COOLING REGIMES OF APOLLO 11 HIGH-TI BASALTS – INSIGHTS FROM QUANTITATIVE TEXTURAL ANALYSIS OF ILMENITE AND PLAGIOCLASE. Zhuqing Xue, 1,2 Donald Welsh, 3 Clive R. Neal, 1 and Long Xiao. 1, 2 School of Earth Sciences, China University of Geosciences, Wuhan, China, 3 Dept. of Civil & Env. Eng. & Earth Sciences, University of Notre Dame, Notre Dame, U.S.A. (zhuqxue@cug.edu.cn; dwelsh1@nd.edu; neal.1@nd.edu; longxiao@cug.edu.cn).

Introduction: Determining a crystal size distribution (CSD) is a quantitative textural analysis that can provide critical information about crystallization histories of magmas. Previous studies have suggested that ilmenite was an early and prolonged crystallizing phase in lunar high-Ti basalts [1-3], which can be a good choice for studying and comparing the evolution history of different high-Ti basalts [4,5]. We present an ilmenite and plagioclase CSD analysis of Apollo 11 (A-11) high-Ti lunar basalts in order to investigate the cooling regimes of different chemical groups. 12 thin sections of A-11 high-Ti basalts (Fig. 1) representing 5 different geochemical groups [6] were analyzed: 5 from Group A, 3 from Group B1, 1 from Group B2, 2 from Group B3, and 1 from Group U (Unclassified). Preliminary CSD analyses of ilmenite and plagioclase from these samples highlighted the variability of textures and thus cooling rates among different A-11 high-Ti basalts [7,8].

Method: The method and principle of CSDs are described in [9]. To summarize, each thin section was photographed using a 4x objective in plain-polarized (ppl), cross-polarized (xpl), and reflected light (rl), and these images were stitched together using Microsoft Image Composite Editor to create a digital photomosaic (Fig. 1). Using Corel Paintshop Pro, ilmenite, plagioclase and the whole sample were traced and filled in and exported as individual files. For ilmenite tracing, rl images were preferred, while for plagioclase tracing, both ppl and xpl images were used. Crystals touching the edge of the section were not included as they may have not been whole crystals. In cases where crystals are overlapping, multiple tracing layers were necessary, as a single layer would erroneously record these crystals as one.

The filled-in layers (for crystals & the sample area) were imported into ImageJ [10]. ImageJ does a pixel analysis and applies a best-fit ellipse to each crystal determining the major and minor axes, roundness, and precise area of each crystal (and the whole sample), from which modal percentages of ilmenite and plagioclase can be determined. Crystals with minor axes <0.03 mm were not included in the final analysis; they are more likely to be a projection of the crystal due to the thickness of the section [9,11]. Major and minor axes of the remaining crystals are exported to CSDSlice [12], and all data to CSDCorrections [13]. The former determines the approximate shape of the 2D traced crystals in 3D. The latter sorts the crystals based on major axis length and plots these in size bins (5 bins per decade) based on the number of crystals present vs. the natural log (ln) of population density. All sections were traced for ilmenite, however, plagioclase in two fine-grained Group A samples - 10049 and 10069 were too tiny to be identified and traced (Figs. 1-3).

Results: In most CSDs, there were downturns at the smallest size bins (Fig. 2) because of the low resolution limit of the tracing process. CSD slopes and intercepts were calculated using size bins for which population density increased with decreasing size (Figs. 2,3), and for plagioclase, only size bins >0.3 mm were used for slope and intercept calculation [9]. The largest size bins of these CSDs are excluded for calculation because of their relatively large errors.

Fig. 1. Whole sample photomicrographs of A-11 high-Ti basalts in ppl, a to l are 10049 (A), 10069 (A), 10057 (A), 10017 (A), 10072 (A), 10003 (B2), 10044 (B1), 10047 (B1), 10058 (B1), 10020 (B3), 10092 (B3), and 10062 (U), respectively. Symbols on the upper right of samples from Groups A and B1 are the same as those in Fig. 3.

Fig. 2. Ilmenite (Ilmn) and Plagioclase (Plag) CSDs from different A-11 high-Ti basalt groups. Errors are calculated from CSDCorrections [12].

