Recycled basaltic material in mantle plumes explains the appearance of the X-discontinuity in the upper mantle beneath the Hawaiian hotspot: 2D geodynamic simulations

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RATIONALE & BOUNDARY CONDITIONS

We explore the potential for the Hawaiian mantle plume to entrain more than the classically postulated amounts of recycled basaltic material from the CMB.
Higher-than-expected degrees of recycling can in turn reconcile the local seismological observations of the X-discontinuity (coesite-stishovite phase transition) at ~300 km depth (see).

While silica availability is compatible with the presence of basaltic material, great discrepancies exist in terms of its potential amounts -- seismological studies[1] argue for >40%, while geodynamic modeling indicates <15-20%.
We address this controversy by means of two strategies:
1. Introducing **denser chemical heterogeneities in a pyrolitic 2D plume conduit entirely driven by boundary conditions**. Specific combinations of density and viscosity then produce variable degrees of segregation of the basalt (*Figure 1, panel a*).
2. A **dynamically consistent rising plume** (*Figure 1, panel b*), where the mantle is treated as a MM (mechanical mixture), and the plume presents variable excess basalt %.

We find that **periodic accumulations of >30% basaltic material are possible** both in the plume conduit and for a self-consistent plume, **even assuming 15-20% material entrainments**. Our observations lay the bases for revisiting plume modeling as well as for better constraining the plume dynamics and compositions.

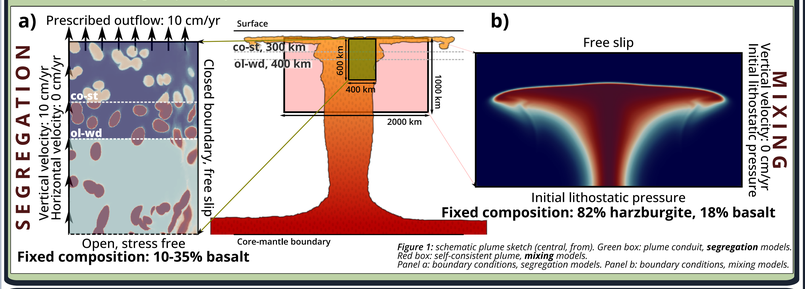

*Figure 1: schematic plume sketch (central, from). Green box: plume conduit, **segregation** models. Red box: self-consistent plume, **mixing** models. Panel a: boundary conditions, segregation models. Panel b: boundary conditions, mixing models.*

METHODS & DENSITY ARRAYS

SEGREGATION

Incompressible

$$-\nabla \cdot [2\eta\dot{\varepsilon}'] + \nabla p = \rho \mathbf{g} \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

Composition

$$\frac{\partial C}{\partial t} + \mathbf{u} \cdot \nabla C = 0 \quad (a)$$

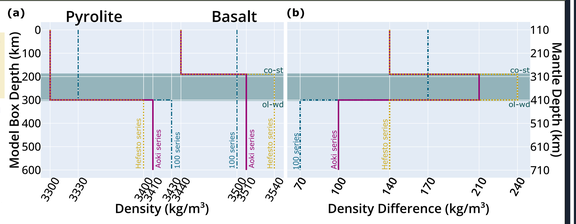

*Figure 2: Density arrays for the **segregation** models. **Panel a:** true densities for pyrolite (left) and basalt (right), all three series. **Panel b:** density difference.*

MIXING

Compressible

$$-\nabla \cdot \tau + \nabla p = \rho \mathbf{g} \quad (3)$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (4)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) - \nabla \cdot (k \nabla T) = \rho H + \tau : \dot{\varepsilon} + \alpha T (\mathbf{u} \cdot \nabla p) + Q_L \quad (5)$$

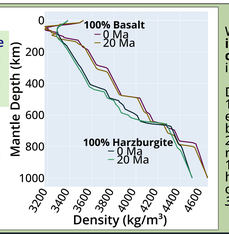

*Figure 3: Density arrays for the **mixing** models, expressed in terms of end member compositions.*

We solve the Stokes system assuming **incompressibility** for the segregation models and **compressibility** for the mixing models, as these take into account plume excess temperatures (200 to 300 K).

