The effects of short-lived radionuclides and porosity on the early thermo-mechanical evolution of planetesimals

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Abstract

The thermal history and internal structure of chondritic planetesimals, assembled before the giant impact phase of chaotic growth, potentially yield important implications for the final composition and evolution of terrestrial planets. These parameters critically depend on the internal balance of heating versus cooling, which is mostly determined by the presence of short-lived radionuclides (SLRs), such as \(26\text{Al}\) and \(60\text{Fe}\), as well as the heat conductivity of the material. The heating by SLRs depends on their initial abundances, the formation time of the planetesimal and its size. It has been argued that the cooling history is determined by the porosity of the granular material, which undergoes dramatic changes via compaction processes and tends to decrease with time. In this study we assess the influence of these parameters on the thermo-mechanical evolution of young planetesimals with both 2D and 3D simulations. Using the code family \textsc{2dElvis}/\textsc{3dElvis} we have run numerous 2D and 3D numerical finite-difference fluid dynamic models with varying planetesimal radius, formation time and initial porosity. Our results indicate that powdery materials lowered the threshold for melting and convection in planetesimals, depending on the amount of SLRs present. A subset of planetesimals retained a powdery surface layer which lowered the thermal conductivity and hindered cooling. The effect of initial porosity was small, however, compared to those of planetesimal size and formation time, which dominated the thermo-mechanical evolution and were the primary factors for the onset of melting and differentiation. We comment on the implications of this work concerning the structure and evolution of these planetesimals, as well as their behavior as possible building blocks of terrestrial planets.

Keywords: Planetary formation, Terrestrial planets, Planetesimals, Interiors, Thermal histories

1. Introduction

During the early stages of planet formation the building material of terrestrial planets like Earth or Mars is distributed within planetesimals with sizes of \(\sim 10^4–10^5\) km (Weidenschilling and Cuzzi\textsuperscript{2006}). It remains unclear how these bodies assembled from sub-micron grains in a circumstellar disk in detail. First order constraints from the standard collisional model for growth relate the doubling time \(t_d \sim \rho_p R_p/(\Sigma\text{disk}\Omega_K)\) of a growing planetesimal to its size \(R_p\) and density \(\rho_p\) as well as to the properties of the disk, namely mass surface density \(\Sigma\text{disk}\) and Keplerian frequency \(\Omega_K\) (Goldreich et al.\textsuperscript{2004}). This formula, however, essentially a cross-section calculation, ignores gravitational focusing and limits to growth, such as the bouncing barrier (e.g., Zsom et al.\textsuperscript{2010}) and the radial migration of solids due to gas drag (Weidenschilling\textsuperscript{1977}). Nonetheless, there are also complex local processes that can enhance the formation of planetesimals with up to several hundred kilometers radii due to particle collection in vortices, pressure bumps, and other effects (e.g., Johansen et al.\textsuperscript{2007}, Cuzzi et al.\textsuperscript{2008}, Morbidelli et al.\textsuperscript{2009}, Chambers\textsuperscript{2010}, Johansen et al.\textsuperscript{2015}). These point to rapid formation on the time scale of \(\sim 10^5\) yr after the formation of Ca-Al-rich inclusions (CAIs), consistent with findings from geochemical data (Kleine et al.\textsuperscript{2009}).

Theoretical models to investigate this epoch after the initial assembly of the planetesimals rely on numerical models of internal dynamics. So far, such models were mostly based on 1D studies, focusing on conductive cooling as the main heat transfer mechanism (e.g., Ghosh and McSween\textsuperscript{1998}, Hevey and Sanders\textsuperscript{2006}, Sahijpal et al.\textsuperscript{2007}). Recent work, however, has shown that more mechanisms need to be taken into account. Firstly, these bodies are supposed to be sufficiently big to become heated by decay of short-lived radionuclides (SLRs), most importantly \(26\text{Al}\) and \(60\text{Fe}\), which would alter their inner structure and evolution dramatically up to the point of silicate melting. For example, bodies greater than \(\sim 10\) km in radius, formed at the time of CAI formation, are supposed to melt completely (Hevey and Sanders\textsuperscript{2006}). Secondly, some meteorite parent bodies seem to have experienced solid-state deformation (Tkalec et al.\textsuperscript{2013}, Tkalec and Brenker\textsuperscript{2014}). These points underline the importance of 2D or 3D thermo-mechanical modeling approaches for the evolution of planetesimals to detect effects such as the differences of the surface-to-volume ratio in 1D, 2D and 3D models or non-axisymmetric advection processes. As a further complicating issue, recent work highlights the potentially important role of porous bulk material on the thermal history of planetesimals, by lowering the thermal conductivity of the silicate material and thus to prevent effective...
heat transport via conduction (Cuzzi et al., 2008; Neumann et al., 2014).

The initial powdery state of the uncompacted material is however reduced in the inner parts of the planetesimals by cold isostatic compaction due to self-gravity (Henke et al., 2012), effectively decreasing its influence with increasing size of the body. Another important aspect is the formation time of the body. As outlined above, the accretion time scale of planetesimals is on the order of $10^5$ yr, which is roughly an order of magnitude shorter than the evolutionary time scale of the protoplanetary disk and the thermo-mechanical evolution of planetesimals on the order of $10^6$ yr. Hence, the quasi-instantaneous formation time sets the limit on the amount of SLRs incorporated into the body.

Additional heat sources for planetesimals can be energy injection during the accretion of the body and later impacts. First, the temperature increase due to the conversion of gravitational energy to heat is low for bodies $< 1000$ km (Schubert et al., 1986; Qin et al., 2008; Elkins-Tanton et al., 2011). Second, during runaway growth, the velocity dispersion of planetesimals is set by the equilibrium between self-stirring and gas drag. Impact velocities are therefore comparable or smaller to the escape velocity (Greenberg et al., 1978; Morbidelli et al., 2015), which drastically limits the amount of injected energy. The formation time thus dominates the energy budget for heating and sets the pace of internal dynamic processes, such as core formation, to the order of several $10^6$ Al half-lives.

Clearly, the thermo-mechanical evolution of planetesimals needs to be treated adequately to achieve a consistent theoretical understanding of this stage of planetary assembly. In this study we assessed the role of the initial size, formation time and porosity of planetesimals on their thermo-mechanical history via 2D and 3D numerical models. In Sect. 2 we describe constraints from earlier work and outline the most important concepts of our numerical model; in Sect. 3 we present the results obtained from the simulation runs, for which we outline the technically inherent limitations in Sect. 4. In Sect. 5 we discuss the physical implications and draw conclusions in Sect. 6. Supplementary material can be found in Appendix A and a list of all simulations is given in Appendix B.

2. Physical and numerical methodology

The physical and numerical methods in this work follow earlier work by Golabek et al. (2014), in which an in-depth analysis of observational constraints on the thermal history for the acapulcoite-lodranite parent body is compiled. In contrast to this study, we focused on the general role of planetesimal evolution and seeked to explore the thermo-mechanical regimes before the onset of the giant impact phase in terrestrial planet formation. The most important physical constants used in the model are explained in the following sections, all others are listed with their respective references in Table 1.

2.1. Fluid flow

As outlined in Sect. 1 we studied the thermo-mechanical evolution of instantaneously and recently formed planetesimals using the t2ELVIS/3ELVIS code family (Gerya and Yuen, 2007). The code solves the fluid dynamic conservation equations using the extended Boussinesq approximation, to account for thermal and chemical buoyancy forces, with a conservative finite-differences (FD) approach on a fully staggered-grid (Gerya and Yuen, 2003), namely the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{v} = 0,$$

with density $\rho$, time $t$ and flow velocity $\mathbf{v}$; the Stokes equation

$$\nabla \sigma' - \nabla P + \rho g = 0,$$

with deviatomic stress tensor $\sigma'$, pressure $P$ and directional gravity $g$ obtained via the location-dependent Poisson equation

$$\nabla^2 \Phi = 4\pi G \rho,$$

with the gravitational potential $\Phi$ and Newton’s constant $G$; and finally the energy equation

$$\rho c_T \left( \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = -\frac{\partial q_i}{\partial x_i} + H_i + H_h + H_{lat},$$

with heat capacity $c_T$, temperature $T$, heat flux $q_i = -k \nabla T$, thermal conductivity $k$, and radioactive ($H_i$), shear ($H_h$) and latent ($H_{lat}$) heat production terms. The energy equation is advanced using a Lagrangian marker-in-cell technique to minimise numerical diffusion and enable an accurate advection of non-diffusive flow properties during material deformation. The staggered-grid FD method permits to capture sharp variations of stresses and thermal gradients with strongly variable viscosity and thermal conductivity. For further details on the code’s features we refer to Gerya and Yuen (2003; 2007).

