CHEMICAL AND ISOTOPIC ANALYSES OF APOLLO 16 GLASSES: AN INTEGRATED APPROACH.

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Introduction: A large compositional range of glasses, mainly of impact origin, occur in the Apollo 16 regoliths [e.g., 1-4]. This compositional range reflects different compositions of targets [e.g., 1,3,4] that were impacted melted, as well as fractional losses of volatile elements during melting at super-liquidus temperatures [e.g., 2,5]. This study has integrated chemical data on 961 glasses (Figure 1: glasses from four regoliths: 60014, 64001, 64501, 66041) with glass morphology and Ar^{39}-Ar^{40} ages to develop a coherent story about one compositional group of Apollo 16 impact glasses.

Results: Refractory lithophile elements are plotted (Figure 1) to infer the compositional nature of the target-materials. This approach avoids the obscuring effects caused by open-system behavior (i.e., fractional volatilization) [e.g., 4,6]. The glasses analyzed in this study were free of clasts and crystals (i.e., not agglutinates).

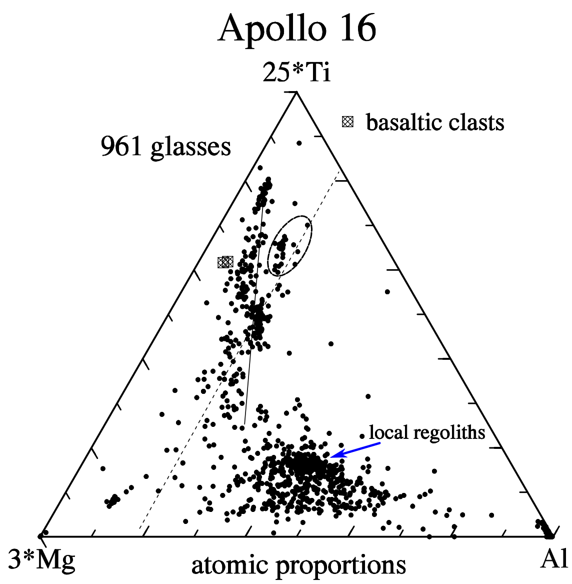

Figure 1: Atomic proportions of refractory lithophile elements in the 961 glasses analyzed from 60014, 64001, 64501, and 66041. Two mare basaltic clasts with ~5 wt% TiO_2 from 64001 are also plotted. The prominent cluster of glasses noted by the blue arrow is compositionally similar to the local Apollo 16 regoliths. Three glasses from the compositional group highlighted by the ellipse were dated by the Ar^{39}-Ar^{40} method (refer to Figure 2).

The dashed line in Figure 1 that is parallel to the Mg-Ti side of the ternary diagram is a boundary between compositions with mare- and KREEP-affinities (left side of this boundary) and compositions with highland-affinities (right side of this boundary). The solid line running from near the 25*Ti corner of the ternary diagram toward the left center of the figure shows the mare/highland mixing line represented by the mare/highland regoliths at the Apollo 17 landing site. These reference locations on Figure 1 are intended to orient the reader within the diagram.

The 961 glasses have been further subdivided into angular fragments (Figure 2), and spherules and broken spherules (Figure 3). Note that while ~35% of the angular fragments have mare- and KREEP-affinities, only ~10% of the glass spherules have those affinities. Notice in Figure 3 that the great majority of glass spherules have compositions that plot at-or-near the compositions of local Apollo 16 regoliths. A higher proportion of angular glass fragments are compositionally exotic to the landing site than the glass spherules.

Three angular glass fragments from 64501 were dated by the Ar^{39}-Ar^{40} method. These glasses are compositionally similar (Table 1), plot within the elliptical region of Figure 1, and are identified by three red arrows in Figure 2. This compositional group of impact glasses was previously described by Ziegler et al [1] ("basaltic-andesitic" group) and interpreted to be exotic to the Apollo 16 landing site, possibly transported from the Procellarum KREEP Terrain. We agree. These glasses plot toward the high-Ti region of the Figure 2 *not* because they are high in Ti (Table 1) but rather because they are distinctively low in Mg (and Al). The Ar^{39}-Ar^{40} ages (with estimated uncertainties of ±50 Ma) of the three fragments from this compositional group are 3785 Ma (sample #223), 3739 Ma (sample #225), and 3781 Ma (sample #185).

Discussion: The proportion of exotic versus locally derived glasses differs significantly between angular glass fragments and glass spherules (Figures 2,3). Spherules are dominated by local compositions, whereas glass fragments have a higher proportion of exotic compositions (i.e., derived from distant sources). Perhaps glasses transported from large distances had traveled at high velocities and were often smashed upon landing. In contrast, locally derived glasses were less likely to reach velocities sufficiently high for them to be broken upon landing.

The Apollo 16 glasses (Figure 1) are the result of impact events into a wide compositional variety of target-materials in mare, KREEP, and ANT regions [e.g., 1-4]. Results from this study show that one compositional group of impact glasses (Figures 1,2) was formed and delivered to the Apollo 16 landing site during an impact event(s) at ~3770 Ma. As our regional petrological map is developed [3], the provenance of these impact glasses will become better defined.

