THE ROLE OF KREEP IN THE PRODUCTION OF Mg-SUITE MAGMAS AND ITS INFLUENCE ON THE EXTENT OF Mg-SUITE MAGMATISM IN THE LUNAR CRUST

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Introduction: The lunar magnesian-suite, or Mg-suite, is a series of ancient plutonic rocks from the lunar crust [1]. They have received a considerable amount of attention from lunar scientists since their discovery for three primary reasons: 1) their ages and geochemistry indicate they represent pristine magmatic samples that crystallized very soon after the formation of the Moon, 2) their ages often overlap with ages of the ferroan anorthosite (FAN) crust, and 3) planetary-scale processes are needed in formation models to account for their unique geochemical features [1-5]. Taken as a whole, the Mg-suite samples, as magmatic cumulate rocks, approximate a fractional crystallization sequence in the low-pressure forsterite-anorthite-silica system [6], and thus these samples are generally thought to be derived from layered mafic intrusions which crystallized very slowly from magmas that intruded the anorthositic crust. However, no direct linkages have been established between different Mg-suite samples based either on field relationships or geochemistry.

The model for the origin of the Mg-suite, which best fits the limited available data, is one where Mg-suite magmas form from melting of a hybrid cumulate package consisting of deep mantle dunite, crustal anorthosite, and KREEP at the base of the crust under the Procellarum KREEP Terrane (PKT) [1,3,7]. In this model, these three LMO cumulate components are brought into close proximity by the cumulate overturn process. Deep mantle dunitic cumulates with an Mg# of ~90 rise to the base of the anorthositic crust due to their buoyancy relative to colder, more dense Fe- and Ti-rich cumulates. This hybridized source rock melts to form Mg-suite magmas, saturated in Mg-rich olivine and anorthitic plagioclase, that have a substantial KREEP component.

Samples of the Mg-suite were found at almost all of the Apollo landing sites, and these samples almost ubiquitously have geochemical features indicating the involvement of KREEP [7]. However, it is not known if KREEP-free Mg-suite magmatism occurred outside of the PKT, or if KREEP is a necessary component in producing Mg-suite magmas. Determining whether the Mg-suite was a Moon-wide magmatic event or was limited to the geographically restricted PKT is important not only for determining the extent of post-magma ocean crust building processes on the Moon, but also for determining the scale of mantle processes such as cumulate overturn. Therefore, we have undertaken high-temperature experiments aimed at determining the effects of KREEP on the production potential of Mg-suite magmas using analog source materials.

Experimental Design: In order to determine the effect of KREEP on Mg-suite melt production, we created an analog for the source materials of Mg-suite magmas using natural and synthetic minerals and oxide powders. The KREEP-free base starting material was a 50:50 mixture of powdered San Carlos olivine and powdered Miyake-jima anorthite. San Carlos olivine has an Mg# of 90, which is very similar to the composition of early LMO dunitic cumulates predicted by Elardo et al. [3] and anorthite megacrysts from the Miyake-jima volcano, Japan have an An# of 97 that is very similar in composition to the lunar anorthositic crust [8]. We also created a synthetic oxide mix with the composition of high-K KREEP from Warren [9]. Four starting materials with 0%, 5%, 10%, and 15% of the KREEP mix by weight were prepared by combining the two starting mixes. All mixes were hand ground under ethanol in an agate mortar and pestle.

Experiments were conducted in a Deltech vertical gas mixing furnace at the Geophysical Lab at an fO_2 corresponding to the IW buffer using a CO-CO_2 mixture. Starting materials were suspended from Re-wire loops using a polyvinyl alcohol solution. Experiments were cooled from 1500 °C to 1250 °C at 30 °C/hour to promote a faster approach to equilibrium than soaking at 1250 °C without a higher temperature step. Future experiments will explore phase relations at higher and lower temperatures, and they will include a time-series to better assess the approach to equilibrium. Preliminary experiments discussed here soaked at 1250 °C for ~5.5 days. Experiments were quenched into distilled water.

Analysis: At the conclusion of the experiments, run products were mounted in epoxy, sectioned through a region close to the center or thickest portion of the bead, and polished for microbeam analyses. Preliminary analyses consisted of whole-section WDS/SDD-EDS X-ray mapping using the JEOL 8530 field emission electron microprobe at the Geophysical Lab. Future work will include quantitative WDS analyses of individual phases. Modal abundances were determined from X-ray maps using the program PhaseQuant [10].

Results: Our four preliminary experiments all contain melt, olivine, plagioclase, and an Mg-Al-rich spinel, as expected from the olivine-anorthite phase diagram [6]. Figure 1 shows Mg kα X-ray maps the KREEP-free and 15% KREEP experiments at 1250 °C. The modal abundance of melt present in experiments with starting materials containing 0%, 5%, 10% and 15% of the synthetic KREEP mix was 22.4%, 9.2%, 36.3% and 34.2%, respectively. The amount of melt present in the experiments generally correlates with the amount of KREEP, with the exception of the experiment containing 5% KREEP. The X-ray maps reveal this experiment was sectioned through a large olivine grain which constituted the majority (71.6%) of the exposed area, resulting in an artificially low melt fraction. Future work will reassess the melt fraction in this experiment.

