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An integrated approach to understanding Apollo 16 impact glasses: Chemistry, isotopes, and shape

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Abstract–The major- and minor-element abundances were determined by electron microprobe in 1039 glasses from regoliths and regolith breccias to define the compositional topology of lunar glasses at the Apollo 16 landing site in the central highlands of the Moon. While impact glasses with chemical compositions similar to local materials (i.e., Apollo 16 rocks and regoliths) are abundant, glasses with exotic compositions (i.e., transported from other areas of the Moon) account for up to ~30% of the population. A higher proportion of compositionally exotic, angular glass fragments exists when compared to compositionally exotic glass spherules. Ratios of non-volatile lithophile elements (i.e., Al, Ti, Mg) have been used to constrain the original source materials of the impact glasses. This approach is immune to the effects of open-system losses of volatile elements (e.g., Si, Na, K). Four impact glasses from one compositionally exotic group (low-Mg high-K Fra Mauro; lmHKFM) were selected for ^{40}Ar/^{39}Ar dating. The individual fragments of lmHKFM glass all yielded ages of ~3750 ± 50 Ma for the time of the impact event. Based on the petrography of these individual glasses, we conclude that the likely age of the impact event that formed these 4 glasses, as well as the possible time of their ballistic arrival at the Apollo 16 site from a large and distant cratering event (perhaps in the Procellarum KREEP terrain) (Zeigler et al. 2004), is 3730 ± 40 Ma, close to the accepted age for Imbrium.

INTRODUCTION

The bombardment history of the inner solar system is a topic of enduring interest and persistent uncertainties (e.g., Cohen et al. 2000; Culler et al. 2000; Hartmann et al. 2000). The chemical and isotopic memories contained within lunar impact glasses (e.g., Barra et al. 2004; Borchardt et al. 1986) and crystalline impact melts (e.g., Cohen et al. 2000; Dalrymple and Ryder 1993, 1996; Duncan et al. 2004; Eberhardt et al. 1973; Ryder et al. 1996) from the current Apollo and lunar meteorite inventories have the potential to provide information in sufficient quantity and with sufficient accuracy to better constrain models for the time-dependent flux of impactors in the inner solar system. While ^{40}Ar/^{39}Ar dating of microgram-size impact glasses with <1000 ppm K is challenging, analytical technologies are steadily improving the precisions and accuracies of the age measurements.

The Apollo 16 mission landed in the central highlands of the Moon (8.973°S, 15.499°E) in April 1972 and returned 95.8 kg of rocks and regoliths to Earth. The current paper deals with chemical analyses that have been conducted on 1039 glasses, principally of impact origin, that occur in regoliths and regolith breccias in the form of <1 mm spheres and fragments, and isotopic analyses of four of these. Previous studies (e.g., Borchardt et al. 1986; Delano 1975,

Table 1. Analyses (wt% oxides; mean ±1σ) of 7 natural glass working standards used in this study to provide information about the analytical precision of our analyses of the Apollo 16 glasses. All 177 analyses of these working standards are plotted in Fig. 1 to show analytical precision.

Sample	S1	S2	S5	S7	87	VG-99	VG-2
No. analyses	42	35	34	30	11	11	14
Provenance	Apollo 14	Apollo 14	Apollo 14	Apollo 14	Apollo 16	Hawai‘i	Juan de Fuca
SiO_2	46.9 (0.5)	46.9 (0.4)	44.5 (0.5)	44.4 (0.5)	45.3 (0.21)	50.2 (0.5)	50.1 (0.3)
TiO_2	0.64 (0.02)	1.47 (0.02)	0.66 (0.01)	2.12 (0.03)	0.22 (0.03)	4.07 (0.08)	1.89 (0. 02)
Al_2O_3	10.3 (0.14)	21.5 (0.2)	24.2 (0.3)	7.60 (0.08)	28.3 (0.40)	12.2 (0.09)	13.7 (0.1)
Cr_2O_3	0.53 (0.02)	0.15 (0.01)	0.16 (0.02)	0.50 (0.02)	0.08 (0.02)	0.01 (0.01)	0.02 (0.01)
FeO	17.4 (0.2)	7.84 (0.12)	9.13 (0.12)	22.3 (0.2)	4.62 (0.11)	13.2 (0.1)	11.6 (0.1)
MnO	0.25 (0.01)	0.10 (0.01)	0.13 (0.02)	0.28 (0.01)	0.07 (0.01)	0.20 (0.02)	0.21 (0.02)
MgO	13.4 (0.1)	8.07 (0.13)	5.74 (0.08)	14.2 (0.2)	4.62 (0.11)	4.98 (0.03)	6.80 (0.05)
CaO	9.87 (0.09)	12.6 (0.1)	14.8 (0.1)	8.36 (0.11)	16.5 (0.21)	9.14 (0.09)	11.0 (0.1)
Na_2O	0.37 (0.04)	0.50 (0.02)	0.29 (0.01)	0.29 (0.01)	0.15 (0.01)	2.67 (0.14)	2.75 (0.03)
K_2O	0.11 (0.01)	0.28 (0.01)	0.04 (0.01)	0.12 (0.01)	0.02 (0.01)	0.83 (0.01)	0.20 (0.01)

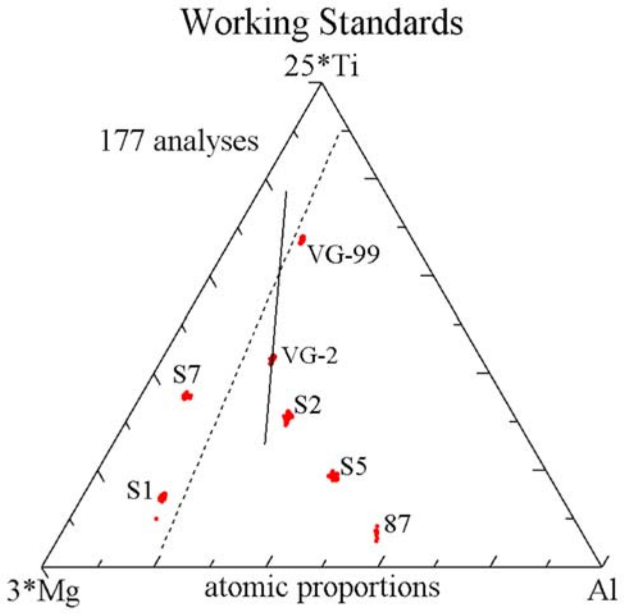

Fig. 1. Analyses of 7 natural glass working standards (Table 1) used for assessing the analytical precision of the Apollo 16 data discussed in this paper. The dashed line is an approximate boundary between mare-dominated lunar compositions (left) and highlands-dominated compositions (right). The solid line is a reference line showing the mixing trend defined by mare and highlands regoliths at the Apollo 17 landing site.

