DETERMINATION OF THE BULK SILICATE MOON FEO CONTENT FROM PETROLOGICAL AND GEOPHYSICAL MODELS

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Introduction: The isotopic similarity of Earth and Moon and the most recent estimates of anorthositic crust thicknesses lead to the consensus that the composition of the Moon is largely Earth-Mantle-like [1]. An exception to that is the FeO content of the bulk silicate Moon (BSM), which has been suggested to be significantly higher than in the Earth's mantle, based on both petrological and geophysical arguments. However, there is no clear consensus on the degree of Fe enrichment and suggested BSM FeO contents vary significantly between ~8 – 17 wt% [2], though most studies seem to favor a moderate BSM FeO content of ~12 – 13 wt% [3].

Seismic velocity data indicate that the lunar mantle is stratified with a pyroxenitic, FeO-rich upper mantle and dunitic, FeO-poorer lower mantle [4]. However, the quality of the available seismic data is insufficient to resolve a potential gradient of the FeO content with depth [4] and distinct compositional reservoirs in the lunar mantle are typically not explicitly considered in seismic studies. The compositions and radial distribution of different mantle reservoirs is also relevant for other physical properties like the bulk Moon density and moment of inertia, which provides further constraints on the BSM FeO content.

Information about possible compositions and relative volumes of distinct mantle reservoirs can be obtained by modeling compositional differentiation during lunar magma ocean (LMO) crystallization and subsequent mixing of primary reservoirs by mantle convection. Employing such models, we investigated the effect of the BSM FeO content on the compositions and relative volumes of mantle reservoirs and tested the consistency of different overturn scenarios with observed bulk moon physical properties.

Methods: *Lunar Magma Ocean Crystallization.* We modeled LMO cumulate mineralogies using a combination [5] of alphaMELTS [6] and FXMOTR [7], that has been validated against recent experiments on LMO fractional crystallization [8, 9]. Thereby we assumed pure fractional crystallization of a deep LMO, that extends to the core-mantle boundary so that the LMO comprises the whole BSM. The LMO composition was chosen based on [10]. FeO/MgO ratios of the bulk LMO composition were varied (8.0-13 wt% FeO) to investigate the effect of the FeO content on the densities and mineralogies of individual cumulate layers. All crystals forming in the LMO 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. The average lunar crust thickness was assumed to be 40 km. Any excess plagioclase that formed after that final crust thickness was reached was assumed to remain in the mantle due to imperfect plagioclase floatation.

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, during which dense material sinks towards the core mantle boundary while lighter material migrates toward the surface. The respective changes in pressure and temperature experienced by individual cumulate layers, as well as mixing and chemical equilibration of different layers during overturn, can affect the mineralogy and physical properties of the lunar mantle.

To investigate these effects, we calculated equilibrium mineral parageneses of different cumulate layers using Perple_X [11]. 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 [12, 13].

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 values proposed in recent studies [14-16].

Results and Discussion: *Effects of BSM FeO content on mantle reservoir properties.* Changing the FeO/MgO ratio of the BSM composition leads to an earlier appearance and higher abundance of Fe-rich minerals in the LMO cumulate. This results in an increased thickness of the late formed, dense ilmenite bearing cumulate (IBC) reservoir, that we defined based on its high density compared to underlying cumulate layers. As a consequence, IBC thickness

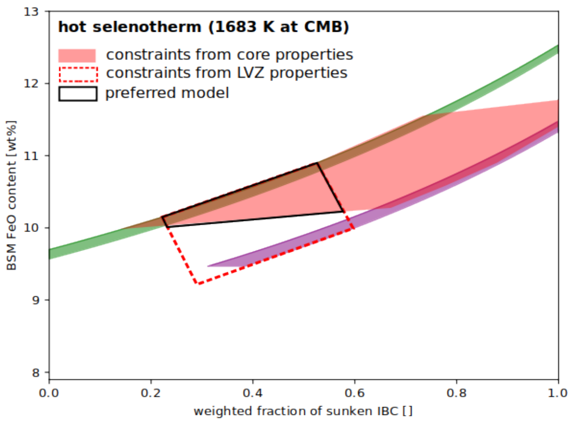

Fig. 1: Range of plausible BSM FeO contents and fractions of sunken IBC for a selenotherm of [13]. Green and purple bands represent two end member mantle stratigraphies consistent with seismic constraints by [4] and mark the parameter space where the models fit the BSM moment of inertia and the bulk Moon density. The red colored area and the red bordered area mark the parameter space consistent with core radii according to [14] and with the low velocity zone properties according to [17], respectively. The black line borders the resulting preferred parameter space, marking the range of BSM FeO contents and radial distributions of IBC material that are consistent with all considered constraints.

correlates linearly with the assumed LMO FeO content, varying by a factor of about 4 over the assumed range of FeO contents. The properties of other mantle reservoirs are only slightly affected by changes in mineral chemistry and a passive reduction in reservoir volume as a result of the growing IBC layer.

Effects of BSM FeO content on bulk Moon physical properties. Due to its high density the radial distribution of IBC material in the lunar interior has a significant effect on the BSM moment of inertia, even though its volume is comparatively small. The effect of the distribution of IBC on the BSM moment of inertia increases systematically with increasing IBC volume, which is in turn linked to the FeO content.

Constraints on the BSM FeO content: To determine realistic ranges of BSM FeO contents and fractions of sunken IBC from our data, we systematically varied BSM FeO contents, calculated the degree of IBC overturn required to fit the observed BSM moment of inertia for each stratigraphic model and assumed selenotherm and tested the compatibility of each model with the bulk Moon density.

To further constrain plausible FeO contents and fractions of sunken IBC, we considered additional information on the lunar mantle stratigraphy and local densities from seismic velocities and selenodetic data, which suggest that the lunar mantle is stratified with a pyroxenitic, FeO-rich upper mantle and dunitic, FeO-poorer lower mantle [4] and provide estimates of the density and thickness of the IBC-bearing low velocity zone at the core mantle boundary [17].

Considering all available constraints on core size and composition and mantle stratigraphy from seismic and selenodetic data as well as numerical models and petrological studies, our model favors BSM FeO contents of 9.4 – 10.9 wt% (with a lowermost limit of 9.0 wt%) and weighted fractions of overturned IBC of 21 – 59 %.

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