Geodynamic controls on melting in TERRA 3D mantle convection models

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I. MOTIVATION

- **He and Ar provide major constraints** on **Earth thermal evolution** and outgassing that **need to be satisfied** within our **geophysical understanding** of the mantle.
- **40-50%** of **produced ^{40}Ar** 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 elements** and allows **transfer to the atmosphere**. It is therefore a **crucial** process to understand **for He and Ar signatures**.

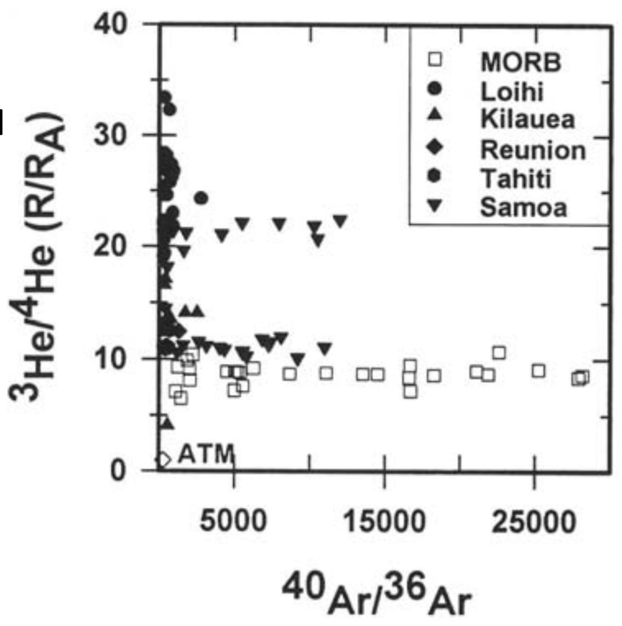


Figure 1 : Helium and argon ratios from OIBs and MORB samples. G.F. Davies, 2010

We investigate the links between geodynamics and melting, i.e. the impact of different amounts of Heat Producing Elements (HPEs), various viscosity settings and densities of enriched material (buoyancy number) on melting in terms of production and type of material processed.

II. METHODS: MELTING IN TERRA

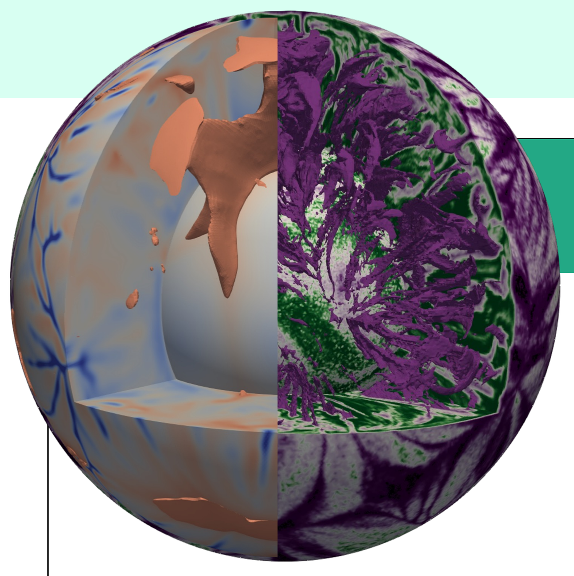
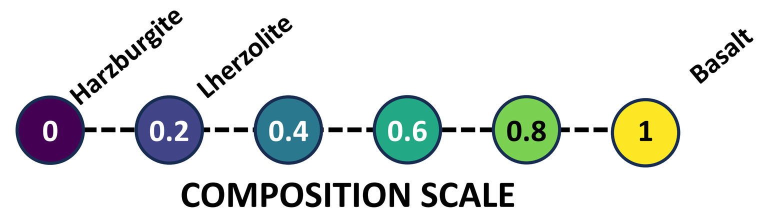


Figure 2: Visualization of a TERRA simulation with the temperature field (left side) and composition field (right side)

- **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 dynamics, 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**.
- **Solidus** is a function of **depth, temperature** and **composition** (figure 3).
- **Melting occurs** when a **particle surpasses its solidus**. As a **particle melts, it is depleted** until the composition gives a melting temperature that is the particle's temperature (figure 3). **The amount of depletion is redistributed to a receiving particle** at the surface.

