The evolution and distribution of recycled oceanic crust in the Earth's mantle: geodynamic models

Jun Yan, Maxim Ballmer and Paul Tackley
Institute of Geophysics, ETH Zurich

1. Introduction

A better understanding of the compositional structure of the Earth's mantle is needed to place the geochemical record of surface rocks into the context of Earth accretion and evolution. Cosmo-chemical constraints imply that lower-mantle rocks may be enriched in silicon relative to upper-mantle pyrolite, whereas geophysical observa-tions tend to support whole-mantle convection and mixing. To resolve this discrepancy, it has been suggested that mid-ocean ridge basalt (MORB) segregates from harzburgite to be accu-mulated in the mantle transition zone (MTZ) and/or the lower mantle (See Fig. 1). However, the key parameters that control MORB segregation and accumulation remain poorly constrained.

we use global-scale 2D thermochemical convec-tion models to investigate the influence of mantle-viscosity profile, plate tectonics and bulk compo-sition on the evolution and distribution of chemi-cal heterogeneity. In particular, we focus on the accumulation of subducted MORB/harzburgite in/beneath the MTZ.

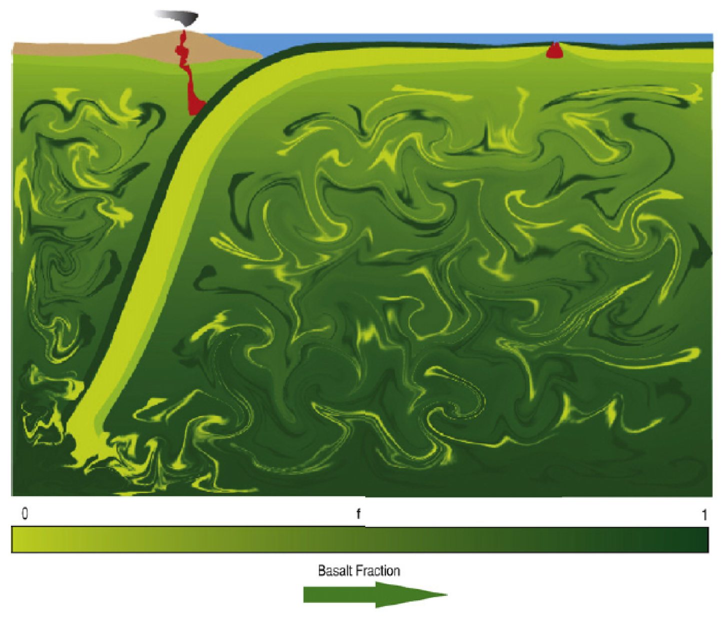

Fig. 1 Xu et al., 2008

2. Methods

(1) Equations

The global-scale thermochemical mantle-convec-tion models are performed by using StagYY (Tackley, 2008), which solves the conservation equations of mass, momentum, energy and bulk chemistry for an anelastic, compressible fluid with infinite Prandtl number.

(2) Rheology

A strongly temperature and pressure-dependent rheology given by the Arrhenius type formulation

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

In order to obtain plate-like behavior, plastic yielding is included using a Drucker-Prager yield criterion with the pressure-dependent yield stress σ:

$$\sigma = C + p\mu$$

where μ is friction coefficient and C is cohesion coefficient.

(3) Composition, phase changes, and melting

Minerals :
Olivine and Pyroxene–garnet , which undergo different solid–solid phase transitions.

Composition:
100% Pyrolite = 20% Basalt + 80%Harzburgite
Basalt = 100% Pyroxene–garnet
Harzburgite = 25% Pyroxene–garnet + 75% Olivine

(4) Partial melting:

It generates basaltic oceanic crust and a complementary depleted residue.

(5) Core cooling

The core cools as heat is extracted by the mantle according to a parameterized heat balance based on Buffett (2002).

