Geodynamic controls on mantle differentiation and preservation of geochemical heterogeneity

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I. MOTIVATION

- **40-50%** of **produced ^{40}Ar** (decay of ^{40}K) is currently in the **atmosphere**.
- **High ^{3}He/^{4}He** and and low **^{40}Ar/^{36}Ar ratios in OIB** samples suggest **preservation of primordial** or **unprocessed material** compared to MORB samples (figure 1).
- **Melting creates compositional heterogeneity**, **segregates incompatible elements** and allows **transfer to the atmosphere**. It is therefore a **crucial process** to understand **for He and Ar signatures**.

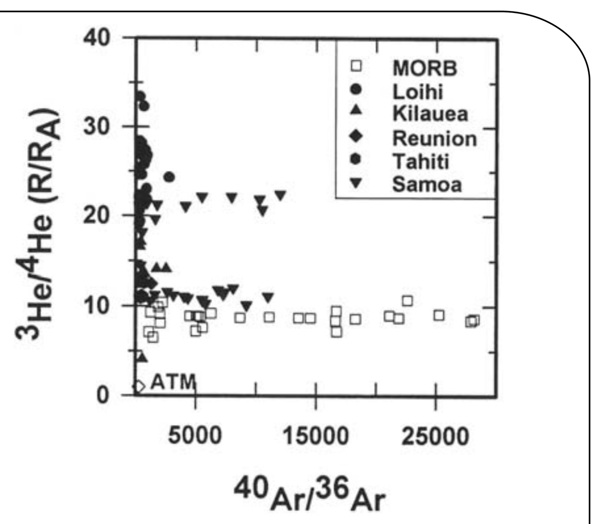
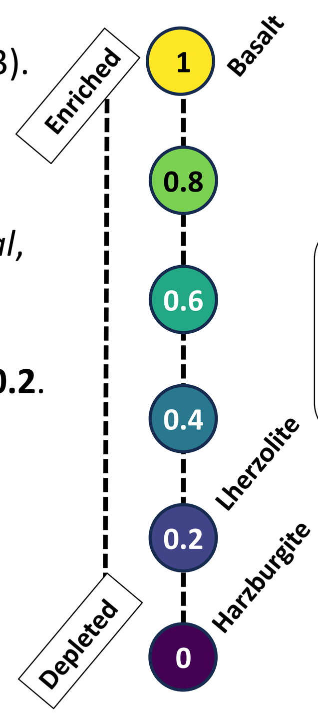


Figure 1 : Helium and argon ratios from OIBs and MORB samples. G.F. Davies, 2010

We investigate the influence of mantle convection on mantle differentiation, as well as its impact on the preservation of primitive material and ^{40}Ar enriched material.

II. METHODS: MELTING IN TERRA

- **TERRA is a 3D finite element code** solving mass, momentum and energy conservation equations for **heat transfer in spherical shell** (J. Baumgardner, 1983).
- **Particles** are advected by the flow and **carry bulk composition** and **isotope information** that impact the flow, as **buoyancy** is **composition dependent** and **radiogenic heating** is **function of local U, Th and K concentrations** (van Heck *et al*, 2016).
- **Melting is differentiating the mantle** from initial homogeneous composition **C=0.2**. It **allows distribution of elements** according to their **geochemical behaviour**.
- **Melting occurs** when a **particle's temperature surpasses its solidus** (function of depth and bulk composition). As a **particle melts**, **it is depleted** until the composition gives a melting temperature that is the particle's temperature .**The amount of depletion is redistributed to a receiving particle** at the surface.



