**DID VOLATILE LOSS PLAY A ROLE IN THE RESTRICTED ANORTHITE CONTENT OF THE FERROAN ANORTHOSITE SUITE?** M.A Torcivia,1 D. Burney,1 C.R. Neal,1 and K. Cronberger1 1University of Notre Dame, Notre Dame IN, 46556; dburney@nd.edu.

**Introduction:** One of the outstanding questions with lunar magma ocean (LMO) theory and the samples returned by the Apollo missions is why the Anorthite (An = Ca/[Ca+Na]*100) content of plagioclase within the ferroan anorthosite suite (FANs) is so restricted (Fig. 1). Terrestrial geology has shown that Mg and Fe bearing phases will progress from Mg towards Fe during magmatic evolution, and the same should occur with Ca to Na in plagioclase. The Mg-Fe variation is recorded in the mafic phases in lunar lithologies, however, the same shift of the corresponding signature of An is not represented in the plagioclases of the FANs. This dichotomy is unexpected from co-genetic phases crystallizing from the LMO.

One hypothesis explaining this dichotomy is based on experimental modeling [1]. This has shown that the An content of plagioclase can be restricted if crystallization occurs at high pressures equivalent to a lunar crustal thickness of ≥70 km [1]. At these conditions, a negative azeotropic condition is developed at high An contents. However, a plagioclase-dominated lunar crust formed through flotation is unlikely to have crystallized at such depths and subsequently collected at the lunar surface unimpeached by other mineral phases or any quenched crust. Additionally, some FAN samples have been shown to have formed at depths much shallower than 70 km based on calculations using companion pyroxenes [2,3]. The goal of this work is to explore any role that the volatile nature of Na played in the restricted An content exhibited by FAN plagioclase.

**Background:** The evolution of the LMO has been modeled extensively both theoretically [4] and experimentally [5]. As the LMO solidified, incompatible elements became enriched in the residual melt while compatible elements will become entrained in the crystallizing mineral phases. The elements Al, Ca, and Na are all incompatible in the early crystallizing phases of the LMO. Elevation of these elements in the residual melt dictates the point at which plagioclase starts to crystallize. For the models presented here, plagioclase doesn’t begin to crystallize until late in LMO evolution at 78 [4] and 88 [5] percent crystallized solid (PCS).

Throughout the process of lunar formation and differentiation there is evidence to show that volatiles were lost [6]. Chlorine isotopic evidence shows that a crustal breaching impact exposed the late-stage LMO and released volatiles from the residual LMO melt through decompression [7]. The An content of the FANs is highly restricted, which shows that the progression towards a more Na-rich (Albitic - Ab) mineral phase did not occur. Na is relatively volatile compared to Ca, so if it degassed from the lunar interior plagioclase would not be able to evolve towards more Ab-rich compositions. By comparing LMO crystallization models to equilibrium liquids calculated from FAN plagioclase analyses, a comparison can be made between the Na content of the LMO and the Na present as FANs were crystallizing. The hypothesis would be that the equilibrium liquids should contain progressively high Na contents as the FANs become younger.

**Methods:** The concentrations reported here for Na in each FAN represent the average of all plagioclase analyses from each thin section for every FAN parent sample. These data represent electron microprobe analyses gathered from a Cameca SX-50 located at the University of Notre Dame. Equilibrium liquids for Na were calculated at 78, 89, and 94 LMO percent crystallized solid (PCS) by dividing the average Na value for each sample by the corresponding partition coefficients listed in [8]. The LMO evolution models of [4] and [5] were chosen as they report Na evolution in the melt and represent a purely theoretical and purely experimental model, respectively.

**Results and Discussion:** The Na content in an evolving LMO is calculated for each model (Fig. 2). The corresponding equilibrium liquid compositions (using the average plagioclase composition) were calculated for each FAN sample at the onset of plagioclase crystallization (78 PCS) as well as later stages of evolution (89 and 94 PCS; Fig. 2). For each FAN sample, the Na content of the equilibrium liquids is lower than the predicted model values of an evolving LMO. This holds true regardless of which models and/or partition
coefficients are used. To achieve the low Na content in the equilibrium liquids calculated from FAN plagioclase analyses, a combination of two end-member scenarios occurred: 1) plagioclase crystallized much earlier than the models have predicted, which is controlled by lunar bulk Al₂O₃ content, or 2) Na was lost from the LMO during LMO evolution and differentiation.

The FAN samples have a range of Sm-Nd ages (compiled from [9] and references therein). If we assume these ages represent initial lunar crust crystallization ages, then those that are most primitive (i.e. with the highest ratio of Ca to Na) should yield the oldest crystallization age. While this appears to be the case for most of the samples reported here (Fig. 3), the oldest FAN analyzed (67016) actually has lower Ca/Na than 3 younger FAN samples. This is contrary to what is expected from an evolving LMO.

Even if it is assumed each sample included here formed at the very onset of plagioclase crystallization of the LMO – which is unlikely given the spread of Sm-Nd ages – it is impossible to reconcile the Na content in these calculated equilibrium liquids with the modeled LMO Na content at 78 PCS. The only exception to this is FAN 60016 that plots just below the expected Na value at 78 PCS for the model of [4] but still well below the Na content for [5]. However, the young age of 60016 precludes it from being the very first crystallizing FAN, so the later partition coefficients (e.g. 89 and 94 PCS) are likely more representative of its equilibrium liquid. At these later PCS values all FANs (including 60016) fall well below both models. We conclude that after the formation of the initial plagioclase-rich crust, represented by 67016, the crust was breeched by (an) impact(s) that caused a decrease in pressure releasing volatile and moderately volatile elements [11] (including Na) into space. After the breach(es) healed, crystal fractionation continued.

**Conclusions:** The implication of these data is that there was a loss of Na (and other volatiles) due to a crustal breeching impact or progressive LMO degassing. This would result in a restricted range of plagioclase compositions due to lack of Na in the LMO.

**Acknowledgements:** This work was supported by NASA grants NNX15AH76G and 80NSSC17K0467.  


---

**Figure 2:** Comparison of Na content in the equilibrium liquids of the average plagioclase composition for a suite of FANs at 3 stages of PCS to LMO models of [4,5]. Different partition coefficients were used at 78, 89, and 94 PCS as found in [8]. Inset included to show separation of each FAN from one another.

**Figure 3:** FAN ages plotted against the cation Ca and Na ratio of average plagioclase in each FAN. Sample 60025 has 2 distinct ages recorded, so it is plotted twice. Ages compiled from [9] and references therein. Symbols are the same as those in Fig. 2.