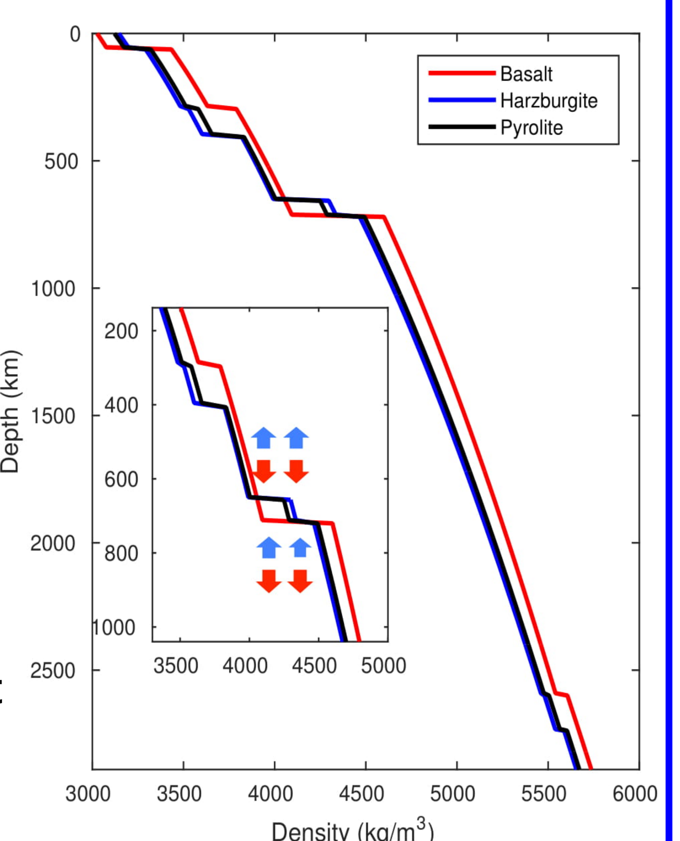

Fig. 2 Density profiles for MORB, harzburgite and pyrolite. Note the density crossover between 660 and 720 km. The red and blue arrows denote the negative and positive buoyancy of MORB and harzburgite away from this crossover region, respectively.

