A STUDY OF APOLLO 16 FELDSPATHIC GLASSES: LOCALLY PRODUCED OR BALLISTICALLY DEPOSITED?
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Introduction: Continuous bombardment by asteroidal and cometary debris over the last 4.5 Ga has churned the lunar surface into a fine-grained regolith. The violent nature of these impacts has largely destroyed the primordial lunar crust, reworking it into a variety of breccia and glass fragments that make up the majority of most Apollo soils. Nowhere is this more true than at the Apollo 16 site, located in the ancient, heavily cratered (even for the Moon) lunar highlands. Numerous investigators have analyzed glass fragments in Apollo 16 soil samples [1-7]. Two recent studies make different assumptions about the provenance of impact glass in the Apollo 16 regolith. The study of Taylor et al. [4] targets “agglutinitic glass.” They assume that most (“>90%” [5]) of impact-produced glass in the regolith derives from agglutinates, that is, that most glass fragments in lunar soils are produced locally by micrometeorite impacts. Delano et al., while acknowledging that a significant proportion of feldspathic glasses appeared to be locally produced (although not necessarily by micrometeorite impacts), suggest that a non-trivial proportion of the glasses (including feldspathic glasses) were produced by large post-basin (<3.9 Ga) impacts at significant distances from the Apollo 16 site and ballistically transported to the Apollo 16 [6].

In this study we have begun a coordinated major-, minor-, and trace-element study of Apollo 16 glasses (concentrating on the feldspathic glasses) to ascertain the relative abundances of glasses that have a “local” composition (essentially the same as the local Apollo 16 soil) or a composition exotic to the Apollo 16 site, suggesting a provenance at a significant distance from the Apollo 16 site.

Methodology: The glasses presented in this study are “clean” glasses found in two grain mounts of the 64-105 μm and 105-210 μm size fractions of sample 61241, a submature Apollo 16 soil (I_s/FeO of 47, [8]). In each grain mount, an area encompassing >1500 particles was imaged in transmitted, cross-polarized, and reflected light as well as with high-resolution backscattered electron image mosaics and elemental x-ray maps. These images were used to identify which particles were glasses, and what their morphologies and textures were. These glasses were then analyzed for major- and minor-elements by EPMA [7].

Petrography: A variety of glass types were identified, including clean (N=379), clast-laden (102), cryptocrystalline (53), vitrophyric (69), and agglutinitic (614) glasses. Only data for the “clean” glasses are presented in this preliminary study. We define a clean glass as a glass fragment lacking schlieren or other compositional zoning and without mineral grains or clasts (small FeNi metal grains or a small amount of soil stuck to the exterior of the grain is permissible). Otherwise clean glasses containing a few small clasts are also included here (the clasts were not included in the analyses). All told, in the 64-105 size range we identified and analyzed 231 clean glasses (out of 2738 total particles and 835 glassy particles) and in the 105-210 size range we identified and analyzed 148 clean glasses (of 1499 particles and 382 glassy particles). The vast majority of clean glass grains analyzed were angular glass fragments; only 19 and 7 glass spheres (or broken spheres) were identified, respectively. Because of our selection criteria, at most only a small fraction of our clean glasses are likely to have originated from agglutinates although some or all may be of local origin [9].