2.2. Heating by short-lived radionuclides

As discussed earlier, the radiogenic heat source term $H_r$ in Equation 4 is dominant for early formed planetesimals. It is driven by the decay of short-lived isotopes $^{26}$Al and $^{60}$Fe and the long-lived $^{40}$K, $^{235}$U, $^{238}$U and $^{232}$Th. Among these $^{26}$Al is by far the most important one and therefore drives the internal heating of the young bodies, as the abundance of $^{60}$Fe is lower by orders of magnitude (Barr and Canup, 2008; Tang and Dauphas, 2012; Mishra et al., 2016). In this work, we considered time-dependent radiogenic heating by $^{26}$Al and the long-lived radioactive isotopes as input for $H_r$ in Equation 4. For the initial $^{26}$Al/$^{27}$Al ratio we adopted an upper-limit value (Jacobsen et al., 2008) of $5.85 \cdot 10^{-5}$ (Thrane et al., 2006) at CAI formation.

2.3. Silicate melting model

For the silicates we assumed a peridotite composition and used the parameterizations by Herzberg et al. (2000) and Wade and Wood (2005) (based on data of Tromms and Frost, 2002) for the solidus and liquidus temperatures $T_{sol}$ and $T_{liq}$, which determine the silicate melt fraction

$$\varphi = \begin{cases} 
0 & : T \leq T_{sol}, \\
\frac{T - T_{sol}}{T_{liq} - T_{sol}} & : T_{sol} < T < T_{liq}, \\
1 & : T \geq T_{liq}.
\end{cases}$$
We took into account both consumption and release of latent heat due to melting and freezing of silicates. Silicate density depends on the melt fraction $\varphi$ as

$$\rho_{\text{eff}}(P, T, \varphi) = \rho_{\text{Si-sol}}(P, T) - \varphi(\rho_{\text{Si-sol}}(P, T) - \rho_{\text{Si-liq}}(P, T))$$  \hspace{1cm} (6)

with solid and liquid silicate densities $\rho_{\text{Si-sol}}$ and $\rho_{\text{Si-liq}}$. For silicate melt fractions $0.1 < \varphi < 0.4$ the effective viscosity (Pinkerton and Stevenson, 1992) is given as

$$\eta_{\text{eff}} = \eta_{\text{Si-sol}} \exp \left( 2.5 + \left( \frac{1 - \varphi}{\varphi} \right)^{0.48} \right) \cdot (1 - \varphi).$$  \hspace{1cm} (7)

Above $\varphi \geq 0.4$ a transition occurs from solid-like structures to low-viscosity crystal suspensions (Solomatov, 2015; Costa et al., 2009), with $\eta_{\text{Si-sol}} = 10^{-4} - 10^{-2}$ Pa s (Bottinga and Weill, 1972; Rubie et al., 2003; Liebske et al., 2005). This effectively increases the Rayleigh number

$$Ra = \frac{\alpha g(T - T_{\text{surf}})\rho_{\text{eff}}^2 c_p D^3}{k\rho_{\text{Si-liq}}},$$  \hspace{1cm} (8)

with thermal expansivity $\alpha$, surface temperature $T_{\text{surf}}$, depth of the magma ocean $D$ and thermal conductivity $k$ and thus enables an efficient cooling process.

Above melt fractions $\varphi \geq 0.4$ our model is restricted by a lower cut-off viscosity $\eta_{\text{num}} = 10^{17}$ Pa s, which preserves numerical stability, but lies orders of magnitude above realistic values of molten state silicate viscosities. To bypass restrictions of the physical interpretation in this melt regime we employed the soft turbulence model by Kraichnan (1962) and Sig-gia (1994), and estimated the convective heat flux as

$$q = 0.089 \frac{k(T - T_{\text{surf}})R^3}{D^{1/3}}.$$  \hspace{1cm} (9)

Using Equation 10 we derived an increased effective thermal conductivity

$$k_{\text{eff}} = \left( \frac{q}{0.089} \right)^{3/2} \frac{1}{(T - T_{\text{surf}})^2 \rho_{\text{eff}} \eta_{\text{num}}} \left( \frac{\alpha g c_p}{\eta_{\text{num}}} \right)^{-1/2},$$  \hspace{1cm} (10)

which approximates correct heat flux for a low viscosity magma ocean (Tackley et al., 2001; Hevey and Sanders, 2006; Golabek et al., 2011). For a more detailed discussion on model limitations due to this issue see Sect. 3.

2.4. Porosity

As already indicated in Sect. 1, the initial porous state of recently accreted planetesimals is thought to be due to cold isostatic pressing with pressure and thus depth into a configuration of closer packing (Henke et al., 2012), via

$$\phi(P) = 0.42 + 0.46 \left( \frac{P}{P_0} \right)^{1.72} + 1,$$  \hspace{1cm} (11)

with $P_0 = 0.13$ bar, which effectively introduces an upper cut-off porosity for depths greater than $\sim 10^2$ m, mostly dependent
on the size of the body. Furthermore, the porosity changes the density of the solid material
\[ \rho_{\text{Si-pore}}(P, T, \phi) = \rho_{\text{Si-sol}}(P, T) \cdot (1 - \phi), \]
and the effective thermal conductivity for porous material
\[ k_{\text{eff-pore}} = \begin{cases} \frac{k_1}{\phi^{3/2}} & : \phi < 0.2, \\ \frac{k_2}{\phi} & : \phi > 0.4, \\ \frac{k_3}{\phi^{1/4}} & : 0.2 \leq \phi \leq 0.4, \end{cases} \]
with constants \( a = -1.2, \phi_0 = 0.08 \) and \( \phi_1 = 0.167 \), fitting lab experiments [Henke et al., 2012; Gail et al., 2015]. Finally, the material compaction is sensitive to sintering effects via
\[ \frac{\partial \phi}{\partial t} = A(1 - \phi) \frac{\sigma^{3/2}}{R^2} \exp \left[ \frac{E_p}{RT} \right], \]
with the effective stress \( \sigma \), the effective grain size \( R \), the gas constant \( R \) and experimentally determined factors \( A \approx 4 \times 10^3 \) and activation energy \( E_p = 85 \text{ kcal mol}^{-1} \) [Henke et al., 2012].

### Table 2: Distinct values of chosen parameter space.

| Parameter                  | Symbol | Value range | Unit          | List of values |
|----------------------------|--------|-------------|---------------|---------------|
| Planetesimal radius        | \( R_p \) | 20–200 km   |              | 20, 50, 80, 110, 140, 170, 200 |
| Instantaneous formation time | \( t_{\text{form}} \) | 0.1–1.75 Myr |              | 0.1, 0.5, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.75 |
| Initial porosity           | \( \phi_{\text{init}} \) | 0.0–0.75     |              | 0.0, 0.1, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75 |

#### 2.6. Parameter space

The goal of this work was to assess the combined effect of radiogenic heating by SLRs and initial porosity on the subsequent evolution of planetesimals. Hence, the parameter space was based on varying the planetesimal radius \( R_p = 20–200 \text{ km} \), the instantaneous formation time \( t_{\text{form}} = 0.1–1.75 \text{ Myr} \) after CAI formation and the initial porosity \( \phi_{\text{init}} = 0.0–0.75 \), in total a set of 616 2D simulations. A full list of all applied values is given in Table 2.

Due to the heavy computational cost of 3D simulations we first analyzed the 2D simulations, categorized them and then performed selected 3D simulations to verify the 2D results.

From our varied parameters, both \( R_p \) and \( t_{\text{form}} \) directly influenced the amount of SLRs present in the body. A list of all simulation runs with corresponding parameters and categories can be found for the 2D simulations in Table B.3 and for the 3D simulations in Table B.4.

### 3. Results

#### 3.1. Thermo-mechanical evolution

In this section we analyze the thermo-mechanical outcome of the simulations. In Sect. 3.1.1 we focus on the temporal evolution of the material properties, i.e., solid or molten, and categorize the 2D results accordingly. Each category is then described and examples are given. In Sect. 3.1.2 we investigate the temperature-dependent maximum temperatures of the bodies and assess the influence of each of the varied parameters on it by constructing \( R_p, t_{\text{form}} \) and \( \phi_{\text{init}} \) isolines. Also, we analyze the influence of \( \phi_{\text{init}} \) on the temperature profile for fixed formation time and planetesimal size.

