Timing and duration of the Mg-suite episode of lunar crustal building. Part 1: Petrography and mineralogy of a norite clast in 15445.

C.K. Shearer[1,2], L. E. Borg[3], P. V. Burger[1], J. N. Connelly[4], and M. Bizarro[4]. [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] Lawrence Livermore National Laboratory, Livermore, California 91125, [4] Centre for Star and Planet Formation, Natural History Museum of Denmark, University of Copenhagen, Denmark.

Introduction: The earliest stages of lunar crustal building are represented by the ferroan anorthosite (FAN) and the highlands Mg-suite (HMS) lithologies. In the simplest differentiation models, the FANs represent primordial lunar crust produced by plagioclase flotation during lunar magma ocean (LMO) crystallization. The HMS post-date LMO crystallization, intrude the primordial FAN crust, and are a product of LMO cumulate mixing and melting [i.e. 1-6]. Although many geochemical observations are consistent with this type of model, crystallization ages for FAN and HMS exhibit considerable overlap, hinting at a more complex processes for the formation of the Moon's early crust [i.e. 6-8]. One example of this ambiguity is HMS norite clast in impact melt breccia 15445. This norite clast (Clast B/Lithology 45D) is the largest clast in 15445 and is surround by a matrix lithology that has been interpreted as an impact melt [9,10]. The bulk norite is slightly LREE enriched ($La_N/Lu_N \sim 1.4$) with a slightly positive Eu anomaly ($Eu_N/Sm_N \sim 1.7$) [11]. Two samples from this clast yield discordant internal Sm-Nd isochron ages and initial ε_{Nd} values [12]. Norite sample 15445,17 yielded a precise internal isochron age of 4.46 ± 0.07 Ga and an initial ε_{Nd} of +0.71, whereas norite sample 15445,247 yielded an internal isochron age of 4.28 ± 0.03 Ga and an initial ε_{Nd} of -0.35 [12]. Shih et al. [12] interpreted these data to indicate that this clast was heterogeneous (i.e. contained two isotopically distinct plutonic lithologies). These two distinctly different ages and initial Nd values have profound implications for the timing and duration of HMS magmatism, its relationship to primordial FAN crust, and post-LMO crustal growth. For example, if the oldest age is correct, then HMS predates ages determined on some FANS (e.g., 62236, 60025, [7-8] and underscore the oversimplification of the simpliest lunar differentiation models. Using previous petrologic and isotopic work as a foundation, we examined the petrographic, mineralogical and geochemical characteristics of norite clast B from 15445 to investigate its heterogeneity as a prelude to revisiting its crystallization age and isotopic composition using multiple chronometers (^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, ^{207}Pb-^{206}Pb).

Analytical Approach: Three thin sections of norite clast B (15445,185, 15445,257, 15445,292) that represent different portions of the clast were selected and analyzed. Small mass of the clast that remained from the initial investigation was also selected for chronology. Thin sections from the surrounding impact melt were also selected and analyzed. Samples were characterized using backscattered electron imaging (BSE) and X-ray mapping using the JEOL JXA-8200 Electron Probe Microanalyzer (EPMA) in the Department of Earth and Planetary Sciences at the University of New Mexico. BSE images and X-ray maps were used to position quantitative analysis at a beam current of 20 nA, using a <1 micron spot. These maps were further used to conduct initial secondary ion mass spectrometry (SIMS) trace element analyses of orthopyroxenes and plagioclase making up the clast. SIMS measurements of the plagioclase and pyroxene follow the methodology of [5]. Measurements of Rb-Sr, ^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, and ^{207}Pb-^{206}Pb follow the approachs outlined by [8].

Results:

Textures: The norite clasts consists of low-Ca pyroxene (30-40%), plagioclase (60-70%) with minor amounts of SiO_2, metal, and ilmenite. The norite is cataclasized, yet coarse grain fragments preserve the remanents of a coarse-grained plutonic texture (Fig. 1A). The impact melt matrix that surrounds the clast consists of a variety of individual mineral grains (olivine, plagioclase, low-Ca pyroxene, and spinel) that exhibit some reaction textures along grain bountaries. The matrix forms a fine-grained boundary (100-400 µm) against the clast and extends into the clast 1 to 2 mm (Fig. 1B).

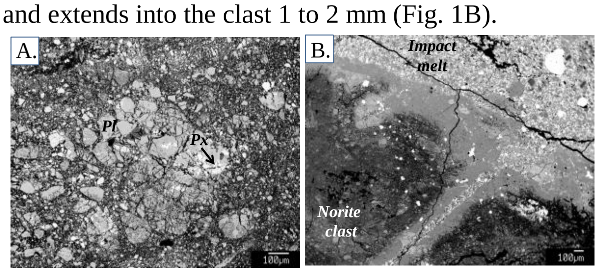

Fig. 1. Textural variations observed in and adjacent to norite clast B in 15445. A. Coarser grained portion of the clast that is dominated by plagioclase and orthopyroxene. B. Boundary between clast and surrounding impact melt.