COMPOSITION SCALE

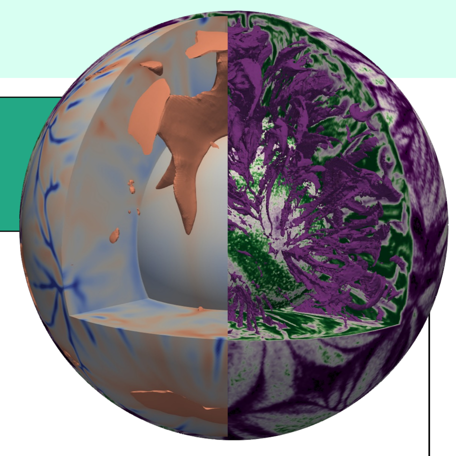


Figure 2: A TERRA simulation. Temperature (left) and Composition (right)

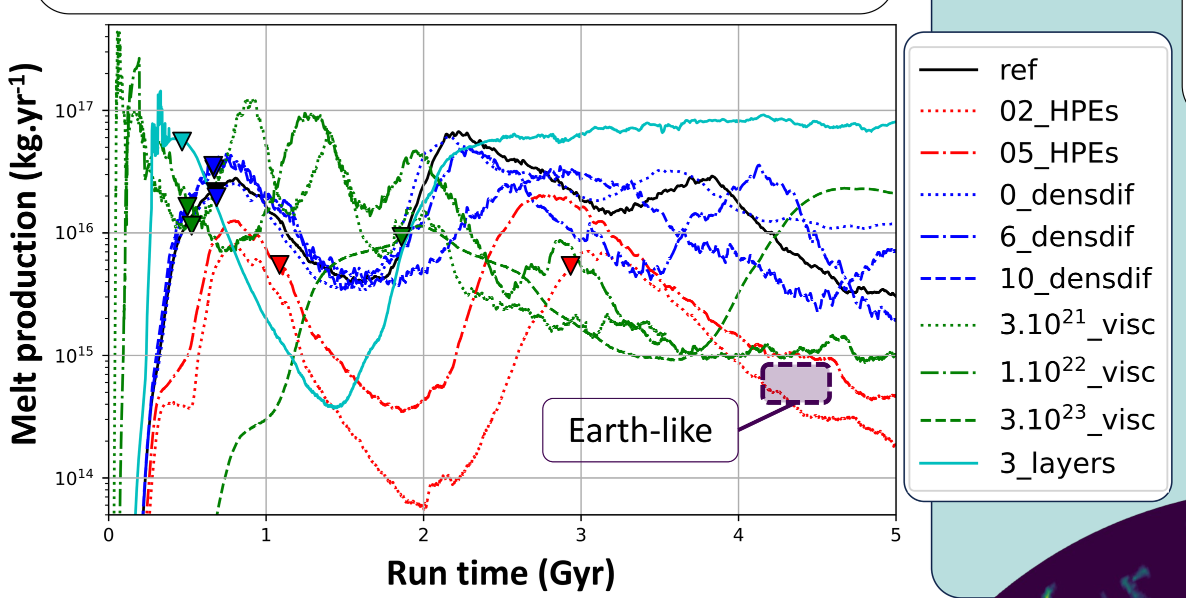
III. RESULTS

TABLE: Presented simulations

Presented simulations are incompressible and Boussinesq

Run name		Reference Viscosity (Pa.s)	Viscosity Structure	Proportion of HPEs	Density excess of basalt (%)
ref	black	3.00E+22	2 layers	1	2
02_HPEs	red	3.00E+22	2 layers	0.2	2
05_HPEs	red	3.00E+22	2 layers	0.5	2
0_densdif	blue	3.00E+22	2 layers	1	0
6_densdif	blue	3.00E+22	2 layers	1	6
10_densdif	blue	3.00E+22	2 layers	1	10
3.10²¹_visc	green	3.00E+21	2 layers	1	2
1.10²²_visc	green	1.00E+22	2 layers	1	2
3.10²³_visc	green	3.00E+23	2 layers	1	2
3_layers	cyan	5.00E+21	3 layers	1	2

Figure 3: Processing rate in function of time. Points indicate time at which one mantle mass has been processed. Current processing rate (box) from J.P. Morgan, 1998



