Forward, Reverse and FXMOTR Modeling of the LMO: A Look at the Bulk Composition of the LMO

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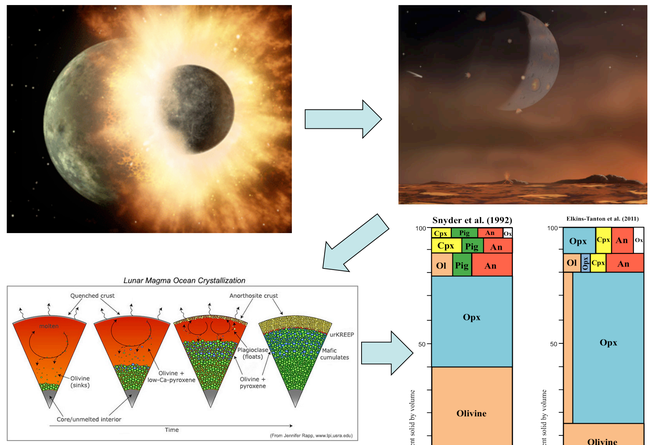
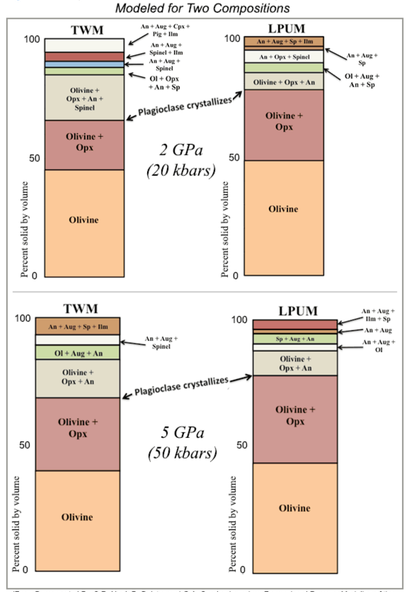
Introduction and Aim of Study

- The LMO is a key concept to understanding the origin and evolution of the Moon, Earth, and other terrestrial planets.
- LMO theory was first established with the return of anorthositic samples from the Apollo missions [1,2,3,4,5].



- **Goal 1:** Recreate LMO model of [6] and vary parameters.
- **Goal 2:** Construct a reverse LMO model [8].
- **Goal 3:** Model LMO crystallization using FXMOTR and investigate presence of garnet in the Lunar Mantle [18].
- Numerical models = valuable tools for understanding LMO evolution.
- But… models must be combined with ground truth → sample and remote sensing.
- Important parameters must be considered to accurately describe the evolution of the LMO (e.g., Initial composition, depth of LMO).

Figure 7. *Crystallization Order of the Lunar Magma Ocean Modeled for Two Compositions*



(From Davenport, J.D., C.R. Neal, D. Bolster and G.A. Snyder, in review, Forward and Reverse Modeling of the Lunar Magma Ocean: Implications for the Bulk Lunar Magma Ocean Composition.)

FXMOTR Modeling

- Using FXMOTR [11], we varied LMO depth (and hence pressure; 2 GPa=400 km & 5 GPa=1000 km) and initial composition between Al-rich and poor compositions (Fig. 7).
- Al-rich compositions (i.e. TWM) produce plagioclase (~65 PCS) on the liquidus before LPUM (~78-80 PCS).
- [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 x Bulk Silicate Earth (BSE) and Al_2O_3 between 1 and 1.5 x BSE.
- FXMOTR consistently generates small quantities (~1-5 wt.%; below 500 km) of garnet in the lunar mantle with Al-rich bulk compositions ([18]).

Reverse Modeling

- Geochemical compositions of *ur*KREEP and FAN are processed in a backwards fashion through various LMO models (Figs. 8-12; [8,9]).
- This allows an estimate of the bulk LMO to be calculated from ground truth, rather than starting with an assumed bulk composition [9].

urKREEP (Warren and Wasson, 1979)	
SiO_2	47.96
TiO_2	1.65
Al_2O_3	16.63
FeO	10.58
MnO	0.14
MgO	10.62
CaO	9.52
Na_2O	0.86
K_2O	0.83
P_2O_5	0.78
Cr_2O_3	1.3

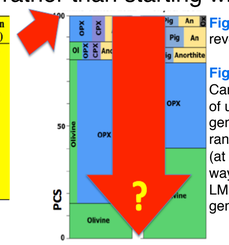


Figure 8 (left). A schematic of reverse LMO modeling.

