C2 On the fate of impact-delivered metal in a rotating terrestrial magma ocean

Introduction

- Giant impacts on Earth caused the formation of a magma ocean and crucially influenced core formation and the subsequent evolution of the Earth's mantle [1].
- Turbulent convection of the melt in magma ocean is strongly influenced by planetary rotation [2-3].
- Planetary rotation crucially influences magma ocean crystallization and determines the locus of the initiation of crystallization with respect to depth and latitude (Fig. 1, rotational strength increases from (a) to (d)).
- The settling of impact-delivered material is potentially strongly influenced by its size-frequency distribution and the convective and rotational magma ocean state.

Questions:

> How much material delivered by giant impacts was incorporated into the core?
> How do the convective state and planform of the magma ocean and the potentially strong planetary rotation affect the settling of impact-delivered material in a global magma ocean?

Mathematical and Numerical Model

To simulate the settling of impactor material in a vigorously convecting and strongly rotating magma ocean, we describe the melt by a Boussinesq fluid. The fluid model is based on the spectral dynamo code MagIC [4]. It uses a poloidal-toroidal decomposition and a spherical harmonics expansion. In radial direction it employs Chebyshev polynomials. The impactor material is described by spherical particles by employing a discrete element method [2]. The initial position, the velocity as well as the density and size of the meta delivered by an impact was provided by vertical 2D simulations performed by L. Manske using the hydrocode iSale (e.g. [5]).

Fluid model

Thermal convection in the Boussinesq limit is described by the following equations:

\[
\nabla \cdot \mathbf{v} = 0 \quad \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \frac{1}{\rho_0 C_p} \nabla^2 T
\]

where \( \mathbf{v} \) denotes the velocity field, \( T \) the temperature, \( C \) the crystal concentration per fluid volume, \( \rho \) the pressure incorporating the hydrostatic component and the centrifugal potential, \( \mathbf{r} \) the position vector, \( r_i \) the radius of the outer boundary and \( \mathbf{v}_i \) the vector of rotation axis. The above equations are in non-dimensional form with the following set of parameters:

\[
P_	ext{r} = \frac{\rho_0 C_p}{\rho_0} \quad E = \frac{\rho_0 C_p}{\rho_0} \quad R_0 = \frac{\rho_0 C_p}{\rho_0} \quad \gamma = \frac{\rho_0 C_p}{\rho_0} \quad \Omega = \frac{\rho_0 C_p}{\rho_0}
\]

where \( \nu \) is the kinematic viscosity, \( \kappa \) the thermal diffusivity, \( \Omega \) the angular velocity, \( \theta \) the thermal expansion coefficient, \( J \) the height of the fluid layer and \( \Delta T \) the temperature difference over \( J \), \( \gamma \) denotes the inner radius of the spherical shell.

Particle model

The particles have a finite size and a spherical shape, experience inertia due to their mass and influence the fluid flow through the concentration field \( C \). Collisions between particles are taken into account. For further details see [2]. The forces on the particles are calculated by the following equations:

\[
F_x = \frac{4}{3} \pi R^3 \left( \rho_0 - \rho_{\text{part}} \right) \mathbf{v}_x \quad F_x = 6 \pi \eta \left( \mathbf{v}_x - \mathbf{v}_p \right) \quad F_{\text{Coriolis}} = \frac{\rho_0 C_p}{\rho_0} \mathbf{v}_x \times \mathbf{v}_i
\]

\( F_x \) is the friction force of the fluid on the particles, \( F_x \) the gravity and \( F_{\text{Coriolis}} \) the Coriolis force, where \( \mathbf{v}_i \) denotes the radius of the outer boundary and \( \mathbf{v}_x \) the velocity of the particles, \( \mathbf{v}_p \) is the velocity of the surrounding fluid.

Exemplary results for 500 km diameter impactor

We employ \( R_0 = 5 \times 10^6 \), \( \rho_0 = 1 \), \( E = 10^4 \), \( \Omega = 0.7 \), \( \gamma = 0.5 \) and free-slip boundary conditions at the top and bottom. The particle size, particle density and the impactor material distribution results from a vertical impact of a 250 km, 500 km or 750 km large differentiated impactor into an 2900 km deep magma ocean at a speed of 11.5 km/s. Impactor material reaching the magma ocean bottom is removed from the system, assuming a percolating into the core.

Impact at the North Pole

- Impact-delivered metal is poorly mixed. Sinking of metal through magma ocean concentrates on polar region for all impactor sizes.

Results for 500 km diameter impactor (cont.)

> Impact at mid-latitudes
- Metal is mixed into the entire magma ocean domain.

> Impact at the equator
- Mass evolution differs depending on impact latitude for all impactor diameters.

Temporal mass evolution of impact-delivered metal

Equilibrated volume during sinking of droplets is approximated after [6,7].
- Temporal evolution of the equilibrated volume differs depending on impact latitude for all impactor diameters.

Scaling of particle mass and equilibrated volume with impactor diameter

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Summary and Outlook

> Distribution and settling history of impact-delivered metal depends strongly on the latitude of the impact, due to the latitude-dependent planform of rotating convection in a spherical shell [3].
> Fastest settling and smallest degree of mixing for polar impacts.
> Highest degree of mixing for equatorial impacts.

References