A crystal stratigraphy approach to understanding melt evolution in the Apollo 12 ilmenite suite basalts. K.M. O'Sullivan[1], C.R. Neal[1], and A. Simonetti[1]. [1]Dept. of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556 USA (kosulli4@nd.edu)

Introduction: In the solidification of Apollo 12 ilmenite suite basalts, pigeonite is considered to have crystallized before augite [1]. Here we emphasize basalt 12062, which was identified by [2] as an ilmenite suite basalt and has not been studied further. Using a crystal stratigraphy approach, a detailed petrogenetic model and crystallization sequence for 12062 is presented here. The aim is to better characterize the petrogenesis of 12062 as part of a larger effort to constrain the petrogenesis of the entire ilmenite basalt suite. The crystal stratigraphy approach used here combines textural analysis (Crystal Size Distributions; CSDs), with major and trace element concentrations of individual zones within pyroxene crystals.

Methods: *CSDs.* CSDs are a useful non-destructive tool to identify crystal groups with potentially different petrogenetic histories to guide subsequent geochemical analyses (e.g., [3-5]). Detailed CSD methodology is outlined in [6]. CSDs are usually presented as plots of Crystal Length vs. ln (population density). A linear CSD indicates texturally equilibrated rock, whereas a curved CSD preserves some of the mechanisms that took place during crystallization [7].

Elemental Data. Major element data and backscatter electron (BSE) images [Fig. 1] were obtained using a JEOL JXA-8200 Electron Microprobe (EMP) at the Washington University Earth and Planetary Sciences Microanalysis Facility in St. Louis. Data acquisition points were selected using BSE images such that each zone of a given pyroxene was analyzed.

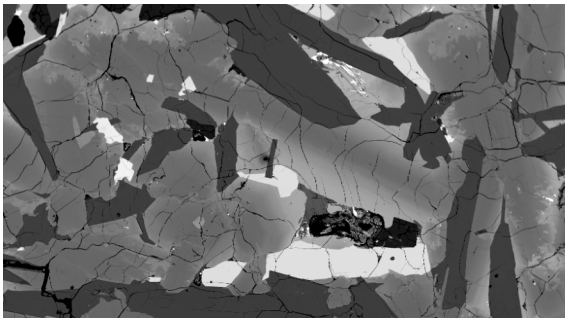

Figure 1. Backscatter image of 12062 showing zoned pyroxene crystals. Image is 1.5 mm across. White = ilmenite, light grey = pyroxene, dark grey = plagioclase, black = glass.

Trace element data was obtained using a Thermo Finnigan Element2 High Resolution ICPMS coupled with a New Wave 213 nm Nd:YAG laser. Laser acquisition points were chosen in the exact location of the EMP points such that CaO wt% contents obtained by EMP were used as the internal standard. NIST SRM 612 glass was adopted as the external standard.

Results and Discussion: *CSDs.* CSDs of plagioclase, pyroxene, and ilmenite are reported in Fig. 2. All CSDs are linear, with minor changes in slope at smaller crystal sizes. Shallow slopes at small crystal sizes can be caused by textural coarsening [8], where the larger crystals grow at the expense of the smaller crystals. In addition, the slope of the ilmenite CSD is more gentle than the plagioclase and pyroxene CSD, indicating it may have experienced some textural coarsening.

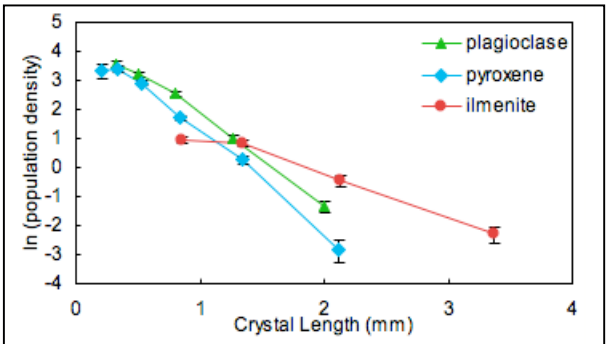

Figure 2. CSDs of plagioclase, pyroxene, and ilmenite.

Elemental Data. Major element data are plotted in Figs. 3 and 4 with arrows indicating the inferred crystallization path. Both figures show that augite is the first phase to crystallize (highest Al/Ti ratio and highest Cr concentration) followed by plagioclase and ilmenite (which decreases the Ti, Al, and Ca in the melt), followed by Mg-rich pigeonite that progressively gets more Fe-rich. This finding is not in agreement with the crystallization sequence of [1].

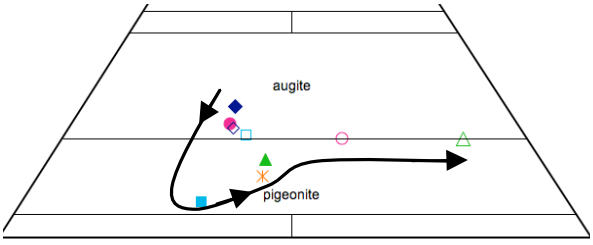

Figure 3. Pyroxene quadrilateral of cores (solid symbols) and rims (open symbols). Each crystal is a different color and shape. Arrows show crystallization path.

