Investigating the Ages and Formation of the Lunar Crust. Torcivia M.A.[1] and Neal C.R.[1] [1]Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame IN, 46556; mtorcivi@nd.edu

Introduction: The ferroan anorthosites (FANs) are believed to have formed as plagioclase flotation cumulates crystallizing out of a primary lunar magma ocean (LMO) [1]. The FANs are therefore thought to represent the primordial lunar crust [2], while Mg-suite and KREEP are believed to post-date FAN formation. FAN samples are notoriously difficult to age date due to their low trace element abundances and low modal% of mafic material. However, assuming that the FANs crystallized out of the LMO, the concentration of incompatible trace elements (ITE) incorporated in the minerals of each FAN sample should increase as the LMO evolved from the point that plagioclase crystallized. In this sense, calculated equilibrium liquids of younger FAN samples should show a relative enrichment in ITEs relative to the older samples. Coupled with existing FAN radiometric age dates recorded in the literature (Fig. 1), it should be possible to construct a relative age date sequence based on these assumptions and calculated parent melts.

Methods: Thin sections for a suite of dated FANs (60025, 67075, 67215, 62236, and 67016) were available for study at Notre Dame. Thin sections were initially photographed on a Nikon petrographic microscope and photos were taken and stitched together using the Microsoft Image Composite Editor to create a photomosaic of each thin section in plane polar (PPL), cross polar (XPL), and reflected light (RL). These photomicrographs serve as both navigation maps for subsequent studies and also to provide context to in-situ analyses, as well as to demonstrate the overall textural variations within the FAN samples. Major and minor element composition of individual plagioclase, pyroxene, and olivine grains were gathered via electron probe microanalysis (EPMA) analysis using a Cameca SX-50 electron microprobe at the University of Notre Dame. Trace element data from plagioclase and pyroxene grains were collected via laser ablation (LA) ICP-MS analysis using an Element 2 ICP-MS instrument connected to a New Wave Research UP-213 laser delivery system at the Midwest Isotope and Trace Element Research and Analytical Center (MITERAC) at Notre Dame. Data were reduced using GLITTER [6], and equilibrium liquids were calculated using the method of [5] for plagioclase and [7,8] for pyroxene.

Results and Discussion: The general trend of ages from oldest to youngest based on Sm-Nd age dating is 67016, 67075, 60025, 67215, and 62236. However, some of these samples (e.g. 67215, 67075) exhibit a large uncertainty regarding their age. In addition, 60025 has 2 distinct age dates reported in the literature [3,4],

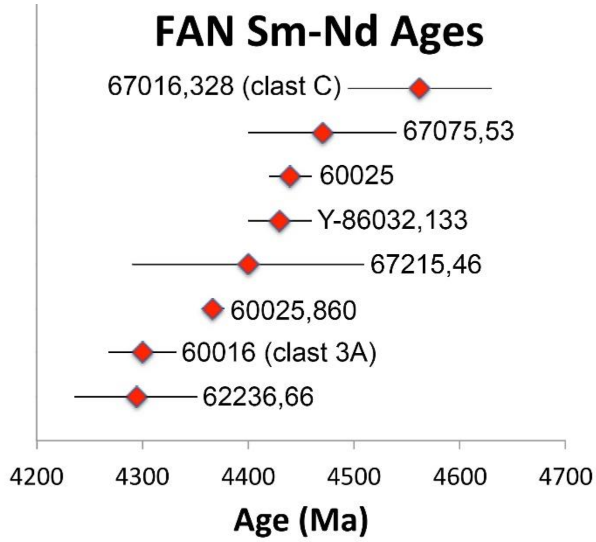

Figure 1: FAN Sm-Nd ages from [9] and references therein.

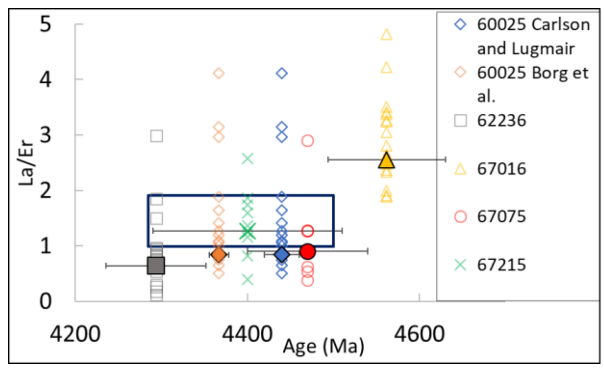

Figure 2: Chondrite normalized La/Er equilibrium liquids for 5 FANs plotted against age. The colored outlines represent individual laser point analyses while filled shapes represent a statistically significant average for each sample (calculated using points within 2σ of the average). The box indicates the range of LMO values as modeled by [10]

so it's placement in the sequence is not completely understood. The evolution of the REE profiles should ideally reflect this sequence.

