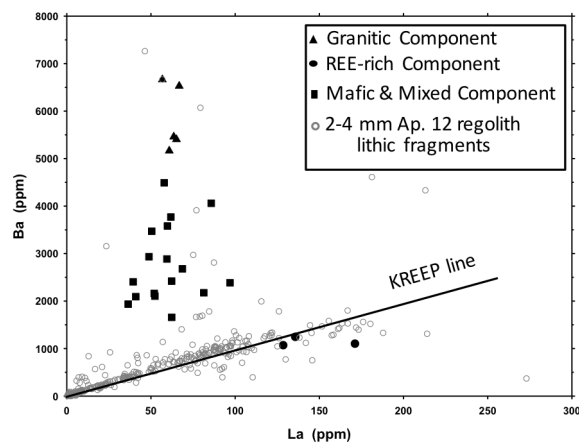


**APOLLO 12 SAMPLE 12013: PETROGENESIS BY SILICATE-LIQUID IMMISCIBILITY OR BI-MODAL VOLCANISM?** S. N. Valencia<sup>1,2</sup>, B. L. Jolliff<sup>3</sup>, and R. L. Korotev<sup>3</sup>. <sup>1</sup>University of Maryland, Department of Astronomy, College Park, MD 20742. <sup>2</sup>NASA Goddard Space Flight Center, Planetary Geology, Geophysics, and Geochemistry Laboratory, Greenbelt, MD 20771 (sarah.n.valencia@nasa.gov). <sup>3</sup>Washington University, Department of Earth and Planetary Sciences St. Louis, MO 63130.

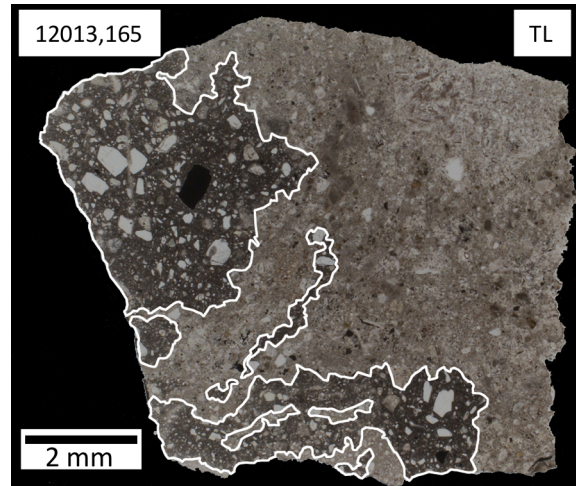
**Introduction:** In 1969, the Apollo 12 mission returned samples from the lunar surface that included the first examples of lunar granite, one of the more rare lithologies in the lunar sample collection. Examination of the Apollo 12 samples also led to the discovery of KREEP, a chemical component on the Moon that has elevated concentrations potassium (K), rare-earth elements (REE), and phosphorus (P), as well as other incompatible elements including Th and U [1-4]. A relationship between KREEP and granite is evident through geochemistry and co-occurrence in samples. However, the physical relationship and petrogenesis of granite and KREEP is unclear. In particular, the petrogenesis of granite under lunar conditions is not yet well understood. The lack of intermediate rock types argues against extended fractional crystallization as a formation mechanism, but evidence exists for both silicate-liquid immiscibility [e.g., 5-9] and bi-modal volcanism [10-12].

Sample 12013, the only large non-mare rock returned



**Figure 1.** Elemental concentrations (INAA) for 25 sub-samples of 12013. The granitic component is represented by filled black triangles, the REE-rich component, filled black circles, and mixtures of the components, including those rich in the mafic component, filled black squares. Open circles represent 2-4 mm lithic fragments in the Apollo 12 regolith from [19]. These analyses demonstrate the distinct chemistry of the 3-component rock relative to the other samples collected during the Apollo 12 mission. Modified from [17].

from the Apollo 12 mission, has elevated concentrations of KREEP elements, and is the largest granite-bearing rock in the Apollo sample collection [13-16]. Its unique composition and petrography have been studied extensively [e.g., 7, 14-16], but questions remain about how the components of 12013 formed. It has previously been characterized as a dilithologic breccia, where both lithologies are themselves breccias [14,16]. Here we build on



**Figure 2.** Transmitted light image of a fragment of Apollo sample 12013, showing the mingled light and dark breccias (outlined in white). The dark breccia is composed predominantly of the REE-rich component. The light breccia is composed predominantly of granitic and mafic components.

our previous work which demonstrated that 12013 is best described as a 3-component system comprising granitic, mafic, and REE-rich components, and explore possible protoliths of the mafic and REE-rich components, and modes of petrogenesis for all three of the components contained in 12013 [17,18] (Figs. 1,2).

