COMPOSITIONS AND AGES OF APOLLO 15 LUNAR IMPACT AND VOLCANIC GLASSES: NEXT RESULTS

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Introduction: Several recent studies have begun to investigate the relationships between ages and compositions of lunar impact glasses, droplets of melt formed in impact events on the Moon, and glasses of volcanic origin. Of enduring interest are questions related to the impact history in the Earth-Moon system [1, 2, 3, 4, 5, 6] and the duration of volcanism on the Moon. Here we discuss the results of our compositional studies of impact and volcanic glasses from the Apollo 15 regolith sample 15221,21 [7]. We additionally present the first $^{40}Ar/^{39}Ar$ ages of Apollo 15 impact glasses, as well as more precise $^{40}Ar/^{39}Ar$ ages of Apollo 15 green and brown/yellow-brown volcanic glasses.

The Apollo 15 Landing Site: On the eastern rim of the Imbrium Basin, the Apollo 15 landing site was selected so that the Apennine Front, most likely formed by ejecta from the Imbrium impact, could be examined. A nearby feature, Hadley Rille, was probably formed by volcanic processes, and so samples from this area could additionally shed light on epochs of lunar volcanic activity.

Previous studies of the Apollo 15 volcanic glasses have revealed over 20 discrete compositional groups, with Mg-numbers ranging from 60 to 67 wt% [8, 9, 10, 11]. Compositional variations within and between these groups have been ascribed to variable melting of distinct source regions, followed in some cases by mixing of chemically distinct magmas prior to eruption [8, 11, 12].

Impact glasses from around the area of the Apollo 15 landing site generally reflect the major- and trace-element composition of the local regolith, though a few glasses with exotic (i.e., not local) compositions have been found [7]. Although 15221,21 was collected at Station 2 on the Apennine Bench and so would be expected to have impact glass dominated by a highlands or KREEPy composition, only 16.5% (19/115) of the glasses analysed thus far have this type of composition [7].

Sample Analyses: Major- and trace- element analyses on 115 impact and volcanic glasses from Apollo 15 regolith 15221,21 were undertaken at the Australian National University in Fall 2011 [as described in 7]; another 21 have since been analyzed for major elements, with trace-element analyses in progress. Impact glasses were distinguished from volcanic (i.e., "pristine" or "picritic") glasses according to their CaO/TiO_2, MgO/Al_2O_3 and CaO/Al_2O_3 compositions [after 13, 14 and references therein]. Based on major- and trace- element analyses, 28% (32/115) of the glasses were of impact origin [7].

Twenty-one glasses, both volcanic and impact, were subsequently irradiated for 40 hours and analyzed in order to determine their $^{40}Ar/^{39}Ar$ formation ages. Ages were calculated relative to the Hb3gr hornblende standard (1081 ± 1 Ma) and using the ^{40}K decay constants of Renne *et al.* [2011]. Laser step-heating on these samples was carried out in Fall 2012 at the Western Australia Argon Isotope Facility at Curtin University.

Discussion: The dated impact glasses had K_2O ranging from 0.01 to 0.45 wt%, and ages ranging from very young (~100 Ma or less) to very old (~3700 Ma). All of the young glasses are spherical and possess a "local" composition. Thus, these glasses most likely represent the background flux of relatively small bodies rather than large events capable of transporting ejecta great distances [6, 15]. Within uncertainty, the oldest age is consistent with the age of four impact glasses from the Apollo 16 landing site [2]. The FeO and Al_2O_3 compositions of this glass are somewhat dissimilar (i.e., "exotic") to those of the local Apollo 15 regolith [16] and it may reflect a large and distant impact event.

Although the crystallization ages of mare basalts have been well-established, uncertainty remains in the eruption ages of the volcanic glasses. Here we present new $^{40}Ar/^{39}Ar$ ages obtained on volcanic glasses. Dominated by solar wind (i.e., high $^{40}Ar/^{36}Ar$ values) and having low K_20 concentration, the ultramafic green glasses were difficult to date, but two $^{40}Ar/^{39}Ar$ plateau ages ranging from from 2835 ± 254 to 3285 ± 89 Ma are consistent with previous values [e.g., 17]. The low-Ti brown glasses [18] yielded more precise data with four plateau ages ranging from 3516 ± 77 to 3612 ± 104 Ma. Considering that these ages reflect a single eruption as suggested by their composition and by the concordance between ages (MWSD = 1.6; P = 0.19), we can calculate a weighted mean eruption age of 3586 ± 19 Ma for the low-Ti glass eruptions. Our new age provides a concise age for the brown glasses compared to previous measurements [ca. 3.62 Ga, no uncertainty quoted, as reported by 17].

Chemical ages of the Apollo 15 impact glasses derived from U-Th-Pb concentrations have been reported [19], and these derived ages provide a reasonable estimate of relative age (i.e., young or old). However, they are not always consistent with ^{40}Ar/^{39}Ar plateau ages, except at the few hundred Ma level (Table 1). The agreement between the ages is encouraging, though, considering the uncertainties on both techniques.

Conclusion: While some impact glasses from 15221,21 possess an "exotic" composition, most of the impact glasses from 15221,21 reflect a local provenance in that their compositions are very similar to the compositional range of the local regoliths [7, 16]. Since several of these impact glasses are also spherical and young, they likely resulted from a background flux of relatively small impact events rather than events capable of transporting material over large distances. On the other hand, the few exotic glasses dated in the present study provide some important age constraints for the larger, less frequent impacts that transported these glasses over long distance. One such glass has an age of 3743 ± 42 Ma.

Ages that have been inferred from the U-Th-Pb concentrations [19] agree with ^{40}Ar/^{39}Ar ages, if those ages are interpreted to be correct, at the level of a few hundred Ma. These U-Th-Pb analyses do provide a quick assessment of approximate ages for large numbers of particles. Such an approach can be used as a guide to determine which glasses may yield young, middle, or old ^{40}Ar/^{39}Ar ages in order to optimize the sample selection for ^{40}Ar/^{39}Ar dating.

If the elemental and age data from these glasses are interpreted in the context of impact glass data from other lunar landing sites, we should be able to more accurately estimate the global impact flux in the Earth-Moon system.

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Table 1. Comparison between model U-Th-Pb ages and measured ^{40}Ar/^{39}Ar ages. ND = not determined.

Sample	TiO_2 (wt%)	U-Th-Pb Age (Ma)	^{40}Ar/^{39}Ar Age (Ma)
Volcanic			
N12	3.75	3840 ± 115	3516 ± 77
N16	3.68	3880 ± 116	3586 ± 21
N32	3.71	ND	3623 ± 67
N39	3.62	3910 ± 117	3613 ± 104
N45	0.43	3800 ± 114	ND
N47	0.40	ND	ND
N20	0.43	3700 ± 111	2835 ± 254
N02	0.45	3700 ± 111	3285 ± 89
N46	0.52	4300 ± 129	ND
Impact			
N22	1.24	220 ± 22	147 ± 20
N18	1.51	3990 ± 120	3743 ± 42
N08	1.04	580 ± 58	168 ± 9
N52	1.26	1030 ± 103	77 ± 223
N09	1.46	90 ± 9	Young
N13	1.37	1280 ± 128	1174 ± 34
N01	1.98	40 ± 4	ND
N21	1.85	180 ± 18	197 ± 73
N26	1.82	150 ± 15	Young
N23	1.88	200 ± 20	494 ± 28
N31	1.76	200 ± 20	549 ± 128
N59	3.05	300 ± 30	ND