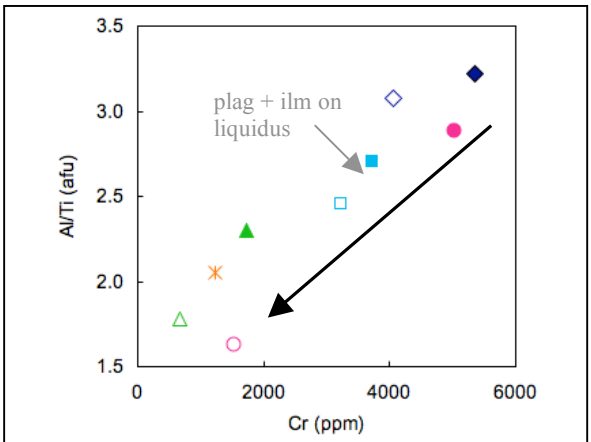

Figure 4. Ti/Al (afu) vs. Cr (ppm). Same symbol scheme as Fig. 3. Arrow shows crystallization path. Al/Ti ratio decreases as plagioclase and ilmenite come on the liquidus. Crystals with the highest Al/Ti ratio and the highest compatible element concentration (i.e. Cr) crystallize before plagioclase and ilmenite.

Crystallization Modeling. Equilibrium liquids are calculated by simply dividing concentration by the relevant partition coefficient. Pyroxene partition coefficients were chosen from published papers whose experiments had major element concentrations similar to those observed in 12062. The most primitive augite composition (solid diamond in Figs. 3, 4, and 5) is used to calculate the parental melt composition, which is then evolved using Raleigh fractional crystallization. Both major and trace elements indicate that augite crystallized before pigeonite (Fig. 4). The petrogenetic model uses the following stages: Stage 1- augite; Stage 2- augite + pigeonite; Stage 3- pigeonite + plagioclase + ilmenite. Fig. 5 shows crystallization paths (dashed line) of compatible (Cr, Co) and incompatible (Y) elements and the corresponding liquid composition of each pyroxene analysis. Most analyses lie on the crystallization path.

This study is part of a larger effort to determine the crystallization history of the entire ilmenite basalt suite [9]. So far, two different crystallization patterns have been identified within the suite. 12016, 12051, 12054, 12056, 12062, and 12063 follow the crystallization sequence described above. The second pattern, exhibited in 12064, crystallizes pigeonite first followed by augite, then plagioclase and ilmenite. Initial Sr isotopes verify that 12064 is derived from an isotopically distinct source from 12063 [10,11], but its initial $^{87}Sr/^{86}Sr$ ratio is within error of that for 12051, but not that for 12056. However, 12063 possesses an I(Sr) that is distinct from all of these [11]. Clearly, the Apollo 12 ilmenite basalts represent a complex suite of lavas.

Conclusions: Crystal stratigraphy of 12062 reveals that augite crystallized first, instead of pigeonite as previously reported [2]. Plagioclase and ilmenite crystallized after augite, followed by Mg-rich pigeonite progressing to Fe-rich pigeonite. Closed-system fractional crystallization appears to account for the majority of compositional variations observed in this sample.

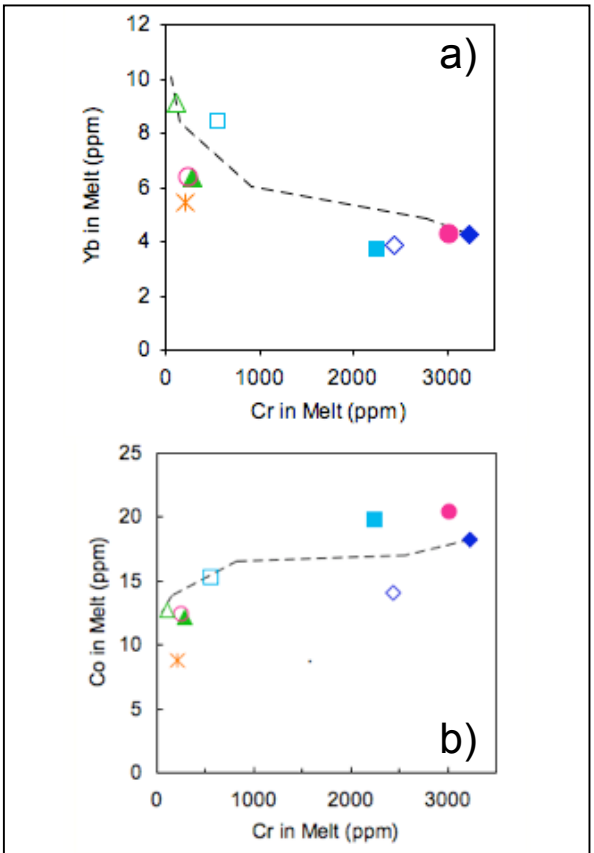

Figure 5. Behavior of select elements in crystallization model. Corresponding equilibrium liquids of analyses are plotted. Dashed line represents the path of the equilibrium liquid as crystallization progresses. Same symbol scheme as Fig. 3. a) Cr (compatible) vs. Y (incompatible), b) Cr (compatible) vs. Co (compatible).

References: [1] Papike J.J. et al (1976) *Rev. Geophys. Phys., 14,* 475-535. [2] Neal C.R. (2001) *J. Geo. Res., 106,* 27865-27885. [3] Marsh B.D. (1988) *Contrib. Mineral. Petrol., 99,* 277-291. [4] Marsh B.D. (1998) *J. Pet., 39,* 553-559. [5] Cashman K.V. and Marsh B.D. (1988) *Contrib. Mineral. Petrol., 99,* 292-305. [6] O'Sullivan K.M. et al., this issue. [7] Higgins M.D. (2006) *J. Volc. Geotherm. Res., 154,* 8-16. [8] Higgins M.D. (2011) *Int. Geo. Rev., 53,* 354-376. [9] O'Sullivan K.M. et al., in prep. [10] Papanastassiou D.A. and Wasserburg G.J. (1970) *EPSL, 8,* 269-278. [11] Nyquist L.E. (1977) *Phys. Chem. Earth 10*, 103-142.