#### 3.1.1. Material properties

Figure 1 illustrates the thermo-mechanical results of the material properties within each 2D simulation run. Each dot represents a single simulation and color indicates in which kind of regime we categorize the simulation. Each of these regimes is described below and an example, illustrating the state for \( \phi, T \) and \( \rho \) at a certain time, is given. Illustrating video files for each of the described regimes below can be found in the supplementary material (see Appendix A).
Solid regime. The blue rendered simulations in Fig. 1 build the class of solid models. These are models which lacked enough heat production by SLRs to experience any sign of transition from the solid silicate to a partially molten silicate state. An example of this kind is given in Fig. 2. The upper left image shows all simulation runs of this class. The composition plot illustrates the unperturbed layered structure of the silicates it is composed of. Because the body never experienced enough heat, no transition to a molten state occurred and therefore the layers resided with their original ordering. The temperature and density plots illustrate these parameters at the same time during the evolution. Since the body experienced some heat from SLRs it heated up and cooled down to the temperature of the surrounding space on the order of several tens of Myr. As shown in Fig. 2, these kinds of models can be found for all tested radii for \( t_{form} \gtrsim 1.7 \) Myr, i.e., when the initial amount of \(^{26}\text{Al}\) has significantly reduced. Additionally, planetesimals with \( R_p = 50 \) km already belong to this class for earlier formation times \( t_{form} \gtrsim 1.6 \) Myr and for \( t_{form} \gtrsim 1.3 \) Myr for bodies with \( R_p = 20 \) km since they cooled more efficiently. Comparison of figures 1 and 2 for bodies with \( R_p = 20 \) km reveals the influence of \( \phi_{init} \). For \( t_{form} = 1.3 \) Myr, the models were solid for \( \phi_{init} \lesssim 0.3 \) and molten for \( \phi_{init} \gtrsim 0.4 \). Hence, the effects of initial porosity only affected this transitional stage for the smallest bodies in our parameter space.

Static melt regime. This class of simulations showed characteristics of phase transitions from solid to molten states, indicated with green circles and diamonds in Fig. 1. For the deviations between these we refer to the discussion of our model limitations in Sect. 4. An example of a static melt model is given in Fig. 3. In the composition Fig. we see molten silicate phases shown in red. As the material in the inner parts could not cool as efficiently as the outer parts higher temperatures occurred and thus silicates in this region tended to melt. Hence, the density in the outer shells was higher than in the inner parts. Simulations of this class were dominant for bodies with \( R_p \leq 50 \) km. For \( R_p = 20 \) km the boundary for the transition from solid to melt was \( t_{form} \approx 1.3 \) Myr, for \( R_p = 50 \) km it was \( t_{form} \approx 1.6 \) Myr. In bodies with \( R_p = 80 \) km this class could be found solely for \( t_{form} = 1.6 \) Myr, marking the boundary to the transition from solid models to more dynamic models displaying convection.
Deformed melt regime. This class marked the transition from the static melt to the mixing regime in the three-dimensional parameter space. A deformation example is given in Fig. 4 for an evolutionary stage with molten silicate phases and deformed layers, which clearly deviated from the initial circular structure. This kind of models reached higher temperatures than their static melt-bearing counterparts. Due to the larger density contrast this leaded to the onset of mass segregation within the body. An interesting case is given for $R_p = 50$ km. These bodies were dominated by deformation for $\phi_{init} \geq 0.4$ and $t_{form} \leq 1.3$ Myr. This type is categorized differently as it indicates the restrictions of our model: if the viscosities fell below $\eta_{num}$, fluid motions could not always be correctly resolved, in spite of accurately modeling the heat flux. Again, for a more detailed discussion on this issue see Sect. 4.

Mixing regime. The class of mixing models was the most dynamic of all types. An example is given in Fig. 5 showing the onset of convection due to extreme heating conditions within the body due to high SLR abundances. In these cases the density contrast of inner and outer layers initiated and drove convectional motion. The subsequent downwellings from the surface layers (cool and dense) to the inner parts (hot and buoyant) are reflected in the composition, temperature and density plots. We will discuss the time evolution of this in Sect. 5.1.4. Models of this kind were only found for bodies with $R_p \geq 80$ km. The formation time is less important than the radius, but showed significant effects by lowering the threshold $t_{form}$ for smaller bodies, i.e., $R_p \leq 140$ km models did not mix anymore above $t_{form} \geq 1.6$ Myr, whereas $R_p \geq 170$ km models did. Even less influential for the qualitative evolution were changes in initial porosity, for which no significant variance was observed.

3.1.2. Heat balance

This section is devoted to an analysis of the energy reservoir in the bodies over time. To analyze the influence of each of the varied simulation parameters we construct isolines, fixing two of the three parameters (see figures 6a and 7). The models which are discussed here were among the simulations with the most extreme differences in peak temperature and are therefore best suited to show general trends in the data.

Influence of planetesimal radius $R_p$. Figure 6a shows the radius isolines for all $R_p$ values for models with $t_{form} = 1.7$ Myr and $\phi_{init} = 0.25$. In general, smaller bodies cooled more efficiently than their larger counterparts, which were prone to reach higher temperatures. This resulted in lower viscosities for the latter and gave them more time to develop deformed structures or convection.

Influence of formation time $t_{form}$. Figure 6b shows the influence of the formation time on models with $R_p = 20$ km and $\phi_{init} = 0.4$. There are two interesting characteristics to note in this plot. Firstly, the bodies with $t_{form} = 0.1/0.5$ Myr showed a steep increase in temperature, compared to all other $t_{form}$ isolines but reached a sudden turning point at $t \approx 7.2 \cdot 10^5$ Myr. These bodies incorporated more $^{26}$Al due to its half-life time of $t_{1/2} \approx 7.2 \cdot 10^5$ Myr. When the temperatures increased, the material transitioned to molten states and viscosities $\eta \leq \eta_{num}$ occurred, the soft turbulence model set in and increased the heat flux, which permitted the body to cool at an elevated rate (see Sect. 4). Secondly, simulations with stronger heating sources and therefore higher peak temperatures showed steeper cooling
curves than models with later formation time. In practice, the ordering of formation isolines is reverted at $t = 8$ Myr. This can be explained with the higher thermal conductivity of molten silicate states. The models with higher peak temperatures reached higher melt fractions than those with lower peak temperatures, and are therefore able to cool down more efficiently.

**Influence of initial porosity $\phi_{\text{init}}$.** Figure 7 shows the contribution of initial porosity on peak temperature deviations in bodies with $R_p = 20$ km and $t_{\text{form}} = 1.75$ Myr. In general, higher porosity increases the voids within the granular material, effectively lowering the thermal conductivity. Therefore, models with higher initial porosity sustained their internal heat by SLRs over a longer time period. Fig. 7 shows an extreme case in the overall parameter range, where the maximum peak temperatures deviated by $\Delta T \approx 120$ K, not enough to achieve qualitative differences, as all peak temperatures were below the melting temperature for silicates.

To check for local variations of the temperature within specific planetesimals, we derive peak temperature profiles by assessing the maximum value from four points at the same distance from the planetesimal center. Therefore, the values in Fig. 7 represent the maximum temperatures at a certain depth, which does not necessarily imply the same average value for this depth for non-axisymmetric behavior. However, irrespective of a few specific cases these are nearly undistinguishable and certainly not in the range in which these differences affect the long-term thermo-mechanical evolution. Hence, we restrict our discussion to the maximum temperature case. The variations in peak temperature with depth were most importantly effecting small bodies, most remarkably $R_p = 20$ km in our parameter space. Therefore, Fig. 7b shows the porosity isolines for the simulation with $R_p = 20$ km and $t_{\text{form}} = 1.75$ Myr at time $t = 4.61$ Myr. Going from the surface of the planetesimal to its center the temperature differences increased.

As displayed in both plots of Fig. 7 in such small planetesimals the peak temperatures were not enough for the onset of melting. Thus, the temperature deviations due to porosity changes did not result in qualitative differences between the displayed models. Since the peak temperature differences between porosity isolines decrease for all other parameter combinations the porosity did not have a significant effect on the thermo-mechanical evolution of the planetesimals.

