Garnet in the Lunar Mantle: Further Evidence from Volcanic Glasses. C. R. Neal[1] and C. K. Shearer[2], [1]Dept. of Civil Eng. & Geological Sciences, Univ. of Notre Dame, Notre Dame, IN 46556 (neal.1@nd.edu), [2]Institute of Meteoritics, Dept. of Earth & Planetary Sci., Univ. of New Mexico, Albuquerque, NM 87131 (cshearer@unm.edu).

Introduction: The returned lunar samples contained no direct samples of the lunar mantle (i.e., mantle xenoliths). Coupled with the ambiguity of the Apollo Seismic Experiment results [1,2], detailed investigations of the lunar interior can only be achieved through analysis of volcanic products. Neal [1] suggested that the ion microprobe data reported by Shearer and co-workers (e.g., [3-6]) contained evidence of garnet being retained in the source. This evidence came from ratioing garnet-compatible elements to garnet-incompatible elements. Samples that contain, for example, Zr/Y ratios greater than mare basalts and KREEP are best modeled by retaining garnet in the residue after melting. This required these glasses to be derived from a source >500 km deep, where garnet is stable. However, the number of garnet-loving elements in the original dataset was limited. The purpose of this study was to collect a comprehensive dataset on low- and high-Ti glasses of trace elements that are sensitive indicators of garnet in their source regions. The elements quantified were Sc, Y, Zr, Nb, Ce, Sm, and Yb. Sc, Y, and Yb are highly compatible in garnet and if garnet is retained in the residue, Sc/Sm will decrease and ratios such as Zr/Y and Sm/Yb will increase.

Samples: Volcanic glasses from Apollo 11, 12, 14, 15, and 17 were analyzed. Each one of the glasses had been previously analyzed for a subset of these elements. The samples were analyzed on polished thin sections. These were 10064,31; 12033,1; 14049,38; 14301,86; 15318,6; 15427,81; and 79135,31. The glasses analyzed range in TiO_2 contents from <0.5 wt% (Apollo 15 green (A-E) and Apollo 17 VLT) to 17 wt% (Apollo 14 black).

Analytical Approach: Selected trace elements (^{45}Sc, ^{89}Y, ^{90}Zr, ^{93}Nb, ^{140}Ce, ^{147}Sm, ^{174}Yb) that would be useful in evaluating the presence of garnet in the source were measured using the Cameca ims 4f operated on the University of New Mexico campus by IOM. Analyses were made using primary O^- ions accelerated through a nominal potential of 10.0 kV. A primary beam current of 20 nA was focused on the sample over a spot diameter of 20 µm. Sputtered secondary ions were energy filtered using a sample offset voltage of 105 V and an energy window of ± 25 V. Analyses involved repeated cycles of peak counting. The analytical procedure included background counting to monitor detection noise. Absolute concentrations of each element were calculated using empirical relationships of Trace $Element^+/^{30}Si^+$ ratios (normalized to previously measured SiO_2 content) to determine element concentrations as derived from daily calibration. Calibration curves were constructed using at least 3 basaltic glass standards for each element. Calibration curves for each element have correlation coefficients of > 0.86.

Results: The analyzed glasses display a range of trace element abundances that span the range defined

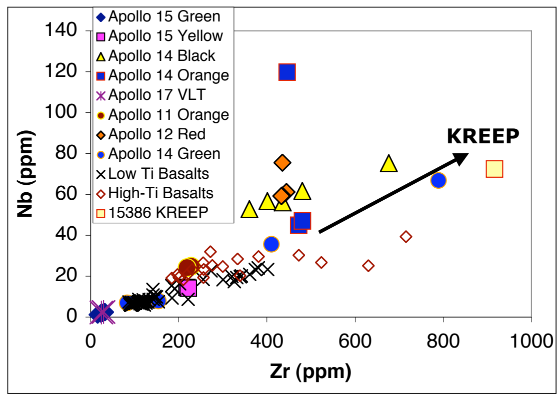

Figure 1: Zr and Nb abundances for the glasses analyzed in this study compared to low- and high-Ti mare basalts and KREEP. Mare basalt & KREEP data from [1].

by the mare basalts. This is exemplified by the incompatible trace elements (ITEs) Zr and Nb (Fig. 1). Some of the glasses parallel the mare basalt trend towards KREEP, but one Apollo 14 orange, the Apollo 14 black and the Apollo 12 red glasses plot above this trend. The only compatible trace element analyzed, Sc, showed a range of ~18-64 ppm with the glasses generally containing lower Sc contents for a given Sm abundance than the mare basalts (Fig. 2). As such that the majority of the analyzed glasses plot below the trend defined by the mare basalts.

Discussion: The majority of glasses analyzed in this study appear to be trending towards KREEP (Figs. 1 & 2), suggesting involvement of this component in volcanic glass petrogenesis (cf. [3-6]). Evaluation of glass source regions was conducted using the ITE ratios Nb/Ce and Nb/Zr (Fig. 3). The vectors on this diagram show the influence of garnet and ilmenite being retained in the source region would have on these ratios. Glasses previously analyzed for Zr, Nb, and Ce [3] parallel the mare basalt trend. It would appear that the Apollo 14

