SHALLOW MAGMA OCEAN ON VESTA AND IMPLICATIONS FOR THE HEDs. W. Neumann(1), D. Breuer(1) and T. Spohn(1,2), (1) German Aerospace Center (DLR), Institute of Planetary Research, Rutherfordstraße 2, 12489 Berlin, Germany (wladimir.neumann@dlr.de), (2) Westfälische Wilhelm-Universität Münster (WWU), Institute for Planetology, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany.

Introduction: The asteroid 4 Vesta is widely held as a differentiated protoplanetary object and as the parent body of the HED meteorites. Both predictions have been supported by the observations of Dawn. However, the origin of the HEDs, which is closely linked to the differentiation processes, is still a subject of debate. The formation of the HEDs is controversially discussed and various differentiation scenarios have been proposed. One scenario suggests that diogenites are solid residues from the partial melting of the silicates[1]. Another scenario favoured by geochemical arguments suggests diogenites being cumulates formed by magma fractionation[2,3]. In the latter case the diogenites could have crystallised either in a global magma ocean[2] or in multiple, smaller magma chambers[3]. Here we present results of numerical calculations of the early thermo-chemical evolution of Vesta, taking into account the insights provided by Dawn and placing constraints on the possible differentiation scenario and on the occurrence and depth of the Vestan mantle magma ocean.

Model: We use a numerical heat conduction code that considers in spherical symmetry accretion, compaction, melting, associated changes of the material properties, partitioning of ^{26}Al, advective heat transport, differentiation by porous flow as well as convection and effective cooling in a magma ocean. 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[4]. Above the RCMF an effective thermal conductivity k_{eff} is computed from the convective heat flux in the soft turbulence regime[5]. The parameter k_{eff} mimics the vigorous convection and heat flux of the magma ocean with a low viscosity. 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).

Results: Our results show that partitioning of ^{26}Al and its transport with the silicate melt is crucial for the formation of a global and deep magma ocean. Previous models that neglect the partitioning of ^{26}Al into the silicate melt[6,7,8] suggest the formation of an internal magma ocean throughout the whole mantle beneath a solid crust.

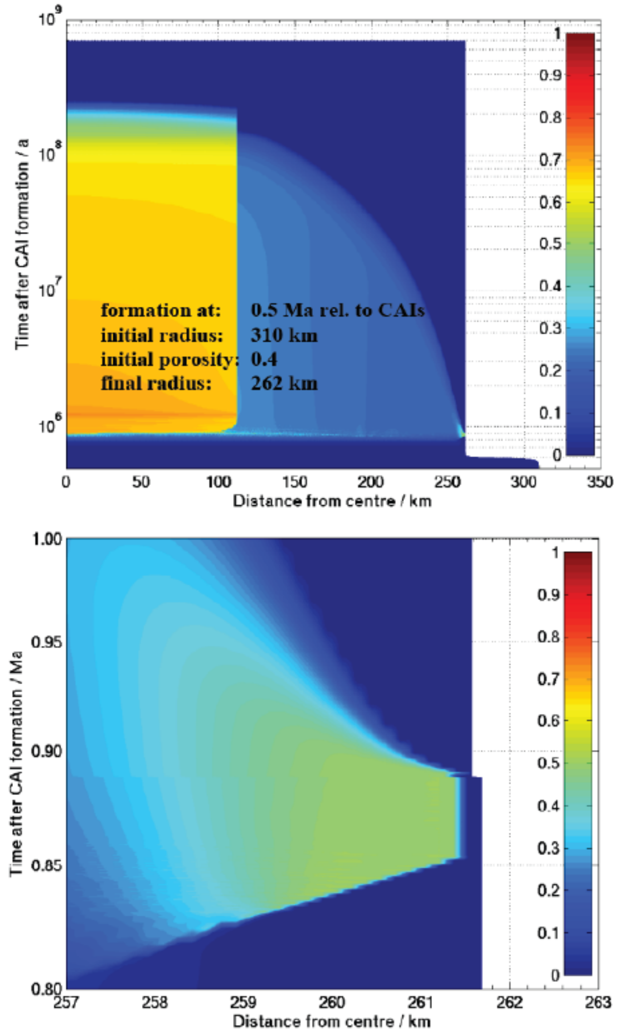

Figure 1: Temporal evolution of the radial distribution of the melt fraction in Vesta (upper panel) and melt fraction in the sub-surface magma ocean (lower panel) for the formation at 0.5 Ma after the CAIs and a melt viscosity of 1 Pa s.