### 3.2. Porous shells

Additional to the marginal effect of porosity changes on the peak temperature and the thermo-mechanical evolution, the majority of our models with initial porosity showed a porous shell feature. As illustrated for several models in Fig. 8 these structures were retained during the thermo-mechanical evolution and formed because of two effects. Firstly, compaction due to self-gravity by cold pressing (Equation 12) lowered the porosity within the body close to $\phi = 0.42$ and consequently increased the density contrast between the outermost layers and the layers deeper inside the body. Secondly, during the temporal evolution of the models the temperatures deep within the planetesimals were by far higher than those close to the surface. The temperatures within the body were high enough for sintering effects, which altered the porosity value according to Equation 15. Because both effects were unimportant closer to the surface, a large subset of the model retained a porous layer throughout their whole evolution. Only the models with the most extreme heating values were hot enough to sinter or melt even their outermost layers. Fig. 8 shows the combined effects of planetesi-
3.3. 3D analogues

As described in Sect. 2.5 we additionally performed a set of 3D simulations for different parameter combinations to check for possible deviations from the 2D results. All 3D models are listed in Table B.4.

In principal, the selected 3D simulations confirmed the general trends we have found in two dimensions before. Smaller bodies with \( R_p \leq 50 \text{ km} \) displayed solid or static molten type and developed no convection patterns, regardless of their formation time. Larger bodies were more likely to experience convectional mixing, as illustrated in Fig. 11. Comparable to the 2D simulations the formation time was the dominant parameter for the thermo-mechanical evolution and the onset of melting processes: early formed bodies experienced stronger heating by SLRs. As expected from the 2D results we also found porous shells in the appropriate parameter ranges.

The 3D models, however, did not perfectly match the results from the 2D simulations, as can be seen for model number 624, with \( R_p = 110 \text{ km}, \phi_{init} = 0.25 \) and \( t_{form} = 1.7 \text{ Myr} \), which evolved to a static molten state and did not retain a porous shell. Its 2D counterpart however was solid throughout its evolution and we found a shell at the end of its thermo-mechanical evolution. In general, as far as we can conclude from the restricted model set of 3D simulations, they seem to have experienced higher temperatures than their respective 2D analogues and thus the whole parameter space was shifted toward a higher fraction of static molten, deformed molten and mixing models. As already mentioned in the introduction, this result is expected and can be attributed to the lower surface-to-volume ratio of 3D models. Hence, planetesimals in 3D experienced a lower heat flux compared to their increased volume and abundance of porous shells.
Figure 4: Example of a deformation model, with $R_p = 50$ km, $t_{\text{form}} = 1.0$ Myr, $\phi_{\text{init}} = 0.75$ at $t = 14.06$ Myr. The temperatures were high enough to initiate the onset of convection but could not sustain these temperatures long enough for mixing to occur.

Figure 5: Example of a mixing model, with $R_p = 140$ km, $t_{\text{form}} = 0.5$ Myr, $\phi_{\text{init}} = 0.4$ at $t = 10.83$ Myr. The density contrast of inner and outer layers drove convection.

SLRs and therefore reached higher internal temperatures.

All in all, our 3D models were capable of reproducing the most important structures, compositional types and porosity features of the 2D models with slightly shifted regime boundaries and therefore verified the main conclusions we have drawn before.

4. Model limitations

The main caveat regarding the evolutionary channels from Sect. 3.1 is the lower cut-off viscosity $\eta_{\text{num}}$, whereas we expect that the real viscosity at melt fractions above 0.4 drops to values orders of magnitudes smaller than the applied lower cut-off viscosity (see Sect. 2.3 for examples). This especially happened for models with early formation times $t_{\text{form}} = 0.1 / 0.5$ Myr, i.e., within the first few half-life times of $^{26}$Al. As mentioned before these low viscosities cannot be resolved numerically.

To estimate which of our numerical models would have experienced convection, that could not be resolved, we estimate the onset time of convection based on the approach of Howard (1964). Since internal heating was important in the models, we employ the Roberts-Rayleigh number (Roberts, 1967), which can be used to compute the boundary layer Roberts-Rayleigh number

$$R_{\text{\alpha}} = \frac{\alpha \rho_0 H_0 \delta^5}{k \eta},$$

with reference density $\rho_0$, boundary layer thickness $\delta$ and thermal diffusivity $\kappa$. For the latter we use the characteristic diff-
phase, it is unlikely for planetesimals to be shaped perfectly symmetric. Irregular body structures would result in higher surface to volume ratios, hence enabling a faster cooling of the body (Davison et al., 2013).

Furthermore, as already discussed in Golabek et al. (2014), a more sophisticated approach for representing melt migration processes, cooling effects via $^{26}$Al partitioning (Sahijpal et al., 2007) and iron-silicate-separation (Schubert et al., 1986) would incorporate a two-phase flow model, which was not featured here. Finally we did not consider the effect of melt composition on melt density, which would influence our melting-mixing boundary (Fu and Elkins-Tanton, 2014).

5. Discussion & implications

In Sect. 4 we have presented the results from our set of 2D and 3D computational models of the thermo-mechanical evolution of recently formed planetesimals with varied radius, instantaneous formation time and initial porosity to gain a better understanding of the processes in the early stages of terrestrial planet formation. We now discuss the key insights of our results.

Initial porosity of the bodies was only of minor importance for the model set we have run here. Although higher initial porosity tended to lower thermal conductivity and therefore favored higher internal temperatures, the thermo-mechanical evolution was only marginally affected.

As expected, radius of the body and formation time had a strong influence on the evolution of a planetesimal. With increasing radius and decreasing formation time the bodies ex-
Figure 11: Density isocontours in a mixing 3D model, with $R_p = 110$ km, $\phi_{\text{init}} = 0.25$ and $t_{\text{form}} = 0.1$ Myr. The density increased from the inside (dark red, $\rho = 3100$ kg m$^{-3}$) to the outside (dark blue, $\rho = 3385.6$ kg m$^{-3}$). Therefore, the model experienced buoyancy driven mass movement.

With decreasing radius of the body the technical assessment of the numerical model became more important, as a thermo-mechanical regime with partially molten, but non-convectional interior was observed (static melt class in Fig. 1). In this regime with $\varphi \leq 0.4$ we expect the Stokes velocity $v_{\text{Stokes}} \sim g/\eta$ for iron droplets to be small, such that the time scale for differentiation is high. These melt-bearing but undifferentiated planetesimals are a potentially important link for impact splash models of chondrule formation (see, e.g., Sanders and Taylor [2005]).

For a more stringent analysis of the importance of these models and corresponding parameter ranges we will further evaluate this connection in future work.

A subset of our models evolved to a state with highly porous outer layers, which altered the cooling history of the planetesimal. These shells occupied a larger fraction of the planetesimal radius with later formation time and smaller radius of the body. Hence, smaller and later formed objects were the most porous bodies, which can have implications on their dynamical behavior during impact processes, as investigated by Jutzi et al. [2008, 2009]. The larger planetesimals in our dataset can either be subject to catastrophic impact events with similar-sized bodies or subject to impacts by smaller bodies. For both cases the state of the material is important for the interaction with the encountered body. All in all these effects tend to influence the dynamical history of the accretion phase of terrestrial planets and cannot be neglected for investigations of collisional growth. Additionally, the thickness of the shells could be used to relate the structure of pristine bodies in the Solar System, which did not experience catastrophic impact events after their rapid formation, to their formation time.

Many of our models reached elevated temperatures, potentially high enough to outgas existing volatile elements. When these models reached a specific boundary the resulting bodies might end up as dry bodies, unable to deliver volatile elements to the forming planets via impacts. Thus, future studies will investigate the effect of SLR heating and initial porosity on the outgassing of volatiles in small bodies and therefore might have implications for the habitability of planetary systems, when related to the delivery to accreting terrestrial planets (e.g., Elser et al. [2012], Ciesla et al. [2015]).

The more moderate models still showed temperatures high enough for hydration and metamorphic transformation processes, potentially creating serpentinites via an exothermic reaction. As discussed in Abramov and Mojzsis [2011], such reactions can provide energy for non-volcanic hydrothermal activity. Within certain depths of onion shell structured planetesimals, which are in accordance with our models and previous work (Weiss and Elkins-Tanton [2013] and references therein), the energy output might be in the right regime for the synthesis of primitive organic compounds, such as basic amino acids (Cobb and Pudritz [2014]). Their synthesis is dependent on the ammonia and water content of the corresponding planetesimal and can also change with radial distance to the central star (Cobb et al. [2015]). Therefore, future studies can be directed to couple interior evolution to exterior formation conditions, i.e., the region in the protoplanetary disk and the appropriate formation time for various size classes, to gain a better understanding of the geological environment of early biological processes in our Solar System.

