Earth and Planetary Science Letters 395 (2014) 267–280

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Differentiation of Vesta: Implications for a shallow magma ocean

Wladimir Neumann[a,*], Doris Breuer[a], Tilman Spohn[a,b]

[a] Institute of Planetary Research, German Aerospace Center (DLR), Rutherfordstraße 2, 12489 Berlin, Germany
[b] Institute of Planetology, Westfälische Wilhelm-University Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany

ARTICLE INFO

Article history:
Received 29 May 2013
Received in revised form 25 February 2014
Accepted 15 March 2014
Available online 16 April 2014
Editor: C. Sotin

Keywords:
asteroids, composition, dynamics
interiors
meteorites
planetary dynamics
planetary formation
planetesimals

ABSTRACT

The Dawn mission confirms earlier predictions that the asteroid 4 Vesta is differentiated with an iron-rich core, a silicate mantle and a basaltic crust, and supports the conjecture of Vesta being the parent body of the HED meteorites. To better understand its early evolution, we perform numerical calculations of the thermo-chemical evolution adopting new data obtained by the Dawn mission such as mass, bulk density and size of the asteroid.

We have expanded the thermo-chemical evolution model of Neumann et al. (2012) that includes accretion, compaction, melting and the associated changes of the material properties and the partitioning of incompatible elements such as the radioactive heat sources, advective heat transport, and differentiation by porous flow, to further consider convection and the associated effective cooling in a potential magma ocean. Depending on the melt fraction, the heat transport by melt segregation is modelled either by assuming melt flow in a porous medium or by simulating vigorous convection and heat flux of a magma ocean with a high effective thermal conductivity.

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. Due to the enrichment of ^{26}Al in the liquid phase and its accumulation in the sub-surface (for formation times $t_0 < 1.5$ Ma), a thin shallow magma ocean with a thickness of 1 to a few tens of km forms – its thickness depends on the viscosity of silicate melt. The lifetime of the shallow magma ocean is $O(10^4)$–$O(10^6)$ years and convection in this layer is accompanied by the extrusion of ^{26}Al at the surface, resulting in the formation of a basaltic crust. The interior differentiates from the outside inwards 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. Our results support the formation of non-cumulate eucrites by the extrusion of early partial melt while cumulate eucrites and diogenites may form from the crystallising shallow magma ocean. Silicate melt is present in the mantle for up to 150 Ma, and convection in a crystallising core proceeds for approximately 100 Ma, supporting the idea of an early magnetic field to explain the remnant magnetisation observed in some HED meteorites.

1. Introduction

The large asteroid 4 Vesta, located in the inner belt at a mean heliocentric distance of 2.36 AU, is the second-most-massive body in the asteroid belt. Ground-based observations indicate a dry, basaltic surface composition, suggesting that melt segregation and core–mantle differentiation must have taken place and that the body has been resurfaced by basaltic lava flows (e.g. Zellner et al., 1997). The Dawn mission recently orbiting Vesta confirms this observation and the notion that this asteroid is the parent body of the HED (howardite, eucrite and diogenite) meteorites (De Sanctis et al., 2012; Russell et al., 2013). HEDs consist mainly of non-cumulate eucrites (pigeonite–plagioclase basalts) and orthopyroxene-rich diogenites. Howardites are impact breccias, composed predominantly of eucrite and diogenite clasts. The igneous lithology is completed with more rare rock types that include cumulate eucrites and olivine-bearing diogenites. This lithology has been used to constrain the interior structure. Vesta is believed to have a layered structure consisting of at least a metallic core, a rocky olivine-rich mantle and a crust consisting mainly of an upper basaltic (eucritic) and a lower orthopyroxene-rich layer (e.g. Delaney, 1995; Ruzicka et al., 1997; Righter and Drake, 1997; Mandler and Elkins-Tanton, 2013). The details in the interior structure vary between the models and depend among others on the assumption of the bulk composition of Vesta. A eucritic upper crust