1991; Delano et al. 1981; Glass 1976; Kempa and Papike 1980; Morris et al. 1986; Naney et al. 1976; Ridley et al. 1973; See et al. 1986; Zeigler et al. 2004) have shown that a large compositional range of impact-produced glasses occurs at the Apollo 16 site, which reflects the variety of regions that have been impact melted over the eons to produce these glasses. Based on knowledge of the characteristic composition of local Apollo 16 regolith (e.g., Taylor 1975), a subset of impact glasses was strategically selected (due to their composition being atypical of the local Apollo 16 regolith composition) for isotopic dating by the laser, step-heating $^{40}Ar/^{39}Ar$ method to determine the age of the impact event that produced each piece of impact glass. Impact glasses in one compositional group showed ages similar to each other, and we try to show that combining chemical and isotopic information on these impact glasses permits more substantive interpretations than would be possible from either data set alone. Subsequent papers will elaborate on additional chemical and isotopic data acquired on other impact glasses and groups of impact glasses from the Apollo 14, 16, and 17 landing sites.

ANALYTICAL PROCEDURES

Chemical analyses were performed using a JEOL 733 Superprobe (electron microprobe) located in the Department of Earth and Environmental Sciences at Rensselaer Polytechnic Institute in Troy, New York, USA. Within the following polished thin sections of regoliths, 752 glasses were analyzed: drive-tube 60014 (polished thin sections: 6017, 6032, 6035, 6038, 6041, 6044), and drive-tube 64001 (polished thin sections: 6023, 6024, 6029, 6032, 6033, 6040, 6041, 6042, 6043). The compositions of these glasses are available upon request. Locations of most glasses in these polished thin sections were also recorded on photomicrographs for future reference. The operating conditions during these analyses were typically 30 nanoamp specimen current, 15 keV accelerating potential, and 50 s counting times on Kα peaks (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K), except that Cr typically involved 100 s counting times. Backgrounds were collected for all elements during analyses of all glasses. Additionally, analyses of 78 glasses from Apollo 16 that were tabulated in Delano et al. (1981) have been included in this study.

Two 5 g samples of Apollo 16 regolith (<1 mm fractions of 64501,225 and 66041,127) were wet-sieved with acetone. The >106-micron fraction was ultrasonically cleaned in acetone. Spheres and fragments of glass (209 glasses total) were handpicked from this size-fraction with

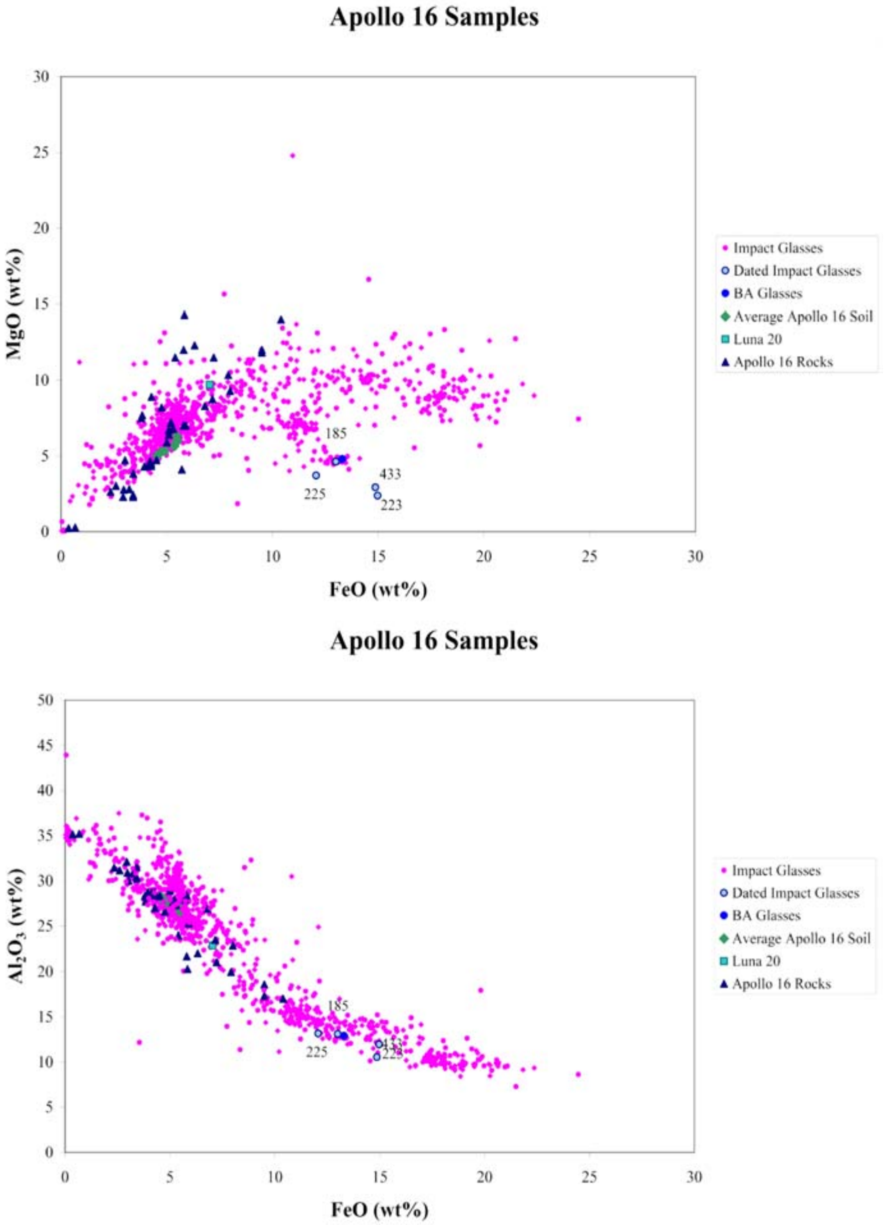

Fig. 2. a) Two-element diagrams showing compositions for the dated impact glasses in this study (labeled 185, 223, 225, 433) along with some representative compositions from Apollo 16 regolith and rock samples. Impact glass data are from Delano (60014; 1991) and Zellner (64501, 66041; unpublished). BA glass composition is from Zeigler et al. (2004). Apollo 16 soil compositions are from Glass (1976), Hubbard et al. (1973), and Ridley et al. (1973). The Luna 20 composition is from Ridley et al. (1973). Apollo 16 rock compositions are from Glass (1976), Ridley et al. (1973), Lindstrom and Salpas (1981), Laul et al. (1974), Hubbard et al. (1973, 1974), and Stöffler et al. (1985).

