Maxim Ballmer, Anna Gülcher, Jun Yan, Matteo Desiderio, Lauren Waszek

The <distribution> of ***primordial*** and ***recycled*** <u>mantle heterogeneity</u> *through* time

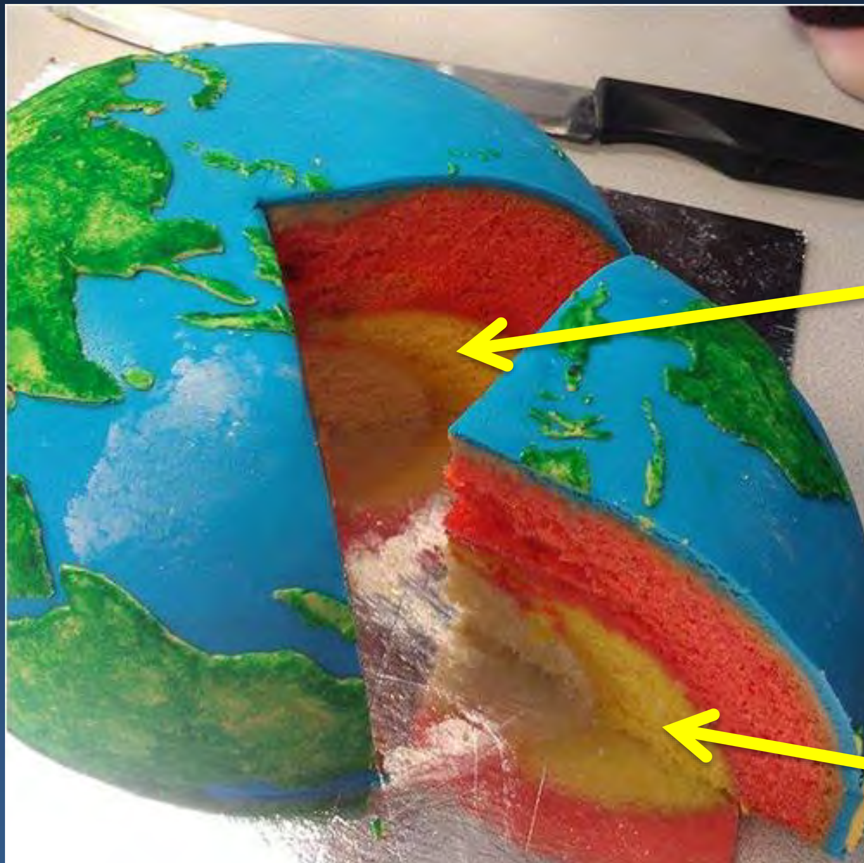
plum pudding

vs.

marble cake

 INTRODUCTION INTRODUCTION

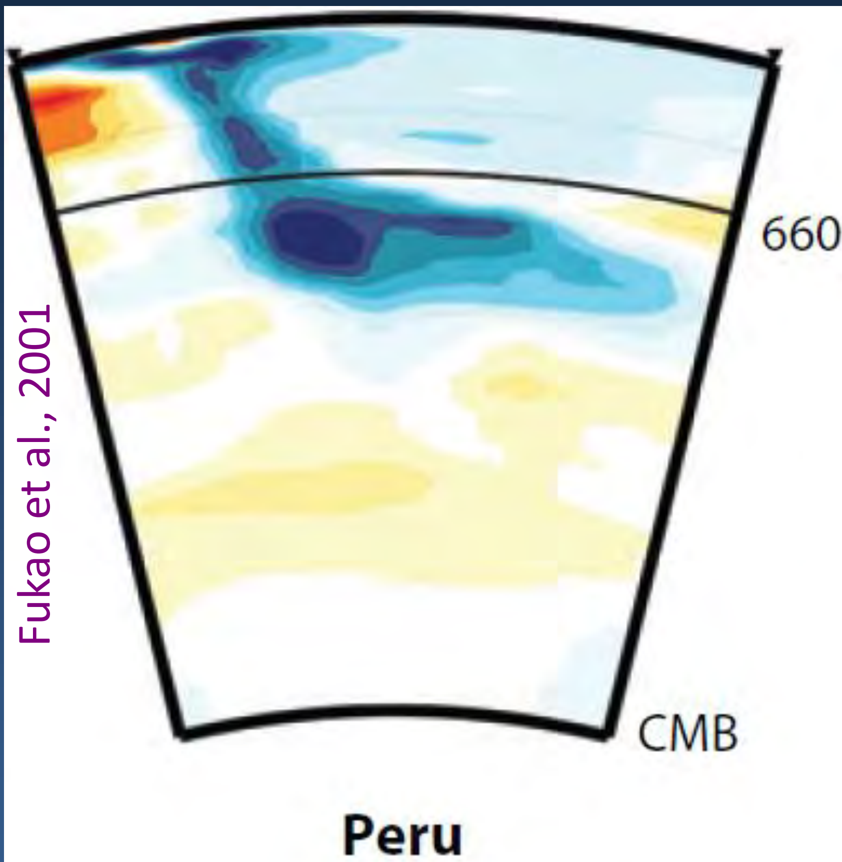
motivation



What is the composition of the Bulk Silicate Earth?

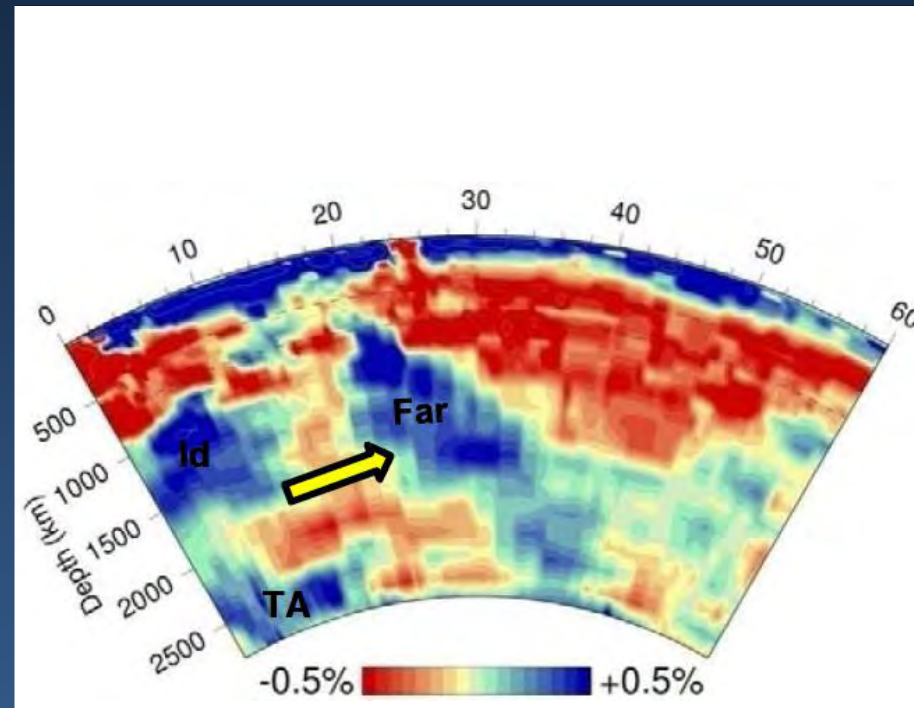
What is the composition of the Lower Mantle?

key geophysical observations



Fukao et al., 2001

Why do some slabs stagnate at about 800-1100 km depth?



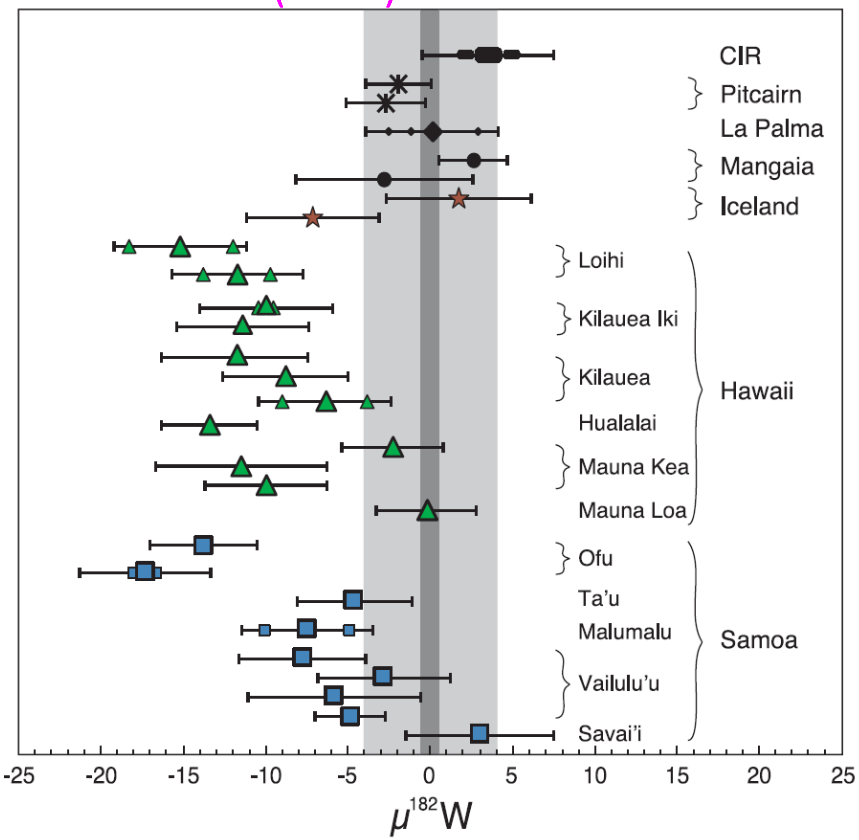
van der Meer, 2010

Seismic imaging of slabs in the lower mantle attests to whole-mantle convection

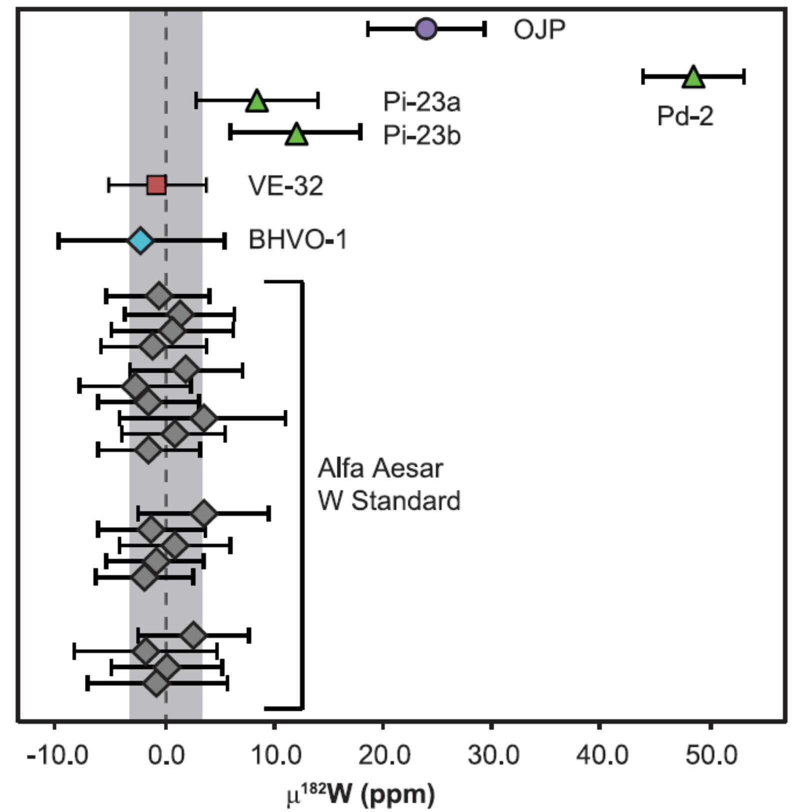
 INTRODUCTION INTRODUCTION

key geochemical constraints

Mundl et al. (2017)

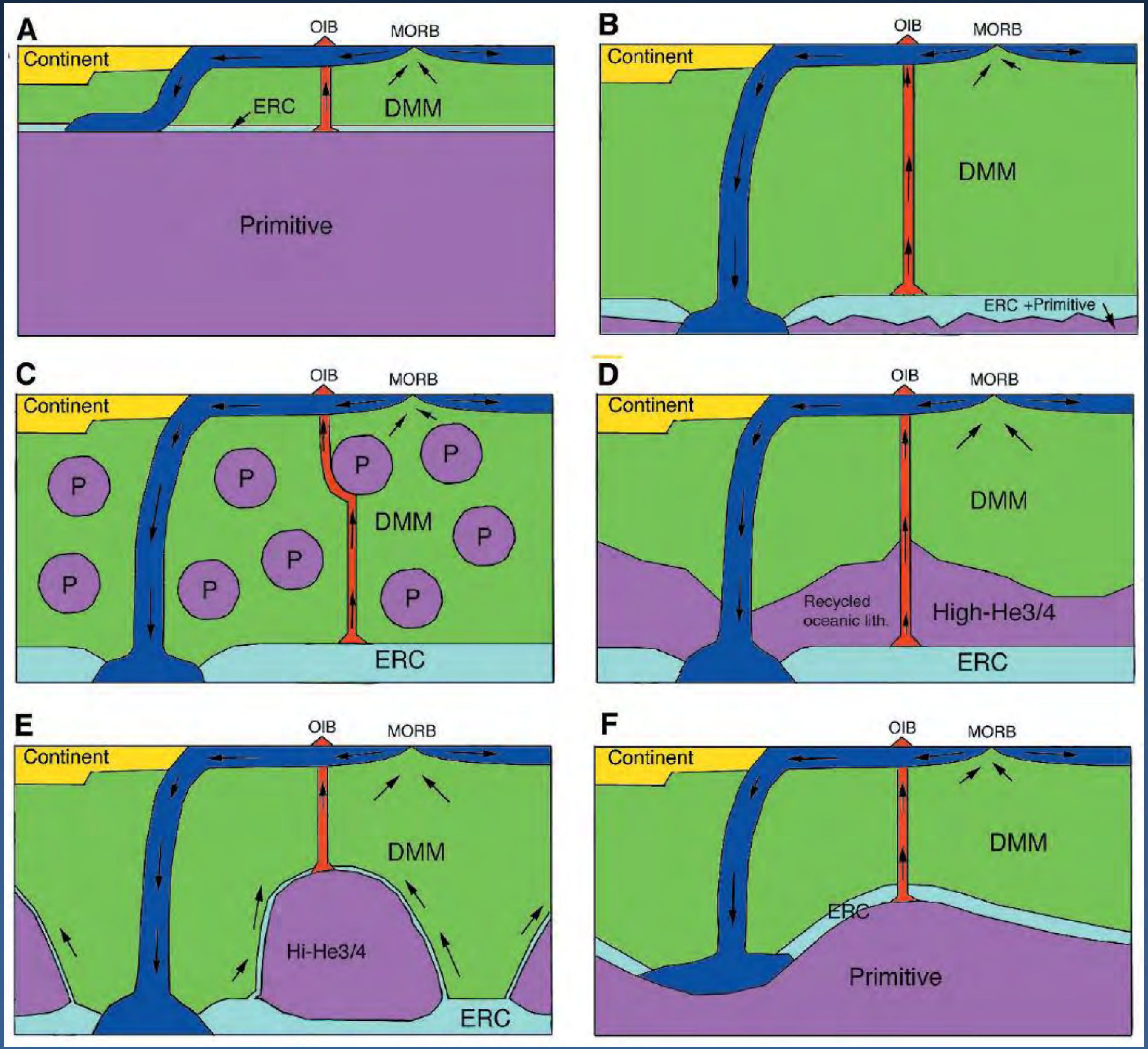


Rizo et al. (2016)



→ ancient/primordial Heterogeneity in the mantle

distribution of mantle heterogeneity ?



Tackley (2000)

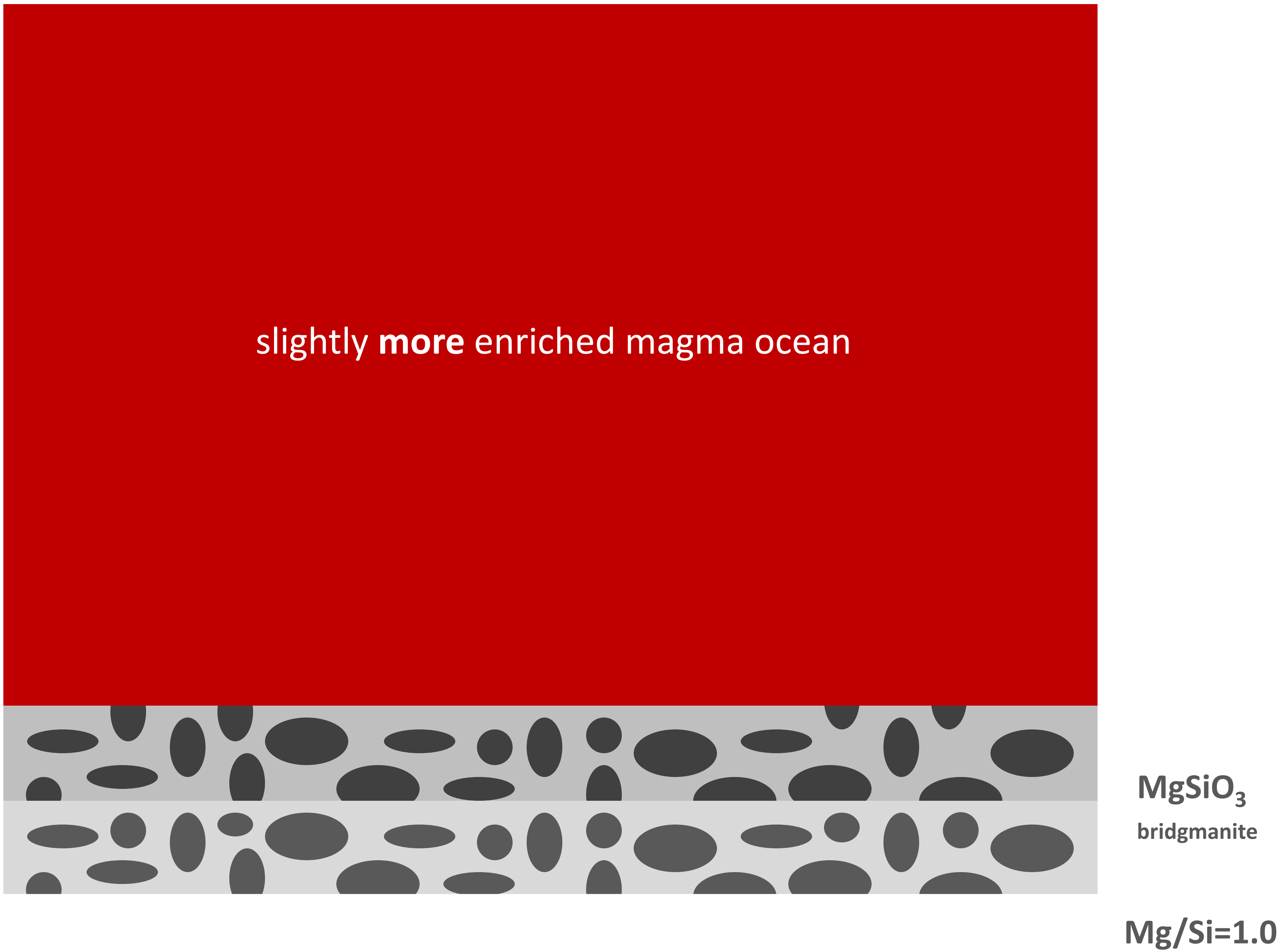
How to create primordial heterogeneity?

