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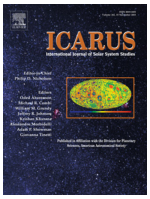

# The effects of short-lived radionuclides and porosity on the early thermo-mechanical evolution of planetesimals

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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 $^{26}$Al and $^{60}$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 I2ELVIS/I3ELVIS 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.

## 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 $\sim 10^1 - 10^2$ km (Weidenschilling and Cuzzi, 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 $t_s \sim \rho_p R_p / (\Sigma_{\rm disk} \Omega_K)$ 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 $\Sigma_{\rm disk}$ and Keplerian frequency $\Omega_K$ (Goldreich et al., 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., 2010) and the radial migration of solids due to gas drag (Weidenschilling, 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., 2007; Cuzzi et al., 2008; Morbidelli et al., 2009; Chambers, 2010; Johansen et al., 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., 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, 1998; Hevey and Sanders, 2006; Sahijpal et al., 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 $^{26}$Al and $^{60}$Fe, which would alter their inner structure and evolution dramatically

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**Table 1**
List of physical parameters in the numerical model.

| Parameter | Symbol | Value | Unit | Reference |
|---|---|---|---|---|
| Density of uncompressed solid silicates | $\rho_{\text{Si-sol}}$ | 3500 | kg $m^{-3}$ | Stolper et al. (1981);<br>Suzuki et al. (1998) |
| Density of uncompressed molten silicates | $\rho_{\text{Si-liq}}$ | 2900 | kg $m^{-3}$ | Stolper et al. (1981) |
| Temperature of space (sticky air) | $T_{\text{space}}$ | 290 | K | Ghosh and McSween (1998);<br>Barshay and Lewis (1976) |
| Activation energy | $E_a$ | 470 | kJ $mol^{-1}$ | Ranalli (1995) |
| Dislocation creep onset stress | $\sigma_0$ | $3 \cdot 10^7$ | Pa | Turcotte and Schubert (2014) |
| Power law exponent | $n$ | 4 | | Ranalli (1995) |
| Latent heat of silicate melting | $L_{\text{Si}}$ | 400 | kJ $kg^{-1}$ | Ghosh and McSween (1998);<br>Turcotte and Schubert (2014) |
| Silicate melt fraction at rheological transition | $\varphi_{\text{crit}}$ | 0.4 | non-dim. | Solomatov (2015);<br>Costa et al. (2009) |
| Heat capacity of silicates | $c_P$ | 1000 | J $kg^{-1}$ $K^{-1}$ | Turcotte and Schubert (2014) |
| Thermal expansivity of solid silicates | $\alpha_{\text{Si-sol}}$ | $3 \cdot 10^{-5}$ | $K^{-1}$ | Suzuki et al. (1998) |
| Thermal expansivity of molten silicates | $\alpha_{\text{Si-liq}}$ | $6 \cdot 10^{-5}$ | $K^{-1}$ | Suzuki et al. (1998) |
| Thermal conductivity of solid silicates | $k$ | 3 | W $m^{-1}$ $K^{-1}$ | Tarduno et al. (2012) |
| Thermal expansivity of molten silicates | $k_{\text{eff}}$ | $\leq 10^6$ | W $m^{-1}$ $K^{-1}$ | Golabek et al. (2014) |
| Minimum thermal conductivity of unsintered solid silicates | $k_{\text{low}}$ | $10^{-3}$ | W $m^{-1}$ $K^{-1}$ | Yomogida and Matsui (1984);<br>Henke et al. (2012) |
| Temperature at onset of hot sintering | $T_{\text{sint}}$ | 700 | K | Yomogida and Matsui (1984) |

up to the point of silicate melting. For example, bodies greater than ~10 km in radius, formed at the time of CAI formation, are supposed to melt completely (Hevey and Sanders, 2006). Secondly, some meteorite parent bodies seem to have experienced solid-state deformation (Tkalcec and Brenker, 2014; Tkalcec et al., 2013). 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 (Elkins-Tanton et al., 2011; Qin et al., 2008; Schubert et al., 1986). 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 $^{26}$Al half-lives.

Clearly, the thermo-mechanical evolution of planetesimals needs to be treated adequatly 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 Section 2 we describe constraints from earlier work and outline the most important concepts of our numerical model; in Section 3 we present the results obtained from the simulation runs, for which we outline the technically inherent limitations in Section 4. In Section 5 we discuss the physical implications and draw conclusions in Section 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-mechnical 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 Section 1 we studied the thermo-mechanical evolution of instantaneously and recently formed planetesimals using the I2ELVIS/I3ELVIS 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

$$\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{v} = 0, \tag{1}$$

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

$$\nabla \sigma' - \nabla P + \rho \mathbf{g} = 0, \tag{2}$$

with deviatoric stress tensor $\boldsymbol{\sigma}'$, pressure $P$ and directional gravity $\mathbf{g}$ obtained via the location-dependent Poisson equation

$$\nabla^2 \Phi = 4\pi G \rho, \tag{3}$$

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

$$\rho c_P \left( \frac{\partial T}{\partial t} + v_i \cdot \nabla T \right) = -\frac{\partial q_i}{\partial x_i} + H_r + H_s + H_L, \tag{4}$$