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Numerical Simulation of Convection in a Partially Molten Planetesimal

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Abstract

Compositional differences between meteorites have been interpreted as being indicative of wide variations in the degree of differentiation of their parent bodies (planetesimals). Differentiated planetesimals must have undergone (at least partial) melting caused by short lived nuclides ^{26}Al and ^{60}Fe [1]. Thermal models [2, 3, 4] have shown that planetesimals may experience differing degrees of partial melting depending on the onset time of accretion relative to the time of formation of the Ca-Al-rich inclusions (CAIs), the accretion time, and the final size of the planetesimals. Even the presence of a magma ocean for these bodies has been suggested in the case of rapid accretion. These thermal models base upon thermal conduction only and disregard the possibility of convection before a magma ocean develops. In fact, convection in a solid planetesimal is unlikely. However, it may set in for a sufficient amount of partial melt even before the existence of a magma ocean — e.g., melt reduces the viscosity of the material by 3–4 orders of magnitude for 25% of partial melt in suspension. Whether the existence of convection is possible can be roughly estimated with the internally heated Rayleigh number (Eq.(2)), i.e., a measure for the strength of convection, as a function of the layer thickness for different values of viscosity (Fig. 1). The result suggests that the interior may actually convect even at small degrees of partial melting. Considering that convection increases the heat transport in the interior and that the planetesimal will cool faster under these circumstances, the thermal evolution of a planetesimal and the amount of partial melt that can be produced may differ from what is predicted in earlier studies [2, 3, 4].

In the present study, we test the existence and strength of convection in a planetesimal (radius of 260 km) and its consequences for the thermal evolution. We use a 3D spherical convection model (*GAIA*) [5, 6] in which the viscosity depends on temperature and the degree of partial melt according the following Arrhenius law:

$$\eta(T,\chi) = \eta_{ref} \exp\left(\alpha_\eta \chi\right) \exp\left(\frac{E}{RT}\right) \qquad (1)$$

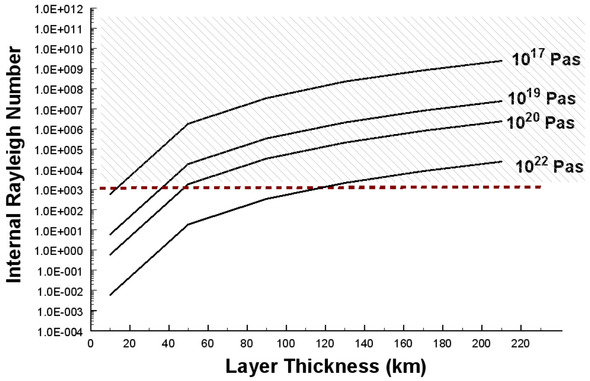

Figure 1: *Internally heated Rayleigh number as a function of layer thickness (radius of the planetsimal) for different values of viscosity. For the calculation of Ra (Eq. (2)), we have assumed a heat source density of* $H = 6.6 \cdot 10^{-5} W/m^3$*. This value corresponds to a heat source density at the time of 2 Ma after CAIs assuming the canonical value of* ^{26}*Al/*^{27}*Al to be* $5 \cdot 10^{-5}$*. The dashed line indicates the critical Rayleigh number above which convection occurs (shaded area). Viscosities lower than about* 10^{21} *Pas are likely if the melt remains in suspension with the silicate (e.g., for 15% melt the viscosity is about* 10^{18} *Pa s for dislocation creep).*

with E the activation energy, R the gas constant, T the temperature, η_{ref} the reference viscosity, χ the melt fraction, and α_η a constant that varies between 26 for diffusion creep and 31 for dislocation creep [7]. A free-slip boundary condition is applied at the surface of a purely internally heated sphere. To take the full sphere geometry into account the acceleration of gravity, g, decreases linearly to zero in the centre. Thus, the Rayleigh number is depth-dependent according to:

$$Ra(r) = \frac{\rho g(r) \alpha H r^5}{k \kappa \eta} \qquad (2)$$

with $g(r) = 4/3\, G\, \rho\, r$, ρ the density, α the thermal expansivity, H the radioactive heat source density, r the planetary radius, k the thermal conductivity, and κ the thermal diffusivity. In this preliminary study we

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do not consider variations of the thermal conductivity or any volcanic heat transport.

We will compare the thermal evolution for models with and without a reduced viscosity due to partial melting. Heat fluxes, temperature distribution (profiles) and melt content in the interior as a function of time are used as basic criteria to determine the differences.

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