PLANETARY DIFFERENTIATION OF VESTA WITH ^{26}Al AND ^{60}Fe AS HEAT SOURCES.

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Introduction: Planetary differentiation of the majority of the differentiated meteorite parent bodies and the minor planet, Vesta, initiated within the initial few million years of the solar system [see e.g. 1,2]. Distinct scenarios have been proposed for the core-mantle and mantle-crust differentiation of these bodies [3-6], specifically, the origin of the basalts. While the experimental petrology indicated that eucrites, the most well-studied basaltic meteorites, were probably derived from the partial melting of the bulk silicate, the detailed studies of the siderophile element partitioning in basaltic component of HED indicate that these were derived from the residual melts of a cooling magma ocean [5,6]. The latter work indicated that the core-mantle differentiation occurred in a molten planetesimal prior to equilibrium crystallization in a cooling magma ocean. The basalts were derived from the residual melt.

In the present work, we have numerically simulated the two distinct scenarios for the origin of basalts in order to understand the differentiation of Vesta. These two scenarios include, i) the partial melt origin of the basalts, and ii) the origin of the basalt from the residual melt of a cooling magma ocean. With the present work along with our earlier studies [1,7] we have accomplished the numerical simulations of the differentiation of accreting planetesimals for the various proposed differentiation scenarios. These scenarios differ from each other in terms of the relative timings of the core-mantle and mantle-crust differentiation. We now make our concluding assessments regarding these scenarios along with their implications on the origin of differentiated meteorite parent bodies

Numerical simulations: In order to solve the partial differential equation we adopted the identical procedure as used in our previous work [1,7]. We have considered a linear growth of un-sintered planetesimals, initiating from the body of size 300 m. The accretion of the body initiates at a time interval t_{Onset} (0-3 Ma; mega annum) after the formation of CAIs and completes within 0.001-1 Ma. A constant surface temperature of 250 K was maintained. The sintering of planetesimals was commenced in the temperature range of 670-700 K. We have considered the melting of Fe-FeS and the bulk silicates in the temperature range of 1213-1233 K and 1450-1850 K, respectively. As a refinement, a non-linear trend in the melting of bulk silicates with temperature was adopted in the present work [4]. $(\text{Fe-Ni})_{\text{metal}}$-FeS melt moves towards the center at 0.4 fraction of the bulk silicate melting and gradually forms the core. In order to perform differentiation, we estimated the mass of $[(\text{Fe-Ni})_{\text{metal}}\text{-FeS}]$ and silicates, in both melt and unmelted forms, within each spatial grid adopted for the finite difference method. Subsequent to 0.4 fraction silicate melting, the $[(\text{Fe-Ni})_{\text{metal}}\text{-FeS}]$ melt pockets of a specific spatial grid were gradually moved towards the planetesimal center. These melt pockets, subsequent to reaching the center, replaced the silicate and pushed the silicate pockets in an upward direction. The differentiation was executed from inside-out, starting from the inner most spatial grid. In order to avoid any discontinuity and mass clumping, the movement of the various pockets was monitored and controlled by suitable parameters. The Al and Fe contents were reevaluated at all the spatial-temporal grids. In order to imitate thermal convection in the molten Fe-FeS core and the mantle subsequent to 0.5 fraction of silicate melting [1,7], a three orders of high thermal diffusivity (5×10^{-4} m^2 s^{-1}) has been incorporated compared to the sintered rock thermal diffusivity (5×10^{-7} m^2 s^{-1}). The mantle-crust differentiation in the present work was performed using two distinct scenarios. This differs in the manner the basaltic melt is generated in a planetesimal.

i) Partial melt origin of basalts (PM)

In this scenario, the mantle-crust differentiation occurs prior to the core-mantle differentiation due to the partial melting of silicate. Al-rich basaltic melt pockets generated at different regions of the planetesimals were moved upwards towards the planetesimal surface at 0.2 fraction bulk silicate melting.

ii) Residual melt origin of basalts (RM)

In this model, we simulated the convective magma ocean beyond the temperature of 1725 K and maintained it until the temperature dropped below 1600 K [5,6]. To thermally mimic the convection in the cooling magma ocean, a high thermal diffusivity of 5×10^{-4} m^2 s^{-1}was used. Upon further cooling below 1600 K, the thermal diffusivity was dropped to 5×10^{-7} m^2 s^{-1} using a sigmoid function to avoid any discontinuity. Even though we could not simulate the gravitational settling of the crystals undergoing equilibrium crystallization in the cooling molten magma, subsequently followed by basaltic volcanism [5,6], the essential features of the model can be understood based on the deduced cooling rates.

