LUNAR SILICIC MAGMA GENESIS: INSIGHTS FROM PETROLOGICAL MODELING. S. Ravi, C.B. Till, and M.S. Robinson, School of Earth and Space Exploration, Arizona State University, Tempe, AZ-85281, USA (E-mail: sravi@ser.asu.edu)

Introduction: The presence of silicic volcanic landforms on the Moon is enigmatic given that the key ingredients essential to producing most large-scale silicic melts on Earth (i.e., water and plate tectonics) are absent in the lunar environment. Constraining the conditions under which silicic melts were produced is essential to understanding the thermal evolution of the Moon. While a few grains of silicic materials were returned by the Apollo missions, none of the Apollo or Luna missions visited a silicic target, thus our knowledge of these terrains is limited to remote sensing observations, thereby motivating the need for petrological modeling, which provide constraints on the P-T-x evolution of these constructs and by extension provide insights into the thermal history and differentiation of the Moon. Therefore, we conducted geochemical modeling and thermal calculations to investigate the efficiency of partial melting of the anorthositic crust with KREEP-rich basaltic magma as a formation mechanism for the lunar silicic volcanic landforms and compared the resulting product to that of returned lunar silicic fragments and remotely sensed observations.

Geological overview: "Red spots" were first proposed to be silicic lithologies based on high albedo and strong absorption in the UV leading **[1]**. The Lunar Prospector Gamma Ray Spectrometer (LP-GRS) showed that these landforms exhibit enhanced thorium abundance **[2]** and thermal observations from the Lunar Reconnaissance Orbiter (LRO) Diviner Radiometer instrument confirmed that these landforms are composed of silicic lithologies (>65 wt% SiO_2) **[3]**. There are two leading formation hypotheses – basaltic underplating (Fig.1(a)) and silicate liquid immiscibility (Fig.1(b); **[2]**). In the former hypothesis, thorium-rich silicic magmas can be produced through partial melting of the pre-existing anorthositic crust by intruding basaltic magma post-basin forming events (Fig. 1(a)). In the second hypothesis, silicate liquid immiscibility occurs when basaltic magma undergoes >90% fractional crystallization, producing two coexisting, yet immiscible melts – one of which is enriched in SiO_2 (felsic component) (Fig. 1(b)). However, experiments simulating silicate liquid immiscibility show that the mafic component is enriched in thorium, whereas the felsic component is depleted in REE, contrary to remotely sensed observations **[2,4]**.

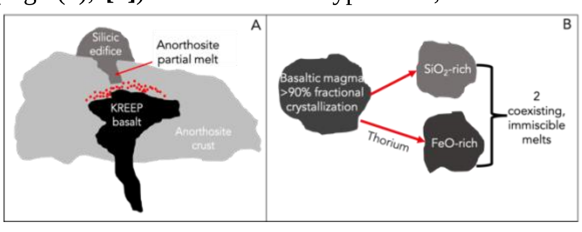

__Figure 1:__ Diagram illustrating the two formation mechanisms, (A) basaltic underplating and (B) silicate liquid immiscibility.

Methods: In order to test the crustal melting hypothesis, we chose a range of lunar anorthosite compositions as a proxy for the lunar crust. Since the lunar silicic landforms are enriched in KREEP, it is hypothesized that the underplating materials could be KREEP basalts. As a result, we chose compositions of KREEP basalts returned by the Apollo 14 and 15 missions in our model (Table 1).

1. __Thermal calculations__

In order to test the plausibility of a KREEP-rich basaltic magma partially melting the preexisting anorthositic crust, we ran a series of thermal calculations **[5,6]**:

$$Initial\ heat\ of\ basalt: T_{basalt} \cdot C_p$$

where, T_{basalt} is the temperature of basaltic magma and C_p is the heat capacity of basalt = 1100 J/kg.K

$$Thermal\ energy\ required\ to\ drive\ crustal\ melting = C_p(T_{melt} - T_{solidus}) + H_f \cdot f_{melt} + C_p(T_{solidus} - T_{crust})$$

where, T_{melt} is the temperature of the partial melt, $T_{solidus}$ is the solidus temperature of the crust (1273 K; **[7]**), H_f is the heat of fusion = 3 x 10^5 J/kg **[6]**, f_{melt} is the melt fraction, and T_{crust} is the temperature of the crust = 873 K **[7]**.

We ran the thermal calculations for anorthosite melt fractions ranging from 0.1-1 to constrain the amount of crustal melting a KREEP-rich basaltic magma can drive.

2. __Rhyolite-MELTS__

Rhyolite-MELTS is a thermodynamic model for phase equilibria in magmatic systems designed and calibrated based on a variety of petrology experiments on silicic volcanic systems on Earth **[8]**. We employed this program to model the pressure and temperature regimes under which silicic melts might have been produced under lunar conditions from the bulk compositions of returned lunar anorthosite samples as a proxy for the lunar crust (Table 1). Modeling was conducted at pressures of 1.1-1.2 kbars and temperatures of 900-1500°C based on the theoretical lunar geothermal gradient **[7]**.

Results: 1. __Thermal calculations__

Our calculations show that the heat input from KREEP basalts range between 1.6 x 10^6 – 1.7 x 10^6 J/kg, and the thermal energy required to partially melt lunar anorthosites ranges from 4.5 x 10^5 – 1.2 x 10^6 J/kg (Fig. 2).