Viscosity structure and surface velocities control the type of material melting

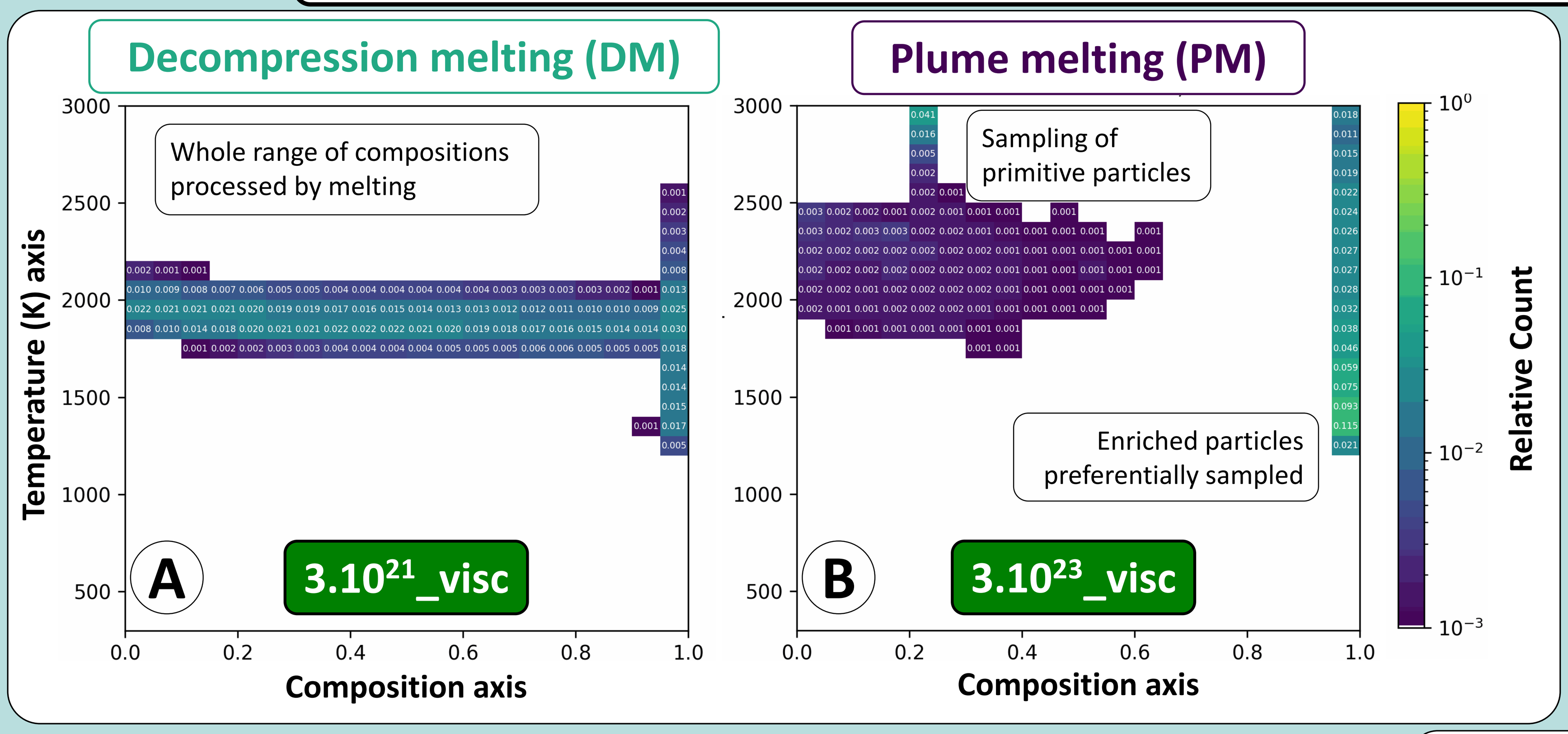
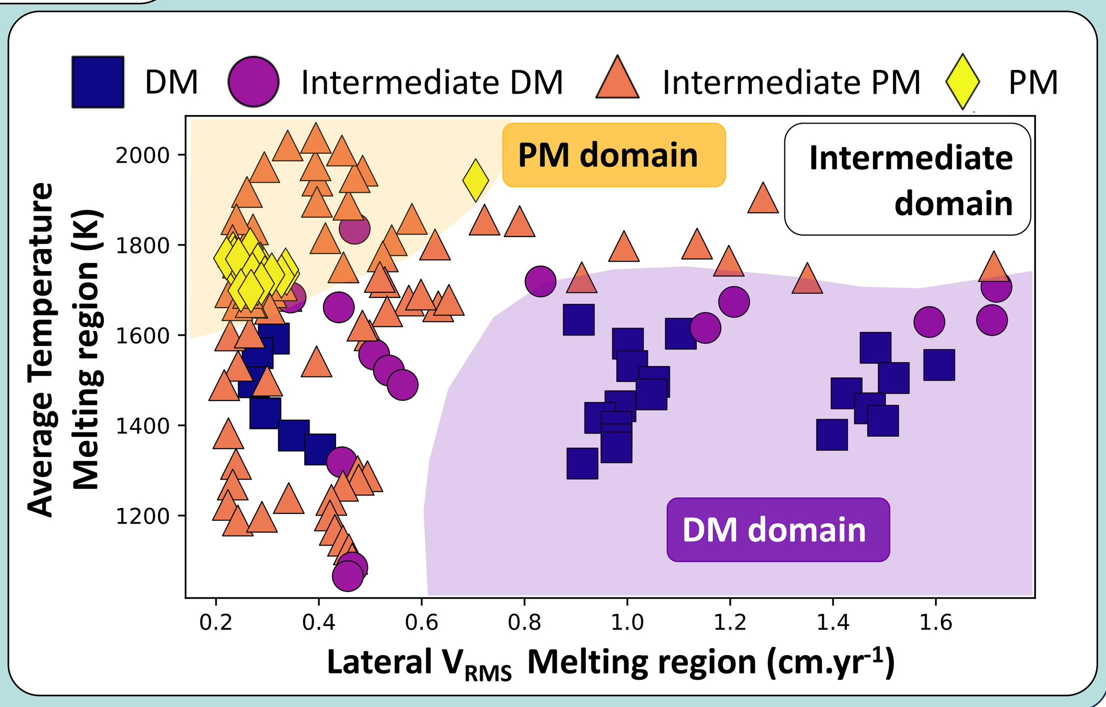