This study shows the value of an integrated approach that uses compositional and Ar^{39}-Ar^{40} isotopic analyses on individual glasses to constrain the Moon's bombardment history. While this integrated approach is recognized as being *essential* for studying crystalline impact melt rocks [e.g., 7,8], technologies now exist that allow this approach to be used on ~100µm impact glasses with ≥1000 ppm K [e.g., 3,9,10]. An improved understanding of the Earth/Moon bombardment history requires this integrated approach.

Figure 1 defines a compositional framework for interpreting all subsequent ages acquired on other chemically defined Apollo 16 glasses. We are also using this approach to study glasses from Apollo 14 and Apollo 17.

References: [1] Ziegler R. A. et al. (2004) *LPS-XXXV*, abstract #2082. [2] Naney M. T. et al. (1976) *PLSC 7th*, 155-184. [3] Zellner N. E. B. et al. (2003) *LPS-XXXIV*, abstract #1157. [4] Delano J. W. (1991) *GCA*, 55, 3019-3029. [5] Keller L. P. and McKay D. S. (1991) *LPS-XXII*, 703-704. [6] Delano J. W. et al. (1981) *PLPSC 12th*, 339-370. [7] Dalrymple G. B. and Ryder G. (1993) *JGR*, 98, 13085-13095. [8] Duncan R. A. et al. (2004) *LPS-XXXV*, abstract #1328. [9] Barra F. et al. (2004) *LPS-XXXV*, abstract #1365. [10] Cohen B. et al. (2000) *Science*, 290, 1754-1756.

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Table 1. *Major-element compositions of three glass fragments from regolith 64501 that were dated by the Ar-Ar method. These compositions are identified in Figure 2 by the red arrows, which belong to the "basaltic-andesitic" group of Ziegler et al. [1].*

Sample #	***223***	***225***	***185***
SiO_2 (wt%)	53.0	55.1	52.8
TiO_2	3.1	3.3	4.0
Al_2O_3	12.0	13.2	13.1
Cr_2O_3	0.1	0.1	0.1
FeO	15.0	12.1	13.0
MnO	0.2	0.2	0.2
MgO	2.4	3.7	4.6
CaO	8.8	9.5	9.3
Na_2O	1.1	0.6	0.5
K_2O	1.5	0.8	0.7
Total	97.2	98.6	98.3
age (Ma)	3785	3739	3781

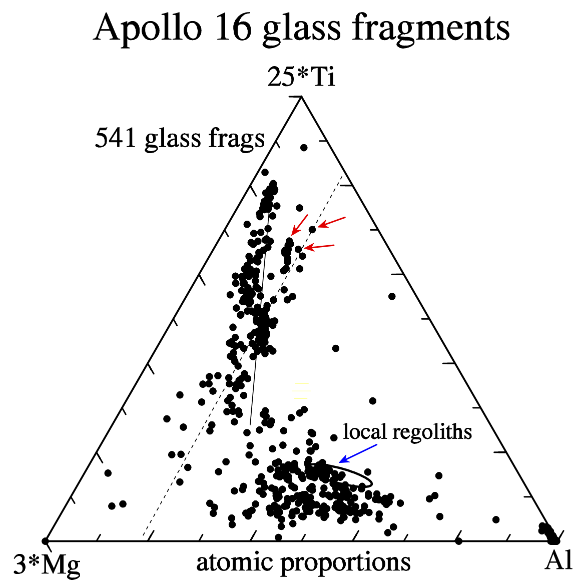

Figure 2: Proportions of refractory lithophile elements in 541 of the 961 glasses analyzed in this study that occur as ***angular fragments***. ~35% of these angular glass fragments have compositions with mare- and KREEP-affinities. Three glass fragments dated by the Ar^{39}-Ar^{40} method are identified by the red arrows. The blue arrow points toward an elliptical region containing the compositions of local Apollo 16 regoliths.

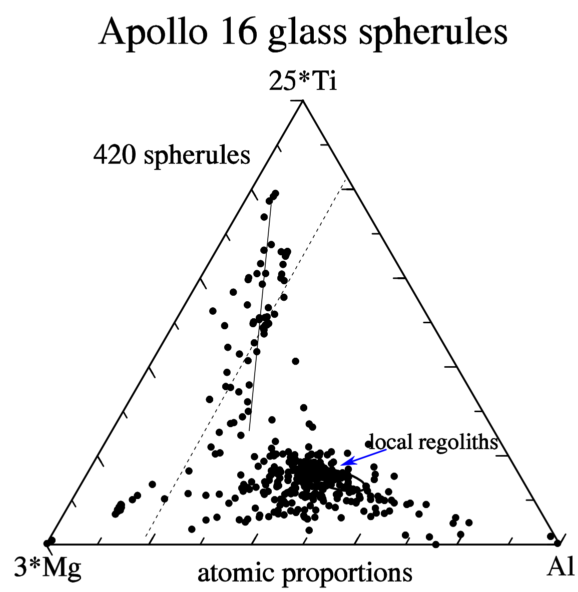

Figure 3: Proportions of refractory lithophile elements in 420 of the 961 glasses analyzed in this study that occur as ***spherules and broken spherules***. Only ~10% of these glasses have mare- and KREEP-affinities, while the majority have compositions similar to the local Apollo 16 regoliths (indicated by the blue arrow).