We 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, the melt fraction increases rapidly due to the over-production of the radiogenic heat. For formation times t_0<1.5 Ma, a thin shallow convecting magma ocean with a thickness of 1 to a few tens of km forms above which a basaltic crust forms (see Fig. 1). The lifetime of the shallow magma ocean is $O(10^4)$-$O(10^6)$ years and convection in

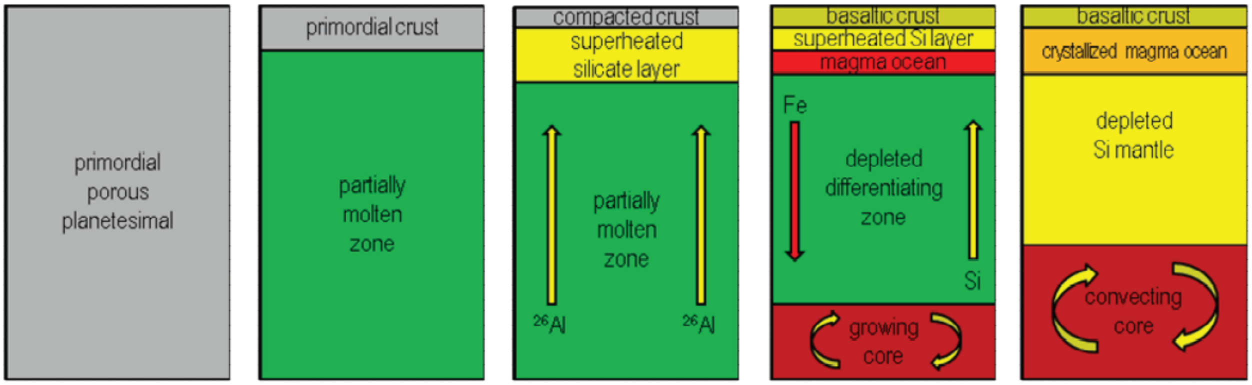

Figure 2: Evolution path of Vesta's interior assuming partitioning of ^{26}Al.

this layer is accompanied by the extrusion of ^{26}Al at the surface. The interior differentiates from the outside inward with a mantle that is depleted in ^{26}Al and core formation is completed within ~0.3 Ma. The lower mantle experiences a maximal melt fraction of 45% suggesting a harzburgitic to dunitic composition.

The above findings of a shallow magma ocean strongly depend on the migration velocity and here the most critical parameter is the silicate melt viscosity – the higher the viscosity, the lower is the migration velocity and the more likely the formation of a global magma ocean and vice versa. In the present model, we have used a silicate melt viscosity of 1 Pas. However, for basaltic melts derived from chondritic precursors, viscosities of ≈1-100 Pa s have been proposed[9]. Further tests with the values of 10 and 100 Pas display lower melt migration velocities, thicker sub-surface magma ocean (e.g. ≈10 km for 10 Pa s in comparison to 1 km for 1 Pa s) and slower silicate separation. The cooling of the magma ocean below the RCMF is prolonged to 1 Ma and the layer is entirely crystallized after 3 Ma. Higher temperatures are obtained in the mantle and in the core, because of the somewhat prolonged radiogenic heating by the slow migrating ^{26}Al. In the extreme case of 100 Pa s, the magma ocean even extends to the depth of ≈100 km. The rest of the mantle reaches melt fractions close to the RCMF and the iron-rich core, the silicate mantle and the crust from almost simultaneously.

Conclusions: Our results suggest that most previous thermo-chemical evolution models for Vesta tend to overestimate the temperature increase in the interior and therefore the amount of partial melting[6,7,8,10]. Those models either neglect efficient heat transport by the partitioning of ^{26}Al into the silicate melt and/or convection in a magma ocean.

Thus, our results contradict the existence of a global and deep magma ocean on Vesta but support the formation of non-cumulative eucrites by percolation of early partial melt whereas diogenites and cumulate eucrites form by rapid crystallization of a shallow magma ocean. The latter is consistent to the rapid time scale for magma ocean crystallization of Al-free diogenites from the abundance of ^{26}Mg[2]. Values of the silicate melt viscosity between 10 to 100 Pas suggest that the subsurface magma ocean can reach a thickness up to 100 km. A sub-surface magma ocean with a thickness of a few tens of kilometres would in fact be consistent with the assumption of Vesta's crust having an average thickness of 35-85 km with an upper eucritic and a lower orthopyroxene-rich layer[11].
Beneath the shallow magma ocean the mantle experiences partial melting of less than 45 %, resulting in a harzburgite mantle. 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. Melt fractions in the core reach values up to 75 % but the core is not entirely molten during its evolution. As a consequence, we assume that a compositional dynamo contributes to the formation of a magnetic field and may explain the remnant magnetisation found in some HED meteorites.

Acknowledgement: This work was supported by the Deutsche Forschungsgemeinschaft (DFG) Priority Programme 1385 "The First 10 Million Years of the Solar System - a Planetary Materials Approach" and by the Helmholtz Association through the research alliance "Planetary Evolution and Life".

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