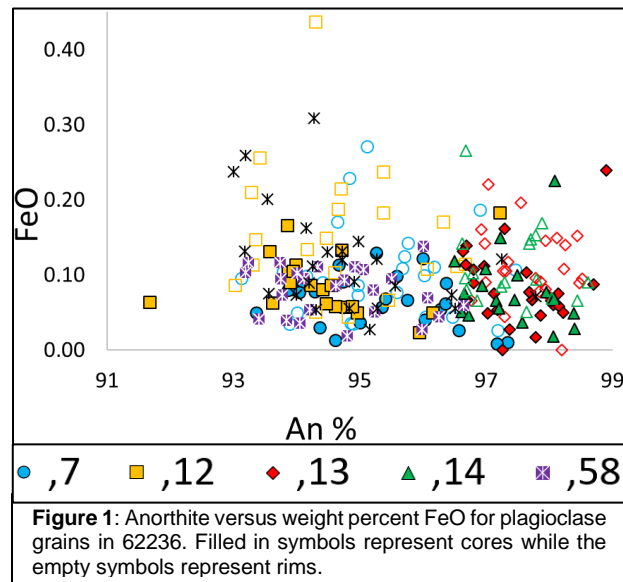
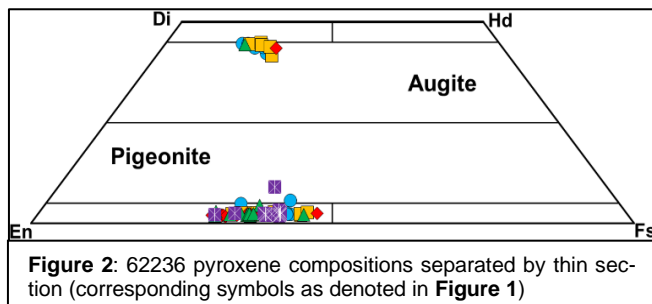


**EVIDENCE FOR AN INITIAL LREE-DEPLETED LMO FROM THE YOUNGEST FERROAN ANORTHOSITE SUITE SAMPLE 62236.** M. A. Torcivia<sup>1</sup> and C. R. Neal<sup>2</sup>, <sup>1,2</sup>University of Notre Dame Department of Civil and Environmental Engineering and Earth Sciences (<sup>1</sup>mtorcivi@nd.edu; <sup>2</sup>neal@nd.edu).



**Introduction:** Lunar sample 62236 is a member of the ferroan anorthosite suite (FAS). It was collected at the rim of Buster Crater during the Apollo 16 mission. Classified as a pristine sample of the lunar crust [1], 62236, in conjunction with other FAS samples, potentially provides invaluable insight into the early history of lunar differentiation. Radiometric dating of 62236 yielded a  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  age of  $4.29 \pm 0.06$  Ga (the youngest dated FAS sample using that chronometer) [2]. The 0.272 Ga range of FAS Sm-Nd ages [17] requires an active LMO beyond which most thermal models can explain without the addition of an insulating lid and extensive tidal heating [3]. This age range is only for the last ~20-25% of LMO crystallization. In addition to the young age, 62236 also yields an initial  $\epsilon\text{Nd}_{\text{CHUR}}$  of  $+3.1 \pm 0.9$  [2] indicating that this sample is derived from a LREE-depleted source, which also challenges conventional LMO evolution models [3,7-10]. Here we present in-situ major and trace element data from 5 sections of 62236 to investigate the mineral components of this unusual sample of the early lunar crust.



