Identifying impact events within the lunar cataclysm from ^{40}Ar-^{39}Ar ages of Apollo 16 impact melt rocks.

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Introduction: The Apollo 16 samples from the lunar highlands include numerous fragments of impact-produced melt rocks, both as discrete fragments and as clasts in breccias. They have a wide range of compositions [1] and petrographic characteristics [2], and are fundamental in understanding the geological history of the Apollo 16 landing site and the impact history of the Moon [3,4]. Most of the Apollo 16 crystalline melt rocks for which geochronological data exist have ages between 3.80 and 3.92 Ga; a few older ages have been claimed (e.g., [5]). One group of aluminous melt rocks, including samples 68415 and 68416 chipped from a homogenous boulder, are clearly younger at close to 3.75 Ga than most other samples (review in [6]). Some glassy melts are rather younger still, reflecting continuing small-scale bombardment of the Moon following heavy bombardment [7].

Most of the chronological data on Apollo 16 impact melts are derived from ^{40}Ar-^{39}Ar determinations made during the first decade of Apollo sample studies. Rb-Sr and Sm-Nd data are sparse, mainly because it is virtually impossible to separate phases from these finely crystalline rocks. The early Ar radiometric ages are based on step-heating experiments with only a few temperature release steps. These studies have not allowed any clear determination of whether different chemical groups have distinct ages. The problem is worsened by the large samples used in these studies, in that significant undegassed clasts are included in the analyzed material, by the large uncertainties (generally ±0.04 or 0.05 Ga) reported, and in some cases by the lack of definitive petrographic and chemical description of the dated samples. One reason this event discrimination is important is that it has been claimed that the Apollo and Luna landing sites, being confined to the frontside equatorial region, may be biased by being the product of a single basin or a small number of basins, and thus they provide no proof of a late “cataclysmic” bombardment of the Moon (e.g. [8]). However, if the Apollo 16 samples are the product of numerous separate and distinct events, then this argument is not valid.

We have improved the chronological data base for Apollo 16 melt rocks by obtaining high-resolution (20-50 steps) ^{40}Ar-^{39}Ar age spectra on 25 samples using a continuous laser heating system on sub-milligram fragments. The tiny size of the samples helps avoid larger clasts, and the large number of steps allows better determination of the structure of the gas release. Both these potentially lead to improved precision and clearer interpretation of the measured ages. The analytical procedures are similar to those reported before for Apollo 15 and Apollo 17 impact melt samples [9,10].

Sample Section: The 25 samples were chosen to represent all chemical groups and subgroups, and the “unclassified” samples, defined in the extensive work on Apollo 16 melt samples [1], with multiple samples in several groups. All are previously characterized in petrography [2] and were selected to be clast-poor. They range from vitrophyric through intersertal and ophitic-subophitic to poikilitic. They are from all across the landing site except the very rim of North Ray crater. They include several samples that have been previously dated, for comparison. Most of our samples were discrete rock and rake samples; none were fines particles.

Methods: We obtained ~110mg splits as interior chips from each rock. Using the neutron activation preparation clean room at JSC, we inspected each chip under binocular microscope to check for homogeneity, lack of obvious large clasts, and freshness of surface. Each chip was then gently crushed, and a few clast-free (as observable) homogenous sub-milligram particles were reserved for the age determinations. The remainder of the sample was ground into a fine powder. Between 40 and 70 milligrams were used for chemical analysis using neutron activation methods. About 10 milligrams were used to make a fused bead for major element analysis using the electron microprobe. The chemical analyses were to ensure that our samples indeed were what we supposed them to be, as well as for further interpretations of the homogeneity and origin of these melt rocks. The new radiometric ages were determined at Oregon State University using a Merchantek 10W CO_2 continuous laser system with integrated IR temperature measurement, a Mass Analyzer Products 215 mass spectrometer, and methods similar to those in previous studies [9, 10]. Samples were irradiated for 300 hours in the OSU TRIGA reactor (OSTR) using hornblende Mmhb-1 (513.9 Ma) as the monitor. Errors are reported at the 2σ level.