Moon-Forming Giant Impact

Courtesy by Miki Nakajima

magma ocean


slightly enriched magma ocean
$MgSiO_3$
bridgmanite
Mg/Si=1.0


slightly **more** enriched magma ocean
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slightly **more** enriched magma ocean
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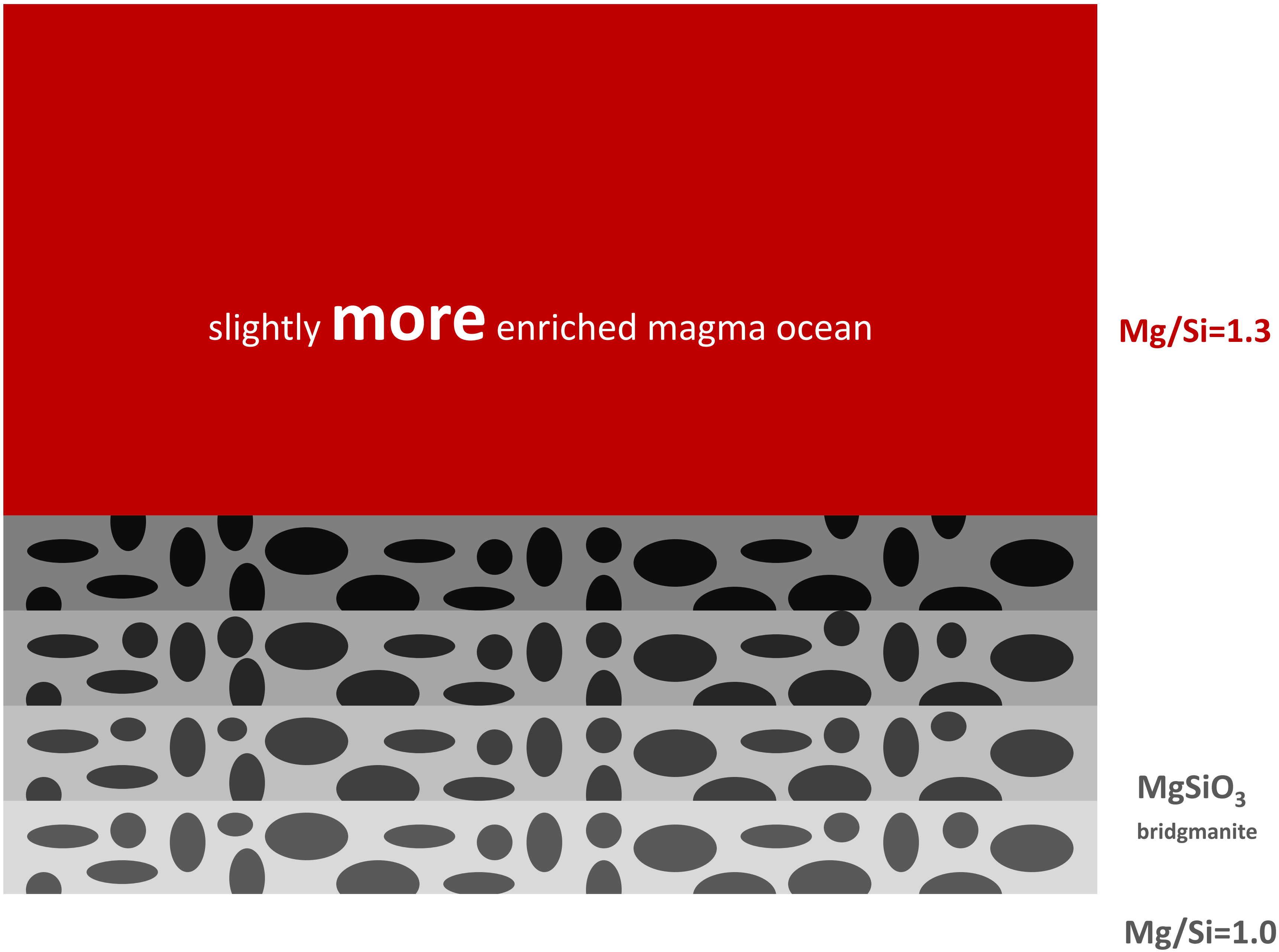
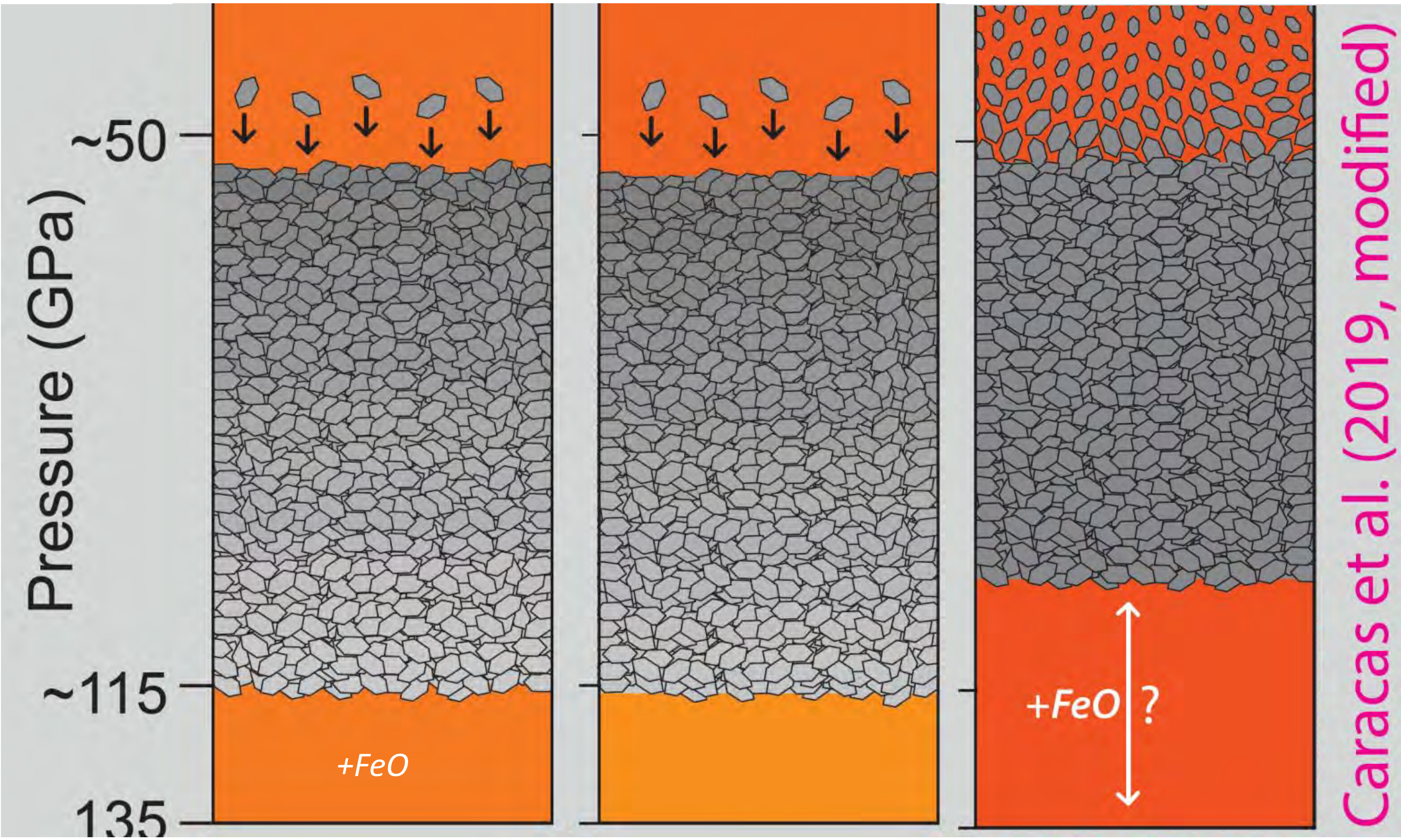

slightly **more** enriched magma ocean
Mg/Si=1.3
$MgSiO_3$
bridgmanite
Mg/Si=1.0

Basal Magma Ocean

Fractional Crystallization density crossover at ~110 GPa:

Batch Crystallization crossover at ~50 GPa:



→ **Basal Magma Ocean with variable size and composition** depending on formation scenario

→ **Basal Magma Ocean cumulates variably Fe-enriched** depending on formation scenario

outline

(1) how can compositional heterogeneity be sustained ?

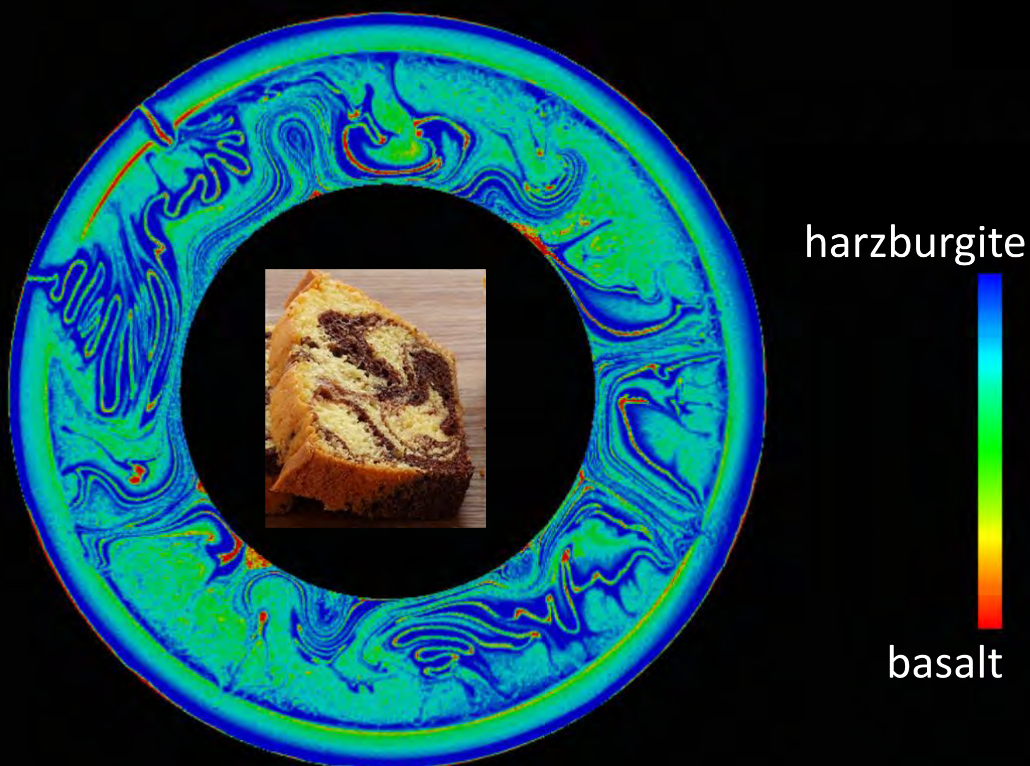
(a) “un-mixing”

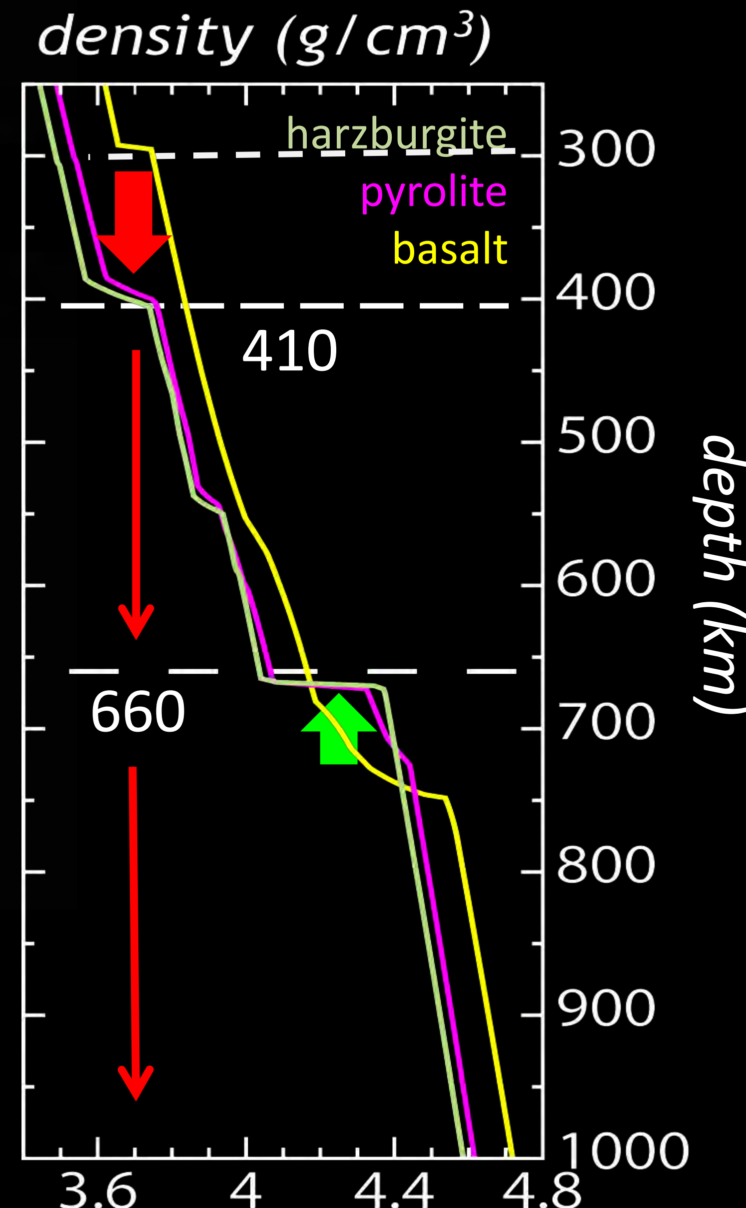
(b) compositional rheology

(2) consistent with geophysical observations ?

