Petrology and chronology of early lunar crustal building 1. Comprehensive examination of a ferroan anorthosite clast in 60016

C.K. Shearer[1,2], P.V. Burger[1], N.E. Marks[3], L.E. Borg[3], and A.M.Gaffney[3]. [1]Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131 (cshearer@unm.edu), [2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, [3] Institute of Geophysics & Planetary Physics, Lawrence Livermore National Laboratory, 7000 East Ave. L-231, Livermore CA, 94550

Introduction: The lunar magma ocean theory predicts that ferroan anorthosites (FAN) are the oldest lunar lithology, are closely related to other lithologies that formed at roughly the same time (e.g., lunar magma ocean (LMO) mafic cumulates of the mare basalt source regions, KREEP-rich LMO horizons), and were intruded by post-LMO magmas (i.e. Mg-suite). Isotopic dating of FANs has proven to be a difficult task because most isotopic systems applied to them show strong evidence for post-crystallization disturbance. Attempts at chronology are further complicated by the fact that the FANs are nearly monomineralic and have extremely low abundances of parent-daughter pairs. As a result, multiple ages determined on single FANs are often discordant and ages are chosen based on arguments for the least amount of isotopic disturbance. As a result, the ^{147}Sm-^{143}Nd isotopic system has become the most effective FAN chronometer because fractionation, mobilization, and contamination of REE during post-crystallization processes is thought to be more difficult than for the other isotopic systems. However, even with this chronometer, the several apparently "pristine" FAN samples that have been dated by the Sm-Nd method yield somewhat controversial results. The Sm-Nd ages of the six dated FANs range from 4.29 to 4.56 Ga and have initial epsilon values that range from +0.5 to +3. These results are not consistent with the magma ocean model of lunar crust formation. Specifically, positive initial ^{143}Nd ε values require the FANs to be derived from source regions that are strongly depleted in LREE relative to chondritic meteorites, and therefore contrast with crystallization models that predict that FANs should be derived from LREE-enriched sources. Furthermore, model ages for the final stages of LMO crystallization (KREEP) and several Mg-suite rocks have Rb-Sr, Sm-Nd, and Pb-Pb zircon ages that are older than the youngest FANs, suggesting that the Sm-Nd chronology of the FANs could be disturbed. If these ages are not disturbed by post-crystallization processes (e.g., impact, long thermal history), this collection of ages for FANs and Mg-suite rocks have profound implications for some of our fundamental concepts of primordial lunar differentiation. For example, if all FANs are flotation cumulates of a magma ocean, the wide range in ages must be in error because they would require plagioclase flotation to occur over ~200 Ma and during periods of post-LMO magmatism. Alternatively, many of the FANs may not be flotation cumulates of the LMO and instead be produced by a different type igneous process that post-date primordial differentiation of the Moon (e.g., serial magmatism). Here, we combine textural, microbeam, and isotopic observations-measurements to decipher the petrogenesis of a fairly crystalline, multimineralic FAN clast in sample 60016 to resolve some of these issues.

Analytical Approach: Sample 60016 is regarded as an "ancient" regolith breccia, presumably formed during the period of basin formation [1]. It has a light grey matrix with both light and dark clasts. Ryder and Norman [2] described this rock as a fragmental polymict breccia. We inspected several slabs and irregular pieces of 60016 looking for ferroan anorthosite clasts. Most of the slabs did not have clasts that were big enough for a detailed collaborative study. Subsample ,196 had the remains of clast 3A. Approximately half of the original clast is present in ,196. This clast was described in the Lunar Sample Newsletter #43 in Appendix 1. Prior to our sample request, we examined the thin section corresponding to the clast (,229). We requested that 3.0 g of this clast and the thin section be allocated to us. Any material left over from our allocation was removed from the slab and preserved separately from the main slab. This is consistent with our philosophy of preserving clasts for follow-on studies by other members of the community. Thin section ,229 was characterized using backscattered electron imaging (BSE) and x-ray mapping. Individual phases were analyzed for major and minor elements using the JEOL JXA-8200 electron microprobe in the Institute of Meteoritics (IOM)-Department of Earth and Planetary Sciences at the University of New Mexico. Modal abundance of phases was determined directly from BSE images. Individual phases were analyzed for trace elements using the Cameca ims 4f ion microprobe at the IOM. Mineral separates were prepared for dating. These results will be reported by Marks et al. in the near future. Splits of these separates and the bulk rock were analyzed for REE and Ba.

Results:

Textures: The FAN clast consists of both high- and low-Ca pyroxene (15.2%), plagioclase (82.6%), olivine (2.2%), and minor amounts of chromite (<<1%). The FAN is not highly cataclastized. Coarse grain fragments of plagioclase preserve the remanents of a coarse-grained plutonic texture. The individual plagioclase grains are subhedral to anhedral and can range up to the mm-scale. The pyroxene and olivine exhibit a poikiloblastic-like texture (Fig. 1). The olivine is anhedral (50-150 µm) and partially to totally surrounded by anhedral pyroxene (100-400 µm). Pyroxene and olivine contain rounded inclusions of plagioclase (10-50 µm). Both pyroxenes exhibiting fine-scale exsolution lamellae (Fig. 1).

