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The effects of rheological and tectonic parameters on the preservation of primordial reservoirs in Earth’s lower mantle: a numerical study

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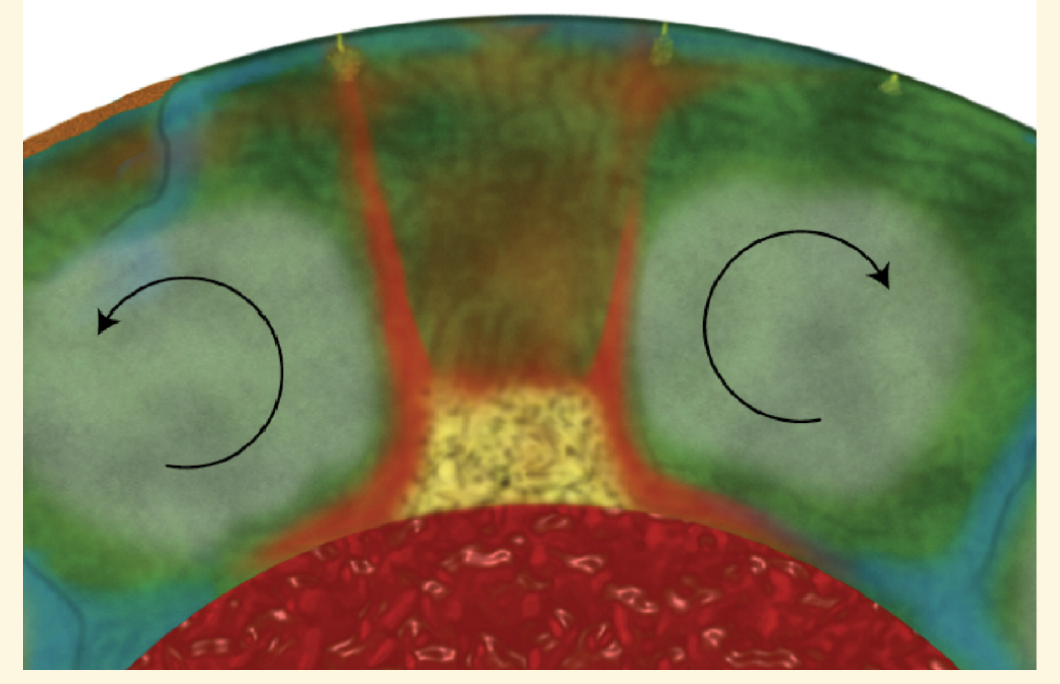
Motivation

Is the Earth’s lower mantle heterogeneous in composition?

Homogeneous, well-mixed mantle *vs.* **Mid-mantle chemical heterogeneities**

Homogeneous, well-mixed mantle		**Mid-mantle chemical heterogeneities**
Seismic imaging of subducted lithosphere[1] and deep-rooted plumes[2] that pervade the whole mantle	*vs.*	Stagnating slabs at ~1000 km depth[4]
Shallow plumes can spatially be related to LLSVP’s[3]		Sharp seismic impedance contrasts at a similar depth range[5,6]
		Primordial $^{182}W/^{184}W$[7,8] and $^{3}He/^{4}He$[9] signatures in basalts

These dicrepancies are incoorporated in a recently proposed convective regime[10]:



Cartoon of the BEAMS hypothesis[10]. The strong BEAMS are shown in light grey, harzburgite rocks in blue, basaltic rocks in dark green and an LLSVP is shown in yellow.

