

PETROLOGICAL INVESTIGATIONS OF VOLATILE-BEARING LUNAR GRANOPHYRES M. D. Mouser^{1,2}, J. I. Simon², R. Christoffersen^{2,3}, and D. K. Ross^{2,3}, ¹Dept. of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA (mmouser@vols.utk.edu), ²Center for Isotope Cosmochemistry and Geochronology, Astromaterials Research & Exploration Science, EISD-XI3, NASA Johnson Space Center, Houston, TX 77058, USA, ³Jacobs-JETS Contract, NASA Johnson Space Center, Houston, TX 77058, USA.

Introduction: Novel studies of apatite [e.g., 1] and nominally anhydrous feldspars [2,3] in ancient lunar materials have yielded results that point to the presence of water on the Moon during its early formation. Given the common enrichment of volatiles in evolved magmas on Earth, similar minerals in felsic lunar samples may hold key information to the origin and distribution of lunar volatiles. Despite growing evidence for the geographic distribution of silicic volcanism on the Moon [e.g., 4], felsic sample lithologies associated with evolved magmas are rare [e.g., 4], and their petrologic histories remain debated [5,6,7].

The intriguing studies of volatiles in lunar rocks has prompted this detailed investigation of felsic clasts from Apollo samples 12013 (,167 and ,141) and 15405,78, for which we have previously reported NanoSIMS measurements of trace water contents in selected feldspathic phases [2,8]. These evolved clasts are embedded in breccias with a complex igneous and impact formation history that has yet to be fully understood.

Methods: Each of the fragments of the 12013 and 15405 samples had been previously embedded in polished indium mounts for NanoSIMS work and were used for the scanning electron microscopy (SEM) and electron probe micro analyzer (EPMA) work reported here. Energy-dispersive X-ray (EDS) element maps and spot analyses and back scattered electron images were obtained on the JEOL 7600F scanning electron microscope at JSC. Quantitative chemical spot analysis of mineral phases, element maps and back scattered electron images were also obtained on the JEOL JXA-8530F EPMA at JSC.

For all feldspar analyses, a beam current of 15nA and a beam diameter of 3 μm was used to reduced potential beam damage to the sample surface, therefore, reducing the potential volatile loss in the feldspars in future NanoSIMS work. A higher beam current of 30nA and a more focused beam diameter was used for all pyroxene analyses.

Results: Felsic clasts in the 15405 and 12013 samples are broadly similar in their nominal phase assemblages, comprised dominantly of phases with alkali feldspar and SiO_2 compositions (Fig. 1). However, 12013 felsic clasts are notable for also containing pyroxene, and minor intermediate plagioclase (An_{55}) [10]. Moreover, the nominal feldspar phase in the 15405 clasts showed significantly low alkali/(Si+Al) ratios in probe analyses, and had a

normalized An-Ab-Or compositional trend that is Na-depleted relative to the alkali feldspar found in 12013 (Fig. 2). This prompted preparation of a focused ion beam (FIB) section from the 15405 clasts for analytical transmission electron microscopy (TEM) work. This revealed that the feldspar-like phase was amorphous, likely due to shock and additional other compositional/thermal effects. The silica phase was still crystalline, however, and was identified as tridymite from TEM electron diffraction patterns.

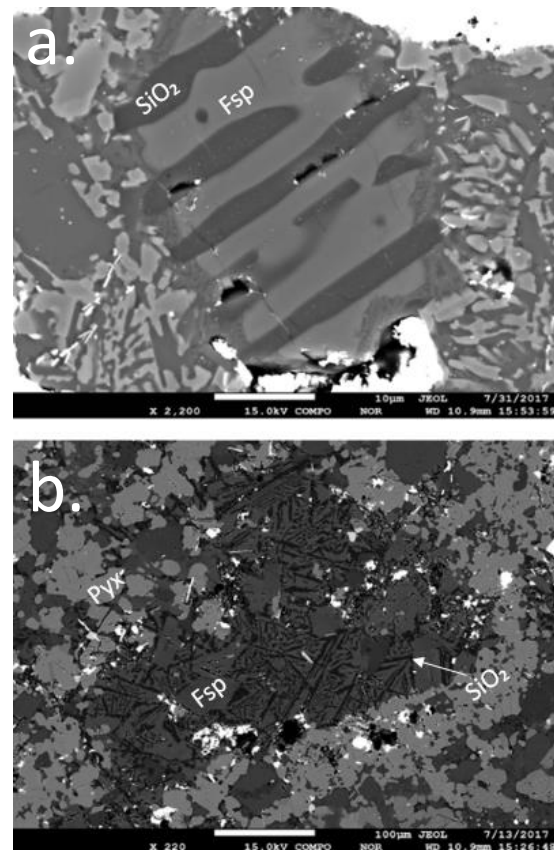


Figure 1. Back-scattered electron images of the textures of felsic clasts in: (a) 15405,78 and (b) 12013,167.

Alkali feldspar in the felsic clasts in the 12013 mounts appear as both subhedral grains with An_{55} plagioclase cores and as interstitial intergrowths with branching silica polymorphs (i.e., granophyre). 12013 samples also contain large fractured plagioclase grains ($\geq \text{An}_{85}$) with alkali feldspar+minor silica filling the fractures. The alkali feldspar in the felsic clasts exhibited Ba zoning, most obviously seen as

enrichments in the celsian (Ce) component from core to rim in the subhedral grains. The alkali feldspar veins in the fractured plagioclase grains had little to no Ce component, making Ce unique to the larger felsic clasts in these samples.

