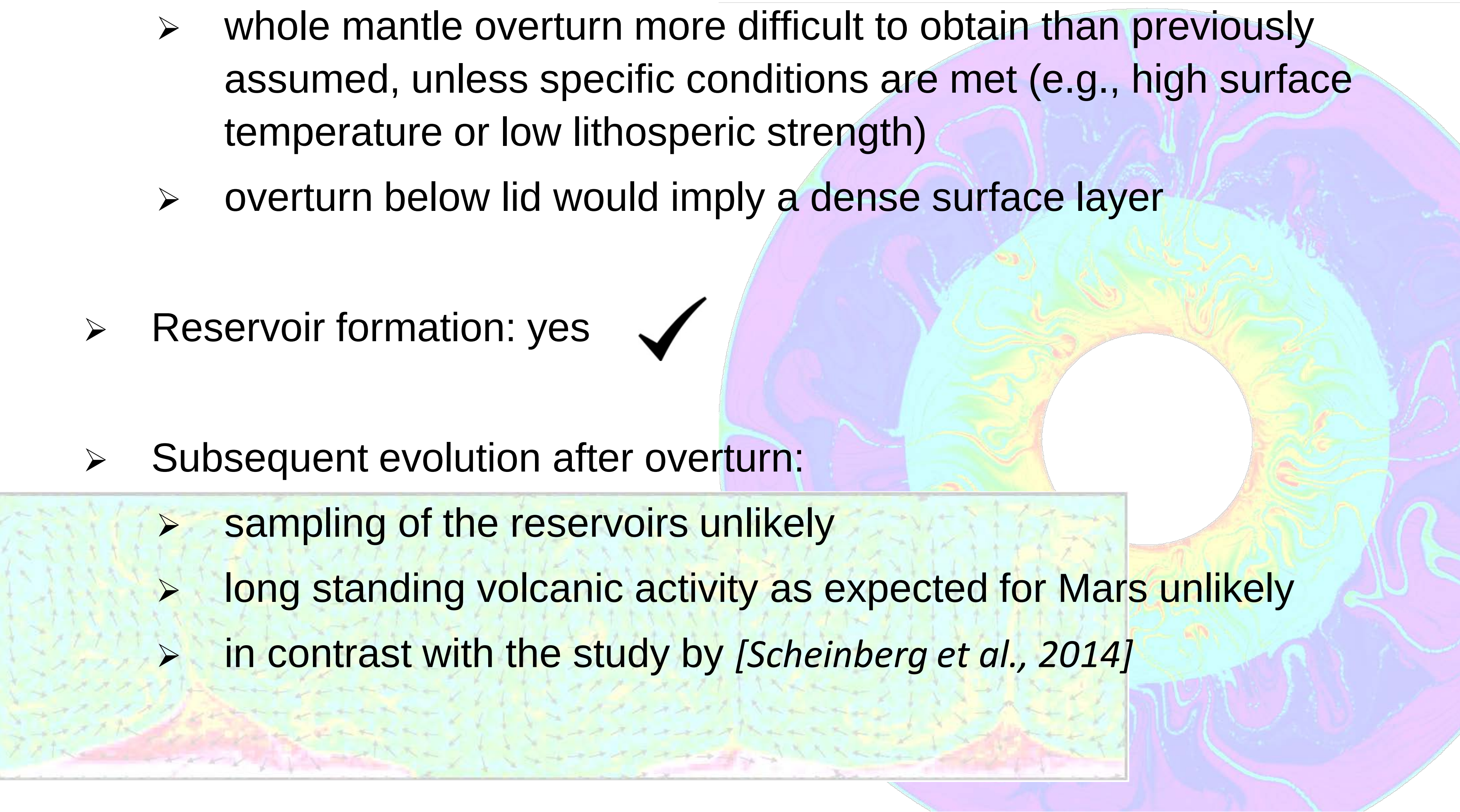


[Plesa & Breuer, 2014]

- Reservoirs may change/new reservoirs can form depending in particular on the density difference between primordial and depleted mantle

Magma Ocean Cumulate Overturn

- Overturn style:
  - whole mantle overturn more difficult to obtain than previously assumed, unless specific conditions are met (e.g., high surface temperature or low lithosperic strength)
  - overturn below lid would imply a dense surface layer
- Reservoir formation: yes ✓
- Subsequent evolution after overturn:
  - sampling of the reservoirs unlikely
  - long standing volcanic activity as expected for Mars unlikely
  - in contrast with the study by *[Scheinberg et al., 2014]*



Alternative scenario: partial melting

- Formation of reservoirs by partial melting and associated density variations due to mantle depletion
    - depending on the density contrast 2 – 4 reservoirs can form and are preserved over the entire planetary evolution
    - this scenario may be compatible with SNC isotopic characteristics but needs to be tested
    - Two-layered mantle may be seen with InSight ?

Future studies

- For a better understanding of the early evolution and differentiation:
  - Density variation in depleted mantle upon melting
  - Solidification of the magma ocean (e.g. distribution of density, composition, temperature)
  - Global magma ocean vs. magma ponds
  - Depth of the magma ocean
  - Role of a primordial atmosphere (surface temperature)