**Samples & Methods:** A previous unstudied portion of 12013 was subsampled and used for 25 instrumental neutron activation analysis (INAA) (Figs. 1,2) [17,18, and here]. Subsequently, those subsamples richest in each of the three components were mounted in epoxy and polished for EPMA (electron probe microanalysis) using the JEOL JXA-8200 at Washington University.

**Protoliths of the Mafic and REE-rich components:** Unlike the granitic component, the protoliths of the REE-rich and mafic components are not readily apparent.

**REE-Rich Component.** From mineral textures and chemistry, the REE-rich component is inferred to be an impact melt [e.g., 7,14,16,18]. The bulk composition of the REE-rich component is distinct from other known impact-melt breccias from the Apollo 12 site [19]. However, the protolith of the REE-rich component remains unknown. The REE-rich component falls away from the KREEP line for La-Ba with increased levels of REEs (Fig. 1). Analyses that fall below the KREEP line are similar to monzogabbro (or monzodiorite) [19,20]. The bulk composition (modal recombination) is similar to

monzogabbro in several major elements, but is significantly more magnesian than previously studied monzogabbros [10,21,22].

**Mafic Component.** The mafic component occurs both as discrete clasts and as a fine-grained groundmass that have similar compositions. The preserved lithic clasts likely represent that protolith of the mafic component. Equilibrated pyroxene compositions in the clasts indicate that the mafic component cooled slowly, either as a basalt at the base of thick lava flow, or as a gabbro in a crustal intrusion. The bulk chemistry of these samples indicate that the mafic component is distinct from other known basalts. Modal recombination for several of the clasts yields an average of 14.1 wt.% FeO. INAA of subsamples richest in the mafic component, however, have a mass weighted average of 17.8 wt.% FeO, indicating that the groundmass contains a more FeO-rich component. Modeling of the compositional variability of all the INAA splits yields a possible mafic endmember with as much as 18.6 wt.% FeO.

#### Petrogenesis of Sample 12013:

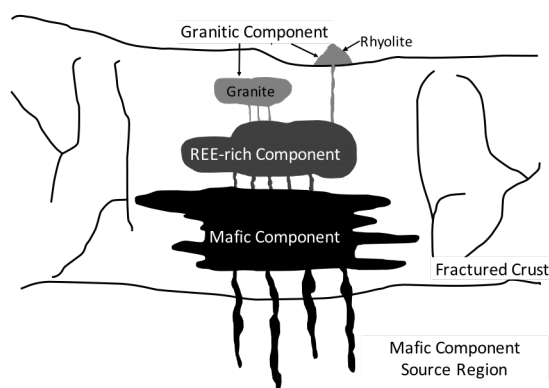
**Silicate Liquid Immiscibility.** On the sample scale, SLI has been implicated as a way to form granitic material [e.g., 5-8]. SLI occurs when lunar melts become highly FeO enriched following extended fractional crystallization, at which time the melt separates into two fractions – one FeO-rich and one SiO<sub>2</sub>-rich [5,6]. SLI has been proposed as the formation mechanism for 12013 owing to a complementary distribution of KREEP elements among the components [e.g., 7]. However, the SLI model does not align with the chemistry of 12013. The granitic component is high in Th, which partitions into the FeO-rich liquid during experiments [23,24]. Additionally, if SLI were the formation mechanism, mineral compositions between the components would be in equilibrium,

but pyroxene in the granitic component is significantly more Fe-rich than in the REE-rich component. Because of these discrepancies in chemistry, we conclude that SLI alone could not be the formation mechanism of 12013.

**Bi-modal Volcanism.** Despite the evidence at the sample level for granite forming by SLI, it is unclear whether this mechanism could be responsible for the formation of large-scale granitic bodies on the Moon [e.g., 10,11]. Bi-modal volcanism due to basaltic underplating is an alternate hypothesis for the formation of large granitic bodies in lunar conditions [10]. In this model partial melting of a (mantle) cumulate source region (i.e., the mafic component) intrudes and ponds in the crust. The heat from the intrusion causes melting of “fertile” crust (e.g., a KREEP-rich lithology of the Procellarum KREEP Terrane) that yields a KREEP-like magma (i.e., the REE-component protolith). Fractional crystallization (possibly coupled with some SLI) and gravity separation then yield a granitic melt (Fig. 3) [10]. While we cannot completely rule out involvement of SLI in the formation of 12013, we find that bi-modal volcanism is a plausible formation mechanism to describe the geochemical relationships of the three main components of 12013. The occurrence of the three lithologies in one breccia support the spatial relationship described during bimodal volcanism.

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**Figure 3.** Schematic of the formation of the three 12013 lithologies by bi-modal volcanism. Here, a basaltic magma (the mafic component) intrudes and ponds in the crust. Heat from the intrusion causes partial melting of the crust, which rises and ponds to become the REE-rich component protolith. Fractional crystallization and possibly some SLI yields the granitic component. Based on diagrams from [10, 25].