3. Reference model

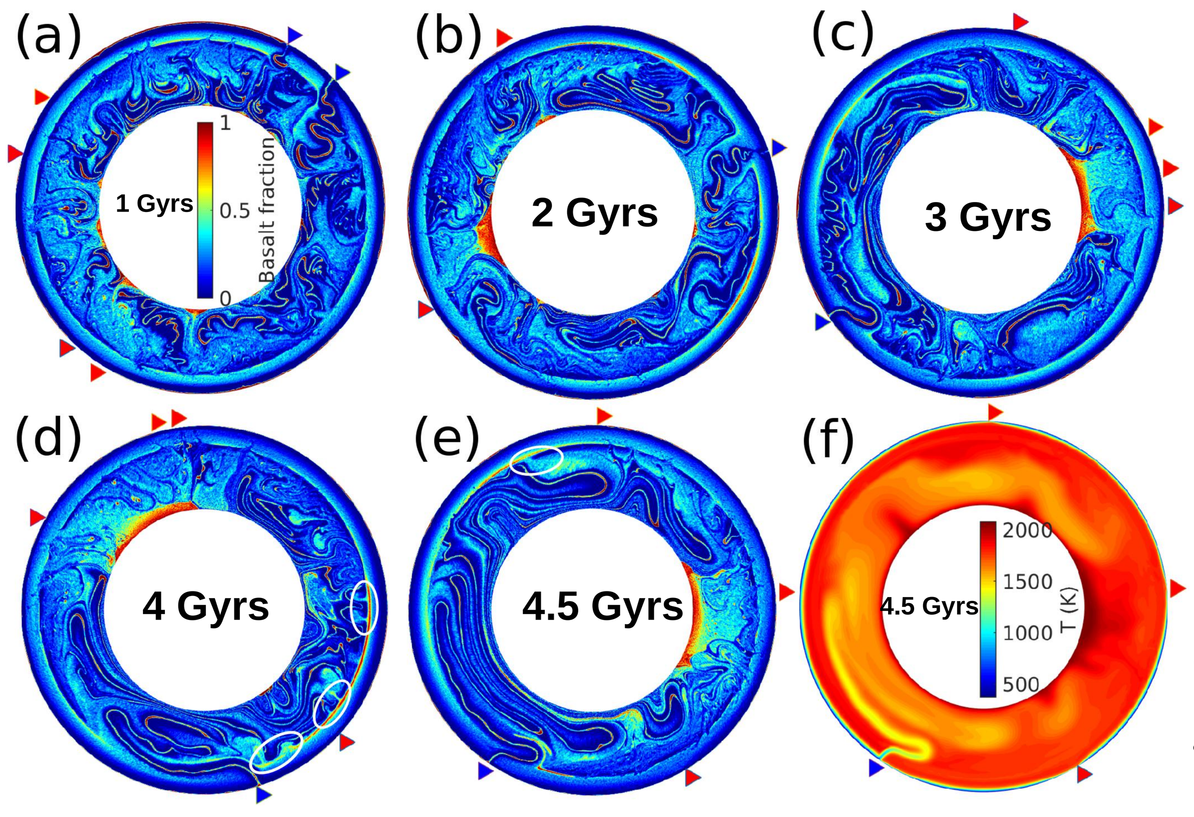

Fig. 3 Snapshots of basalt fraction and potential temperature at different model times. Blue and red triangles refer to subduction zones and mid-ocean ridges, respectively. White ellipses denote the diapiric basaltic avalanches (Yan et al., 2020).

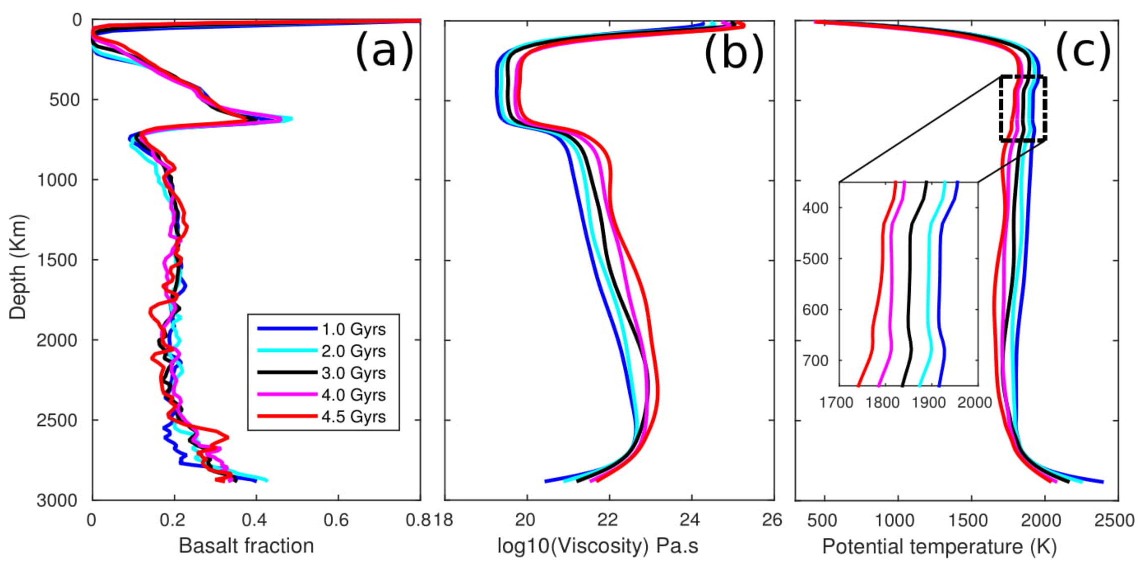

Fig. 4 Radial average profiles of (a) basalt fraction, (b) viscosity, and (c) potential temperature at different model times (from 1.0 to 4.5 Gyrs as labeled).

Key observations:

- **Our reference model predicts that deep-rooted plumes as well as stagnant slabs deliver MORB to the MTZ to establish the MORB-enriched reservoir.**
- **A MORB-enriched reservoir is commonly formed over large regions at the base of the MTZ (i.e., just above 660 km depth), and a complementary harzburgite-enriched reservoir is formed just below 660 km depth.**
- **The basalt fraction in the MTZ reservoir (as well as the harzburgite fraction in the reservoir just beneath the MTZ) remain constant to the first order with second-order variations controlled by the process of episodic removal.**