6. Conclusions

The initial state of planetesimals in the early Solar System crucially affected their thermo-mechanical evolution, which yields implications for terrestrial planet formation theories. We have conducted numerous 2D and 3D finite-difference fluid dynamics simulations of planetesimals with varying radius, formation time and initial porosity. From these we have determined the parameter space for various thermo-mechanical regimes and the influence of initial porosity. Our conclusions are the following:

- Typically, planetesimals with large size, early formation time and high initial porosity tended to develop convection. Small radii, late formation times and low porosities led to bodies which did not experience silicate melting.
- A third thermo-mechanical regime with largely molten bodies without convectional mixing existed for an intermediate parameter range with a trend toward small bodies and formation times $t_{\text{form}} \approx 1.1–1.5$ Myr after CAI formation.
• The effects of initial porosity were by far outweighed by those of planetesimal size and formation time, scarcely affecting the qualitative evolution of a planetesimal.

• A majority of models retained a shell of highly porous material in their outer layers, which was not affected by melting and sintering processes inside the bodies. The depth of these shells increased with later formation times and decreased planetesimal size.

With our models we were able to constrain stringent parameter ranges for the major thermo-mechanical regimes and to show that porosity is not a primary factor for the evolution of planetesimals. Future investigations will link these results to specific aspects of terrestrial planet formation, like volatile degassing and chondrule formation. Moreover, connecting these results with SLR enrichment mechanisms in stellar clusters (e.g., Parker et al. 2014, Parker and Dale 2016), and thus probably strongly varying abundances of SLRs, would be beneficial for a comprehensive theory of planetary assembly and habitability on interstellar or galactic scales.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2016.03.004.

Appendix B. List of simulation runs

Table B.3: List of all 2D simulations with radius \( R_p \) (km), formation time \( t_{\text{form}} \) (Myr) and initial porosity \( \phi_{\text{init}} \) (non-dim.). Grid specifies the number of nodes in the finite-difference grid, Shell indicates whether the corresponding model retained a porous shell after its thermo-mechanical evolution, Thermom. regime indicates the evolutionary channel of the model and Unr. Conv. states whether the model resolved the internal fluid motion.

```
| No. | \( R_p \) | \( \phi_{\text{init}} \) | \( t_{\text{form}} \) | Grid | Shell | Thermom. regime | Unr. Conv. |
|-----|-----------|----------------|----------------|------|-------|----------------|-----------|
| 001 | 20        | 0              | 0.1            | 501² | No    | Static melt    | Yes       |
| 002 | 20        | 0              | 0.5            | 501² | No    | Static melt    | Yes       |
```

