

**LMO THEORY, REVERSE MODELING, KREEP, AND GROUND TRUTH: CLUES TO THE BULK LMO COMPOSITION?** J. Davenport<sup>1</sup> and C. R. Neal<sup>1</sup>, <sup>1</sup>Dept. of Civil and Environmental Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (jdavenport1@nd.edu; neal.1@nd.edu).

**Introduction:** It is generally accepted that the lunar crust and at least the uppermost (500 km) mantle was formed by crystallization of a magma ocean. The details of how the lunar magma ocean (LMO) cooled and crystallized are still under debate. This investigation aims to take a more in-depth look at the initial bulk LMO using reverse modeling from an urKREEP composition (*ur*=primeval; enriched in Potassium, Rare Earth Element, Phosphorous; [1-3]).

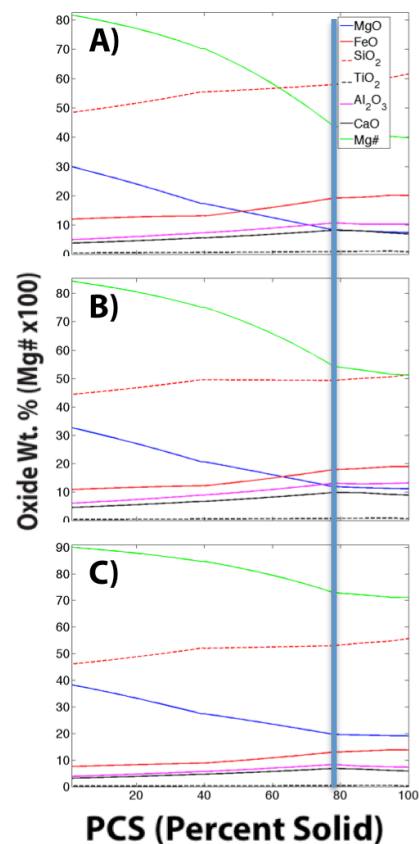
**Previous Work:** Initial models considered the effects of initial LMO bulk composition on the cumulate products, whereas later models examine the depth of the LMO, and if an overturn event occurred [4-9]. More recently, [10] found discrepancies in the model of [4]. Most importantly, crystallization of the final stages of the LMO was found to be inconsistent with geophysical and remote sensing observations.

According to LMO theory, urKREEP formed from the final stages of crystallization of the LMO. If the LMO was a Moon-wide event, an urKREEP-rich layer would exist uniformly throughout the Moon [1]. However, KREEP-rich areas are not found on the lunar farside, not even in the bottom of the South Pole-Aitken Basin [9-10]. Elemental maps produced from Lunar Prospector data show that KREEP components are concentrated only in certain regions on the near side, collectively termed the Procellarum KREEP Terrane (PKT; [11]).

**Modeling Methods:** Using the approach detailed in [4], 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 [12] of urKREEP [1] compositions was then implemented using the crystallization scheme of [4]. Incorporation of Monte Carlo Simulations into the revised model as well as the Reverse LMO Model was executed to gain a more robust compositional spectrum of bulk LMO compositions. Monte Carlo Simulations follow this general format: 1) define a domain of possible inputs, 2) generate inputs from this domain from a probability distribution, 3) perform the predetermined computation on the inputs, and 4) assemble the results. Thus, the

question of initial bulk LMO composition is approached using previous work as a foundation [12]. This approach does have a few limitations: 1) the percentage and exact composition of urKREEP is not known and 2) the exact modal mineralogy of urKREEP is not well constrained.

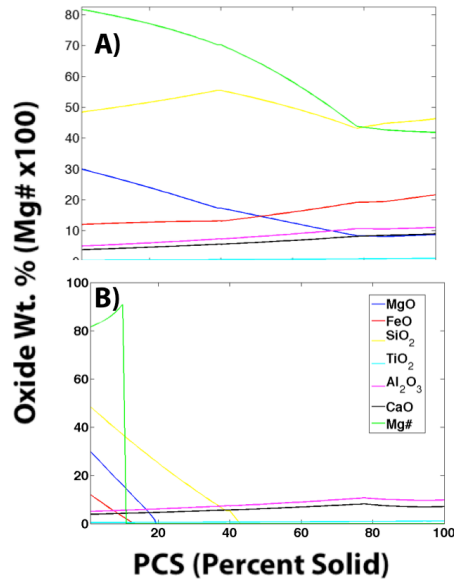
**Results:** Fig. 1 shows three initial bulk LMO compositions [4,7,8] inputted into the revised model and how the final compositions differ based on the abundance of various oxides.



**Fig 1.** Initial bulk compositions from LMO models of A) [4], B) [7], and C) [8]. Far left is the initial bulk composition to 100% crystallization on the right. Left of the line represents equilibrium crystallization and fractional crystallization to the right and where plagioclase crystallizes.