4. Effects of mantle viscosity

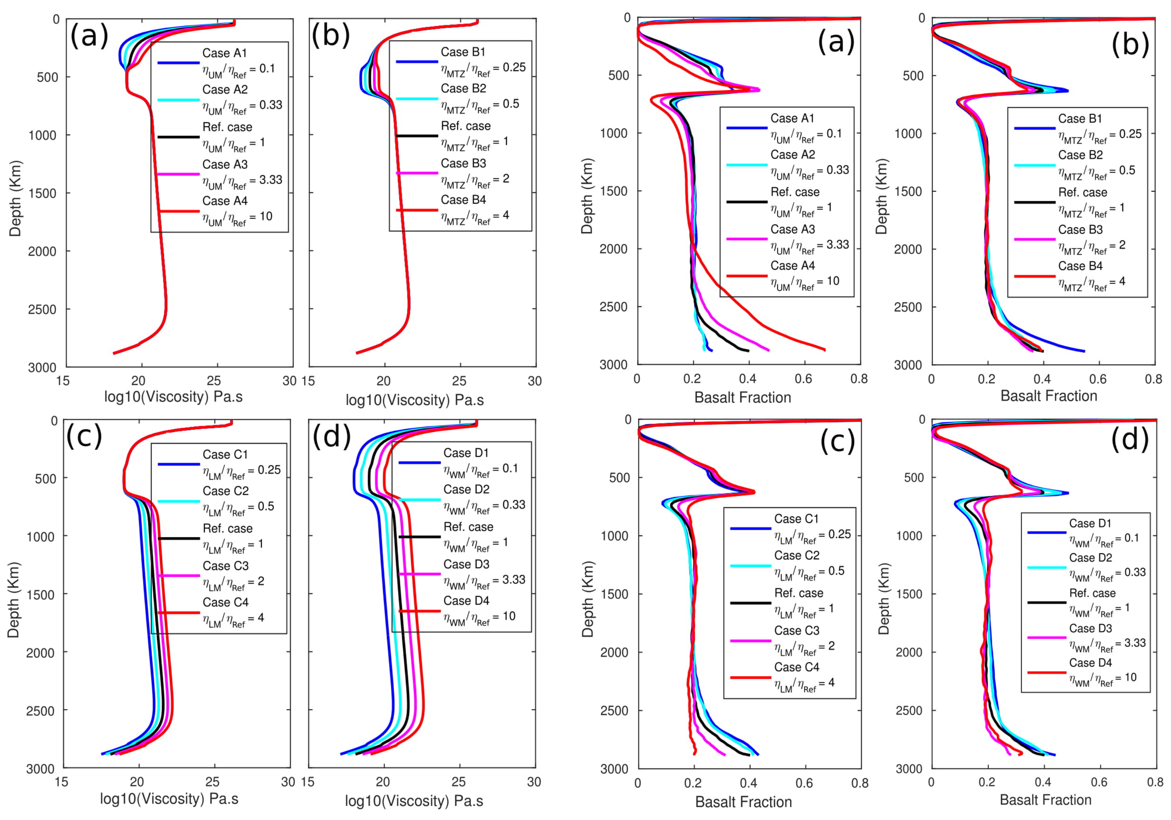

Fig. 5 Left (a-d): radial viscosity profiles for all cases in groups A-D as labeled. η_{UM}, η_{MTZ}, η_{LM} and η_{WM} denote uppermost-mantle viscosity, MTZ viscosity, lower-mantle viscosity, and whole-mantle viscosity, respectively. Correspondingly, η_{Ref} denotes the viscosity of the reference case. Right (a-d): radial profiles of basalt fraction, averaged laterally and over time (i.e., between 2 and 4.5 Gyrs).