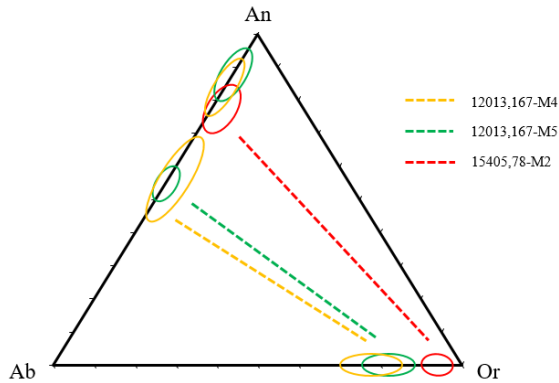


Figure 2. Feldspar ternary composition diagram showing the compositional trends for feldspars in the 12013,167 felsite clasts (yellow and green), compared to those in 15405,78 (red).

The silica polymorph intergrown with alkali feldspar in the 12013 granophyre regions was identified as α -quartz from FIB-TEM, as also described in [10]. Tridymite has also been previously identified in the 12013 breccia by optical methods [7,9]. The minor amounts of a silica polymorph that occur in the shocked plagioclase fracture-filling assemblage in 12013 will be identified in future FIB-TEM work.

High and low Ca pyroxenes are observed in 12013, which have similar Mg# ($Mg/(Mg+Fe) = 55 \pm 5$). Larger grains typically occur along the edges of the clasts and rarely within them. The pyroxenes exhibit fine exsolution lamellae, $\leq 1 \mu m$ in width, of both high and low Ca composition.

Other minor phases identified in the felsic clasts in the samples included apatite, ilmenite, zircon and sulfides.

Discussion: The felsic clasts in these breccias were derived from evolved melt, as indicated by their bulk compositions, sodic plagioclase, and zoned feldspar, e.g. [9] and this work. They were probably emplaced as shallow magma(s) that cooled relatively quickly, as shown by their fine-grained texture. This magma likely experienced a magma mixing event that enriched the alkalis (i.e., Ba) in the system, which can be seen in the relict subhedral alkali feldspar zoning in 12013.

The impact event(s) that formed the breccias played a major role in reconstructing the felsic clasts viewed in these samples, and likely lead to the feldspar with intermediate compositions, indicated by mixing trends in Fig. 2. Impact appears to have fractured and dispersed the felsic clasts (i.e., with An_{55} plagioclase), partially

melted some of the felsic clasts that then quenched to form patches of granophyric intergrowths of alkali feldspar and the SiO_2 phase (Fig. 1). The branching or wormy textures of the silica polymorph are quench textures that preserved tridymite, which is indicative of high temperature formation. The lack of crystal structure in the 15405,78-M2 alkali feldspars potentially indicates more of an effect from impacts than the 12013 clasts sustained. In the fractured plagioclase grains, there is both alkali feldspar and sodic rich plagioclase present in the cracks along with silica. This implies remobilization of not only alkali elements and silica near the lunar surface, but potentially, volatiles during this recrystallization process.

Overall, we find it significant that in assessing the composition of plagioclases associated with these felsic clasts, we observe them to have average An_{55} compositions that are more evolved relative to the typical lunar plagioclase suite $\geq An_{85}$ (Fig. 2). Further details on the occurrence of these plagioclases throughout the 12013 breccias are discussed in our companion abstract to this study [10]. In a possibly related observation, the compositional trend line of the normalized feldspathic component in the shock-modified 15405 clasts, although likely affected by Na loss relative to Ca, is also slightly An-depleted relative to typical lunar plagioclase (Fig. 2). The presence of this more evolved plagioclase component in both samples may offer an important link to the igneous suite that was ultimately the parent for the clast compositions. Similarly, the relatively iron-rich pyroxene compositional relations we have determined for the 12013 clasts may be related to this igneous source rock.

The relatively complex igneous and impact history of these lunar felsic clasts imply two scenarios for the presence of hydroxyl in the feldspar crystal structure [3,5]. First, the impactor could have contained hydrous material that ultimately introduced water into the system before and/or during recrystallization. Secondly, water could have existed in the lunar interior, and its abundance was recorded (as being partially) by relict grains in the felsic clasts before being remobilized at the surface along with other volatiles (K and Na) and silica during the recrystallization process.

References: [1] McCubbin F. M. et al. (2010) *PNAS*, 107, 11223-11228. [2] Mills R. D. et al. (2017) *Geochem. Persp. Let.*, 3, 115-123. [3] Hui et al. (2013) *Nature Geoscience*, 6, 177-180. [4] Glotch, T.D., et al. (2010) *Science* 329, 1510–1513. [5] Quick J. E. et al. (1981) *Proc. Lunar Planet. Sci.*, 12B, 117-172. [6] Jolliff B.L., et al (1999), *Am. Min.* 84, 821-837. [7] Ryder, G. (1976) *EPSL* 29, 255-268. [8] Simon J. I. et al. (2017) LPS XLVIII, Abstract #1248. [9] Seddio S. M. et al. (2015) *Am. Min.*, 100, 1533–1543. [10] Christoffersen R. et al. (2018) this meeting.