[http://matplotlib.org](http://matplotlib.org)
[http://bokeh.pydata.org](http://bokeh.pydata.org)
[http://www.paraview.org](http://www.paraview.org)
| No. | R_0 | \(\varphi_{sat}\) | t_{conv} | Grid | Shell | Thermol. regime | Unb. Conv. |
|-----|-----|-----------------|----------|------|-------|----------------|-----------|
| 003 | 20  | 0.4  | 1  | No | Static melt | No | |
| 004 | 20  | 0.4  | 1  | No | Static melt | No | |
| 005 | 20  | 0.4  | 1  | No | Static melt | No | |
| 006 | 20  | 0.4  | 1  | No | Static melt | No | |
| 007 | 20  | 0.4  | 1  | No | Static melt | No | |
| 008 | 20  | 0.4  | 1  | No | Static melt | No | |
| 009 | 20  | 0.4  | 1  | No | Static melt | No | |
| 010 | 20  | 0.4  | 1  | No | Static melt | No | |
| 011 | 20  | 0.4  | 1  | No | Static melt | No | |
| 012 | 20  | 0.4  | 1  | No | Static melt | No | |
| 013 | 20  | 0.4  | 1  | No | Static melt | No | |
| 014 | 20  | 0.4  | 1  | No | Static melt | No | |
| 015 | 20  | 0.4  | 1  | No | Static melt | No | |
| 016 | 20  | 0.4  | 1  | No | Static melt | No | |
| 017 | 20  | 0.4  | 1  | No | Static melt | No | |
| 018 | 20  | 0.4  | 1  | No | Static melt | No | |
| 019 | 20  | 0.4  | 1  | No | Static melt | No | |
| 020 | 20  | 0.4  | 1  | No | Static melt | No | |
| 021 | 20  | 0.4  | 1  | No | Static melt | No | |
| 022 | 20  | 0.4  | 1  | No | Static melt | No | |
| 023 | 20  | 0.4  | 1  | No | Static melt | No | |
| 024 | 20  | 0.4  | 1  | No | Static melt | No | |
| 025 | 20  | 0.4  | 1  | No | Static melt | No | |
| 026 | 20  | 0.4  | 1  | No | Static melt | No | |
| 027 | 20  | 0.4  | 1  | No | Static melt | No | |
| 028 | 20  | 0.4  | 1  | No | Static melt | No | |
| 029 | 20  | 0.4  | 1  | No | Static melt | No | |
| 030 | 20  | 0.4  | 1  | No | Static melt | No | |
| 031 | 20  | 0.4  | 1  | No | Static melt | No | |
| 032 | 20  | 0.4  | 1  | No | Static melt | No | |
| 033 | 20  | 0.4  | 1  | No | Static melt | No | |
| 034 | 20  | 0.4  | 1  | No | Static melt | No | |
| 035 | 20  | 0.4  | 1  | No | Static melt | No | |
| 036 | 20  | 0.4  | 1  | No | Static melt | No | |
| 037 | 20  | 0.4  | 1  | No | Static melt | No | |
| 038 | 20  | 0.4  | 1  | No | Static melt | No | |
| 039 | 20  | 0.4  | 1  | No | Static melt | No | |
| 040 | 20  | 0.4  | 1  | No | Static melt | No | |
| 041 | 20  | 0.4  | 1  | No | Static melt | No | |
| 042 | 20  | 0.4  | 1  | No | Static melt | No | |
| 043 | 20  | 0.4  | 1  | No | Static melt | No | |
| 044 | 20  | 0.4  | 1  | No | Static melt | No | |
| 045 | 20  | 0.4  | 1  | No | Static melt | No | |
| 046 | 20  | 0.4  | 1  | No | Static melt | No | |
| 047 | 20  | 0.4  | 1  | No | Static melt | No | |
| 048 | 20  | 0.4  | 1  | No | Static melt | No | |
| 049 | 20  | 0.4  | 1  | No | Static melt | No | |
| 050 | 20  | 0.4  | 1  | No | Static melt | No | |
| 051 | 20  | 0.4  | 1  | No | Static melt | No | |
| 052 | 20  | 0.4  | 1  | No | Static melt | No | |
| 053 | 20  | 0.4  | 1  | No | Static melt | No | |
| 054 | 20  | 0.4  | 1  | No | Static melt | No | |
| 055 | 20  | 0.4  | 1  | No | Static melt | No | |
| 056 | 20  | 0.4  | 1  | No | Static melt | No | |
| 057 | 20  | 0.4  | 1  | No | Static melt | No | |
| 058 | 20  | 0.4  | 1  | No | Static melt | No | |
| 059 | 20  | 0.4  | 1  | No | Static melt | No | |
| 060 | 20  | 0.4  | 1  | No | Static melt | No | |
| 061 | 20  | 0.4  | 1  | No | Static melt | No | |
| 062 | 20  | 0.4  | 1  | No | Static melt | No | |
| 063 | 20  | 0.4  | 1  | No | Static melt | No | |
| 064 | 20  | 0.4  | 1  | No | Static melt | No | |
| 065 | 20  | 0.4  | 1  | No | Static melt | No |
| No. | $R_e$ | $\phi_{sat}$ | $t_{com}$ | Grid | Shell | Thermo. regime | Unr. Conv. |
|-----|------|--------|------|-----|-----|---------------|-----------|
| 129 | 50  | 0.25   | 1.5   | 501  | Yes  | Static melt   | No        |
| 130 | 50  | 0.25   | 1.6   | 501  | Yes  | Solid         | No        |
| 131 | 50  | 0.25   | 1.7   | 501  | Yes  | Solid         | No        |
| 132 | 50  | 0.25   | 1.75  | 501  | Yes  | Solid         | No        |
| 133 | 50  | 0.3    | 0.1   | 501  | No   | Static melt   | Yes       |
| 134 | 50  | 0.3    | 0.5   | 501  | Yes  | Static melt   | Yes       |
| 135 | 50  | 0.3    | 1     | 501  | Yes  | Static melt   | Yes       |
| 136 | 50  | 0.3    | 1.1   | 501  | Yes  | Static melt   | Yes       |
| 137 | 50  | 0.3    | 1.2   | 501  | Yes  | Static melt   | Yes       |
| 138 | 50  | 0.3    | 1.3   | 501  | Yes  | Static melt   | Yes       |
| 139 | 50  | 0.3    | 1.4   | 501  | Yes  | Static melt   | No        |
| 140 | 50  | 0.3    | 1.5   | 501  | Yes  | Static melt   | No        |
| 141 | 50  | 0.3    | 1.6   | 501  | Yes  | Solid         | No        |
| 142 | 50  | 0.3    | 1.7   | 501  | Yes  | Solid         | No        |
| 143 | 50  | 0.3    | 1.75  | 501  | Yes  | Solid         | No        |
| 144 | 50  | 0.4    | 0.1   | 501  | No   | Static melt   | Yes       |
| 145 | 50  | 0.4    | 0.5   | 501  | Yes  | Def. melt     | Yes       |
| 146 | 50  | 0.4    | 1     | 501  | Yes  | Def. melt     | Yes       |
| 147 | 50  | 0.4    | 1.1   | 501  | Yes  | Def. melt     | Yes       |
| 148 | 50  | 0.4    | 1.2   | 501  | Yes  | Def. melt     | Yes       |
| 149 | 50  | 0.4    | 1.3   | 501  | Yes  | Def. melt     | Yes       |
| 150 | 50  | 0.4    | 1.4   | 501  | Yes  | Def. melt     | No        |
| 151 | 50  | 0.4    | 1.5   | 501  | Yes  | Static melt   | No        |
| 152 | 50  | 0.4    | 1.6   | 501  | Yes  | Solid         | No        |
| 153 | 50  | 0.4    | 1.7   | 501  | Yes  | Solid         | No        |
| 154 | 50  | 0.4    | 1.75  | 501  | Yes  | Solid         | No        |
| 155 | 50  | 0.5    | 0.1   | 501  | No   | Static melt   | Yes       |
| 156 | 50  | 0.5    | 0.5   | 501  | Yes  | Def. melt     | Yes       |
| 157 | 50  | 0.5    | 1     | 501  | Yes  | Def. melt     | Yes       |
| 158 | 50  | 0.5    | 1.1   | 501  | Yes  | Def. melt     | Yes       |
| 159 | 50  | 0.5    | 1.2   | 501  | Yes  | Def. melt     | Yes       |
| 160 | 50  | 0.5    | 1.3   | 501  | Yes  | Def. melt     | Yes       |
| 161 | 50  | 0.5    | 1.4   | 501  | Yes  | Static melt   | No        |
| 162 | 50  | 0.5    | 1.5   | 501  | Yes  | Static melt   | No        |
| 163 | 50  | 0.5    | 1.6   | 501  | Yes  | Solid         | No        |
| 164 | 50  | 0.5    | 1.7   | 501  | Yes  | Solid         | No        |
| 165 | 50  | 0.5    | 1.75  | 501  | Yes  | Solid         | No        |
| 166 | 50  | 0.75   | 0.1   | 501  | No   | Static melt   | Yes       |
| 167 | 50  | 0.75   | 0.5   | 501  | No   | Def. melt     | Yes       |
| 168 | 50  | 0.75   | 1     | 501  | Yes  | Def. melt     | Yes       |
| 169 | 50  | 0.75   | 1.1   | 501  | Yes  | Def. melt     | Yes       |
| 170 | 50  | 0.75   | 1.2   | 501  | Yes  | Def. melt     | Yes       |
| 171 | 50  | 0.75   | 1.3   | 501  | Yes  | Def. melt     | Yes       |
| 172 | 50  | 0.75   | 1.4   | 501  | Yes  | Static melt   | No        |
| 173 | 50  | 0.75   | 1.5   | 501  | Yes  | Static melt   | No        |
| 174 | 50  | 0.75   | 1.6   | 501  | Yes  | Solid         | No        |
| 175 | 50  | 0.75   | 1.7   | 501  | Yes  | Solid         | No        |
| 176 | 50  | 0.75   | 1.75  | 501  | Yes  | Solid         | No        |
| 177 | 80  | 0      | 0.1   | 501  | No   | Mixing        | Yes       |
| 178 | 80  | 0      | 0.5   | 501  | No   | Mixing        | Yes       |
| 179 | 80  | 0      | 1     | 501  | No   | Mixing        | Yes       |
| 180 | 80  | 0      | 1.1   | 501  | No   | Mixing        | No        |
| 181 | 80  | 0      | 1.2   | 501  | No   | Mixing        | No        |
| 182 | 80  | 0      | 1.3   | 501  | No   | Mixing        | Yes       |
| 183 | 80  | 0      | 1.4   | 501  | No   | Mixing        | Yes       |
| 184 | 80  | 0      | 1.5   | 501  | No   | Def. melt     | No        |
| 185 | 80  | 0      | 1.6   | 501  | No   | Static melt   | No        |
| 186 | 80  | 0      | 1.7   | 501  | No   | Solid         | No        |
| 187 | 80  | 0      | 1.75  | 501  | No   | Solid         | No        |
| 188 | 80  | 0.1    | 0.1   | 501  | No   | Mixing        | Yes       |
| 189 | 80  | 0.1    | 0.5   | 501  | No   | Mixing        | Yes       |
| 190 | 80  | 0.1    | 1     | 501  | Yes  | Mixing        | Yes       |
| 191 | 80  | 0.1    | 1.1   | 501  | Yes  | Mixing        | Yes       |
| No. | \(R_P\) | \(\phi_{tot}\) | \(\theta_{tot}\) | Grid | Shell | Thermol. regime | Unr. Conv. |
|-----|--------|------------|-------------|------|-------|-----------------|----------|
| 255 | 80     | 0.75       | 0.5         | 501^2| No Mixing | Yes             | 318       |
| 256 | 80     | 0.75       | 1           | 501^2| Yes Mixing | Yes             | 319       |
| 257 | 80     | 0.75       | 1.1         | 501^2| Yes Mixing | Yes             | 320       |
| 258 | 80     | 0.75       | 1.2         | 501^2| Yes Mixing | Yes             | 321       |
| 259 | 80     | 0.75       | 1.3         | 501^2| Yes Mixing | Yes             | 322       |
| 260 | 80     | 0.75       | 1.4         | 501^2| Yes Mixing | No              | 323       |
| 261 | 80     | 0.75       | 1.5         | 501^2| Yes Mixing | Yes             | 324       |
| 262 | 80     | 0.75       | 1.6         | 501^2| Yes Static melt | Yes             | 325       |
| 263 | 80     | 0.75       | 1.7         | 501^2| Yes Solid  | No              | 326       |
| 264 | 80     | 0.75       | 1.75        | 501^2| Yes Solid  | No              | 327       |
| 265 | 110    | 0         | 0.1         | 501^2| No Mixing  | Yes             | 328       |
| 266 | 110    | 0         | 0.5         | 501^2| No Mixing  | Yes             | 329       |
| 267 | 110    | 0         | 1           | 501^2| No Mixing  | Yes             | 330       |
| 268 | 110    | 0         | 1.1         | 501^2| No Mixing  | Yes             | 331       |
| 269 | 110    | 0         | 1.2         | 501^2| No Mixing  | Yes             | 332       |
| 270 | 110    | 0         | 1.3         | 501^2| No Mixing  | Yes             | 333       |
| 271 | 110    | 0         | 1.4         | 501^2| No Mixing  | Yes             | 334       |
| 272 | 110    | 0         | 1.5         | 501^2| No Mixing  | Yes             | 335       |
| 273 | 110    | 0         | 1.6         | 501^2| No Def. melt | No              | 336       |
| 274 | 110    | 0         | 1.7         | 501^2| No Solid   | No              | 337       |
| 275 | 110    | 0         | 1.75        | 501^2| No Solid   | No              | 338       |
| 276 | 110    | 0.1       | 0.1         | 501^2| No Mixing  | Yes             | 339       |
| 277 | 110    | 0.1       | 0.5         | 501^2| No Mixing  | Yes             | 340       |
| 278 | 110    | 0.1       | 1           | 501^2| Yes Mixing | Yes             | 341       |
| 279 | 110    | 0.1       | 1.1         | 501^2| Yes Mixing | Yes             | 342       |
| 280 | 110    | 0.1       | 1.2         | 501^2| Yes Mixing | Yes             | 343       |
| 281 | 110    | 0.1       | 1.3         | 501^2| Yes Mixing | Yes             | 344       |
| 282 | 110    | 0.1       | 1.4         | 501^2| Yes Mixing | No              | 345       |
| 283 | 110    | 0.1       | 1.5         | 501^2| Yes Mixing | Yes             | 346       |
| 284 | 110    | 0.1       | 1.6         | 501^2| Yes Def. melt | No              | 347       |
| 285 | 110    | 0.1       | 1.7         | 501^2| Yes Solid  | Yes             | 348       |
| 286 | 110    | 0.1       | 1.75        | 501^2| Yes Solid  | No              | 349       |
| 287 | 110    | 0.2       | 0.1         | 501^2| No Mixing  | Yes             | 350       |
| 288 | 110    | 0.2       | 0.5         | 501^2| No Mixing  | Yes             | 351       |
| 289 | 110    | 0.2       | 1           | 501^2| Yes Mixing | Yes             | 352       |
| 290 | 110    | 0.2       | 1.1         | 501^2| Yes Mixing | Yes             | 353       |
| 291 | 110    | 0.2       | 1.2         | 501^2| Yes Mixing | Yes             | 354       |
| 292 | 110    | 0.2       | 1.3         | 501^2| Yes Mixing | Yes             | 355       |
| 293 | 110    | 0.2       | 1.4         | 501^2| Yes Mixing | No              | 356       |
| 294 | 110    | 0.2       | 1.5         | 501^2| Yes Mixing | No              | 357       |
| 295 | 110    | 0.2       | 1.6         | 501^2| Yes Def. melt | No              | 358       |
| 296 | 110    | 0.2       | 1.7         | 501^2| Yes Solid  | No              | 359       |
| 297 | 110    | 0.2       | 1.75        | 501^2| Yes Solid  | No              | 360       |
| 298 | 110    | 0.25      | 0.1         | 501^2| No Mixing  | Yes             | 361       |
| 299 | 110    | 0.25      | 0.5         | 501^2| No Mixing  | Yes             | 362       |
| 300 | 110    | 0.25      | 1           | 501^2| No Mixing  | Yes             | 363       |
| 301 | 110    | 0.25      | 1.1         | 501^2| Yes Mixing | Yes             | 364       |
| 302 | 110    | 0.25      | 1.2         | 501^2| Yes Mixing | Yes             | 365       |
| 303 | 110    | 0.25      | 1.3         | 501^2| Yes Mixing | Yes             | 366       |
