

The solidification of a magma ocean of Vesta

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Asteroid 4 Vesta is the only preserved intact example of a large, differentiated protoplanet. Observations of surface spectra of Vesta provide convincing evidence for a differentiated interior. Vesta is considered as the parent body of HED meteorites.

Whether growing mineral grains remain suspended in the magma ocean or settled out is crucial for the primary interior structure of a planet.

The purpose of this study is to understand the role of grain size of crystals on solidification of a magma ocean under a turbulent flow. We select asteroid 4 Vesta as a subject of this study due to the presence of HED chondrites as a reference. In this study, we consider the solidification before the rheological transition occurs.

We assume that the interior structure of Vesta had already differentiated to form a core. We use the bulk silicate Vesta composition proposed by Righter and Drake (1998), which is a mixture of L and CV chondrites with the ratio of 7 to 3 adjusted for core separation. We calculate liquidus, solidus and solid fractions using the MELTs program (Ghiorso and Sack 1995; Asimow and Ghiorso 1998). In vigorously convective systems such as magma oceans, the temperature distribution is nearly adiabatic and isentropic (Solomatov, 2000).

The heat flux can be calculated with the help of the blackbody radiation. This heat flux must match the heat flux transported to the surface by convection. Convection changes to a regime sometimes called hard turbulence at very high Rayleigh number such as those in the magma ocean, of which heat flux is shown by Siggia (1994).

To describe the rate at which particles settle out of a turbulently convective fluid, we use the model by Martin & Nokes (1989). The particle number is calculated by

$$dN/dt = N(-g\Delta\rho a^2)/(18\nu h)$$

where N is the particle number, g is the acceleration due to gravity, a is the diameter of the particle, $\Delta\rho$ is the density difference between the crystal and the magma, ν is the kinematic viscosity, and h is the depth of the fluid layer (Martin & Nokes, 1989).

The adiabat, liquidus and solidus of the magma ocean of Vesta are very steep, that is, they have negligibly small dependence on pressure.

Thermodynamic calculations with the MELTs program showed that olivine is the first liquidus phase at ~1900K, followed by orthopyroxene and spinel. At the very late stage, clinopyroxene appears consuming orthopyroxene if chemical equilibrium is maintained.

The fluid dynamic evaluation shows that a very small fraction of crystals are separated from the magma ocean until the rheological transition which varied from 100 μ m to 1cm in the current work. The thickness increases with time, which is shown in Figure.

Evaluation of fluid dynamic regime shows that the magma ocean on Vesta was at the hard turbulence regime, suggesting near equilibrium crystallization until the rheological transition takes place at the crystal fraction of 60% at 1649K.

The role of grain size on fluid dynamics is very small, but the amount of crystals settled down to the bottom of the magma ocean has small dependence on the grain size. If the crystal size is 1cm, 1km thickness bottom layer is formed.

The fluid dynamic regime changes into soft turbulence in 100 years in the order in the magma ocean of Vesta.

The summary of our conclusion is as follows.

- (1) The pressure effect in the interior of Vesta is negligibly small.
- (2) The solidification of a magma ocean of Vesta before the rheological transition follows batch solidification.
- (3) The size of crystallizing grains has a minor effect on the evolution of magma ocean until the rheological transition.
- (4) The mantle would be harzburgite if the interstitial melt was effectively extracted at the later soft turbulence stage.

Fig. The thickness of the bottom layer consisting of settled crystals from the main body of a magma ocean.

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