the aid of a binocular microscope. Each piece was individually mounted in aluminum tubing 6 mm in diameter with Crystalbond adhesive and carefully ground and polished to produce a smooth, planar surface (with minimal mass loss of the sample) that could be chemically analyzed by electron microprobe. Following chemical analysis, the surface of each sample was repolished to remove the carbon coating needed for the electron microprobe analysis. Samples were then individually removed from the Crystalbond adhesive and cleaned in acetone (Crystalbond 509-3 is acetone-soluble; Aremco Products, Inc.) to remove organics from the surfaces of those glasses that had been selected (based on their chemical compositions and masses) for isotopic dating.

Seven homogeneous natural glasses (Table 1) were used as working standards during this investigation to assess the analytical precision of our chemical analyses (Fig. 1). Those working standards were the following: S1 = Apollo 14 VLT volcanic glass (Delano 1988) spherule #127 from 14259,624; S2 = Apollo 14 "Medium-K Fra Mauro" (e.g., Ridley et al.

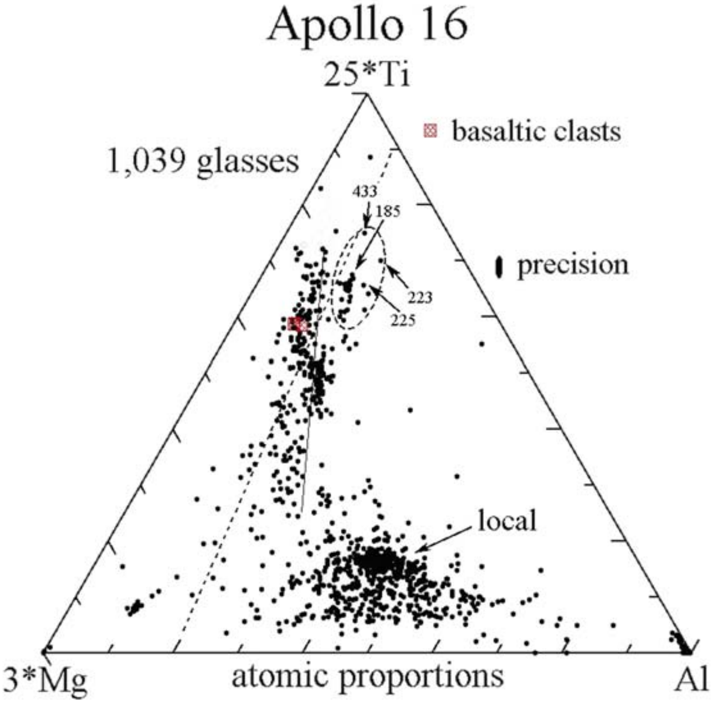

Fig. 2. *Continued.* b) Proportions of non-volatile lithophile elements (Ti, Mg, Al) in 1039 glasses from the Apollo 16 site that have been determined by electron microprobe. Locally derived glasses (i.e., within compositional range of regoliths and rocks at the Apollo 16 site) and exotic glasses (i.e., non-local compositions) are evident, as noted by previous investigators (e.g., Ridley et al. 1973; Naney et al. 1976). Four glasses (185, 223, 225, 433) within the dashed elliptical region have been dated at ~3730 Ma in the current study using the laser, step-heating ^{40}Ar/^{39}Ar method. For reference, the solid line is the mare/highland mixing trend defined by Apollo 17 regoliths. The dashed line is a convenient, but only approximate, boundary between mare-derived compositions (left side) and highland-derived compositions (right side). Two, highly shocked, mare basaltic clasts from polished thin sections 64001,6040 and 64001,6043 have compositions similar to some mare-derived impact glasses.

1973) impact glass fragment #128 from 14259,624; S5 = Apollo 14 “Highland Basalt” (e.g., Ridley et al. 1973) impact glass fragment #131 from 14259,624; S7 = Apollo 14 green “A” volcanic glass (Delano 1988) spherule #133 from 14259,624; 87 = Apollo 16 “Highland Basalt” (e.g., Ridley et al. 1973) impact glass fragment #87 from polished thin section 64001,6043; VG-2 = terrestrial volcanic glass from the Juan de Fuca Ridge; VG-99 = terrestrial volcanic glass from the Makaopuhi Lava Lake, Hawai‘i, USA.

Glasses from 64501,225 and 66041,127 having chemical compositions of special interest were selected for isotopic dating, placed in aluminum sample holders, and irradiated for ~300 h in the Phoenix Ford Reactor at the University of Michigan along with a) MMhb-1 hornblende to determine the neutron fluence and b) CaF_2 salt to correct for reactor-produced interferences. The J factor for the irradiation of the lmHKFM glasses discussed in this paper was 0.05776 ± 0.00030. Samples were analyzed in the noble gas mass spectrometry laboratory of The University of Arizona. Each sample was degassed in a series of temperature extractions using a continuous Ar-ion laser heating system. In the first heating step, a 5A beam was passed over the sample. The amperage was increased incrementally until ^{40}Ar counts from the sample peaked, and then decreased to background levels. The isotopic composition of the released Ar was measured with a VG5400 mass spectrometer. Data corrections included system blanks, radioactive decay, reactor-induced interferences, and cosmic ray spallation. Three-isotope plots were used to determine the ^{40}Ar/^{36}Ar ratio for the trapped solar wind within each sample, and that contribution was subtracted. The ages discussed in this paper were derived from plateaus. In addition, several spherules of Apollo 15 volcanic green glass from 15426 (e.g., Delano 1979; Steele et al. 1992), with a well-defined ^{40}Ar/^{39}Ar age (~3340 Ma: Podosek and Huneke 1973; Huneke et al. 1974; K ~200 ppm) were used as isotopic working standards in order to assess whether or not the data reduction procedure resulted in expected ages within uncertainties.

