TRR 170
LATE ACCRETION
ONTO TERRESTRIAL PLANETS

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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.

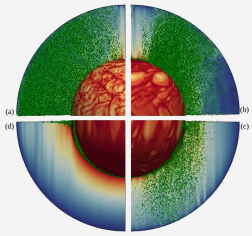


Figure 1: Summary of the influence of planetary rotation on magma ocean crystallization [3].

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 vigourously 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 metal delivered by an impact was provided by vertical $2D$ simulations performed by L. Manske[2] using the hydrocode iSale (e.g. [5]).

> Fluid model

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

$$\nabla \cdot \mathbf{v} = 0 \qquad \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \frac{1}{Pr} \nabla^2 T$$

$$\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \frac{2}{Ek} \left(\mathbf{e}_\Omega \times \mathbf{v} \right) + \nabla^2 \mathbf{v} + Ra_T (T - BC) \frac{\mathbf{r}}{r_0}$$

where $\mathbf{v}$ denotes the velocity field, T the temperature, C the crystal concentration per fluid volume, p the pressure incorporating the hydrostatic component and the centrifugal potential, $\mathbf{r}$ the position vector, r_0 the radius of the outer boundary and $\mathbf{e}_\Omega$ the vector of rotation axis. The above equations are in non-dimensional form with the following set of parameters:

$$Pr = \frac{\nu}{\kappa}, \; Ek = \frac{\nu}{\Omega d^2}, \; Ra_T = \frac{g_0 \alpha d^3 \Delta T}{\nu^2}, \; B = \frac{(\rho_c - \rho_{fl})}{\rho_{fl} \alpha \Delta T}, \; \gamma = \frac{r_i}{r_0}, \; Ro = \sqrt{\frac{Ra Ek^2}{Pr}}$$

where ν is the kinematic viscosity, κ the thermal diffusivity, Ω the angular velocity, α the thermal expansion coefficient, d the height of the fluid layer and ΔT the temperature difference over d, r_i 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:

$$\mathbf{F}_g = \frac{4}{3} \pi \mathbf{g} r_c^3 \left(\rho_c - \rho_{fl} \right) \qquad \mathbf{F}_r = 6 \pi r_c \eta \left(\mathbf{v}_c(x_i) - \mathbf{v}_i \right)$$

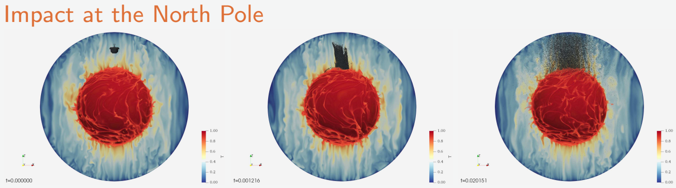
$$\mathbf{F}_{cor} = \frac{8}{3} \pi \Omega r_c^3 \left(\rho_c - \rho_{fl} \right) \left(\mathbf{e}_\Omega \times \mathbf{v}_c \right)$$

$\mathbf{F}_r$ is the friction force of the fluid on the particles, $\mathbf{F}_g$ the gravity and $\mathbf{F}_{cor}$ the Coriolis force, where r_c denotes the radius and $\mathbf{v}_c$ the velocity of the particles, $\mathbf{v}_{fl}$ is the velocity of the surrounding fluid.

Exemplary results for 500 km diameter impactor

We employ $Ra_T = 5 \cdot 10^7$, $Pr = 1$, $Ek = 1 \cdot 10^4$, $Ro = 0.7$, $\gamma = 0.5$ 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.

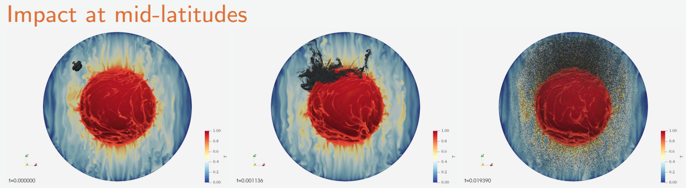
> Impact at the North Pole



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

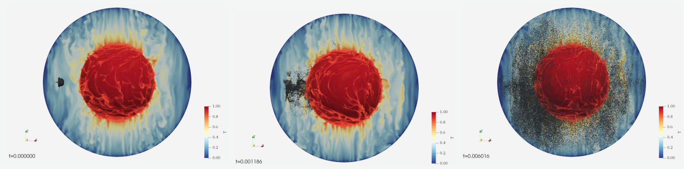
Results for 500 km diameter impactor (cont.)

> Impact at mid-latitudes



- Mixing of metal into the entire impacted hemisphere. Low particle concentration on southern hemisphere.

> Impact at the equator



- Metal is mixed into the entire magma ocean domain.

Temporal mass evolution of impact-delivered metal

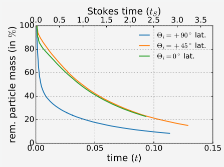


Figure 2: $250\,km$ impactor.

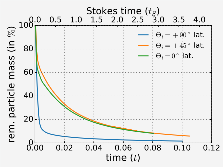


Figure 3: $500\,km$ impactor.

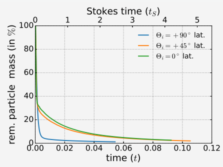


Figure 4: $750\,km$ impactor.

- Mass evolution differs depending on impact latitude for all impactor diameters.

Settling history of impact-delivered metal

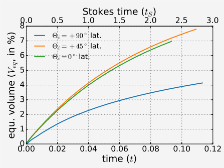


Figure 5: $250\,km$ impactor.

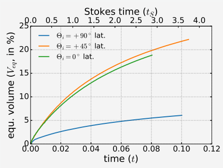


Figure 6: $500\,km$ impactor.

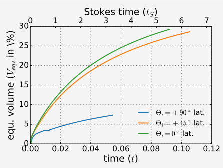


Figure 7: $750\,km$ impactor.

- 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

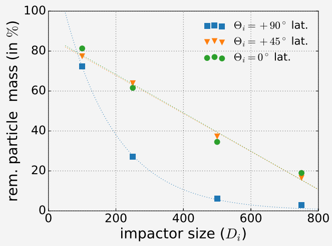


Figure 8: Scaling of the remaining particle mass.

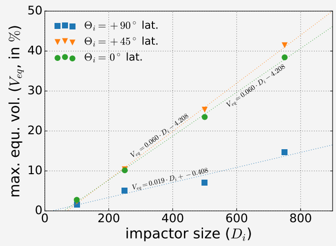


Figure 9: Scaling of the equilibrated volume.

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

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