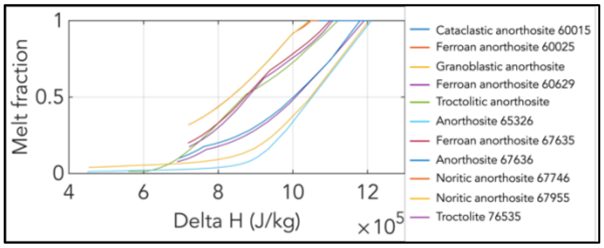

Figure 2: Thermal energy required to drive crustal melting on the Moon.

2. Rhyolite-MELTS modeling

Based on our rhyolite-MELTS model, minimal partial melting (10-20%) of two starting compositions of lunar crustal lithologies (i.e., anorthosite 65326 and noritic anorthosite 67955), produce >60wt% SiO_2 (andesitic-dacitic) melts at 1.1 kbar pressure and 900°C temperature (Fig. 5). Partial melting of all other starting compositions produce melts that are relatively more mafic than the proxies for the lunar silicic volcanic compositions.

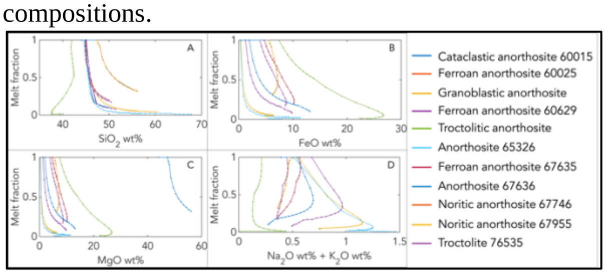

Figure 3: Partial melting of various lunar anorthosite compositions using rhyolite-MELTS at 1.1-1.2 kbar pressure range and 900-1500 C temperature range.

Discussion: Here we have tested the hypothesis that silicic magmas are generated partial by melting of the lunar anorthositic crust. Results from our theoretical thermal models show that a KREEP-rich basaltic magma has approximately an order of magnitude greater heat capacity than is required to partially melt the pre-existing anorthositic crust of a wide range of compositions (Fig. 3). However, our rhyolite-MELTS model shows that only a small amount of partial melt (10-20%) of anorthosite 65326 and noritic anorthosite 67955 produces magma with >60% SiO_2, the likely composition of lunar silicic volcanic lithologies.

While this result is consistent with both remotely sensed datasets and returned silicic fragments, the question remains as to the mechanisms that enable any generated melt to erupt to the surface to form dome-like landforms like the Gruithuisen and Mairan domes. Eruption of these silicic melts could result from a nearby impact, as was proposed for Lassell Massif (Glotch et al., 2010). The other caveat is the total alkali (Na_2O wt% + K_2O wt%) content of the simulated silicic melt is significantly lower than returned fragments (Fig. 3; Table 1). While we have access to the bulk composition of returned lunar silicic fragments to compare our model with, they may not be representative of the silicic landforms as the latter have not yet been sampled.

While we have narrowed the conditions under which silicic melts could have been generated in the lunar environment, the formation mechanism is still not obvious. We have shown that crustal melting is plausible, however, the volume of magma required to generate silicic melts is still unknown, and the simulated compositions do not entirely match with returned samples, as is the case with studies that tested the silicate liquid immiscibility hypothesis **[4]**.

Future sample return missions are needed to unambiguously determine the bulk composition, minor element composition, and by extension the mode(s) under which these enigmatic landforms where formed.

References: [1] Malin M.C. (1974) *EPSL*, *21*, 331-334. [2] Hagerty J.J et al. (2006) *JGR*, *111*, E06002. [3] Glotch T.D. et al. (2010) *Science*, *329*, 1510-1513. [4] Gullikson A.L. et al. (2016) *Am. Min.*, *101*, 2312-2321. [5] Sparks R.S.J. and Marshall L.A. (1986) *JVGR*, *29*, 99-124. [6] Till C.B. et al. (2019) *Nature Comm.*, 1-10. [7] Toksöz N.M. (1974) *Annu. Rev. Earth Planet Sci*, 151-177. [8] Gualda et al. (2012) *J. Petrology*, *53*, 875-890.

Table 1: Bulk compositions of some lunar samples relevant for this study returned by the Apollo missions (in wt%).
Source: Lunar Sample Compendium

Sample	**SiO_2**	**TiO_2**	**Al_2O_3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**
Anorthosite 65326	44.5	0.02	35.6	0.23	-	0.07	19.1	0.45	0.06
Noritic anorthosite 67746	46.1	0.21	24.8	5.46	0.07	9.77	11.2	0.42	0.05
KREEP basalt 14726	47.6	1.2	21.3	7.94	0.12	7.1	13.2	0.72	0.48
KREEP basalt 15382	46.1	4.14	10.5	19.9	0.27	6.38	11.7	0.3	0.07
Potash rhyolite 12070	70.8	0.6	12.7	6.3	0.01	0.4	1	1.1	7.4
Pristine granite clast 14321	74.2	0.33	12.5	2.32	0.02	0.07	1.25	0.52	8.6