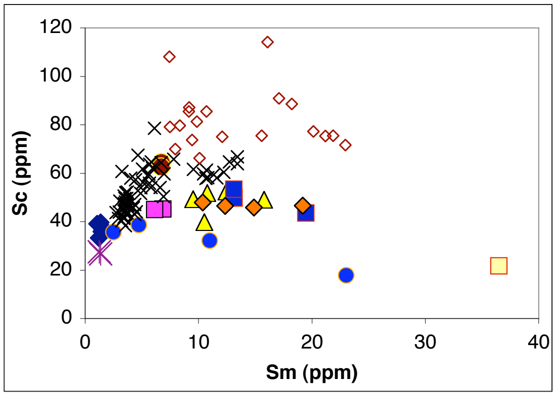

Figure 2: Sc and Sm abundances for the glasses analyzed in this study compared to low- and high-Ti mare basalts and KREEP. Mare basalt & KREEP data from [1].

orange, Apollo 14 black and the Apollo 12 red glasses formed from distinct source regions compared to the mare basalts and other volcanic glasses. As these glasses have elevated TiO_2 contents (12-17 wt% TiO_2), the influence of both ilmenite and garnet are recorded. Since $D_{Ce} < D_{Nb} \sim D_{Zr}$ for ilmenite, this phase will fractionate Nb/Ce more than Nb/Zr. For garnet, $D_{Ce} \sim D_{Nb} < D_{Zr}$ so garnet influence will fractionate Nb/Zr more than Nb/Ce.

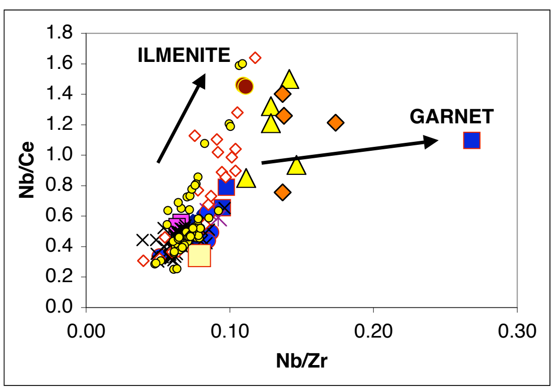

Figure 3: Nb/Zr vs. Nb/Ce for the glasses analyzed in this study compared to low- and high-Ti mare basalts and KREEP (from [1]) and other volcanic glasses shown as yellow circles (from [3]).

To further examine the possible influence of garnet on the volcanic glasses, ratios of $(Sm/Yb)_N$ (where "N" signifies that the ration is normalized to chondritic abundances), Zr/Y, Zr/Yb and Sc/Sm were evaluated relative to mare basalts and KREEP (again, data from [1]). The slope of the REE profile, as measured by $(Sm/Yb)_N$ is not significantly greater in the glasses we analyzed than KREEP or some of the low-Ti (Apollo 14) mare basalts. The steepest REE slopes are in the Apollo 14 black and Apollo 12 red glasses (Fig. 4A). These glasses, however, exhibit significantly higher Zr/Y and Zr/Yb ratios than the mare basalts and KREEP, and low Sc/Sm (Fig. 4 A,B,C).

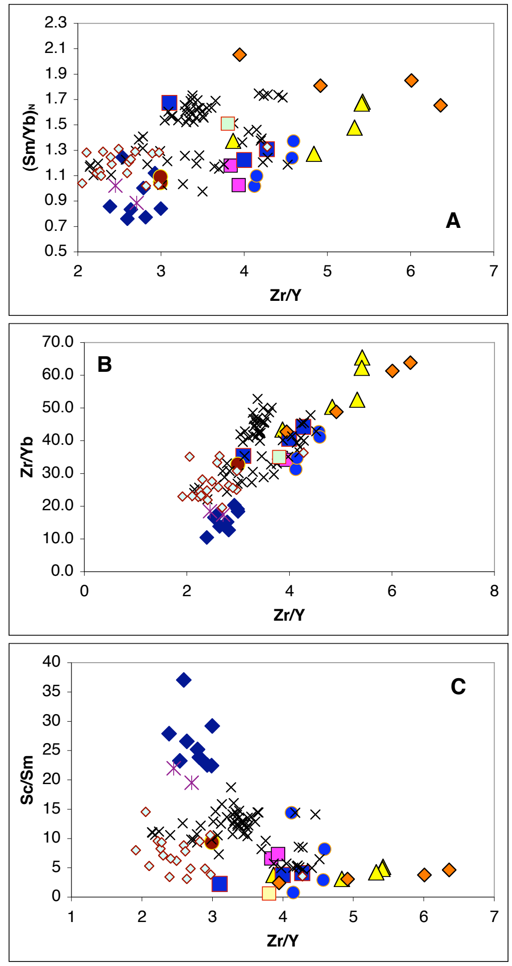

Figure 4: Elevated values of $(Sm/Yb)_N$, Zr/Y, and Zr/Yb, greater than those of KREEP and mare basalts, coupled with low Sc/Sm is indicative of garnet being retained in the source region.

We interpret the new glass data to indicate the presence of garnet in the residue after melting of the Apollo 12 red and the Apollo 14 black glasses. The remaining glasses, including the primitive Apollo 15 green glasses, do not show any evidence of garnet influence either because of shallow derivation (i.e., < 500 km) or because garnet was exhausted. As trace element evidence is now suggesting garnet in the mantle, a return to the Moon to set up a seismic network would be critical in testing the presence of garnet in the deep lunar mantle [2].

References: [1] Neal (2001) JGR 106, 27865. [2] Neal et al. (2004) LPSC 35. [3] Shearer et al. (1996) GCA 60, 3521. [4] Shearer et al. (1990) GCA 54, 851. [5] Papike et al. (1990) Geology 18, 295. [6] Shearer et al. (1994) GCA 58, 5349.