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** are 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).

Forward Modeling

- [6] created a crystallization model (Fig. 2) of the LMO, but did not explain major or trace element modeling in detail.
- [8] 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). Forward, Reverse and FXMOTR Modeling of the LMO: A Look at the this study’s recreation of [6]’s trace element model.

Figure 3. 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.

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

Figure 5 (left). Forward Monte Carlo modeling of the Lunar Magna Oceans. 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, SiO₂, and anorthosites projected from Cpx plotting the Snyder [6]. TWM and LPUM compositions in filled symbols and respective final compositions in open symbols.

Figure 7. Crystallization Order of the Lunar Magna Ocean. A) TWM evolution, B) [6] evolution, C) LPUM evolution and D) the recreation of [6].

Conclusions & Future Work

- Higher alumina content implies the following about the LMO and the Moon needs to be reconciled with [10].
  1. Earlier crystallization of plagioaplite
  2. Earlier, earlier formation of LMO, 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 is 200 km garnet crystals in small quantities. Similar results were found by laboratory experiments in [20].

- Need to incorporate more parameters as any overam event into the experiments (at 0 PCS). This is a very simple way to compare modeled initial LMO compositions with those generated from ground truth.

- 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 (~75-80 PCS).
- [10], using MELTS, has proposed that the Moon is more enriched in FeO and Al₂O₃ than previously thought, consistent with our results.
- They argue that bulk Moon FoO can be constrained to between 1.3 and 1.8 x Bulk Silicate Earth (BSE) and Al₂O₃ 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 (118).

Reverse Modeling

- Geochemical compositions of urKREEP 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].

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

Figure 9 (right). Reverse Monte Carlo modeling of the LMO. A range of urKREEP compositions are generated with the range of initial LMO compositions at 100 PCS. This is a very simple way to compare modeled initial LMO compositions with those generated from ground truth.

Figure 10 (right). Reverse Modeling.

Figure 11 (left). A schematic of reverse modeling.

Acknowledgements

The authors would like to thank Brandon Schneider and Linda Elkins-Tanton for their help with MCM/C code and implementation. This work is supported by NASA/Cosmochronology NNX14AH05G and MLS fellowship to the LPI to Clive Neal.

References