CONTRIBUTION OF IMPACT MATERIAL TO THE LUNAR MAGMA OCEAN LIQUID AND SOLID CUMULATES

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Motivation: During its accretion and early evolution, the Moon experienced an ongoing bombardment by impacting material. As a consequence, the lunar magma ocean (LMO) did not crystallize as a closed system but was influenced by the influx of accreting material that modified its thermal state and chemical composition.

Depending on the size, density and degree of melting of the projectiles, impacting material could either have been mixed into the LMO or sunken through the LMO and contributed to the bottom cumulate. By combining impact and LMO solidification models, we aim to obtain quantitative information on how much of the material that accreted during LMO solidification has been mixed into the LMO liquid and how much in the solid cumulate, how the relation of these contributions changed with time and how this affected the thermochemical evolution of the LMO and the composition of lunar mantle reservoirs.

Methods: We combine different modeling approaches to simulate the processes relevant for assessing the fate of solid material impacting the LMO, including LMO solidification and the associated changes in depth, temperature and viscosity, heating, melting and fragmentation of the projectiles upon impact, as well as further heating and melting of fragments during sinking through the magma ocean.

Projectile fragmentation. We assume that the early Moon is impacted by a distribution of solid projectiles during its MO phase and assume that the size distribution is governed by re-impacting debris produced during the Moon forming giant impact (e.g. [1]). Depending on their size and velocity, solid projectiles impacting the LMO experience different degrees of melting and fragmentation. We use the shock physics code iSALE-2D [2, 3] with an Euler grid and a recently developed extension for more realistic fragmentation behavior. With this we model the melting and fragmentation of solid projectiles of different sizes impacting the LMO at a range of different velocities. From this model we can assess which fraction of impacting material is melted by the impact and obtain a range of possible solid fragment sizes that sink through the magma ocean.

Fragment sinking. During sinking, the fragments can partially or completely melt before reaching the bottom cumulate. To simulate this process, we developed a 1D model that calculates diffusive heating and melting of projectile fragments. Solidus and liquidus temperatures of the projectiles as well as the latent heat of melting were calculated with alphaMELTS [4], assuming projectiles of bulk Moon composition. The motion of projectile fragments after an impact was assumed to be completely determined by gravity, buoyancy and drag. This means that the time scale of sinking for an individual fragment is depending on its size and density as well as the density and viscosity of the surrounding magma. Accordingly, the change of a fragment's size due to melting must be taken into account. From the trajectories we calculate the residence time of the projectile fragments in the LMO before reaching the LMO bottom.

LMO chemical evolution. We use results from the fractional crystallization model by [5] that simulates the thermochemical evolution of a full-mantle LMO with an Earth-mantle-like composition [6] enriched in FeO. The magma ocean depth, temperature, liquid density and viscosity at different stages of LMO solidification are used as input for the projectile fragmentation and fragment sinking models.

Application: Applying the projectile fragmentation model to an initial size distribution of impacting material will allow us to assess how the size distribution was modified by projectile fragmentation, which fraction of impacting material was melted upon impact, and at which depth the fragments are implanted into the magma ocean.

Further melting of fragments during sinking through the magma ocean can be quantified to calculate the fraction of fragments that reaches the bottom of the magma ocean in a solid state and can hence be incorporated into the bottom cumulate.

By applying this combined modeling approach to different stages of LMO evolution we aim to assess how the contribution of impacting material to the bottom cumulate changed with time. Such results can be employed in future studies to quantify the effect of impacts on the trace element budgets of different lunar mantle reservoirs.

In addition, our expected results may contribute to further constrain the effect of impacts on the total crystal budget of the LMO at different stages during its evolution and any associated effects on LMO dynamics, crystal fractionation and thermal evolution.

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