

**FORWARD, REVERSE AND FXMOTR MODELING OF THE LMO: A NEW LOOK AT THE BULK COMPOSITION OF THE LMO** J.D. Davenport<sup>1,2,3</sup>, C. R. Neal<sup>2,3</sup>, G.A. Snyder<sup>4</sup>, D. Bolster<sup>2</sup> and J. Longhi<sup>5</sup> <sup>1</sup>Centre de Recherches Petrographiques et Geochimiques, Vandoeuvre-les-Nancy, France 54501; <sup>2</sup>Dept. of Civil and Env. Eng. & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA; <sup>3</sup>NASA Lunar Science Institute, U.S.A.; <sup>4</sup>3673 Maybank Hwy, PO Box 125, Johns Island, SC 29457 USA; <sup>5</sup>Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA (jessedvnprt@gmail.com; neal.1@nd.edu).

**Introduction:** Understanding the dynamics and geochemical evolution of the lunar magma ocean (LMO) is a key concept for understanding the origin and evolution of not only the Moon, but also Earth and other terrestrial planets. It is also important for future lunar exploration, mineral resource extraction, and possible colonization. LMO theory has evolved significantly since the U.S.A. embarked on the groundbreaking Apollo missions, the return of anorthositic samples and the subsequent postulation of the LMO hypothesis [1,2].

Numerical models can be a valuable tool in predicting and understanding the ways in which the LMO could have crystallized. However, numerical modeling investigations are not complete without comparison to sample and remote sensing data that has been compiled throughout the past 40+ years. There are a number of parameters to consider in order to accurately and succinctly describe the evolution of the LMO.

**Previous Work:** Without the work of many lunar scientists in the Apollo era and beyond, our current understanding of the LMO and its dynamics would be unattainable. A complete and succinct review of the LMO can be found in [5].

The first goal of this study was to recreate the model proposed by [6] in a MATLAB format for general use by lunar researchers. This can be found in [7]. Once the Snyder model was recreated, we introduced variability of different parameters into the model. The second goal of this study was based around using the recreation of the Snyder model to construct a reverse model [8]. Most models start with an assumption of a bulk Moon composition and crystallization parameters, whereas a reverse model used data such as urKREEP compositions and back-calculates the initial bulk Moon composition. We used the reverse model as an application to re-investigate two main questions that a LMO model can give insights to: bulk LMO composition and LMO depth. Using the various initial bulk LMO compositions and depths found from previous modeling studies, this study investigated various crystallization schemes to determine which is best suited for describing LMO crystallization. The reverse modeling aspect of this research

served as a check of the validity of these assumed bulk starting compositions as well as a way to guide the formulation of new bulk LMO compositions.

**Modeling Methods:** Using the approach detailed in Appendix A of [9], a revised crystallization model of the LMO was coded into MATLAB (Mathematical Laboratory). This model was integrated with parameters from previous work (see above). Reverse modeling, described in detail in Appendix B of [9], of urKREEP [10] compositions was then implemented using the crystallization scheme of [6]. The question of initial bulk LMO composition is approached using previous work as a foundation [6-10].

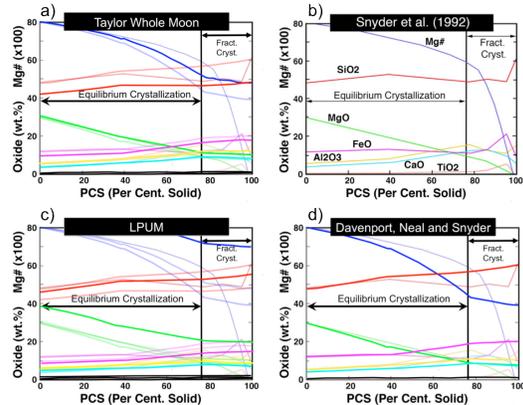
Finally, FXMOTR [11] is used to calculate new crystallization sequences based on variations in LMO bulk composition and the initial depth of the LMO. Using more Al-enriched compositions, we can also investigate the presence of garnet in the deep lunar mantle. FXMOTR is available, for free, from the authors or is available, with all files, from within the LPI Computational Tools webpage (<http://www.lpi.usra.edu/lunar/tools/crystallizationcalculation/>).

**Results:** Fig. 1 shows three initial bulk LMO compositions [6,12,13] inputted into the revised model and how the final compositions differ based on the abundance of various oxides.