RESULTS

Each impact glass is believed to retain a compositional memory about its target materials in the ratios of nonvolatile lithophile elements (e.g., Delano et al. 1981; Delano 1991). Since hypervelocity impacts can generate temperatures that far exceed the nominal liquidus temperatures of the source

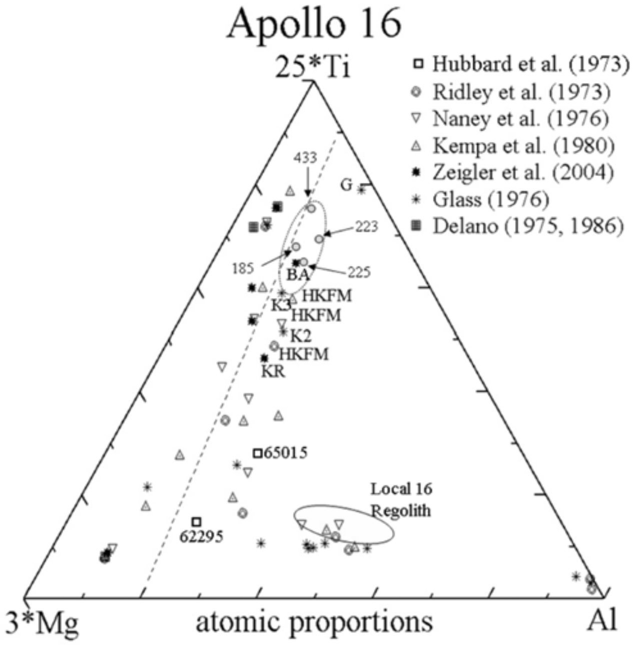

Fig. 3. Average compositions of glass groups from Apollo 16 that have been reported in the published literature along with 2 impact melt rocks analyzed by Hubbard et al. (1973). Four glasses (185, 223, 225, 433; blue circles) within the dashed elliptical region have been dated at 3730 ± 40 Ma in the current study using the laser, step-heating ^{40}Ar/^{39}Ar method. The glasses are compositionally similar to the following groups: HKFM (high-K Fra Mauro; Kempa et al. 1980; Naney et al. 1976), BA (basaltic-andesitic; Zeigler et al. 2004), and K3 (Glass 1976). The dashed line is an approximate boundary between mare-dominated compositions (left) and highlands-dominated compositions (right).

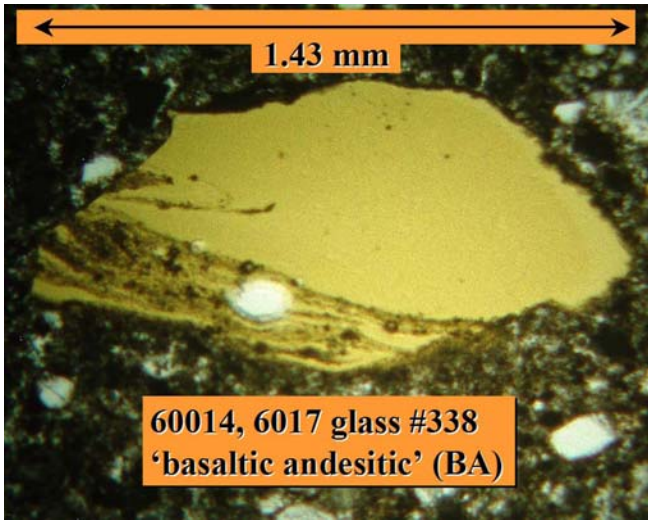

Fig. 4. Photomicrograph of a large fragment (1430 microns) of ropy lmHKFM glass analyzed (Table 2) in a polished thin section from the uppermost 3 cm of double drive tube, 60014. Ropy glasses are commonly thought to have formed during large impact events (e.g., Fruland et al. 1977; Meyer et al. 1971). The subrounded white portion near the lower edge of this glass fragment is a vesicle. The dark schlieren in the lower portion of this impact glass contain streams of microscopic vesicles and mineral inclusions.

materials (e.g., Koeberl 1997), impact melts (e.g., depending on the size of the melt domain; time spent at super-liquidus temperatures) can become open systems to losses of volatile elements (e.g., HASP glasses; Naney et al. 1976; Keller et al. 1991; Delano et al. 1981), such as Si, Na, and K. In addition, some transition elements, most notably Fe, can be reduced from FeO (moderately refractory) to metallic Fe (moderately volatile) during impact melting in the lunar environment. Without the use of refractory element ratios, this open system behavior would obscure the compositional nature of the original target materials that were melted to form the impact glass.

Two-element diagrams (Fig. 2a) have been used to show the relationships among impact glasses, Apollo 16 regoliths, and Apollo 16 rocks. Impact glass samples 185, 223, 225, and 433 have compositions that fall outside of the range of Apollo 16 regolith and rock compositions and are the topic of this study. Ternary diagrams involving three non-volatile lithophile elements (Figs. 2b and 3: Mg, Ti, Al) have also been used in this paper. Figure 2b shows the compositions of 1039 glasses from regoliths (64501; 66041), polished thin sections of drive tubes (e.g., 60014; 64001), and regolith breccias (e.g., 61295). Since the ternary diagram is a plot of the ratios of these conserved elements, fractional losses of volatile elements do not affect the location of a glass composition in the diagram. Coefficients of 3 and 25 have been applied to Mg and Ti, respectively, in the ternary diagram (Figs. 1, 2b, and 3) to compensate for the (generally) lower atomic abundances of these elements relative to Al. These weightings cause the data to be more widely distributed throughout the ternary diagram, thereby allowing compositional relationships to be more easily visible (instead of crowding in a small portion of the diagram in the absence of these coefficients). The analytical precision of the analyses shown in Figs. 2b and 3 can be assessed by referring to Fig. 1, which shows multiple analyses of 7 natural glass working standards (Table 1). The compositions of two heavily shocked, crystalline mare basalt clasts from 64001,6040 and 64001,6043 are also shown to chemically resemble some of the Apollo 16 impact glasses (Fig. 2b).