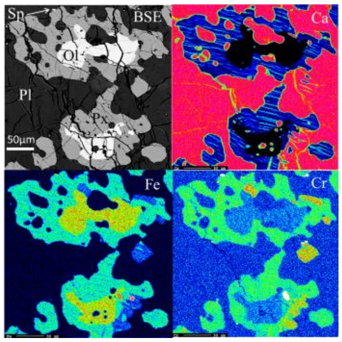

Fig. 1. BSE and X-ray maps (Ca, Fe,Cr) of FAN clast in 60016. Phases include olivine (Ol), 2 pyroxenes (Px) each exhibiting exsolution, plagioclase (Pl), and chromite (Sp). Scale bar is on the BSE.

Major-minor element mineral chemistry: The compositions of the high-Ca and low-Ca pyroxenes are presented in Fig. 2. Compositions lie along tie lines with variable wollastonite (Wo) component due to the exsolution exhibited by the pyroxenes. Plagioclase that occurs as rounded inclusions in the mafic phases and as large individual grains exhibit a fairly limited compositional range ($An_{96-94.5}$). Olivine has a Mg# that ranges from 67-65 (Fig. 3).

Whole rock and mineral trace element chemistry: REE data illustrates the following (Fig. 4): The REE pattern of a bulk clast is LREE enriched (La_N~0.2xCI) relative to the HREE (Yb_N~0.035xCI) with a positive Eu anomaly (Sm_N/ Eu_N =0.06).The REE pattern of a low-Ca pyroxene separate is LREE depleted (La_N=0.02xCI) relative to the HREE (Yb_N=0.1xCI) with a positive Eu anomaly (Sm_N/ Eu_N =0.2). The positive Eu anomaly is most likely the result of minor plagioclase contamination of the mineral separate. The REE patterns of the plagioclase are LREE enriched (La_N=0.4 to 2.4 xCI) relative to the HREE (Yb_N=0.6 to 0.08xCI) with a positive Eu anomaly (Sm_N/ Eu_N =0.058). The ion microprobe analyses of the plagioclase overlap with the mineral separate analyses.

Discussion: The clast in 60016 has undergone partial recrystallization as suggested by the textures observed in the pyroxene and olivine. These textures can be used to reconstruct a straightforward cooling history involving subsolidus pyroxene growth and exsolution. Major and trace element analyses of the bulk rock and individual mineral phases indicate that this clast represents a FAN lithology. The Mg# of the mafic phases and the An composition of the plagioclase plot in the FAN field (Fig. 3). REE patterns of plagioclase and pyroxene and Ni-Co of olivine indicate a FAN origin [3-5].

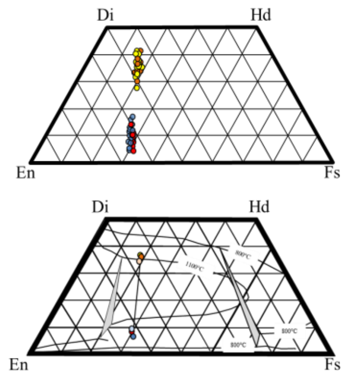

Fig 2. Pyroxene quadrilateral illustrating compositional variation in pyroxenes from FAN clast in 60016 and "bulk" pyroxene compositions placed in the context of pyroxene solvi at 1100 and 800°C.

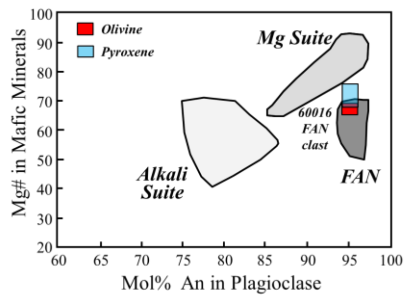

Fig. 3. Feldspar, pyroxene, and olivine chemistry plotted within the context of An in plagioclase and Mg# in mafic silicates. Fields for FANs, Mg suite, and Alkali suite are plotted.

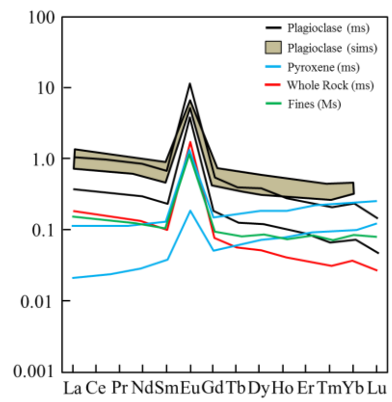

Fig. 4. Chondrite normalized REE patterns for 60016 whole rock and individual mineral phases determined by secondary ion mass spectrometry (SIMS) and mass spectrometry (MS).

References: [1] McKay et al. (1986) Proc. 16th Lunar Planet. Sci. Conf. in J. Geophys. Res. 91, D277-D303. [2] Ryder and Norman (1980) Catalog of Apollo 16 rocks (3 vol.). Curator's Office pub. #52, JSC #16904. [3] Papike et al. (1997) G.C.A, 61, 343-2350. [4] Shearer et al. (2006) Reviews in Mineralogy and Geochemistry. RiMG 60, 365-518. [5] Shearer and Floss (2000) In Origin of the Earth and Moon (eds. K. Righter, R. Canup), 339-360.