Geochemistry: Although the majority (87%) of glasses in this study are feldspathic in nature (<7 wt% FeO, >22 wt% Al_2O_3), the overall range of major element compositions is considerable (Fig. 1). We have divided the clean glasses into 5 groups based primarily on their FeO and K_2O concentrations: maskelynite (<1 wt% FeO), feldspathic glass (1-7 wt% FeO), mare-highlands glass (7-15 wt% FeO, <0.1 wt% K_2O), KREEPy glass (7-15 wt% FeO, >0.1 wt% K_2O), and basaltic glass (>15 wt% FeO). Just over half the clean glasses in this study (52%) are maskelynite grains (<1 wt% FeO). These are plagioclase grains that were disordered by impact generated shock waves. The second largest compositional glass group (35%) are feldspathic glasses. These glasses display a wide range of MgO concentrations (2-15 wt%; Fig 1b), especially relative to their somewhat restricted alumina and FeO compositional ranges, which in turn leads to a wide range of Mg’ (molar Mg/Mg+Fe*100: 43-87). The concentrations of incompatible elements in the feldspathic glasses (e.g., K, Na, P; Fig. 1c) is also variable (0-0.8 wt% K_2O), although this is in part due to the volatile nature of these elements. The mafic glass groups are present in relatively minor amounts: 3% basaltic glass, 5% KREEPy glass, 5% mare-highlands glass. Two grains of the isotropic SiO_2 glass lechatelierite are also present, as are a handful (~8) of HASP glasses [2].

Discussion: The likely provenances of the mafic and KREEPy glass groups are relatively straightforward. The KREEPy glass at Apollo 16 originated within the PKT [7] and was delivered as Imbrium ejecta (or ejecta from another impact into the PKT). The basaltic and mare-highlands glasses were likely transported to the Apollo 16 site by small to medium sized post basin

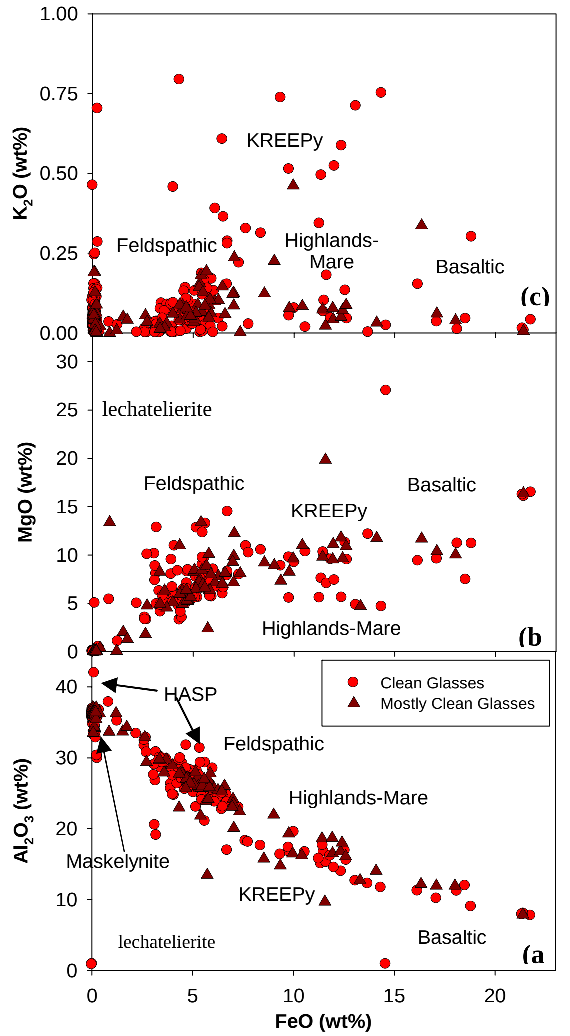

Figure 1: (a) FeO vs. Al_2O_3 **(b)** FeO vs. MgO **(c)** FeO vs. K_2O in all clean glasses from this study.

impacts into the maria nearest the Apollo 16 site, namely Mare Nectaris and Tranquillitatis [7]. The provenance (local vs. distant) of the maskelynite clasts cannot usually be determined, since most highlands plagioclase has a very similar major-element composition. Recent work on the variability in trace-element (Sr, Ba) concentrations in lunar plagioclase may ultimately prove useful in placing constraints on the origin of some maskelynite grains, but the technique is still in development [10].