„un-mixing“ of recycled heterogeneity

Mantle stirring of Basalt & Harzburgite

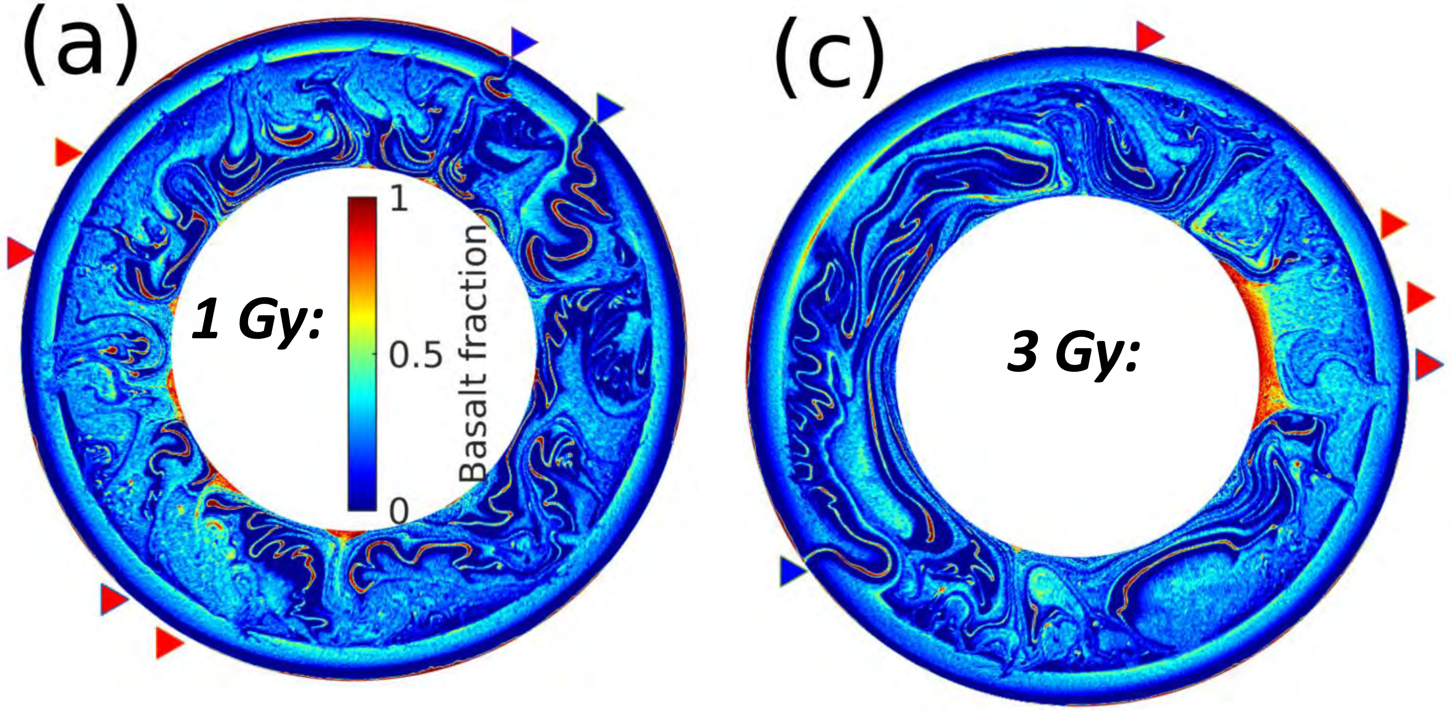


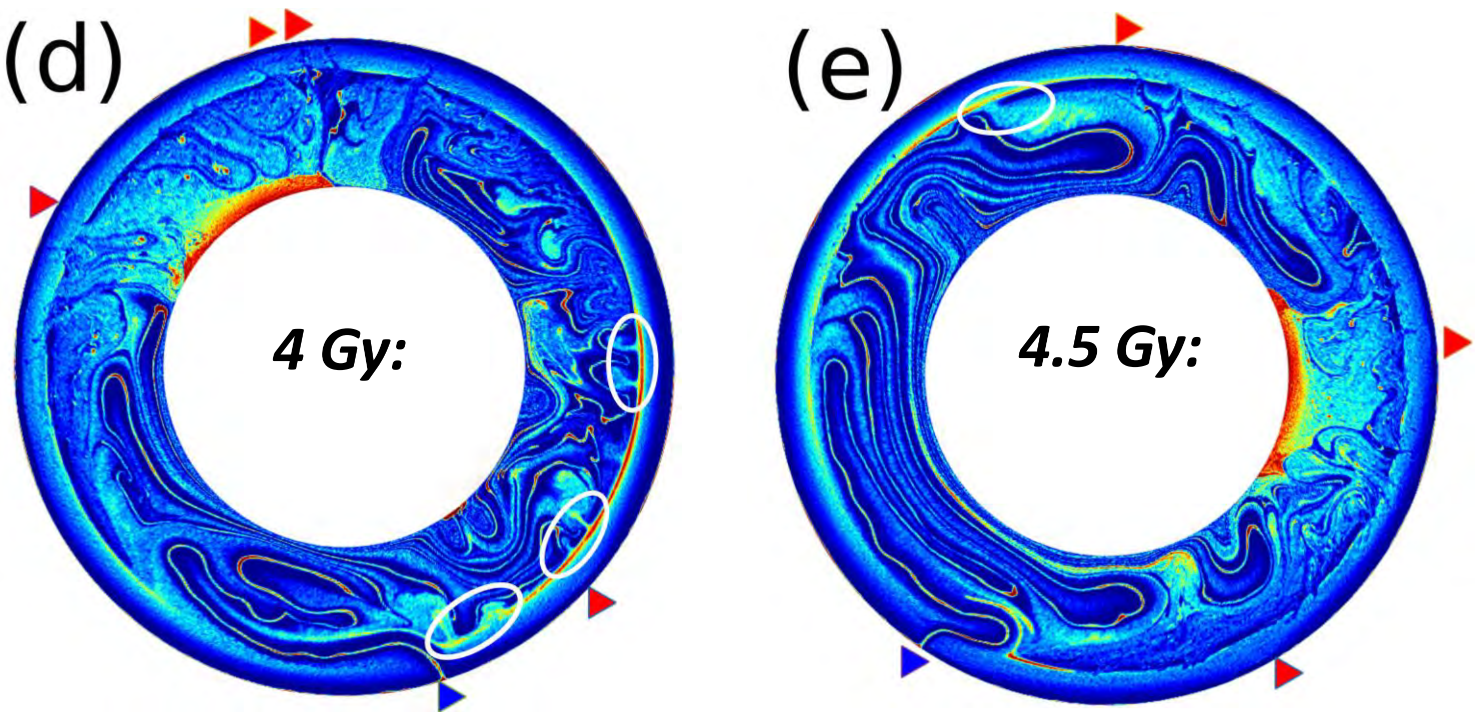


basalt/eclogite tends to sink…

⇔

harzburgite tends to rise

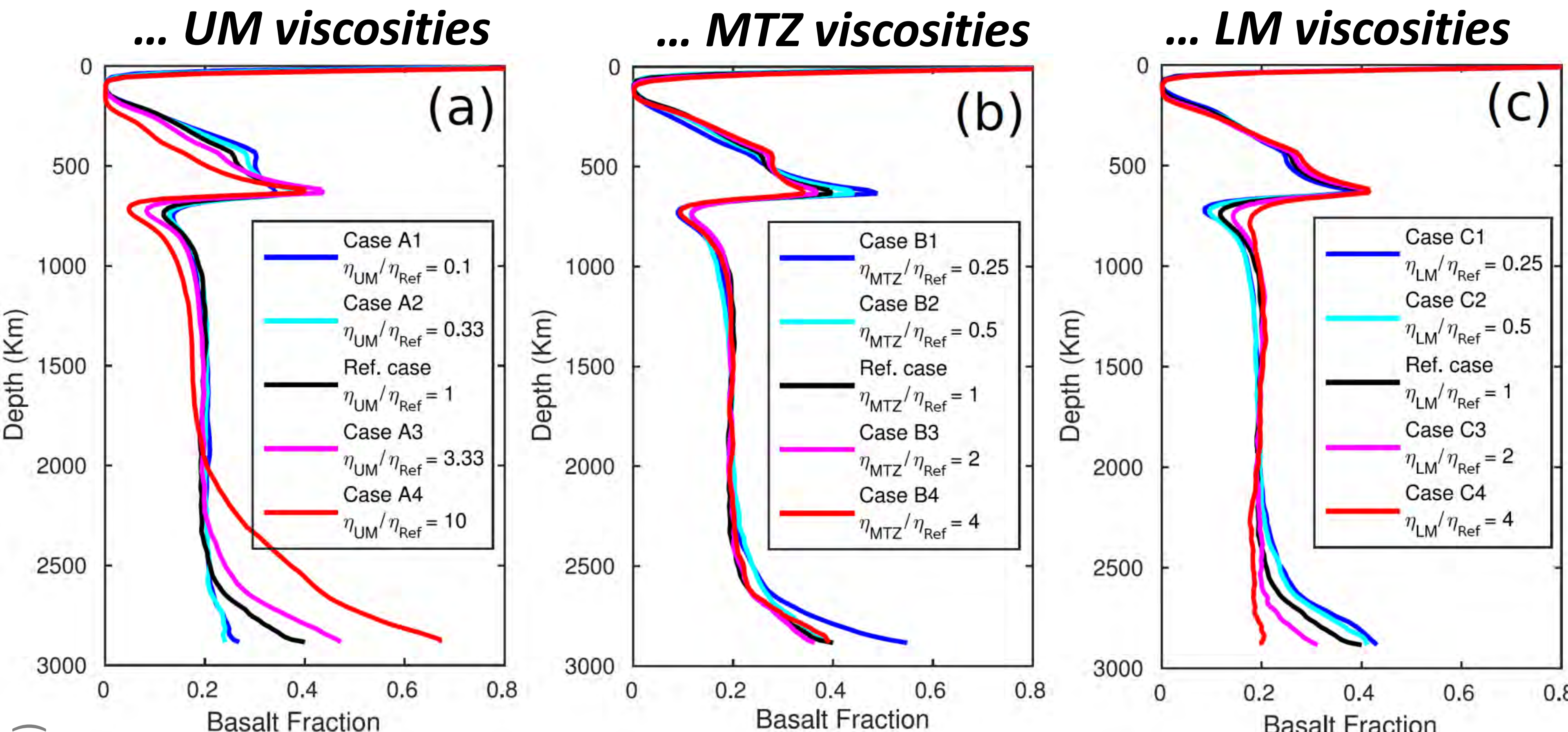




Jun

Yan et al. (2020)

Mantle compositional profiles for different …

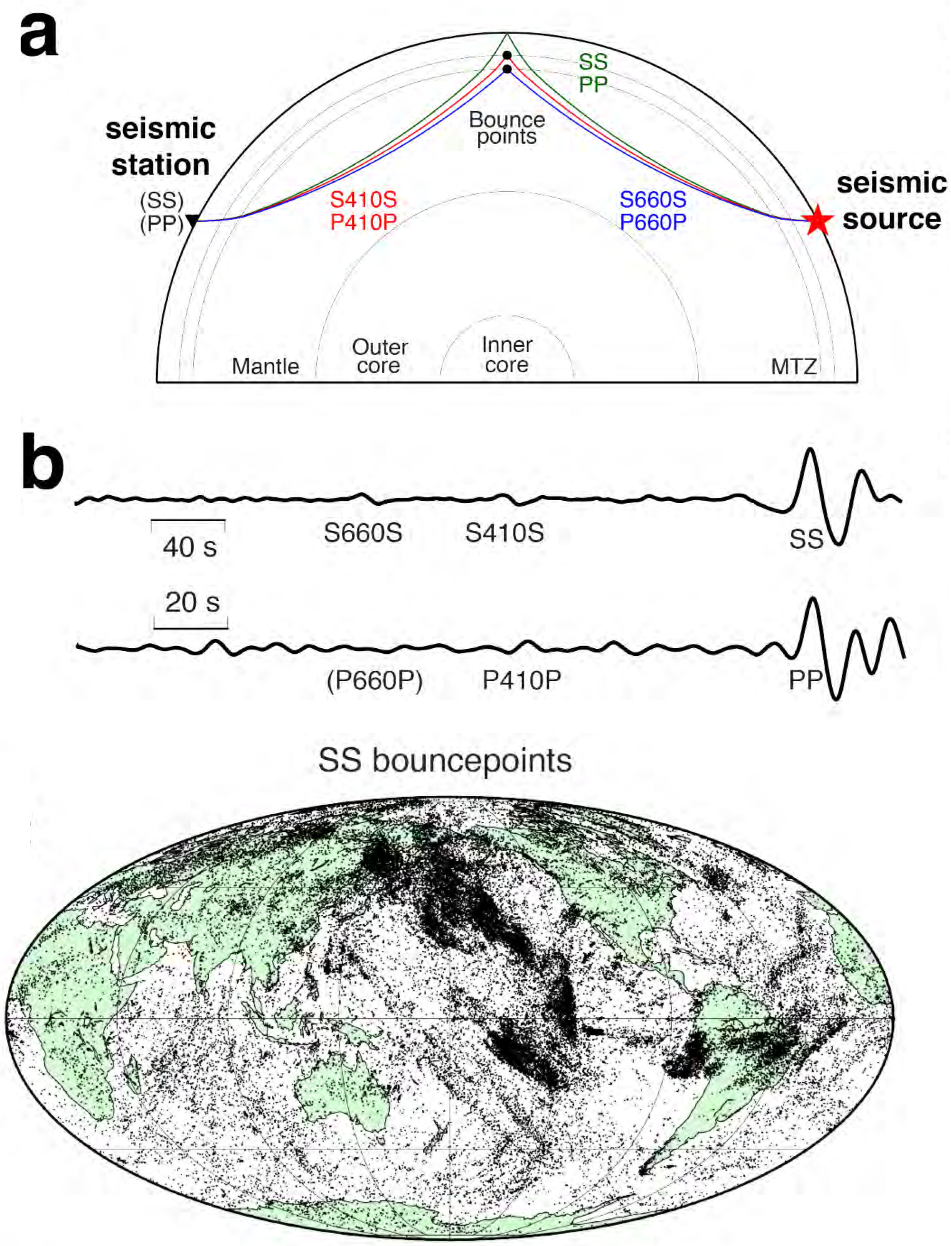


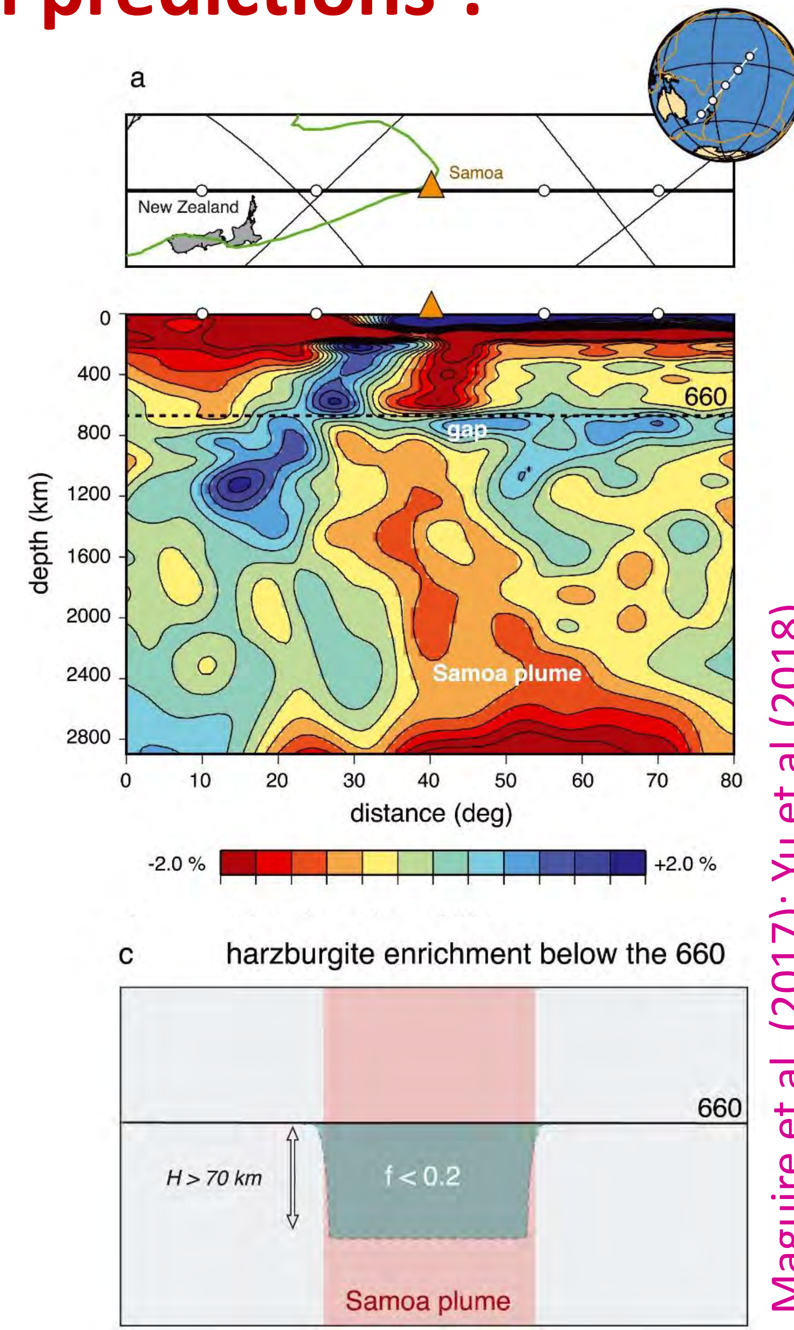
Predicted compositional stratification with basalt/harzburgite enriched reservoirs above/below the 660 is highly robust

Lower mantle and MTZ are enriched in recycled "basalt" → BSE is enriched

Yan et al. (2020)

How to test these model predictions ?

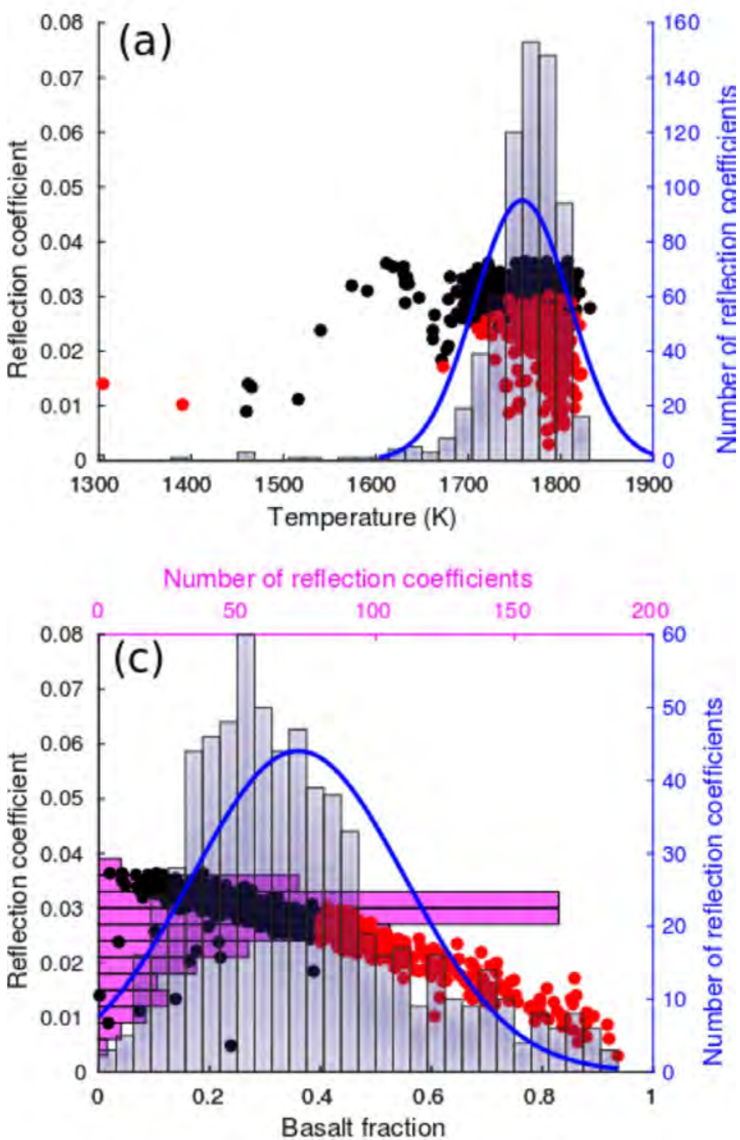




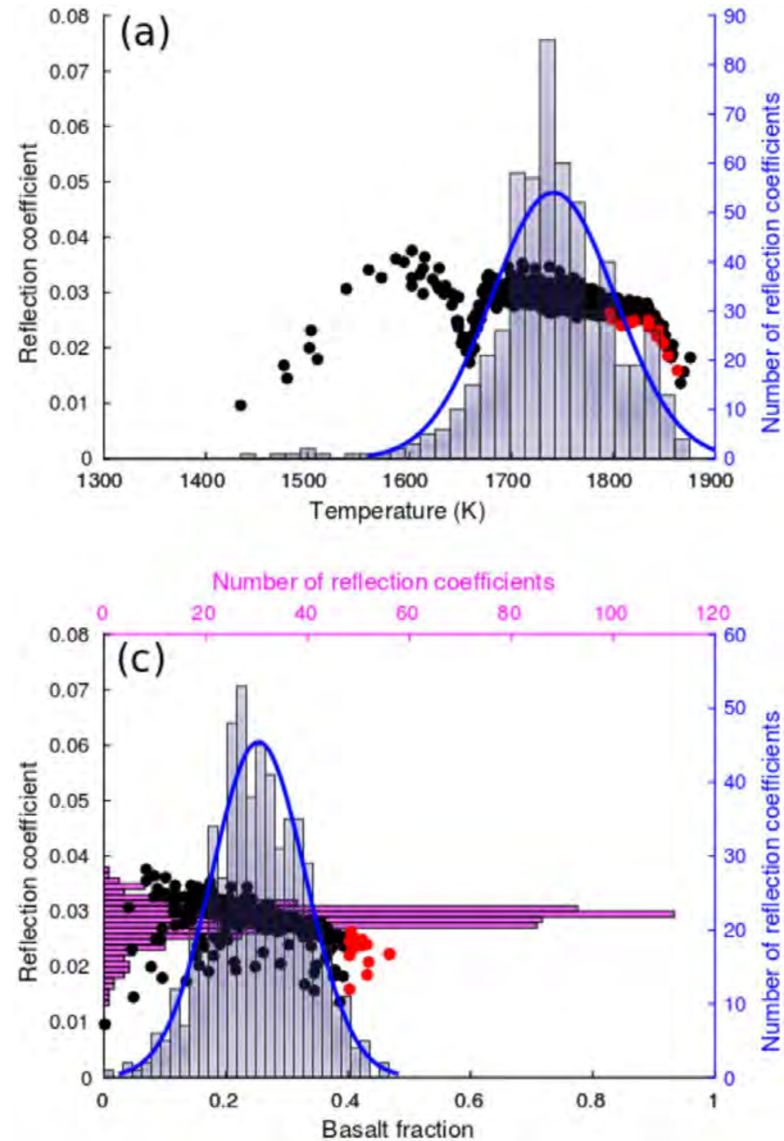
Waszek et al. (in press)

Maguire et al. (2017); Yu et al (2018)

Predicted reflection coefficients (far from subduction zones)