A number of studies have looked at the extent of fractional [13] and equilibrium crystallization [6] and concluded that either fractional or equilibrium crystallization could have been dominant throughout the entire LMO crystallization. However, we contend that having fractional crystallization be the dominant process

is not possible because the LMO would be depleted of its constituent phases well before the final stages of crystallization (as seen in the immediate depletion of nearly all oxides in Fig 2b). Conversely, if equilibrium crystallization was the sole process (Fig 2a), not enough of the constituent phases would crystallize to produce the observed lunar highland lithologies [6]. In both cases, it is difficult to produce the estimated urKREEP compositions [1-3].



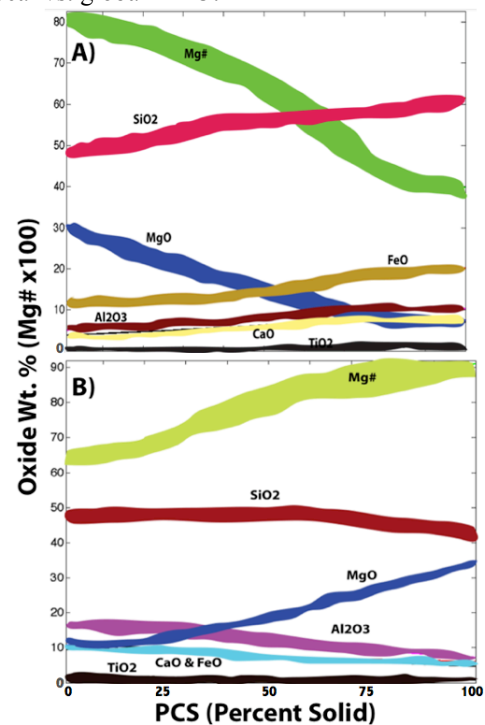
**Fig 2.** A) 100% Equilibrium crystallization and B) 100% fractional crystallization. Notice that all oxides are consumed early in B). In A) plagioclase would unlikely come on the liquidus due to the nature of equilibrium crystallization. In B) the Mg# drops to zero due to MgO and FeO compositions dropping into negative values.

Fig. 3 shows results for forward and reverse models. The forward model (Fig. 3a) uses the initial bulk compositions of [4,7,8] and is thus plotted as a range. Fig 3b shows the reverse model using urKREEP [12] as the starting material. A number of major elements (i.e. Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>) in the bulk LMO composition derived from the reverse model (Fig 3b) are significantly higher compared to forward bulk LMO initial compositions (Fig. 3a). Higher Al<sub>2</sub>O<sub>3</sub> implies earlier plagioclase crystallization. Additionally, if the LMO extended below 500 km, garnet could be a crystallizing phase [14], which would dramatically increase the Bulk Moon Al<sub>2</sub>O<sub>3</sub>.

**Conclusions:** Two important conclusions emerge from the combination of forward and reverse modeling: 1) the bulk initial composition of the LMO needs to be revised; 2) LMO

crystallization requires a combination of fractional and equilibrium processes.

**Future Work:** The model presented here will incorporate new crystallization sequences, extend the LMO to a depth of 1000 km, modify existing crystallization sequences, and re-run reversely calculated bulk LMO compositions back through the forward model after adjusting the crystallization sequence to account for the new bulk composition. To ensure ground truth, the methods of [15] will be used to calculate the lunar crust composition via mineral abundances. This can then be used as the starting composition in the reverse model. This approach will yield insight not only into possible initial bulk compositions but also into the possibility of a local vs. global LMO.



**Fig 3.** A) Forward and B) reverse models with [4] initial compositions using Monte Carlo.

**References:** [1] Warren, P.H. and J.T. Wasson (1979) *Rev. Geophys. Space Phys.* 17, 73-88. [2] Warren, P.H. (1988) *Proc. Lunar Sci. Conf. 18<sup>th</sup>*, 233-241. [3] Warren, P.H. (1989) *LPI Tech. Rept. 89-03*, 149-153. [4] Snyder G.A. et al. (1992) *GCA* 56, 3809-3823. [5] Elkins-Tanton L.T. et al. (2011) *EPSL* 304, 326-336. [6] Elardo S.M. et al. (2011) *GCA* 75, 3024-3045. [7] Taylor S.R. (1982) *Planetary Science, A Lunar Perspective*. Lunar Planet. Inst., Houston. [8] Longhi J. (2006) *GCA* 70, 5919-5934. [9] Namur O. et al. (2011) *GCA* 75, 4998-5018. [10] Davenport J. and C.R. Neal (2012) *43rd LPSC*, abstract #1546. [11] Joliff et al. (2000), *JGR* 105, 4197-4216. [12] Davenport J. and C.R. Neal (2012) *Proc. NLSI LSF*. [13] Rapp J.F. and D.S. Draper (2012) *43<sup>rd</sup> LPSC*, abstract #2048. [14] Neal C.R. (2001) *JGR* 106, 27865-27885. [15] Li, S. et al. (2012) *Icarus* 221, 208-225.