Low-Mg High-K Fra Mauro (lmHKFM) Glasses at Apollo 16

Compositional groups of glasses have been defined by earlier investigations of Apollo 16 glasses (Borchardt et al. 1986; Delano et al. 1981; Delano 1975, 1991; Glass 1976; Kempa and Papike 1980; Morris et al. 1986; Naney et al. 1976; Ridley et al. 1973; Ryder and Blair 1982; See et al. 1986; Zeigler et al. 2004). These average compositions are plotted on the ternary diagram (Fig. 3), along with the composition of the local Apollo 16 regolith. The impact

Table 2. Compositions (wt%), ^{40}Ar/^{39}Ar ages (Ma; $\pm 2\sigma$), cosmic ray exposure (CRE) age ranges (Ma), atomic coordinates in ternary diagrams, shape of glass (F = angular fragment), optical appearance through microscope in transmitted light (c = inclusion-free glass; t = translucent; r = ropy), and a measure of the ^{40}Ar/^{36}Ar ratio of trapped solar wind for Apollo 16 low-Mg HKFM (lmHKFM) glasses from the following regoliths: 64501,225; 66041,127; and 60014,6017. Sample #338 in polished thin section 60014,6017 is a large fragment of ropy, low-Mg HKFM glass (Fig. 4).

Sample no.	223 (G1)	225 (G3)	185 (A5)	433 (E5)	338
Group	lmHKFM	lmHKFM	lmHKFM	lmHKFM	lmHKFM
Regolith	64501	64501	64501	66041	60014
SiO_2 (wt%)	53.0	55.1	52.8	52.5	52.3
TiO_2	3.06	3.26	3.99	4.06	3.57
Al_2O_3	12.0	13.2	13.1	10.6	12.7
Cr_2O_3	0.09	0.12	0.12	0.09	0.12
FeO	15.0	12.1	13.0	14.9	13.4
MnO	0.19	0.18	0.18	0.19	0.16
MgO	2.37	3.71	4.62	2.93	4.82
CaO	8.75	9.53	9.31	9.15	9.06
Na_2O	1.08	0.55	0.46	1.12	1.00
K_2O	1.51	0.84	0.66	1.06	0.75
Total	97.1	98.6	98.2	96.6	97.9
Age (Ma)	3785 (10)	3739 (20)	3781 (18)	3721 (60)	
Percent ^{39}Ar in plateau	90.8	99.8	94.0	99.7	
CRE ages (Ma)	315–420	125–165	570–760	1050–1400	
25*Ti	70.1	65.6	67.5	74.9	64.8
Al	17.1	16.6	13.9	12.2	14.4
3*Mg	12.8	17.8	18.6	12.9	20.8
Shape	F	F	F	F	F
Appearance	t, r, yellow	c, yellow	t, r, yellow	c, yellow	r, yellow
Solar wind (^{40}Ar/^{36}Ar)	7.55	2.45	0.44	1.24	

glasses that are the topic of this paper (within dashed ellipse in Figs. 2b and 3) are compositionally most similar to the "basaltic-andesitic" glasses (BA: Figs. 2 and 3) of Zeigler et al. (2004), and broadly similar to the familiar suite of glasses known as high-K Fra Mauro (HKFM) (e.g., Ridley et al. 1973). We have inserted the prefix of low-Mg to the familiar lunar designation of HKFM in this paper to more accurately describe the distinctive compositions of these glasses. This low-Mg HKFM (lmHKFM) group of impact glasses accounts for ~2% of all Apollo 16 glasses analyzed in the current study. This variety of KREEP glasses is distinctive by its high Si, high K, moderate Fe, moderate Al, and especially low Mg (Table 2). We have searched the published literature for glasses from other Apollo or Luna landing sites having this composition, but have so far not found a match.

Figure 4, which shows a 1.43 mm piece of lmHKFM glass in a polished thin section of double drive tube 60014, demonstrates that this compositional group is ropy glass. Other compositions of glasses with ropy textures have been identified and analyzed at other Apollo sites (e.g., Apollo 15 yellow impact glasses: 15010,3189: Delano et al. 1982; Taylor et al. 1980; Spangler and Delano 1984; 3350 ± 50 Ma; Apollo 12 ropy KREEP glasses: 12033: Barra et al. 2004; Meyer et al. 1971; Alexander et al. 1976, 1977; Silver 1971; Eberhardt et al. 1973; 800 ± 40 Ma; Apollo 15 moderate-Ti impact glass: 15434,28: Ryder et al. 1996; 1647 ± 11 Ma; and Apollo 17 ropy glass: Fruland et al. 1977). Although these specific examples of ropy lunar glass are all compositionally distinct from each other, they share an important characteristic of being compositionally exotic to landing sites where they are found. Consequently ropy glasses have commonly been interpreted as having been formed by large cratering events (e.g., Apollo 12 ropy KREEP glasses by the Copernicus cratering event; Eberhardt et al. 1973; Meyer et al. 1971; McKay et al. 1971) that ballistically transported them long distances (e.g., ~2400 km, if Apollo 17 ropy glasses came from the Tycho event [Fruland et al. 1977]; but see also Korotev and Kremser [1992]).

Four pieces of the Apollo 16 lmHKFM glasses (Table 2) were handpicked from regoliths 64501 and 66041, chemically analyzed, and selected for isotopic dating by the laser, step-heating ^{40}Ar/^{39}Ar method in this study (Fig. 5). Two of the glasses are inclusion-free glasses (Fig. 5: #225 and #433), while the other two pieces are ropy, inclusion-bearing glasses (Fig. 5: #223 and #185). The inclusion-free glasses (#225 and #433) yielded ^{40}Ar/^{39}Ar ages ($\pm 2\sigma$) of 3739 ± 20 Ma and 3721 ± 60 Ma, while the inclusion-bearing ropy glasses (#223 and #185) yielded greater ages of 3785 ± 10 Ma and 3781 ± 18 Ma (Figs. 6 and 7). Ages reported here were determined after correcting for solar wind contributions and by including as many steps as possible

