ANCIENT IGNEOUS DIFFERENTIATION TRENDS IN THE MOON'S CRUST CAN BE PRODUCED BY SECONDARY MAGMATISM FROM A COMMON SOURCE. S. M. Elardo and D. F. Astudillo Manoslava. The Florida Planets Lab, Department of Geological Sciences, University of Florida, Gainesville, FL 32611, USA. selardo@ufl.edu.

Introduction: The distinction between primary lunar magma ocean (LMO) derived crustal rocks and those produced by post-LMO secondary magmatism was established by the recognition of apparent differences in major element differentiation trends [e.g., 1]. These differing trends are clearly observed in the oft-reproduced plot of the Mg# in mafic minerals vs. An# in plagioclase (Fig. 1). Geochemical analyses of crustal lithologies have shown that ferroan anorthosites (FANs) and the secondary crustal rocks of the Mg- and alkali-suites define different crystallization trends in Mg# vs. An#. These trends are interpreted to be the products of the different origins for these lithologies [e.g., 2]. As nearly pure anorthosite floatation cumulates, the near-vertical trend in Mg# vs. An# observed in FANs is likely the result of crystallization of mafic minerals from trapped intercumulus melt, wherein the cumulus plagioclase composition remains constant as the Mg# of intercumulus mafic minerals decreases with crystallization or the timing of formation from the LMO. Conversely, as intrusive plutonic rocks, the simultaneous decrease in both Mg# and An# in Mg- and alkali-suite rocks is likely an igneous fractional crystallization trend produced by removal of plagioclase and mafic silicates. Together these differing trends are widely cited as evidence for the formation and building of the crust through different types of early magmatism.

The continued discovery and analysis of feldspathic lunar meteorites, which sample a much larger swath of the crust than did the Apollo missions, have added complexity to crustal petrogenetic models. Whereas the compositions of Mg-suite samples and FANs are distinct in Mg# and An#, rock clasts in feldspathic meteorites overlap with the high Mg#s of the Mg-suite while also showing little variation in An#, thus overlapping the compositions of FANs [3 and refs therein], and also extending a wider range in Mg#. Assigning provenance to these magnesian anorthosite samples, however, is difficult. As primarily small clasts in meteoritic breccias, the representativeness of their modal abundances is questionable and radiogenic isotopic ages and compositions are often difficult or impossible to obtain. Although some clasts are likely to represent primary igneous rock fragments of either LMO-derived crust or secondary magmatism [e.g., 3], it is possible others are impact-derived mixtures of different lithologies [e.g., 4] and it is not always straightforward to separate igneous from non-igneous examples. This naturally complicates the use of magnesian anorthosites in constraining the origin and evolution of the lunar crust and the diversity in igneous rock types found within it.

In this work, we have approached this problem through modeling the fractionation trends of partial melts derived from hybrid source regions akin to those of the Mg-suite that contain variable amounts of KREEP. In the previous experimental study of Elardo et al [5], experiments were conducted that simulated equilibrium partial melting of Mg-suite source regions consisting of dunite and anorthosite with variable amounts of KREEP from 0% to 50%. Here we examine the differentiation of those partial melts and the implications for the lunar crust.

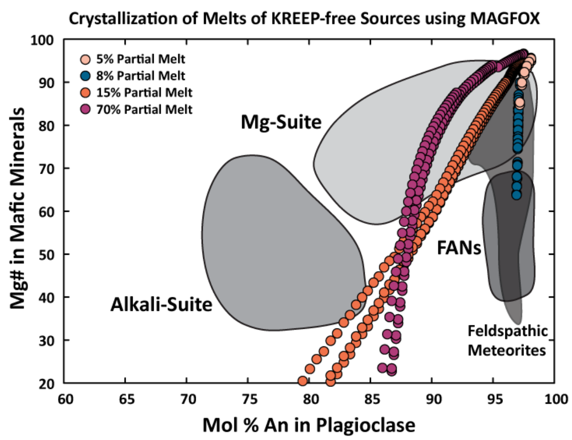

Figure 1: Plot of Mg# of mafic minerals vs. An# in plagioclase for lunar crustal rock suites (gray fields) and for the results of fractional crystallization modelling of partial melts from KREEP-free sources.

Modeling: The process of partial melting of dunite + anorthosite ± KREEP that was experimentally simulated by Elardo et al. [5] was recreated numerically here using the pMELTS algorithm. This was done in order to produce melt compositions that contained alkalis, since controlled-atmosphere furnace experiments such as those in Elardo et al. [5] commonly lose Na_2O and K_2O. Partial melts of the same degrees produce by Elardo et al. [5] were then used for fractional crystallization calculations using both pMELTS [6, 7] and the MAGFOX program [8-10]. For pMELTS, we used the "MELTS-batch" build of the algorithm (from the MELTS repository), edited it to default calculations to the pMELTS version, and wrote a Python script to run it sequentially through the different melt compositions. The fO_2 of each starting composition was set at the iron-wüstite buffer at the beginning of the pMELTS calculations. Solid phases were fractionated until the calculations terminated. The

FORTRAN version of MAGPOX was edited to bypass input requests and a similar Python script was written to sequentially process each composition through fractional crystallization.