Figure 4: 2D histograms categorizing melting particles by their composition and temperature for named models at 2 Gyr (similar processing rates). Color scale and bin numbers represent relative count of particles (1 is the sum of all melting particles)

- **Surface velocities** dictate the **renewal rate of material** within the melting region. **Higher surface velocities**, encouraged by lower viscosity, favour **higher processing rates** (figure 3) and **decompression melting** (DM, figure 4A and 5).
- However, with a **lower reference viscosity**, the **mantle can get rid of its heat efficiently**, the average mantle temperature decreases, as a result **the processing rate decreases accordingly** (figure 3).
- The **plume melting regime** is favoured by **low convection velocities** (higher viscosity), where **heat cannot escape efficiently** and temperature reach higher values (figure 4B and 5).

Figure 5: Melting regime diagram compiling models **ref**, **02_HPEs**, **3.10²¹_visc**, **1.10²²_visc**, **3.10²³_visc**, **3_layers** from 1 Gyr to end of run every 200 Myr. If more 20 % of the melting material is more than 100K above solidus, it is at least **PM**, if more than 80 % is enriched, it is **PM**. Otherwise, it is at least **I DM**, if 90 % of material is melting at less than 100K above solidus it is **DM**.



Less internal heating favours preservation of primitive material

- When the **amount of HPEs is reduced** (model 05_HPEs and 02_HPEs), less heat is provided and **the mantle starts cooling earlier** in the simulation. This results in **less melt production** (figure 3) because of a **global lower temperature difference** between the mantle and the solidus.