CSD profiles exhibit a range in slopes and crystal sizes (0.4-7.2 mm for Ilmn and 0.3-2.7 mm for Plag; Fig. 2). Ilmn CSDs appear to correlate with chemical groups: Group B3 typically has curved CSDs, while those from Groups A and B2 are linear to sub-linear. Group A has Ilmn CSDs with the steepest slope, highest population densities of small crystals, and smallest crystals. The one exception is 10072, whose Ilmn CSD is concave upwards, similar to Group B3, this sample also has the largest ilmenite crystals (Fig. 2). The only Group U
(10062) has a concave upward Ilmn CSD, similar to Group B3 and 10072 (A). For these concave upward CSDs, only the smaller size bins (<1 mm; Fig. 2) were used for the slope calculation (Fig. 3). Group B1 basalts are special because of kinked Ilmn CSDs, which can be divided into “large” and “small” populations at ~0.6 mm (Fig. 2), two different slopes and intercepts are calculated for each Ilmn CSD, and they are linked by lines (Fig. 3). The relationship between texture & chemical group for Plag CSDs is similar to that for ilmenite, but less extreme. Most of them are sub-linear to linear (Fig. 2). Group B1 & 10017 (A) show the smallest plagioclase slope and largest crystal size, while Group B3, B2, and 10057 (A) generally have steeper plagioclase slope and larger population of small crystals (Fig. 2).

The slope and intercept of Ilmn and Plag CSDs in Fig. 3, show that ilmenite spans a larger range of slope-intercept, especially for Group A, while plagioclase data are more compressed. Also, the three Group B1 basalts with kinked Ilmn CSDs have Plag CSDs that define linear CSDs [7,8] (Figs. 2,3). Each A-11 basalt group has unique CSD features for both Ilmn and Plag. Group B1 has the shallowest Ilmn and Plag CSD slopes; Group A, has the steepest Ilmn slope (except for 10072) and displays the largest slope range for both Ilmn and Plag, with the smallest CSD slopes (10072 for Ilmn and 10017 for Plag) similar to Group B1; The two samples (10049 and 10069) without plagioclase CSD have the largest Ilmn slopes; Groups B2 and B3 are intermediate between Groups A and B1 (Figs. 3a,b). 10062 (U) is similar to 10072 (A) and Group B3 (Figs. 3a,b).

Discussion: Different A-11 basalt groups have different Ilmn and Plag CSDs (Figs. 2,3), reflecting different textures and processes experienced by different groups, while consistent CSDs within individual groups (Figs. 2,3) indicate similar textures and cooling conditions. This implies textures could be used to distinguish between different chemical groups of A-11 basalts. The linear CSD profiles indicate relatively simple cooling histories at a constant rate (i.e., on the lunar surface).

For Groups B3, U, and the unique Group A basalts 10072 (Fig. 2), ilmenite accumulation and/or textural coarsening (i.e., growth of larger crystals at the expense of smaller ones) may have occurred [4,9]. Group B1 with kinked ilmenite CSDs (Fig. 2) indicates cooling in two different regimes, i.e. Ilmn phenocrysts crystallized at depth followed by more rapid matrix crystallization on the surface after eruption.

The fact that Plag always has sub-linear CSD slopes regardless of kinked congeneric ilmenite CSDs (Figs. 2,3) suggests plagioclase cooling in one regime-late crystallization on the lunar surface after eruption. The more restricted slopes of Plag relative to Ilmn (Figs. 3a,b) is also consistent with Plag being a late stage crystallizing phase (i.e., forming after eruption). Group A basalts display the largest range of both Ilmn and Plag slopes, indicating largest variety of cooling rates and grain sizes, which is consistent with Figs.1a-e. Also, Group A displays the steepest Ilmn slopes (Fig. 3a), corresponding to fastest cooling rates and smallest grain sizes (Figs. 1a-c). 10017 and 10072 have the lowest Plag and Ilmn CSD slopes among Group A, respectively (Figs. 3a,b), indicating slowest cooling rates, consistent with grain size (Figs. 1d,e). 10049 and 10069 with the largest Ilmn slopes have no Plag CSD (Figs. 3a,b), suggesting they are quenched lavas that were saturated in ilmen when erupted. Group B1 basalts have the lowest Ilmn and Plag CSD slopes (Figs. 3a,b), indicating slowest cooling rates, consistent with the textures (Figs. 1g-i). Basalt 10062 (U) is similar to 10072 (A) and Group B3 for both Ilmn and Plag CSDs (Figs. 2,3), suggesting similar cooling conditions.

Textures and CSDs are sometimes influenced by composition [9], the average whole rock values for TiO2 and Al2O3 for each A-11 basalt [14] were then plotted with Ilmn and Plag slopes in Fig. 3, in order to see if composition controls textures of A-11 basalts. Generally, higher bulk TiO2 and Al2O3 contents can support crystallization earlier and longer for Ilmn and Plag, respectively, and thus much smaller CSD slopes will conduct [9]. The generally positive relationship between Plag CSD slope and Al2O3 contents in Fig. 3d indicates composition has influenced Plag textures. Though without Plag CSDs, the two most quenched Group A-10049 and 10069 were saturated in Ilmn when erupted, consistent with their highest bulk TiO2 contents (Fig. 3c).

In conclusion, there appears to be an influence of bulk rock composition on A-11 high-Ti basalts textures, but this is blurred by fast cooling rates to some extent.