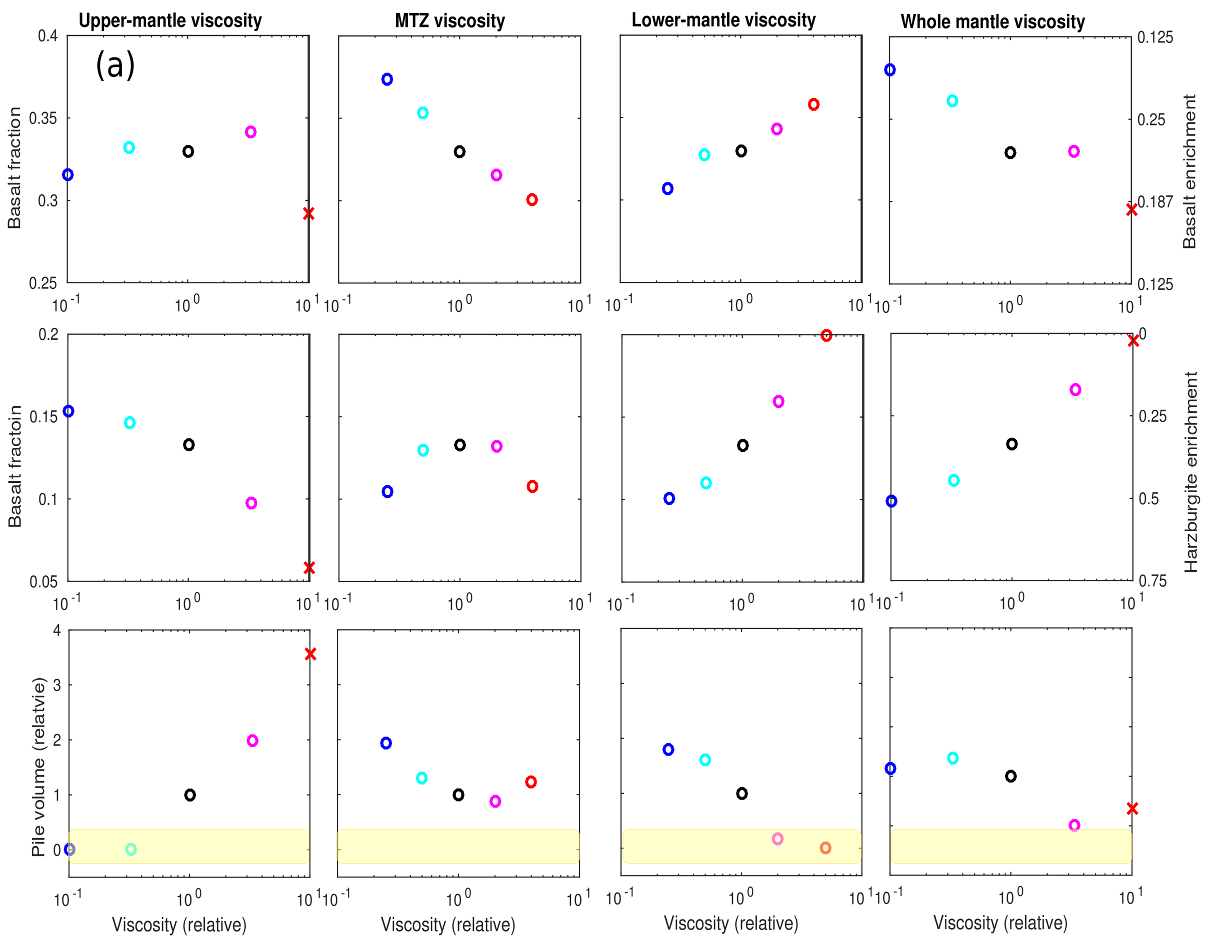

Fig. 6 Parameter sensitivity of the predicted composition of mantle layers. Top row: basalt fraction, and corresponding basalt enrichment in the MTZ (i.e., at depths of 560-660 km) , averaged laterally and over time (i.e., from 2 to 4.5 Gyrs) for all cases in groups A-D (from left to right columns). Middle row: basalt fraction and corresponding harzburgite enrichment just beneath the MTZ (i.e., at depths of 660-760 km) for all cases in groups A-D. Bottom row: relative volume of MORB-enriched thermochemical piles above the CMB (i.e., relative to the pile volume of the reference case at 4.5 Gyrs (see Fig. 3e)). Crosses denote cases that do not match our criteria for Earth-like tectonic style. The light yellow area shows cases with very small or no piles. For colors, see Fig. 5 legend (Yan et al., 2020).

Key observations:

- **The predicted basalt contents in the MTZ are fairly robust over a wide rang of viscosity profiles.**
- **While relatively low local mantle viscosity can promote the segregation and accumulation of MORB in the MTZ, average basalt fraction in the MTZ ranges from 0.3 to 0.35 for most cases, and up to 0.4 only for a few cases.**
- **Similarly, the average harzburgite content in the thin layer just below 660 km depth is mostly viscosity-independent. The overall harzburgite enrichment beneath the MTZ of most cases (except cases that are not Earth-like) only varies between 25% to 50%.**
- **In turn, the volume of piles above the CMB is strongly sensitive to the mantle viscosity profiles.**
- **Overall, our models suggest that the balance between delivery and removal controls the content of MORB/harzburgite in various mantle reservoirs.**

