

# Evolution of Lunar Mantle Properties during Magma Ocean Crystallization and Mantle Overturn

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## Abstract

We apply petrological models to investigate the evolution of lunar mantle mineralogy, considering lunar magma ocean (LMO) crystallization and overturn of cumulate reservoirs. The results are used to test the consistency of different LMO compositions and mantle overturn scenarios with the physical properties of the bulk Moon.

## 1. Introduction

The mineralogy of the lunar mantle has been shaped by a sequence of several processes since the formation of the Moon, including lunar magma ocean crystallization, cumulate overturn and partial melting during convection. We investigated the mineralogical composition of cumulates crystallized from the lunar magma ocean and their changes during mantle overturn by applying different petrological models in order to identify possibilities to further constrain the properties of the lunar mantle and the conditions of its evolution.

## 2. Methods

### 2.1 Magma Ocean Crystallization

LMO cumulate mineralogies were modeled using a combination [1] of alphaMELTS [2] and FXMOTR [3], that has been validated against recent experiments on LMO fractional crystallization [4, 5]. We assumed fractional crystallization in a full mantle LMO with a bulk composition based on [6]. FeO/MgO ratios were varied (8.0–12.5 wt% FeO) to investigate the effect of the FeO content on cumulate densities and mineralogies. All crystals were assumed to sink and equilibrate with the liquid at the bottom of the magma ocean prior to fractionation, except for plagioclase which was assumed to float to the surface to form anorthositic crust.

### 2.2 Mantle Mixing and Overturn

As a consequence of the higher compatibility of lighter Mg compared to denser Fe in the LMO cumulate minerals, the density of the cumulate increases with progressing LMO solidification. This results in a gravitationally unstable cumulate stratification that facilitates convective overturn. The changes in pressure and temperature a cumulate layer experiences during overturn as well as mixing and chemical equilibration of different layers can affect the mineralogy and physical properties of the lunar mantle. To investigate these changes, we calculated equilibrium mineral parageneses of different cumulate layers using Perple\_X [7]. For simplicity we considered five homogeneous cumulate reservoirs (olivine-dominated, pyroxene-dominated, IBC, KREEP and crust), whose compositions were derived from the results of the LMO crystallization models by averaging the compositions of adjacent cumulate layers with similar mineralogies. The mineralogies and densities of each reservoir were calculated as a function of depth along different selenotherms [8, 9]. To evaluate the effect of mixing and chemical equilibration, we made the same calculations for different compositional mixtures of the layers. The results of these calculations were used as input in a simple density structure model in order to investigate the effect of mantle overturn on the bulk lunar density and moment of inertia. Lunar core sizes and densities were thereby varied within the range of proposed values [10, 11].

## 3. Results

### 3.1 Effects of FeO content

We found that increasing FeO/MgO ratios in the LMO lead to higher cumulate densities but do not significantly affect cumulate mineralogies, except for an increased abundance of Fe-rich minerals appearing late in the crystallization sequence. This higher abundance of Fe-rich minerals leads to an

increased thickness of the late forming dense ilmenite bearing cumulate layer (IBC), that we defined not based on mineralogy but based on its high density compared to underlying cumulate layers.

### 3.2 Effects of cumulate mixing

Models assuming moderate mixing and chemical equilibration (i.e. assuming separate reservoirs of olivine, pyroxene and IBC cumulates in the lunar mantle) have systematically higher densities than more strongly mixed models (i.e. assuming that the olivine and pyroxene layers have mixed and chemically equilibrated). This is primarily due to differences in the distribution of Ca and Al in the cumulate. In moderately mixed models, local Ca and Al concentrations in the pyroxene-dominated reservoir are high enough to facilitate the local formation of dense garnet, while in strongly mixed models Ca and Al are sufficiently diluted to impede garnet formation.

### 3.3 Effects of cumulate overturn

Due to its high density the overturn of the IBC layer has a significant effect on the bulk lunar moment of inertia, even though its thickness is comparatively small with a few tens of kilometers. For thick IBC layers associated with high FeO contents the effect of IBC overturn on the bulk lunar moment of inertia can even exceed the effect of the overturn of the larger olivine and pyroxene dominated mantle reservoirs. The cumulate mineralogies typically do not change significantly during overturn. An exception are layers containing sufficient amounts of  $\text{Al}_2\text{O}_3$  and CaO to allow garnet formation at increased pressures. Such high concentrations of  $\text{Al}_2\text{O}_3$  and CaO can be reached in late forming pyroxene layers, especially if plagioclase floatation is impeded and plagioclase is partially trapped in the cumulate.

## 4. Discussion

Our results indicate that the bulk lunar density and moment of inertia are consistent with bulk silicate Moon (BSM) FeO contents of 8.1 – 11.7 wt% for the assumed LMO properties and the considered uncertainties in temperature, degree of cumulate overturn, chemical equilibration of cumulate reservoirs, core size and core density. The range of plausible FeO contents could be narrowed down further by studying the relations between these

parameters in more detail, e.g. by modeling the effects of rheological properties of cumulate materials on both the degree of IBC overturn (e.g. [12]) and the chemical mixing of different reservoirs. Based on seismic properties of the lunar mantle, [13] proposed a pyroxenitic upper mantle and Mg-rich lower mantle, which suggests that the overturn of the lunar mantle was incomplete. Their pyroxenitic upper mantle composition is consistent with a mixture of our pyroxenite reservoir with about 6% trapped plagioclase, while their Mg-rich lower mantle composition is consistent with the mixture of our olivine-dominated reservoir with 14% IBC and 9% crustal material. According to our models, an incomplete overturn of the lunar mantle as suggested by the results of [13] is associated with high moments of inertia, that need to be compensated by high degrees of IBC overturn to fit the bulk lunar moment of inertia. Such high degrees of IBC overturn have implications for the rheological properties of the lunar mantle ([12]). However, the compositional models proposed by [13] do not consider the presence of a distinct IBC reservoir, even though dynamical models suggest that mixing of IBC and lower mantle material is limited ([12]). Hence further study is required to specifically test the consistency of our lunar mantle models with seismic properties of the lunar mantle.

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