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No global magma ocean in Vesta's mantle

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Abstract

The Dawn mission confirms predictions that the asteroid 4 Vesta is differentiated in an iron rich core, a silicate mantle and a basaltic crust and supports its identification as the parent body of the HEDs. Also, revised values of e.g. the mass, the bulk density, the dimensions and the surface of the asteroid 4 Vesta are now available. Although no distinct volcanic regions have been identified[1], resurfacing by igneous processes distinguishes Vesta from asteroids like Ceres with its primitive surface characterised by aqueous alteration, or Lutetia, which retained its primordial surface composition (and may still be partially differentiated, see [2]). From the mass concentration towards the centre, Vesta's core radius is estimated to be 107 - 113 km[3,4]. Here we present results of numerical calculations of the early thermo-chemical evolution of Vesta, taking into account the insights provided by Dawn.

1. Model

From our previous numerical studies of ordinary chondritic planetesimals[5] with melt fractions of ≤ 50 % a thermal evolution and differentiation code is available, which includes accretion, compaction, melting, associated changes of the material properties, partitioning of ^{26}Al, advective heat transport and differentiation by porous flow. We have expanded this code by considering convection and thus effective cooling in a magma ocean to analyse its formation and evolution on Vesta. For melt fractions below the rheologically critical melt fraction (RCMF) of ≈ 50% the heat transport by melt segregation is modelled assuming melt flow in porous media and by supplementing the energy balance equation with additional advection terms. Above the RCMF an effective thermal conductivity k_{eff} is computed from the convective heat flux in the soft turbulence regime[6]. The parameter k_{eff} mimics the vigorous convection and heat flux of the magma ocean with a low viscosity. It amounts to $O(10^6)$ W m^{-1} K^{-1} and substitutes the thermal conductivity in the energy balance equation. We consider instantaneous formation of Vesta (as an approximation of the runaway accretion scenario) and compare the evolution scenarios arising from different formation times t_0 (relative to the formation of the CAIs).

2. Results

Core formation in Vesta is possible for formation times of up to 2.7 Ma after the CAIs. It has been realized that during differentiation, an important process for the formation and evolution of a magma ocean is the partitioning of ^{26}Al and its relocation with the silicate melt. Because ^{26}Al is an incompatible element and is saturated in the liquid silicate phase during the melting of the silicates, the migration of the silicate melt has serious effects on the thermal evolution. Previous models (e.g. [7], [8] and [9]) suggest the formation of an internal magma ocean throughout the whole mantle beneath a solid crust. Thereby, the partitioning of ^{26}Al into the silicate melt is neglected. We will show that in contrast to this previous finding a global magma ocean does not form if partitioning of ^{26}Al is considered: Radioactive nuclides are enriched in the melt and relocated towards the surface. In a shallow layer close to the surface temperature and melt fraction increase rapidly due to the over-production of the radiogenic heat (see Fig. 1). Below a rigid undifferentiated shell and a thin partially molten layer the melt fraction rises up to the RCMF and convection starts in an approximately 1 km thick sub-surface magma ocean. Close vicinity to the surface and effective cooling prevent the magma ocean from extending to the surface. However, a basaltic crust is formed (for t_0 < 1 Ma) by the extrusion of the silicate melt. Due to the associated extrusion of ^{26}Al and the radioactive decay the thin magma ocean vanishes after $O(10^4)$-$O(10^5)$ a. Simultaneously, the interior differentiates from outside inward into a core which is heated by ^{60}Fe and a mantle which is depleted in the heat sources. The mantle remains partially molten below the RCMF. Some melt percolation in the mantle takes place until the interior cools below the solidus temperature of the silicates (1425 K), but no convecting whole-mantle magma ocean forms.

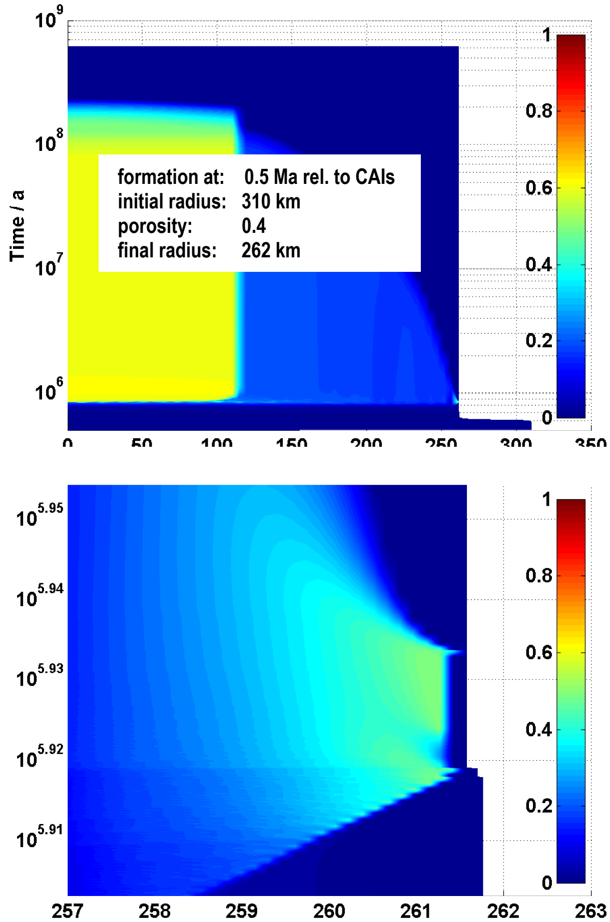

Figure 1: Temporal evolution of the radial distribution of the melt fraction in Vesta (upper panel) and melt fraction in the sub-surface magma ocean (lower panel) for the formation at 0.5 Ma after the CAIs.

3. Conclusions

Our results support the formation of eucrites by percolation of early partial melt and contradict the residual melt origin of the eucrites and diogenites from the crystallisation of a global magma ocean. In our simulations non-cumulative eucrites originate from the extrusion of the melt through the surface. The ongoing melt percolation in the upper mantle can be interpreted as the origin of cumulative eucrites and diogenites. The silicate partial melt is present in the mantle of Vesta at depth for up to 150 Ma after the CAIs provided early formation of the body. Because the silicate melt fraction of 50 % is obtained at the temperature of ≈ 1640 K the mantle material of Vesta did not experience higher temperatures. By contrast, higher melt fractions are obtained in the core (up to 75 %), because the liquidus temperature of the Fe,Ni-FeS system is considerably lower, than that of the silicates. The thermal convection in the core is maintained for approximately 100 Ma which could contribute to the formation of a magnetic field producing core dynamo and explain the remnant magnetisation found in some HED meteorites.

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