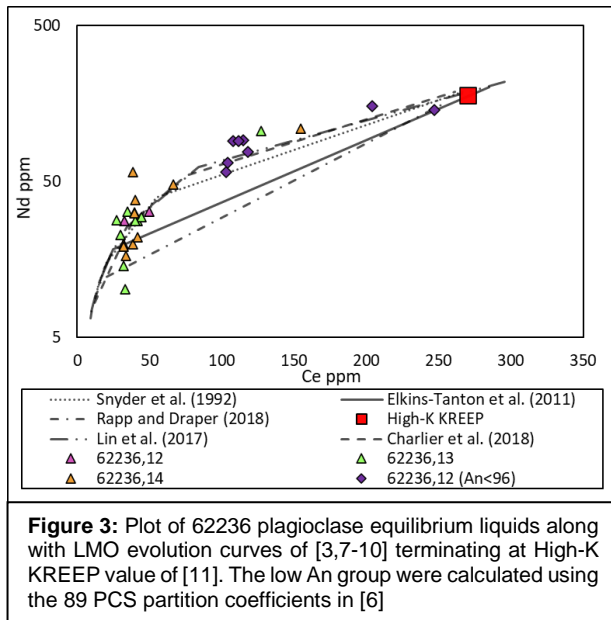
**Methods:** Thin sections 62236,7 and ,58 were imaged in cross polarized (XPL), plane polarized (PPL), and reflected (RF) light. As sections ,12; ,13; and ,14 are thicker (~100 microns) they were only imaged in RF. These provided context to in-situ analyses and served as navigation maps for those analyses. Major element data for plagioclase, pyroxene and olivine were gathered using a CAMECA SX-50 electron microprobe at the Material Characterization Facility of Notre Dame. Trace element data for plagioclase and pyroxene data were gathered on the three thicker sections of 62236 via laser ablation ICP-MS analysis at the University of Notre Dame's MITERAC facility and were reduced using the GLITTER software package [4]. The NIST-612 glass was used as the external standard [5] and Ca as the internal standard.

### Results and Discussion

**Major Element Analysis:** Plagioclase major element data show that the plagioclase in 62236 can be broadly separated into 2 major groups based on anorthite (An) content at  $\text{An}_{96}$  (Fig. 1). FeO shows no such distinction and, due to low abundances, could have been affected by post-crystallization metasomatism (*cf.* [15]). High-(augite) and low-Ca (Opx) are present (Fig. 2).

**Trace Element Analysis:** Calculation of plagioclase equilibrium liquids requires partition coefficients appropriate for the conditions present during crystallization from the LMO. Several options are provided for plagioclase crystallizing out of the LMO at 3 separate stages of solidification (or percent crystallized solid – PCS [6]). The young age of 62236 coupled with the presence of 2 plagioclase groups suggests that 2 coefficient sets are most appropriate representing an earlier (78 PCS,  $\text{An}_{>96}$ ) and later (89 PCS,  $\text{An}_{<96}$ ) stage of crystallization for the plagioclase present in this sample. The calculated equilibrium liquids show material that likely crystallized at different stages of LMO evolution (Fig. 3) following a crystallization trend from LREE-depleted  $\rightarrow$  LREE-enriched sources (Fig. 4). This LREE-depleted source signature is consistent with the reported  $+\epsilon\text{Nd}$  value reported by [2] but not predicted by conventional models of LMO evolution (e.g. [3,7-10]). The presence of a LREE-enriched source for the  $\text{An}_{<96}$  plagioclase material suggests that 62236 represents a mix of both earlier and later stage crystallized LMO products. This does require that the early LMO is LREE depleted.

In addition to the partition coefficients of [6], calculated plagioclase partition coefficients were



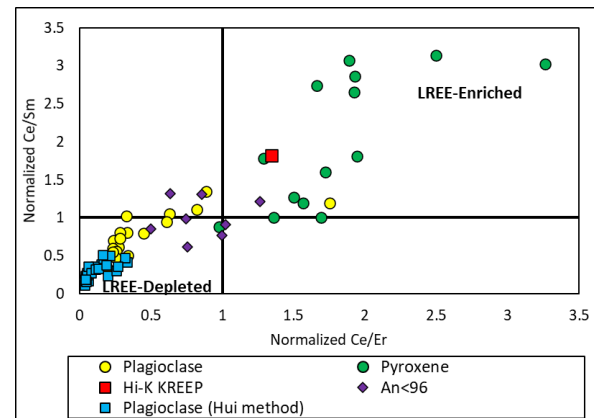
derived following the method of [16]. This method allows for targeted partition coefficients for each crystal based on the major element composition (An%). The resulting equilibrium liquids using this method are all LREE-depleted, with the An<sub>>96</sub> group being more LREE depleted than the low An group (Fig. 4). Compared to LMO models, this method results in equilibrium liquids that fall in a similar concentration to the low An group using the 89 PCS values of [6] in Fig. 3. As seen in Fig. 5, there still is significant scattering of the data along the different LMO evolution paths indicating that this sample is heterogeneous in nature, but the grouping produced by the method of [6] is no longer apparent.

