CRYSTAL STRATIGRAPHY OF APOLLO 12 BASALTS. K. M. O'Sullivan[1], C. R. Neal[1], and A. Simonetti[1] [1]Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (kosulli4@nd.edu; neal.1@nd.edu; simonetti.tony@gmail.com)

Introduction: In this study we examine the petrogenesis of Apollo 12 basalts using crystal stratigraphy. Crystal stratigraphy utilizes Crystal Size Distributions (CSDs), which allow for identification of multiple crystal populations [1-4] that can then be analyzed. In-situ spot analyses across compositional zones within crystals from different populations are then used to unravel the crystallization history of the magma. Here we use zoned pyroxene crystals because they came on the liquidus early and remained there for a relatively long time. We selected samples from the Apollo 12 ilmenite and pigeonite basalt suites, as well as 12038, the only member of the Apollo 12 feldspathic suite. Previous studies used whole rock compositions to model the petrogenesis of the Apollo 12 ilmenite and pigeonite basalt suites [5,6]. Crystal stratigraphy allows for a more detailed examination of these whole-rock petrogenetic models.

Methods:

CSDs. Thin sections were photographed under 5x magnification and all pyroxenes were traced in *Adobe Photoshop*. Traces were then input into *ImageTool* [1] to get the length and width of each crystal. These results were then input into *CSDslice* [7] to get the most probable crystal shape and to determine goodness of fit. Crystal lengths, widths, and shapes were then input into *CSDcorrections* [1] to get the CSD plot. CSDs are plotted as corrected crystal size versus population density [2,3]. A curved CSD indicates a complex crystallization sequence, a linear CSD indicates a relatively simple crystallization history, and a kinked CSD indicates multiple crystal populations [1,4].

Major Element Analysis. Major element concentrations were obtained using a JEOL JXA-8200 Electron Microprobe (EMP) at Washington University. EMP points were obtained for individual compositional zones within 5-10 pyroxene crystals in each thin section. EMP points were obtained using a 25nA beam current, a 5 micron spot size and a 30 second count time on each element peak. Data were reduced using *Probe for Windows* software.

Trace Element Analysis. In-situ trace element analysis was conducted at the University of Notre Dame using Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS); an *Element 2* high resolution ICP-MS combined with a *New Wave* 213nm Nd:YAG laser ablation system. Laser spots were chosen to correspond to the EMP points so that CaO could be used as the internal standard. NIST 612 glass was used as the external standard. Data were reduced using the *Glitter* software [8].

Crystallization Modeling. We calculated parental liquid compositions by dividing the elemental concentration by the respective partition coefficient. Partition coefficient values are therefore very important and must be chosen carefully. The values used here were taken from studies using undoped crystals with major element compositions similar to those in this study. We then modeled the pyroxene middle and rim zones using the parental liquids derived from the cores of crystals, using Equilibrium, In-situ, Fractional (closed system), and Assimilation Fractional (open system) crystallization. This approach tests the open- versus closed-system nature of basalt petrogenesis and allows an evaluation of the petrogenetic models determined for these basalts [6].

Results and Discussion:

CSDs. CSDs of selected samples are plotted in Figure 1. The feldspathic sample (12038) and ilmenite samples (12051, 12054, 12063, and 12064) have sub-linear CSDs, indicating a relatively simple crystallization history (i.e., a linear cooling rate). The pigeonite samples (12007, 12019, 12021, 12031, and 12039) have larger crystals and exhibit kinked CSDs, indicating multiple crystal populations. Multiple crystal populations can be indicative of magma mixing or crystal accumulation.

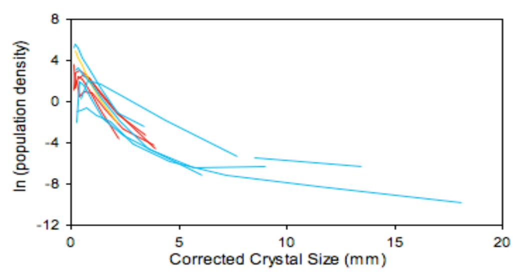

Figure 1. Pyroxene CSDs of ilmenite (red), pigeonite (blue) and 12038 (yellow).

Major Element Analysis. TiO_2 vs. Al_2O_3 for the ilmenite suite and pigeonite suite are plotted in Figure 2. Crystals that have a higher TiO_2/Al_2O_3 ratio fall on the 2:1 line and crystallized earliest before plagioclase and ilmenite. Crystals that have a lower TiO_2/Al_2O_3 ratio fall on the 1:1 line and crystallized during or after plagioclase and ilmenite.

Pyroxene crystals in the ilmenite basalts (Fig. 2a) had low TiO_2/ Al_2O_3 at the earliest stages of crystallization, and then gradually increased in TiO_2 and Al_2O_3

but with the same ratio. Many crystals have the higher TiO_2/Al_2O_3 ratio, indicating that many of the pyroxenes analyzed here crystallized before plagioclase and ilmenite.

Pigeonite suite pyroxene crystals (Fig. 2b) have low TiO_2 and Al_2O_3 concentrations at the very earliest stages of crystallization. Only pyroxene crystal cores have this low concentration and high ratio. Middle and rim zones were next to crystallize, having higher TiO_2 and Al_2O_3 concentrations, but with the same ratio as cores. The next crystals to come on the liquidus had significantly lower TiO_2 and Al_2O_3 concentrations, indicating that plagioclase and ilmenite came on the liquidus and perhaps completely finished crystallizing before these zones did. Pyroxene therefore records many of the changes in the magma during the crystallization of the pigeonite basalt suite.

