REVIEWER #2

In this article, the authors investigate the influence of recycled oceanic crust properties (density excess and viscosity) on the preservation of lower Earth mantle primordial heterogeneities, consisting of bridgmanite material resulting from the crystallization of the Earth early magma ocean, and which are referred to as BEAMS. For this, they perform more than 20 simulations of thermo-chemical convection with three sorts of material, including basalts, harzburgite and primordial material (BEAMS), and varying both the viscosity and the density of basalts. After 4.5 Gyr, simulations may be sorted out in 4 regimes or sub-regimes depending on the evolution of the BEAMS and recycled basalts. These include full mixing of both basalts and BEAMS with harzburgite, mixing of BEAMS with the formations of basal piles of basalts, and preservation of BEAMS either with the formation of piles of basalts or with basaltic layering above the CMB. The authors note that the occurrence of each regime is controlled by the excess density of basalts and, to a lesser extent, by their viscosity. They conclude that dense recycled basalts is needed to preserve BEAMS over periods of time comparable to the age of the Earth, and that higher viscosity further helps this preservation. This article is well written, and the research it present fits well the scope of Solid Earth. The simulations of convection are clearly described and are carefully performed with a state-of-the code. Results and interpretation are also clearly discussed and are supported by the authors simulations. I have only minor comments, mainly points of discussion on BEAMS, and I recommend this article for a publication in Solid Earth after some minor to moderate revisions. Below are some comments and suggestions that the authors may include in the revised version of their paper.

We thank the reviewer for their work and for their valuable comments, that we address below.

1. The authors neglect internal heating. This is fine, except that they probably underestimate the potential effect of internal heating, and that this aspect should deserve more discussion. Adding internal heating is likely to affect the balance between plumes rising from the CMB and descending slabs in the favor of the later. I guess that more vigorous slabs may have some impact on the preservation of BEAMS. Second, it is (as the authors pointed out) likely that heat producing elements will concentrate in basalts. This may in turn affect the evolution of basaltic piles or layering in a way similar to the impact of excess heating in primordial material (as recently investigated by Guerrero et al., 2024). Finally, adding internal heating is important for the mantle heat budget and in particular to

get CMB heat flux within the expected range of values. Again, no additional simulation is needed here, but an extended discussion on that topic would be welcome.

To address these points, we ran 4 additional cases with internal heating and with HPE partitioning as suggested, now described at the end of the Results section (lines 332-335) and in detail in Appendix C, starting at line 620 (accompanied by an updated video supplement). We also expanded the Discussion accordingly (lines 516-531).

2. To separate the different regimes, the authors use threshold values of the local fractions in primordial material and basalts, and in the fraction of CMB area covered by basalts. Are they any specific reasons for fixing these parameters to the values chosen by the authors (if yes, explain), or are these values mostly arbitrary?

We selected those values as follows: first, we inspected the models visually to draw out boundaries between regimes, then we checked if these corresponded to reasonable numerical thresholds: we chose these values as boundaries between regimes to obtain a quantitative measure. These thresholds could be slightly varied within reasonable ranges without changing the regime boundaries.

3. I find the discussion on the characteristic viscosity for each regime (page 10) and the corresponding figure 4 not very convincing. More precisely, when accounting for the variability of viscosity within each regime, the difference between two different regimes sounds less significant. I agree that there is a general trend (models that preserve BEAMS have on average higher viscosity), but the most viscous model in MP have nearly the same viscosity than the less viscous model in BL, so I'm not sure that these profiles are a key aspect of the authors results. Also, MP and MO regimes have less simulations than BL, and I guess than running more models would enlarge the range of viscosity. Finally, it would be interesting to show (or say) which model correspond to the upper and lower bounds of each radial viscosity profiles in figure 4.