| 304 | 110    | 0.25      | 1.4         | 501^2| Yes Mixing | No              | 367       |
| 305 | 110    | 0.25      | 1.5         | 501^2| Yes Mixing | No              | 368       |
| 306 | 110    | 0.25      | 1.6         | 501^2| Yes Def. melt | No              | 369       |
| 307 | 110    | 0.25      | 1.7         | 501^2| Yes Solid  | No              | 370       |
| 308 | 110    | 0.25      | 1.75        | 501^2| Yes Solid  | No              | 371       |
| 309 | 110    | 0.3       | 0.1         | 501^2| No Mixing  | Yes             | 372       |
| 310 | 110    | 0.3       | 0.5         | 501^2| No Mixing  | Yes             | 373       |
| 311 | 110    | 0.3       | 1           | 501^2| Yes Mixing | Yes             | 374       |
| 312 | 110    | 0.3       | 1.1         | 501^2| Yes Mixing | Yes             | 375       |
| 313 | 110    | 0.3       | 1.2         | 501^2| Yes Mixing | Yes             | 376       |
| 314 | 110    | 0.3       | 1.3         | 501^2| Yes Mixing | Yes             | 377       |
| 315 | 110    | 0.3       | 1.4         | 501^2| Yes Mixing | No              | 378       |
| 316 | 110    | 0.3       | 1.5         | 501^2| Yes Mixing | No              | 379       |
| 317 | 110    | 0.3       | 1.6         | 501^2| Yes Def. melt | No              | 380       |
| No. | $R_p$ | $\phi_{min}$ | $t_{geom}$ | Grid | Shell | Thermol. regime | Unr. Conv. |
|-----|-------|--------------|------------|------|-------|----------------|------------|
| 381 | 140   | 0.2          | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 382 | 140   | 0.2          | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 383 | 140   | 0.2          | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 384 | 140   | 0.2          | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 385 | 140   | 0.2          | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 386 | 140   | 0.25         | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 387 | 140   | 0.25         | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 388 | 140   | 0.25         | 1          | 501$^2$ | Yes   | Mixing        | No         |
| 389 | 140   | 0.25         | 1.1        | 501$^2$ | Yes   | Mixing        | No         |
| 390 | 140   | 0.25         | 1.2        | 501$^2$ | Yes   | Mixing        | No         |
| 391 | 140   | 0.25         | 1.3        | 501$^2$ | Yes   | Mixing        | No         |
| 392 | 140   | 0.25         | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 393 | 140   | 0.25         | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 394 | 140   | 0.25         | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 395 | 140   | 0.25         | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 396 | 140   | 0.25         | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 397 | 140   | 0.3          | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 398 | 140   | 0.3          | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 399 | 140   | 0.3          | 1          | 501$^2$ | Yes   | Mixing        | No         |
| 400 | 140   | 0.3          | 1.1        | 501$^2$ | Yes   | Mixing        | No         |
| 401 | 140   | 0.3          | 1.2        | 501$^2$ | Yes   | Mixing        | No         |
| 402 | 140   | 0.3          | 1.3        | 501$^2$ | Yes   | Mixing        | No         |
| 403 | 140   | 0.3          | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 404 | 140   | 0.3          | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 405 | 140   | 0.3          | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 406 | 140   | 0.3          | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 407 | 140   | 0.3          | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 408 | 140   | 0.4          | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 409 | 140   | 0.4          | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 410 | 140   | 0.4          | 1          | 501$^2$ | Yes   | Mixing        | No         |
| 411 | 140   | 0.4          | 1.1        | 501$^2$ | Yes   | Mixing        | No         |
| 412 | 140   | 0.4          | 1.2        | 501$^2$ | Yes   | Mixing        | No         |
| 413 | 140   | 0.4          | 1.3        | 501$^2$ | Yes   | Mixing        | No         |
| 414 | 140   | 0.4          | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 415 | 140   | 0.4          | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 416 | 140   | 0.4          | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 417 | 140   | 0.4          | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 418 | 140   | 0.4          | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 419 | 140   | 0.5          | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 420 | 140   | 0.5          | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 421 | 140   | 0.5          | 1          | 501$^2$ | Yes   | Mixing        | No         |
| 422 | 140   | 0.5          | 1.1        | 501$^2$ | Yes   | Mixing        | No         |
| 423 | 140   | 0.5          | 1.2        | 501$^2$ | Yes   | Mixing        | No         |
| 424 | 140   | 0.5          | 1.3        | 501$^2$ | Yes   | Mixing        | No         |
| 425 | 140   | 0.5          | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 426 | 140   | 0.5          | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 427 | 140   | 0.5          | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 428 | 140   | 0.5          | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 429 | 140   | 0.5          | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 430 | 140   | 0.75         | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 431 | 140   | 0.75         | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 432 | 140   | 0.75         | 1          | 501$^2$ | Yes   | Mixing        | No         |
| 433 | 140   | 0.75         | 1.1        | 501$^2$ | Yes   | Solid        | No         |
| 434 | 140   | 0.75         | 1.2        | 501$^2$ | Yes   | Mixing        | No         |
| 435 | 140   | 0.75         | 1.3        | 501$^2$ | Yes   | Mixing        | No         |
| 436 | 140   | 0.75         | 1.4        | 501$^2$ | Yes   | Mixing        | No         |
| 437 | 140   | 0.75         | 1.5        | 501$^2$ | Yes   | Mixing        | No         |
| 438 | 140   | 0.75         | 1.6        | 501$^2$ | Yes   | Mixing        | No         |
| 439 | 140   | 0.75         | 1.7        | 501$^2$ | Yes   | Solid        | No         |
| 440 | 140   | 0.75         | 1.75       | 501$^2$ | Yes   | Solid        | No         |
| 441 | 170   | 0            | 0.1        | 501$^2$ | No    | Mixing        | No         |
| 442 | 170   | 0            | 0.5        | 501$^2$ | No    | Mixing        | No         |
| 443 | 170   | 0            | 1          | 501$^2$ | No    | Mixing        | No         |
| No. | $R_F$ | $\phi_{init}$ | $t_{form}$ | Grid | SHELL | THERMOM. regime | Unr. Conv. |
|-----|-------|---------------|----------|------|-------|-----------------|-----------|
| 507 | 170   | 0.5           | 0.1      | 501$^2$ | No Mixing | No               | No        |
| 508 | 170   | 0.5           | 0.1      | 501$^2$ | No Mixing | No               | No        |
| 509 | 170   | 0.5           | 1        | 501$^2$ | Yes Mixing | No               | No        |
| 510 | 170   | 0.5           | 1.1      | 501$^2$ | Yes Mixing | No               | No        |
| 511 | 170   | 0.5           | 1.2      | 501$^2$ | Yes Mixing | No               | No        |
| 512 | 170   | 0.5           | 1.3      | 501$^2$ | Yes Mixing | No               | No        |
| 513 | 170   | 0.5           | 1.4      | 501$^2$ | Yes Mixing | No               | No        |
| 514 | 170   | 0.5           | 1.5      | 501$^2$ | Yes Mixing | No               | No        |
| 515 | 170   | 0.5           | 1.6      | 501$^2$ | Yes Mixing | No               | No        |
| 516 | 170   | 0.5           | 1.7      | 501$^2$ | Yes Def. melt | No       | No        |
| 517 | 170   | 0.5           | 1.75     | 501$^2$ | Yes Solid  | No               | No        |
| 518 | 170   | 0.75          | 0.1      | 501$^2$ | No Mixing  | No               | No        |
| 519 | 170   | 0.75          | 0.1      | 501$^2$ | Yes Mixing  | No               | No        |
| 520 | 170   | 0.75          | 1        | 501$^2$ | Yes Mixing  | No               | No        |
| 521 | 170   | 0.75          | 1.1      | 501$^2$ | Yes Mixing  | No               | No        |
| 522 | 170   | 0.75          | 1.2      | 501$^2$ | Yes Mixing  | No               | No        |
| 523 | 170   | 0.75          | 1.3      | 501$^2$ | Yes Mixing  | No               | No        |
| 524 | 170   | 0.75          | 1.4      | 501$^2$ | Yes Mixing  | No               | No        |
| 525 | 170   | 0.75          | 1.5      | 501$^2$ | Yes Mixing  | No               | No        |
| 526 | 170   | 0.75          | 1.6      | 501$^2$ | Yes Mixing  | No               | No        |
| 527 | 170   | 0.75          | 1.7      | 501$^2$ | Yes Def. melt | No       | No        |
| 528 | 170   | 0.75          | 1.75     | 501$^2$ | Yes Solid   | No               | No        |
| 529 | 200   | 0             | 0.1      | 501$^2$ | No Mixing  | No               | No        |
| 530 | 200   | 0             | 0.5      | 501$^2$ | No Mixing  | No               | No        |
| 531 | 200   | 0             | 1        | 501$^2$ | No Mixing  | No               | No        |
| 532 | 200   | 0             | 1.1      | 501$^2$ | No Mixing  | No               | No        |
| 533 | 200   | 0             | 1.2      | 501$^2$ | No Mixing  | No               | No        |
| 534 | 200   | 0             | 1.3      | 501$^2$ | No Mixing  | No               | No        |
| 535 | 200   | 0             | 1.4      | 501$^2$ | No Mixing  | No               | No        |
| 536 | 200   | 0             | 1.5      | 501$^2$ | No Mixing  | No               | No        |
| 537 | 200   | 0             | 1.6      | 501$^2$ | No Mixing  | No               | No        |
| 538 | 200   | 0             | 1.7      | 501$^2$ | No Mixing  | No               | No        |
| 539 | 200   | 0             | 1.75     | 501$^2$ | No Solid   | No               | No        |
| 540 | 200   | 0.1           | 0.1      | 501$^2$ | No Mixing  | No               | No        |
| 541 | 200   | 0.1           | 0.5      | 501$^2$ | No Mixing  | No               | No        |
| 542 | 200   | 0.1           | 1        | 501$^2$ | Yes Mixing  | No               | No        |
| 543 | 200   | 0.1           | 1.1      | 501$^2$ | Yes Mixing  | No               | No        |
| 544 | 200   | 0.1           | 1.2      | 501$^2$ | Yes Mixing  | No               | No        |
| 545 | 200   | 0.1           | 1.3      | 501$^2$ | Yes Mixing  | No               | No        |
| 546 | 200   | 0.1           | 1.4      | 501$^2$ | Yes Mixing  | No               | No        |
| 547 | 200   | 0.1           | 1.5      | 501$^2$ | Yes Mixing  | No               | No        |
| 548 | 200   | 0.1           | 1.6      | 501$^2$ | Yes Mixing  | No               | No        |
| 549 | 200   | 0.1           | 1.7      | 501$^2$ | Yes Mixing  | No               | No        |
| 550 | 200   | 0.1           | 1.75     | 501$^2$ | Yes Solid  | No               | No        |
| 551 | 200   | 0.2           | 0.1      | 501$^2$ | No Mixing  | No               | No        |
| 552 | 200   | 0.2           | 0.5      | 501$^2$ | No Mixing  | No               | No        |
| 553 | 200   | 0.2           | 1        | 501$^2$ | Yes Mixing  | No               | No        |
| 554 | 200   | 0.2           | 1.1      | 501$^2$ | Yes Mixing  | No               | No        |
| 555 | 200   | 0.2           | 1.2      | 501$^2$ | Yes Mixing  | No               | No        |
| 556 | 200   | 0.2           | 1.3      | 501$^2$ | Yes Mixing  | No               | No        |
| 557 | 200   | 0.2           | 1.4      | 501$^2$ | Yes Mixing  | No               | No        |
| 558 | 200   | 0.2           | 1.5      | 501$^2$ | Yes Mixing  | No               | No        |
| 559 | 200   | 0.2           | 1.6      | 501$^2$ | Yes Mixing  | No               | No        |
| 560 | 200   | 0.2           | 1.7      | 501$^2$ | Yes Mixing  | No               | No        |
| 561 | 200   | 0.2           | 1.75     | 501$^2$ | Yes Solid  | No               | No        |
| 562 | 200   | 0.25          | 0.1      | 501$^2$ | No Mixing  | No               | No        |
| 563 | 200   | 0.25          | 0.5      | 501$^2$ | No Mixing  | No               | No        |
| 564 | 200   | 0.25          | 1        | 501$^2$ | Yes Mixing  | No               | No        |
| 565 | 200   | 0.25          | 1.1      | 501$^2$ | Yes Mixing  | No               | No        |
| 566 | 200   | 0.25          | 1.2      | 501$^2$ | Yes Mixing  | No               | No        |
| 567 | 200   | 0.25          | 1.3      | 501$^2$ | Yes Mixing  | No               | No        |
| 568 | 200   | 0.25          | 1.4      | 501$^2$ | Yes Mixing  | No               | No        |
| 569 | 200   | 0.25          | 1.5      | 501$^2$ | Yes Mixing  | No               | No        |

