

Crystal Stratigraphy of Lunar Troctolite 76535: Implications for Mg-suite Origins and Evolution.

K.M. O'Sullivan¹ and C. R. Neal¹, ¹Dept. of Civil and Environmental Engineering & Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (tokatieosullivan@gmail.com; neal.1@nd.edu).

Introduction: The origin of lunar Mg-suite troctolites has remained an enigmatic problem ever since they were first studied 40 years ago (e.g., [1]). Troctolites exhibit primitive mineral compositions [olivine Fo₈₆ to Fo₈₇; Anorthite-rich plagioclase ~An₉₅], but elevated (evolved) trace element contents [1]. Shearer & Papike [2] provided a summary of the various models previously proposed for Mg-Suite petrogenesis and concluded that the suite was formed by dense olivine cumulates that suffered decompression melting and brought to the base of the crust during overturn. Elardo et al. [3] provided a detailed version of this model that explained the unexpectedly low levels of Cr and Co in olivine. They proposed that the olivine rich cumulates that reached the base of the crust mixed with the anorthositic crust and the KREEP layer, forming a hybridized source. Partial melts of this source would be saturated with both olivine and plagioclase and have a KREEP-like trace element signature.

Determining the petrogenetic history of troctolite 76535 will yield insights into the composition of the parental melts and therefore their origin. This study determines the crystallization history of troctolite 76535 by using in-situ trace elemental abundances across olivine and plagioclase crystals and calculating equilibrium liquids to track the evolution of the parent melt.

Methods: Backscatter electron images, major, and minor elements of thin section 76535, 55 and 7535, 57 were obtained with a JEOL JXA-8200 Electron Microprobe (EMP) at the Washington University (St. Louis) Earth and Planetary Sciences Microanalysis Facility. Analyses were acquired using Probe for Windows and JEOL analysis software. Trace element data were obtained at the Notre Dame Midwest Isotope and Trace Element Research Analytical Center, using a Thermo-Finnigan Element2 High Resolution Inductively Coupled Plasma Mass Spectrometer coupled with a New Wave 213nm Nd:YAG laser (LA-ICPMS). Time resolved data were reduced using the Glitter© software to determine concentration, detection limit, and internal uncertainty.

Results: Plagioclase compositions analyzed in this study are An₉₅₋₉₇ and contain subparallel

LREE enriched chondrite normalized Rare Earth Element (REE) profiles with a positive Eu anomaly. Olivine compositions have a narrow range from Fo_{74.8} to Fo_{76.1}. Seven trace elements in olivine (Sc, Ti, V, Cr, Co, Ni, and Y) were quantified. Cr and Co concentrations are low but are still the most abundant trace elements, ranging from 100-392 ppm and 50-63 ppm, respectively.

Discussion: In order to test the recent models of Mg-Suite troctolite formation [2,3], equilibrium parental liquids are calculated for olivine and plagioclase (Fig 1). In order to calculate the most realistic equilibrium liquids, partition coefficients are chosen from undoped experiments (because it has been shown that trace element concentrations in the melt can also affect their partition coefficient; [4,5]), similar major element abundances, and higher pressures when possible (because 76535 is intrusive and thought to have crystallized at 40-50 km in depth [6]).

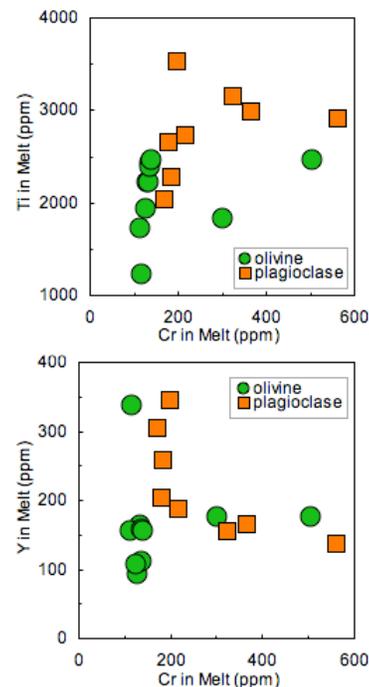


Figure 1. Examples of calculated equilibrium liquid concentrations of Ti (a) and Y (b) plotted against Cr.

Fig. 1 reveals that the calculated equilibrium liquids for plagioclase and olivine contain

similar concentrations in both compatible and incompatible elements. This is interpreted to mean that olivine and plagioclase co-crystallized.

REE profiles of plagioclase equilibrium liquids have a KREEPy signature (Fig. 2), which is consistent to the model of [3]. Parental liquids from plagioclase exhibit a KREEP-like pattern. While the HREE are more depleted in the calculated liquids than in KREEP, this is most likely due to the coupled effect of low concentrations of HREE in the plagioclase analyzed here and the weakly constrained partition coefficients for HREE as detailed by Aigner-Torres et al. [7].

