PREDICTING THE SOURCES AND FORMATION MECHANISMS OF EVOLVED LUNAR CRUST BY LINKING K/Ca RATIOS OF LUNAR GRANITES TO ANALOGOUS TERRESTRIAL IGNEOUS ROCKS.

R. D. Mills and J. I. Simon, Center for Isotope Cosmochemistry and Geochronology, Astromaterials Research, NASA Johnson Space Center, Houston, TX, 77058 (rdmills@unc.edu; justin.i.simon@nasa.gov).

Introduction: Although silicic rocks (i.e. granites and rhyolites) comprise a minor component of the sampled portion of the lunar crust, recent remote sensing studies [e.g., 1-4] indicate that several un-sampled regions of the Moon have significantly higher concentrations of silicic material (also high in [K], [U], and [Th]) than sampled regions. Within these areas are morphological features that are best explained by the existence of chemically evolved volcanic rocks. Observations of silicic domes [e.g., 1-5] suggest that sizable networks of silicic melt were present during crust formation. Isotopic data indicate that silicic melts were generated over a prolonged timespan from 4.3 to 3.9 Ga [e.g., 6-8]. The protracted age range and broad distribution of silicic rocks on the Moon indicate that their petrogenesis was an important mechanism for secondary crust formation. Understanding the origin and evolution of such silicic magmas is critical to determining the composition of the lunar crustal highlands and will help to distinguish between opposing ideas for the Moon's bulk composition and differentiation.

The two main hypotheses for generating silicic melts on Earth are fractional crystallization or partial melting. On the Moon silicic melts are thought to have been generated during extreme fractional crystallization involving end-stage silicate liquid immiscibility (SLI) [e.g. 9, 10]. However, SLI cannot account for the production of significant volumes of silicic melt and its wide distribution, as reported by the remote global surveys [1, 2, 3]. In addition, experimental and natural products of SLI show that U and Th, which are abundant in the lunar granites and seen in the remote sensing data of the domes, are preferentially partitioned into the depolymerized ferrobasaltic magma and not the silicic portion [11, 12]. If SLI is not the mechanism that generated silicic magmas on the Moon then alternative processes such as fractional crystallization (only crystal-liquid separation) or partial melting should be considered as viable possibilities to be tested.

Fractional crystallization of a basaltic source without SLI is an inefficient process for generating silicic melts. This is because the distilling process must proceed to completion, which is physically difficult in terms of the degree of crystallization. For example, on the Moon a basaltic magma with K_2O/CaO of ~0.03 must fractionate to ~7 (granite clast from 14321). Figure 1 shows the relationship between crystallization and the predicted fractionation of K and Ca during magma ocean solidification. Results indicate that it is unlikely that fractional crystallization alone can produce K/Ca ratios greater than 0.2. Likewise, segregation and extraction of highly-polymerized viscous melt from a highly crystalline mush is nearly impossible without strong external forces [13] (e.g., gravitational and/or secondary impacts).

Because it is difficult to produce such chemically "evolved" melts solely by fractional crystallization, partial melting of preexisting crust may also have been important and possibly the primary mechanism which produced the silicic magmas on the Moon. Terrestrial studies (e.g., [14]) demonstrate that partial melting of gabbroic rock under mildly hydrated conditions can produce granitic compositions and it has been suggested by [1] that partial melting by basaltic underplating is the mechanism by which silicic melts were produced on the Moon. Isotopic and elemental data can help decipher what source rocks were partially melted and when the melting occurred.

K/Ca isotopic data from a mineral isochron [15] for a granite clast from sample 14321 indicate that the parental material of this silicic magma had a K_2O/CaO ratio of at least 0.8, significantly higher than most known crustal rock types, including KREEP-rich materials [e.g. 16, 17]. This suggests that granite in sample 14321 was produced by partial melting of an already "evolved" rock. Next we use terrestrial chemical data as a proxy for igneous rocks in the lunar crust which allow us to hypothesize what type of rock may have been parental to granite found in Apollo breccia sample 14321.

Terrestrial data: Geochemical data for igneous rocks from the western United States were extracted from the NAVDAT online repository. The ~4000 data with variable L.O.I. represent multiple tectonic settings, including subduction, rifting and anorogenic; however, the ~2200 data from low L.O.I. rocks (likely from relatively dry magmas) define a similar trend on a plot of K_2O/CaO vs SiO_2.

Interpretation: Data from Apollo sample 14321 granite clast [15] indicate that the parental material to the granite had already evolved on a K_2O/CaO trend of approximately 1, consistent with an intermediate/felsic terrestrial magma (Fig. 2). One of the objections to the fractional crystallization model is the lack of intermediate compositions. Taken at face value, the bulk composition implied by the data of [15] could represent an example of the missing intermediate composition, although it does not provide a unique solution to the problem. More evidence of this type is needed to critical test the mechanism(s) that generated silicic magmas on the Moon.

