INSIGHTS INTO THE PETROGENESIS OF APOLLO 17 HIGH-TI MARE BASALTS.

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Introduction: Lunar volcanism provides evidence with which to interpret the magmatic evolution of the Moon. Specifically, lunar basalt geochemistry is the basis for the current hypothesis of basaltic magma generation [e.g., 1]. Of the myriad geochemical data on basalts, stable oxygen isotopes in lunar basalts can supply critical constraints on the composition and origin of the Moon's mantle [2, and references therein].

Lunar basalts from the Apollo and Luna collections are traditionally divided into three major groups based on titanium content: high (>6 wt. %; HTB), low (1-6 wt. %; LTB) and very-low Ti basalts (<1.5 wt. %; VLT) [1]. Recent study of bulk-rock O and Fe isotopes of the high- and low-Ti basalts has shown an apparent division of $\delta^{18}O$ among the high-Ti basalts: between samples with <12 wt % TiO_2 versus those with >12 wt % TiO_2, to $\delta^{18}O$ values of ~5.7 and 5.4‰, respectively [2-3]. We will refer to these as low-HTB and high-HTB. These authors suggested that different $\delta^{18}O$ values within high-Ti basalts result from either different mantle sources or closed-system fractional crystallization, the latter of which requires crystallization of large abundances of 9 wt. % olivine, 9.5 wt. % armalcolite, and 14 wt. % augite [3]. Similar suggestions were made by Rhodes et al. [4] and Warner et al. [5]. However, armalcolites have not been observed in such high abundances in lunar basalts and are generally present in small quantities <1 vol. % [e.g., 6]. This apparent discrepancy warrants a close examination of high-Ti basalts. Here, a detailed study was conducted on several Apollo 17 samples studied in [2-3, 7] to identify differences between the high-Ti basalt subgroups using petrography, modal analysis, and mineral chemistry.

Samples and Method: Thin sections *75035,76*, *75015,28*, and *71539,5* of the **low-HTB** (~9 wt. % TiO_2), and *70035,17*, *70215,156*, *70017,115* of the **high-HTB (**~13 wt. % TiO_2) basalts were examined and analyzed using Cameca SX 100 electron microprobe. Low-HTB sample 71539,5 has never been studied in detail. Both coarse- and fine-grained samples were studied. EMP wave-length dispersive x-ray maps of Si, Mg, Ca, and Ti were made of the entire thin-section for each sample.

Results: Low-HTBs and high-HTBs display differences in their texture, mineralogy, and mineral chemistry.

Petrography. All **low-HTBs**, except for sample 75015, show uniform distribution of minerals. Sample 75015,28 (low-HTB) appears to contain an ilmenite-rich zone juxtaposed to an ilmenite-free zone; however, the area studied is small (~36 mm^2), and studies of additional thin sections are needed to verify this observation.

The coarse-grained **high-HTBs** are texturally distinct from the coarse-grained low-HTBs and typically contain both large poikiolitic pyroxene (~2-3 mm) and areas of acicular pyroxene (Fig. 1). Ilmenite grains (~0.5-2 mm) occur as amoeboid inclusions in the large pyroxene oikiocrysts cores and as partially enclosed elongated grains in these pyroxene rims [6]. The ilmenites contain rutile and chromite exsolution. Olivine occurs in the cores of pyroxenes and within the anhedral plagioclase in the high-HTBs (Fig. 1). Armalcolites are enclosed in cores of pyroxenes only in high-HTBs.

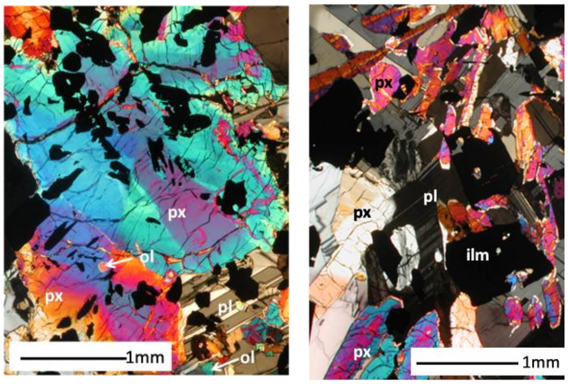

Figure 1. Microphotographs in cross-polarized light of high-HTB textures (*70035,17*). Right: large poikiolitic px; left: acicular px.

Fine-grained, low- and high-HTBs samples consist of microphenocrysts generally of the same phases as their corresponding coarser-grained samples. Ilmenite and pyroxene show cross-cutting relationships.

Crystallization sequences for each group were deduced from textural relationships and indicate ilmenite is an early crystallizing phase in the low-HTBs, and olivine, spinel, and armalcolite are the earliest crystallizing phases in the high-HTBs. This is consistent with previous studies [e.g., 8-12].

Mineral abundances and whole-rock chemistry. Low-HTBs and high-HTBs differ in their mineral abundances, similar to previous reports [e.g., 8-10]. The low-HTBs have noticeably greater abundance (2.8-3.3 vol. %) of Si-polymorphs (tridymite) than the high-HTBs (<1.2 vol. %) (Fig. 2). Another major difference between the samples is the presence of olivine and chromite? in the high-HTBs and absence of these two in the low-HTBs [e.g., 7-9]. These two observations are consistent with CIPW-norms calculated from whole-rock chemistry.

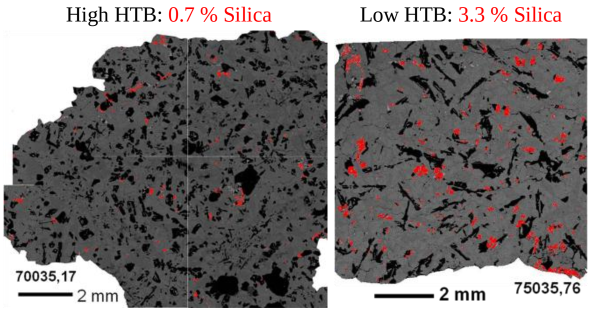

Figure 2. Si Kα x-ray maps of example Apollo 17 high and low HTBs. Silica phases are highlighted in red for comparison.