The co-crystallization of olivine and plagioclase indicates a cotectic mineral assemblage on the Forsterite-Anorthite-Silica (Fo-An-Si) phase diagram [8]. Using this phase diagram projected from an Mg# of 0.7 (the bulk rock Mg# of 76535) at different pressures [8-11], the major element composition of the parental liquid can be estimated. The composite phase diagram is presented in Fig. 3. The 1 and 10 kbar phase boundaries are plotted in Fig. 3 and, points a, b, c, and d represent the compositional range that could produce olivine and plagioclase co-crystallization for the pressures at which 76535 formed. This range is found to be 28-38% olivine, 27-36% anorthite, 26-45% silica. Using these mineral assemblages major elemental abundances can be back calculated and are found to have SiO₂ ranging from 46-52%, Al₂O₃ 19-22%, FeO 8-10%, MgO 10-13%, and CaO to be 10-12%. This shows 76535 crystallized from a highly aluminous melt, indicating the source region must have had a significant crustal component, but could still produce primitive olivine compositions that co-crystallized with the plagioclase. Alternatively, there may be significant sources of Al₂O₃ in the deep lunar mantle. If this latter conclusion is correct, our assumptions about the bulk Moon composition may need to be revisited.

Conclusions: Using crystal stratigraphy of large plagioclase and olivine crystals we have determined that these minerals co-crystallized in troctolite 76535. Calculated liquids from these minerals show similar concentrations in both incompatible and compatible elements, suggesting that they appeared on the liquidus at the same time. Plagioclase REE produce equilibrium liquids that exhibit a KREEP signature, consistent with the Elardo et al. [3] model. Major element modeling demonstrates

that 76535 crystallized from a Mg-rich, yet highly aluminous parental melt.

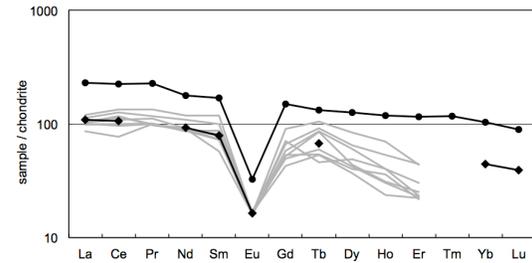


Figure 2. Chondrite normalized REE patterns of plagioclase equilibrium liquids (grey) compared to whole rock KREEP basalts 15386 [12] in circles, and 72275,359 [13] in diamonds.

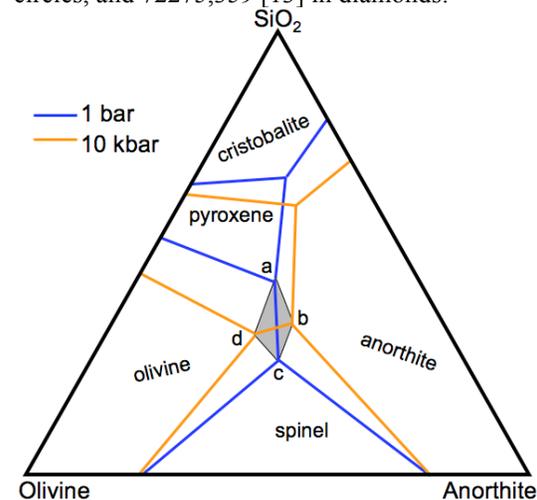


Figure 3. Fo-An-Si phase diagram projected from Mg# 0.7 with various pressures. Points a, b, c, and d define the range of co-crystallization compositions.

References: [1] Gooley et al. (1974) *GCA* **38**, 1329-1338. [2] Shearer and Papike (1999) *Am. Mineral.* **84**, 1469-1464; [3] Elardo et al. (2011) *GCA* **75**, 3024-3045; [4] Bindeman et al. (1998) *GCA* **62**, 1175-1193; [5] Bindeman and Davis (2000) *GCA* **64**, 2863-2878; [6] McCallum and Schwartz (2001) *JGR* **106**, 27969-27983; [7] Aigner-Torres et al. (2007) *Contrib. Min. Pet.* **153**, 647-667; [8] Andersen (1915) *Am. Jour. Sci.* **232**, 407-454; [9] Sen and Presnall (1984) *Contrib. Min. Pet.* **85**, 404-108; [10] Walker et al. (1973) *LPSC 4th* 1013-1032; [11] Gross and Treiman (2011) *JGR* **119**, E10009; [12] Neal and Kramer (2006) *Am. Min.* **91**, 1521-1535; [13] Salpas et al. (1987) *JGR* **92**, E340-E348.