Results and Interpretations: The results of fractional crystallization calculations using MAGFOX on partial melts derived from a KREEP-free (farside analogous) source are shown Fig. 1. The most striking observation from these results is that both of the major igneous differentiation trends observed in lunar crustal rock suites can be produced by fractionation of melts produced by this single source. At low degrees of partial melting, the Na_2O contents of the melts are low, as plagioclase retains Na during melting. Fractional crystallization of these Na-poor, high Mg# melts results in little variation in plagioclase composition, thus producing the near-vertical trend of magnesian and ferroan anorthosites. Higher degrees of partial melting produce melts with more Na_2O, which then fractionate cumulates that overlap the compositions of many Mg-suite rocks. Calculations using pMELTS show similar trends for partial melts of KREEP-free sources (Fig. 2).

The fractionation trends of selected melts from KREEP-bearing sources calculated using both modelling programs are shown in Fig. 2. MAGFOX and pMELTS produce similar, but not identical results. However, modelling using both programs demonstrates that the Mg-suite to alkali-suite fractionation trend and the production of troctolite-norite-gabbronorite cumulates is consistent with partial melting of hybridized sources containing early LMO dunites, crustal anorthosite, and variable amounts of KREEP, followed by intrusion and fractional crystallization of those melts.

More interestingly, our results suggest that at least some magnesian anorthosites, and possibly even some FANs, may be the product of secondary (i.e., post-LMO) crustal magmatism produced from KREEP-free Mg-suite source rocks. This formation mechanism obviates the need to invoke LMO alternatives such as serial magmatism to explain these lithologies. Detailed trace element and/or isotopic studies of individual samples would likely be required to differentiate between an LMO origin vs. a KREEP-free Mg-suite secondary magmatism origin. The global extent of Mg-suite magmatism is unclear and KREEP-rich Mg-suite magmatism is likely far more common than KREEP-free Mg-suite magmas [5]. However, these results demonstrate that the near-vertical differentiation trend in Mg# vs. An# is not necessarily attributable solely to lithologies produced in the LMO and could, at least in part be the result, of other processes.

References: [1] Warner et al. (1976) *7th Lunar Sci. Conf.*, 915-917. [2] Shearer et al. (2015) *Am. Min.* **100** 294 – 325. [3] Gross et al. (2014) *EPSL* **338**, 318-328. [4] Cahill et al. (2004) *MaPS*, **39,** 503-529. [5] Elardo et al. (2020) *Nat. Geosci.*, **13** (5), 339-343. [6] Ghiorso and Sack (1995) *Cont. Min. Pet.* **119,** 197-212. [7] Smith and Asimow (2005) *G^3*, **6,** Issue 2, 1-8. [8] Longhi J. (2002), *Geochemistry, Geophys. Geosystems*, 3, 1–33. [9] Longhi J. (1992), *Proc. Lunar Planet. Sci.*, 22, 343–353. [10] Longhi J., (1991) *Am. Mineral.*, 76, 785–800.

Acknowledgements: S. M. E. acknowledges NASA Solar System Workings grant 80NSSC19K0752.

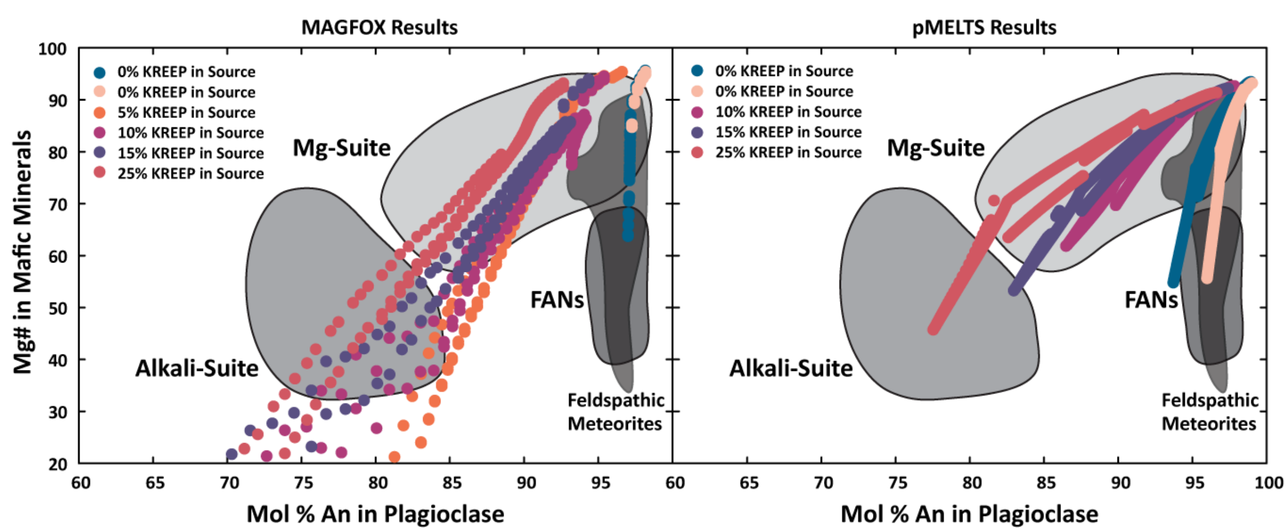

Figure 2: Plot of Mg# of mafic minerals vs. An# in plagioclase for lunar crustal rock suites (gray fields) and for the results of fractional crystallization modelling of possible Mg-suite parental magmas produced from KREEP-bearing sources.