GARNET IN THE LUNAR MANTLE: FURTHER EVIDENCE FROM VOLCANIC GLASS BEADS.

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Introduction: Volcanic glass beads returned from the Moon represent a unique class of igneous material through which the interior of the Moon can be studied. Their major element compositions demonstrate that they are distinct from the crystalline mare basalts [1-5] and are relatively rich in volatiles [6,7]. Neal [8] noted that some of the picritic glass compositions contained signatures consistent with garnet being retained in the source regions after melt removal. Neal & Shearer [9] undertook a preliminary study of a variety of volcanic glass beads (VLT-High-Ti) concentrating on the garnet compatible elements Sc, Y, and Yb, as well as the garnet incompatible elements Zr, Nb, Ce, and Sm. The results indicated that the garnet signatures were present in high-Ti glasses. We report here the results of our continuing investigation of garnet signatures recorded by high-Ti volcanic glass beads.

Samples: The samples analyzed in this study have been previously examined by Shearer & co-workers [2-5] and were reanalyzed to obtain a comprehensive dataset of the garnet compatible elements. Thin sections 14301,84, 14307,45, & 14313,44 were examined and the data combined with those from [9].

Analytical Methods: Major element data for the glass beads analyzed in this study were reported elsewhere [2-5]. Trace elements ([45]Sc, [89]Y, [90]Zr, [93]Nb, [140]Ce, [147]Sm, [174]Yb) were quantified using the Cameca ims 4f at the University of New Mexico campus operated 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 105V and an energy window of ±25 V. Analyses involved repeated cycles of peak counting. Background counting was included 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 used at least 3 basaltic glass standards for each element, and for each element have correlation coefficients generally > 0.85.

Results: The analyzed glasses cover a wide range of major & trace element abundances (Fig. 1a,b), representing all compositions from VLT to high-Ti glasses.

Discussion: The A-12 red, A-14 black, & A-14 orange high-Ti glasses are distinct from the high-Ti basalts (Fig. 1b). Trends of mare basalts in Figure 1b


Figure 1a

Figure 1b
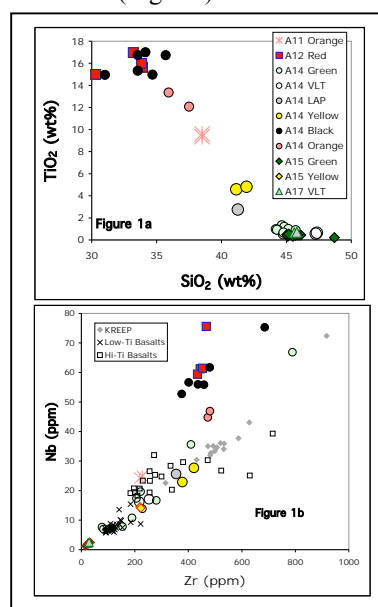
extend toward KREEP (both low- and high-Ti variants), as do the low-Ti glasses and the Apollo 11 glasses. High-Ti glasses from A-12 and A-14 form a distinct trend of Nb enrichment for a given Zr abundance (Fig. 1b). Partition coefficients for Zr and Nb in ilmenite (0.406 and 0.8, resp. [10,11]) indicate that neither fractional crystallization of ilmenite nor partial melting of an ilmenite-bearing source would increase the Nb/Zr ratio enough to produce the high-Ti glass compositions (Fig. 1b). However, experiments on high-Ti basalts & glasses [12], and specifically the A-14 black glasses [13,14], show that ilmenite is **not** a residual phase. It was demonstrated [12] that at least the A-17 (high-Ti) orange glass was never saturated with ilmenite at any pressure, although this could indicate ilmenite was exhausted during partial melting. Wagner et al. [14] came to a similar conclusion for the A-14 black glasses, but suggested the high-Ti composition was produced through assimilation of ilmenite-rich cumulates by a superheated low-Ti parent magma.

The experimental work on VLT, low- and high-Ti glasses [12-16] demonstrates that garnet is potentially stable at high pressure (>2.4 GPa or >480 km depth in the Moon). We contend the elevated Nb/Zr ratios of the A-12 and A-14 high-Ti glasses (Fig. 1b) are the result of garnet being retained in the source regions of these glasses: D-values for Zr and Nb in garnet are 0.32 and 0.04, respectively [16,17].

Further evidence for garnet is seen in Figure 2 where the A-12 and A-14 high-Ti glasses exhibit higher Zr/Y and higher Sm/Yb ratios than KREEP

and mare basalts. The KREEP signature is derived from the garnet-absent crystallization of the lunar magma ocean. The elevated Sm/Yb ratios exhibited by the high-Ti glasses cannot be due to the influence of KREEP, but are consistent with garnet being a residual phase in the glass source regions (cf. [8,9]).