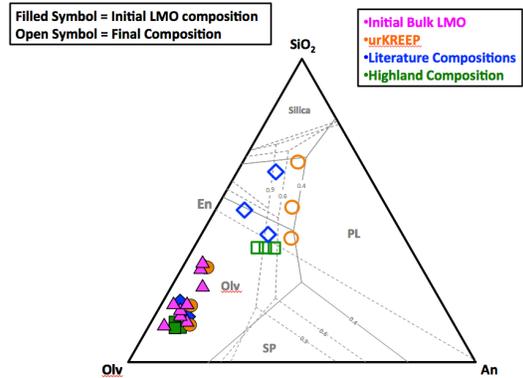
Fig. 2 shows a pseudo-ternary plot displaying all forward and reverse modeling results. It seems as though the TWM composition produces the Highland compositions rather accurately. The Snyder composition most closely produces a final composition similar to an urKREEP composition.

**LMO Depth and Mineralogy:** Despite several decades of LMO research, a number of fundamental parameters have not been well constrained. For example, [6] sets the LMO depth at 400 km, while [3] sets the depth at 1000 km. This, coupled with variations in the initial LMO composition, produce variations in the mineralization sequences for LMO crystallization. Here, FXMOTR is used to calculate various mineralization sequences to crystallize the LMO assuming LMO depths of

400 km and 1000 km (20 and 50 kbar, respectively) and the TWM and LPUM LMO bulk initial compositions taken from the literature. Figure 3 shows some of these results.



**Fig 1.** Major element evolution of the Lunar Magma Ocean. A) Taylor Whole Moon evolution, B) Snyder evolution, C) Lunar Planetary Upper Mantle evolution and D) the recreation of the Snyder et al. (1992) model.

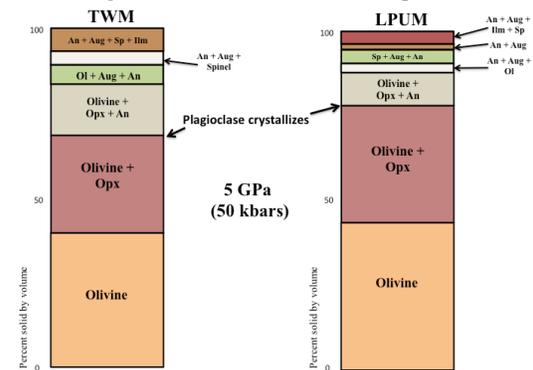


**Fig 2.** A pseudo-ternary plot of initial bulk LMO, urKREEP, literature and Highlands compositions. Open symbols represent final modeled compositions. Filled symbols represent bulk LMO and reversely modeled compositions.

**Discussion/Conclusions:** Recent GRAIL data are consistent with a bulk Moon  $Al_2O_3$  composition of ~4 wt.% with an average crustal thickness between 34-43 km [14]. However, this assumes that the majority of  $Al_2O_3$  is sequestered in the lunar crust and does not indicate the presence of an aluminous phase, i.e. garnet or spinel, in the lunar mantle. If garnet is present at depth, the bulk  $Al_2O_3$  of the Moon would need to be increased. A higher  $Al_2O_3$  content for the bulk Moon would facilitate earlier crystallization of plagioclase and other aluminous phases if the LMO was deeper than ~500 km. In turn, this would allow plagioclase to crystallize earlier and form the lunar crust, the yielding the inherent negative Eu anomaly in the mare source regions

(requiring either a somewhat muted overturn of the cumulate pile or no overturn). Earlier crust formation would generate an insulating lid and promote a longer-lived LMO, as postulated by [15] and [3]. More recently [16], using MELTS, has proposed that the Moon is more enriched in FeO and  $Al_2O_3$  than previously thought, consistent with our results. They argue that bulk Moon FeO can be constrained to between 1.3 and 1.8 xBSE (Bulk Silicate Earth) and  $Al_2O_3$  between 1 and 1.5 xBSE.

**Future Work:** To enhance the knowledge of the LMO and the Moon as a whole, global knowledge of the lunar interior is required.



**Fig. 3** Cumulate stratigraphy (TWM left, LPUM right). Solidifying mantle mineral assemblages used in this paper. Opx = orthopyroxene; Ilm = ilmenite; Pig = pigeonite; Sp = spinel; Arm = armalcolite; An=anorthite feldspar (plagioclase); Aug = augite.

The work presented here greatly stands to benefit from an updated partition coefficient database as well as the incorporation of an overturn event, geo-chronology, and the effects of turbulent mixing and Rayleigh forces during LMO crystallization. Finally, a look into the global or local nature of the LMO will be investigated through reverse modeling and the procedures published in [17].

**References:**

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