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Core and crust formation on Vesta: Controlling factors

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Abstract

We evaluate the differentiation history of Vesta as a function of the initial composition, density contrasts between the melt and the matrix, partitioning of ^{26}Al, grain growth via Ostwald ripening, and the viscosity of the melt. To this end, we consider a partially molten planetesimal consisting of iron and silicates in the spherical symmetry, and compute the segregation of iron and silicate melt according to the flow in porous media theory by using the Darcy flow equation.

1. Introduction

Recent observations by Dawn confirmed Vesta as a differentiated body with an iron rich core, a silicate mantle and a basaltic crust. Its core radius is estimated to be $105 - 126$ km [1] and its crust to be at least $30 - 45$ km thick [2]. Vesta is the only known intact differentiated asteroid and is widely held as the parent body of the HED meteorites. The origin of the HEDs is closely related to the differentiation history. The chronological records of HEDs seem to indicate that the core-mantle differentiation likely precedes the mantle-crust differentiation [3]. However, the formation scenarios of the eucrites and diogenites are discussed contradictory and either assume the solidification of the early partial melt of the silicate phase [4], or magma fractionation in a magma ocean or magma chambers [5],[6].

Here, we investigate the differentiation of Vesta by porous flow, evaluating thereby the influence of several parameters on the timing of core, mantle and crust formation, as well as on the possibility of the formation of a magma ocean.

2. Model

We use our thermal evolution model from previous studies [7], [8], which considers thermal and structural evolution of ordinary chondritic planetesimals including differentiation. In these studies, it has been recognised that, in particular, the velocity of the melt relative to the solid matrix determines the timing of the differentiation events and the existence of a whole-mantle magma ocean.

The melt velocity relative to the solid matrix, Δv, is computed from the Darcy law:

$$\Delta v = \frac{K \Delta \rho g}{\varphi \eta} \tag{1}$$

with the permeability $K = \frac{b^2 \varphi^n}{\tau}$, the grain size b, the volume fraction of the melt φ, the Darcy coefficient τ, the Darcy exponent n, the density contrast $\Delta \rho$, the gravity g, and the viscosity of the melt η.

3. Results

We investigate the influence of the following factors on the process of melt segregation in a partially molten system.

1) Grain size b and Ostwald ripening: Metal melt segregation can occur prior to silicate melting for large grains (e.g., 10^{-2} m), or is negligible prior to the melting of the silicate phase for small grains ($\approx 10^{-4}$ m). Ostwald ripening can cause a rapid increase of the grain size and, thus, of the permeability. It is in particular important for the formation of the basaltic crust due to the ascending silicate melt, taken a strong cooling in the shallow depths.

2) Composition and corresponding solidus and liquidus temperatures of silicates and iron-rich components: Adopted mineral abundances determine the volume fraction of the silicate and metal phases. Thus, after the onset of melting of, e.g., metal, the melt in a composition with more metal (e.g., H chondritic relative to L or LL chondritic ones) will have a higher segregation velocity. Furthermore, the solidus and liquidus temperatures T_S and T_L of the phases determine the melt fraction at a given temperature and, therefore, the segregation velocity. Note that most numerical studies used a melting window for the metal phase of only 20 K between 1213 K and 1233 K, which results in an unrealistically high metal melt fraction

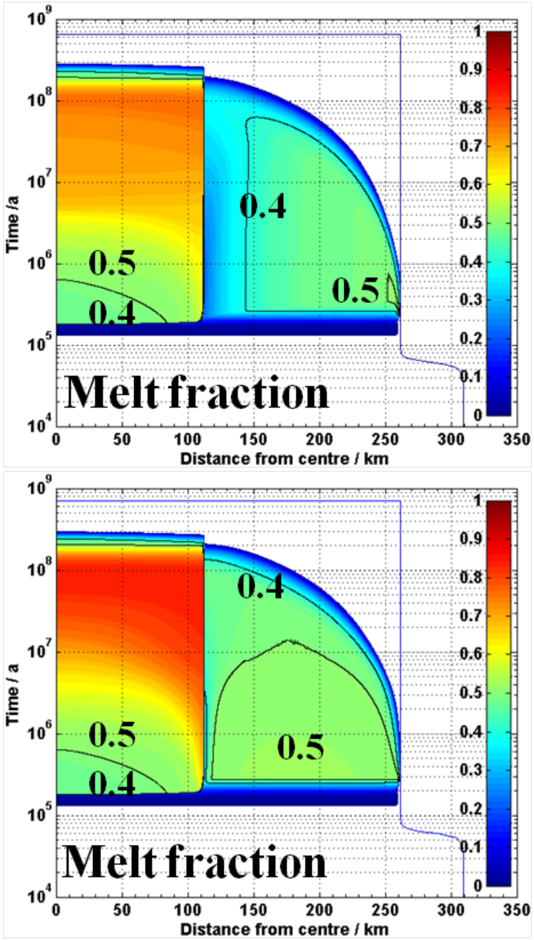

Figure 1: Melt fraction as a function of radius and time. Considered is a Vesta-like body which forms contemporaneously with the Ca-Al-rich inclusion. Here, the viscosity of either 10 Pa s (upper panel) or of 100 Pa s (lower panel) is used.

and in the core formation long before the melting of silicates.

3) Density contrast between the melt and the solid matrix $\Delta\rho$: Some silicate melts are weakly positively, or even negatively buoyant relative to a silicate matrix [9]. Such melts would remain in the mantle and would not contribute to the crust thickness.

4) Partitioning of ^{26}Al into the silicate melt: This process is important for the differentiation in the shallow depths and for the formation of the basaltic crust, due to the accumulation of ^{26}Al in the sub-surface and a possible formation of a shallow magma ocean [8].

5) Viscosity of the silicate melt η: A large variation by several orders of magnitude makes this the most important parameter for the formation of a basaltic crust. It determines furthermore, whether a shallow magma ocean or a whole-mantle magma ocean forms (Fig. 1).

Our work provides constraints on the differentiation event on Vesta. We will show evolution scenarios that are consistent with the observational constraints such as the core size and crustal thickness, as well as with the experimental results implying that the relative timing of the core-mantle differentiation likely precedes the mantle-crust differentiation.

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