**CHRONOLOGY OF 15445 NORITE CLAST B AND IMPLICATIONS FOR MG-SUITE MAGMATISM.**

A. M. Gaffney[1], L. E. Borg[1], C. K. Shearer[2] and P. V. Burger[2], [1]Lawrence Livermore National Lab., Livermore, CA 94550, gaffney1@llnl.gov, [2]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131.

**Introduction:** The oldest ages preserved by lunar rocks are found in samples from the ferroan anorthositic suite (FAS) and highlands Mg-suite. The magma ocean model for lunar differentiation predicts that FAS samples are flotation cumulates from the primordial lunar magma ocean, and therefore are the oldest rocks on the Moon. Mg-suite magmatism is thought to have commenced after complete, or near-complete, solidification of the magma ocean, and therefore is expected to postdate FAS magmatism. However, the ages determined for these suites of samples overlap, and in some cases individual ages determined for Mg-suite samples are older than the ages of some FAS samples [e.g., 1-3]. If these chronological relationships are accurate, this indicates that early lunar differentiation and crust building processes are more complex than predicted by the conventional magma ocean model.

One Mg-suite sample yielding an old age is 15445 norite clast B. As for many lunar highlands rocks, the age of this sample is ambiguous because two age determinations made on two different pieces of this clast yield discordant ages that differ by 180 My. The older age, 4.46 ± 0.07 Ga (15445,17) [1], is the oldest Sm-Nd age determined for an Mg-suite sample, and is older than several FAS samples. The younger age determined for this sample, 4.28 ± 0.03 Ga (15445,247) [1], is concordant with the majority of the ages reported for individual Mg-suite samples and a peak in zircon ages [e.g., 4-7; summarized in 8]. The difference in the two ages obtained for 15445 norite clast B has been interpreted to result from lithologic heterogeneity in this sample [1]. If 4.46 Ga is the true crystallization age of the sample, then this has wide-reaching implications for the timing of lunar differentiation and the petrogenetic processes involved in early crust building magmatism. In the effort to evaluate whether this clast is composed of two lithologies characterized by distinct ages, we have undertaken a petrological, geochemical and isotopic study of 15445 clast B.

**Methods:** We obtained a ~1 g allocation, 15445,289, taken from norite clast B in breccia 15445. The sample was gently crushed in a sapphire mortar and pestle. Sample pieces containing visible amounts of breccia matrix and impact melt were removed, and the remaining sample was passed through 100 mesh, 200 mesh and 325 mesh sieves. The 100-200 and 200-325 mesh fractions were passed through a Frantz magnetic separator to obtain mineral separates. These are designated Px-A (100-200 mesh pyroxene), Px-B (200-325 mesh pyroxene), Plag-1 (100-200 mesh plagioclase), Plag-2 (200-325 mesh plagioclase) and Int (100-200 mesh intermediate). The mineral separates were hand-picked under a binocular microscope to remove impact melt and breccia matrix. Sample fractions were spiked with mixed Rb-Sr, Lu-Hf and Sm-Nd (99.998% $^{150}$Nd) tracers and samples were purified using our established methods [9]. Analyses of Sm, Nd, Rb and Sr were completed on the Triton TIMS at LLNL, and Lu and Hf were analyzed with the Nu Plasma MC-ICP-MS at LLNL [9]. The Sm and Hf isotopic compositions measured on the unspiked WR-2 sample fraction (comprising <325 mesh sample powder) are used to correct the $^{176}$Lu/$^{177}$Hf, $^{147}$Sm/$^{144}$Nd, Hf isotopic and Nd isotopic ratios for the effects of neutron irradiation [9].