Density arrays:
1. ***Segregation models***: three series (100, Aoki, Hefesto), each with its own density array for both pyrolite and basalt (*Figure 2, panels a and b*).
2. ***Mixing models***: density arrays are obtained with respect to two potential end members: 100% basalt and 100% harzburgite. The true composition of each model has a composition falling between the two sets of curves, accounting for the mechanical mixture (*Figure 3*).

RESULTS: REGIMES & ACCUMULATIONS

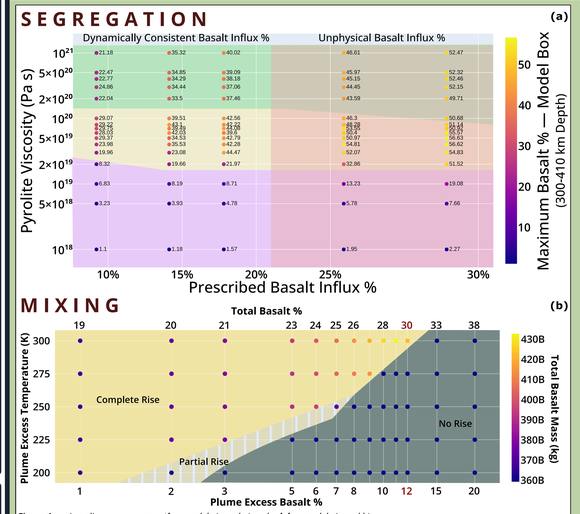

*Figure 4: regime diagrams, **segregation** models (panel a) and **mixing** models (panel b). Segregation model regimes in Figures 5, 6, and 7. See Figure 1, panel b in reference of the mixing models "complete rise" regime.*

SEGREGATION REGIMES

Rising
Heterogeneities and background have the same velocity.
No deformation, no segregation.

Mixed
Rising, sinking, ponding of the denser material in the 300-410 depth range, due to the optimal combination between density difference and pyrolite viscosity.

Sinking
Extreme deformation due to the pyrolite viscosity being too low to keep material entrained.
No accumulation, high velocities.

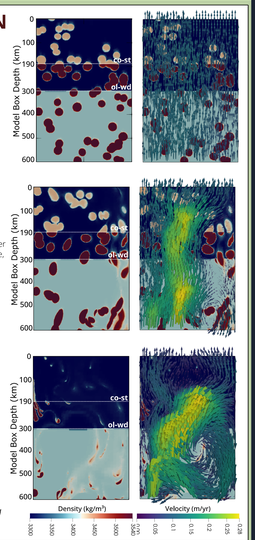

*Figure 5: **segregation** models regimes. Boxes show density and velocity distributions (with vectors) for each.*

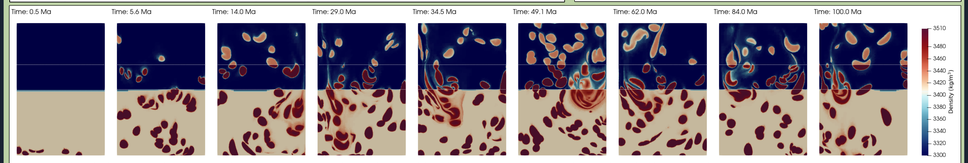

Figure 6: snapshots displaying the evolution over time for a segregation model in the mixed regime of the Aoki series. Note how the material accumulation builds up and evolves over time. Pyrolite viscosity: 6×10^{19}. Prescribed basalt influx: 20%.

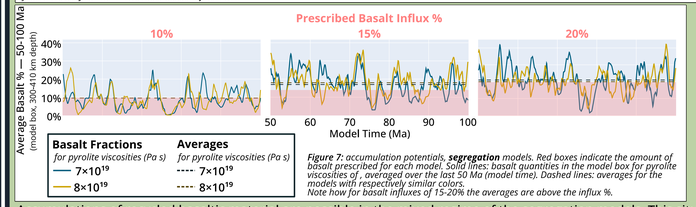

*Figure 7: accumulation potentials, **segregation** models. Red boxes indicate the amount of basalt prescribed for each model. Solid lines: basalt quantities in the model box for pyrolite viscosities of , averaged over the last 50 Ma (model time). Dashed lines: averages for the models with respectively similar colors.
Note how for basalt influxes of 15-20% the averages are above the influx %.*

Accumulations of recycled basaltic material are possible in the mixed regime of the segregation models. This situation is entirely dependent on the tradeoff between pyrolite viscosity and density of the heterogeneties (as well as the pyrolite itself).
In the mixed regime, the great density difference in the 300-410 km depth range allows ponding of the heterogeneities as well.