What is the provenance for the feldspathic glasses in the Apollo 16 soils? If they were not all produced locally, how would we tell? The key to answering these questions lies in the compositions of the feldspathic lunar meteorites (FLMs), most of which are samples of regolith from randomly distributed locations in the highlands. The composition of the regolith at the Apollo 16 site is richer in incompatible elements by a factor of 4–6 compared to typical feldspathic lunar meteorites because of the site's proximity to the Procellarum KREEP Terrane and the presence of Th-rich Imbrium ejecta in the Apollo 16 regolith [11]. FLMs also have a wide range in Mg', 60-77 [11-12], whereas mature regolith from Apollo 16 has a narrow range, 65–67. Thus feldspathic glasses at the Apollo 16 site with low concentrations of incompatible elements or high Mg' would likely come from points in the highlands distant from the Apollo 16 site.

Figure 2 shows that there are indeed feldspathic glasses at the Apollo 16 site that have low concentrations of incompatible elements, elevated Mg', or both. Unfortunately, the impacts that produce lunar glasses are known to vaporize volatile elements during glass formation (Na, K, P, Fe, and even Si) [2]. This means that there is the possibility that these glasses with high Mg' and low K_2O are due to impact processes rather than a reflection of the soils from which they were formed. The problems of volatilization can be mitigated by using more refractory trace-elements (Sc/Cr ratio instead of Mg', REEs instead of K_2O), and these measurements are currently underway on the Cameca 3f SIMS at Washington University in St. Louis.

References: [1] Naney M. T. et al. (1976) *PLSC*, *7*, 155-84. [2] Kempa M. J. and Papike J. J. (1980) *PLPSC*, *4*, 1635-61. [3] Ridley W. I. et al. (1973) *PLSC*, *4*, 309-321. [4] Taylor L. A. et al. (2003) *LPS XXXIV*, Abstract #1774. [5] Taylor L. A. et al. (2001) *JGR* 106, 27,985–27,999. [6] Delano, J.W. et al. (2007) *M&PS* 42, 993–1004. [7] Zeigler et al. (2006) *GCA*, *70*, 6050-67. [8] Morris R. V. (1978) *PLPSC*, *9*, 2278-97. [9] Morris R. V. et al. (1986) *PLPSC*, *17*, E21–42. [10] Zeigler et al. (2008) *GCA abstracts*, #2069. [11] Korotev R. L., et al. (2003) *GCA* 67, 4895–923. [12] Korotev R. L. et al (2006) *GCA* 70, 5935–56. **Acknowledgements:** We thank the JSC curatorial facility for preparing the grain mounts used in this study. This work was funded by NASA grant NNG06GF67G (Korotev).

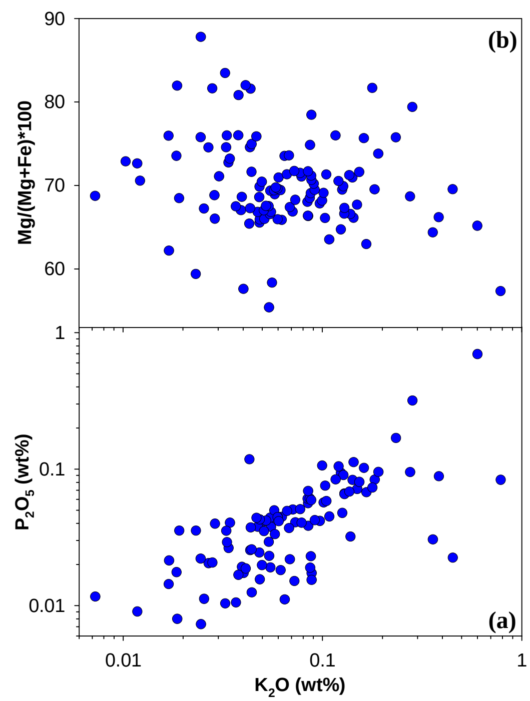

Figure 2: (a) K_2O vs. P_2O_5 **(b)** K_2O vs. Mg' in all clean feldspathic glasses (1-7 wt% FeO) from this study.