Pyroxene partition coefficients were calculated following the methods of [12-14]. They more consistently result in a LREE-enriched signature (Fig. 4) with many plotting beyond the value of High-K KREEP [11] suggesting that these pyroxene crystals are sourced from a similar later stage of LMO evolution as the low An group, or possibly from a later LMO stage unrelated to the plagioclase.

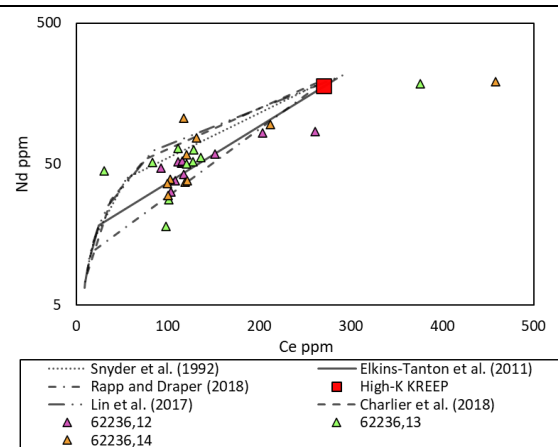
**Conclusions:** Sample 62236 is a severely cataclitized sample of the lunar crust that appears to contain material sourced from different stages of LMO evolution. The An<sub>>96</sub> plagioclase represents an early LREE-depleted LMO source while the An<sub><96</sub> group could represent the more evolved LREE-enriched LMO stage or at least a less LREE-depleted stage. The pyroxene equilibrium liquids are consistent with crystallization from the later stages of LMO evolution, being derived from a LREE-enriched magma. Assuming that all mineral components in 62236 are LMO-derived, an original LREE-depleted LMO is required to produce the range of compositions present in this sample as analyzed here,

consistent with the Sm-Nd isotopic systematics [2]. This work demonstrates the need for careful re-examination of FAS ages.

**References:** [1] Warren P. & Wasson J. (1977) *PLSC* 8, 2215-2235. [2] Borg L. et al. (1999) *GCA* 63, 2679-2691. [3] Elkins-Tanton L. et al. (2011) *EPSL* 304, 326-336 [4] van Achterbergh E. et al. (2001) *MSA, Short Course* 29, 239-243. [5] Pearce N. et al. (1997) *Geostds. Nwslet.* 21, 115-144. [6] Sun C. et al. (2017) *GCA* 206, 273-295 [7] Snyder G. et al. (1992) *GCA* 56, 3809-3823 [8] Rapp J. and Draper D. (2018) *MaPS* 53.7, 1432-1455. [9] Lin Y. et al. (2017) *EPSL* 471, 104-116. [10] Charlier B. et al. (2018) *GCA* 234, 50-69. [11] Warren P. (1989) *Moon in Transition: Apollo 14 LPI Tech. Rpt.* 89-03, 149-153. [12] Sun C. & Liang Y. (2012) *CMP* 163, 807-823. [13] Yao L. et al. (2012) *CMP* 164, 261-280. [14] Sun C. & Liang Y. (2013) *GCA* 119, 340-358. [15] Neal C.R. & Taylor, L.A. (1989) *GCA* 53, 529-541. [16] Hui H. et al. (2011) *GCA* 75, 6439-6460. [17] Alibert C. (1994) *GCA* 58, 2921-2926.



**Figure 4:** Normalized equilibrium liquid ratios for 62236 minerals. The low An group (An<sub><96</sub>, purple diamonds) represent equilibrium liquids calculated using the 89 PCS coefficients listed in [6]. The blue squares represent plagioclase equilibrium liquids calculated by the method of [16]



**Figure 5:** Plagioclase equilibrium liquids calculated for 62236 plagioclase using the method of [16]