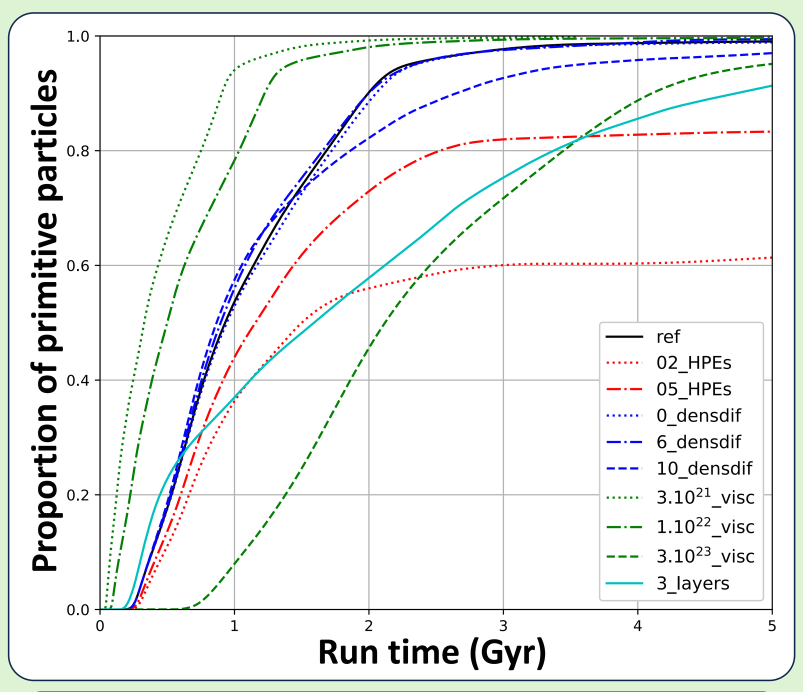


Figure 6: Proportion of primitive particles processed by melting

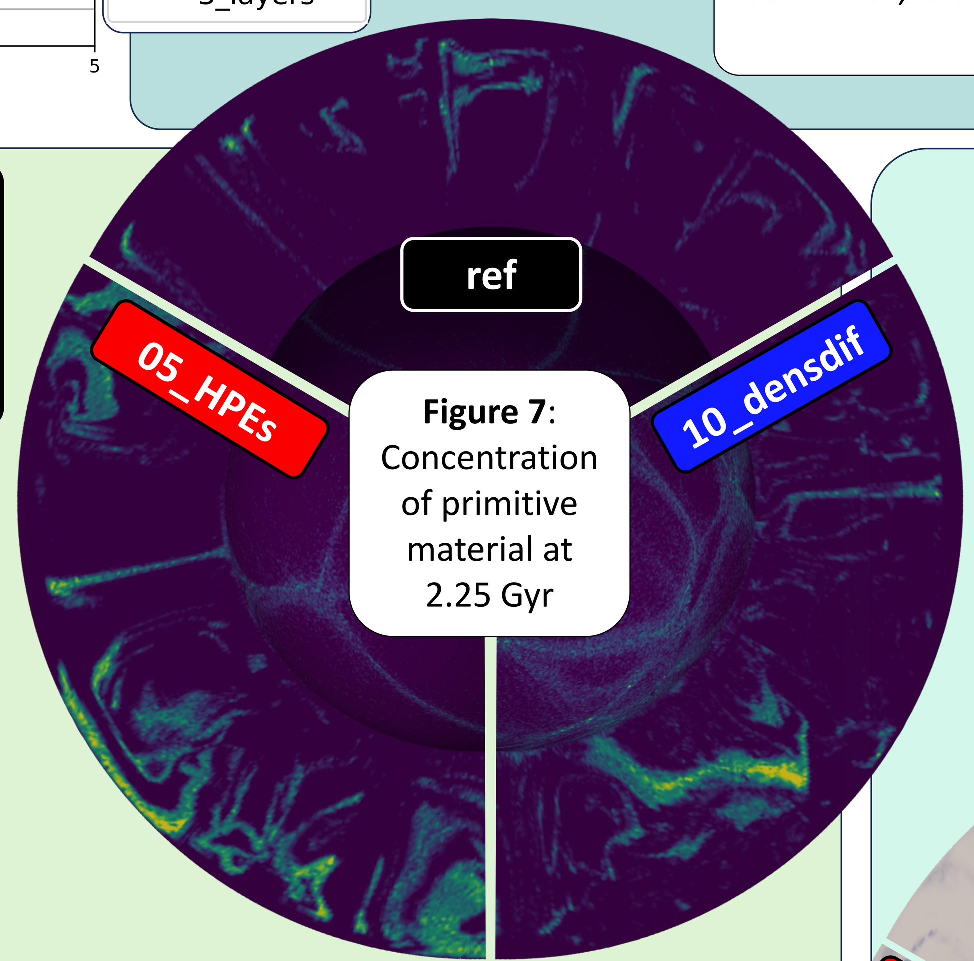


Figure 7: Concentration of primitive material at 2.25 Gyr

- **Because of lower processing rates**, some **primitive particles** are cooling so that they **can't be processed by melting** (figure 6). **Primitive material** domains are principally **in the lower mantle** (figure 7).
- **The extraction of the continental crust**, thought to happen rather early in Earth history (Guo & Korenaga, 2019), **could concentrate** enough incompatibles and **HPEs** to promote **preservation of primitive particles** (figure 7), reproduce **more realistic processing rates** (figure 5) and **increase preservation of material** in the lower mantle (figure 9).

Intrinsically dense enriched material retain ^{40}Ar in the lower mantle longer

- Early **enriched material is a potential candidate for ^{40}Ar storage** because they **concentrate K** when they form (half-life of ^{40}K is 1.2 Gyr).
- When the **excess density of enriched material** is **increased**, the **residence time** of slabs in the deep mantle is **prolonged**. This leads to an ^{40}Ar enriched lower mantle in case **10_densdif** compared to **ref** (figure 8).