Figure 2
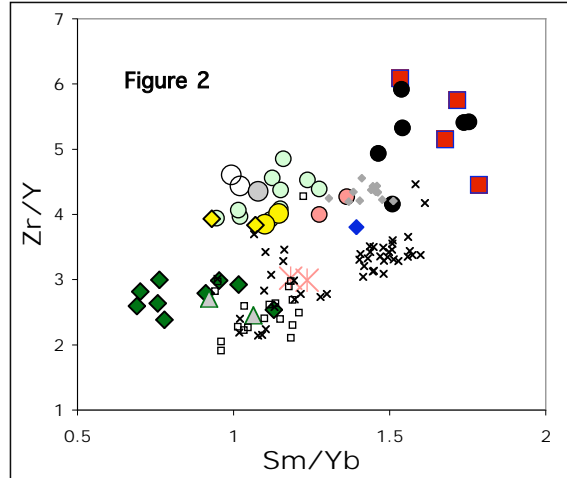
Modeling. Petrogenetic modeling was conducted assuming that the glasses were derived by non-modal batch melting. A variety of sources were initially used: bulk Moon composition [18]; bulk Moon + ilmenite; a hybridized source of early- (olivine+Opx) and late-stage cumulates (ilmenite+Cpx) +/- KREEP. When ilmenite was included in the source, it was exhausted during melting as required by [12,14]. The modeling also explored if the high-Ti glasses could be generated solely by partial melting or if ilmenite assimilation was required (cf. [14]). The assimilant used in the modeling was ilmenite after 95 PCS & KREEP after 99.5% PCS [19]. Partition coefficients were taken from [11,16,17,19].

Results. The Sm/Yb and Sc/Sm ratios of the A-12 & A-14 high-Ti glasses can be generated by partial melting that leave garnet in the residue. However, this underestimates the Zr/Y ratios and does not generate Nb/Zr and Nb/Ce. Assimilation (cf. [14]) is required to generate these signatures in the high-Ti glass. The assumptions used for the assimilant were that is composed of ilmenite from 95 PCS of the LMO and it was metasomatized by KREEPy liquid from 99.5% PCS in the proportions of 49:1. The A-12 & A-14 high-Ti glass data are best modeled using 2% garnet in the source also containing 78% olivine & 20% Opx that experiences 5-10% partial melting. The melt encounters an easily assimilated hot ilmenite+KREEP component, (r=0.9). The melting paths (Fig. 3) are in 1% increments. AFC paths are in 2% FC increments of 9:1 olivine:spinel crystallization.

Conclusions: The A-12 & A-14 high-Ti volcanic glass beads have compositions consistent with derivation from a low-Ti garnet-bearing source, which would need to be located >500 km within the Moon. This is required to account for the Sm/Yb & Sc/Sm ratios. Creating a Lunar Seismic Network is required to test the presence of garnet in the lunar mantle. A combination of garnet in the source and assimilation of an ilmenite-rich component is required to generate the Nb/Zr, Nb/Ce, and Zr/Y ratios.

Figure 3a

Figure 3b
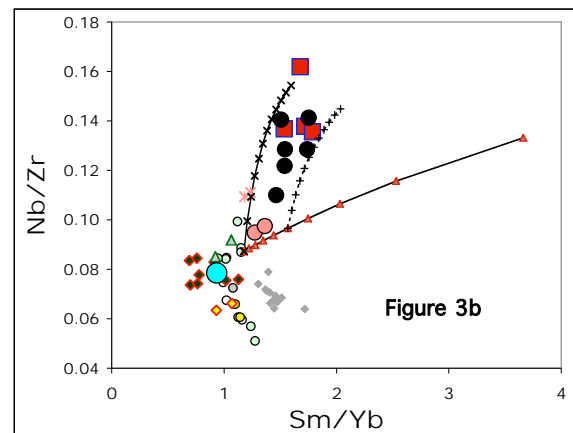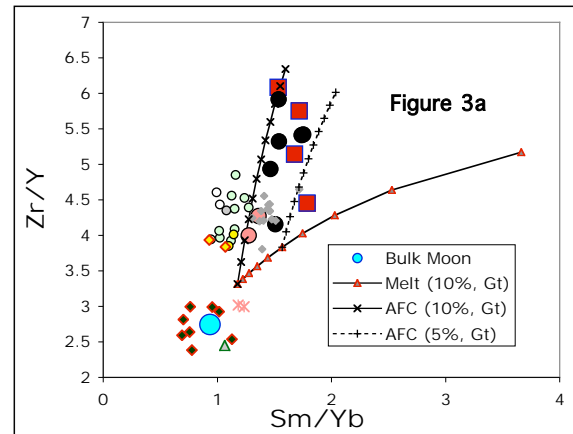
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