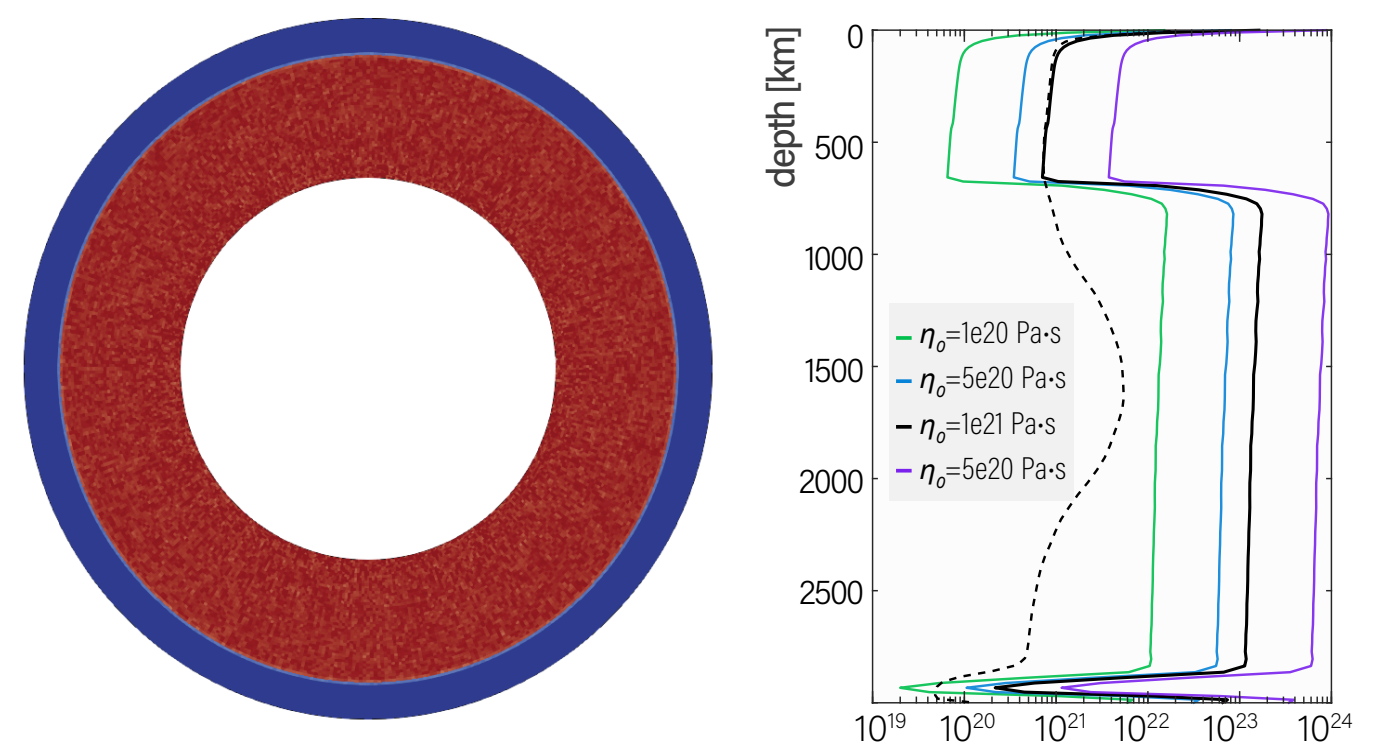
- Large, intrinsically **viscous domains** persist in the mid-mantle, with whole-mantle circulation being accommodated around them
- Domains believed to be enriched in the strong lower-mantle mineral **bridgmanite** $(Fe,Mg)SiO_3$, resulting from a fractional crystallizing magma ocean

This regime has succesfully been reproduced in 2D spherical annulus geometry models using composition-dependent rheology[11], but lacks a thorough assessment of tectonic/rheological parameters.

What are the effects of rheological and tectonic parameters on the style of mantle mixing and heterogeneity preservation?

Methods

- **Thermomechanical convection** with 2D spherical annulus geometry using **StagYY**[12]
- Initial two-layered set-up with **composition-dependent rheology**[11]: compared to ***pyrolite***, ***primordial material***
  - is more ***viscous*** in the lower mantle (SiO_2 enrichement)
  - is slightly more ***dense*** (FeO enrichement)
  - has a higher ***bulk modulus*** in the lower mantle[13]



(Top left) Initial model set-up: 2230 km-thick primordial layer in the lower mantle and pyrolitic material in the upper mantle, resolved by a grid of 512x96 cells. *(Top right)* Initial viscosity profiles of models with different reference viscosities, dotted profile is the reference model at 4.5 Gyr.

Symbol	*Definition*	*Value*
h	Mantle domain thickness	2980 km
g	Gravitational acceleration	9.81 ms^{-2}
T_S	Surface temperature	300 K
T_{CMB}	CMB temperature	4000 K
T_0	Reference temperature	1600 K
σ_{yield}	Yield stress	20e6 MPa*
σ'_{yield}	Yield stress depth derivative	0.01
η_0	Reference viscosity	1e21 Pa·s*
E	Activation energy	35 KJ/mol
λ_{prim}	Lower mantle viscosity contrast	300
$\Delta\rho_{prim}$	Surface density contrast	0.4%
$K_{0,prim}$	Lower mantle bulk modulus (primordial)	230 GPa
K_0	Lower mantle bulk modulus (pyrolite)	210 GPa

- **Visco-plastic rheology** in which viscosity is T-dependent following the **Arrhenius law**:

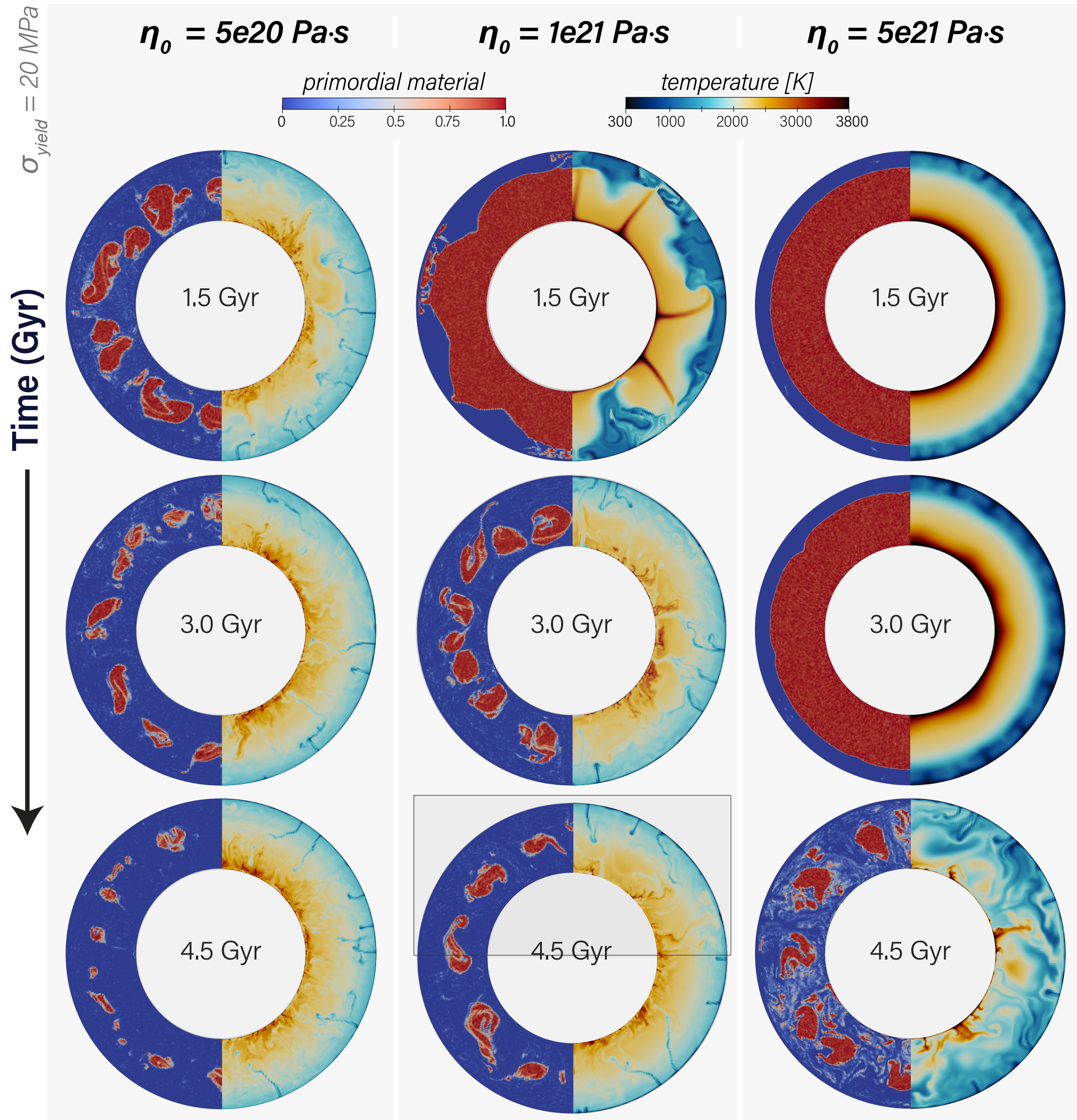
$$\eta(T,p) = \eta_0 \exp\left(\frac{E}{RT} - \frac{E}{RT_0}\right)$$

- **“Plastic yielding”** breaks stagnant-lid to give plate-like behavior:

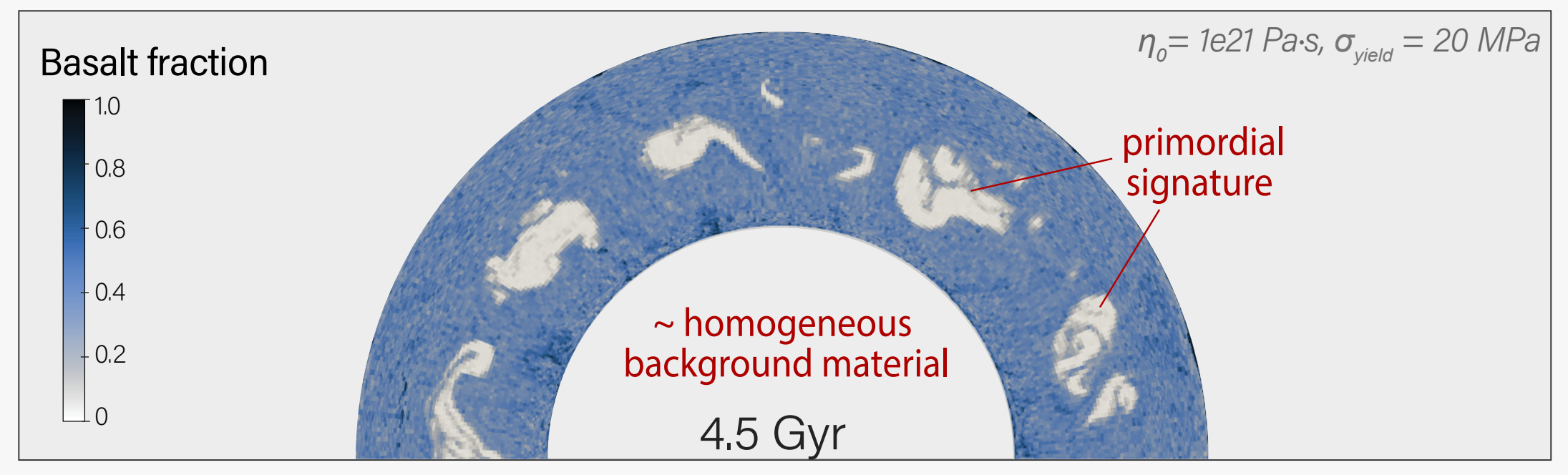
$$\sigma^{eff}_{yield} = \sigma_{yield} + \sigma'_{yield} \cdot p$$

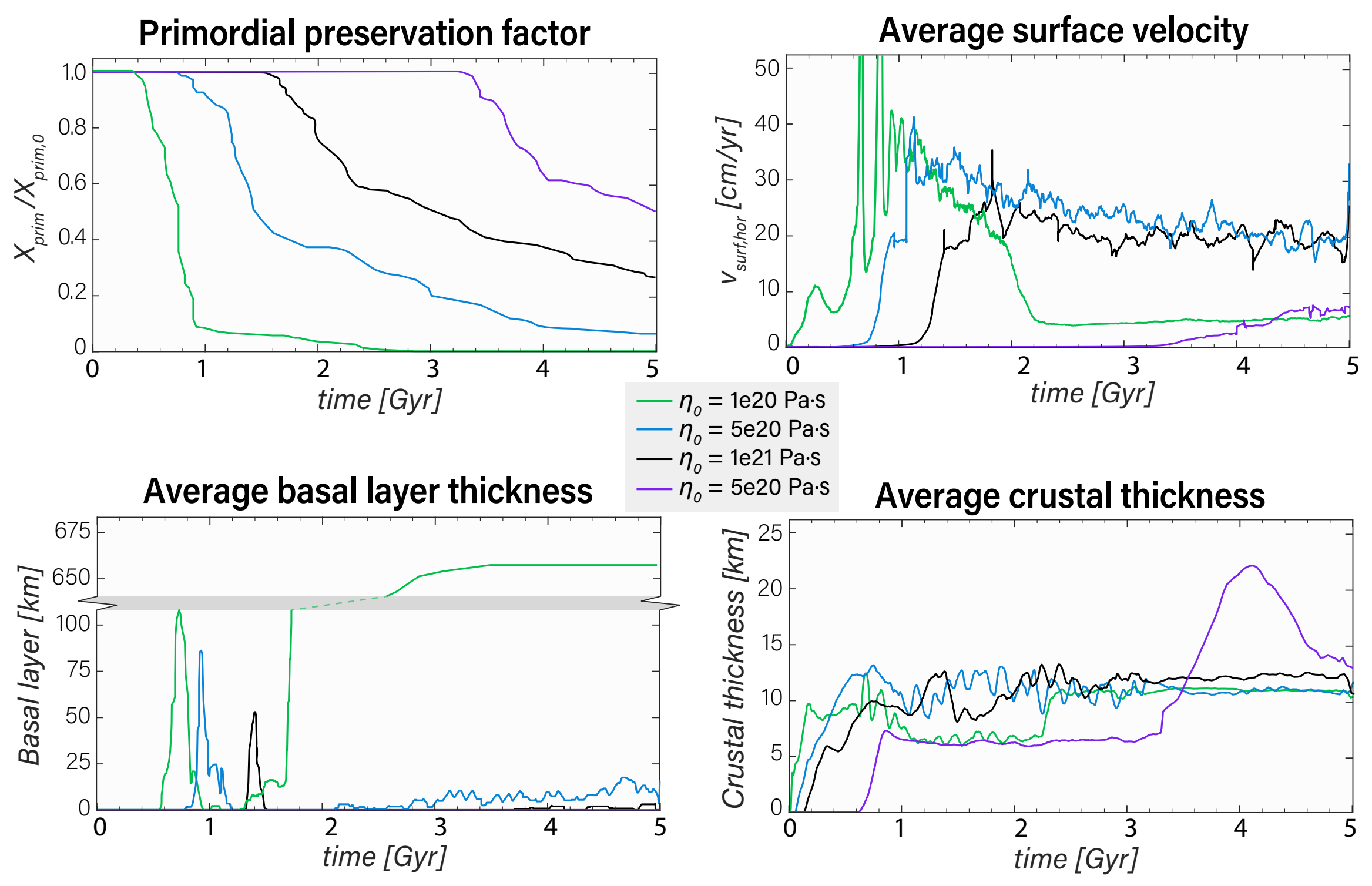
- **Phase changes** at 410, 660 and pPv boundaries
- Primordial-to-basalt/harzburgite tracer conversion at 125 km depth (depth of pyroxenite melting[14]). A **melting law** produces basalt and residue harzburgite from mantle material.