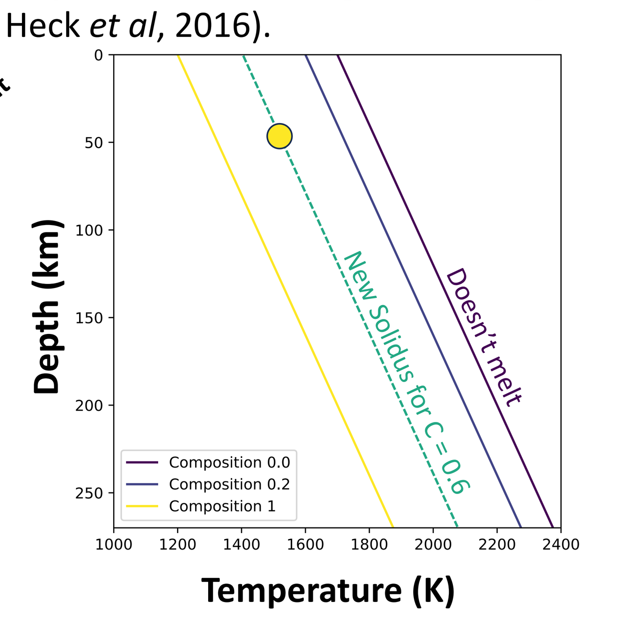


Figure 3: Solidi and melting in TERRA

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 enriched material (%)
ref	3.00E+22	2 layers	1	2
02_HPEs	3.00E+22	2 layers	0.2	2
05_HPEs	3.00E+22	2 layers	0.5	2
0_densdif	3.00E+22	2 layers	1	0
6_densdif	3.00E+22	2 layers	1	6
10_densdif	3.00E+22	2 layers	1	10
3.10^{21}_visc	3.00E+21	2 layers	1	2
1.10^{22}_visc	1.00E+22	2 layers	1	2
3.10^{23}_visc	3.00E+23	2 layers	1	2
3_layers	5.00E+21	3 layers	1	2

Viscosity structure and surface velocities control the type of material melting

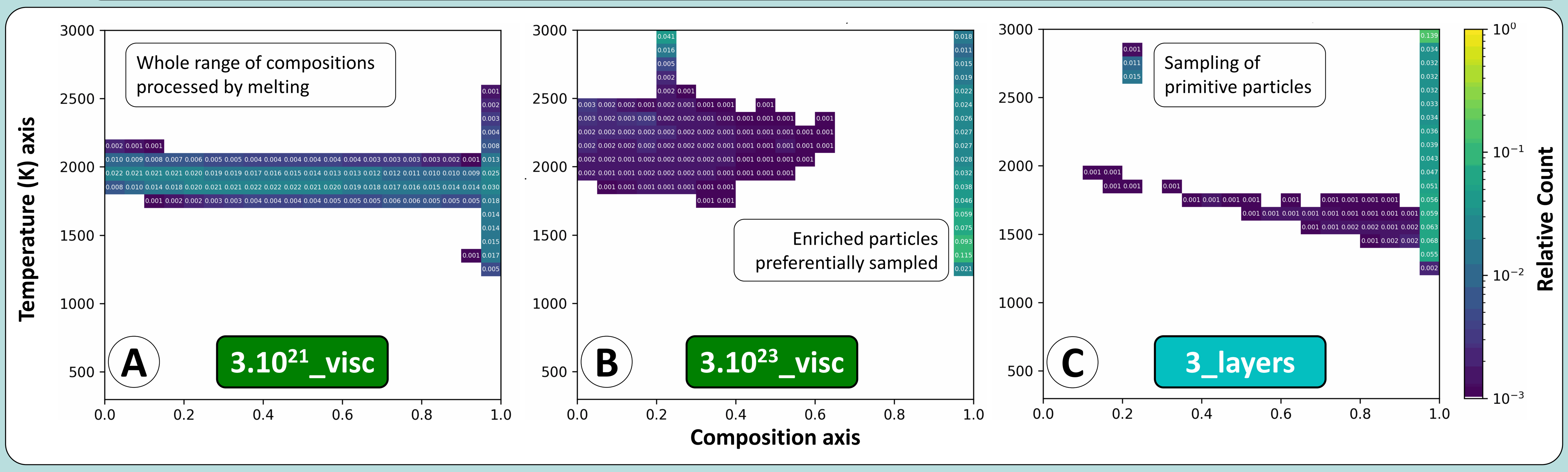


Figure 6: 2D histograms categorizing melting particles by their composition (x axis) and temperature (y axis) for named models at 2 Gyr (similar processing rates). Color scale and bin numbers represent relative count of particles (1 is the sum of all melting particles)

