CONSTRAINTS ON THE BULK SILICATE MOON FEO CONTENT FROM PETROLOGICAL AND GEOPHYSICAL MODELS. S. Schwinger[1] and D. Breuer[1], [1]German Aerospace Center (DLR), Rutherfordstr. 2, 12489 Berlin, sabrina.schwinger@dlr.de.

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 ~9-17 wt% FeO [1, 2]. In addition, seismic velocity data indicate that the lunar mantle is possibly 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 hence 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 the formation and modification of these reservoirs by differentiation and mixing processes during early lunar evolution. The differentiation of distinct mantle reservoirs likely occurred during fractional crystallization of a global lunar magma ocean (LMO), which also produced the anorthositic lunar crust. Convection of the solid mantle during and after LMO solidification and related mixing and partial melting of the primary mantle reservoirs further modified the compositional structure of the lunar mantle.

We modeled the formation of primary mantle reservoirs during LMO solidification to investigate the effect of the BSM FeO content on the reservoir compositions and relative volumes 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 crystallization algorithms from the software packages alphaMELTS [5] and SPICES [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 bulk LMO composition was chosen based on the estimate of [9], who assumme an FeO content of 12.4 wt%. 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 an anorthositic crust. The average lunar crust thickness was assumed to be 40 km in accordance with recent GRAIL data [10]. 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. Since the LMO solidifies from bottom to top, 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 also made the same calculations for a homogeneous mixture containing the olivine- and pyroxene-dominated mantle layers and a second mixture containing all three mantle layers (olivine, pyroxene and IBC). 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 todays bulk lunar density and moment of inertia. Lunar core sizes and densities were thereby varied within the range of proposed values [14, 15].

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 the FeO/MgO ratios assumed for the bulk 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, which we have defined not on the basis of mineralogy but due to 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 (from 7-28 km) 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. Lunar mantle 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 at larger depths, 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 properties and BSM FeO content.* The modeled bulk Moon density depends 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 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. 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 [16]. This distribution suggests that the low seismic velocity zone at the core mantle boundary [14, 17] might consist largely of IBC material. Hence, the thickness and density of this low seismic velocity zone [14, 17] can be used to estimate the amount of IBC that has sunken to the core mantle boundary. This establishes a relation between the total volume of IBC (and hence BSM FeO content) and the BSM moment of inertia.

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 and bulk Moon density for each stratigraphic model and assumed selenotherm.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 further limits the range of plausible stratigraphic models. Considering this additional constraint, our model 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.

Acknowledgments: This work was funded by the Deutsche Forschungsgemeinschaft (SFB-TRR170, subproject C5).

References: [1] Jones and Delano (1989), Geochim. Cosmochim. Acta, 53 (2), 513-527. [2] Warren (1986), JGR: Solid Earth, 91 (B4), 331-343. [3] Gagnepain-Beyneix et al. (2006), Physics of the Earth and Planetary Interiors, 159 (3-4), 140-166. [4] Schwinger and Breuer (2018), AGU Fall Meeting, Washington, USA. [5] Smith and Asimow (2005), G³, 6.2. [6] Davenport (2013), Planet. Sci Res. Disc. Report 1, 173. [7] Rapp and Draper (2018), Meteoritics & Planet. Sci. 53.7, 1432-1455. [8] Charlier et al. (2018), Geochim. Cosmochim. Acta, 234, 50–69. [9] O'Neill (1991), Geochim. Cosmochim. Acta, 55 (4), 1135-1157. [10] Wieczorek et al. (2013) Science, 339, 671. [11] Connolly (2005), EPSL, 236 (1-2), 524-541. [12] Kuskovand Kronrod (1998), Physics of the Earth and Planetary Interiors, 107.4, 285-306. [13] Laneuville et al. (2013), JGR: Planets, 118 (7), 1435-1452. [14] Weber et al. (2011), science, 331 (6015), 309-312. [15] Garcia et al. (2011), Physics of the Earth and Planetary Interiors, 188(1-2), 96-113. [16] Yu et al. (2019), JGR: Planets, 124 (2), 418-436. [17] Matsumoto et al. (2015), GRL, 42 (18), 7351-7358.