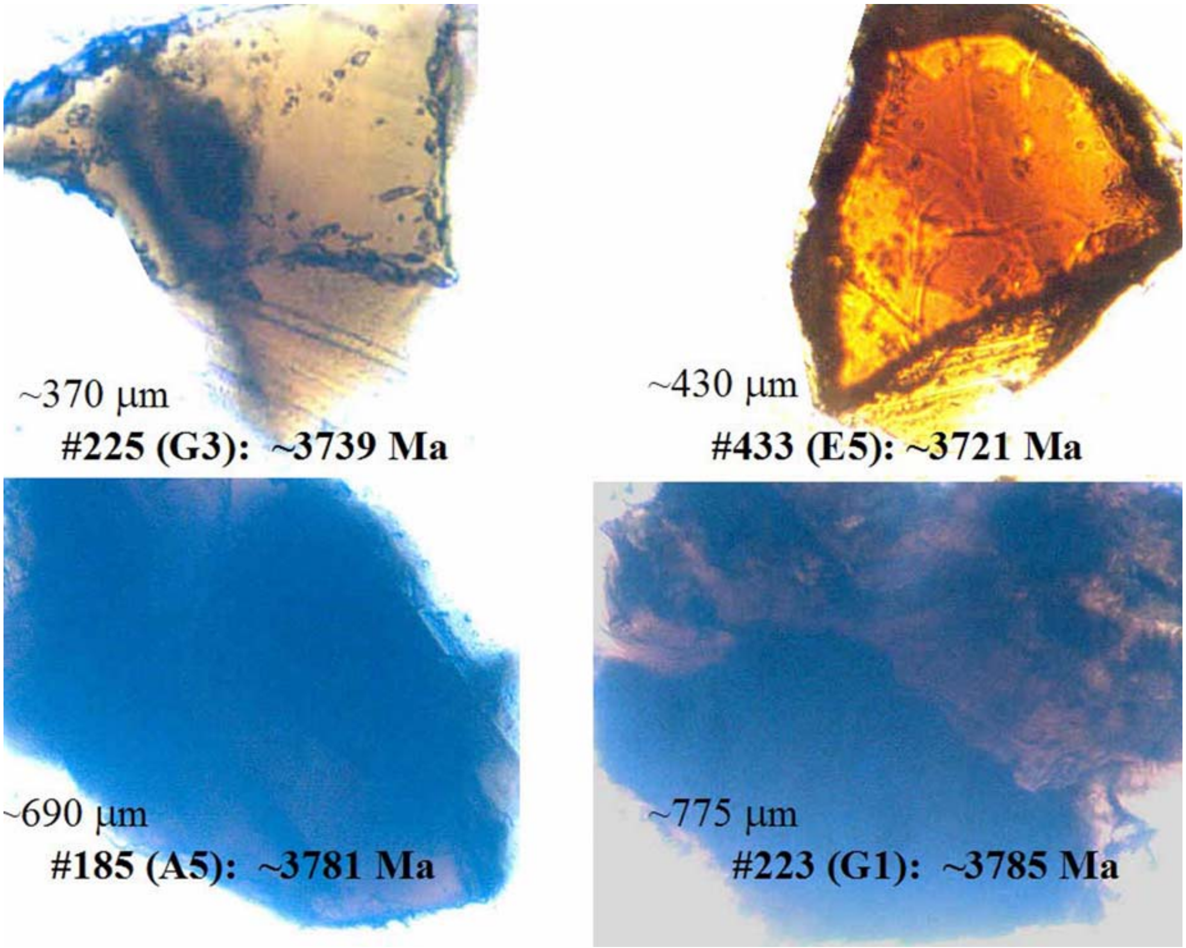

Fig. 5. Photomicrographs (transmitted light) of the four fragments of lmHKFM glasses that were chemically and isotopically analyzed in this study (Table 2). These fragments are shown mounted in Crystalbond adhesive (Aremco Corp.) with the upper surface having been ground and polished in preparation for electron microprobe analysis prior to isotopic dating. The varying shades of orange/yellow on the surface of sample #433(E5) are due to a discontinuous carbon coating subsequent to electron microprobing. All samples were cleaned to remove carbon coating and Crystalbond prior to their being neutron irradiated and isotopically dated. Samples #225(G3) and #433(E5) are inclusion-free glasses, whereas samples #185(A5) and #223(G1) are inclusion-bearing glasses (i.e., ropy). The maximum dimension of each fragment is shown.

within reasonable uncertainties, as seen in Fig. 6. Minimum cosmic-ray exposure (CRE) ages were determined by taking the samples' Ca contents and assuming the maximum production rate of ^{38}Ar from Ca (Hohenberg et al. 1979); all CRE ages are less than the impact ages of the samples. The observed values of reimplanted ^{40}Ar to solar wind ^{36}Ar are >1, which is consistent with old ages for these impact glasses (Table 2).

Fragments versus Spherules

The chemical compositions of glass fragments and glass spherules have been compared (Fig. 8). Though the compositional range of fragments and spherules at Apollo 16 are similar, the proportion of local versus exotic compositions varies significantly. While ~40% of glass fragments have compositions that are exotic to the Apollo 16 region, only ~10% of glass spherules have exotic compositions. Glass fragments are more frequently the product of distant impact events than glass spherules.

The number of glasses plotted in Fig. 8 (961 glasses) is less than 1039 (Fig. 2b) due to incomplete records having been kept, most notably by Delano (1975) and Delano et al. (1981), concerning the shape of the individual glasses analyzed.

DISCUSSION

Integrated Approach

We have argued in this paper that compositional (Table 2) and petrographic (Figs. 4 and 5) information on glasses selected for ^{40}Ar/^{39}Ar dating is necessary for providing more substantive interpretations. This is not a novel concept, since lunar scientists have long recognized that this integrated approach is necessary for interpreting data from crystalline