Discussion: The discussion on whether KREEP is necessary for the production of Mg-suite magmas focuses on two ways in which KREEP can produce these magmas from olivine-plagioclase source rocks: increased heat from radioactive decay and increased melt production due to melting point depression [1]. The short time interval between crystallization of the anorthosite crust and the formation of Mg-suite plutons [2, 4] may limit the effectiveness of radioactive decay as a heat source for Mg-suite magmas under the PKT. Our results are preliminary, but the difference in degree of partial melting between a KREEP-free olivine-plagioclase source and a source containing 10 – 15% KREEP is modest (22% vs ~35%). This effect may become more prominent near the solidi in these compositions, so further experiments are required to completely assess the melting point depression model. However, if the presence of KREEP in Mg-suite source materials results in only a modest increase in melt production of KREEP-free sources, it may suggest KREEP-free Mg-suite rocks should be expected to exist in regions of the lunar crust away from the PKT.

References: [1] Shearer et al. (2015) *Am. Min.*, **100**, 294-325. [2] Borg et al. (2015) *MaPS*, **50**, 715-732. [3] Elardo et al. (2011) *GCA **75***, 3024-3045. [4] Carlson et al. (2014) *Phil. Trans. Royal Soc. A*, **372**. [5] Hess (1994) *J. Geophys. Res.*, **99**, 19,083-19,093. [6] Osborn and Tait (1952) *Am. J. of Sci.*, **250**, 413-433. [7] Shearer and Papike (2005) *GCA*, **69,** 3445-3461. [8] Amma-Miyasaka and Nakagawa (2002) *J. Vol. Geothem. Res.*, **117**, 263-283. [9] Warren (1989) *Apollo 14 Workshop*, 149-153. [10] Elangovan et al. (2012) *Comps. and Geosci.*, **48**, 323-329.

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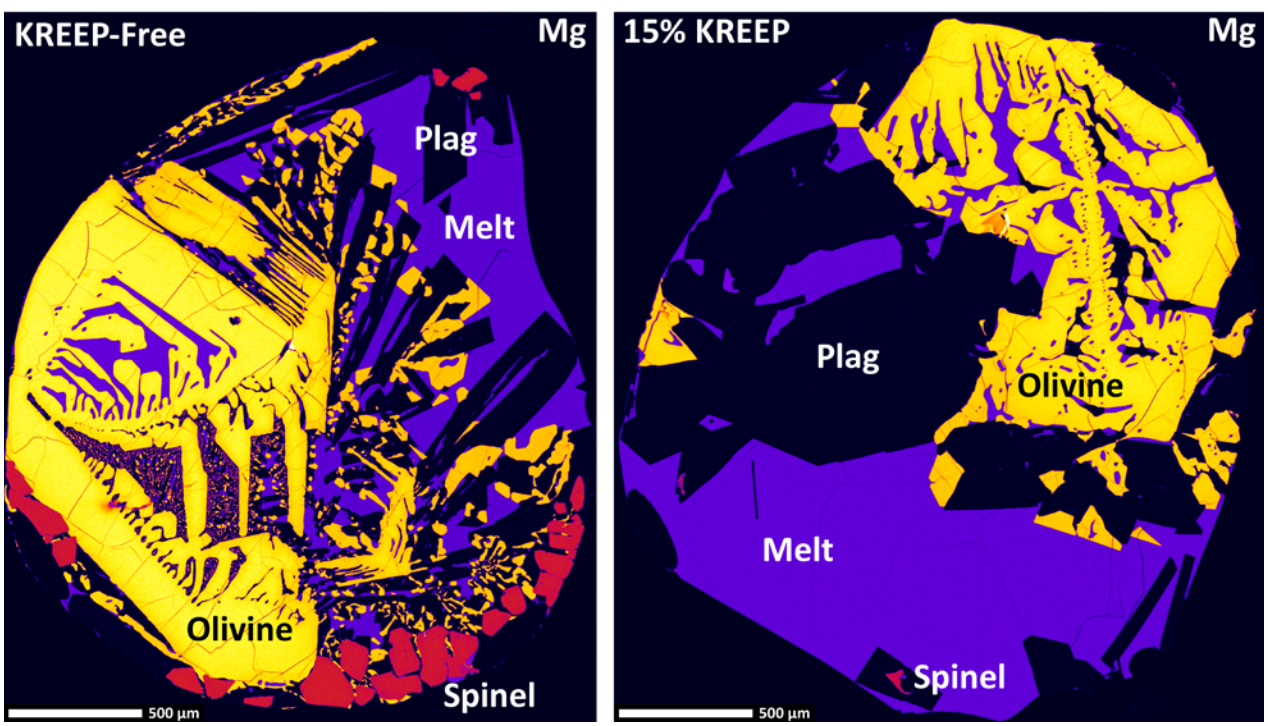

Figure 1: Mg kα X-ray maps of two experiments showing melt with olivine, plagioclase and an Mg-Al-rich spinel.