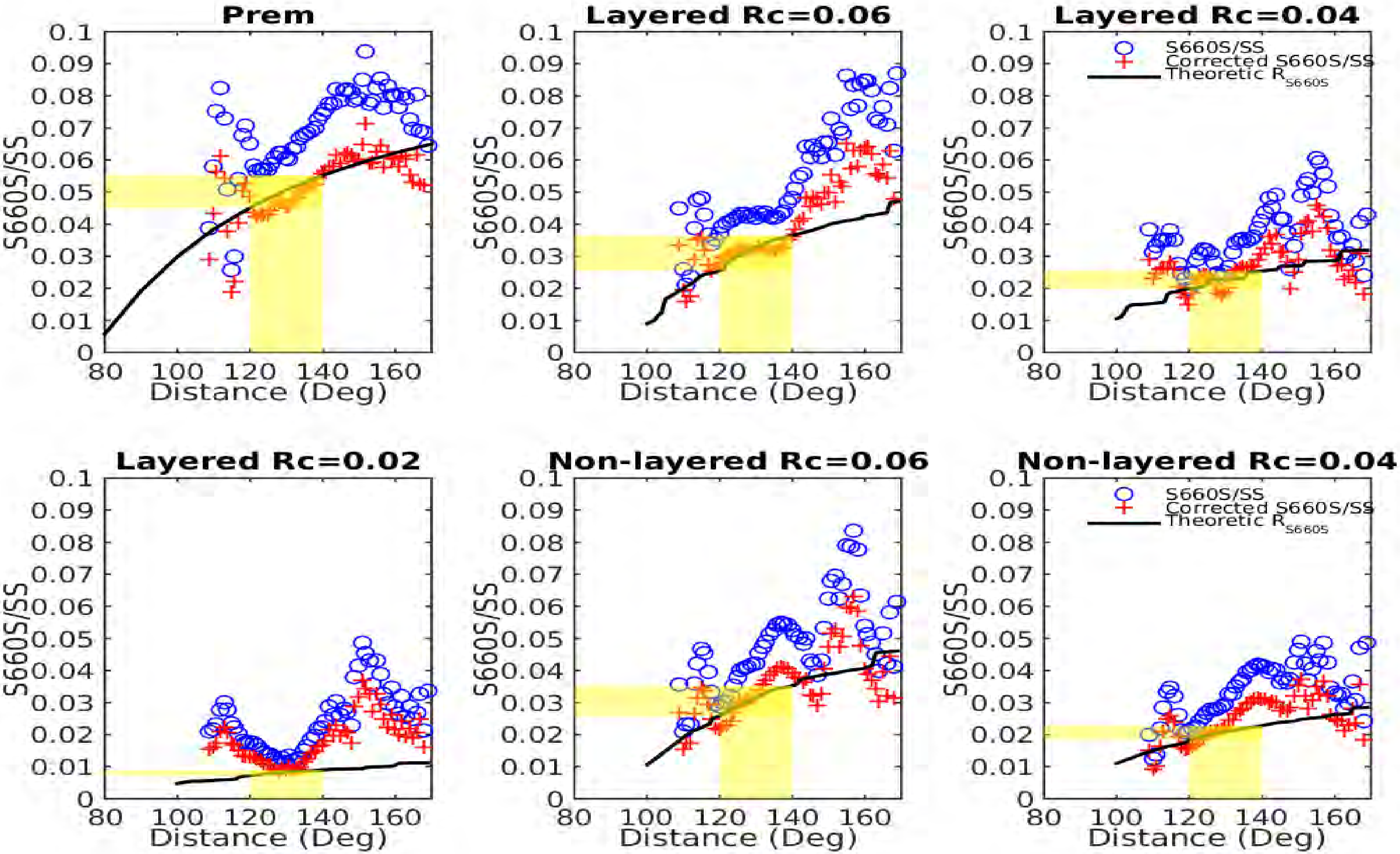


"layered" model as predicted

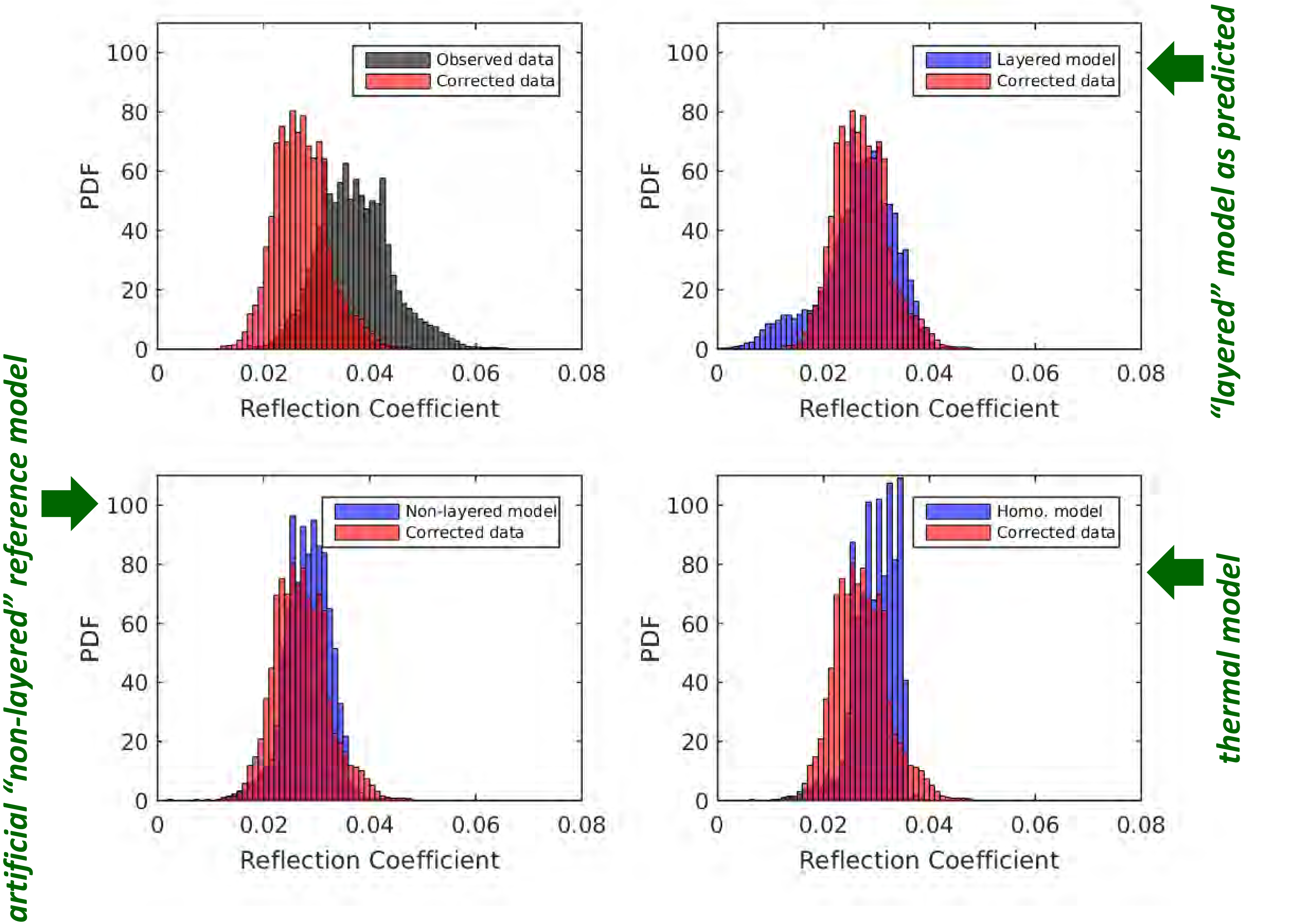


artificial "non-layered" reference model

5.5 Synthetic test and observation

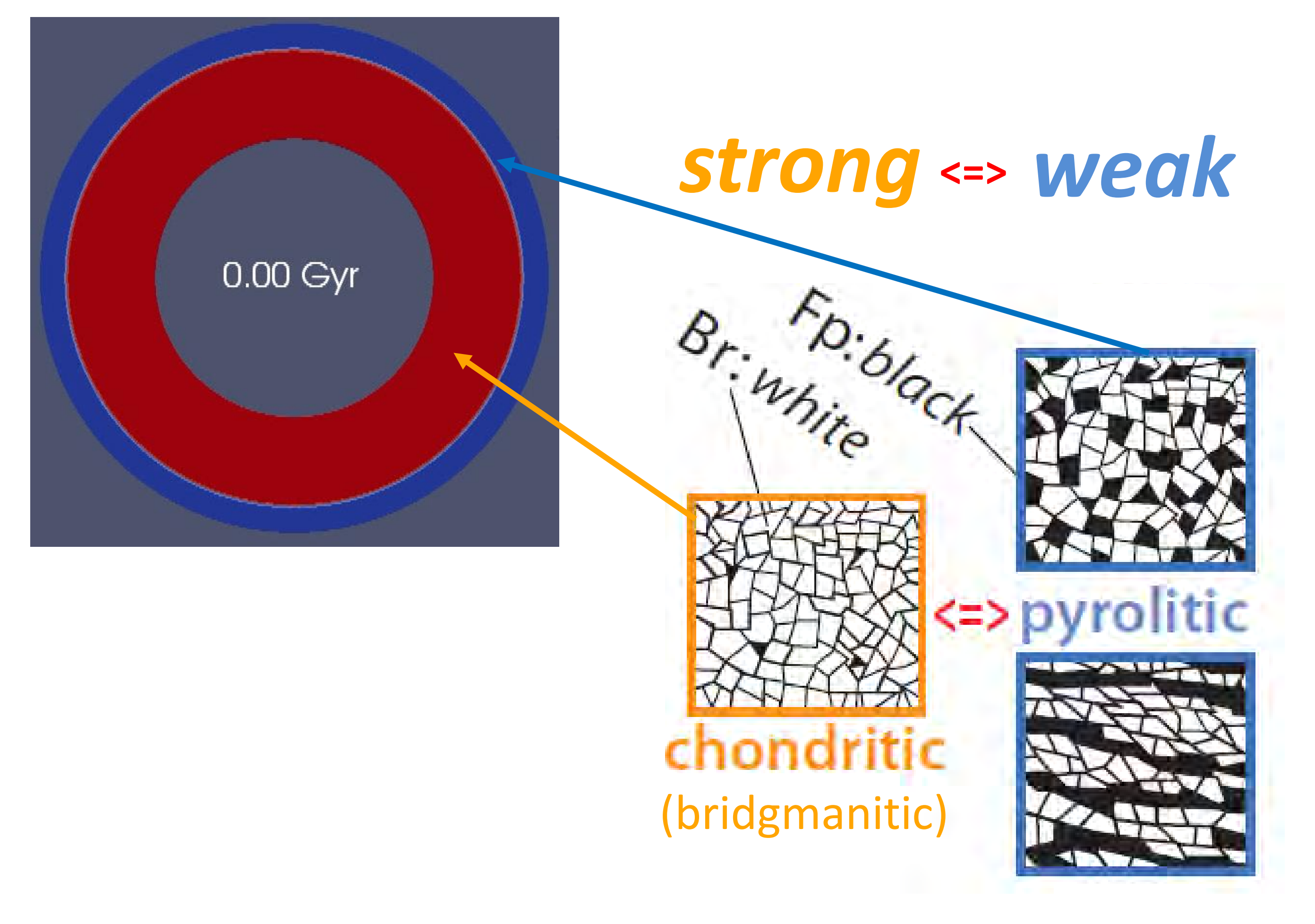


Predicted vs. observed reflection coefficients



effects of compositional rheology

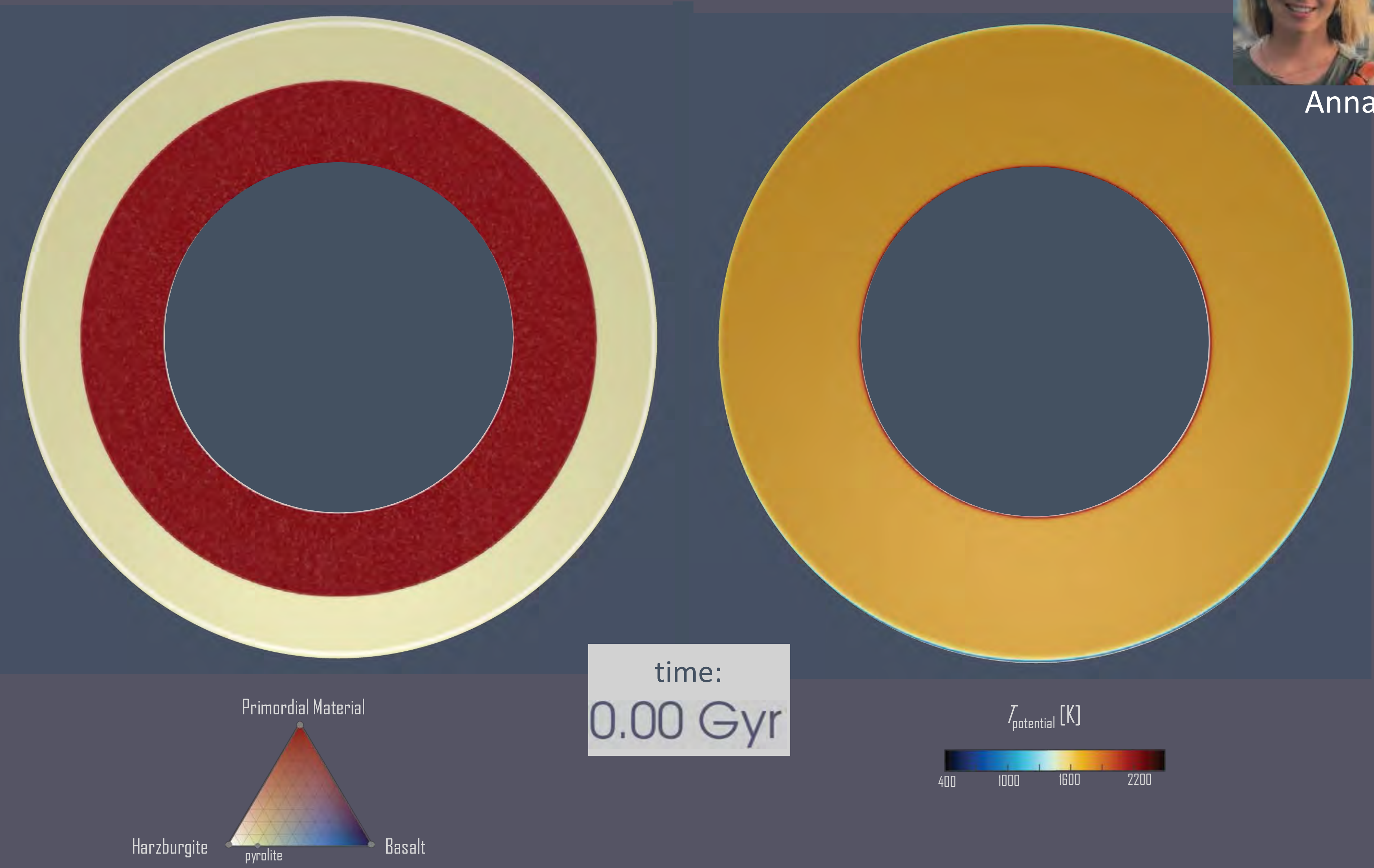
compositional rheology in the lower mantle



for a viscosity contrast of a factor ~100
=> distinct dynamic behaviour

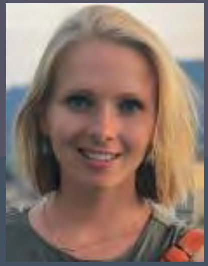
Thermochemical Mantle Evolution

Anna

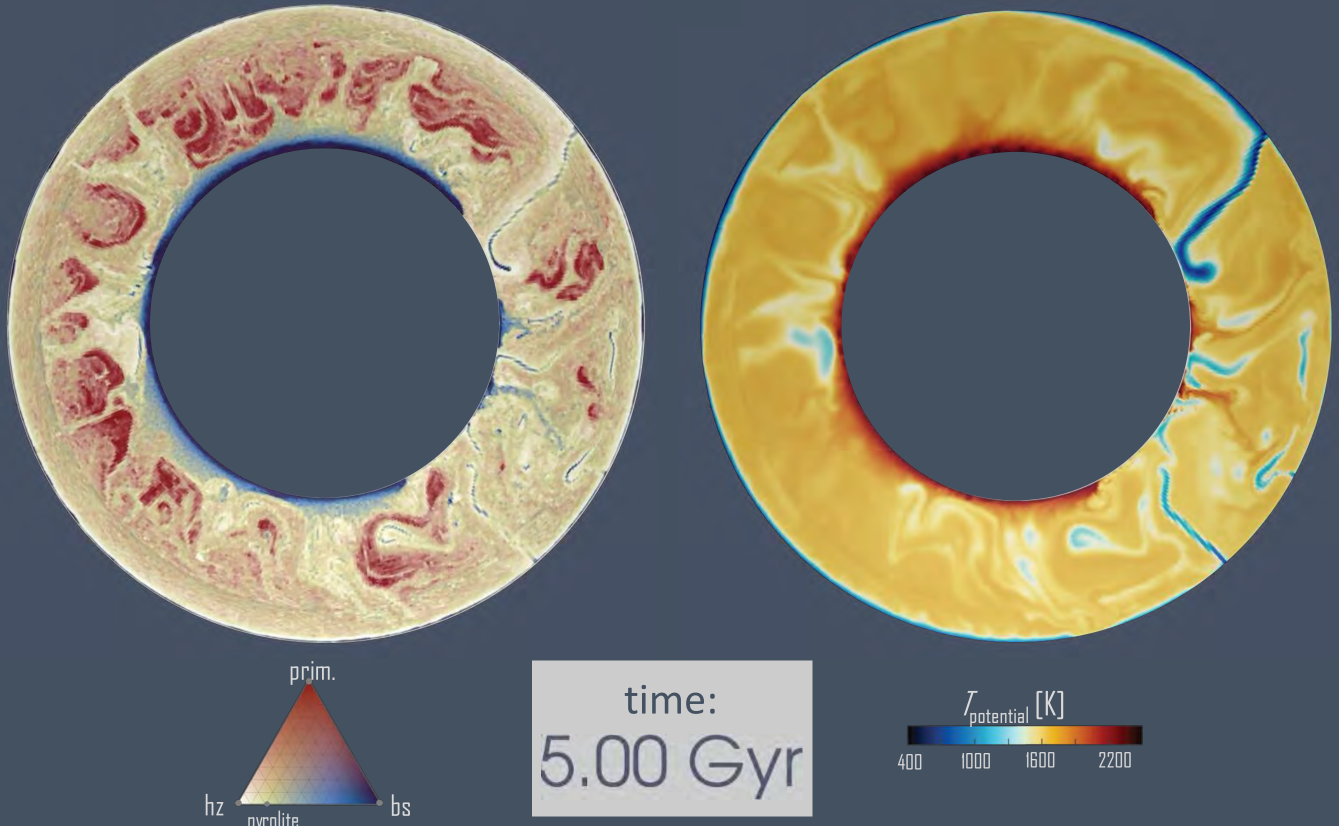


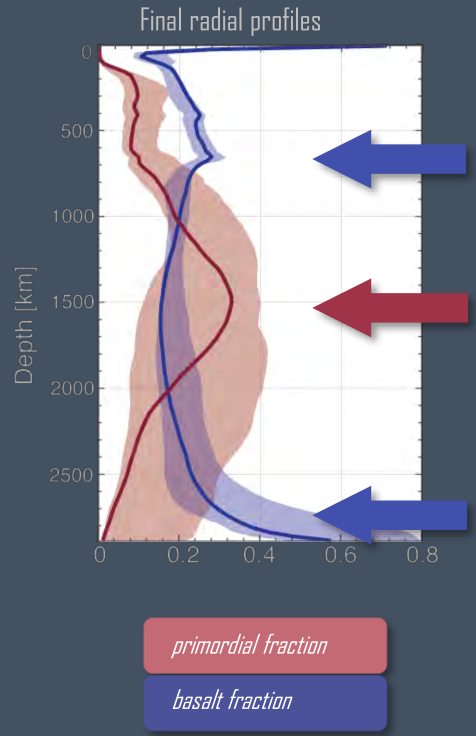
Gülcher et al., 2021

Thermochemical Mantle Evolution



- ROC heterogeneity as **dense piles**, an **enriched MTZ** and "**marble cake**" streaks
- Primordial heterogeneity (*Br*-enriched) as **blobs** and **streaks** in the mid-mantle





Gülcher et al., 2021

Thermochemical Mantle Evolution

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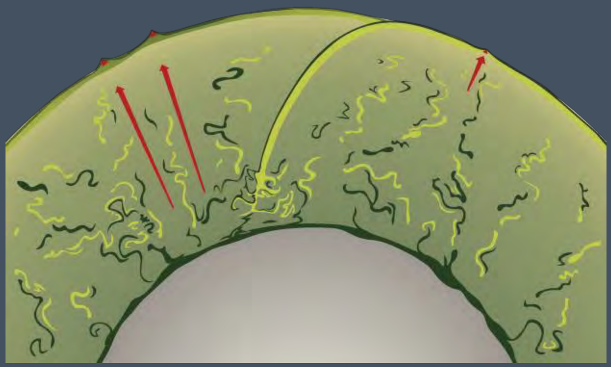

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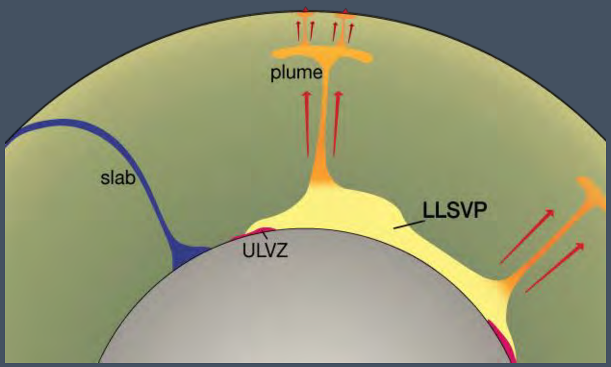