* Corresponding author. Tel.: +49 3067055395; fax: +49 3067055303.
E-mail addresses: Wladimir.Neumann@dlr.de (W. Neumann), Doris.Breuer@dlr.de (D. Breuer), Tilman.Spohn@dlr.de (T. Spohn).

http://dx.doi.org/10.1016/j.epsl.2014.03.033
0012-821X/

and orthopyroxene-rich lower crust have been also identified by Dawn, in particular, in the Rheasilvia basin (De Sanctis et al., 2012; Prettyman et al., 2012). The huge basin allows the identification of material that was formed down to a depth of 30–45 km and has been excavated or exposed by an impact (Jutzi and Asphaug, 2011; Ivanov and Melosh, 2013). Interestingly, olivine-rich and, thus, mantle material has not been found in a significant amount, i.e. not above the detection limit of $<25\%$, suggesting a crustal thickness of at least 30–45 km (McSween et al., 2013). This finding may also explain the lack of olivine-rich samples in the HED collection. It should be noted, though, that several olivine-rich terrains were actually detected by Dawn in the northern hemisphere (De Sanctis et al., 2013; Ruesch et al., 2013).

Two possible differentiation scenarios have been associated with the formation of the basaltic achondrites (i.e., eucrites and diogenites). The first scenario suggests that eucrites and diogenites originated from the partial melting of the silicates (e.g. Stolper, 1975, 1977; Jones, 1984; Jones et al., 1996) with the extraction of basaltic (euritic) magma leaving behind a harzburgite, orthopyroxenite or dunite residual depending on the degree of partial melting. The other scenario favoured by geochemical arguments suggests achondrites being cumulates formed by magma fractionation. In the latter scenario the diogenites could have crystallised either in a magma ocean (Ikeda and Takeda, 1985; Righter and Drake, 1997; Ruzicka et al., 1997; Takeda, 1997; Warren, 1997; Drake, 2001; Greenwood et al., 2005; Schiller et al., 2011) or in multiple, smaller magma chambers (Shearer et al., 1997; Barrat et al., 2008; Beck and McSween, 2010; Mandler and Elkins-Tanton, 2013). Eucrites are then products from the magmas that had earlier crystallised diogenites.

Eucrites exhibit siderophile depletions that indicate the formation of an iron-rich core prior to their crystallisation and within $\sim$1 to 4 Ma of the beginning of the solar system (Palme and Rammensee, 1981; Righter and Drake, 1997; Kleine et al., 2009). Assuming core densities between 7000 and 8000 $kg\,m^{-3}$, the core radius of Vesta is estimated to lie between 105 and 114 km (Raymond et al., 2012; Russell et al., 2012), approximately half of the asteroid's radius. Some HEDs (e.g. Millbillillie and Allan Hills A81001), furthermore, show a remnant magnetisation suggesting a formerly active dynamo in a liquid metallic core (Fu et al., 2012a, 2012b).

To understand Vesta's thermal and geological evolution, several numerical and experimental studies (e.g. Righter and Drake, 1997; Ghosh and McSween, 1998; Drake, 2001; Gupta and Sahijpal, 2010) have been performed. Questions these studies want to answer are related to the timing of accretion and core formation and the history of volcanism, especially the formation of the basaltic crust. Related to the last issue is, in particular, the question about the origin of the HED meteorites that either originated from the partial melting of the silicates or are residual melts of a crystallising and formerly convecting whole-mantle magma ocean. It should be noted, though, that in most models the formation of core and crust has not been modelled self-consistently; rather some specific scenario has been assumed and its consequences for the thermal evolution on Vesta have been studied.

Righter and Drake (1997) considered core formation and crystallisation of a cooling magma ocean using a numerical physicochemical model. They suggested that after cooling to a crystal fraction of 80%, residual melt percolated from the former extensive magma ocean to form eucrites at the surface and diogenites in shallow layers by further crystallisation. In their model complete crystallisation occurred within 20 Ma after the formation of Vesta.