Results: A summary of the results of 29 experiments (25 samples, 4 repeats) are reported in Table 1. All are affected to some extent by post-crystallization reheating (later impacts). However, 22 of these produced precise, multi-step plateaus in age spectra that we interpret as crystallization ages, of which 20 fall in the range 3.75 to 3.90 Ga. From coherent ages, compositions and textures we identify at least 3, and possibly 4 or 5 different impact events. Six poikilitic Group 1 samples present a mean age of 3865 Ma; there is no difference in age between mafic (1M) and felsic (1F) variants. We conclude that these rocks are products of the same impact event. Samples 61156 and 61569 also have poikilitic textures but more aluminous bulk compositions, and they appear to be distinctly younger (3749 to 3793 Ma). A plagioclase-subophitic group (63537, 63549, 63545, 64817) with coherent ages (mean = 3839 Ma) are significantly younger than the Group 1 samples. Troctolitic samples 62295 and 64576 (2Mo) may represent a separate event of about the same age as the impact that produced the poikilitic Group 1 rocks.

Dimict breccias (64568, 61015, 64585) produced a rather large age range despite having clear compositional and textural affinities, which we ascribe to incomplete degassing, similar to [11]. Rather older ages (>4.0 Ga) appear from Group 4 rocks, which could reflect incompletely degassed anorthositic clasts from the North Ray crater area. This conclusion is tentative, as sample 63506 did not produce a reliable plateau in two attempts, while sample 63525 produced good plateaus but different ages. We will be analyzing more material from this area soon.

Table 1. Summary of ^{40}Ar-^{39}Ar incremental heating ages from Apollo 16 impact melt rocks (including results from [12]).

Sample	Subgroup [1]	Plateau description	Plateau 39Ar % of total	Plateau 39Ar steps	Plateau Age Ma ± 2s
60315	1M	good	42	9 of 34	3868±31
69945	1M	excellent	68	27 of 47	3877±11
64816	1M	good	50	11 of 30	3852±12
63596	1Fv	excellent	67	19 of 30	3860±13
65015	1F	excellent	71	16 of 28	3854±14
62235	1F	good	49	26 of 50	3876±32
61225	2M	fair	36	10 of 32	3885±36
61225rpt	2M	good	48	13 of 22	3907±15
63545	2M	fair	33	5 of 20	3839±23
60666	2Mo	none	0	0 of 26	>3820
64576	2Mo	excellent	64	14 of 25	3852±10
62295	2Mo	good	58	10 of 22	3866±12
61015	2DB	fair	25	7 of 29	3899±36
64568	2DB	excellent	65	18 of 37	3867±9
66095	2DB	fair	19	5 of 25	3676±16
64585	2DB	good	46	8 of 23	3962±15
61156	2F	good	42	7 of 28	3749±36
68519	2F	none	0	0 of 31	>3931
65785	2NR	poor	16	3 of 22	3826±20
63537	3n	excellent	56	8 of 23	3838±12
63549	3n	excellent	67	15 of 34	3840±11
63549rpt	3n	none	0	0 of 24	>3817
63506	4s	poor	8	4 of 30	>4043
63506rpt	4s	none	0	0 of 23	>4000
63525	4m-i	excellent	95	24 of 28	4190±24
63525rpt	4m-i	good	63	11 of 24	3895±36
64815	unclass.	excellent	84	24 of 39	3886±9
61569	unclass.	excellent	58	16 of 25	3793±13
64817	unclass.	excellent	76	8 of 18	3835±18

Summary: The recognition of correlated ages and compositions within the Apollo 16 impact melt rocks supports the conclusion that numerous impact events occurred on the lunar surface within a relatively narrow time interval, providing additional evidence of a heavy bombardment of the Moon (cataclysm), and presumably the Earth, during the period 3.75 to 3.90 Ga.

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