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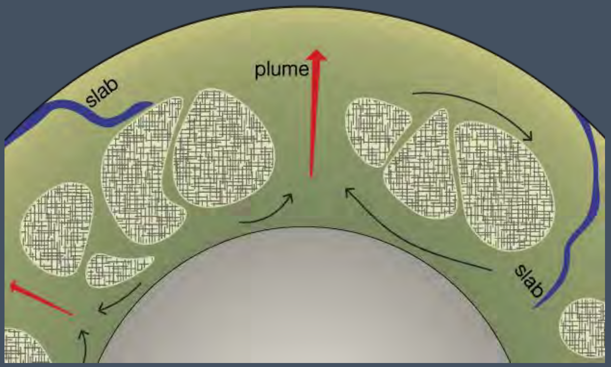
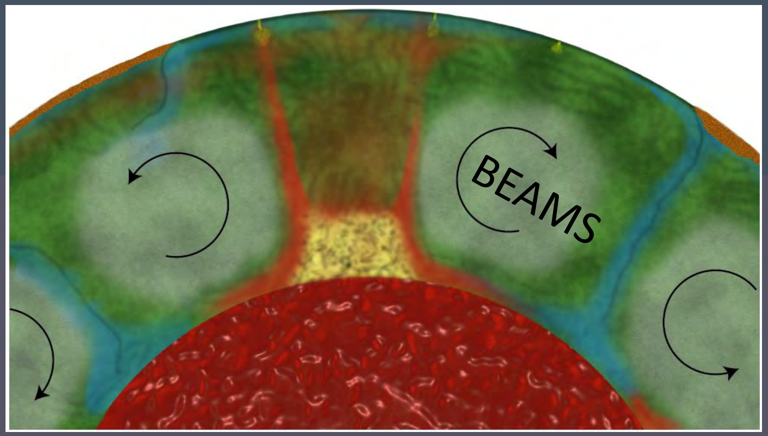
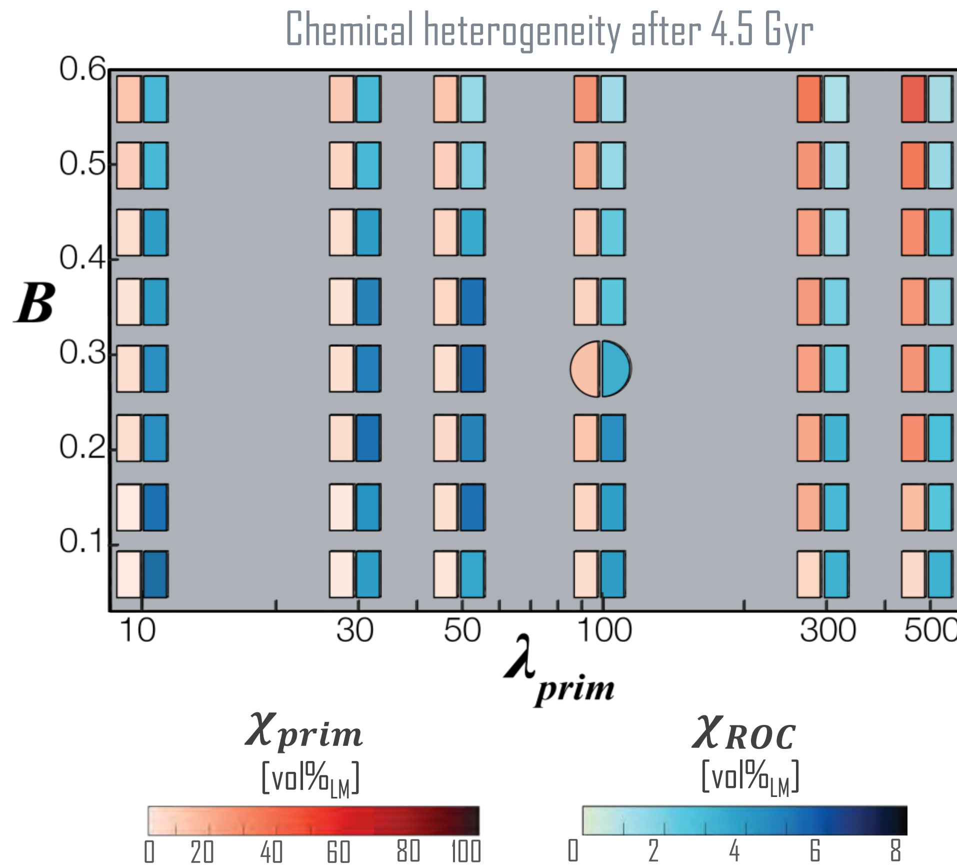


= geodynamically viable!

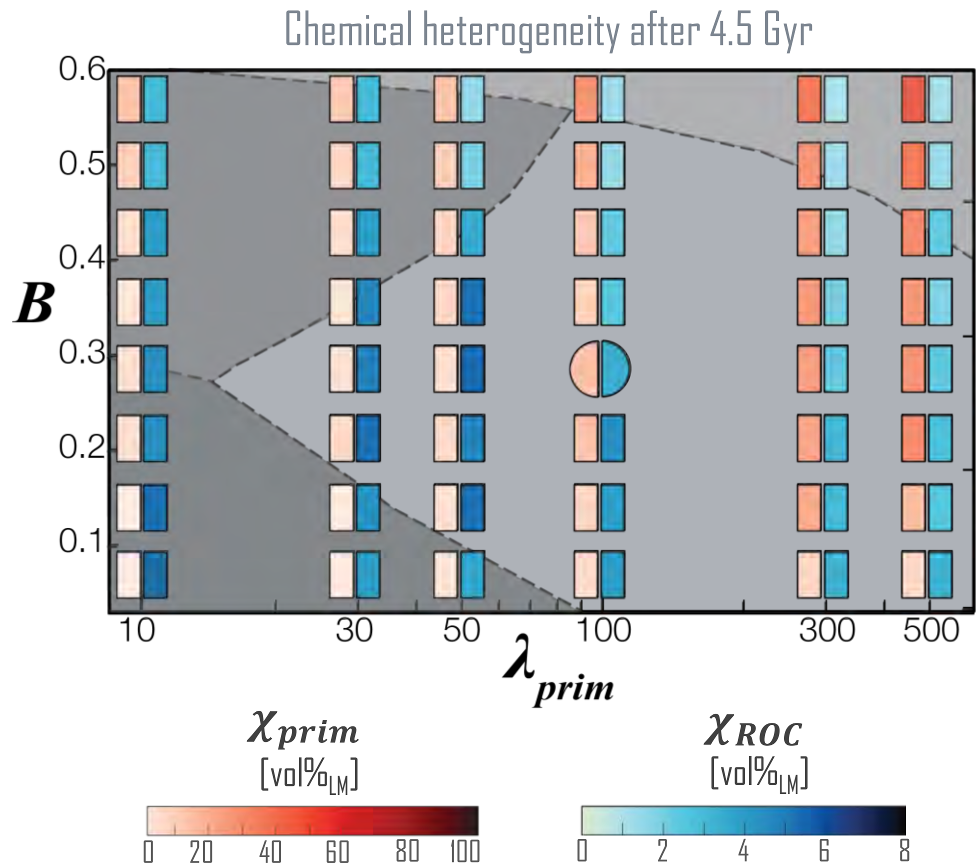


Parameter Sensitivity of Model Predictions



Gülcher et al. (2021)

Parameter Sensitivity of Model Predictions



Gülcher et al. (2021)

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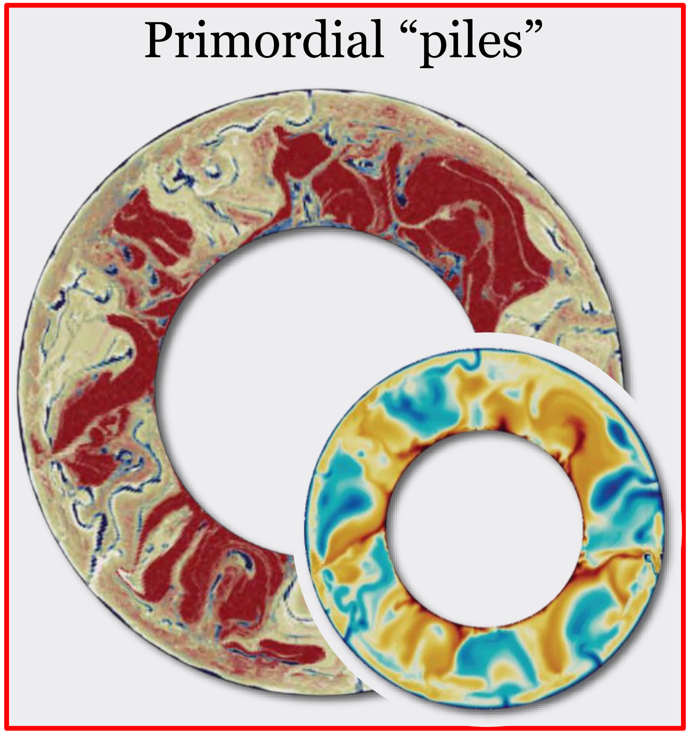

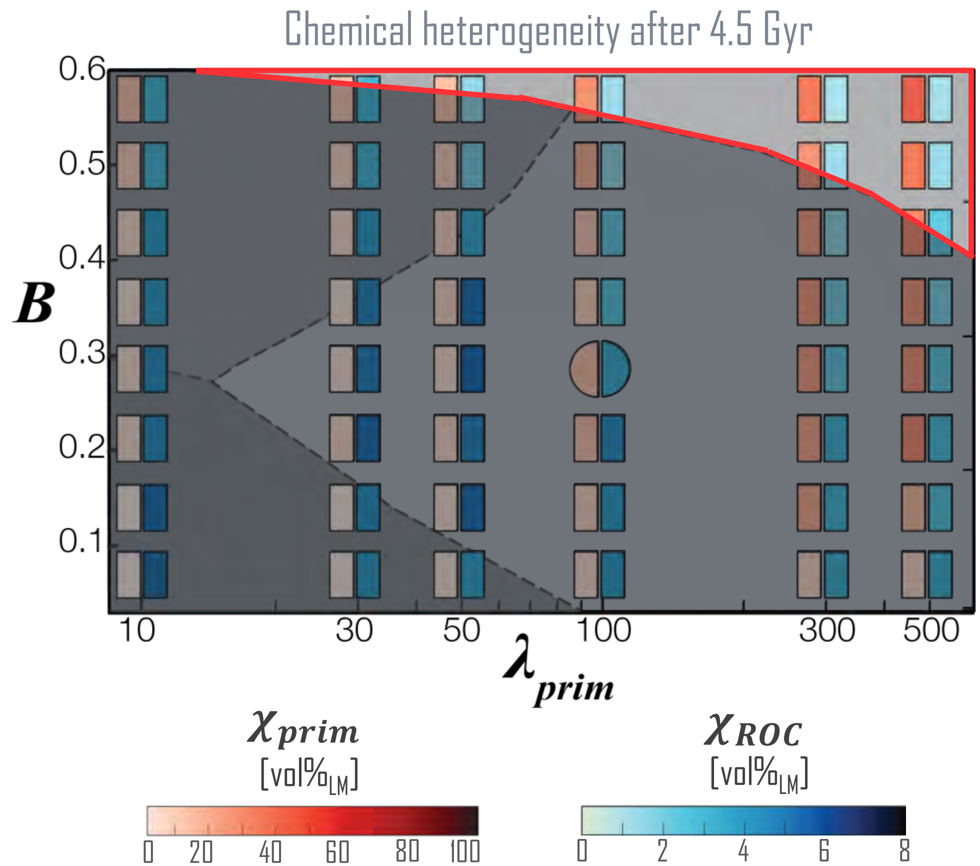

Gülcher et al. (2021)

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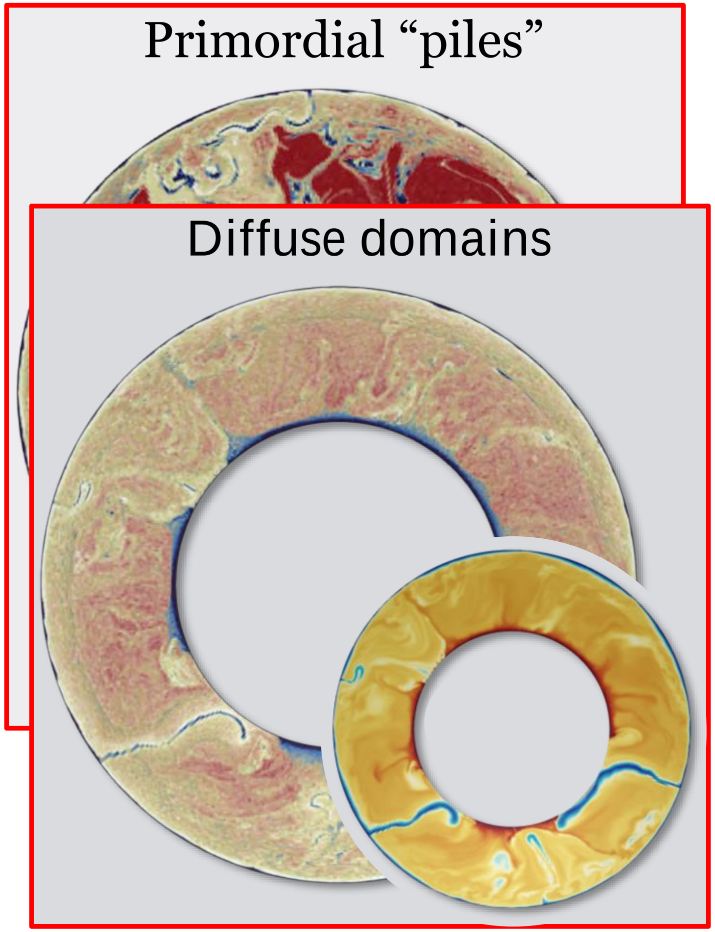

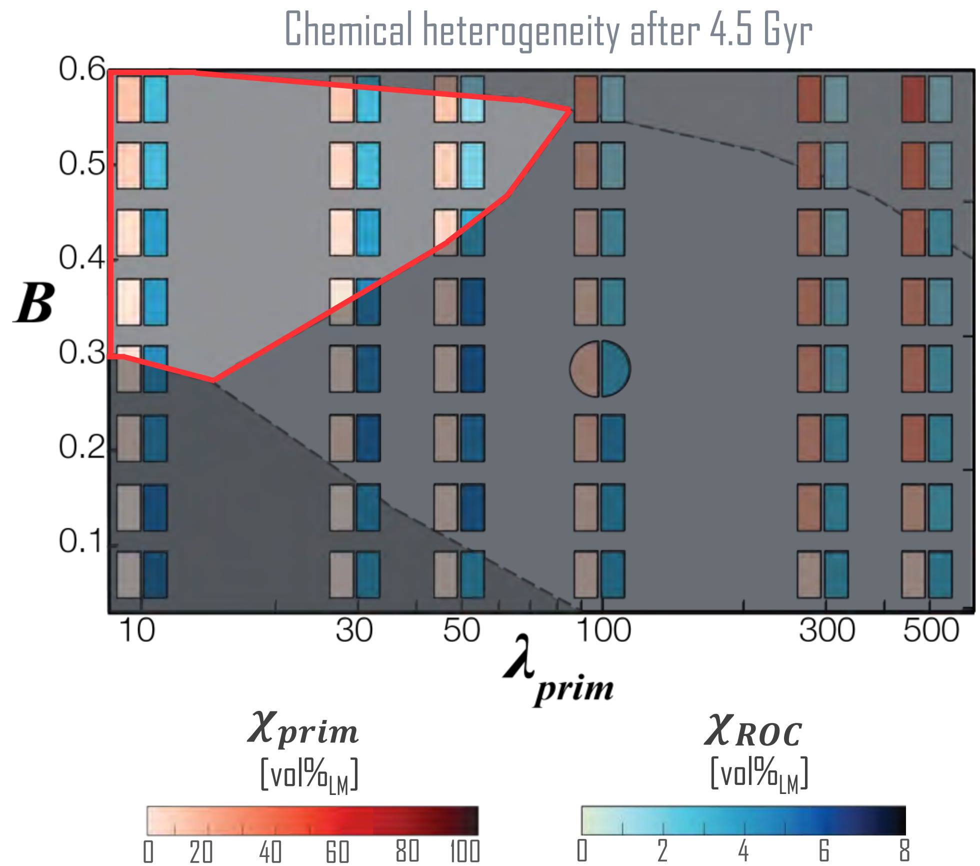

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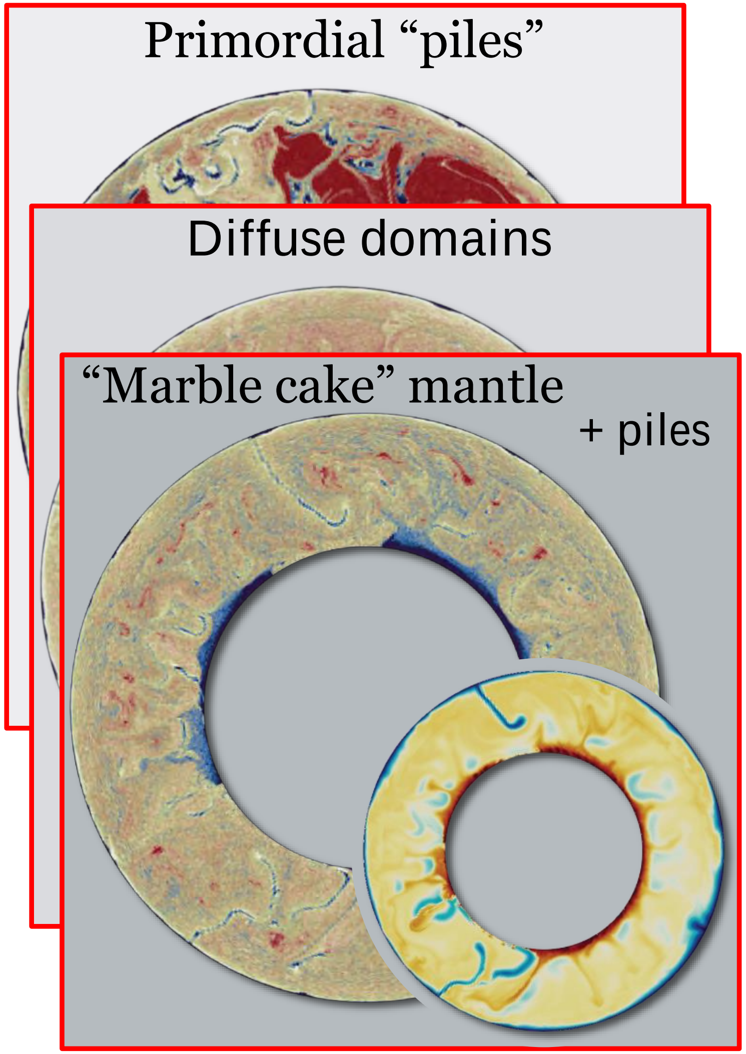

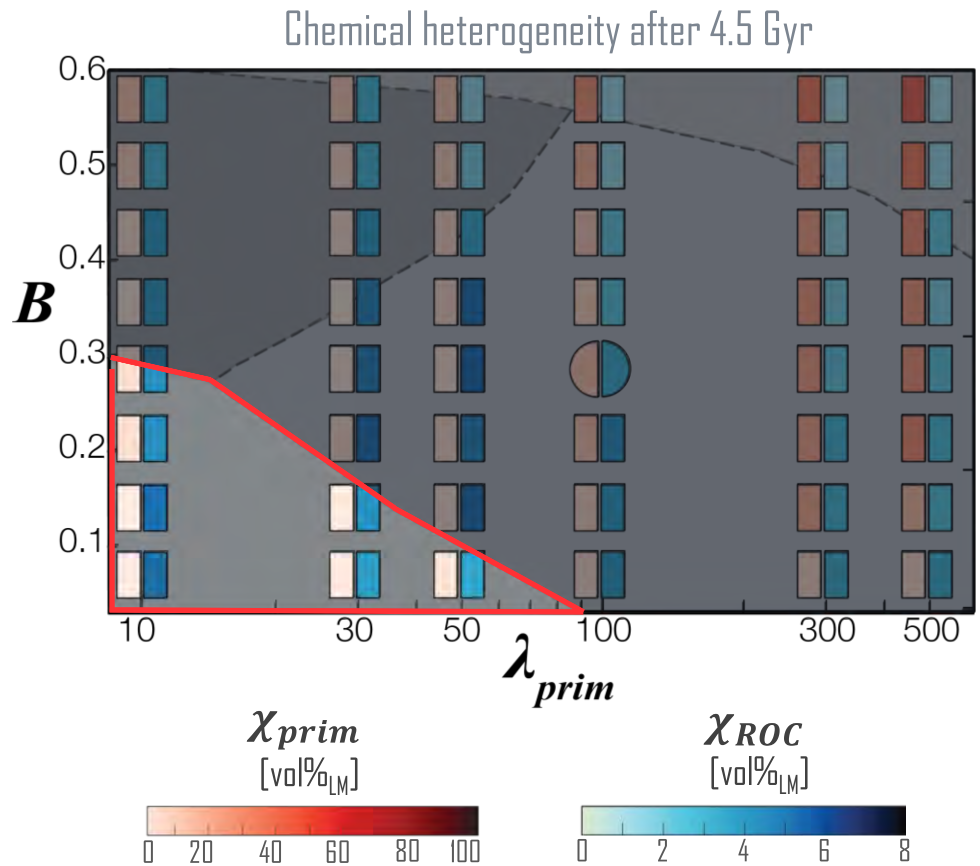

Gülcher et al. (2021)