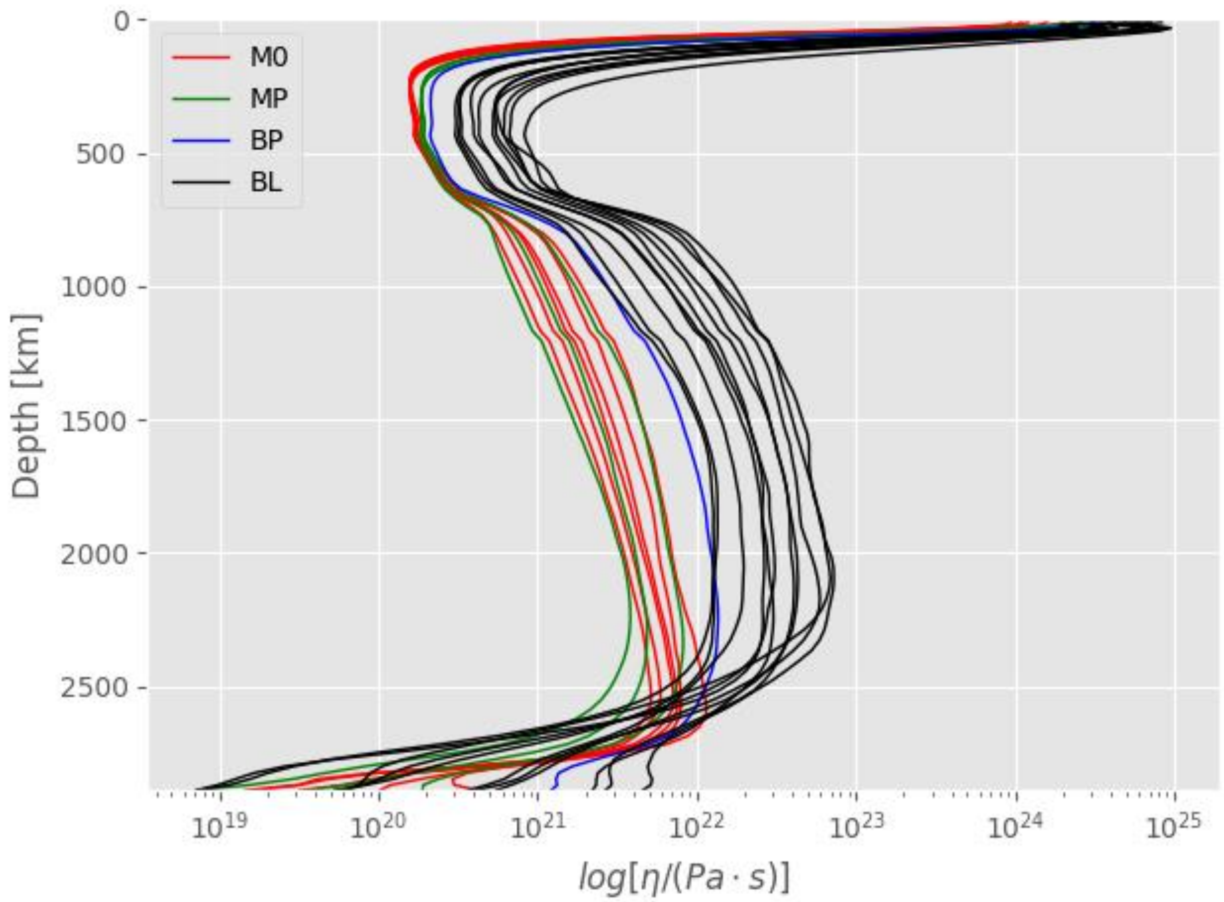
The viscosity profiles in figure 4 are reported for the sake of completeness and, indeed, are not used to support our discussion or drive any particular point about trends. Incidentally, we note that "**the most viscous model in MP"** and **"the less viscous model in BL**" are separated by at least a factor 2 (e.g. at 1500 km depth). The figure attached in this response also shows that the viscosities of M0 are similar to those of MP; the viscosity for BP is comparable to the lower end of the range shown for BL viscosities (the text has been updated to highlight this: see lines 292-294). We also update the caption of figure 4 with information about the upper and lower bounds of each visc. profile. The minimum and maximum boundary of the viscosity ranges in the figure correspond to models with:

dRho = 1%, ζ = 1.0, and dRho = 1%, ζ = 100.0;

dRho = 2%, ζ = 0.1, and dRho = 2%, ζ = 10.0;

dRho = 3%, ζ = 0.1, and dRho = 5%, ζ = 1.0;

for regimes M0, MP and BL, respectively. Overall, this supports our point that ROC density and viscosity both enhance primordial preservation by reducing convective vigor.



4. Line 286. qbot (bottom heat flux, I guess), has not yet been defined in the paper. It might also be interesting to plot the evolution of qbot and q top with time.

