urKREEP ORIGIN OF ENIGMATIC SILICIC LUNAR MAGMAS

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Introduction: The occurrence of exotic lunar felsic rocks has remained largely contested since their initial discovery [1]. The key ingredients for granite petrogenesis on Earth: water and active plate tectonics, are visibly absent on the Moon which has made lunar granites and rhyolites a long standing enigma. Granites and felsites have been observed in the Apollo sample collection [e.g., 2,3] and have been hypothesized to be genetically related to features like the rhyolitic Gruithuisen domes and other red spots [4-6].

When the lunar magma ocean (LMO) was cooling and had almost entirely crystallized, the final residuum became extremely enriched in the incompatible elements including volatiles. This shallow mantle reservoir is commonly referred to as the urKREEP [7,8]. Initially the lunar interior was thought to have been bone-dry (<1 ppb H) [9]. However, recent estimates of water in the urKREEP range from 50-2000 ppm [e.g., 2]. The discovery of volatiles in the shallow mantle significantly eases its partial melting by lowering the solidus temperature [e.g., 10]. Intrusion of hot basaltic magma underneath the thinner nearside crust [e.g., 11, 12] or large scale fissures on the thinner nearside crust due to planetary contraction [13] may have led to partial melting of the urKREEP mantle horizon. We study these partial melts to investigate if their differentiation and evolution could generate silicic magmas on the Moon. Silicic magma genesis on the Moon are subject to two competing hypotheses: (i) fractional crystallization [14] and (ii) silicate liquid immiscibility (SLI) [15]. The SLI mechanism is debated because Th preferentially partitions into less polymerized Fe-rich melts [16], which contradicts with the rhyolite domes being hotspots for Th. The alternative fractional crystallization process is not backed by any experimental studies. Therefore, we are investigating a petrogenetic scenario to examine if partial melting of the Fe-Ti-rich shallow urKREEP due to basaltic underplating or decompressional melting (Figure 1) could lead to genesis of silicic magmas.

Methods: We conducted partial melting experiments of the urKREEP at 0.5 GPa from 1100°C to 1040°C using the piston cylinder apparatus at the University of Arizona. The choice of urKREEP bulk composition was LPUM/04-1.5gl [17] with 0.5 w.t. % H_2O. The addition of 0.5 w.t. % water to the starting material is justified to reflect the volatile enrichment of the late stage residual LMO [18]. These experiments were performed in a graphite capsule to resemble reduced fO_2 conditions of the Moon and then encased in a Pt-jacket to minimize the loss of water during the duration of the experiment. Textural relationships and major element phase compositions were analyzed using the CAMECA SX100 electron microprobe at the Michael J. Drake Electron Microprobe Laboratory, University of Arizona.

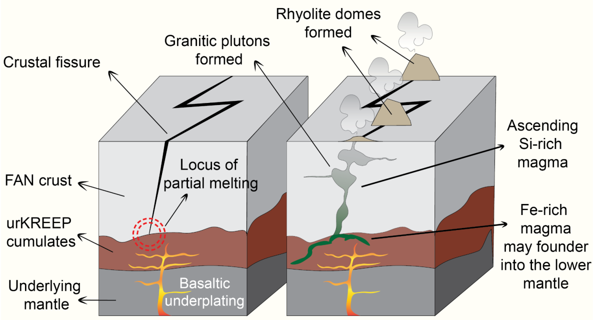

Figure 1. Schematic petrogenetic model showing the partial melting of urKREEP reservoir due to basaltic underplating or decompressional melting. The partial melts undergo SLI. The buoyant Si-rich melts rise and likely erupt as silicic lunar constructs while the denser Fe-rich melts remain stationary or founder.

Results: The partial melting experiments of urKREEP assemblage display SLI between 1060°C and 1040°C. Figure 2(a) shows the experiment at 1040°C which has an assemblage of quartz + augite + plagioclase + ilmenite + Fe-rich-liquid (L_Fe) + Si-rich-liquid (L_Si) + apatite. We note the evolution of the two liquids composition from 1060°C to 1040°C, as L_Si becomes more Si-rich and the L_Fe counterpart becomes more Fe-rich in the colder experiment.

Discussion: Since our experiments show that low to intermediate degrees (F ≈ 1-10%) of partial melt produced from the urKREEP mantle are already immiscible, we rule out the fractional crystallization hypothesis. The SLI sets in the basaltic partial melts because low water content and reduced fO_2 conditions suppress the magnetite liquidus [e.g., 15] making the magma increasingly ferrous resulting in the immiscibility.