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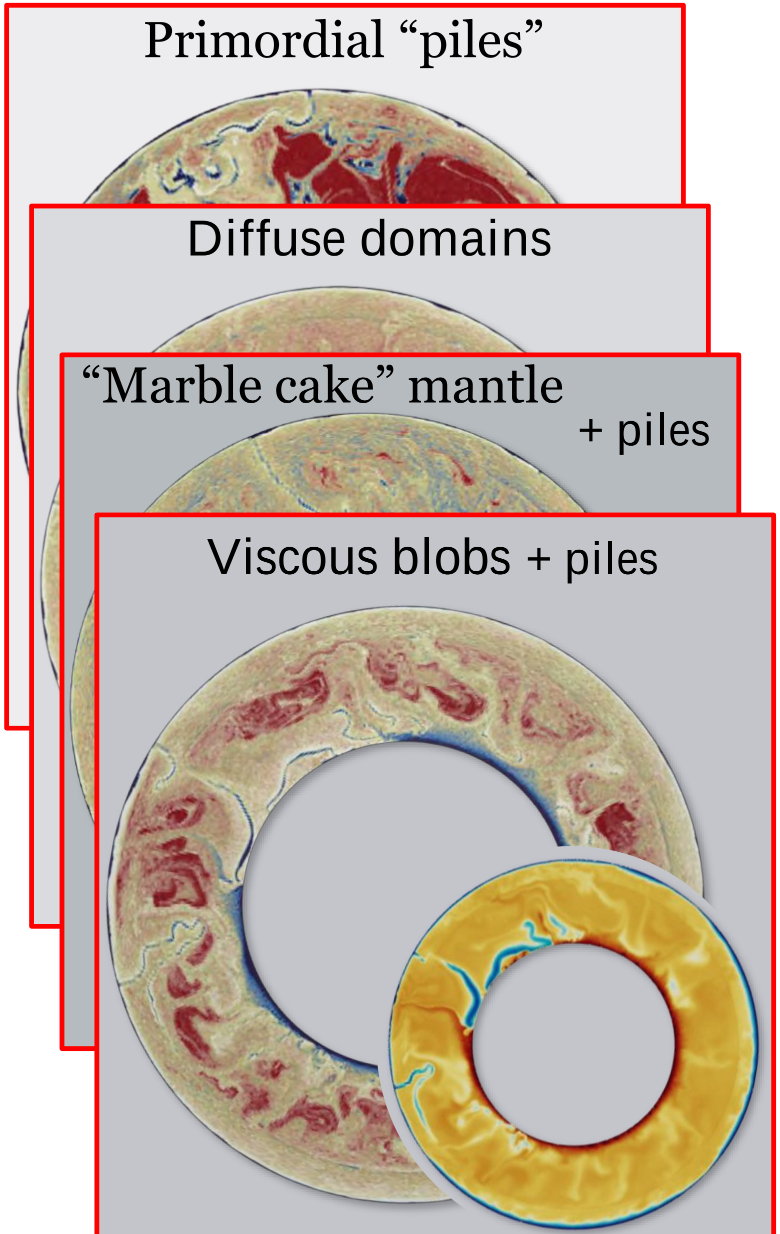
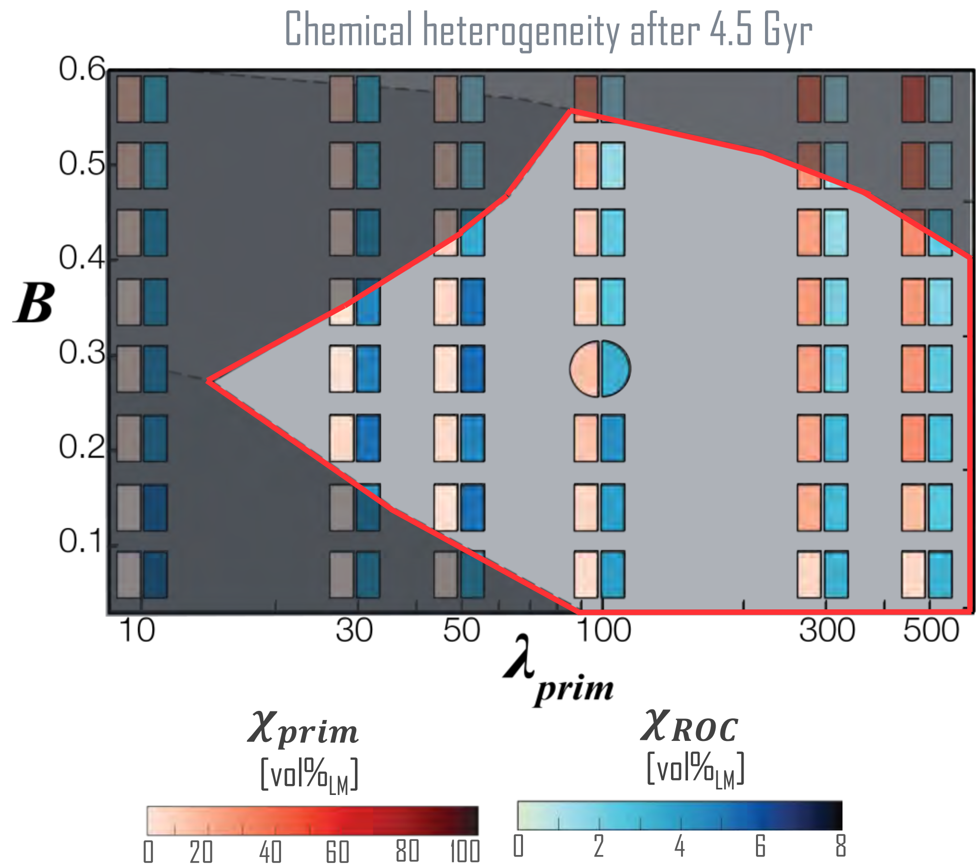
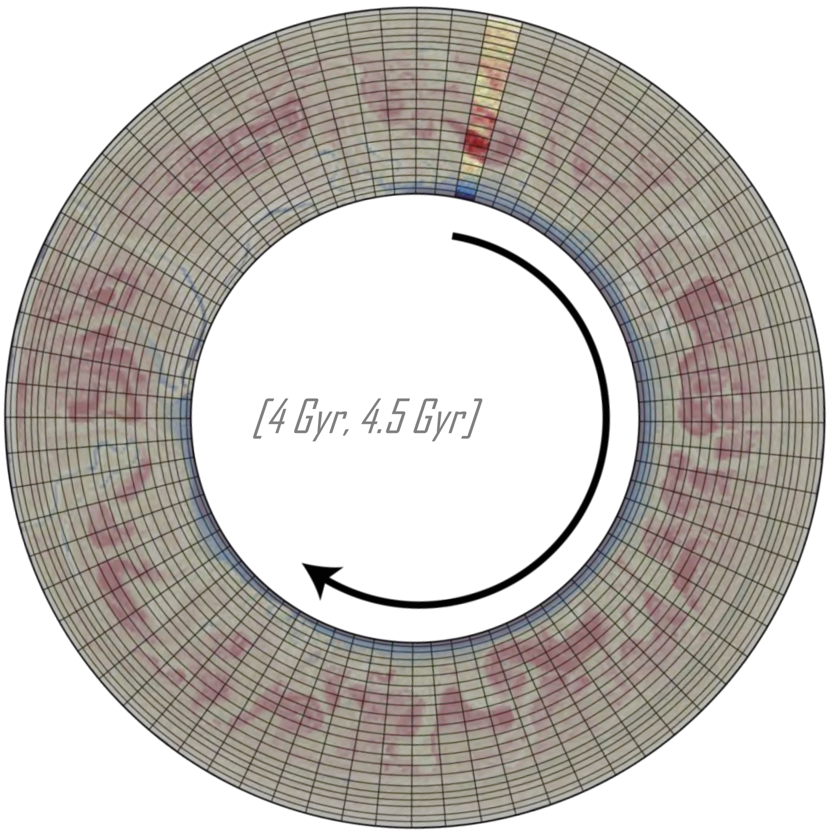




Gülcher et al. (2021)

Relationship mantle domains and flow



Mid-mantle characteristics:

- Primordial material fraction f_{prim}

- Radial velocity V_z

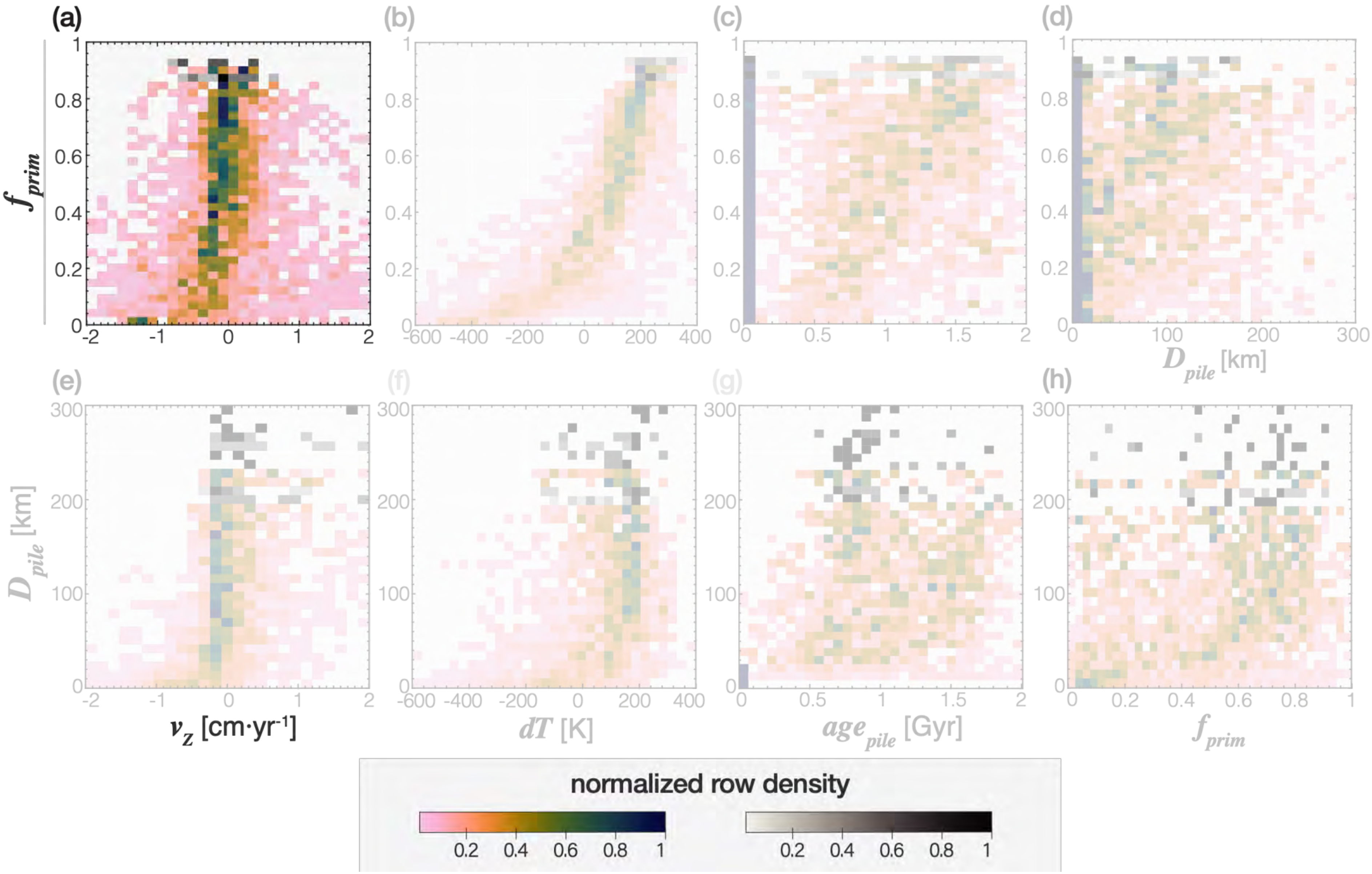
- Horizontal T anomaly dT

Pile characteristics:

- **Pile thickness** D_{pile}
- Average pile material age

Gülcher et al. (2021)

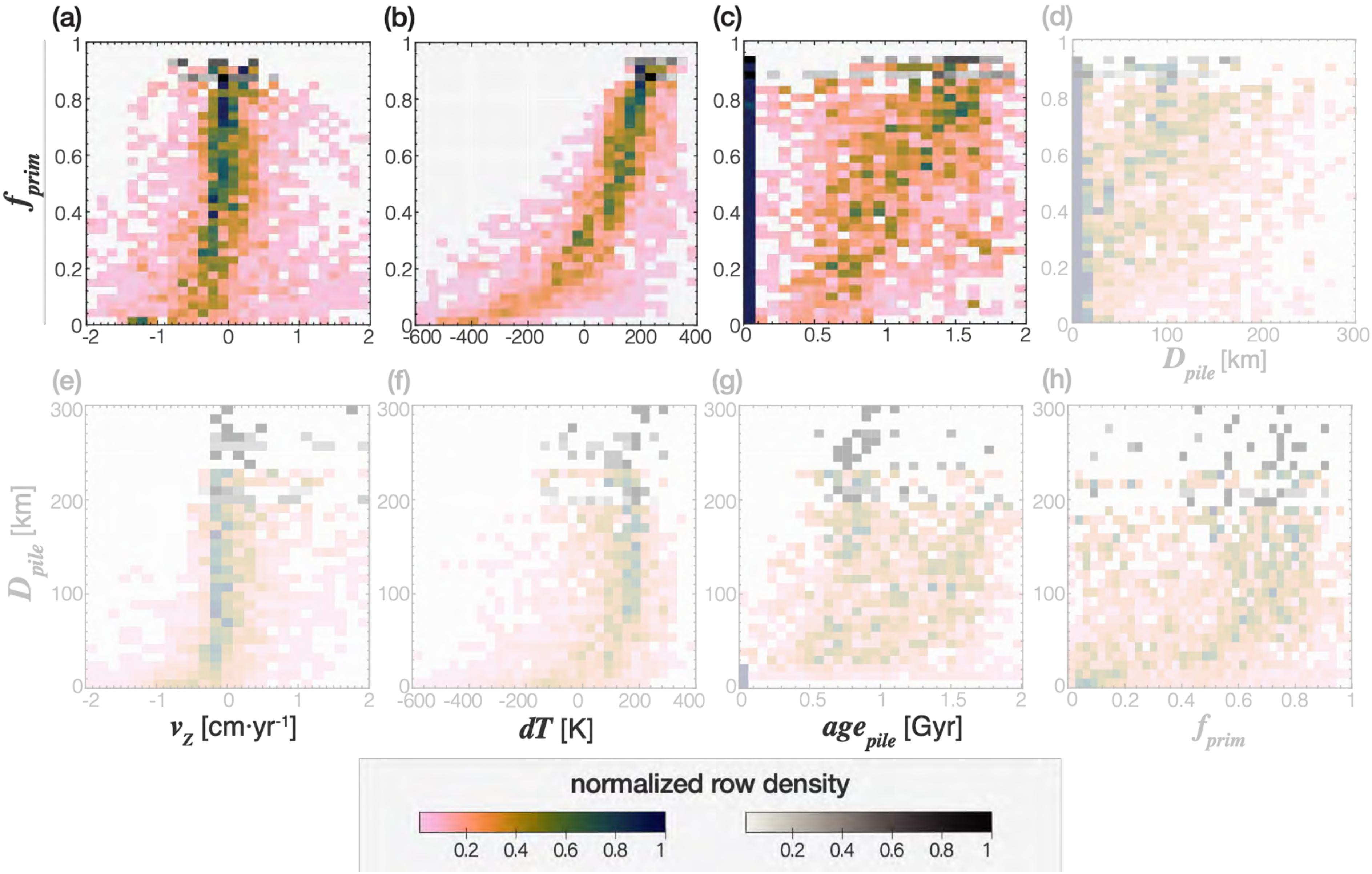
Correlation of Blobs and Piles



Gülcher et al. (2021)

[4 Gyr, 4.5 Gyr]

Correlation of Blobs and Piles



Gülcher et al. (2021)

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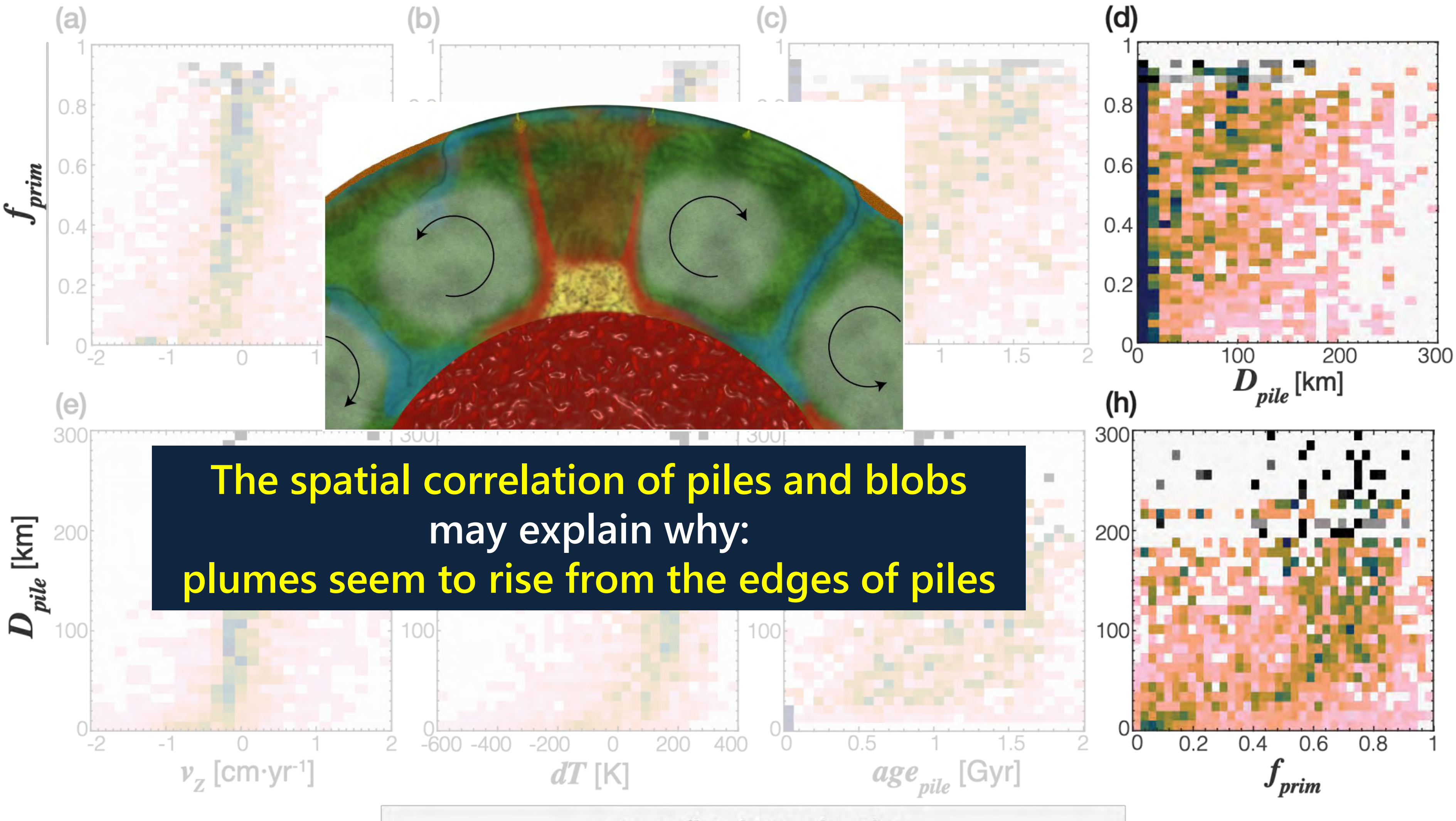