Results: reference viscosity

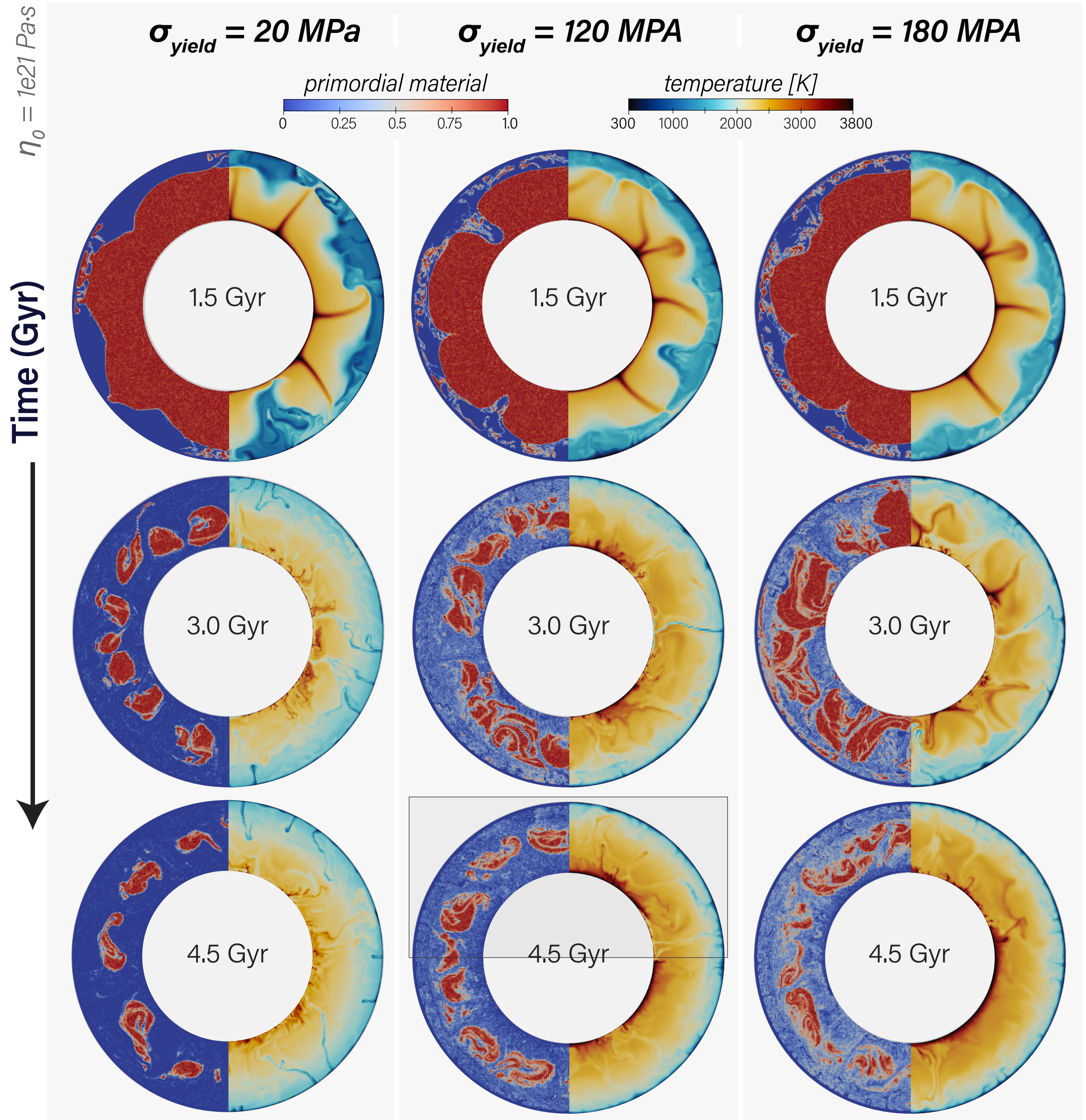


η_0 = 5e20 Pa·s	η_0 = 1e21 Pa·s	η_0 = 5e21 Pa·s
Early overturn Higher efficiency of mantle mixing	Moderate heterogeneity preservation as primordial blobs in the mid-mantle *(reference model)*	Very late overturn Inefficient mixing of mantle material

