

**Are Ferroan Anorthosites Direct Products of the Lunar Magma Ocean?** C. R. Neal<sup>1</sup> and D. S. Draper<sup>2</sup>, <sup>1</sup>Dept. Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (neal.1@nd.edu), <sup>2</sup>ARES, NASA Johnson Space Center, 2101 NASA Parkway, Houston TX 77058, USA (david.draper@nasa.gov).

**Introduction:** According to Lunar Magma Ocean (LMO) theory, lunar samples that fall into the ferroan anorthosite (FAN) category represent the only samples we have of the primordial crust of the Moon (e.g., [1]). Modeling indicates that plagioclase crystallizes after >70% LMO crystallization and formed a flotation crust (e.g., [2-6]), depending upon starting composition. The FAN group of highlands materials has been subdivided into mafic-magnesian, mafic-ferroan, anorthositic-sodic, and anorthositic-ferroan, although it is not clear how these subgroups are related [7]. Recent radiogenic isotope work has suggested the range in FAN ages and isotopic systematics are inconsistent with formation of all FANs from the LMO [8-12]. While an insulating lid could have theoretically extend the life of the LMO to explain the range of the published ages [3], are the FAN compositions consistent

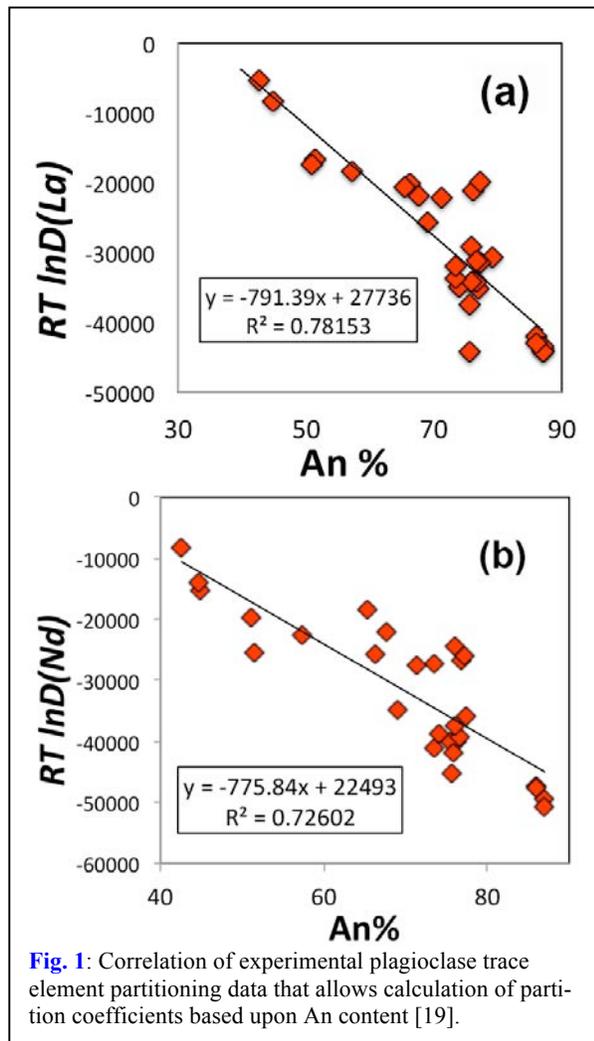
with crystallization from the LMO? As part of a funded Emerging Worlds proposal (NNX15AH76G), we examine this question through analysis of FAN samples. We compare the results with various LMO crystallization models, including those that incorporate the influence of garnet [13,14].

**Samples and Methods.** As an initial step in this project, we use published data to examine the hypothesis that FANs are a direct product of the LMO. Plagioclase major and trace element data from FAN samples are used [15,16]. Partition coefficients are calculated using the method of [17,18] that was modified by [19]. This method uses the Anorthite (An) content of the plagioclase to calculate partition coefficients using an array of experimental data to define a correlation between  $An\%$  and  $RT \ln D$  (Fig. 1). This approach allows realistic estimates of the liquid compositions from which the plagioclase in each FAN sample crystallized. The equilibrium data are then compared with the models of LMO crystallization [2-7].