The spatial correlation of piles and blobs
may explain why:
plumes seem to rise from the edges of piles

PhD student
Matteo Desiderio

Gülcher et al. (2021)

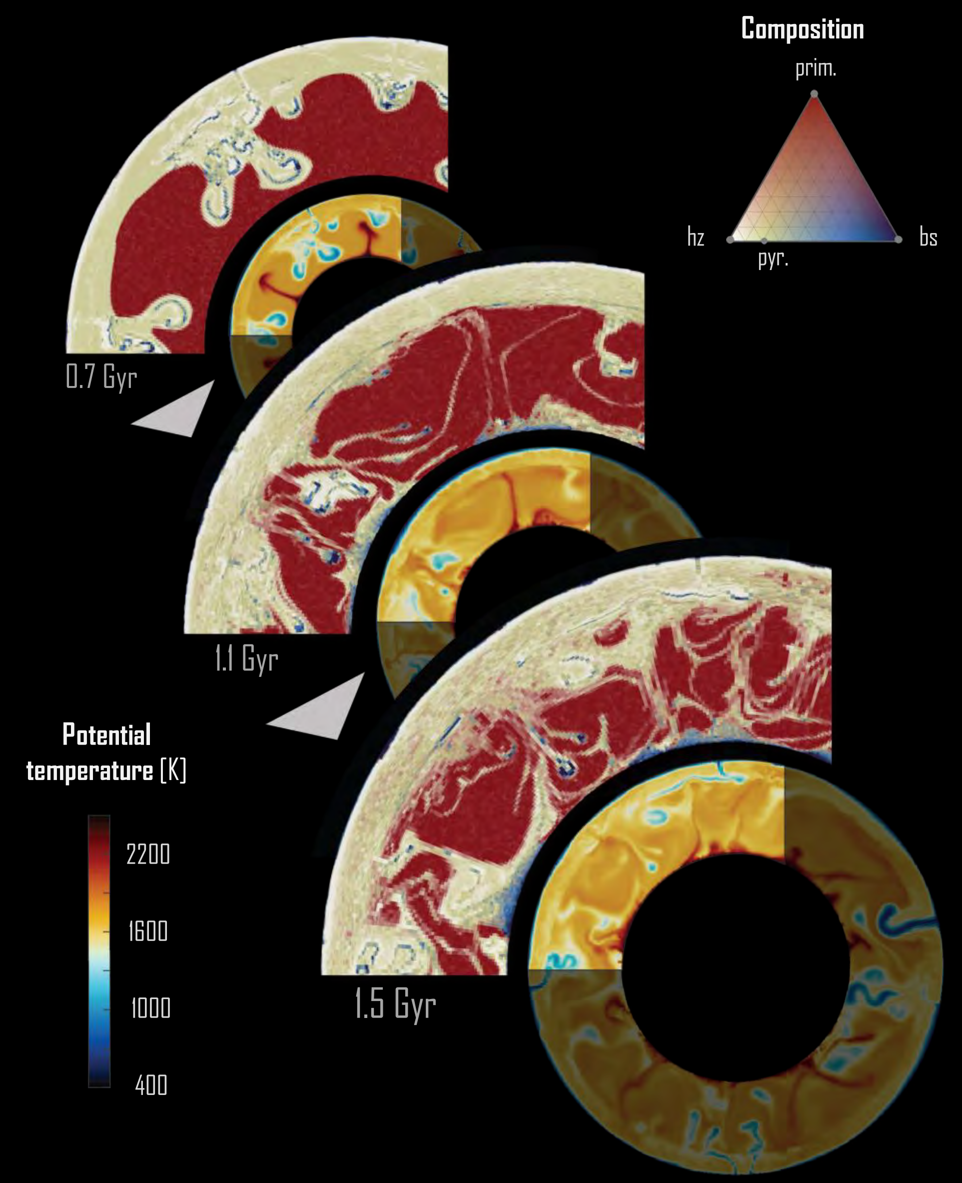
Breakdown of primordial layering

All the models in this study involve a
compositional overturn,
i.e., the breakdown of the initially layered mantle

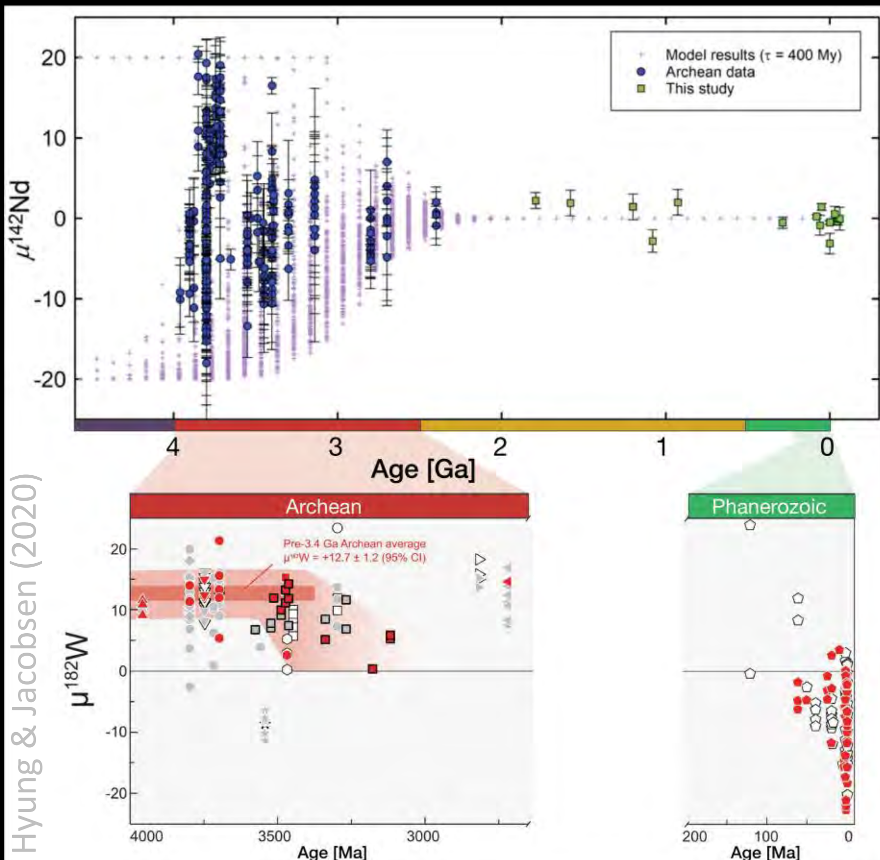
This overturn occurs after 0.5-1.2 Gyr
(dependent on model parameters)

During this overturn, major geodynamic changes occur.
This short period is associated with:

- A burst of melting activity and ROC recycling
- **The onset of ...**
  - ... **whole-mantle convection**
  - ... **deep plume sampling**
  - ... **material mixing**
  - ... **plate-tectonic behavior**

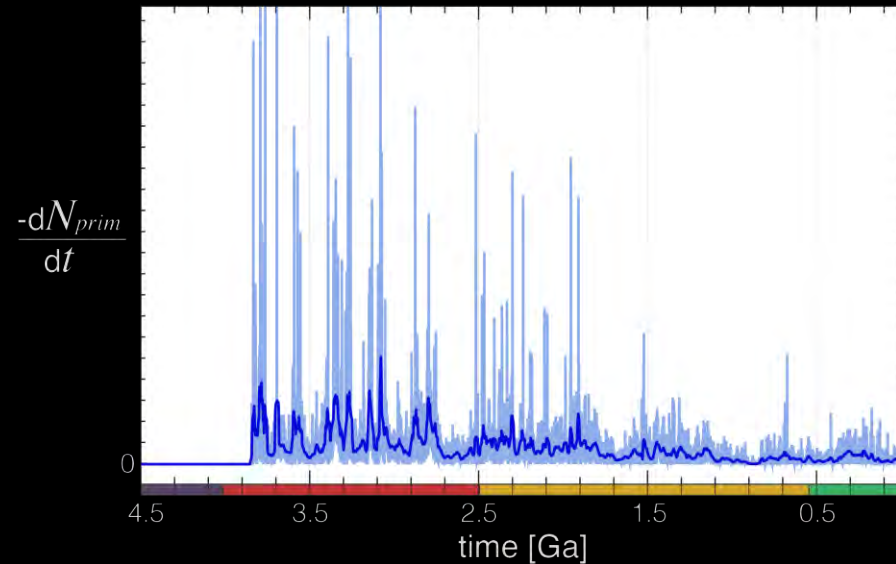


Breakdown: comparison with geochemistry



Many geochemical studies show evidence for a rapid change in isotopic signatures (i.e., $^{142}Nd/^{144}Nd$ and $^{182}W/^{184}W$) in basalts in the Archean Earth.

Processing rate of primordial material

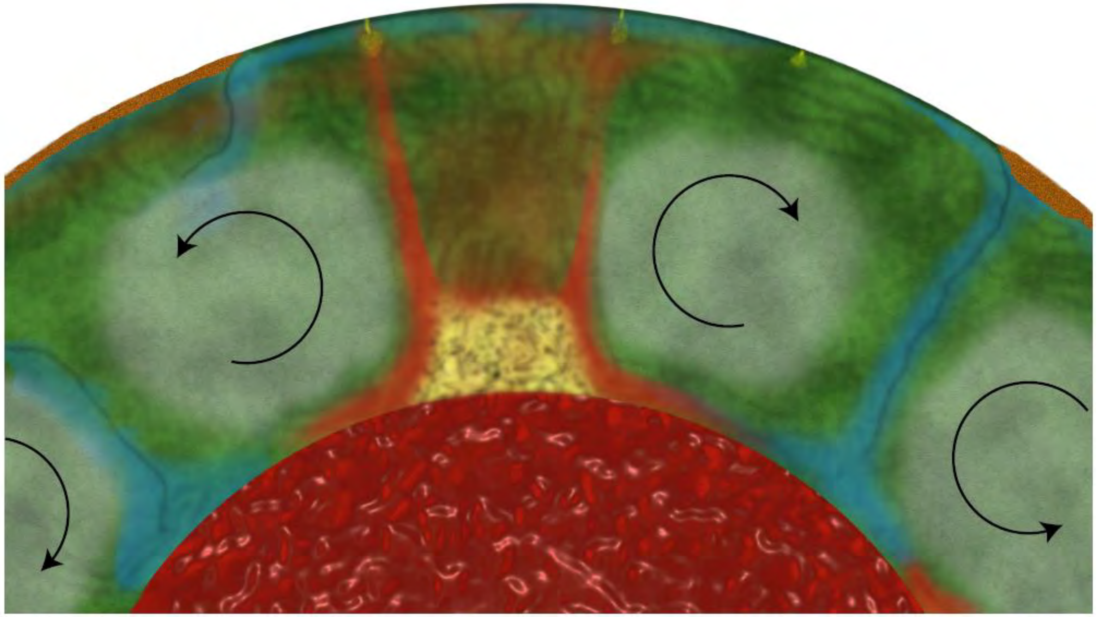


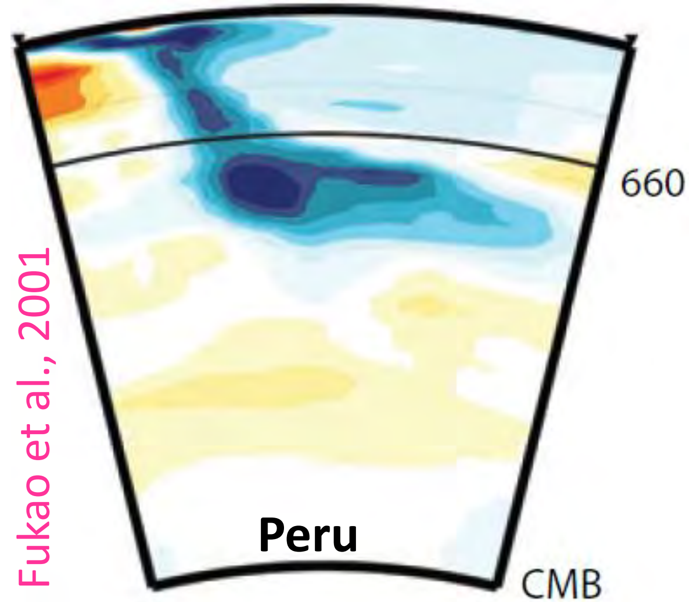
In our numerical models, primordial material is mostly processed (~**melting**) shortly after the compositional overturn.

The processing rate of primordial material (~melting rate) **gradually decreases** over time

How to test these model predictions ?

compare predictions with observations

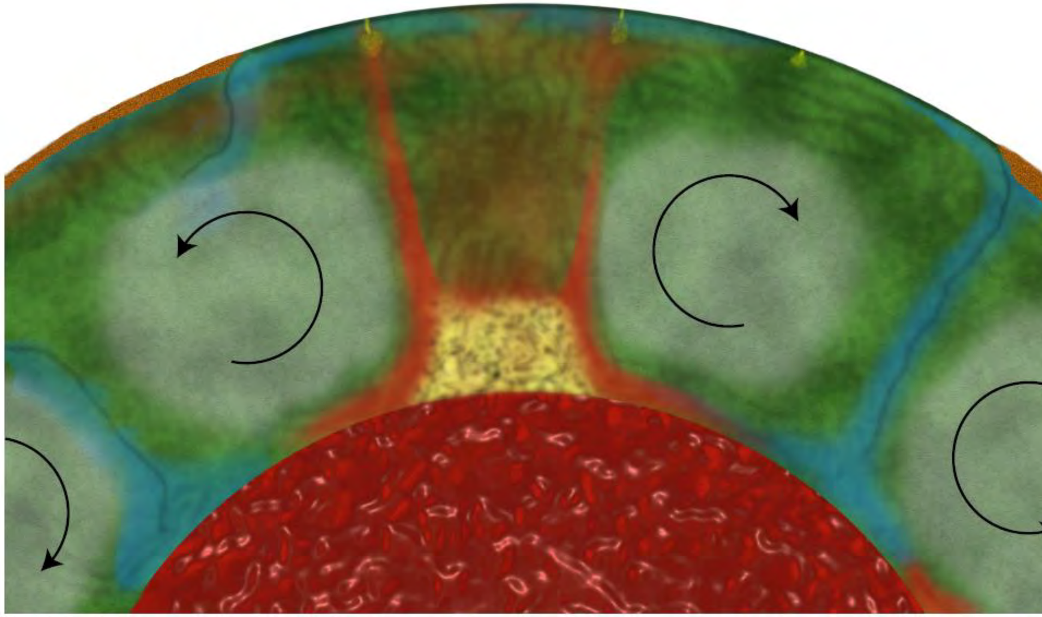


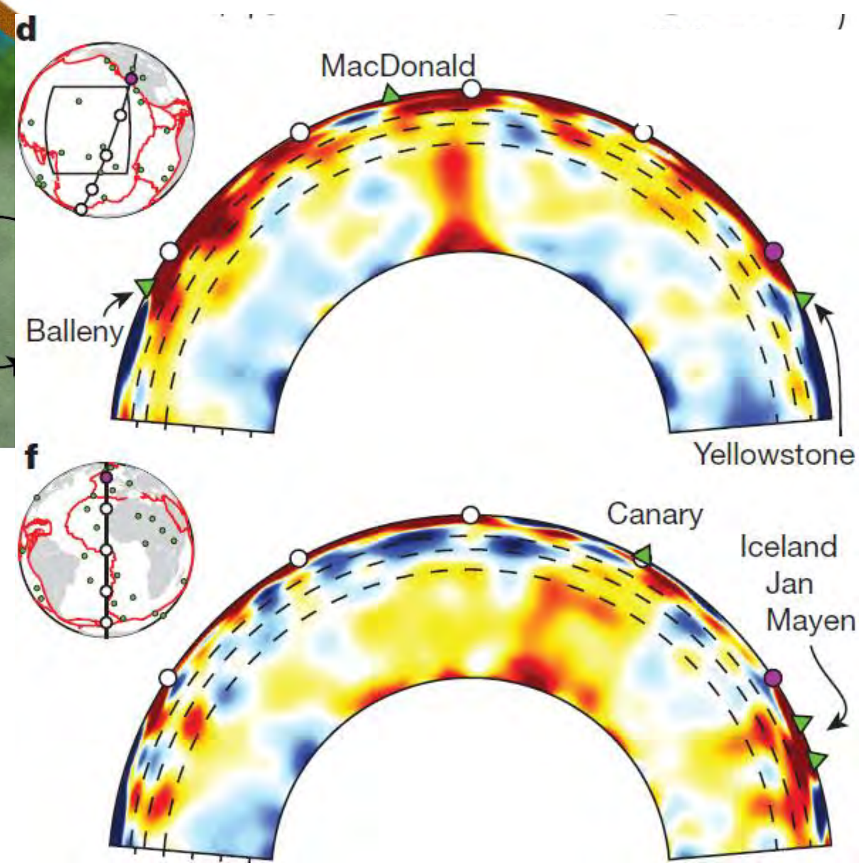


Fukao et al., 2001

- **Slab Stagnation**
- Plume Deflection
- Mid-mantle Reflectors
- Primordial Geochemical Reservoirs
- balance Si-budget

compare predictions with observations





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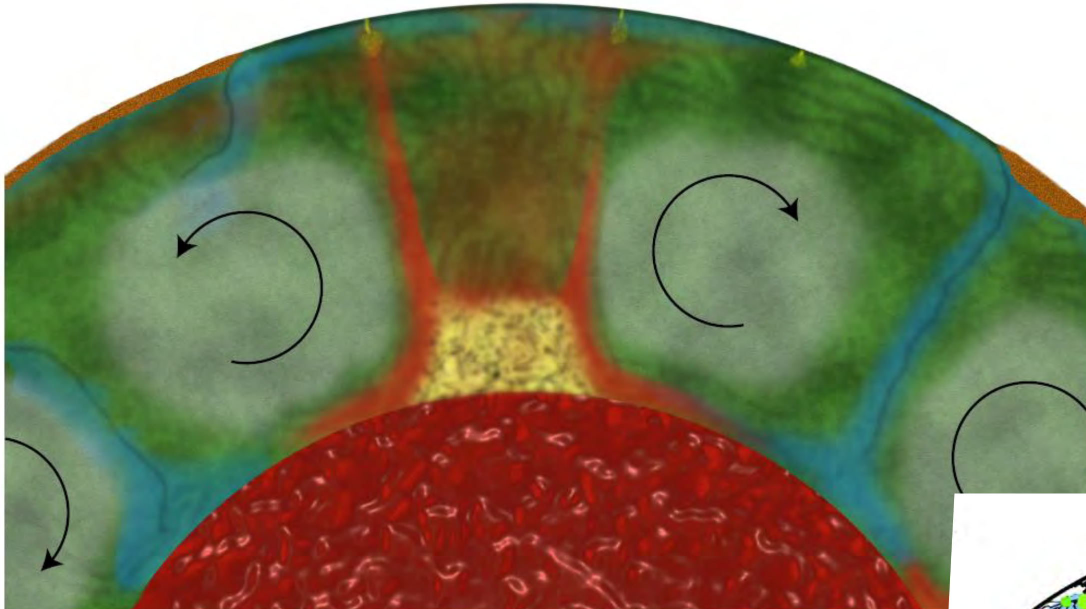
French & Romanowicz, 2015

compare predictions with observations



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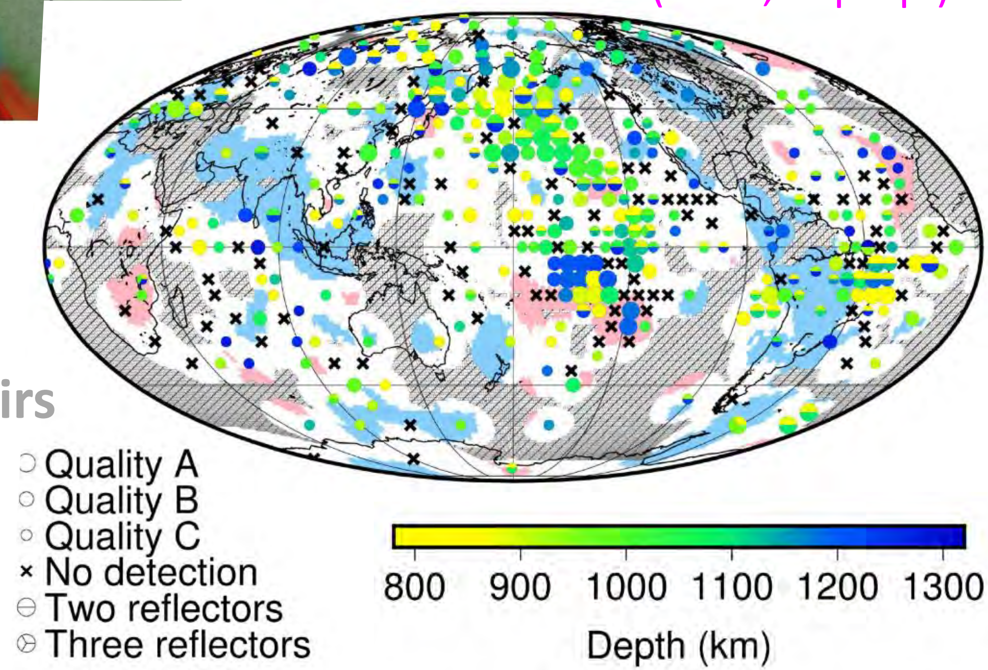
Waszek et al. (2018; in prep.)