Next Step: Future investigations will carry out extensive searches for additional evolved igneous rock clasts in Apollo samples and lunar meteorites primarily for K-Ca isotope measurements. As in [15], these data will be used to define the bulk compositions of the source(s) of evolved materials that make up the lunar crust. The search for source(s) will be further refined by comparison of radiogenic isotope compositions (inferred initial $^{40}Ca/^{44}Ca$, $^{87}Sr/^{86}Sr$, and $^{176}Hf/^{177}Hf$ isotopic compositions and isochron ages) in these clasts to the compositions of known lunar rock types.

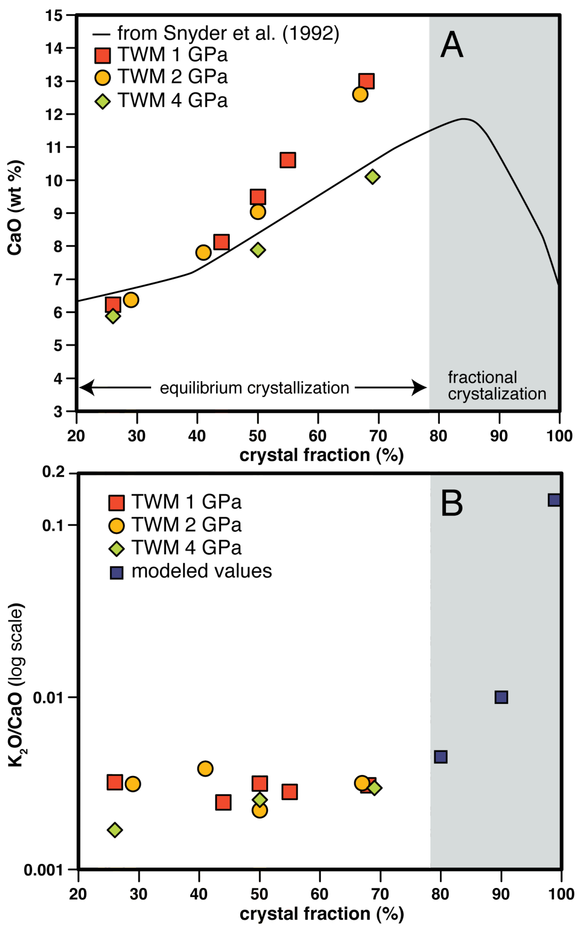

Fig. 1 (A) Plot of CaO vs crystal fraction of the Moon with experimental results [18] from equilibrium crystallization of a Taylor Whole Moon (TWM) composition at 1, 2 and 4 GPa, and modeled results of equilibrium then fractional crystallization [19]. (B) Plot of K_2O/CaO (log-scale) vs crystal fraction of the Moon with data from [18] and modeled values using CaO values from [19] and assuming K behaves completely incompatible.

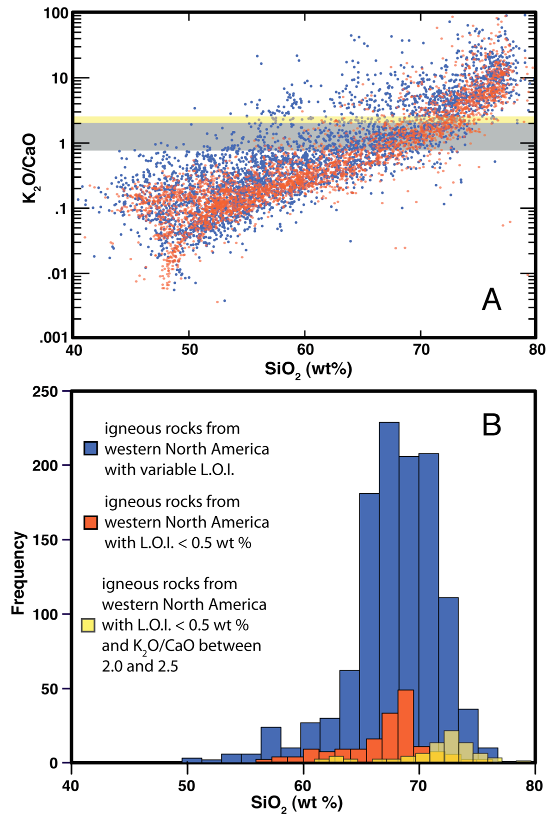

Fig. 2 (A) Plot of K_2O/CaO vs SiO_2 with 4000 igneous rocks from the western US with variable L.O.I. and 2200 igneous rocks from the western US with L.O.I. < 0.5 % (all data extracted from www.navdat.org). Gray bar is the calculated K_2O/CaO ratio of the parental material for granite clast from Apollo sample 14321 [15], and yellow bar is the upper estimate using the FAN age from [20] (B) Histogram of SiO_2 for data that fall in the gray bar and yellow bar in A.

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