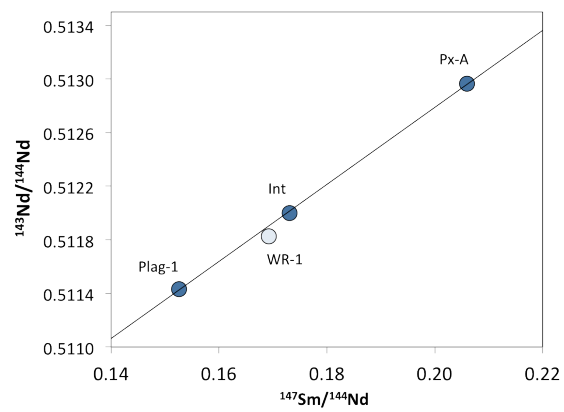


***Figure 1.*** *The best-fit $^{147}$Sm-$^{143}$Nd isochron through the Plag-1, Px-A and Int fractions from 15445,289 yields an age of 4332 ± 79 Ma and an initial $\varepsilon_{Nd}$ value of 1.1 ± 1.9.*

**Results:** The $^{147}$Sm-$^{143}$Nd isochron shown in Figure 1 is based on results from mineral and whole rock fractions that contained sufficient Nd to analyze as Nd+. These measurements were completed using a TIMS analysis routine that yields a static measurement of $^{143}$Nd/$^{144}$Nd and a multidynamic measurement of $^{142}$Nd/$^{144}$Nd. Two smaller mineral fractions, Plag-2 and Px-B, will be analyzed as NdO+. The Plag-1, Px-A and Int fractions define the best-fit isochron with an age of 4332 ± 79 Ma. The WR-1 fraction lies below the isochron. This is most likely due to trace amounts of breccia matrix and impact melt contained in the bulk rock fragment processed for WR-1. This isochron yields an initial $\varepsilon_{Nd}$ value of 1.1 ± 1.9. These results are preliminary, and will likely be revised after analysis of the Plag-2 and Px-B mineral fractions. Figure 2 shows the $^{142}$Nd-$^{143}$Nd isochron for this sample. The line regressed through all 5 sample fractions yields an age of

4320 +82/-196 Ma. This age is concordant with the $^{147}$Sm-$^{143}$Nd isochron age for this sample.

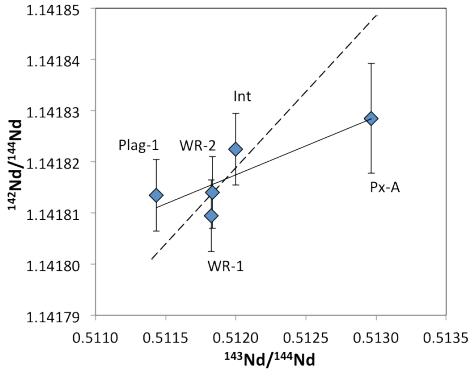


***Figure 2.*** *Internal $^{142}$Nd-$^{143}$Nd isochron for 15445,289 defines an age of 4320 +82/-196 Ma, using all 5 measured fractions ($^{146}$Sm t½ = 103 Ma). Dashed line is 4.46 Ga slope.*

The Lu-Hf and Rb-Sr isotope systematics of this sample are disturbed. The Lu-Hf data are shown in Figure 3. These data fail to yield a 3- or 4-point isochron or a 2-point tie line with an age that is concordant with the Sm-Nd and $^{142}$Nd-$^{143}$Nd ages. The Rb-Sr data also show considerable scatter, although a tie-line between the Int and Plag-2 fractions yields an age of 4395 ± 110 Ma, which agrees with the $^{147}$Sm-$^{143}$Nd and $^{142}$Nd-$^{143}$Nd ages.

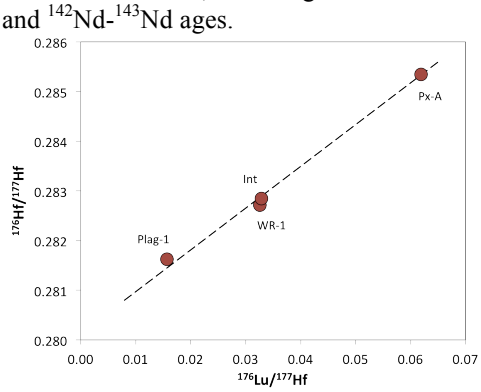


***Figure 3.*** *The Lu-Hf isochron for 15445,289 shows disturbance in the mineral and WR fractions, and fails to yield a sample age. Dashed line is 4.33 Ga reference isochron.*