The FeO versus SiO_2 Harker plot in Figure 2 shows L_Si compositions from this study as well as L_Si reported from other experimental studies [16,19].

Si-rich melts from our experiments appear to coincide with the FeO range measured by Diviner for the three Gruithuisen domes [20] as well as the bulk compositions of lunar granites (Appendix 1, [3]). Thus, our results demonstrate that SLI is a viable mechanism for generating silicic magmas under lunar conditions.

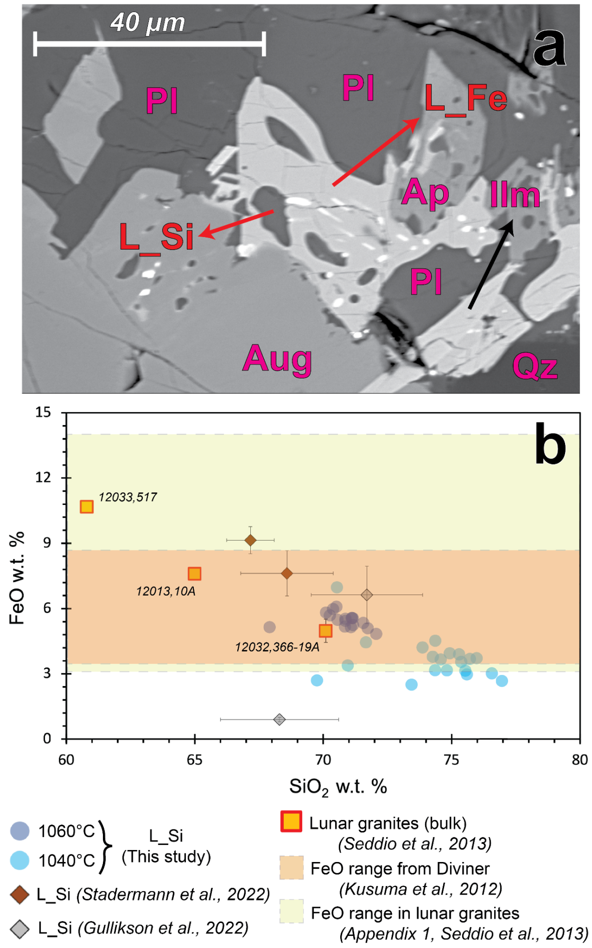

Figure 2. Back scattered electron image of experiment at 0.5 GPa and 1040°C. Phases are annotated in accordance with IMA approved mineral abbreviations, L_Fe = Fe-rich liquid, L_Si = Si-rich liquid. (b) FeO versus SiO_2 Harker plot showing Si-rich liquids (L_Si) from this study (circles) and other experimental studies (diamonds) demonstrating SLI . Lunar granites 12033,517, 12013,10A and 12032,266-19A are denoted as 'squares'. Shaded areas show range in FeO for both the Gruithuisen domes from Diviner (in pink) and bulk analyses of Apollo granites (in green). Errors are 1-sigma.

Previously, [16] argued against the SLI hypothesis citing that Th is more compatible in the less polymerized Fe-rich liquid over their felsic counterparts ($D^{Th}_{L\_Fe/L\_Si}$ ≈ 1.4). Therefore, SLI-aided lunar granite petrogenesis had been invalidated due to the absence of high-Th, high-Fe reservoirs on the Moon. Our experimental results show that the complementary Fe-rich magma is enriched in FeO by a factor of 2.5-3 compared to previous studies [16,19]. As a result the immiscible Fe-rich counterparts to the Si-liquid become very dense which significantly increases the efficiency of the process of density-driven segregation between the two magmas. The very efficient removal and sinking of Fe-rich magmas from the more buoyant silicic magmas are thus able to explain the absence of Th-Fe-rich reservoirs [16] which likely foundered into the deeper mantle.

Whether SLI would occur or not, the temperature range across which it occurs and the compositions of the immiscible liquids are dependent on the choice of urKREEP composition as the bulk starting composition. Given the large uncertainty in the composition of urKREEP, we acknowledge that our study depicts the results of using LPUM/04-1.5gl [17] as the chosen urKREEP composition. Future studies examining a wider compositional space of urKREEP composition are needed to better understand the occurrence of SLI, and thus, disentangle the long-standing lunar granite problem.

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