Crystallization of the lunar magma ocean and the primordial mantle-crust differentiation of the Moon

Bernard Charlier a,b,c,\*, Timothy L. Grove a, Olivier Namur b,d, Francois Holtz b

*a Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge, MA 02139 USA*

*b Institut für Mineralogie, Leibniz Universität Hannover, 30167 Hannover, Germany*

*c Department of Geology, University of Liège, 4000 Sart Tilman, Belgium*

*d Department of Earth and Environmental Sciences, KU Leuven, 3000 Leuven, Belgium*

\* Corresponding author. *Email address*: b.charlier@ulg.ac.be (B. Charlier)

Present address: Department of Geology, University of Liege, 4000 Sart Tilman, Belgium

We present crystallization experiments on silicate melt compositions related to the lunar magma ocean (LMO) and its evolution with cooling. Our approach aims at constraining the primordial internal differentiation of the Moon into mantle and crust. We used graphite capsules in piston cylinder (1.35-0.80 GPa) and internally-heated pressure vessels (< 0.50 GPa), over 1580 to 1020°C, and produced melt compositions using a stepwise approach that reproduces fractional crystallization. Using our new experimental dataset, we define phase equilibria and equations predicting the saturation of liquidus phases, magma temperature, and crystal/melt partitioning for major elements relevant for the crystallization of the LMO. These empirical expressions are then used in a forward model that predict the liquid line of descent and crystallization products of a 600 km-thick magma ocean. Our results show that the effects of changes in the bulk composition on the sequence of crystallization are minor. Our experiments also show the crystallization of a silica phase at ca. 1080°C and we suggest that this phase might have contributed to the building of the lower anorthositic crust. Calculation of crustal thicknessclearly shows that a thin crust similar to that revealed by GRAIL cannot have been generated through solidification of whole Moon magma ocean. We discuss the role of magma ocean depth, trapped liquid fraction (with implication for the alumina budget in the mantle and the crust), and the efficiency of plagioclase flotation in producing the thin crust. We also constrain the potential range of pyroxene compositions that could be incorporated into the crust and show that delayed crustal building during ca. 4% LMO crystallization on the nearside of the Moon may explain the dichotomy for Mg-number. Finally we show that the LMO can produce magnesian anorthosites during the first stages of plagioclase crystallization.