Figure 11 (right). Reverse Monte Carlo modeling of LMO. A range of urKREEP compositions were generated in order to generate a range of initial LMO compositions (at 0 PCS). This is a very simple way to compare modeled initial LMO compositions with those generated from ground truth.

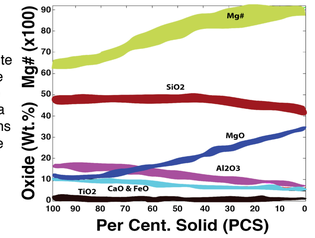


Figure 9 (below). urKREEP compositions A) Warren & Wasson [10], B) Warren [21]; C) Warren [22]. Reversely modeled compositions give higher concentrations of Al_2O_3, TiO_2, & FeO.

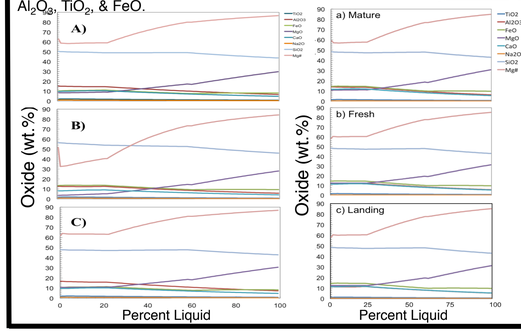
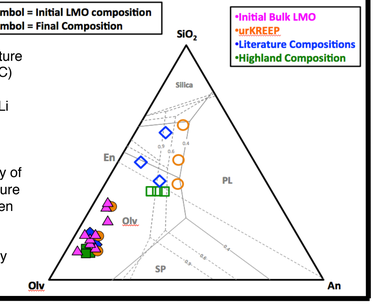


Figure 10 (left). A) Apollo 16 Mature site, B) Apollo 16 Fresh site and C) Apollo 16 Landing Site. Surface compositions provided by Shuai Li using the methods of [17] to calculate surface mineralogy.

Figure 12 (right). Pseudo-ternary of initial bulk LMO, urKREEP, literature and Highlands compositions. Open symbols represent final modeled compositions. Filled symbols represent bulk LMO and reversely modeled compositions.

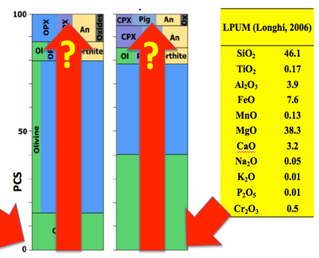


Forward Modeling

- [6] created a crystallization model (Fig. 2) of the LMO, but did not explain major or trace element modeling in detail.
- [6] shows a progressive depletion of MgO after 78 PCS (Percent Solid; Plag. on liquidus); subsequent, rapid depletion of Mg# (Fig. 3-6; TWM [12] & LPUM [13] for comparison).
- Trace element modeling is recreated here (Fig. 4).
- [6] predicts 0 wt% MgO for urKREEP, but calculated compositions predict ~10 wt% MgO (e.g., [10]).
- [9] predicts 7-10 wt% MgO for urKREEP with an appropriate Mg# to match (~.40).

Figure 2. Schematic of forward LMO modeling. A bulk LMO is crystallized through a specific sequence and the resulting final liquid compositions are compared to urKREEP compositions.

TWM (Taylor, 1982)	
SiO_2	44.4
TiO_2	0.31
Al_2O_3	6.1
FeO	10.9
MnO	0.15
MgO	32.7
CaO	4.6
Na_2O	0.09
K_2O	0.01
P_2O_5	0.01
Cr_2O_3	0.61



LPUM (Longhi, 2006)	
SiO_2	46.1
TiO_2	0.17
Al_2O_3	3.9
FeO	7.6
MnO	0.13
MgO	38.3
CaO	3.2
Na_2O	0.05
K_2O	0.01
P_2O_5	0.01
Cr_2O_3	0.5

Figure 3. Major element evolution of the Lunar Magma Ocean. A) TWM evolution, B) [6] evolution, C) LPUM evolution and D) the recreation of [6].

