

**A new petrogenetic model for the Shergotty meteorite.** K.M. O'Sullivan<sup>1</sup>, C.R. Neal<sup>1</sup>, and A. Simonetti<sup>1</sup>. <sup>1</sup>Dept. of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556.

**Introduction:** Using crystal stratigraphy, a new petrogenetic model is proposed for the crystallization of the Shergotty meteorite. Shergotty is thought to be a cumulate which co-crystallized pigeonite and augite cores, and subsequently crystallized Fe-rich rims and other phases. Previous studies have attempted to experimentally reproduce the co-crystallization of the pigeonite and augite cores, but none have been successful [e.g., 1, 2, 3]. In addition, the parental melt from which the Fe-rich pyroxene rims crystallized has yet to be reproduced or related to the melt from which the augite and pigeonite cores crystallized [1, 2, 3].

Crystal stratigraphy combines textural analysis (Crystal Size Distributions; CSDs), with elemental data obtained via Electron Microprobe, and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (ICPMS) to determine major and trace element concentrations within individual zones of pyroxene crystals. Using this novel approach, the evolution of the liquids parental to the different zones within pyroxene is successfully modeled for the first time.

**Methods:** CSDs. CSDs are a useful non-destructive tool to identify crystal groups with potentially different petrogenetic histories before any geochemical analyses are conducted [e.g. 4, 5, 6]. A linear CSD indicates texturally equilibrated rock, whereas a curved CSD preserves some of the mechanisms that took place during crystallization [7]. Curved CSDs can result from a variety of factors, such as change in nucleation or growth rate, textural coarsening, or crystal accumulation within the magma chamber [4].

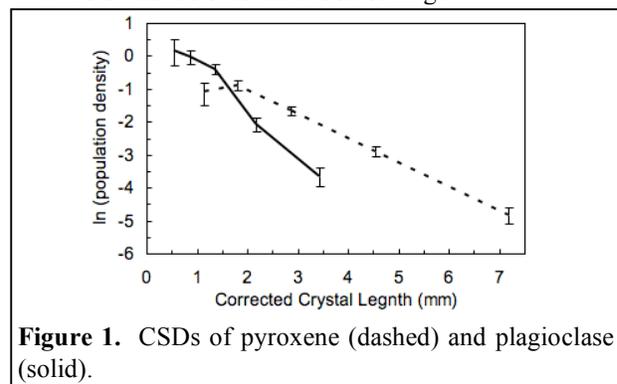
*Elemental Data.* Major element data and electron backscatter images were obtained using a JEOL JXA-8200 Electron Microprobe at the Washington University Earth and Planetary Sciences Microanalysis Facility in St. Louis. Data acquisition points were selected based on backscatter electron images such that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

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 microprobe analyses so that CaO wt% obtained by the latter were used as the internal standard. NIST SRM 612 glass was used as the external calibration standard.

In addition to spatial analysis of crystals, whole rock trace element abundances were determined using solution mode-ICPMS. Approximately 50mg was

taken from a 1 g powdered aliquot and dissolved and analyzed by the method detailed by [8].

**Results and Discussion:** CSDs. CSDs of pyroxene and plagioclase are reported in Fig. 1. The pyroxene CSD is linear with a positive slope from 1-2 mm and a negative slope from 2-7mm. A change in slope at small sizes can indicate textural coarsening [9]. Unlike previous studies [10], our pyroxene CSD does not indicate multiple periods of crystallization, but reflects textural coarsening. The plagioclase CSD is linear with no evidence of textural coarsening.



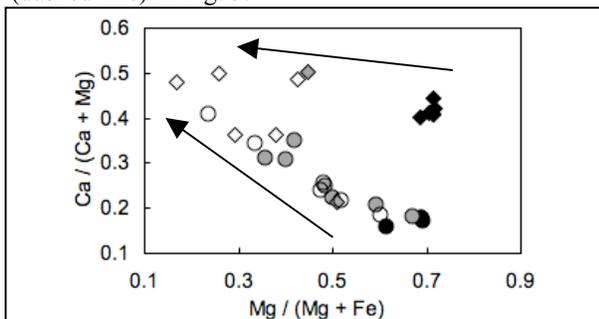
**Figure 1.** CSDs of pyroxene (dashed) and plagioclase (solid).

*Elemental Data.* Backscatter electron images and quantitative analytical work reveal two types of zonation present. The first is pigeonite cores that evolve to Fe-rich pigeonite rims; the second type is augite cores with Fe-rich pigeonite rims, a zonation previously reported to be rare [2].

*Modeling.* We calculate equilibrium liquid compositions by simply dividing elemental concentrations by their respective partition coefficient. Partition coefficients were carefully selected from published papers; i.e. pyroxene compositions are similar to those in Shergotty [e.g. 11].