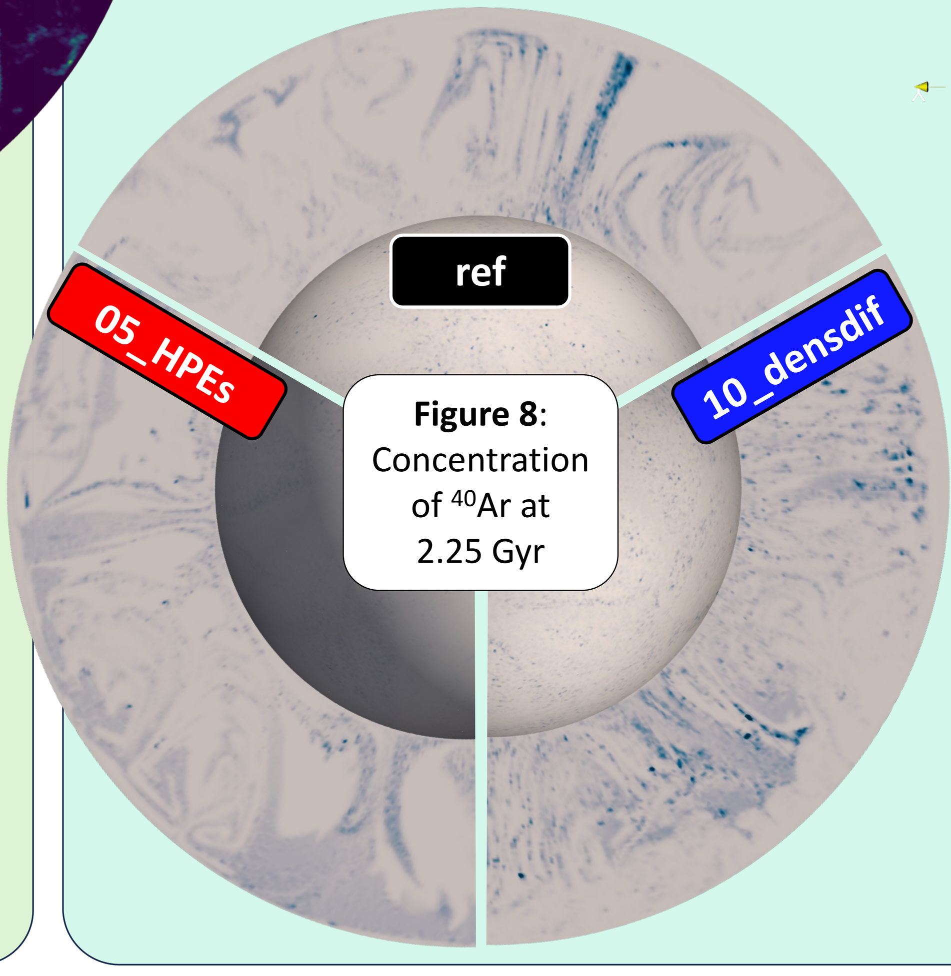


Figure 8: Concentration of ^{40}Ar at 2.25 Gyr

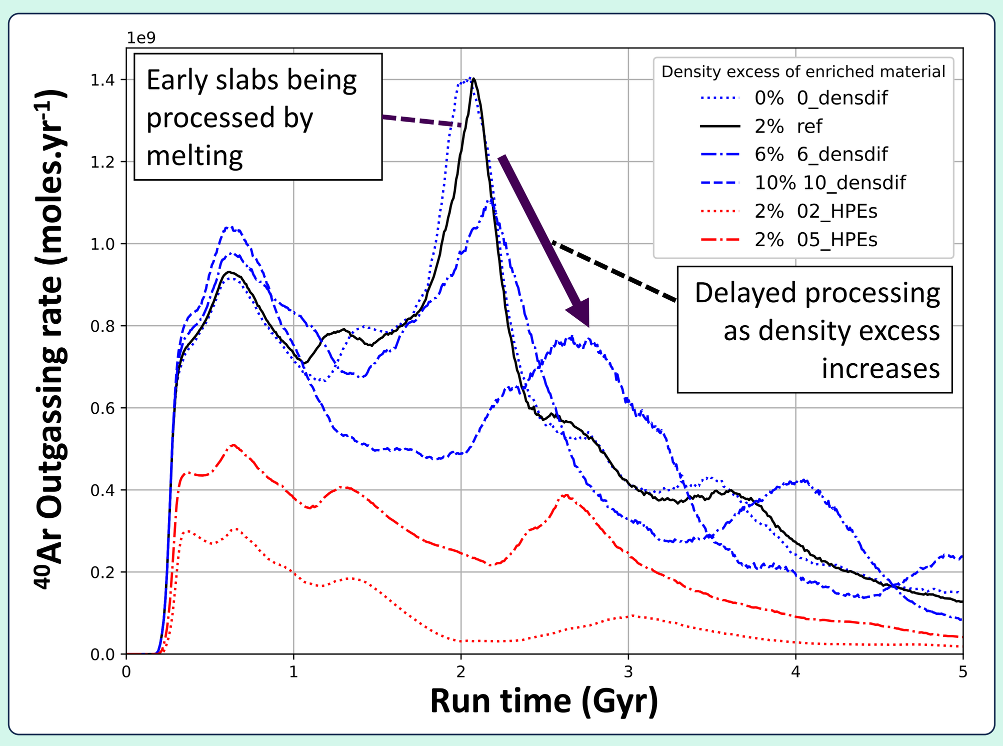


Figure 9: Outgassing rate of ^{40}Ar

- When **this material** is **reprocessed by melting**, **^{40}Ar** is **released to the atmosphere**, leading to an **increased** outgassing rate (figure 9). The **higher** the **density excess of enriched material**, the **later** and the **less efficient** the **outgassing of ^{40}Ar**.

IV. FUTURE WORK

Realistic processing rates

- In order to have more realistic processing rates (figure 5), we need our models to not overheat in first Gyr with a more appropriate initial condition.
- It has been shown that taking into account the latent heat in melting can reduce the processing rate by half (Li *et al*, 2016)

Earth-like models

- Circulation models (plate motion history)
- Influence of continental crust extraction on pile stability, ^{40}Ar outgassing and primitive material preservation

Other things to look at

- Investigate what type of material thermochemical piles are made of (compositions, ages)

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