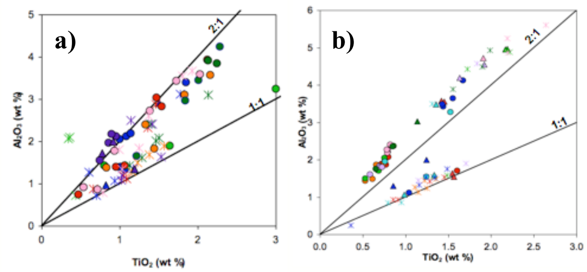

Figure 2. TiO_2 vs. Al_2O_3. Pyroxene cores are circles, middle zones are triangles, and X's are rims. Black lines are 2:1 and 1:1 ratios. (a) ilmenite suite basalts: 12016 (pink), 12051 (light green), 12054 (blue), 12056 (dark green), 12062 (red), 12063 (orange), 12064 (purple). (b) pigeonite suite basalts: 12007 (red), 12017 (orange), 12019 (light green), 12021 (light blue), 12039 (dark blue), 12043 (purple), 12052 (pink), 12053 (dark green).

Trace Element Analysis. Chondrite normalized rare earth element profiles for pyroxenes are plotted in Figure 3. The ilmenite suite pyroxenes (Fig. 3a) are all sub-parallel with the exception of a few analyses. This indicates that the majority of the crystals in this suite show no signs of open system processes.

Pyroxene data for the pigeonite suite (Fig. 3b) also show mostly sub-parallel rare earth element profiles, again with the exception of a few analyses. Samples in the pigeonite suite show much more variation in element concentrations, which also supports the hypotheses that pyroxenes in these samples recorded most, if not all, of the pigeonite basalt suite crystallization history.

Crystallization Modeling. Closed system fractional crystallization accounts for the majority of pyroxenes in the ilmenite basalt suite. However, this scheme does not account for the pigeonite suite basalts. We are currently investigating assimilation fractional crystallization processes.

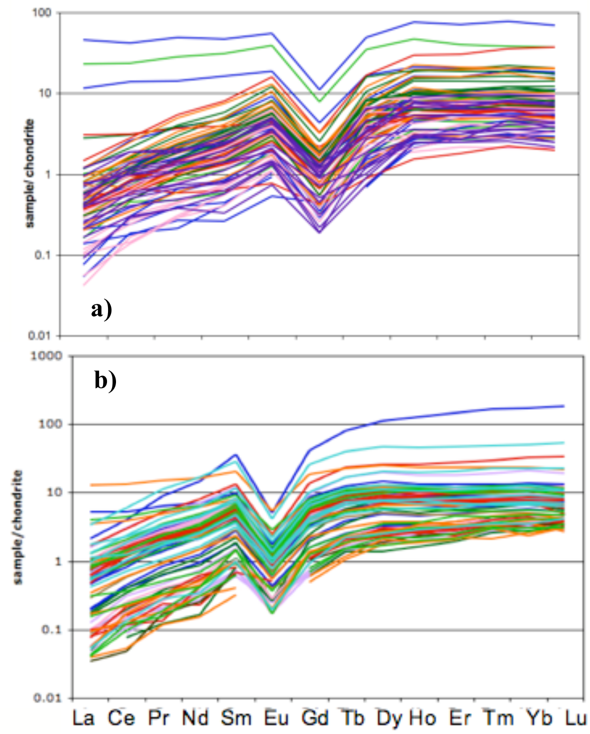

Figure 3. Chondrite normalized rare earth element data of pyroxenes in the ilmenite suite (a) and the pigeonite suite (b). Same color scheme are Fig. 2.

Conclusions: Crystal Stratigraphy allows for a more detailed look into petrogenesis than whole rock modeling alone. CSDs for the ilmenite suite are sub linear, indicating no open system processes.

However, some of the pigeonite suite CSDs are kinked, indicating a possible assimilant during crystallization. Assimilant compositions are currently being investigated. TiO_2/Al_2O_3 ratios allow for identification of crystals that came on the liquidus early, before plagioclase, as well as during or after plagioclase and ilmenite. Sub parallel rare earth element profiles indicate that most analyses show no signs of open system processes. Crystallization modeling will determine the exact processes occurring within the magma chamber.

References: [1] Higgins M.D. (2000) *Am. Mineral.* **85**, 1105-1116. [2] Marsh B.D. (1988) *Contrib. Mineral. Petrol.* **99,** 277-291. [3] Cashman K.V. and Marsh B.D. (1988) *Contrib. Mineral. Petrol.* **99,** 292-305. [4] Marsh B.D. (1998) *J. Petro.* **39,** 553-559. [5] Neal C.R., et al (1994a) *Meteoritics* **29**, 334-348. [6] Neal C.R., et al (1994b) *Meteoritics* **29**, 349-361. [7] Morgan D.J. and Jerram D.A. (2006) *J. Volcan. Geotherm. Res.* **154,** 1-7. [8] Simon Jackson Macquarie University <http://www.glitter-gemoc.com/>.