Since pyroxene is the earliest phase to crystallize in Shergotty [1, 2, 3], pyroxene cores record the nature of the parental magma. Pyroxene crystallization also continued late into the sequence [1, 2, 3], therefore an extensive record of magma evolution is preserved. Both pigeonite and augite cores have the same Mg# and form two distinct trace element trends that converge during rim crystallization (Fig. 2), which indicates that pyroxene cores crystallized from two separate magmas. In addition, calculated equilibrium liquids from both augite and pigeonite cores should be identical if they crystallized from the same magma, which is not the case here (Fig. 3). Parental augite and pigeonite (solid circles and diamonds) compositions are plotted with 30% fractional crystallization trends

(grey lines), as the array indicates there was some fractional crystallization occurring before mixing. Each magma appears to have behaved differently; for example, Y appears to be buffered in the augite magma, but is fractionated in the pigeonite magma. A 50/50 mixture (open square) of the most primitive augite and pigeonite core was taken to represent the parental magma from which the middle and rim zones (grey and open symbols, respectively) crystallized. This 50/50 mixture also matches well with the whole rock composition (grey square). The 50/50 mixture representing the mixed magma is evolved via fractional crystallization with the following stages: Stage 1 (up to 30% total crystallization): augite + pigeonite + phosphate (apatite); Stage 2 (30%-80% total crystallization): pyroxene rims; Stage 3 (80%-99% total crystallization): pyroxene rims + plagioclase + ilmenite + magnetite + phosphate. Phosphate is included in the model in stages 1 and 3 because it is present as both inclusions within pyroxene and as a late stage accessory mineral. Each of these stages is governed by a different bulk distribution coefficients and therefore changes the direction of the crystallization path (dashed line) in Fig. 3.

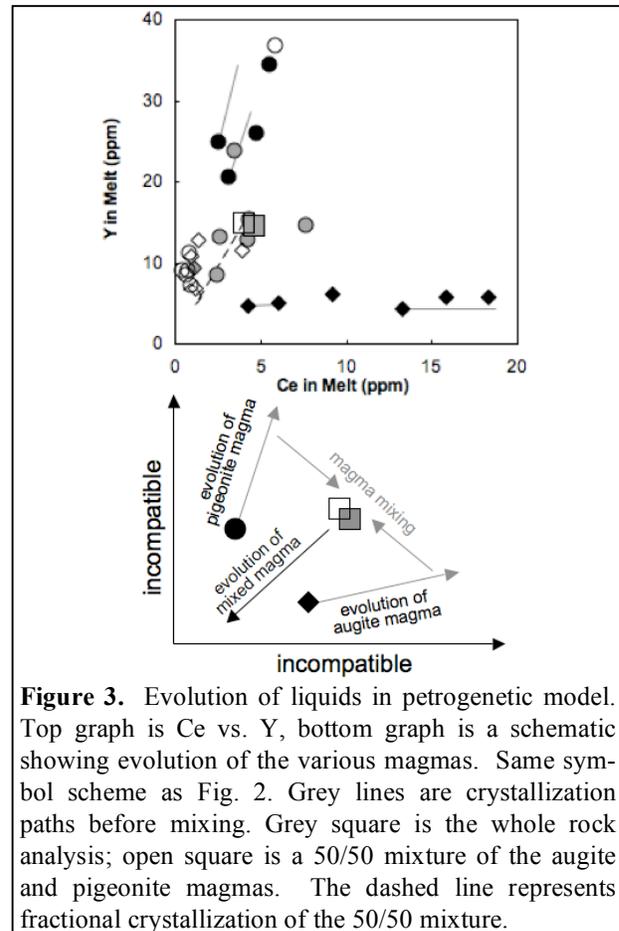


**Figure 2.** Mg # vs. Ca# of pyroxene analyses. Arrows show crystallization trend. Circles are pigeonite, diamonds are augite. Cores are black, middle zones are grey, and rim zones are open.

**Conclusions:** The crystal stratigraphy method for exploring igneous petrogenesis details within crystal populations and individual crystals that cannot be witnessed through whole rock analyses. Whole rock analyses represent an average composition of the crystallization processes that have affected a sample. The use of crystal stratigraphy in the study of Shergotty shows that pigeonite and augite cores began to crystallize in separate magmas that independently experienced a maximum of 30% fractional crystallization. These magmas mixed, which facilitated pyroxene middle and rim zones to crystallize along with phosphate, plagioclase and opaque phases. Plagioclase equilibrium liquid compositions confirm that it came on the liquidus when pyroxene rims were crystallizing,

as equilibrium liquid elemental abundances calculated from both compositions are essentially identical.

It is concluded that Shergotty is a good illustration of magma mixing followed by subsequent crystallization. Carefully constructed CSDs are a useful complement to geochemical analyses in that they allow for identification of crystallization processes such as textural coarsening. Crystal stratigraphy provides new insights into the crystallization of Shergotty and allows for a more detailed petrogenetic model to be formulated.



**Figure 3.** Evolution of liquids in petrogenetic model. Top graph is Ce vs. Y, bottom graph is a schematic showing evolution of the various magmas. Same symbol scheme as Fig. 2. Grey lines are crystallization paths before mixing. Grey square is the whole rock analysis; open square is a 50/50 mixture of the augite and pigeonite magmas. The dashed line represents fractional crystallization of the 50/50 mixture.

**References:** [1] Stolper E. and McSween Jr. H.Y. (1979) *GCA*, 43, 1475-1498. [2] Hale V.P.S. et al. (1999) *GCA*, 63, 1459-1470. [3] Dann J.C. et al. (2001) *MAPS*, 36, 793-806. [4] Marsh B.D. (1988) *Contrib. Mineral. Petrol.*, 99, 277-291. [5] Marsh B.D. (1998) *J. Pet.*, 39, 553-559. [6] Cashman K.V. and Marsh B.D. (1988) *Contrib. Mineral. Petrol.*, 99, 292-305. [7] Higgins M.D. (2006) *J. Volc. Geotherm. Res.*, 154, 8-16. [8] Neal C.R. (2001) *J. Geo. Res.*, 106, 27865-27885. [9] Higgins M.D. (2011) *Int. Geo. Rev.*, 53, 354-376. [10] Lentz R.C. and McSween Jr. H.Y. (2000) *MAPS*, 35, 919-927. [11] Jones R.H. and Layne G.D. *Am. Mineral.*, 82, 534-545.