Mineral Compositions. Although olivine, spinel, and armalcolite are the earliest crystallizing phases, they are volumetrically insignificant. We focus on the comparison of pyroxene and ilmenite between high- and low-HTBs. Pyroxenes in the high-HTB ($\text{Wo}_{41\text{-}8}\text{Fs}_{13\text{-}65}$) vary primarily from augite to pigeonite with less Fe-enrichment in the rims, while the low-HTB show increasing Fe enrichment from augite ($\text{Wo}_{43}\text{Fs}_{15}$) to pyroxferroite ($\text{Wo}_{10}\text{Fs}_{90}$). The earliest crystallized pyroxenes in the high-HTBs contain Mg# of ~76, which is slightly higher than those in low-HTBs (Mg# 73). The earliest pyroxenes to crystallize in the high-HTBs correspond with the olivine core values of ~Fo_{75} suggesting that olivine was in Fe-Mg equilibrium with pyroxene. In the low-HTBs, a few pyroxene grains were found to contain an augite core with a pigeonite mantle, which has not been reported before.

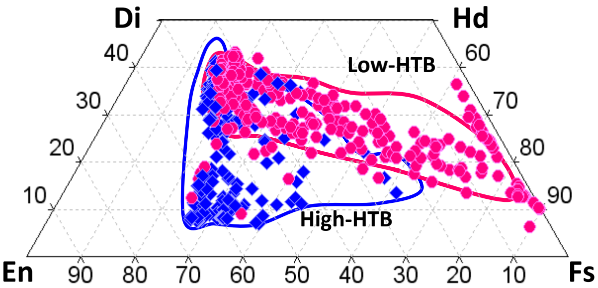

Figure 3. Quadrilateral showing low-HTBs (pink circles) and high-HTBs (blue diamonds) pyroxene compositions. The matching color fields represent data compiled from the literature [8-11, 13].

In the high-HTBs, ilmenite located within the pyroxene cores contains higher Mg# of ~17-23 than the subophitic grains at the pyroxene rims (Mg#: ~5 to 13). The more Ti- and Mg-rich grains with amoeboid morphology may represent the replacement of armalcolite, although other possibilities exist [e.g. 6, 8]. The low-HTB ilmenite compositions are more Fe-rich with Mg# of ~2-5 and also with >0.1 wt% ZrO_2, suggesting crystallization from a more evolved melt (Fig. 4).

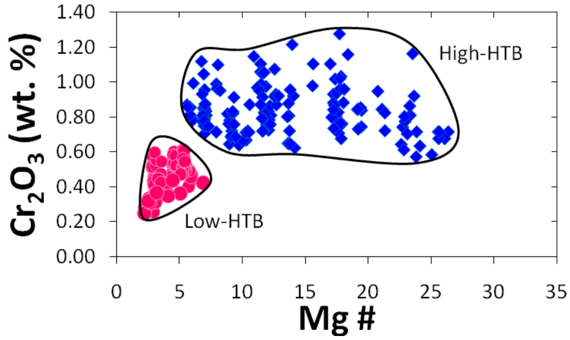

Figure 4. Mg# versus Cr_2O_3 (wt. %) for the Apollo 17 low- and high-HTBs. All data collected plot within fields shown.

Discussion: Overall, results from this study have shown that the low-HTBs crystallized from a more evolved melt than the high-HTBs. Several lines of evidence support this observation. First, the low-HTBs contain primary tridymite, which indicates that the parent melt is silica-saturated. Second, early pyroxene and ilmenite in the high-HTBs are generally more Mg-rich than those in the low-HTBs. Third, the absence of olivine in the low-HTBs compared to olivine in equilibrium with pyroxene in the high-HTBs, suggests the high-HTBs are more primitive than the low-HTBs. A more evolved melt for low-HTBs is generally consistent with fractional crystallization as suggested in [2, 4, 9]. One possible explanation for the decreased amount of armalcolite and olivine is that these minerals were fractionated by settling from the evolving melt. Another possible explanation could be the reaction of olivine and armalcolite in the evolving liquid. Ongoing research will test these different hypotheses.

Summary: In this study, the differences found between the low- and high-HTBs shows these rocks have experienced varying histories after separation from their sources. The combination of these observed petrographic differences indicates that the low-HTBs experienced greater fractionation than the high-HTBs basalt, why and how remains to be determined.

References: [1] Neal C. R. and Taylor L. A. (1992) *GCA, 56,* 2177-2211. [2] Liu et al. (2009) *LPSC XL,* 2291. [3] Liu et al. (2009), *GCA,* submitted. [4] Rhodes et al. (1976) *PLPS, 7,* 1467-1489. [5] Warner et al. (1975) *Origins of Mare Basalts and Their Implications for Lunar Evolution, LPI,* 179-183. [6] Warner et al. (1978) *Am. Min., 63,* 1209-1224. [7] Spicuzza et al. (2007) *EPSL, 253,* 254-265. [8] Papike et al. (1974) *LPSC V,* 451-504. [9] Longhi et al. (1974) *LPSC V,* 447-469. [10] Dymek et al. (1975) *LPSC VI,* 49-77. [11] Brown et al. (1975) *LPSC VI,* 1-13. [12] Papike et al. (1976) *Rev. Geophy. Sp. Sci., 14,* 475-540. [13] Hill et al. (2006) *LPSC XXXVII,* Abstract # 2067.