Ghosh and McSween (1998) investigated the differentiation of Vesta by assuming instantaneous core formation in the temperature interval of 1213–1223 K (assumed solidus and liquidus temperature of Fe–FeS) and that HED meteorites are the product of 25% partial melting. To obtain such a scenario, they concluded that Vesta must have accreted at 2.85 Ma, differentiated at 4.58 Ma and formed a basaltic crust at 6.58 Ma relative to the formation of the CAIs. Furthermore, they suggested that the mantle remained hot for 100 Ma after its formation and that some near-surface layers may have remained undifferentiated.

The latter models suggesting a global magma ocean neglect efficient cooling due to convection in the magma ocean and partitioning of ^{26}Al into the silicate melt and of its migration towards the surface. So far, there have not been many attempts to model magma ocean convection in planetesimals. A first model to study the influence of a convecting magma ocean that formed due to heating by ^{26}Al in planetesimals with radii of less than 100 km was presented by Hevey and Sanders (2006). Convection and the associated heat transport have been simulated by increasing the thermal conductivity by three orders of magnitude upon reaching a melt fraction of 50% – at this rheologically critical melt fraction (RCMF) a strong decrease in the viscosity is expected, resulting in vigorous convection and efficient heat transport (Marsh, 1988). As an important consequence, it has been shown that the excess radiogenic heating does not raise the temperature of the convecting interior. Thus, not the degree of the partial melting in the magma ocean, but rather the extent of the molten zone increases.

Gupta and Sahijpal (2010) adopted this approach in their simulations for Vesta by varying the thermal diffusivity by three orders of magnitude between the melt fractions of 50% and 100% (thereby, the thermal conductivity was increased). They investigated two evolution paths, namely the formation of basaltic achondrites in Vesta via partial melting of silicates or as residual melts after crystallisation of a convecting magma ocean. They concluded that, depending on the formation time, melt extraction is possible between 0.15 and 6 Ma after the CAIs and that differentiation proceeds rapidly within $O(10^4)$ a. For the scenarios where accretion was completed within 2 Ma after the CAIs, a magma ocean formed, which did not crystallise completely for at least 6–10 Ma. We will later show that for magma oceans comprising a large part of the mantle, the convective heat flux is underestimated in the studies Hevey and Sanders (2006) and Gupta and Sahijpal (2010) in comparison to that of the soft turbulence regime that is valid when the viscosity is small and convection is extremely turbulent, as in the case of magma oceans (Solomatov, 2007). In fact, as we point out further below, the effective thermal conductivity of the magma ocean is underestimated by up to three orders of magnitude.

The importance of equilibrium partitioning of ^{26}Al into the silicate melt and of its migration toward the surface has been shown by Moskovitz and Gaidos (2011) for planetesimals smaller than Vesta. They concluded that migration of ^{26}Al-enriched melt towards the surface inhibits a further increase of internal temperatures and partial melting. In their model, only subsequent heating by ^{60}Fe generates melt fractions of over 50% completing the differentiation of the bodies of interest. Although Vesta was not considered in their study, the partitioning of ^{26}Al, its extrusion to the surface and the associated depletion of the interior would have a strong impact on its thermal evolution.

As a general conclusion from the previous thermal models, one can state that Vesta should have finished its accretion by $\approx$3 Ma after the CAIs due to the decrease of the radiogenic heating by ^{26}Al and ^{60}Fe with time. Whether the basaltic crust, i.e. eucrites and diogenites, did form after the core–mantle separation due to the crystallisation of a global magma ocean (residual melt origin) or prior to the core–mantle separation due to the extrusion of the first partial melts (partial melting origin) remains an open issue, although geochemical models suggest that core formation precedes crust formation (e.g. Kleine et al., 2009). Which scenario is more likely also depends on the competition between heating by