**LMO Crystallization.** Crystallization of the LMO has been modeled in several studies, both theoretical (e.g., [2,3]) and experimental [4-6]. The trace element composition of the LMO can be modeled assuming a starting composition ( $3 \times$  chondrites after [2]). As shown by [14], the different mineral proportions in the models of [2-6] can approximate KREEP REE patterns, but these are better generated by incorporation of 3-5% garnet once the LMO has become saturated in  $Al_2O_3$  (see [2-6] for details). Following the methods of [20], the REE evolution of each LMO model has been calculated. These evolution paths have been compared with the equilibrium liquid compositions of the FAN plagioclases. Results are shown in Figs. 2 & 3.

**Discussion.** The LMO models terminate at  $\geq 99\%$  crystallization, which is considered to be the amount of crystallization required to generate urKREEP. The high-K KREEP composition of [20] is plotted in Figs. 2 & 3 for comparison. In the LMO modeling, various amounts of garnet are included at the expense of plagioclase when plagioclase is a liquidus phase. If the FANs crystallized from the LMO, the equilibrium liquids should plot along the LMO evolution lines where plagioclase is a liquidus phase.

The slope of the light REE is examined by plotting La vs. Nd (Fig. 2), and the slope of the overall REE profile is examined by plotting La vs. Er (Fig. 3). The FAN plagioclase equilibrium liquids do plot along the LMO evolution paths in regions where plagioclase is a liquidus phase. The equilibrium liquids can be generat-



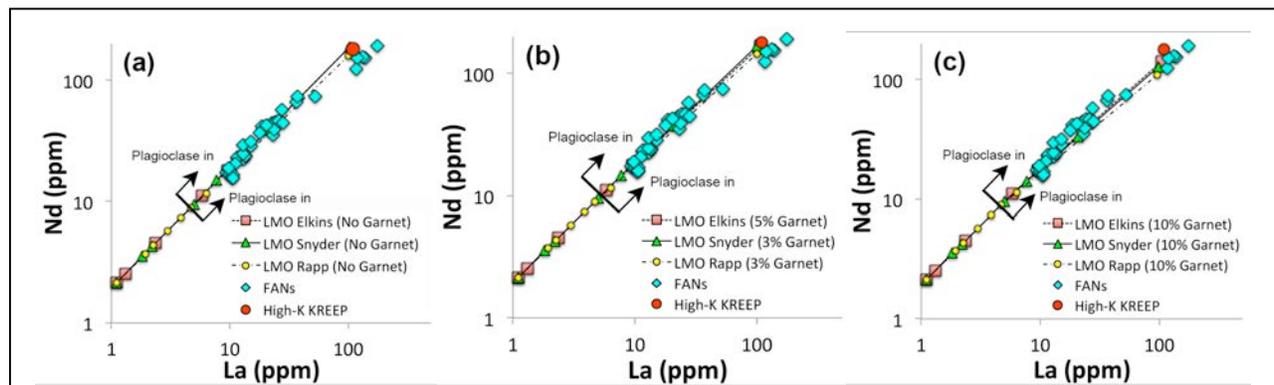
**Fig. 1:** Correlation of experimental plagioclase trace element partitioning data that allows calculation of partition coefficients based upon An content [19].

ed by either the “No Garnet” or “3-5% Garnet” evolution lines (Figs. 2ab, 3ab). These model results permit up to 10% garnet fractionation from the LMO. Our subsequent work will evaluate this possibility in more detail.

