Analysis of Plagioclase-Pyroxene Partition Coefficients in Ferroan Anorthosites: Determining Cogenetic Relationships.
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Introduction: The ferroan anorthosites (FANs) are a suite of lunar material that is believed to have been originally derived from the crystallization of the lunar magma ocean (LMO) [1,2]. As such, the FANs represent the only direct sampling of the LMO available for study. They are distinct because of their high anorthite plagioclase content coupled with lower Mg content in companion mafic minerals (Fig. 1). Additionally, the FANs are some of the oldest lunar samples to have been radiometrically dated (Fig. 2). However, there exists some overlap in the crystallization ages of some FAN samples with the Mg-suite, which supposedly intruded the FAN samples. This presents an unresolved issue for the LMO model, which has led to the rise of alternative hypotheses for lunar differentiation and formation of the FANs, such as through a process of serial magmatism [3]. The plagioclase-rich nature of the FANs have presented a significant challenge for geochronologic studies to overcome, but this problem has been abated by identifying and analyzing mafic mineral-rich portions of the host sample in a quest to obtain a well-constrained isochron [e.g., 4]. However, the general paucity of mafic material in FANs coupled with their cataclastic and brecciated nature has led to speculation regarding the relationship between the plagioclase and companion pyroxenes in FAN samples [5]. Here we describe a method in which we have calculated partition coefficients to determine equilibrium liquids to examine whether pyroxenes and plagioclase are cogenetic in a number of FAN samples.

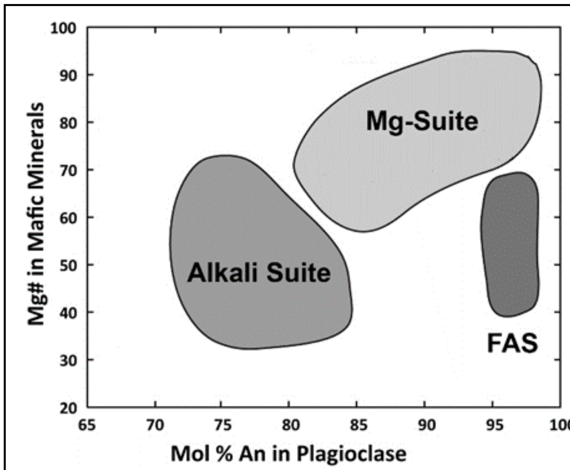

Figure 1: Relationship between FANs (or FAS), Mg-Suite, and Alkali Suite regarding Anorthite and Mg# modified from [16]

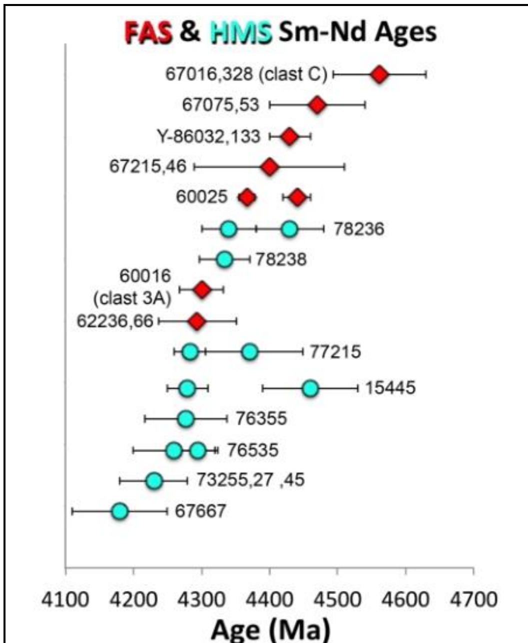

Figure 2: Sm-Nd ages of a group of FANs and Mg-suite samples compiled from [6] and references therein

Methods: Four FAN samples in the form of nine sub-sample thin sections were analyzed at the University of Notre Dame. Major element data were collected via electron microprobe analysis using a Cameca SX-50 electron microprobe. Partition coefficients for plagioclase were calculated using the method described in [7] that uses the relationship $RTlnD_i=A*An\%+B$ where A and B are experimentally determined coefficients. The temperature of calculation was determined using Equation 3 from [8] which yielded a temperature of 1000˚C assuming an initial 1000 km deep magma ocean and plagioclase crystallizing at between 70-80% solidification of the LMO [8,9]. Pyroxene partition coefficients were calculated using the methods described in [10-12] that use a lattice strain model. Pyroxene partition coefficients also were calculated assuming 1000˚C in order to maintain consistency in calculations. Plagioclase and low-Ca pyroxene partition coefficients were then compared to one another using the method outlined in [13] to determine whether plagioclase and low-Ca pyroxenes in each thin section are cogenetic.