Plagioclase Trace Elements. Figure 2 displays the chondrite normalized La/Er equilibrium liquids of each sample plotted against its recorded Sm-Nd age date in the literature. As stated above, 60025 has 2 distinct age dates, therefore, it is plotted twice. The data show that FANs that yield older age dates, such as 67016, have higher La/Er values and La and Er concentrations than younger dated FANs (Fig. 2, 3). This apparent trend indicates that older FANs have more LREE-enriched profiles compared to younger FANs. This relationship seems contrary to what is expected from an evolving

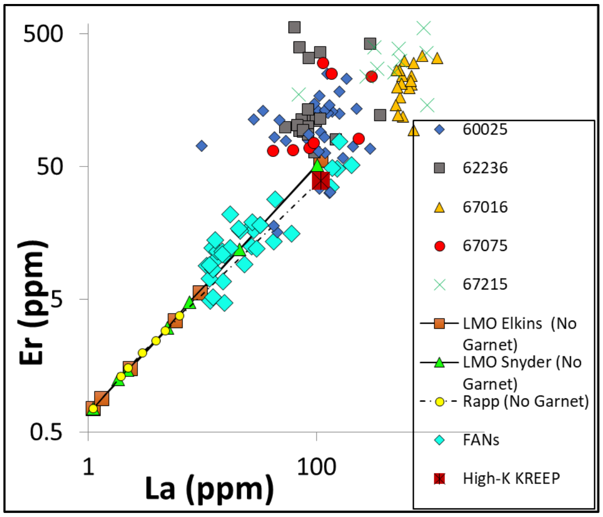

Figure 3: La v Er plot of equilibrium liquids for FANs from this study along with previous FANs and LMO models

magma such as the LMO. Figure 3 additionally displays how a majority of the equilibrium liquids for the FANs analyzed in this study plot well beyond modeled LMO values and plot off of the evolution curves determined by [10,11]. As plagioclase begins to crystallize out of the LMO (70-80% solidification [10,11]), the equilibrium liquid of the parent melt should be flat lying (e.g. [10,11]) and then become progressively more LREE enriched as crystallization proceeds until a more KREEP-like signature is achieved as the melt reaches 99+ percent solidification [13]. The data here show an opposite trend with the earliest FANs crystallizing out of a more KREEPy(?) or LREE-enriched melt and subsequent FANs crystallizing out of a more flat lying and then LREE-depleted source. Alternatively, removing 67016 as possibly not crystallizing from the LMO results in little to no trend in the shape of the REE profiles as a function of age (i.e. they cluster around La/Er = 1 or a flat REE profile).

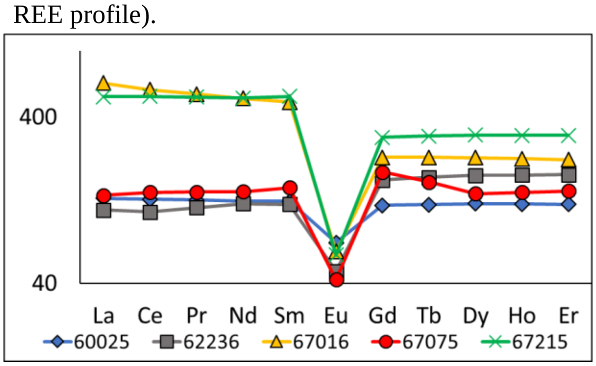

Figure 4: Average chondrite normalized plagioclase equilibrium liquids for 5 FANs

Figure 4 shows average plagioclase equilibrium liquid REE profiles normalized to C1 chondrite values [12] for each FAN. From this plot it is apparent that the FANs sampled do display marked differences in REE concentrations from one another. The average of both 67016 and 67215 REE profiles are LREE enriched and their LREE concentrations are much higher than that of the average equilibrium liquids REE profiles of the other FANs. However, the average profile of 62236 is unusual in that it is LREE depleted and plots somewhat intermediate regarding overall REE concentration. Its enrichment in the HREE is inconsistent with models of plagioclase crystallizing out of the LMO [10,11]. 60025 and 67075 both display a somewhat flat profile with 60025 displaying the lowest ITE concentrations in the HREE, suggesting crystallization soon after plagioclase came on the liquidus in the LMO. This would suggest that the older age for 60025 [3] is the one that represents the age of crystallization from the LMO.

Conclusions: The data presented here for the REE evolution of this suite of FANs is contrary to established LMO models, suggesting these FANs contain lithologies unrelated to the LMO. The average REE profile of 62236 is also inconsistent with models of a FAN crystallizing out of the LMO, although this may mean that non-LMO-derived lithologies also dominate this breccia. The evolution of REE concentrations for these FANs also do not match the Sm-Nd age date sequence established from the literature. Of course, it is possible that the analyzed thin sections from these FANs used for this study contain mostly non-LMO related material and are not related to the area sampled for the Sm-Nd chronology work. This is certainly possible for the thin sections for 60025 and the area analyzed for the younger age [4].

References: [1] Toksöz M. & Solomon S. (1973) EMP 7, 251-278. [2] Dowty E. et al. (1974) EPSL 24, 15-25. [3] Carlson R. & Lugmair G. (1988) EPSL 90, 119-130. [4] Borg L. et al. (2011) *Nature* 477, 70-72. [5] Hui H. et al. (2011) GCA 75, 6439-6460. [6] van Achterbergh E. et al. (2001) *Mineralogical Association of Canada, Short Course* 29, 239–243. [7] Sun C. & Liang Y. (2013) GCA 119, 340-358. [8] Yao L. et al. (2012) *Contributions to Mineralogy and Petrology* 164.2, 261-280. [9] Carlson R. et al. (2014) *Phil. Trans. Roy. Soc. A* 372, 2024. [10] Snyder G. et al. (1992) GCA 56, 3809-3823. [11] Elkins-Tanton L. (2011) EPSL 304.3, 326-336. [12] Anders E. & Grevesse N. (1989) GCA 53.1, 197-214. [13] Neal C. & Davenport J. (2014) LPSC 45, #1181.