5. Effects of plate-tectonic style and initial mantle composition

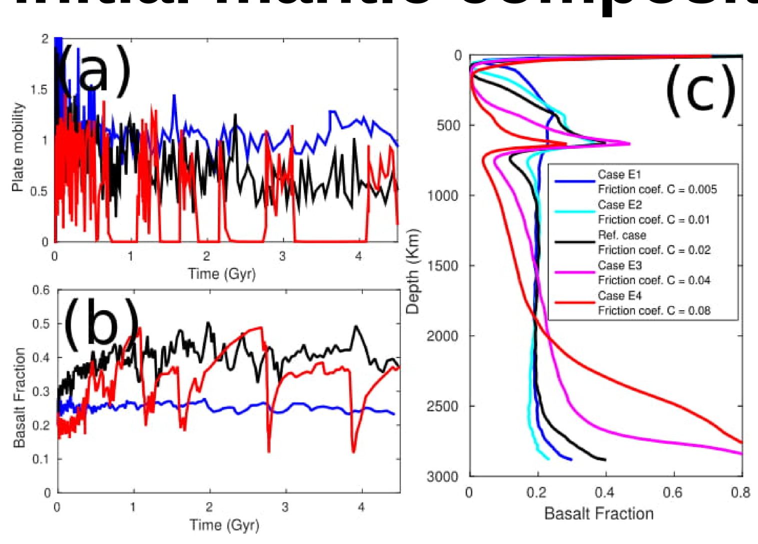

Fig. 8 (a) Plate mobility, (b) radial average basalt fraction in the MTZ from 0 to 4.5 Gyrs, and (c) radial average basalt fraction between 2 and 4.5 Gyrs for cases with different friction coefficients (Yan et al., 2020).

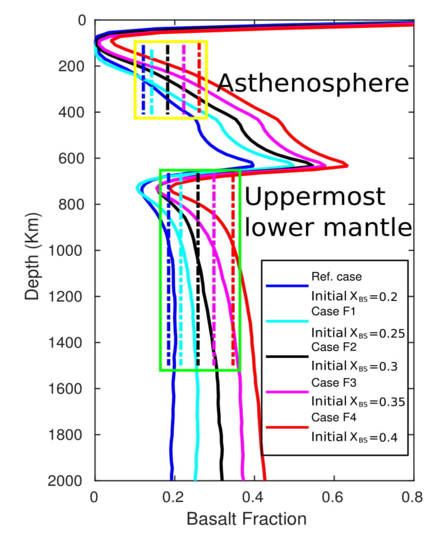

Fig. 9 Radial average basalt fraction between 2 and 4.5 Gyrs for cases with different initial basalt fraction. Dashed lines in the yellow and green boxes denote average basalt fraction in the asthenosphere and upper lower mantle, respectively.

Key observations:

- **Slab and crustal thicknesses have a strong effect on the segregation of heterogeneity in the lower mantle.**
- **Case F2 and F3 display asthenospheric average compositions similar to pyrolite. It is mostly silicate perovskitic (bridgmanitic) in case F3 with a 1.08 Ma/Si ratio.**