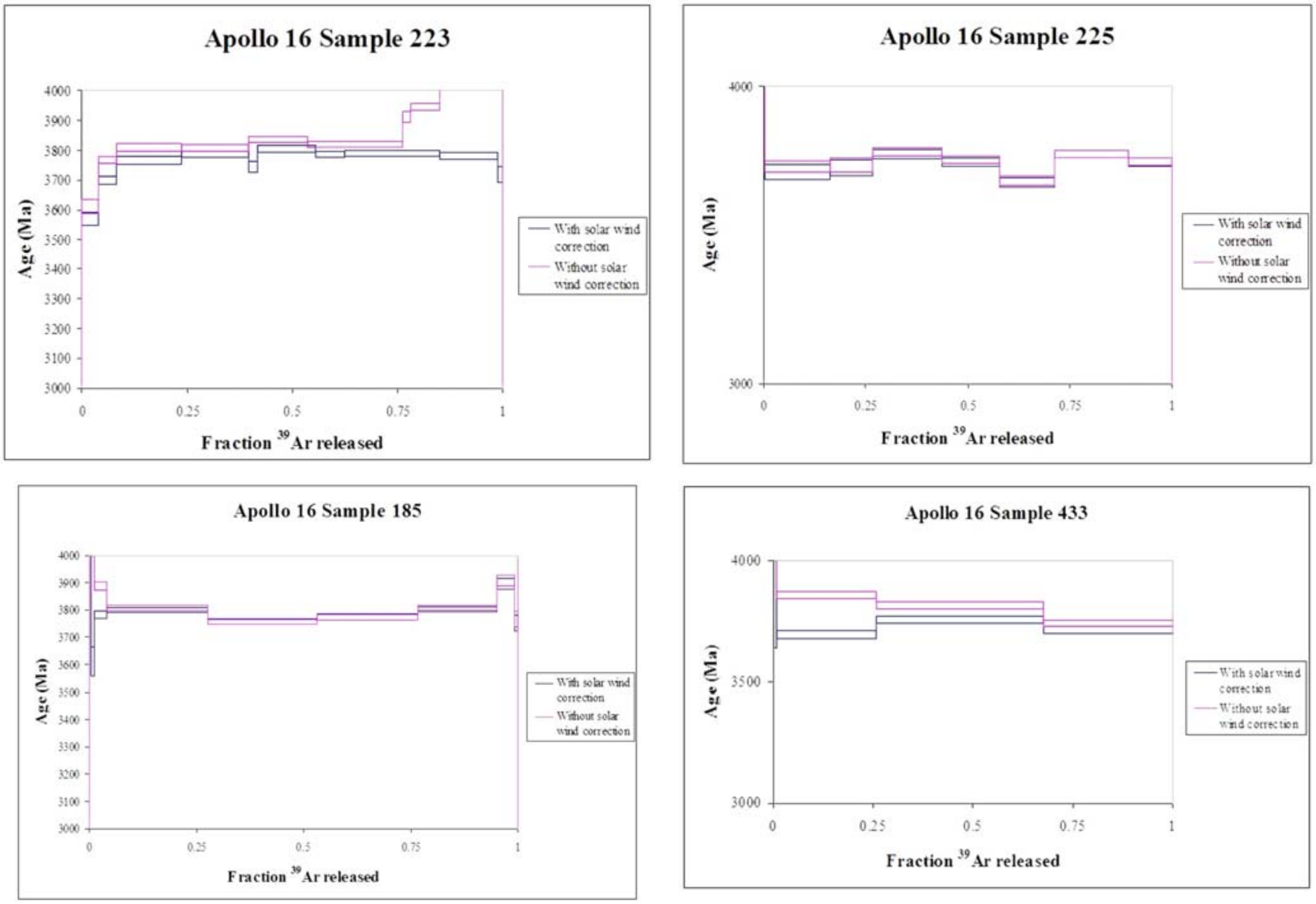

Fig. 6. Laser step-heating of the impact glasses yielded these release patterns from which impact ages could be determined. Table 2 lists the percentage of total ^{39}Ar comprising each 3-isotope plot. Cosmic-ray exposure ages are less than the impact ages of the samples, and the observed values of reimplanted ^{40}Ar to solar wind ^{36}Ar are >1, which is consistent with old ages for these impact glasses. Pink lines represent the uncorrected apparent ages for each impact glass.

rocks. The challenge in this and future studies is acquiring this information for samples that are commonly in the size range of 100–300 microns. In addition, it is also important to have a thorough knowledge of the compositional topology of glasses at a given site (Figs. 2a and 2b) for interpreting the isotopically dated glasses in that context.

Chemical analysis of lunar glasses is essential for distinguishing between volcanic glasses (e.g., Delano 1986) and impact glasses. Without this latter discrimination, volcanic ages contaminate histograms of ages (Apollo 14: Culler et al. 2000), which add “noise” to histograms purporting to describe the impact flux during the known interval of mare volcanism at ~3200–3800 Ma. This is a problem for studies that claim to report ages of impact-produced glass spheres (e.g., Culler et al. 2000) since volcanic glasses are typically spheres and can comprise a substantial fraction (e.g., 8–47%) of the total population of glasses in regoliths and regolith breccias (e.g., Apollo 14: Delano 1988). It is tempting to speculate that the six prominent peaks in the age-histogram of Culler et al. (2000) within the 3200–3800 Ma interval correspond to the eruption ages of the six compositional groups of volcanic glasses that have been documented at the Apollo 14 site (Delano 1988). The possibility that volcanic ages compose a significant fraction of the “impact” histogram from Culler et al. (2000) at the Apollo 14 site underscores the importance of determining the chemical compositions of all glasses to ensure that only impact glasses are selected for isotopic dating.

In this current investigation of Apollo 16 lmHKFM glasses, the chemical, petrographic, and isotopic data indicate that these impact glasses were produced by one large cratering event at a distant location (Zellner et al. 2005). If only isotopic ages (i.e., no compositional information) had been available for these glasses, these data could have been interpreted as representing four distinct impact events somewhere on the Moon, superficially inflating the impact flux at this time. Additionally, there would be no information as to whether those events were small local events or large distant events. Therefore, the breadth of information associated with our integrated approach (i.e., petrography, chemical composition, isotopic age) provides better constraints on the impact history of the Moon.

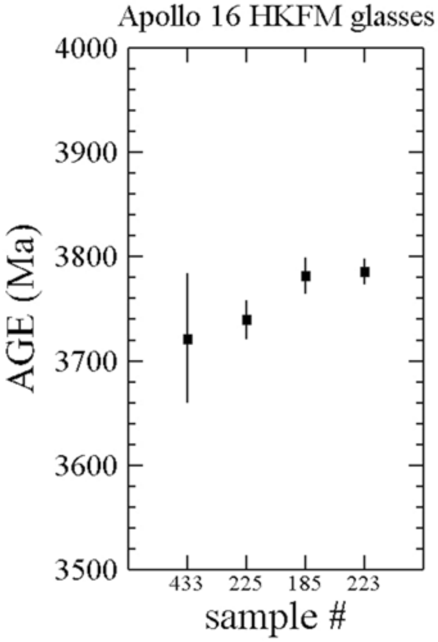

Fig. 7. $^{40}Ar/^{39}Ar$ ages ($\pm 2\sigma$) of the four Apollo 16 lmHKFM glasses analyzed in this study. The chemical compositions of these glasses are listed in Table 2. Note that the inclusion-free lmHKFM glasses (#433 and #225; Fig. 5) have lower apparent $^{40}Ar/^{39}Ar$ ages than the inclusion-bearing ropy lmHKFM glasses (#185 and #223; Fig. 5).