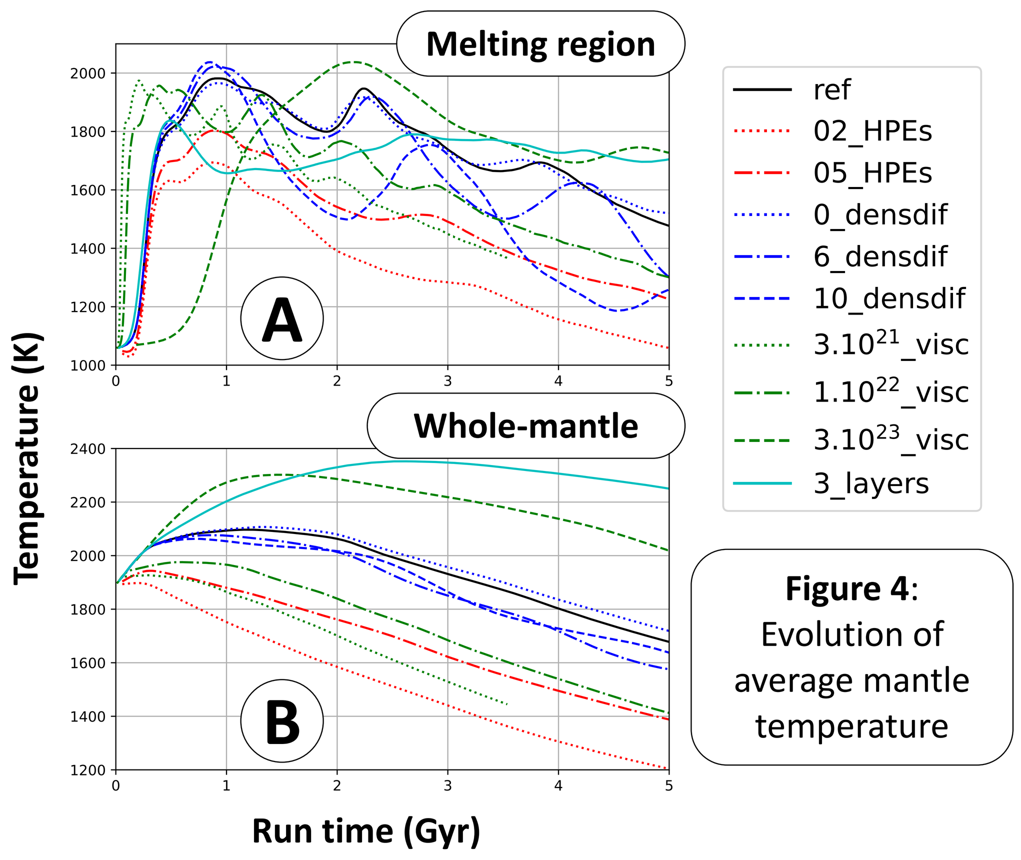


Figure 4: Evolution of average mantle temperature

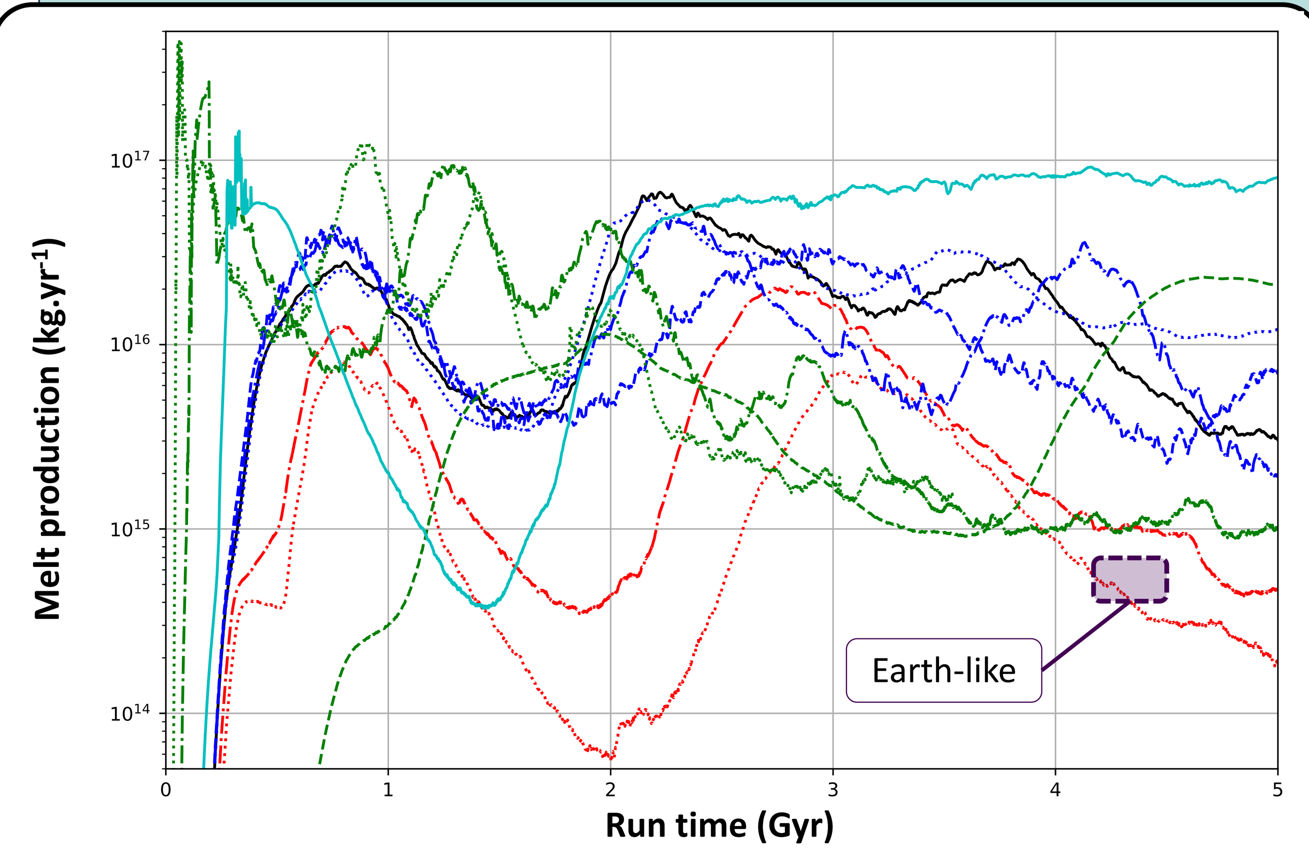


Figure 5: Processing rate in function of time. Current processing rate (box) from J.P. Morgan, 1998

- **Surface velocities** dictate the **renewal rate of material** within the melting region. **Higher surface velocities**, encouraged by lower viscosity, favour **higher processing rates** (figure 5) and **decompression melting** (figure 6A).
- However, with a **lower reference viscosity**, the **mantle can get rid of its heat efficiently**, the average mantle temperature decreases (figure 4A, 4B), as a result **the processing rate decreases accordingly** (figure 5).
- By imposing a **higher reference viscosity**(figure 6B) or a highly **viscous lid** (3 layers viscosity structure, figure 6C), the **mantle can't get rid of its heat as efficiently** (figure 4A, 4B). Consequently, the **melt production varies drastically** and reaches **higher values for model 3_layers** (figure 5).

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 (figure 4B). This results in **less melt production** (figure 5) because of a **global lower temperature difference** between the mantle and the solidus (figure 4A).
- **Because of lower processing rates**, some **primitive particles** are cooling so that they **can't be processed by melting** (figure 7).
- **The extraction of the continental crust**, thought to happen rather early in Earth history (Hawkesworth *et al*, 2019), **could concentrate** enough incompatibles and **HPEs** to promote **preservation of primitive particles** (figure 7), reproduce **more realistic processing rates** (figure 5) and **increase longevity of piles** in the deep mantle (figure 8).