Table B.4: List of all 3D simulations with radius $R_F$ (km), formation time $t_{form}$ (Myr) and initial porosity $\phi_{init}$ (non-dim.). Grid specifies the number of nodes in the finite-difference grid, SHELL indicates whether the corresponding model retained a porous shell after its thermo-mechanical evolution ended and THERMOM. regime indicates the evolutionary channel of the model.
whether the corresponding model retained a porous shell after its thermo-mechanical evolution.

| No. | $R_p$ (km) | $\phi_{init}$ | $t_{form}$ (Myr) | Grid | Shell | Therm. regime |
|-----|------------|---------------|-----------------|------|-------|---------------|
| 625 | 140        | 0.2           | 0.5             | 261  | No    | Mixing        |
| 626 | 140        | 0.4           | 1.0             | 261  | No    | Mixing        |
| 627 | 170        | 0.4           | 1.3             | 261  | No    | Mixing        |

Table B.5: List of all 2D simulations of thermo-mechanical type static melt, for which the numerical model is consistent with the analytical solution. Parameters are radius $R_p$, formation time $t_{form}$ (Myr), initial porosity $\phi_{init}$ (non-dim.), Grid specifies the number of nodes in the finite-difference grid, Shell indicates whether the corresponding model retained a porous shell after its thermo-mechanical evolution.

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