Major-minor element mineral chemistry: The composition of pyroxene (n=40) in the clast exhibits very little variation in quadrilateral components (Fig. 2) and overlaps with compositions in the impact melt and

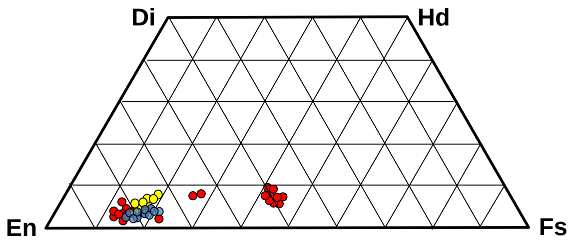

Fig. 2. Pyroxene quadrilateral illustrating variations in pyroxene composition in the clast (blue), surrounding impact melt (red), and reaction rim around clast (yellow).

reaction rim around the clast. The impact melt does show a greater diversity in pyroxene compositions. The plagioclase composition in the clast ranges from An_{95-96} (n=35). As expected, the plagioclase in the surrounding matrix exhibits much more variation with compositions from An_{72-97} (n=25). In the reaction rim between the clast and surrounding matrix, the plagioclase composition is similar to the norite (An_{94-95} {n=10}). Olivine was not identified in the clast, but it occurs in the matrix and has a large compositional ranging from Fo_{59-95} (n=50). The olivine in the reaction rim has a composition of Fo_{81} (n=6). The clast plots with the Mg-suite field in Figure 3, whereas the individual mineral fragments in the impact melt potentially define a much broader range in highland lithologies.

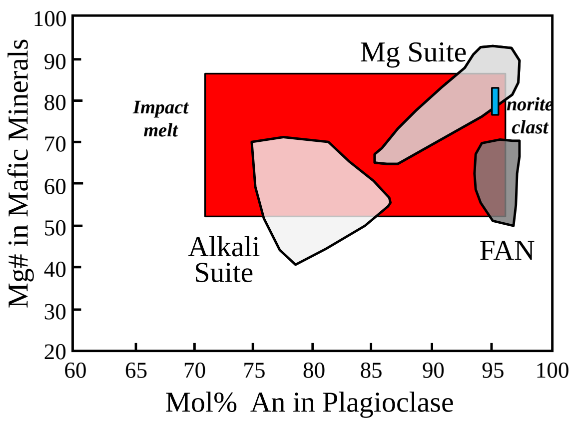

Figure 3. Plagioclase composion (An) plotted against the Mg# of mafic silicates (low-Ca pyroxene) from the norite (blue field) and surrounding impact melt within the context of important lunar highland lithologies.

Trace element mineral chemistry: Initial REE data illustrates the following: The REE patterns of the low-Ca pyroxenes are LREE depleted (La_N=0.5xCI) relative to the HREE (Yb_N=10-15xCI) with a relatively large negative Eu anomaly (Sm_N/ Eu_N =30-50). The REE patterns of the plagioclase are LREE enriched (La_N=10-20xCI) relative to the HREE (Yb_N=1xCI) with a positive Eu anomaly (Sm_N/ Eu_N =0.15-0.20). Based on the few analyses done at this time, there appears to be little variation in the REE characteristics of either the plagioclase and pyroxene in the clast.

Discussion: Prior to unraveling the crystallization age and isotopic composition of norite clast B from 15445 using multiple chronometers, we are conducting a mineralogical-geochemical study of this clast. A portion of this study is to determine mineral compositions and textural relationships with the adjacent impact melt to enable a well developed strategy for mineral separations. Some factors which must be taken into consideration include: (1) the limited variation in plagioclase composition and minimal variations in the Mg# of the low-Ca pyroxene, (2) the large variation in grain size from <1 µm to 200 µm due to the cataclasized texture of the norite and (3) "veins" of impact melt (Fig. 1B) that penetrate the clast and consist of mineral compositions and mineral phases (olivine, glass) that differ from the clast (Fig. 2).

The second part study is to evaluate whether this clast represents a single or multiple lithogies. Electron microprobe analyses of pyroxene and plagioclase indicate that the clast is homogeneous with regards to the major and minor composition of minerals. However, as correctly stated by Shih et al. [12], lithologies with similar mineralogy and mineral chemistries may have different isotopic characteristics. On the other, hand, these data show that the norite represents HMS magmatism (Fig. 3) and should have a characteristic KREEP signature. A HMS heritage suggested by major element characteristics of the silicates is consistent with the REE patterns of both plagioclase and orthopyroxene which have similarities to other HMS norites [13,14]. Further, these data are unable to distinguish more than one lithology. Additional, REE measurements must be made to confirm these observations. As with other KREEPy plutonic and volcanic rocks, it should be expected that this norite plots on the KREEP evolution trajectory in ε_{Nd}-T plots.

References: [1]Taylor and Jakês (1974) PLSC 5, 1287-1305. [2] Warren (1985) Ann. Rev. Earth Planet. Sci. 13, 201-240.[3] Warren (1988) PLPSC 18, 233-241.[4] Shearer and Papike (1999) Amer. Mineral. 84, 1469-1494. [5] Shearer and Papike (2005) GCA 69, 3445-3461. [6] Shearer et al. (2006) New Views of the Moon 365-518.[7] Borg et al. (1999) GCA 63, 2679-2691. [8] Borg et al. (2011) Nature 477, 70–72. [9] Ryder and Bower (1977) PLSC 8th, 1895-1923. [10] Lunar Sample Compendium. http:// curator.jsc.nasa.gov/ lunar/lsc/66095. pdf. [11] Ridley et al. (1973) J. Geol. 81, 621-631. [12] Shih et al. (1993) GCA 57, 915-931. [13] Papike et al. (1994) Am. Mineral 79, 796-800. [14] Papike et al. (1996) GCA 60, 3967-3978.