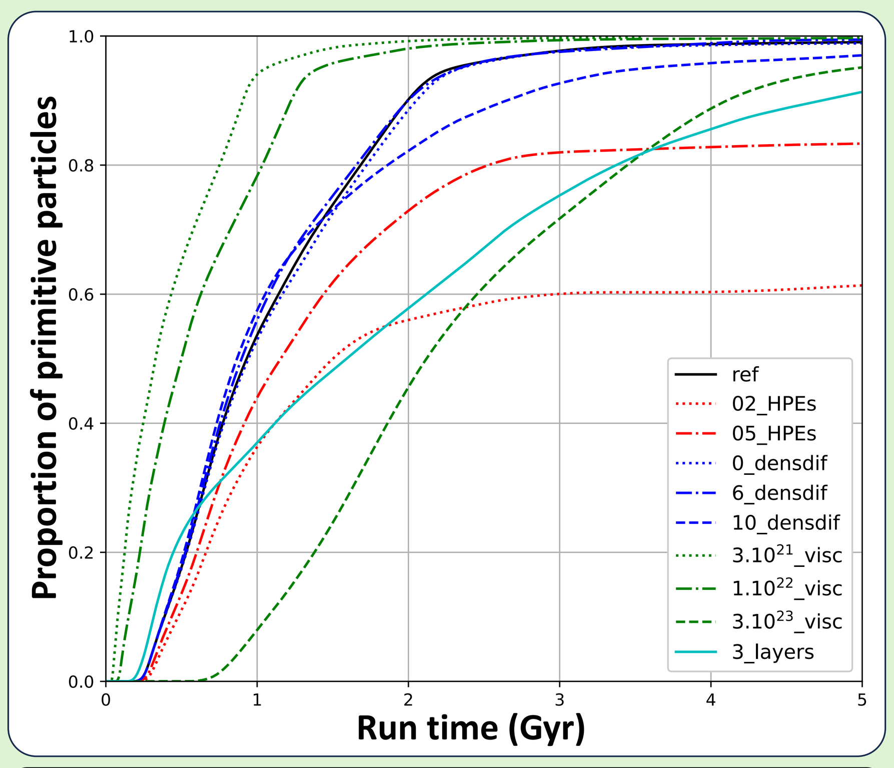


Figure 7: Proportion of primitive particles processed by melting

Intrinsically dense enriched material retain ^{40}Ar in thermo-chemical piles longer

- When the **excess density of enriched material** is **increased**, the **residence time** of slabs in the deep mantle is **prolonged**.
- The **first generation** of slabs is highly **enriched in ^{40}K** because they **form early** (half-life of ^{40}K is 1.2 Gyr).
- When **this first generation of slabs** is **reprocessed by melting**, **^{40}Ar** product of ^{40}K is **released to the atmosphere**, leading to an **increased outgassing rate** (figure 8).
- The **higher** the **density excess of enriched material**, the **later** and the **less efficient** the **outgassing of ^{40}Ar**.

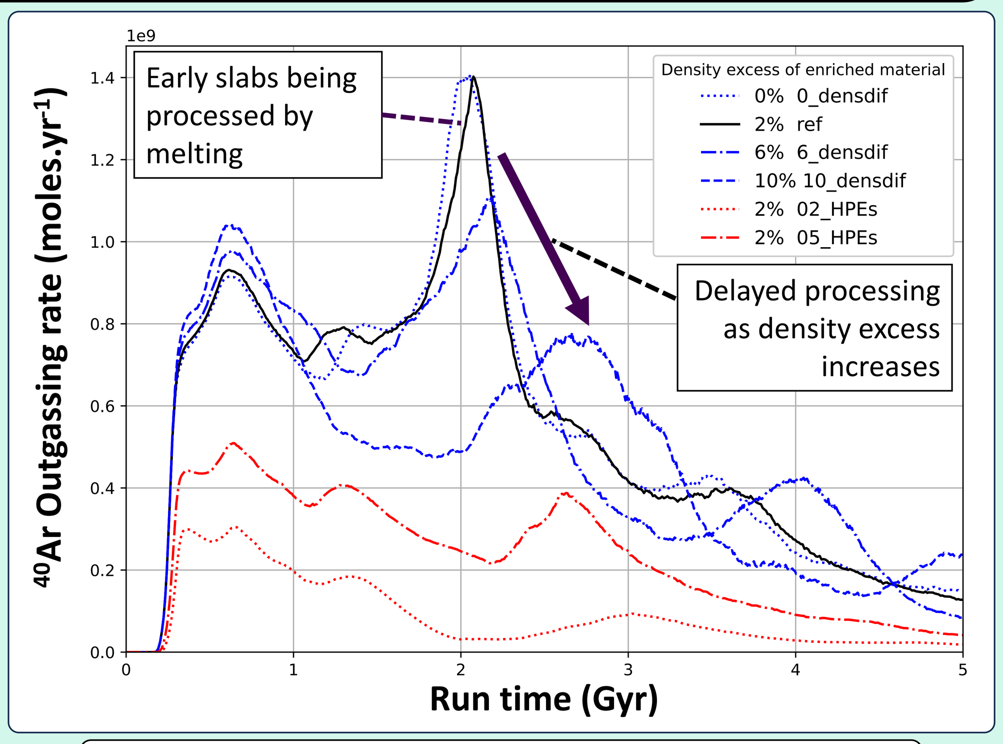


Figure 8: Outgassing rate of ^{40}Ar

IV. FUTURE WORK

Realistic processing rates

- In order to have more realistic processing rates (figure 5), implement a more sophisticated solidus.
- It has also 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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