Results and Discussions: The thermal profiles and planetary differentiation for a set of simulations are presented in figure 1 for the two set of models. In the case of the PM model depending upon the onset time of the planetesimal accretion, the onset of the basaltic melt extrusion will initiate any time from ~0.15-6 Ma after the condensation of CAIs. This is consistent with the published ages of basaltic achondrites within 2-6 Ma [2] except for the near absence of a specimen from the initial couple of million years. In case of the RM model even in the presence of high thermal diffusivity in the cooling magma ocean we have not observed the significant cooling of the planetesimals within 6 Ma for planetesimals of sizes >50 km. The situation becomes even worse in the case of 270 km sized minor planet, the Vesta that can retain its internal heat for a long time on account of its massive size (fig.1). Hence, we do not anticipate major equilibrium crystallization in the magma ocean of a 270 km sized asteroid within the initial ~6 Ma that would produce residual melts for the basalts. This is in contradiction with the published ages of the basaltic meteorites that cluster within the initial 2-6 Ma [2]. The reason for the inefficient cooling is partially due to the presence of an 'insulating' lid that survives on the surface of the planetesimal [5,6] in the outermost spatial grid, and partially due to the ongoing radioactive heating [8]. In order to make the residual origin of the basaltic melt model viable, it would be essential to completely remove the insulting lid. This has to be achieved by a continuous bombardment of the cooling crust by small planetesimals that would maintain a convective magma ocean up to the surface, without the presence of an insulating lid. Additional cooling may be required to circumvent the accumulation of radiogenic heating and produce basalts within 2-6 Ma in the early solar system.

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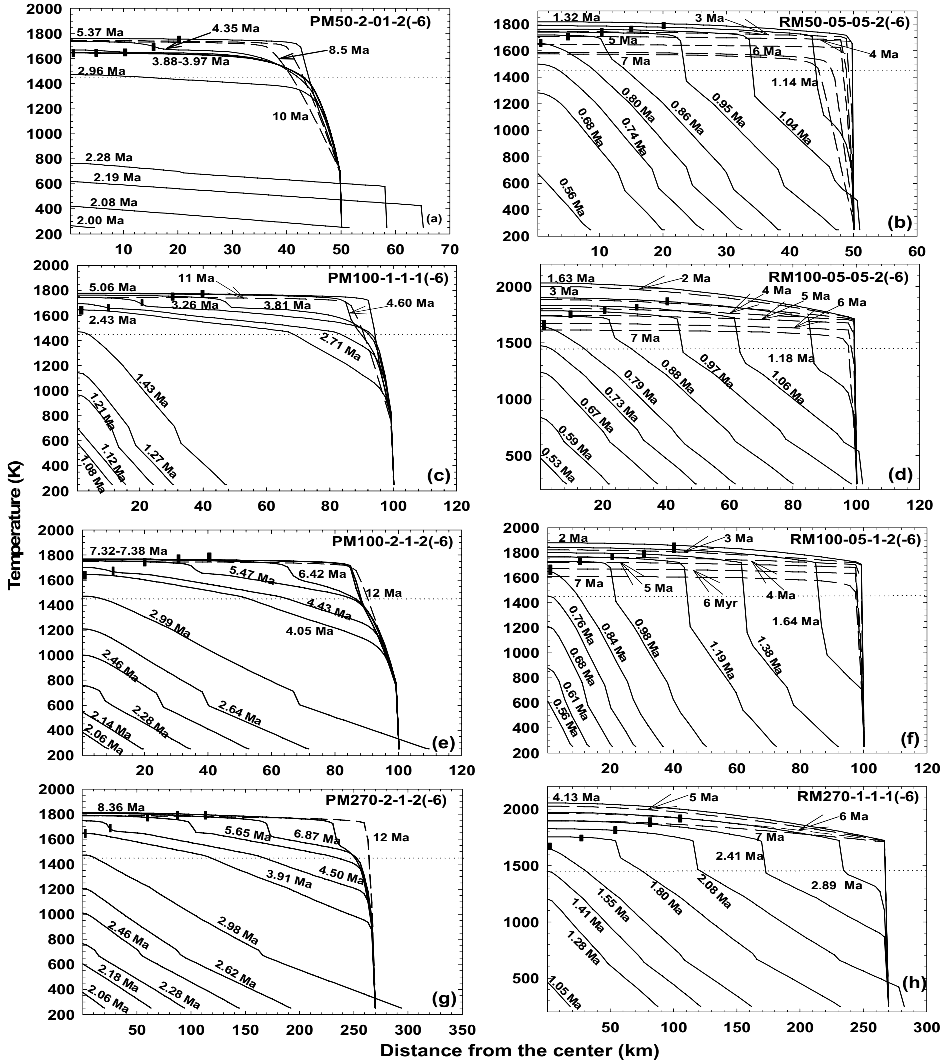

Figure 1. Thermal profiles of the planetesimals during the accretion and planetary differentiation with H chondritic composition. All time spans are marked with respect to the initiation of the formation of CAIs. The thick vertical bars represent the core size at a given time. The thermal profiles subsequent to the cooling of the planetesimals are represented by dashed curves for an easier view. Simulations are titled according to the choice of the various parameters. These parameters are separated by hyphens. In order these parameters are; i) the simulation type PM or RM and the radius of the planetesimals subsequent to complete sintering, ii) the onset time, t_{Onset}(Ma) iii) the accretion duration, $t_{Duration}$(Ma), of the planetesimals, iv) initial ratio of $^{60}Fe/^{56}Fe$ that varies from $(0.5\text{-}2)\times10^{-6}$ with the canonical value of $^{26}Al/^{27}Al$. Simulations (g) and (h) represent the case for Vesta.