CONSTRAINTS ON THE BULK SILICATE MOON FEO CONTENT FROM PETROLOGICAL AND GEOPHYSICAL MODELS.

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Introduction: Estimates of the bulk silicate Moon (BSM) composition have been proposed based on a number of different geochemical, petrological and geophysical arguments but have yet to arrive at a general consensus. Most notably the amount of FeO in the lunar interior is still poorly constrained with estimates varying between ~9-17wt% FeO [1, 2].

In addition, seismic velocity data indicate that the lunar mantle is stratified with a pyroxenitic, FeO-rich upper mantle and dunitic, FeO-poorer lower mantle [3]. However, the quality of the available seismic data is insufficient to resolve a potential gradient of the FeO content with depth [3] 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 [4] of alphaMELTS [5] and FXMOTR [6], that has been validated against recent experiments on LMO fractional crystallization [7, 8]. 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 [9]. 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 [10]. 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 [11,12].

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 [13, 14].

Results:

Effects of BSM FeO content on mantle reservoir properties. The compositions and volumes of the early formed olivine- and pyroxene dominated reservoirs remain almost unaffected by increasing FeO/MgO ratios in the LMO. Instead, higher BSM FeO contents lead to higher concentrations of FeO in the rest melt and an earlier appearance of Fe-rich minerals in the crystallization sequence. This earlier appearance and higher abundance of Fe-rich minerals leads to an increased thickness of the late formed, dense ilmenite bearing cumulate (IBC) reservoir, that we defined not based on mineralogy but based on its high density compared to underlying cumulate layers. As a consequence, IBC thickness correlates linearly with the assumed LMO

FeO content, varying by a factor of about 4 over the assumed range of FeO contents. In addition, changing LMO FeO contents affect the bulk IBC mineralogy in that the fraction of fayalitic olivine increases with increasing FeO content.

Effects of reservoir mixing. Models assuming only 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, especially if plagioclase floatation is impeded, so that plagioclase is partially trapped in the cumulate. In strongly mixed models Ca and Al are sufficiently diluted to impede garnet formation, which leads to lower bulk densities.

Discussion:

Linking bulk Moon Physical properites and BSM FeO content. The modeled bulk Moon densities depend on several factors, including BSM FeO content, the assumed selenotherm and the assumed core size and density. The uncertainties in present-day temperatures of the lunar interior and the properties of the lunar core make it difficult to unambiguously link bulk Moon density and BSM FeO content without additional constraints.

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 thickness is comparatively small with a few tens of kilometers. 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.

Dynamical models of the sinking of IBC in a cooling Moon suggest that at present most of the IBC material is located either at the core mantle boundary or got stuck in the lithosphere right beneath the crust [15]. This distribution suggests that the low seismic velocity zone at the core mantle boundary [13, 16] might consist largely of IBC material. Hence, the thickness and density of this low seismic velocity zone [13, 16] can be used to estimate the amount of IBC that has sunken to the core mantle boundary.

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 and calculated the corresponding degree of IBC overturn required to fit the observed BSM moment of inertia for each stratigraphic model and assumed selenotherm. In addition we tested the compatibility of each model with the bulk Moon density to further constrain plausible FeO contents. The resulting FeO contents for all considered models range from 8.3 – 12.8 wt%.

Seismic data suggest a mantle stratigraphy with a pyroxenitic upper mantle and a dunitic lower mantle, which limits the range of plausible stratigraphic models. Considering this additional constraint, our data favor a BSM FeO content of about 8.5 – 11.5 wt% and exclude FeO contents > 12.8 wt% for the selected selenotherms. This range of FeO contents is generally consistent with petrological constrains on lunar mantle compositions and could be determined more precisely given tighter constraints on the present day selenotherm and the properties of the lunar core.

Conclusion: We investigated the effect of the BSM FeO content on the properties of lunar mantle reservoirs formed during LMO solidification and found that the amount of ilmenite bearing cumulates varies systematically with the BSM FeO content. We demonstrate that this relation can be used to establish links between the BSM FeO content and the present day physical properties of the Moon, including the bulk Moon density, the BSM moment of inertia and seismic and selenodetic constraints on the properties of the lunar interior.

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