**Discussion:** The two discordant ages determined for different pieces of 15445 norite clast B by Shih et al. [1] were interpreted to result from two or more lithologies present in this sample. To evaluate this hypothesis, we completed electron microprobe and SIMS analyses of this sample [10], using thin sections that were made from 3 different parts of the clast as well as the surrounding impact melt. The analyses of the 3 norite thin sections show homogeneous major element compositions for pyroxene, plagioclase and olivine. Furthermore, SIMS analyses show that the REE concentrations in pyroxene and plagioclase are invariant between two thin sections (Figure 4). The absence of evidence for mineralogical heterogeneity is not consistent with the presence in this clast of two geochemically distinct norite lithologies.

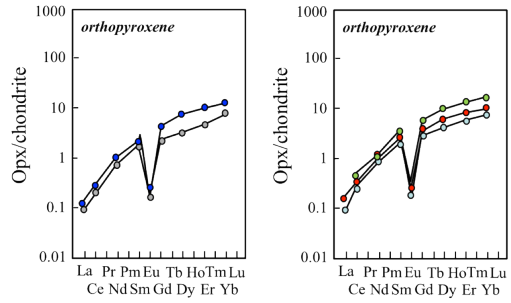


***Figure 4.*** *SIMS analyses of orthopyroxene in thin section 15445,292 (left) and 15445,257 (right) show homogeneous REE compositions in two different parts of clast B.*

The new $^{147}$Sm-$^{143}$Nd and $^{142}$Nd-$^{143}$Nd isochrons for 15445,289 record concordant ages of ca. 4.33 Ga. This age is concordant with the 4.28 Ga age determined for 15445,247 [1], but is discordant with the older 4.46 Ga age determined for 15445,17 [1]. Whereas the initial $\varepsilon_{Nd}$ value of 15445,247 is negative [1], the new initial $\varepsilon_{Nd}$ value determined for 15445,289 is positive. This is not consistent with the inferred petrogenesis of this Mg-suite norite, which shows REE characteristics consistent with derivation from a KREEP-rich source and major element mineral compositions showing that this sample is a member of the Mg-suite.

The positive initial $\varepsilon_{Nd}$ value, combined with the scatter in the Lu-Hf and Rb-Sr systematics of this sample, indicate that it has experienced disturbance at some point in its history. It is therefore not unexpected that two discordant ages were previously determined for two different pieces of the clast [1]. The best age we determined for this sample is 4.33 ± 0.08 Ga, as recorded by the $^{147}$Sm-$^{143}$Nd system (Fig. 1). The lack of variation in $^{142}$Nd/$^{144}$Nd between mineral fractions supports this young age (Fig. 2) and clearly indicates this sample is younger than 4.46 Ga. The best age determined for 15445 norite clast B is in good agreement with the majority of ages determined for Mg-suite rocks; $^{142}$Nd/$^{144}$Nd, $^{147}$Sm-$^{143}$Nd and Lu-Hf magma ocean model ages; and the peak of zircon Pb-Pb ages [summarized in 8]. These new results for 15445 norite clast B provide additional support for a widespread magmatic event on the Moon at ca. 4.35 Ga.

**References:** [1] Shih et al. (1993) *GCA* **57**:915-931; [2] Nyquist et al. (1981) *PLPSC* **12**:67-97; [3] Borg et al. (2011) *Nature* **477**:70-72; [4] Edmunson et al. (2009) *GCA* **73**:514-527; [5] Nakamura et al. (1976) *PLPSC* **7**:2309-2333; [6] Grange et al. (2009) *GCA* **73**:3093-3107; [7] Nemchin et al. (2008) *GCA* **72**:668-689; [8] Borg et al. (2014) doi: 10.1111/maps.12373; [9] Gaffney & Borg (2014) *GCA* **140**:227-240; [10] Shearer et al. (2012) *LPSC* **XLIII** abs. 1421. This work performed under the auspices of the U.S. DOE by LLNL under contract DE-AC52-07NA27344.