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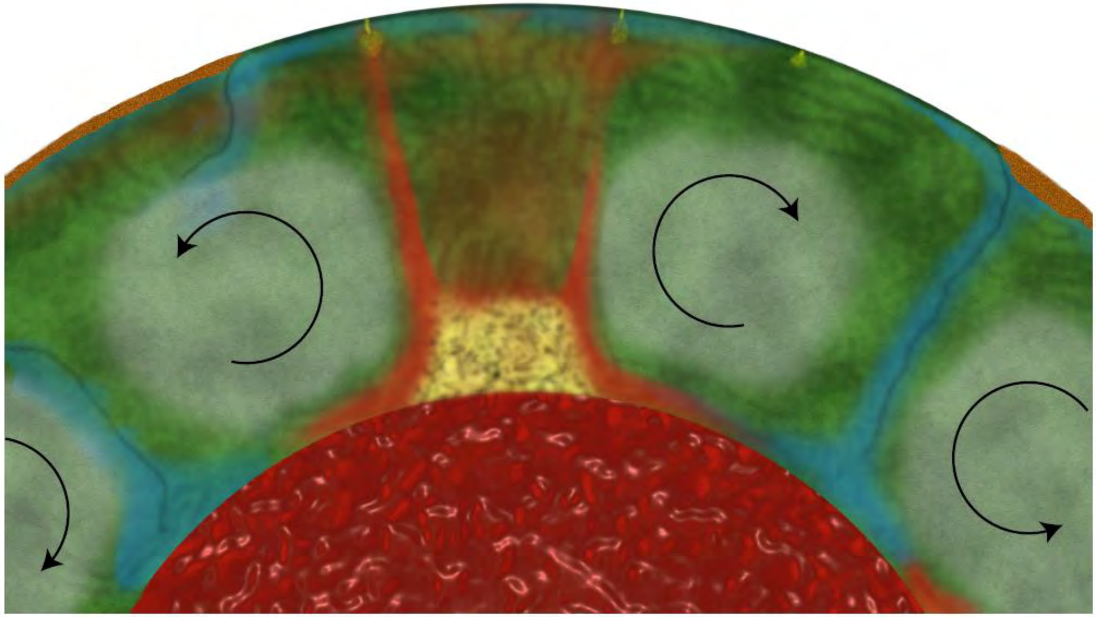

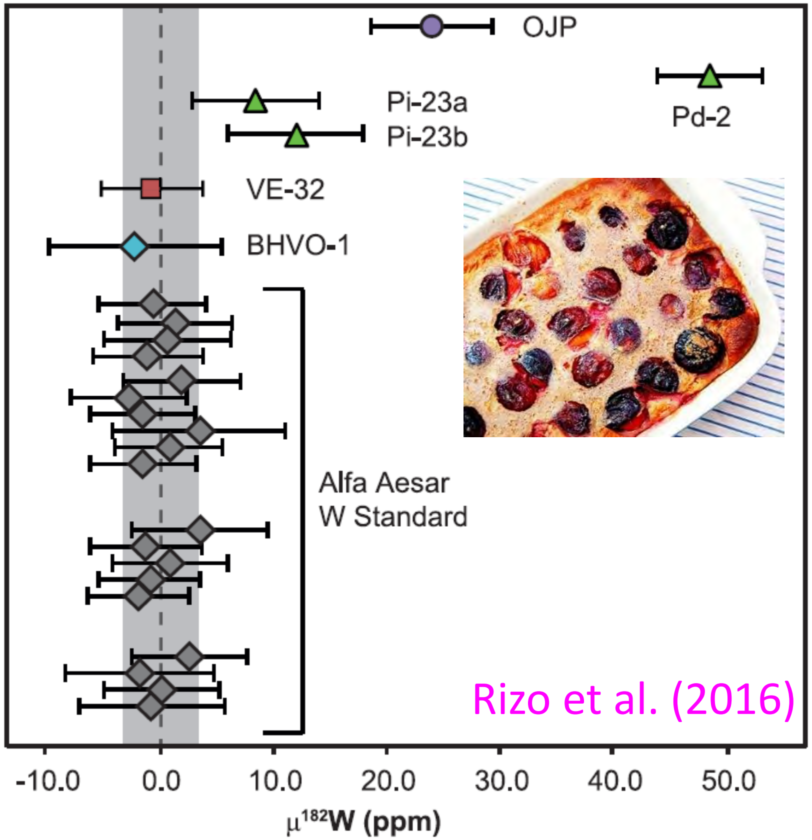

- **Slab Stagnation**
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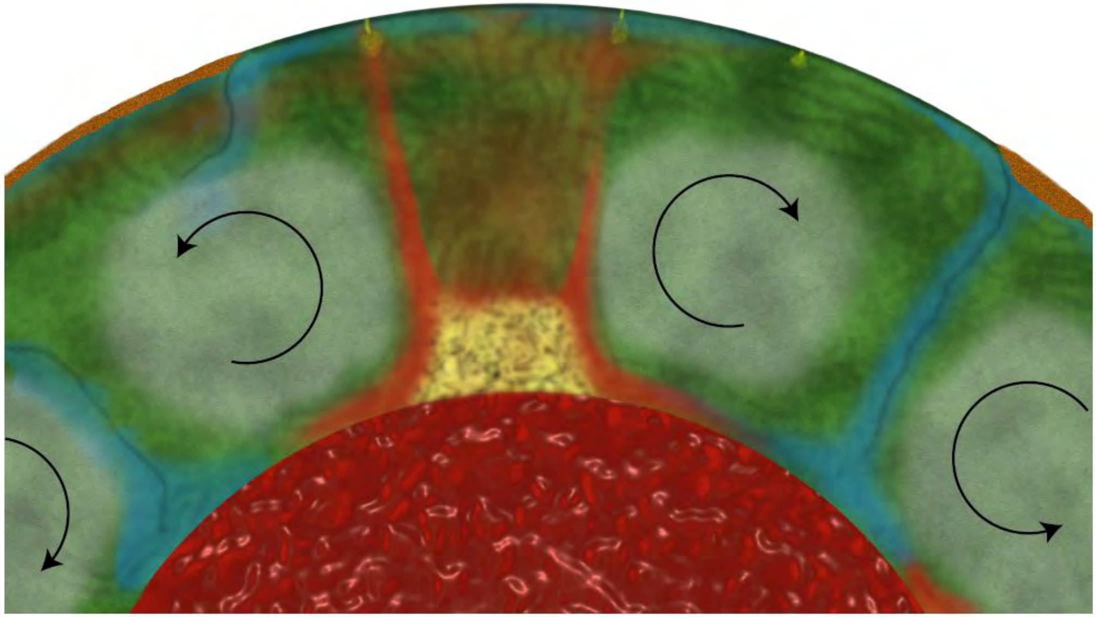
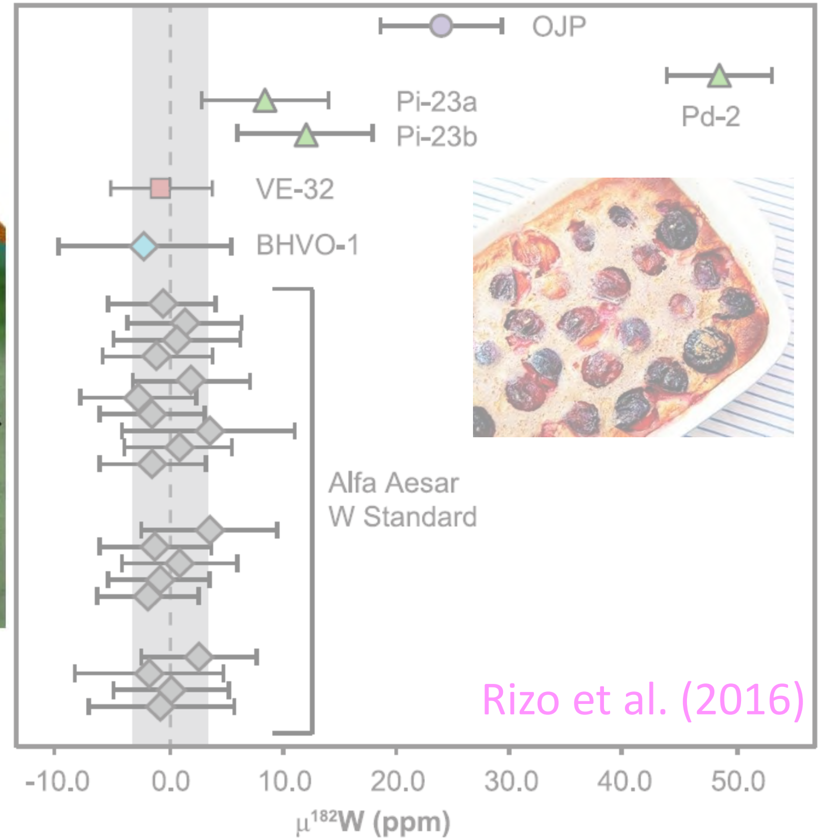




- **Slab Stagnation**
- **Plume Deflection**
- **Primordial Geochemical Reservoirs**
- **balance Si-budget**

Comparison with Seismic Tomography

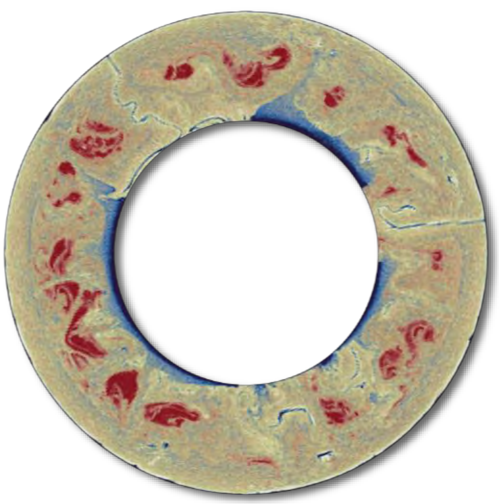
Primordial domains:

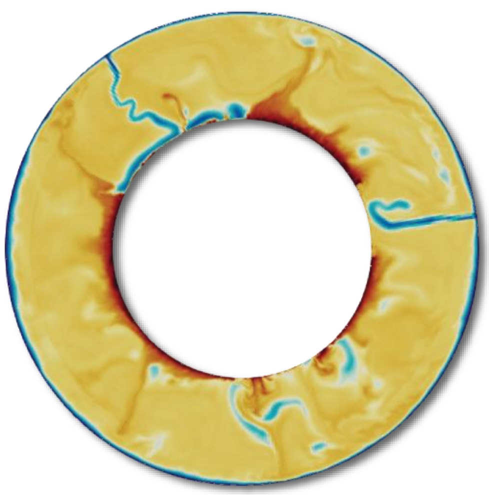
- **Thermal** effect (slightly warmer)
- **Compositional** effect ($MgSiO_3$-enriched)

-dVs

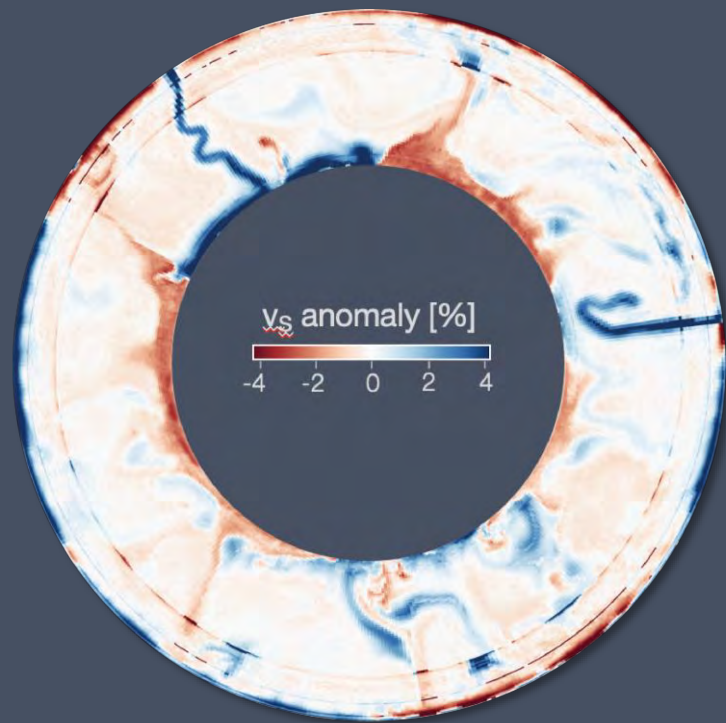
+dVs

→ Translate *c,T,P* into **seismic velocities** using *Perple_X*



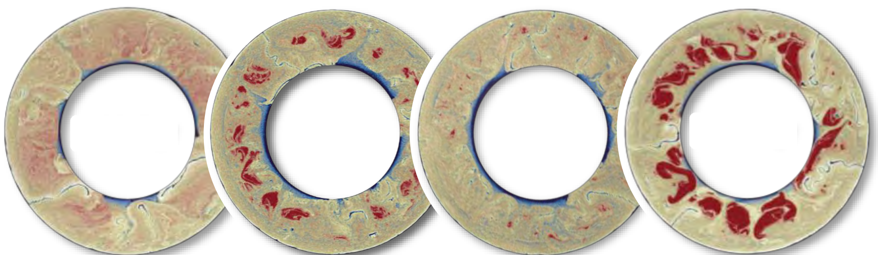


"**hidden**" from seismic tomography?



Seismic signatures

- Compare seismic signatures of **different** mantle **heterogeneity styles**



- Compare (quantitatively) with **seismic tomography** or other seismic observations

- Waveform modelling

- 3D models vs. 2D models

Preliminary results

PhD student
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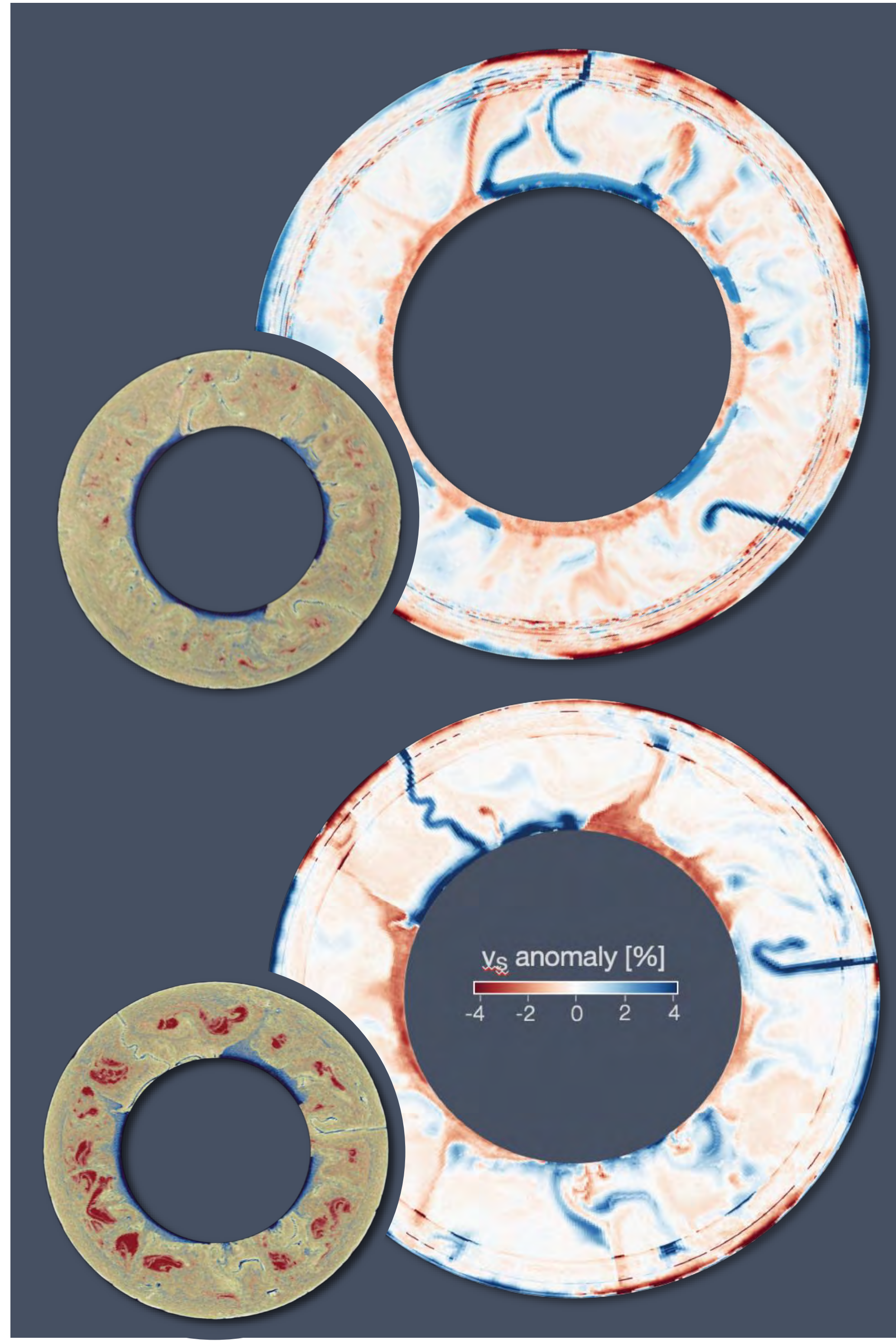

Conclusion / Highlights

A basalt/harzburgite enriched layer above/below the 660 can be maintainted in the mantle that covects as a whole due to gravitational “un”-mixing

Intrinsically-strong (bridgmanitic) heterogeneity can be preserved as mid-to-large sized blobs in the mid-mantle for a wide range of conditions (geodynamically viable), but their geophysical signatures need further testing