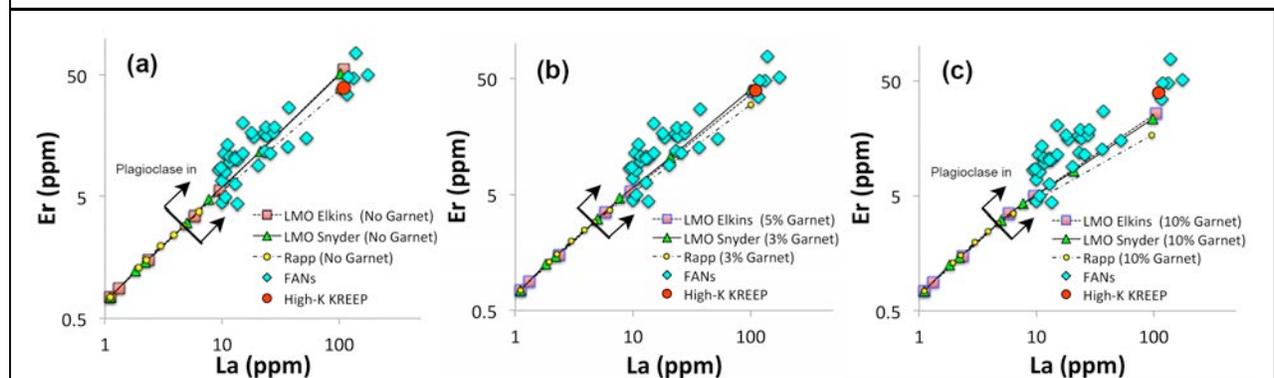
**Conclusions.** The data presented here are consistent with the FANs crystallizing from the LMO. The range of equilibrium compositions also demonstrates that plagioclases contained in FANs crystallized throughout the final stages of LMO solidification, including when urKREEP was formed. The range of FAN ages reported in [12] appears inconsistent with a direct origin from the LMO. However, a combination of an insulating “lid” coupled with tidal friction could extend the crystallization of the crystallizing LMO to account for the FAN age range [3]. Elkins-Tanton et al. [3] concluded “*The resulting crust will be heterogeneous and nonmonotonic in age and composition as a function of depth, and it would be expected to contain rocks with ages ranging over ~200 Ma.*” The fact that FAN subgroups are difficult to relate to each other is consistent with this. The range of equilibrium liquids calculated in this study are consistent with an extended lunar crust formation. This initial study of FAN petrogenesis posits that those FANs with plagioclase that

crystallized from a liquid with relatively low REE abundances are older than those that crystallized from liquids containing high REE abundances. This hypothesis remains to be tested.

**References:** [1] Dowty E. et al. (1974) EPSL 24, 15-25. [2] Snyder G.A. et al. (1992) GCA 56, 3809-3823. [3] Elkins-Tanton L.T. et al. (2011) EPSL 304, 326-336. [4] Rapp J. & Draper D. (2012) LPSC 43, abstract #2048. [5] Rapp J. & Draper D. (2013) LPSC 44, abstract #2732. [6] Rapp J. & Draper D. (2014) LPSC 45, abstract #1527. [7] James O.B. et al. (1989) Proc. LPSC 19, 219-243. [8] Boyet M. & Carlson R. (2007) EPSL 262, 505-516. [9] Boyet M. et al. (2015) GCA 148, 203-218. [10] Borg L.E. et al. (1999) GCA 63, 2679-2691. [11] Norman et al. (2003) MaPS 38, 645-661. [12] Borg L.E. et al. (2011) Nature 477, 70-72. [13] Neal C.R. (2001) JGR 106, 27865-27885. [14] Neal C.R. & Davenport J.D. (2014) LPSC 45, abstract #1181. [15] Papike J.J. et al. (1997) GCA 61, 2343-2350. [16] Floss C. et al. (1998) GCA 62, 1255-1283. [17] Blundy J. & Wood B.J. (1991) GCA 55, 193-209. [18] Bindeman I.N. et al. (1998) GCA 62, 1175-1193. [19] Hui H. et al. (2011) GCA 75, 6439-6460. [20] Warren P.H. (1989) LPI Tech. Rpt. 89-03, 149-15.



**Fig. 2.** La vs. Nd for LMO evolution with no garnet (a), 3-5% garnet (b), and 10% garnet (c). The LMO models are from [2] (LMO Snyder), [3] (LMO Elkins), and [4-6] (LMO Rapp). High-K KREEP is from [20] FAN data are from [15,16].



**Fig. 3.** La vs. Er for LMO evolution with no garnet (a), 3-5% garnet (b), and 10% garnet (c). The LMO models are from [2] (LMO Snyder), [3] (LMO Elkins), and [4-6] (LMO Rapp). High-K KREEP is from [20] FAN data are from [15,16].