Results and Discussion: Figure 3 displays the results of the partition coefficient calculations and analysis applying the method described in [13]. The oxygen fugacity conditions on the Moon are at or below the

Iron-Wüstite buffer, therefore any cogenetic plagioclase and low-Ca pyroxene grains in these samples should plot at or above the intersection of the buffer with the experimentally determined trend line at the I-W fO_2 if they represent an equilibrium assemblage. The majority of samples analyzed in this manner produce plagioclase/pyroxene partition coefficient ratios that are consistent with cogenetic plagioclase and pyroxene crystallizing under lunar conditions (i.e., low oxygen fugacity). However, thin section 60025,21 has a markedly lower ratio that is inconsistent with crystallizing out of an environment with an oxygen fugacity at or below the Iron-Wüstite buffer. Therefore, we interpret this to indicate that thin section 60025,21 contains plagioclase and pyroxenes that do not represent an equilibrium assemblage, whereas those in other sections do. Since FAN 60025 yields two distinct crystallization ages using the Sm-Nd isotopic system (Fig. 2) [4,13], evidence for the presence of disequilibrium between plagioclase and pyroxene at least in certain portions of the cataclastic FAN could be consistent with the distinct ages reported for this sample. This conclusion is consistent with major and trace element data for FAN 60025 [15].

Conclusions: The FAN suite is comprised of samples that represent an ancient suite of lunar material with a complex petrologic history not yet fully understood. These samples have experienced the violent environment of the lunar surface potentially for billions of years, which is reflected in the cataclastic nature of the FAN suite [e.g., 5,15]. The comparison of a group of radiometrically age dated FANs here provides some insight into the relationship between plagioclase grains and companion pyroxenes in thin section. Using this method, it is possible to determine the likelihood of a thin section to contain minerals that are still in equilibrium. In this group of FANs analyzed, only one thin section – 60025,21 – proved unable to satisfy the required criteria for plagioclase and pyroxenes to be in equilibrium. This does not negate the LMO origin for the FANs, but it highlights the need for extreme care to be used when choosing minerals for isochron determinations.

References: [1] Toksöz M. & Solomon S. (1973) *EMP* 7, 251-278. [2] Dowty E. et al. (1974) *EPSL* 24, 15-25. [3] Walker D. (1983) *JGR* 88, B17-B25. [4] Borg L. et al. (2011) *Nature* 477, 70-72. [5] James O.B. et al. (1989) *PLPSC 19*, 219-243. [6] Carlson R. et al. (2014) *Phil. Trans. Roy. Soc. A* 372, 2024. [7] Hui H. et al. (2011) *GCA* 75, 6439-6460. [8] Elkins-Tanton L. (2011) *EPSL* 304.3, 326-336. [9] Snyder G. et al. (1992) *GCA* 56, 3809-3823. [10] Sun C. & Liang Y. (2012) *Cont. to Min. and Petrology* 163(5), 807-823. [11] Yao L. et al. (2012) *Cont. to Min. and Petrology* 164(2), 261-280. [12] Sun C. & Liang Y. (2013) *GCA* 119, 340-358. [13] McKay G. (1989) *Reviews in Min. and Geochem.* 21, 45-77. [14] Carlson R. & Lugmair G. (1988) *EPSL* 90, 119-130. [15] Torcivia M. & Neal C. (2018) *LPSC* 49, #1331. [16] Shervais J.W. & McGee J.J. (1998) *GCA* 62, 3009-3023

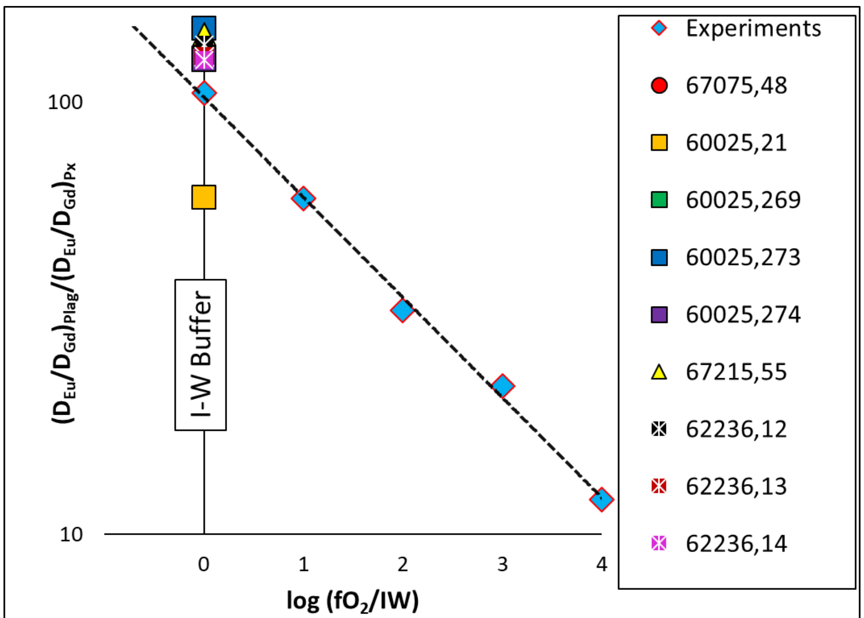

Figure 3: Eu/Gd ratios of calculated partition coefficients of plagioclase and pyroxene against $\log(fO_2/IW)$. Experimental data points estimated from [12]