We corrected this, see lines 288 and 289. We added this plot in appendix C (Fig C6).

5. The authors point out that the basal basaltic layer is animated by convection. I'm not sure this is the case. The fact that the radial velocity is not zero and vary laterally within these structures does not guarantee that convection operates in them. First the authors should compare these velocities with those in the mantle. Second, and more importantly, if the basal layer is animated by convection, the temperature profile within this layer should consist of a thermal boundary layer at both the top and the bottom and an adiabatic region in between. If the temperature profile is linear, then the layer is not animated by convection, and heat is transported by conduction. Same thing for the piles of basalts. For similar reasons,

on line 345, I would change 'reduces convective vigor within the piles' to 'reduces heat transfer within the piles'.

To check for convection, we visually inspected the movies (which are accessible via link in the video supplement), where convection in the Bs-enriched regions is apparent in the velocity field: in particular, convection cells in Bs-rich regions are visible in some models while absent in others (with our choice of colorscale), depending on viscosity (as described in the manuscript): see the vigorous vertical positive/negative velocities in the movies close to the CMB, inside the contours for composition. We note that the temperature profiles shown in the paper would not be suitable to observe the gradients described by the reviewer, given they are both spatial and temporal averages. To address the point brought up by the reviewer, we add Figs. B3 and B4 to appendix B (see lines 316-320, 611-618). The figures show the gradients described by the reviewer, supporting our conclusions in terms of convection in the piles/layers.

6. I'm less optimistic than the authors regarding the seismic signatures of BEAMS. First, BEAMS are large structures, so I guess they would be resolved by the most recent tomographic maps, especially those based on waveform inversion. Second, while excess bridgmanite have no or very slight effect on shear-velocity, the BEAMS enrichment in iron (~ 2-3%) should produce a relatively strong signature (namely, a substantially reduced shear-wave velocity), enhanced by the fact that BEAMS are slightly hotter than average mantle. Overall, I do not see any reasons why BEAMS shouldn't be detected by available tomographic models.

Our primordial material density profile is consistent with (Mg,Fe)SiO_3 perovskite with a Fe# 0.12, equivalent to 6% FeO of molar fraction in Bridgmanite, similar to the molar fraction of FeO in pyrolite (see e.g. Table 1 from Xu et al. 2008): thus, BEAMS are not enriched in iron. Indeed, MgSiO3 perovskite is expected to be seismically 'faster' than the ambient mantle, at the same temperature (Wentzcovitch et al., 2004): this compositional effect on velocity may be compensated by the relatively warm temperature of the BEAMS (Gülcher et al. 2021).

More importantly, it tends to be difficult for tomography to resolve structures in the mid-mantle. We here attach some additional seismic-modelling results (in prep. for future publication) based on the predictions of our geodynamic models from this study. The attached snapshots represent seismic velocity anomalies associated to the pressure-temperature-compositional fields predicted by our numerical models, using the thermodynamic database by Stixrude & Lithgow Bertelloni, 2011 (via Gibbs energy minimization, Connolly 2008). The compositions for Hz & Bs are taken from Xu et al., 2008. These results show that a negative velocity anomaly is associated to BEAMS, but has a very low amplitude (~-1.5% at most). We assess whether these anomalies could be discriminated via mantle tomography by processing the models using 'filtering' operators (e.g. Ritsema et al., 2007) based on the SGLOBE-rani tomographic model

(Chang et al., 2015). Arrows indicate BEAMS. Case B, C correspond to model with visc ratio=10/dens.contr.=2% and visc ratio=1/dens.contr.=3%. Case A is a model from Desiderio and Ballmer, 2024 - with no prim. Odd/even rows depict the unfiltered/filtered snapshots. The first 2 rows test the effect of filtering in an optimal scenario where BEAMS occur in areas beneath dense seismic-station coverage (USA), as opposed to a low-coverage scenario (bottom 2 rows, Africa). As expected, anomalies are dampened and smeared (<1% negative anomaly amplitude), suggesting that identification of BEAMS-like anomalies in the mantle may remain challenging. These results have been presented previously (Desiderio et al. - AGU Fall Meeting Abstracts, 2023; Desiderio et al. - Ada Lovelace Workshop on Modelling Mantle and Lithosphere Dynamics, 2024), and included in the PhD thesis of one of the authors (Desiderio, 2024), incidentally with the editor involved as an external examiner.