Fragments versus Spherules

This investigation has found that a higher proportion of glass fragments have exotic compositions (distant sources) than do glass spherules (Fig. 8). If the compositionally exotic glass fragments were ballistically transported long distances at suborbital speeds (≤1 km/s) by large impact events that produced them, the original glasses in the form of spherical melt blobs may have been a centimeter or greater in size that shattered into smaller fragments upon landing. In contrast, locally produced glasses may have been formed by smaller cratering events that generated smaller quantities of impact melt droplets that landed on the nearby surface at modest speeds without shattering.

Age of the Apollo 16 Low-Mg HKFM Cratering Event

While the $^{40}Ar/^{39}Ar$ ages of all four lmHKFM glasses are ~3750 Ma, the inclusion-free glasses (#433 and #225: Fig. 5) are interpreted as being more reliable than the inclusion-bearing glasses due to the lower likelihood of them having retained older, radiogenic ^{40}Ar following the fusion event. Consequently, while the weighted mean age is 3775 ± 4 Ma, the preferred age of the impact event that generated the Apollo 16 lmHKFM glasses, and possibly transported them to the Apollo 16 site, is 3730 ± 40 Ma (Fig. 7).

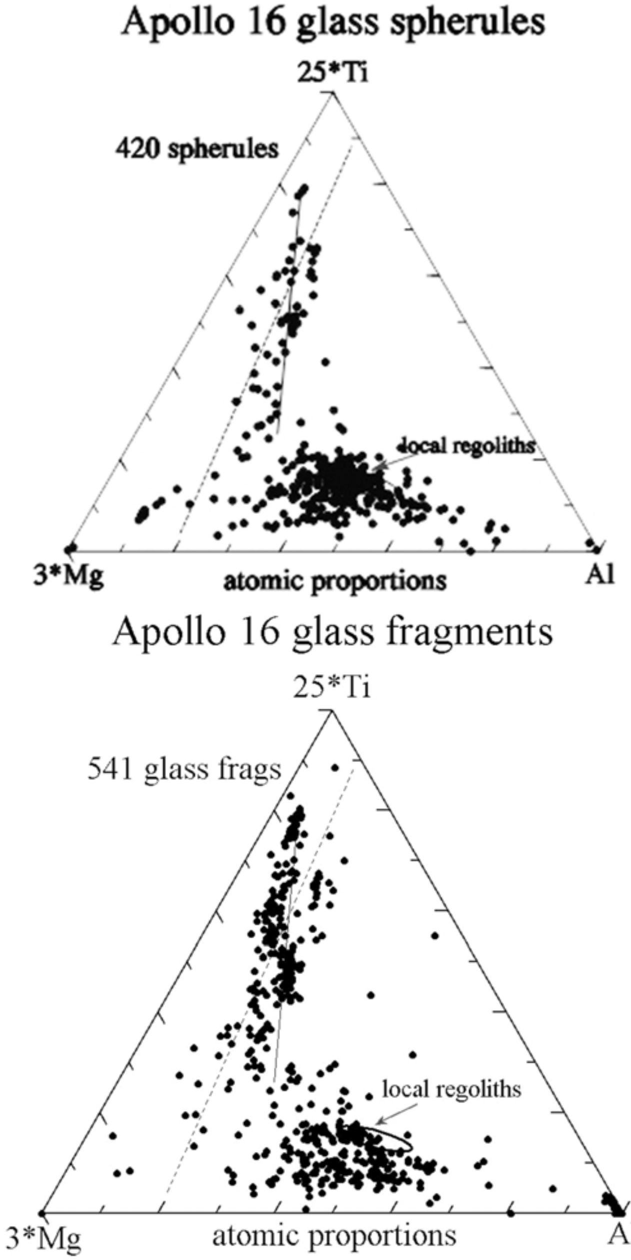

Fig. 8. The proportion of locally derived compositions versus exotically derived compositions varies between glass spherules and glass fragments. As shown by these two figures, ~40% of glass fragments have exotic compositions (i.e., not locally derived) compared to ~10% of glass spherules. The total number of glasses shown in these two figures (961) differs from the total number of glasses analyzed in this study (1039) (Fig. 2b) due to incomplete recording of glass morphologies during the analyses.

This age is tantalizingly close to the accepted age for the Imbrium basin, 3.84–3.85 Ga (Dalrymple and Ryder 1993) and even closer to the age of 3.77 Ga argued by Stöffler and Ryder (2001). It is also on the tail end of the purported terminal lunar cataclysm (late heavy bombardment) (Tera et al. 1974). However, without a large set of well-characterized samples, we are hesitant to support this hypothesis one way or another. Additionally, it is unclear as to how inclusions in the samples and Ar diffusion in the regolith may be influencing the reported ages for our samples and possibly other samples (Swindle et al. 2005).

Provenance

Constraining the source-crater with an age of ~3730 ± 40 Ma, from which the Apollo 16 lmHKFM glasses were derived, is a challenging task. For example, although a) the Apollo 12 mission landed on a bright ray from the crater Copernicus, and b) light-colored KREEP glasses were found concentrated on the surface by the Apollo 12 astronauts, questions still remain as to whether the ~800 Ma KREEP glasses were derived from the Copernicus event (e.g., Alexander et al. 1977; Barra et al. 2004; Eberhardt et al. 1973). Since there is no obvious ray system at the Apollo 16 site that might be argued to be associated with the ~3730 Ma HKFM glasses, their provenance is more tenuous than that of the Apollo 12 KREEP glasses. Our approach for identifying potential source craters of the Apollo 16 lmHKFM glasses relies on orbital geochemistry from the Lunar Prospector and Clementine missions in combination with glass compositions (e.g., Zellner et al. 2002, 2003). No candidate craters have yet been identified that satisfy the both age and compositional constraints.

CONCLUSIONS

The compositional range of glasses that occur at the Apollo 16 landing site has been determined through the analysis of more than one thousand samples. Ratios of nonvolatile lithophile elements that retain a chemical memory of the original target materials that were melted to form impact glasses were determined. Within this context, four KREEP-rich glasses belonging to one compositional suite (lmHKFM) have been dated by the ^{40}Ar/^{39}Ar method at 3730 ± 40 Ma. These glasses are compositionally exotic to the Apollo 16 region, and were likely produced by one large and distant impact event (and not 4 individual impact events). This study illustrates the value of interpreting the ages of impact glasses in the context of their chemical compositions and petrography in order to better assess the impact flux in the Earth-Moon system.

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