6. Distribution of chemical heterogeneity and seismic observations

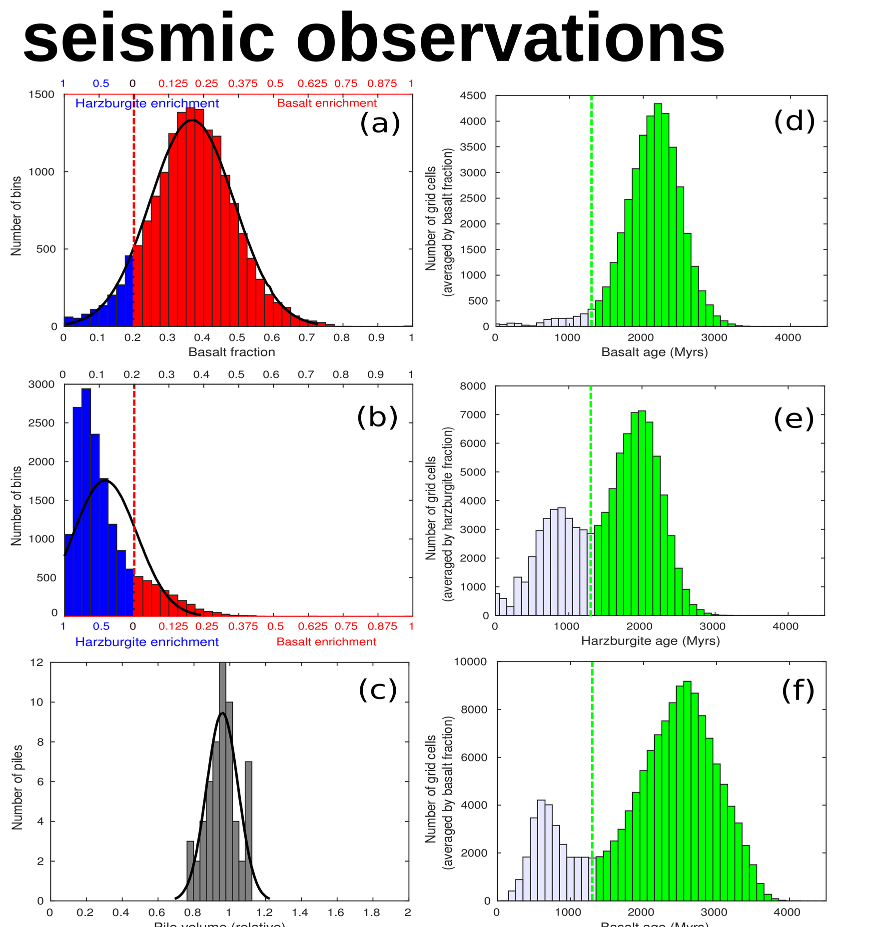

Fig. 9 Distribution of heterogeneity (i.e., in terms of basalt fraction, basalt age and relative volume) in the MTZ (a and d), just beneath the MTZ (b and e), and above the CMB (c and g). Note that the black curve in each histogram is the normal distribution, plotted for reference. Red vertical dash line denotes the boundary between basalt enrichment and harzburgite enrichment (Yan et al., 2020).

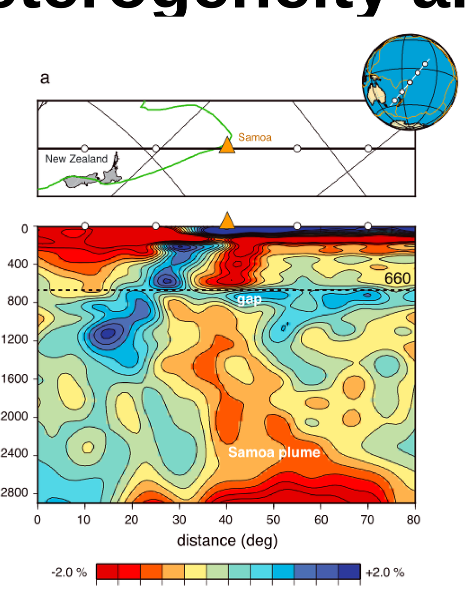

Fig. 10 Maguire et al., 2017

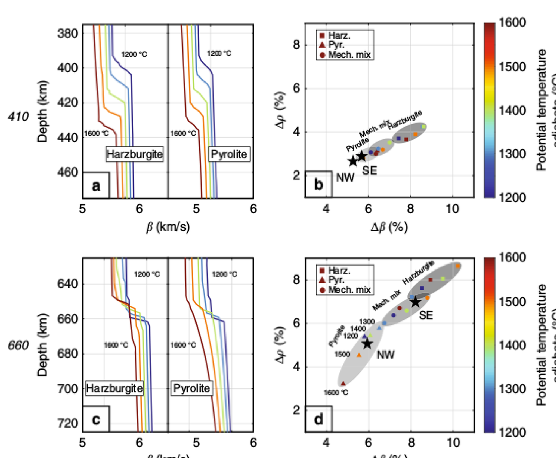

Fig. 11 Yu et al., 2018

7. Conclusions

- **Our models robustly predict that, for all cases with Earth-like tectonics, a MORB-enriched reservoir is formed in the MTZ, and a corresponding harzburgite-enriched reservoir is formed just beneath the MTZ, which are independent of a large range of viscosity structures.**
- **The enhancement of MORB and harzburgite in and beneath the MTZ, respectively, are laterally variable, ranging from 30% to 50% basalt fraction, and 40% to 80% harzburgite enrichment relative to pyrolite, which can potentially be tested using seismic observations.**
- **The composition of bulk-silicate Earth may be shifted relative to the upper-mantle pyrolite if indeed significant reservoirs of MORB exist in the MTZ and lower mantle.**