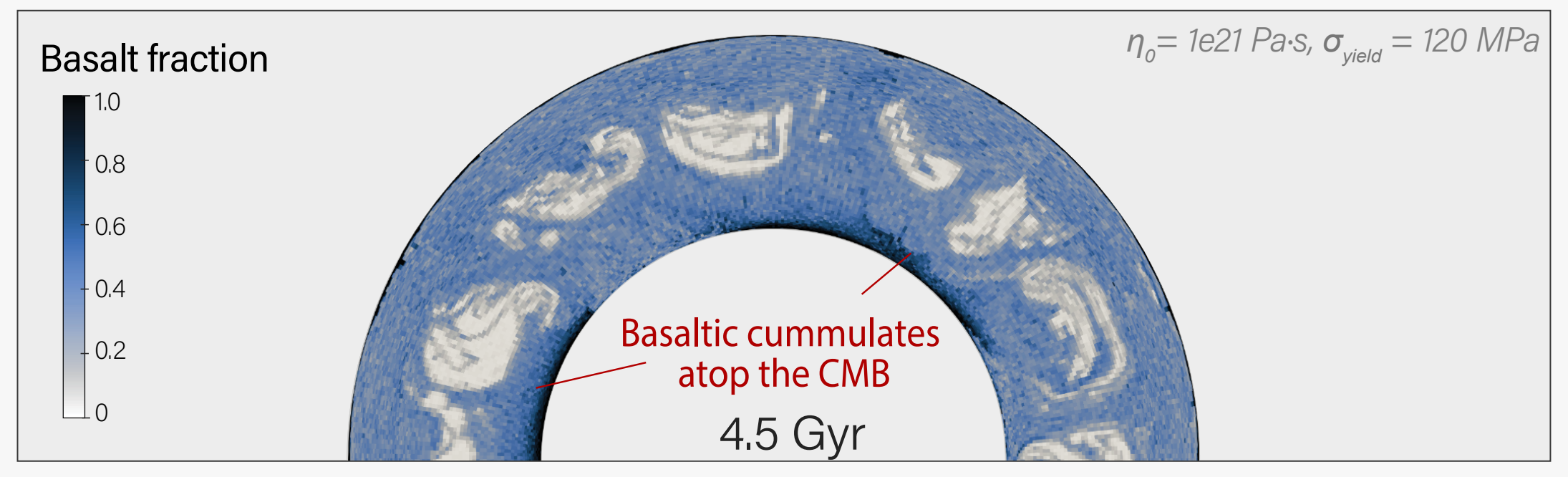


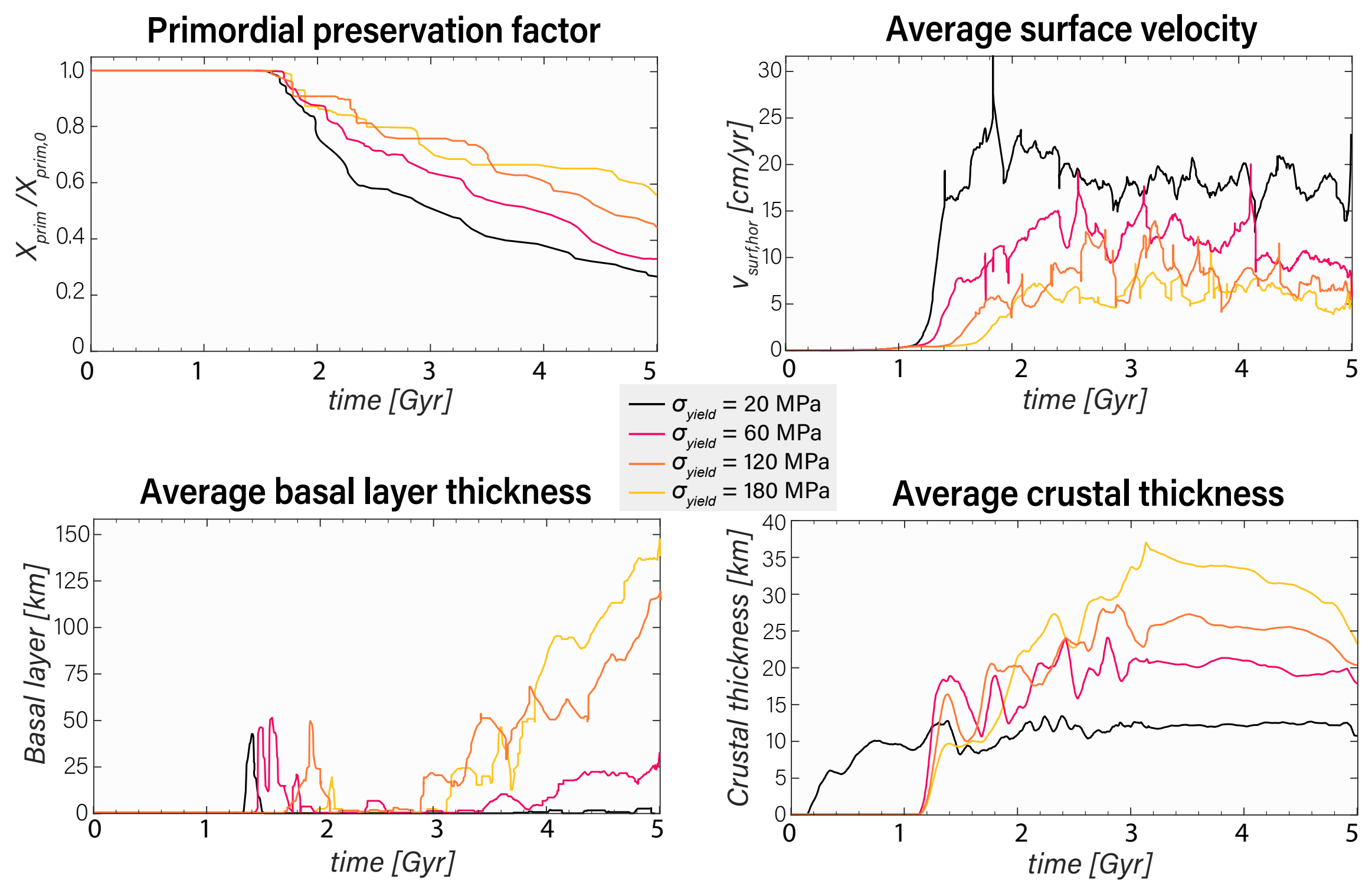


Results: yield strength



σ_{yield} = 20 MPa	σ_{yield} = 120 MPA	σ_{yield} = 180 MPA
Frequent lithospheric drips into lower mantle Efficient mixing of mantle material in background flow *(reference model)*	Fewer downwellings and a warmer lower mantle Primordial material entrained in background flow	Hot lower mantle Fragmented primordial domains in the mid-mantle Inefficient mixing of mantle material in background flow





Conclusions

The style of mantle mixing and heterogeneity preservation is greatly influenced by the tectonic style and mantle rheology:

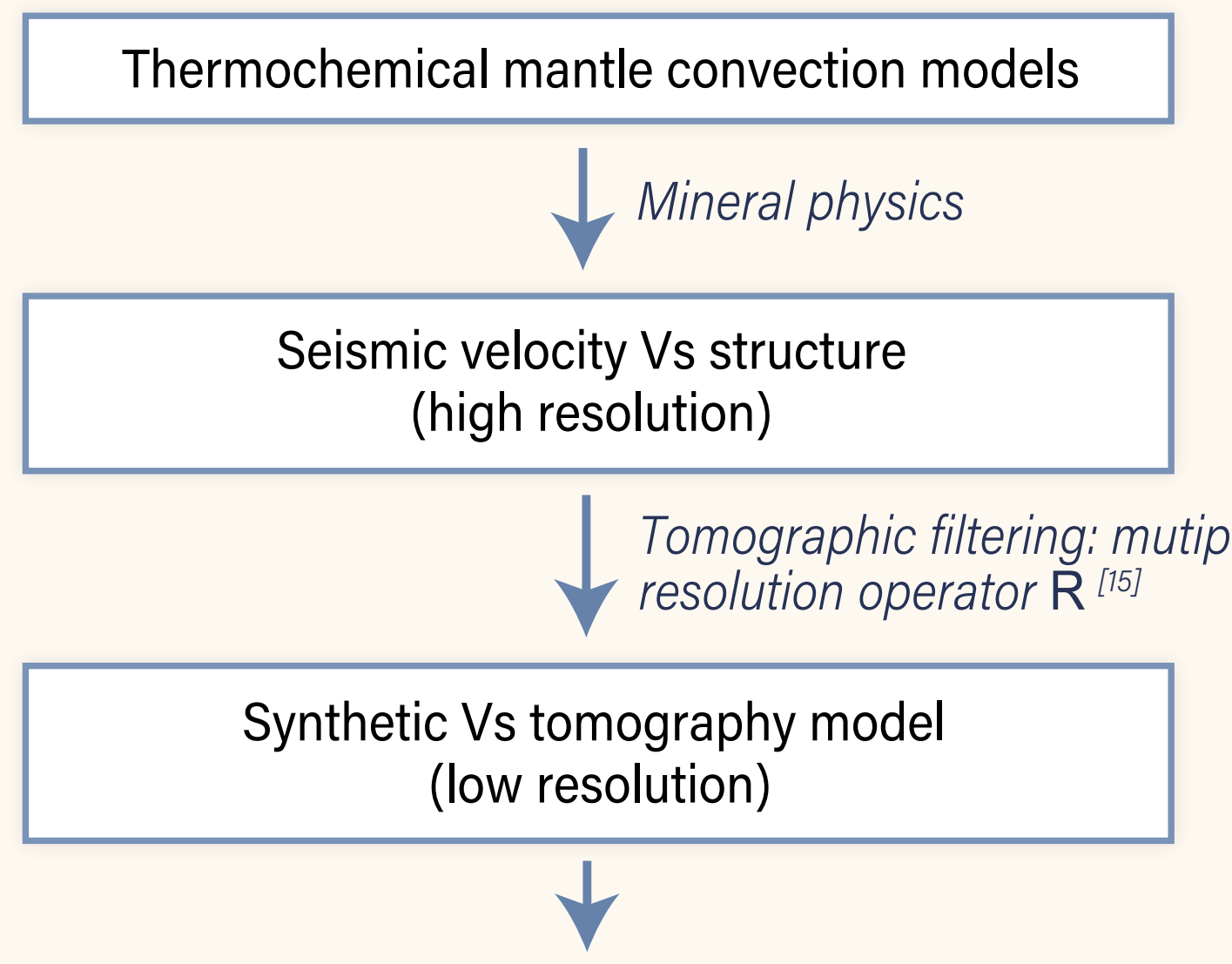
- The reference viscosity affects the **convective vigor** and thereby the **timescale** of model evolution; lower values promote efficient mixing of primordial material into the ambient mantle.
- The plate yielding strength controls the **abundance** and **stiffness** of subducting slabs that in turn interact with the primordial domains.
- Stronger slabs enhance primordial **fragmentation** but **reduce mixing effiency** of primordial with pyrolitic material.
- In addition, greater yield strengths promote a **thicker basaltic crust** at the surface and **accumulation of basaltic material** atop the **CMB**, underlying the neutrally buoyant bridgemanitic-enriched domains in the mid-mantle.

Outlook

Future work will involve:

- Expanding the rheological parameter space by including the effect of T- and P-dependence of viscosity (via the Arrhenius law), and assessing which models are most Earth-like
- Integrating our numerical results with geophysical observations: *(suggestions welcome)*

How would our geodynamic models translate to seismic tomography?



Thermochemical mantle convection models

Mineral physics

Seismic velocity Vs structure
(high resolution)

Tomographic filtering: mutiply with resolution operator R [15]

Synthetic Vs tomography model
(low resolution)

Investigate the correlation between our chemical heterogeneities and Vs heterogeneities in the tomographic model

- Exploring heterogeneity preservation in **3D** numerical models
- Incoorporating strain-dependent rheology as a means to focus deformation in the weaker, relatively bridgmanite-depleted mantle pyrolite[16]

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