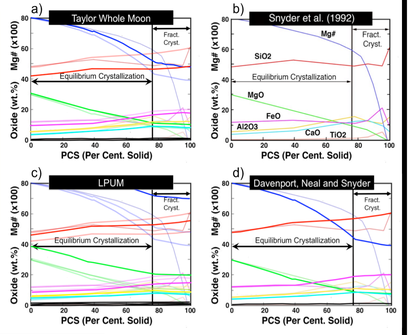
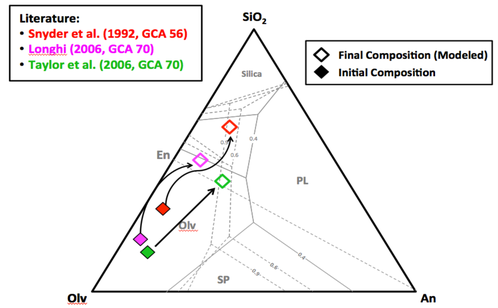


Figure 5 (left). Forward Monte Carlo modeling of the Lunar Magma Ocean. A range of compositions was generated from the literature, a normal distribution populated a set amount of numbers in that range and the program runs the predetermined amount of iterations resulting in a range of final LMO compositions (at 100 PCS).

Figure 6 (right). A pseudo-ternary plot of Olivine, SiO_2 and anorthosite projected from Cpx plotting the Snyder [6], TWM and LPUM compositions in filled symbols and respective final compositions in open symbols.

Literature:
- Snyder et al. (1992, GCA 56)
- Longhi (2006, GCA 70)
- Taylor et al. (2006, GCA 70)



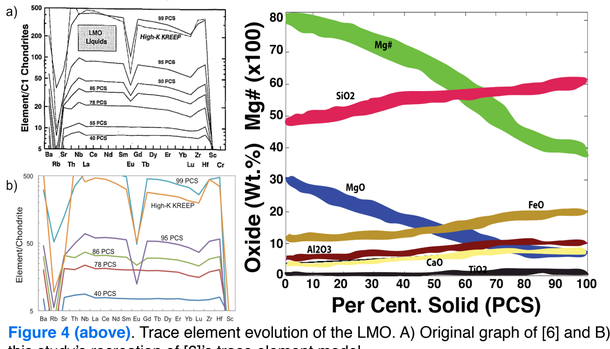


Figure 4 (above). Trace element evolution of the LMO. A) Original graph of [6] and B) this study's recreation of [6]'s trace element model.

Conclusions & Future Work

- Higher alumina content implies the following about the LMO and the Moon (needs to be reconciled with [14]):
  1. Earlier crystallization of plagioclase
  2. Hence, earlier formation of the crust, and insulating layer on surface
  3. Longer-lived magma ocean because of the insulating lid
  4. Earlier development of an europium anomaly, so is there a need for mantle overturn?
  5. If the LMO ≥500 km garnet crystallizes in small quantities. Similar results were found by laboratory experiments in [20].
- Need updated partition coefficient databases.
- Need to incorporate other parameters such as any overturn event into model.
- Look at the global and local nature of the LMO through reverse modeling and procedures published in [17].

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References

[1] Wood et al. (1970) *Proc. Apollo 11 Lunar Sci. Conf.*, 965-988 [2] Smith et al. (1970) *Proc. Apollo 11 Lunar Sci. Conf.*, 897-925 [3] Elkins-Tanton L.T. et al. (2011) *EPSL 304*, 326-336 [4] Spera, F., (1992) *GCA 56*, 2253-2265 [5] Jolliff et al. (2000) *Eos. Trans.* AGU, 349-355 [6] Snyder G.A. et al. (1992) *GCA 56*, 3809-3823 [7] Davenport J. and C.R. Neal (2012) *43rd LPSC*, abstract #1546. [8] Davenport J. and C.R. Neal (2012) Proc. NLSI LSF [9] Davenport et al. (under review) *GCA* [10] Warren, P.H. and J.T. Wasson (1979) *Rev. Geophys. Space Phys. 17*, 73-88 [11] Davenport et al. (in prep.) *Comp. Geosci.* [12] Taylor et al. (2006) *GCA 70*, 5904-5918[13] Longhi, J., (2006) *GCA 70*, 5919-5934 [14] Wieczorek et al., (2013) *Science 339*, 671-675 [15] Borg et al. (2011) *Nature 477*, 70-73 [16] Sakai et al. (2014) *Icarus 229*, 45-56. [17] Li, S. et al. (2012) *Icarus 221*, 208-225. [18] Neal C.R. and J.D. Davenport (2014, this conference) abstract #1181. [20] Elardo et al. (2011) *GCA 75*, 3024-3045. [21] Warren P. (1988) PLPSC 18, 233-241; [22] Warren P. (1989) LPI Tech. Rpt. 89-03, 149-153.