The dynamically consistent rising plume corroborates our observations: a mantle plume can still rise while entraining denser basalt.

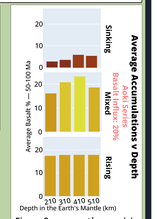

*Figure 8: **segregation** models. Type distribution of eclogite vs depth. All regimes, adjusted for real mantle depths.*

DISCUSSION: PEAK ACCUMULATIONS

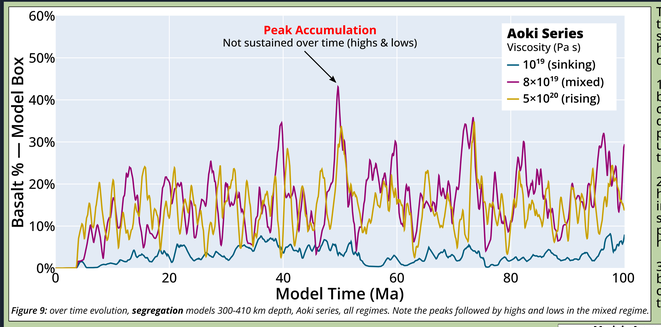

*Figure 9: over time evolution, **segregation** models 300-410 km depth, Aoki series, all regimes. Note the peaks followed by highs and lows in the mixed regime.*

The evolution over time of the segregation models highlights three different patterns:

1. **Sinking regime**: basalt quantities are consistently low, due to the low pyrolite viscosities, unable to sustain the heterogeneities

2. **Mixed regime**: highs and lows indicate that rising, sinking, and ponding are happening

3. **Rising regime**: basalt quantities consistent all throughout.

The peaks in the basaltic material are always not sustainable over time, and rather happen as discrete peaks in the curve, as shown in Figure 9.

The probability of having high (>35%) basalt peaks is displayed in Figure 10.
In particular:
1. Basalt influxes of 10% cannot lead to accumulations of 35% or more
2. The presence or absence of the **co-st phase transition has a negligible role** in the accumulation behavior. The 100 (no co-st) and Aoki (co-st present) series have the same count of models (12) with >35% basalt peaks
3. The Hefesto series, which features the densest basalt v the lightest pyrolite also shows the least probability of high accumulations
4. The highest peak in accumulation probability happens for a model that features the most optimal distribution of pyrolite viscosity v density values. With respect to the general trend, this model is to be considered as an outlier
5. The 100 series shows the most accumulations at the lowest viscosities due to the light basalt. Accumulations towards the higher end of the mixed regime are observed for the Aoki series
6. Typical **peak accumulation probabilities are around 1-3%**, with particular consistency for the Aoki series

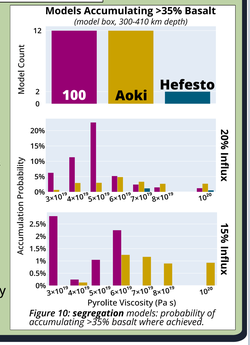

*Figure 10: **segregation** models: probability of accumulating >35% basalt where achieved.*

CONCLUSIONS & PERSPECTIVES

We tested the potential for the Hawaiian mantle plume to accumulate denser recycled basaltic material between 300 and 410 km depth, so as to provide a viable explanation for the occurrence of the X-discontinuity beneath the hotspot.
We found that:
1. Accumulations in a plume conduit can be possible through achieving material segregation (mixed regime).
2. Segregation is in turn obtained for viscosity values consistent with those of the Hawaiian mantle plume, and for density and length scales of the basaltic heterogeneities well accounted for.
3. While basalt peaks only happen for small amounts of model time, the average accumulations still remain high, even with prescribed influxes of 15-20%
4. The above were then probed through a self-consistent rising plume, which can still rise up to the surface when 18% + 12% basalt is present.

Our work provides a mechanism for basalt recycling in the Hawaiian plume and sheds further light on its complex dynamics. Future perspectives involve adding the discrete heterogeneities into the self-consistent plume, so as to explore the full recycling potentials and the ascent patterns.